IAEA-TECDOC-913

Manual for troubleshooting and upgrading of neutron generators

INTERNATIONAL ATOMIC ENERGY AGENCY

The IAEA does not normally maintain stocks of reports in this series. However, microfiche copies of these reports can be obtained from

INIS Clearinghouse
International Atomic Energy Agency
Wagramerstrasse 5
P.O. Box 100
A-1400 Vienna, Austria

Orders should be accompanied by prepayment of Austrian Schillings 100,— in the form of a cheque or in the form of IAEA microfiche service coupons which may be ordered separately from the INIS Clearinghouse.

The originating Section of this publication in the IAEA was

Physics Section
International Atomic Energy Agency
Wagramerstrasse 5
P O Box 100
A-1400 Vienna, Austria

MANUAL FOR TROUBLESHOOTING AND UPGRADING OF NEUTRON GENERATORS
IAEA, VIENNA, 1996
IAEA-TECDOC-913
ISSN 1011-4289

Printed by the IAEA in Austria
November 1996

FOREWORD

During the past 20-25 years the IAEA has provided many new laboratories in the developing world with simple low voltage accelerators for the production of neutrons via the well known $^{2}H(d,n)^{3}He$ and $^{3}H(d,n)^{4}He$ reactions. (These neutron generators were originally supplied mainly for purposes of neutron activation analysis). However, the operation of these machines can often be halted or compromised by a lack of special or short lifetime components. Serious problems can also arise when the original well-trained technical staff leave the laboratories and when the new operators have less experience in accelerator technology.

This manual is intended to assist operators in troubleshooting and upgrading of neutron generators. It is directed particularly to operators and technicians in less experienced laboratories and therefore the descriptions of the principles and techniques of these machines are operator oriented. In addition to a discussion of the main characteristics of neutron generators, detailed information is given on the function of particular commercial units, on common problems related to specific components of accelerators, and on methods of troubleshooting and repair. Detailed schematic and circuit diagrams are provided to help operators in the development and improvement of the generators.

The problems treated in the Manual have been collected during several IAEA missions in developing countries.

The IAEA is grateful to T. Sztaricskai, who performed the major part of the drafting of the manuscript, and also to J. Csikai and S. Szegedi for their contribution to the drafting. The IAEA officer responsible for this publication was R.L. Walsh, Physics Section, Division of Physical and Chemical Sciences.

CONTENTS

1. INTRODUCTION

Neutron generators are small accelerators consisting of vacuum, magnetic, electrical and mechanical components, radiation sources, cooling circuits and pneumatic transfer systems. There are various types of ion sources, beam accelerating and transport systems, targets, high voltage and other power supplies, neutron and tritium monitors and shielding arrangements.

The operation, maintenance and troubleshooting of a neutron generator require well trained technicians who can successfully undertake not only preventive maintenance of the machine but also its upgrading.

Troubleshooting and the locating of faults in components can be just as difficult as their prevention. Thoughtless component exchange in an accelerator may cause additional problems: the correct choice of component for a given function in the machine requires complete understanding of the operation of the generator as well as the role of the component in the machine.

In troubleshooting for neutron generators, as with other sophisticated equipment, it may be that the cause of malfunction stems from a single fault and that an investigation of the whole system is both time consuming and unnecessary. However, an electrical failure in the high voltage power supply or a discharge in the accelerating tube could be caused by trouble in the high vacuum system. An experienced troubleshooter can avoid unnecessary investigation of a number of subunits.

This Manual has been prepared not only for operators but also for those who are dealing experimentally with the upgrading of neutron generator laboratories. Principles of operation and output characteristics of neutron generators can be found in Refs [1-3]. This Manual is restricted to practical information required by the operator and service personnel. The functions of the subunits are described and proposals for troubleshooting in case of malfunction of a component are outlined. The Manual contains descriptions of some symptoms and proposals for their repair. The proposed repair and maintenance methods have been chosen bearing in mind that some laboratories may have poor infrastructure.

The Manual contains a short description of the commercially available neutron generators, including the sealed tube and intense models. The description of the operation of a specific component is usually followed by a general guide to troubleshooting and repair. As this is **NOT A SERVICE MANUAL**, the guidelines for troubleshooting and maintenance are not given for all types of neutron generator, although the information herein can be used for any type of low voltage accelerator. The detailed description of some methods, such as pulsing or the associated particle technique, is intended to help in improving and widening the applications of the original machine. The list of manufacturers and other sources of components in Annex A is intended to assist laboratories in developing countries to find suppliers for spare parts or improved components. The short review of the hazards related to accelerators is particularly directed towards operators who have less experience in these matters and should be read with care by them. The detailed schematic and workshop drawings should be useful in upgrading neutron generators and accelerators as well in setting up new experiments.

2. PRINCIPLES OF OPERATION

The low voltage (a few 100 kV) neutron generators produce neutrons by the following reactions:

$^2H(d,n)^3He$	Q= 3.268 MeV	(1)
$^3H(d,n)^4He$	Q=17.588 MeV	(2)

The large cross section of the $^3H(d,n)^4He$ reaction permits high yields of fast neutrons to be obtained even at low deuteron energy (150-200 keV). The 0° differential cross sections of reactions (1) and (2) are 2.6 mb/sr and 400 mb/sr, respectively. The total cross section of the $^3H(d,n)^4He$ reaction has a broad resonance with a maximum value of 5 barns at E_d = 107 keV. At this deuteron energy the total cross section of the $^2H(d,n)^3He$ reaction is about 20 mb; therefore, the contribution of the D-D background neutrons to those emitted in the D-T reaction can be neglected. As the D-T cross section has a peak at around 107 keV, and the tritium targets are thick metal titrides, the neutron yield shows an increasing trend up to about 400 keV bombarding energy (see Fig.1). The D-D reaction is used for neutron production mainly by electrostatic accelerators or cyclotrons, where the neutron energy is changed by changing the deuteron

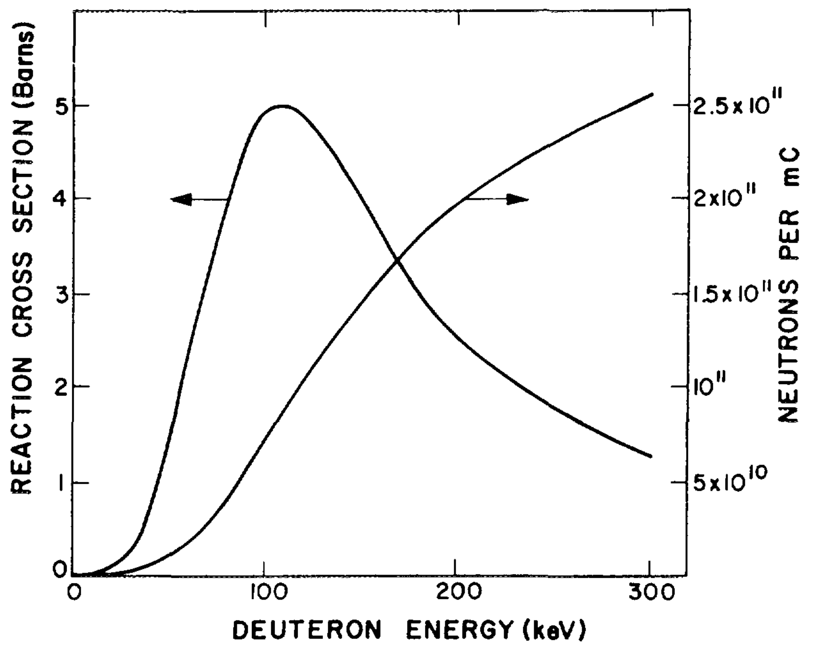


Fig.1 *Neutron production cross section and the total yield of neutrons for a $Ti_1T_{1.6}$ thick target vs deuteron energy*

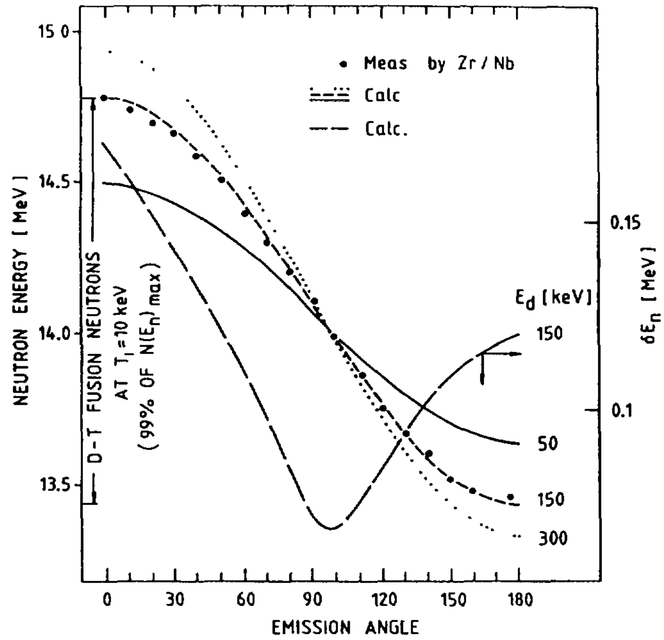


Fig.2 *Thick target neutron energy vs emission angle at different bombarding deuteron energies. The angular dependence of the neutron energy spread relates to E_d= 150 keV. The energy broadening of D-T plasma neutrons at T_i= 10 keV* [6], *is also shown*

energy. However, monoenergetic neutrons can be produced only at E_d < 4.45 MeV, below the deuteron break-up threshold.

The energy of the emitted neutrons in reactions (1) and (2) depends on the bombarding deuteron energy and the emission angle of neutrons to the direction of the deuteron beam.

The thin target data recommended [4] for the angular (Y_n) and energy (E_n) distributions of neutrons emitted in the D-D and D-T reactions can be well approximated by the following expressions [1, 6] in laboratory system:

$$Y_n(E_d,\theta) = Y_o(E_d) + \sum_{i=1}^{n} Y_i(E_d)\cos^i\theta \tag{3}$$

$$E_n(E_d,\theta) = E_o(E_d) + \sum_{i=1}^{n} E_i(E_d)\cos^i\theta \tag{4}$$

In eqs (3) and (4), n = 5 and 3 for D-D while n = 3 and 2 for D-T reac tions. The evaluated data [5] for thick targets can also be described by eqs (3) and (4). The values of the Y_o, Y_i, E_o and E_i coefficients from a least-squares fit are given in Tables 1-5 for the 20-500 keV deuteron energy range [1,6]. In the case of the D-T reaction, eqs (3) and (4) have been checked by experiment using a point source in a scattering-free arrangement [1] and the Zr/Nb, Zr/Au, Zr/Ta activity ratio method [7,8]. The $E_n(E_d,\theta)$ functions at E_d = 50, 150 and 300 keV for a thick tritium target are shown in Fig.2.

Table 1.

Recommended parameter values for calculation of thin target angular distributions of D-T source yields in laboratory system (equation 3) normalized to 90°

E_d(keV)	A_0	A_1	A_2	σ (90°) (mb/sr) [Ref.4]
20	1	0.0220	0.00025	4.2942
30	1	0.0227	-0.0093	19.6126
40	1	0.0310	0.0007	52.8382
50	1	0.0344	0.0010	105.4180
60	1	0.0518	-0.0035	173.2630
70	1	0.0407	0.0011	249.3768
100	1	0.0482	0.0011	393.3834
150	1	0.0599	0.0009	316.3704
200	1	0.0678	0.0005	198.4180
250	1	0.0685	-0.0104	132.8133
300	1	0.0818	0.0005	95.0878
350	1	0.0904	0.0028	77.3864
400	1	0.1003	-0.0008	63.4112
450	1	0.1140	-0.0101	53.0290
500	1	0.1273	-0.0187	45.5970

Data obtained from the $^{89}Zr/^{92m}Nb$ above activity ratio [6] produced in (n,2n) reactions prove the possible use of the analytical expressions. The calculated energy spread (δE_n) [6] of neutrons (1/2 FWHM) as a function of emission angle for a thick TiT target is also shown in Fig.2 at E_d = 150 keV. Typical shapes of the distributions [9] calculated by the Monte Carlo simulation code PROFIL [10] are shown in Fig.3.

The neutron energy spreads refer to the following circumstances: E_d = (190±10)keV, point-like beam spot, D^+ analyzed beam, 11.5 cm sample-target distance, and 8 mm x 16 mm sample dimension. Recently, Kudo and Kinoshito [11] have developed a method based on the pulse height distribution of the recoil edge for ^4He nuclei in a ^3He proportional counter for the determination of the energy

Table 2.

Coefficients of Legendre polynominals for calculation of thin target, angular distributions of D-D source yields in laboratory system (equation 3) normalized to 90°

E_d (keV)	A_o	A_1	A_2	A_3	A_4	A_5	σ(90°) (mb/sr) [Ref.4]
50	1	0.11787	0.58355	-0.11353	0.04222	0.16359	0.32016
100	1	0.01741	0.88746	0.22497	0.08183	0.37225	1.01828
200	1	-0.03149	1.11225	0.38659	0.26676	0.11518	1.95031
300	1	-0.10702	1.64553	0.63645	0.67655	0.35367	2.66479
400	1	0.02546	1.05439	0.21072	0.81789	0.59571	3.32222
500	1	-0.10272	1.09948	0.29820	1.09435	0.76159	3.63084

Table 3.

Coefficients in equation 3 for the calculation of the D-T thick target neutron yield vs emission angle

E_d (keV)	D - T		
	A_o	A_1	A_2
50	1	0.03003	0.00035
100	1	0.04087	0.00062
150	1	0.04727	0.00083
200	1	0.05124	0.00096
250	1	0.05419	0.00110
300	1	0.05651	0.00119
325	1	0.05616	0.00119

spread and the mean energy of the D-T neutrons. The detector is calibrated at the reference energy point of 14.00 MeV obtained at 96°-98° emission angles. The energy spread of neutrons $\delta E \leq 10$ keV obtained at these angles seems to be too small.

The following variables can strongly influence the neutron energy distribution: 1) the types of target atoms, 2) the ratio of atomic to molecular ions,

Table 4.

Values of parameters in equation 4 for the calculation of thin target neutron energy vs emission angle in laboratory system

E_d	D - T			D - D			
(keV)	E_o	E_1	E_2	E_o	E_1	E_2	E_3
50	14.04814	0.47679	0.00834	2.46073	0.24848	0.01282	0.00031
100	14.06732	0.67488	0.01719	2.47303	0.35237	0.02524	0.00062
200	14.10711	0.95596	0.03320	2.49771	0.50072	0.05044	0.00242
300	14.14704	1.17282	0.04923	2.52289	0.61581	0.07530	0.00589
400	14.18670	1.35640	0.06527	2.54798	0.71456	0.10013	0.00757
500	14.22569	1.51899	0.08249	2.57246	0.80285	0.12592	0.01024

Table 5.

Values of parameters in equation 4 for the calculation of thick target neutron energy vs emission angle in laboratory system

E_d	D - T			D - D			
(keV)	E_o	E_1	E_2	E_o	E_1	E_2	E_3
50	14.06520	0.42329	0.00682	-	-	-	-
100	14.07883	0.57613	0.01222	2.46674	0.30083	0.01368	-
150	14.08942	0.66776	0.01600	-	-	-	-
200	14.09680	0.72427	0.01908	2.47685	0.39111	0.04098	0.02749
250	14.10286	0.76661	0.02167	-	-	-	-
300	14.10803	0.80001	0.02374	2.49712	0.47697	0.05124	0.02957
325	14.10723	0.79477	0.02347	-	-	-	-
400	-	-	-	2.50981	0.55825	0.07125	0.02474
500	-	-	-	2.52140	0.62147	0.09816	0.03307

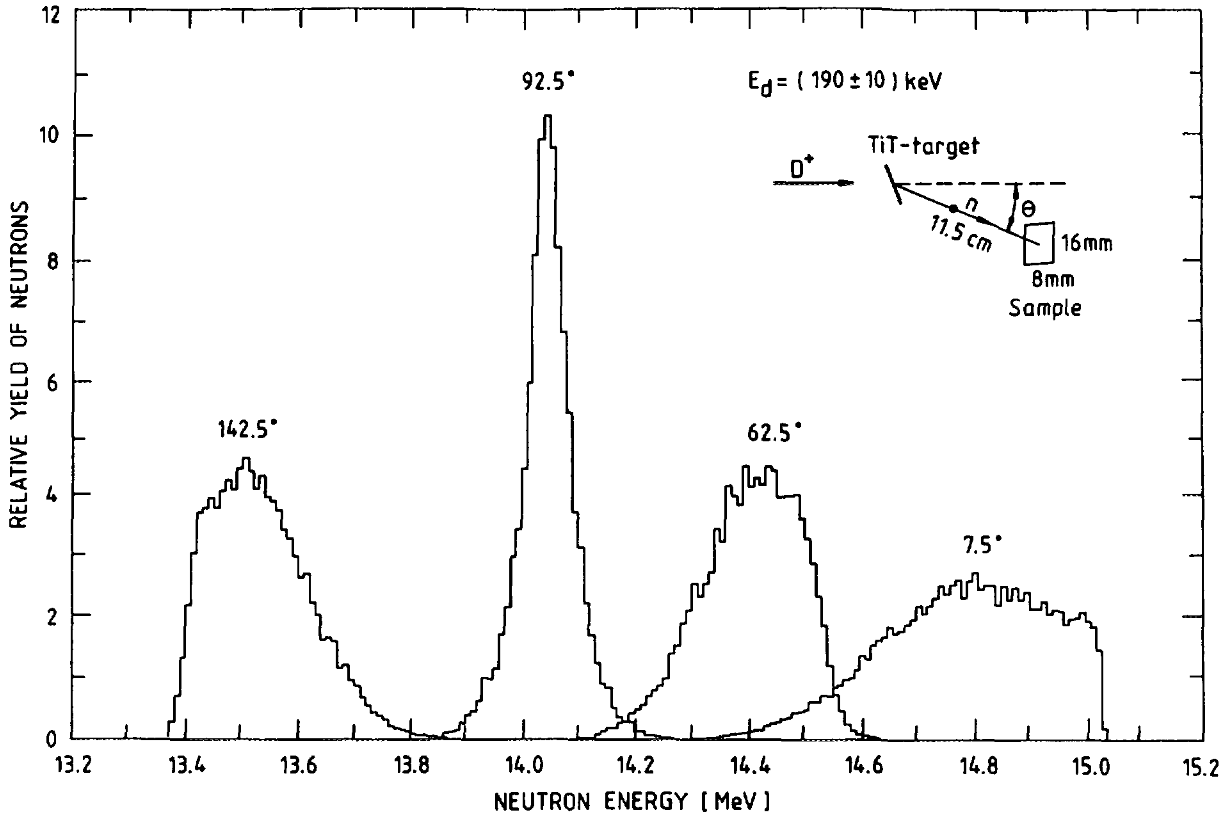


Fig.3 *Calculated neutron energy distribution profiles for D-T reaction* [9]

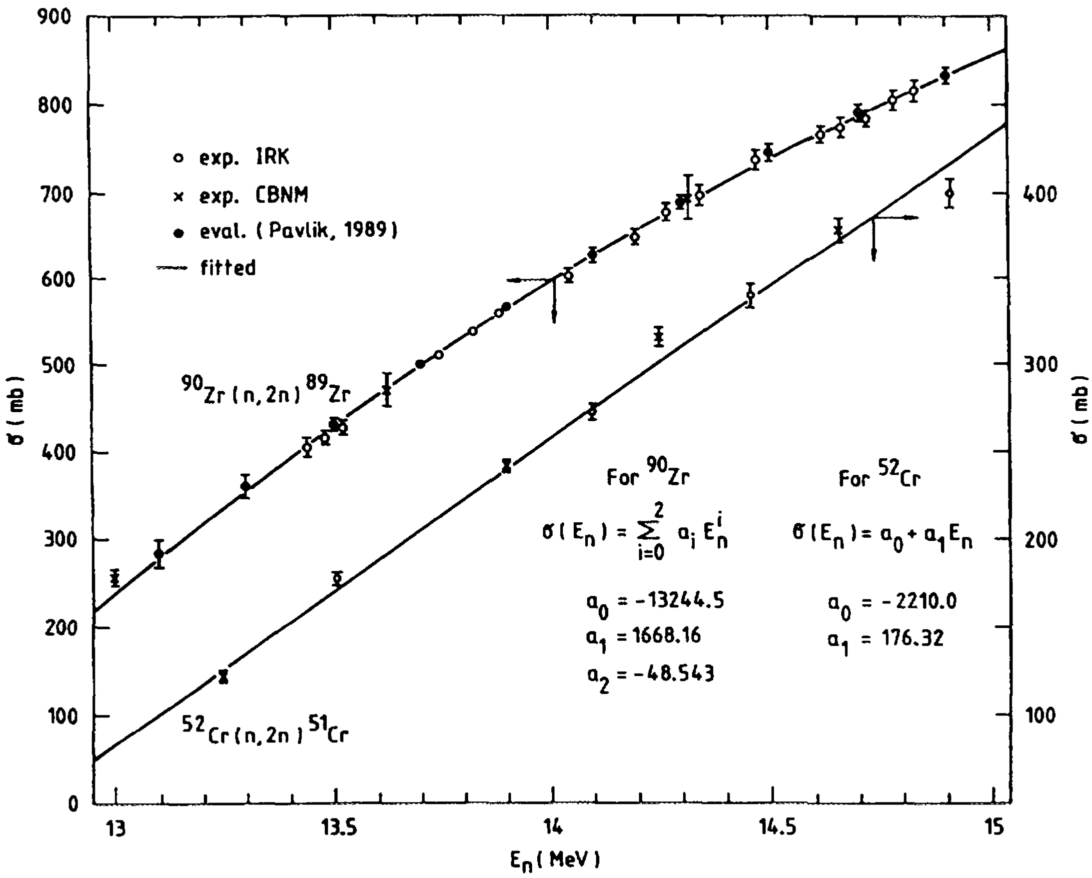


Fig.4 *Parameters of energy standard reactions* [12]

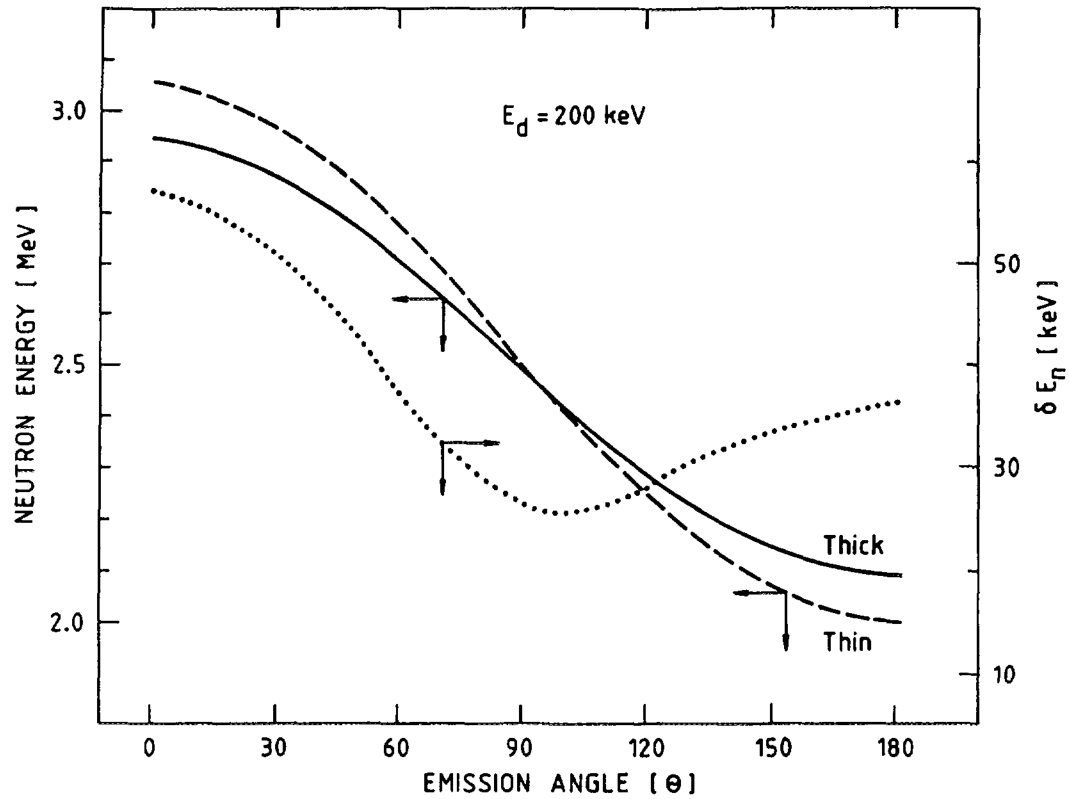


Fig.5 *Neutron energy vs emission angle for D-D reaction at* E_d *= 200 keV*

3) the energy spread of ions, 4) the slowing down and scattering of projectiles in the target. Therefore, a value of (14.00 ± 0.07) MeV at 96°-98° is recommended as a reference for absolute normalization of the energy scale with D-T neutrons. Shapes and parameters of the $\sigma(E_n)$ curves for ^{90}Zr(n,2n)^{89}Zr and ^{52}Cr(n,2n)^{51}Cr energy standards given in Ref. [12] are shown in Fig. 4. A value of (460 ± 5)mb is recommended for the cross section of the ^{93}Nb(n,2n)^{92m}Nb fluence monitor around 14 MeV.

The error of this method is determined by the shapes of the ^{90}Zr(n,2n) or the ^{52}Cr(n,2n) cross section curves and the source-sample geometry, but it does not exceed 50 keV, while the sensitivity between 13 and 15 MeV is, on average, 50 %/MeV and 64 %/MeV for Zr and Cr, respectively. The activity ratio is measured with an accuracy of better than 1 % and so the error in the determination of the mean neutron energy at 14.1 MeV is about 20 keV.

This method is also applied to determine the mean neutron energy for an extended sample. In this case the Zr and Nb foils are placed back-to-back in different positions inside the sample.

The calculated energy-angle functions $E_n(\theta)$ for D-D reaction are shown in Fig.5 for thin and thick targets at E_d = 200 keV.

The measurements of the mean energy and its spread require appropriate energy and fluence monitors. The angular yield of the D-D neutrons can be measured either by the $^{238}U(n,f)$ using a depleted U layer in a fission chamber or by the $^{115}In(n,n')^{115m}In$ reaction. The $\sigma_{n,f}(E_n)$ curve is relatively well known [13] and its change between 2 and 3 MeV is within 2.0 % (see Fig.6). For $^{115}In(n,n')^{115m}In$ reaction, the high cross section value in this energy range is advantageous; however, this inelastic process is sensitive for the scattered neutrons.

Measurements carried out in Debrecen, Jülich, Dhaka and Khartoum have indirated that the discrepancies in the $\sigma(E_n)$ data between 2 and 3 MeV originate mainly from the presence of room scattered neutrons and self-target build-up in beam apertures. The contamination of the neutron spectrum by the scattered neutrons can be decreased if a scattering-free arrangement is used. The contribution of the scattered neutrons to the activity can be checked [14] via the $1/r^2$ relation between the apparent activity and the flux values.

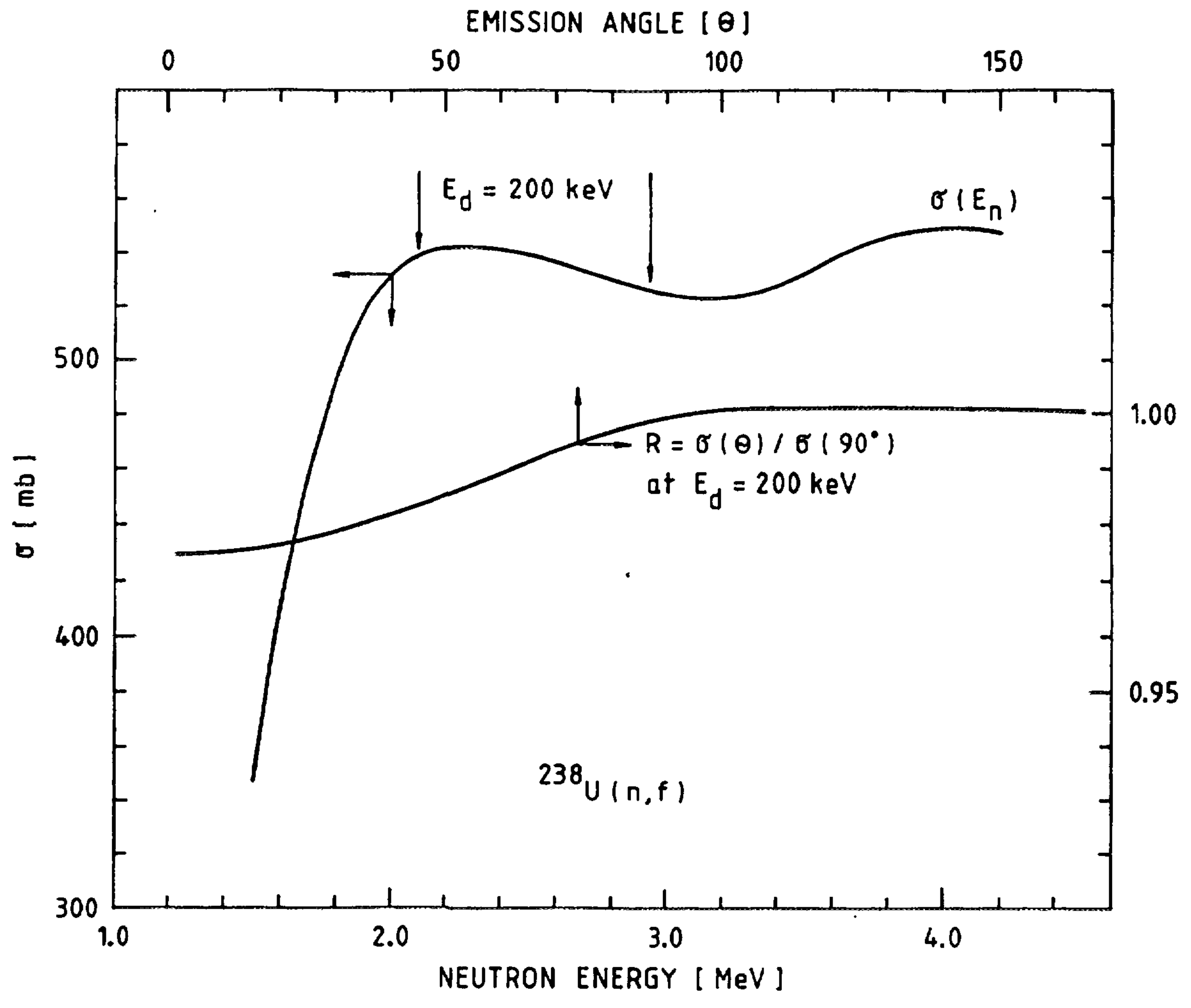


Fig.6 *Absolute and relative cross section curves for the $^{238}U(n,f)$ reaction between the threshold and 14 MeV neutron energy*

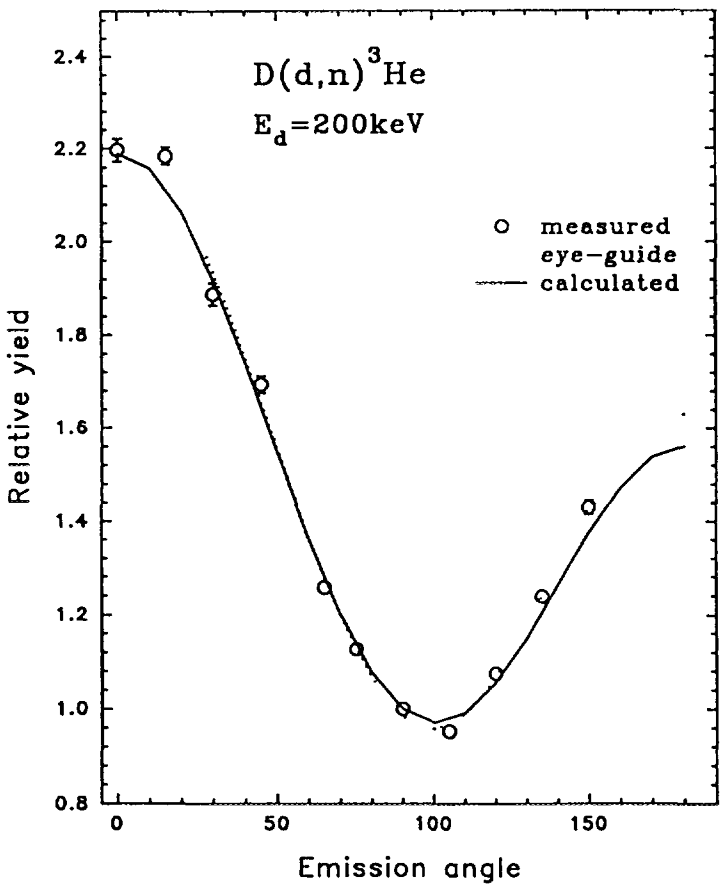


Fig.7 *Measured and calculated angular yields of D-D neutrons*

Table 6.

Recommended cross sections of energy monitors for D-D neutrons

Neutron energy	σ(mb) ^{64}Zn (n,p)	σ(mb) ^{58}Ni (n,p)	σ(mb) ^{31}P(n,p)
1.9 - 2.0	6.095	36.8	8.353
2.0 - 2.1	8.635	46.28	9.338
2.1 - 2.2	11.65	60.12	14.57
2.2 - 2.3	15.82	73.95	24.04
2.3 - 2.4	20.14	87.79	31.86
2.4 - 2.5	26.77	101.6	38.02
2.5 - 2.6	34.36	117.1	46.50
2.6 - 2.7	43.10	134.3	57.30
2.7 - 2.8	54.70	151.6	62.52
2.8 - 2.9	66.45	168.8	62.17
2.9 - 3.0	78.80	186.0	61.49

Table 7.
Energies of residual particles emitted in $T(d,n)^4He$, $D(d,n)^3He$, and $D(d,p)^3H$ reactions

Residual particles	Bombarding deuteron energy (MeV)	Energy of residual particles (MeV)		
		0^0	90^0	180^0
n	0.050	14.554	14.068	13.599
from D-T	0.100	14.783	14.088	13.432
reaction	0.150	14.960	14.108	13.304
	0.200	15.117	14.128	13.203
	0.250	15.259	14.148	13.117
	0.300	15.390	14.167	13.042
n	0.050	2.723	2.462	2.225
from D-D	0.100	2.852	2.474	2.146
reaction	0.150	2.958	2.486	2.090
	0.200	3.052	2.498	2.045
	0.250	3.139	2.511	2.009
	0.300	3.220	2.524	1.978
^4He	0.050	4.041	3.531	3.086
from D-T	0.100	4.261	3.520	2.910
reaction	0.150	4.436	3.551	2.779
	0.200	4.587	3.501	2.672
	0.250	4.723	3.491	2.581
	0.300	4.848	3.481	2.499
^3He	0.050	1.093	0.807	0.596
from D-D	0.100	1.223	0.795	0.516
	0.150	1.329	0.782	0.460
	0.200	1.423	0.769	0.416
	0.250	1.510	0.757	0.380
	0.300	1.591	0.745	0.349

Table 7. (cont.)

Residual particles	Bombarding deuteron energy (MeV)	Energy of residual particles (MeV) 0^0	90^0	180^0
p	0.050	3.324	3.036	2.772
from D-D	0.100	3.465	3.048	2.657
reaction	0.150	3.579	3.061	2.617
	0.200	3.681	3.073	2.566
	0.250	3.773	3.085	2.523
	0.300	3.860	3.098	2.486
^3H	0.050	1.311	0.997	0.758
from D-D	0.100	1.451	0.984	0.668
reaction	0.150	1.565	0.971	0.603
	0.200	1.666	0.959	0.552
	0.250	1.758	0.946	0.509
	0.300	1.844	0.933	0.472

The $^{64}Zn(n,p)^{64}Cu$, $^{58}Ni(n,p)^{58}Co$ and the $^{31}P(n,p)^{31}Si$ reactions are recommended as energy monitors for D-D neutrons in the 2-3 MeV range. The latter is a pure beta emitter. Cross sections in the 2 and 3 MeV neutron energy range are summarized in Table 6.

The angular yield of D-D neutrons is measured by the $^{115}In(n,n')^{115m}In$ reaction at 200 keV [15] bombarding deuteron energies. As can be seen in Fig.7, the measured and calculated thick target yields are in good agreement with each other, proving the flat shape of the cross section curve of $^{115}In(n,n')^{115m}In$ reaction in the 2.1-2.9 MeV range. A value of σ = 325 ± 5 mb is recommended between 2.1 and 2.9 MeV range for the determination of the D-D neutron fluence.

For D-D reaction the neutron energy at $\Theta = 100^0$ is almost constant in the $50 \leq E_d \leq 500$ keV range. A value of $\bar{E}_n(100^o) = (2.414 \pm 0.010)$ MeV can be accept ed for normalization of the energy scale with D-D neutrons using 100-200 keV incident deuteron energies. Considering the possible sources of the energy spread, the FWHM value must be in the 100 and 25 keV range between 0 and 100 degrees, respectively. From the pulse height spectra measured at different emission angles by a ^3He proportional counter, the mean energy and its spread can be derived [16].

The absolute source strength of the $^{3}H(d,n)^{4}He$ and $^{2}H(d,n)^{3}He$ reactions can be measured accurately (<0.5%) by means of the associated particle method (APM), i.e. by the registration of the ^{4}He and ^{3}He particles from the D-T and D-D reactions, respectively, by an alpha detector in a given solid angle.

The differential cross sections of the $^{2}H(d,n)^{3}He$ and $^{2}H(d,p)^{3}H$ reactions are the same at 90° up to a few 100 keV deuteron energies [17]. Therefore, the source strength can be determined by observing the recoil tritons or protons with a silicon surface barrier detector. In Table 7 energies of the residual particles produced in the D-T and D-D reactions are summarized.

In addition to the $^{93}Nb(n,2n)$, the $^{27}Al(n,\alpha)$ activation detector is also a good fluence monitor for D-T neutrons. Fission chambers with ^{238}U and ^{232}Th foils, long counters and liquid scintillators are used as prompt monitors for recording the source strength as a function of time.

The spectra of background neutrons are determined either by the activation threshold foils method or by prompt spectrometry based for example on an NE-213 liquid scintillator.

The ideal 14 MeV neutron field of the neutron generators is contaminated in practice by lower energy groups to some extent. The most important sources of these non-14 MeV neutrons are:

1) Elastic and inelastic scattering of the original 14 MeV neutrons in the target target assembly, sample holders, bulk samples, APM head and electronics, air, construction materials of the target room.
2) The D+D neutrons from the drive-in target, resulting in a 0.1-1% of the D-T yield depending on the condition of the tritium target.
3) D+D neutrons from the beam apertures (i.e. beam accelerating and transport systems, diaphragms, etc.).
4) Contribution of the D_2^+ and D_3^+ ion induced reactions in the case of nonanalyzed beam.

In order to decrease the influence of these parasitic neutrons, the target should be placed in the center of the target room at equal distances from the walls, floor and ceiling. Thin wall, air cooled target holders [1] are ideal to get low contributions of the background neutrons. The thick, water cooled targets in a heavy-set target holder and the mixed beam neutron generators (i.e. sealed tubes) may produce a contaminant of non-14 MeV neutrons of about 10%.

3. DETERMINATION OF THE BEAM ENERGY

According to eqs (3) and (4) the angular yield and energy of neutrons depend on the incident deuteron energy.

The absolute energy of an ion beam can be measured by using an electrostatic, a 180° magnetic or a velocity analyzer. In addition to the absolute methods, the energy calibration of particle accelerators is usually performed by a 90° magnetic analyzer which must be calibrated with nuclear reactions having accurately known resonance and threshold energies.

A magnetic analyzer containing entrance and exit slits is transparent only for ions with charge Q and energy E

$$E = Kf^2Q^2/m \tag{5}$$

where K is the analyzing magnet calibration factor, f is the NMR frequency if the strength of the magnetic field is measured by a nuclear-magnetic-resonance probe (usually a proton probe) and E is the nonrelativistic kinetic energy [18], i.e the analyzer is a tool for Q/m separation and for measuring the energy E.

In addition to the absolute methods, measurements of current through a bank of resistors is widely used - because of its simplicity - below a few hundred kV terminal voltage. However, at high voltage, discharges on the surface of the resistors and their unstable values can cause an uncertainty of about ± 5 kV.

During the last decades, new methods based on nuclear reactions have been developed for precise beam energy measurement. For instance, by using a Ge(Li) detector to measure the energy of the direct capture gammas emitted in the $^{12}C(p,\gamma)^{13}N$ non-resonant reaction, the absolute proton beam energy between 150 and 350 keV could be determined with a precision of about 0.4 keV [19]. The absolute energy calibration is possible even below 100 keV by using the $D(p,\gamma)^3He$ nonresonant reaction [20]. This process was observed [21] as low as E_p = 25 keV. The Q values of the $D(p,\gamma)^3He$, $^{12}C(p,\gamma)^{13}N$ and $^{16}O(p,\gamma)^{17}F$ are 5.4936, 1.9435 and 0.60035 MeV, respectively. The nonresonant direct capture method has been developed [22] in an experimental arrangement as shown in Fig.8.

The γ-ray yield curves are measured at target location 1 with a NaI(Tl) detector. At the second location, the γ-ray transitions can be measured with a high resolution Ge detector at 0 and 90 degrees. According to the kinematics of an $X(p,\gamma)Y$ reaction, the energy of a gamma photon emitted by a nucleus decaying at rest is

$$E_o = Q + E_p \frac{M_x}{M_x + m_p} \tag{6}$$

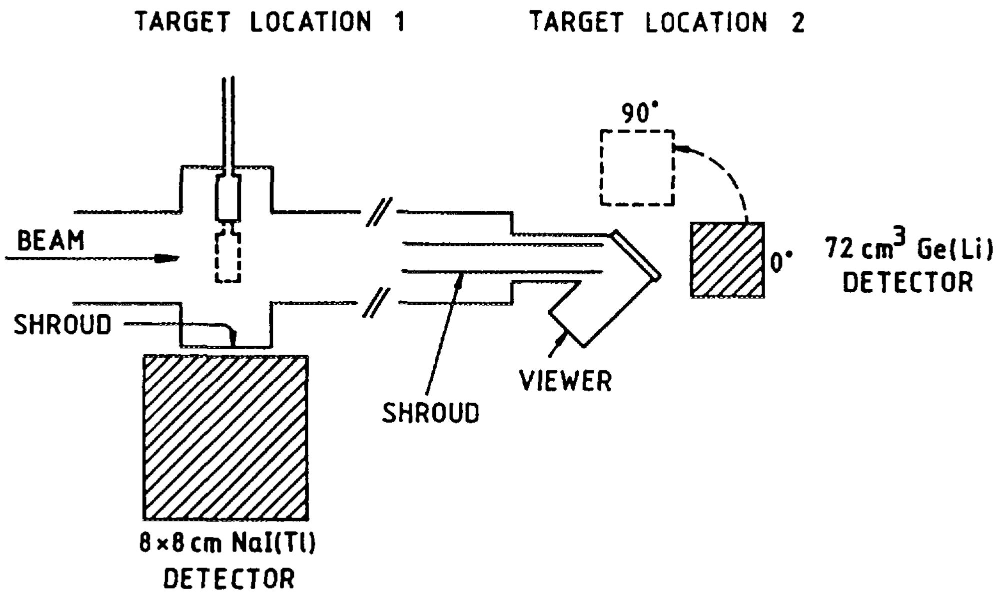


Fig.8 *Experimental setup for measuring proton beam energy via the γ-ray detection emitted in non-resonant (p,γ) reactions*

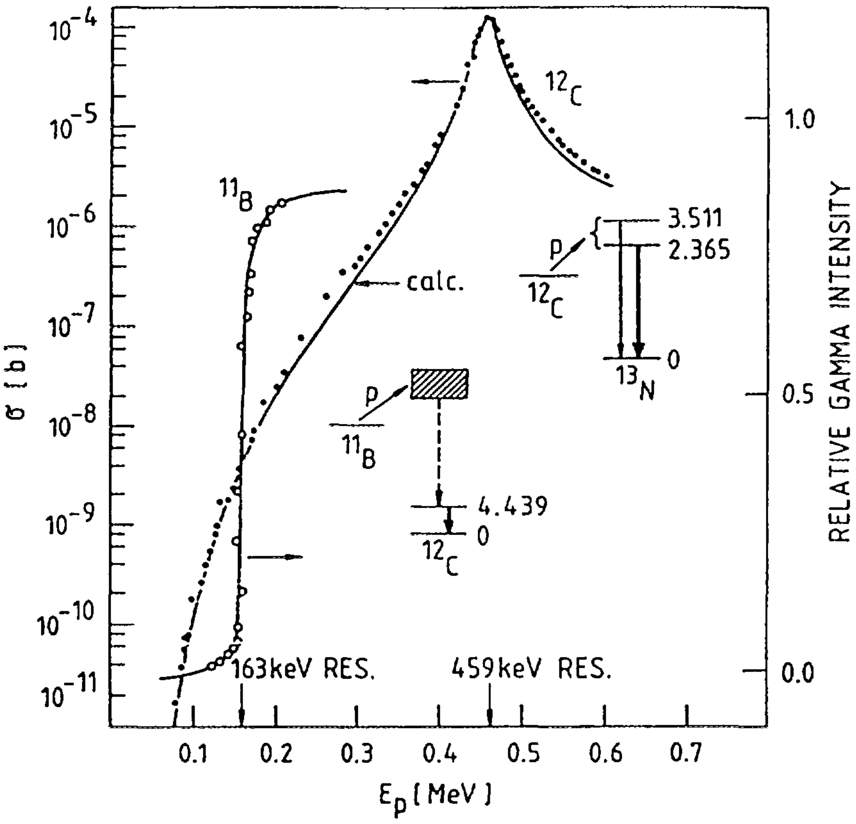


Fig.9 *Yield curves of (p,γ) reactions on ^{11}B and ^{12}C*

Because of the Doppler and recoil effects, the energy of detected gammas E_s differs from E_o. The relation between E_o and E_s is

$$E_s = E_o \frac{(1-\beta^2)^{1/2}}{1-\beta\cos\theta} - \frac{E_o^2}{2M_y c^2} = E_o(1+\beta\cos\theta) - \frac{E_o^2\,(\mathrm{MeV})}{M_y\,(\mathrm{u})}\,0.53678\ \mathrm{keV} \quad (7)$$

where $\beta = v_y/c$ and θ is the angle between the directions of M_y and the γ-ray. By measuring E_s at 90°, the energy of protons can be determined from eqs (6) and (7). Equation (7) shows that at 90°, only the recoil effect must be taken into account. The calibration of the Ge detector for high energy gammas is a difficult task. If the measurements are based on the $D(p,\gamma)^3He$ reaction, the 6.12917 MeV gamma line with its single and double escape peaks at 5.61817 and 5.10717 MeV, respectively, can be used for calibration. Such a gamma line is emitted by ^{16}N produced in the $^{16}O(n,p)$ reaction. The ^{66}Ga isotope is also a good energy standard in the 833.6 – 4807.0 keV range. High energy gamma-ray standards for detector calibration are summarized in Ref. [23]. Procedure of the energy calibration by non-resonant reactions has been described in detail in Refs [1, 19, 20, 22, 24].

Typical yield curves for the (p,γ) reactions on thick ^{11}B [1] and thin ^{12}C [25] targets are shown in Fig.9.

There are a number of resonance reactions recommended for energy calibration. However, below 200 keV proton energy only a single calibration point, the $^{11}B(p,\gamma)^{12}C$ resonance at E_p = (163.1 ± 0.2) keV, is available.

Precise energy calibration of low voltage neutron generators is especially important if the machine is used as a charged particle accelerator for the determination of atomic and nuclear data with a high accuracy as well as for the improvement of various technological applications (e.g. ion-beam imaging, ion microtomography, particle-induced X-ray emission, Rutherford backscattering, ion implantation, prompt radiation analysis).

Therefore, improvement of the neutron generators with a **beam energy analyzer** and a beam **profile detector** is strongly **recommended**.

4. TYPES OF NEUTRON GENERATORS

The principle of the neutron generator is shown in Fig.10. This schematic applies for all particle accelerator. A schematic drawing of a home-made generator working in Debrecen is shown in Fig. 11. From this figure it is easy to follow the functions of each unit and its position.

The ion source, the extraction, the focusing, and the gas supply units placed on the HV terminal need electric power, cooling and insulated remote control systems. The ion source is RF or Penning type for standard (commercial or medium size) neutron generators while it is a duoplasmatron (duopigatron) if high currents are required. The deuterium gas flow is regulated into the ion source by needle, thermomechanical or palladium leaks. As the ion beam analyzer requires relatively high power, the separation of the D^+beam is made usually after acceleration.

The pulsing of the ion source allows the production of a pulsed beam, i.e. 14 MeV neutron burst, in the μs range, while the nanosecond pulsing can be made before and after acceleration using special bunching units.

The acceleration tube is generally a homogeneous field type allowing a high pumping speed for the vacuum pumps situated at the ground potential. The intense neutron generators (beam current over 10 mA) utilize strong focusing single-gap or two and three gap tubes by which the space charge effects are taken into account.

The high voltage power supplies are usually Cockcroft-Walton voltage multipliers, Felici-type electrostatic machines, medium frequency Allibone-type voltage multipliers, insulated core transformer HV supplies or parallel powered Dynamitron voltage multipliers.

In a number of commercial neutron generators, separate insulating transformers are used to supply and control the HV terminal. These types are as follows: SAMES J-15 and J-25, TMC A-111 and KAMAN 1254 models. Most of the non-commercial neutron generators use a single insulating transformer or an insulated motor driven generator (see Fig. 11), to ensure the power for the units placed on the HV terminal. The control of these power supplies and other components like needle valves can be performed by insulating electromechanically driven rods (MULTIVOLT, KFKI and TOSHIBA neutron generators) or by insulated optical fibers (SAMES series T neutron generators, INGE-1 in Dresden, RTNS-II at LLL, OCTAVIAN and FNS in Japan). The optical cables between the HV terminal and the control desk give the computer control and regulation of the whole neutron generator.

Most neutron generators have ion beam handling facilities: magnetic or electrostatic quadrupole lenses, beam profile monitors, ion beam analyzers (simple electromagnet or Wien-filter), beam stops and scanners, etc. The size and the

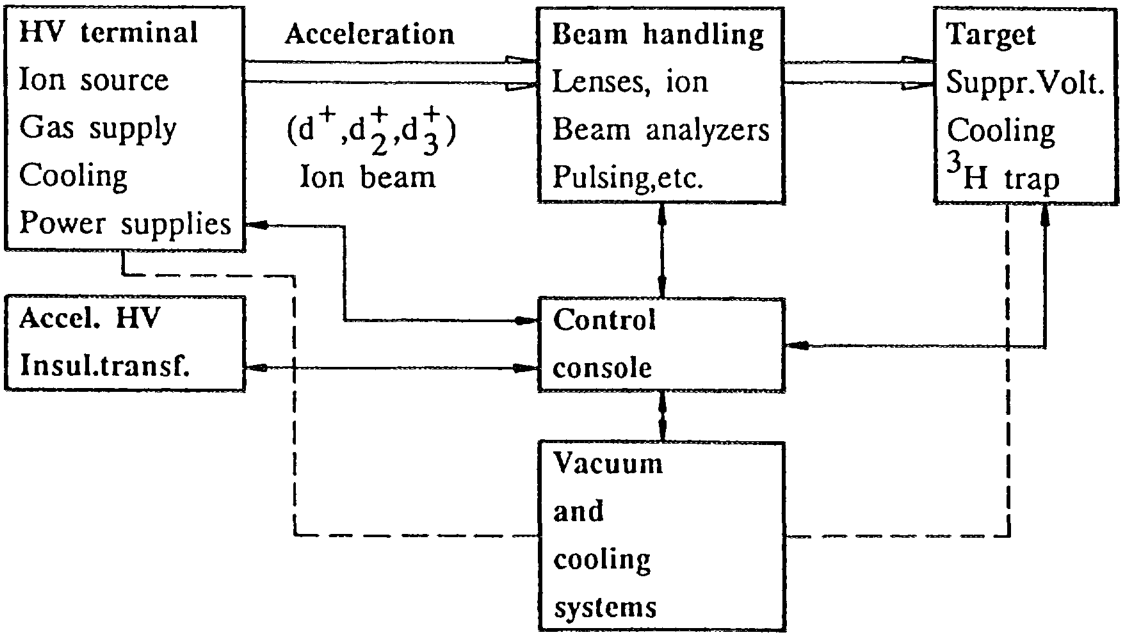


Fig.10 *Block-diagram of neutron generator*

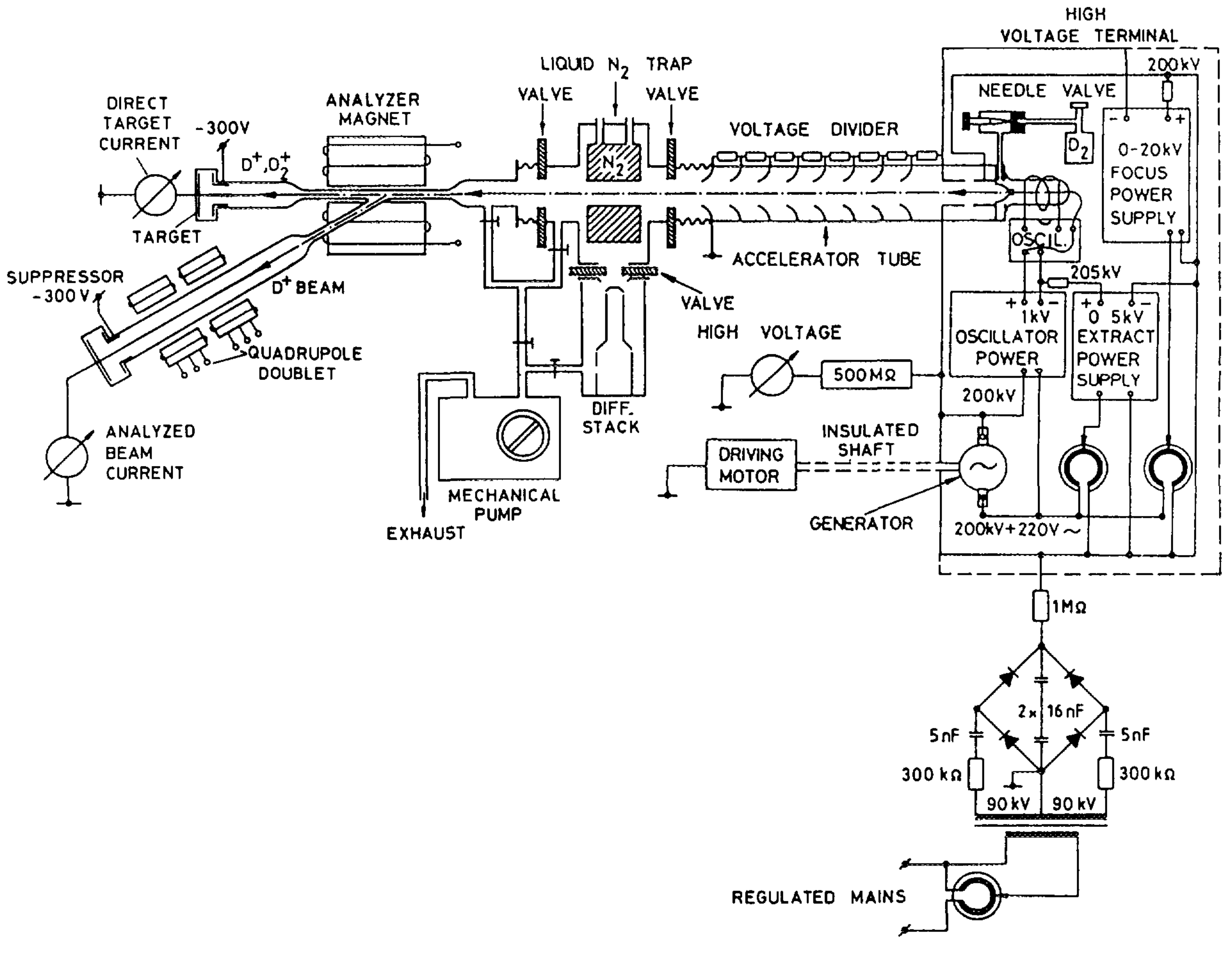


Fig.11 *Diagram of a working neutron generator*

technical solution of the target holder depends on the purpose of the neutron generator. A neutron generator utilized mainly for activation analysis, neutron therapy or materials research may have a bulky water cooled target holder, especially for a few mA target current. The intense neutron generators, having several kW target loads, can manage this load only with water cooled rotating targets. The thin wall, low mass target holders with air jet cooling [1] are recommended for "clean" neutron work, around 2 and 14 MeV.

The vacuum system of a neutron generator consists of prepumps (mechanical, cryogenic) and high vacuum (diffusion, ion getter, turbomolecular) pumps. The advantages of the diffusion pumps are as follows: low cost, high pumping speed simple maintenance, long lifetime, no mobile components. Their disadvantages are: oil vapour contamination of the accelerator components and the target which can be decreased by using of FLOMBIN or SANTOVAC oils and liquid nitrogen traps (see Fig. 11) not only at the inlet of the diffusion pump but also along the beam lines.

The titanium getter pumps can assure clean vacuum and high pumping speed for hydrogen (deuterium) gas; however, the high absorption rate for tritium released from the target makes it difficult to handle the used pump elements because of their high activity, even in the case of moderate commercial neutron generators. The cleanest vacuum can be achieved by using turbomolecular pumps. Their disadvantages are the relatively high cost and the possibility of mechanical damage. In general, Pirani and thermocouple vacuum gauges are used for measuring the forevacuum. The high vacuum is measured mostly with Dushman type or Penning type gauges. The use of the vacuum controllers makes possible the automation of the neutron generator control. The rubber or Viton O-rings are changed these days for metal gaskets: the contemporary neutron generators use bakeable vacuum components as well.

With neutron generators used for research purposes, control is mostly manual, but the principle of minimal interlock and other control inputs is also followed with commercial generators. The multipurpose and intense neutron generators use microcomputer and computer control systems. The choice of neutron generator depends on its construction and purpose.

This Manual outlines the commercial (medium), intense (high current) pulsed and sealed tube neutron generators, dealing with their operation, technical solutions, maintenance and repair as well as with updating with a view to extending their utilization in science and technology.

4.1 COMMERCIAL NEUTRON GENERATORS

The commercial neutron generators are modest machines with production yields of about 10^{11} n/s and 10^{9} n/s for D-T and D-D reactions, respectively. They are utilized in basic nuclear research, education and technology, for measurement of nuclear data, and in laboratory exercises to study the different interactions of neutrons, detection of charged particles and neutrons. They are also used in accelerator technology for activation analysis, prompt radiation analysis, irradiation effects of fast neutrons, neutron dosimetry, etc. Practically no technological development in the field of commercial neutron generators has been reported in recent years and only a few companies are producing these moderate (150-300 kV, 1-2 mA) machines.

The existing manufacturers are IRELEC (formerly AID and SAMES) in France, KFKI in Hungary, the EFREMOV Institute in Russia, and MULTIVOLT in the United Kingdom. The sealed tube replacement is still made by KAMAN NUCLEAR in the USA. These types of neutron generator are still in operation in many countries. As these machines are excellent devices for pure and applied research, service and education, the IAEA has provided them to the following developing countries: Albania, Algeria, Bangladesh, Bolivia, Burma, Costa Rica, Cuba, Equador, Hungary, Indonesia, the former Yugoslavia, Lebanon, Malaysia, Mongolia, Morocco, D.P.R. of Korea, Nigeria, Pakistan, Peru, Singapore, Sudan, Thailand, Turkey, Zambia. Unfortunately some of these generators are now out of order, and, in addition to repair of the machines, it is recommended that they be fitted with some upgrading components. For example, determination of the nuclear level schemes and neutron cross sections requires microsecond and nanosecond pulsing units. These systems have been developed almost entirely in the laboratories where the neutron generators were constructed and are not available commercially. Therefore, strong co-operation is required between the developing and advanced laboratories for upgrading the commercial neutron generators with pulsing units and other components.

As a number of manufacturers have closed down in the last decade, some "second hand neutron generator" companies (POTENTIAL in the USA or MULTIVOLT in the UK) have started to buy used machines and restore them to their original conditions. POTENTIAL specializes in neutron generators manufactured by TEXAS NUCLEAR [29], while MULTIVOLT deals with those made by SAMES. The lack of spare parts and components causes many problems for the users - especially in the industrially less developed countries - in the field of maintenance and repair. Dealing with "second hand neutron generators" is particularly important for the developing countries. Table 8 lists the most popular commercial neutron generators. Improvement of the original characteristics of a commercial neutron generator, i.e. analyzing magnet, quadrupole lenses, pulsing systems, associated target assemblies, etc., needs local or international co-operation with experienced laboratories. An excellent example of such international co-operation is the Fast Neutron Research

Table 8.
Commercial pumped neutron generators

Manufacturer	Type	U/I [kV/mA]	Yield [n/s]	Pulsing
TMC	A-111	180/1.5	$>10^{10}$	μs
TEXAS NUCL.		280/7	$>10^{11}$	---
KAMAN	A-1254	190/2.2	$>10^{11}$	ns-μs
TOSHIBA	NT-200-5	200/1	$>10^{10}$	---
KFKI	NA-4B	120/1.3	$>10^{11}$	---
HIGH VOLTAGE	LN-S	300/2	$4\text{x}10^{10}$	---
ACCEL.		150/3.5	$3\text{x}10^{10}$	μs
MULTIVOLT	NA-150-2	150/1.5	$>10^{10}$	μs
	NA-150-4	150/3.5	$8\text{x}10^{11}$	μs
SAMES	J-15	150/1.5	$>10^{10}$	μs
	J-25	150/2.5	$2\text{x}10^{10}$	μs
	JB	150/2.5	$2\text{x}10^{11}$	μs
	TB	300/8	$\sim10^{12}$	---
	D	150/1.5	$5\text{x}10^{10}$	μs
EFREMOV	NG-150-I	150/3	$\sim10^{11}$	---
	NGP-11	150/2	$2\text{x}10^{11}$	---
	NGP-11M	175/5	$5\text{x}10^{11}$	---
	NG-12-1	250/10	$\sim10^{12}$	---

Facility at Chiang Mai University, Thailand, where the commercially built SAMES J-25 neutron generator has been completed with a post-acceleration nanosecond pulsing system and an associated particle target head. This effort resulted in a good time-of-flight spectrometer laboratory based on a modest commercial neutron generator. These were originally small compact machines, manufactured mainly for activation analysis.

A comparision of the commercial neutron generators (see Tables 9 and 10) can help users to select the appropriate machine for a specific application, while knowledge of the technical solutions of these generators may help in the improvement of their own machines and in repair and troubleshooting. Some components can be similar enough to be used in their own systems. The main characteristics and

Table 9.
Comparison of different commercial neutron generators

	S A M E S					TMC	KAMAN		T*	KFKI	MULTIV.		EFREMOV
Type No.	1	2	3	4	5	6	7	8	9	10	11	12	13
Neutron yield [n/s]													
$>10^{10}$	+	+				+			+	+	+		
$=10^{11}$		+		+			+						+
$<10^{12}$			+		+			+				+	
$=10^{12}$					+								
Beam energy [keV]													
<150										+			
$=150$ [keV]	+	+		+							+	+	+
<200						+	+	+					
>200			+		+				+				
Beam current [mA]													
>1	+	+	+	+		+	+		+	+	+		
>3					+			+				+	+
>5					+								
Ion source													
Penning	+					+	+	+					
RF		+	+	+	+			+	+	+	+		
Duoplasmatron					+								+
Gas supply													
PD leak	+	+	+	+	+				+	+	+	+	
Electrolyzer									+	+			
Mechanical						+	+						+
Sealed tube								+					
HV supply													
Electrostatic	+	+	+	+	+								
Mains frequency					+	+	+	+	+	+			+
Medium frequency											+	+	
Terminal control by													
Ins.transfor.	+	+				+	+	+					+
Ins.rod									+	+	+	+	+
Fiber optics			+	+	+								

* TOSHIBA

Table 9. (cont.)

	SAMES					TMC	KAMAN		T*	KFKI	MULTIV.		EFREMOV
Type No.	1	2	3	4	5	6	7	8	9	10	11	12	13
						Accel.tube							
Homogeneous	+	+	+	+	+				+	+	+	+	+
Inhomogeneous						+	+	+					
						Vacuum system							
Diff.pump	+	+	+	+	+				+	+	+	+	+
Titan getter	+	+	+			+	+	+		+			
Turbomolecular		+	+	+						+	+	+	
Pneumatics		+	+	+									
						HV terminal insulation							
Air		+	+						+	+	+	+	
Oil	+					+							
SF-6				+	+		+	+					solid
						Cooling system							
Open	+	+	+	+	+				+	+	+	+	+
Closed circuits						+	+	+					
						Power consumption							
<2.5 kVA	+												
>2.5 kVA		+				+	+	+					
>4 kVA		+		+					+	+	+	+	
>8 kVA			+		+								+
						Optional pulsing							
< 100 μs	+	+	+	+	+	+	+	+			+	+	
> 100 μs	+	+	+	+	+	+	+	+			+	+	
Beam stop	+	+	+	+	+				+	+			+
						Spare parts							
Easy	+	+								+	+	+	
Available				+	+	+	+	+					
Not easy	+								+				+
						Maintenance of the machine							
Comfortable		+	+						+	+	+	+	
Not comfort.	+			+	+	+	+	+					+

*TOSHIBA

Table 10. Advantages and limitations of the commercial neutron generators

TYPE	ADVANTAGES	DISADVANTAGES
SAMES-D	Simple construction Simple insulation (oil) Small room for installation Electrostatic HV unit	Mixed beam Not easy maintenance and repair of HV terminal Horizontal use only
SAMES-J	Easy maintenance Reliable electropneumatic safety system Easy beam line assembling	Mixed beam Unreliable and too numerous insulating transformers Electrostatic HV unit
SAMES-T	Easy maintenance and repair Reliable electropneumatic safety system Electrostatic HV unit Insulator shaft motor generator	Mixed ion beam The maximum HV can be achieved only in an environment that is not humid AC power at the HV terminal
SAMES-JB	Compactness Small room for installation Simple installation and position change Safe operation in humid or low pressure atmosphere	Mixed ion beam Not easy maintenance and repair Special tools
SAMES-TB	Compactness, small room for installation Simple position change Safe operation in humidty	Mixed ion beam Not easy dismantling, repair and maintenance Special tools
TMC A-111	Compactness, easy achievement of horizontal or vertical beam Simple closed circuit cooling	Mixed ion beam Not easy dismantling, repair and maintenance Unreliable needle valve
KAMAN A-1254	Compactness, small room for installation Simple position change SF_6 insulation FREON 113 cooling	Mixed ion beam Unreliable needle valve
TOSHIBA NT-200	Long life D_2 supply Compactness 200 kV acceleration voltage	Mixed ion beam Unavailable spare parts
KFKI NA-4	Compactness Long life D_2 supply Small room for installation	Mixed ion beam Low acceleration voltage (120 kV)
MULTIVOLT NA-150	Compactness Availability of spare parts and components	Mixed ion beam Relatively low yield High D_2consumption

technical solutions are given in Table 9, where the numbers correspond to the following manufacturers and types:

SAMES (D, J, T, JB, TB) Type No. 1, 2, 3, 4, 5
TMC (A-111) Type No. 6
KAMAN (A-1254, A-711) Type No. 7,8
TOSHIBA (NT-200) Type No. 9
KFKI (NA-4) Type No. 10
MULTIVOLT (NA 150-02 and NA 150-04) Type No. 11,12
EFREMOV (NG-150 I) Type No. 13

4.2 SEALED TUBE NEUTRON GENERATORS

The sealed tube neutron generators or neutron tubes are 14 MeV neutron sources used in in-situ geological measurements (bore-hole logging), in hospitals and in chemical, biological and industrial laboratories. Most neutron tubes have a Penning ion source, a one- or two-gap acceleration section, a tritium target and deuterium-tritium gas mixture filling system. The pressure of the gas is controlled by a built-in ion getter pump and/or gas storage replenisher. The tritium displaced from the target during the operation is absorbed by the gas occlusion elements and is accelerated later back into the target, resulting in an extended target life [26]. The operation principle of a typical sealed tube generator is shown in Fig.12. The first sealed tube neutron generator was developed by PHILIPS [27] and its originally low neutron yield could increase up to over 10^{12} n/s. The advantage of the neutron tubes is their small size which makes them suitable for geological bore-hole logging or isocentric cancer therapy in hospitals. The disadvantages are their limited lifetime and the relatively high neutron production cost. Typical applications of the neutron tubes (with built-in high voltage power supplies and neutron detectors) are as follows: Bore-hole logging, deposit evaluation, uranium exploration and processing, mineral exploration, coal exploration and processing, oil well logging, gas well logging, under-sea exploration and such utilization where the small diameter and the remote detection are important. For cancer therapy the isocentric irradiation is most important: the neutron source and the neutron collimator are rotated around the malignant tumour in the same way as in linear accelerators or at radioactive sources.

The deuteron ions - bombarding the tritium target - are produced in a Penning ion source. The ion source is powered by a 0 - 10 kV HV power supply consisting of an insulating high voltage step-up transformer and single wave rectifier. The discharge current of the ion source can be observed by an I_S ion source amp meter. Owing to the negative resistance of gas discharges, a damping resistor

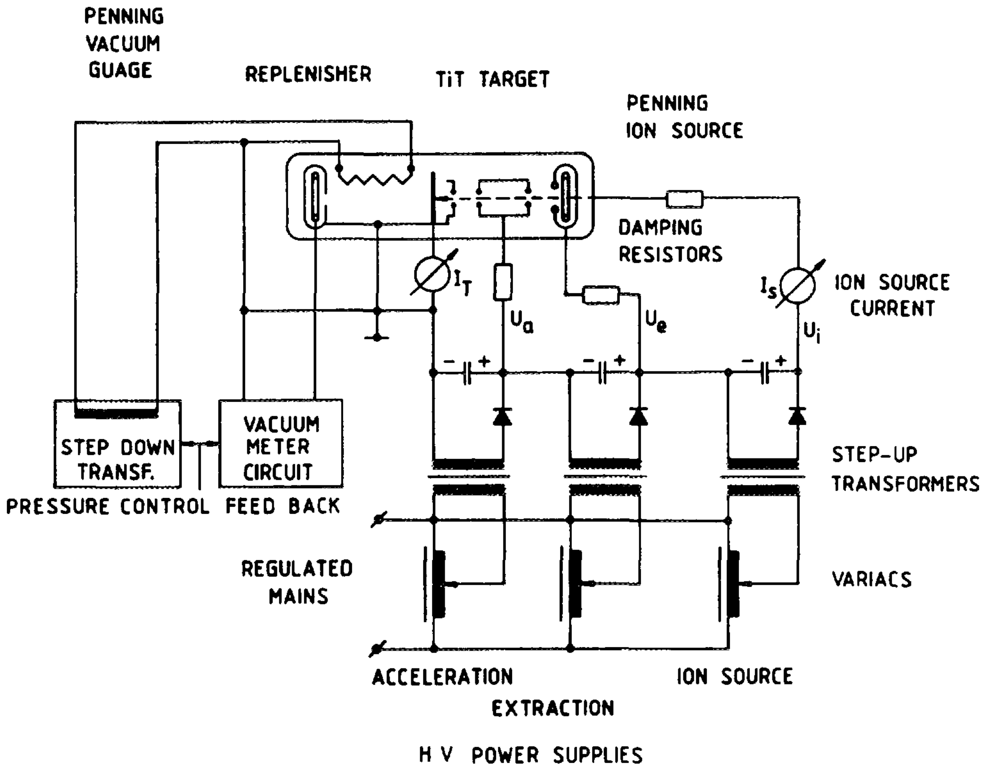


Fig.12 *Schematic diagram of sealed tube neutron generator*

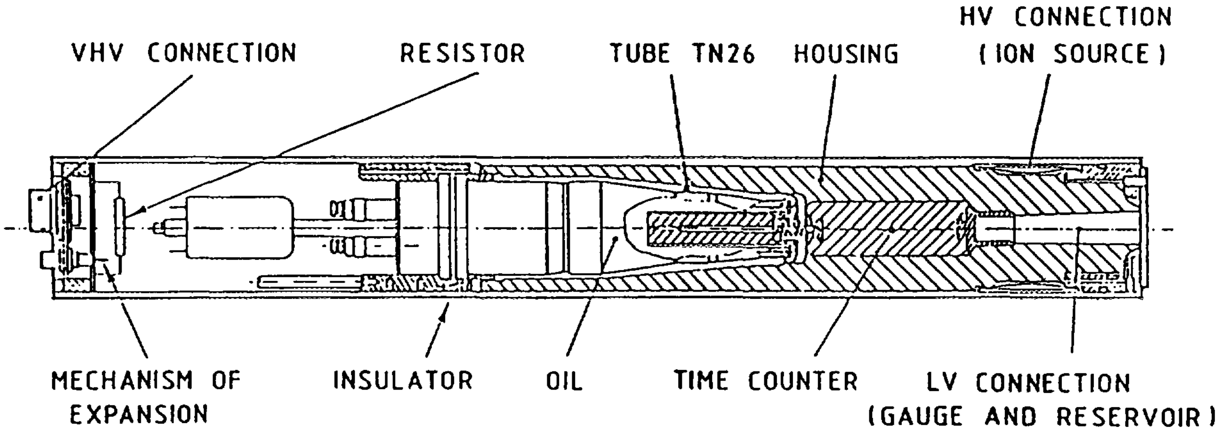


Fig.13 *Schematic diagram of the SODERN sealed tube neutron generator for bore-hole logging* [28]

protects the ion source power supply. This power supply floats at the voltage of the sum of U_a accelerating voltage and U_e extraction voltage. The U_i ion source voltage can be regulated by the right hand side variac. The D^+ and T^+ mixed ions are extracted by the U_e extraction voltage into the first acceleration gap and accelerated by the U_a acceleration voltage within the second gap towards the TiT target. The operation of the sealed tube requires a definite gas pressure in the tube. The gas pressure is regulated by heating the gas replenisher (mainly zircon or titanium). The gas pressure is measured mainly by a Penning type vacuum meter. Some sealed tube neutron generators utilize feedback control between the neutron monitor and the replenisher to achieve a constant neutron yield.

Sulphurhexafluoride (KAMAN 711), oil (several PHILIPS sealed tubes) or solid plastic materials (SODERN tubes) are used for the insulation of the sealed tube generator head [28].

The KAMAN 711 sealed tube is placed in a pressure vessel under the insulating compressed sulphurhexafluoride gas. The ion source is cooled by electrically insulating liquid FREON 113, while the target is cooled by circulated water outside the pressure tank. The arrangement makes it possible for the small so-called accelerator head - which has only two pairs of coolant pipes and a couple of cables - to be moved easily and adapt to the circumstances of the investigations. This sealed tube neutron generator delivers over 10^{10} n/s during its guaranteed life-time of 200 hours.

The PHILIPS sealed tube type 18601 has a built-in Dushman type ionization vacuum gauge, a pressure regulating replenisher and a high voltage damping resistor in its 737 mm long, 70 mm diameter, usually oil filled, metal tube container. This typical bore-hole logging neutron tube has a pulsing capability between 5 and 1000 μs. A schematic diagram of a recent solid insulation tube packed SODERN neutron generator is shown in Fig.13 [28].

Therapeutic use of neutron generators assumes a minimum 14 MeV neutron yield of $>10^{12}$ n/s. The relatively small size of the neutron tubes is an advantage in fast neutron therapy: they can be easily installed in the neutron collimators of the isocentric treatment geometry. The problems related to tritium handling in pumped neutron generators do not exist in the case of the sealed tube, so sealed tube intensive neutron generators are ideal for fast neutron cancer therapy. The MARCONI-ELLIOTT [30] and the HAEFELY (the KARIN or KORONA) are sealed tube neutron generators that can meet the criteria of the high neutron yield and relatively long life-time. The MARCONI has a mixed D^+, T^+ beam containing a refillable sealed tube with typical high frequency ion source and a homogeneous field acceleration tube. The target material is Er, to achieve high thermal stability. The manufacturer can renew the system, and this is advantageous for situations where regular change of used sealed tubes is required. For cancer therapy, the sealed tube in the collimator is changed regularly every week.

