# Development of Advanced Neutron/Gamma Generators for Imaging and Active Interrogation Applications

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## ABSTRACT

We report here on the development of neutron and photon sources for use in imaging and active interrogation applications, where there is a growing urgency for more advanced interrogation tools. These devices include high yield D-D, D-T and T-T fusion reaction based neutron generators and also low energy nuclear reaction based high-energy gamma generators. One common feature in these various devices is the use of a high-efficiency, RF-induction discharge ion source. This discharge method provides high plasma density for high output current, high atomic species from molecular gases for high efficiency neutron or gamma generation and long lifetime. Predictable discharge characteristics of these plasma generators allow accurate modeling for both the beam dynamics and for the heat loads at the target spot. Current status of the neutron and gamma generator development with experimental data will be presented.

Key words: Neutron Generator, Gamma Generator, Low energy accelerator, Neutron interrogation

## 1. INTRODUCTION

The radiation producing devices developed by Plasma and Ion Source Technology Group at Lawrence Berkeley National Laboratory are utilizing powerful RF-induction discharge, low energy accelerator structures and actively water-cooled beam targets. The RF-induction discharge method provides high plasma density for high ion output current, high atomic species from molecular gases, such as hydrogen, deuterium and tritium, long life operation with stable operation characteristics and versatility for various discharge chamber geometries enabling development of devices of diverse geometries. DC beam accelerators are utilized either in single gap diode or multigap accelerator column configurations. The actively water-cooled target provides high beam power handling capability with various target materials. Three devices are discussed in this presentation: two neutron generators, one for neutron imaging applications and one for Pulsed Fast Neutron Transmission Spectroscopy (PFNTS) based cargo interrogation system and a gamma generator for active interrogation of nuclear materials based on photofission and photoneutron detection. Some of these sources have been highlighted in previous conferences[1,2,3]. The specifications of these sources are given in the following chapters, highlighting the applications, the performance and experimental data for each of these three sources.

## 2. D-D NEUTRON GENERATOR FOR IMAGING APPLICATIONS

Fast neutron radiography is a nondestructive testing technique complementary to conventional radiography[4,5]. In x- and gamma radiography, attenuation increases uniformly with mass number and density, whereas, with neutrons, attenuation

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is random with a tendency for certain light elements such as hydrogen to absorb and scatter neutrons well. Higher Z elements such as Fe and even U can transmit fast neutrons well, thus permitting the imaging of voids and hydrogen-bearing materials inside high density materials.

As in all imaging, both contrast and resolution will determine if the image is adequate for proper identification of the object or defect. The contrast that is obtained in neutron radiography is quite different from that obtained with x-rays. Indeed, since the process of absorption is different (one is nuclear while the other in atomic in origin) there is no rule that describes the difference between neutron and x-ray attenuation and contrast. In addition, neutrons behave very differently at fast and thermal neutron energies.

A high brightness fast neutron source is much easier to obtain since no moderator is required. Compared to thermal neutrons, there is very little attenuation among elements with fast 1.9 MeV neutrons. However, the attenuation is low for MeV energy neutrons. This allows fast neutrons to penetrate very thick materials. The fast neutron penetration does depend upon nuclei density, and thus regions with significant density variation such as cracks and voids can be imaged. Indeed, from comparing the linear attenuation coefficients of materials for x-rays and neutrons, it is evident that fast neutrons can penetrate some materials far more readily than can 10 MeV photons. In addition, fast neutrons retain their high absorption in hydrogen bearing materials. Consequently, there will be some inspections that are ideally suited for fast neutron imaging.

Recently demonstrated systems have utilized the ability of fast neutron radiography to identify the composition of imaged materials, including elemental information. Already, a system has been brought out of the laboratory and into the commercial world. That system, using fast-neutron radiography, is currently in operation at Brisbane International Airport, Australia, and is regularly used for air cargo container screening[6]. Historically, neutron radiography has not moved out of the research reactor laboratory to wider industry use. The reasons have been the need for an intense neutron source to replace the neutron-producing reactor, and the low resolution of neutron detectors, most of which are not electronic. The development of imaging techniques that require lower total neutron exposures than traditional methods, coupled with improvements in a higher intensity compact source, suggests that broader applications of neutron radiography may be imminent. The Plasma and Ion Source Technology Group has developed a neutron generator design with high beam power capability for imaging applications of water-cooling pipes in a reactor environment. The imaging neutron generator has a 4 mm spot size on the axis. Assuming the pipe sizes that we want to image are roughly 10 cm in diameter and that the detector is placed directly behind the pipe, then the resolution will be 0.4 mm for a source-to object distance of 1 m. Smaller spot sizes are possible depending upon the geometry adopted.

