COMPACT NEUTRON GENERATOR DEVELOPMENT AND APPLICATIONS

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Abstract: The Plasma and Ion Source Technology Group at the Lawrence Berkeley National Laboratory has been engaging in the development of high yield compact neutron generators for the last ten years. Because neutrons in these generators are formed by using either D-D, T-T or D-T fusion reaction, one can produce either mono-energetic (2.4 MeV or 14 MeV) or white neutrons. All the neutron generators being developed by our group utilize 13.5 MHz RF induction discharge to produce a pure deuterium or a mixture of deuterium-tritium plasma. As a result, ion beams with high current density and almost pure atomic ions can be extracted from the plasma source. The ion beams are accelerated to ~100 keV and neutrons are produced when the beams impinge on a titanium target. Neutron generators with different configurations and sizes have been designed and tested at LBNL. Their applications include neutron activation analysis, oil-well logging, boron neutron capture therapy, brachytherapy, cargo and luggage screening. A novel small point neutron source has recently been developed for radiography application. The source size can be 2 mm or less, making it possible to examine objects with sharper images. The performance of these neutron generators will be described in this paper.

Introduction: The RF-driven multicusp ion source developed at Lawrence Berkeley National Laboratory (LBNL) has found numerous applications ranging from neutral beam injection systems for fusion reactors to particle accelerators, proton therapy machines and ion implantation systems. Such sources are simple to operate; have long lifetimes, high gas efficiencies and provide high-density plasmas with high monatomic species yields. These characteristics make the RF-driven ion source a viable candidate for the next generation of compact, high-output, sealed-tube neutron generators, utilizing the D-D, T-T or D-T fusion reactions.

Recently, LBNL has developed compact, sealed-accelerator-tube neutron generators capable of producing 10^9 – 10^{10} D-D neutrons per second. There are several enabling technologies contributing to a higher neutron yield in these neutron generators: (a) D^+ yields over 90% have been achieved using 13.5 MHz RF-driven multicusp sources. High monatomic yields are essential for high neutron outputs in low energy accelerator; (b) The source could be operated at low gas pressure (~ 2 mTorr). Low gas pressure operation is necessary to reduce both charge exchange processes and high-voltage breakdown in the accelerator column. These experimental findings will enable one to develop a new generation of compact, high-output, sealed-tube 14 MeV neutron generators based on the D-T fusion reaction. Described below are three different types of neutron sources developed at LBNL for luggage and cargo container inspection.

Results: *I. Compact Axial Extraction Neutron Generator*

The compact axial extraction neutron generator is approximately 40 cm in length and 15 cm in diameter. The ion source is a quartz-tube incorporating external antenna. The back plate has the deuterium gas and pressure read-out feed-throughs. The target is housed in an aluminium vacuum vessel and it is insulated from the ground potential with an HV insulator. Figure 1 shows a drawing of the axial extraction neutron tube. The ion beam is extracted from a 3-mm-diameter aperture and accelerated to a target at 100 kV. The target is water-cooled and is made of explosive-bonded titanium-on-aluminum material

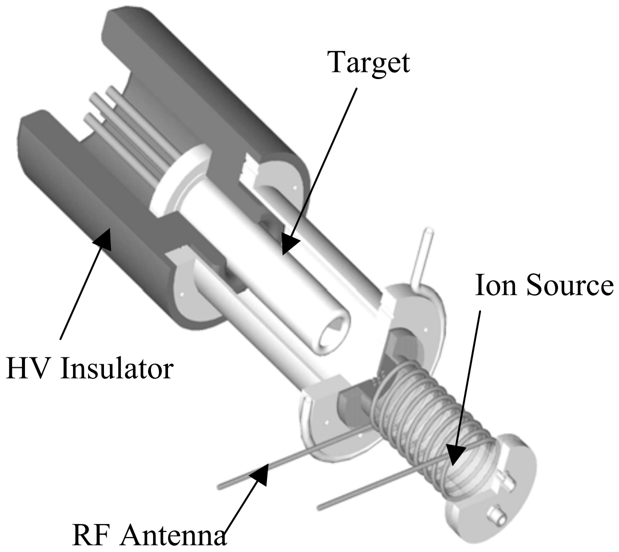

Figure 1. The axial extraction neutron generator

The axial neutron generator is mainly used in pulsed mode experiments[1]. The pulsing is performed by switching the RF power on and off. The current RF power supply is limited in pulse length of 2 ms. The rise time of the plasma can be as short as a few micro-seconds, which is achievable using a fast rise-time RF generator.

