Accelerator Technology

Summary talk

A.J.Kreiner

CNEA, Argentina

Research Applications and Utilization of Accelerators, AccApp '09, Vienna, 4-8 May 2009.

IAEA
International Atomic Energy Agency
Atoms for Peace

AMERICAN NUCLEAR SOCIETY

I apologize in advance for errors, omissions and inaccuracies.

Please comments, corrections, additions, etc., to make the report more complete.

I have followed IAEA conventions wherever possible: alphabetical order.

Statistics (this conference)

Limitations (selfimposed) of summary:

1. No electron machines (only hadronic probes). Refer to SM/EB sessions on Friday morning.

2. Emphasis on machine or whole system development (less on ancillary equipment and no applications).

- **4 specific sessions on (ion) accelerator technology:**

Monday: AT/INT-01..05 (actual talks: 5 (3))

Wednesday: AT/OC(Operation-Control)-01..05 (4(1))

Wednesday: AT/RD (R&D)-01..05 (4(1))

Friday: AT/RD (R&D) (5(3))

TOTAL: 18(8). Others: 15. Grand total: 33(23).

Countries engaged in development of ion accelerator technology (contributing to this meeting):

- **Argentina, Belgium, China, France, Germany, Italy, India, Japan, Korea, Russian Federation, Switzerland, Ukraine, United States.**

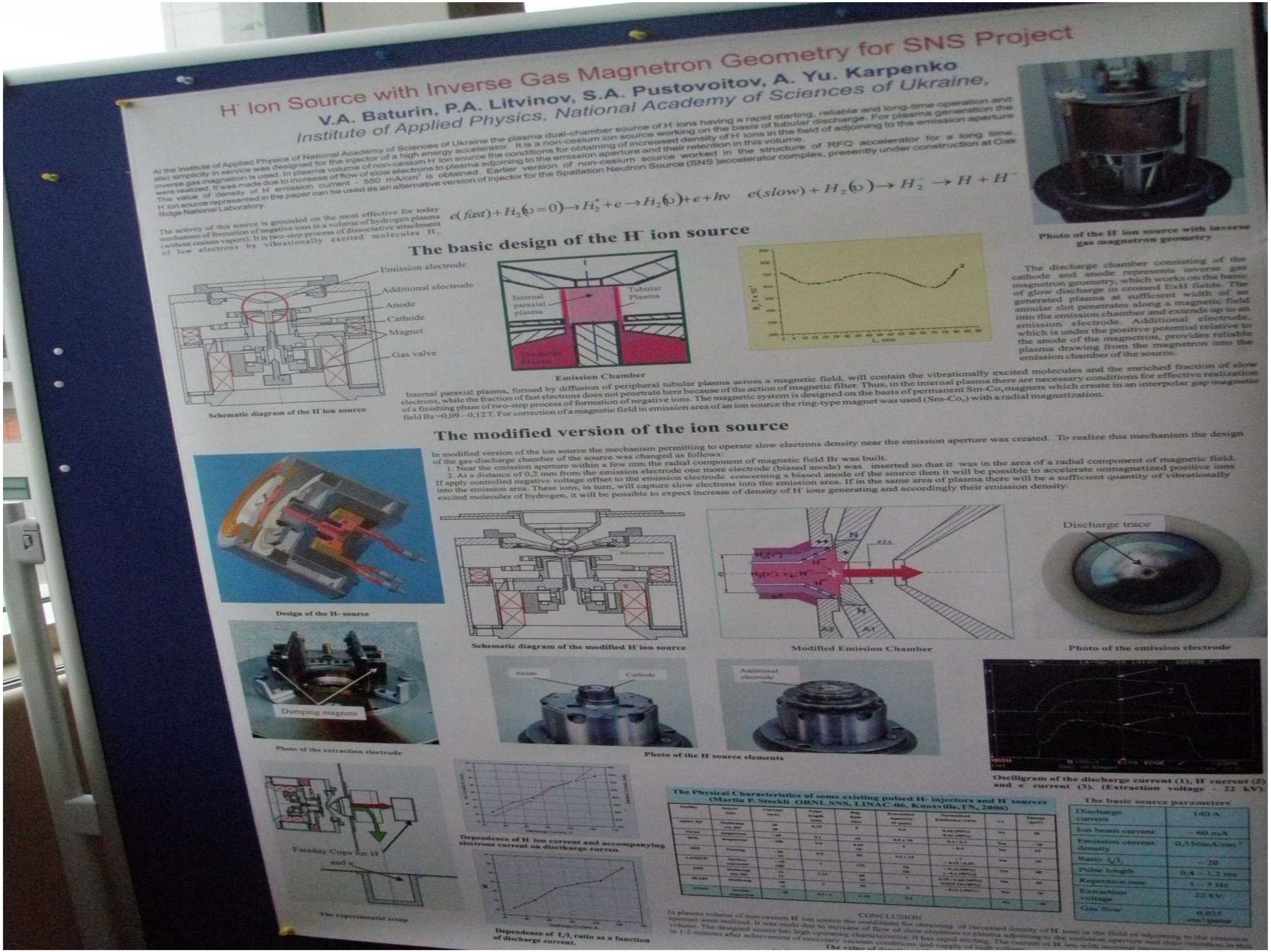
- **Green: well established main players**
- **Blue: some tradition and new active programs**
- **Red: newcomers**

Energy regimes and machines

1. **Electrostatic devices and accelerators**

- **0-80 keV: ion sources:**

a. **H- Ion source with ..Magnetron geometry (Baturin et al., AT/P5-05).**
b. **High intensity ECR source (Roychowhury, AT/P5-17).**
c. **High brightness source (Storizhko et al., AT-P5-19).**