The KARIN tube is manufactured by HAEFELY in Basel. This generator has an annular shaped Philips ion gauge (PIG) ion source at the ground potential, while the cylindrical or conical target is on the high voltage potential and in the

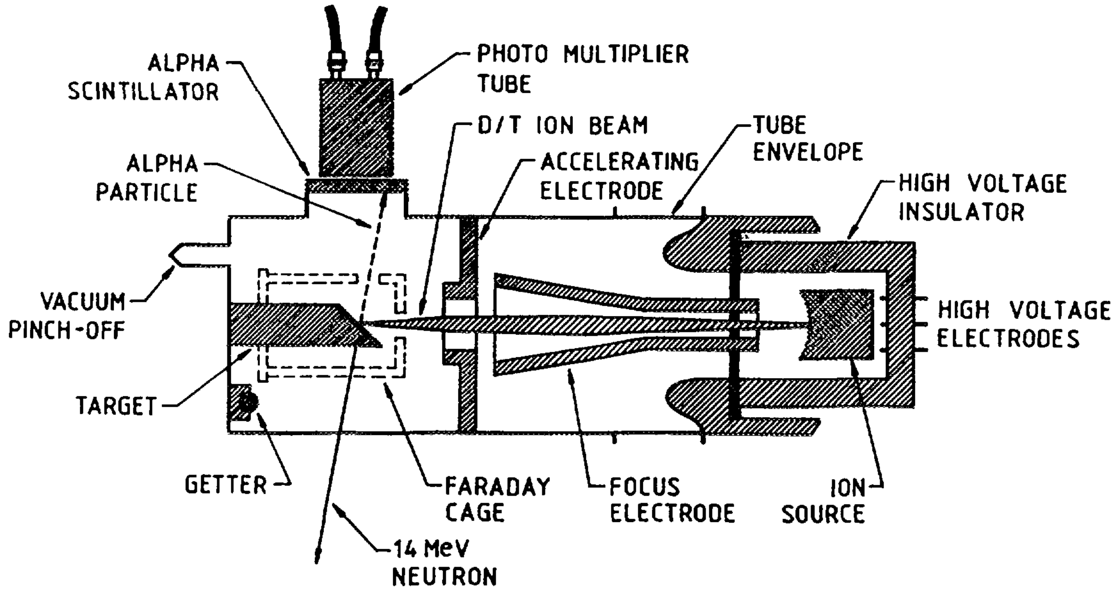


Fig.14 *A sealed tube neutron generator combined with APM head for time correlated measurements*

Table 11.

Comparison of sealed tube neutron generators

Type/Name	Manufacturer	Life-time	Acc.voltage/Beam current [kV/mA]	Yield [n/s]
A-3045/6	KAMAN	200 h	200 kV/5 mA	$3x10^{10}$
A-3041-4	KAMAN	$2x10^6$ pulses		$5x10^7$
A-3043	KAMAN	100 h		$5x10^7$
18601	PHILIPS	1000 h	125 kV/0.1 mA	$>10^8$
18604	PHILIPS	400 h	200 kV/8 mA	$>10^{12}$
TN-26	SODERN	2500 h	125 kV/0.1 mA	$2x10^8$
	MARCONI	200 h	200 kV/20 mA	$>10^{12}$
KARIN	HAEFELY	400 h	200 kV/500 mA	$5x10^{12}$
TN-46	SODERN	>1000 h	225 kV/2 mA	$>10^{11}$

center of the annular ion source and spherical collimator. A cylindrical pneumatic rabbit system (sample transfer) can be introduced into the center of the target along its axis by an insulating polyethylene tube to achieve a homogeneous sample irradiation, especially if the sample is rotated during irradiation in the hollow target. The conical targets are used almost only for neutron therapy. The target is produced from scandium titride. The tube can give $> 10^{12}$ n/s yield during its guaranteed life-time of 400 hours.

The long life-time criterion of the sealed tube neutron generators seems to be fullfilled by the new generation of SODERN (France) neutron tubes. Some parameters of these neutron generators are summarized in Table.11.

The combination of the sealed tube accelerator with the associated particle method (APM) [28] (Fig.14) for field analysis of bulk mineral samples, verification of chemical and nuclear weapons [29,30], and three dimensional elemental analysis in solids [28] has great importance. A schematic diagram of such a combined generator is shown in Fig.14.

4.3 INTENSE NEUTRON GENERATORS

Recently, 14 MeV neutron generators with a yield higher than $>10^{12}$n/s were developed for fusion related applications, neutron cross section measurements, production of long-lived isotopes, investigations on radiation effects, cancer therapy and elemental analysis of small samples. The original DC intense neutron generators were equipped later with pulsing systems to measure the secondary and leakage neutron spectra. Such experiments require about 100 times higher neutron yields than that of today's intense neutron generators to achieve the required accuracy of data for fusion reactor design. These programs became more important after the first successful experiment with DT fusion in the Joint European Torus in Abingdon (UK, 1991). The design of a fusion reactor needs accurate data for tritium breeding, nuclear heating, bulk shielding, secondary reactions and gas production. The accuracy of the energy and angular distributions of secondary neutrons - DDX measurements - for blanket and other structural materials should also be increased [31,33,34].

For calculations of the induced activity, more accurate activation cross sections are needed not only for the materials of the major components but also for their impurities. Precise activation data are required mainly for the dosimetry reactions and for unfolding the neutron field in different parts of the fusion reactor.

During the early intense neutron generator period (second half of the seventies) when several such machines had been constructed for fusion oriented research and neutron therapy, it became clear that these originally DC generators would be more suitable for fusion studies if a pulsing system helped the DDX and neutron transport measurements. The Osaka OCTAVIAN generator and the JAERI FNS were equipped with nanosecond pulsing units as the first intense neutron generator, the RTNS-I at LLL.

There are some limitations of the recent generators in determination of the data required for fusion reactors (low yield, small irradiated volume, large gradient of the neutron fluence in the sample). Therefore, new machines are under

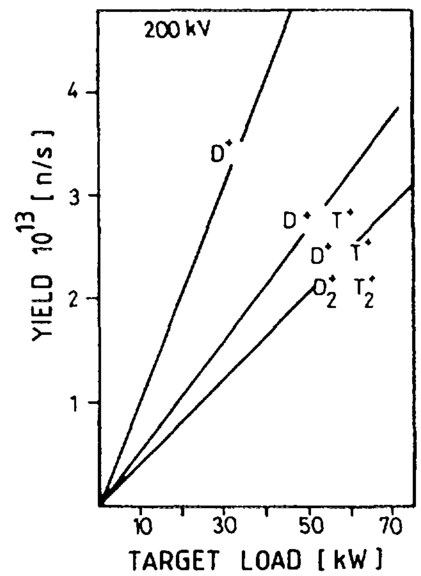


Fig.15 *Specific neutron yield vs specific target load for solid tritium targets* [35]

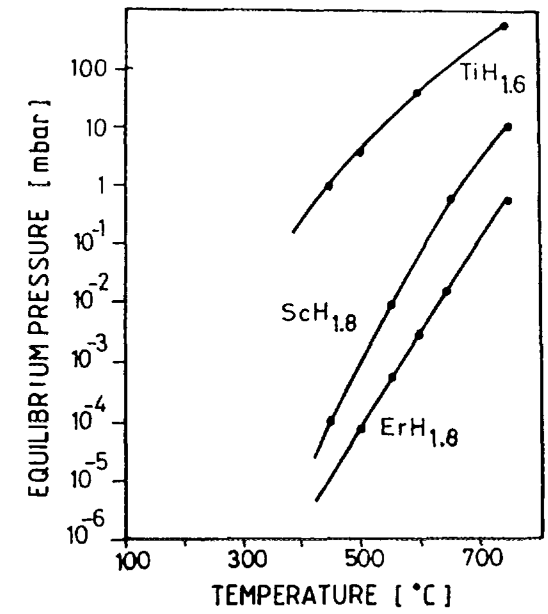


Fig.16 *The equilibrium pressure for some metal hydride systems vs temperature*

construction or improvement, e.g. the conceptionally new Osaka generator and the Los Alamos supersonic gas target system.

A 200 kV acceleration voltage and 50 mA current produce a load of 10 kW on the target, which gives about 10^{13} n/s yield if the beam is selected for D^+ (see Fig.15) [34].

Since the thermal stability of the tritium targets depends on the equilibrium pressure of the metal titride system at a given temperature, the use of more

Table 12.

Some characteristics of intense neutron generators [32]

Name	Yield 10^{12}[n/s]	V_{acc}/I_{target} [kV/mA]	Beam diam. [mm]	Application
RTNS-I	6	400/22	6	irradiation, TOF
RTNS-II	30	380/130	10	irradiation
LANCELOT	6	160/200	50	irradiation
OCTAVIAN	4	300/35	30	irradiation, TOF
LOTUS	5	250/500	(50 cm^2)	irradiation
Chalk River	4	300/25	10	irradiation
Lewis/NASA	>1	300/30	54	therapy
Sandia	4000	(200/40A*)	(200 cm^2)	irradiation
" 6'x6' "	10	250/250	1800	radiobiology
NRPB	>1	600/10	6	irradiation
DYNAGEN	3	500/12	20	therapy
FNS	5	400/20	15	irradiation, TOF
AWRE	2.5	300/12	10	---
Bratislava	>1	300/10	10	irradiation, TOF
Kiev	>1	250/15	10	irradiation
INTTF	>10	180/200	16	target devel.
Dresden	>1	300/20	15	irradiation
Debrecen	>1	200/20	10	irradiation
Wisconsin	>1		(gas)	therapy
Lanzhou	<1	300/5	10	irradiation

*Note the high current (40 A) for the Sandia generator

stable titrides than TiT has many advantages. The target cooling is a fundamental problem for intense neutron generators, and therefore the use of a technically perfect gas target assembly is recommended to increase the yield of present-day neutron generators. At an equilibrium pressure of 100 Pa the corresponding temperature for the TiH, ZrH, ScH, ErH and YH systems are 390, 590, 700, 790 and 860 Celsius, respectively. The behaviour of the TiH, ScH and ErH systems is shown in Fig.16 [35], and a survey of these generators is given in Table 12.

Most of these neutron generators have solid rotating targets and minimal beam line components to achieve the highest possible neutron output. The mixed (DT) beams were used to increase the target life at LANCELOT and LOTUS. A gas

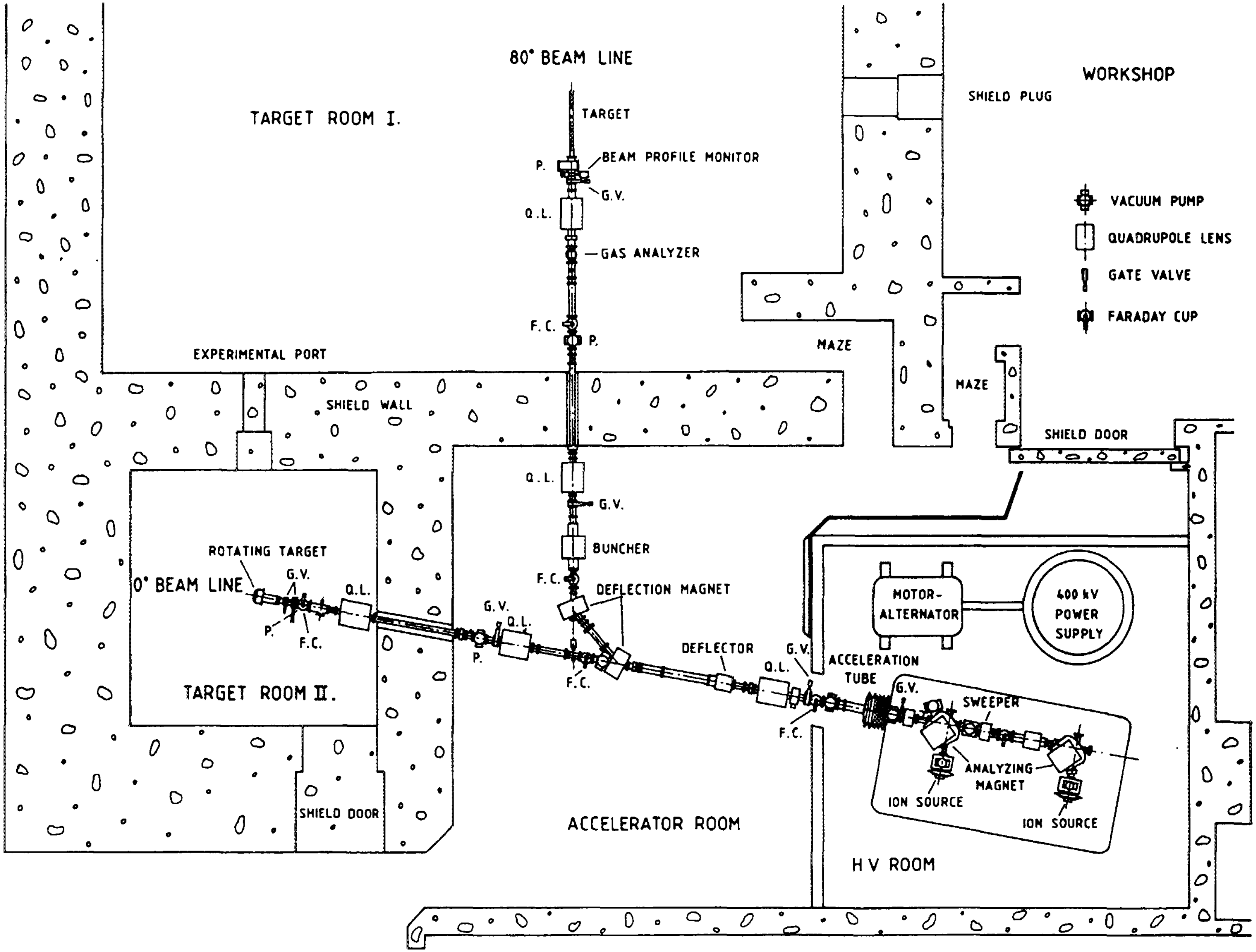


Fig.17 *Top view of the FNS facility at JAERI, Tokai-mura, Japan*

target is used only at Wisconsin University. The target problems, the tritium handling and the shielding require special buildings in the case of intense neutron generators. RTNS-II, OCTAVIAN and FNS were constructed in their own building together with the supporting electronic and mechanical workshops. The relative amount of associated equipment inside and outside the generator hall can be estimated on the basis of the top view of the FNS facility in Tokai-mura (see Fig. 17) [36].

5.0 ION SOURCES: OPERATION PRINCIPLES, MAINTENANCE AND TROUBLESHOOTING

5.1 HIGH FREQUENCY ION SOURCES

Low voltage D-T generators employ three types of ion source: radiofrequency [37-39], Penning [also called PIG (Philips Ion Gauge)] [26,27,40,41], and duoplasmatron (DP) [31,42-44]. A comprehensive monograph on atom and ion sources has been published by Vályi [44], discussing in detail both theoretical and practical aspects. The advantage of RF sources is their high monatomic ratio (~ 90 %), while PIG and DP have high currents.

The high frequency ion source proposed by Thonemann and co-workers [45] and improved at Oak Ridge [37] is applied in different versions in many laboratories.

The high frequency discharge in HF ion sources can be generated by an inductively or a capacitively coupled oscillator of 15 to 100 MHz frequency with a power consumption of 100 to 400 W. The discharge generated by the high frequency electric field applied to two electrodes placed outside or inside the discharge tube is called either capacitively coupled or linear high frequency discharge. This type of ion source is used in the SAMES (called later AID), MULTIVOLT, etc., neutron generators (see Fig.18) [37].

The discharge generated by the high frequency magnetic field in the discharge tube placed inside the solenoid of the high frequency oscillator is called inductively coupled or ring high frequency discharge. This type of HF ion source, used at KFKI, Toshiba, etc., neutron generators is shown in Fig.19 [39].

In both cases the discharge chamber of about 30 to 50 mm diameter and 100 to 200 mm long is made of Pyrex or quartz glasses.

The free electrons are accelerated by the induced alternating electric field E and will oscillate at the same frequency as the oscillator. For the condition of ignition of the ring HF discharge it was found that the maximum value H_0 of the applied alternating magnetic field ($H = H_0 \sin\omega t$) must satisfy the equation

$$rH_0 \frac{e}{m_e} = \frac{\frac{2E_i}{m_e} + (\omega\lambda_e)}{\omega\lambda_e} \qquad (8)$$

where r is the radius of the tube, ω is the angular velocity of the high frequen cy field, and m_e is the mass of the electron. The collisions between electrons and gas particles lead to ionization only if $E_e = eE\lambda_e \geq E_i$, where λ_e is the mean free path of electrons of energy E_e and E_i is the ionization energy.

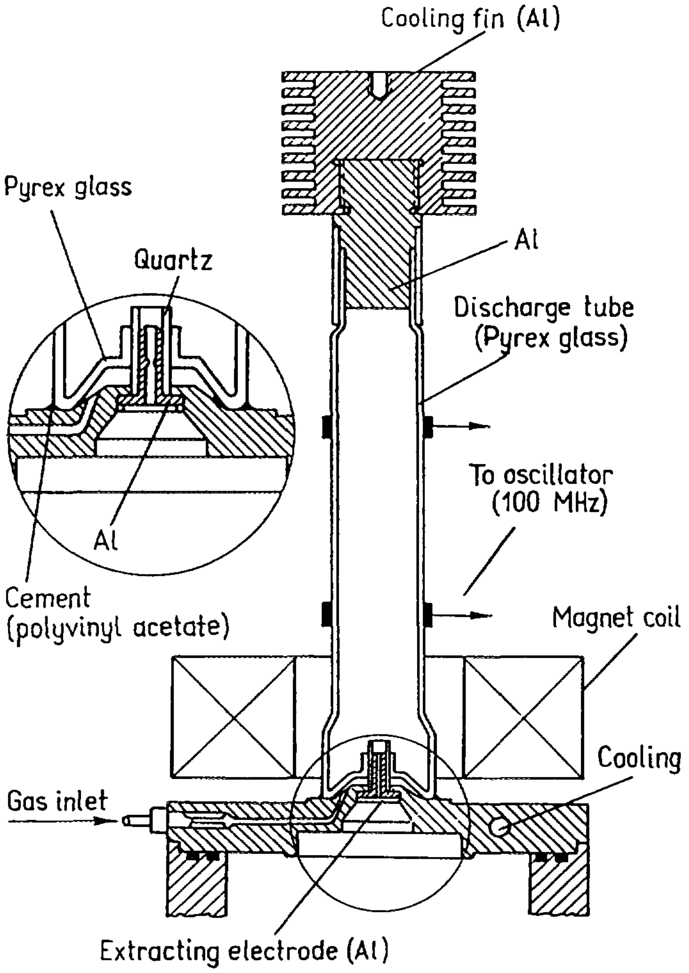


Fig.18 *Capacitively coupled high frequency ion source* [37]

The ignition voltage U_b of the gas discharge depends on λ_e and $\omega = 2\pi f$. The dependence of U_b on f for different gases (at the same pressure) is shown in Fig. 20. In Fig. 21 the curves show the $U_b = U_b$ (f) function for argon gas at different gas pressures. It is obvious that the minimum value of U_b and that of the associated frequency increases with increasing pressure [44].

Experiments show that the ignition voltage at pressures below 10^{-2} mbar is independent of the nature and pressure of the gas in the discharge tube and that its value is primarily determined by the secondary electron emission coefficient of the discharge at the wall. In high frequency ion sources, the walls of the discharge tubes are important because, in a real case, the secondary electrons play a role owing to the impurities on the wall, which are usually caused by electrode evaporation. The impurities will reduce the extracted ion current and thus the efficiency of the ion source.

As can be seen in Fig. 18, the ions are extracted through a 1-4 mm diameter and 5-20 mm long channel in the hard aluminium extracting electrode using a po-

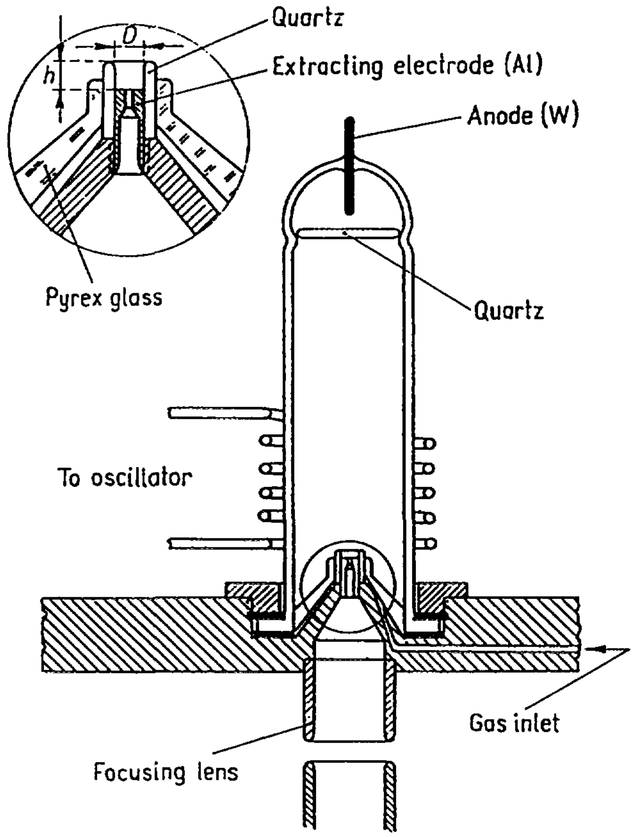


Fig.19 *A version of a high frequency ion source* [44]

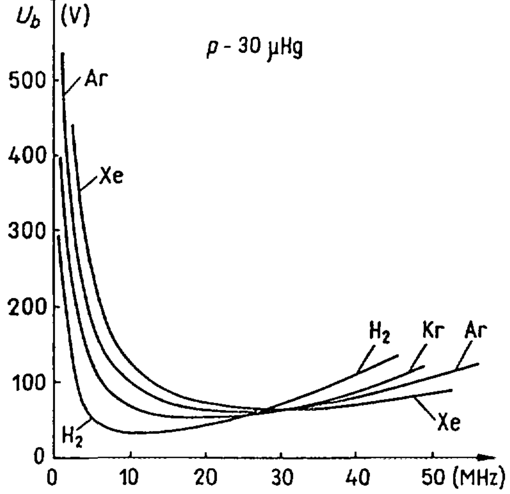


Fig.20 *Ignition voltage vs frequency*

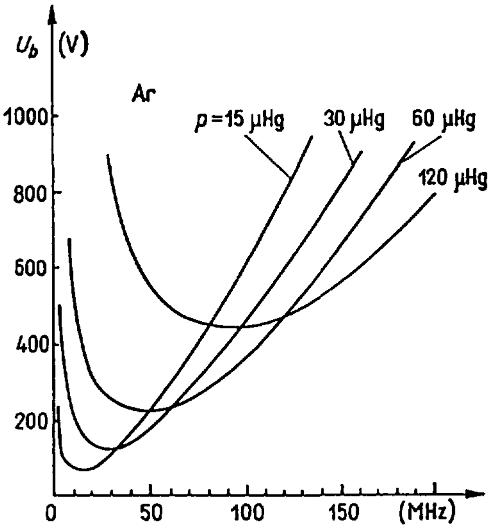


Fig.21 *Ignition voltage vs gas pressure*

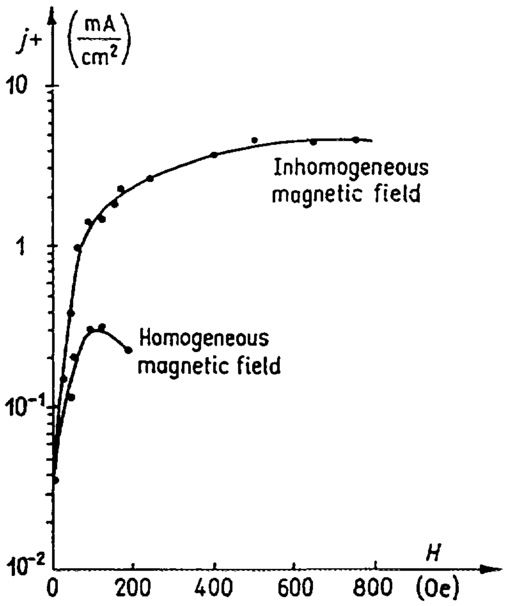


Fig.22 *Extracted ion beam density in HF discharges vs static magnetic field*

tential difference variable from 2 to 10 kV. To decrease the power and gas consumption, a permanent magnetic field is applied to the discharge volume either transverse or axial to the axis of the tube. By an axial magnetic field the ion concentration at the extracting electrode can be increased because the electrons will circulate on a helical orbit at a Larmor frequency

$$f_L = \frac{eB}{4\pi m} \qquad (9)$$

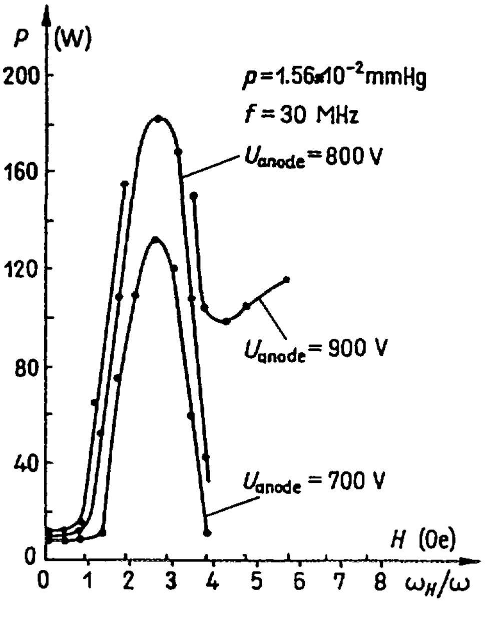


Fig.23 *Dependence of the power consumption vs magnetic field and extracted ion density vs high frequency power* [44]

and consequently the ionization probability will increase. Furthermore, the plasma with diamagnetic behaviour is compressed in the presence of a magnetic field.

The magnetic field parallel to the electric field can be either homogeneous or inhomogeneous. It was found that the ion current density in the linear high frequency discharge is substantially higher in the presence of an inhomogeneous magnetic field (see Fig. 22).

The power consumption of the discharge and the luminosity of the plasma show a resonance type increasing in a given interval of the static magnetic field (see Fig.23). This resonance phenomenon can be observed at a pressure of p $=1\text{x}10^{-3}$ to $5\text{x}10^{-2}$ mbar. The resonance in high frequency ring discharges (inductively coupled HF ion sources) has been observed in transversal magnetic fields at frequencies:

$$\omega_H = 1.5\ \omega \quad \text{to} \quad 3\ \omega \tag{10}$$

while in longitudinal fields at frequencies:

$$\omega_H = 3\ \omega \quad \text{to} \quad 6\ \omega \tag{11}$$

5.2 EXTRACTION OF IONS FROM ION SOURCES

Well collimated ion beams with small diameter, which are mainly required in neutron generators, can be obtained only from sources equipped with an ion extracting system. The probe-type and the diaphragm-type extraction systems are generally utilized in the neutron generators. In ion sources (mostly HF ion sources) with probe-type ion extraction and in those utilizing the expanded plasma surface, the ion-optical system is similar to an **immersion lens** (objective).

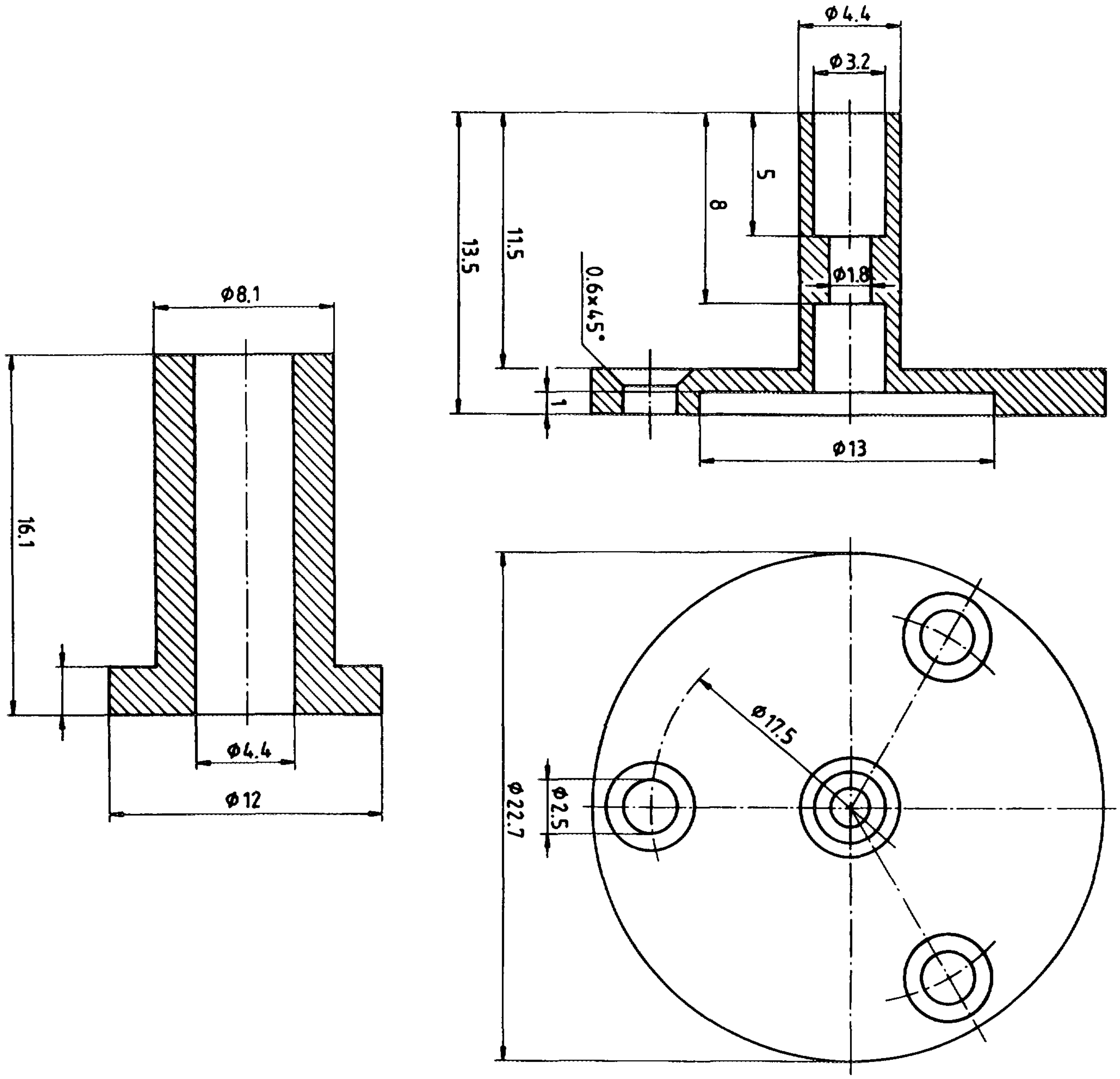


Fig.24 *Probe-type ion extraction system (quartz sleeve and extractor electrode of SAMES neutron generators), Sizes are in mm*

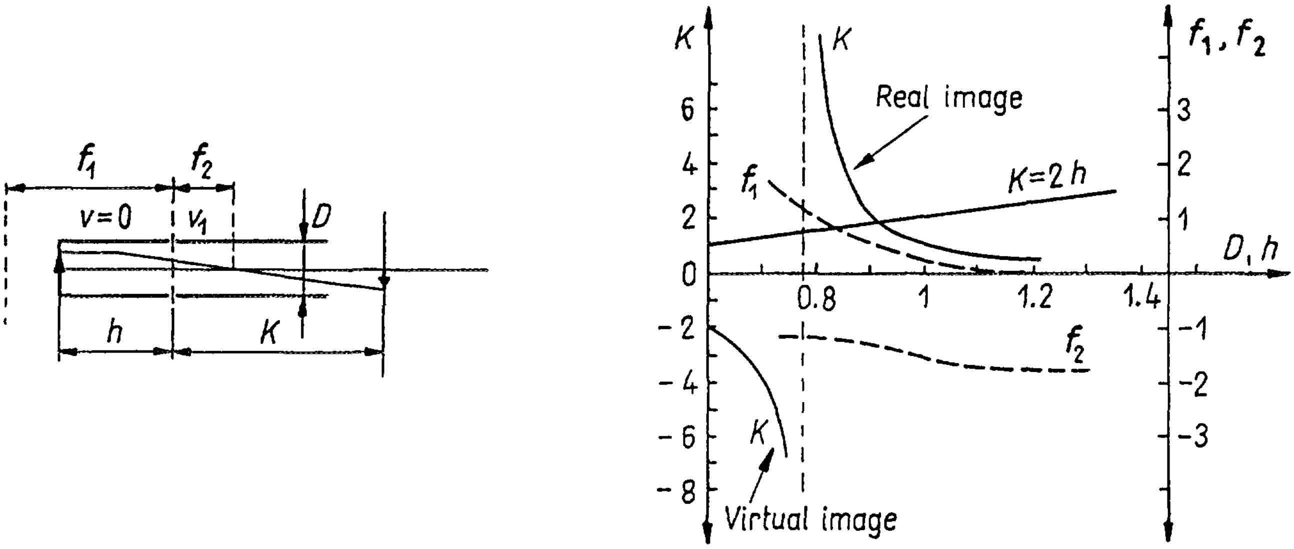


Fig.25 *Schematic diagram of electrostatic immersion lens-type extraction and the relation between the parameters*

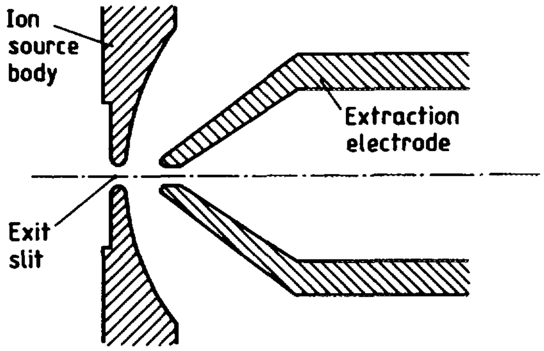
In ion sources (mostly Penning ion sources) with diaphragm-type ion extraction, where the electrodes are shaped so as to reduce the space charge effect in the ion beam, the extracting system is similar to a **quasi-Pierce-type** ion-optical system. The scheme of a probe-type extracting system is shown in Fig.24.

An immersion lens (objective) consists of two electrodes, both with diameter D. One of them is of length h and closed at one end while the other electrode (open at both ends) is placed at some distance from the first. The relations between the parameters of this simple immersion lens are shown in Fig.25 (graph). It can be seen from the figure that for $h<0.785D$, the distance K of the image is negative. It means we have a virtual image: for $h = 0.785D$, the distance $K = \pm\infty$ and for $h < 0.785D$ the image is real and the distance of the image decreases as h increases.

In the optimum case the parameters of the extracting system are chosen so that the total cross section of the ion extracting channel in the electrode is fully utilized while the ion current on the channel wall is diminished. Therefore, the magnification h of the immersion lens defined by

$$M = \frac{K}{2h} \tag{12}$$

should be chosen to have a value close to unity ($K \sim 2h$). For other values of this magnification the transmitted ion current decreases and for its low values the angle of divergence of the ion beam increases on leaving the channel. Under



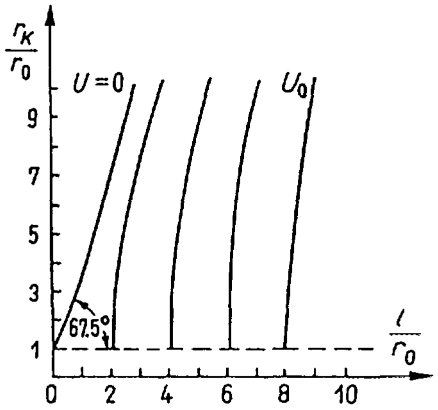


Fig.26 *Diaphragm-type ion extraction and its focusing characteristics*

these conditions, the h and D parameters of the probe-type extraction system are restricted to the values in the range of

$$0.6D \leq h \leq 0.9D \qquad (13)$$

The actual characteristics for J_i ion current versus extraction voltage U_{ext} should be determined experimentally.

The diaphragm-type extracting system is applied in Penning and duoplasmatron ion sources. This system can ensure a precise geometry with a well defined emitter plasma surface, and it can also be used for HF ion sources.

In the Pierce-type optical systems the electrodes are shaped to prevent the divergence due to the space charge effect in intense ion beams. This ion-optical system is based on the principle that the direction of a charged beam between the two surfaces of two concentric spheres with different radii is not affected by the space charge (see Fig.26).

The relation between the extracted ion current J_i and the extraction voltage U_{ext} is given by

$$J_i = KU_{ext}^{2/3} \qquad (14)$$

The most important parameters are the length l of the metal probe (aluminium) sonde and the length h of the quartz sleeve over the metal probe (see Fig.24).

An extraction arrangement of a quasi-Pierce geometry is shown in Fig.26 with electrodes of approximately ideal shape.

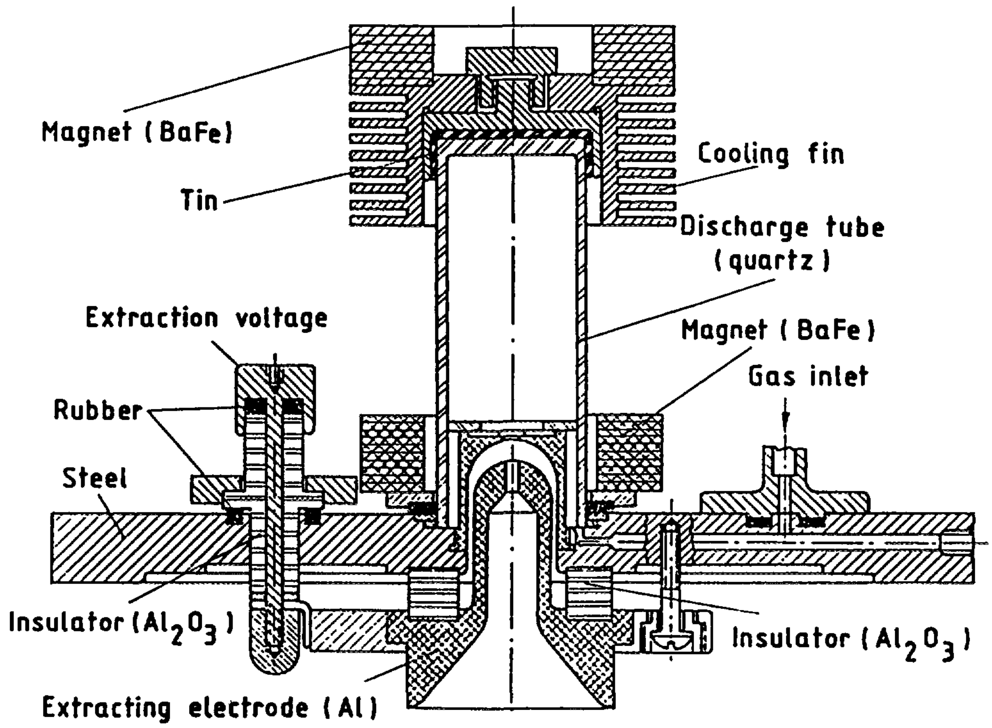


Fig.27 *Capacitively coupled HF ion source with quasi-Pierce extraction*

The quasi-Pierce-type extraction systems consisting of two conical electrodes are used in duoplasmatrons, Penning (PIG) and duopigatron type ion sources with oscillating electrons.

The quasi-Pierce-type extraction system is used with HF ion sources as well, especially in those neutron generators where the HV terminal and the accelerator are placed in a tank under pressure of SF_6 or oil. Fig.27 shows such an HF ion source with high (5-10 mA) extracted ion current.

In an arrangement shown in Fig.19, by applying a frequency of ~ 45 MHz at 100 W output power and U_{extr} = 6 kV, an ion current of 5 mA with a gas consuption of ~ 15 cm^3/h has been achieved [31].

5.3 MAINTENANCE OF GAS DISCHARGE PYREX BOTTLE

After several hundred hours of operation, a thin metallic layer is deposited on the inner wall of the discharge bottle, which can lead to a reduction in the atomic ion ratio of 40 to 50 %. Metals are good catalysts for the recombination of atomic ions; this should be considered in construction of ion sources. The recombination coefficient on a relative scale for most metals is about unity, while for Pyrex: 2×10^{-5}; quartz: 7×10^{-4}; aluminium: 0.3. The surface recombination of the ions at the exit canal is decreased by applying a quartz sleeve that acts as a virtual anode and focuses the positive ions into the channel in the presence of extracting voltage. During the operation, aluminium sputtered from the extraction channel is deposited onto the inner surface of the quartz sleeve, causing an increase in the fraction of molecular ion component to well over 40 %. This means that after a long-term operation (50 to 100 h) the glass balloon and the quartz shield surrounding the canal must be cleaned or changed.

For cleaning, a solution consisting of 80 % HF (40 %) and 20 % HNO_3 (100 %) is recommended. The layer deposited from the inner surface will disappear within 10-15 minutes if the discharge balloon is rotated around its axis horizontally in the presence of a few mm thick layer of the solvent. After cleaning, the balloon should be washed carefully with distilled water. The same procedure is required to clean the quartz sleeve. The metal extractor tips (soldered into the ion source balloons) should not be etched with the HF + HNO_3 solution.

The brownish deposit - carbon layer from the oil vapour - is a very adhesive layer on the surfaces of the glass, and it can be removed only by mechanical procedure.

The aluminium extractor tip (canal) should be changed in every case. The mechanical cleaning of its surface is simpler but the diameter of the hole must remain.

Cleaning the dirty glass parts of the HF ion source usually results in a shorter lifetime of the component. Use the "cleaned" balloons and quartz sleeves only in case of emergency because, after cleaning, they will always give a lower beam current.

Before starting a long irradiation (> 20 hours) always change the extractor tip, quartz sleeve and Pyrex bottle.

5.4 HIGH FREQUENCY OSCILLATORS

The high frequency oscillators in the 15-100 MHz range are coupled to the discharge balloon inductively, while at frequencies >100 MHz they are coupled capacitively. The high frequency oscillators are fed by a ca. 500-1500 V, 0.5 A anode power supply. The active component of the oscillator is an HF triode, tetrode or pentode type transmitter electron valve. The circuit diagram of a simple but reliable oscillator of about 100 W output power is shown in Fig.28. The circuit is a three point type oscillator and it oscillates at about 27 MHz frequency. The coil L_1 is the inductive coupling coil of the oscillator, surrounding the Pyrex discharge balloon of the ion source. The 5 nF capacitor and the coil L_2 protect the anode power supply against the high frequency. The grid and the cathode resistors (7.5 kΩ and 220 Ω respectively) are high power (ca. 20-30 W)

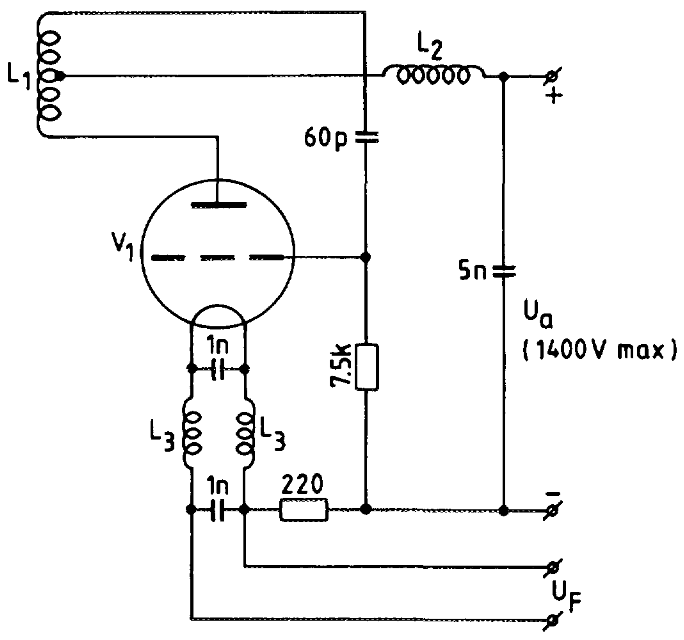


Fig.28 *Circuit diagram of a 27 MHz - 100 W ion source oscillator (V_1 = OT 100 or GL8005; L_1 = 50 mm dia, 2 x 5 windings, 4 mm dia CuAg; L_2 = 18 mm dia, 3 x 12 windings, 0.8 mm dia Cu; L_3 = 18 mm dia, 40 windings, 1.0 mm dia Cu)*

wire wound resistors. The 60 pF resonant circuit capacitor is ceramic high voltage tube type; the 1 nF and 5 nF capacitors are inductance-free disk type.

The shape of the high frequency may be observed by an oscilloscope probe placed in the vicinity of the oscillator. The bandwidth of the oscilloscope should be at least 30 MHz.

To pick up the signal from the oscillator, a simple wire, as aerial, or small coil on the end of the coaxial cable input may be used. Use always the 1:10 probe at the AC input of the oscilloscope to avoid accidental damage to the vertical input. If the shape of the oscillation is not sinusoidal and shows some saturation, this is an indication of the abnormal operation point of the oscillator valve: the tube or the grid resistor should be changed.

A push-pull type oscillator of 100 MHz frequency, using two triodes, is shown in Fig.29. The output power is about 200-250 W, and the circuit forms a grounded-grid, symmetrical oscillator. The metal ceramic plane valves are vented by forced air by a normal fan (like fans in the 19" cabinets) and they are placed in two metal tubes. The feedback trimmers are air insulated disk type; the grid-to-cathode resistors are 50 W wire-wound. The current consumption of this oscillator is about 200-400 mA at the maximum anode voltage. The advantage of this oscillator is the easy and distortion-free output power, which can be changed

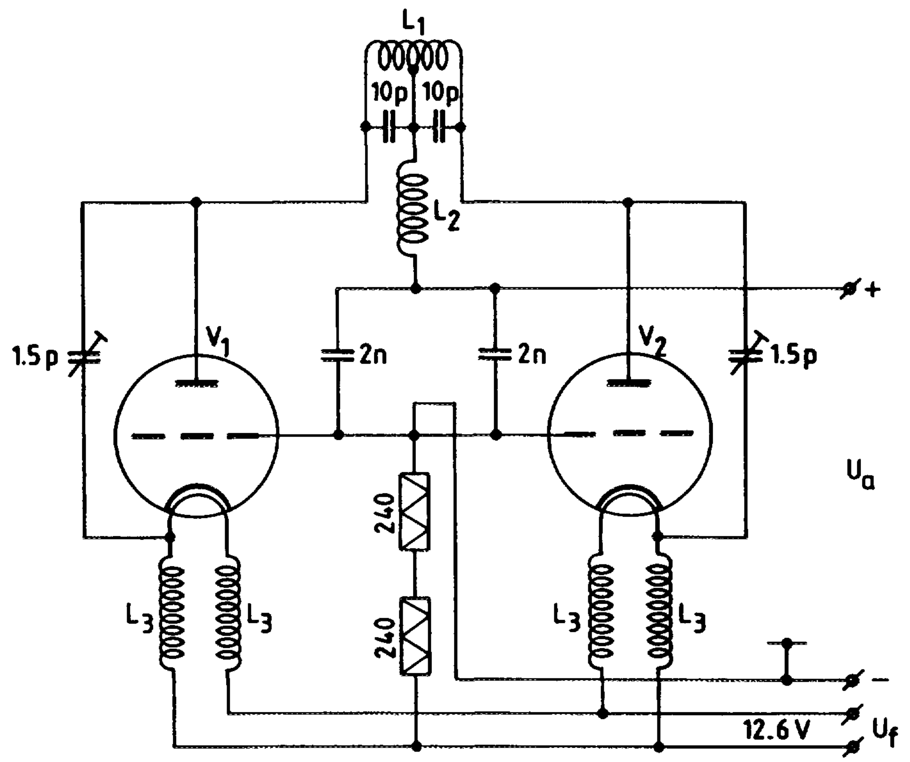


Fig.29 *Push-pull oscillator for HF ion sourceswith 200 W output power (L_1= 40 mm dia, 5.5 windings, 3.0 mm dia CuAg; L_2= 24 mm dia, 4 x 20 windings, 0.6 mm dia Cu; L_3= 20 mm dia, 40 windings, 0.7 mm dia Cu; V_1=V_2= GS-90B or GU-6B or TL2/300)*

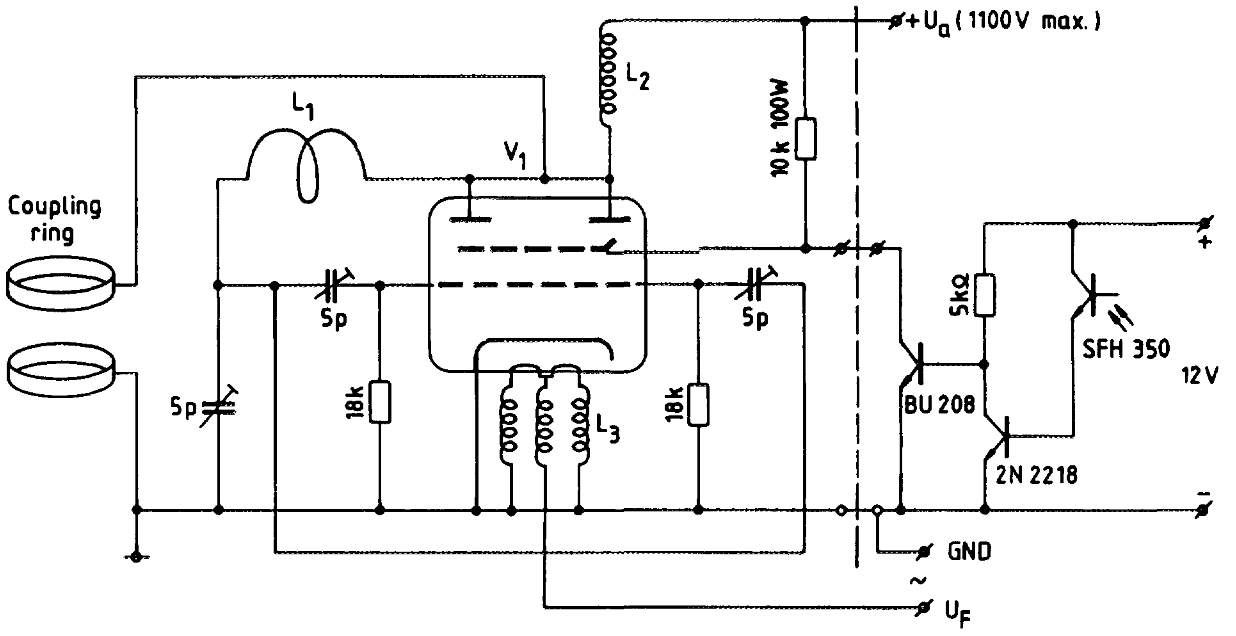


Fig.30 *Capacitively coupled HF oscillator with optical pulser (L_1= 100 mm dia, 2 windings, 4 mm dia CuAg; L_2= 8 mm dia, 50 windings, 0.8 mm dia Cu; L_3= 8 mm dia, 11 windings, 1.0 mm dia Cu; V_1=QQE 06/40)*

by the anode voltage. The diameter of the coil L_1 fits that of the ion source balloon used. This oscillator is utilized at the KFKI neutron generator.

A capacitively coupled oscillator of about 200 MHz frequency is utilized in the SAMES neutron generators. This push-pull oscillator is constructed on the basis of a double tetrode. The output power is coupled to the ion source bottle by two metal rings. The use of the double tetrode allows an easy pulsing possibility by grounding the suppressor grid through a high voltage, high frequency switching transistor, which is driven by an optical cable. For the DC mode neutron generator, disconnect the wire between the suppressor grid to the collector of the BU 208A transistor and ground the collector of the transistor. The optical coupling between the ground and the HV terminal may be light cable or (screened) Perspex rod. The circuit diagram of the oscillator and the pulsing unit's receiver is shown in Fig.30. The transmitter of the light pulser may be a commercial pulse generator-fed infrared LED.

5.4.1 Troubleshooting of high frequency oscillators

The discharge tube (ion source balloon) is made of glass, so the colour of the HF discharge gives information on:

- the vacuum condition of the system
- the condition of the gas supply
- the power of the HF oscillator.

The HF oscillator should be tested if the discharge in the ion source bottle is poor or totally absent but the vacuum system and the gas supply operate correctly. The operation of the oscillator can be detected by a neon lamp or a tube light. If a small neon lamp, fixed on a 20-30 cm long Perspex (or any other isolator) rod is placed near the oscillator (close to the anode or to the coil), the lamp should light when the HF oscillator operates (see Fig.31). A tube light (18-40 W of power) already indicates the output power of the oscillator placed in the vicinity of the HF coil (Fig.32). The tube light will light up if the oscillator works. The intensity of the tube light depends on the output power of the oscillator.

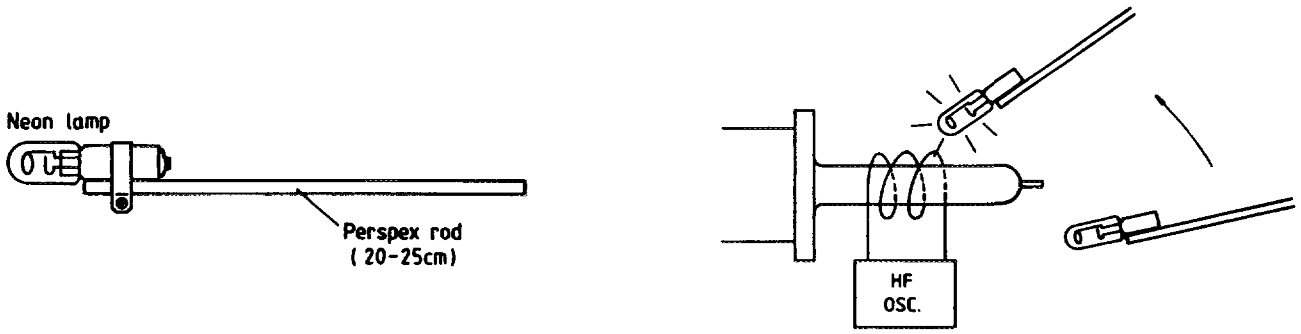


Fig.31 *The neon lamp indicator of HF oscillation*

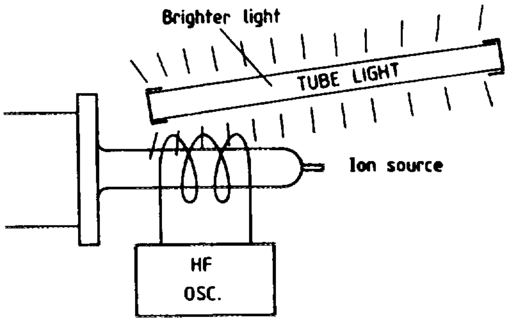


Fig.32 *The use of tube light for testing an HF oscillator*

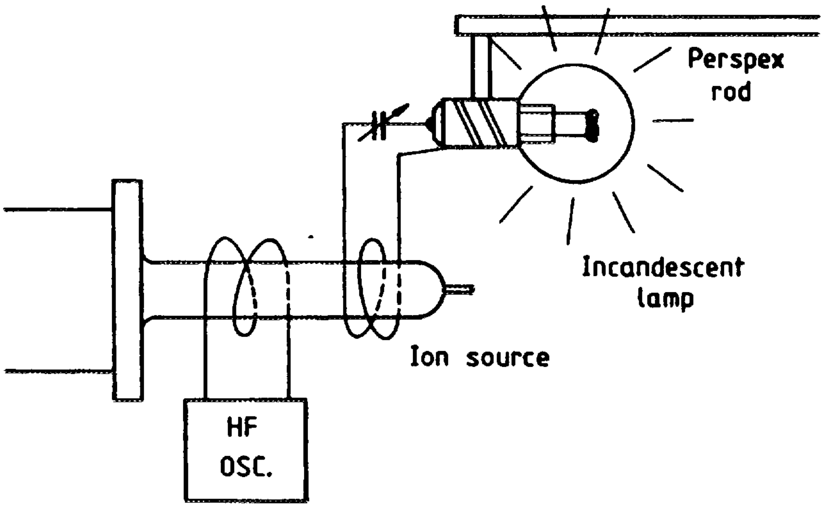


Fig.33 *Qualitative measurement of the output power by incandescent lamp*

The incandescent lamp also gives a qualitative indication of the output power of the high frequency oscillator: for higher power the light is brighter (Fig.33).

If the tube light or neon lamp lights up in the vicinity of the oscillator but there is no light in the discharge tube, this indicates that vacuum is bad (high pressure) in the whole system.

In normal operating conditions the light emitted from the balloon is vivid reddish-violet or bright pink. A light blue colour indicates bad vacuum in the discharge balloon or that the D_2 gas is dirty, containing air.

For testing the neutron generators the use of H_2 gas instead of deuterium is recommended. The difference is only the lack of neutron production on the blind target or constructional parts, which is an advantage when testing and repairing neutron generators. (The bremsstrahlung still exsists!) If the discharge is greyish-pink or light blue and the extraction current shows a weak plasma, it can happen that there is no more D_2 gas in the bottle or that there are problems with the pressure regulator valve (palladium leak, thermomechanical leak or needle valve). If the D_2 bottle has a built in manometer, check the pressure in the bottle.

ATTENTION: All maintenance, troubleshooting and repair on the HV terminal must be done only after first **grounding the HV terminal**. If the terminal is not grounded, the 500-1000 V anode voltage can be lethal. The neon lamp and incandescent lamp may only be used with a sufficient long isolator (Perspex) rod.

When the indicators do not show HF oscillation, the HF oscillator should be checked. Test the following components and parts:

1) All of the electromechanical connections of the oscillator.
2) At power on, check:
   - Filament voltage and current
   - Anode voltage and current
   - Suppressor voltage and current (if it exists).
3) At power off, check:
   - Conductivity between the contacts, coils and along the condensers
   - Resistance of the resistors.
4) The operation of vacuum valve(s) of the oscillator.
5) The operation of the anode power supply.

For capacitively coupled ion sources of some 100 MHz, the twin tetrode QQE 06/40 is used. Because the two anodes are connected by a thick, rectangular, silver plated copper bar which can span the two anode pins, the glass-metal soldering of the anode pin sometimes cracks, leading to the exposure of the vacuum valve to air. If this happens, a larger white area can be observed on the glass wall of the tube, which is caused by the chemical reaction between the getter material and the air. In push-pull HF oscillators - used usually in inductively coupled ion sources - the changing of the two tubes should be carried out simultaneously. A test circuit for determination of the operational characteristics of the vacuum tubes is recommended: the lack of oscillation in the case of a push-pull oscillator may have been due to the poor characteristics (emission) of one or both tubes.

For the repair of HF oscillators always use the same quality components:

- Silver coated electromechanical component should not be used without a reason (e.g. HF coil, anode-, grid- connections, capacitor holder).

- The wire-wound resistors should be changed to the same size and value (in ohms and watts) components.
- The condensers used in the HF oscillators should be inductance-free (mostly mica) and high voltage capacitors.
- The trimmer condensers are usually air insulated. The actual size and details related to the mechanical mounting can be copied from the original solution.
- The some 100 W power of the HF oscillator is high; therefore, for the measurements on an operating HF oscillator do not use electronic (i.e. digital) multimeters. The simple ANALOG MULTIMETERS are recommended.

5.5 PENNING ION SOURCES

The cold cathode arc discharge ion sources with oscillating electrons in the magnetic field are known as PIG-type sources. The operating principle of this source is demonstrated in Fig.34. The K_1 and K_2 plane electrodes are at the same negative potential to the ring-shaped A anode of R radius. The electric field drives the electrons towards the anode. If a magnetic field B with a direction indicated in the figure is also present, the electrons will move along expanding helical trajectories. The maximum radius of the electron trajectory $r_{e,max}$ at given geometrical arrangement depends on the magnitudes of E and B, as well as on the direction of the electron velocity to the magnetic field. With a sufficiently high B value, the $r_{e,max} < R$ requirement can be assured, and thus the electrons from K_2 will continue to proceed towards the K_1 electrode. The negative potential of the K_1 electrode prevents the electrons - which lost a part of their energy in

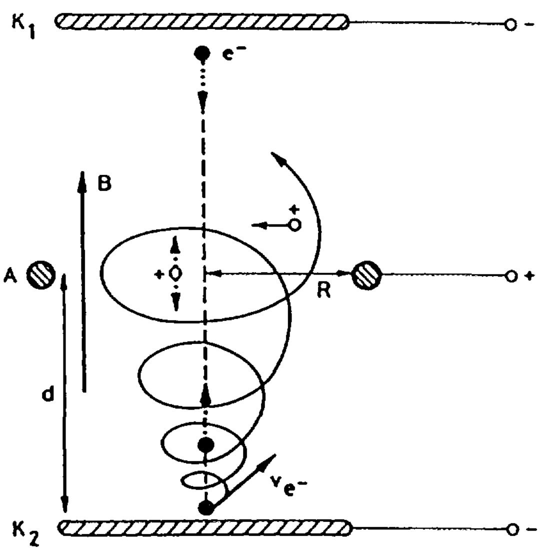


Fig.34 *Operating principle of the Penning-type ion source*

elastic and inelastic collisions - from reaching the surface of K_1, and they will return towards the K_2 electrode. This process is repeated at the K_1 and K_2 electrodes and the electrons create an intense gas plasma by further collisions. If the energy of electrons decreases below a critical value, they can strike the anode.

The number of oscillations n of the primary electrons can be calculated from the $\bar{x}$ mean freee path covered by the electrons in the oscillation [44]:

$$n = \frac{\bar{x}}{2d} \tag{15}$$

where d is the distance between the cathode surface and the anode ring.

The value of depends on the pressure p and the probabilities of the inelastic ω_{ie} and elastic ω_e collisions:

$$\bar{x} = \frac{1}{(\omega_{ie} + \omega_e)p} \tag{16}$$

The number of the collisions will decrease with increasing pressure in the ion source. The mean free path $\bar{x}$ can vary for different gases. For example, for electrons of 100 eV energy in H_2 gas, $\bar{x} \cong 500$ cm ($n \cong 20$); in He gas $\bar{x} \cong 800$ cm ($n \cong 32$); and in N_2 gas $\bar{x} \cong 140$ cm ($n = 6$).

In the case of the Penning source, the extracted beam contains only about 40 to 60 % of atomic ions as a maximum. In spite of the low atomic ion fraction, PIG ion sources are often applied in neutron generators, even for deuteron energies lower than 200 keV, because of their simple construction, cooling, power supply system, inlet gas-flow requirement, and long operating lifetime. The U_a is usually about 5-10 kV; the I_a is in the range of mA. The current from the ion source the density of the plasma - can be regulated by changing the anode voltage. The Penning ion sources are usually equipped with permanent magnets, so they are ideal ion sources for sealed tube neutron generators.

The extraction of the ions from the discharge in the Penning ion sources is usually made by a diaphragm-type extraction system.

The self-maintaining discharge is influenced by the cathode material through the secondary electron emission induced by positive ions striking the surface. Al, Mg, and Be cathodes coated with oxides require low ignition voltage (U_i = 300 to 400 V). The oxide layer can be regenerated by operating the ion source for 10 to 30 min with oxygen gas. The lifetime of oxide cathodes substantially increases if 2 to 10 % oxygen gas is admitted to the ionized gas. Low ignition voltage (400 to 800 V) is required also in the case of Fe, U, and Ti cathodes. Metals suitable

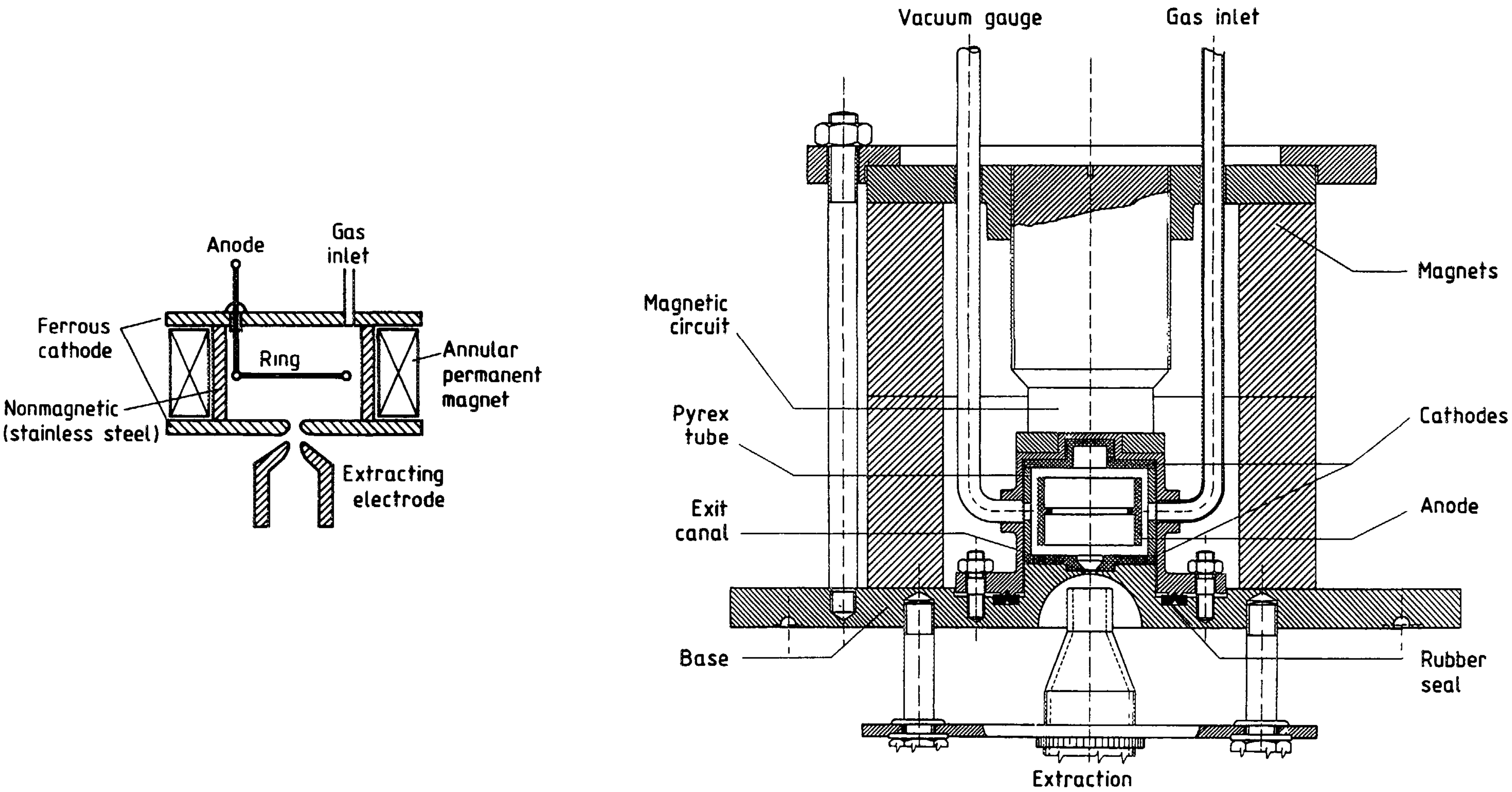


Fig.35 *Typical Penning ion source - schematic (left) and actual scheme (right)*

for use as cathode materials with high U_i values are as follows [44]: Ni, Zn, Al, Cu, C, W, Mo and Ta, for which the ignition voltage is between 3600 and 1700 V. In most cases, Ta cathodes are applied (U_i = 1700 V); however, Mg, Al, and aluminium alloys have also been used as cold cathode material because of their high sputtering thresholds [46].

A cold cathode PIG ion source with axial extraction is shown in Fig.35. A magnetic field of about 0.03 to 0.7 W/m^2, supplied either by a permanent magnet or by a solenoid, is applied between the electrodes. The PIG sources are operating with gas pressures in the discharge volume of 0.1 to 2.5 Pa at gas consumption of 20 to 500 cm^3/h NTP. A typical PIG source can operate continuously over 200 h at about 2 mA beam current without the need for replacing the cathode or anode.

A typical HV power supply feeding a Penning ion source is shown Fig.36. Since the ion source requires a $U_p \sim 10$ kV potential, this high voltage is usually produced by a voltage doubling circuit.

5.5.1 Troubleshooting of Penning ion sources

The **problems** causing improper operation of this ion source can be divided into three groups: **magnetic, mechanical, electric.**

The **magnetic** problems are caused by the decreased field strength of the permanent magnet so that the radius of the electron trajectory increases - resulting in a lower discharge current I_p than during normal operation at the same U_p voltage. Similarly, every shunting of the magnetic circuit will have similar effects.

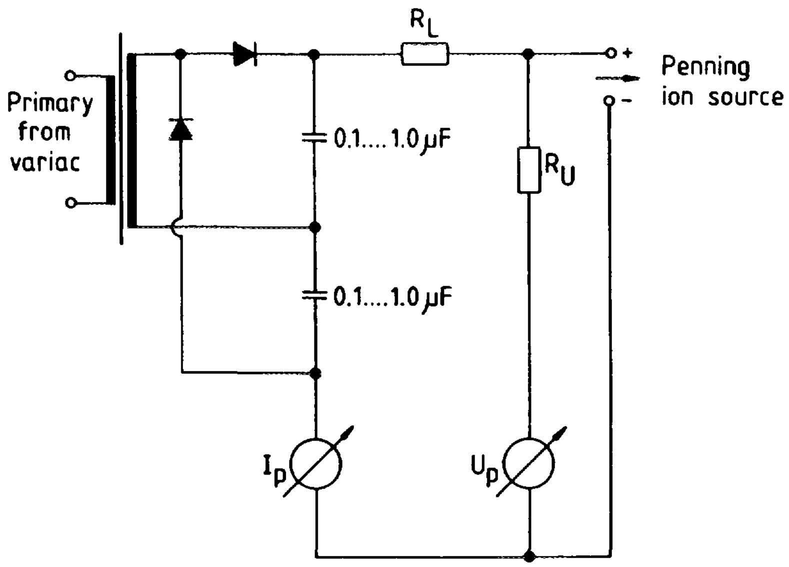


Fig.36 *A voltage-doubling HV power supply of a Penning ion source*

The **mechanical** problems may be caused by:

- contaminated cathode surface (due to the oil vapour in the vacuum system),
- alteration of the original anode-ring-cathode geometry,
- a change in the geometry or surface properties of the extraction slit.

The **electrical** problems can be caused by the:

- HV power supply: transformer, rectifiers, condensers, limiting resistor R_L,
- HV connectors: on the HV supply or on the Penning ion source (the HV feedthrough),
- HV cable between the power supply and the ion source.

Testing the **magnetic** circuit needs some magnetic field measuring instrument, but the field strength in the ion source must not be tested directly. Some iron objects (bolts, screws, etc.) accidentally bypassing the magnetic circuits can be observed visually, while the magnetic short circuits inside the ion source can be found only after dismantling the source.

If the source is opened, carefully clean the ceramic HV leadthrough, the cathode and the anode surfaces. The oil deposit on the cathode can be removed only by sandpaper and polishing paper. After drying the surfaces, clean them with organic solvents. When the components are dry, assemble the ion source. If the extraction slit becomes bored out by backstreaming secondary electrons, replace the plasma extraction cup with a new orifice insert (if it was used in the original ion source). Test the mechanical position of the extraction electrode.

The electric test of the power supply and the ion source requires a high voltage voltmeter (up to 30 kV) and a MΩ meter, using a couple of hundred volts.

Test the HV transformer, the rectifiers and the condensers. The components can be checked with a normal, everyday multimeter through an HV probe. The resistors R_L and R_U can be tested similarly with the same multimeters. Test the HV cable and the connectors under working conditions as well. The operation, the insulation of the HVPS and the source can be tested at atmospheric pressure. If the system seems to be working electrically normally the fault should be searched for elsewhere, for example in the gas supply or in the vacuum system.

6.0 DEUTERIUM LEAKS

The ratio of atomic to molecular ions depends on the operating time of the ion source, the pressure in the discharge volume, and the purity of the gas entering the plasma. A carefully designed pressure regulator must be applied to guarantee the stable flow rate and the purity of the gas during long operation time. The three most commonly used deuterium leaks in neutron generators are **palladium leak, thermomechanical leak** and the **needle valve.**

The palladium leak can be utilized for the regulation of hydrogen gas (isotopes) flow which discriminates against other gases. The thermomechanical leak and the needle valve are suitable for the regulation of all types of gases. As the neutron generator uses deuterium for feeding the ion sources, all of these leaks may be found in the vicinity of the ion sources on the high voltage terminal.

6.1 THE PALLADIUM LEAK

One of the best gas regulators is the "palladium leak", constructed of palladium-silver alloy [2]. Palladium has temperature-dependent permeability to the passage of hydrogen isotopes and discriminates against contaminant gases between 300 and 400°C. Characteristics of the H_2-Pd system make it possible to supply the low intensity RF and PIG ion sources with the necessary amount of hydrogen or deuterium gases at a consumption of 10 to 20 cm^3/h NTP. Permeation of hydrogen through a palladium tube of 2 mm diameter, 100 mm length, and 0.1 mm wall thickness is about 5 cm^3/h at 400°C, which value is enhanced significantly by the use of Pd-Ag alloy. The rate of permeation of hydrogen through palladium is higher than that of deuterium, the ratio P_H/P_D ranging from about 1.2 to 2.5 depending on temperature and the condition of the Pd metal [47,48].

The usual setup of a palladium leak consists of a palladium tube closed at one end which is heated either indirectly by a separate heater spiral or directly by resistance heating. The palladium metal has special features: about one litre of hydrogen gas can be absorbed by one gram of palladium. The two usual constructions of Pd leaks are shown in Fig.37.

The indirectly heated palladium leak manufactured of glass is usually connected to heavy water electrolyzers. The directly heated Pd tube is placed inside a high pressure D_2 tank.

A common disavantage of palladium leaks is ageing. After about 150-200 h operating time the transparency of the palladium will decrease at a given temperature and the leak gives a lower D_2 flowrate. If this takes place the heating of

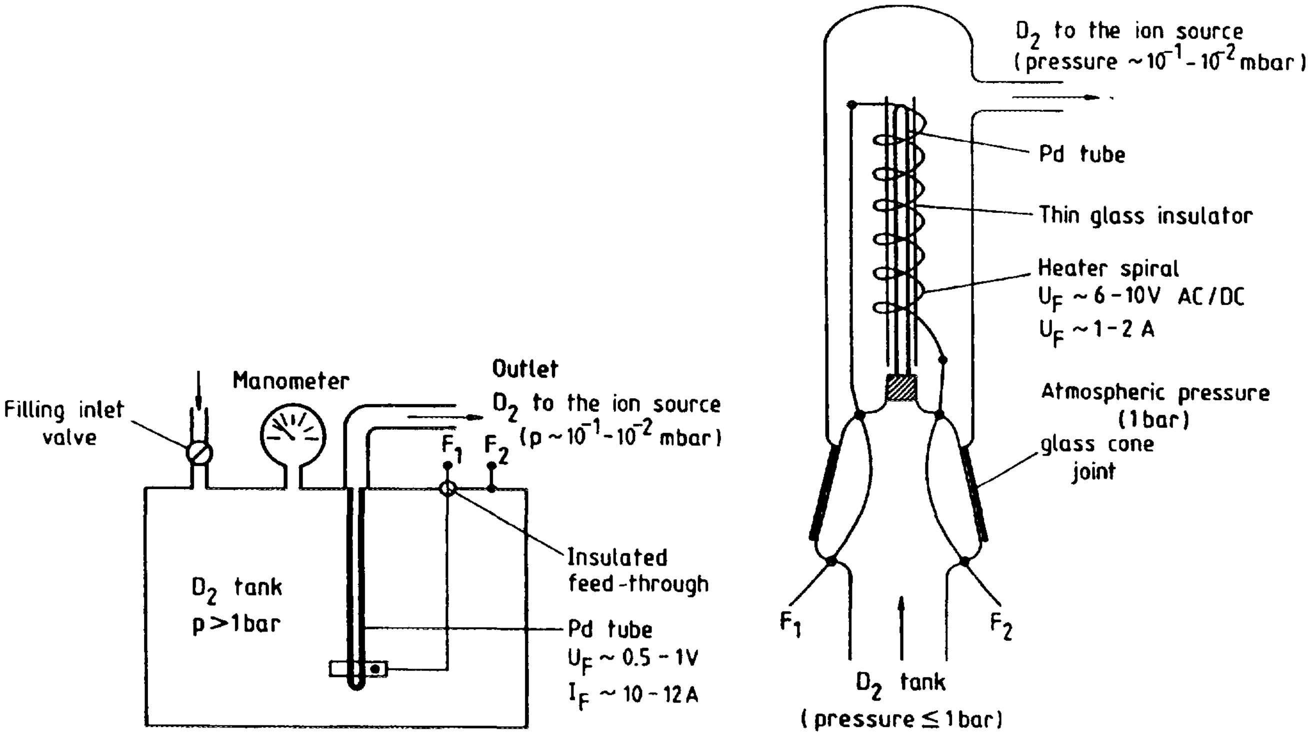


Fig.37 *Directly and indirectly heated Pd leaks*

the Pd tube should be increased. As the heating in both cases (indirect and direct) is resistive, the heating can be increased by changing the heating voltage or by reduction of the resistance of the heater.

In the case of an indirectly heated Pd tube, the heater spiral should be shortened (cutting off 10-20 % of length). In direct heating, the palladium tube itself is the load of the low voltage power supply (transformer): the Pd tube resistance can be decreased by sliding the isolated F_1 contact towards the lid of the D_2 tank. Shortening the original tube length by 20-50 % is a successful solution for improvement of the maximum D_2 transparency of the Pd leak. At a given potential difference the energy is dissipated in the resistor at a rate $I_0^2R_0$, and so, if $R = R_0/2$, then $I = 2I_0$, i.e. the energy is doubled.

The glass-ware palladium leaks may break. If they do, lower pressure - vacuum or ion source - side should be tested by usual vacuum testing if there are improper (gray coloured) gas discharges in the HF ion sources. The vacuum testing of directly heated palladium leaks is carried out in a similar way. In the case of an overpressure greater than 1 bar D_2 in the tank, the sealing of the tank should be adequate. All of the seals at the connection of the manometer, the tank closing valve and the heater electrode should be checked regularly.