The compact axial extraction neutron generator is constantly being evacuated by a turbo molecular pump. This is possible because no radioactive tritium gas is used. Some applications of the neutron generator require portability and/or the use of tritium for 14 MeV neutron production. In these cases, the generator has to be operated in sealed (no pumping) condition.

Ion source operation at low neutral gas pressure has been studied extensively. In order to reduce the source operating pressure, two techniques have been implemented; first, a low RF discharge in cw mode, second, an axial magnetic field in the plasma chamber to confine the electrons. In order to introduce an axial magnetic field to the discharge chamber, a novel solution of using the RF induction coil to carry the dc current was used. In this arrangement, the RF current and the dc current are using the same conductor. No extra coils are needed and the electron confining magnetic field can be easily added to the existing hardware.

The neutron flux measurements were performed using ^{3}He neutron monitors calibrated by foil activation methods. The accuracy of these measurements is +/- 20%. The D-D neutron output was measured as a function of the accelerator voltage. In this measurement, the generator was operating at 10% duty factor. With an acceleration voltage of 100 kV and peak current of 60 mA, a D-D neutron output of 10^9 n/s has been achieved.

The 10^9 D-D n/s flux corresponds to 10^{11} n/s for the more widely used D-T reaction because of the much higher cross-section of the later reaction. The flux is limited mainly by the available high voltage and /or the maximum duty factor that the generator can be operated.

II. High Yield Radial Extraction Neutron Generator

For applications that require high neutron output from a relatively compact dimensions, a new type of coaxial, radial extraction neutron generators have been developed. In this generator, the main task has been to produce high neutron flux in cw-mode for applications such as medical treatments (BNCT), neutron activation analysis (NAA) and prompt gamma activation analysis (PGAA).

In this coaxial design, the plasma is also formed by utilizing 13.5 MHz RF induction discharge[1]. In this generator, the ion source chamber is in the middle of the tube and the target surrounds the source. Therefore, the beam can be extracted radially from the ion source to the surrounding target panels. These coaxial cylinders are surrounded by a HV insulator cylinder, which in the case of this generator is made of pyrex glass. The advantage of this coaxial design is that the target area can be maximized in a given volume and the HV insulator is protected from the sputtered target particles. The outer dimensions of the coaxial neutron generator are: 30 cm in diameter, 40 cm in height (see figure 2).

The beam is extracted from 24 small apertures, each 1.5 mm in diameter. The water-cooled target plates are within 63 mm distance from the plasma chamber wall. The generator is pumped by using two 63 mm diameter pumping ports and a turbo-molecular pump. Each of the target plates has a pair of permanent magnets which acts as an individual secondary electron emission filter. These target plates are individually water-cooled. The surface temperature of the target plates has been calculated by using the ANSYS-modelling program. This program gives the temperature distribution at the target, starting from a beam spot size predicted by the IGUN ion optics code.

The coaxial neutron generator is operating currently with D-D neutron flux as high as 10^{10} n/s. Stable operation at that flux level can be achieved at ~1 minute after cold start. The upgrade path for output flux of 10^{11} D-D n/s is designed and implemented.

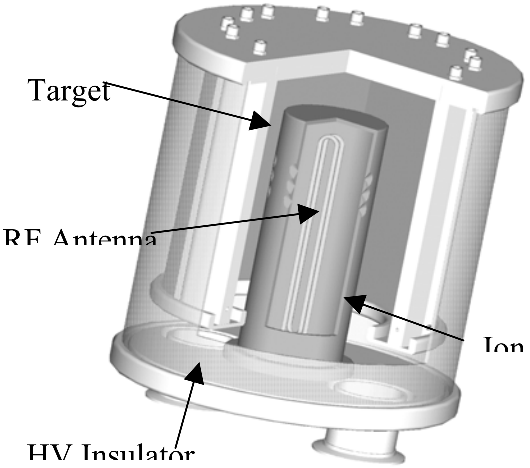

Figure 2. The coaxial type neutron generator

III. Point Neutron Source for Pulsed Fast Neutron Transmission Spectroscopy

It has been demonstrated that pulsed fast neutron transmission spectroscopy (PFNTS)[2] can detect conventional, unconventional, and improvised explosives; and, special nuclear material (SNM). This technique uses a neutron probe to accurately measure the elements and their ratios in an areal projection through a container. The elemental ratios of explosives and SNM produce unique signatures so that an enhanced security system may accurately identify the explosives by using a neural network.