### 2.1. Specifications of the Imaging Neutron Generator

The baseline design of the Imaging Neutron Generator (ING) follows closely the design of the previous generation axial D-D neutron generators. While this previous generation of single ion beam axial neutron generators can provide up to $10^8$ n/s D-D neutron yield, the specification for the imaging neutron generator was 10 times higher. The beam power goal is 1000 W in cw operation. Special emphasis was put into developing a target that can be reliably operated at high beam power with a small beam spot. It has been shown before[1] that in the case of beam loaded neutron target, the surface temperature of the target has a critical role in the neutron yield. If a titanium target surface is operated at excessive temperature (>200 $^{o}$C), the neutron yield will drop due to deuterium desorption from the titanium bulk. This can be avoided if the beam power density is lowered or more heat resistant hydrogen absorbing material is used. The approach chosen for the ING is to use conical shape target to increase the surface area of the target, while on the axis, retaining a small neutron emission area. The specifications of the ING are highlighted in Table 1.

Table 1. The specifications of the D-D Imaging Neutron Generator

| Beam Spot Size [mm] | Beam Current [mA] | Acceleration Voltage [kV] | Target Cone Length [mm] | Target Cone Diameter [mm] | Neutron Yield [n/s] |
|---|---|---|---|---|---|
| $\phi$4 | 6 | 120 | 60 | 6 | $10^9$ n/s |

### 2.2. Ion Optics Simulations

The ion optics design was an important consideration for the ING. There are two separate goals for the ion beam trajectory analysis: first to determine the beam spot size on the axis of the generator, and second to determine the ion beam generated heat load on the target surface. The first is an important consideration for the minimum resolution obtained from the imaging system and the second is important for the neutron output of the generator. The neutron yield is dependent on the surface temperature of the target layer. The widely known limit for the surface target temperature is approximately 200°C–250°C[7]. Target surface temperatures are difficult to measure directly with required accuracies. ANSYS[8] calculations were made to determine the dependence of the beam power density at the target surface and the beam power density when 0.5 mm titanium layer on actively water-cooled copper bulk is used. The result is shown in Figure 1.

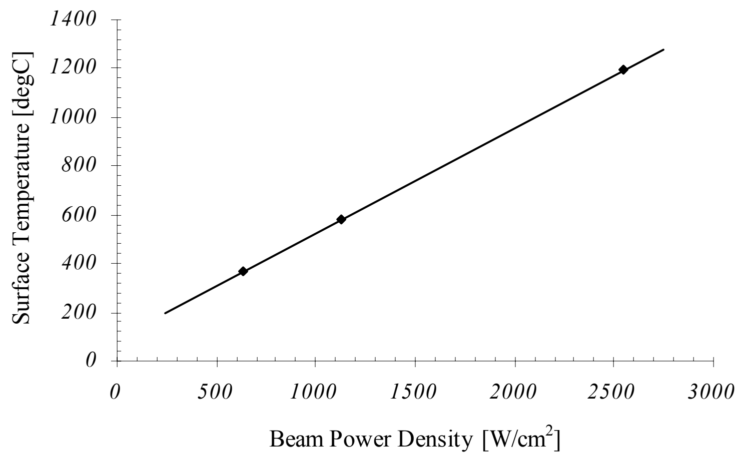


Fig 1. Surface target temperature as a function of beam power density on 0.5 mm titanium layer on copper.

The maximum power density at the target is thus 500 W/cm$^2$ in the case where the titanium layer is relatively thick and the backing material is well water-cooled. For the higher power neutron generators, the target surface area has to be increased to compensate for the increased power. In the case of the ING, a conical shape target was chosen. The target was fabricated at Advanced Powders and Coatings at Montreal, Canada. The company has a proprietary process, which allows deep, small angle titanium coated metal cones to be manufactured. The target that is used in the ING, is 6 mm in diameter opening and 60 mm deep with 0.5 mm titanium coating on a copper backing. In order to determine the power density at the target surface of the cone, the ion beam optics had to be simulated. The beam optics were simulated with the 2D ion extraction and simulation code IGUN[9]. The result of the simulation is shown in Figure 2.

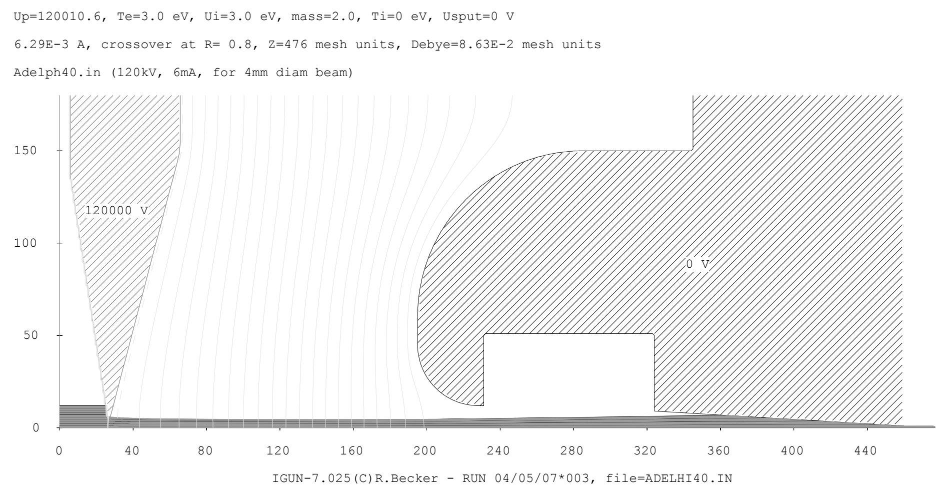


Fig. 2. The ING ion beam extraction and transport simulation. The beam spot size at the target cone is ~4 mm in diameter.

