Title
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Compact Neutron Generator Development at LBNL

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Abstract. *A wide variety of applications ranging from medical (BNCT, Boron Neutron Capture Therapy) and basic science (neutron imaging, material studies) to homeland security (explosive detection and nuclear material non-proliferation) are in need of compact, high flux neutron generators. The Plasma and Ion Source Technology Group in the Lawrence Berkeley National Laboratory is developing various neutron generators for these applications. These neutron generators employed either the D-D or the D-T fusion reaction for the neutron production. The deuterium or deuterium-tritium gas mixture is ionized in an RF-driven plasma source. The ions are then accelerated to ~100 keV energy using high current, high voltage DC-power supply to a target where the 2.45 MeV (for D-D reaction) or 14 MeV (for the D-T reaction) neutrons are generated. The development of two different types of neutron tube***s** *are being discussed in this presentation, namely compact, pulsed operation neutron generator***s** *and cw, high yield neutron generators. These generators are currently operating at D-D neutron yields of 10^8 n/s and 10^9 n/s respectively. A facility, incorporating the larger neutron generator, has been constructed for Prompt Gamma Activation Analysis (PGAA) and Neutron Activation Analysis (NAA) measurements.*

I. INTRODUCTION

The RF-driven multicusp ion source developed at Lawrence Berkeley National Laboratory has found numerous applications ranging from neutral beam injector systems for fusion reactors to particle accelerators, proton therapy machines and ion implantation systems. Sources such as this are simple to operate, have long lifetime, high gas efficiency and provide high-density plasmas with high yield of monatomic species. These characteristics make the RF driven multicusp source a viable candidate for high-output, neutron generators, utilizing the D-D and D-T fusion reactions.

Various types of neutron generator systems have being made and tested at the Plasma and Ion Source Technology Group in Lawrence Berkeley National Laboratory. Two main developments are being discussed in this presentation, namely the compact, axial extraction neutron generator and the large yield, radial extraction, co-axial neutron generator. Both of these neutron generators are using the D-D fusion reaction. Other similarities between these two neutron generators are the RF-driven ion sources and the explosive-bonded, titanium-on-aluminum targets.

A new neutron science facility has been set-up in the Plasma and Ion Source Technology Group, which enables PGAA and NAA measurements to be performed and provides adequate shielding for the neutron flux from the high yield neutron generators. The first measurements performed in that facility are presented in this conference (G. English *et. al.*).

II. D-D NEUTRON GENERATORS

The plasma is generated in the neutron generators using RF induction discharge. A 13.5 MHz RF power supply is used to drive plasma in either cw or in pulsed operation mode. The RF system consists of a RF power supply and a matching network, which matches the few ohm impedance of the plasma and the 50 Ohm impedance of the antenna and the coaxial transmission line. The RF discharge is shown to produce high plasma densities and high atomic species fractions for hydrogen-type gases[1]. For this reason it is an excellent candidate for a high power neutron generator plasma source.

The neutron generators developed in the Plasma and Ion Source Technology Group are using explosive bonded titanium-on-aluminum target material, developed and manufactured by ATLAS Technologies. The targets are water-cooled and in the case of the co-axial generator, secondary electron emission is filtered by permanent magnets.

II.A. 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 aluminum vacuum vessel and it is insulated from the ground potential with an HV insulator. Figure 1 shows a drawing of the axial extraction neutron generator. The ion beam is extracted from a single 3 mm diameter hole and accelerated at 100 kV to a target. The plasma electrode is a water-cooled molybdenum disk.

The axial neutron generator is mainly used in pulsed neutron experiments. The pulsing is performed by pulsing the RF power. The current RF power supply is limited in minimum pulse width of 2 ms. The rise time of the plasma can be as low as a few micro-seconds, which is achievable using a fast rise-time RF generator[2].

The compact axial neutron generator is constantly being evacuated by turbo molecular pumps. 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 applications the neutron generator has to operate in sealed (no-pumping) condition. The ion source operation at low gas pressure was extensively studied. To enhance the operation of the ion source at low source pressures, two techniques were implemented. First a low power RF discharge in cw mode[**3**], second, an axial magnetic field in the plasma chamber to confine the electrons.