H- Ion Source with Inverse Gas Magnetron Geometry for SNS Project
V.A. Baturin, P.A. Litvinov, S.A. Pustovoitov, A. Yu. Karpenko
Institute of Applied Physics, National Academy of Sciences of Ukraine,
At the Institute of Applied Physics of National Academy of Sciences of Ukraine the plasma dual-chamber source of H- ions having a rapid starting, reliable and long-time operation and also simplicity in service was designed for the injector of a high energy accelerator. It is a non-cesium ion source working on the basis of tubular discharge. For plasma generation the inverse gas magnetron is used. In plasma volume of non-cesium H- ion source the conditions for obtaining of increased density of H- ions in the field of adjoining to the emission aperture were realized. It was made due to increase of flow of slow electrons to plasma adjoining to the emission aperture and their retention in this volume. The value of density of H- emission current - 550 mA/cm² is obtained. Earlier version of non-cesium source worked in the structure of RFQ accelerator for a long time. H- ion source represented in the paper can be used as an alternative version of injector for the Spallation Neutron Source (SNS) accelerator complex, presently under construction at Oak Ridge National Laboratory.
The activity of this source is grounded on the most effective for today mechanism of formation of negative ions in a volume of hydrogen plasma (without cesium vapors). It is two-step process of dissociative attachment of low electrons by vibrationally excited molecules H2.
e(fast) + H2(υ=0) → H2* + e → H2(υ) + e + hν
e(slow) + H2(υ) → H2- → H + H-
The basic design of the H- ion source
Emission electrode
Additional electrode
Anode
Cathode
Magnet
Gas valve
Schematic diagram of the H- ion source
Internal paraxial plasma
Tubular Plasma
Emission Chamber
Photo of the H- ion source with inverse gas magnetron geometry
The discharge chamber consisting of the cathode and anode represents inverse gas magnetron geometry, which works on the basis of glow discharge in crossed ExH fields. The generated plasma at sufficient width of an annular slot penetrates along a magnetic field into the emission chamber and extends up to an emission electrode. Additional electrode, which is under the positive potential relative to the anode of the magnetron, provides reliable plasma drawing from the magnetron into the emission chamber of the source.
Internal paraxial plasma, formed by diffusion of peripheral tubular plasma across a magnetic field, will contain the vibrationally excited molecules and the enriched fraction of slow electrons, while the fraction of fast electrons does not penetrate here because of the action of magnetic filter. Thus, in the internal plasma there are necessary conditions for effective realization of a finishing phase of two-step process of formation of negative ions. The magnetic system is designed on the basis of permanent Sm-Co5 magnets which create in an interpolar gap magnetic field Bz ~0,09 – 0,12 T. For correction of a magnetic field in emission area of an ion source the ring-type magnet was used (Sm-Co5) with a radial magnetization.
The modified version of the ion source
In modified version of the ion source the mechanism permitting to operate slow electrons density near the emission aperture was created. To realize this mechanism the design of the gas-discharge chamber of the source was changed as follows:
1. Near the emission aperture within a few mm the radial component of magnetic field Br was built.
2. At a distance of 0,2 mm from the emission electrode one more electrode (biased anode) was inserted so that it was in the area of a radial component of magnetic field. If apply controlled negative voltage offset to the emission electrode concerning a biased anode of the source then it will be possible to accelerate unmagnetized positive ions into the emission area. These ions, in turn, will capture slow electrons into the emission area. If in the same area of plasma there will be a sufficient quantity of vibrationally excited molecules of hydrogen, it will be possible to expect increase of density of H- ions generating and accordingly their emission density.
Design of the H- source
Schematic diagram of the modified H- ion source
Modified Emission Chamber
Discharge trace
Photo of the emission electrode
Dumping magnets
Photo of the extraction electrode
Anode
Cathode
Additional electrode
Photo of the H- source elements
Oscillogram of the discharge current (1), H- current (2) and e- current (3). (Extraction voltage - 22 kV).
Faraday Cups for H- and e-
The experimental setup
Dependence of H- ion current and accompanying electrons current on discharge current.
Dependence of I-/Ie ratio as a function of discharge current.
The Physical Characteristics of some existing pulsed H- injectors and H- sources (Martin P. Stockli ORNL SNS, LINAC-06, Knoxville, TN, 2006)
The basic source parameters
Discharge current 140 A
Ion beam current ~ 60 mA
Emission current density 0,550 mA/cm²
Pulse length 0,4 - 1,2 ms
Repetition rate 1 - 5 Hz
Extraction voltage 22 kV
CONCLUSION

Energy regimes and machines (Cont')

1. **Electrostatic devices and accelerators**

- **80-150 keV (kV): neutron generators (d-d, d-t)**

  Traditional vendors: France, USA,..

  In this meeting: 1. NSD-Fusion (Sved): no target, reactions in gas-plasma. 2. Adelphi (Fuller): open tube. 3. ULIS: portable.. (Le Tourneur). 4. Powerful..(Gribkov).

- **150- 500 keV (kV): Smaller deuteron electrostatic accelerators (Cockcroft-Walton type) for neutron production in ADS systems (TiT targets), e.g.:**

a. **GENEPI-3C (see Baylac ADS/ET-01).**

b. **Yalina (see Yalina collaboration, ADS/et-02-..04).**

c. **India (see Nema ADS/INT-03).**

d. **Subcriticality facility at Kyoto (Pyeon et al., ADS/ET-03),..**

GENEPI-3C beam specifications

- **GEnerator of NEutrons Pulsed & Intense**
  - Electrostatic Deuteron accelerator (240 keV)
  - Neutron (14 MeV) production via $T(d,n)^4He$

- Accelerator capable of producing **alternatively**
  - **Intense pulsed mode**
    40 mA peak current
    FWHM < 1 µs
    repetition rate : 10-5000 Hz
  - **Continuous mode**
    DC beam
    programmable beam trips

DC mode

Mean current	160 µA to 1 mA
Beam trip rate	0.1 to 100 Hz
Beam trip duration	~ 20 µs to 10 ms
Transition edge	~ 1 µs
Beam spot size	Φ ~ 20-40 mm
Maximum n rate	$\sim 5 \times 10^{10}$ n/s
Pulse stability	~1%

- **Designed & built by CNRS/IN2P3 collaboration**
  IPN Orsay - LPC Caen - IPHC/DRS Strasbourg - LPSC Grenoble

Energy regimes and machines (Cont')

- **0.5-20 MeV protons (up to aprox. 10 MV): Single ended machines (Cockroft-Walton, Dynamitrons), Tandems:**

a. **Electrostatic accelerators of IPPE.. (Gulevich, AP/AM-09).**

b. **Development of high power Tandem-ESQ (Kreiner, AT/OC-01).**

Development of a Tandem-Electrostatic-Quadrupole Facility for Accelerator-Based Boron Neutron Capture Therapy

A. J. Kreiner[1,2,3,*], W. Castell[1], H. Di Paolo[1,2], V. Thatar Vento[1], J. Bergueiro[1], A. A. Burlon[1,2], J.M.Kesque[1], P. Levinas[1,3], A. A. Valda[1,2], H. R. Somacal[1,2], M. Obligado[1], D. Cartelli[1]

