High-Yield D-T Neutron Generator[*]

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Abstract

A high-yield D-T neutron generator has been developed for neutron interrogation in homeland security applications such as cargo screening. The generator has been designed as a sealed tube with a performance goal of producing $5{\cdot}10^{11}$ n/s over a long lifetime. The key generator components developed are a radio-frequency (RF) driven ion source and a beam-loaded neutron production target that can handle a beam power of 10 kW. The ion source can provide a 100 mA D^+/T^+ beam current with a high fraction of atomic species and can be pulsed up to frequencies of several kHz for pulsed neutron generator operation. Testing in D-D operation has been started.

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1. Introduction

The need to inspect cargo containers, trucks, and other cargo for Sensitive Nuclear Materials (SNM), explosives, or chemical weapons has renewed the interest in neutron sources. Active neutron interrogation can play an important role in these inspection tasks because neutrons penetrate cargo and shielding materials and generate specific signatures. Neutron induced fission in nuclear materials stimulates the emission of β-delayed γ-rays and neutrons that are characteristic signatures of SNM [1]. Another promising neutron-based method for the detection of nuclear materials is Pulsed Neutron Differential Die Away Analysis [2]. Furthermore, neutron induced nuclear reactions in many materials generate characteristic prompt γ-rays that can provide valuable information about the chemical composition of the cargo [3,4].

Neutron generators offer important advantages over other neutron sources. They can be rapidly turned on and off, in contrast to radioactive sources, and are significantly smaller and less costly than accelerator-driven neutron sources operating at higher beam energies. D-T generators produce two orders of magnitude higher yields than D-D generators under the same operating conditions. The 14 MeV neutrons generated by the $T(d,n)^4He$ reaction are highly penetrating, an important benefit in the screening of cargo containers, but they also lead to activation of cargo and a increased likelihood of interfering radiation signals.

Neutron generators, which were first developed more than 40 years ago [5], are limited in output and lifetime [6]. In recent years continuously pumped D-D generators, which use radio-frequency (RF) driven ion sources [7] for generating high beam currents and beam-loaded Ti-targets [6], have been developed at the Lawrence Berkeley National Laboratory (LBNL) [8,9]. Described here is an effort to develop a D-T generator that produces an order of magnitude higher neutron yield than currently available devices and for an extended lifetime.

2. Neutron Generator Concept

In a neutron generator a high-voltage is applied to extract a D^+/T^+ beam from an ion source and accelerate it towards the target where neutrons are produced in D-T, D-D, or T-T reactions. The neutron yield increases with acceleration voltage, limited by HV breakdown across the acceleration gap, and with beam current, limited by the ion source output and the ability of the target to handle the beam power.

In the generator described here a high beam current is extracted from an RF-driven ion source and accelerated towards the target. The generator is operated with a D-T gas mixture and a beam-loaded target, i.e., the D^+/T^+ beam is driven into the target matrix, for achieving acceptable lifetimes. The requirements of a sealed tube for tritium operation posed several design challenges including UHV compatible construction, low pressure ion source operation, and the need to limit the tritium inventory. An RF-driven ion source was developed that operates at pressures down to 2 mTorr, well within the desired pressure range for sealed tube operation (<4 mTorr). Low pressure operation was achieved with a rather large, 4 inch diameter, cylindrical source chamber and an RF power frequency of 27 MHz. The extracted proton current densities exceeded 50 mA/cm^2 and the atomic species fraction reached 80%. A high atomic species fraction is an important benefit because the atomic ions are much more efficient in producing neutrons than molecular ions.

Titanium is a well established target material that can store high concentrations of deuterium and tritium, up to a ratio of 1:2 [6] and can be deposited as a thin layer on a metal backing. The optimal thickness of the titanium layer is a trade-off between the need to make it sufficiently thick so that it is not to sputtered away too quickly and the need for a thin layer to limit the surface temperature and the total amount of activity stored in the target. Molybdenum is a good backing material because of its mechanical strength and good thermal conductivity. Titanium-coated and bare molybdenum targets were tested in D-D operation. The neutron yield for the bare molybdenum target was surprisingly high, only about a factor of two less than the yield for the titanium targets. In spite of its lower yield, molybdenum is a potentially attractive target material for a high-yield generator. Because of molybdenum’s good thermal conductivity, the target can be thick so that its lifetime is not limited by sputtering. Furthermore, molybdenum stores D/T to a lesser degree than titanium which could lead to a significantly reduced tritium inventory. However, more testing is required to better characterize molybdenum’s properties as a neutron generator target.