In this point neutron source, the plasma is produced by RF induction discharge. This type of discharge can provide high current density with atomic ion concentration greater than 90%.

The gas employed will be a mixture of 50% deuterium and 50% tritium for 14 MeV D-T neutron production and pure tritium gas for “white” (0 – 9 MeV) neutron production. The discharge will be operated in pulsed mode with a 3 kW, 13.5 MHz RF generator. Multiple beamlets will be extracted from the plasma source. The ions of each beamlet will be accelerated to 100 kV and focused down to a beam spot size of ~2-mm-diameter. These beamlets will irradiate the Ti target uniformly. The Ti target surface will be loaded with deuterium or tritium atoms. When the incoming ions impinge on these atoms, neutrons will be generated via the D-T or T-T fusion process. The neutrons produced will appear to come from a small “point source” with diameter no larger than 2 mm. They will then be directed to the target object for interrogation study.

The power density deposited by the focused ion beams on the target surface can be maintained at ~500 W/cm^2. This modest heat load can be easily removed by using an oscillating, water-cooled target stage. The entire neutron generator is about 20-cm diameter by 20-cm high. The side and top views of the neutron generator assembly are shown in Figs. 3 (a) and (b) deuterium-tritium plasma is first generated in a toroidal quartz or ceramic chamber by means of 13.5 MHz RF induction discharge. The antenna is a copper or aluminum coil wrapped around the plasma chamber as shown in the figures. Since the antenna is located outside the plasma chamber, there is no limitation on its lifetime.