The resulting beam power density at the target surface in the case of ING's cone shaped target is approximately 270 W/cm$^2$. The relatively high beam power with small beam spot on the axis of the neutron generator can be achieved.

## 2.3. Imaging Neutron Generator Design

The neutron generator has three main components: the ion source, target and an accelerator system with HV insulator. For the ING there were special requirements for the target, mentioned above. Also the ion source had, preferably, to operate at few mTorr internal deuterium gas pressures for low a gas load in the pumping system. For the same reason the ion source should generate relatively high plasma density and high extractable current density. Also it is important to have high atomic ion species distribution from the ion source for high efficiency operation. Two options for the ion source were considered. The first option utilizes an innovative spiral RF-antenna ion source with actively water-cooled quartz RF-windows. This type of RF-antenna arrangement has been successfully operated with air-cooling. The challenge was to develop active water-cooling for the quartz window that would allow high power operation. An approach was chosen in which the quartz disk is edge-cooled with water. Due to the low heat expansion coefficient of the quartz, the temperature gradient across the surface would not compromise the integrity of the disk. The second option for the ion source is to extend the standard external antenna, water-cooled design to larger diameter (from 3" to 4") in order to enable lower pressure operation. The drawback of such a design is the lower plasma density leading to lower extractable current density compared to a 3" source design. The final source version will be selected based on the performance of these two ion source approaches. The target assembly of the ING will position the target cone in a holder structure, which allows the cooling water to flow around the cone. The holder structure is designed in a manner that facilitates the easy replacement of the cone itself. It also positions the target opening accurately on the axis of the generator. A third unique feature of the ING is the use of a semiconducting high voltage insulator and shroud support. The semiconducting insulator is made by Elcon Inc. at San Jose, CA using a proprietary processes. The insulator is coated with a $TiCrO_3$ layer. This allows the resistivity of the alumina to drop from >$10^{14}$ Ohm·cm to ~$10^{10}$ Ohm·cm which creates a small current drain along the surface of the insulator. This in turn minimizes the sparking caused by charge accumulation on the insulator surface. The overall design of the ING is shown in Figure 3. The ING will be fabricated and assembled at Plasma and Ion Source Technology Group at LBNL during early spring 2007.

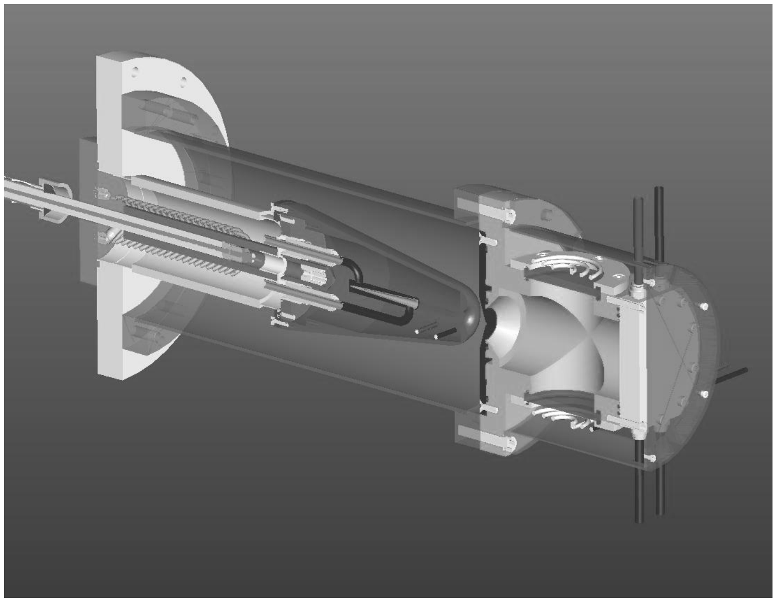

Fig. 3. Imaging Neutron Generator. Note the two-window, actively water-cooled, spiral antenna ion source, cone shape target and high voltage insulator with low resistivity coating.

