D-D Neutron Generator Development at LBNL ‡

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Abstract. The Plasma and Ion Source Technology Group in Lawrence Berkeley National Laboratory is developing advanced, next generation D-D neutron generators. There are three distinctive developments, which are discussed in this presentation, namely; multi-stage, accelerator-based axial neutron generator, high output co-axial neutron generator and point source neutron generator. These generators employ RF-induction discharge to produce deuterium ions. Distinctive feature of the RF-discharge is its capability to generate high atomic hydrogen species, high current densities and stable and long-life operation. The axial neutron generator is designed for applications that require fast pulsing together with medium to high D-D neutron output. The co-axial neutron generator is aimed for high neutron output with cw or pulsed operation, using either the D-D or D-T fusion reaction. The point source neutron generator is a new concept, utilizing a torroidal-shaped plasma generator. The beam is extracted from multiple apertures and focus to the target tube, which is located at the middle of the generator. This will generate a point source of D-D, T-T or D-T neutrons with high output flux. The latest development together with measured data will be discussed in this article.

INTRODUCTION

The RF-driven multicusp ion source developed at Lawrence Berkeley National Laboratory has found numerous applications from semiconductor industry and accelerator injectors to sophisticated neutron generators. Typical feature of these plasma generators is their ability to generator high atomic deuterium or tritium species, high current densities, long life-time and stable and consistent pulsing characteristics.

The Plasma and Ion Source Technology Group at Lawrence Berkeley National Laboratory is developing neutron generators[**1**],[**2**] for various applications. These applications include PGAA (Prompt Gamma Activation Analysis), FNAA (Fast Neutron Activation Analysis) and PFNTS (Pulsed Fast Neutron Transmission Spectroscopy) for material characterization and detection techniques and BNCT (Boron Neutron Capture Therapy) for the medical applications. In this presentation, several new neutron generator developments will be presented. They are designed to function in different applications, these generators include sectioned insulator axial neutron generator, high power co-axial neutron generator and a new fast pulsing, point neutron generator. All of these generators are operated with RF-induction discharge to ensure high efficiency and long life-time.

Most of the neutron-based material identification and interrogation systems require pulsed neutron beams. Various ways of pulsing the primary ion beam, and therefore the neutron beam, can be used, for example, RF-discharge, puller electrode and beam sweeper-based pulsing. RF-discharge pulsing is discussed and results are shown in this presentation.

1. AXIAL, SECTIONED ACCELERATOR NEUTRON GENERATOR

The axial, sectioned insulator neutron generator utilizes external-antenna driven RF-plasma generator with 13.56 MHz, see Figure 1. The alumina (Al_3O_2) discharge chamber of the ion source is actively water-cooled and thus can operate reliably at cw mode with more than 3 kW of discharge power. The main characteristics of this type of ion source is the high current density, j ~ 100 mA/cm^2 at 3 kW of discharge power, (see Figure 2), and high atomic species, the H^+ fraction > 90% at RF power ~1 kW (see Figure 3). More detailed measurements and discussion is presented in Ref. [**3**].

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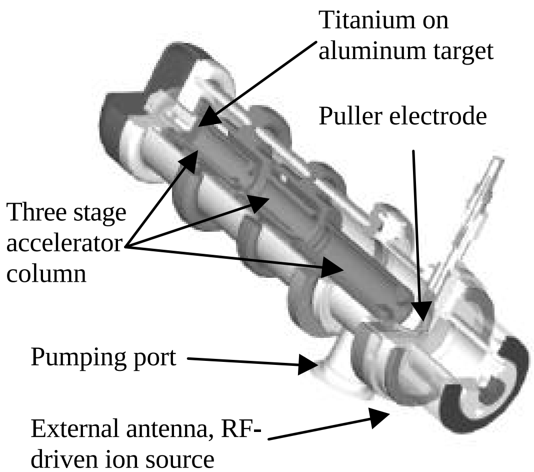

Figure 1. *Sectioned insulator, axial neutron generator with a multi-stage accelerator structure. The alumina plasma generator is water-cooled and driven by a external RF-antenna. Puller electrode can be pulsed.*

The ion beam current is a function of various parameters, like the RF-power and the source pressure. The external antenna ion source can be operated at a wide range of operating parameters, depending on the needs of the application. The hydrogen current as a function of pressure and RF-power is shown in Figure 2.