In the case of defective operation of the palladium leak (if the operation of the ion source shows some problems related to the gas supply) test the following:

- The colour of the discharge of the HF ion source: if the discharge is weak and is slightly pink, the gas supply is not adequate - e.g., the electrolyzer does not work properly, the filling valve is leaking and the D_2 gas is exhausted or the heating power is not enough (contact failure).
- The palladium (tube) leaks: this can be observed if the discharge in the ion source bottle cannot be extinguished by switching off the filament. A hole in the thin wall palladium tube can be detected by usual vacuum leak testing methods, and the repair requires **soldering with silver** at the workshop of a **precision goldsmith** if there is no replacement for the defective Pd.

6.2 THE THERMOMECHANICAL LEAK AND THE NEEDLE VALVE

These two mechanical leaks have two major problems: they can fail to close properly or they cannot be opened. Their repair requires a well equipped precision mechanical workshop and an experienced tradesman. The electrical troubleshooting of a thermomechanical leak is similar to that of a palladium leak. The high flow rate in the case of a closed valve can be caused by stain or dirt in the canal of the leak. The dismantling, cleaning and assembly should be carried out with precautions. Anybody who is not familiar with the structure of these leaks must not open them for cleaning or repair. The best solution for the repair of these elements is to send them back to the manufacturer for repair and readjustment.

6.2.1 The thermomechanical leak valve

The operation of the thermomechanical leak is based on the differential thermal expansion coefficients of different materials. The leak itself consists of a metal ball held by a ceramic rod against a precision seat with an orifice. The orifice and the ball form the valve seal. The outer cylinder, the container wall around the ball and the ceramic rod are directly heated electrically. The expansion of the cylinder is greater than that of the ceramic rod, so the seal between the ball and its seat will be gradually opened.

The leak rate of the thermomechanical leak valve depends on the temperature of the outer wall of the leak, i.e. on the electric current used for heating the wall. In the case of a heating current switch-off or power failure, the ball will be reseated to the seat and the valve closes. In the case of an electric power cut-off, this valve will protect the neutron generator against exposure to atmo-

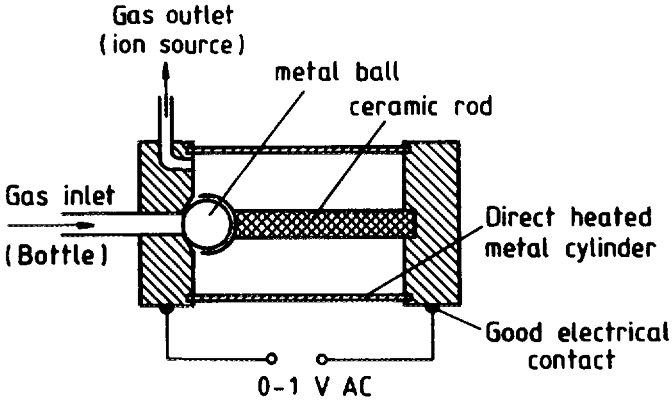


Fig.38 *Schematic diagram of a thermomechanical leak valve*

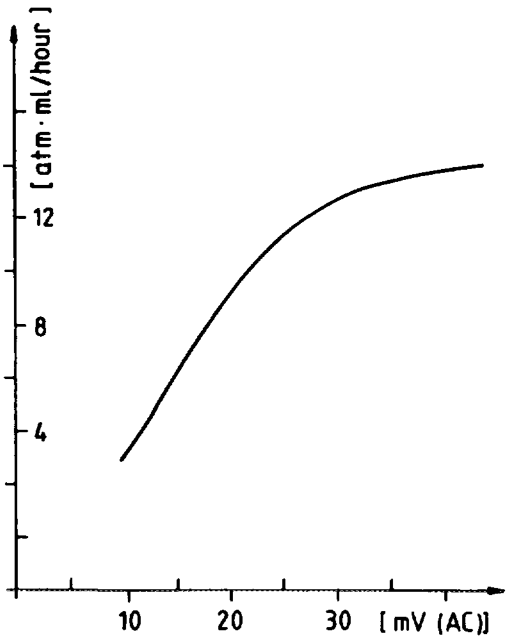


Fig.39 *The leak rate vs heating voltage of a thermomechanical leak*

spheric or D_2 pressure. The operational principle of a thermomechanical leak is shown in Fig.38.

The thermomechanical leak is a precise component and therefore the concurrent exposure to corrosive gases and atmospheric moisture may damage the valve. A typical leak rate (torr l/s) or gas consumption (bar ml/h) is shown in Fig.39 as a function of the heating voltage of the outer wall of a thermomechanical valve.

6.2.2 Maintenance and troubleshooting of thermomechanical leaks

The thermomechanical leak valves should be connected to the vacuum system (ion source) in a correct way relative to the direction of the gas flow. The direction of the gas flow is usually indicated on the valve. Flush the thermomechanical leak valve with dry nitrogen (or other dry gas) in the case of uncertain operation. Check the electric contacts of the leak valve. As the heating current of the cylinder is usually higher than 10 A, the electrical connections should be checked and cleaned regularly. As accurate AC current measurement in the range of several tens of amperes is not simple (it can be done by a digital clampmeter for AC heating current), calibrate the heating voltage along the cylinder while it is working properly. The voltmeter contacts should be separately connected to the cylinder: in case of a bad contact between the filament transformer and the leak body, this voltmeter will indicate the condition of the contacts. **Opening the welded body may kill the whole leak valve.**

In case of lack of heating test the following:

- The primary side of the stepdown transformer (voltage and current)
- The secondary voltage across the leak valve (it should be the nominal value)
- The voltage drop across the secondary coil and thermomechanical leak contacts. There should be a small (~ 1-10 mV) voltage drop along a good contact.

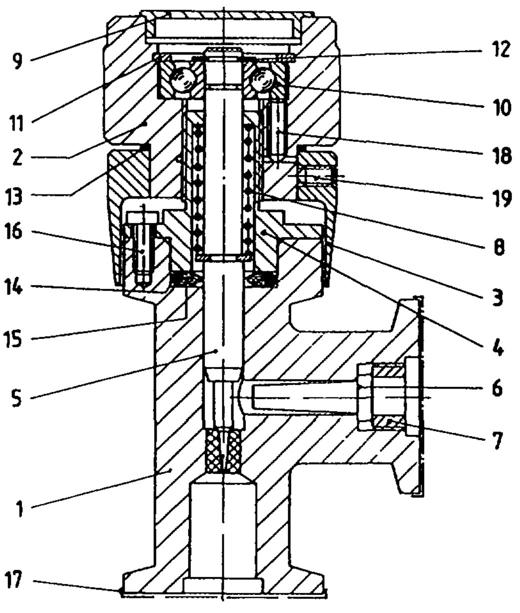
If the contacts are defective, clean them and test again.

If there is a grayish-pink discharge in the RF ion source, check the vacuum and deuterium connections. If these connections are in good condition, there may be some cracks along the body of the leak.

6.2.3 Needle valves

Needle valves are used for controlled admittance of fine gas flows into the ion sources. They can be operated either manually or electromechanically. Reliable and popular needle valves for ion sources are the BALZERS EVN 010 H1 and EDWARDS FCV 10K types. The variable leak needle valve of VARIAN includes a movable piston with an optically flat sapphire which forms a variable seal completely free from friction, seizing and shear. All these valves can be used for very fine gas streams for adjustment of the gas pressure in the ion sources. The fine adjustment of the stream is performed by adjustment of the position of the needle or the sapphire piston. The movement of the needle is controlled through a threaded shaft or a threaded shaft-and-lever mechanism having a mechanical advantage of up to 10,000 to 1 [49].

For a BALZERS EVN 010 H1 valve an exchangeable, easy-to-clean dust filter is fitted into the lateral small flange port by which the valve can be connected to the gas bottle of the ion source. The main parts of the valve are made of stainless steel or rustproof material, and the valve seat is made of lead. In a closed position the valve needle is forced into the preformed conical seat by a spring



1 HOUSING	11 GUARD RING
2 KNOB	12 LOCKING WASHER
3 SCALE DRUM	13 NEOPRENE O-RING
4 SOCKET	14 VITON O-RING
5 NEEDLE	15 SEAL
6 FILTER	16 SCREW
7 NUT	17 COVER
8 SPRING	18 THREADED PIN
9 COVER	19 THREADED PIN
10 BALL BEARING	

Fig.40 *A typical needle valve*

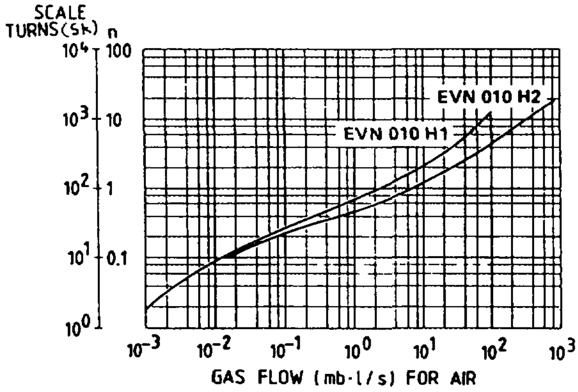


Fig.41 *Gas flow rate curves for BALZERS needle valves* [49]
(Sk= scale marks of the micrometer-like scale drum
n= number of turns of flow rate adjusting knob)

which ensures a constant closing pressure. Over-tightening the valve during closing may damage the needle and/or the valve seat. Moving axially in one direction the needle is coupled to the actuating knob over a ball bearing. The fine thread of the knob ensures that the needle is lifted reproducibly from the seat. The scale ring and actuating knob are coupled to each other for easy adjustment. This allows a simple setting of the opening point at any time and marking a specific gas flow as 0-point for accurate reproducibility. Usually, the adjustment of this valve tends from a maximum conductance of ca. 130 mbar l/s to a minimum of 1×10^{-9} mbar l/s NTP (i.e. the leak rate in closed position). The construction of the needle valve is shown in Fig. 40 [49]. The gas flow rate - the air admittance - of the EVN 010 H1 (and EVN 010 0 H2) is shown in Fig.41.

The conductance of a needle valve depends on the viscosity of the gas to be admitted into a vacuum chamber. If gas other than air is used, the original calibration curve can be utilized only by taking into account the viscosity of the given gas related to air. Table 13 shows the viscosity of the most frequently used gases [49].

Table 13.
Viscosity of the most frequently used gases

Gas	η Viscosity[Poise]	K = η air / η gas
Air	180	1
Nitrogen	173	1.04
Carbon monoxide	172	1.05
Oxygen	200	0.9
Carbon dioxide	145	1.24
Hydrogen	87	2.07
Water vapor	93	1.97
Helium	194	0.93
Argon	220	0.82
Crypton	246	0.73
Xenon	225	0.8

For a laminar gas flow in the needle valve, the following equation can be used for correction of the flow rate Q of the admitted gas:

$$Q_{gas} = \eta_{air} / \eta_{gas} \times Q_{air} = K \times Q_{air} \quad [\text{mbar l/s}] \qquad (17)$$

Example 1:

For a neutron generator, where the ion source should be fed by deuterium gas ($\eta D_2 \cong \eta H_2$), the preset conductance of 10^{-1} mbar l/s for air (Sk scale mark of needle valve EVN 010 H1 is about 13, based on Fig. 41) will be higher than for air owing to the K value of hydrogen (2.07).

As Fig.41 shows the gas flow is higher than 0.001 mbar l/s, a flowrate below

this

value can be set reliably if a vacuum gauge is used. The gas flow can then be calculated on the basis of

$$Q = \Delta p \times S \text{ [mbar l/s]} \qquad (18)$$

where the gas flowrate is Q [mbar l/s]. the pressure change in the vacuum chamber is Δp [mbar] and the pumping speed of the vacuum pump is S [l/s].

Example 2:

If the pressure in the vacuum system is increased from a value of 2×10^{-6} to 3×10^{-6} mbar and the pumping speed is 100 l/s, the value of Q will be:

$$Q = 10^{-6} \times 100 = 10^{-4} \text{ [mbar l/s]} \qquad (19)$$

Gas flows below 10^{-4} mbar l/s can be set relatively easily by means of a vacuum gauge. Experience has shown that a lower limit of ca. 10^{-6} mbar l/s can be reached, but that the long term stability of the valve begins to decline at gas flowrates below 10^{-5} mbar l/s.

6.2.4 Maintenance of needle valves

Needle valves do not require any maintenance, in general. In the course of time, however, some contamination effects will become apparent. Very fine dust particles can still pass through the filter of the inlet port of the needle valve and they can settle in the gap between the needle and the needle seating. Adjustment of the low gas flows becomes difficult and the leak rate of the closed valve deteriorates. These symptoms indicate that the valve requires cleaning.

The dismantling and cleaning procedure of needle valves is described for BALZERS EVN 010 H1 type valve in the manufacturer's Manual [49].

a) Dismantling the valve (see Fig.40)

- Take off the cap (9) from the actuating knob (2)
- Remove locking washer (12) from spindle needle (5)
- Unscrew knob (2) with scale drum (3) counterclockwise from sleeve-socket (4)
- Remove screws (16) and sleeve-socket (4)
- Pull out carefully spindle (5) together with spring (8) and K (shape) ring (14) from valve body (1)
- Undo the screw (7) and remove filter (6).

b) Cleaning the dismantled valve parts

Wash needle (5) seating, filter (6) and the hole in the valve body (1) with chloroethane or similar, using a soft brush. Carefully remove any deposits from the needle using a soft tool of wood or plastic. Then rub the needle vigorously but carefully with a cloth drenched in solvent cleaner. Make sure the needle surface is clean and smooth.

IMPORTANT NOTE: DO NOT BEND THE NEEDLE DURING THE CLEANING !

Rinse all parts in alcohol or acetone (in an ultrasonic bath if possible) and dry them. Blow out the seating with clean compressed air or hair dryer. Be sure that the seating surface is score-free and smooth. Wipe the holes and sealing surfaces of sleeve (4) and valve body (1) with lint-free cloth drenched in alcohol, remove all dirt and dust. Finally rinse O-ring (15) and K-ring in alcohol or acetone (if possible in an ultrasonic bath).

c) Reassembling the valve

- Slightly grease O-ring (14) and K-ring (15) with Flombin grease (or silicon grease) and slide them onto spindle (5).

Be sure to protect the needle from contact with lubricant !

- Carefully insert spindle needle (5) with washer under the spring into the valve body (1) until needle rests in the seating
- Slide spring (8) onto spindle (5)
- Fasten sleeve (4) to valve body (1) using screw (16)
- Screw actuating knob (2) with scale drum (3) clockwise onto sleeve (4) until groove of spindle (5) protrudes clearly over ball bearing (10)
- Attach locking washer (12)
- Close the actuating knob (2) with cap (9).

d) Adjusting the spindle clearance

- Take off the cover-cap (9) from the actuating knob (2)
- Remove locking washer (12), guard ring (11) and ball bearing (10)
- Adjust clearance with threaded pin (21)
- Assemble in reverse sequence.

e) Testing the needle valve after cleaning

- Open and close the valve about 10 times to compensate for any rough spots.

The leak-tight valves should fulfill two requirements:

- Leak tightness of the valve seat in closed position (needle/seating)
- Leak tightness between valve interior and valve surrounding.

Tightness of the second type is less important because such leaks merely result in gas losses to the atmosphere if the needle valve is used to regulate the gas consumption of ion sources from gas tanks of more than 1 bar pressure.

If the valve operates correctly it must be possible to alter the gas flow smoothly, without steps. If the direction of the rotation is changed the valve must react immediately. The values of the calibration curves for 0.01 or 0.1 mbar l/s should be reproducible within about 10%.

f) Leak testing the valve with vacuum gauge

The leak-tightness of a valve can be checked with the vacuum gauge which is normally installed in any vacuum system.

- **Valve seat:** Evacuate the closed needle valve to a low pressure and close the gas inlet flange with a blanking plate. Open the valve slowly about five turns to evacuate also the valve interior. Close the valve and wait until the pressure stabilizes. Remove the blanking plate abruptly and observe the meter. If there is a leak at the valve seat there will be a pressure rise in the vacuum chamber which will be indicated by the meter.
- **Valve interior:** The valve interior is sealed by a K-shaped ring, the K-ring. Again, the gas inlet flange must be closed by a blanking plate and the valve opened. If the valve interior is leak-tight, the same pressure must be reached irrespective of whether the valve is open or closed. As mentioned above, a leaking valve interior only means a certain loss of the gas admitted.

Compared with the results obtainable with sensitive leak detectors, this testing method yields a relatively low detection limit. For qualitative testing this is normally sufficient because leaks, which would be detrimental to the vacuum system, can be detected easily by a vacuum gauge. Leaking valve seats can only be repaired by the manufacturers. Leaks in the valve interior are mainly caused by contaminated or damaged seals.

g) **Testing leaks with halogen or helium detector**

- **Valve seat:** Connect the closed valve to the leak detector and admit test gas into the gas inlet port via a fine (dust) filter.
- **Valve interior:** Cover the gas inlet port with a blanking plate and slowly open the valve about five turns. This also evacuates the valve interior. Now, blow the outside of the valve with test gas.

If the valve is in good condition, the leak-tightness values must reach the technical data. Similar halogen or helium leak testing procedures can be used in thermomechanical valves.

6.3 CALIBRATION OF LEAK VALVES: GAS CONSUMPTION MEASUREMENTS OF ION SOURCES

In the case of abnormal operation of leak valves, their transmission should be tested. The gas consumption of the ion sources is usually measured in a practical unit of ml/h NTP (Normal Temperature and Pressure), i.e. 20°C and 1 bar; the gas consumption unit is ml bar/hour, which can be converted into the usual flow rate, pumping speed unit of l mbar/s . The gas consumption of the HF or Penning ion sources at the neutron generators is in the range of 1 to 10 ml/h NTP, while the duoplasmatrons and other high current ion sources consume 10 to 100 ml/h NTP gas. This means, the leaks should assure the gas flow into the ion sources in the range of 1 to 100 ml/hour NTP gas. The U shaped manometer - which is the usual equipment for determination of the pumping speed of the vacuum pumps - can be used for the measurement of the gas consumption and the characteristics of the gas adjusting valves. For the determination of the gas consumption

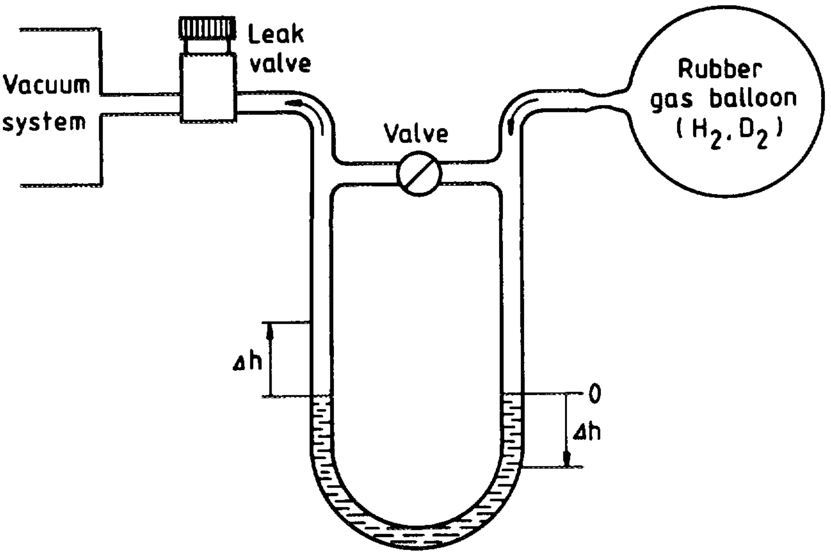


Fig.42 *Setup for the measurement of flow rate of ion source leaks*

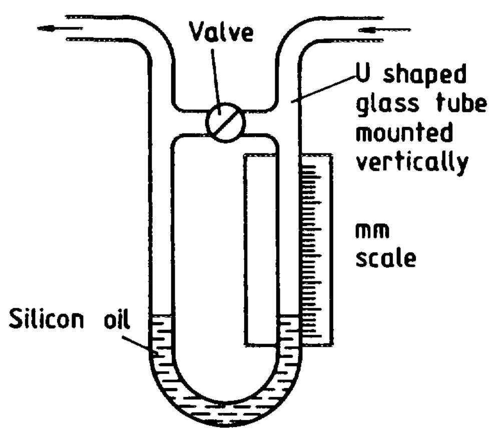


Fig.43 *The U shaped glass tube manometer used to determine the pumping speed and gas consumption of ion sources through the measurement of the flow rate*

of the ion sources, a good gas adjusting valve, the U shaped manometer and an extra gas container (usually plastic balloon) is needed (Fig.42).

The setup with the U shaped glass tube filled with silicon oil for the calibration of gas leaks and pumping speed measurements is shown in Fig.43.

The valve connecting the upper part of the U shaped manometer serves to equalize the pressure in the two separate vertical legs of the manometer.

6.3.1 Measurement

Regulate the gas leak for the required value of the gas flow. This can be detected, for example, by the optimal colour gas discharge in the HF ion source. The valve connecting the two legs of the U tube is open. The flow rate (gas consumption of the ion source) can be measured in such a way that the volume of the gas entering from the plastic balloon into the gas leak valve (into the ion source) in a given time will be determined.

Close the valve which bypasses the legs of the U tube manometer and start a stop watch. The gas entering into the leak valve will flow from the left leg of the U tube, causing a pressure drop against the right leg of the U tube. The level of the silicon oil will rise at the left hand side and decrease at the right hand side. While waiting for an easily observable volume of gas consumption (say 1-3 ml) stop the stop watch. If the fall of the silicon oil level took a time Δt, the flow rate through the gas leak (the gas consumption of the ion source) will be

$$x = \frac{d^2 \pi \Delta h}{4 \Delta t} \qquad (20)$$

where d is the inner diameter of the U shaped glass tube. If the diameter d and the Δh oil level change is measured in cm and the Δt time in hours, the flow rate and the gas consumption of the ion source will be given in ml/h NTP. This unit is suitable for other purposes as well: based on the consumption, the normal operation time of an ion source (neutron generator) can be calculated from the D_2 gas container volume.

The gas flow rate value may also be calculated for other pressures. In the case of a needle valve the adjustable flow rate is usually given at lower pressures, e.g. in mbars. This measurement makes it possible to check the characteristics of leak valves given in manufacturers' data sheets and their recalibration after repair.

The U shaped tube filled to half height with silicon oil is also a useful tool for determination of the pumping speed of vacuum pumps. Pumping speed measurements will be found in Section 9, which describes the vacuum systems and vacuum components of neutron generators.

7. DEUTERIUM ELECTROLYZERS

Deuterium gas needed for the operation of neutron generators is commercially available, but many laboratories produce their own D_2 gas to supply their accelerators. The deuterium consumption of a RF or Penning ion source is below 10 ml/h NTP, while a duoplasmatron needs about 20-100 ml/h. These gas consumptions can be satisfied by a simple laboratory electrolyzer. The Toshiba and the KFKI neutron generators even have their own electrolyzers with palladium leak on the HV terminal to supply the HF ion source.

The Toshiba neutron generator uses a heavy water electrolyzer of a few ml heavy water with a built-in palladium leak. The construction of this Pd leak with heavy water electrolyzer is shown in Fig.44 [50] .

The production rate of the electrolyzer can be adjusted by setting the conductivity, the pH value, of the heavy water electrolyte. The solution is usually alkaline: by putting a couple of KOD or KOH tablets into the heavy water. If the electrolyzer produces more deuterium gas than the consumption of the ion source, the water level will sink in the central glass tube and the cathode contact will be cut off.

This electrolyzer works normally if the conductivity of the electrolyte is set up properly, i.e. in the 0.2 Ω^{-1} cm^{-1} range. A part of the tip of the cathode electrode is immersed in the electrolyte, which can sometimes cause a KOH deposit formation on the cathode surface. This insulating layer can prevent the

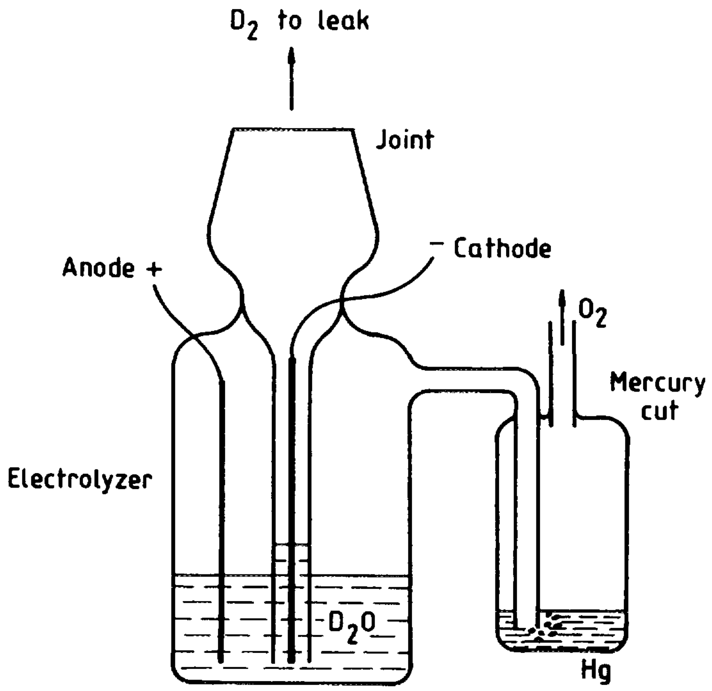


Fig.44 *Heavy water electrolyzer of the TOSHIBA NT-200 neutron generator*

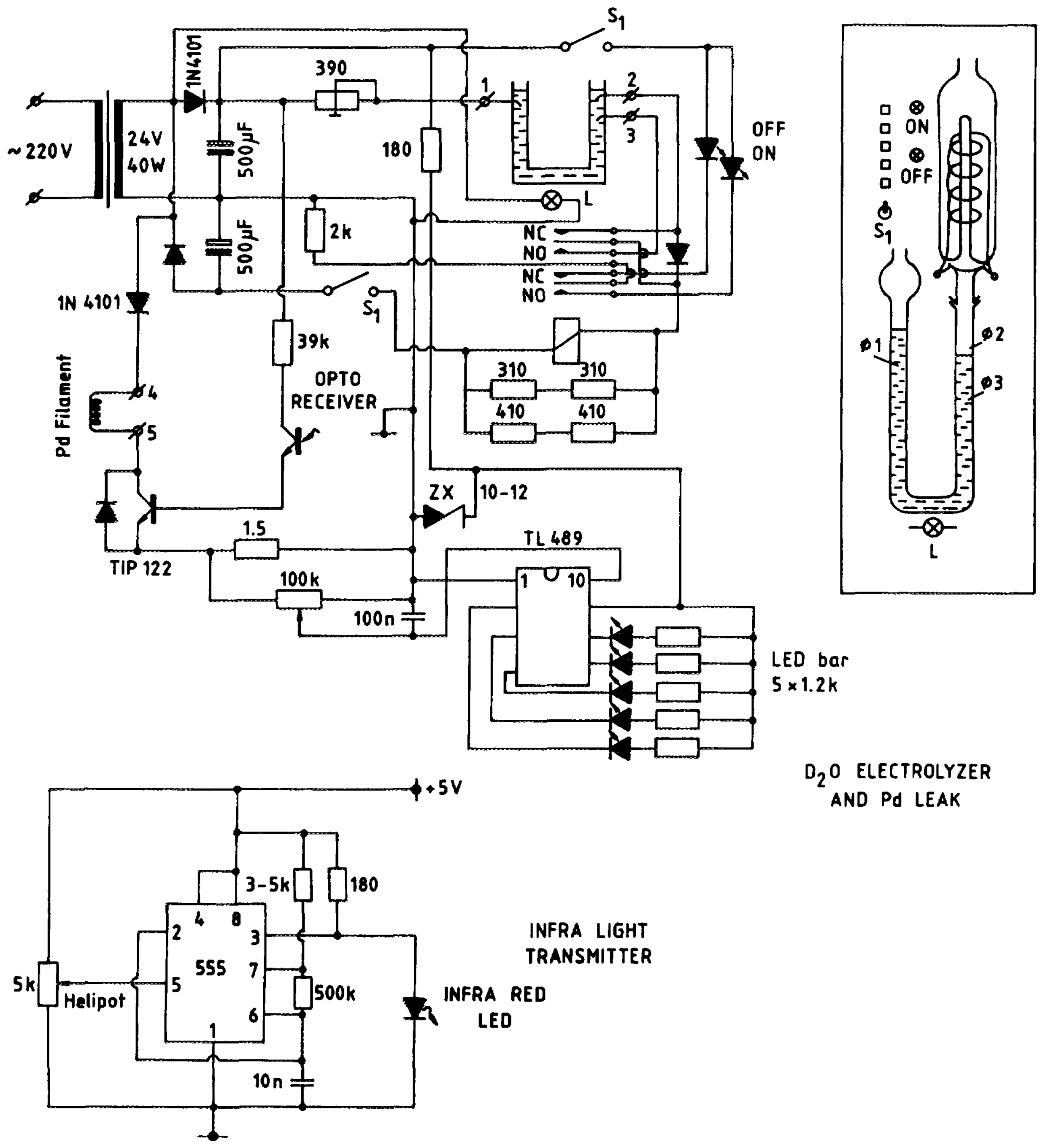


Fig.45 *Optical fiber isolated Pd leak control and electrolyzer for the deuterium supply of ion sources on the HV terminal*

flow of the electric current from the electrolyte, especially if the neutron generator has been out of action for a long time.

This disadvantage of the simple electrolyzers was eliminated by KFKI [51] in their U shaped electrolyzer-Pd leak system, by using two cathodes. The upper cathode (electrode No.2 in Fig.45) switches on a relay which remains switched on through the lower cathode of the electrolyzer (electrode No.3 in Fig.45) until the electrolyte level sinks under the level of the tip of the lower cathode. As the electrolyte level rises again up to the upper cathode - due to the gas consumption of the ion source - the relay switches on and the electrolyte level sinks again due to the operating condition. Using this hysteresis principle of the KFKI electrolyzer, a heavy water electrolyzer-Pd leak system with optical fiber connection for the regulation of the deuterium flow into the ion sources has been constructed. This system can be used for the gas supply of the HF, Penning and duoplasmatron ion sources. The circuit diagram of the system is also shown in Fig.45 [52].

The electrolyzer works on the hysteresis principle described above. The heater of the Pd tube is controlled by a switching (Darlington) power transistor. The on-off ratio of the transistor is controlled through a LED phototransistor optical link by an astable multivibrator at the ground potential. The optical connection can be a simple 3 mm diameter Perspex rod or plastic (insulating) fiber cable which endures the high voltage differences between the electrolyzer (on the HV terminal) and the LED driving pulse generator (at the ground potential of the control desk). The effective heating current of the Pd leak is controlled by the duty-cycle of the astable multivibrator pulse generator. The heating current of the Pd leak is displayed on the electrolyzer by a simple linear 5 LED bar indicator. Similarly, the D_2 level status of the "hysteresis" switching relay is shown by a green and a red LED.

The electrolyzer-Pd leak systems are very economical solutions for the deuterium supply of a neutron generator.

The deuterium supply of commercial neutron generators can be solved also by separate heavy water electrolyzers at the site of the neutron generator laboratories. An electrolyzer for filling the ion source deuterium vessels can be constructed on the basis of Fig.46. This electrolyzer can produce 100-500 ml/h NTP deuterium gas with a simple (sometimes not water cooled) electrode stucture and can serve as the deuterium supplier for the neutron generator and other utilizers. The whole glass system of the electrolyzer can be manufactured by a skilled glass-blower or made of commercial laboratory glassware.

Before starting the heavy water electrolysis, the electrolyzer and the deuterium vessel should be evacuated. A simple mechanical pump is used after opening the valves V_1, V_2, and V_3. The mercury level in the long (800 mm) vertical glass tube indicates when the whole system is evacuated. Closing the valve V_3, the mercury level, as in a manometer, shows the tightness of the system. The mercury level should not sink if the vacuum-tight system is properly sealed. If the Hg level does not sink within about 10 minutes, the heavy water electrolyzer can be put into operation. To get clean deuterium gas, heavy water and deuterized alkalis (D_2O + NaOD, KOD, LiOD) as electrolyte can be used. Since the amount of hydrogen

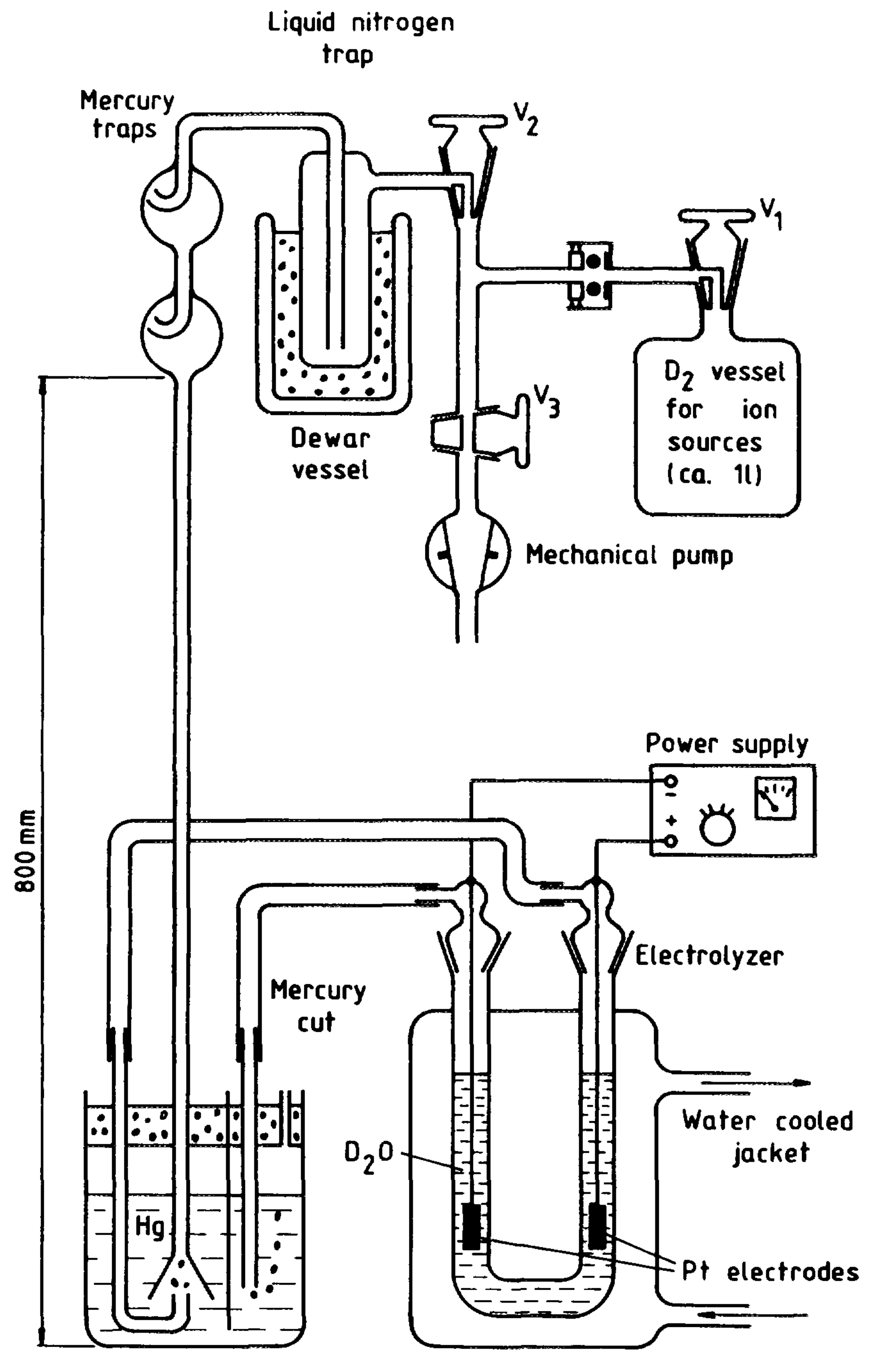


Fig.46 *Electrolyzer for filling deuterium tanks of neutron generator ion sources*

in the solution of 1-2 g NaOH or KOH is negligible compared to the 100-200 ml D_2O, the utilization of normal alkalis to set the conductivity is not usually a problem. Depending on the thickness of the Pt tube electrodes and the Pt wires, the power supply is a 20-50 V/2-3 A unit. A full wave rectifier with variable output voltage is suitable. The output voltage is usually regulated by a variac or triac on the primary side of the step down transformer.

The electrolysis should start with low current. The voltage (and the current) of the electrolysis should be increased gradually. To prevent the conical taps from falling out, the deuterium vessel should not be filled up to the atmospheric pressure. When the electrolysis stops, the V_1 and V_2 glass taps should be closed, and the O-ring sealed connection between the electolyzer and the deuterium vessel can be vented into the atmosphere by the valve V_3. With two identical deuterium vessels, the deuterium supply of the accelerator will be smooth and uninterrupted by the use of the electrolyzer.

7.1 THE FLOAT REGULATOR ELECTROLYZER

The regulation and stabilization of the deuterium pressure in the ion source need some control circuits related to the different gas valves. The combination of an electrolyzer with a mechanical float regulator can serve as a reliable gas

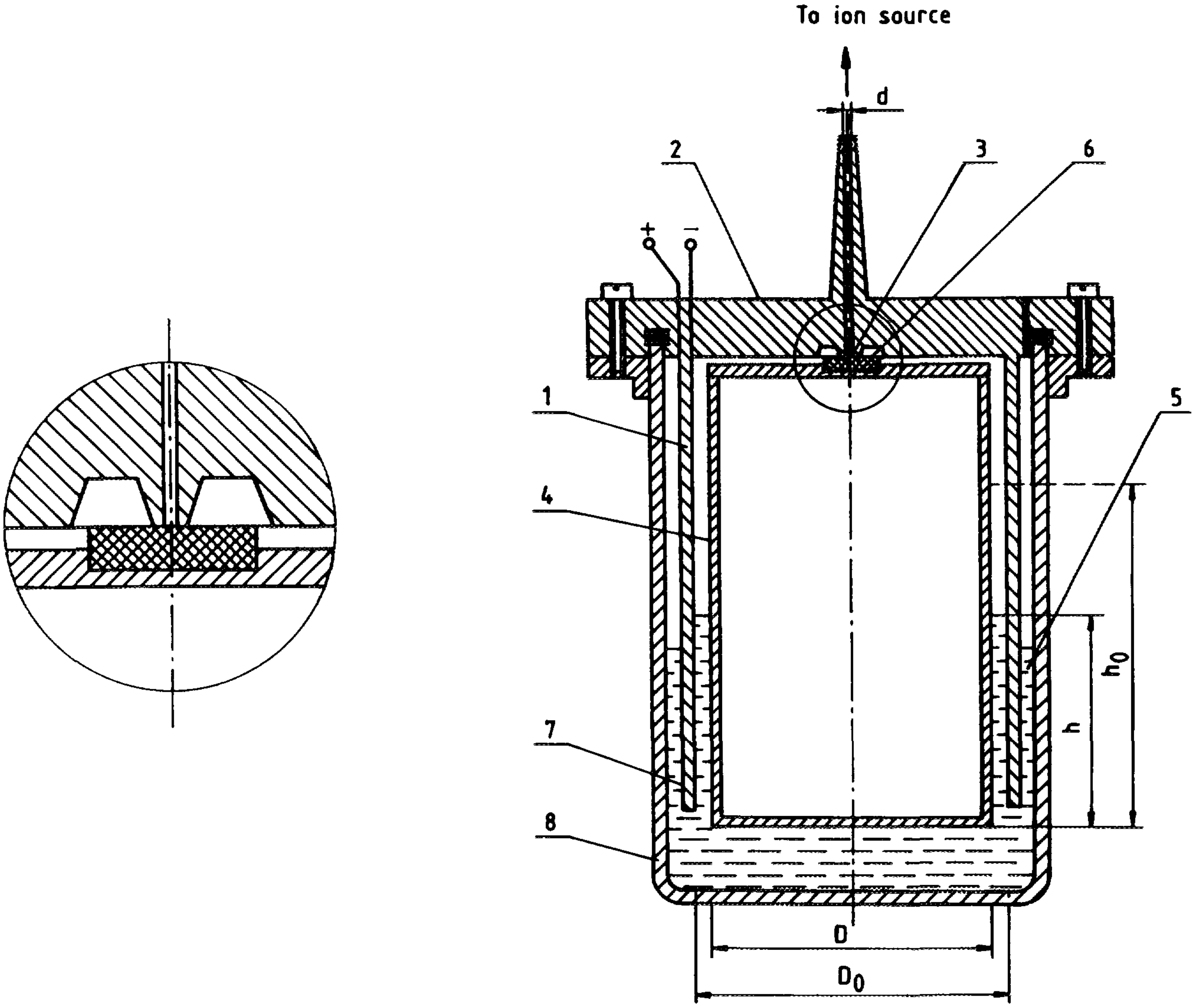


Fig.47 *Construction of the float regulator-electrolyzer* [53]
(numbers are explained in the text)

supply for the ion source. The regulating electrolyzer, described below, has been used satisfactorily for a long time at Bratislava [53].

The construction of the regulating electrolyzer is shown in Fig.47. The main component is a float (4) filling almost the whole volume of the cylindrical chamber (1). The electrolyzer is closed from the upper side of the flange (2) in the center where there is a nozzle (3). The float has small points (5) round its circumference that prevent the float jacket from directly touching the inner surface of the chamber and at the same time allows the float to move freely along the axis of the chamber. In the center of the upper lid of the float there is an elastic rubber seal (6). On the inner and outer walls of the lower edge of the float are the platinum electrodes (7) of the electrolyzer. The chamber and the float are placed in a glass vessel (8) partly filled with the electrolyte D_2O with the addition of KOD. The material of the float, the nozzle and the float chamber is Perspex (Plexiglas).

In order to understand the operation of the regulating electrolyzer, let us assume that the whole free space of the float chamber is filled with the electrolyte, so the float is pushed upwards till it closes the inlet of the nozzle by its elastic seal. If DC voltage of appropriate polarity is applied to the electrodes, the electric current starts to flow between them, and deuterium gas production starts at the inner negative electrode. The deuterium gas gradually fills the space between the float and the inner surface of the float chamber, pushing the electrolyte out. With a gradual decrease of the electrolyte level in the float chamber, the force P, by which the float presses the seal to the nozzle, will also decrease. The force P can be described by

$$P = \frac{\pi}{4} D^2 sh - G + \frac{\pi}{4} d^2 (p_2 - p_1) \qquad (21)$$

where

D = diameter of the float

s = specific density of the electrolyte

h = height of the electrolyte level measured from the bottom of the float

G = weight of the float

d = diameter of the inlet of the nozzle

p_2 = deuterium gas pressure above the electrolyte

p_1 = deuterium pressure at the inlet of the nozzle

The size and mass of the float as well as the diameter of the nozzle inlet should be chosen so that the following relations for each term of eq. (21) are fulfilled:

$$\frac{\pi}{4} D^2 sH > G \text{ and } G >> \frac{\pi}{4} d^2 (p_2-p_1) \qquad (22)$$

where H is the height of the float.

If the construction of the regulating electrolyzer obeys these conditions, the force P at a certain electrolyte level $h = h_o$ decreases so much that a leakage appears between the rubber seal and the nozzle edge and deuterium flows from the float chamber into the vacuum system of the ion source. The leakage grows with further decrease of the electrolyte level until the gas quantity q that flows through the leakage into the ion source equals the quantity Q originated by the electrolysis, i.e. until

$$q = Q \qquad (23)$$

becomes valid. If the electric current in the electrolyzer circuit is changed, the quantity of the gas achieved by electrolysis is changed as well. By the corresponding change of the electrolyte level in the float chamber the leakage between the rubber seal and the edge of the nozzle is also automatically changed (as well as the quantity of q) in such a degree that a new equilibrium is achieved, i.e. a state at which the eq.(23) is valid. When the electric current is switched off, the electrolyte level gradually rises up to the level at which the nozzle actually gets completely closed. The time behaviour of the equilibrium settling after the change of Q is given by the equation:

$$dh/dt = 4 [Q - q(h)]/\pi (D_o^2 - D^2) \qquad (24)$$

where the meaning of D and D_o is evident from Fig.47, and q(h) is the function of the escaping deuterium quantity from the float chamber into the ion source during unit time of the electrolyte level h. The behaviour of this function is characteristic for each construction of a regulating electrolyzer, since it depends on the geometry and the mechanical properties of the nozzle and the seal as well as on the geometry of the float.

The experimental function q(h) for a given geometry and construction of a regulating electrolyzer is shown in Fig.48. The rough surface rubber float shows a faster rising function while the fine surface silicon rubber float gives a relatively easy way to change the gas admittance characteristic of the regulating-electrolyzer [53].

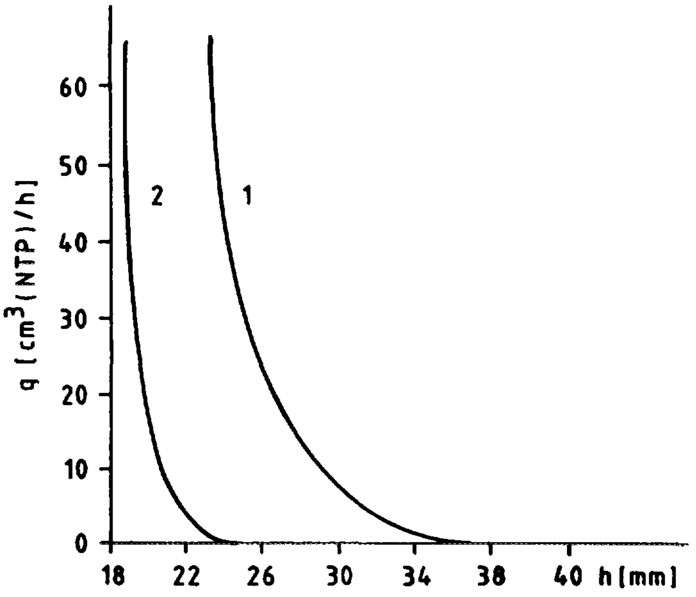


Fig.48 *The ion source gas consumption q vs height of electrolyte for the rough surface (1) and fine surface (2) silicon rubber seal on the top of the float*

Fig.48 shows a relatively easy way to change the gas generation. It can be done by adjustment of the electrolyte level. When a regulated current source is used for the supply of the electrolyzer, the gas admission into the ion source will be stable. The **advantages** of this float regulating electrolyzer are:

- It enables the gas supply of the ion sources to be stabilized by the regulation of the current in the electrolyzer.
- The insulated distance control of the current is relatively simple.
- If the electrode current is switched off the ion source will be closed.

8. REMOTE CONTROL OF THE HIGH VOLTAGE TERMINAL

The ion source, the ion source power supplies, beam handling facilities, etc., placed on the HV terminal of a neutron generator require normal control during operation. Regulation of the ion source and the related devices needs a control through the acceleration high voltage. The terminal control of a neutron generator can be carried out by:

- mechanical control using insulators (manual drive by Perspex rod or nylon fiber),
- electromechanical control (motor gear driven insulating rod or nylon fiber),
- insulation transformer control of the power supplies on the HV terminal,
- optical insulation in the control line of the HV terminal units,
- computer (microprocessor) control of the terminal units with serial optical links between the ground and the HV terminal.

8.1 MECHANICAL CONTROL

This is the simplest solution for the distance control of mechanical leaks and variacs at the HV terminal. Insulating (Perspex, Bakelite) rods are fastened to the shaft of the needle leak or variac and there is a suitable knob to turn the insulating rod at the ground potential. Since the insulating rod - especially in high humidity - may conduct, the ground side of the rod should be grounded between the the manually touched knob and the HV terminal to avoid an electric shock to the operator. If the mechanical transmission is made of nylon fibers, similar precautions should be taken to avoid an electric shock. A schematic representation of this simple distance is shown in Fig.49 .

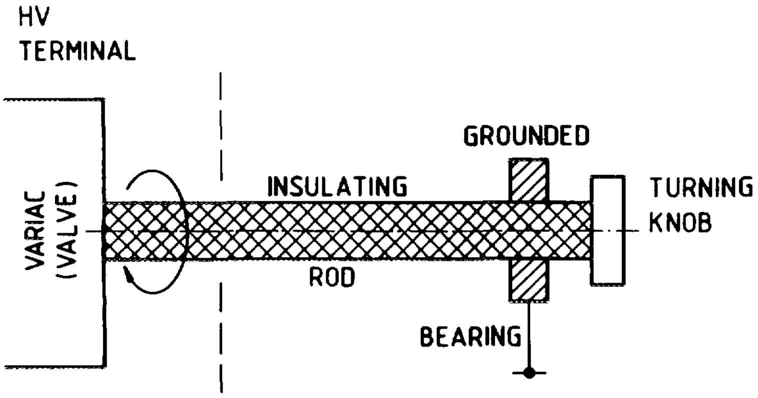


Fig.49 *Insulating rod control of the regulation elements at the HV terminal*

8.2 ELECTROMECHANICAL CONTROL

The electromechanical control of the units at the HV terminal is similar to the mechanical control. However, instead of manual control, the rods (or fibers) are driven electrically by servo motors, DC motors with gear, etc. The insulation between the HV terminal and the ground is the same. Since the servo motors and especially the DC motors with gear may produce a higher momentum, the mechanical overload of the insulating rod, fiber or variac, and needle valve should be avoided This is why position limiting switches are used for the electromechanically driven variacs, potentiometers, needle valves, etc. These switches protect the system against mechanical overdrive and, in the case of the lower or upper mechanical limit, allows the opposite direction drive only. The limit switches are usually microswitches with NO (Normal Open) and NC (Normal Closed) contacts. The principle of such a mechanical overload protection is shown in Fig.50.

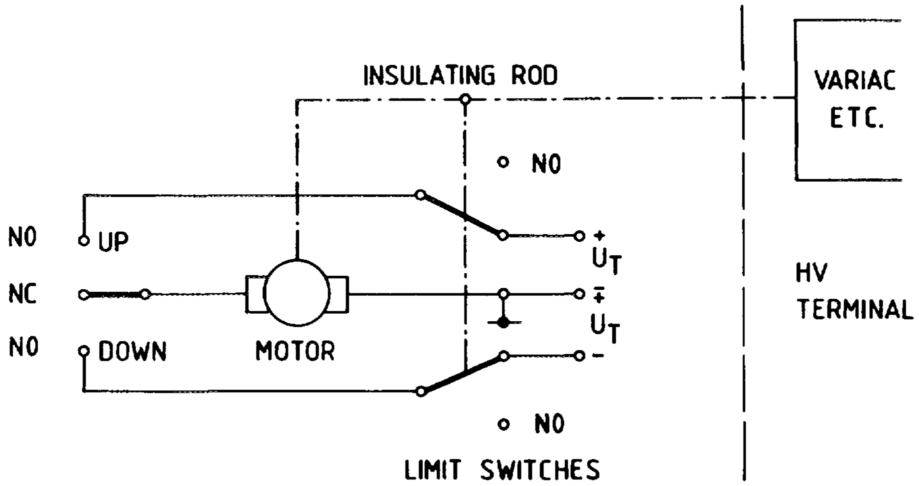


Fig.50 *Principle of mechanical protection of the electromechanical drives*

This mechanical protection utilizes a twin DC power supply for the DC motor gear driving insulating rods or fibers. The motor can be switched to the forward or backward direction by the UP/DOWN switch. This switch is a key with normal open position. For forward motion the motor will be powered by positive voltage, and for backward direction it will be connected to the negative voltage. The two limit switches break the positive or negative supply when the position of the rod (fiber) reaches the upper or lower limit. These switches ensure the return of the gear in the opposite direction after the positive or negative supply has been switched off.

This type of electromechanical remote control (from the control desk) is utilized at the Toshiba, KFKI and MULTIVOLT neutron generators.

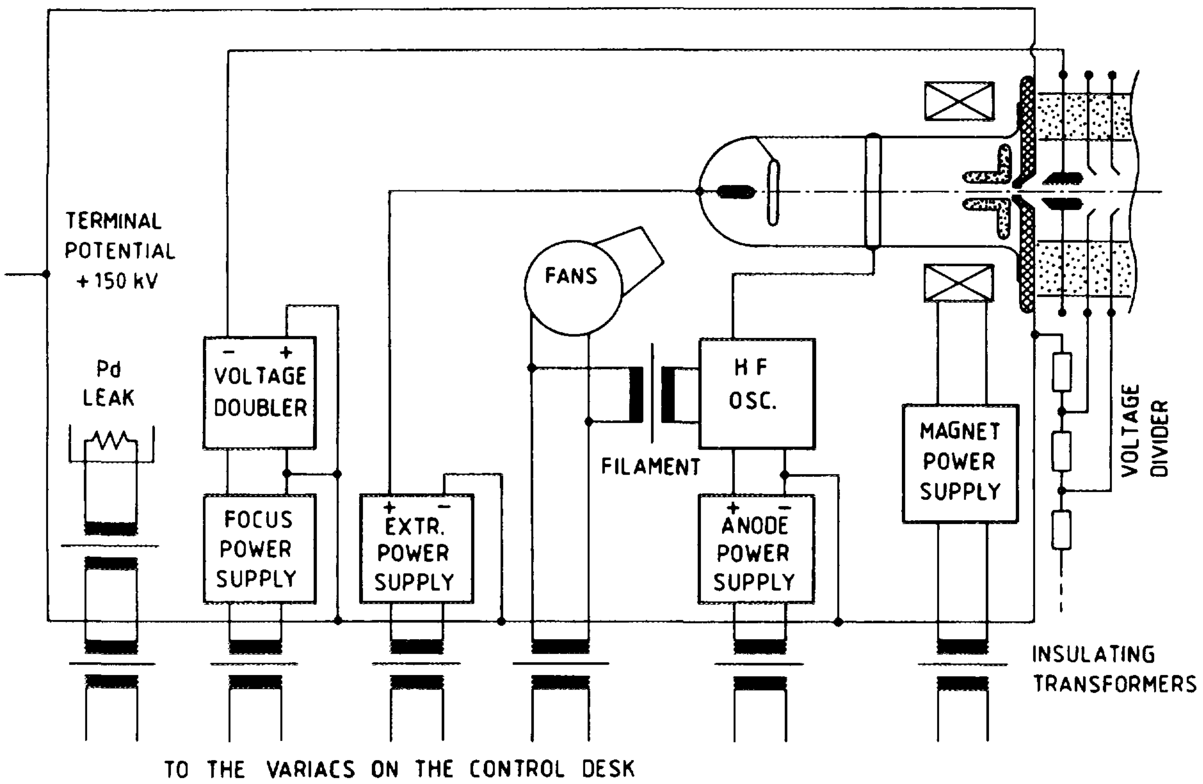


Fig.51 *Insulating transformer control of HV terminal (SAMES J-15 and J-25 neutron generators)*

8.3 INSULATION TRANSFORMER CONTROL

This type of ion source control is a solution for the control of a Penning ion source or an extraction voltage. For RF or duoplasmatron ion sources the insulation transformer control is less reliable due to the high number of insulation transformers connected to the HV terminal. The KAMAN (TMC) A-111, A-1254 and A-711 and the SAMES type D neutron generators utilize this method for insulation remote control of the equipment at the HV terminal. In the case of a Penning ion source this is a simple method while the RF type requires a number of separate insulating transformers: as many as five or six, as at the SAMES J-15 and J-25 neutron generators. The probability of sparking along the surface or between the primary and secondary sides in a single transformer is much lower than in the five or six insulating transformers. The utilization of a single, high power insulating transformer is typical for neutron generators and small accelerators. Figure 51 shows a block diagram of the insulation transformer remote control of the SAMES J-25 [54].

The only advantage of insulating transformers is the easy variac control at the ground potential.

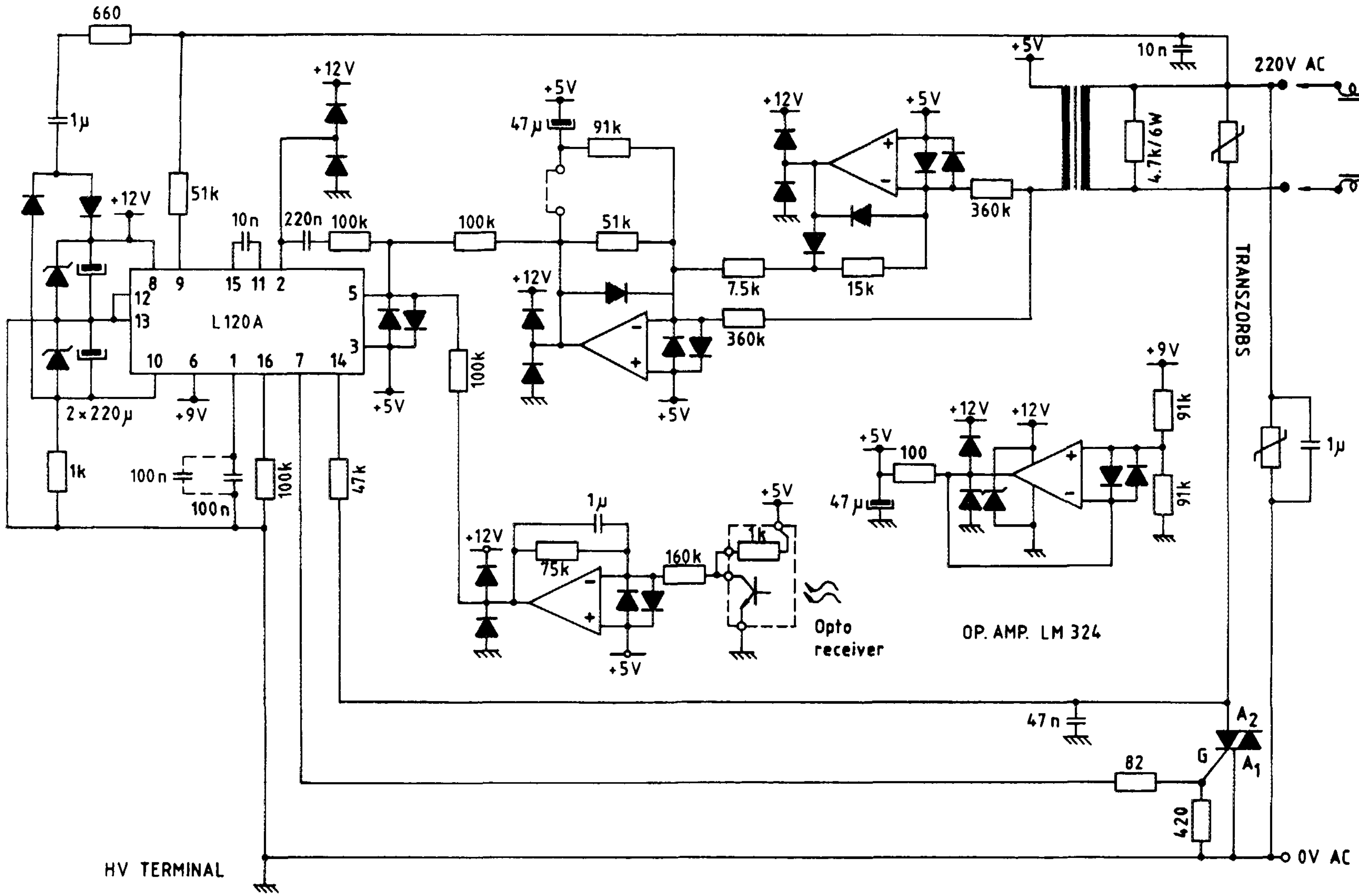


Fig.52 *Optoisolated triac control of mains transformers to the power control at HV terminal*

The disadvantage of this type of remote control, in addition to the high probability of electrical breakdown along the surface of the transformers, is that repair of the insulated secondary coils is impossible in practice.

8.4 OPTICAL INSULATION CONTROL

The control of HV terminal equipment by optical fiber insulation can be ANALOG or DIGITAL. Analog control is mostly used for neutron generators. However, some sophisticated neutron generators (RTNS-II, OCTAVIAN, etc.) use microcomputer control.

Analog control of equipment at the acceleration high voltage (HV terminal) requires power supplies and other units where the regulating input needs DC voltages. This input is the usual remote input of the medium frequency power supplies and other electronically controlled devices. In a simple power supply using one mains transformer, the variac type input voltage regulation can be changed to a DC voltage input controlled triac control circuit. This circuit is the usual power electronic circuit: the required DC input control voltage can be produced after the optical insulation by simple circuits.

A typical triac control circuit with optical input is shown in Fig.52, based on the AID (SAMES) T type neutron generator [55]. This circuit has a pulse generator unit at the ground potential which drives the infrared light-emitting diode. This light source transmits the light pulses to the optical receiver photo transistor by an electrically insulating optical fiber cable. The optoreceiver is on the HV terminal. The output pulses of the optoreceiver are integrated and the integrator output drives the DC input of the triac (or thyristor) controller chip. The pulse generator works at constant repetition rate (constant pulse frequency). The duty cycle of the pulses will be transformed into voltage at the integrator. Figure 52 shows this universal triac controller circuit utilized by SAMES. The transmitter can be a TL494 pulse width modulation circuit or a NE555 timer circuit in astable multivibrator mode [56].

From a practical point of view, it is very important to use transient suppressors at the small transformer, giving a phase control signal, and parallel to the triac. The operational amplifiers may be any of the usual types. The thyristor controller circuit may be one of the commercial type IC proposed by the semiconductor manufacturers. The optical fiber can be substituted by Perspex rods; the optotransmitter and receiver are recommended to be a matched pair (like optical gate).

8.5 COMPUTER CONTROL

Increasing application of microcomputer techniques has promoted the development of a control system for processes related to accelerators. An up-to-date

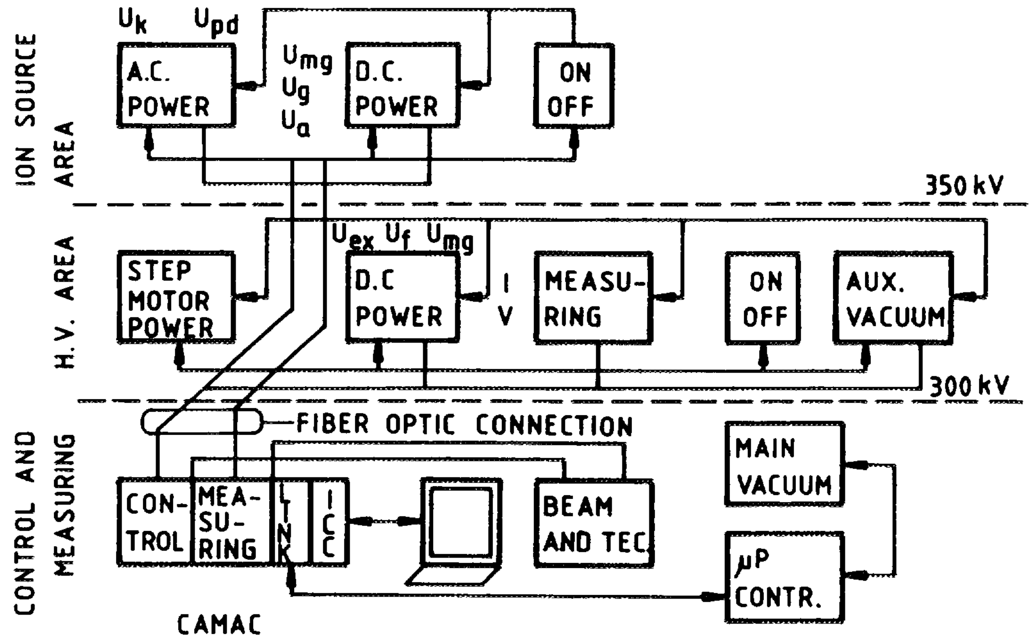


Fig.53 *Block diagram of the ion source control by CAMAC at the neutron generator using intelligent CAMAC crate controller* [57]

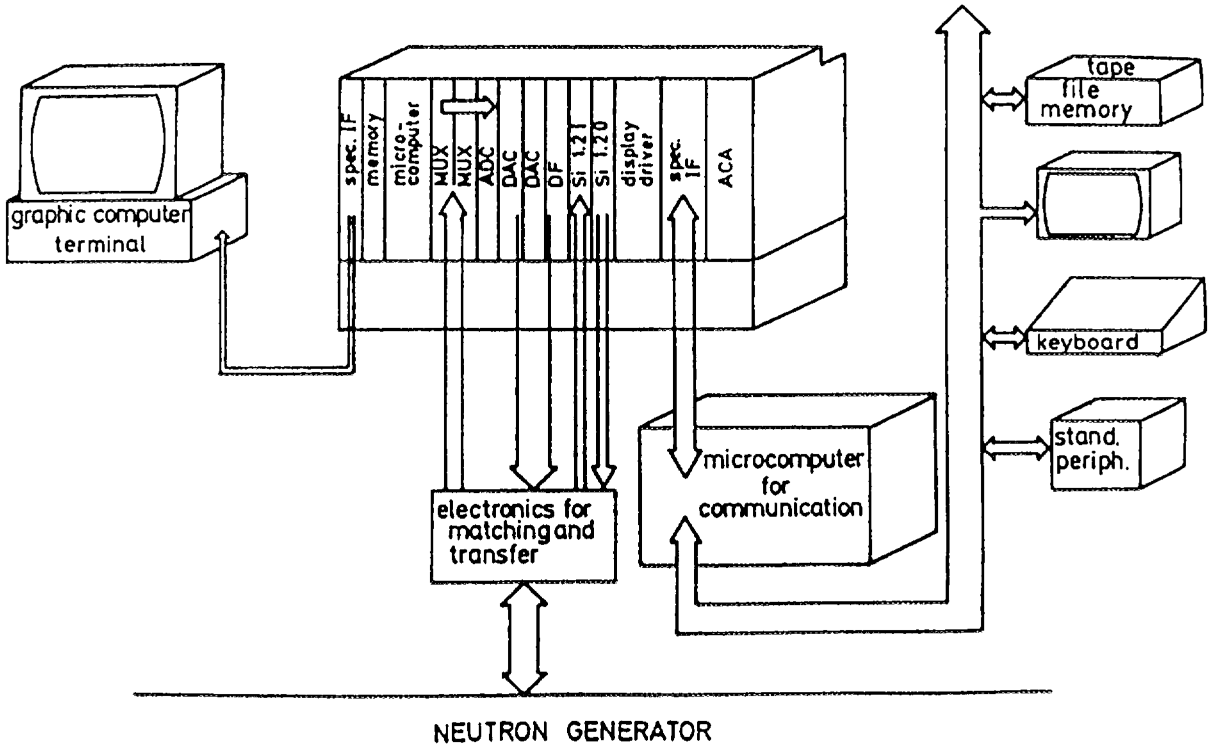


Fig.54 *Hardware system block diagram of a neutron generator control*

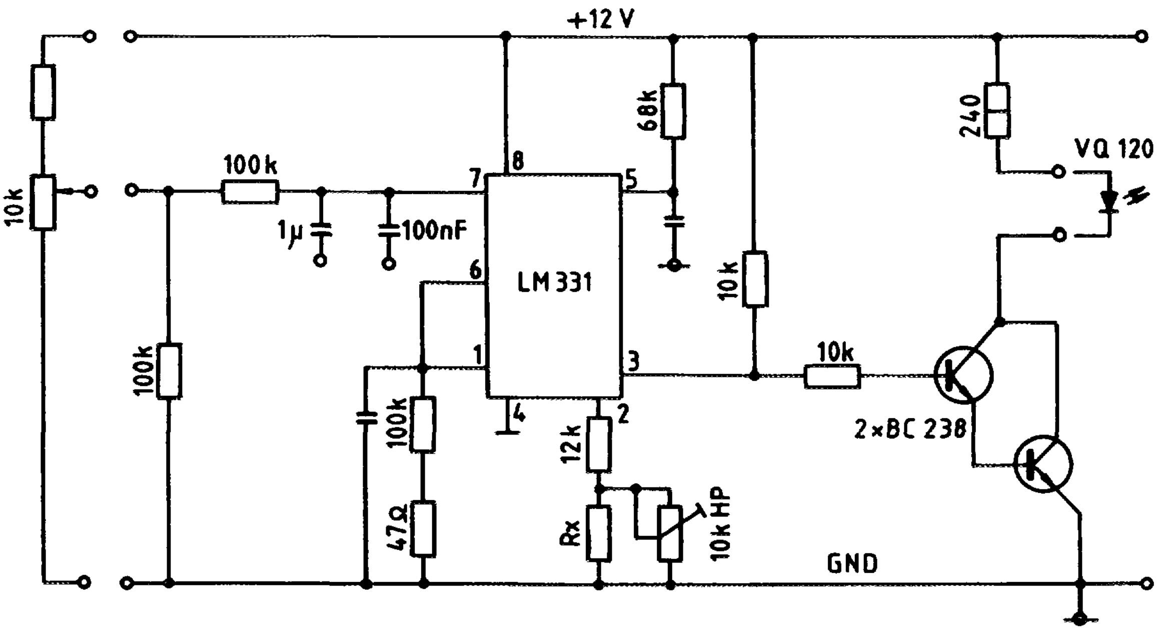


Fig.55 *Optical transmitter of analog signals from control console to HV terminal*

computer control system for such purposes represents an on-line closed loop system consisting of one central computer and additional microcomputers for special tasks. Such a system reduces operating expenses and is necessary for testing and operation of the automation of the accelerators. The microprocessor system for neutron generators requires solution of problems related to the operation and construction of a (cascade) generator. The open loop systems can be utilized at the manual control of the generator, while the closed loop systems can handle the entire control of the neutron generator operation.

The modules of the accelerator (neutron generator) control are almost standard: CAMAC or, more recently PC cards. A block diagram of a neutron generator (with duoplasmatron ion source) control is shown in Fig. 53 [57]. In this neutron generator the ion source is floating on the HV terminal at the potential of the acceleration voltage + extraction voltage. The optical fiber cables allow excellent insulation between the HV terminal and the subterminal of the ion source. The sensors and controllers are at different potentials, in the HV area and the ion source area, so they are connected by different fiber cables. The intelligent CAMAC controller at the ground potential controls the ion source power supplies and the gas supply. The measured parameters - e.g. arc current, arc voltage, pressure in the ion source - are transmitted back to the ground potential. The software of the system has been designed to meet requirements like starting the generator operation, controlling the operational parameters of the generator, as well as operator-aided control and safety control in breakdown situations.

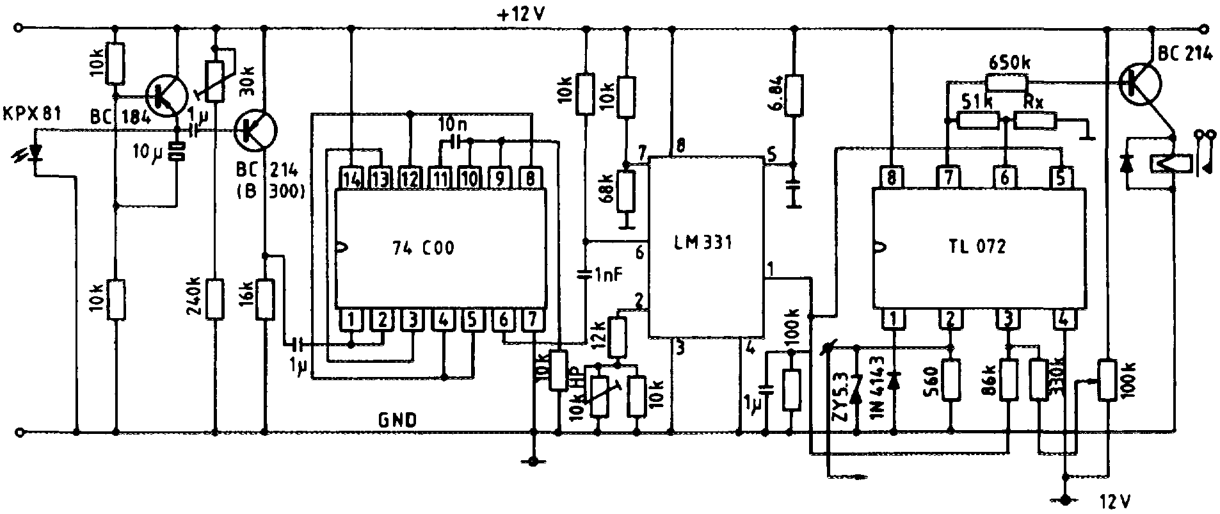


Fig.56 *Optical receiver of analog signals at HV terminal with a switch-on option*

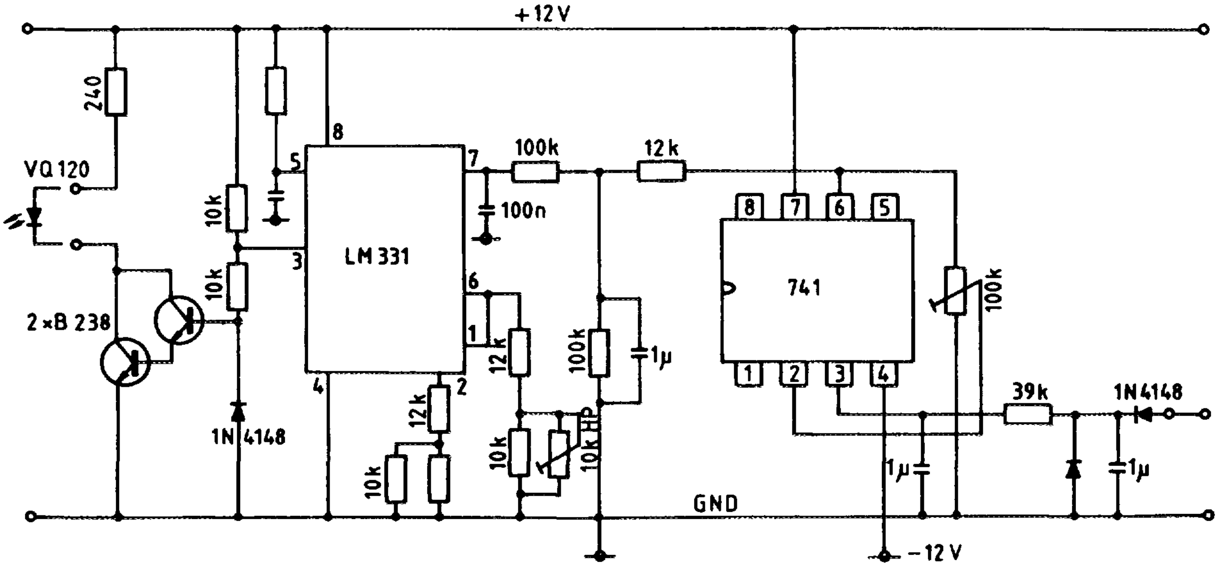


Fig.57 *Optical transmission circuit of signals from HV terminal to ground (HV terminal to control desk)*

A similar system using CAMAC data way is shown in Fig.54 [58]. The lower part of this diagram shows the microcomputer configuration (Z-80 based). The measured ion source parameters and the output control values are using the CAMAC data way in digital form. The analog values measured at the HV potential are connected to a multiplexer between the ADC to obtain more input. The analog output of the DAC is also demultiplexed.

The transmission techniques and the electronic equipment in the vicinity of the neutron generator were designed and developed taking into consideration the noise immunity and protection from corona discharges and sparking along the system. The analog and digital (binary) signals are transmitted and received by

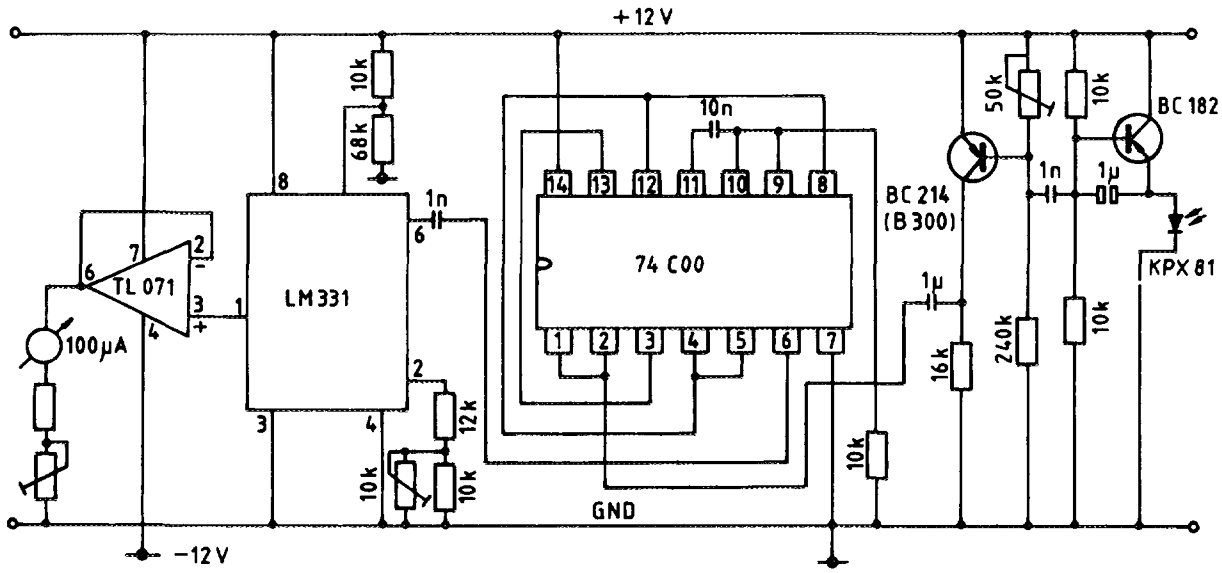


Fig.58 *Optical receiver of the signals from the HV terminal (analog meter driving frequency to voltage converter in the control desk)*

glass fiber optics. The electronic components used in the terminal blocks are radiation hardened.

