Applications for Gas-Plasma Target Neutron Generators

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Abstract. The NSD-Fusion GmbH commercial development of Inertial Electrostatic Confinement fusion devices as neutron generators started in 1996. Technical progress was positive but business and finance circumstances where the delay factors. For commercial success the NSD neutron generator has to deliver approximately ten times longer operational lifetime or endurance and ten times greater output for a competitive price. There are additional characteristics which users deem to be advantageous. A range of conceptual applications are described with the intent to alert innovative applications developers to the potential of the NSD neutron generator family of products.

1. Introduction

The NSD-Fusion GmbH commercial development of Inertial Electrostatic Confinement fusion devices as neutron generators started in 1996 [1]. Technical progress was positive but business and finance circumstances where the factors which delayed market entry until recently. As this paper was being prepared the small NSD-Fusion company was being heavily loaded with contracted work for production of the basic neutron generator and accessories as well as preparations for several customer specified increased output neutron generator variants. Parallel to this growth of business activity the financial base that is needed to expand the business infrastructure was at last being realised.

For commercial success the NSD neutron generator has to deliver approximately ten times longer operational lifetime or endurance and ten times greater output for the price. There are additional unique characteristics which users deem to be advantageous. The range of technical characteristics is described below in order to teach about conceptual applications; some of which are described. Innovative developers may be alerted to the potential of the NSD neutron generator family of products for their applications. NSD-Fusion will enter into a project contract to further develop its product family to meet the customers' specifications. Over time these variants will be adapted for further applications.

2. Equipment

The neutron generator set consists of four main functional modules: the reaction chamber which emits neutrons, the high voltage power supply, a cooling sub-system and a central control unit.

2.1 Emission Unit

A linear geometry Inertial Electrostatic Confinement reaction chamber can be cylindrical or a planar array of neutron emission units. Rather than the classic spherical IEC, the linear configuration can have a central cathode electrode of arbitrary length. Together with the coaxial anode grounded vacuum vessel body this geometry delivers a fusion grade plasma gas zone of neutron emission. The standard NSD reaction chamber has an internal chamber diameter of approximately 70 mm. The neutron emissions are mostly in the central axial zone. The external diameter of the tubular housing is 135 mm. The vessel wall and heat transfer fins constitute the wall structure. At one end the high voltage ultra high vacuum feed through assembly is attached. At the other end a module houses the getter pump assembly. The reactant gas is stored within the sealed tube in the getter material. At a high temperature the partial pressure of Hydrogen or its isotopes Deuterium or Tritium is sufficient to enable a glow discharge plasma. The positive ions are attracted towards the cage like cathode by the electrostatic field with up to 120 kV applied. There are many charge exchange mechanisms within the plasma-gas mixture. Electrons are also accelerated towards the chamber wall. Bremsstrahlung radiation corresponding to the glow discharge voltage is therefore emitted.

2.1.1 No Solid Target

The commercial neutron generator development has produced high reliability components for the demanding plasma reaction chamber. A vital aspect is the longevity of the reaction chamber. The well known limitations of solid targets is avoided. There is no solid target. Conventional solid target seal tube neutron generators suffer from sputter erosion which leads to metal coatings on insulating surfaces and short circuits in the very high voltage environment. A further failing that many users of such devices have mentioned to NSD-Fusion is the accelerated failure of the sintered metal targets when subjected to extreme and frequent thermal cycling. In applications such as security inspection systems such neutron generators are required to be operated at full output for perhaps 30 seconds or longer and then switch off for a longer period of minutes before repeating the cycle. The thermal shock results in a metal fatigue failure mode leading to erratic neutron output. With a plasma-gas "target" this phenomena cannot occur. The cathode electrode is not immune from ion bombardment but it is a less severe factor. The original device which we refer to as the Mk0 spherical precursor to the present NSD device was operated at high input power for almost one year before management ordered the project to be cancelled. Diagnostic indicators showed that the sealed reaction chamber could have continued to operate for many years. The present NSD reaction chamber features a cathode which has been developed to entirely mitigate thermal shock and erosion ageing.

2.1.2 Re-usability

Unlike the classic sealed tube neutron generator devices the central assembly does not have to be destroyed by the manufacturer after it fails in service. Indeed ageing-like failure modes have been tested during the development of the NSD-NG. Even with an overheated and partially melted or vaporised electrode a high neutron yield continued. After replacement of the damaged component and cleaning the reaction chamber was as good as new. The NSD reaction chamber can be dismantled completely, refurbished and reassembled. Thus the few components can be replaced if necessary. Servicing intervals can be far apart. The use of Tritium will drive the fuel replenishment towards five years in order to maintain the D:T ratio. Sensitivity to Tritium decay has been tested.. Only a fill port has to be attached to the gas handling equipment for a purge and reload cycle. Activation of the reaction chamber or any other equipment in the neutron emission field is an issue which needs to be assessed for each new application.