## 3. COMPACT AXIAL-TYPE GAMMA TUBE

Detecting and characterizing shielded fissionable material is a difficult problem. Conventional passive methods rely on spectroscopy of low-energy (less than 500 keV) gamma rays from natural decay, but this approach is not suitable when thick shielding is present. For example, the attenuation of 500 keV gamma-rays is such that only about 20% (1%) penetrate 2.54 cm of steel (or lead) shielding. Higher energy gamma-ray signals can be produced by the fission products resulting from photofission-induced active interrogation. Earlier studies of the mass distributions resulting from photofission of uranium and plutonium isotopes[10] found that the centroid for the high mass distribution is nearly constant, while the low mass distribution changes almost linearly with the mass of the target. These observations suggest that unique higher energy gamma-ray intensity distributions exist for each fissionable isotope and, thus, it may also be possible to perform isotopic assays of shielded nuclear materials. Typically a high-energy bremsstrahlung source (linac) would be used to interrogate the nuclear material, but the drawbacks to this type of source are that most of the produced photons are too low in energy to cause photofission and only contribute to the resulting dose.

One type of Gamma Tube (GT) we are developing will be capable of producing monochromatic 6 MeV and 12 MeV gamma-rays for photofission interrogation of fissile material. The GT is based on using low-energy (few hundred keV) proton-induced nuclear reactions that can be reached by a compact low energy beam generator, thus eliminating the need for a large particle accelerator. The operational basis for the system draws from an axial-type RF-ion source driven neutron generator system developed at LBNL. In the case of a Gamma Tube, low-energy protons bombard a target, rich with element generating gammas by the (p,$\gamma$)-reaction. The photofission cross section for both $^{235}$U and $^{238}$U slightly above the 5.8 MeV threshold is approximately 5 mb while, at 12 MeV energy, the photofission cross sections are 250 mb and 100 mb, respectively. By operating as a dual-energy photon source one would have the capability to perform isotopic assays of shielded nuclear materials by selecting the photon energies to either be near or well above the threshold for photofission. A fluorine-based target provides 6 MeV photons via the $^{19}$F(p,$\alpha\gamma$)$^{16}$O reaction at 340 keV proton energy. Similarly, the $^{11}$B(p,$\gamma$)$^{12}$C reaction at 163 keV could be used to produce 12 MeV photons. Other interesting reactions[11] are highlighted in Table 2. Additional enrichment information could also be obtained by spectroscopic analysis of the delayed gamma-rays from photofission[12]. Detecting the delayed gamma signatures would require operating in a pulsed mode, which would also have the added benefit of improving the signal-to-noise by incorporating background subtraction.

The purpose of the gamma generator development program is to explore suitable technologies to be able to fabricate a relatively compact device that would be able to operate reliably at the required voltages. The device fabrication for the 6/12-MeV GT is divided into two phases: in the first phase a $^{11}B(p, \gamma)^{12}C$-reaction capable tube will be designed and fabricated, while in the second phase a second device is fabricated, capable of operating with both the $^{11}B(p, \gamma)^{12}C$-reaction and $^{19}F(p, \alpha\gamma)^{16}O$-reaction. The first phase of the project has been finished. The 180 kV capable gamma tube design is highlighted in the following.

Table 2. Low energy nuclear reactions for high energy gamma generation with Gamma Tube

| Proton Energy [keV] | Reaction | Gamma Energy [MeV] | Cross Section [mb] |
|---|---|---|---|
| **163** | **$^{11}B(p, \gamma)^{12}C$** | **11.7** | **0.157** |
| 224 | $^{19}F(p, \alpha\gamma)^{16}O$ | 6.1, 6.9, 7.1 | 0.2 |
| 330 | $^{9}Be(p, \gamma)^{10}B$ | 5.2, 6.2, 6.9 | - |
| **340** | **$^{19}F(p, \alpha\gamma)^{16}O$** | **6.1** | **160** |
| 441 | $^{7}Li(p, \gamma)^{8}Be$ | 12.2, 14.7, 17.6 | 6 |

### 3.1. Specifications of the First Generation Gamma Tube

A $^{11}B(p, \gamma)^{12}C$-based axial-type Gamma Tube has been designed and fabricated at the Plasma and Ion Source Technology Group at LBNL. The design of the tube follows the LBNL single beam axial neutron generator design approach, where an RF-induction ion source is used together with an accelerator section and target. The differences between these two devices are mainly in replacing deuterium with hydrogen as the operating gas in the ion source, the acceleration column design, the choice of target material, and the design of the pumping section of the tube. Generally the neutron generators are single gap accelerator devices, where the $D^+$ ions are accelerated in the tube with a potential difference set in a single gap. In the case of gamma tube, the higher voltage requirement necessitated the use of a multi-gap acceleration column. These columns are commercially available, and the one used in the first generation gamma tube is manufactured by National Electrostatics Corporation[13] (NEC). The specifications on the acceleration column require the use of pressurized $SF_6$ gas-insulation outside the column. Also the specified maximum pressure inside the column is $<10^{-5}$ Torr. These two requirements meant that the Gamma Tube has to be designed with $SF_6$ pressure vessel surrounding the accelerator column and differential pumping in order to reduce the gas pressure inside the column. The boron-rich target selected for initial use in the Gamma Tube is $LaB_6$ because its high temperature properties are well suited for the target applications.