The optical transmission system utilized for the transmission of the measured and control voltages is shown in Figs 55 and 56. Fig.55 shows the transmitter-receiver configuration related to the operator console (ground potential) while Figs 57 and 58 show the HV terminal-to-ground optical insulation circuits. The circuit in Fig.55 is a voltage-to-frequency converter with infrared LED output. This circuit is utilized both on the ground potential and at the HV terminal. The optical receiver, frequency-to-voltage converter is shown in Fig.56. This circuit also has a comparator actuating a limit switch. This limit switch is utilized as a mains switch-on device at the HV terminal. The analog output of the LM 331 integrated circuit utilized in frequency-to-voltage mode is led to the remote control input of the power supplies on the terminal [59].

9. VACUUM SYSTEMS OF NEUTRON GENERATORS

9.1 IMPORTANT TERMS AND UNITS IN VACUUM TECHNOLOGY [60]

9.1.1 Terms

The terms used in descriptions and technical data for the pumps and components in catalogues are standardized. The more important terms given below have been chosen to assist those less experienced in vacuum technology in the use of the catalogues and to extend their utilization.

An **absolute pressure gauge** is a pressure gauge used to determine the pressure from the normal force exerted on a surface divided by its area. An absolute pressure gauge is independent of the gas type used.

Absorption is a type of sorption in which the gas (absorbed) diffuses into the bulk of the solid or liquid (absorbent).

Adsorption is a type of sorption in which the gas (adsorbed) is retained at the surface of the solid or liquid (adsorbent).

Backing pressure is the pressure at the outlet of a pump which discharges to a pressure below atmospheric only.

Compression ratio is the ratio between the outlet pressure and the inlet pressure of a pump for specific gas.

Concentration of molecules is the number of molecules contained in an adequately chosen volume divided by that volume.

Intrinsic conductance is conductance in the special case where the orifice or duct connects two vessels in which Maxwellian velocity distribution prevails. In the case of molecular flow, intrinsic conductance is the product of the conductance of the inlet port of the conductance of the duct section and the transmission probability of the molecules. In this flow range, it is independent of the pressure.

Degassing is a desorption which is accelerated by physical processes.

Desorption is the liberation of gases absorbed by a sorbent material. The liberation can be spontaneous or can be accelerated by physical processes.

Gas **diffusion** is the movement of a gas in another medium due to its concentration gradient. The medium may be gaseous, liquid or solid.

Flow:

Viscous flow is the passage of a gas through a duct under conditions such that the mean free path is very small in comparison with the smallest internal dimension of a cross section of the duct. The flow is therefore dependent on the viscosity of the gas and may be laminar or turbulent. In the case of viscous flow, the resistance is a function of the pressure.

Turbulent flow (eddy flow) is a viscous flow with mixing motion above a critical Reynolds number (For circular cylindrical pipes, Re = 2300).

Laminar flow (parallel flow) is a viscous flow without mixing motion at small Reynolds numbers.

Molecular flow is the passage of a gas through a duct under conditions such that the mean free path is very large in comparison with the largest internal dimensions of a cross section of the duct. In the case of molecular flow, the resistance is independent of the pressure.

Gas is matter in a state of aggregation in which the mean distances between the molecules are large in comparison with their dimensions, and the mutual arrangement of the individual molecules is constantly changing. **Gas** in the stricter sense is matter in gaseous state which cannot be brought to a liquid or solid state by compression at the prevailing temperature.

Gas ballast is the inlet of a controlled quantity of a gas, usually into the compression chamber of a positive displacement pump, so as to prevent condensation within the pump.

Gettering means bonding of gas, preferably by chemical reactions. Getters (getter materials) often have large real surfaces.

Leaks in a vacuum system are holes or voids in the walls or at joints, caused by faulty material or machining or wrong handling of the seals.

Leak rate is the throughput of a gas through a leak. It is a function of the type of gas, pressure difference and temperature. The unit for the leak rate is: $1 \text{ Pa m}^3 \text{ s}^{-1} = 1\text{W} = 10 \text{ mbar l s}^{-1}$.

Maximum tolerable water vapour inlet pressure, p_{wo}, is the highest inlet pressure at which a vacuum pump can continuously pump pure water vapour under ambient conditions of 20°C and 1013 mbar.

The **mean free path** is the average distance which a molecule travels between two successive collisions with other molecules.

Outgassing is a spontaneous desorption.

Partial pressure is the pressure due to a specified gas or vapour component of a gaseous and/or vapour mixture.

Permeation is the passage of gas through a solid barrier or a liquid of finite thickness. Permeation involves diffusion and surface phenomena.

The **pressure** of a gas on a boundary surface is the normal component of the force exerted by the gas on an area of a real surface divided by that area.

The legal **pressure units** are: Pascal as the SI unit (abbreviation Pa) and bar as a special unit designation for 10^5 Pa.

$$1 \text{ Pa} = 1 \text{ N m}^{-2}$$

$$1 \text{ bar} = 1000 \text{ mbar} = 10^5 \text{ N m}^{-2} = 10^5 \text{ Pa}$$

The unit commonly used in vacuum technology is the millibar.

Quantity of gas (pv value) is the product of the pressure and volume of a specified quantity of gas at the prevailing temperature. If the pv value is to be used as a measure for the quantity of substance or gas, this must be an ideal gas whose temperature must be specified.

The **resistance** is the reciprocal of the conductance.

The **Reynolds number** is the nondimensional quantity

$$Re = \frac{\rho \cdot v \cdot l}{n} \qquad (25)$$

where

ρ = Density of fluid

v = Average flow velocity

l = Characteristic length (e.g. pipe diameter)

n = Dynamic viscosity

Re < 2300 : Laminar flow

Re > 4000 : Turbulent flow

The **saturation vapour pressure** is the pressure exerted by a vapour which is in thermodynamic equilibrium with one of its condensed phases at the prevailing temperature.

Sorption is the taking up of gas (sorbate) by a solid or a liquid (sorbent). Sorbents are also called sorption agents.

The **standard reference condition** is the condition of a solid, liquid or gaseous substance determined by the standard temperature and standard pressure. The abbreviation is **NTP** : Normal **T**emperature and **P**ressure.

Standard temperature: T_n = 273.15 K σ_n = 0°C

Standard pressure: p_n = 101325 Pa = 1013.25 mbar

The **throughput** is the quantity of gas (in pressure-volume units) passing through a cross section in a given interval of time at the prevailing temperature, divided by that time.

The **throughput of a pump** is the throughput of gas pumped.

The **total pressure** is the sum of all partial pressures present. This term is used in contexts where the shorter term "pressure" might not clearly distinguish between the individual partial pressures and their sum.

The **ultimate pressure** is the value which the pressure in a standardized test dome approaches asymptotically, with normal operation of the vacuum pump and without gas inlet. Distinction can be made between the ultimate pressure which is due to noncondensable gases, and the ultimate pressure which is due to gases and vapours (ultimate total pressure).

Vacuum is the state of a gas with the concentration of molecules being less than that of the atmosphere at the earth's surface. Vacuum is the state of a gas

Table 14. Vacuum ranges

	mbar	Molecule concentration*
Low vacuum (GV)	1000	$2.5x10^{25}$ - $2.5x10^{22}m^{-3}$
Medium vacuum (FV)	$1\text{-}10^{-3}$	$2.5x10^{22}$ - $2.5x10^{19}m^{-3}$
High vacuum (HV)	10^{-3}- 10^{-7}	$2.5x10^{19}$ - $2.5x10^{15}m^{-3}$
Ultra high vacuum (UHV)	$< 10^{-7}$	$< 2.5x10^{15}m^{-3}$

*The molecule concentrations refer to a temperature of 20°C.

with a pressure below atmospheric pressure, i.e. the air pressure prevailing at the respective location. The vacuum ranges are given in Table 14. The relationship between pressure p and concentration of molecules n (for ideal gases) is:

$P = n\,K\,T$

$K = 1.3807 \times 10^{-23} J\ K^{-1}$ (Boltzmann constant)

T = Thermodynamic temperature

Vapour is a substance in gas phase which is either in thermodynamic equilibrium with its liquid or solid phase (saturated vapour), or can be brought to thermal equilibrium by compression (condensed) at the prevailing temperature (unsaturated vapour).

Note: In vacuum technology, the word "gas" has been loosely applied to both the noncondensable gas and the vapour, if a distinction is not required.

The **vapour pressure** is the partial pressure of a vapour.

The **volume flow rate** is the volume of gas passing through the duct cross section in a given interval of time at a specified temperature and pressure, divided by that time.

The **volume flow rate S** is the average volume flow from a standardized test dome through the cross section of the pump's intake port. Units for the volume flow rate are $m^3\ s^{-1}$, $l\ s^{-1}$, $m^3\ h^{-1}$.

The **water vapour capacity C_{Wo}** is the maximum mass of water per unit of time which a vacuum pump can continuously take in and discharge in the form water vapour under ambient conditions of 20°C and 1013 mbar. It is given in $g\ h^{-1}$. The relationship between water vapour capacity D_{Wo} and maximum tolerable water vapour inlet pressure p_{Wo} is :

$$C_{Wo} = 217\ \frac{S p_{Wo}}{T} \quad \text{in g j}^{-1} \qquad (26)$$

S = Volume flow rate, in $m^3\ h^{-1}$, at inlet pressure p_{Wo}

p_{Wo} = Maximum tolerable water vapour inlet pressure, in mbar

T = Thermodynamic temperature of the water vapour pumped, in K

Table 15A. Multiples and units

Power of 10	Prefix	Designation
10^9	giga	G
10^6	mega	M
10^3	kilo	k
10^{-1}	deci	d
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p

Table 15B. Vacuum technological quantities [62]

Quantity	Symbol	SI units	Recommended units
Pressure	p	N/m^2,Pa	bar, mbar
Total pressure	p_t		mbar
Partial pressure of gas constant "i"	p_i		mbar (e.g. p_{H_2},p_{N_2})
Saturation vapour pressure	p_s		mbar
Vapour pressure	p_d		mbar
Residual total pressure	p_r		mbar
Residual gas pressure	p_{rg}		mbar
Residual vapour pressure	p_{rd}		mbar
Ultimate pressure	p_{end}		mbar
Mean free path	r, λ	m	m, cm
Collision rate	z	1/s	s^{-1}
Collision rate related to area	z"	$1/s\ m^2$	$s^{-1}\ m^{-2}$, $s^{-1}\ cm^{-2}$
Particle density	n	$1/m^3$	m^{-3}, cm^{-3}
Throughput	q_{pV}	N m/s	mbar l/s
Leak rate	q_L	N m/s	mbar l/s
Pumping speed	S	m^3/s	l/s, m^3/h
Conductance	C	m^3/s	m^3/s, l/s
Impedance	R	s/m^3	s/m^3, s/l
Conductance	L	l/s	l/s

Table 16. Conversion tables

(a) Temperature

	K	°C	°F
Kelvin	1	°C+273.15	5/9 (°F+459.67)
°Celsius	K-273.15	1	5/9 (°F-32)
°Fahrenheit	9/5 K-459.67	9/5 °C+32	1

(b) Pressure

	Pa	mbar	bar	torr	atm
1 N/m^2 = 1 Pascal	1	0.01	10^{-5}	$7.5x10^{-3}$	-
1 mbar	100	1	10^{-3}	0.75	-
1 bar	10^5	1000	1	750.06	0.98
1 torr = 1mm mercury	133.32	1.33	-	1	-
1 atm	101325	1013	1.013	760	1
1 at = 1 kp/cm^2	98066.5	981	0.981	735.6	0.97
1 m of water	9806.65	98.1	0.098	0.097	0.1
1 lb/ft^2 = 1 psf	47.88	0.47	-	0.36	-
1 lb/in^2 = 1 psi	6894.8	68.95	-	51.71	0.068

	at = kp/cm^2	mW s	psf	psi
1 N/m^2 = 1 Pascal	-	-	-	-
1 mbar	-	0.0102	2.09	0.014
1 bar	1.82	10.19	2089	14.50
1 torr = 1mm mercury	-	-	2.78	0.019
1 atm	1.033	10.33	2116.2	14.69
1 at = 1 kp/cm^2	1	10	2048.2	14.22
1 m of water	0.1	1	204.82	1.42
1 lb/ft^2 = 1 psf	-	-	1	-
1 lb/in^2 = 1 psi	-	-	144	1

Table 16 (Cont.)

(c) Volume flow rate, Conductance

	m^3/s	l/s	m^3/h	ft^3/min
1 m^3/s	1	1000	3600	2118.88
1 l/s	10^{-3}	1	3.6	2.119
1 m /h	$2.78x10^{-4}$	0.278	1	0.59
1 ft^3/min	$4.72x10^{-4}$	0.47	1.69	1

(d) pV throughput, Leak rate

	W	mbar l/s	torr l/s	cm^3/m (NTP)
31 Pa m^3/s=1W	1	10	7.5	592
1 mbar l/s	0.1	1	0.75	59.2
1 torr l/ls	0.133	1.33	1	78.9
1 cm^3/m (NTP)	$1.69x10^{-3}$	0.017	0.013	1

(e) Ion source gas consumption (pV throughput) unit

1 ml atm/hour = $2.8x10^{-4}$ mbar l/s at **Normal Temperature and Pressure (NTP)**

9.1.2 Units [61]

The basic units were established in October 1954 at the First General Conference for Mass and Weight in Paris. This uniform system was given the internationally binding initials "SI" (from the French, Systeme International d'unites). The recommended units are mostly multiples of fractions of the SI units (Table 15A). As exceptions to this, some units which have become customary in certain branches are recommended (see Table 15B). For convenience, a conversion table is given in Table 16.

9.2 VACUUM PUMPS

When selecting the most appropriate vacuum system for a neutron generator the following important factors should to be taken into account:

(a) The value of the ultimate pressure to be attained for normal operation:

The aim of all vacuum systems for a neutron generator, as for a charged particle accelerator, is that the accelerated deuteron ions should reach the tritium target without collision. To do this, it is necessary to keep the pressure in the accelerating tube so low that the mean free path of air molecules should exceed the length of the accelerating tube.

Data at different pressures - as can be seen in Table 17 - show that the above requirements for the mean free path values for neutron generators at pressures of 10^{-5}-10^{-6} mbar are in the range of some meters. These ultimate pressure values, in Table 17, have to be taken into account, at least when selecting the most appropriate type of vacuum pump [63].

Table 17. Mean free path vs pressure

Pressure (mbar)	Mean free path (cm)
atmospheric	6×10^{-6}
1	5×10^{-3}
10^{-3}	5×10^{0}
10^{-6}	5×10^{2}
10^{-9}	5×10^{6}

(b) Gas intake (due to lakage, the ion source, etc.) to be accounted for during the run of the accelerator:

The pumping speed is an important consideration. Its required value should be determined, first, by the regularly occurring gas intakes. Note that the pressure in the system must not be changed during operation: for example, at a neutron yield of 10^{10} n/s in the case of a commercial neutron generator with a beam current of 1-2 mA, the D_2 gas intake is 4-5 cm^3/h.

(c) Economic considerations:

- The greatest possible simplicity in handling the pumps and the entire vacuum system (start, stop);
- The lowest possible probability of failures (the pumps may break down, espe-ally during long irradiations);
- The least possible reconstruction requirements during maintenance (to repair any parts of the system might be difficult owing to tritium contamination);
- The best possible accommodation for the existing laboratory conditions (various supplies, e.g. for electric power, water and liquid nitrogen; replacement possibilities of failed parts of instruments, workshop background for maintenance and renewal, etc.). Fig.59 shows the best known pump types, made by well known manufacturers.

Taking into account both the pumping rates and cost during operation, the manufacturers of neutron generators use in practice one of the following pump combinations to obtain the 10^{-5}- 10^{-6} mbar ultimate pressure (necessary for a neutron generator):

- oil diffusion pump - rotary pump
- turbomolecular pump - rotary pump
- Ti-ion getter pumps (+ rotary pump).

The working principles of these pumps, vacuum gauges and other vacuum technical equipment, as well as the most important details of the operation of vacuum systems containing the above fittings, are discussed below.

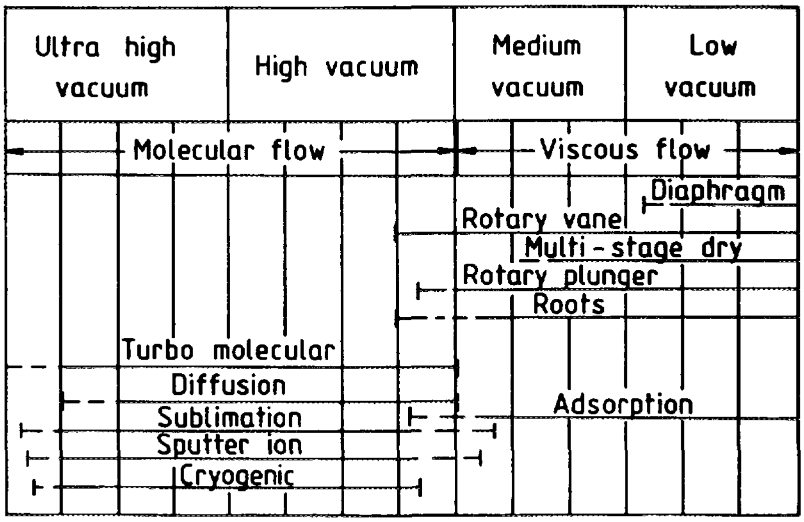


Fig.59 *The operation pressure range of different vacuum pumps*

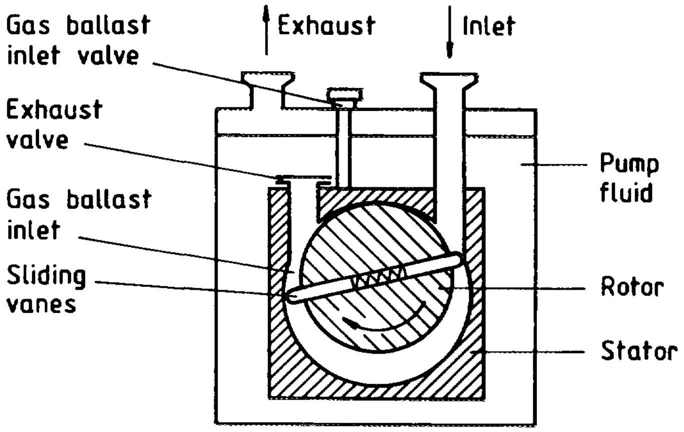


Fig.60 *The rotary vane vacuum pump*

9.2.1 Vacuum system based on a combination of oil diffusion and rotary pumps

(a) The rotary vane pump

This is probably the most widely used pump and is well established as a backing pump in many compound systems.

An eccentrically placed slotted rotor turns in a cylindrical stator (Fig.60) driven by a directly coupled electric motor. In the slots are two (or three) sliding vanes which are in continuous contact with the walls of the stator. Air drawn in is compressed and expelled through a spring loaded exhaust valve.

The vanes and rotor are sealed by a fluid film and the stator is immersed in the fluid to provide heat transfer to the pump casing. Rotary pump fluids are usually selected from high quality mineral oil with low vapour pressure and good lubricating properties. Suggested types of oil are:

Shell Rotary Vacuum Pump Oil
Gluvacol R 910
Alcatel 1DO
ELF MOVIXA PV100
TURBELF SA 100
ELFLL BARELF F 100
BP CS 100
INLAND 15
INVOIL 2D
SHELL VITREA 100
TOTAL CORTIS 100

Two-stage rotary pumps are frequently used, in which the exhaust from the-first stage is internally connected to the inlet of the second stage (Fig.61).

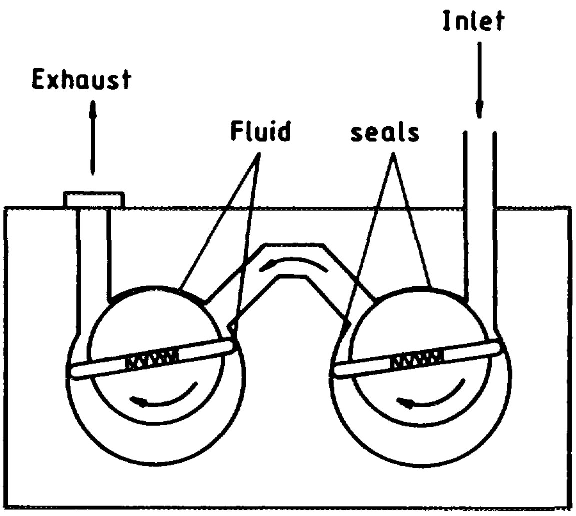


Fig.61 *Cross section of a two-stage rotary vane pump*

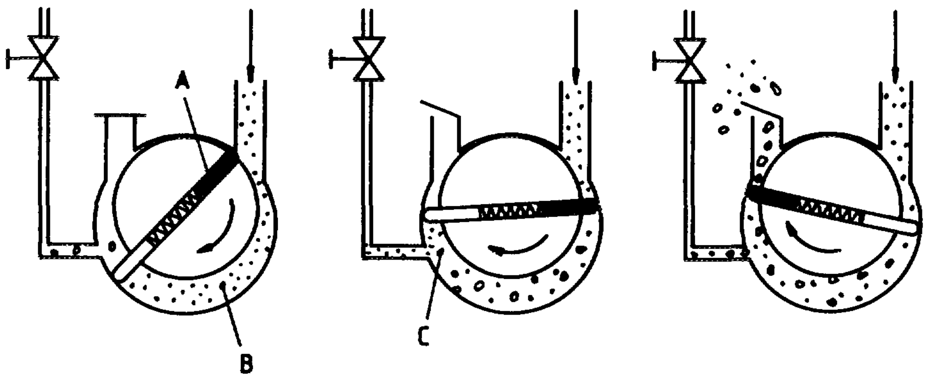


Fig.62 *The operation of the gas ballast in a rotary vane pump*

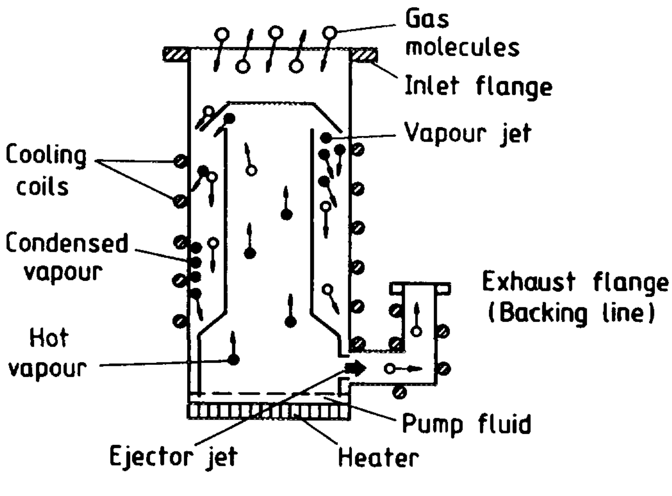


Fig.63 *Schematic cross section of a diffusion pump*

This solution improves the ultimate pressure of the pump by reducing the back leakage where the rotor and stator are fluid sealed.

To reduce the condensation of vapours during the compression cycle, gas ballasting can be used, where a controlled quantity of a suitable noncondensable gas (usually air) is admitted during compression (Fig.62).

In Fig.62, vane A is about to close the crescent-shaped chamber B containing the gases and condensable vapours being pumped. As this volume is sealed from the inlet, a controlled volume of air at atmospheric pressure is admitted at point C. The air intake raises the pressure in B and prevents condensation of vapour by opening the exhaust valve before the conditions of condensation are reached.

(b) The diffusion pump

The operation of the diffusion pump can be seen in Fig.63. The pump fluid (usually oils with large molecules) is heated electrically and the oil vapour streams through the chimneys. Then the vapour molecules - emerging from the (ring-shaped) nozzles with supersonic speed - are directed toward the cooled pump wall, where condensation takes place. The vapour condensate reflows to the bottom of the boiler. This process can be maintained continuously by permanent heating.

Air molecules in the pump - and in the connected vessel - can be mixed by Brownian movement (diffusion) between the oil molecules while moving towards the wall; thus, in all probability, air molecules can get - by collisions - a velocity component directed downwards because their mass number is much smaller than that of the oil molecules. Gases compressed in this way in the lower part of the pump can be removed by the backing pump.

The condition of the operation is that the mean free path of the oil molecules should be greater than the distance from the nozzle to the wall. This condition can be reached in such a way that - before switching on the diffusion pump - the whole vacuum system should be evecuated to a forevacuum (10^{-1}-10^{-2}mbar) by applying a forepump (usually rotary type) as backing pump to the diffusion pump. In addition, the rotary pump must be kept in operation as long as the diffusion pump works in order to prevent the disintegration of the lowest vapour jet stream system because of the accumulation of gases from the diffusion pump at the exhaust passage towards the backing. On disintegration, the velocity of the air molecules in the upward direction is the same as that in the downward direction. This is interesting because a jet's disintegration leads to a gradual breaking down of the pumping ability.

The value of the necessary forevacuum at the exhaust passage of a diffusion pump is at least 10^{-1}-10^{-2} mbar. However, the pumping speeds of the rotary pumps in this pressure range are usually quite low (see later). It is usual to insert a so-called booster-pump in between the two pumps if the gas intake is high.

In older vacuum systems, an overheated diffusion pump, only at the pressures 10^{-1}- 10^{-2} mbar, was used as a booster. In this way, the exhaust pressure of the booster increased into the mbar region, where the rotary pumps also have high enough pumping speeds.

In contemporary diffusion pumps the booster stages are originally built in the housing (stator). Fig. 63 shows that the outstreaming of the oil vapour - from the pipe directed towards the exhaust passage - operates as an oil vapour ejector pump.

Table 18. Technical data for diffusion pump fluids [64]

	Mineral oils BALZERS		Silicon oils		Pentaphenylaether
	61	71	DC704	AN175	SANTOVAC 5
Theoretical vapour pressure [mbar]	$2x10^{-7}$	$2x10^{-8}$	$2x10^{-8}$	$4x10^{-10}$	$1x10^{-10}$
Viscosity [mm^2/s] (at 25^oC)	171	410	39	175	1000
Chemical resistance	good	good	better	better	best
Thermal resistance	good	good	better	better	very good
Pressure range	10^{-2}-$5x10^{-6}$	10^{-3}- 10^{-7}	10^{-3}-10^{-7}	10^{-5}-10^{-8}	10^{-3}-10^{-8}
Price	low	low	medium	medium	high

Suggested types of diffusion pump fluids are as follows (Table 18):

Mineral oils

These oils are manufactured by molecular distillation of crude oil and they are suitable for general applications down to a pressure of 10^{-7} mbar. They will not withstand repeated exposure to atmosphere in a hot state because the exposure will produce carbonaceous compounds with high vapour pressures which decrease the performance of the pump. Their deposits on the inner surface of the accelerator system will produce conducting layers.

Silicon oils

These oils are exceptionally stable compounds at high temperatures and they will provide an ultimate pressure between 10^{-5} to 10^{-9} mbar. Their deposits on the electrodes of an accelerator will produce an insulating layer. These fluids are poor lubricants.

Pentaphenylaether

These fluids have exceptionally low vapour pressure and are thermally very stable. They will not backstream in a properly designed pump and baffle, and they are chemically stable. Their break-up on the surfaces of the electrodes of an accelerator will produce a conducting layer. They are good lubricants, but they are expensive.

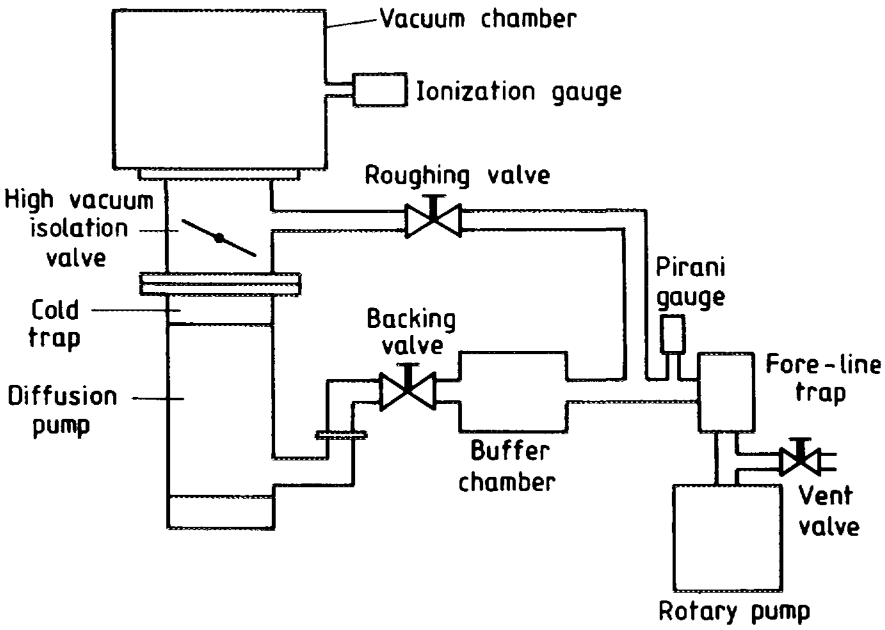


Fig.64 *Typical diffusion pump vacuum system*

(c) Combination of diffusion and rotary pump

A typical system consisting of an oil diffusion pump and a rotary pump can be seen in Fig.64.

As mentioned earlier, selection of the appropriate diffusion pump is determined, first of all, by the gas consumption of the ion source. On the other hand, for the selection of the rotary pump - to be fitted to the diffusion pump - the pumping speed of the diffusion pump as well as the maximum permissible pressure at the exhaust have to be taken into account.

For example, in the case of a diffusion pump having 1000 l/s pumping speed: if a pressure as low as 10^{-4} mbar is assumed for the pumped volume (in fact, it should be higher than that), then a 3.6 m^3/h pumping speed is necessary at the exhaust side with a 10^{-1} mbar pressure. Such a pumping speed can be achieved even by the simplest rotary pumps with a pumping speed of 6-8 m^3/h in practice (see the pumping speed diagrams).

Cooled vapour traps: The so-called foreline traps - liquid nitrogen traps - between the rotary and diffusion pump protect the diffusion pump from the oil vapour of the rotary pump. This must be impeded in order to prevent mixing the rotary pump oil with the much finer diffusion pump oil. This is necessary because such mixing would spoil the diffusion oil (the molecular size being much larger for diffusion than for rotary pump oils).

A vapour trap has another very important role: it prevents the vapours (especially steam), generally present in vacuum systems, from getting into the rotary pump. A rotary pump cannot completely remove such water (or even steam). Practical experience shows that the use of a trap improves the vacuum by at least half an order of magnitude.

The FREON-12 cooled traps are advantageous in laboratories where liquid nitrogen supply is either difficult or impossible to obtain. The manufacturers of diffusion pumps usually stock this type of refrigerator operating cooled traps as well.

Fig.65 shows some simple forms of cooled vapour traps. It is quite practical to put a vacuum trap in the inlet chamber of the diffusion pump; this reduces the risk of getting diffusion oil into the accelerator tube and helps to limit the different vapours present in the vacuum system. Further questions on the correct use of a vapour trap are discussed later.

Buffer chamber: Sometimes it is worth while to insert a buffer chamber with a volume of 3 to 5 litres - usually made of stainless steel - between the oil diffusion and the rotary pumps (see Fig.64). In the case of power cut-off, the buffer chamber will play an important role and take over the duty of the rotary pumps for a short time (until the diffusion pump cools down). Owing to its relatively large volume, it can pump out, for a while, air from the exhaust port of the diffusion pump that is still working and reduce the contact of its oxygen with the still hot oil vapours.

Isolation valves: Diffusion oils in contact with air may absorb a lot of humidity from the air and gaseous material, which will be released again when the pump is started up and results in extra gas intake. Therefore, after stopping the vacuum system of the generator, it is worth while to isolate the diffusion pump

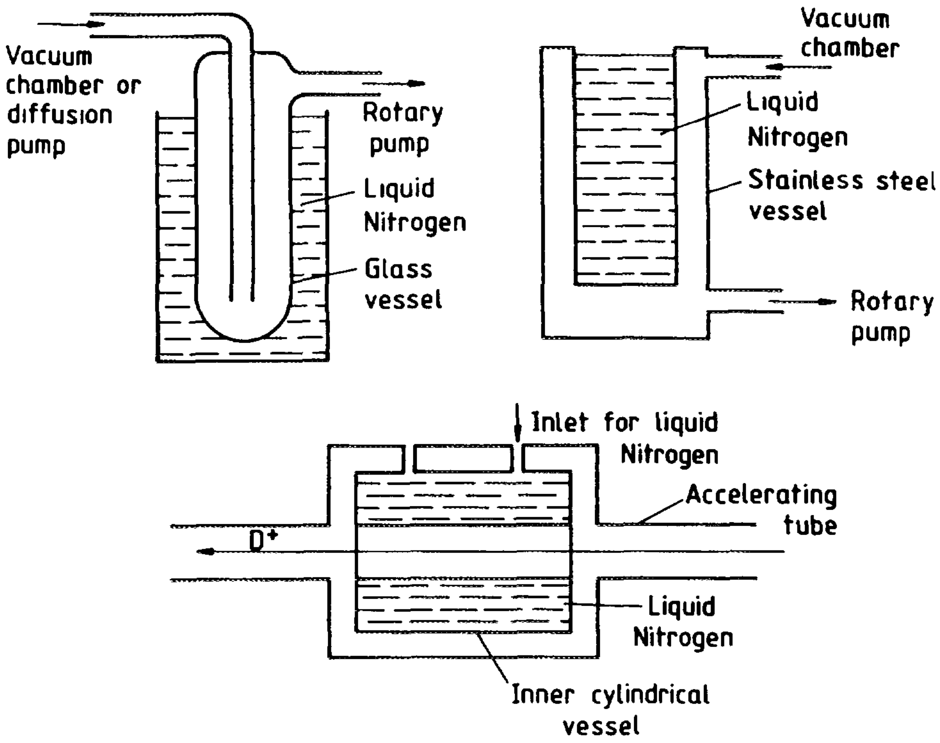


Fig.65 *Liquid N_2 cooled traps*

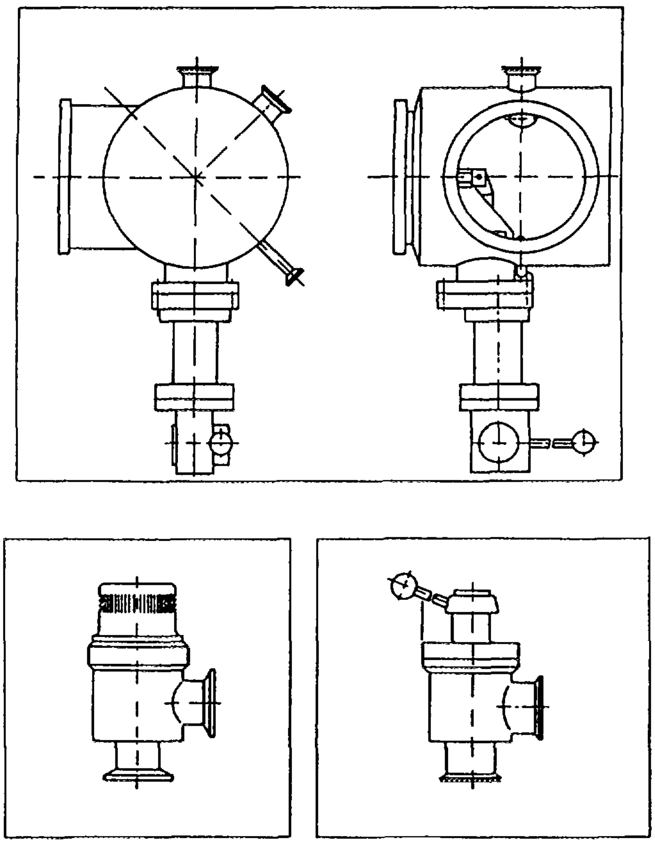


Fig.66 *Different types of isolation valves* [65]

from the other parts of the vacuum system by valves (see Fig.66). These valves are usually quarter swing or butterfly valves. The acceleration tube and the target beam line are usually isolated by gate valves. In this way, air is admitted only into the small space just at the inlet of the rotary pump by the air admittance valve, while the other parts of the system keep the vacuum.

After switching off the vacuum system, the backing valve prevents the vapours of the warming-up trap from streaming back towards the diffusion pump. The role of this valve is similar to that of the high vacuum isolation valve.

For the safe running of the vacuum system, it is worth while to control the cooling water supply of the diffusion pump continuously by a pressure switch; this switches off the pump heating automatically if the water supply cuts off.

A relay indicating the pressure level - built into the electronic unit of the vacuum gauge (vacuum gauge controller) - can also be used for a similar purpose; this relay stops (or inhibits switching on) the heating of the diffusion pump if the gas intake exceeds the upper limit set in the controller.

If a neutron generator - with its vacuum system - is operated for a long time, it is advisable to control continuously the temperature of the diffusion pump by a thermocouple or thermal switch.

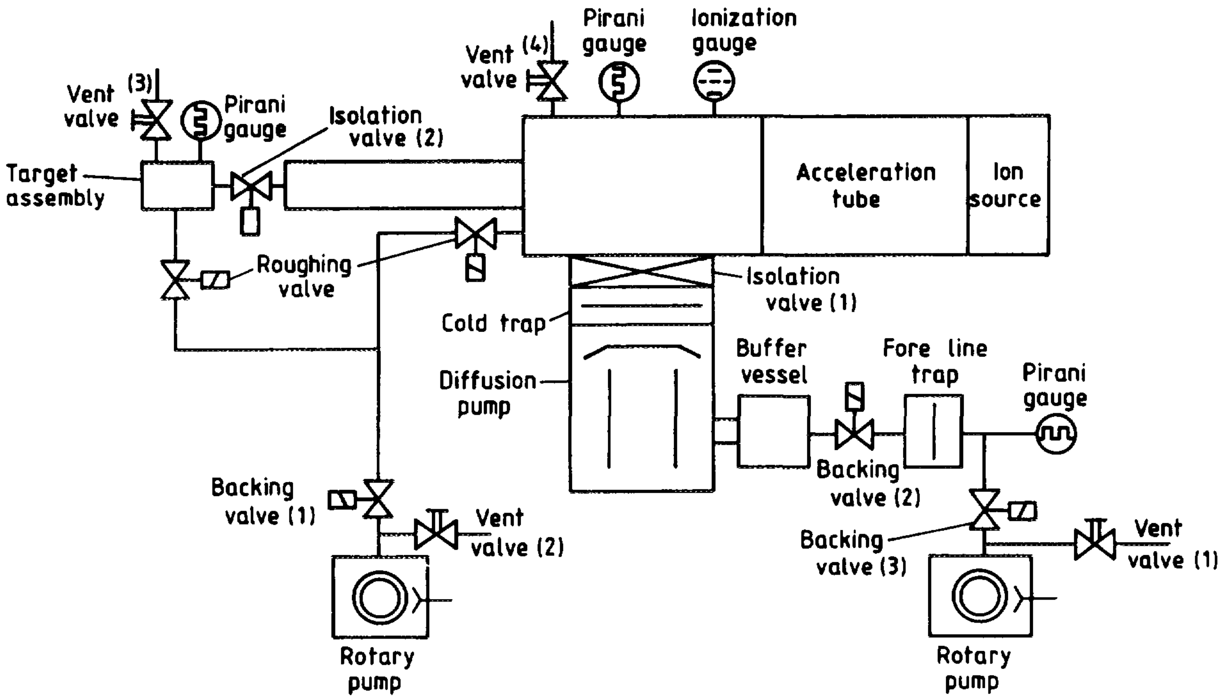


Fig.67 *General vacuum system for a neutron generator*

During operation of the vacuum system of a neutron generator consisting of a rotary as well as diffusion pumps (see. Fig.67), the following important instructions should be followed:

A. Switching on the vacuum system

a) Switch on, first, the rotary pump (backing valve 3 is opened and the vent valve 1 is closed automatically). Let the rotary pump run for 5-10 minutes with gas ballast valve open. During this time the pump house warms up to operation temperature (the vapours do not condense later), and, in addition, it will be possible to release the gases and condensed vapours from the foreline trap.
After this "cleaning", the foreline trap has to be filled by liquid nitrogen.

b) Open the backing valve 2.

c) Open the isolation valve 1.

d) Switch on the heating of the diffusion pump when the correct forevacuum value - in the whole system - is reached.

e) After another period of 10-15 minutes has elapsed - this depends on the heating-up time of the diffusion pump - the cold trap (on the top of the diffusion pump) has to be filled up with liquid nitrogen.

B. Switching off the vacuum system

a) Close the isolation valve 1.

b) Empty the cold trap (by warming or compressed air). During this operation, the greater part of the adsorbed gases and vapours will be released, and the diffusion pump that is still working will transport them to the foreline trap (within about 10-20 minutes - depending on the size of the traps).

c) Switch off the heater of the diffusion pump; let it cool down below operation temperature.

d) Close the backing valve 2.

e) Switch off the rotary pump (now, the valves 3 and 1 will automatically be turned off and on, respectively).

This vacuum system - as can be seen in Fig. 67 - involves the possibility of the tritium target exchange and the exchange of the old ion-source components - using a second rotary pump - without switching off the diffusion pump. In such a case, the required part of the vacuum system - after closing the isolation valve 1 - can be exposed to the atmosphere. After the necessary changes have been made, the upper part of the vacuum manifold can be evacuated by the second rotary pump in order to reach the required forevacuum value and, finally, it can be connected - by opening the isolation valve 1 or the isolation valve 2 - to the high vacuum manifold.

9.2.2 Vacuum system based on Ti-ion getter pump

The sputter ion pump is a getter ion pump in which ionized gas is accelerated towards a getter surface, continuously renewed by cathodic sputtering. The basic sputter ion pump consists of two flat titanium cathodes, a cylindrical anode and an axial magnetic field as shown in Fig.68.

A typical Ti getter pump consists of two flat rectangular titanium cathodes with a stainless steel anode between them consisting of a large number of open ended boxes (see Fig.69).

The pump, mounted inside a narrow stainless steel box and attached to the vacuum system, is surrounded by permanent magnets. The anode is operated at a potential of some kV whereas the cathodes are at ground potential. The cold discharge is initiated by stray electrons produced by cold field emission. These electrons execute a helical motion around the magnetic field lines and they oscillate to and fro in the axial direction between the cathodes, as in the case of PIG ion sources or Penning vacuum gauges. The positive gas ions formed by ionization bombard the titanium cathode, sputtering titanium to form getter films on the anode and the opposite cathode. The titanium reacts with all active gases, forming stable compounds, and a considerable number of bombarding gas molecules will be buried in the cathode.

Noble gases (He, Ar, Ne) are pumped by burial under the layers of titanium on the pump walls and anode, while the other gases are buried in the cathode. Unfortunately as further sputtering takes place, the previously buried molecules can be released, giving rise to instability in pumping. Various solutions to the pumping of noble gases have been attempted, for example the use of differential cathode materials, where one is titanium and one is tantalum, and the use of slotted cathodes where the bombarding ion arrives at a glancing angle. However, the most successful has been the triode ion pump configuration (Fig.70), in which the whole pump body (B) is grounded and, being at the same potential as the anode cylinder (A), acts as an auxiliary anode. The ions, produced as in the diode pump, now graze the titanium lattice (C) giving a high sputtering rate, the sputtered titanium forming preferentially on the pump body.

Energetic neutral particles created by ions glancing off the cathode are buried on the surface of the pump body or are reflected and pumped at the anode. Any positive ions arriving at the pump body are repelled by its positive potential and do not touch the surface. Buried or implanted noble gases covered with fresh

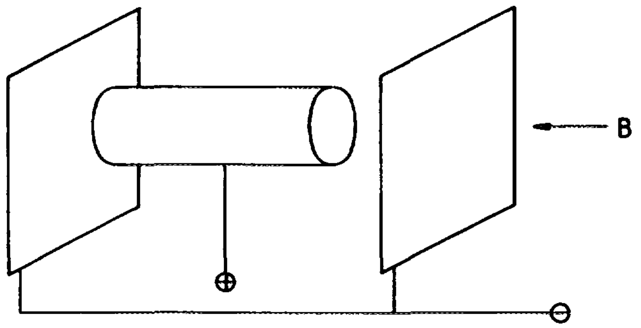


Fig.68 *Schematic diagram of a single cell sputter ion pump*

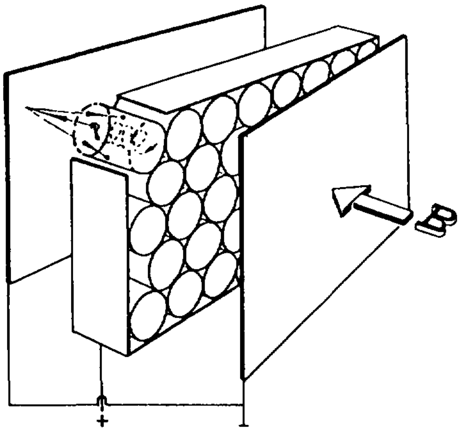


Fig.69 *Operation of the diode type sputter ion pump*

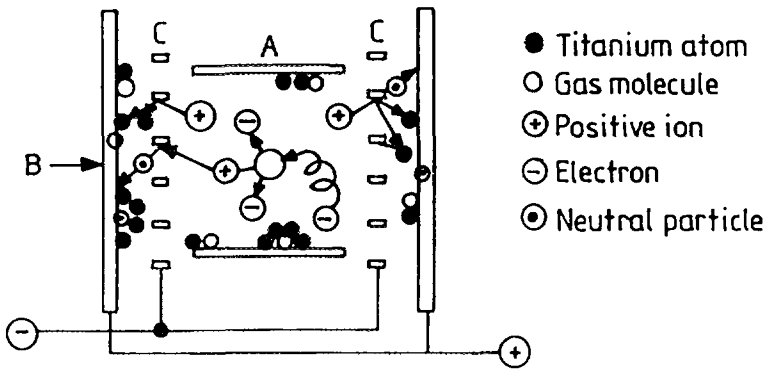


Fig.70 *The triode-type ion getter pump*

titanium are left generally undisturbed, leading to a higher net pumping speed for these gases.

Before the titanium ion getter pumps start, it is necessary to reach the fore vacuum in the vacuum system of the accelerating tube by a rotary pump. A cooled trap between the rotary pump and the sputter ion pump adsorbs the vapours and the humidity of the air.

As soon as the rotary pump reaches the ultimate vacuum, the ion getter pump should be switched on for a short time. The starting current of the Ti getter pump at the forevacuum pressure is usually high, which leads easily to overheating of the ion pumps. The switch on and off procedure should be repeated several times as the loading current of the getter pump reaches the normal working current range. During this time, the isolation valve between the rotary pump and the getter pump should be closed, and the rotary pump should be switched off, exposing to the atmosphere its inlet through an air admission valve. The normal work of the ion getter pump - in a leak-free vacuum system - will be indicated by a decreasing getter pump current.

9.2.3 Vacuum system based on turbomolecular pump

The principle of the molecular pump is based on the fact that the gas particles to be pumped receive, through the impact with the rapidly moving surfaces of a rotor, an impulse in a required flow direction. The surface of the rotor, usually disc shaped, forms with the stationary surface of a stator, intervening spaces in which the gas is transported to the backing port. In the original Gaede molecular pump and its modifications, the intervening spaces were very narrow, which led to construction difficulties.

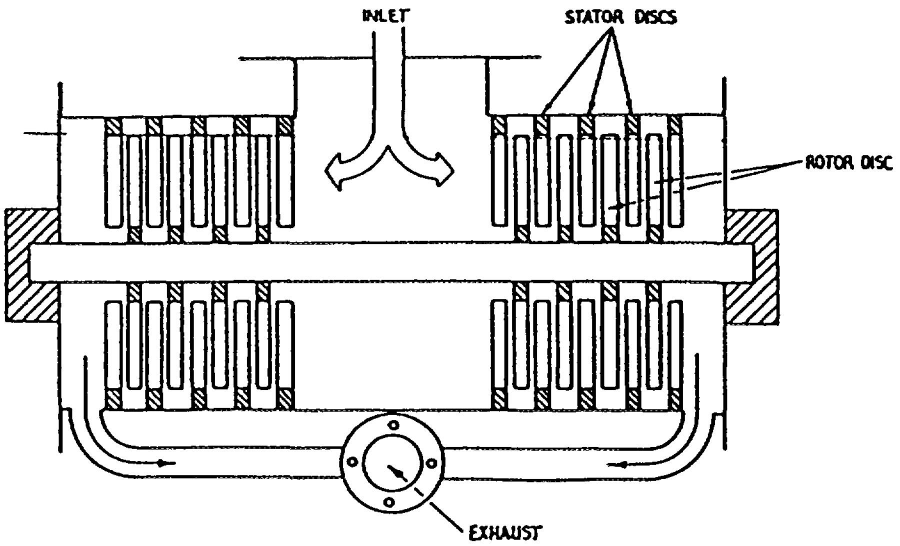


Fig.71 *Schematic diagram of the turbomolecular pump*

Using a turbine form of blading of the rotor, the so-called "turbomolecular pump" was developed as a technically viable pump.

A typical double flow pump can be seen in Fig.71. The rotor revolving at a very high speed carries the air - by molecular impacts - towards the backing pressure channel. In the case of lower vacuum needs - e.g. for neutron generators - mainly rotary pumps are utilized as backing pumps. The turbomolecular pumps have the advantage over oil diffusion as well as ion getter pumps in many respects: they can be put into operation quickly (in only a few minutes); the vacuum system is much less polluted by oil vapours; an unexpected exposure of the vacuum to the atmosphere does not damage the pump.

Important instructions on the use of turbomolecular pumps are as follows:

a) It is worth while to insert a cooled trap between the turbomolecular pump and the rotary pump; this improves the ultimate vacuum and protects the turbomolecular pump and the recipient from the oil vapours of the rotary pump.

b) Before starting up the turbomolecular pump, it is important to check the operation of water cooling. In most vacuum systems, water cooling starts automatically and the operation of the turbomolecular pump is interlocked by a pressure switch on the drain leg of the water cooling pipes. If the water cooling is not automatically switched on by the forevacuum pump, wait until the pressure in the vacuum system has reached the forevacuum level. The interlock circuit of the forevacuum controller will inhibit the manual switch-on of the turbomolecular pump.

c) The use of an isolation valve (quarter swing or butterfly valve) is advisable between the inlet of the turbomolecular pump and the vacuum manifold of the neutron generator. This butterfly valve is common in most neutron generators. The operation of the isolation valves is manual, electromagnetic or pneumatic. For smooth operation of the neutron generator, the vacuum in the manifold (and in the acceleration tube, beam line, etc.) should be kept, but the housing of the turbomolecular pump has to be vented to atmosphere to avoid oil infiltration from bearing lubricating oils. The use of dry nitrogen is advisable.

d) After switch-off, the rotor of the turbomolecular pump remains whirling for a period of 10-15 minutes. During this time, it is advisable to leave the rotary pump running and only at the end of this period to vent the pump housing to atmosphere.

Experience has shown that uninterrupted operation of turbomolecular pumps gives a longer lifetime than frequent switching on and off.

It is important to know that structural changes may take place in the bearing materials of a turbomolecular pump even if the pump is not used. Therefore, it is advisable to review bearings every three to five years.

9.3 PRESSURE (VACUUM) MEASUREMENTS

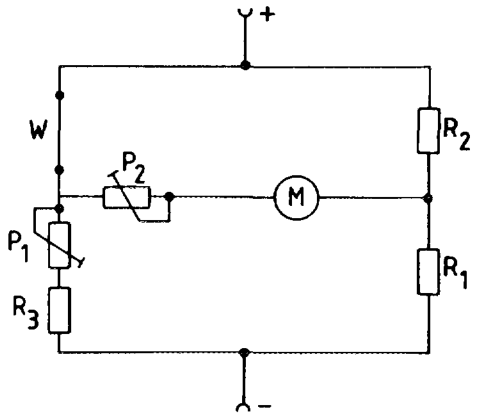
Neutron generators of various types use the following vacuum gauges:

1. Thermal conductivity gauges (Pirani and thermocouple gauges) for forevacuum measurements;
2. Ionization gauges (thermionic ionization or Bayard-Alpert type and cold cathode or Penning type ionization gauges) for high vacuum measurements.

The principles of these gauges are summarized in the following.

9.3.1 Thermal conductivity gauges

It is well known that for higher pressures (greater than about 10-20 mb) the thermal conductivity of a gas is independent of pressure (in this case the mean free path of the molecules is much smaller than the dimensions of a typical vacuum vessel). At lower pressures (from 0.5 to 5×10^{-4} mb), the thermal conductivity of a gas is proportional to the gas pressure. The Pirani and thermocouple gauges operate efficiently at such pressures.



W. GAUGE HEAD
R1, R2, R3· BRIDGE RESISTORS
P1, P2· BALANCE POTENTIOMETERS
M AMMETER

Fig.72 *Circuit diagram of a variable resistance thermal conductivity gauge (Pirani vacuum gauge)*

The Pirani sensor consists of an electrically heated filament (the heating is direct electric current - sometimes regulated - see Fig.72). The temperature, and therefore also the resistance, of the filament depends on the thermal conductivity of the surrounding air. The resistance change of the filament can be calibrated for pressure. The thermocouple gauge operates on the basis of similar principles, where the temperature of the filament is measured by a thermocouple [66]. Both types of gauge have an accuracy of about ± 10%.

In the case of a neutron generator, Pirani or thermocouple gauges - as forevacuum meters - can be connected as follows:

- Close to the accelerating tube for measurement of the forevacuum (usually on the vacuum manifold of the neutron generator);
- Between the high vacuum (e.g. oil diffusion, turbomolecular) pump and the rotary pump for controlling the forevacuum needed for the high vacuum pump;
- Somewhere to the target chamber for measurement of the forevacuum after a target exchange while the the main vacuum system of the accelerator is running (see Fig.67).

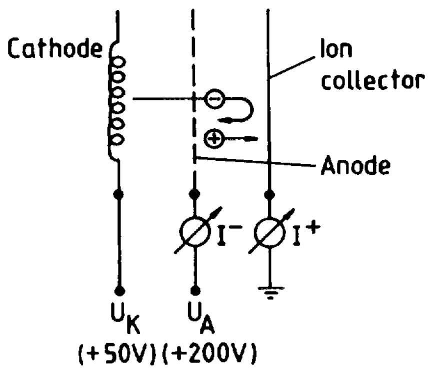


Fig.73 *Operation principle of thermionic vacuum gauge*
(I^+ = ion current; I^- = electron current)

9.3.2 Ionization gauges

(a) Thermionic ionization gauges

The construction of the thermionic ionization gauge is similar to a triode electron valve (see Fig.73). The operation principle is the following: Electrons emitted by the incandescent cathode are accelerated towards the anode and they ionize air molecules along their way. Positive ions produced in this process are collected by the grid having negative potential and, therefore, the grid current intensity in the circuit will be proportional to the gas pressure in the gauge.

The normal operation range is in the 10^{-3} - 10^{-8} mbar range, in general. At higher pressures, the incandescent filament may burn out; on the other hand, the extension of measuring ranges towards smaller pressures would be limited by secondary electrons released from the collector by X-rays generated by the electron bombardment of the anode. The electronics, connected to the gauge, usually has built-in filament protection, which interlocks the switch-on of the gauge whenever the pressure is higher than 10^{3} mbar.

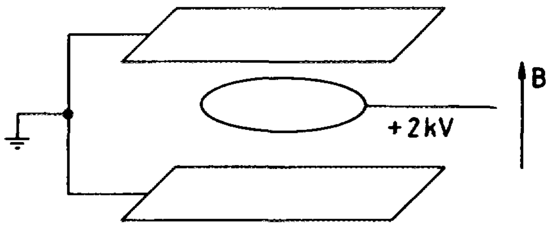


Fig.74 *Operation principle of cold cathode ionization vacuum gauge*

(b) Cold cathode or Penning ionization gauge

The construction of this gauge can be seen in Fig. 74. The operation principle is very similar to the ion sources with the same name. Electrons emitted by cold emission from the two flat cathodes as a result of having some kilovolts on the ring anode ionize the gas molecules in the gauge head. The positive ions produced in this way run up towards the negative electrode and therefore they change - proportionally to the gas pressure - the electric current in the anode or cathode circuit. The magnetic field B (generated by a permanent magnet) forces the electrons between the anode and the cathode onto a long helical path and therefore the efficiency of ionization and the sensitivity of the pressure measurement increase (Penning principle, like the ion sources of the same name).

The ionization vacuum gauges with cold cathode can generally be used within the range from 10^{-3} down to 10^{-7} mbar having a direct meter readout; however, this range can be extended by the use of current amplifier down to as low as 10^{-12} or even 10^{-13} mbar.

In spite of vacuum gauges with hot cathode, the cold cathode ionization gauges have the advantages of a much higher lifetime and needing simpler electronics for operation and readout.

On the other hand, there is the disadvantage that, from time to time, the gauge needs cleaning. This is because the cold emission depends strongly on the cleanliness of the cathode surface. Meticulous care should be taken, especially in vacuum systems with an oil diffusion pump. Oil deposits and any other contamination on the surface of a cathode decrease emission capability, and therefore higher and higher vacuum will be "measured" by the contaminated gauge. It is worth while to clean the dismantled gauge head by washing it with hot water and household detergent, distilled water, alcohol and any other organic solvent.

9.4 PRESSURE MONITORING AND LEAK DETECTION

9.4.1 Leak rate measurement

The pressure in a vacuum chamber that is to be evacuated by any pump system will decrease with time (after switching on the system), as shown on the curves in Fig.75. If at all the connections of the system the gaskets are well fitted to result in hermetic sealing, and the inflow is very small, the pressure will decrease from the initial p_0 value, as described by curve (1). The pressure decrease continues until the ultimate pressure - whose value depends on the pumping speed and the hermeticity of the vacuum system - is reached. The time necessary to attain the ultimate pressure is determined by the pumping speed of the pump.

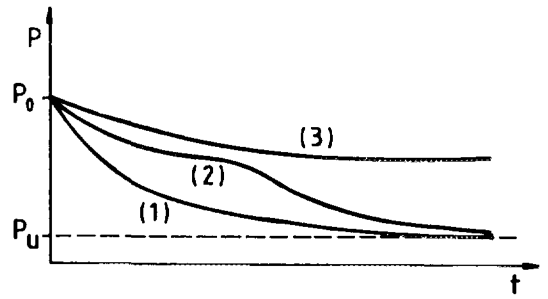


Fig.75 *Pressure change in vacuum chamber vs pumping time*

Curve (2) shows the case when the usual ultimate pressure can be reached later: after switch-on of the gas ballast of the rotary pump. This phenomenon indicates the presence of different vapours.

Curve (3) describes a situation when the ultimate pressure can't be reached even after switching on the gas ballasting valve. This indicates a higher than usual intake from the outer atmosphere. In this case, the pumping speed of the pump is not high enough to decrease further the pressure in the vessel to be evacuated. The dynamic equilibrium will be reached when the gas outflow - produced by the pump - is the same as the leak current, that is the intake from the outside.

In case (3), it is not advisable to leave the vacuum system in operation. A leak test should be carried out: search for the defective gaskets and change them for a new (or properly sealing) one! At the installation of a new neutron generator, after assembling the vacuum system, it is very important to determine which of these three cases exists. This kind of pumping speed determination - as a test - may also be needed several times, especially if some changes have been made on the vacuum system of the accelerator (e.g. inserting a new cooled trap; replacing valves; dismantling, cleaning and re-filling (by oil) of a diffusion pump; etc.).

The best method to check the hermeticity of a vacuum system is by measuring the leak rate, which can be done as follows:

Measure the pressure p_1 at a moment t_1 and then separate the pump from the evacuated vessel. The pressure will increase slowly due to the air intake through the leak, and later, at moment t_2, we may measure the pressure p_2.

The air intake, β, is by definition

$$\beta = \frac{p_2 - p_1}{t_2 - t_1} V_e \tag{27}$$

where V_e is the volume of the evacuated system. If the pressure difference is measured in mbars, the time in seconds and the volume in litres, then β will be obtained in mbar l/s.

In practice (utilizing a pump of usual power and a vacuum system with rubber seals and gaskets), if β is equal to or lower (in order of magnitude) than 10^{-4} mbarl/s, then the hermeticity of the system (i.e. the effectiveness of the sealing) can be considered acceptable. If the hermeticity of the system is not good enough, further leak tests should be carried out.

9.4.2 Pumping speed measurement

A very important part of the vacuum system design is determination of the pumping speed, which must be known in order to attain the required ultimate pressure. This is a basic problem at the different accelerators, where the ion source naturally consumes gas. When a new neutron generator is put into operation - and also later, when a modification has been made - the pumping speed of the system should be tested.

When connecting a pump to a vacuum system of volume V, the pressure change with time during operation will be:

$$-\frac{dp}{dt} = S\frac{p}{V} \tag{28}$$

where S is the pumping speed. The negative sign corresponds to the fact that the pressure decreases with time. If constant pressure is maintained by a needle valve controlling the air intake from the atmosphere, the pumping speed will be:

$$S = \frac{dV}{dt} \qquad (29)$$

In practice, when the pumping speed is to be determined, a definite change in atmospheric pressure air volume during the corresponding time interval has to be measured. This can be done by using the equipment shown in Fig.76. This setup is also used for measuring ion source gas consumption [66].

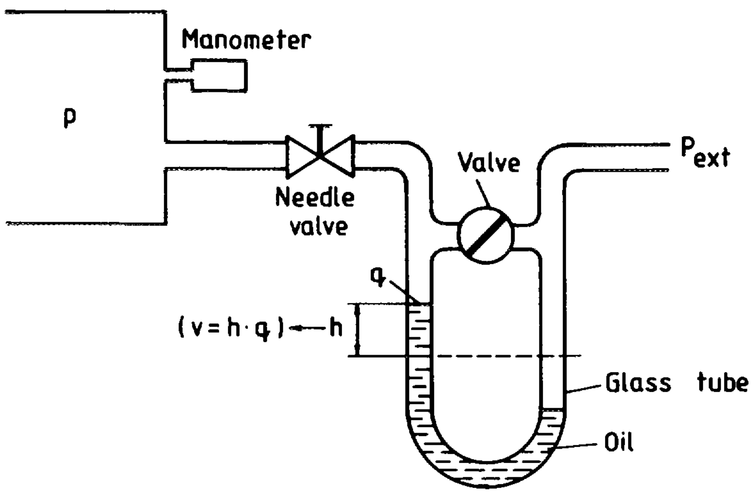


Fig.76 *Equipment for the measurement of pumping speed*

The pressure p in the vessel under evacuation is adjusted by a needle valve in the ON position of the valve V. In equilibrium the pump removes the amount of air inflows into the system through the needle valve. Turning the valve V in the OFF position, air from the left side of the U shaped glass tube will flow into the vessel under evacuation; therefore, the liquid level will rise on this side. Using a stopwatch, the time interval can be measured during which the liquid level rises from the lower to the upper mark in the U shaped glass tube. The volume of air v - having the external atmospheric pressure - between the marks can also be determined.

From the expression $p_{ext}v = pV$, it follows that the volume of air that flowed into the vessel:

$$V = \frac{p_{ext}\, v}{p} \qquad (30)$$

and therefore the pumping speed:

$$S = \frac{\Delta V}{\Delta t} = \frac{p_{ext}\ v}{p\ t} \tag{31}$$

Typical pumping speed versus pressure functions are shown in Fig.77 and Fig.78 for a rotary and an oil diffusion pump, respectively. It is characteristic for both cases that the real pumping speed becomes zero at the ultimate pressure, i.e. when the pumping causes a dynamic equilibrium: then the pump removes just as much air from the system as the air intake due to the ineffective sealing. The pumping speed is given - for both types of pump - at the constant section of the pumping speed function (in l/s for a diffusion pump and in m^3/h for a rotary pump in general).

These pumping speed values - given by the manufacturers - are measured at the inlet of the pumps, but the realistic pumping speed far from the inlet is below this catalog value because the resistance of different elements of the vacuum system decreases the pumping speed. This can be seen in Fig.79, where changes in the pumping speed functions for an oil diffusion pump are shown with different cooled traps. For neutron generators, it is advisable to carry out the pumping speed measurements of the vacuum system according to the arrangement shown in Fig.80.

The most important task is first of all to check whether the required vacuum can be guaranteed by the available pumping system along the whole length of the accelerator tube (having dimensions negligible compared to the mean free path) with the deuterium consumption necessary for normal operation of the accelerator.

For pumping speed measurement it is advisable to connect the U tube to the gas inlet of the ion source via a needle valve and to let an amount of deuterium gas flow into the system which corresponds to the actual gas consumption. If, for economic reasons, D_2 cannot be used, hydrogen gas may serve the same purpose, like at the installation of a new or repaired neutron generator.

Most commercial neutron generators with a deuteron beam of 1-2 mA have a deuterium gas consumption equivalent to 4-5 cm^3/h at NTP. Therefore, the pumping speed measurement should be carried out at this gas inlet with very great precision.

The pumping speed of the pumping systems can change for the following reasons:

- Decreased heating power of the oil diffusion pumps: This can be an electrical failure, but the problem may arise even if the water cooling loop is very close to the heater of the pump or if the oil level in the pump is

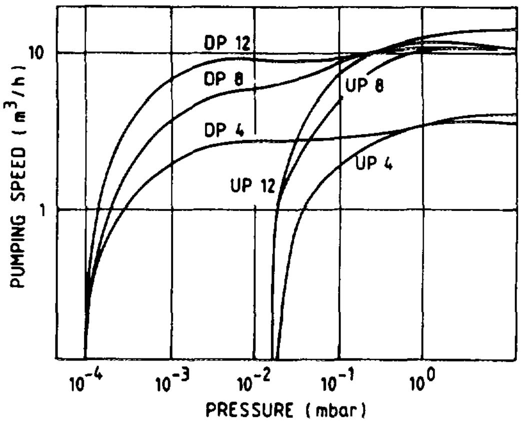


Fig.77 *Pumping speed characteristics of a twin stage (DP) and a single stage (UP) TUNGSRAM rotary pump* [65]

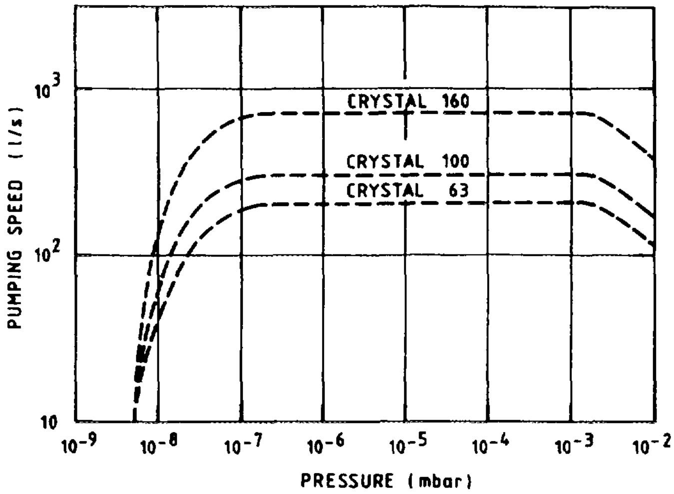


Fig.78 *Pumping speed vs pressure characteristics of ALCATEL diffusion pumps* [64]

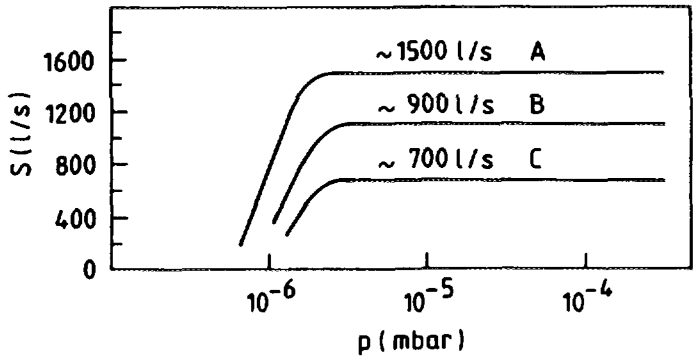


Fig.79 *Pumping speed of a diffusion pump (A: without traps, B: with water cooled trap C: with water and liquid N_2 cooled traps)*

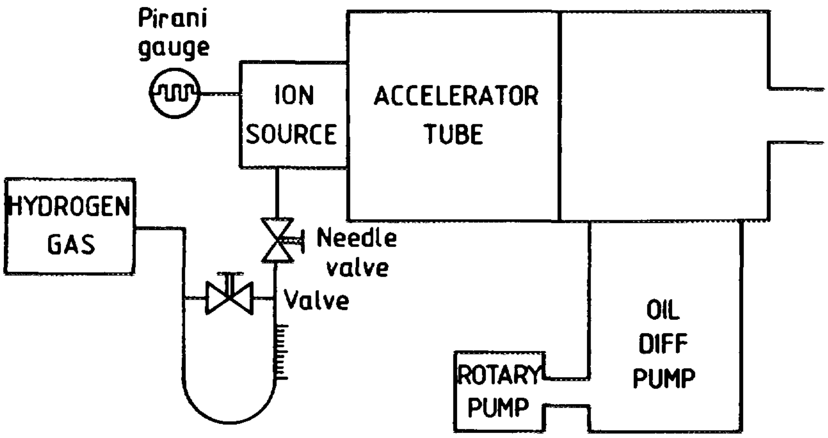


Fig.80 *Arrangement for the pumping speed measurement on a neutron generator*

less than is needed. Normal oil level is 8-10 mm high measured from the bottom of the diffstack.

- In rotary pumps, the lower pumping speed stems mainly from problems with the oil level, so this should be checked regularly.
- In ion getter pumps, the contaminated cathode surfaces (mainly by oil) decrease the electron emission, which may cause a fairly large decrease in the pumping speed.

9.4.3 Leak detection

As mentioned in Section 9.4.1, if the measured intake exceeds a value of about 10^{-4} mbar l/s, then the vacuum system is not tight enough and therefore a leak detection becomes necessary. There are many technical methods available to detect a leak, starting from single vacuum gauges to the most modern mass spectrometers [67].

However, before starting any leak detection, it is worth checking the whole system again. Most problems are caused by rubber gaskets (it may happen that the gaskets are not fitted properly to the metal surfaces in the joints, or the gaskets might be missing by mistake). It is advisable to check the valves and the air admittance valves. A particularly careful test should be carried out on any part of the neutron generator where some alteration has been made recently, e.g. target exchange, exchange of glass balloon in the ion source, placing or replacing a new vacuum gauge, etc. If the check seems to be unsuccessful, some method of leak detection should be carried out.

Some methods - which can be easily accomplished in a neutron generator laboratory - are described below.

The simplest solution is the use of a vacuum gauge, which is a normal accessory in any vacuum system. The use of Pirani gauges for leak detection is based on differences between thermal conductivities of different gases (e.g. the conductivity of hydrogen is much higher than that of air). The Pirani gauge uses the thermal conductivity in the pressure measurement of gas: therefore the leak detection should be carried out as follows:

- Using a cylinder of hydrogen, with the corresponding pressure regulator, a narrow jet of H_2 should be blown onto the wall of the vacuum vessel, where the leaks are being looked for. Test carefully the gaskets and the joints. The hydrogen creeps into the vacuum vessel at that area of the wall where a leak exists. Therefore, the Pirani gauge will show a higher pressure due to the higher heat conductivity of the hydrogen, indicating the position of the suspected leak.
- Ionization vacuum gauges may also be used to search for a leak if vapour of some organic liquids (e.g. ether) is used as a "test gas". In this case, of course, a vacuum value has to be attained which is at least within the range of applicability valid for the given gauge (this value is between 10^{-3} and 10^{-8} mbar, depending on the type of gauge).

Both methods described above are suitable for a quick search for rather coarse leak sites (i.e. intense air intakes); this quick and rough method is the most expedient to detect what has happened to a neutron generator during dismantling and reassembly.

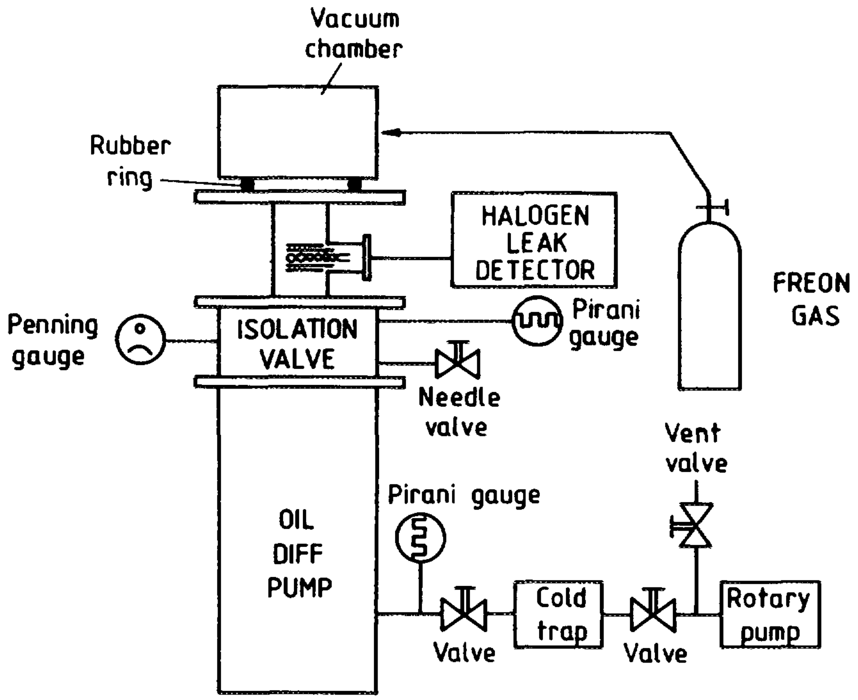


Fig.81 *Vacuum test stand with halogen leak detector*

When an ion getter pump is used in the vacuum system, this pump can also be used for leak detection. This is because the pumping speed of an ion getter pump is different for different gases: for example, it is three or four times smaller for argon than for oxygen. Therefore, if argon is used in the test gas jet the ammeter of the pump power supply will show a higher power consumption.

Leaks causing smaller inflows - which cannot be detected by common vacuum gauges - will occur due to mechanical imperfections (e.g. imperfect welding). This could occur e.g. when a new target-holder or a new cold trap is assembled onto the vacuum system. It is advisable to test them - with the help of a separate simple vacuum system - before installation. Such a vacuum system equipped with a halogen leak detector is shown in Fig.81.

The measuring gauge of the halogen leak detector contains an indirectly heated platinum probe - like a cathode - emitting alkali ions, and their current is measured by an ammeter or is indicated by audio signal. The ion emission increases considerably whenever halogen gas gets into the measuring gauge. This phenomenon can be used for leak detection in any vacuum system. The test gases containing halogen are usually fluorocarbons which may be easily purchased on the market. FREON-12 is the usual gas used in cooling machines, refrigerators and air conditioners: it has a boiling point of $30^{o}C$, while FREON-112 is a liquid, with a boiling point of $93^{o}C$. Both can be utilized for halogen leak detection. The FREON liquid or gas gets easily into the vacuum chamber through the leaks in the wall (and improves sealing) of the vacuum vessel from the outside and therefore an increased ion current will be detected by the electronics.

In order to achieve the highest possible sensitivity in the leak detection process, it is advisable to place the halogen gauge as close as possible to the vacuum vessel to be checked for leaks (short interconnection). Vacuum gauges mounted on a vacuum stand can give - even before the halogen-using in-situ leak detection process - rough preliminary information on the expected leak, if it exists. A needle valve can be used to simulate a leak, and therefore to check the leak detector.

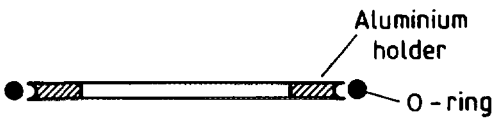


Fig.82 *Typical O-ring seal for interconnection*

The vacuum vessel to be tested should, of course, be well fitted to the vacuum system for the leak test. For this it is advisable to use a well fitting O-ring, for example one like that shown in Fig.82. The diameter of the ring is determined by the diameter of the vessel and by the opening at the top of the vacuum test stand. High vacuum plastics (like Viton) - available from a couple of manufacturers - can be used as well.

It should be noted that the halogen leak detector can also be connected to the vacuum system of a neutron generator. The most advantageous place for the gauge is near the forevacuum pump. In this case, the test gas will probably reach the detector.

The most sensitive leak detection can be performed by a mass spectrometer leak detector, which is an essential piece of equipment in almost any laboratory involving vacuum equipment and its associated technologies. This may be an existing residual gas analyzer or He leak detector, according to whether it is a magnetic sector or quadrupole type, but it does not need a very high resolution because it is only necessary to separate the two most commonly used gases, hydrogen and helium, at mass numbers 2 and 4 respectively.

The conventional mass spectrometer leak detector is normally a portable unit having its own vacuum system including a rotary and a turbomolecular pump (liquid nitrogen trap), gauges and electronics, as shown schematically in Fig.83.