2.2 Stability of output

After a brief running-in and electrode conditioning, the neutron output is steady. The voltage is determined by the glow discharge gas pressure. The output is a function of the voltage and current. In a DC system the current is regulated by the power supply electronics. The gas pressure is regulated by the getter pump which is temperature controlled to maintain the desired voltage. The stability of the system is remarkable. The repeatability of neutron output for the same voltage and current is similarly remarkable.

2.3 Quick start

A consequence of the non solid target and high repeatability of output with voltage and current is the ability to have a near instant switch in to high output. There is no need to run the generator up from a low power input start. Thus security neutron interrogation applications can benefit.

The reaction chamber is however required to be in stand-by mode first. This means that the getter pump has been pre-heated for approximately 15 minutes so that the gas pressure is ready for operation. The getter pump heat power requirement is only 10 W in steady state after warm-up.

2.4 Configurations

Conventional solid target neutron generators are mostly point sources. Some recently developed neutron generator devices feature solid targets that are conical or annular cylinder or linear rods. Changing the form of these appears to be prohibitively complicated.

2.4.1 Line Source

The NSD-NG has a potential versatility for industrial applications. A point source or nearly point source will give rise to the well known inverse square law of attenuation of the emitted flux. Utilization of a line source or even a planar source can mitigate the distance related losses in the near field to the linear or planar source. The figure 1 illustrates some configurations which can be readily achieved.

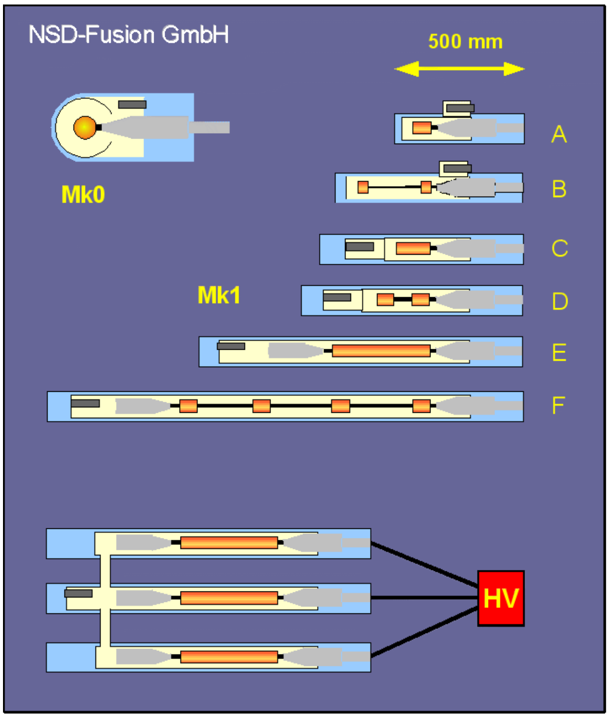

Fig. 1 Linear configuration possibilities

2.4.2 Short Electrode

The length of a short electrode version has to be matched to the maximum input power. The present lowest power system is rated to 1.8 kW. Figures 2 and 3 show the short electrode reaction chamber which is capable of 2×10^7 DD n/s (or 1.6×10^9 DT n/s) in DC non pulsed mode. This unit is force air cooled.

Fig. 2 Reaction chamber with cowling cover installed

Fig. 3 Reaction chamber without the cover

2.4.3 Long Segmented Source

A particularly important class of configuration is the long segmented electrode. The segmentation takes into account the necessity to support a long structure. The segments are electrodes while the inter-electrode conductors are shielded by high voltage stand-off support structures. It is feasible to construct such a neutron generator to be many meters in length. Indeed a goal is to develop a 12 m long segmented electrode sealed reaction chamber for illumination of inter-modal transport containers (see section 3.1).

2.4.4 Planar and Coded Source

In the planar electrode configuration an improvement can enable a high efficiency radiography. Imposing a coded aperture mask between the ion beam and the solid target has been proposed [2]. However this concept would suffer losses when the ion beam hits the mask. More complex switching strategies can be envisaged but this would add to the complexity. The planar IEC type electrode grid enables another form of coded aperture where there is no mask to greatly increase losses [3]. The planar cage array is selectively blocked so that some of its cells are open and some are blocked by suitable ceramic insulation material. The ionization energy is redistributed to the available open grid cells. The result is a rectilinear raster pattern of emission zones which provide the image deconvolution source data. The characteristic dimensions of the coded source array can be some metres if required.