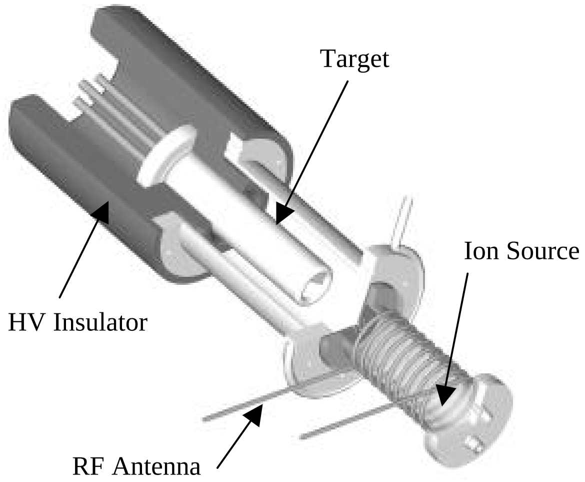

Figure 1. The axial extraction neutron generator.

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 case 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.

II.B. High Yield Radial Extraction Neutron Generator

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

In this co-axial design, the plasma is also formed by utilizing 13.56 MHz, RF-induction discharge. In this generator the ion source chamber is in the middle of the tube and the target surrounds the source, so that the beam can be extracted radially from the ion source to the surrounding target pieces. These co-axial cylinders are surrounded by a HV insulator cylinder, which in the case of this generator is made of pyrex glass. The advantage of this co-axial 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 co-axial neutron generator are: 30 cm in diameter, 40 cm in height (see figure 2.).

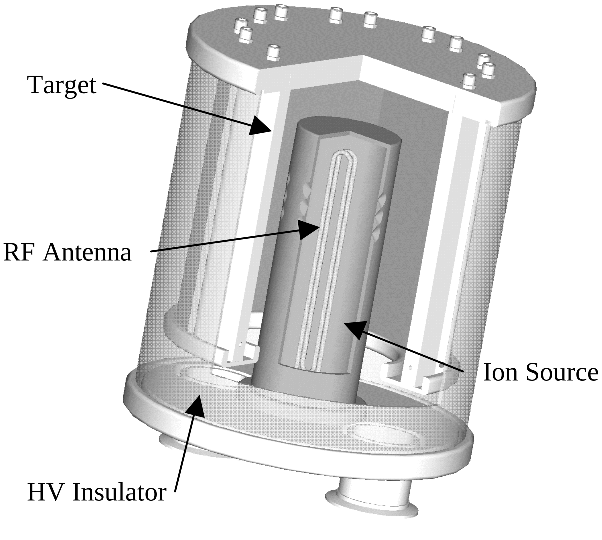

Figure 2. Co-axial neutron generator. RF-antenna inside the plasma chamber, surrounded by the target pieces. The outer pyrex cylinder is the HV insulator

The beam is extracted from 24 holes, 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 using two 63 mm in 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 high voltage power is provided from two HV power supplies, one floating on the other one. Maximum HV power is 10 kW (170 kV/60 mA).

III. NEUTRON GENERATOR PERFORMANCE

The neutron flux measurements were performed using ^{3}He-detectors calibrated by gold-foil activation methods. The accuracy of these measurements is ±20%.

III.A. Compact Axial Neutron Generator

The D-D neutron output was measured as a function of the accelerator voltage. In this measurement the generator was operating at 10% duty cycle and the peak current was 60 mA.

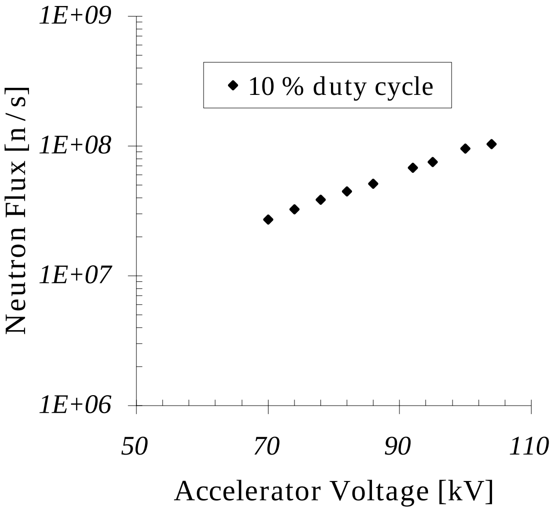

Figure 3. The neutron flux as a function of the accelerator voltage of the compact axial extraction neutron generator. In this measurement the voltage was limited to 104 kV and the current to 60 mA.