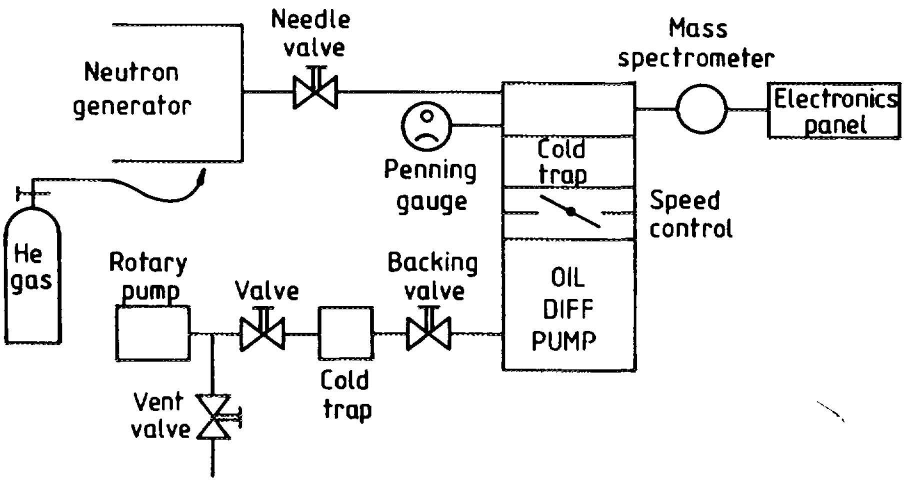


Fig.83 *Utilization of mass spectrometer as leak detector*

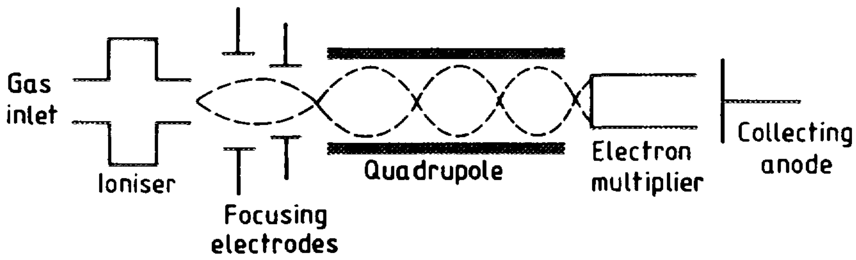


Fig.84 *Schematic diagram of a quadrupole mass spectrometer*

The most specialized mass spectrometer leak detector is usually quadrupole, in view of its small flange-mounted gauge head and easy operation. The ion beam produced by electron collision in the ion source is accelerated and injected into a quadrupole separation system having four electrodes of hyperbolic cross section (see Fig.84) [69].

A constant high frequency voltage U (f = 2.5 MHz) and a superimposed DC voltage V are applied to the electrodes. As the value of U and V are increased simultaneously, the mass will be scanned from an initial value up to a maximum, whereby the ratio U/V must be kept precisely constant.

The mass number of the ions emerging through the separation system and being detected must satisfy the following conditions:

$$M = \frac{V}{7.2\, f^2\, r_0^{\,2}} \qquad (32)$$

where r_0 is half the distance between two opposite electrodes.

As a result of the linear dependence of the mass M and the voltage V, a linear mass scale may be obtained by a linear scan of V and U.

The filament of the ion source in the spectrometer is switched on when the pressure in its own vacuum system is less than $\sim 5 \times 10^{-4}$ mbar and the vacuum system of the neutron generator under test is to be tested with a helium gas jet. The leak is detected by the audio indication and/or by the analog meter in the readout. The sensitivity of this detector can be improved by increasing the gain of the electrometer amplifier and/or reducing the effective pumping speed of the high vacuum pump by adjusting the speed control valve but still maintaining the maximum pressure at which the filament operates.

10. BEAM ACCELERATION AND BEAM TRANSPORT SYSTEMS

10.1 ELECTROSTATIC LENS

The electrostatic lens is the most usual focus device in low energy accelerators and neutron generators. The energy of the ion beam extracted from the source is a few tens of keV. This beam can be focused easily by an electrostatic lens. The magnetic lens is very rarely used in neutron generators. The preacceleration lens is usually an electrostatic diaphragm, immersion or unipotential lens. The unipotential lenses is also known as the Einzel lens (its original German name) [69]. A typical single gap diaphragm lens acceleration tube is shown in Fig.85. This acceleration tube has an extraction gap (focusing gap: due to the focusing behaviour of the first diaphragm) and an acceleration gap. The size of the electrodes for 150 kV acceleration voltage is indicated in the figure [70].

An immersion lens is an electrostatic lens which has equipotential regions on both sides of the lens. It can be constructed of diaphragms or cylinders. Fig.86 shows an immersion lens consisting of two equal diameter cylinders. The immersion lens - depending on the polarity of the voltage drop of the lens gap - can be analogous with convex and concave or concave and convex lenses [71].

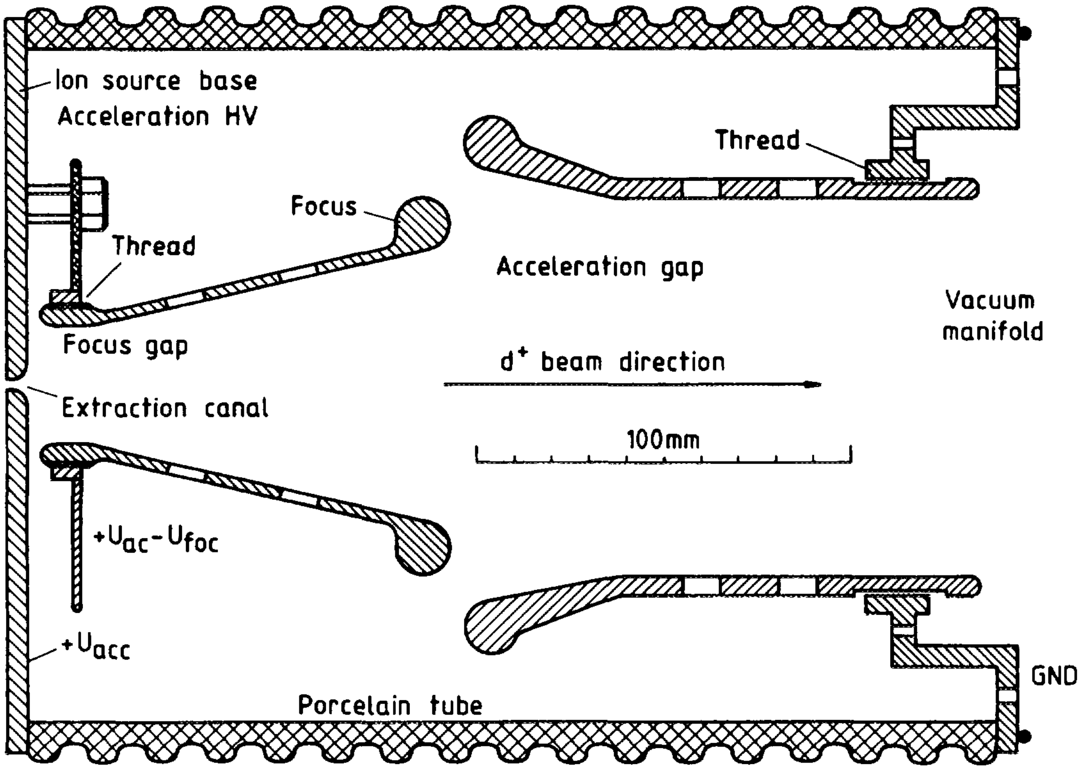


Fig.85 *Immersion lens equivalent single gap acceleration tube for 150 kV neutron generator*

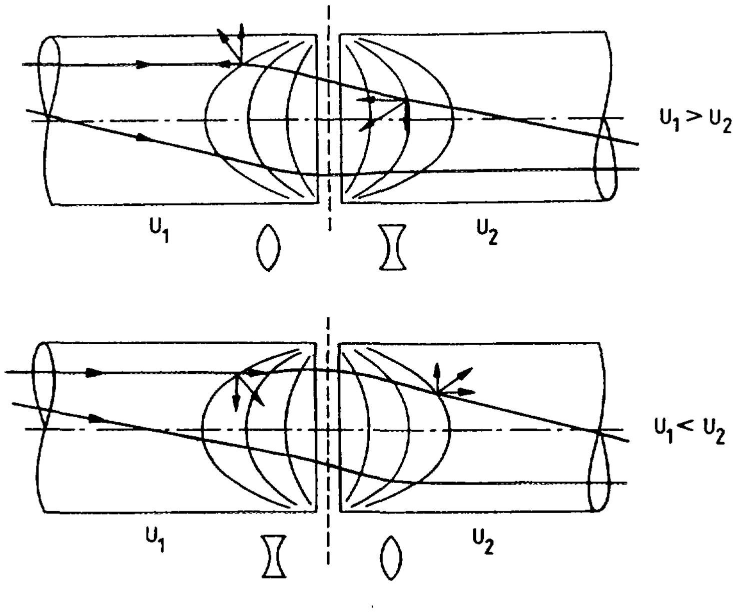


Fig.86 *Electrostatic immersion lens (consisting of two cylinders) with its optical analog*

10.2 UNIPOTENTIAL OR EINZEL LENS

The Einzel lens is an electrostatic lens in which the energy of the beam does not change because of the symmetrical potential of the electrodes. The unipotential lens focuses the ion (electron) beams with positive or negative U_C potentials of the middle electrode. Fig.87 represents the optical analog convex-concave-convex lens system of the Einzel lens for a deuteron beam. The Einzel lens is symmetrical: the focal length on the object and the image side have the same f value. The d focusing power and the f focal length for a unipotential lens is shown in Fig.88.

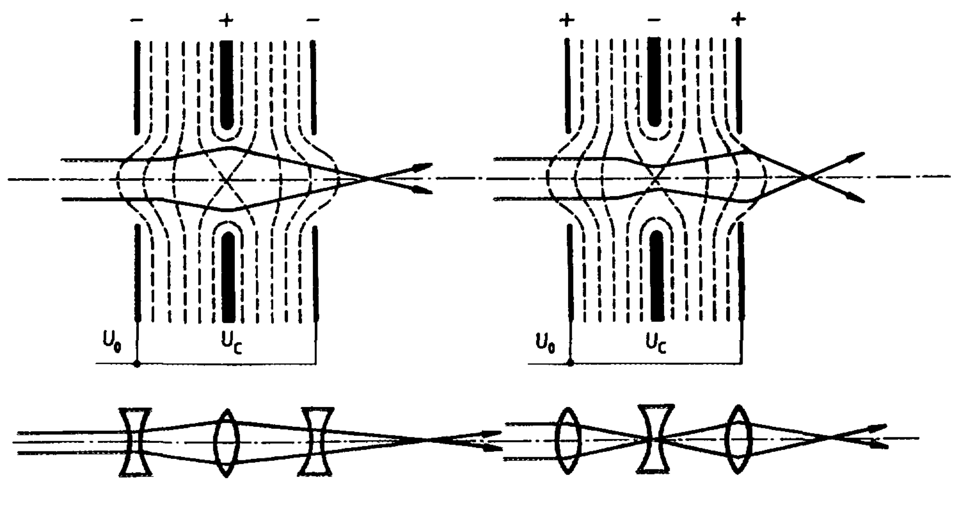


Fig.87 *The unipotential (Einzel) lens with its optical analog*

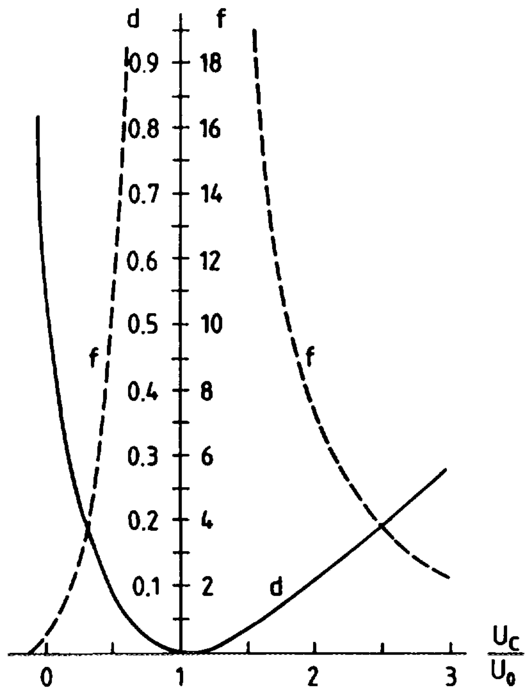


Fig.88 *The focusing power and focal length of the unipotential lens*

The focal lenses of the low energy accelerators (neutron generators) are usually immersion or unipotential lenses. In a unipotential lens the diaphragm or cylinder close to the ion source serves as an extracting electrode. The exit electrode of the unipotential lens is connected to the potential of the first electrode of the (multielectrode or homogeneous field) accelerator tube. The focus voltage source is on the acceleration high voltage terminal (see Fig. 11). As the focus electrodes and the accelerator tube electrodes should be aligned, the beam position at the exit of the acceleration tube is almost off axis. The steering and positioning of the beam after acceleration is usually carried out by biased quadrupole lenses. For RF, PIG and DP ion sources, the current can be substantially increased in a wide range by increasing the extracting voltage [72], i.e. the current is proportional to the energy of extracted ions. For typical extraction geometries, the maximum voltage V is given by the relation [73] $V \cong 5 \times 10^4 d^{1/2}$, where d is the gap spacing in centimeters.

10.3 TROUBLESHOOTING OF ELECTROSTATIC FOCUS LENSES

If the properties of the electrostatic focus lens are unsatisfactory the following should be tested:

- Vacuum in the system,
- Focus voltage on the focus electrode,
- The correct operation of the ion source and the extracting system.

Bad vacuum (oil vapour, high pressure in the focusing space) can easily lead to surface contamination of the focus lens electrodes. In the case of high pressure, a glow discharge can be built up between the focus electrodes and can contaminate the surface of the electrodes. In the case of oil vapour, the surface layer may insulate the electrode (silicon oil!), and the distribution of the potential between the lens electrodes will be changed. This can lead easily to the deterioration of the focusing properties of the lens. Observation of the focus electrodes - after a long term operation of the vacuum system of the accelerator - is important. In the case of blackish-brown electrodes, clean them with organic solvents and polish their surfaces. After dismantling the focus lens, the polished surfaces should be washed (if possible in organic solvent and an ultrasonic bath) and carefully reassembled in the vacuum system. Test the high vacuum feedthrough of the focus electrode. If the surface is contaminated, clean the feedthrough as well. Test the conductivity and the isolation of the assembled system. A thick conducting carbon layer on the surface of the insulator of the focus electrode (from hydrocarbon oil contamination in the system) may produce a bypass current and a change in the focus voltage. As the focus power supply is usually protected against breakdowns due to discharges between the focus electrodes, the voltage test of the focus voltage may give an indication on the surface contamination in the focus electrode region.

If malfunction of the focus power supply is detected, troubleshooting and repair should be done on the basis of the instruction manual, in which the necessary procedures will be described in detail in the section on high voltage power supplies.

10.4 THE ACCELERATION TUBE

The acceleration tube of neutron generators consists of annular electrodes separated by a hollow cylindrical insulator of glass or ceramic. The insulators and the metal electrodes are bonded together either with epoxy resin or with polyvinylalcohol (PVA) glue to form vacuum tight joints. There are various simple designs for accelerating tubes with homogeneous or inhomogeneous field of low voltage accelerators [74-77]. The transport of the beam over long distances is simple if the currents do not exceed a few milliamperes. The homogeneous field acceleration tube, i.e. the multigap tube, consists of more acceleration gaps using diaphragms, cylinders, hollow cones, etc., as electrodes, which are fed by an equiresistance voltage divider resistor chain. The inhomogeneous field or single, two, etc., gap acceleration tube consists of cylindrical or conical immersion lenses (see Fig.85). This tube is common in fixed acceleration voltage machines such as the sealed tube neutron generators. Two-gap acceleration tubes are used in TMC A-111 and KAMAN A-1254 neutron generators. The first gap is for focusing and the second for acceleration.

Recently, accelerating tubes with either a single-gap [74,78-80] or special multigap arrangements [81-84] are used in improved neutron generators. The single-gap, high gradient system requires particular attention to the purity of vacuum and the manufacturing of the electrode. During operation, a pressure higher than 10^{-3} Pa must be assured in the cavity, free from hydrocarbon molecules. A carefully polished and cleaned titanium electrode is needed to maintain a field strength of 200 kV/cm. Secondary electrons - ejected by positive ions from the neutral atoms in the beam and on the electrode surface - are accelerated towards the high voltage terminal. The intensities, maximum kinetic energies, and mean energy values of electrons can be deduced from the measurements of the bremsstrahlung. These data can give information on the optical behaviour of accelera tion tubes with different field structures [85-86]. The acceleration tube in a neutron generator also:

- Accelerates the extracted D^+ ions;
- Keeps together the D^+ ion beam or focuses it;
- Holds the vacuum in the neutron generator;
- Holds (sometimes) the voltage divider resistor chain and the ion source.

The electrodes should screen the insulator walls of the tube to protect them from oil vapour or carbon layer deposit due to the ion beam scattering on the oil vapour in the vacuum.

The manufacture of an acceleration tube requires a well equipped workshop with special tools for glueing and bonding the components of the tube as well as for its alignment. The bonding is usually carried out under pressure. The use of PVA requires a polymerization process under high temperature in a special oven. The resin and glue are squeezed out to form a fillet both on the inside and the outside of the metal insulator joint. This fillet can cause problems because it is situated at the point of the highest electric tension and because it outgasses into the vacuum during the operation of the tube. In some tubes the accelerator electrodes are not flat diaphragms but are strongly dished or are cone shaped to shield the fillets and insulators against the electric charges, scattered oil and other vacuum dirt. The electrodes of an accelerator tube - especially the multi-electrode homogeneous field accelerator tubes - will increase the vacuum resistance of the accelerator tube as a vacuum component. As the ion source (the gas inlet) is situated at one end of an acceleration tube and the vacuum pumps are situated at the other (at the ground potential), the accelerating electrodes of an acceleration tube are usually perforated to form a lower vacuum resistance between the ion source and the vacuum pumps.

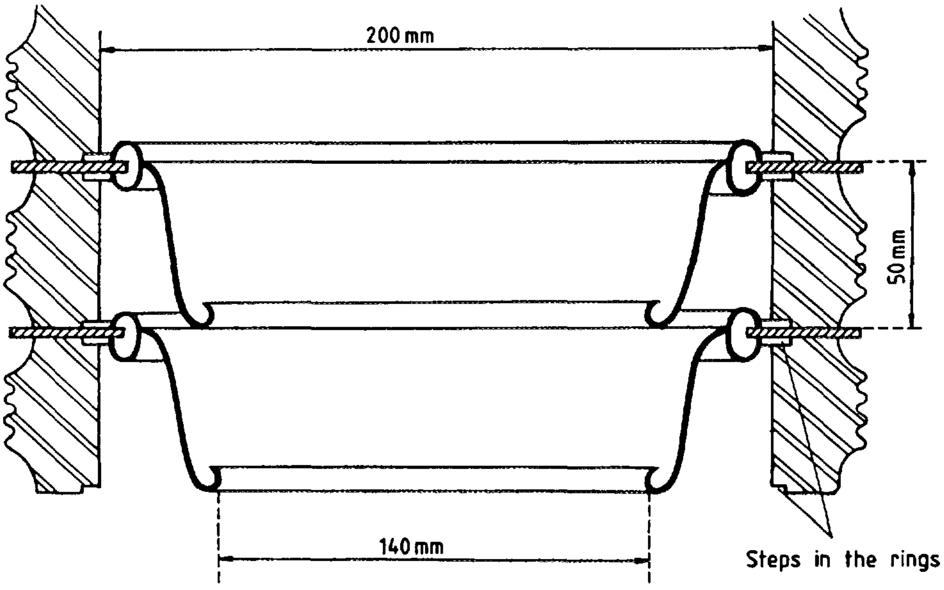


Fig.89 *The structure of a homogeneous field accelerator tube*

The structure of a homogeneous field acceleration tube is shown in Fig.89 [69]. This tube consists of conical acceleration electrodes and ceramic insulating rings. The cone shaped electrodes protect the walls of the ceramic insulator rings against contamination. The tube's lifetime is limited for the following reasons:

- Secondary electrons produced by ions from the residual gas (not only oil vapour!) in the acceleration tube accelerating and bombarding the electrodes and insulators;
- Electrons bombarding the epoxy resin or PVA fillet at the bond between the insulators and the metal electrodes;
- Poor vacuum in the tube;
- Heavy ions or molecular ions formed from the ion or electron bombardment of residual gas and from electron bombardment causing sputtering of the metal accelerating electrodes;
- X-ray or ultraviolet photons causing photoelectric emission of electrons;
- Field electron emission from the metal electrodes.

It is probable that all of these processes contribute to a greater or lesser extent to the operation of conventional acceleration tubes, but it is clear that electrons, whatever their source, play the major role. The lifetime of the acceleration tubes can be increased by the following means:

- Maintaining a good vacuum in the acceleration tube in the order of 1.3×10^{-5} to 10^{-3} Pa;
- Using the electrode shape which shields the insulator ring and bonding fillets from the electron or heavy ion bombardment;
- Constructing the electrode system from aluminium;
- Using the secondary electron suppressor -300V to -400V before the target to protect the residual gas and electrodes from secondary electron bombardment.
- The use of deflecting magnets or electrostatic deflector plates may protect the accelerator tube as well [87].

10.5 TROUBLESHOOTING OF ACCELERATION TUBES

In an improperly working acceleration tube the ion beam current will be low or diffused. The first thing to be done is to check and test the ion source. The steps are as follows:

1) Check the vacuum.
2) Check and test the resistor divider of the acceleration tube. As the resistance between two electrodes is usually in the order of 10-100 MΩ, the use of a megaohm-meter is recommended. Check the contacts between the electrodes and the resistor chain. A faulty contact between the voltage divider and the electrode may disrupt the ion beam: the isolated accelerating electrode will be charged to a positive potential and it will deflect the original ion beam from the original axis of the beam line.
3) Test the insulation between the accelerating electrodes with a high voltage insulation tester. Testing voltage of several kV is recommended. In case of sparks along the surface of the isolator rings, some metal or carbon tracks can be observed. Clean the outer surface of the isolators with polishing paper and organic solvents.
4) Observe the inner side of the acceleration tube. When the ion source and the extraction system can be easily dismantled, open the ion source end of the acceleration tube. Light the inside of the acceleration tube. If the electrodes (not only the accelerator electrodes but also the extraction and focus) show some contamination such as oil vapour in the form of brownish-black layers clean the electrode surfaces. Polishing and washing with organic solvents (N-hexane, petroleum-ether, acetone, etc., depending on the materials used) should be done carefully. The form of the oil deposits on the electrodes can give some information about what is making the ion beam current decrease. The eroded surfaces indicate the effects of the electron bombardments along the acceleration tube, and give an indication on the poor vacuum or other contamination sources. Check for continuity between the inner electrodes and the outer contacts.

11. PRINCIPLES OF BEAM FILTERS

11.1 ELECTROSTATIC AND MAGNETIC BEAM DEFLECTION

The accelerated deuteron beam contains D^+, D_2^+, D_3^+ ions and also other ion species (N^+, O^+) from the residual gases and vapour of the oil or grease. This vapour will cover the surface of the target. The target lifetime in a neutron generator depends very strongly on the quality of the vacuum. The deflected beam results in a more clear emitted neutron spectrum.

The beam filters of neutron generators utilize electrostatic or electromagnetic separators or both, in the straight-line Wien filter. It is well known that in an E electrostatic field perpendicular to the direction of the ion beam, as shown in Fig.90, the deflection y_e along the plates of length l is given by

$$y_e = \frac{eE}{2m}\left(\frac{l}{v}\right)^2 \tag{33}$$

where E is the electric field strength (E = U/d). For small angles the deflection angle is

$$\vartheta_e = \frac{eEl}{mv^2} = \frac{Ul}{2U_o d} \tag{34}$$

where U_o is the accelerator voltage.

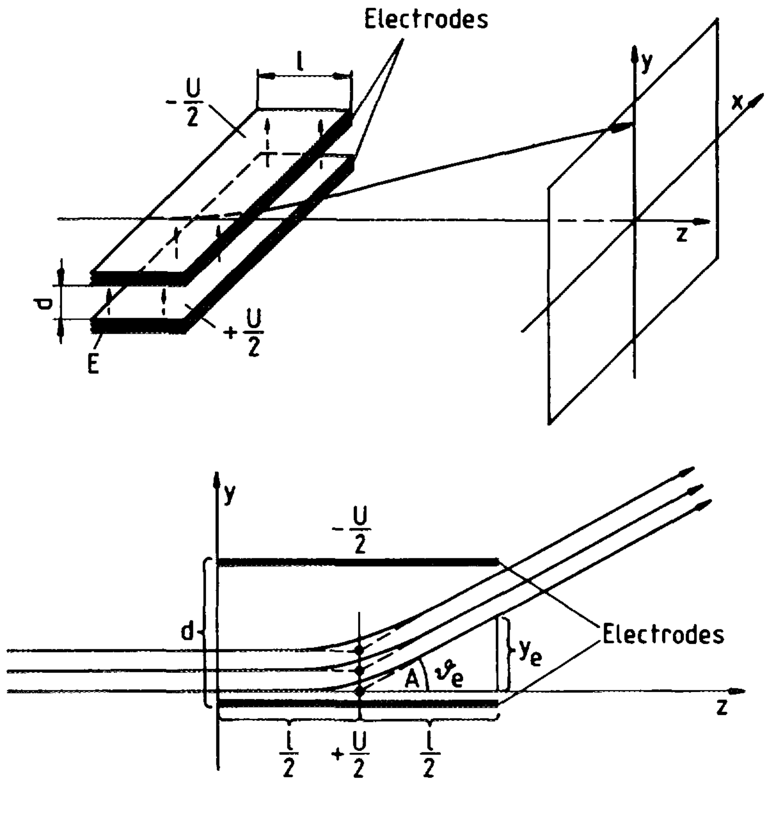


Fig.90 *Electrostatic deflection of charged particle beams*

Results show that by the small angle electrostatic deflection the beam components cannot be separated for e/m. However, the neutral beam components (oil vapour, residual gas) will be separated from the ions. Electrostatic beam deflection is normally used to produce a pulsed beam at the neutron generators.

The magnetically deflected beam has a circular trajectory (Fig.91) and the $\vartheta_m \cong l/\rho$ deflection angle is given by

$$\vartheta_m = lB(e/2mU_0)^{1/2} \qquad (35)$$

where B is the the magnetic field strength. Equation (35) shows that the deflection angle of an accelerated ion beam depends not only on the U_0 acceleration voltage, B magnetic field strength, but also on the specific charge e/m of the given ion.

The Wien filter utilizes perpendicular E and B fields. The ϑ_m magnetic deflection of a given ion can be compensated by the ϑ_e electrostatic deflection: so the Wien filter forms a straight-line ion selector. When $\vartheta_e = \vartheta_m$ only a single ion of specific charge e/m may pass through the exit slit of the filter [88]. The value of v is constant and depends on U_0 voltage: $m = 2eU_0(B/E)^2$.

The $\Delta m/m$ mass resolution of the Wien filter - as for other (magnetic) analyzers - strongly depends on the width of the entrance and exit slits of the vacuum chamber and the length of the filter.

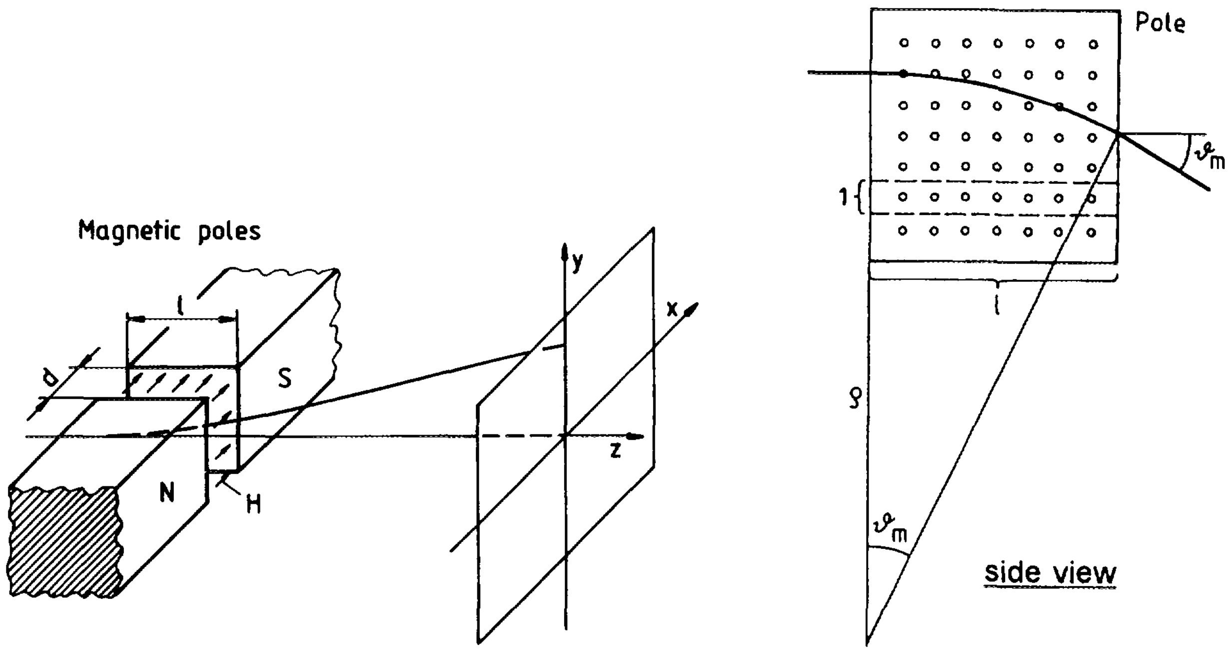


Fig.91 *Schematic representation of magnetic deflection*

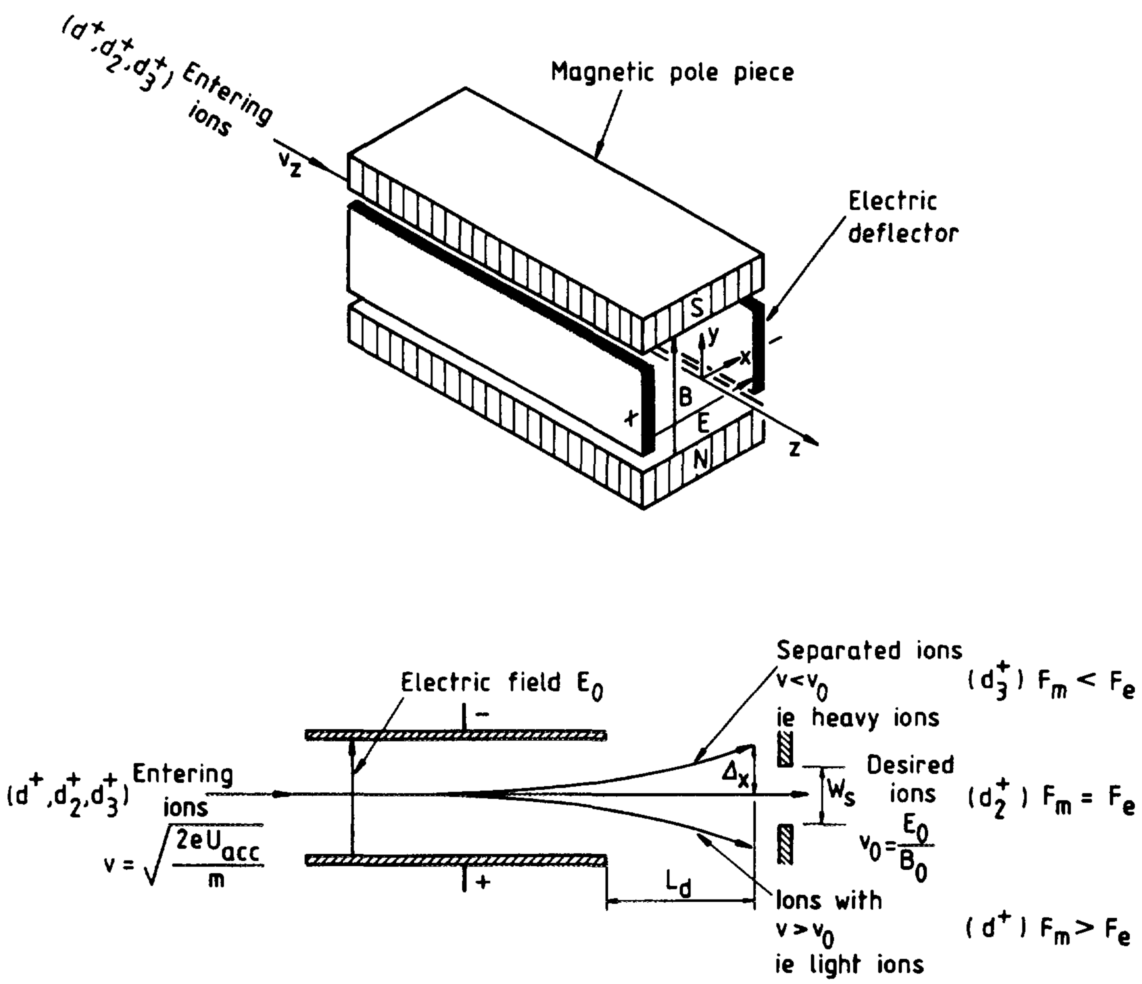


Fig.92 *Schematic diagram of a Wien filter*

The capability of a Wien filter is determined by D, the dispersion between the selected mass M and (M-ΔM). The dispersion D of the filter is determined by the expression:

$$D = \frac{l_d \cdot a \cdot E \cdot \Delta M}{4 \cdot U_a \cdot M} \qquad (36)$$

where l_d is the distance of the exit slit from the filter, a is the length of the filter (magnetic poles and static deflectors) and M is the mass number. A schematic diagram of a Wien filter is shown in Fig.92.

11.2 TROUBLESHOOTING OF ELECTROSTATIC DEFLECTORS

In the case of improper operation of a static deflector (pulser), the problems can be of mechanical or electrical origin. The mechanical problems are mainly in the vacuum chamber of the deflector, so it is necessary to open the vacuum system and inspect the deflector plates. A broken contact or deflector plate holder can be found easily, and the electric contacts of the deflection voltage should be tested. During conductivity measurements, the occasional resistive conductivity between the deflector plate to the vacuum vessel should also be tested. Sometimes the isolators can be covered by conducting (evaporated metal or carbon) layers, so a proper resistance test should be carried out at high voltage of the same order as the value of the original deflection voltage.

Every breakdown between the deflector plate and the ground means a reflection HV pulse along the high voltage cables connecting the HV supply to the deflector chamber. The cable end should be tested carefully because an unterminated cable end could carry a doubly high voltage due to the reflection from the shorted cable end. This means the cable short circuits are usually at the HV power supply end (connector) of the high voltage cables. Test carefully the HV vacuum feedthrough for conductivity and HV insulation.

11.3 ANALYZING MAGNETS OF NEUTRON GENERATORS

The analyzing magnets of neutron generators are as follows:

- ion species selectors for the D^+, D_2^+ and D_3^+ components of the accelerated beam;
- selectors of charged particles from neutral particles e.g. oil vapour, oxygen and nitrogen molecules from the residual vacuum.

As the magnetic field selects the ion species by e/m, even a slight deflection - larger than the diameter of the beam on the original place - may select the charged and uncharged components of the beam. The selection of the charged and neutral beam components increases the target lifetime, protecting the target surface from oil vapour contamination in the vacuum system.

The analyzing magnets are made of soft iron. The main problem in the construction of an analyzing magnet is procurement of the proper soft iron. Iron sheets with carbon content less than 0.06 % are suitable material for deflection analyzing magnets [89]. The power consumption of the coils is usually in the range of a couple of hundred watts, so correct cooling of the coils is recommended. As the metal wires of the magnet have positive temperature coefficient, regulation of the magnet current is advisable. Two magnet constructions are shown in Fig.93 (and in Fig.97). The first is easy to construct, having two half disc shaped pole pieces. This solution allows a relatively high deflection angle, with the given coil data up to 60^o- 70^o . The pole pieces have a shape that is easy to manufac-

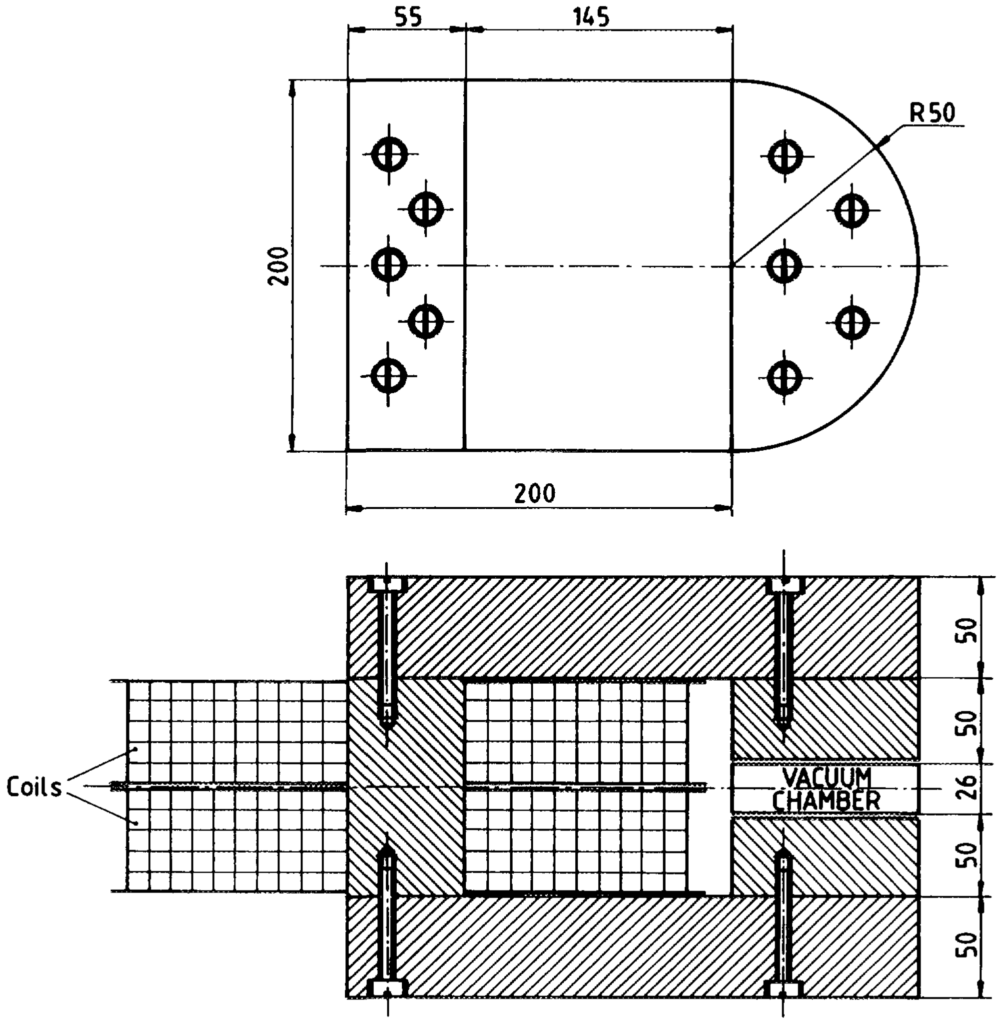


Fig.93 *Schematics of a 60^{O} deflecting magnet (sizes in mm)*

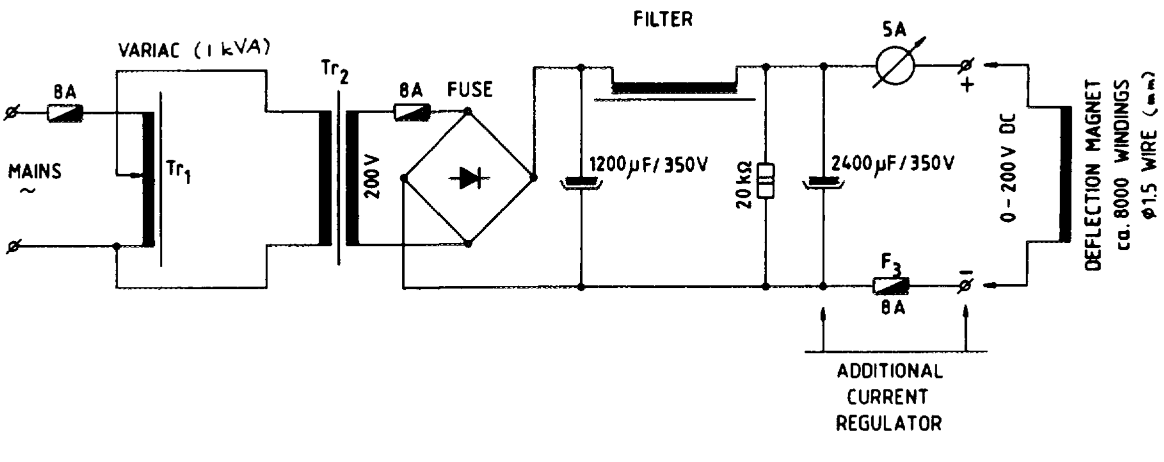


Fig.94 *Power supply of the deflection magnet shown in Fig. 93*

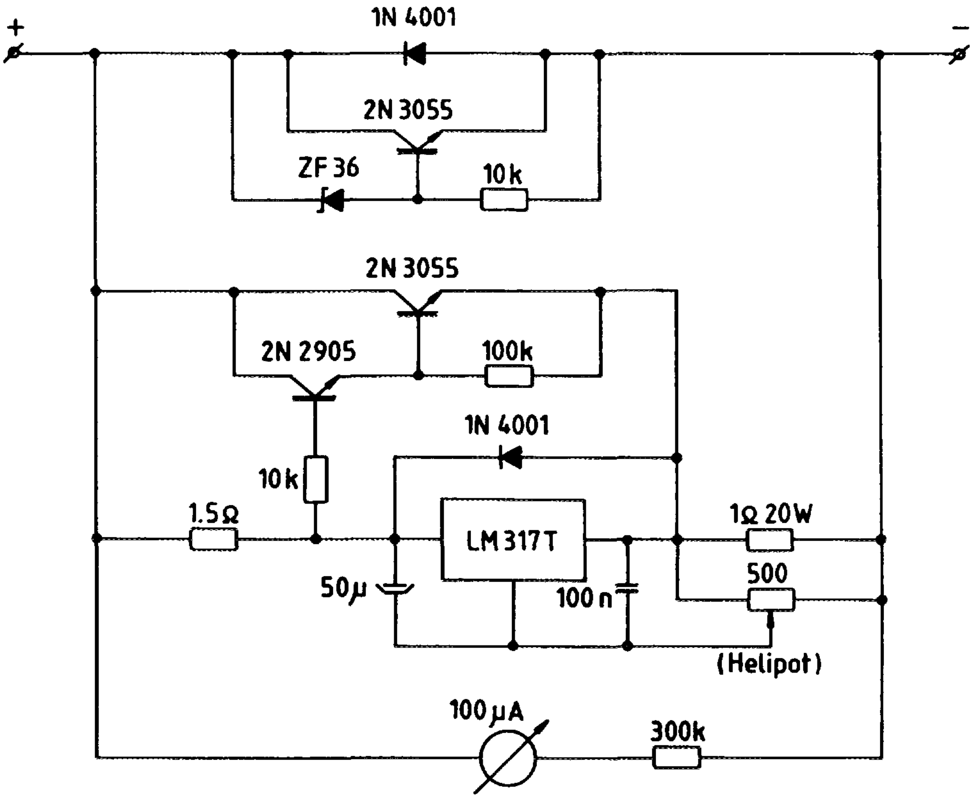


Fig.95 *Current regulator circuit of a magnet power supply*

ture, and they can be machined on a lathe. The manufacture of the rectangular components does not even require a milling machine. The coil is about 5000-8000 windings of 1.6 mm dia wire [90].

This coil requires a 150-180 V DC power supply with an output current of 3-5 A. The power supply can be made from a variac (Tr_1 in Fig.94) controlled isolation transformer (Tr_2) rating 1 kVA. The rectifiers are air cooled, mounted on a suitable radiator. The wire of the filter coils is made of 2.0 mm dia wire. The condensers are parallel connected and inexpensive (similar to those used in TV power supplies). An additional current regulator can be attached to the system, for example, instead of the F3 fuse. This current regulator may be constructed on the basis of power transistors cooled effectively by a fan. A principle diagram of the power supply is shown in Fig.94.

The power consumption of the relatively large coil is about 500-600 W in the case of separation of a 200 keV ion beam at a deflection angle of 60^0. Water cooling of the coil does not compensate for the growth in the resistance of the coil due to warming up. A simple current regulator can be attached to the original - full wave rectifier - power supply , corresponding to the marked places in Fig. 94.

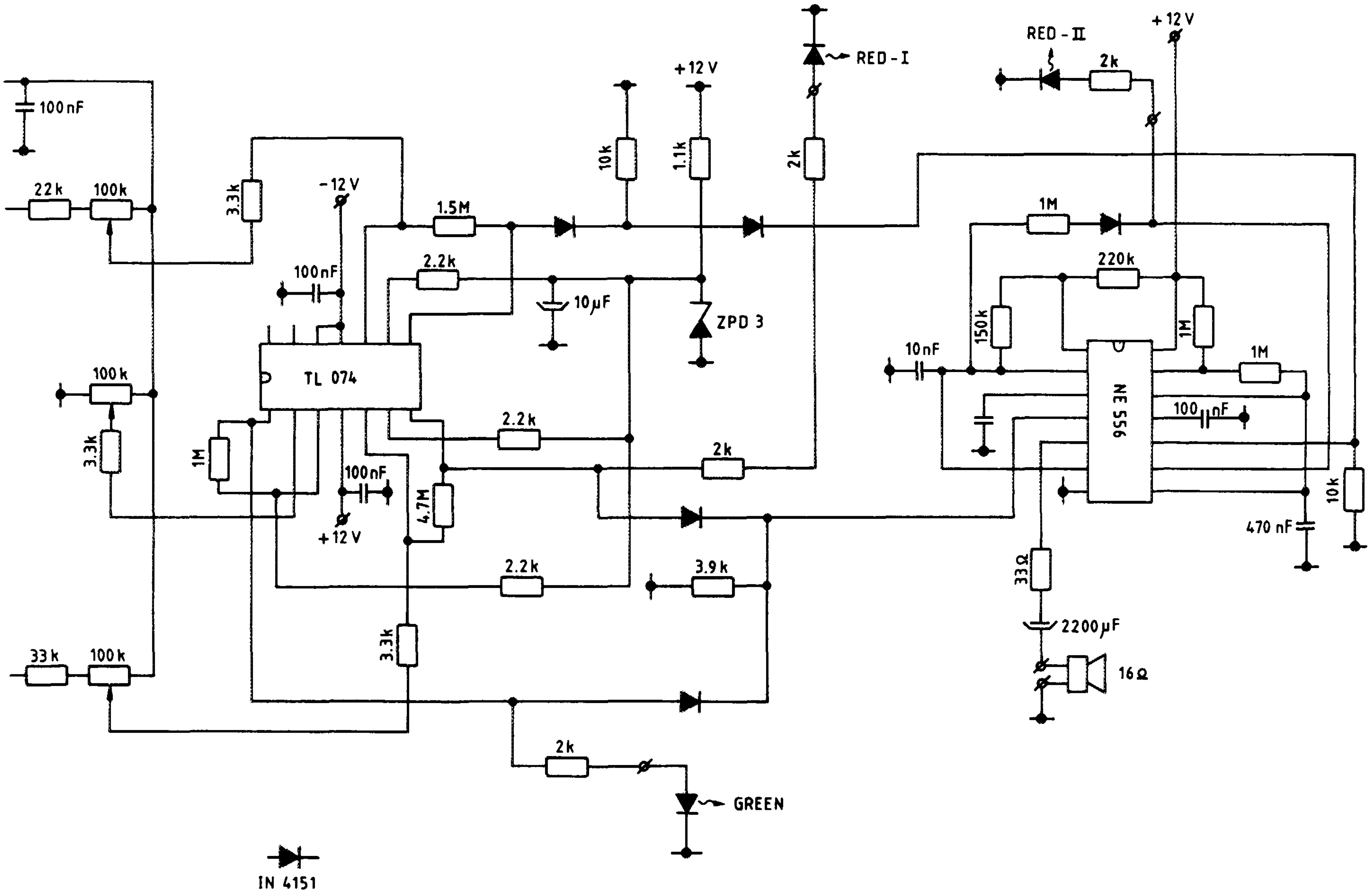


Fig.96 *Operator alarm circuit for the magnet current regulator shown in Fig. 95*

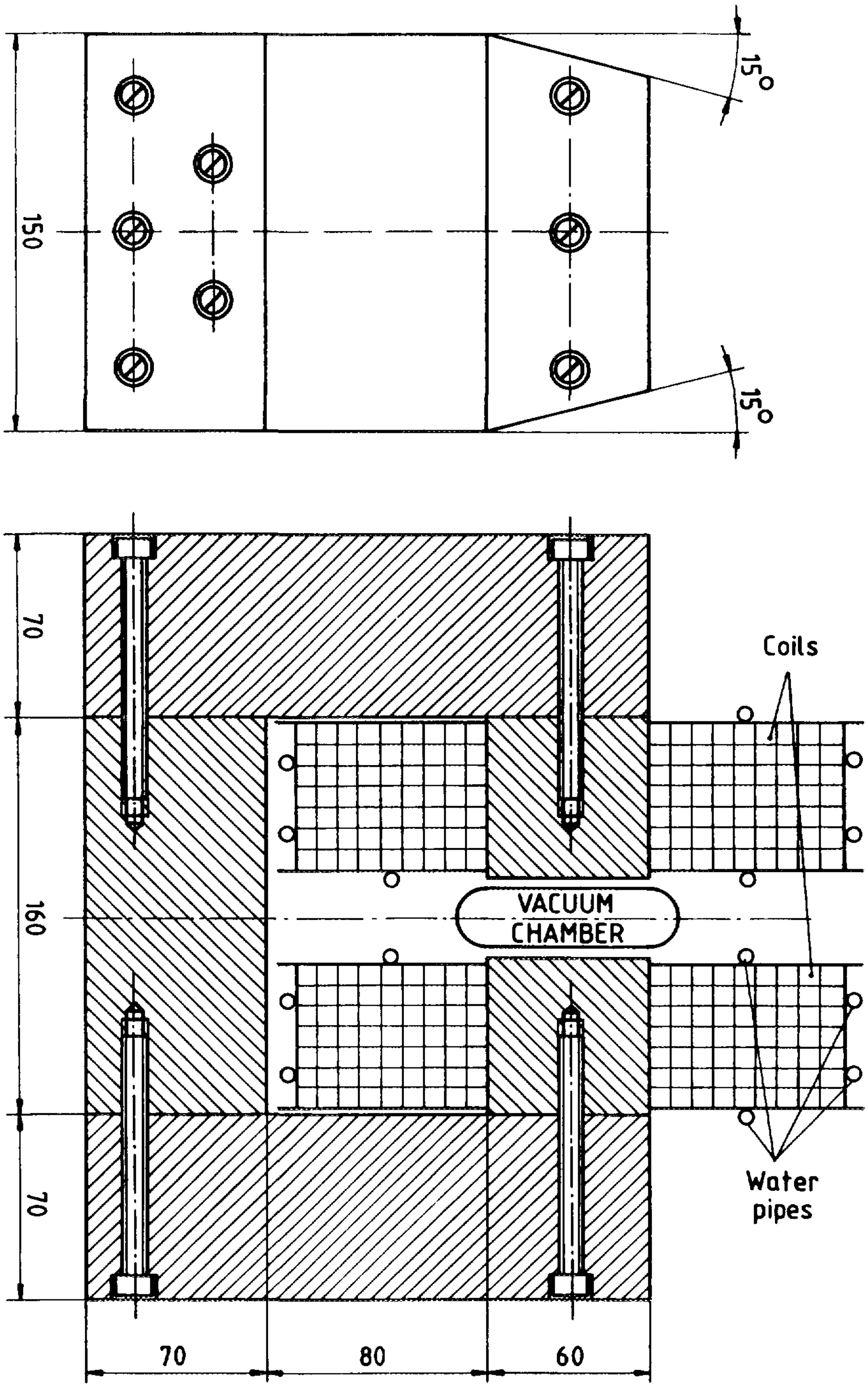


Fig.97 *A 30° deflection magnet for neutron generators (sizes in mm)* [91]

The current stabilizer series circuit is shown in Fig. 95. It is based on the commercial voltage regulator circuit LM 317. The LM 317 load current is shunted by the usual PNP transistor equivalent complementary Darlington circuit. The magnet current can be regulated by the helical potentiometer connected parallel to the 1 Ω reference resistor at the output of the LM 317. This resistor should be a high power resistor with low thermal coefficient. The resistor itself is assembled into a cylindrical hole of the radiator of the regulating LM 317 and 2N3055 transistor. A second 2N3055 transistor (with 36 V Zener diode in the basis circuit) protects the current regulating circuit against transients. The voltage drop on the current regulator can be read by a voltmeter connected parallel to the current controlling unit. The optimal voltage drop on the current regulator is between 10 and 30 V.

An advanced voltage regulator circuit, the LM338K, may replace the LM317 and 2N3055 based circuit in the above described magnet current regulator circuit. As the absolute maximum rating of the voltage difference between the input and the output is the same, the overvoltage protection (ZF36 and 2N3055) should not be changed.

The operator alarm circuit - connected to one of the above current regulators - is shown in Fig.96. The circuit, powered by its own twin 12V power supply, has three voltage comparators, three indicator LEDs and an acoustic alarm device [90].

As the voltage drop across the LM317 or LM338K for an output current of about 3-4 A should be more than 10 V during normal operation, the first comparator detects the < 10 V voltages. In this case the green LED lights up and the acoustic alarm gives a continuous alarm signal. These warnings inform the neutron generator operator that the resistance of the deflecting magnet has increased due to the warming of the coil, and that the voltage drop along the current regulator is below 10 V. As the output voltage of the magnet powering rectifier can be raised by turning up the variac (in Fig.94), the operator should turn up the variac. If the operator turns it up, and the voltage drop on the current regulator is higher than 10 V, the alarm signal stops and the green LED goes out. If the operator turns more than is needed, and the voltage drop is over 27 V, the alarm starts to sound again and the red LED comes on. As the voltage drop should be between 10 and 27 V, if the red light comes on, the variac should be turned downwards.

When the voltage drop on the current regulator reaches the absolute maximum ratings of the regulator circuits (36 V), the ZF36 and 2N3055 based protection circuit starts to shunt the current regulator; the third comparator will start the second red LED flashing and the continuous alarm signal starts to be pulsed. This indicates that the absolute maximum permissible voltage has been reached.

As the magnet coil warms up, its resistance increases; normally the current regulator circuit should be set below the upper voltage drop limit (27 V). The voltage drop along the current regulator circuit is displayed by the 100 μA analog meter as shown in Fig. 95.

A deflection angle as small as 30° is usually enough to separate the ions and the uncharged components of the beam. A simple 30° analyzing magnet is shown in Fig.97. The deflection coil is divided into two parts to allow a more effective cooling of the coil. The same solution applies in the case of the previous deflection magnet: however, it is more difficult to wind a semicircular coil than a rectangular coil. The coil is about 3000 windings if the power supply of Fig.94 is utilized. Both magnets may use other coils with thicker wires and lower resistance, but they suffer from the disadvantage that they would need larger buffer condenser banks and higher electronic current regulation.

The power supplies of the magnets - if they are regulated - can be calibrated for beam energy, utilizing the monoatomic ions of the neutron generator target beam line. In a properly regulated magnet power supply, the change in beam energy (due to the change of accelerating voltage or extraction voltage) may be detected by the change of the deflection current needed to achieve the maximum beam current.

11.4 VACUUM CHAMBERS OF DEFLECTING MAGNETS

The vacuum chambers of deflection magnets should fit the vacuum system (the beam line and the target holder) of the neutron generator. If the the monoatomic

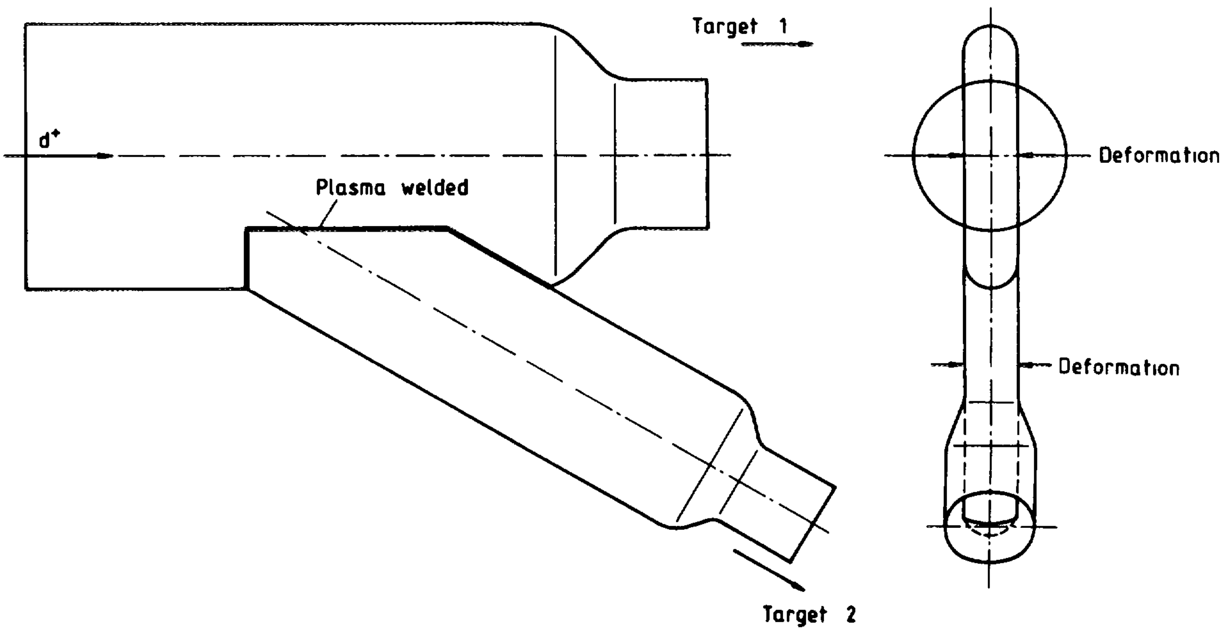


Fig.98 *Vacuum chamber of deflection magnet using oval tubes*

beam component is selected, then the molecular and three-atomic components usually thermally load the wall of this chamber. The corresponding chamber surface should be cooled properly. The deflection magnet vacuum chamber is usually made of stainless steel, but other suitable metals (e.g. copper) can also be used. The vacuum chambers of the analyzing magnets are usually connected to the beam line of the neutron generators by elastic joints, like bellows, which make alignment of the beam line easy.

A very simple vacuum chamber construction is shown in Fig.98. The chamber was manufactured of two stainless steel tubes with their original circular shape pressed into an oval form and welded to each other, and fitted to the 30^o deflection magnet. The undeformed ends of the circular tubes can be fitted easily to the beam line components of the neutron generator. Vacuum chambers for different magnets can be manufactured in a similar way.

11.5 PROBLEMS WITH ANALYZING MAGNETS

For a correct analyzing magnet the shape of the beam is narrow. The beam profile observed by quartz or other visual detectors depends on the energy spread of the beam and the ripple of the magnet current. The high ripple (> 1 %) in the magnet current may come from the malfunction of the current regulating transistors (see e.g. Fig.95.); the breakdown between collector to emitter will shorten the regulating circuit, and the original ripple of the full wave rectifier will cause a spread in the deflection. The punchthrough is a typical problem with power transistors and it can be detected by testing the diode base to emitter and base to collector. Both junctions will indicate correct operation, while the emitter to collector shows total short circuit. The extraordinary warming up of the coils shows the short circuit within the coil. The cold and warm resistance of the magnet coil should be tested and checked and regularly recorded in the log book of the neutron generator during maintenance work.

12. QUADRUPOLE LENSES

Magnetic or electrostatic quadrupole lenses are commonly used as post-acceleration ion beam lenses at almost all accelerators. For neutron generators such as low energy accelerators, the magnetic quadrupole is the most frequently used lens. Electrostatic quadrupole lenses are more simple, but they need power supplies and high voltage feedthrough into the vacuum system. Furthermore, a high vacuum is required in the system to avoid corona discharges. The relatively low energy ion beams in neutron generators need simple low voltage magnet power supplies, and the lack of vacuum feedthrough makes the magnetic lenses much simpler to use. The only drawback of the magnetic quadrupole lenses is the relatively heavy weight of the coils and the iron cores of the lenses.

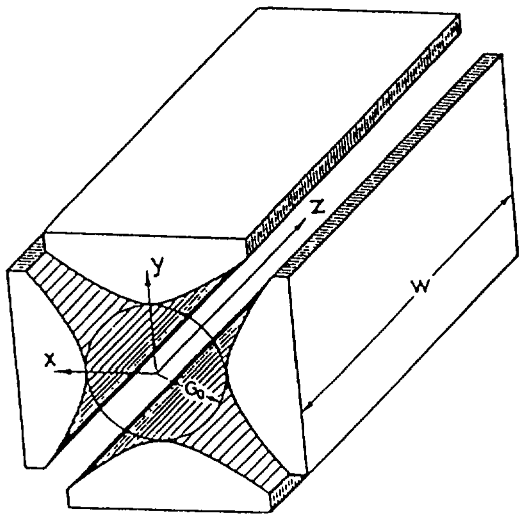


Fig.99 *Electrostatic quadrupole lens focusing in the horizontal or vertical plane*

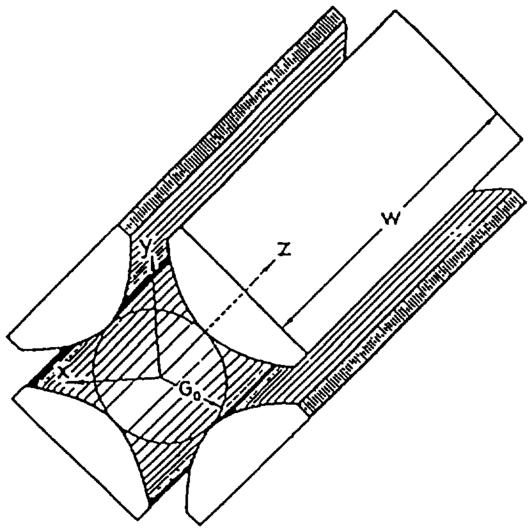


Fig.100 *Magnetic quadrupole lens focusing in the horizontal or vertical plane*

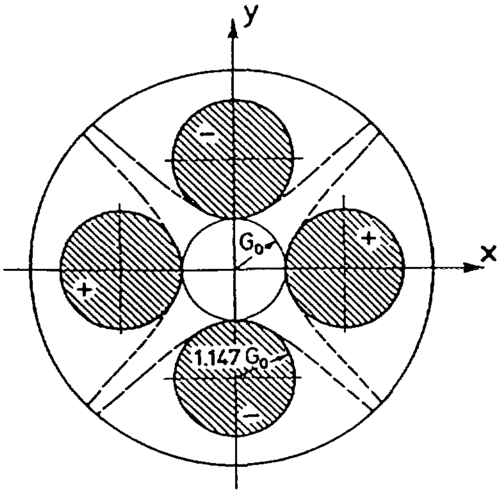


Fig.101 *Approximation of the hyperbolic electrode by circles (cylinders) (electrostatic quadrupoles)*

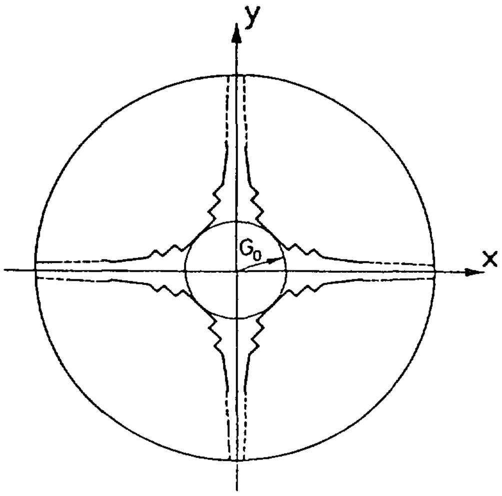


Fig.102 *Approximation of the magnetic pole faces by steps*

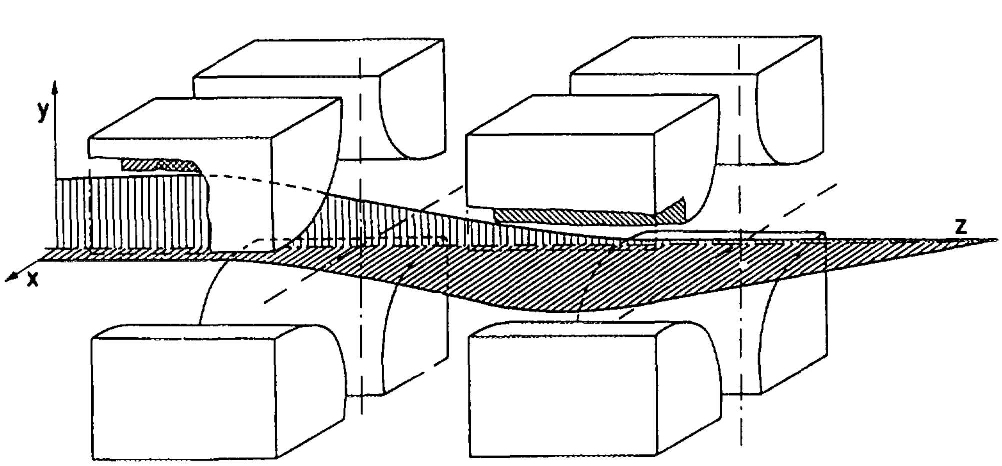


Fig.103 *Focusing particle trajectories of a quadrupole doublet*

The quadrupole lens consists of four hyperbolically shaped pole faces or electrodes. The quadrupole lense focuses in one plane and defocuses in the perpendicular plane. Thus, several such lenses must normally be combined to make a useful lens system. Usually quadrupole doublets and triplets are in use at neutron generators. Since the hyperbolic pole faces or electrodes are difficult to fabricate, the shape is approximated by circles or steps.

If the focus plane of the quadrupole lens is in the vertical or horizontal plane, the beam directions (z axis) of the electrostatic and the magnetic quadrupole lenses will have the shape shown in Fig. 99 and Fig. 100 (45^o rotation!), respectively.

In practice the hyperbolic pole shapes are approximated by cylinders (electrostatic quadruplets) and by steps (magnetic quadrupoles). These approximations are shown in Fig.101 and Fig.102.

As the quadrupole singlet focuses in one plane and defocuses in the perpendicular direction, minimum doublets are therefore always used. The particle trajectories started at the center of the object ($x = 0$ and $y = 0$) in a double focusing doublet, as shown in Fig.103. The doublet is a double focusing system.

The calculation of the ion trajectories along the quadrupole lenses can be found in Ref. [91]. The exact calculation and lens design is beyond the scope of this Manual. A magnetic quadrupole doublet is described in Section 12.1.

12.1 THE BIASED QUADRUPOLE LENS

The biased quadrupole lens is powered asymmetrically, so that the particle beams are focused and steered. The repeated and, hopefully, always convergent alignment of the beam line element by the steering effects of the quadrupoles can be eliminated.

Instead of mechanical adjustment, it is quite practical to make an electrical alteration of the effective position of the quadrupole by unbalancing the voltages of the segments (or the current through the coils).

The circuits of the quadrupole biasing network are very simple [92]. The magnetic quadrupole lens has four equivalent coils and in the simplest case the current flows in series through the coils. When the symmetrical supply of the coils is altered, the different pole pieces will be magnetized differently. The balanced supply of the quadrupole can be changed by an external bypass branch. If the serial connected coils and an external potentiometer are connected parallel and the central tap of the potentiometer is connected to the center of the serially connected coils, the balanced bias of the lens can be altered by sliding the potentiometer. This is the principle of the biased quadrupole lens. The circuit diagram of a biased magnetic quadrupole lens is shown in Fig.104.

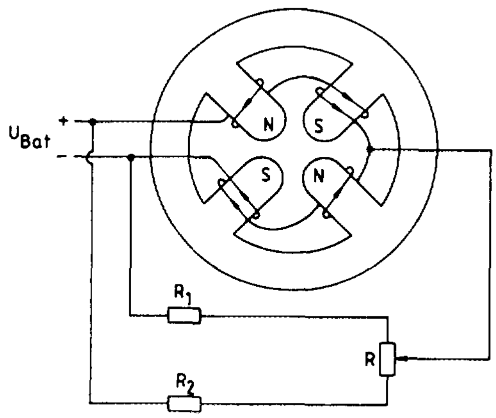


Fig.104 *Circuit diagram of a biased magnetic quadrupole lens*

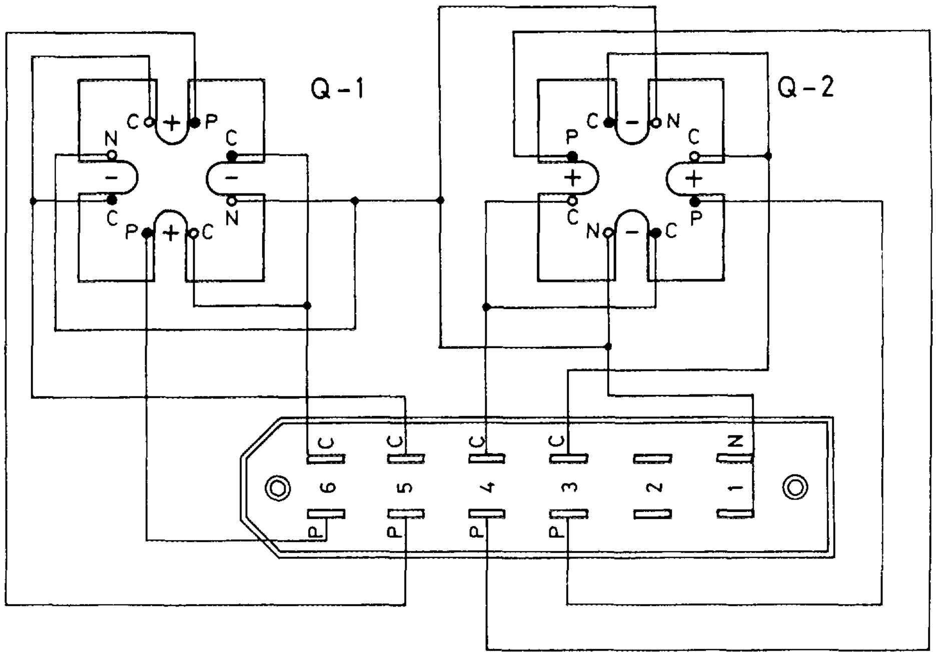


Fig.105 *Circuit diagram of a quadrupole doublet*

The biased quadrupole lens (both magnetic and electrostatic) requires in practice split power supplies. We now discuss a magnetic quadrupole doublet lens for neutron generators up to an accelerating voltage of 150-200 keV. The focusing distance of the quadrupole doublet is about 60-80 cm and the beam can be steered at this distance both horizontally and vertically in a range of a few centimeters. The power supply of the coils is a voltage source (it can be a current source as well) and instead of a center tapped power potentiometer, an electronic equivalent (potentiometer and emitter follower) is used [93]. The circuit diagram of the quadrupole doublet is shown in Fig. 105 and that of one with split power supplies is shown in Fig.106.

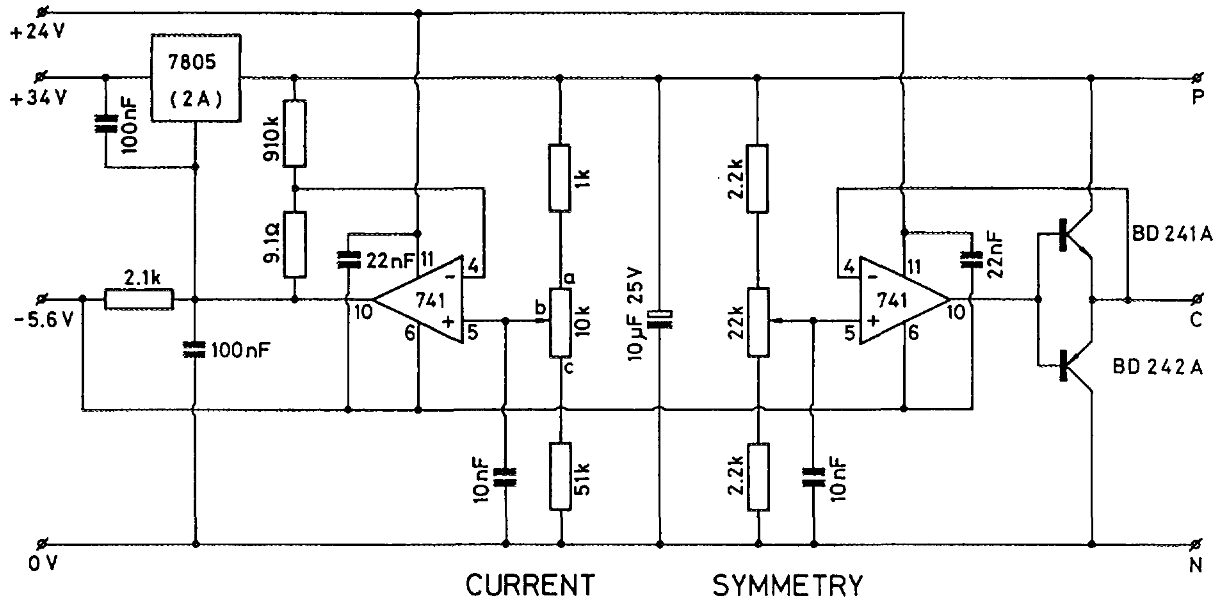


Fig.106 *Split power supply (1/4) of the quadrupole doublet shown in Fig. 105*

The focus of the beam can be changed by the current potentiometers controlling the output voltages of the power supply while the biasing of the upper - or lower - pole pairs is done by the symmetry potentiometer controlling the bypass of the upper or lower pairs of coils.

The strong focusing property of quadrupole lenses makes them particularly suitable for use along the beam line in neutron generators. The commercial neutron generators, which are mainly manufactured for fast neutron irradiation and activation analysis, are not usually equipped with this strong focusing component. As the magnetic quadrupoles are simple, they are therefore recommended in addition to the beam deflecting or analyzing system for upgrading commercial neutron generators.

12.2 THE BIASED MAGNETIC QUADRUPOLE DOUBLET

The quadrupole lens described above has been designed and constructed for focusing the D^+ beam of 150 keV - 200 keV energy used in small neutron generators. The pole face aperture of 82 mm diameter fits the beam tubes of almost all commercial neutron generators. The properties of this lens allow the D^+ beams to be focused down to 40-50 cm for 150 keV beam energy. The 850 winding of the coils were designed for a 50 cm focal length. Changing the standard coils of the quadrupole lens pair will ensure a different focal length. Increasing the current

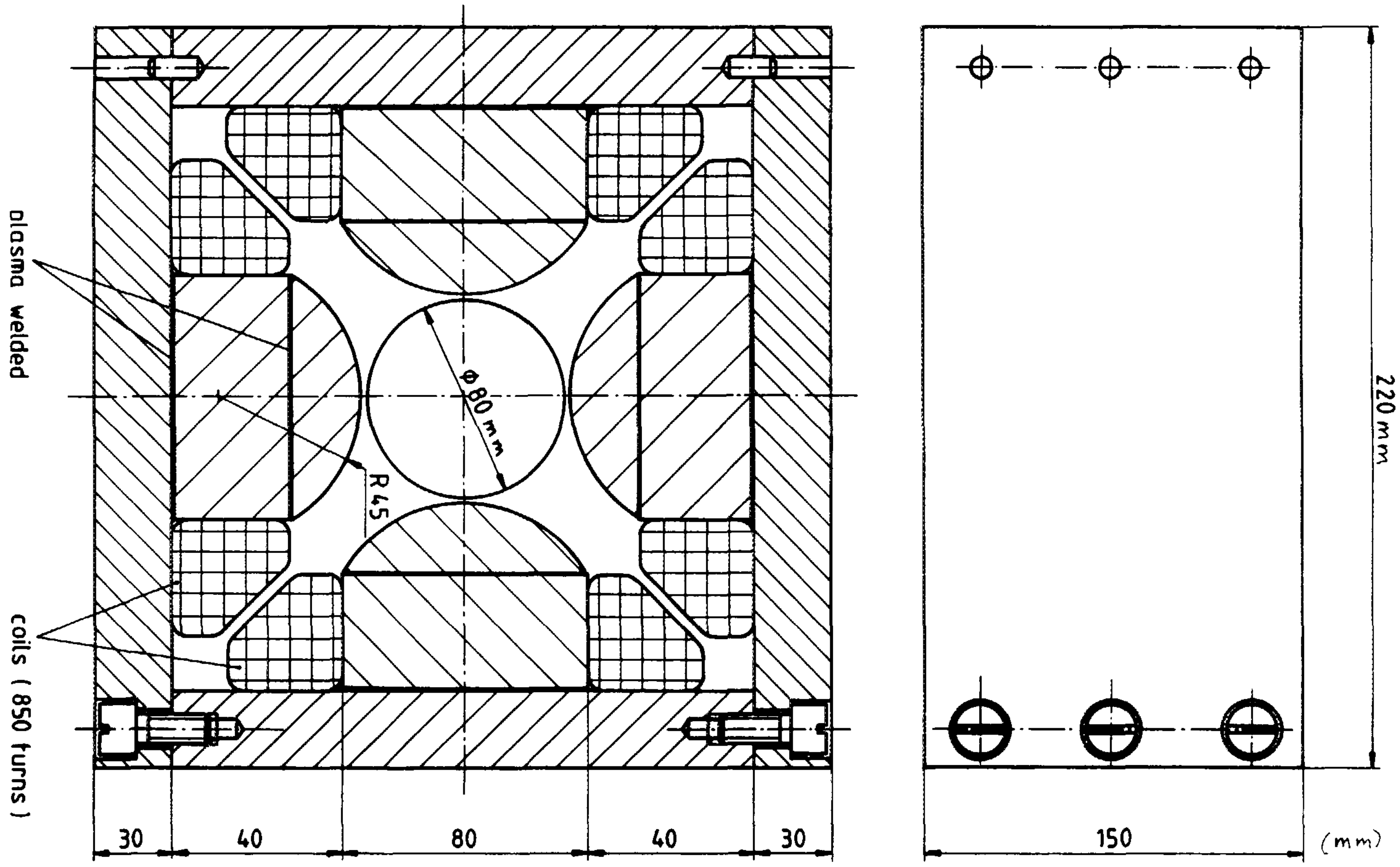


Fig.107 *Mechanical diagram of a quadrupole magnet for neutron generators*

flow through the coil will shorten the focal length. The f_x focal length of this quadrupole lens can be calculated by:

$$f_x[\mathrm{cm}] = \frac{2 \times 10^4 [\mathrm{A.turns.cm}]}{I \times N\ [\mathrm{A \cdot turns}]} \tag{38}$$

where f_x is the focal length of the quadrupole lens in the focusing plane, N is the number of turns of a single coil and I is the current in amperes. The power supply of the quadrupole doublet is based on a simple standard 24 V AC secondary transformer. The supply of the quadrupole is asymmetrical, using the biased quadrupole principle.