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[2] Escuela de Ciencia y Tecnología. Universidad Nacional de San Martín, M. De Irigoyen 3100, 1650, San Martín, Buenos Aires, Argentina.
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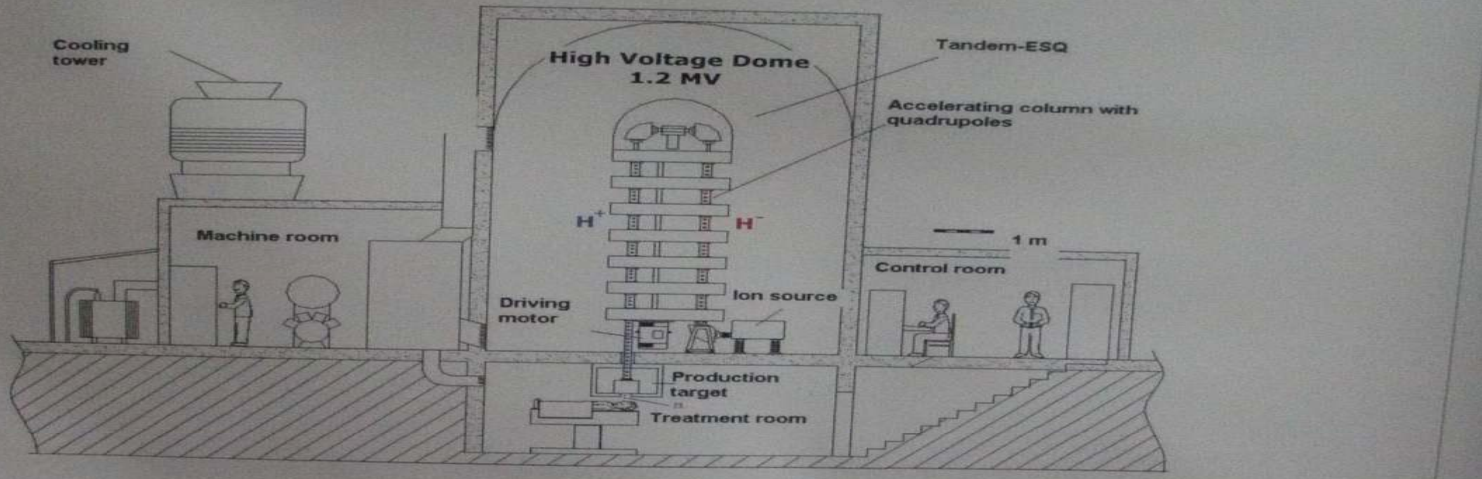
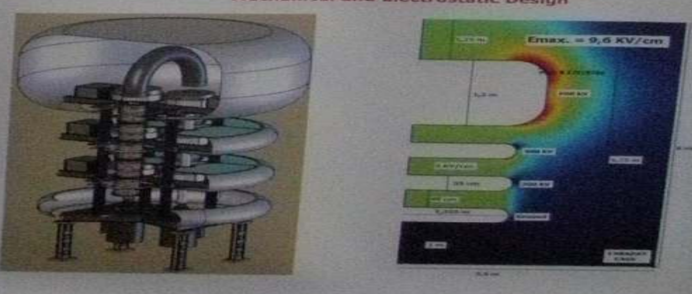
In this work we describe some aspects of the current status of an ongoing project to develop a **T**andem-**E**lectro**S**tatic-**Q**uadrupole (TESQ) Facility for **A**ccelerator-**B**ased **B**oron **N**eutron **C**apture **T**herapy (AB-BNCT) at the Atomic Energy Commission of Argentina. The project final goal is a machine capable of delivering 30 mA of 2.4 MeV protons to be used in conjunction with a neutron production target based on the $^{7}Li(p,n)^{7}Be$ reaction slightly beyond its resonance at 2.3 MeV. Here the focus is set on the development of a 0.6 MV prototype.

General Layout of the Accelerator Facility



Module Components:
- AC Generator
- Power Supplies
- Insulating rotating shafts
- Insulating supports

600 kV Prototype Mechanical and Electrostatic Design



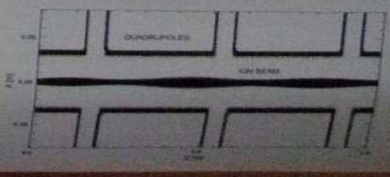
Module Support Structure

Insulating Support

Rotating Shaft

Accelerator Tube with Quadrupoles

Beam Transport Simulations



* Email: kreiner@tandar.cnea.gov.ar

Energy regimes and machines (Cont')

2. RF machines

- **1-5 MeV: RFQ's, cavities:**

a. **The 600 MeV EUROTRANS Proton Driver Linac (Podloch et al, AT/INT-03)**

b. **China High-Intensity Accel. Developments…(Wei et al., AT/INT-04)**

c. **Recent High Power RFQ Dev. (Bechthold et al., AT/RD-01)**

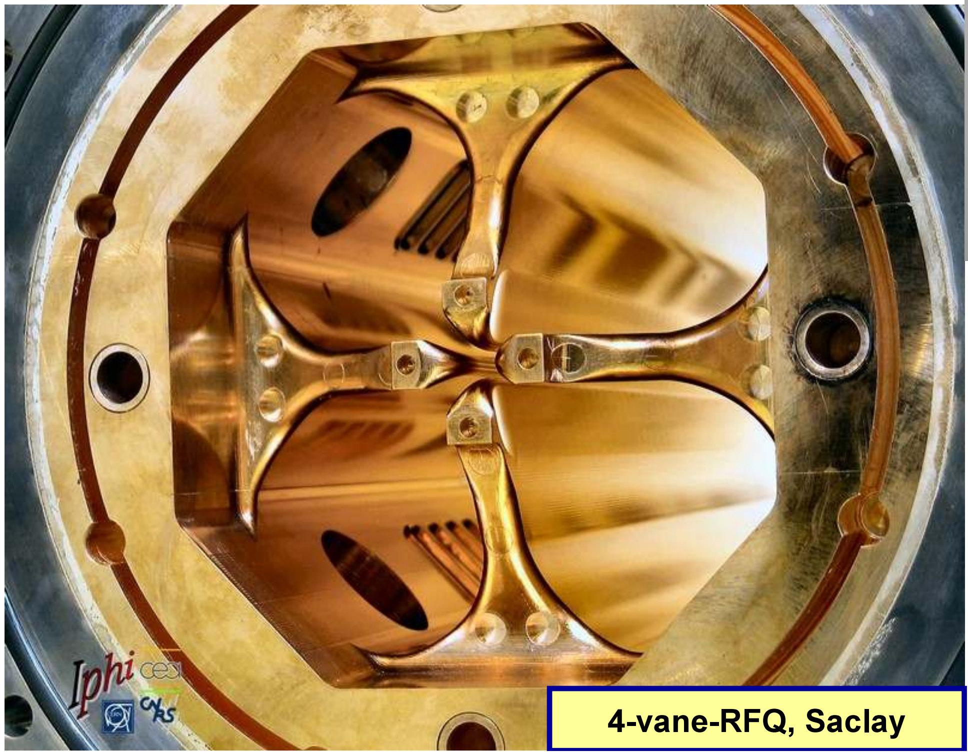
d. **Design and Development of Quads for DTL(Malhotra et al., AT/P5-18).**

e. **Proton LINAC FRANZ (Meusel et al., AT/RD-07).**

Radio Frequency Quadrupole (RFQ)- Podlech et al.

cw operation @352 MHz → 4-vane-RFQ

A 100 mA, 3 MeV RFQ under construction at CEA Saclay (IPHI)