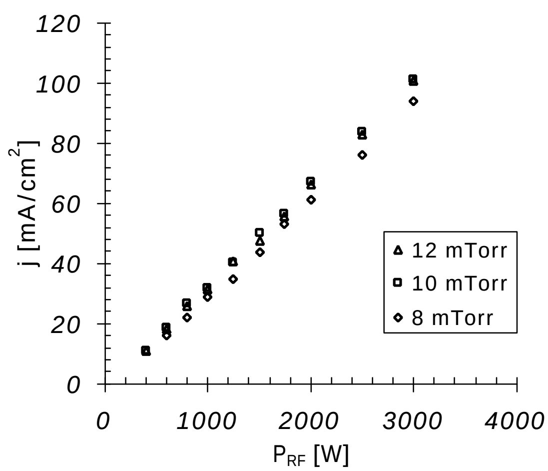

Figure 2. *Hydrogen current as a function of the RF-discharge power, and the operating pressure.*

The ion species distribution is an important parameter in determining the overall efficiency of the neutron generator. Some of the widely used neutron generator ion sources produce significant fraction of molecular ion species, thus reducing the energy per nuclei. The RF-discharge has demonstrated nearly mono-atomic ion species with a wide range of operating parameters. This can be seen in Figure 3, where the hydrogen species are measured as a function of the discharge power.

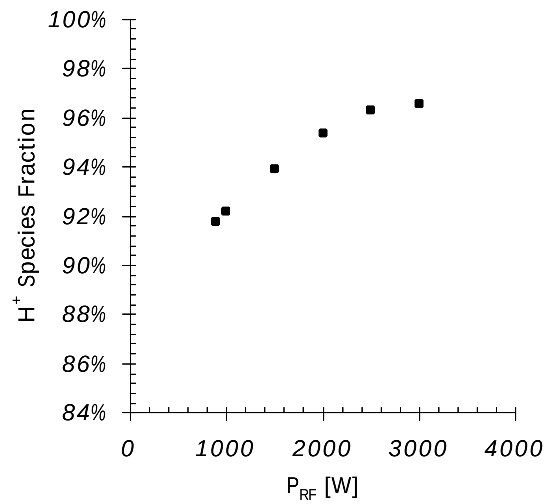

Figure 3. *H^+ species fraction as a function of the RF-discharge power.*

For the D-T neutron generation the maximum neutron yield occurs at about 120 kV, when solid targets and mono-atomic deuterium and tritium ions are used. Thus reliable operation at this voltage regime is needed for future D-T neutron generator development. A new accelerator section was designed for the purpose of being able to operate in the range of 100 – 120 kV range. The column is an air-insulated structure with three accelerator electrodes. The voltage is divided between these accelerator electrodes using an external high voltage divider-stack, which is made of high voltage elements connected with target cooling lines. The LCW (low conductance water) acts as series resistors between these elements and thus divides the primary voltage evenly between the ground potential and the full voltage. Secondary electron emission is suppressed by biasing the target shroud more negatively in relative to the target.

The target material is explosive bonded titanium on aluminum from Atlas Technologies Inc. The target and the puller electrode are both water-cooled. The ion beam optics in the column has been simulated with a ion extraction and trajectory code IGUN[**4**]. The design parameters were 100-120 kV of voltage and 1-2 mA of current. The simulation for the column is shown in Figure 4.

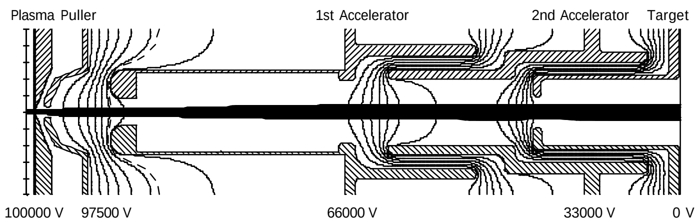

Figure 4. *The accelerator column IGUN simulation. The voltage in the simulation is 100 kV and beam intensity 1.12 mA.*

The sectioned, axial neutron generator is currently operated by using deuterium gas and it is actively evacuated with a turbo-molecular pump. The total operation hours of the generator is approximately 200 hours. Typical run of the axial neutron generator is shown in Figure 5.