A diagram of half of this quadrupole is shown in Fig.107. The material of the iron core is manufactured from low carbon content iron (C-10 type). The pole pieces are plasma-welded onto the planed iron sheets and the four iron sheets are screwed together by Allen type bolts. The pole pieces were shaped on a lathe and the connecting surfaces were manufactured on a milling machine.

The wiring diagram of the quadrupole lens pair is shown in Fig.105. Note that the coils of the perpendicular segments are connected in series. The coils, of 0.8 mm dia double emailed copper wires, each coil with 850 turns, were wound. The surface of each coil is large enough for the dissipation of 10-15 VA. The coils are connected to a 12-blade socket fixed to aluminium sheet that fastens the pairs.

The rectifier circuit serves for the supply of the voltage regulation of the magnet. As the dissipation of the coils is low, the change of resistance of the coil can be ignored, which means that this magnet does not need a constant current supply. The two transformers supply the two full wave rectifiers and the two Zener diodes regulating circuit, with AC voltage. The +34 V DC voltage is the input voltage of the voltage regulators (7805) while the +24 V and the -5.6 V DC sources are needed for the operational amplifiers (Fig.108).

The regulator of the quadrupole lenses is a voltage regulator based on the three-terminal 7805 circuit, which gives adjustable output voltage through the first 741 operational amplifier. The center tap of the series-connected coils is powered by the "electronic potentiometer" built from an emitter follower. The center tap of the two coils and the currents flowing through the coils can be changed by the symmetry potentiometer. The basic voltage regulator is shown in Fig.106. A quadrupole **doublet** requires **four** regulator units.

The quadrupole lenses can be mounted onto the beam line by removing the top lid of the quadratic shaped lens. The beam line of the neutron generator should

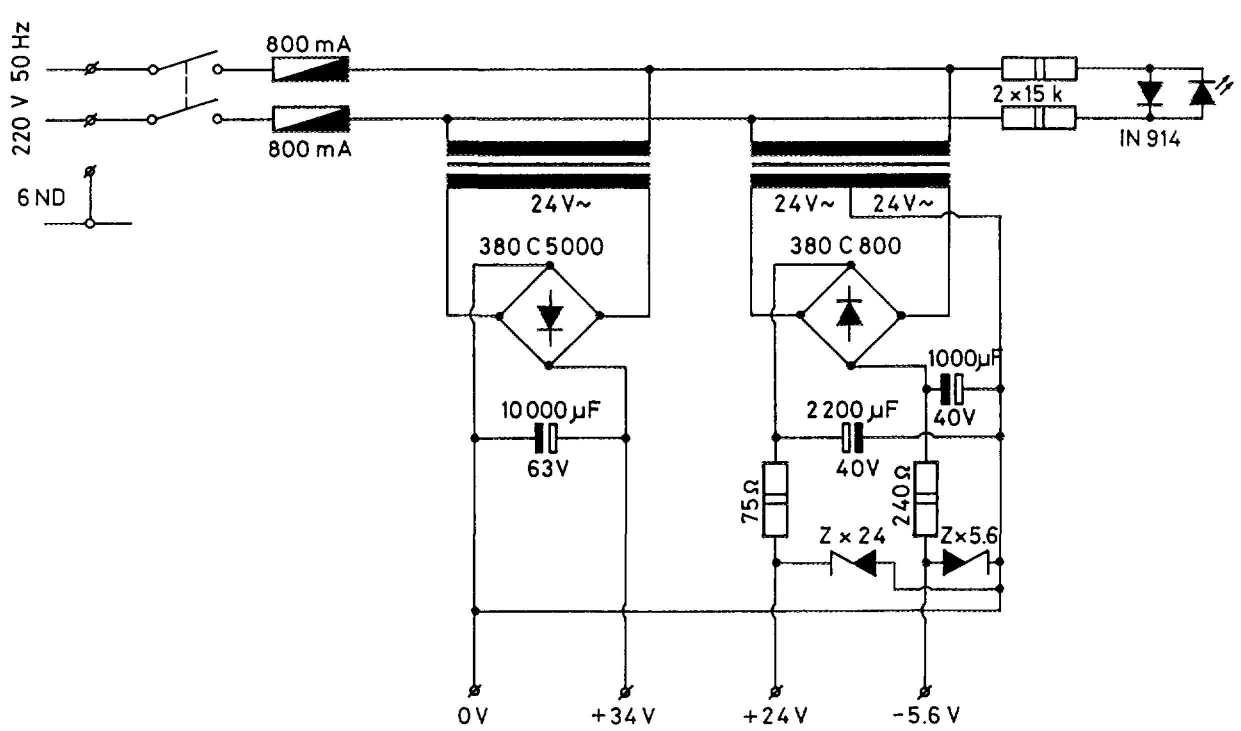


Fig.108 *Rectifier circuit of the biased quadrupole lens pair*

be placed between the pole pieces and returned to the upper part of the lens. The pole pieces are vertical and horizontal, respectively.

A quartz or Pyrex glass target 5-8 mm thick can be used to observe the focusing properties of the lenses. As the beam of a commercial neutron generator with about 100-200 W power can heat up the glass, it is recommended that a copper mesh screen be placed just in front of the quartz. As soon as the beam glows on the quartz, increase the lens current by the "current" potentiometers of one of the lenses. If the lens current seems to be at optimum, a 45° line will appear on the glass target. The position of the line focused beam can be changed, on the biased quadrupole principle, by the "symmetry" potentiometers. These potentiometers control the emitter follower shunt. The optimal position of the beam is in the center. When the first lens has been tested, turn down the "current" potentiometers and activate the second quadrupole lens. A line perpendicular to the previous one will show the focusing of the second lens in the perpendicular plane. When the optimal position for both lenses has been found, the focus of both lenses can be activated.

If the user does not like the two perpendicular 45° plane focusing feature of this quadrupole doublet, the doublet should be turned 45°. This means that the stand - with horizontal table - should be replaced by a stand holding the outer magnet planes 45° to the horizontal plane.

12.3 TROUBLESHOOTING OF A MAGNETIC QUADRUPOLE LENS

The effects of improper operation of a quadrupole lens can be as follows:

a) The beam is not focused or is deflected in spite of the activation of the current and symmetry potentiometers. This shows the currentless state of the coils. Test:
   - the interconnection of the magnet and the power supply,
   - the output voltage of the power supplies,
   - the wall outlet of the mains,
   - the continuity of the coils.

The repair of the faulty component depends on the fault found.

b) The doublet lens does not focus in one plane. Check the corresponding circuits.
c) The lens does not focus in both planes and it works only horizontally or vertically. Activation of both quadrupole lenses results in a beam which cannot be focused by the two lenses together. This can cause a faulty rectifier. Test:
   - the buffer condensers of the rectifier,
   - the rectifier diodes,
   - the voltage regulator IC.
d) Bad focusing conditions can also be caused by poor vacuum conditions. Test and improve the vacuum in the system.
e) Strange magnetic fields may cause the focusing properties of a quadrupole lens to deteriorate. If the quadrupole lens (pair) is close to the beam analyzing magnet, the deflection magnet may magnetize the quadrupole lens. This effect can be observed from the strange focusing behaviour of the quadrupole lens while the power supplies and coils work normally. In this case a magnetic shield may help to improve the focusing properties.

13. HIGH VOLTAGE POWER SUPPLIES

High voltages are extensively used in physics (accelerators, electron microscopy, etc.), for electromechanical (X-ray) equipment and industrial applications (precipitation and filtering of exhaust), and in communication (radio stations). The requirements for voltage level, current ratings and short or long term stability for every DC HV power supply may differ widely. High voltage power supplies are used in neutron generators for extraction, focusing, acceleration, etc. of the deuteron ions.

Rectification of the alternating current is the most usual method to obtain DC high voltages. (A typical circuit is shown in Fig. 112). Most of the rectifier diodes nowadays adopt Si-type, and although the peak reverse voltage is limited to less than ca. 2.5 kV, rectifier stacks up to tens and hundreds of kV can be made by series connection of more diodes. The use of the old selenium rectifiers has the advantage of serial connection without resistor chain, but the voltage drop and the power consumption are high during the conducting period. As the serial connection of the diodes for a high voltage over 100 kV causes more problems, the high voltage power supplies over 100 kV use mainly voltage multiplier circuits.

The electrostatic high voltage generators, manufactured by SAMES (Societe Anonyme de Machines Electrostatiques, Grenoble, France) or its successors, AID (Assistance Industrielle Dauphinoise, Zirst-Meylan, France) and ENERTECH, France, are electrostatic machines converting the mechanical energy into DC high voltages. Such electrostatic generators are called Felici generators, after the inventor (as the insulating ribbon electrostatic HV machines are called Van de Graaff generators).

13.1 ELECTROSTATIC (FELICI) HIGH VOLTAGE GENERATOR

The Felici generator [94] replaces the belt of the Van de Graaff generators by a rotating insulating cylinder, which can sustain a perfectly stable movement against the rubber belt, which tends to vibrate even at high speeds. The principle of the Felici generator is shown in Fig.109. The main components of the Felici generator are:

- The **rotor**, which is a tube-like cylinder, made of insulating material. The rotor is driven by an electric motor and charges are deposited on the surface of the rotor. The rotating cylinder is the only moving part of this electrostatic generator.

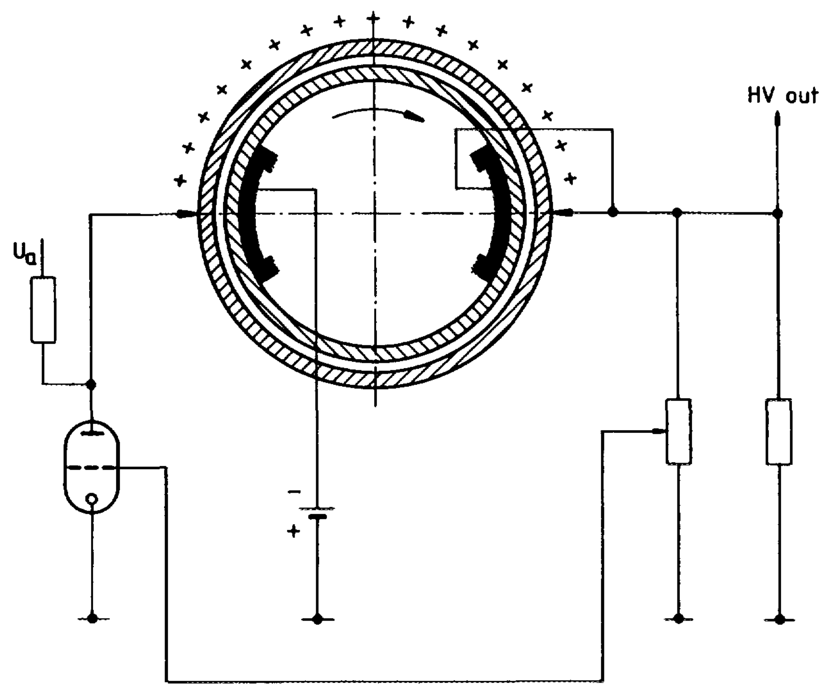


Fig.109 *Diagram cross section of the Felici generator*

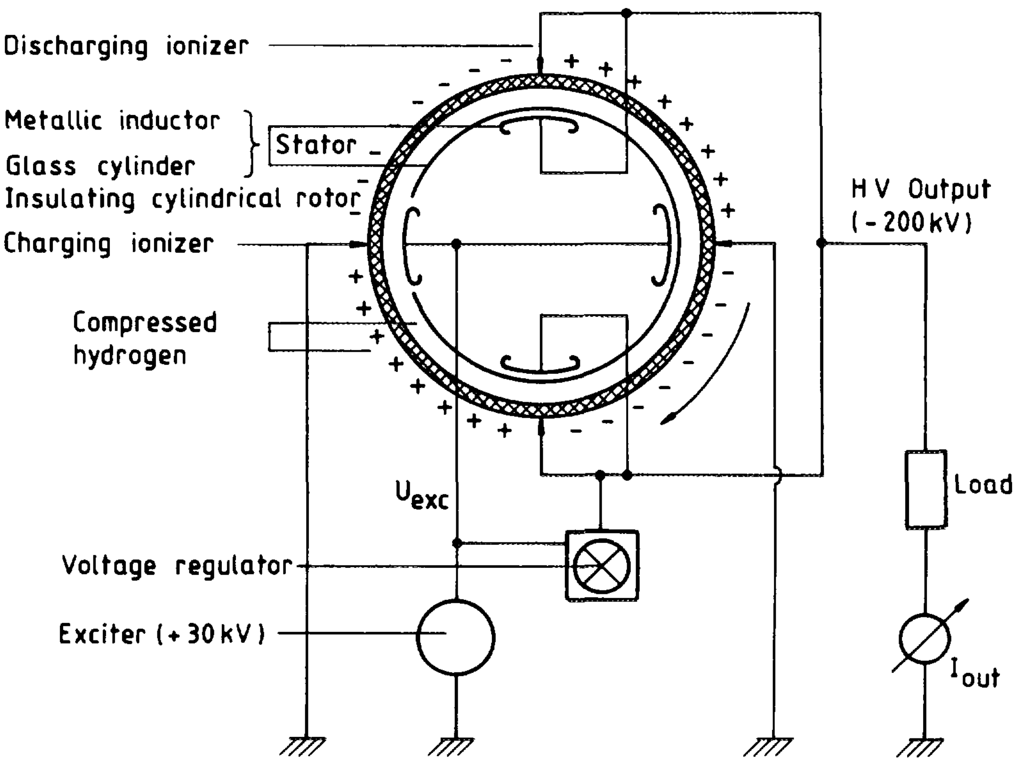


Fig.110 *Principle diagram of a regulated two-pole Felici HV generator*

- The **ionizer electrodes**, which are very thin metallic needles (blades) placed in close proximity to the rotating cylinder. The charging needles spray the electric charges by corona discharge onto the surface of the rotor while the discharging electrodes (needles) collect the charges by drawing them off the surface of the rotor.
- The **segments** or **inductors**, which induce a strong electric field on the sharp edge of the ionizers. The inductor electrodes are placed behind a slightly conductive (ca. 10^{12} Ω/cm) special glass cylinder. The excitation inductors lay the electric charges onto the surface of the rotor whilst the extracting ting inductor withdraws them. The charge collecting (ionizer) electrode and the inductor pair on the opposite side are called a pole of the machine. The diagram cross section in Fig.109 shows a single-pole machine, and Fig.110 shows a two-pole machine. The maximum number of poles is usually 8.
- The inductor and the conductive glass cylinder are together called the **stator.** The stator, the rotor and the ionizer electrodes are closed hermeticallly in a tank under pressure of compressed hydrogen.

The U_{exc} excitation voltage in Fig.110 produces a potential difference between the excitation inductors and the charging electrodes (inductors) sufficient to get an electric field on the edge of the charging ionizer high enough to create the local ionization on the surface of the rotor. The insulating rotor transfers the electric charge towards the collecting electrodes which collect the charges. The C capacitance between the discharging ionizer and the inductor is several times less than the capacitance between the charging ionizer electrode and its inductor: so the U_{out} output voltage will be several times higher than the U_{exc} charging potential.

The U_{out} potential of the collecting ionizer at any instant is about $U_{out} = Q/C$ above the ground, where Q is the charge collected and C is the capacitance of the HV electrode to the ground. The potential of the HV electrode (i.e. the voltage of the HV terminal of the neutron generator) rises at a rate given by the expression $dU/dt = I/C$ where I is the net charging current to the terminal, $I = sbv$ where s is the charge density on the the surface of the cylinder in Coulomb/cm^2, b is the height of the cylinder and v is the tangential velocity of the cylinder in m and m/s respectively.

As the loading behaviour of the Felici generator depends on the dU/dt charging capability of the construction, the larger size of the insulating cylinder ensures a larger loading possibility of the HV generator as well.

The output high voltage will be controlled by the regulation of the U_{exc} charging voltage using a feedback loop consisting of an R_h - R_1 voltage divider and an operational amplifier.

The maximum charge density on the rotor surface is about 0.01 - 0.02 $\mu C/cm^2$; the tangential field on the surface of the rotor is maximum 15 kV/cm. The output current of the HV output varies between 100 μA and 15 mA depending on the speed of the rotation, the surface size of the rotor and the number of charge collecting inductor-ionizer pairs (poles). Figure 110 shows a two-pole machine. The maximum achievable output current of the Felici generator depends on the number of poles; its maximum output voltage is approximately proportional to the distance between the poles. For a given diameter of the rotor, the output voltage is inversely proportional to the number of poles [95].

The motor driving the HV generator rotor rotates at a speed below 3000 rpm. This usually corresponds to a velocity of 15-25 m/s of the surface of the rotor. The efficiency of the HV generator is between 80-90%. This is a remarkably high value compared with the efficiency of the usual voltage multipliers.

The utilization of pure dry hydrogen (10-25 bar pressure) gives an excellent insulation, ion transfer onto the surface of the rotor, and good thermal conductance (i.e. cooling). The tank of the Felici generator does not need any extra cooling facility: in some Felici generators utilized at neutron generators the HV tank is sometimes cooled by the same cooling water as the vacuum pumps and the target.

The rotor, the ionizers, the stator, the driving motor and the precision resistor chain (R_h) are enclosed in the air-tight tank, called the hermetically sealed unit. The unit does not require any maintenance and it can be repaired only at the manufacturer's. In case of any difficulties related to the hermetically sealed unit, the whole unit should be replaced. The **only duty** related to the hermetically sealed unit is the regular (say monthly) **checking** of the **hydrogen pressure** in the tank. The pressure gauge can be found usually at the bottom of the pressure tank.

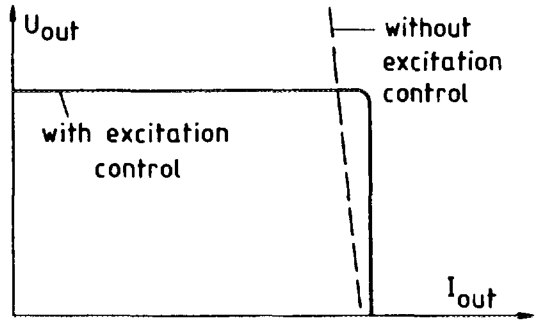


Fig.111 *Load characteristics of the Felici type HV generator*

The Felici generator has an ideal low short circuit current and ideal CV-CC (Constant Voltage - Constant Current) output characteristics. The fluctuation in voltage is less than 0.1 % below the critical loading current. The loading characteristics of this type of HV generator are shown in Fig.111, with and without excitation charge control.

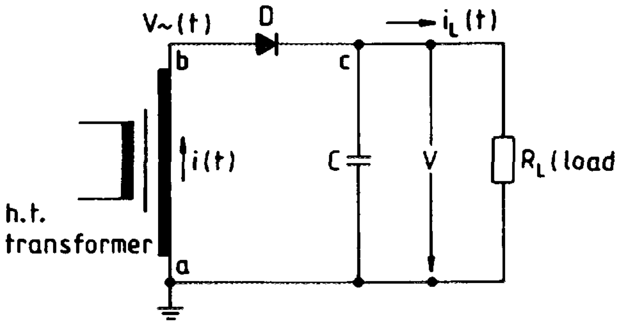


Fig.112 *The half wave rectifier*

13.2 AC-DC CONVERSION HIGH VOLTAGE POWER SUPPLIES

13.2.1 The single phase half wave rectifier

The single phase half wave rectifier with capacitive smoothing shown in Fig.112 is of basic interest. Neglecting the reactance of the HV transformer and the internal impedance of the D diode during the conduction, capacitor C is charged to the maximum voltage of the AC voltage $V \sim (t)$ of the transformer if the D diode conducts. The D diode must be dimensioned to withstand a peak reverse voltage of $2V_{max}$. This would also be the case if the HV transformer is grounded at the terminal b instead of the terminal a. The output voltage V no longer remains constant if the circuit is loaded. During one period, T = 1/f, of the AC voltage a charge Q is transferred to the load R, which is represented as

$$Q = \int_T i_L(t)\, dt = \frac{1}{R_L} \int_T V\,(t)\, dt = IT = I/f \qquad (38)$$

I is therefore the mean value of the DC output $i_L(t)$, and V(t) is the DC voltage which includes a ripple, as shown in Fig.113. If we introduce the ripple factor σV we may easily see that V(t) now varies between V_{max} and V_{min} and $V_{min} = V_{max} - 2\,\sigma V$. The charge Q is also supplied from the transformer within a

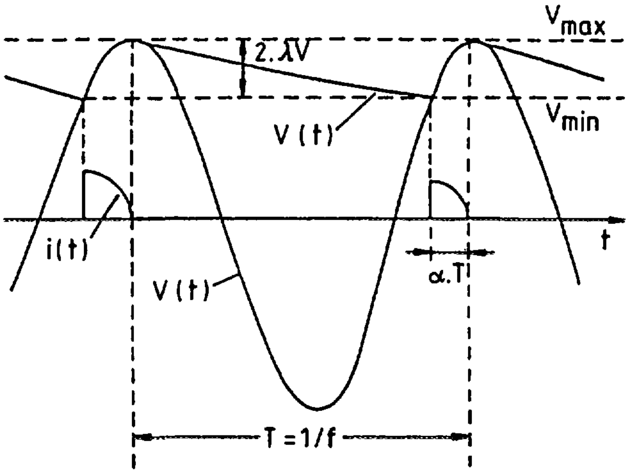


Fig.113 *The output voltage and charging current of the half wave rectifier with buffer condenser C and load R_L*

short conduction time $t_c = \propto T$ of the diode D during each cycle. Therefore, Q also equals

$$Q = \int_{\propto T} i_L(t)\, dt = \int_{T} i_L(t)\, dt \qquad (39)$$

As $\propto \ll 1$, the transformer current i(t) is pulsed as shown for an idealized form in Fig.113 . The ripple σV is given by

$$Q = 2\sigma VC = IT \qquad \sigma V = \frac{IT}{2C} = \frac{1}{2fC} \qquad (40)$$

This relation shows the interaction between the ripple, the load current and the circuit parameter design values f and C. As, according to the ripple, the mean output voltage will also be influenced by σV, even with a constant AC voltage $V \sim (t)$ and a loss-free rectifier D, no load-independent output voltage can be reached. The product of fC, is therefore an important design factor.

For neutron generator circuits (oscillator, focus, etc., power supplies), a sudden voltage breakdown at the load ($R_L \longrightarrow 0$) must always be taken into account. The disadvantage of the single phase half wave rectifier concerns the possible saturation of the HV transformer if the amplitude of the direct current is comparable to the nominal alternating current of the transformer. The biphase half wave rectifier shown in Fig.114 overcomes this disadvantage, and does not change the fundamental efficiency, since two HV windings of the transformer are

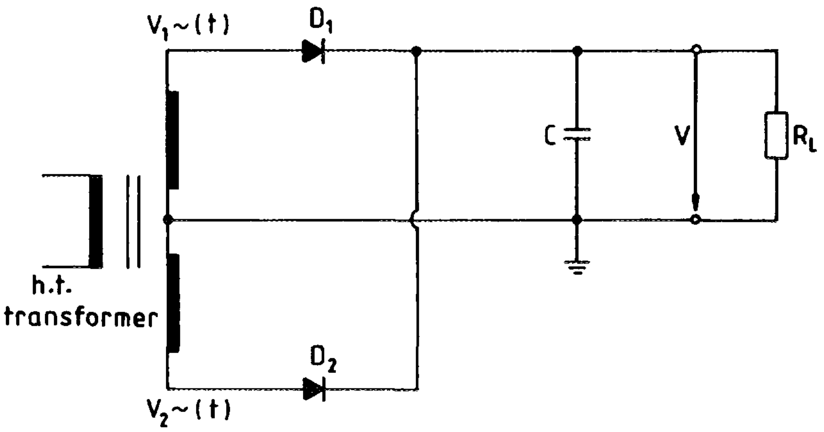


Fig.114 *Full wave single phase rectifier*

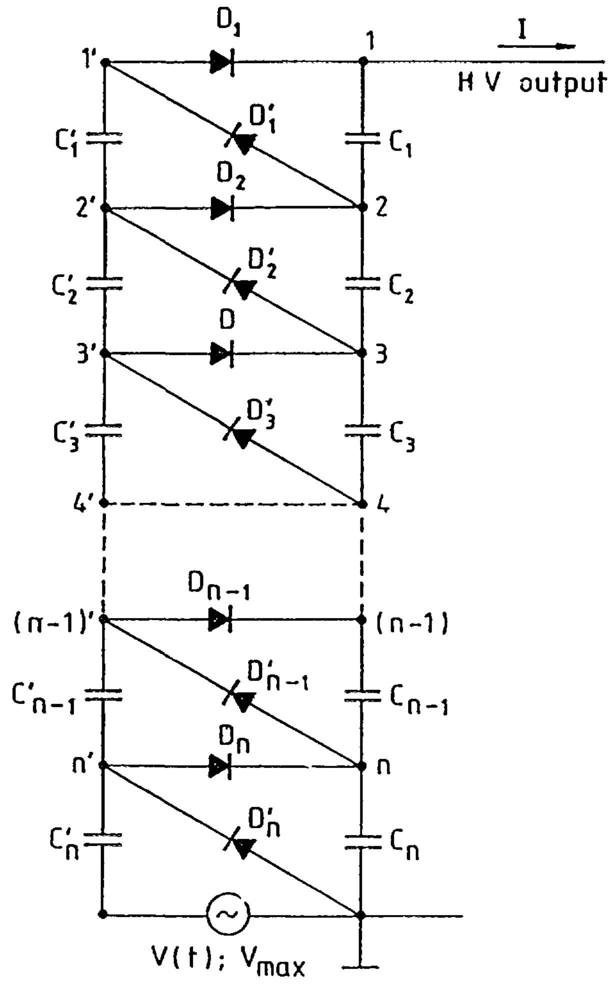
now available. With reference to the frequency f during one cycle, now each of the diodes D_1 and D_2 is conducting for one half cycle with a time delay of T/2. The ripple factor is therefore halved.

Thus single phase full wave circuits can only be used for HV applications if the HV coil of the transformer can be earthed at the midpoint and if the DC output is single-ended grounded.

13.2.2 Cascade generators

The first voltage multiplying circuit was published by Greinacher [97] in 1920 and was improved in 1932 by Cockcroft and Walton in the first accelerator. Such cascade circuits are known as Cockcroft-Walton [98] generators. An n-stage cascade circuit of Cockcroft-Walton type is shown in Fig.115 together with the main working parameters. From Fig.116 it can be seen that:

- the potential at all nodes 1',2',...n' are oscillating due to the voltage oscillation of V(t);
- the potential at the nodes 1,2,...n remain constant with reference to the ground potential;
- the voltages across all capacitors are of DC type, the magnitude of which is $2V_{max}$ across each capacitor stage, except the capacitor $C_{n'}$ which is stressed with V_{max} only;
- every rectifier D_1 ; $D_{1'}$; D_2 ; $D_{2'}$;...D_n ; $D_{n'}$ is stressed with $2V_{max}$ or twice AC peak voltage; and
- the HV output will reach a maximum voltage of $2nV_{max}$.



Ideal output voltage:	$V = 2nV_{max}$
Output voltage ripple:	$V = \frac{In}{2fC}(n+1)$
	f = frequency
	I = loading current
Voltage drop:	$\Delta V = \frac{I}{fC}\frac{2}{3}(n^3 + \frac{n}{3})$
Loaded HV output:	$V_o = 2nV_{max} - \frac{I2n^3}{3fC}$

Fig.115 *Circuit diagram of Cockcroft-Walton HV generator*

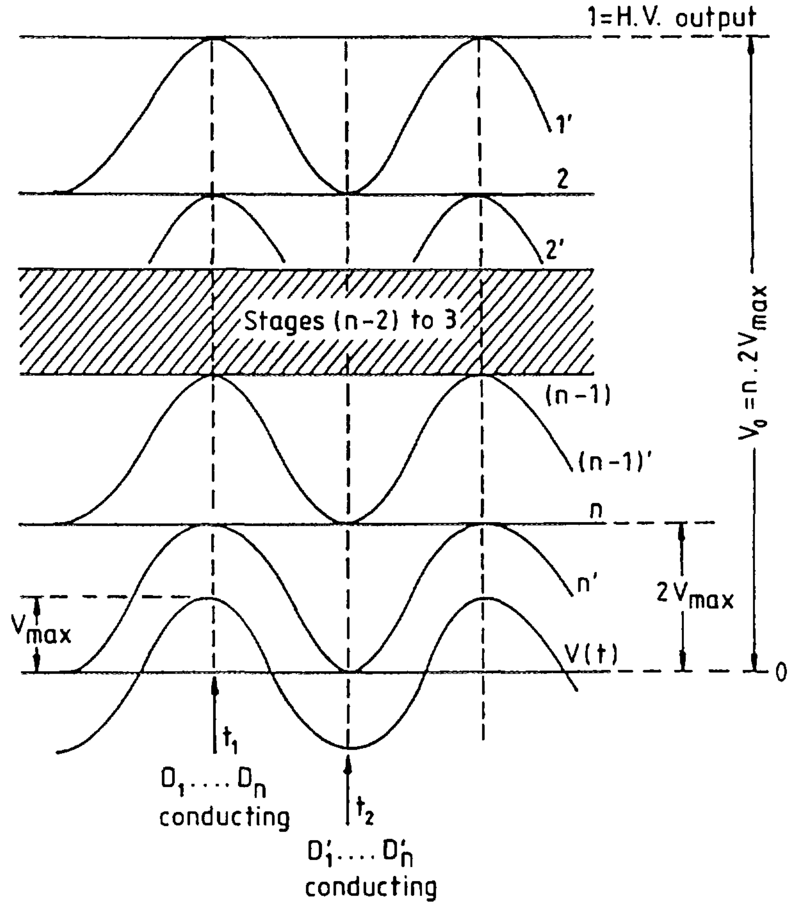


Fig.116 *Waveforms of the potentials at the nodes of the Cockcroft-Walton cascade circuit*

Loaded HV output (I>0):

If the generator supplies any load current I, the output voltage will never reach the value $2nV_{max}$ as shown in Fig.116. There will also be a ripple on the voltage, and therefore we have to deal with two quantities: the voltage drop V_o and the peak-to-peak ripple of $2\sigma V$. The sketch in Fig.116 shows the shape of the output voltage and the definitions of V_o and $2\sigma V$. The peak-to-peak ripple is given by

$$2\sigma V = IT(1/C_i) \tag{41}$$

The total ripple will be [96]

$$V = \frac{1}{2f}(1/C_1 + 2/C_2 + 3/C_3 + \ldots + n/C_n) \tag{42}$$

For a given load, V_o may rise initially with the number of stages n, but reaches an optimum value and even decays if n is too large. For constant values of I, V_{max}, f and C the "optimum" number of stages is obtained by differentiating the equation for V_{omax} with respect to n, i.e. from $\frac{dV_o}{dn}$ [96]:

$$V_{omax} = 2nV_{max} - In^3/3fC \qquad \text{we have} \qquad n_{opt} = \sqrt{\frac{V_{max} f C}{I}} \qquad (43)$$

For a Cockcroft-Walton generator with V_{max} = 100 kV, f = 500 Hz and I = 500 mA n_{opt} = 10. It is, however, not desirable to use the optimum number of stages, as then V_{omax} is reduced to 2/3 of its maximum value ($2nV_{max}$) and the voltage variations for different loads will increase too much.

The DC voltages produced with a cascade circuit may range from some 10 kV up to more than 2 MV, with current ratings from some 10 μA up to some 100 mA. The supply frequencies of 50/60 Hz heavily limit the efficiency; therefore, higher frequencies up to some 10 kHz are dominating. A 50 Hz transformer circuit needs a much larger capacitor than 10 kHz, so the breakdown along the smoothing column much more likely to damage the acceleration tube or other ion optical components than the low value capacitor stack of a medium frequency cascade circuit.

13.2.3 Improved cascade circuits

A number of improved HV power supplies have been developed: e.g. the insulated core transformer (ICT), the Allibone voltage multiplier, the cascade circuit with cascaded transformers, the "Deltatron" and the parallel, capacitively powered "Dynamitron".

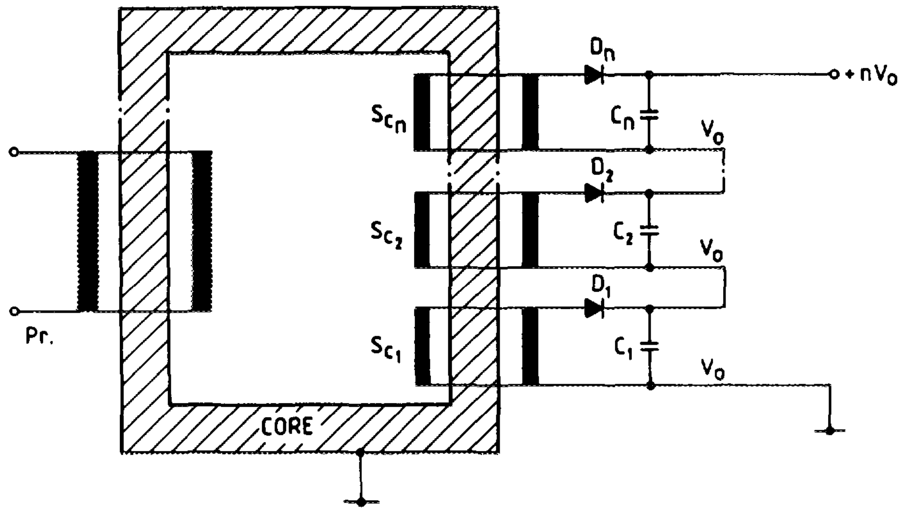


Fig.117 *Insulated core transformer (ICT) high voltage power supply*

(a) Insulated core transformer type HV power supply

The insulated core transformer based power supply (Fig.117) is a series connection of single (or full wave) rectifiers on different - well insulated from the transformer core and from each other - secondary coils of a transformer. Each rectifier circuit will produce a V_0 output voltage, so the n stage of rectifiers will produce nV_0 output voltage. The advantages of the circuit are the loadability, and that the highest stack and its secondary coil should be insulated only from the transformer core and primary coil over the nV_0 output voltage.

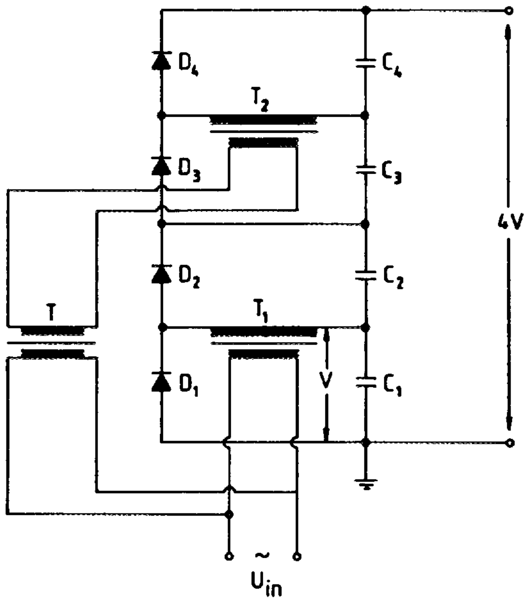


Fig.118 *Voltage multiplier circuit according to Allibone*

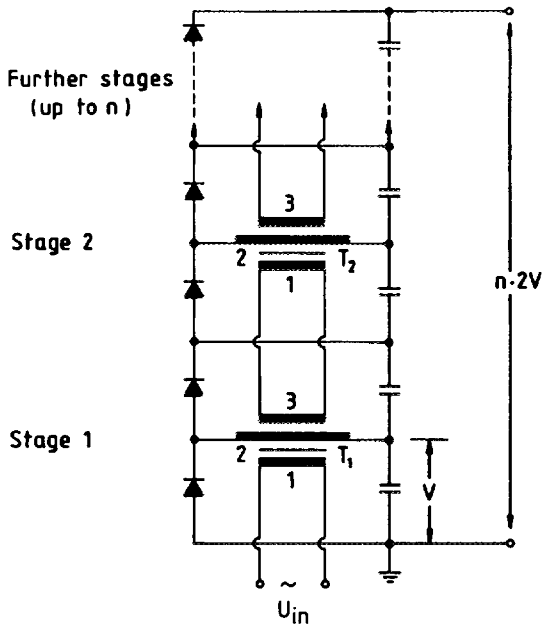


Fig.119 *HV cascade circuit with cascaded transformers*

(b) Allibone voltage multiplier

The Allibone voltage multiplier is based on higher voltage transformers. Each stage comprises one HV transformer which feeds two half wave rectifiers. As the storage capacitors of these half wave rectifiers are series connected, the HV secondary coil T_1 cannot be grounded. This means the main insulation between the primary and the secondary coils of T_1 has to be insulated for a DC voltage of V_{max}, the peak value of the secondary coil of T_1. The same is necessary for T_2, but here the HV secondary coil is at a potential of $3V_{max}$. Increasing the number of stages will increase the insulation problem related to the secondary to primary insulation, as in the case of the insulated core transformer. The Allibone HV multiplier circuit is shown in Fig.118.

(c) DC cascade with cascaded transformers

The increasingly better insulation between the transformer core and the secondary coils in the ICT HV generators can be moderated by the cascaded transformer method. In this circuit, every transformer per stage consists of a low voltage primary, a high voltage secondary and a low voltage tertiary coil. The third low voltage coil excites the primary coil of the next stage. The operation of the circuit may be understood from the circuit diagram shown in Fig.119.

The advantage of this circuit is that each stage is identical: there are no higher insulation problems between the primary and secondary coils than V. Although there are limitations on the number of stages, as the lower transformers have to supply the energy for the upper ones, this circuit, excited with mains frequency, provides an economical DC power supply with moderate ripple factors and high output power capability.

(d) The Deltatron HV generator

A sophisticated cascade transformer system is the Deltatron HV DC power supply. These generators might be limited in power output up to about 1 MV and some mA. The very small ripple factor, the high stability, the fast regulation and the small stored energies are essential capabilities of this circuit. The circuit shown in Fig.120 consists of a series connection of transformers, which do not have an iron core.

Connected to every stage is the usual Cockcroft-Walton cascade circuit, which has only a small input voltage (some kV) but produces output voltages of some 10 kV per stage. The storage columns of these cascades are then connected in direct series, providing the high DC output voltage for the whole cascade HV generator unit. Typically, up to about 25 stages can be used, every stage being modular-constructed as indicated in Fig.120. These modules are quite small; they can be

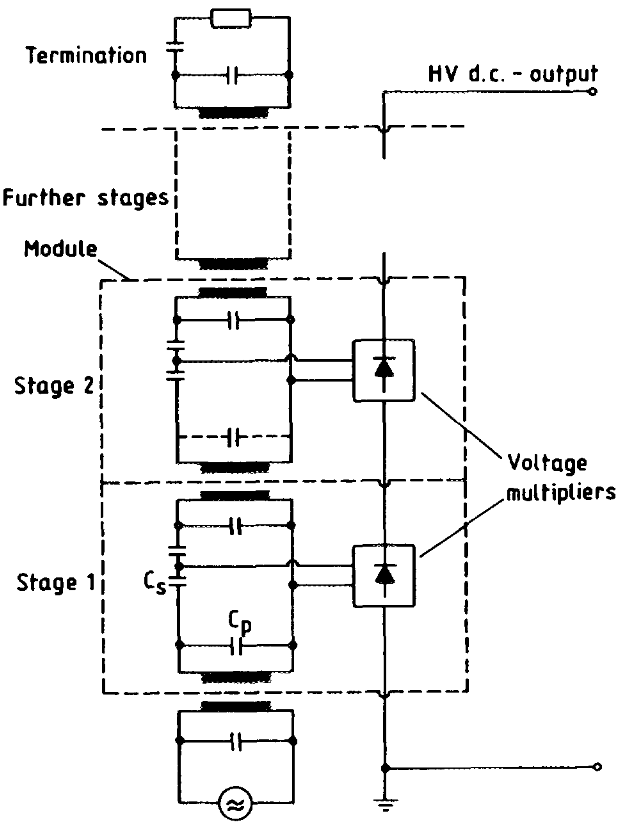


Fig.120 *The Deltatron high voltage generator*

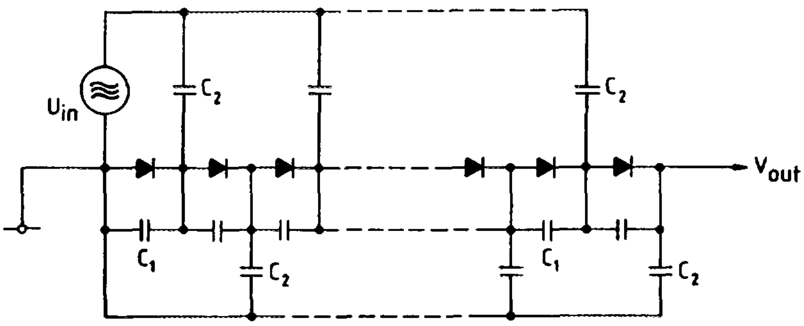


Fig.121 *Circuit diagram of the Dynamitron HV cascade*

stacked in a cylindrical unit, sometimes under SF_6 pressure. The output voltage is usually controlled by regulation of the primary side. The stages of the multipliers usually have an HV voltage divider for feedback. As the supply frequency ranges from several kHz up to 100 kHz, the voltage divider for regulation of the output is a combined R-C voltage divider. The modular power supplies of the WALLIS HIVOLT (United Kingdom), GLASSMANN Highvolt (USA) and the Technical University Buadapest (Hungary) have a similar structure. These HV generators are used as acceleration, extraction and focus power supplies in neutron generators, as well as for the supply of electrostatic quadrupole lenses.

(e) The Dynamitron HV power supply

The Dynamitron power supply is a parallel fed cascade circuit using high frequency of a few MHz. The MHz range has the advantage of using the parallel charging capacitors (C_2 in Fig.121) constructed as simple spray capacities between the nodes of n and n' of the original Cockcroft-Walton voltage multiplier. The loadability of the Dynamitron is several tens of mA with a V_0 output voltage of MV range. The voltage multiplier system of the Dynamitron is usually placed in the SF_6 pressure vessel of the accelerator, and the stages sometimes power the homogeneous field acceleration tube directly. A Dynamitron type high voltage power supply utilized in a neutron generator is in operation for 14 MeV neutron therapy at the Eppendorf Hospital in Hamburg.

A comparison of the main parameters for the single wave, full wave Cockcroft-Walton cascades and the Dynamitron is shown in Table 19 [99].

TABLE 19.

Main parameters of Cockcroft-Walton cascades and Dynamitron

Circuit	Single wave	Full wave	Dynamitron
V_0 (unloaded)	$U = 2NU_0$	$U = 2mU_0$	$U = \frac{NU_0}{1+4C_1/C_2}$
Ripple	$U = \frac{I_0(N+1)M}{2fC}$	$U = \frac{I_0 N}{2fC}$	$U = \frac{I_0}{efC_2}$
Voltage drop	$\sigma U_0 = \frac{I_0}{fC}(2n^3/3+N/3)$	$U_0 = \frac{I_0}{fC}(N^3/6+N/3)$	$U_0 = \frac{I_0}{fC_2}\left(\frac{N}{1+\frac{4C_1}{C_2}}\right)$
Usual V_{out}	0.1 - 1 MV	0.1 - 2.5 MV	0.7 - 7 MV
I_{max}	~ 1 A	~ 500 mA	~ 50 - 100 mA

13.3 TROUBLESHOOTING OF HIGH VOLTAGE POWER SUPPLIES

The malfunction of a high voltage power supply is usually caused by improper operation of the components, e.g. transformer, rectifier(s), buffer condensers, filter (resistive or inductive), regulating system (electronics), contacts or insulations.

In troubleshooting of a neutron generator with HF ion source, an analog (without active semiconductors) multimeter is recommended. The output power of an HF oscillator is a few 100 W which can easily kill an LSI-based digital or FET transistor, amplifier based electronic multimeter. Similarly, every possible high energy discharge (e.g. buffer condenser of a mains frequency Cockcroft-Walton circuit) can induce enough power in the circuit of an electronic multimeter to kill the active components.

In troubleshooting and repair of high voltage units, maximum precautions should be taken during the work. The voltage and energy of the HV power supplies of a neutron generator are high enough to kill the service personnel; therefore, troubleshooting and repair should be carried out **with great care** and **never alone.**

For work on high voltage power supplies, insulated-handled tools, test pins and other proper instruments should be used. The recommended HV meter for measurement of the output voltage is the usual TV service voltmeter. This is a cheap, commercially available meter, measuring voltages up to 30 kV, with a properly insulated handle. For AC voltage measurements, the similarly constructed HV voltage dividers (HV test probe) are recommended for use with analog multimeters. For HV measurements, the grounding of the ground contact of the HV meter or HV probe should be tested carefully before switch-on of the power supply.

A second important instrument for HV power supply testing is an ohmmeter working with a few hundred volts for the measurement of high resistances over 10 MΩ, and for testing rectifying diodes as well as HV condensers or insulations. As every neutron generator laboratory has nuclear electronic instruments, rectifiers and high value resistors can be tested by using a nuclear detector high voltage power supply. A component can only be tested under working conditions: the total test of a component can be carried out in its own circuit.

The housing of the high voltage power supplies should always be opened in a switched-off and output-grounded condition. Even a switched-off and output-shortened power supply may contain charged high voltage capacitors: precautions should be taken in dismantling the covers of the HV power supplies; the body of the power supply should be grounded and the repairing personnel should wear shoes with **insulated** toes. After removal of the covers, try to **discharge** every high voltage condenser.

The troubleshooting of a high voltage power supply usually starts with visual or small inspections. If there is a lack of output voltage, the output wiring and/or connectors should be inspected. The measurement of the continuity between the output of the power supply and the load **should be done without output voltage** and the unit should be grounded (if it floats at the terminal voltage of the neutron generator). The conductivity can be measured with the usual multimeter (digital or analog). Discharging of the output buffer condenser is advisable. If there is a lack of output voltage (and the built-in HV voltmeter does not indicate any output voltage), discharge, shorten the output and inspect the fuse (or fuses) in the circuit. Blown fuses often indicate some malfunction in the circuit. **Do not use higher rating fuses** than the original value; this could cause some problems, and as the condensers in the HV power supplies usually store high energy, the use of a higher rating fuse can even cause a fire! Recommended tests are described below.

(a) Testing the main components

Testing a high voltage power supply should start from the power (mains) side. Check the primary side of the HV transformer. The test of the HV transformer starts with measurements on the unloaded transformer. Remove the load from the secondary side of the transformer. Test the primary current versus primary voltage. In the meantime the secondary voltage should be measured by an AC HV meter. The primary current should be in the interval indicated by the parameters, and the ratio of the secondary to primary coil voltage should be almost constant. If there is some short circuit between the windings (primary or secondary), the temperature of the transformer will rise. If the HV transformer is found to be operating normally, test the rectifiers and the buffer condensers.

(b) Testing HV rectifiers

The data sheet usually contains all of the parameters which should be tested and measured to find the trouble with the rectifier. The HV rectifiers are silicon diodes and usually in series connected controlled avalanche diodes. A rectifier diode with one pn junction may withstand a 1000-1500 V reverse avalanche breakdown voltage, while the controlled avalanche rectifier stacks withstand voltages in the range of 100-150 kV. Depending on the speed of the diodes, they can operate at up to 20-30 kHz frequencies if the charge storage in the pn junction is low enough. Testing these rectifiers (diodes) in the forward direction is simple; the reverse voltage bias requires a reverse bias voltage equal to the operational voltage of the HV power supply itself or higher. The forward characteristics of these diodes can be measured by a slightly higher voltage (300-500 V) power supply, and the reverse current of the rectifiers can only be checked by a nuclear detector power supply.

(c) Testing forward characteristics

The forward characteristics and the reverse bias current of the HV rectifiers can be tested by a circuit shown in Fig. 122.

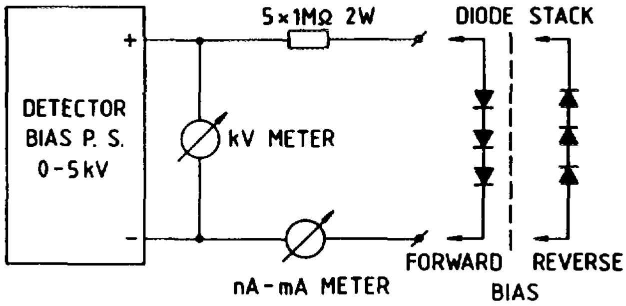


Fig.122 *Circuit for HV rectifier testing*

For forward characteristics of a 100-150 kV crest working reverse voltage rectifier stack, the forward voltage drop of the rectifier stack at the nominal (say 50 mA) forward current is about 100-180 V, indicating an equal voltage drop at all of the rectifier tablets.

The rectifier stacks can be tested in their original circuit in such a way that the rectifier diode should be loaded only resistively and the shape of the rectified current should be observed by an oscilloscope. This test can only be carried out in simple (variac controlled, mains powered transformer) HV power supplies. The shape of the rectified voltage and the reverse conducting (not only due to the charge storage of the pn junctions) can be observed on the screen of the oscilloscope. As this method requires some experience in electric and electronic measurements it is recommended only for personnel well trained and experienced in electronics.

(d) Testing the buffer condensers

The capacitance of the condensers should be in the + 30 % and - 20 % range of the nominal one. As the low capacitance of a buffer condenser may cause a higher ripple in the output voltage, the correct value of the buffer condenser is important. In high voltage condensers the stored energy is usually high, so a breakdown inside the condenser may cause blowing and evaporation of the outer contact of the condenser. Therefore the capacitance test is an important duty. The stored energy in the condenser can also be tested by a discharging resistor: the resistor should be fixed onto an insulating rod and the two arms of the resistor should touch the two terminals of the high voltage condenser. If there are "healthy" sparks the condenser can store higher energies. This discharging method always gives an indication on the condition of the condenser, especially when the person troubleshooting is experienced in discharging condensers in normally operating power supplies. The discharging resistor should be long enough (corresponding to the voltage conditions of the HV power supply) and have high enough wattage to prevent the power from dissipating during the condenser discharge.

(e) Testing the resistors

Testing the resistor, like any other test, should start with visual inspection. The brownish-blackish colour of the resistors indicates an overload or burn off of the resistors. In the case of a high voltage drop on the serial resistor, the interruption in the resistors leads to sparks; these can be observed on the surfaces of the painted resistors. High voltage resistors covered with epoxy resin layers also show some coloured regions in the case of malfunction. Lower value resistances (in the range of 1-20 MΩ) can be tested by the usual multimeters, but the higher (10-100 MΩ) resistors requires megaohmmeters or a few hundred volts power supply and a suitable micro-nanoammeter. The usual 3-digit hand held multimeters can be used for this purpose. The ammeter should always be connected between the ground terminal of the power supply and the output voltage should be connected to the resistor. The voltage across the resistor and the measured current determines the resistance of the resistor.

The resistance of the insulators, connectors and other insulating components can be measured by the same method, utilizing a nuclear detector HV power supply and suitable nanoammeters.

14. BEAM LINE COMPONENTS

14.1 BEAM STOPS

A fast switch-on and switch-off of the neutron production at a neutron generator can be carried out by pulsing the ion source, by deflection of the accelerated beam from the target or by a mechanical shutter closing the path of the accelerated beam to the target. This mechanical shutter is called a beam stop. The beam stop has a metal sheet - usually water cooled - which shuts off the beam in front of the target. This shutter can be operated electromagnetically or pneumatically. The response time of the beam stops is relatively fast: they close and open the beam within almost one second. The ion source and the extraction voltage pulsation or the electrostatic beam deflection are faster. The principles of the two main types of beam stop are indicated in Figs 123 and 124 [50].

14.2 BEAM SCANNERS

In general, the scanners consist of two wires, one rotating around the horizontal axis, scanning the beam vertically, while the other moves perpendicularly to the first and gives the beam a horizontal profile. The planes scanned by the two wires are perpendicular to the deuteron beam direction. If the two wires move (rotate) synchronously, the shape of the accelerated beam can be determined. The principle of the single-axis rotating beam scanner is shown in Fig.125 and of the two-axis beam scanner in Fig.126.

14.2.1 Determination of the beam profile

Let us suppose a homogeneous beam of radius r along the x axis in the Cartesian coordinate system. The rotating wire rotates along the y axis with radius R.

The thickness of the scanning wire is much less than the radius r of the beam. Similarly the radius r of the beam is much less than the radius R of the rotating wire. If the wire rotates with an angular velocity ω, the shape of the i(t) ion current in time will be described by

$$i(t) = 2r\sqrt{\left(\frac{R}{r}\right)^2(\cos^2\omega t - 1) + 1} \tag{44}$$

which is based on the usual geometric formula. As the wire intercepts the beam twice during a single cycle, as in Fig.127, the oscilloscope connected to the wire shows the shapes demonstrated in the positions I - V described below.

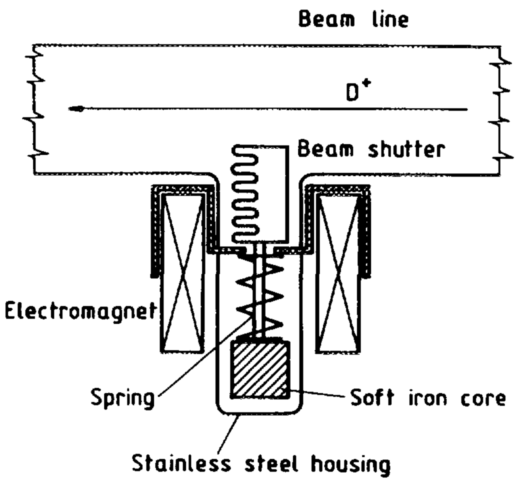


Fig.123 *Schematic diagram of an electromagnetically activated beam stop without water cooling*

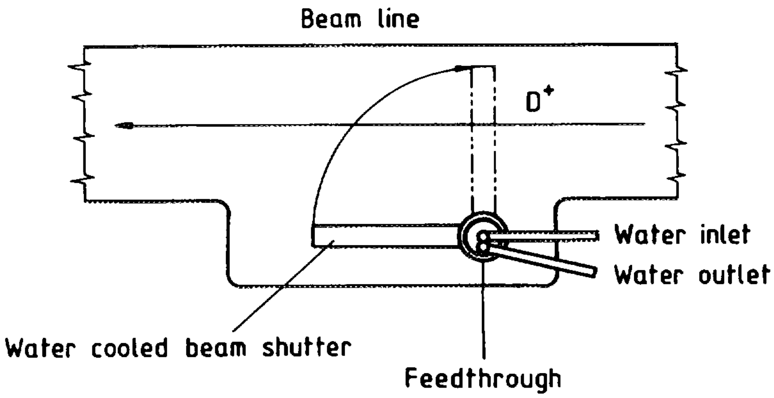


Fig.124 *Schematic diagram of a water cooled beam stop utilizing a vacuum feedthrough*

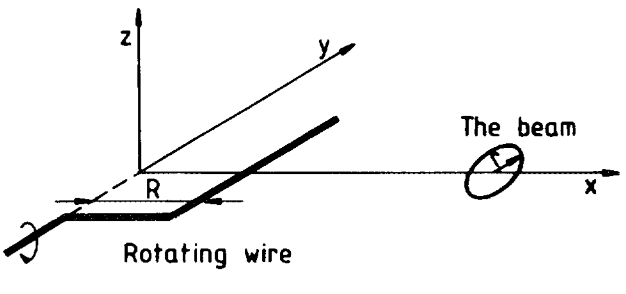


Fig.125 *Principle of a rotating beam scanner*

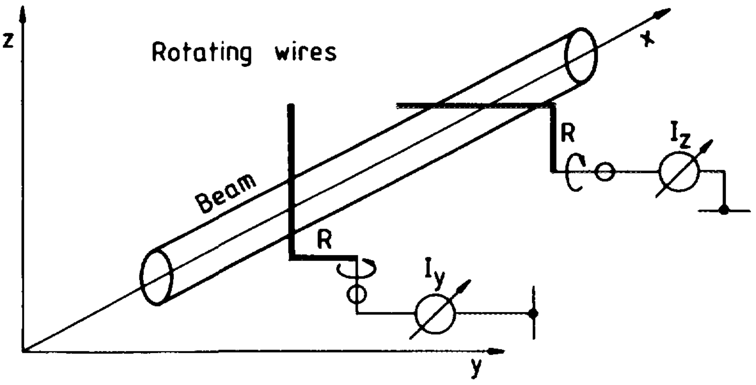


Fig.126 *The principle of a two-axis beam scanner*

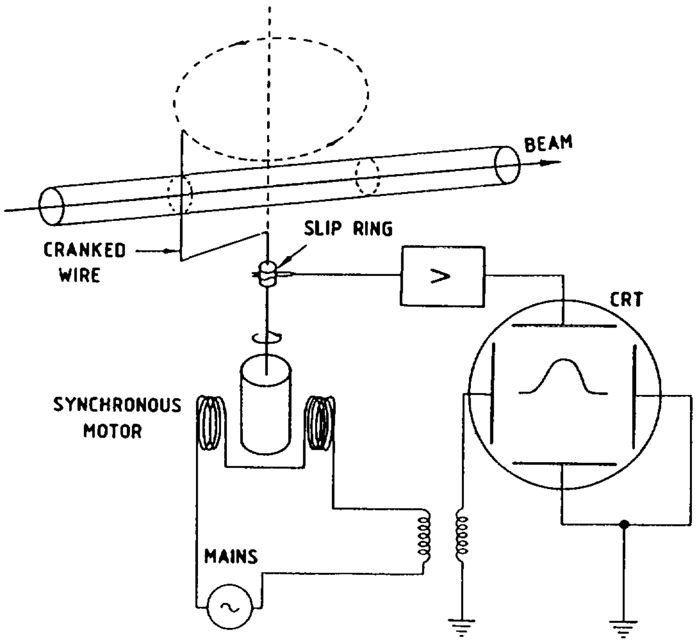


Fig.127 *Arrangement of a beam scanner*

If the beam is centered along the time intervals b and c between the up-to-down and the down-to-up, the currents will be equal. In case of a

circular beam: b = c

eccentric beam: b = c

the diameter of the beam can be calculated from the following expression:

$$d = 2\ R\ \sin \frac{\pi a}{b} \tag{45}$$

For narrow beams, when a « b, in eq. (45) the $\sin \frac{\pi a}{b}$ can be replaced by $\frac{\pi a}{b}$ and so

$$d = \frac{2R\pi a}{b} \tag{46}$$

The single rotating wire scans the beam along the Z axis. To get the whole picture of the beam profile, a second wire, rotating in a perpendicular plane around the Z axis is needed. This means that two synchronously rotating wires can scan the beam shape and position [87].

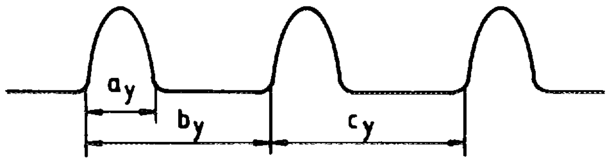
These two wires scan the beam current along the Z axis (I_z) and along the Y axis (I_y). The horizontally (I_y) and the vertically (I_z) scanned beam currents can be displayed together on the screen of a double trace oscilloscope. If the rotating mechanism ensures a $\pi/2$ (90°) phase difference between the two wires, the exact position of the beam can be determined [54].

The following oscillographic pictures of I_y or I_z can indicate the behaviour the beam:

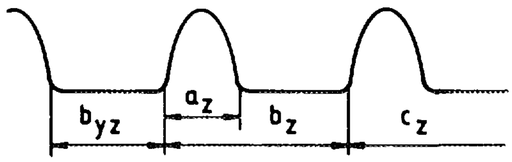
I.  Unstable beam current (improper operation of ion source, ion optics)

II.  Stable beam current

III. In the case of perpendicular, synchronous two-wire beam scanning:



Horizontal scanning



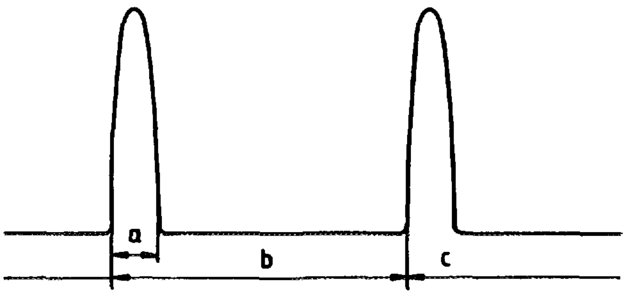
Vertical scanning

For an absolutely concentric beam in the target tube we have

$$b_{yz} = \frac{b_y}{2} = \frac{b_z}{2} \tag{47}$$

The well focused beam shows on the oscilloscope a small duty cycle: $\frac{a}{b+c} \ll 1$

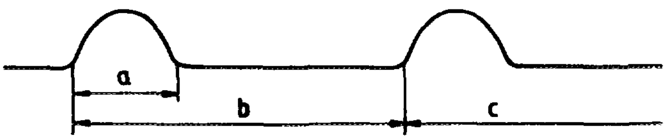
IV.



Horizontal or vertical scanning

while for a wide beam $\frac{a}{b+c} \sim \frac{1}{2}$.

V.



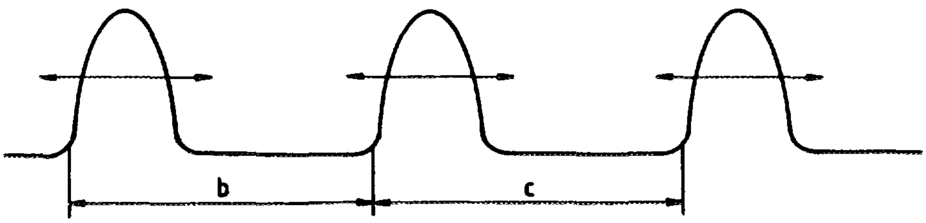
It should be noted, however, that the two wires can be replaced by a single wire with a special curvature [100] for scanning the beam simultaneously in the horizontal and vertical planes.

14.2.2 Problems with rotating beam scanners

1) **Vacuum problems:** As the rotating beam scanners require rotating feedthroughs: the usual seal testing should be carried out. Similarly, if the stator and the rotor of a synchronous motor are in the atmosphere, or in vacuum, respectively, the problems observed are sometimes at the electric feedthrough of the scanning wires.

2) **Mechanical problems:** As this scanner requires a smoothly rotating wire, every mechanical problem (stain, dirt in the bearings) may make the operation of the scanner unnstable. These mechanical instabilities can be observed on the screen of the oscilloscope:

VI.



The length of the pulse and the period of time will appear jerky on the screen. If there is no pulse the wire may have stopped. If the wire intercepts the beam, some DC current can be observed by the oscilloscope. Dismantling and cleaning the mechanical part of the scanners should be done carefully.

3) **Electrical problems:** The isolation of the wire output and the conductivity between the scanning wire and the off-vacuum connector should be tested periodically. The ceramic insulation of the wires is usually covered by a sputtered metal layer: they should be cleaned both mechanically and chemically.

The usual synchronous motors rotating the wire scanners should stopped off-beam to avoid sputtering due to the beam. This is assured by an electric contact fitted to the axis of the synchronous motor (end position switch). If this contact does not work properly the synchronization of the y and z scanning wires will be unstable. The proper operation of the contact can be checked by the oscilloscope observing the signals of the beam scanner while the synchronous motors are switched on and off several times. The phase position of both the Z and Y signals should be in contact. The oscilloscope should not indicate any DC level in the case of a stopped beam scanner.

14.3 WIRE ELECTRODE (MATRIX) BEAM SCANNERS

The development of microelectronics and the spread of personal computers have made beam scanning easy even at the lower end of accelerators. The typical multiwire sensors of a beam monitor - used earlier in the expensive machines - consist of a vertical and horizontal grid of thin wires. These wires collect the ion beam and the current is converted into voltages. These voltages are multiplexed into an analog to digital converter. The multiplexing and the processing of the measured current data are carried out by computer [101]. In this Manual, only a general description of such systems will be given.

The wire chamber of a beam scanning electrode consists of two normal glass laminated epoxy printed circuit boards which hold the vertical and the horizontal wires. The wires are made mainly of tungsten, electroplated with gold. The usual diameter of the gold plated tungsten wires, which can be soldered easily, is about 20 μm. Depending on the number of the input of the analog multiplexer, the wires cover an active area of about 50 mm x 50 mm square. The vertical and horizontal wires are mounted through the square using conventional soft soldering technique directly onto the printed circuit board. The wire holding the printed circuit board will be connected to the screening diaphragms and vacuum system flange holders by epoxy resin. Without epoxy resin bonding, the printed circuit boards can be vacuum sealed by Teflon (PTFE) gaskets. The printed circuits are

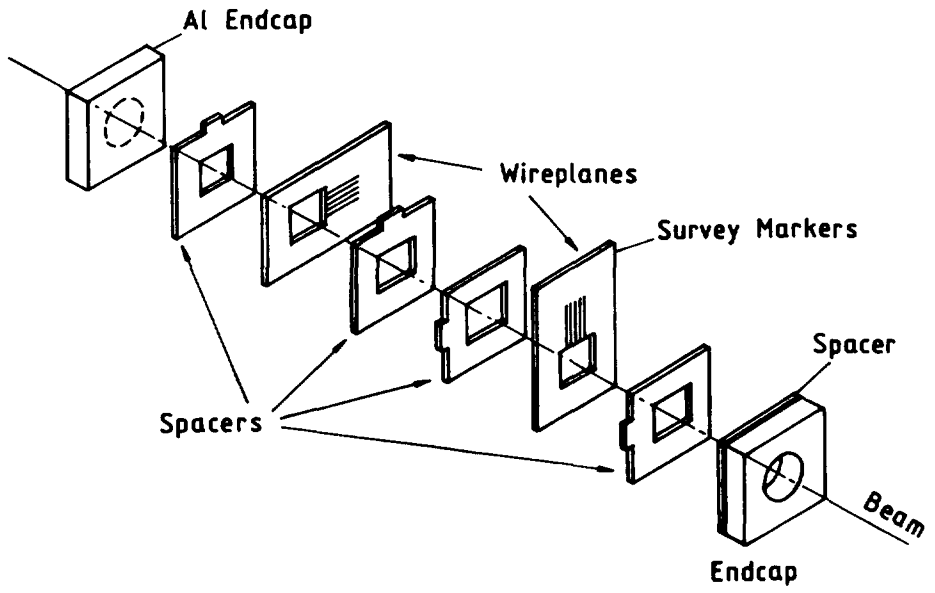


Fig.128 *Assembly drawing of a multiwire beam scanner* [102]

conventionally etched and connected by the usual ribbon cables to the individual amplifiers and to the multiplexer of the data processing unit. The assembly drawing of a multiwire beam scanner is shown in Fig.128 [102].

14.4 THE FARADAY CUP

Most experiments with neutron generators and charged particle accelerators require knowledge of the beam intensity and the position at the target. The simplest method for detection of a charged particle beam is to intercept the beam with an insulated metal plate of sufficient thickness. The ion current striking this plate is measured by an analog meter if the mean current is greater than 10^{-6} A, which is the case for neutron generators. Complications arise because the ion beam to be detected is accompanied by a diffuse secondary electron beam. The utilization of beam line components like deflection magnets and quadrupoles will remove the electron component of the beam, but this can be rebuilt near the target.

The upper limit of the energy spectra of the secondary electrons induced by the accelerated ions in the target does not exceed about 100 eV depending on the target material. However, the X-rays produced in the target when it is bombarded by protons or deuterons can contribute significantly to the high energy tail of the electron spectrum. The problems related to the secondary electrons can be overcome by obtaining reliable measurements of the beam current by the suppression of the high flux of the fast primary electrons, as well as the emitted slow secondary electrons.

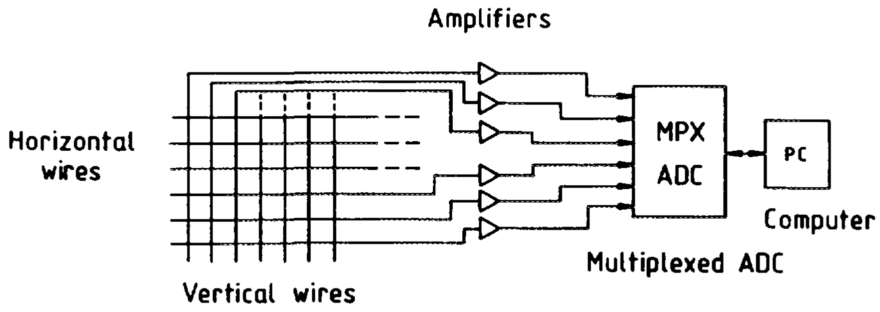


Fig.129 *Electronic block diagram of a multiwire beam scanner* [101]

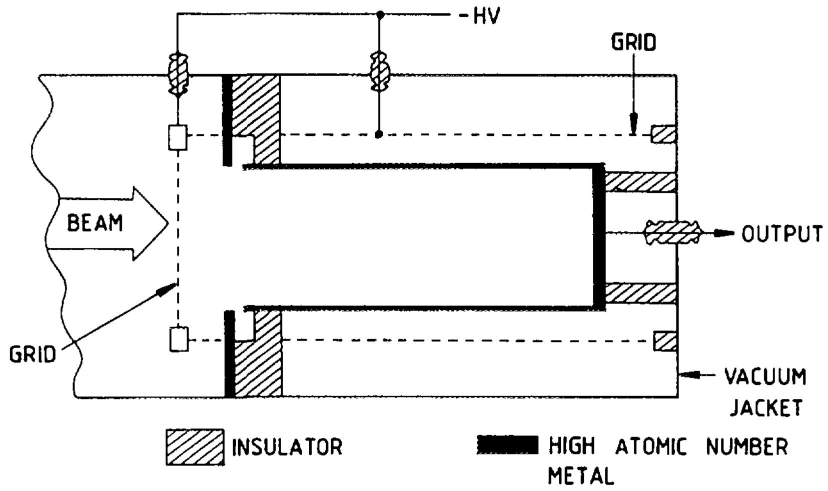


Fig.130 *Schematic representation of a Faraday cup for measurement of the beam current*

Starting from the fact that the main electron component is slow and that the number of fast electrons reaching the current collectors (target), either from the residual gas or from the target, is small, it is possible to suppress the electrons by surrounding the target with a negatively biased mesh screenmaintaned at a voltage of 200 V. In addition, the collector itself can be biased positively and thus re-collect all the slow secondary electrons.

The schematic representation of an electrically suppressed beam current collector (Faraday cup) is shown in Fig.130. The grid placed in front of the beam collector cup is usually also replaced by diaphragms. The external cylindrical mesh screens secondary electrons emitted from the the outer side of the Faraday cup due to X-ray production by the ion beam [87]. In a neutron generator, the Faraday cup is the target holder.

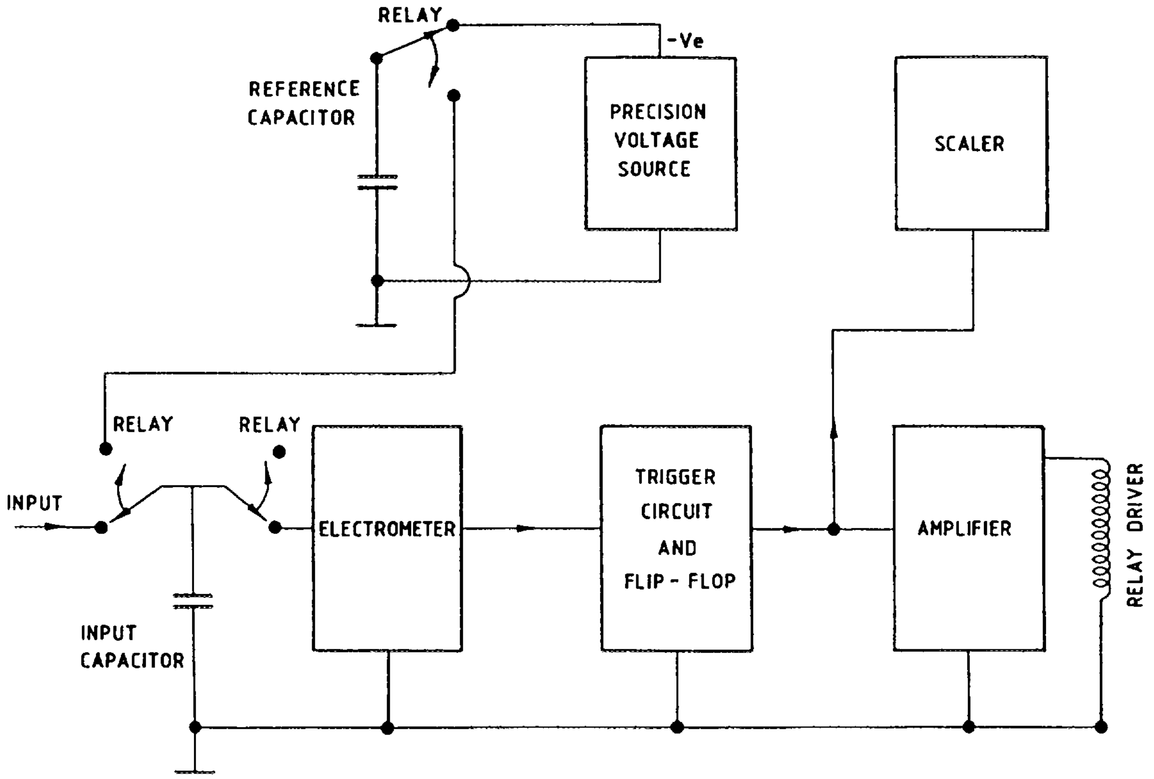
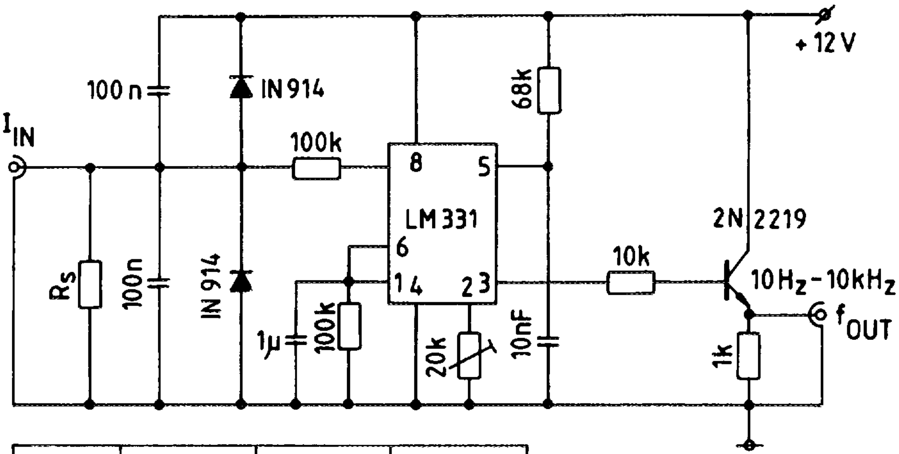


Fig.131 *The principle of the target current integrator*



$I_{IN\,max}$	0.1mA	1mA	10mA
R_S	100k	10k	1k

Fig.132 *Circuit diagram of a V/f converter-based current integrator*

14.4.1 Beam current integration

In all of the experiments carried out with charged particle beams, the measurement of the total beam charge, or the number of incident particles that reached the target during a given time, is required. This requires an integration of the beam current detected in the given time interval. For the integration of the beam current the Faraday cup (target) is fed to a large high-quality capacitor. The voltage across the capacitor increases with the collected charge and reaches some predetermined level. At this voltage a fast acting flip-flop will be triggered. This trigger operates an electromechanical relay for counting the charge, or in a more advanced form it is fed an accurately known quantity of charge of inverse polarity to the input capacitor to discharge it.