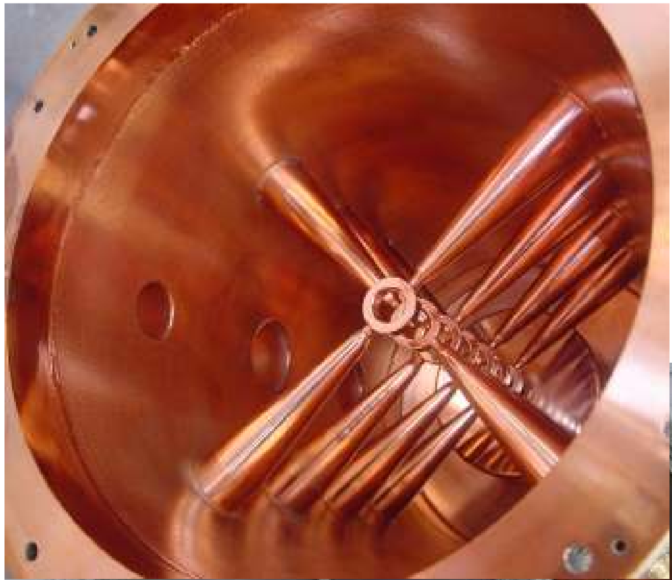
4-vane-RFQ, Saclay

For EUROTRANS a dedicated design for lower beam current

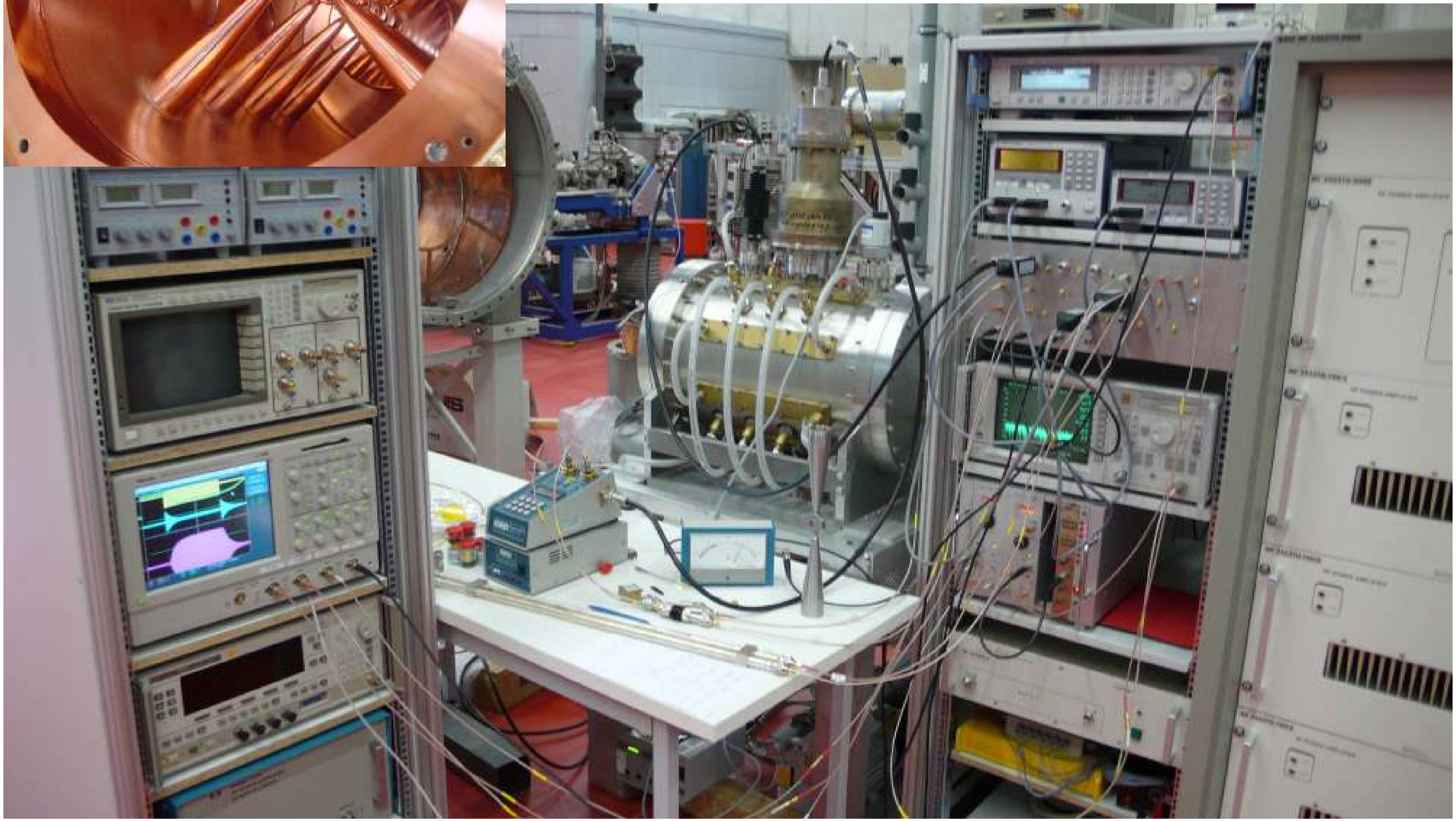
→ less RF power

→ shorter (L=4.3 m)