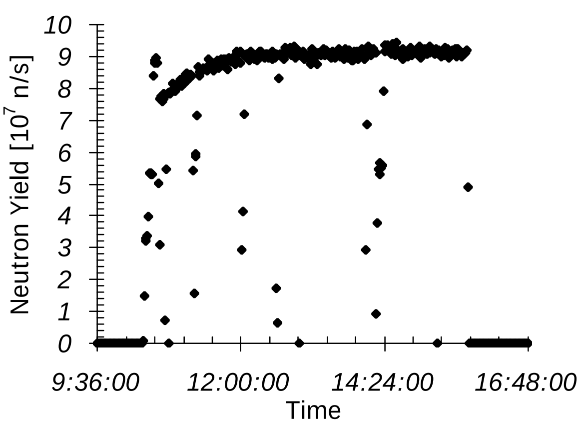

Figure 5. *Typical run of the sectioned, axial neutron generator. Total time for this run was 5 hours, with four short interruptions because of voltage break-downs. The output at this run was 9x10^7 n/s.*

The generator has demonstrated a D-D neutron yield of 3x10^8 n/s with 115 kV and 1.2 mA of current.

2. High Power Co-Axial Neutron Generator for Medical Applications

The co-axial neutron generator has the capability of operating at high beam power. This is possible, because of the unique target arrangement of the generator. The basic structure of the co-axial neutron generator consists of an ion source with an internal antenna, a target cylinder surrounding the ion source and an insulator-cylinder surrounding the target. We have previously achieved a D-D neutron output close to 10^{10} n/s. For BNCT application the required yield with D-T neutrons is estimated to be in the order of 10^{13} n/s, depending on the moderator efficiency and the required treatment time. This is a beam power equivalent to D-D generator with neutron output of 10^{11} n/s. We are currently working in a project together with an Italian consortium to develop an accelerator based BNCT treatment system. The first step for this project is to develop a co-axial neutron generator capable of producing 10^{11} n/s in D-D operation and later on converting it to D-T operation with similar beam power.

Based on the previous experiments with titanium targets in the axial neutron generators, the ion beam voltage and current requirements for the 10^{11} n/s are ~110-120 kV of acceleration voltage and ~300-350 mA of beam current. A 10 cm diameter prototype ion source was constructed to measure the current density obtainable from a internal antenna plasma generator with appropriate dimensions. In Figure 6, the current density is shown as a function of the RF-discharge power. The highest current density obtained is 42.5 mA/cm^2 with 2.5 kW.

The effect of the ion source gas pressure to the output current was also studied. Figure 7 shows the current density as a function of the source pressure. This is an important factor for the future D-T upgrade, where the generator has to be operated in a sealed-tube mode, in which there is no pressure gradient in the accelerator gap. Experiments show that even with the prototype's fairly weak magnetic confinement, a stable operation can be achieved with only a few mTorr of gas pressure.

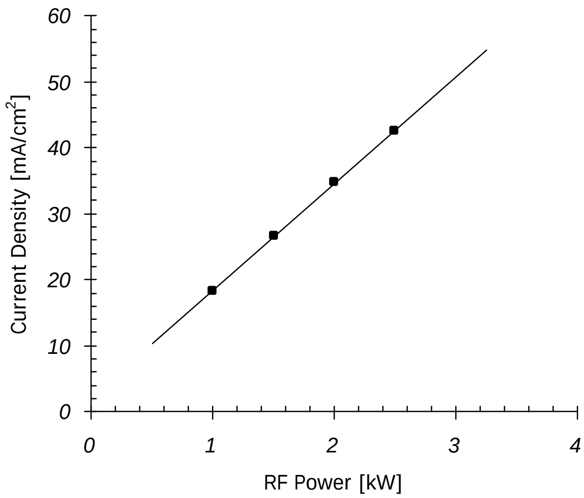

Figure 6. *Current density as a function of the RF-discharge in a 10 cm in diameter, internal antenna plasma generator. More than 40 mA/cm^2 is achieved at 2.5 kW of discharge power.*

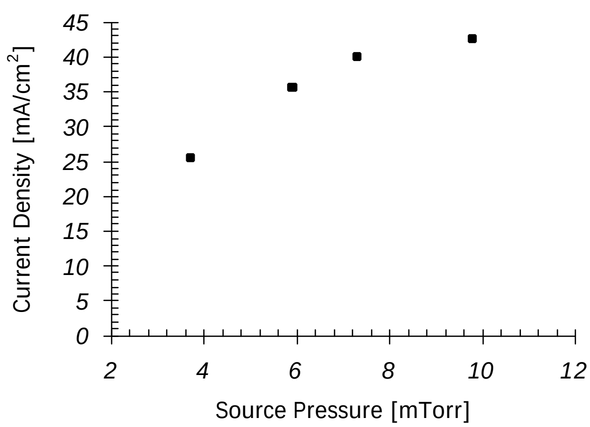

Figure 7. *Current density as a function of the source pressure at 2.5 kW of discharge power. The ion source operates stably at wide range of gas pressures.*

The extraction aperture design is based on these current density measurements. The generator will have seven 1.5 mm wide slit-apertures of 75 mm in height. The total extraction area is ~8 cm^2. When the ion source is operated at 2.5 kW, more than 330 mA of ion beam is being extracted.