To reduce the footprint of the first gamma tube, the RF-matching network and the turbo molecular pumps were integrated at the tube. Initially the Gamma Tube was designed for cw operation with moderate beam current. During the course of the screening system study, the need for pulsed beams was expressed. Presently, the first phase Gamma Tube can pulse the beam by switching the RF-power. The RF-switching has been shown to be able to generated pulse widths of few hundred micro-seconds[14]. The specifications of the first generation Gamma Tube are highlighted in Table 3. It also shows the estimated maximum performance of the device.

Table 3. The specifications of the Gamma Tube. The nominal values are highlighted in bold. Also the estimated maximum values are shown.

| | |
|---|---|
| **Nominal Beam Energy** | **200 keV** |
| Maximum Beam Energy | 355 keV |
| **Nominal Beam Current** | **2 mA** |
| Maximum Beam Current | 20 mA |
| **Target Material** | **$LaB_6$** |
| Alternative Target Material | Boron Chrystal |
| **Nominal Operation Mode** | **cw** |
| Pulsing Capability | Yes |
| Method of Pulsing | RF switching |
| Pulse width | >2 ms |
| Repetition Rate | >1% |
| **Gamma Yield (est.)** | **$10^5$-$10^6$ $s^{-1}$** |

### 3.2. Ion Optics Simulations for the Gamma Tube

The Gamma Tube ion extraction and accelerator system consists of a puller electrode, accelerator column and a biased target. The ion optics considerations for the Gamma Tube are important, although the emphasis of the simulations is different than in the case of neutron generators. The ion beam has to be extracted from the ion source in a manner that stray beam cannot impinge on the accelerator column electrodes. This would result a high voltage breakdown, due to high energy avalanche of secondary electrons. The beam spot considerations on the other hand were a secondary issue. In the Gamma Tube case, the target is not beam loaded, rather the bulk of the material inherently contains the target atoms needed for the nuclear reaction, namely $^{11}B$. Thus temperature considerations of the target were merely to ensure the mechanical integrity of the target. The ion beam behavior at the extraction and at the accelerator column was simulated with IGUN. An ion optics simulation of the Gamma Tube is shown in Figure 4.

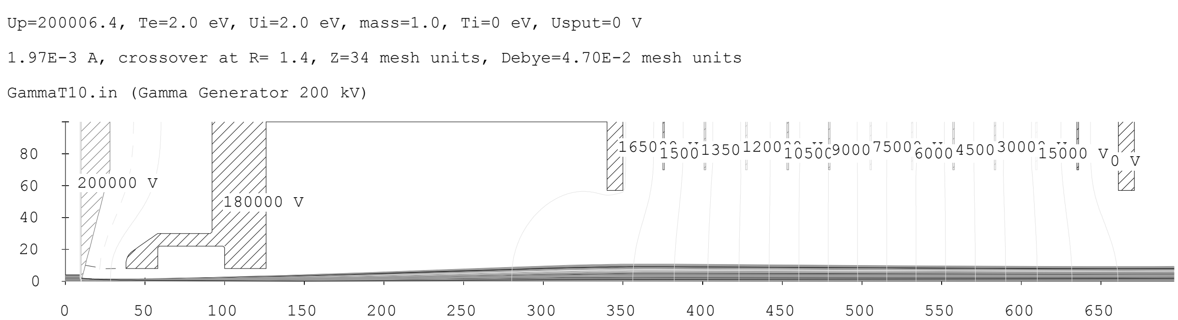


Fig. 4. Ion beam extraction and transport simulation. The ion beam has end energy of 200 keV and the current is ~2 mA. The beam spot size in the end of the simulation is ~9 mm. The length of the simulated area is ~ 150 mm.

The simulation shows clearly that the ion beam will be accelerated through the column section of the Gamma Tube without impinging the electrode structure. Thus reliable, long life-time operation is expected.

### 3.3. Axial-Type Gamma Tube Design

The design of the Gamma Tube had two distinctive goals. First, the auxiliary systems such as pumps and RF-matching network had to be integrated into one, small footprint device. Secondly, the accelerator potential requirement of 200 kV had to be reliably achieved. This meant that the accelerator column manufacturer's specifications for the internal pressure and external insulation had to be taken into account, while the device was designed. The overall design is shown in Figure 5. The main elements of the Gamma Tube are shown and include the matching network for the RF-matching, RF-driven external antenna ion source, differential pumping chamber with puller electrode, accelerator column, actively water-cooled target, high voltage feed-through and cable, $SF_6$ pressure vessel and the supporting stand. The overall height of the Gama Tube is 120 cm.