Other neutron generator components are a gas reservoir and pressure regulator for supplying the D/T gas mixture and keeping a stable pressure inside the tube, and an ion getter pump for the removal of helium and other contaminant gases.

The expected 14 MeV neutron yield for a 100 keV, 50% T^+/50% D^+ beam impinging on a fully loaded Ti-target (TiDT) is about $2.2 \cdot 10^{13}$ n/C. However, extrapolation from our experimental results for beam-loaded D-D generators gives about half that value, likely due to an incomplete beam-loading of the titanium layer [10]. Therefore, the neutron yield for a 100 keV, 100 mA T^+/D^+ beam is estimated as $\sim 1 \cdot 10^{12}$ n/s for a Ti-target and $\sim 5 \cdot 10^{11}$ n/s for a Mo-target.

3. Engineering Design and Construction

The neutron generator was designed and constructed as a sealed tube suitable for operation with tritium. The UHV compatible construction uses brazed joints and conflat seals for accommodating vacuum bake-out. A 3D model of the neutron generator is shown in figure 1. The beam is extracted from the ion source and accelerated to the target through slit apertures in the source, extraction, and acceleration electrodes. Both, the extraction and the acceleration electrode, shape the field at the source electrode for forming the plasma meniscus and accelerating the beam onto the target. The target itself is biased by an array of Zener diodes at 1 kV against the shroud surrounding it and the acceleration electrode to prevent secondary electrons from being accelerated back to the ion source. The target is supported by the HV insulator section through which the HV cable is brought to the target. This way the outside of the tube is kept on ground potential. Attached to the tube are a titanium-soot based D/T gas pressure regulator [11] and an ion pump. Ion source, extraction electrodes, and target are water cooled.

The ion source operates at pressures of 2-4 mTorr using 1-2 kW of RF power at 27 MHz. With a 0.6 cm x 6 cm source electrode aperture, an extracted current density of 25 mA/cm^2 is needed for a 100 mA beam current. The ion source consists of an alumina cylinder with a metal back plate and extraction electrode. An external, water-cooled antenna is wound around the alumina tube as shown in figure 2. An external antenna design was selected because it eliminates the possibility of the plasma damaging the antenna and an uptake of tritium by the cooling water. Furthermore, the antenna is bonded to the alumina for cooling the ion source wall. The source is constructed by hydrogen brazing of a molybdenum plasma electrode and a molybdenum back plate to a 4” diameter alumina tube. The connection between the ceramic tube and the end plates is made by a thin molybdenum wall that is sufficiently flexible to provide stress relief (see figure 2.b). Thermal distributions and mechanical stresses were evaluated in a finite element analysis (ANSYS). Initial source tests revealed that bare molybdenum surfaces of the endplates had a detrimental effect on the atomic fraction. Subsequent coating of those surfaces with aluminum produced a significant improvement in the atomic species fraction.