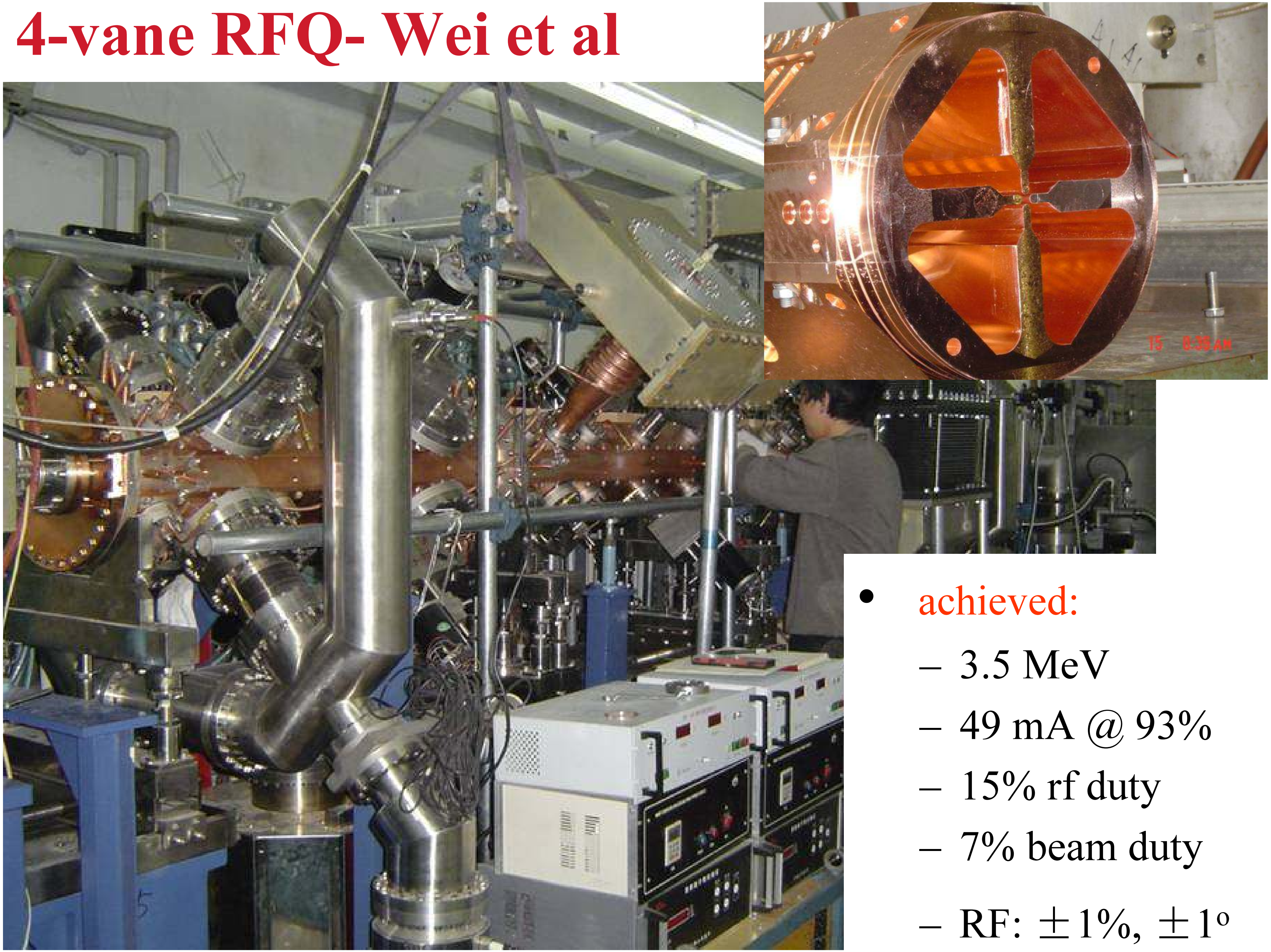
→ more reliable



RF Power Test of rt CH-Cavity- Podlech et al



4-vane RFQ- Wei et al



- achieved:
  - 3.5 MeV
  - 49 mA @ 93%
  - 15% rf duty
  - 7% beam duty
  - RF: ±1%, ±1^{o}

SARAF RFQ at Soreq Israel-Bechthold et al

Parameter	*Value*
frequency f_0 [MHz]	176
input energy W_{in} [keV/u]	20
output energy W_{out} [keV/u]	1500
max. mass to charge ratio A/q	2
inter electrode voltage V_{el} [kV]	65
electrode length [cm]	390
duty factor [%]	100
thermal load [kW/m]	62.5

•Most recent high power 4-rod-RFQ in operation.

•Has proven stable operation at 47.5 kW/m (!), which already exceeds the ever reached thermal load on a 4-rod structure by a factor of 2.4

•85% dc reached at 250 kW (spec.).

•will serve as a prototype for upcoming high power applications.

Energy regimes and machines (Cont')

2. RF machines

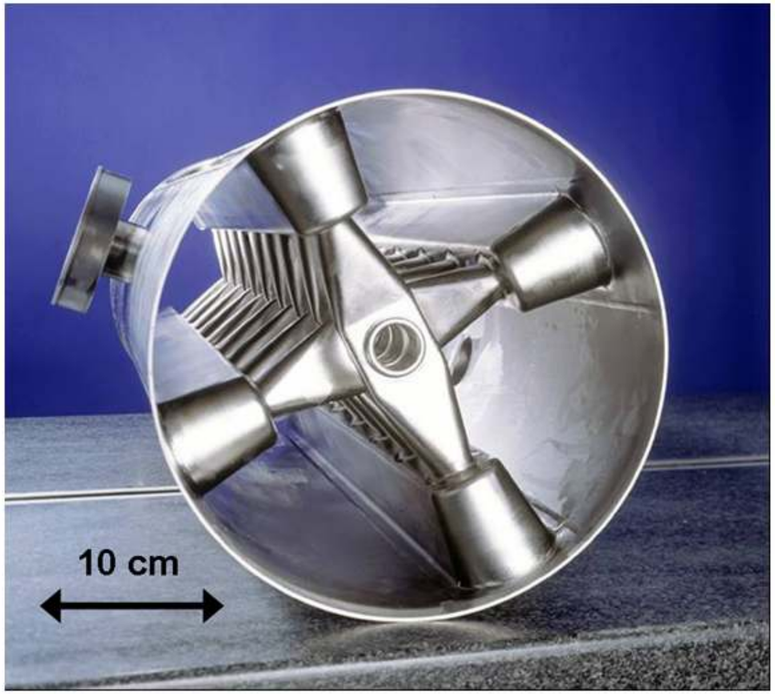
- **5 MeV to GeV energies: LINACS (e.g., DTL,s, Superconducting technology), Cyclotrons, Synchrotrons.**

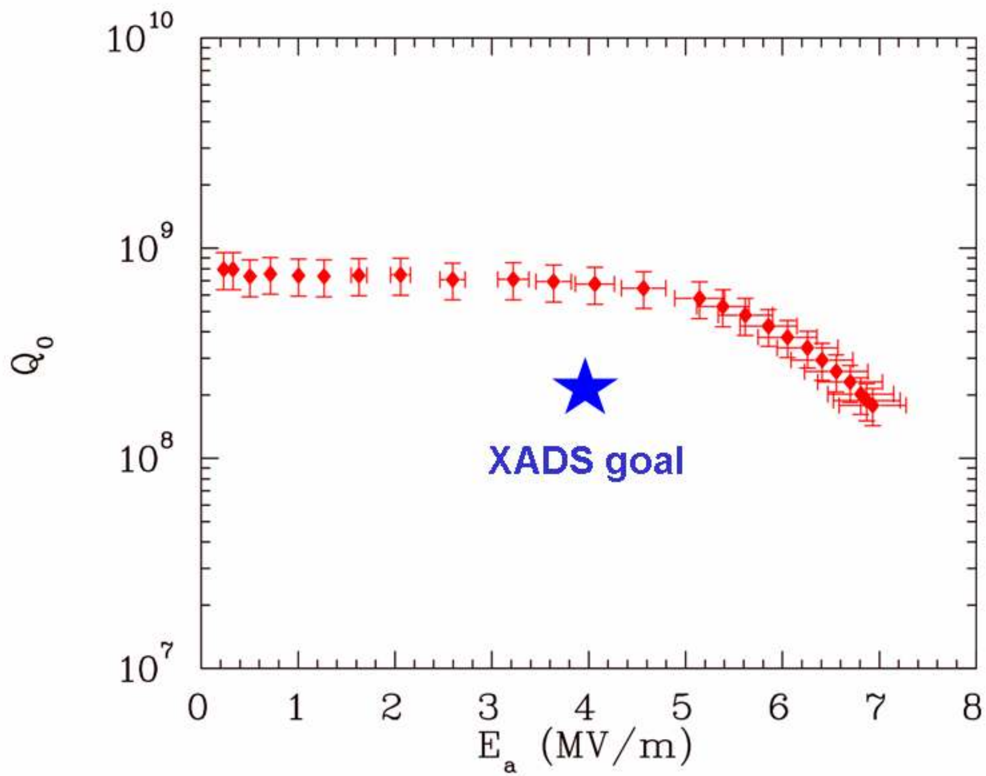
a. **The 600 MeV EUROTRANS Proton Driver Linac (Podloch et al, AT/INT-03).**

b. **China High-Intensity Accel. Developments…(Wei et al., AT/INT-04).**

c. **Multipurpose Accel-Accum ITEP-TWAC..(Sharkov et al., AT/INT-02).**

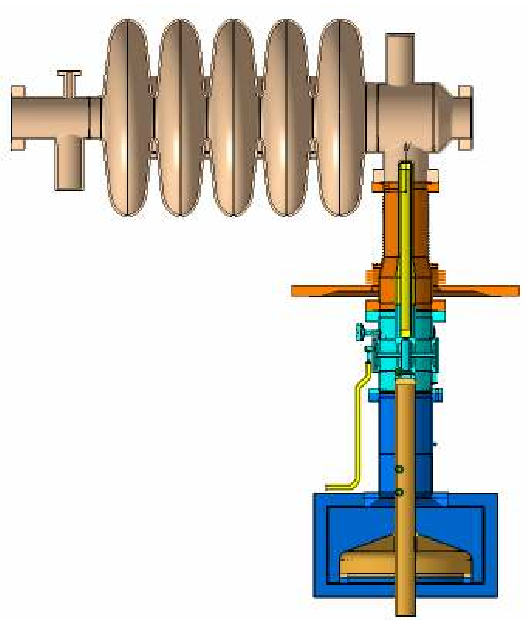
Experimental Results Superconducting solenoids
CH-Cavity, Podlech et al.