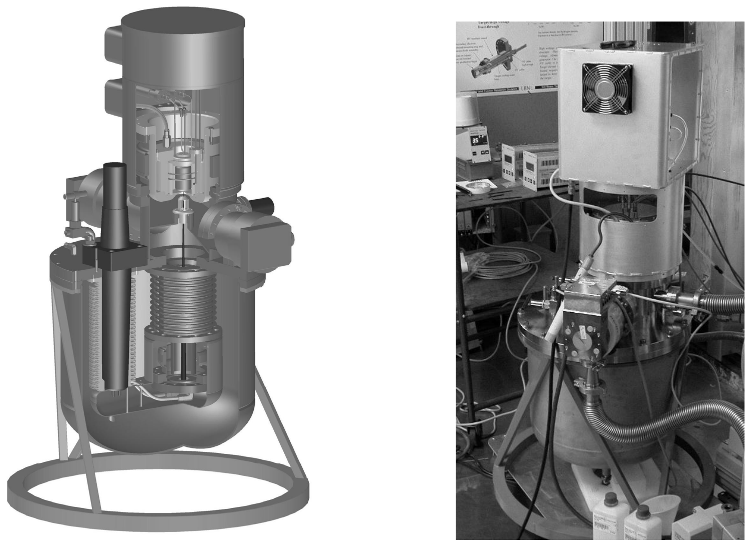

Fig. 5. The first generation axial-type Gamma Tube on it's stand. The overall height of the system is 120 cm with the stand, while the ion source/matching-network is 40 cm in height, as well as the high voltage feed-through structure with accelerator column and target. On the right, the Gamma Tube is being tested at LBNL.

The full acceleration potential is divided between the ion source potential and the target potential. The ion source can be independently biased up to +20 kV, while the target can be biased to >300 kV if required. For the first experiments with $^{11}B$, the target will biased to a maximum of –200 kV. The accelerator column is surrounded by 80 psi $SF_6$ gas, for insulation, while the high voltage cable is rated at 350 kV. The ion source is identical in design to an external antenna, actively water-cooled ion sources used in our axial neutron generators. For the initial experiments, the Gamma Tube is designed to operate with up to 2 mA of protons. The ion source can produce current densities up to 100 $mA/cm^2$ at 3 kW of discharge power. This translates to 7 mA of extracted current from the Gamma Tube's 3 mm diameter extraction hole. Thus, the Gamma Tube will be operated conservatively at 1.5 kW of discharge power for the initial experiments. The prototype Gamma Tube was delivered to Sandia National Laboratory on March 2, 2007. The experiments for highenergy gamma generation are underway, and the progress of these experiments will be reported later.

## 4. T-T POINT NEUTRON GENERATOR

Neutron transmission spectroscopy has been shown to be a powerful tool to identify H, C, N and O in both samples and in luggage[15,16]. It can determine the amounts of H, C, N, and O in bulk samples ranging from chemical samples to cereal grains while Miller *et. al.*, have applied the general technique to airport security[17]. Neutron transmission spectroscopy is a technique similar to optical spectroscopy, where a 'white light' source is passed through a gas sample and unknown gases in the sample are identified by comparing the resulting light attenuation to known cases. In the case of neutron attenuation, a beam of white neutrons is passed through a sample. By measuring the neutron attenuation as a function of neutron energy and using known cases, elements like H, C, N and O can easily be identified. Tensor Technology Inc. Madison, AL is actively developing an airline cargo screening system for airport security based on a technique that uses Pulsed Fast Neutron Spectroscopy (PFNTS).

### 4.1. Specifications of Pulsed White Neutron Generator

The Plasma and Ion Source Technology Group at LBNL has been developing a T-T fusion based, wide energy spectrum neutron generator for this application[1,2]. T-T fusion neutrons generate neutron energies from 0 MeV to 9 MeV. The aim for the T-T Point Neutron Generator project was to develop a device, which would provide relatively high instantaneous neutron yield and would be able to pulse the beam with nanosecond range pulse widths and high repetition rate. In addition, it will provide a small beam spot and fit into the existing neutron shield/collimator structure presently available[1] at Tensor Technology's laboratory at the University of Auburn, AL. The specifications of the Pulsed White Neutron Generator (PWNG) is shown in the Table 4.

Table 4. The specifications of the PWNG

| | |
|---|---|
| **Neutron Energy** | 0 - 9 MeV (T-T) |
| **Peak Neutron Yield** | ~$10^{11}$ n/s |
| **Total Beam Current** | 200 mA |
| **Accelerator Voltage** | 120 kV |
| **Pulse Width** | < 5 ns |
| **Duty Factor** | 0.25 % |
| **Repetition Rate** | >150 kHz |

The ion beam pulsing system and the ion source of the PWNG have been described in detail previously[18,19]. In this presentation the new sapphire window assembly and the fast switch assembly will be discussed.