At the small end of the equipment size spectrum, internal neutron emission topology may be used. If viewed end-on the channelled ions within the glow discharge plasma may have a neutron origin topology somewhat like flower petals. This topology can also be utilized for fast neutron radiography image deconvolution as illustrated in figure 4.

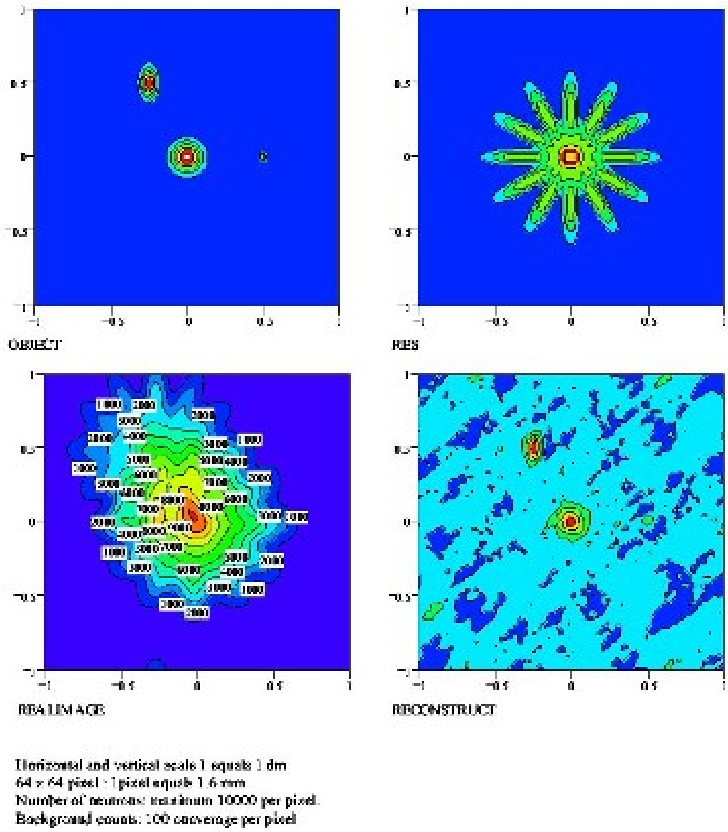

Fig. 4 Example of deconvolution based on neutron origin topology within the linear IEC device viewed end-on. Simulation by V. de Haan

2.4.5 Multi-head

It is feasible to manifold a cluster of reaction chambers to use one common gas source. The pressure is then the same in each chamber without great measurement and control system complexity. Such an approach may be expedient for very high output systems. Common already developed hardware can be clustered for greater neutron output.

2.5 Pulse Mode

Pulsed neutrons are often specified for enhancement of Prompt Gamma Neutron Activation Analysis and other methods which require quiet time between bursts or pulses.

The pulse durations utilized for some Time of Flight methods are not regarded as feasible in the IEC type of plasma device. A pulse duration in the range of 2 to 20 μsec is regarded as useful for a wide range of pulsed neutron applications.

Pulsed high voltage power brings an advantage over DC operation. The IEC research literature has reported that neutron yield above that of proportionality to the input current has been observed. The super linearity factor may be current to the power 1.5. This may sound minimal but it is close to a gain of 10 over the DC case. A pulsed high voltage power supply is more costly that its DC power equivalent but the tenfold gain of neutron output makes this affordable.

NSD-Fusion was, at the time of writing, preparing for a an experiment to measure the temporal profile of neutrons pulsed from a version of the NSD-NG. Development of the high end pulser was scheduled to begin for another corporate customer. High density high voltage and high current per pulse power technology has been adopted for the pulsed neutron variants.

2.6 Specifics

A specific performance of 1 kW of input power per 20 mm of cage electrode length is the design rule. With 115 kV and 15 mA of DC power a steady and stable Deuterium-Deuterium yield of 2E7 n/s is achieved. By lengthening the electrode more input power can be accepted. A Deuterium-Tritium gas mixture gives a factor of approximately 80 yield gain.

3 Applications

Practical applications of point neutron sources, radionuclide or electric generator are of course well documented. In some cases multiple point sources are arranged to provide a quasi line source. Even planar sources based on ^{252}Cf enclosed in a suitable planar form have been considered.