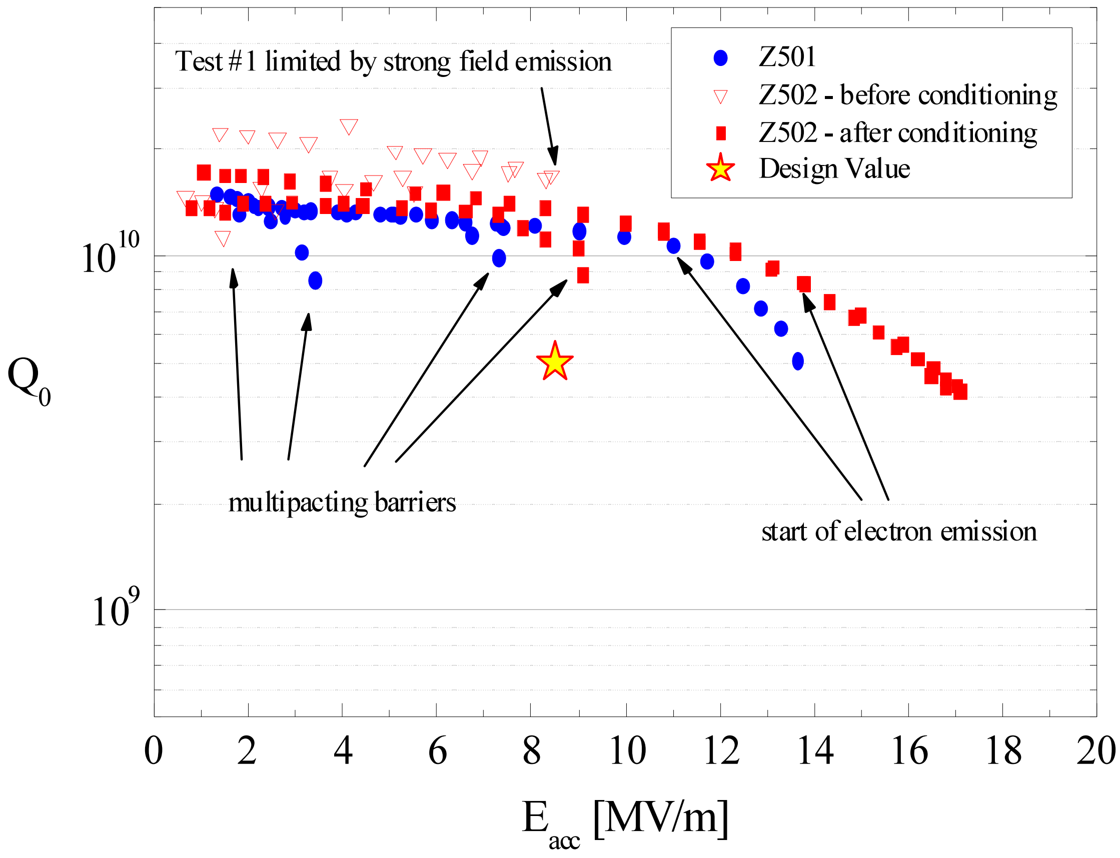
Gradient based on βλ-definition

Superconducting 5-Cell Elliptical Cavities- Podlech et al.



High power test foreseen in 2010

INFN Milano



Gradient based on βλ-definition

Energy regimes and machines (Cont’)

2. RF machines

- 5 MeV to GeV energies: LINACS (e.g., DTL,s, Superconducting technology), Cyclotrons, Synchrotrons.

a. Performance of the PSI High Power Accel. (Seidel et al, AT/RD-10). Cyclotrons vs LINAC’.

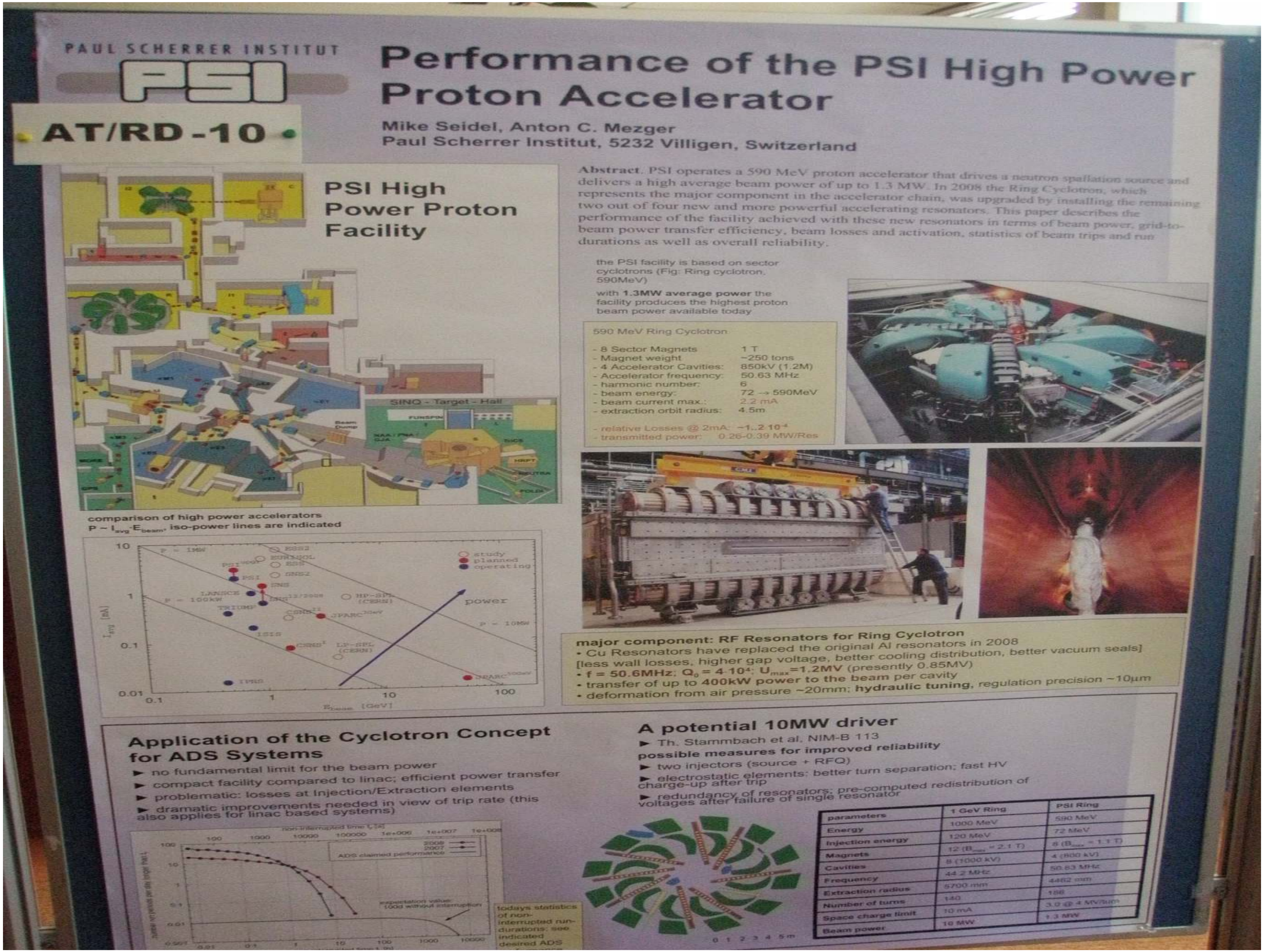
b. R&D Prog. On ADS in JAE (Takei et al., ADS/INT-04).