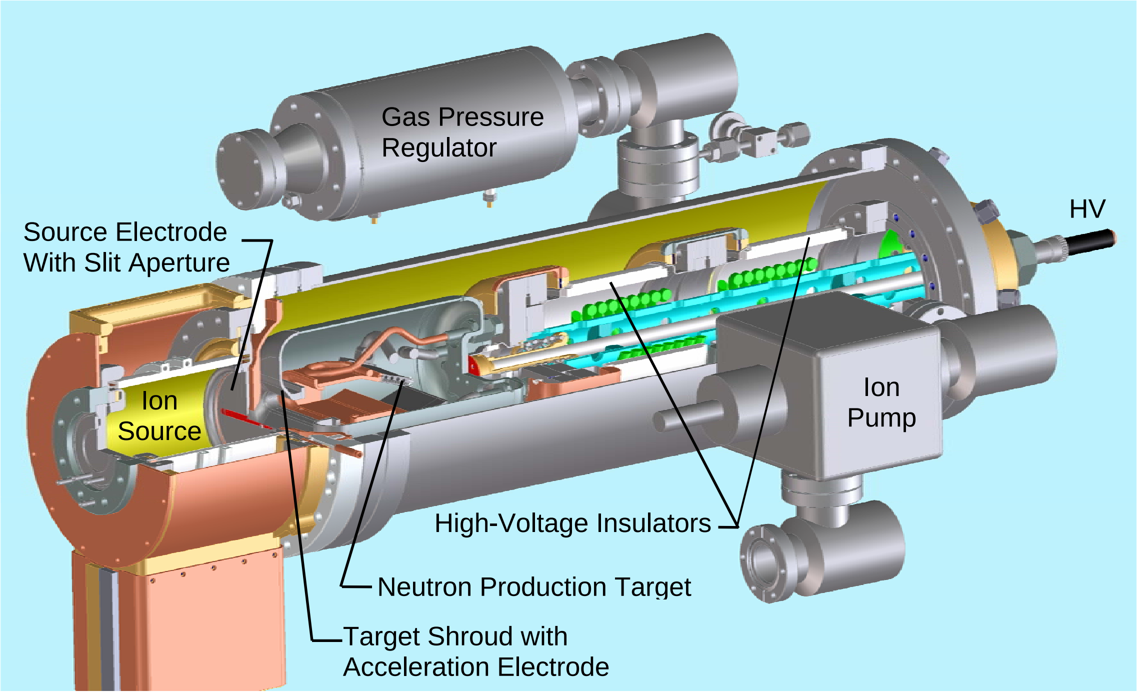

Figure 1: 3D model of neutron generator. The beam is extracted from the ion source on the left and accelerated towards the target which is supported by the HV insulators. The HV cable is brought in from the right through the oil-filled HV insulator section.

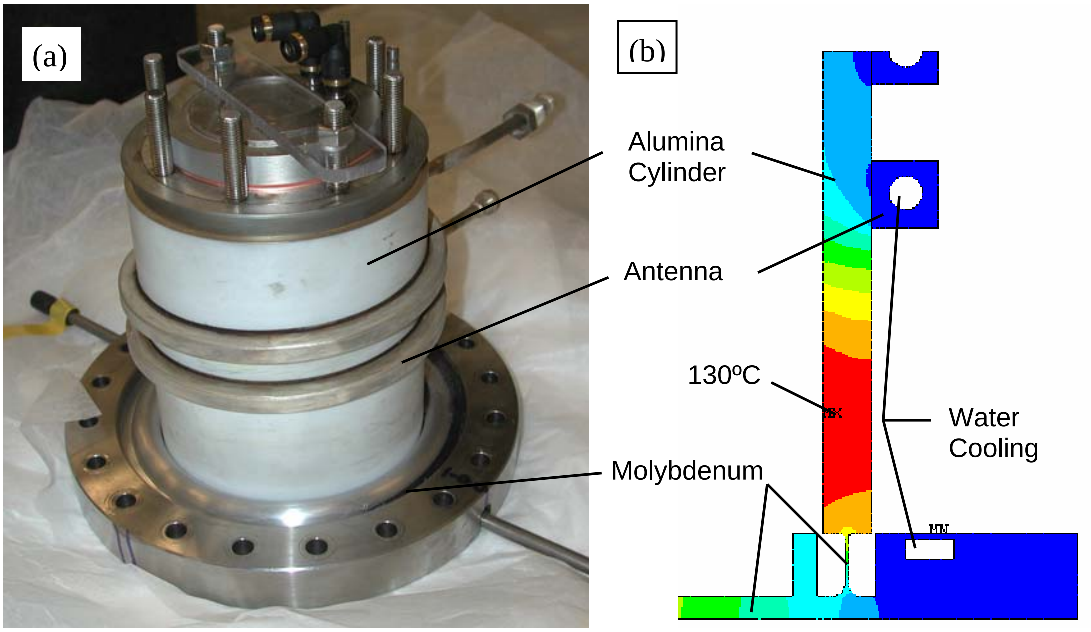

Figure 2: Ion source (a) and thermal response (b).