The 10^8 n/s D-D neutron flux corresponds to 10^{10} n/s for the more widely used D-T reaction, because of the much higher cross-section of the latter reaction. The flux is limited mainly by the available voltage and/or the maximum duty cycle that the generator can be operated.

The minimum operational pressure of the tube is a critical parameter for the future development of sealed neutron generator for high flux operation. Both above-mentioned methods have been investigated, namely low power, cw, RF-discharge and the axial magnetic field. The results are shown in figure 4. The pressure is measured at the plasma chamber using a barocell manometer.

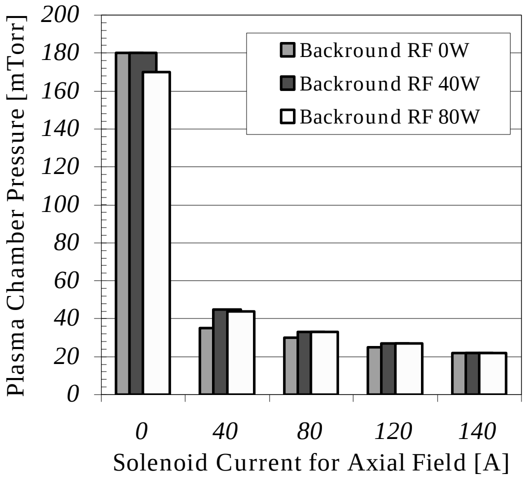

Figure 4. The minimum operation pressure of the axial extraction neutron generator ion source at various strength of the axial magnetic field and cw low power RF-discharge. Approximately 150 Gauss magnetic field is generated on the axis of the plasma source at 100 A of current.

From figure 4 it is clear how the ion confinement does lower the minimum operation pressure. The low power cw RF discharge on the other hand seems to lower the minimum pressure only when there is no axial magnetic field.

III.B. High Flux, Co-axial Neutron Generator

Detailed ion beam trajectory analysis and temperature load analysis was performed in the case of the co-axial neutron generator. Reliable operation with high neutron fluxes can thus be achieved. In figure 5, there is a sample calculation of the ion beam trajectories at approximately 20 mA of total ion beam current at 100 keV of beam energy. The beam dynamic simulations were performed using IGUN ion beam extraction and ion trajectory simulation program.

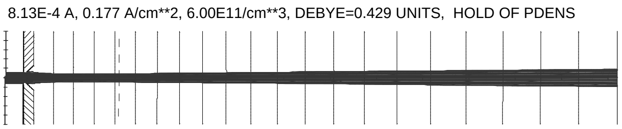

Figure 5. Ion beam dynamics simulation using IGUN. The extractor aperture is 1 mm in diameter and the gap is 63 mm in length. Each of the 24 beam-lets are carrying ~ 0.8 mA of ion current.

The temperature loads of the target were calculated using ANSYS-modeling program. This program gives the temperature distribution at the target, starting from a beam spot size predicted by the IGUN simulations.

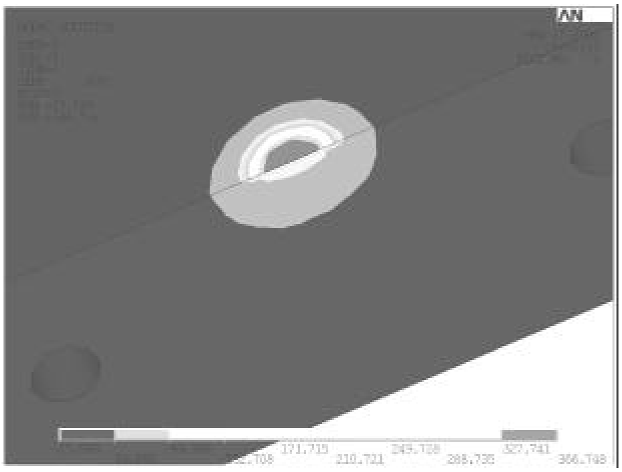

Figure 6. Temperature distribution at the target for the beam spot size calculated using the IGUN. The surface temperature of the titanium in this case is 366 °C.