c. JINR-Dubna, e.g. Nuclotron: SC Synchrotron for Q-G Plasma.

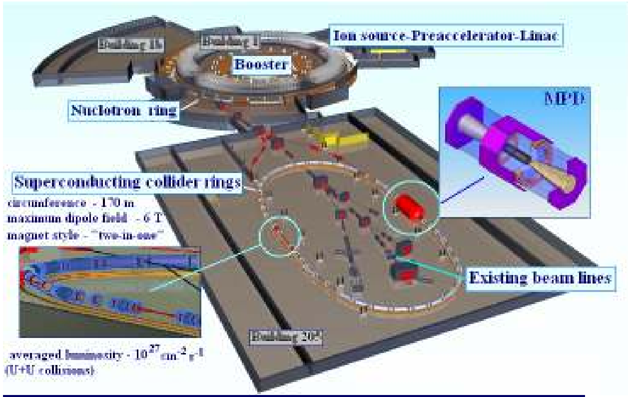
d. The Proton Eng. Frontier Proj. (Kim et al,AP/IA-08), LINAC.

e. ARRONAX, 70 MeV Cyclotron (Martino et al., AP/IA-11).

f. Very compact SC Cyclotrons (Lanza et al.)

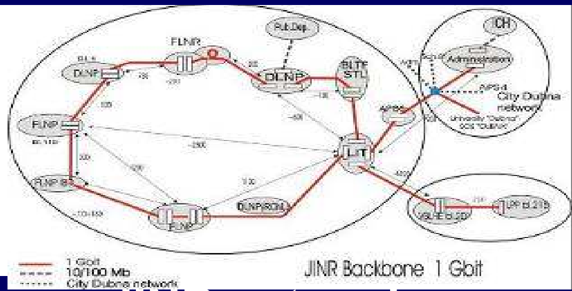

PAUL SCHERRER INSTITUT
PSI
AT/RD -10
Performance of the PSI High Power Proton Accelerator
Mike Seidel, Anton C. Mezger
Paul Scherrer Institut, 5232 Villigen, Switzerland
Abstract. PSI operates a 590 MeV proton accelerator that drives a neutron spallation source and delivers a high average beam power of up to 1.3 MW. In 2008 the Ring Cyclotron, which represents the major component in the accelerator chain, was upgraded by installing the remaining two out of four new and more powerful accelerating resonators. This paper describes the performance of the facility achieved with these new resonators in terms of beam power, grid-to-beam power transfer efficiency, beam losses and activation, statistics of beam trips and run durations as well as overall reliability.
PSI High Power Proton Facility
SINQ - Target - Hall
the PSI facility is based on sector cyclotrons (Fig: Ring cyclotron, 590MeV)
with 1.3MW average power the facility produces the highest proton beam power available today
590 MeV Ring Cyclotron
- 8 Sector Magnets 1 T
- Magnet weight ~250 tons
- 4 Accelerator Cavities: 850kV (1.2M)
- Accelerator frequency: 50.63 MHz
- harmonic number: 6
- beam energy: 72 → 590MeV
- beam current max.: 2.2 mA
- extraction orbit radius: 4.5m
- relative Losses @ 2mA: ~1..2 10⁻⁴
- transmitted power: 0.26-0.39 MW/Res
comparison of high power accelerators
P ~ I_avg·E_beam, iso-power lines are indicated
study
planned
operating
power
P = 1MW
P = 100kW
P = 10MW
E_beam [GeV]
I_avg [mA]
major component: RF Resonators for Ring Cyclotron
• Cu Resonators have replaced the original Al resonators in 2008
[less wall losses, higher gap voltage, better cooling distribution, better vacuum seals]
• f = 50.6MHz; Q₀ = 4·10⁴; U_max=1.2MV (presently 0.85MV)
• transfer of up to 400kW power to the beam per cavity
• deformation from air pressure ~20mm; hydraulic tuning, regulation precision ~10µm
Application of the Cyclotron Concept for ADS Systems
► no fundamental limit for the beam power
► compact facility compared to linac; efficient power transfer
► problematic: losses at Injection/Extraction elements
► dramatic improvements needed in view of trip rate (this also applies for linac based systems)
ADS claimed performance
todays statistics of non-interrupted run-durations: see indicated desired ADS
A potential 10MW driver
► Th. Stammbach et al, NIM-B 113
possible measures for improved reliability
► two injectors (source + RFQ)
► electrostatic elements: better turn separation; fast HV charge-up after trip
► redundancy of resonators; pre-computed redistribution of voltages after failure of single resonator
parameters | 1 GeV Ring | PSI Ring
Energy | 1000 MeV | 590 MeV
Injection energy | 120 MeV | 72 MeV
Magnets | 12 (B_max = 2.1 T) | 8 (B_max = 1.1 T)
Cavities | 8 (1000 kV) | 4 (800 kV)
Frequency | 44.2 MHz | 50.63 MHz
Extraction radius | 5700 mm | 4462 mm
Number of turns | 140 | 186
Space charge limit | 10 mA | 3.0 @ 4 MV/turn
Beam power | 10 MW | 1.3 MW

Upgrade and Development of JINR Basic Facilities

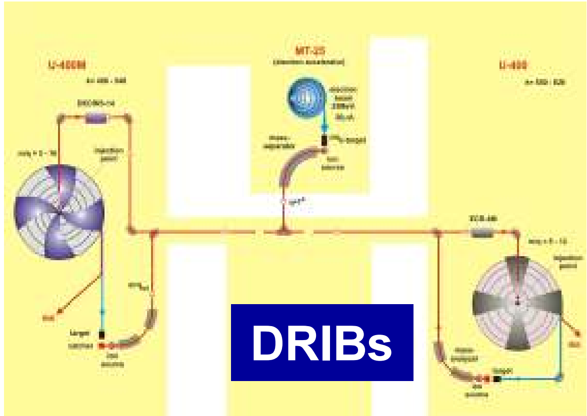


Upgraded Nuclotron-M (2009) + NICA (2013-2014)