In the circuit shown in Fig.131, the input capacitor is charged by the input current (beam current) and it is discharged by the reference voltage source. In principle all of the voltage-to-frequency converters work similarly.

The voltage-to-frequency converter chips can be used in simple target current integrators in the range of 10 nA to a couple of mA. A simple target current integrator utilized at neutron generators with beam current of several tens of μA is shown in Fig.132. This integrator is a useful device for the observation of the burn-off of the tritium targets [103].

14.5 TARGET ASSEMBLIES

The target assemblies of neutron generators are constructed to fulfil the following requirements: target holding; target cooling; target current measurement; to suppress the secondary electrons; to achieve the shortest distance between the target spot to the sample to be irradiated.

The usual target holders are cooled with water or air. Water cooled target holders are used at beam current higher than 500 μA when more than 100 W target load is present in the case of 200 kV acceleration voltage.

Water cooled target holders are used mainly for activation analysis, where distortion of the original 14 MeV neutron spectrum does not influence too much the accuracy of the elemental analysis using reference sample of similar composition.

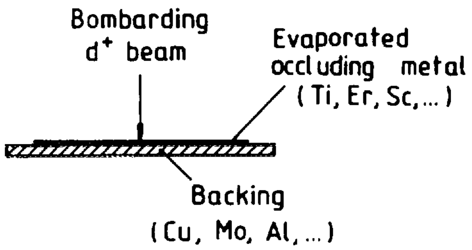


Fig.133 *The construction of a target*

The tritium or deuterium target used at the neutron generators consists of a good heat conducting backing (made of Cu, Mo or Al, etc.) covered with thin vacuum evaporated layer of hydrogen-occluding metal (usually Ti, Er, Sc, etc.) (see Fig.133). The heavy hydrogen isotopes (tritium or deuterium) form a quasichemical compound with the occluding metal. In principle the tritium concentration can achieve the stoichiometric ratio $Ti_1T_{1.9}$. This ratio depends on the temperature, because the disintegration of Ti_xT_y "molecules" is significant over 400°C. The loss of tritium (or deuterium) from the targets in neutron generators is proportional to the energy dissipation of the accelerated D^+ beam. The tritium implantation, using a mixed D^+, T^+ beam, as is usual in sealed tube neutron generators, can delay the burn-up of the tritium targets by a factor of about 1.5-1.7.

In low voltage generators the most common targets are deuterium or tritium absorbed in thin metal layers. Besides titanium and zirconium, Er, Sc, Y and U are also used to produce intermetallic compounds with deuterium or tritium. Theoretically, the ratio of tritium to titanium atoms is about 1.9:1, but in the case of commercial targets it is about 1.5:1. To produce a thin target a 0.2 to 2.5 mg/cm^2 thick layer of Ti or Zr is evaporated onto Cu, Ag or W backing metal. A 1 mg/cm^2 titanium layer loaded with tritium or deuterium up to this atomic ratio corresponds to 0.23 cm^3/cm^2, or 0.6 Ci/cm^2 for tritium only. For a thick target 1-2 cm^3/cm^2 gas is absorbed into Ti or Zr. The range of D^+ ions in a $TiT_{1.7}$ target is between 0.12 and 1.05 mg/cm^2 for incident deuteron energies from 25 to 400 keV respectively [1]. Therefore, a TiT target of 5-10 mg/cm^2 is about 10 times thicker than the range of the deuteron ions of a few 100 keV. For the calculation of the range a simple approximation is given in Ref. [104].

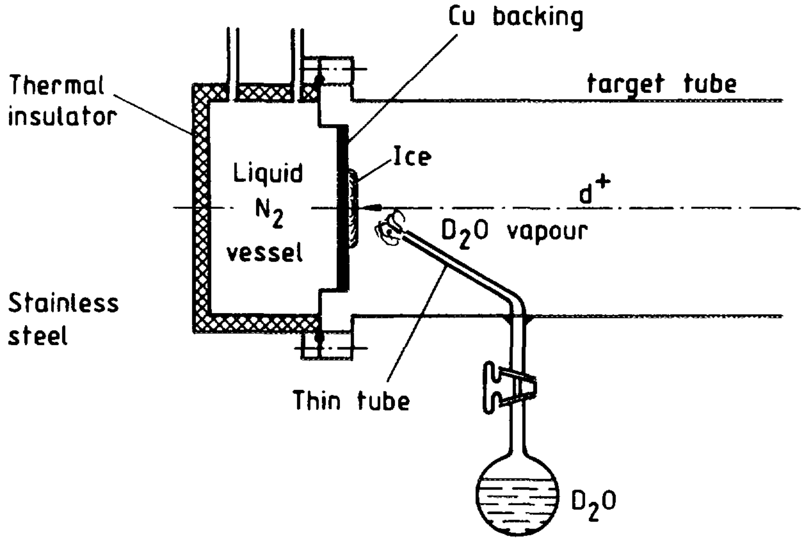


Fig.134 *Heavy ice deuterium target for neutron generators*

Heavy water (D_2O) in frozen form may be used as a target material. The principle of heavy ice target formation in the vacuum system of a neutron generator is shown in Fig.134. The target holder is made of a thermally well conducting backing directly cooled by liquid nitrogen. Control of the amount of heavy water vapour will balance the amount of the evaporated heavy ice.

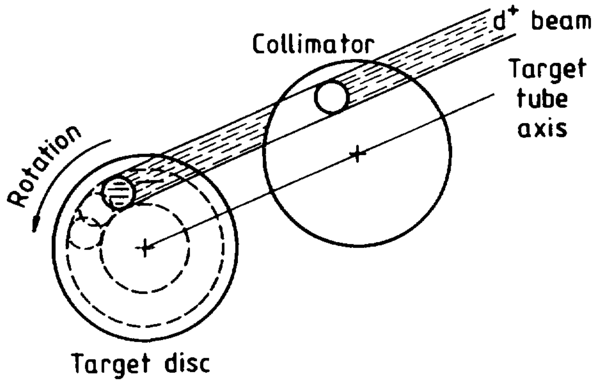


Fig.135 *The off-axis target arrangement to utilize the whole surface of TiT targets*

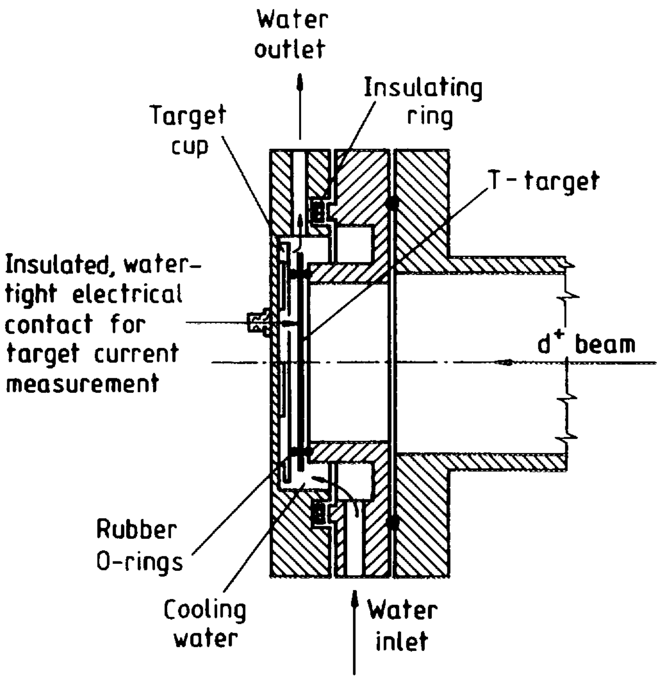


Fig.136 *Schematic diagram of a water cooled target assembly*

Various methods to achieve higher source strengths and target lifetimes have been developed [1]. A small rotary target is more economical than a stationary one [61] and is ideal for applications with medium ion beams, especially to maintain constant high neutron flux over a long period of irradiation. The main characteristics of such targets [105] are: maximum beam power 600 W, rotating speed 60 rev/min, active target area 100 cm^2, half-life 300 mA·h [106]. The cost is about 40 % of that of the respective number of stationary disc targets.

The target lifetime can be increased significantly with an off-axis deuteron beam, by which an annular surface of the target will be used. This target-beam geometry is sketched in Fig.135.

A water cooled target assembly, shown in Fig.136, is able to dissipate a few hundred W/cm^2.

The target assembly is one of the most important parts of the neutron generator, containing a large amount of tritium and induced radioactivity. Therefore the **target** and the **target assembly should be handled with caution!**

14.5.1 Target replacement

Switch on the exhaust of the target room. Opening a target assembly involves the exposure of tritium to atmosphere. Close the gate valve of the target tube (if the high vacuum pump(s) is still working). Slowly expose the vacuum part of the target assembly to atmosphere using dry nitrogen. If dry nitrogen is not available, use the vent valve of the target tube. The following description of target exchange is based on the hypothetical target holder shown in Fig.136.

Close the water inlet of the target cooling. Be sure that the water has left the target cooling cup: blow out the water with compressed air or a blower. Disconnect the target current meter cable. **Opening** the target cup should be done with **the same tools, used only for target assembling**. These tools should be stored separately in a vented glove box: they are expected to be polluted with tritium.

During the dismantling of the target assembly rubber gloves should be worn. Put polyethylene foil on the floor under the target assembly. Two polyethylene bags should be kept in the vicinity of the target assembly: when the vacuum system has been opened, the target assembly should be put into the first plastic bag to avoid further tritium pollution. The second plastic bag should be pulled onto the open end of the target (beam line) tube. A tritium gas monitor should be ready to monitor the tritium contamination during the assembling of the target holder.

Hold the tritium target with tweezers or with medical rubber glove covered fingers. The removal of the old target and its replacement with a new one should be done by a person wearing **gloves** and **mouth mask**.

When replacing the old target with a new one, make sure that the gray side (the titanium layer) is on the side of the vacuum!

When a new target is placed in the seat of the target holder, switch on the forevacuum pump of the target tube. The vacuum will hold the target: the O-ring on the vacuum side should seal properly. This can be observed by the Pirani or thermo-pair vacuum meter of the target tube. The O-ring of the vacuum side should be cleaned with organic solvent and greased slightly with high vacuum silicon grease. The tissues used for cleaning the target assembly and the old O-rings should be handled as radioactive litter and stored in the special bin for radioactive litter.

When the target sealing on the vacuum side seats properly, assemble the water sealing O-ring and the water cooling cup. As the tritium target backing seats in the isolated seat between the two O-rings, the cup should be tightened carefully. During the tightening of the water cooling cup, observe the vacuum meter of the target tube. The sealing, both on the vacuum side and on the water side, should be done properly. When the cup of the target holder has been fixed, connect the water line. Check the target assembly. If the water drops from the target holder, the cup should be tightened even more.

Attention! When the target separates the water from the vacuum (tritium !!) side, every operation on the target assembly should be carried out carefully. Details of the radiation protection procedures related to neutron generators can be found in Refs [107,108].

The electrical connection in Fig.136 is a spring. The proper connection between the target backing and the connector (the figure shows a female BNC connector) can be ensured by the proper contact. After reassembling the target holder, the target connector should be tested for conductivity between the target connector and the target housing. A couple of MΩ resistance - especially with cooling water - does not influence the accuracy of the target current measurement if the target current meter circuit has an input resistance in the range of kΩ. (The cooling water usually gives a specific resistance of MΩ cm between the target and the target housing; if the resistance is measured by the usual multimeter, which uses a couple of volts at resistance measurements.) This **water resistance** between the target and its housing should be taken into account when a target current integrator is used. The lower input impedance of the integrator can ensure the higher accuracy of the target current measurements.

When the target exchange has been completed and the seals and contact have been tested and found to be normal, close the valve of the forevacuum pump, sucking down the target tube, and open the gate valve isolating the high vacuum part of the neutron generator from the target tube. The reading of the high vacuum meter should reach the normal value in about ten minutes. If the reading of the high vacuum does not reach the normal value, it is an indication of some leaking.

When the target exchange is finished, collect the plastic foil from the floor and put it into the plastic bag which had previously covered the target tube. Place the plastic bag (and other probably tritium contaminated litter) into the radioactive litter bin. Put back the used target - with its container - into the vented target storage glove box, in the place for used targets. Put back the tools and gloves used for the target exchange into the same vented glove box that stores the tritium targets. Wash your hands, and test with a tritium monitor whether they were properly washed. **Do the required administration related to the targets!**

Attention! Tritium targets should be handled carefully. The biological half-life of tritium gas in human organs is about 11 days, but the small chips and powder from the titanium layer absorbing the tritium has a much longer biological half-life in the human body and they will act as "hot spot" intense beta radiation sources.

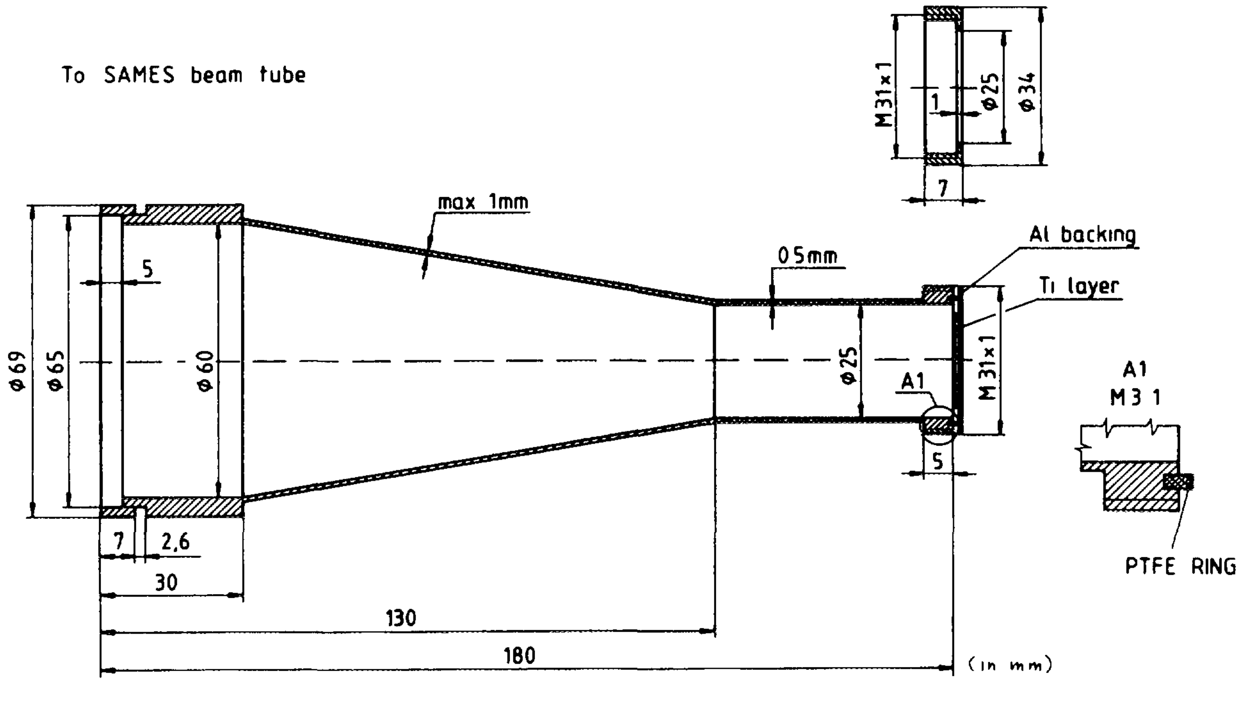


Fig.137 *Thin wall tube, air cooled target holder for SAMES neutron generators*

14.5.2 Air cooled target holder

The air cooled target holder shown in Fig.137 can be connected to the beam line of a SAMES neutron generator. The target holder is made of AlMgSi alloy having a relatively low inelastic scattering cross section. The target is held by the thin wall tube and is isolated electrically by a Teflon ring seal on the vacuum side and a thin Teflon ring on the backing. The small amount of scattering material around the target does not disturb the 14 MeV neutron field around the target spot, so this arrangement is proposed for accurate neutron data measurements. A ring shaped sample is usually fixed around the target spot for alteration of the neutron energy. The cooling of the target needs compressed air to blow the target through a nozzle (air jet). The same nozzle is utilized to hold the spring contact of the target current measuring meter. This arrangement with the sample holder is shown in Fig.138 [1].

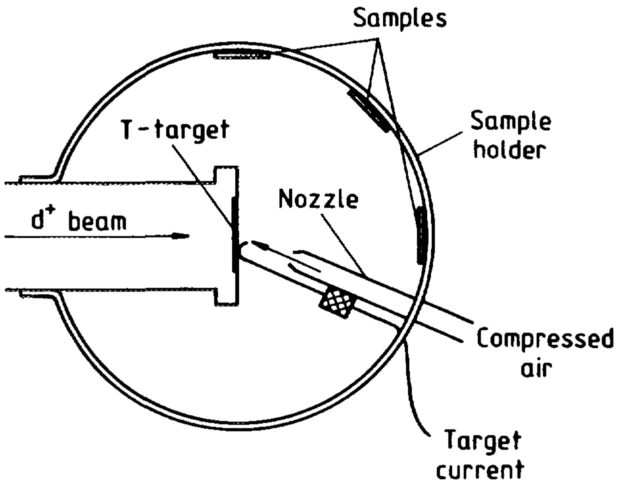


Fig.138 *Air cooling of an air cooled target holder with ring shape sample holder*

14.5.3 Replacement of the target at air cooled target holders

Attention! As the compressed air is sometimes not dehumidified, the air cooling should be checked - specially at the beginning - because the compressed air can blow water to the target holder. During the operation of the neutron generators the high voltage power supplies should be interlocked by a **flow switch** of the target cooling water or compressed air. A well collimated ion beam may melt the target backing without cooling, releasing the whole tritium content into the vacuum system of the neutron generator. The beam heated target can melt the vacuum seals or a well collimated beam can even punch the target disc itself. Both lead to a fast pressure increase in the vacuum system - i.e. the destruction of the high vacuum - which can be fatal for the high voltage power supply or for the whole neutron generator.

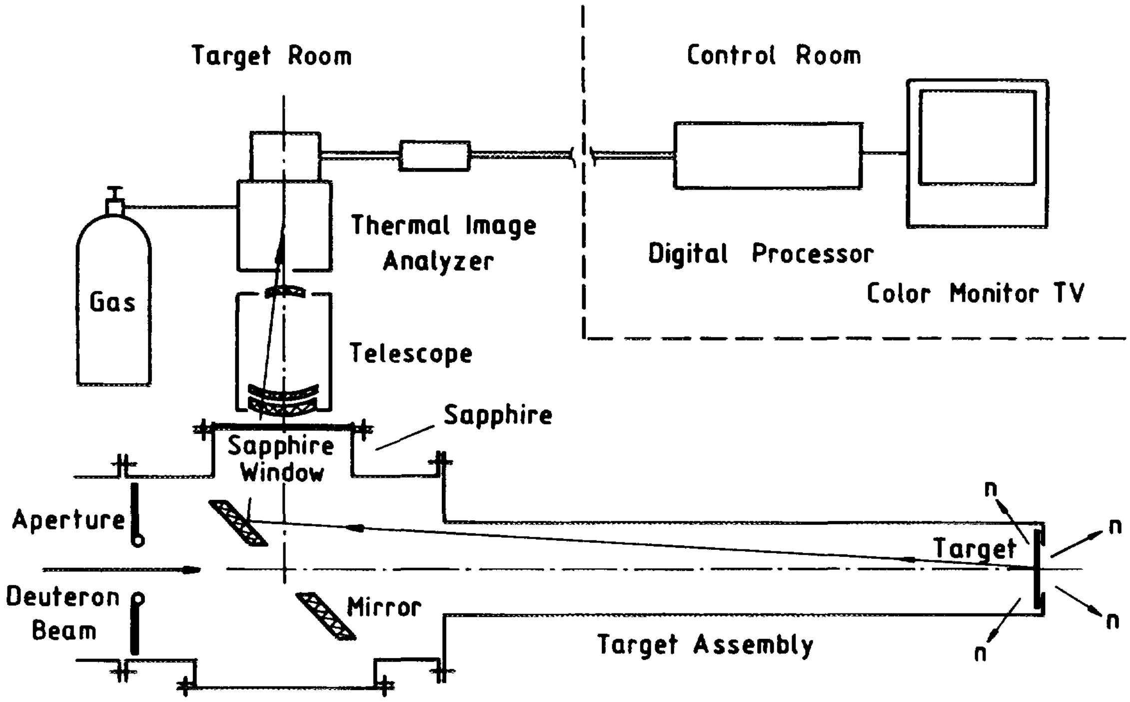


Fig.139 *The FNS (JAERI) target surface temperature and beam profile monitor*

Bad electrical contact between the target and the target current meter can cause an electrical breakdown between the target and the ground.

In addition to the thermocouple or thermistor, the video equipment with the necessary electronics is sometimes useful equipment for monitoring the temperature of the target. However, a CCD device or similar radiation-sensitive semiconductor must not be placed in close contact with the target assembly, in order to avoid radiation damage to these components. It is therefore essential that a suitable distance is ensured by an optical connection between the target observing mirror and the infrared sensitive camera. A monitoring system complying with this requirement is shown in Fig.139. This system is utilized at the 80° beam line of the FNS at JAERI [109].

This equipment is basically a sort of scanning infrared telescope camera. The infrared radiation originating from the deuteron beam bombarded target surface is taken out, by means of a mirror and a sapphire window, to the outside of the vacuum beam duct.

The thermal image is transformed by the analyzer into video signals and they are transmitted to the digital processor of the analyzer in the control room, after the necessary data processing in the commercial model. The thermal image of the object - the target surface - is displayed on a colour monitor screen in a

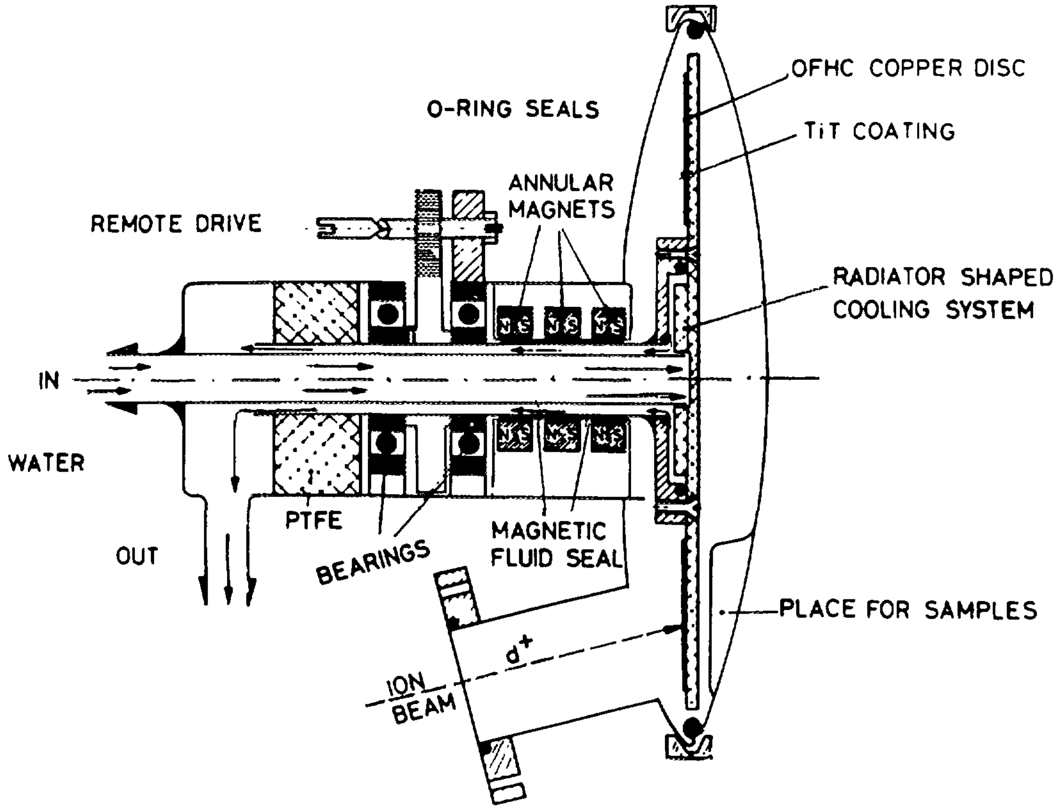


Fig.140 *The schematics of the MULTIVOLT rotating target with water cooling and magnetic fluid seal feedthrough*

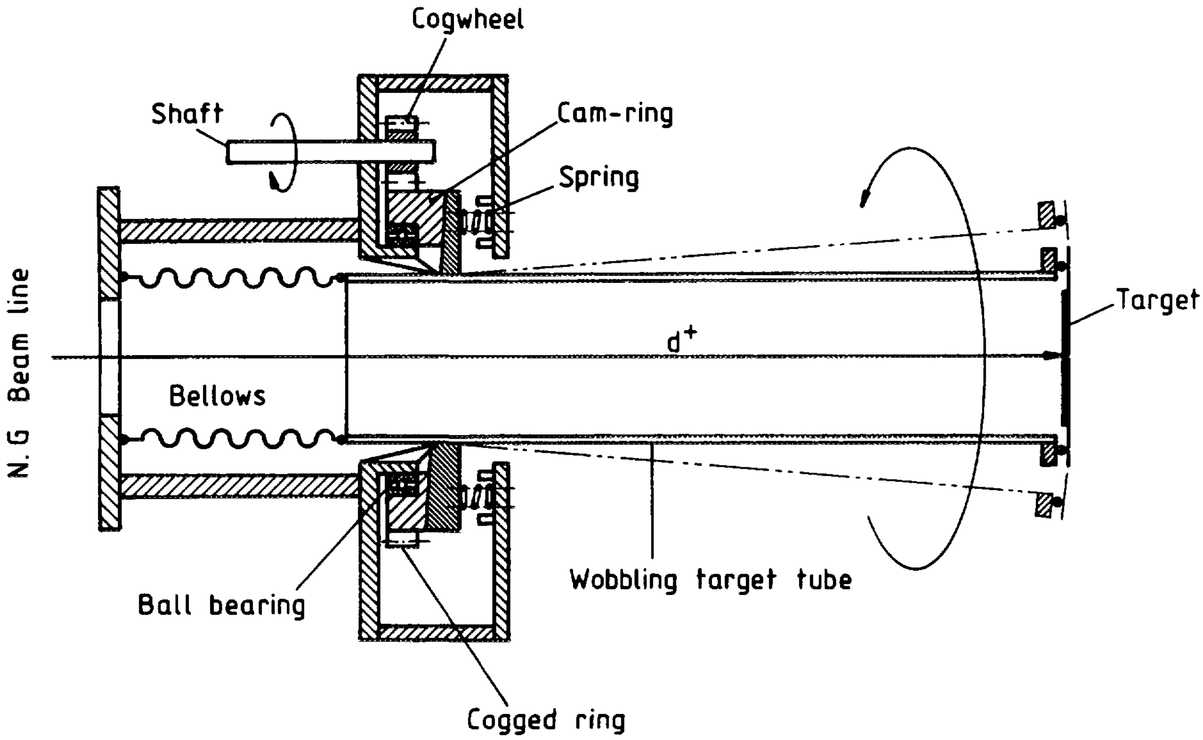


Fig.141 *Operation principle of a wobbling target holder*

16-colour temperature scale. The use of this equipment at the higher kW power beams is important to increase the target life and decrease the tritium pollution round the neutron generator and in the vacuum exhaust. Similar equipment is used in Dresden [110].

14.5.4 Rotating and wobbling target holders

The thermal load of the tritium targets can be decreased by rotating or wobbling the targets around the beam. The targets rotate at a speed of several hundred revolutions per minute. The vacuum feedthrough of these rotating targets allows a maximum 1000 rpm. The commercially available rotating and water cooled target holders are manufactured by MULTIVOLT, Crawley, United Kingdom.

The schematics of a MULTIVOLT rotating target are shown in Fig.140. The wobbling target holders do not require vacuum feedthrough. Below 200 W target load the wobbling system is recommended for use at the whole target surface and in order to increase the target lifetime. As the target moves around a circle, the beam will utilize an annular surface of the tritium target. The speed of the rotation is a few revolutions per minute, so the mechanical and vacuum problems of the target rotation can be solved by simple bellows or other elastic tube [105].

A typical wobbling target is presented in Fig.141. The circular rotation of the target is carried out by a cam-ring. This cam is fixed onto a cogged ring driven by a cogwheel. The cogged ring is rotated around a ball bearing on the standing part of that ball bearing. The target tube is forced by springs onto the cam. The connection of the wobbling target tube to the beam line tube is made of stainless steel bellows. This bellows allows a slight circular movement caused by the rotating cam. The excentricity of the target rotation - wobbling - can be adjusted by the position of the wobbling target tube by holding the flange of the target holder. In this way, the total surface of the tritium targets can be utilized and the target lifetime will be increased by a factor of 5-10. The manufacture of wobbling target holders requires a well equipped mechanical workshop and well trained staff.

15. CLOSED CIRCUIT COOLING SYSTEMS

The cooling water consumption of the usual neutron generator is about 0.5 to 1.5 m^3/h, which can supply the target and the high vacuum (diffusion or turbomolecular) pumps. As the public water supply in many developing countries is unreliable, closed circuit cooling systems are recommended. In tropical or subtropical regions, the circulated water should be cooled and chilled. However, commercialal water chillers consume a lot of energy, so other types of heat exchanger may sometimes be preferable.

15.1 THE KAMAN COOLING SYSTEM

The A-711 sealed tube generator and the A-1254 pumped neutron generator have the same combined cooling system. The Penning type ion sources of these generators are located on high voltage terminal and need external cooling. The insulation problems related to high voltage are solved by circulating the electrically insulating FREON-113 coolant. For other neutron generators, the ion source or high voltage terminal cooling uses petroleum or transformer oil coolant [110].

The cooling system of the KAMAN neutron generator is a compact unit: it has two closed circuit coolant loops with circulating pumps and a refrigerator. The heat exchanger of the cooling unit chills both the circulated target cooling water and the ion source cooling FREON-113. The operation of the cooling system is controlled by the temperature of the circulated water and by the coolant flow detectors. A schematic representation of the KAMAN cooling unit is shown in Fig.142. The two coolant flow switches detect the loss of the coolants and interlock the operation of the neutron generator.

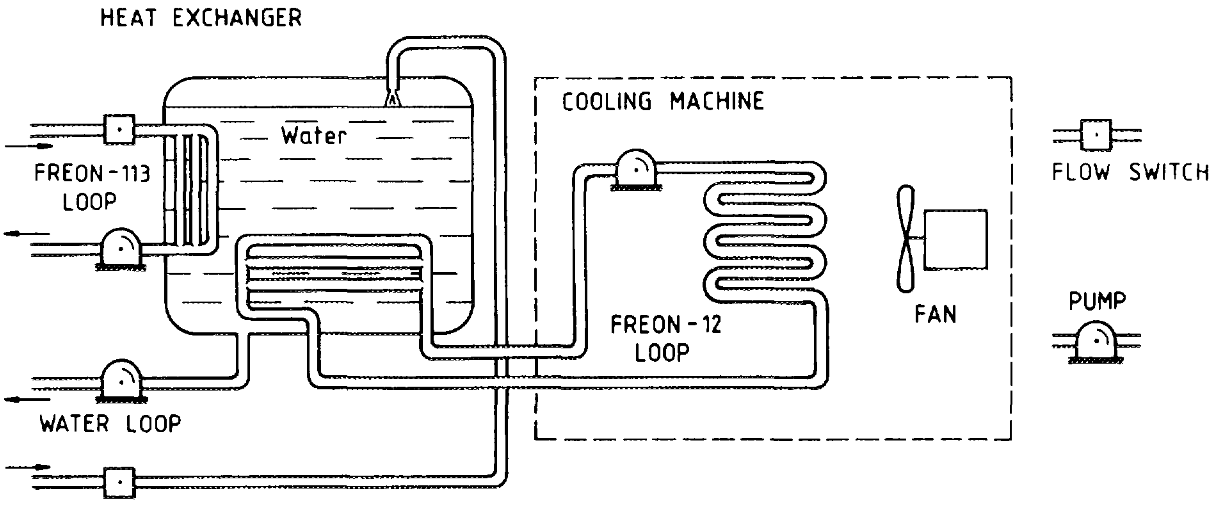
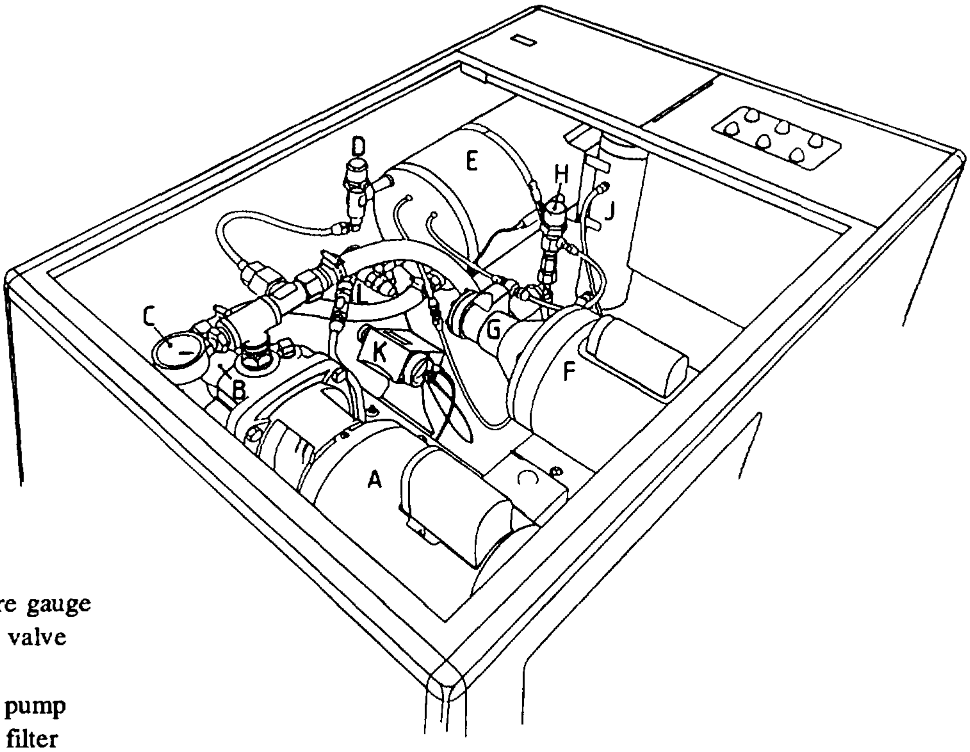


Fig.142 *Schematic diagram of the* **KAMAN** *cooling unit*



A: water pump
B: water filter
C: water pressure gauge
D: water bypass valve
E: water sump
F: FREON 113 pump
G: FREON 113 filter
H: FREON 113 bypass valve
J: FREON 113 sump
K: temperature control (RAMCO)
L: liquid-eye sight glass

Fig.143 *Location of the main components of the* **KAMAN** *cooling unit*

15.1.1 Maintenance

The smooth operation of the cooling system and the neutron generator requires regular daily and monthly inspection of the coolant levels in the FREON-113 and the heat exchanger water sumps. The lost of FREON-12 in the cooling machine can be observed through the liquid-eye sight glass of the compressor. Regular inspection of the coolant tubing and joints is recommended. The built-in filters and flow switches must be cleaned at monthly intervals depending on working hours and conditions. If a coolant becomes coloured (especially FREON-113) replace it with a fresh one.

The whole system is relatively simple. The cooling machine can be repaired by a technician from a commercial refrigerator or air conditioner service. Troubleshooting and repair of the two-coolant circulating system can be done by the operator of the neutron generator. The location of the main components of the cooling unit is shown in Fig.143.

The monthly maintenance routine - based on the description in the Instruction Manual for the A-711 neutron generator, KAMAN, February 1976 edition, is as follows:

I. Ion source cooling loop

- Check the FREON-113 filter screen
- Check the flow rate and FREON-113 either monthly, if the atmosphere is humid (rainy season), or at least every three months under normal condition. If FREON-113 becomes contaminated or dirty it should be replaced even sooner. (Don't forget to find the source of dirt and stop it!)
- If necessary, adjust the FREON-113 pump bypass valve for correct flow rate.

II. Target cooling loop

- Clean the water filter screen. If the water is extremely dirty and rusty, check the flow rate and change the water. Unless, during regular cleaning of the filter, the screen shows the water to be dirty and rusty, it is not necessary to drain and refill.
- Check the water pressure. If necessary, adjust the water pump bypass valve.
- Check the temperature rise of the cooling water during operation of the neutron generator.

III. Check the oil level in the compressor of the cooling unit.

NOTE: During all these maintenance procedures, the main power cable is disconnected from the junction box as a safety precaution to prevent inadvertent energizing of the system while the personnel are working on the equipment. The maintenance operator should hang a "DO NOT SWITCH ON" board on the control console of the generator. There is no possibility of neutrons being generated when the main power cable to the central control console is disconnected.

The test of the cooling unit should be carried out after maintenance with the service jumper cable, without switching on the whole neutron generator. The maintenance procedure should follow the instruction in the Manual of the given neutron generator.

The normal flow rates of the coolants of the cooling system (they should be measured periodically) are:

FREON-113: 2 gallons/min (8.9 l/min)
WATER : 7.5 gallons/min (28 l/min)

The temperature of the water in the water sump after 40-60 minutes of operation is $5^{o}C$ or $40^{o}F$.

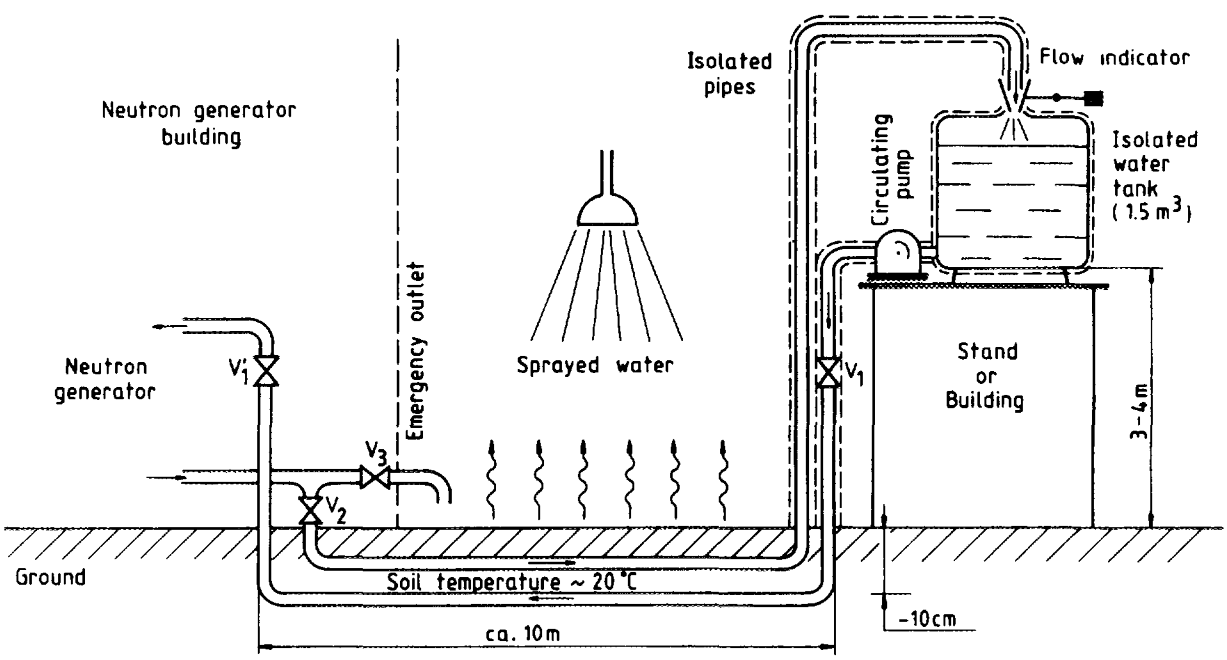


Fig.144 *Closed circuit water cooling system with buried soil-cooled pipes*

15.2 CLOSED CIRCUIT COOLING SYSTEM WITH SOIL HEAT EXCHANGER

A simple closed circuit water cooling system can be constructed in tropical and subtropical regions with a heat exchanger, consisting of two water pipes buried in the soil, taking advantage of the cooling down of the soil due to the evaporation of the water from the soil. Such a system has been built, tested and utilized at the Physics Department of Chiang Mai University, Thailand [112].

The schematic diagram of the system is shown in Fig.144. The water tank of 1500 litres volume is thermally isolated and placed on the roof of next building. The circulation pump is also placed there and connected to the bottom of the tank. The water pipes are thermally isolated in the air and buried without any isolation in the soil between the neutron generator building and the building housing the tank. The two 1/2" dia pipes were buried 10 cm deep in the normal soil. There was no grass or other plants over the tubes. The temperature of the soil remained always around 20°C even during the hottest days of the dry season, when the temperature of the air rose to 28°C during the night and 39°C during the day. The low temperature of the soil was achieved by spraying the soil with water two or three times a day. Evaporation of water consumes energy, so the drying of the soil cools it down. This "heat exchanger" worked satisfactorily when sprayed with water a couple of times a day. The system also worked satisfactorily during the long working days, without any decrease in pumping speed of a 2000 l/s diffusion pump.

REMARK: As the evaporation of the water from the soil is utilized for chilling the coolant circulated in the closed circuit, the area of the buried pipes should be sprayed with water about one hour before the operation of the cooling system so as to start with water chilled in the soil.

This system has some extra taps in case of emergency. As the neutron generator needs only electric energy, the cutoff of the electric power and the utilization of a diffusion pump require some precautions. The normal flow of the water is detected in the return pipe to the water tank by a flow-actuated switch as shown in Fig.145.

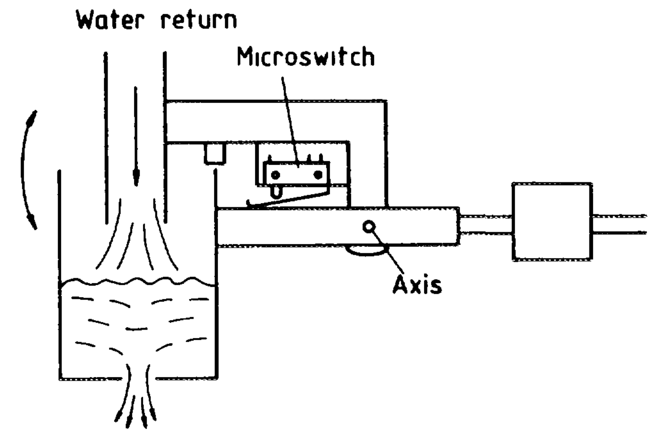


Fig.145 *Water flow detection switch for water cooling systems*

The water from the return pipe of the cooling water loops flows through a hollow cylinder. The weight and pressure of the flowing water pushes down the cylinder and, through it, the contact of a microswitch. The threshold of the switching depends on the water flow rate of the coolant and it can be adjusted by the balancing weight of the lever. The tank of the cooling water should be protected against dirt with a filter mesh.

In case of emergency (cutoff of the electric power), when the diffusion pump needs further water cooling, the water can flow through the circulation pump owing to the height difference between the tank and the diffusion pump. In this case the operator of the system should close the V_2 valve in the return leg and open the emergency water outlet periodically by the valve V_3 (see Fig.144). Depending on the water consumption of the diffusion pump, the water should be removed from the diffusion pump every 2-3 minutes. The cooling time of the diffusion pump is about 30 min. This means that the V_3 valve should be opened and closed 10 times for about 20-30 seconds. Using a fast cooling loop around the diffusion pump, in case of emergency the cooling down of the diffusion pump will be faster, and water consumption from the tank will be less.

16. PNEUMATIC SAMPLE TRANSFER SYSTEMS

A pneumatic transfer system is required to transport samples between the irradiation and measuring sites. Such systems are used for activation analysis by reactors or by intense radioactive neutron sources (Cf,AmBe,PuBe,etc). In a reactor, the neutron field is homogeneous, while for neutron sources or neutron generators in a nonmoderated arrangement, the irradiation is carried out by point sources. These two cases are demonstrated in Fig.146.

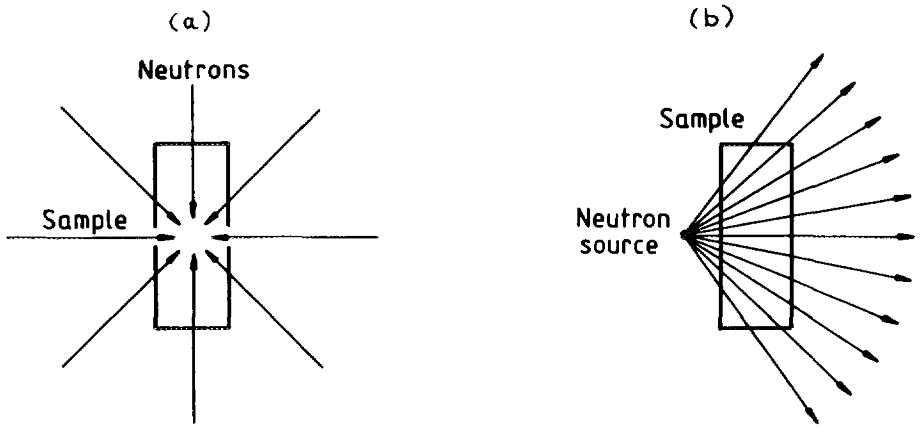


Fig.146 *Irradiation of samples in isotropic and nonisotropic neutron fields*
(a) Reactor irradiation of thin, nonabsorbing sample in an isotropic neutron field
(b) Irradiation of a scattering-free sample in a neutron field produced by a point source

For a reactor, the average activating flux depends on the flux distortion and self-absorption caused by the sample, while for a point source of fast neutrons the average fluence is determined by the source-sample geometry. In addition to the geometry, the neutron attenuation in a thick sample can influence the activity distribution, demanding a careful evaluation of the measured gamma-line intensities. Therefore, during irradiation and measurement, the cylindrical samples are rotated around two axes perpendicular to each other. This solution is used at the KAMAN twin tube pneumatic system. Unfortunately, this method requires complicated sample holders at the irradiation and measuring sites. In the case of periodical irradiation and measurement (required for short half-life isotopes) the positions can change randomly, resulting in an average value for the activity. A proper pneumatic transfer system for activation analysis with neutron generators should be a twin tube with:

a) Sample rotating system for cylindrical samples, or
b) Rectangular tubes for disc shaped samples (irradiated in the direction of the axis of the sample) which do not need rotation of the sample,
c) Neutron production (e.g. ion source) switch on and off facility,
d) Accurate time controller for the irradiation and measurement,
e) Sample position detectors at the irradiation (neutron generator) and measurement (gamma detector) side, and a
f) Loading (ejecting) port for the samples.

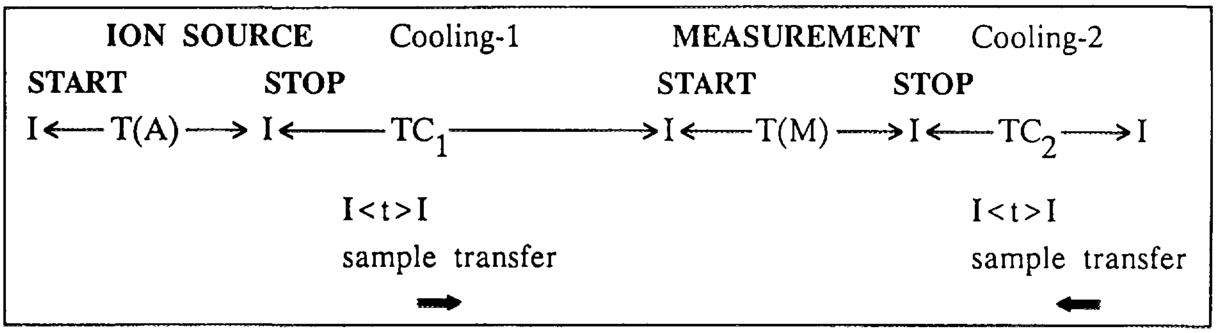


Fig.147 *Timing diagram of a pneumatic sample transfer system for periodic irradiation and measurements*

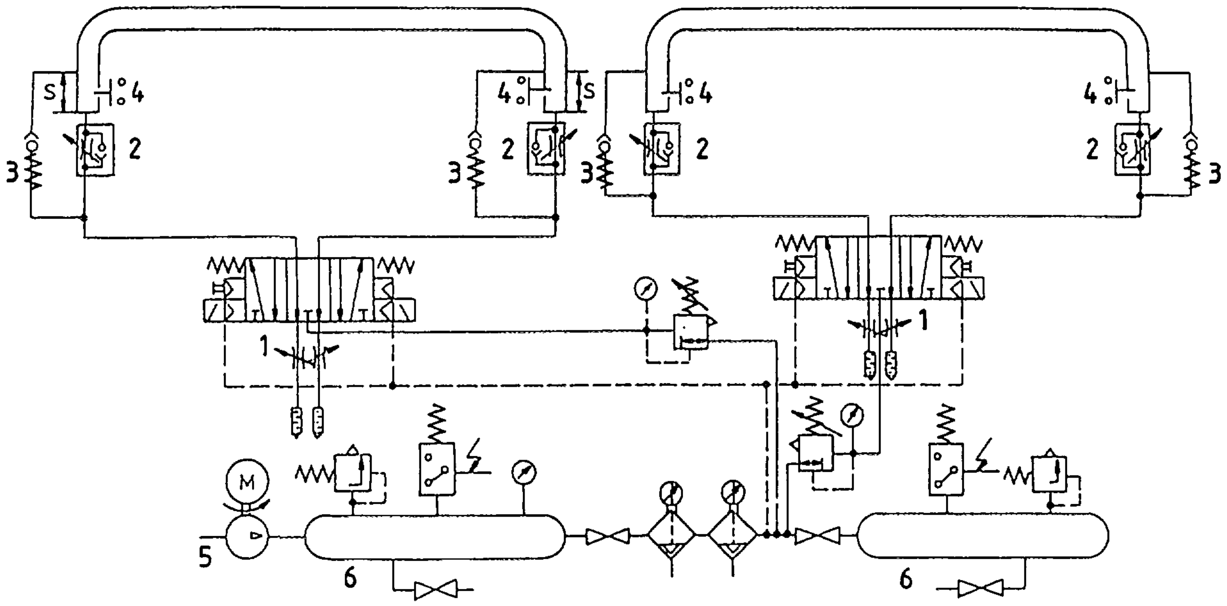


Fig.148 *Twin rectangular tube pneumatic transfer system for activation analysis by neutron generator*

The time programmer should ensure the change of the irradiation cooling and measuring times in a wide range. A typical cyclic timing diagram of a pneumatic sample transfer system is shown in Fig.147. The cycle starts with the activation time TA, followed by the first cooling TC_1, measuring TM and the second cooling TC_2 times [113].

The schematics of a pneumatic transfer system with twin rectangular tubes, developed for the special requirements of activation analysis with neutron generators, are shown in Fig.148.

The two separate rectangular tubes transporting the sample and the standard sample are controlled by two electropneumatic valves (1). The slowing down or breaking of the samples at the irradiation or detector position is carried out by the valves (2) and (3). These valves ensure the "soft" arrival of the samples in the irradiation or measurement positions. The microswitches (4) detect the arrival of the samples in the correct positions. The compressed air supplied by the compressor (5) is buffered by the buffer tank (6). The whole system [114] is controlled by a microprocessor controller. The timer-controller can be made from a parallel input/output card of a personal computer or other independent industrial timer.

17. NANOSECOND PULSED NEUTRON GENERATORS

The nanosecond bunching of steady deuteron beams for the production of short 14 MeV pulses can be done before or after the acceleration. Two typical systems will be described here: a pre- and a post-acceleration bunched neutron generator. A description of the principles of their operation is far beyond the scope of this Manual.

17.1 PRE-ACCELERATION NANOSECOND BUNCHED ION BEAM NEUTRON GENERATOR

The block diagram of a pre-acceleration bunched nanosecond neutron generator is shown in Fig.149 [115]. This neutron generator has the following characteristics:

- Average neutron output: $< 10^9$ n/s
- Neutron yield in pulses: 4×10^{10} n/s
- Average target current: 10-30 μA
- Beam diameter: 8 mm
- Beam current during the pulses: > 1 mA
- Acceleration voltage: maximum 300 kV
- Target on the acceleration high voltage
- HV power supply: single wave Cockcroft-Walton circuit
- Ion source: RF (200 W push-pull oscillator)
- Extraction voltage: 0-15 kV
- Focus voltage: 0-20 kV
- Gas consumption of the ion source: 4-5 ml/hour NTP D_2
- Vacuum system: 1200 l/s oil diffusion pump with booster, 20 m/h mechanical duplex pump, liquid nitrogen trap
- Final vacuum: $< 2 \times 10^{-6}$ mBar with liquid nitrogen trap
- Pulsing: twin gap klystron bunching with chopper and selector plates and X steerers
- Compression factor: > 10
- Pulse width of the neutron pulses: ~ 1 ns
- Repetition rate of the neutron pulses: 1.25 - 10 MHz
- Target holder: 0.3 mm aluminum tube with aluminium backing TiT target
- Target cooling: by compressed air
- Power consumption of the generator: ca. 5 kVA
- Water consumption of the vacuum system: ca. 5 l/min
- Compressed air consumption: ca. 5000 l/h

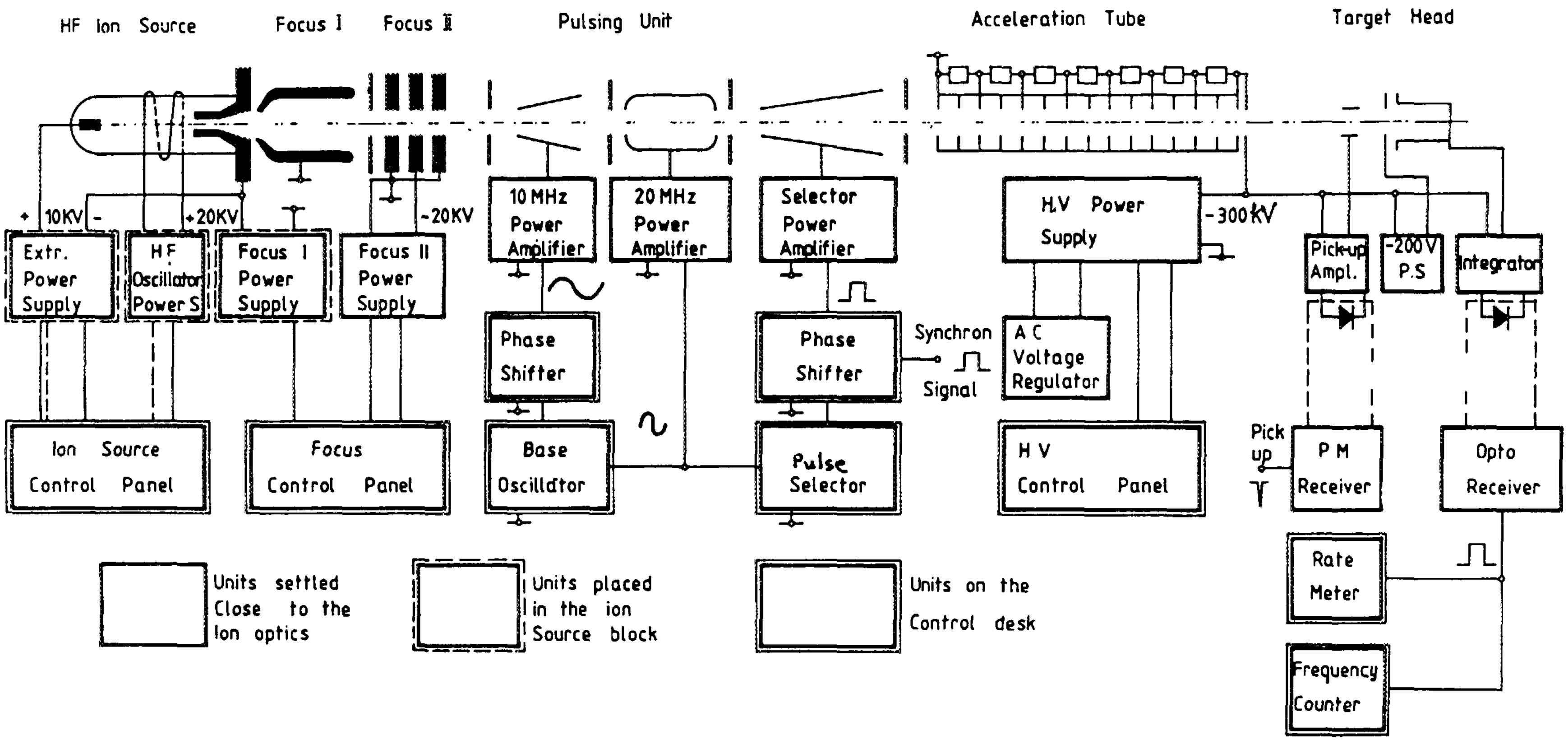


Fig.149 *Block diagram of a pre-acceleration nanosecond pulsed neutron generator*

The peculiarity of this generator is that the target is placed at the high voltage. As the shadow bar and the neutron detector or gamma detector in time-of-flight measurements should be placed at a certain distance from the sample, and may be placed also at the acceleration high voltage, the benefit of this system is the easy pulse control of the extracted and pre-accelerated deuteron beam. The use of the deuteron beam pulse pick-up signal needs optical insulation. The target current is similarly converted into frequency and optically connected to the integrator placed at the ground potential.

As the beam chopper, the beam buncher and the selector electrodes are at the ground potential, the ion source is floating at the voltage of the first focus (pre-accelerating) power supply. This focus lens is an immersion type cylindrical lens , focusing the extracted and pre-accelerated deuteron beam through the main vacuum manifold into the entrance of the second Einzel focus lens. The Focus-II unit consists of three diaphragms with a short focus. This lens focuses the deuteron beam into the twin gap buncher. The chopper-steerer deflector plates (two pairs) in front of the buncher chops the steady deuteron beam with a frequency of 10 MHz. The position of the beam can be controlled by the UD_1 and UD_2 steering voltages. The second deflector plate pair deflects and chops the pre-accelerated deuteron beam - whose energy is determined by the sum of the extraction voltage and the voltage of the first focus electrode. As the chopping frequency is 10 MHz, the buncher electrode works at a 20 MHz frequency. The phase control between the 10 MHz and 20 MHz signals is made in the pulse control unit. As the energy of the pre-accelerated deuteron beam is relatively low, the diaphragm between the chopper and the buncher electrode does not need any extra (water) cooling. This diaphragm is made of stainless steel and its chopper side is covered by a titanium sheet. Similarly, a titanium sheet covers the selector side of the post-selector diaphragm. The pulses of the bunched 20 MHz repetition rate ion beam can be selected at 1.25 - 10 MHz. As this selection is controlled by normal frequency dividers and phase shifting units, the additional use of a pseudo-random pulse selecting unit is easy [116].

The geometry of the ion optical system of this nanosecond pulsed accelerator is shown in Fig.150. The first focus lens was necessary to get pre-accelerated deuteron beam (and to decrease the ion beam scattering of the residual vacuum along the 80 cm long path in the main vacuum manifold). The Einzel lens - as it does not change the energy of the focused beam - easily focuses the pre-accelerated deuteron beam into the chopper-buncher-selector-acceleratortube ion optical line.

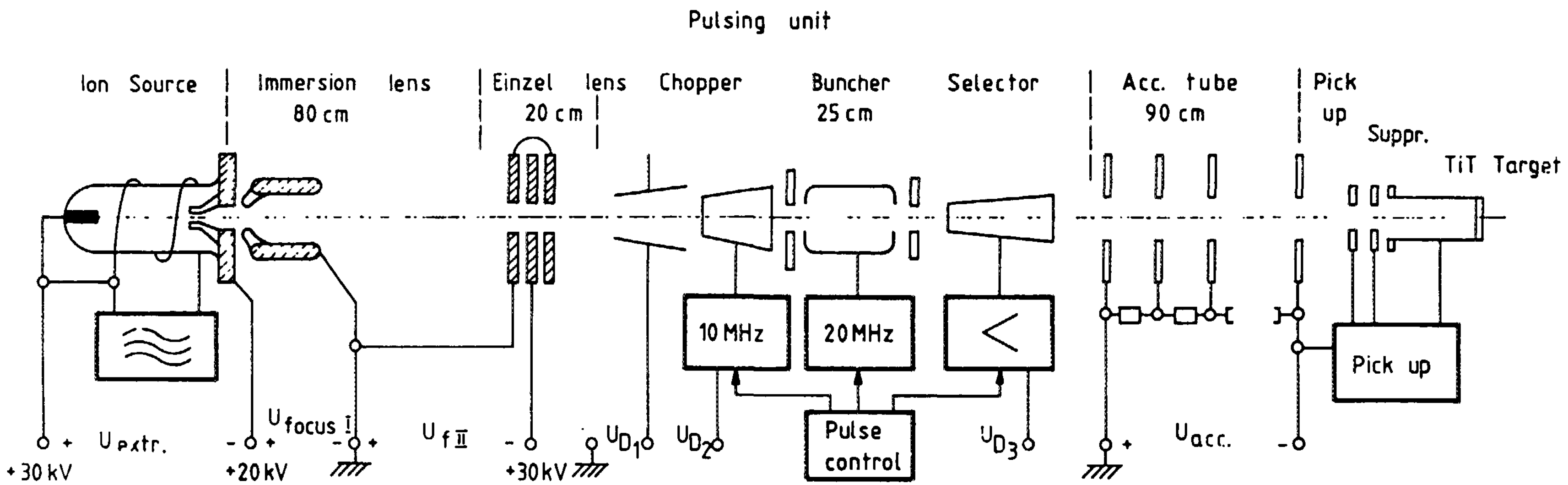


Fig.150 *Geometry of the pre-acceleration bunched nanosecond neutron generator*

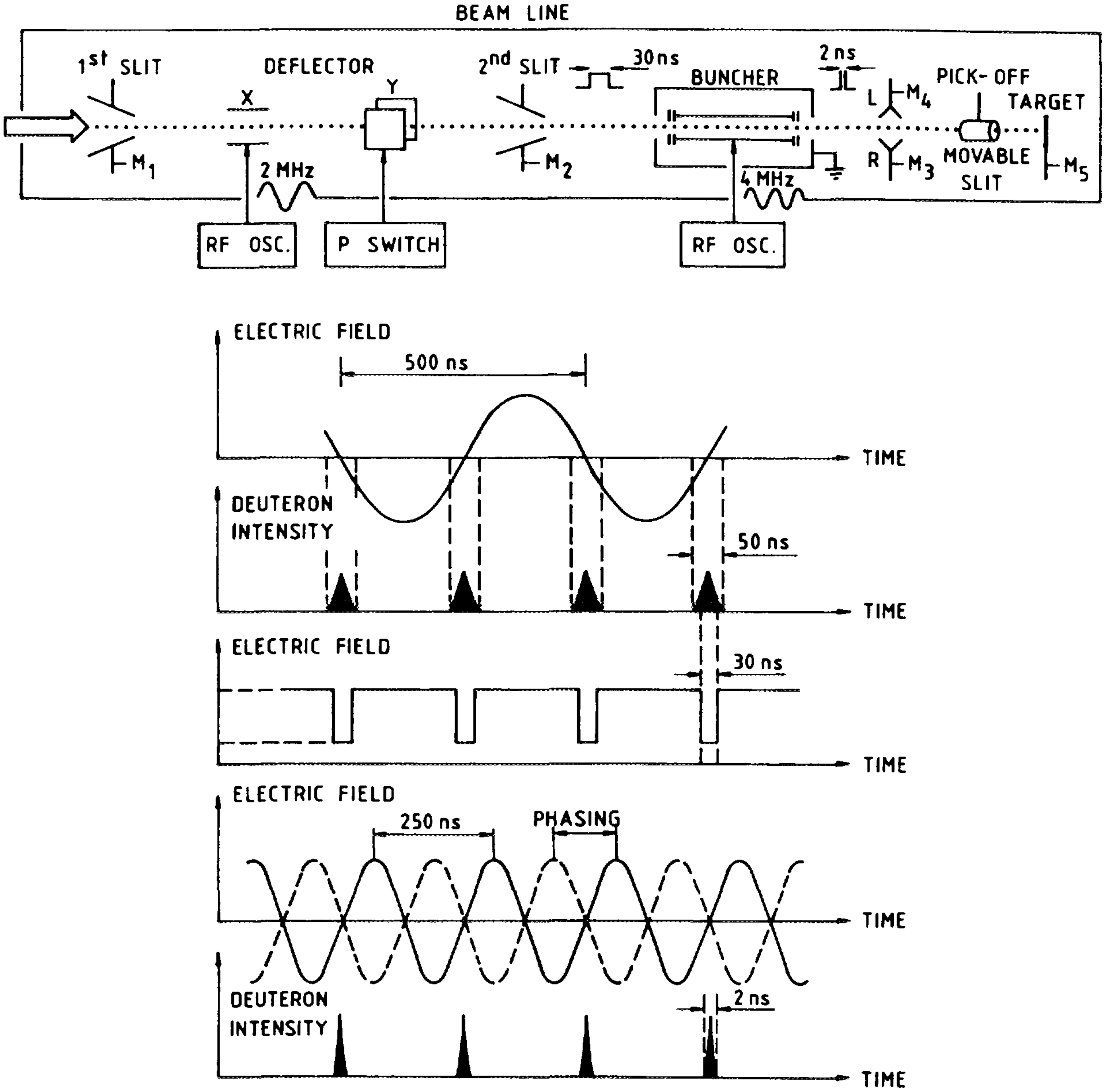


Fig.151 *Typical post-acceleration klystron bunched neutron generator based on a commercial neutron generator*

17.2 POST-ACCELERATION KLYSTRON BUNCHING OF A COMMERCIAL NEUTRON GENERATOR

A post-acceleration klystron bunching nanosecond neutron generator was constructed in Chiang Mai (Thailand) based on a commercial SAMES J-25 neutron generator. The extracted and accelerated beam is chopped by a 2 MHz electrostatic deflector and bunched by a 4 MHz two-gap klystron. The schematic representation of the post-acceleration nanosecond pulsing is shown in Fig.151. The operation of the system is shown by the corresponding waveforms [117].

The 150 keV energy - previously selected - deuteron beam enters the bunching section of the generator through the first water cooled slit. The horizontal de-

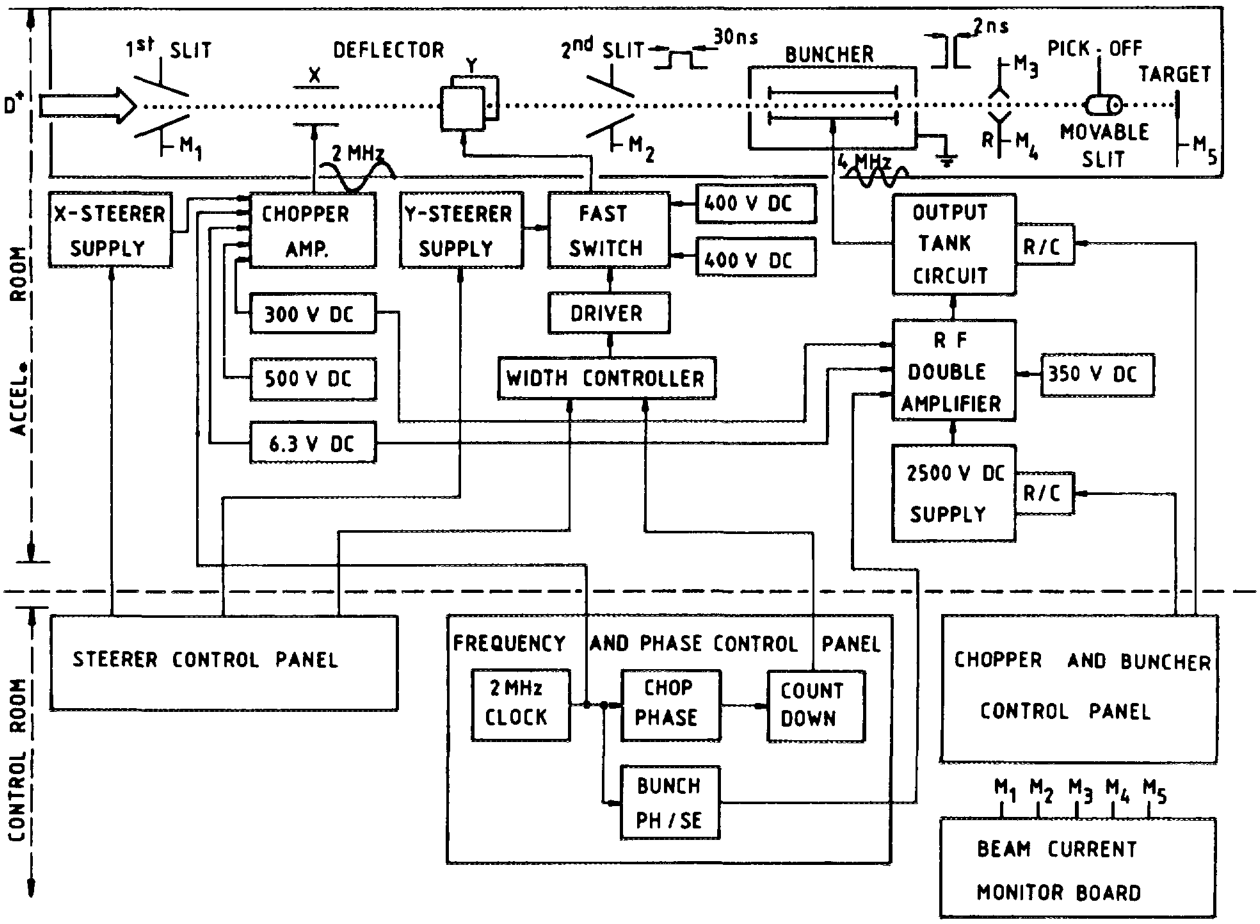


Fig.152 *Block diagram of klystron bunched J-25 neutron generator*

flector plates chop the deuteron beam by 2 MHz sinusoidal voltage ((a) in Fig.151). The selection of the pulses, by changing the repetition frequency, is carried out in front of the klystron buncher by the second vertical deflection pairs. The horizontal deflection results in about 50 ns wide triangular pulses (b). These deuteron pulses are selected by the Y deflector plates (c). The deflected pulses hit the second slit in the beam line before the two-gap klystron. The klystron itself works at a frequency of 4 MHz (d) and bunches the chopped deuteron beam onto the target. The deuteron pulses of 2 ns width (e) are detected by a capacitive pick-off electrode in the vicinity of the target [118].

The steering of the deuteron beam is solved by additional steering voltages on the deflector plates X and Y. The control of the nanosecond mode of the neutron generator is monitored by oscilloscopic observation of the M_2 , M_3 and M_4 slits. The pulse forms give good information on the problems related to the operation of the system. A block diagram of the nanosecond pulsing of this J-25 commercial neutron generator is shown in Fig.152. The horizontal dashed line divides the block diagram into the accelerator hall and the control room. The beam current and beam monitor panel is the unit where the beam shapes and beam currents at the diaphragms and at the target are monitored.

18. THE ASSOCIATED PARTICLE METHOD

The associated particle method (APM) is widely used for determination of the absolute neutron emission rates and to ensure the electronic collimation of the neutron beam in TOF (time-of-flight) and other coincidence measurements. The alpha particles emitted in the $^{3}T(d,n)^{4}He$ reaction are detected in a well defined solid angle around a given emission angle to the incident deuteron beam, the error in the neutron yield being minimized for an alpha detector placed at 90° to the deuteron beam. In this geometry the spread in the neutron energy is the lowest. Generally, a surface barrier Si detector is used to detect the alpha particles.

In the case of a fast charged particle detector (usually thin plastic scintillators) the timing feature is excellent to give the start signal in TOF measurements, and the solid angle of the alpha detector - due to the reaction kinematics - will determine a coincidence cone of the fast neutrons from the target. These fast neutrons will be utilized later as the primary neutrons for the study of neutron induced reactions.

A typical APM target head - utilized at a commercial neutron generator - is shown in Fig.153. The deuteron beam is collimated and focused on the target and the alphas are detected by a scintillation detector. The scintillation detector foil (0.05 mm thick NE 102A) is mounted inside the target chamber, while the photomultiplier is optically connected by a light-guide Perspex cone. The solid angle in which the coincidence 14 MeV neutrons can be detected is also indicated [119].

The surface barrier (SB) detectors have excellent energy resolution (compared to the scintillators) which allows the measurement of the deuteron or helium buildup within the tritium target. The tritium is radioactive and decays to ^{3}He by beta emission. During one year about 6% of the tritium will be replaced by ^{3}He, causing a background in the associated alpha particle detector from the reaction $^{3}He(d,p)^{4}He$. The energy of the alpha particles from the $^{3}H(d,n)^{4}He$ and $^{3}He(d,p)^{4}He$ reactions are almost the same and can only be separated by a detector of high resolution. Fortunately the reaction on ^{3}He has a resonance at 440 keV, while the reaction on tritium is at 110 keV. On the other hand, the ^{3}He particles can escape from the target, depending on the temperature. At about 400 keV incident deuteron energy (this is not rare at neutron generators) the cross sections of the two processes become equal, which can cause large errors in the determination of the neutron yield if this effect is neglected [120].

For a 400 kV neutron generator using a one year old tritium target, an excess count of about 6% will come from the helium reaction. As the energy of the

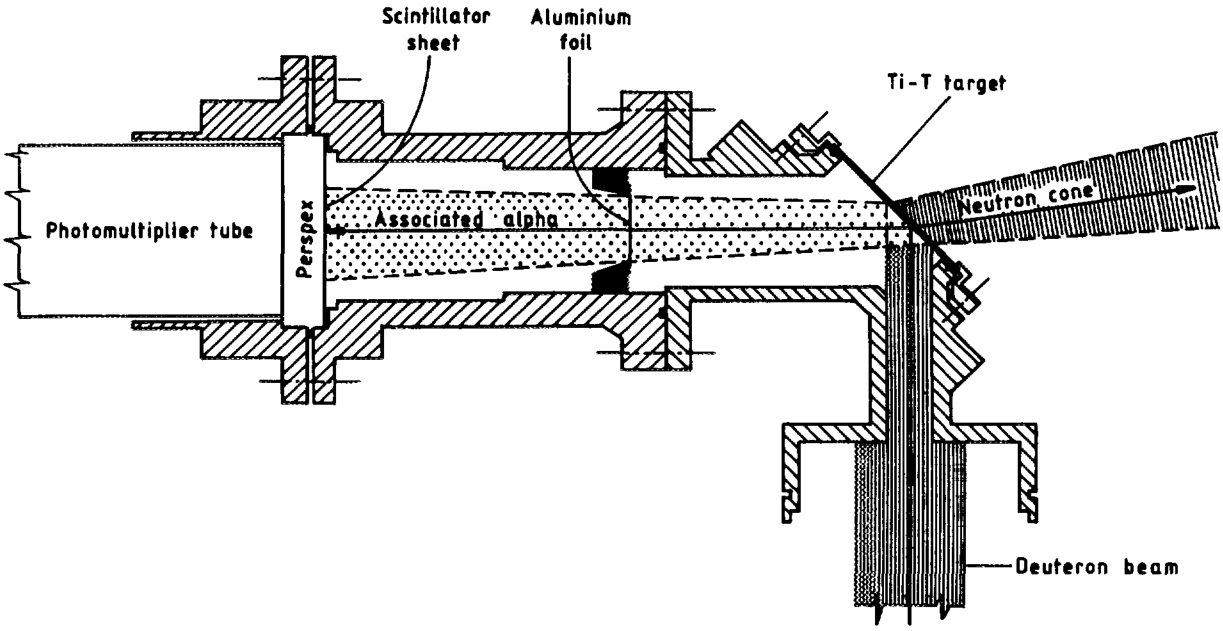


Fig.153 *Associated alpha particle target head using thin plastic scintillation detector*

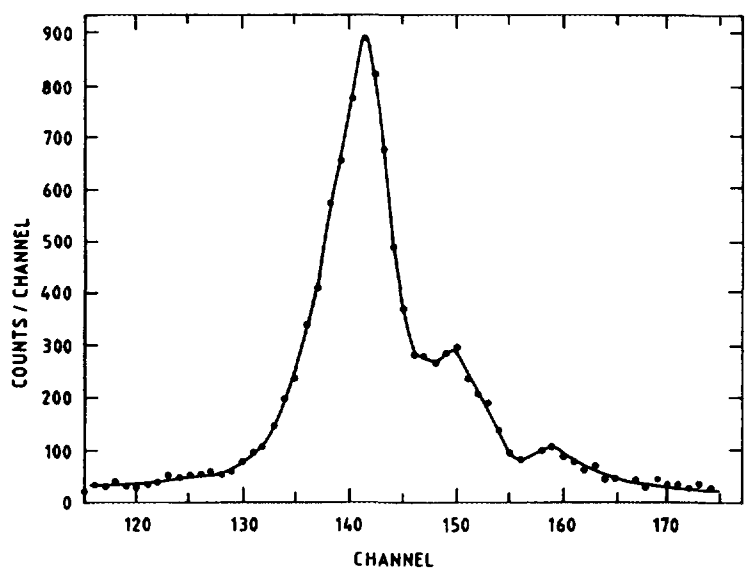


Fig.154 *Associated alpha particle spectrum showing effect of the* $^3He(d,p)^4He$ *and* $^2H(d,p)^3H$ *reactions*

incident deuteron energy is lowered the effect is reduced, but even at energies of 200 keV in a fairly new target this kind of error could result in an uncertainty of 0.5 %.