The high power co-axial neutron generator has a 4" diameter ion source, secondary electron shield structure, titanium coated aluminum target and Al_3O_2 ceramic insulator cylinder. It also has a pumping chamber with a turbo molecular pump for deuterium gas evacuation. See Figure 8 for a schematic of the generator. The generator is completed for testing and will be shipped to Italy in September 2004.

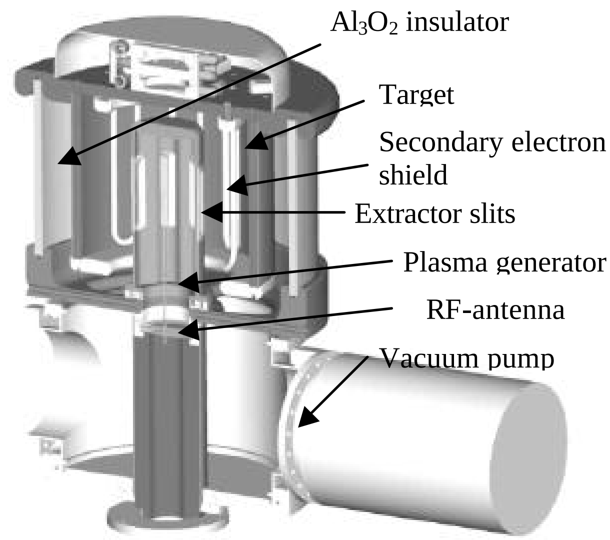

Figure 8. *The main features of the 10^{11} n/s D-D co-axial neutron generator.*

3. POINT NEUTRON GENERATOR

The point neutron generator is a new method of making a small point neutron source. The concept relies on a new toroidal-shaped plasma generator. The operation of this geometry was tested earlier using a prototype plasma chamber and based on this design the first point source prototype was constructed. The prototype neutron generator was built according to the specifications of Tensor Technology Inc., which included a beam sweeper, beam pulsing system for ToF (Time of Flight) measurements. The first prototype was constructed using organic seals and limited cooling capabilities, thus the maximum duty cycle for the plasma operation was limited to 1% at 5 kW of peak discharge power. The source operation and beam extraction has been demonstrated at 80 kV of accelerator voltage and ~1 mA of beam current. Sweeper-based beam pulsing system has been operated and the pulse width measurements are underway. Figure 9 is a picture of the point source in the test stand.

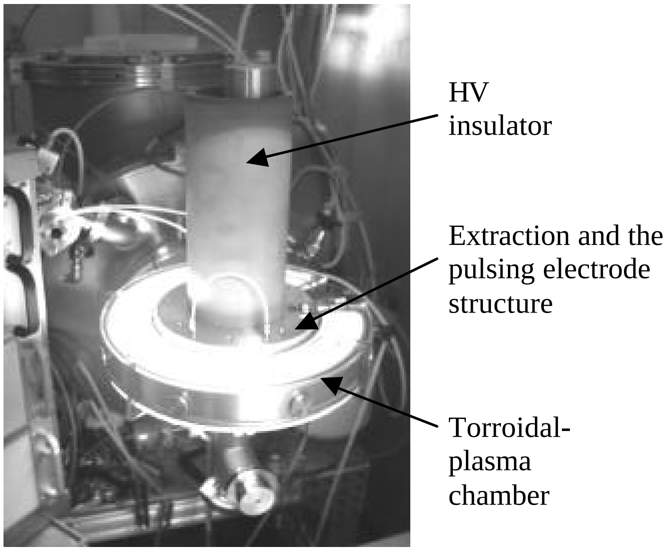

Figure 9. *Point neutron generator at the test stand. The limited power beam extraction with hydrogen is demonstrated, and the beam pulsing and pulse width measurements are on the way.*

4. PLASMA PULSING

Some of the potential neutron generator applications, especially in the field of material detection and interrogation require a pulsed neutron beams. Pulsing can be achieved either by switching the high voltage, switching an intermediate electrode in the extraction system, sweeping the ion beam across a collimator or by switching the discharge plasma with the input RF-power. For high voltage, high current switching it has been shown that pulse rise times in the order of 1 μs can be achieved[5].