The experiments together with the IGUN and ANSYS analysis have shown that in the case of D-D reaction and with constant beam loading, the maximum temperature of the target surface at the position of the beam spot can be fairly high without drastically affecting the neutron output of the generator. Even in the case of surface temperature at the beam spot reaching 800-900 °C the neutron flux stays constant. Although the deuterium is desorbed from the heated target it is at the same time constantly loaded by the beam. In figure 7, the neutron flux as function of beam power and time is shown.

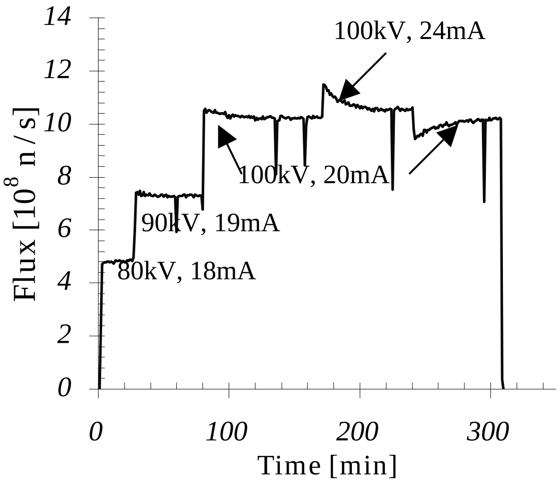

Figure 7. The neutron flux from the co-axial neutron generator as a function of the beam power and the time. At 2.4 kW the target temperature rises beyond a critical temperature, which then results in decreasing flux. When the beam power is again reduced to 2 kW the value of flux stabilizes to the original value.

The co-axial neutron generator is operating currently with D-D neutron fluxes of more than 10^9 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^{10} n/s is designed and implemented.

IV. NEUTRON FACILITY

A new neutron generator test-stand and neutron science facility has been constructed at the Plasma and Ion Source Technology Group. This facility enables high flux neutron generator testing and development together with neutron science measurements, namely NAA, FNAA and PGAA experiments. The first phase of this small-scale facility is completed and it is being currently used for neutron generator testing and for NAA experiments using High Purity Germanium (HPGe) detector. Figure 8 shows an overview of the facility.

The second phase of the neutron facility consists of a generator setup capable of operating at 10^{10} n/s or higher and a PGAA experiment setup together with rapid sample handling system. These changes will be made during the spring and summer of 2003.

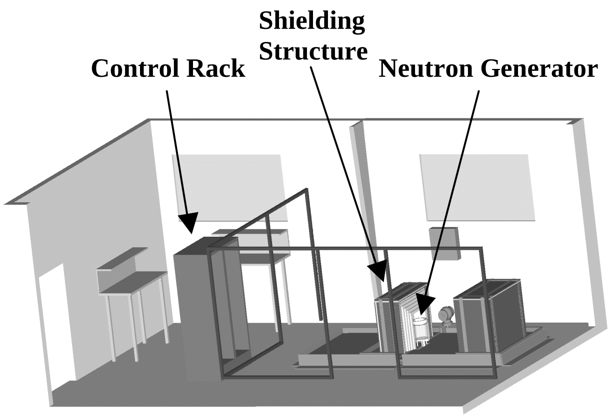

Figure 8. Neutron generator and neutron science facility. The first phase includes the radiation shielding structure suitable for high yield neutron generators, all the necessary utilities and a simple NAA measurement station with a HPGe detector.

V. CONCLUSION

Two different types of D-D neutron generators have been developed in the Plasma and Ion Source Technology Group in LBNL.

The compact axial extraction neutron generator is being operated at the D-D neutron fluxes of 10^8 n/s. The plasma chamber neutral gas pressure has been successfully lowered by using an axial magnetic field. This field is formed using 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 10^9 n/s in pulsed operation.

The high yield (10^9 n/s) co-axial neutron generator is being operated regularly in the new neutron facility. The upgrade of the co-axial generator to the neutron flux of 10^{10} n/s is well under way, using the methods and tools like IGUN and ANSYS to model the target surface behavior in high beam power conditions.

The neutron facility is currently in its phase one development. Current capabilities include high flux neutron generator testing and NAA experiments. In phase two, this facility can be used as a small neutron science facility, including PGAA experiments. The facility serves also as a model for a small-scale neutron science facility together with reliable, safe, long-life and high flux D-D neutron generator.

VI. ACKNOWLEDGEMENTS

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