### 4.2. RF-window assembly for PWNG

Originally the PWNG was designed to use a single large opening window. A detailed analysis of the window structure revealed problems with the original design, and led us to select an alternative approach  In this new approach, the structural integrity of the PWNG is maintained by installing multiple round windows along the plasma chamber lower half, instead of relying on one large window opening. Initially, commercially available sapphire windows were tried, but these windows had a limited power handling capability in a powerful RF-field due to their use of magnetic KOVAR as a window frame. Large induced currents were created in the frame causint it to heat up, and by heat expansion, the frame broke the brazed bond between the KOVAR and the sapphire disk, thus leading to failure. Multiple options were explored to solve the RF-window issue. The window frame had to be water-cooled and the sapphire had to be brazed into the frame, to ensure Ultra High Vacuum capability of the sealed, tritium filled PWNG. A window design was developed thatincorporated hard-sealed construction of 3" diameter sapphire disk by brazing, frame cooling via a water-channel and the use of relatively high heat conductivity sapphire. The windows were manufactured with a proprietary method by Thermo Fusion Inc. at Hayward, CA. This design is shown in Figure 6.

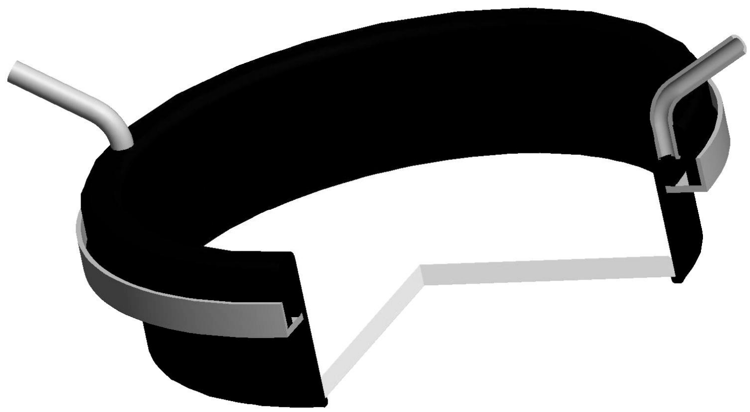

Fig. 6. 3 inch diameter actively water-cooled sapphire RF-window for the PWNG. The window frame is made of copper for low inductive heat and the construction is fully UHV compatible and bakeable to 450 °C.

The requirement for the window is to operate reliably in the 500–1000 W range of RF-power. The PWNG will have ten windows installed on the ion source. The windows are being tested with a prototype ion source at one of the test stands of Plasma and Ion Source Technology Group. Initial experiments have shown a reliable operation at power levels up to 2000 W without failures. More detailed measurements will be reported later.

**4.3. Fast Switches for Beam Pulser System**

The neutron energy measurement of the Tensor Pulsed Fast Neutron Transmission Spectroscopy (PFNTS) screener is based on time-of-flight technique. In order to gain good time resolution, the neutron beam has to be pulsed with pulse widths of few nano-seconds. The basic principle of pulsing at PWNG is to sweep the ion beam with parallel plates across a collimator structure. The faster the voltage sweep, the faster the beam pulse. The beam travel across the slit in the PWNG is a factor of three longer than the beam width. In order to create a 5 ns beam pulse, the voltage sweep at the parallel plates has to be on the order of 15 ns. This can be accomplished by using fast switches to change the potential of the parallel plates. Initially commercial fast switches were used. Due to their construction (components cast in epoxy), they were very difficult to repair in case of a failure. An alternative approach was developed at LBNL using MOSFET switches at +-750 V. These switches are good for MHz repetition rates with a suitable load. For the first prototype system, the switches were operated at up to 150 kHz, limited by the cooling. A parallel plate arrangement, similar to the one used for the PWNG was used to test the switch system by simulating the correct load. Plate potential rise and fall time of 12 ns were achieved with ±750 V. The measured rise-and fall-time of the parallel plate potential is 12 ns. This will produce a neutron pulse of ~4 ns, meeting the pulse width requirement. The switches can be operated at much higher repetition rate if they are actively water-cooled. A water cooling system is being designed.