3.1 Large Objects

The neutron interrogation of large objects has been implemented by various researchers and commercial groups by means of point source solid target neutron generators. Large objects may be defined as those where the attenuation with distance of the neutron flux becomes too low at the extremities of the large object. By reducing the sensitivity to distance through a line or planar source the size of the object may be increased.

An EU funded project was started recently. Previous attempts have been made with neutrons to analyse the alloy element bulk composition of steel scrap. These we not successful. One factor was the limitation of using a point source neutron generator with limited output. The present Scrap-Probe project will use MCNP and similar radiation transport modelling tools to assess PGNAA system configurations that can take advantage of the availability of the versatile NSD-NG. Only after the system model optimization will the achievable NSD-NG be specified.

Another application in this class is the so called ContainerProbe. A separate paper discusses the concept. The research and development goal is to achieve a commercially viable system to obtain neutron interrogation profiles for each and every shipping container that passes through the measurement portal while in motion.

At the small end of the object size spectrum applications are envisaged for luggage interrogation while in motion. The concept was first described by STC RATEC of St. Petersburg, Russia in the early 1990's [4]. However the need for a series of point sources was an inhibiting factor. The long segmented electrode NSD neutron generator is now incorporated into plans for the "tunnel" baggage inspection system. Precursor RATEC baggage interrogation systems will utilize long NSD-NGs for better "illumination" of the baggage items and much improved neutron generator life. Such a system could also be adapted to parcel security checks without imaging the contents. As each object moves through the "tunnel" a commutation process accumulates the observation time so that the necessary gamma detection and spectroscopy statistical significance can be increased.

Another adaptation of the long neutron generator is a mail bomb detection system. In this application the transit time of a letter is so fast that a scanner may not provide sufficient time for prompt gammas to be detected. The exposure and detection time need to be increased. Having the letters take a spiral locus about the line source would mitigate neutron flux intensity and consequential system shielding. Various other applications using this type of feature have and may be envisaged. Detailed systematic project work is only beginning for some of the examples or it is poised to begin with the creation of a business initiative.

Industrial applications ranging from materials recycling to agriculture and the classic mineral PGNAA sector are seeking a better neutron source. NSD-Fusion and probably its commercial competitors are receiving ever more frequent enquiries from a wide range of industries which need neutron based quality assurance techniques. Many of these emerging applications definitely require the line source characteristic as well as economic life cycle costs. Longevity of the neutron generator on a scale of years in running mode is a key factor.

3.2 Nuclear Power Industry

Enquiries from the nuclear fission power industry indicate a growing concern or dissatisfaction with ^{252}Cf or similar sources and with the presently available solid target neutron generators. NSD-Fusion is engaged to develop its high end pulsed neutron generator for a corporate customer who has been developing a quality assurance measurement technique.

Accelerator driven systems developers should take a look at the potential to use a cluster of long neutron generators. The dimensions are similar to those of fuel or control rods. The development of a high temperature environment variant for in core operation appears to be feasible.

3.3 Radiography and Tomography

Illumination of objects to be imaged by fast neutron scattering or by tomographic gamma imaging means requires characteristics which have been mentioned above.

Enquiries from industries such as semiconductor, aerospace and precision machinery component manufacturers to aircraft maintenance operators show that neutron imaging has much potential.

3.4 Activation Survey

There is little information available about the relationship between exposure to neutron flux and the consequential level of activation. A broad survey project with many nuclear engineering and radiochemistry departments participating can be envisaged. A vital standard component for such a distributed project will be the neutron source. The reader should not be surprised that we advocate the NSD-NG.

4. Market Cultivation

NSD-Fusion does not offer a one stop shop service to develop neutron applications system. However many enquiries a seeking such a service. Our solution is to engage a network of selected technical consultants in university or research institutes and self employed specialists with unique skills and tools who have be engaged for specific projects for the client. By this arrangement an applications system can be designed and implemented as a prototype. The client corporation then has the option of taking the project further for a single installation or a global market. This business model has already been successful in gaining phased development contracts from major corporate customers and single purchase customers. In the later case NSD-Fusion was asked to implement a mobile shielding system for a research institute client. This has enabled the initial development of a cost effective shielding material at a relatively low cost of manufacture. The availability of this peripheral accessory which is tailored to accommodate the basic NSD-NG reaction chamber provides the solution to those who need neutrons but lack a dedicated radiation "bunker" facility.

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