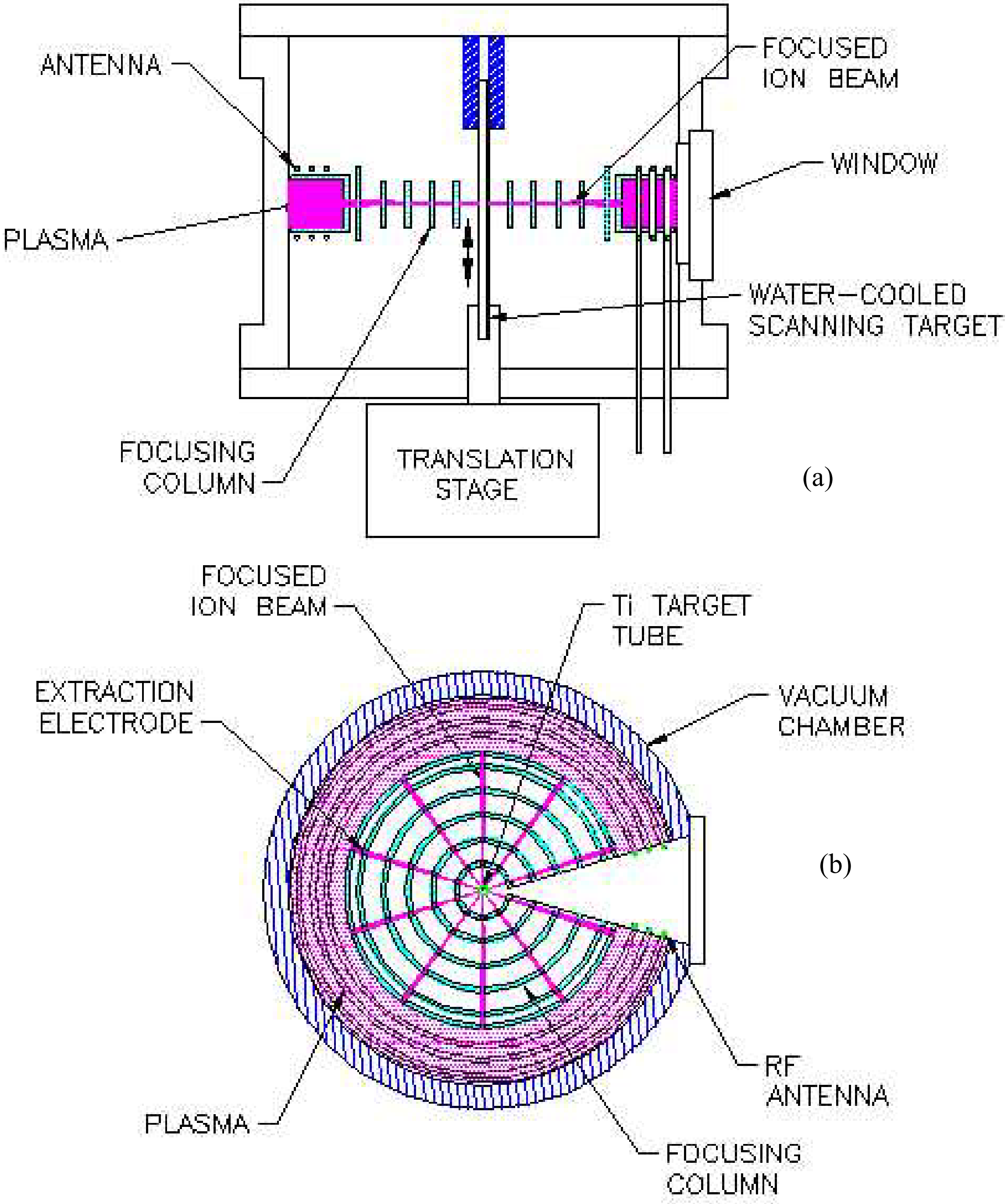

Figure 3 (a) Side view of point neutron source, and **(b)** Top view of point neutron source.

In order to achieve 10^{12} D-T n/s or 10^{10} T-T n/s, the total beam power deposited on the target is 120 kV, 10 mA. The target is a Ti tubing with an outer diameter of 2-mm. Water is running through the center for heat removal. Ti is used as the target material because it can absorb deuterium or tritium atoms efficiently. The beamlets will irradiate the target tubing uniformly as shown in Fig. 3. The 14 MeV or "white" neutrons (Figure 4) will be generated isotropically by the D-T fusion reaction. Some of these neutrons will pass through a window and they are directed onto the object for identification study.

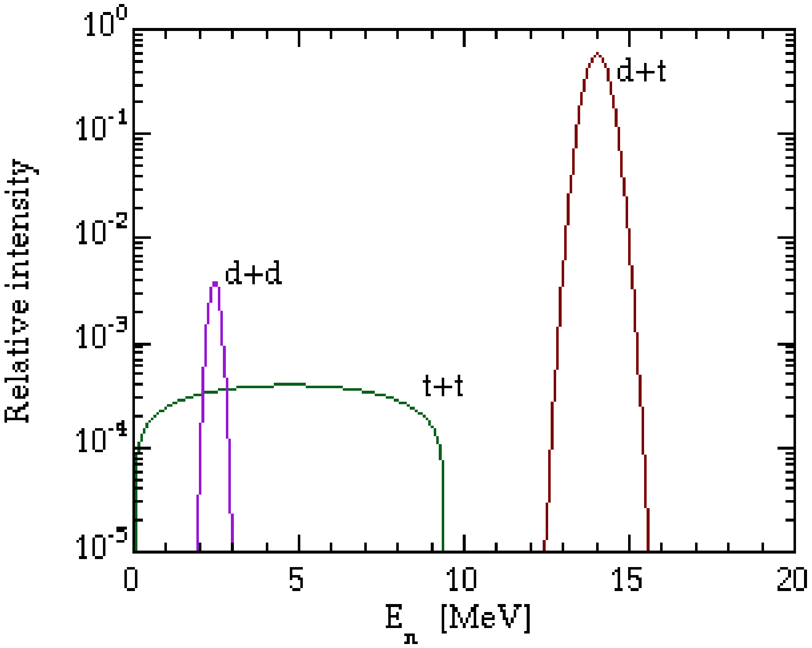

Figure 4. Fusion neutron energy spectra.

Conclusions: The Plasma and Ion Source Technology Group at LBNL have developed three different types of neutron generators. The compact axial extraction neutron generator is being operated at D-D neutron yield of 10^9 n/s. The neutral gas pressure in the plasma chamber has been successfully lowered by applying an axial magnetic field. This field is formed by passing a dc-current in the RF induction coil. This has resulted in reduction of approximately one order of magnitude in gas pressure. Together with improved power handling capability for both the plasma source and the target, the compact axial neutron generator will be capable of reaching 10^{10} n/s in pulsed operation.

The high yield coaxial neutron generator is being operated regularly in a new neutron facility. The upgrade of the coaxial generator to D-D neutron flux of 10^{11} n/s is well underway, using the methods and tools like IGUN and ANSYS to model the target surface temperature under high beam power conditions.

A proto-type of the point neutron source has been operated successfully with beam chopping capability. Beam pulse as short as 5 ns has been demonstrated. Integration of this point neutron source with the fast pulsed neutron transmission spectroscopy system is planned in the near future.

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References:

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