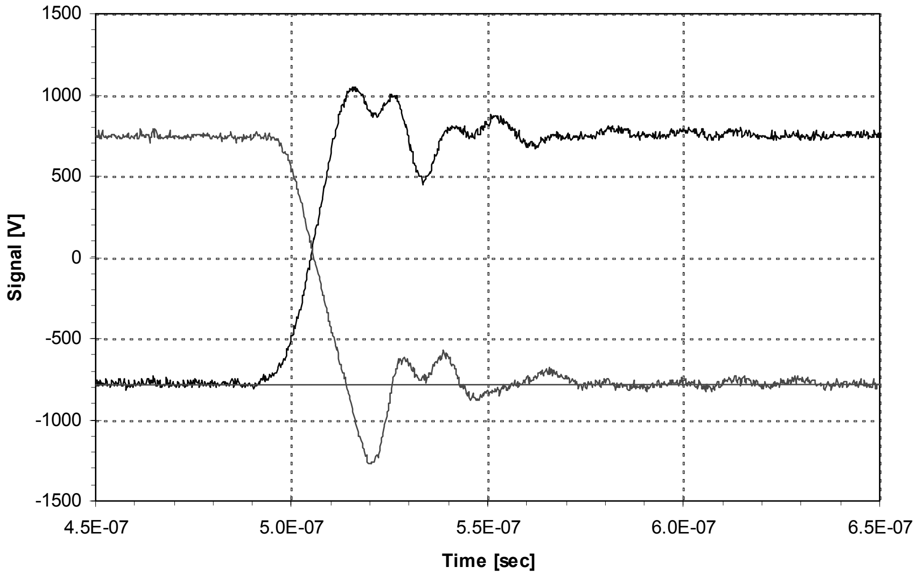


Fig. 7. The fall- and rise-time of the simultaneous voltage pulses of the parallel plates. The measurement is performed by measuring directly the voltage at the plates. A voltage rise- and fall-time of 12 ns is achieved.

### 4.4. Status of the PWNG

The Tensor Technology Inc. PWNG is under assembly at Plasma and Ion Source Technology Group. All of the sub-assemblies have been fabricated and being assembled in the system. After the assembly the PWNG will be UHV processed at LBNL by baking the generator at 200 °C with argon flow at atmospheric pressure to clean the inside of the tube. The tritium fill of the PWNG will be done at LLNL. After the fill, the generator will be shipped to Auburn, AL for testing at the Tensor Technology PFNTS facility with airline cargo containers. The testing of the system will be done during summer and fall of 2007.

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## REFERENCES

1 J. Reijonen, Neutron Generators Developed at LBNL for Homeland Security and Imaging Applications, CAARI 2006, to be published in NIM B 2007

2 J. Reijonen, Compact Neutron Generators For Medical, Homeland Security and Planetary Exploration, Invited. Proc. Particle Accelerator Conference '05, Knoxville TN, USA, May 16 – 20, 2005

3 A. Antolak, B. Doyle, K.-N. Leung, D. Morse and P. Provencio, Proc. of SPIE 592303-1

4 Hall, J, Dietrich, F., Logan, C., Rusnak, B., "Recent Results in the Development of Fast Neutron Imaging Techniques," Appl. of Accelerators in Research and Industry-16$^{th}$ Conf. American Institute of Physics pp1113-1117 (2001).

5 Hall, J., "Uncovering Hidden Defects with Neutrons", S&TR, Lawrence Livermore National Laboratory, May 2001, http://www.llnl.gov/str/May01/Hall.html.

6 Eberhardt, J., Liu, Y., Rainey, S., Roach, G., Sowerby, B., Stevens, R., Tickner, J., "Fast Neutron/Gamma-ray Radiography Scanner for the Detection of Contraband in Air Cargo Containers", Applied Radiation and Isotopes, **63** (2005), pp. 179-188

7 S. S. Nargolwalla and E. P. Prszybylowicz , Activation Analysis with Neutron Generators, John Wiley & Sons, New York, 1973

8 http://www.ansys.com/

9 R. Becker and W. Herrmannsfeldt, Rev. Sci. Instrum. **63**, 2756 (1992)

10 D. De Frene et al, Phys. Rev. **C28** (1984) 1908.

11 Handbook of Modern Ion Beam Materials Analysis, p.575 (1995), ISBN 1-55899-254-5

12 C.L. Hollas, D.A. Close and C.E. Moss, Nucl. Instr. Meth. **B24/25** (1987) 503.

13 http://www.pelletron.com/

14 J. Reijonen, F. Gicquel, S. K. Hahto, M. King, T-P Lou and K-N Leung, D-D Neutron Generator Development at LBNL, Applied Radiation and Isotopes, **63**, 757 (2005)

15 J. C. Overley, "Determination of H, C, N, O Content of Bulk Materials from Neutron-Attenuation Measurements", Int. J. Appl. Radiat. Isot., **Vol. 36**, No. 3, pp. 185-191, 1985

16 T. G. Miller and W. K. Makky, "Application of Fast Neutron Spectroscopy/Radiography (FNS/R) to Airport Security", Proceedings of the SPIE, **Vol. 1737** Neutrons, X-Rays, and Gamma Rays, pp 184-196, 1992

17 T. G. Miller, "Use of Neutron Tomography for Airline Security", Proceedings of the SPIE, **Vol. 2093**, pp 204-217, 1994

18 S. K. Hahto, S. T. Hahto, K. N. Leung, J. Reijonen, T. G. Miller and P. K. Van Staagen, Fast ion beam chopping system for neutron generators, Rev. Sci. Instrum. **76**, 23304 (2005)

19 T. Kalvas, S. K. Hahto, F. Gicquel, M. King, J. H. Vainionpaa, J. Reijonen, K.–N. Leung and T. G. Miller, Fast Slit Beam Extraction and Chopping for Neutron Generator, Rev. Sci. Instrum. **77**, 03B904 (2006)