Fig.154 shows an associated particle spectrum around the alpha peak for an old tritium target at 400 keV bombarding deuteron energy. Peaks 1 and 2 correspond to the alpha particles from the ^{3}H and the ^{3}He reactions. Peak 3 is the result of the proton buildup from the ^{2}H(d,p)^{3}H reaction. The energy difference of the two alpha peaks is about 350 keV but the energy resolution of the detector does not allow a better separation [120].

18.1 SELF-TARGET FORMATION BY DEUTERON DRIVE-IN

The associated particle target head with semiconductor detector is a good tool for studying the buildup of the deuterons in the target and the beam aperture materials. The presence of the self-target will contaminate the 14 MeV neutron spectrum through the D-D reaction. A sketch of an APM target head - made for the study of self-target formation and (with plastic scintillators) time-of-flight measurements - is shown in Fig.155.

Based on an APM head, the neutron yield and contamination of the D-T neutron spectrum can be determined by observation of the charged particle spectrum. The charged particle spectrum measured by a surface barrier semiconductor detector can give information on the condition of the tritium target and the background neutrons. A typical APM spectrum is shown in Fig.156, which shows the

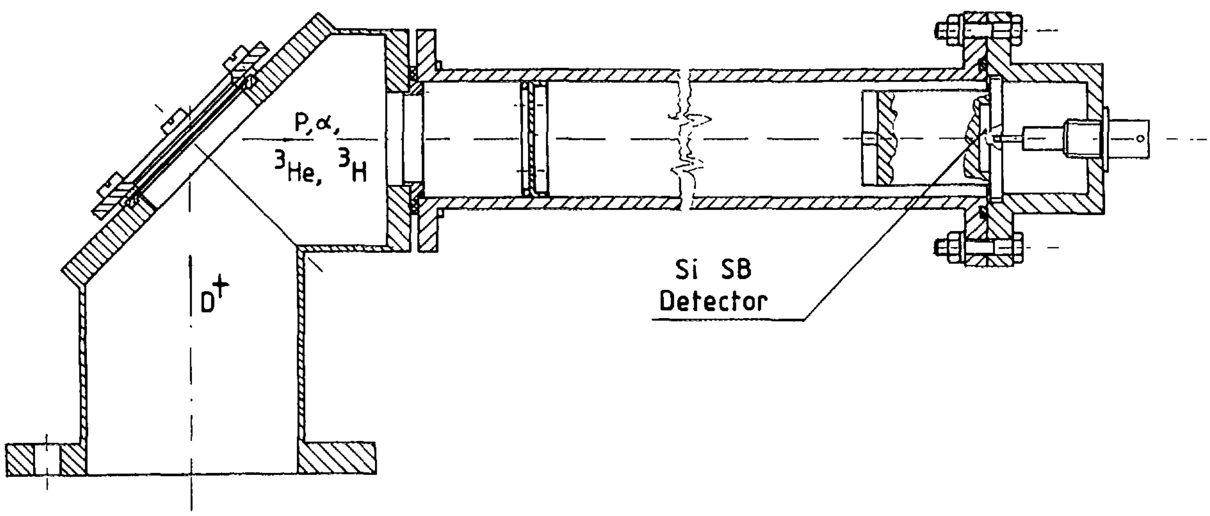


Fig.155 *Associated particle target head used for self-target formation and fast neutron time-of-flight spectrometry*

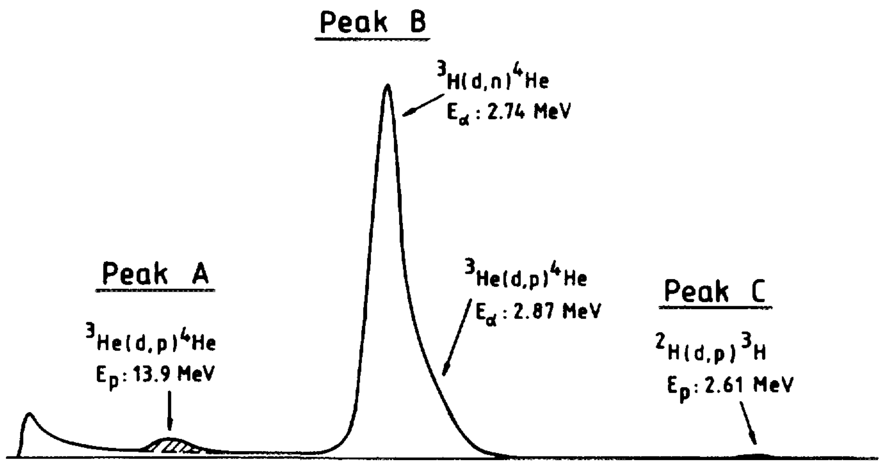


Fig.156 *Typical pulse height distribution of the charged particles detected by surface barrier detector using APM target head*

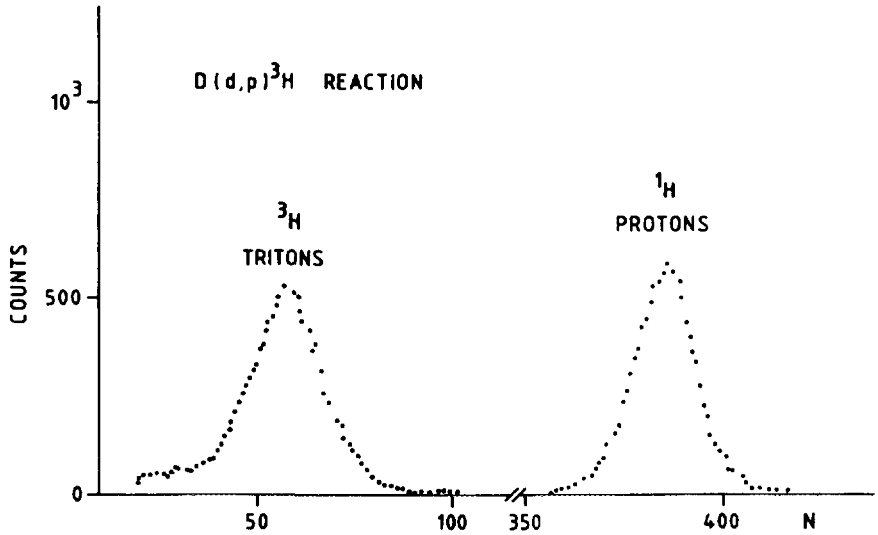


Fig.157 *Charged particle spectrum measured by APM from the $^2H(d,p)^3H$ reaction*

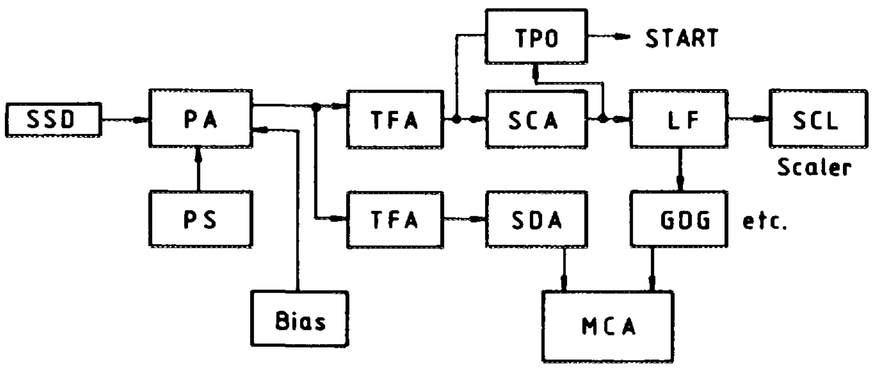


Fig.158 *Block diagram of the electronics needed for studies with a simple associated particle target head*

peaks of the alpha particles and protons from the $^{3}H(d,n)^{4}He$, $^{3}He(d,p)^{4}He$ and the $^{2}H(d,p)^{3}H$, $^{3}He(d,p)^{4}He$ reactions, respectively. The tritons originating from the D-D reaction can be observed at low channel numbers [121].

Observation of the peak A gives a possibility for correction of the counts detected in the peak B originating from the alphas. The peak of the protons from the $^{2}H(d,p)^{3}H$ reaction gives a good possibility to monitor the amount of drive-in deuterons in the tritium target. The charged particle pulse height spectrum from D-D reactions is shown in Fig.157.

The electronics of the APM technique depends on the purpose of the measurement. For monitoring or self-target buildup studies, a simple linear amplifier line shown in Fig.158 can be utilized. The MCA can be replaced by a single channel analyzer and a counter for recording the alpha particles and protons from the $^{3}H(d,n)^{4}He$ and $^{2}H(d,p)^{3}H$ reactions, respectively.

An electronic system required for producing the start signal at TOF measurements is presented in Fig.158. This system can also be used for monitoring.

19. NEUTRON MONITORS

Monitoring the neutron yield of neutron generators during the irradiation of samples is important for determination of nuclear cross sections or in activation analysis. The neutron field can be monitored by:

a) Alpha particle detection, using the associated particle method;
b) Proton recoil detector (e.g. hydrogen filled proportional counters, organic scintillators, etc);
c) Long counter;
d) Fission chambers.

Monitoring neutron production by alpha particles has been treated in the pre-previous section. The use of a proton recoil detector is not discussed in this Manual, but it is treated in Refs [1,2,123].

19.1 MONITORING BY LONG COUNTER

The long counter is the simplest neutron monitor, with a flat-shaped energy efficiency curve in a wide energy range. These broad, flat energy efficiency curves allow easy absolute calibration by a standard neutron source. As the long

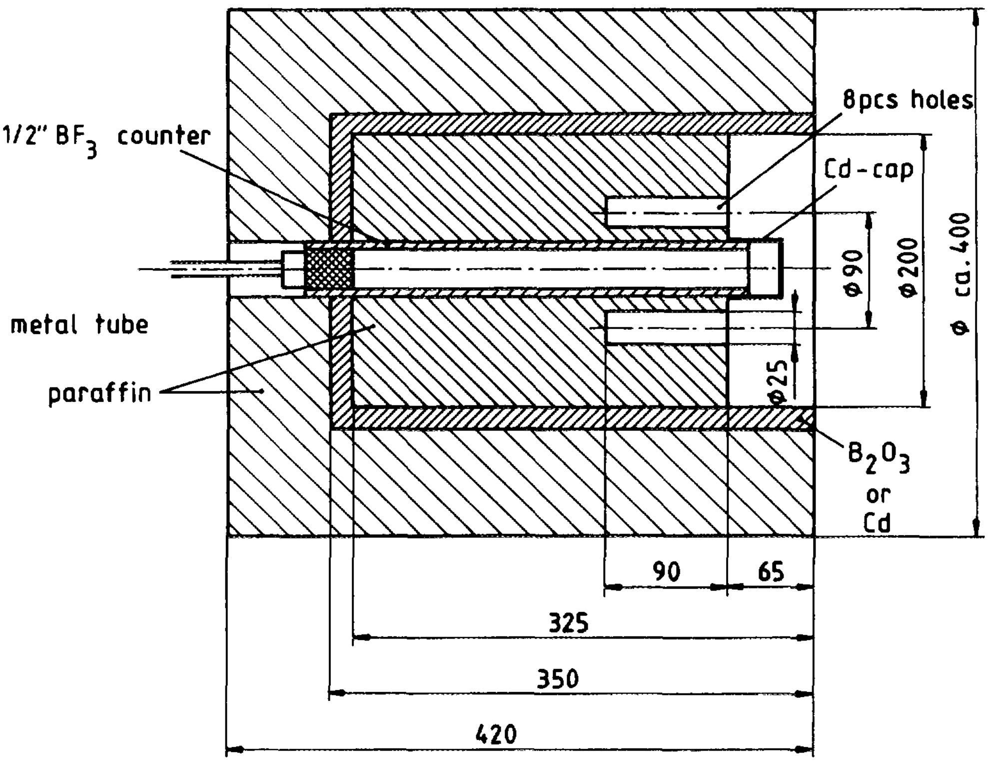


Fig.159 *Schematic diagram of a long counter (sizes in mm)*

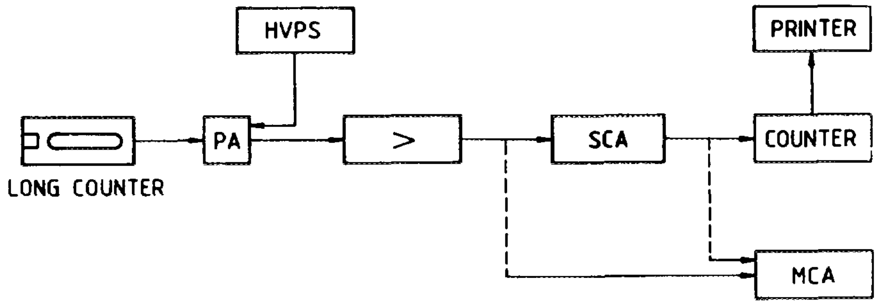


Fig.160 *Electronics for a neutron long counter*

counter detects the neutrons by the $^{10}B(n,\alpha)^{7}Li$ reaction (after thermalization), the pulses from the gamma rays associated with the neutron field can be well separated. The long counter is a direction-sensitive detector; its construction is shown in Fig.159 [122].

The setup of a long counter's electronics is shown in Fig.160. As can be seen in Fig. 160, setting the optimal discrimination level can be helped by a multichannel analyzer. For monitoring and recording the neutron flux, a multichannel analyzer may be used in the multiscaler mode [123].

The mechanical construction of a long counter depends on the neutron moderator material. In the case of polyethylene or similar good machineable materials containing high concentrations of hydrogen, the internal cylinder and the external shield can be machined by lathe.

19.2 FISSION CHAMBER MONITORING

The fission chamber is a cheap and reliable piece of equipment for recording fast neutrons through the detection of fission fragments from the fission of ^{232}Th or ^{238}U. Thorium dioxide or uranium tertafluoride layers 0.2 mg/cm^2 thick and 15-20 mm dia are used. The chamber shown in Fig.161 was constructed from a thin-wall aluminium cosmetic cream box. The pressure of the counting gas (methane or argon) is just slightly over the atmospheric pressure [124].

The pressure in the fission chamber can be regulated by a regulator valve. The thin wall aluminium box is simply sealed by self-adhesive tape. The gas inlet and outlet tubes are thin polyethylene tubes. The detection of counting gas flow and over-pressure is carried out by a small silicon oil bubbling glass vessel.

The height of the silicon oil in the vessel is about 2-4 cm. With methane, the exhaust of the fission chamber should be led outside to prevent the formation of an explosive methane-air mixture. The collector is a well polished thin metal disc held by a metal rod soldered to a high voltage BNC socket. The usual voltage applied to the fission chamber through the simple preamplifier is about 600 V.

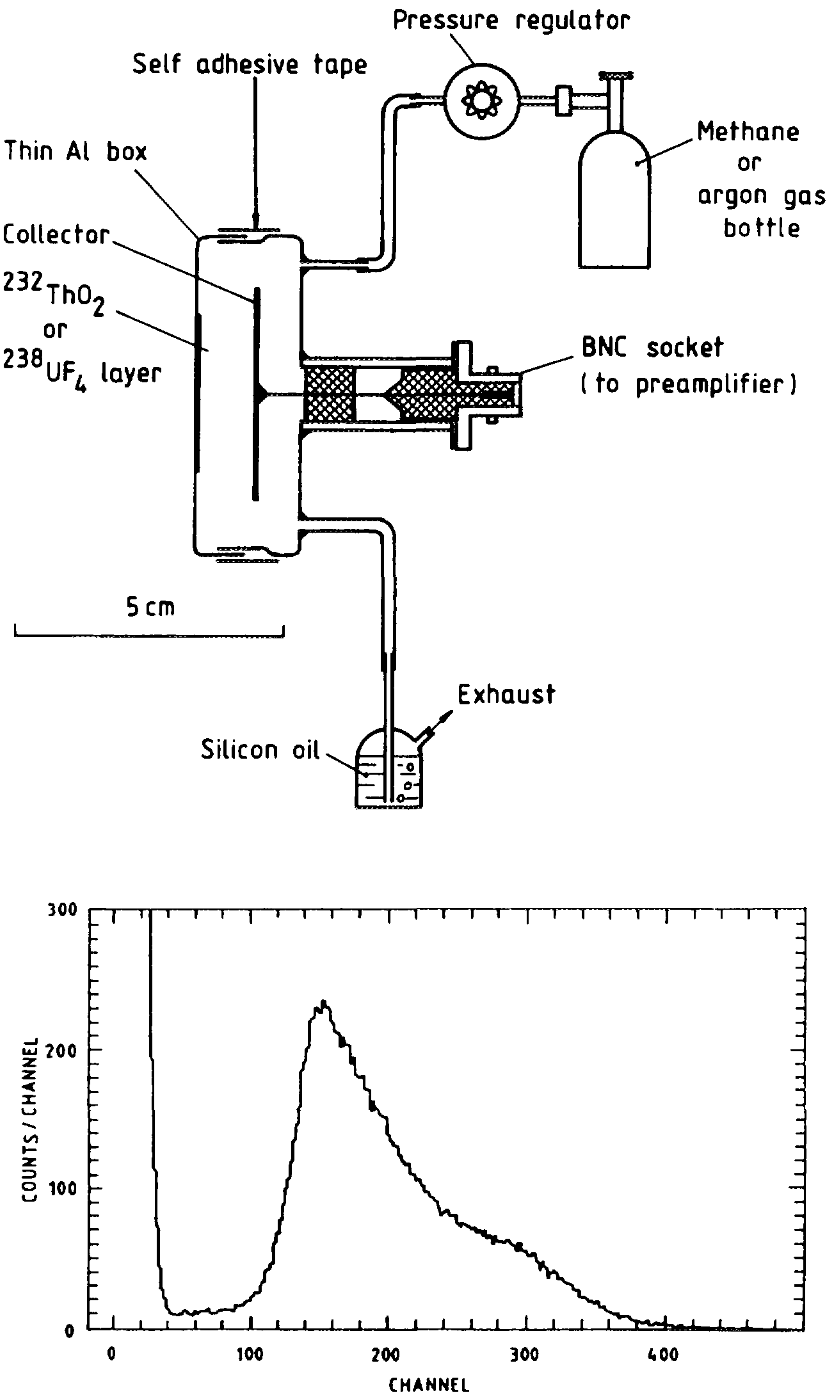


Fig.161 *Schematics of a fission chamber and typical pulse height distribution of the fragments*

The insulating feedthrough is made of Teflon (PTFE) or similar good insulator. The whole monitor counter consists of the fission chamber, preamplifier, high voltage power supply, main (spectroscopy) amplifier, multichannel analyzer and single channel analyzer-counter. For longer irradiations a monitor counter with time-programmed printer or MCA in multiscaling mode is recommended. A typical pulse height distribution of the fragments is shown in Fig. 161.

If the shape of the fission fragments spectrum has changed, check the over-pressure in the detector box. The bubbling gas flow indicator indicates the proper pressure in the chamber. If there are no bubbles, check the built-in manometer of the gas cylinder. If the cylinder is not empty, the manometer shows over-pressure. Close the polyethylene tube (by a clip) between the fission chamber and the regulator and check the leak in the fission chamber or between the chamber and the bubble vessel.

20. SAFETY: HAZARDS RELATED TO NEUTRON GENERATORS

The main sources of hazards related to the operation, maintenance, trouble-shooting and repair of neutron generators are as follows:

Neutron and X-ray radiation;
Open radioactive source (tritium);
Residual radiation of the neutron-irradiated construction materials;
High voltage power supplies for ion source, extraction, focus and acceleration;
Mains voltages;
Pneumatic pressure vessels and tubes;
Vacuum vessels and chambers;
Poisonous gas (SF_6) pressure;
Flammable deuterium gas (D_2);
Flammable insulating transformer oil.

20.1 Radiation hazard

Maintenance and repair of neutron generators must be performed either by personnel trained by the manufacturers or other by experts in high vacuum and high voltage techniques and in handling tritium.

In designing the shielding, consideration should be given to the fact that radiation levels from neutrons as high as 2 Sv/h (200 rem/h) are common at 1 m from a neutron generator [107].

The shielding material for a laboratory often costs as much as or more than the actual neutron generator, and care is needed in designing a building to house such equipment. The maximum recommended weekly dose to personnel for all types

Table 20.
Maximum permissible neutron fluxes and fluences to personnel

E_n(MeV)	Flux (n/cm^2 s)	Fluence (n/cm^2)
Thermal neutrons	268	38.8×10^6
0.1 MeV neutrons	32	4.8×10^6
0.2 MeV neutrons	8	1.16×10^6
10-30 MeV neutrons	4	6.0×10^5

of radiation is 4×10^{-4} Sv/40 h (40 mrem/40 h) or 1.0×10^{-5} Sv/h (1.0 mrem/h). Particle fluxes (n/cm^2 s) equivalent to 1.0×10^{-5} Sv/h and fluences (n/cm^2) delivering 4×10^{-4} Sv are given in Table 20.

The maximum recommended dose for the public is 0.5×10^{-6} Sv/h; that is, about 0.2 n/cm^2 s. Neutron generators can produce 3 MeV and 14 MeV neutrons in D-D and D-T reactions, respectively. The yield of D-D reaction is lower than that of D-T by a factor of 100, and the energy of neutrons is also lower for D-D. Therefore, shielding should be constructed for a radiation hazard of 14 MeV neutrons. The flux of neutrons is given by the following expression:

$$\phi = \frac{S}{4\pi R^2} e^{-\Sigma x} \tag{48}$$

where S is the source intensity (e.g. 2.5×10^{11} n/s), R is the distance between the source and the given point where the radiation exposure should be determined, x is the thickness of the shielding, and Σ is the removal cross section,

Table 21.
Removal cross sections of shielding materials for fission and 14 MeV neutrons

Material	Fission neutrons		E_n = 14.5 MeV	
	Σ (cm^{-1})	λ (cm)	Σ (cm^{-1})	λ (cm)
Water	0.103	9.7	0.079	12.7
Iron	0.158	6.3	0.112	8.9
Concrete (2.4 g/cm^3)	-	-	0.077	13.0
Concrete (3.5 g/cm^3)	0.094	10.6	0.08	12.5
Barytes concrete (3.5 g/cm^3)	0.095	10.6	0.083	12.1
Ironshot concrete	-	-	0.071	14.3
Gravel (1.83 g/cm^3)	-	-	0.052	19.2
Sand (1.6 g/cm^3)	-	-	0.047	21.3
Brick (1.83 g/cm^3)	-	-	0.048	20.8
Graphite (1.83 g/cm^3)	0.079	12.7	0.058	17.2
Paraffin	-	-	0.071	14.1
Aluminium	-	-	0.063	15.9
Lead	-	-	0.088	11.4

$\Sigma = 1/\lambda$, where λ is the relaxation length of fast neutrons in the shielding material (in Table 21, the removal cross sections are given for some shielding materials). The dose level obtained for a source intensity of 2.5×10^{11} n/s indicates that, at a distance of at least 2 m from the target, an additional 1.5 m wall of concrete (ρ = 2.3 g/cm^3) is needed.

On the basis of the removal cross sections summarized in Table 21, the doses can be estimated both for D-D and D-T neutrons.

The macroscopic removal cross section is given by

$$\Sigma_r = \frac{0.602\sigma_r\rho}{A}\ (\mathrm{cm}^{-1}) \tag{49}$$

where σ_r is the microscopic removal cross section in barns, ρ is the density, and A is the atomic weight. The macroscopic removal cross section for a material comperising several elements is obtained by simple summation over its constituents:

$$\Sigma_{r,}\ \text{compound} = \left(\frac{\Sigma_r}{\rho}\right)_1 \rho_1 + \left(\frac{\Sigma_r}{\rho}\right)_2 \rho_2 + \ldots \tag{50}$$

where $(\Sigma_r/\rho)_i$ is calculated by the data in Table 21 of the i-th compound (cm^2/g), and ρ_i is the effective density of the i-th element (g/cm^3).

Neutrons scattered by air can contribute significantly to the total dose. If a barrier shield were used, air scattering above the source ("skyshine") would contribute more to the dose than to the transmitted radiation. Thus, there is no point in attempting to shield the direct radiation unless skyshine is also reduced by the provision of a shielding roof. The presence of ducts, voids, passageways, and safety doors all require careful consideration in the design of the final facility [1].

Table 22.
Expected levels of induced radioactivity at 10 cm after 1 h of operation with a neutron generator yield of 2.5×10^{11}n/s

Reaction	Exposure rate at 10 cm		
	$\left(\frac{\mathrm{mR}}{\mathrm{h}}\right)$	$\left(\frac{\mu\mathrm{C}}{\mathrm{kg \cdot h}}\right)$	Half-life
^{27}Al(n,p)^{27}Mg	200	52	9.5 min
^{27}Al(n,α)^{24}Na	30	7.7	14.9 h
^{63}Cu(n,2n)^{62}Cu	60	15	9.8 min
^{65}Cu(n,2n)^{64}Cu	60	15	12.8 h

Gamma radiation produced by the scattered and captured neutrons in the shield can contribute significantly to the radiation hazard. Calculation and measurements show that for thick ($\geq$ 1 cm) concrete shields, the gamma dose rate is about half that due to epicadmium neutrons. In water, the gamma dose exceeds the fast neutron dose if the thickness is greater than 75 cm. The prompt gamma emission of 4 to 7.6 MeV from the $^{56}Fe(n,\gamma)^{57}Fe$ reaction is a problem if the shielding contains iron.

The neutron-induced radioactivity of structural materials can become a significant problem. In the air and the cooling water the $^{14}N(n,2n)^{13}N$ and $^{16}O(n,\alpha)^{13}N$ reactions will take place.

Some expected exposure rates at 10 cm following 1 h of operation at 2.5×10^{11} n/s produced by the target material are summarized in Table 22.

Backstreaming electrons can produce bremsstrahlung at the high voltage terminal, with a dose rate of about 600 to 800 mR/h for a nonanalyzed beam. The dose rate of bremsstrahlung can be decreased significantly if an electron suppressor is applied close to the target.

During the operation of D-T neutron sources, contamination or radiological hazard can occur in the environment caused by tritium outgassed from the target.

A potential tritium hazard exists also when the system is opened to the atmosphere for any reason (i.e. repair, maintenance, target replacement, deuterium (leak) replacement, HF ion source balloon replacement, breakage, pump exhausting into the generator hall, etc.).

It has been proven that the tritium in gas and T_2O vapour forms takes part in chemical reactions in the same manner as the hydrogen gas and H_2O vapour. The half-life of tritium is relatively long: it is about 12 y. The specific activity for T_2O is 9.99×10^{13} Bq/g. Tritium is uniformly distributed in the body within 90 min. The biological half-life of tritium is short - about 12 days. The gaseous T_2 - H_2O vapour atmospheric exchange rate is in the order of 1 % per day. Tritium in gaseous form is absorbed by the lungs at a rate of 0.1 %. The maximum permissible air concentration for tritium is 10^{-2} Bq/cm^3. A few hours after exposure, the body fluids contain the same concentration of HTO and T_2O; therefore urine analysis indicates the level of incorporation. A tritium concentration of 1 Bq/l in urine represents the maximum permissible dose.

All components of the ion source, accelerating tube, beam transport system, target system, vacuum equipment, exhaust lines, and target cooling water system become tritium-contaminated. A small amount, about 5 %, of the total tritium released from the target is deposited on the static components of the generator. The bulk of the tritium is accumulated in the pump oil and the elements of ion pump or vented to the atmosphere by the roughing pump. In the forepump oil the contamination was found to be 10 to 20 times higher than in the oil of the diffusion pump. During repair and maintenance, contamination must be kept as low as possible. For example, components in the vacuum system of RTNS-II near the target have 10^6 to 10^7 dpm/cm^2 of surface contamination which is detectable by wiping. Routine target changes can cause tritium incorporation by personnel at a level which is observable in urine. The handling and replacement of tritium targets require the use of a well ventilated glove box to reduce the hazards from inhalation of tritium gas, especially the large tritium-carrying chunks created by surface erosion. For an intense neutron source, the amount of tritium released in a year is too great to exhaust into the atmosphere.

There are two capture techniques to retain the tritium released from the target: (1) trapping in ion pumps and bulk sublimators or (2) using a tritium scrubber that converts the tritium to water and binds it on a molecular sieve bed. It was found that tritium released from the gas-in-metal target with an output value of 10^{11} to 10^{12} Bq/h through the scrubber system is typically less than 3×10^7 Bq/d. The tritium evolution rate during storage depends on the type of carrier gas and has a lower value for argon than for air.

Special attention should be paid at neutron generators with titanium getter pumps. The amount of tritium ($\sim 10^{11}$ Bq/h) will be captured mainly by the ion getter pump. The estimated amount of tritium found in a gaseous state at any time during the operation of the neutron generator is about 10^7 Bq.

The ion getter pump goes through a heating stage when it is started, and consequently tritium is released into the vacuum system.

20.2 RADIOACTIVE MATERIAL STORAGE AND WASTE DISPOSAL HAZARD

Neutron generators utilize tritium targets of $3\text{-}37 \times 10^{10}$ Bq (approx. 1-10 curie) activity. Spare targets may also be stocked as replacements. All of this radioactive material must be used or stored in an exclusion or storage area in accordance with the regulations. During the operation of neutron generators, a certain amount of radioactive waste will be accumulated (used targets, components sorption and getter pumps, tritium contaminated oils, etc.), and disposal must be in accordance with the regulations.

20.3 HIGH VOLTAGE HAZARD

The high voltage power supply housing should always be connected to a good ground. A neutron generator uses 150 - 200 kV; therefore, care should be taken when working in its vicinity without protective covers or devices. **Discharge all capacitors** of the HV units before attempting power supply maintenance or repair. The use of an **isolated handle discharge rod** is recommended for such purposes. **Ground the HV terminal with the same rod if the generator doesn't operate with HV!** The 1-20 kV power supplies of ion sorces and extraction and focus system and ion getter pump are **lethal voltages,** necessitating **extreme caution**, when working on the HV terminal or ion pump supplies.

20.4 IMPLOSION HAZARD

The neutron generator is basically a vacuum vessel and presents the same implosion hazard to accidental breakage as does a TV picture tube.

20.5 PRESSURE HAZARD

Some neutron generators have about 2 bars SF_6 isolation gas on the high voltage and in the HV power supplies. The pressure must be reduced to atmospheric before opening the pressure dome. Removing the dome without reducing the pressure could cause a serious accident. Similarly, the pressure used in pneumatic systems should be reduced to atmospheric pressure before opening the system. The SF_6 tanks should be opened in well ventilated rooms. Handle with care the hermetic units of the SAMES HV (Felici) generators!

20.6 FIRE HAZARD

The deuterium gas and some transformer oils are flammable. Avoid electric sparks and avoid open fire while opening D_2 gas vessels and oil transforms. The organic solvents (acetone, benzene, alcohol, n-hexane, etc.) used in cleaning the neutron generator components are flammable; use them with caution. In the case of an accidental fire in the neutron generator hall use carbon dioxide fire extinguishers. Water, foam or powder extinguishers can cause fatal damage in the neutron generators and the related instrumentation.

21. CONSTRUCTION OF A NEUTRON GENERATOR LABORATORY

21.1 CONSTRUCTION DETAILS

Many factors must be taken into account in establishing a neutron generator laboratory; the most important topics are listed (based on the proposal for the local staff in a developing country) below:

(1) The thickness of the biological shielding can be calculated. In general, around the source at a distance of at least 2 m an additional 1.5 m wall of poured concrete (ρ = 2.3 g/cm^3) is needed.

(2) The inner surface of the neutron generator room (NGR) must be covered with washable oil or plastic paint. A thin plastic foil is advised for covering surface constructed of concrete blocks.

(3) The door between the NGR and the control room must be airtight and protect the measuring laboratories from contamination by radioactive gases. To increase the efficiency of the ventilation in the target storage glove box and target areas, the door between the NGR and control room constructed of paraffin or polyethylene blocks should be covered by plastic foils.

(4) A crane with a 2.0 - 2.5 t capacity is recommended for transporting large parts and heavy equipment (e.g. source container, lead spectrometer, subcritical tank, etc.).

(5) Three chimneys are needed for ventilation:
   a) One to refresh the air in the closed NGR about 5 times per hour to ensure that the concentration of tritium does not exceed the value of 5×10^{-6} μCi/m^3.
   b) One to ventilate the glove-box when it is in use: this can be done by placing a small fan in the appropriate chimney.
   c) One (a 10 cm diameter tube) which can be connected to the exhaust of the forevacuum pump. At the top of this chimney the tritium content should be controlled continuously.

(6) Fresh air for ventilation can be supplied through the measuring room by a tube system (e.g. using the channels for cables and pneumatic transfer).

(7) In humid climates dehumidifiers are needed: at least one in the NGR and one in the measuring room.

(8) To avoid noise and contamination in the NGR, the compressor and the ventilators should be placed in a separate room. The compressed air requirement varies between 4 and 10 m^3/h depending on the dimensions and distance of the transfer system tubes. Working pressure of the network must not be less than 6 bar. A buffering air-tank of about 100 l should be placed close to the pneumatic transfer system.

(9) A pipeline for cooling water in the NGR with a flow-rate of about 100 l/h is needed. If there is no outlet to a canalized water network, forced water circulation is necessary through a cooling system. Another pipeline at normal pressure should be introduced into the measuring center. The same pipeline can be used for the whole neutron generator laboratory (NGL).

(10) Neutron generators, in general, are operated and controlled by a central Generator Control Unit (control desk) which can be located at a distance of 10-15 m far from the machine. The power requirement of the whole labotory is not more than 10 kVA including the operation of a compressor which needs about 4 kVA, 220/380 V, 3-phase. For the generator 3-phase, 5 kVA, 220/380V, 50 Hz are required. Considering the further development of a final NGL as well as the energy consumption of the measuring and operating equipment, it is advisable to design the supporting cables and transformers for about 25 kVA. Every room in the NGL should be supplied with a one- and three-phase network system. The cables from the control room to the NGR can be placed either along the wall or through channels in the wall. For electric cables, about four 5-cm dia channels should be constructed of steel tubes in the wall close to the ceiling of the control room. The unused channels can be closed with iron bars.

(11) For the pneumatic transfer system, 5x3 cm and 8x4 cm channels should be constructed by steel profile tubes in the wall. The unused channels can be closed with an iron plug. Although the pneumatic tubes could run from the generator to the measuring rooms along the wall, it is nevertheless advisable to construct the proposed channels.

(12) It is necessary to construct lead boxes in the wall of the NGR for storage of radioactive sources and tritium targets. The boxes should measure 30 cm x 30 cm x 30 cm and be completely surrounded by a 5 cm thick layer of lead.

(13) Warning signs and light beacons should be installed in the control room to warn of high voltage hazards.

(14) The generation of neutrons should be indicated by a warning light or rotating beacon connected to the HV on switch and to the neutron flux monitor.

(15) An HV interlock system should be installed at the NGR door.

(16) Water-safe lamps and plugs must be used for the lighting and electrical connections in the NGR.

(17) The floor of the NGR must be able to carry about 20 t/m^2 and have an outlet tube to a water sink.

(18) In tropical climates an air conditioning system is required in all rooms of the NGL.

(19) A water tank with a pump is needed for closed circuit cooling.

(20) It is advisable to construct a channel for water pipelines and cables with a removable cover plate below the floor from the control room to the NGR 15 cm deep and 20 cm wide.
(21) A combined ventilation and cooling system is recommended for the NGR.
(22) Further improvement of a neutron generator would make possible to use a TOF spectrometer; therefore, a channel of about 10 cm dia between the NGR and the control room should be constructed.

21.2 WORKSHOPS

It is recommended to complete the neutron generator laboratory with a mechanical workshop containing the usual locksmith's tools, table top drill, lathe (500 - 1000 mm) and milling machines. Arc, plasma or acetylene welding is sometimes useful, but these facilities are usually available at other units at the site of the laboratory.

It is recommended that frequently needed materials be stored in the workshop. These are as follows: steel, aluminium, brass, plastic and Perspex rods (5 to 50 mm dia), screws, nuts; steel, aluminium and bakelite or Perspex sheets up to a thickness of 10 mm. Standard profiles for stands and holders are also recommended.

The usual tools and instruments in the electronics workshop are: pliers, soldering irons, multimeters, oscilloscopes. It is also advisable to complete the list with some high voltage meters (as used for TV repair) and some home-made high frequency test instruments and tools (e.g. resonant circuit with incandescent lamp, etc). The short-lived components of the neutron generator or their equivalents should be procured. The usual stock of active and passive components are recommended to complete the HV and HF components and insulating materials, such as epoxy resin.

As laboratories - especially in the developing world - do not usually have staff skilled in vacuum technology, and since vacuum materials and components are difficult to obtain, the person in charge of the neutron generator should be careful to maintain the supply of frequently needed components and materials. Spare oil for the diffusion and mechanical pumps, silicon high vacuum grease solvents, the most important O-rings, rubber sheets, spare Pirani and other vacuum gauges should be kept in store.

The **store-room** attached to the mechanical and electronic workshop should be clean and equipped with shelves and cabinets. As it is usually locked, the store-room is the best place to store radioactive materials, targets and radioactive litter, in locked bins and cabinets. The operator of the neutron generator

- usually a technician - is a skilled worker, so he may use both the workshop and the store. The keys of the radioactive material storage cabinets and ventilated glove box in this store-room must not be available to the general personnel in the workshop, but the neutron generator operator should be able to get into the workshops at any time, especially during the long irradiations (at night), to perform maintenance and repairs. A glove box for tritium target storage may be constructed by experienced local personnel.

21.3 LABORATORY LOG BOOK

The operation of neutron generators, like all complicated equipment, requires regular maintenance duties and regular exchange of the short-lived components. The operator of the neutron generator should record the working parameters in a log book. This log book should show the time of every operation and record the exchange of short-lived components (e.g. target, ion source balloon, quartz sleeve).

The neutron generator log book is a good basis for planning maintenance and repair as well as operation.

A typical laboratory log sheet:

Date:			Supported by:	
Project:			Project leader:	
Operator:		Beam branch:	Direct:	Deflected:
Target: None		Deuterium:	Tritium:	Others:
Dose during the operation:				
Vacuum:	Gauge No.1:		Gauge No.2:	Gauge No3.:
			10^{-3} mbar	10^{-6} mbar
Starting time:	hours	minutes		
Ion source gas:	(relative unit)			
High frequency:	V	mA		
Magnet current:	(relative unit or A)			
Extraction:	V	mA	(relative unit)	
Focus:	V	mA	(relative unit)	
Accelerating high voltage:		kV	mA	
Deflecting magnet:		A	(relative unit)	
Quadrupole lenses:	A	A	A	A
			(or relative units)	
Target current:	mA (direct)			
	mA (deflected)			
Target and target holder activation:			(relative unit)	
Beam current on isolated slit:			mA	
Monitor counter:		counts		
Remarks:				

REFERENCES

[1] J. Csikai, Handbook of Fast Neutron Generators, CRC Press Inc., Boca Raton, Florida (1987) Vol I-II

[2] S.S. Nargowalla, E.P Przybylowicz, Activation Analysis with Neutron Generators, John Wiley and Sons, New York (1973)

[3] J. Csikai, Use of Small Neutron Generators in Science and Technology, Atomic Energy Review **11** (1973) 415

[4] H. Liskien, A. Paulsen, Nuclear Data Tables **1** (1973) 569

[5] J.D. Seagrave, E.R. Graves, S.J. Hipwood, C.J. McDole, $D(dn)^3He$ and $T(dn)^4H$ Neutron Source Handbook, LAMS-2162, Los Alamos Scientific Lab., NM (1958)

[6] J. Csikai, Zs. Lantos, Cs.M. Buczkó, IAEA-TECDOC-410, Vienna (1987) p.296

[7] V.E. Lewis K.J. Zieba, Nucl. Instr. Meth.**174** (1980) p.141

[8] J. Csikai, in Proc. Int. Conf. Nuclear Data for Science and Technology, Antwerp, Reidel, Dordrecht (1983) p.414

[9] M. Wagner, G. Winkler, H. Vonach, Cs.M. Buczkó, J. Csikai, Ann. Nucl. Energy **16** (1989) p.623

[10] A. Pavlik, G. Winkler, Report INDC(AUS)-011/LI, IAEA, Vienna (1986)

[11] K. Kudo, T. Kinoshito, Fusion Energy and Design **10** (1989) p.145

[12] J. Csikai, Cs.M. Buczkó, R. Pepelnik, H.M. Agrawal, Ann. Nucl. Energy, **18** (1991) p.1

[13] Z. Bődy, in Handbook on Nuclear Activation Data, Technical Report Series, No.273, IAEA, Vienna (1987) p.29

[14] Cs.M. Buczkó, J. Csikai, T. Chimoye, B.W. Jimba, Proc. Conf. Nuclear Data for Science and Technology, Jülich, Springer Verlag, Berlin (1992) p.656

[15] J. Csikai, R. Raics, in Progress Report (HUN), IAEA, Vienna (1991)

[16] K. Kudo, N. Takeda, Matiullah, A. Fukada, Proc. Conf. Nuclear Data for Science and Technology, Jülich, Springer Verlag, Berlin (1992) p.533

[17] N. Jarmie, R.E. Brown, Nucl. Instr. Meth. **D10/11** (1985) p.405

[18] New Uses for Low Energy Accelerators, National Academy of Sciences, Washington, D.C. 1968

[19] T. Freye, A. Lorenz-Wirzba, B. Cleff, H.P. Trautvetter, C. Rolfs, Z.Physik, **A281** (1977) p.211

[20] J. Szabó, P. Raics, in Proc. XIX-th Int. Symp. on Nuclear Physics, ZfK-733, Dresden, 1989, p.266

[21] G.M. Griffiths, E.A. Larson, L.P. Robertson, Can. J. Phys. **A40** (1962) p.402

[22] C. Rolfs, S. Rodney, S. Durrance, H. Winkler, Nucl.Phys. **A240** (1975) p.221

[23] X-ray and Gamma-Ray Standards for Detector Calibration, IAEA-TECDOC-619, Vienna (1991)
[24] Z.E. Switkowski, P.D. Parker, Nucl. Instr. Meth. **13** (1975) p.263
[25] D.F. Hebbard, J.L. Voglh, Nucl.Phys. **21** (1960) p.652
[26] F.M. Penning, J.H.A. Moubis, Physica **4** (1937) p.1190
[27] C.W. Elenga, O. Reifenschweiler, Proc.Symp.Pulsed Neutron Research, Karlsruhe, May 10-14, 1965, Vol.2, IAEA, Vienna (1965) p.609
[28] C.M. Gordon, C.W. Peters, Nucl.Geophys. **2** (1988) p.123
[29] SODERN Data Sheets on Sealed Tube Neutron Generators, France (1990)
[30] C.M. Gordon, C.W. Peters, T.K. Olson, Conf. Accuracy in Trace Analysis, Gaithersburg, MD,USA, 28 Sept. - 1 Oct. 1988
[31] T. Sztaricskai, ATOMKI Közl. **22** (1980) p.47 (in Hungarian)
[32] T. Sztaricskai, Neutron Generators, Proc. IAEA Advisory Group Meeting on Small Accelerators, 1-5 June, 1992, Debrecen (to be published)
[33] T. Sztaricskai, Proc. XIV-th Int. Symp. Interaction of Fast Neutrons with Nuclei, Nov.19-23, 1984, Gaussig, ZfK-652, INDC/GDR/-40/G, p.10
[34] H.H. Barshall, Proc.Int. Conf. Fast Neutron Physics, May 26-31, 1986, Dubrovnik, Yugoslavia, p.188
[35] J.C. Crawford, W. Bauer, ANL-CTR-75, 4, Argonne Nat. Lab. (1975) p.227
[36] H. Maekawa, JAERI-M-83-219, Japan Atomic Energy Res. Inst. (1983)
[37] C.D. Moak, H. Reese, W.M. Good, Nucleonics, **9** (3) (1951) p.18
[38] Z. Szabó, Nucl.Instr.Meth **78** (1970) p.199
[39] E. Pásztor, Isotopenpraxis **3** (1965) p.259
[40] K.W. Ehlers, B.F. Gavin, E.L. Hubbard, Nucl. Instr. Meth. **22** (1963) p.87
[41] J.L. Nagy, Nucl. Instr. Meth. **32** (1965) p.229
[42] Sun Biehe, Wang Fulin, Chen Quin, Proc. XIV-th Int.Symp. Interaction of Fast Neutrons with Nuclei, Gaussig, 19-23 Nov, 1984, ZfK-652
[43] D.D Armstrong et al., Nucl. Instr. Meth. **145** (1977) -127
[44] L. Vályi, Atom and Ion Sources, John Wiley & Sons, London (1977)
[45] P.C. Thonemann et al., Proc. Phys. Soc., London, **61** (1948) p.483
[46] G. Wehner, Phys. Rev. **93** (1954) p.653
[47] D.P. Smith, Hydrogen in Metal, Chicago University Press, Chicago (1948)
[48] W. Jost, Diffusion in Solids, Liquids and Gases, Academic Press, New York (1960)
[49] Manual of Needle Valve EVNO1H1, Balzers AG, Liechtenstein
[50] Instruction Manual of TOSHIBA NT-200 Neutron Generator, Tokyo
[51] Instruction Manual of KFKI NA-4C Neutron Generator, Budapest
[52] T. Sztaricskai, Remote control of Pd leak-electrolyzer (unpublished)
[53] S. Bederka, J. Král, Nucl. Instr. Meth. **145** (1977) p.441

[54] Instruction Manual of J-25 Neutron Generator, SAMES, Grenoble
[55] Instruction Manual of T Neutron Generator, SAMES, Grenoble
[56] J. Pivarc, Proc. XIV-th Int Symp. Interaction of Fast Neutrons with Nuclei, Nov.19-23 1984, Gaussig, ZfK 652, p.16
[57] P. Eckstein et al., Proc. XIV-th Int. Symp. Interaction of Fast Neutrons with Nuclei, Nov.19-23, 1984, Gaussig, ZfK 652, p.24
[58] M. Pöthig, P. Eckstein (personal communication)
[59] M. Sándor, D. Bolyán, T. Sztaricskai (to be published)
[60] Product Catalogue, BALZERS AG, Lichtenstein
[61] Vacuum Technology, its Foundation, Formulae and Tables, Leybold-Hereus GmbH, Germany
[62] High Vacuum Products, EDWARDS, Crawley, England (1984)
[63] N. S. Harris, Vacuum Technology, EDWARDS High Vacuum, Crawley, Sussex, England
[64] High Vacuum Technology, Vacuum Components, ALCATEL, France (1980)
[65] High Vacuum Components, TUNGSRAM, Budapest, Hungary
[66] S. Dushman, Scientific Foundation of Vacuum Technique, John Wiley and Sons, New York (1968)
[67] A. Chambers, R.K. Fitch, B.S.Halliday, Basic Vacuum Technology, Adam Hilger, Bristol and New York (1980)
[68] J.F.O'Hanlon, A User's Guide to Vacuum Technology, Wiley Interscience, New York (1975)
[69] M. von Ardenne, Tabellen der Elektronenphysik, Ionenphysik und Uebermikroskopie, VEB Deutscher Verlag der Wissenschaften, Berlin (1956) (in German)
[70] J. Kliman (personal communication)
[71] V.M. Kellmann, S.J. Javor, Eletronoptics, Akadémiai Kiadó, Budapest (1965) (in Hungarian)
[72] M.D. Gabovich, Physics and Technology of Ion Sources, Atomizdat, Moscow (1974) (in Russian)
[73] M.R. Shubaly, M.S. de Jong, IEEE Trans. Nucl. Sci. **NS-30** (1983) p.1399
[74] J.B. Hurst, M. Roche, Acta Physica Slovaca **30** (1980) p.137
[75] A. Galejs, P.H. Rose, Focusing of Charged Particles, Academic Press, New York (1967) p. 297
[76] B. Gyarmati, E. Koltay, Nucl. Instr. Meth. **66** (1969) p.253
[77] G. Liebmann, Proc. Phys. Soc. London Sect. **B-62,** part 4 (1949) p.352
[78] J.B. Hourst et al., Nucl. Instr. Meth. **145** (1977) p.19
[79] E. Koltay et al., ATOMKI Közl. **22** (1980) 155
[80] J.B. Hourst, M. Roche, Nucl. Instr. Meth. **92** (1971) p.589

[81] M.R. Cleland, B.P. Offermann, Nucl. Instr. Meth. **145** (1977) 41
[82] J.C. Davis et al., IEEE Trans. Nucl. Sci. **NS-26** (3) (1979) p.3058
[83] R. Booth et al., Nucl. Instr. Meth. **145** (1977) p.25
[84] K. Sumita et al., Proc. 12th Symp. Fusion Technology, Vol.I, Pergamon Press, New York (1982) p. 675
[85] A. Kiss, E. Koltay, Gy. Szabó, Nucl. Instr. Meth. **117** (1974) p.325
[86] A. Kiss, E. Koltay, Gy. Szabó, Nucl. Instr. Meth. **212** (1983) p.81
[87] J.B. England, Techniques in Nuclear Structure Physics, MacMillan (1974)
[88] R.G. Wilson, G.R. Brewer, Ion Beams, Wiley Interscience, London (1973)
[89] S. Humphries, Principles of Charged Particle Acceleration, Wiley Interscience, New York (1978)
[90] T. Sztaricskai, Regulated analyzing magnet for NGs (unpublished)
[91] L. Csánky (personal communication)
[92] S. Williams et al., Nucl. Instr. Meth. **185** (1971) p.353
[93] T. Sztaricskai, Quadrupole doublet for Thailand (unpublished)
[94] N.J. Felici, Direct Current **1** (1953) p.122
[95] E.G. Komar, Fundamentals of Accelerator Technique, Atomizdat, Moscow (1975), (in Russian)
[96] E. Kuffel, W.S. Zaeng, High Voltage Engineering, Pergamon Press (1972)
[97] Handbuch der Elektrotechnik, Siemens, Müchen (1971), (in German)
[98] J.D. Cockcroft, E.T.S. Walton, Proc. Roy. Soc. Ser.**A-129** (1930) p.477
[99] G. Petö, Izotóptechnika **16** (1973) p.561 (in Hungarian)
[100] J. Takács, IEEE Trans.Nucl.Sci. **NS-12** (3) (1965) p.980
[101] T. Sztaricskai et al., IAEA Int.Data Committee, INDC/GDR/-21/6/Spec, ZfK-476 (1982) p.95
[102] D.G. Shurley et al, Nucl. Instr. Meth. **187** (1981) p.347
[103] T. Sztaricskai (unpublished)
[104] C.S. Zaidins, Nucl. Instr. Meth. **120** (1974) p.125
[105] D.D. Cossutta, Proc.Conf. Use of Small Accelerators in Technical Research, Oak Ridge, Tennessee, CONF-700322 (1970)
[106] G.I. Primenko et al., Izv. Vuzov, Physica No.5 (1985) p.17 (in Russian)
[107] Radiation Protection Procedures, Safety Series No.38, IAEA, Vienna (1973)
[108] R.F. Boggs, Radiological Safety Aspects of the Operation of Neutron Generators, Safety Series No.42, IAEA, Vienna (1976)
[109] H. Maekawa et al., JAERI-M 83-219, Japan Atomic Energy Res. Inst. (1983)
[110] M. Buttig, INDC/GDR/-40/6, ZfK-562 (1985) p.56
[111] Instruction Manual of KAMAN-711 Sealed Tube Neutron Generator, Colorado Springs, USA
[112] T. Sztaricskai, B. Yotsombat (to be published)

[113] T. Sztaricskai, ATOMKI Közl. **13** (1971) p.117
[114] G. Pető, Pneumatic Sample Transfer System for Neutron Generators (to be published)
[115] T. Sztaricskai et al., ATOMKI Közl. **27** (1985) p 105
[116] B.V. Anufrienko et al., FEI-307, Fiziko-Energ. Inst., Obninsk (1971) (in Russian)
[117] N. Chirapatpimol et al., INDC(TAI)-004/GI, IAEA, Vienna (1986)
[118] T. Vilaithong et al., Proc. Conf. Nuclear Data for Science and Technology, Jülich, Springer Verlag, Berlin (1992) p.486
[119] S. Singkarat et al., Proc. Conf. Nuclear Data for Science and Technology, Myto, Japan (1988)
[120] J.C. Robertson, K.J. Zieba, Nucl. Instr. Meth. **45** (1960) p.179
[121] C.M. Herbach et al., Techn. Univ. Dresden Report 05-06-85 (1985)
[122] Neutron physics (in Hungarian), Editors: D. Kiss and P. Quittner, Akadémiai Kiadó, Budapest (1971)
[123] G.F. Knoll, Radiation Detection and Measurements, John Wiley and Sons, New York (1981)
[124] S. Nagy, Thesis, Debrecen (1976)
[125] T. Sztaricskai, Troubleshooting and Maintenance of Neutron Generators, Proc. IAEA Advisory Group Meeting on Small Accelerators, 1-5 June 1992, Debrecen, Hungary (to be published)

ANNEX A

LIST OF MANUFACTURERS AND COMPONENT DEALERS

The authors are not responsible for the correctness of this list. Telephone (Fax, Telex) and postal code numbers may have changed and small firms may have closed. Readers of this Manual are advised to contact local representatives of multinational manufacturers for current addresses and up-to-date information on the available products. The multinational manufacturers are marked in the list with an asterisk (*).

LEYBOLD *
Bonnerstrasse 489
D-5000 Koln 51
P.O.Box 510760
GERMANY
Tel:(0221) 347-0
Telex: 888 481-20
Fax: (0221) 3471250
Products: vacuum components, pumps, materials, systems, technologies

EDWARDS High Vacuum *
Crawley
West Sussex
RH10 2lW
ENGLAND
Phone: 0293 28844
Telex: 87 123
Fax: 0293 33453
Products: components, materials, pumps, systems, technologies

BALZERS *
FL-9496 Balzers
LIECHTENSTEIN
Tel 075 44111
Telex: 889 788
Fax: 075 42 762
Products: components, materials, pumps, systems, technologies

VARIAN *
12 Hartwell Avenue
Lexington
MA 02173
USA
Phone: (617) 273 6146
Telex: 710 321-0019
Fax: (617) 273 6150
Products: pumps, components, materials, systems, technologies

PFEIFFERS *
Arthur Pfeiffer Vacuumtechnik
P.O.Box 1280
D-6334 Assiar
GERMANY
Phone:(06441) 802-0
Telex: 483 859
Fax: (06441) 802-202
Products: turbomolecular pumps, other components (member of BALZERS group)

VAT
CH-9469 Haag
SWITZERLAND
Phone: (085) 70161
Telex: 855 162
Fax: (085) 74 830
Products: Vacuum valves, gate valves

ALCATEL *
41 rue Perkier
F-92120 Montrose
FRANCE
Tel:(1657) 1100
Telex: 270 431
Products: components, materials, systems, pumps, technologies

HUNTINGTON LABORATORIES
1040 L'Avenida, Mountain View
CA-94043
California
USA
Tel: (415) 964 3323
Fax: (415) 964 6153
Product: vacuum components

MAC VACUUM
23842 Cabot Boulevard,
Hayward
CA-94545-1651
California
USA
Phone: (415) 887-6100
Telex: 910 383 2023
Fax: (415) 887 0626
Products: vacuum components, materials, systems

SHADIER SCIENTIFIC
2976 Arf Avenue
P.O.Box 57287
Hayward
CA-94545
California
USA
Tel: (415) 783 0552
Fax:(415) 783 7245
Products: vacuum materials, components, systems

MEGAVOLT
Cornhill Ilminster
Somerset
TA19 0AH
ENGLAND
Tel: (44) 460 57 458
Fax: (44) 460 54 972
Products/services: accelerator tubes, ion sources, beam handling devices, target assemblies (repair, maintenance, second hand accelerator components)

TECHNABEXPORT
Starimonetni pereulok 26
1091800 - Moscow
RUSSIA
Tel: 2392-885
Fax: 70-952-302-638
Telex: 41328 TSE SU
Products: neutron generators, tritium and deuterium targets
Contact person: Mr. Borodulin and Mr. Basov, Mr.Grigorjev (targets)

ATOMKI
Bem ter 18/C
H-4001 Debrecen
P.O.Box 51
HUNGARY
Tel: (36) 52 317-266
Telex: 72 210
Telefax: (36) 52-316-181
Products: Diffusion pumps, vacuum meters, components, quadrupole mass spectrometers, for leak testing, accelerator components, acceleration tubes, lenses, magnets, etc.
Contact person: Mr. S. Bohatka, Mr.E. Koltay

TUNGSRAM
H-1125 Budapest P.O.Box 7
Szilagy u 26
HUNGARY
Tel: (36)-1-169 2800 or(36)-1-169 3800
Telex: 225 058 or 225 458
Fax: (36)-1-169 2868 or (36)-1-169 1779
Products: mechanical pumps, components, UHV components, vacuum materials

NATIONAL ELECTROSTATIC CORPORATION
Graber Rd
P.O.Box 310
Middleton Wisconsin
53562
USA
Phone:(608) 831-7600
Telex: 26 5430
Fax:(415) 783 7245
Products: accelerators, accelerator components, RF and duoplasmatron ion sources, acceleration tubes, beam line components, related equipment like gas leaks

KFKI
Central Research Institute for Physics
Dept. Material Sciences
Budapest 114
P.O.Box 49
H-1525
HUNGARY
Phone:(36)-1-1166 540
Telex: 224722
Fax: (36)-1-155 3894
Products: neutron generators, components, neutron generator laboratories
Contact person: Dr Istvan Krafcsik

IRELEC (formerly **AID**, and previously **SAMES**)
20 rue du Tour de l'Eau
Postal adress:
BP 316-38407 ST MARTIN D'HERES Cedex
FRANCE
Tel: 76 44 12 96
Fax: 76-63 19 68
Telex: 980167
Contact person: Mr. Rechaten
Products: electrostatic HV (Felici) generators, neutron generators, neutron generator components, accessories

AMERSHAM INTERNATIONAL
Amersham Laboratories, White Lion Road
Amersham, Buckingshamshire
HP7 9LL
ENGLAND
Tel: (44) 494 543 488
Fax: (44) 543 242
Telex: 83 141
Products: tritium and deuterium targets for neutron generators, radioisotopes
Contact person: Mr.Keith L. Fletcher
(subsidiaries in North and South America, Asia and Europe)

NUKEM
Industriestrasse 13
D-8755 Alzenau
P.O.Box 1313
GERMANY
Tel:(49) 6023 500 0
Fax: (49) 6023 500 222
Telex: 418 4123
Products: tritium technology, tritium targets, glove boxes

MULTIVOLT
26 Loppets Rd
Crawley, Sussex
RH10 5DW
ENGLAND
Tel:(44) 293 22630
Fax: (44)-273-747 100
Products: neutron generators,components, SAMES neutron generator components,
Contact person: Mr. D.Cossutta

KAMAN NUCLEAR
1500 Garden of Goods Rd.
Colorado Springs,
Colorado 80933
P.O.Box 7463
Tel:(303) 599 1500
Telex: 452 412
USA
Products: neutron generators, sealed tube neutron generators,neutron generator components, related equipment
Contact person: Mr. Frey

MF PHYSICS
4720 Forge Rd. Suite 112
Colorado Springs
Colorado 80907-3549
USA
Tel: 719-598 9549
Fax: 719-598 2599
Products: KAMAN components, equipments, sealed tube neutron generators

SGN
Societe generale pour les techniques nouvelles
1 rue des Herons,
Montigny le Bretonneux,
F-78182
Saint-Quentin en Yvelex Cedex
FRANCE
Tel: (33) 1 3058 6814
Fax: (33) 1 3058 6852
Telex: 698316
Products: neutron generators, neutron detectors
Contact person: Mr B. Vigreux, director

INTERATOM
Friedrich Ebert Strasse
D-5060 Bergisch-Gladbach
GERMANY
Tel: (49) 2204 840
Fax: (49) 22004 843 045
Telex: 887 857
Pruducts: accelerators, neutron generators,
Contact person: Mr. K.H. Weyers

IMAGING AND SENSING TECHNOLOGY
Westinghouse Circle
Horsehead
NY 14845 USA
Tel: (1) 607 796 3400
Fax: (1) 607 796 3279
Telex: 490 998 9073 Products: neutron generators, neutron detectors
Contact person: Mr. Wiliem Todt

EFREMOV
Scientific Research Institute of
Electrophysical Apparatus
189631 St.Peterburg, Russia
Tel.:(7)-812 265 7915 or 265 5658
Fax: (7)-812 265 7974 or 463 9812
E-mail: ROZHKOV@NIIEFA.SPB.SU
Products: Neutron generators, accelerators and their components, upgrading components
Contact person: Nicolay Tolstun

SODERN
Societe anonyme d'etudes et realisations nucleares
1 avenue Descartes
94451 Limeil-Brevannes Cedex
FRANCE
Tel: 33(1) 45 69 96 00
Telex: 270 322
Fax: 33(1) 45 69 14 02
Products: sealed tube neutron generators for borehole logging, related equipment
Contact person: Mr Serge Chezeau

PHILIPS
Eindhoven
P.O.Box 5600
90050
NETHERLAND
Tel: 40 783 749
Products: sealed tube neutron generators

GLASSMAN
Route # (EAS) Salem Industrial Park
P.O.Box 555
Whitehouse Station
N.J. 08889
USA
Tel:(201) 534 9007
Telex: 710 480 2839
Products: High voltage power supplies (medium frequency 3-400kV) 1-250 mA

HAEFELY
Lehenmattstrase 353
Basel
CH-4028
SWITZERLAND
Tel: (41) 61 535 111
Telex: 62469
Products: high voltage test equipments, insulating transformers, mains frequency HV power supplies, sealed tube neutron generators

TECHNICAL UNIVERSITY BUDAPEST
Institute for Automation
H-1117 Budapest
HUNGARY
Tel:(36)-1-166 4527
Fax:(36)-1-166 6808
Telex:225 931
Products: high voltage and high current stabilized power supplies for accelerators and X ray equipment
Contact person: Dr. I. Ipsits

PULSE ELECTRONIC ENGINEERING
3-15,Tatekawa 4-chome,
Sum ida-ku,
Tokyo,130
JAPAN
Tel: (03) 633 6101
Fax: (03) 634 0636
Products: high voltage DC powers supplies, stabilized constant current power supplies, special HV equipment

INSTITUTE OF EXPERIMENTAL PHYSICS KOSSUTH UNIVERSITY
H-4001 Debrecen
Bem ter 18/A
HUNGARY
Tel: (36) 52 415 222
Fax: (36) 52 315 087
Telex: 72 200 univk h
Products: accessories, components for neutron generators and related equipment (target holders, quadrupole lenses, associated particle target heads, wobbling target holders, ion source components) neutron monitors and sample holders, pneumatic sample transfer systems for neutron generators, design and manufacturing services for neutron generator laboratories
Contact person: Head of the Institute

ALFAX
Malmo
Lundanvagen 143
212 24
SWEDEN
Tel: 040-189 000
Telex: 32504
Products: heavy water, compressed deuterium gas in gas cylinder

INSTITUTE OF NUCLEAR RESEARCH
Prospekt Nauki 119
252650 Kiev-28
UKRAINE
Products: tritium and deuterium targets
Contact person: Mr Kolomentzev

RADIOISOTOPE CENTRE POLAND
Foreign trade office POLATOM
Ottwock-Swierk
05-400
POLAND
Tel.: 4822 798 435
Telex: 812202
Fax: 4822 797 381
Products: deuterium and tritium targets, deuterium gas.

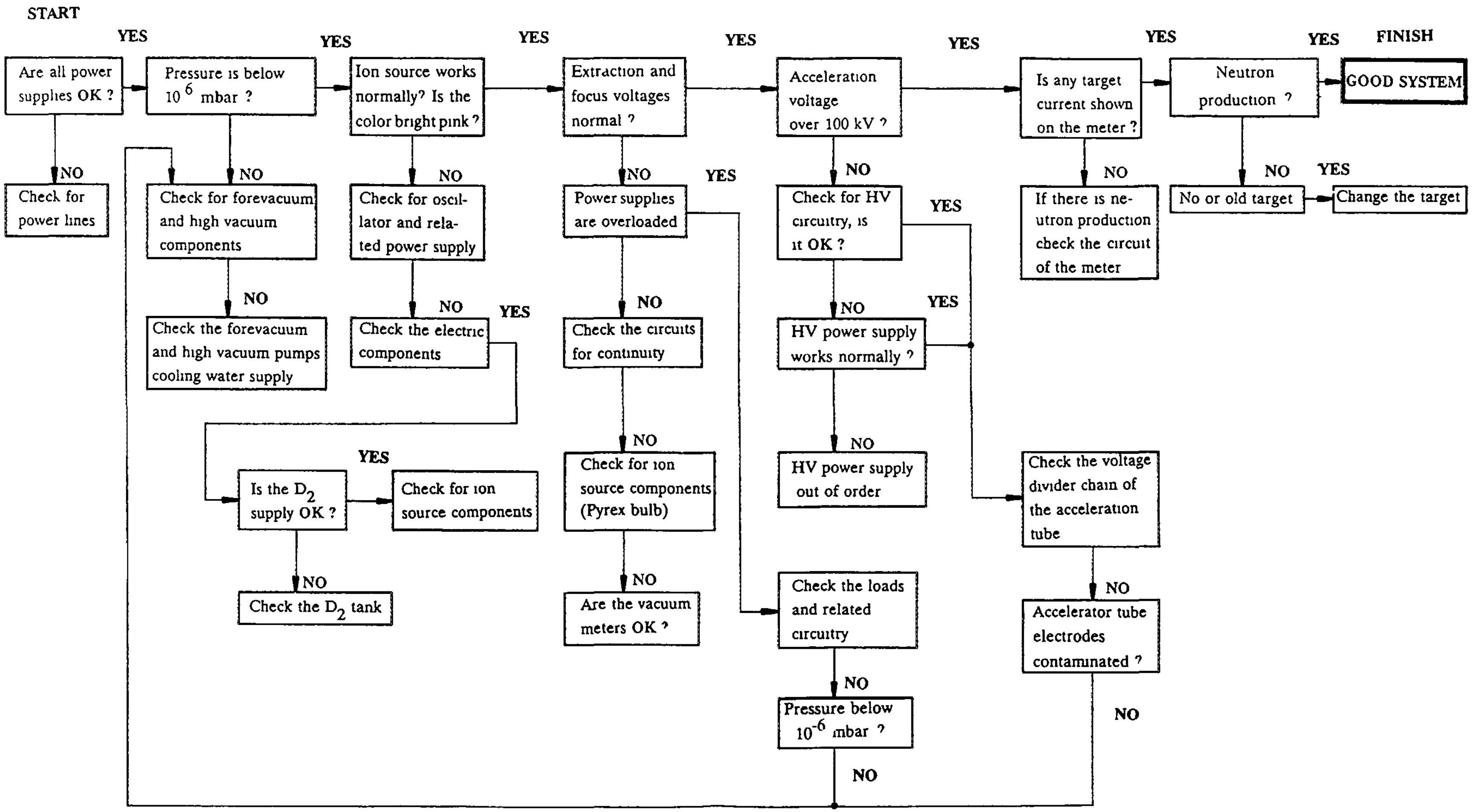
CHINA INSTITUTE OF ATOMIC ENERGY
P.O.Box:275
Beijing 102413
PEOPLES REPUBLIC OF CHINA
Tel: Beijing, (86) 1 935 7312
Telex: 222 373 IAE CN
Fax: (86) 1 935 7003
Products: radiochemicals, labelled compounds, targets for neutron generators
Contact person: Mr Yu-shan Wang (neutron generator targets)

WALLIS HIVOLT
Dominion Way
Worthing, Sussex
BN14 8NW
ENGLAND
Tel: (44)-903-211 241
Fax: (44)-903-208 017
Telex: 877 112
Products: medium frequency high voltage power supplies up to 200 kV (500-2000W)

MARCONI AVIONICS
Neutron Division
Elstree Way
Borehamwood
Hertfordshire
WD6 1RX
ENGLAND
Tel: (44) 1-953 2030
Telex: 22 777
Product: sealed tube neutron generators

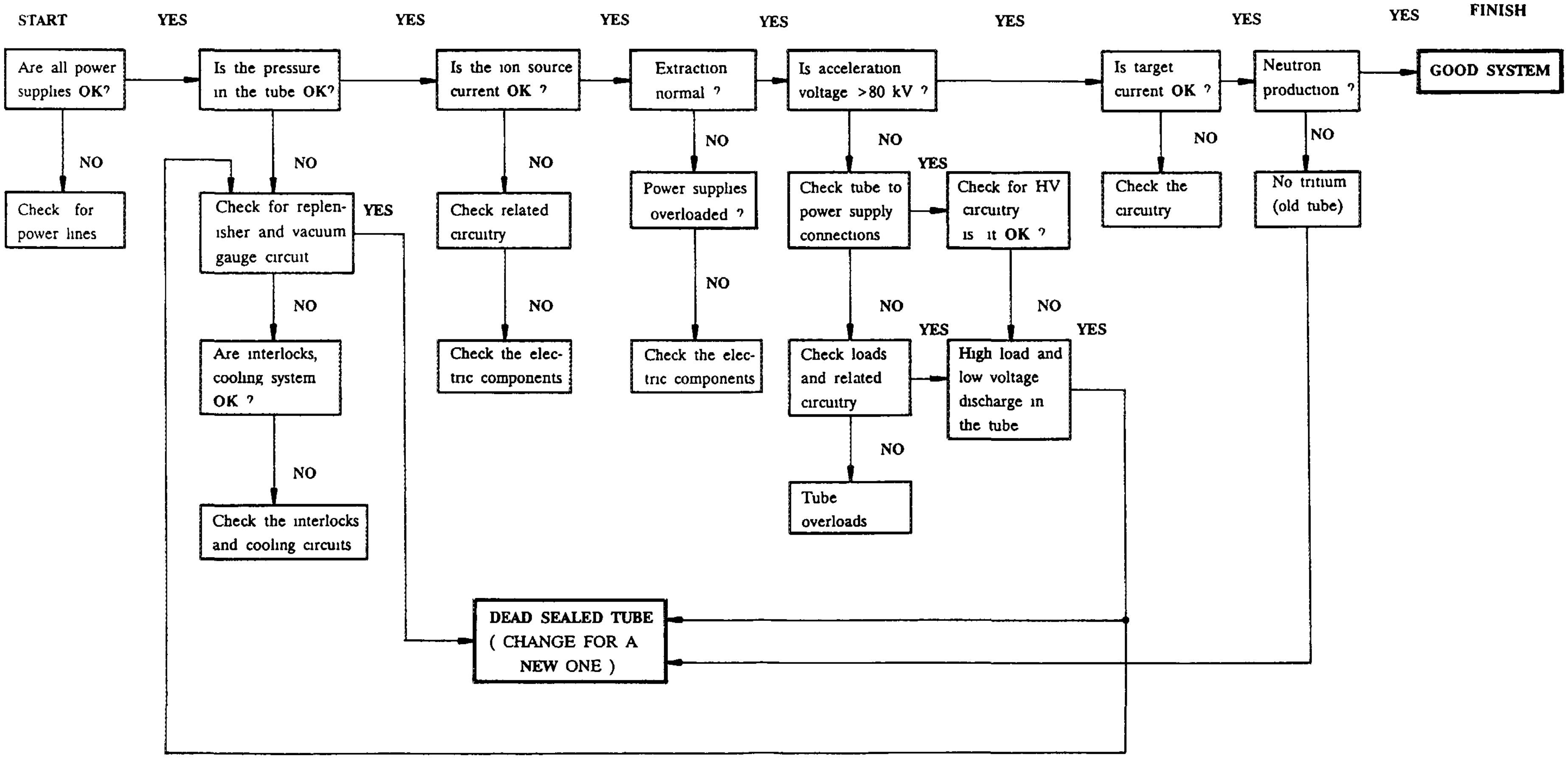
ANNEX B

TROUBLESHOOTING FLOW CHART FOR NEUTRON GENERATORS WITH RF ION SOURCE



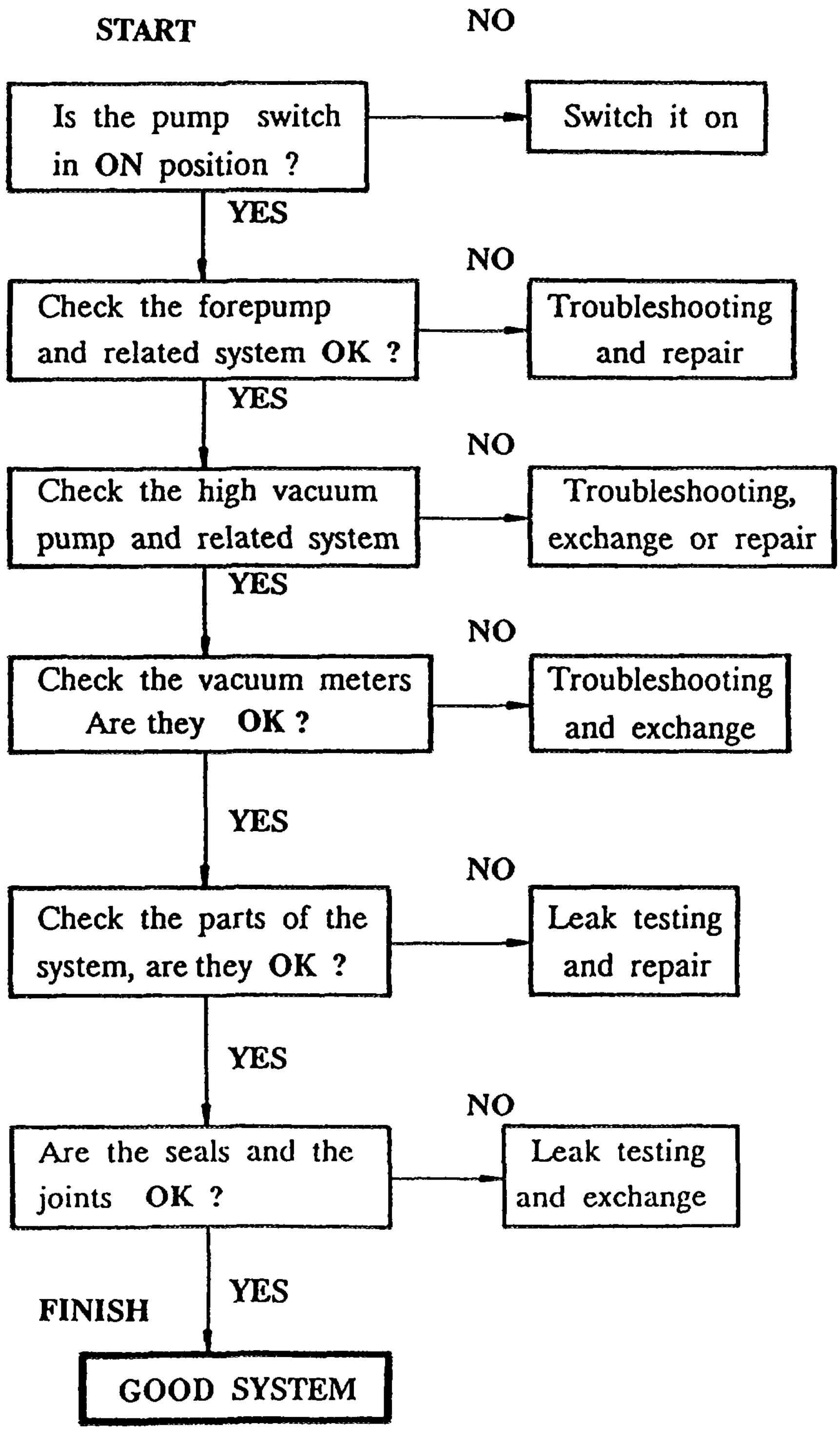
ANNEX C

TROUBLESHOOTING FLOW CHART FOR SEALED TUBE NEUTRON GENERATORS



ANNEX D

TROUBLESHOOTING FLOW CHART FOR NEUTRON GENERATOR VACUUM SYSTEM



CONTRIBUTORS TO DRAFTING AND REVIEW

Csikai, J.	Institute of Experimental Physics, Kossuth University, Debrecen, Hungary
Darsono	Yogyakarta Nuclear Research Centre Indonesian Atomic Energy Commission, Yogyakarta, Indonesia
Dolnicar, J.	International Atomic Energy Agency, Vienna, Austria
Li Gwang Nyong	Institute of Nuclear Physics, Pyongyang, Democratic People's Republic of Korea
Molla, N.I.	Atomic Energy Establishment, Dacca, Bangladesh
Raics, P.P.	Institute of Experimental Physics, Kossuth University, Debrecen, Hungary
Sanchez, A.A.	Nuclear Engineering Department, National Polytechnic Institute of Mexico, Mexico City, Mexico
Szegedi, S.	Institute of Experimental Physics, Kossuth University, Debrecen, Hungary
Sztaricskai, T.	Institute of Experimental Physics, Kossuth University, Debrecen, Hungary
Walsh, R.L. (*Scientific Secretary*)	International Atomic Energy Agency, Vienna, Austria