Telecommunication channels:
77 Gbps – November 2008,



JINR networks, including GRID technology

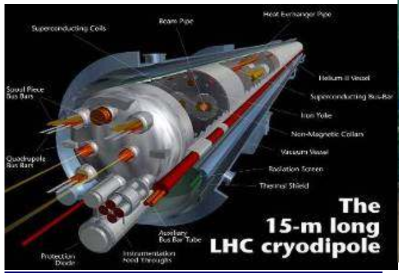


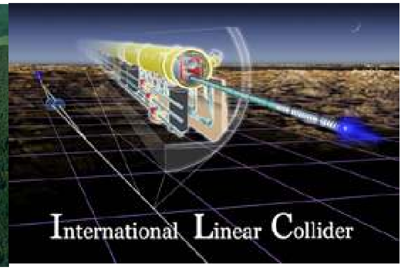
DRIBs

second phase 2009

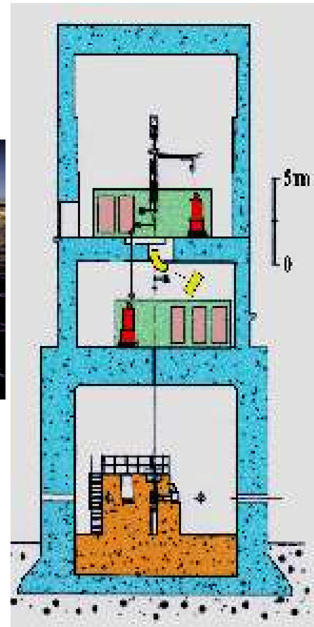
Participating in LHC, RHIC, TEVATRON…
In future: FAIR, ILC …

New reactor IBR-2M 2010





IREN-I 2008



1. The Proton Engineering Frontier Project
Overview of PEFP
Project : Proton Engineering Frontier Project (PEFP)
21C Frontier R&D Program, MEST, Republic of Korea
Objectives :
- To develop a High Power Proton Linac (100MeV, 20mA)
- To develop Beam Utilization & Accelerator Application Technologies
- To Industrialize Developed Technologies
Period : July 2002 – March 2012 (10 years)
Budget : 128.6 B KRW (Gov. 115.7 B, Private 12.9 B)
(Gyeongju City : Site, Buildings & Supporting Facilities)
Schematics of PEFP Linac & Beamlines
Beam Dump
DTL II
MEBT
DTL I
RFQ
Injector
100 MeV
20 MeV
3 MeV
50 keV
TR105
TR101
TR25
TR21
AC
100 MeV Beamlines
20 MeV Beamlines
TR104
TR103
TR102
TR24
TR23
TR22
Parameter | DTL I | DTL II
Energy (MeV) | 20 | 100
Peak Beam Current (mA) | 1 ~ 20 | 1 ~ 20
Max. Beam Duty (%) | 24 | 8
Avg. Beam Current (mA) | 0.1 ~ 4.8 | 0.1 ~ 1.6
Pulse Length (ms) | 0.1 ~ 2 | 0.1 ~ 1.33
Max. Repetition Rate (Hz) | 120 | 60
Max. Avg. Beam Power (kW) | 96 | 160
3. Status of Beam Utilization and Applications
User Program Development (2003~)
Built up a strong community of proton beam users
Diversified R&D fields using proton beam
Proton beam users
Irradiated Samples
R&D Activities
Application of ion-cut technology
SOI, GOI wafer fabrication
Control carrier lifetimes of semiconductor
Improved switching speed of FRD & IGBT by more than 5 times
Before irradiation
After irradiation
Fabrication of hybrid nano-logic device
- n-type nanowire + p-type nanotube
Developed mutants of plants & vegetables
Developed biodegradable plastic materials
Fabrication of metallic nano-particles
Gold, Platinum, Silver
Silver nano particle (SEM images)
Mutated E-coli to produce PHB, PHBV
Silver nano crystal (Flower) formation
Application of accelerator technology
Developed an ion implanter and installed at Advanced Radiation Technology Institute
Transferred industrial ion implanter tech
Application of ion beam mixing technology
SiC film coating on Mg alloy
Medical applications
Radio isotope production
Investigated mechanism
Energy | 50 ~ 300 keV
Beam current | 5 mA
Ions | H, He, N, Ar, Kr, Xe
*This work was supported by the Ministry of Education, Science and Technology of the Republic of Korea
2. Status of Accelerator & Beam Facility Develop
Status of Accelerator Development
PEFP 20 MeV Linac
Extracted first beam (July 2005)
Obtained operation license (June 2007) : Avg. current: 0.1 μA, Rep. Rate: 0.1 Hz, 4 hr
Started beam service (June 2007) : 281 irradiation experiments performed
Revised operation permit (April 2008) : Avg. current: 1.0 μA, Rep. Rate: 1 Hz, 4 hrs/we
Achieved designed performance (May 2008)
Klystron (RFQ)
Waveguide
Klystron (DTL)
Target Station
Beam Profile
4cm
Peak Beam
Beam Energy
Ion Source
LEBT
3 MeV RFQ
20 MeV DTL
Development of Beam Facilities
20 MeV Beamlines
100 MeV Beamlines
Quadrupole
AC Dipole
4. R&D Activities for the Future
An Expansion Option of the PEFP
Phase II (2012 ~)
Phase I (2002 ~ 2012)
RCS
Neutron Facility
Muon Facility
100 MeV Beam Facilities
20 MeV Beam Facilities
Spallation Neutron Source
- 100 (200) MeV Linac + 1 (2) GeV RCS
- Beam Power : ~ 0.5 MW
- Slow Extraction (@ 450 MeV)
R&D Activities
- 1(2) GeV Rapid Cycling Synchrotron
- Superconducting Linac (200 MeV)
- RF Source (700 MHz, 1 MW CW Klystron)
- Spallation Neutron Target (MEGAPIE)
SRF Cavity
700 MHz, 1 MW (CW) Klystron
5. Summary
100 MeV, 20 mA Proton Linac & Beamlines
20 MeV Linac :
- Completed & in beam service
- Achieved designed beam energy & current
Higher energy part:
- 20~57 MeV DTL : fabricated and tested
- > 57 MeV DTL : to be produced as schedule
To relocate the 20 MeV linac to the site in April 2011
To complete the 100 MeV linac & beamlines by March 20
User Programs & Facilities
Cultivated and fostered user programs in wide R&D fields
Produced promising outcomes
Activities for the Future (a Spallation Neutron Source)
R&D in SCL, RCS, RF Power Source, Spallation Neutron Target

Final remarks

- This meeting proves that there is a significant activity in accelerator development due to the highly relevant applications in such fields as:
  1. ADS programs for nuclear waste transmutation and power generation.
  2. Medicine: Proton and hadrontherapy (including BNCT), Isotope production,..
  3. Accelerator-based neutron sources for: cargo inspection, neutron diffraction (material research..), nuclear physics (astro, structure,..), ..
  4. Accelerators for: industrial applications (implantation,..), ion beam analysis, damage simulation, environmental problems, nuclear physics, education and training, etc., etc.

We thank IAEA, ANS, and all organizers and contributors for this excellent meeting.