For neutron generator, the switching voltage in this case would be in the order of 100 kV, which makes this approach expensive and would require additional hardware. Another method, namely RF-switching was studied. The experiment was performed using an internal antenna plasma generator with magnetic cusp structure and utilizing a Dressler, Cesar 1330, 13.56 MHz RF-amplifier. The RF-amplifier can switch on and off into a 50 Ohm load in sub-microsecond timescales. To the real load of the plasma and the matching box, the switching is slower. The current pulses measured from a faraday-cup when the plasma was switched by the RF-amplifier are shown in Figure 10 and 11.

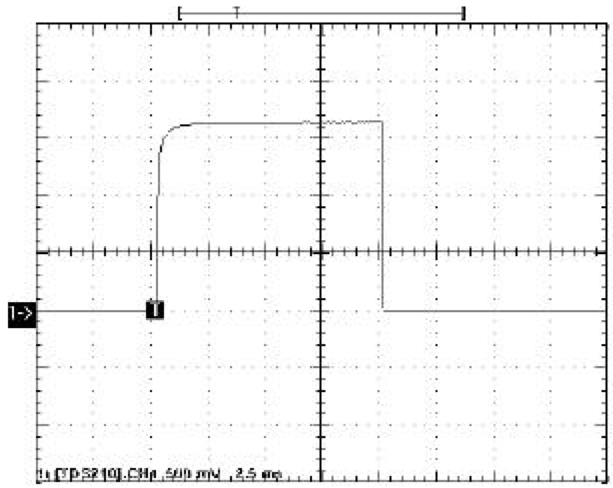

Figure 10. *Ion beam current pulse shape of a RF-switched ion source. The pulse width is 10 ms and the beam current is 1.5 mA*

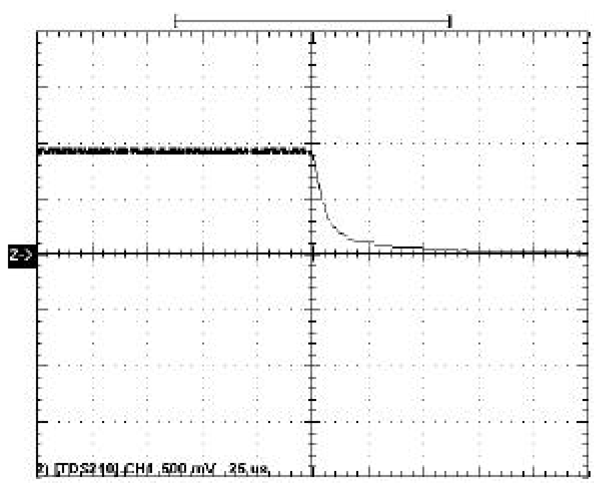

Figure 11. *The current pulse falling edge. The fall-time is in the order of 20 ms.*

The pulse rise time is significantly slower than the fall-time. In this experiment the rise-time was in the order of 300 micro-seconds. It has been shown that with optimized conditions the plasma ignition time can be as fast as few micro-seconds[6]. The fall-time is depending mainly on the confinement time of the plasma, when the RF is switched off. In the discharge chamber used in this experiment the fall-time is in the order of 15-20 μs.

5. DISCUSSION

Three different type neutron generators have been developed in the Plasma and Ion Source Technology Group in Lawrence Berkeley National Laboratory. All of these neutron generators are utilizing the RF-induction discharge plasma generator. The current density and the deuterium ion species were measured using the external antenna plasma generator in the axial, sectioned-insulator neutron generator. The generator is running routinely with D-D neutron output $>10^8$ n/s. Another development is the high power co-axial neutron generator for BNCT. The performance goal for the generator is 10^{11} n/s with ~ 40 kW of beam power. This generator will serve as a phase I development for the sealed D-T generator for 10^{13} n/s. The third development is the unique point neutron generator. It uses a toroidal-shaped plasma chamber and focused ion beams to generate a point source for neutron emission. Fast neutron beam switching was also studied. The internal antenna plasma generator was operated with a pulsing RF-amplifier. Fall-time of ~20 μs was measured at a repetition rate of up to 20 kHz.

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