The target consists of two plates mounted in a "V" configuration with a 19° angle of incidence and aligned with the slit apertures in the electrodes. The "V" configuration allows spreading the heat flux over a larger area as shown in figure 3 and the re-deposition of sputtered material. The target plates (2 cm x 10 cm each) are made of arc-recast molybdenum on which a titanium layer can be deposited. The target is water cooled by forced convection through a fin and rib structure cut into the molybdenum plates. The round passages seen in the molybdenum plate in figure 3 were needed for cutting the cooling channels above and were subsequently filled. A finite-element thermal and stress analysis showed that the target can handle a heat flux of 650 W/cm^2. The maximum temperature of 240°C on the surface of a 90 μm thick titanium layer is sufficiently low to retain deuterium and tritium. The target can handle a total beam power of 10 kW.

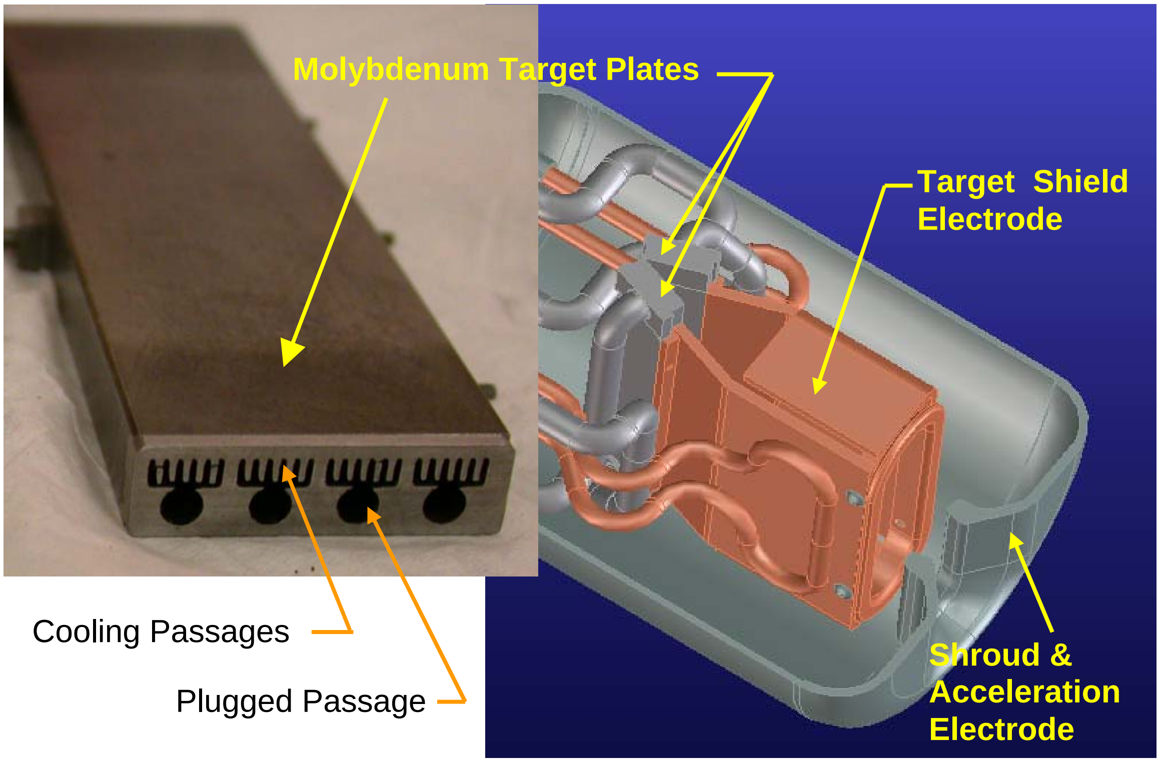

Figure 3: Target assembly with V-shaped target plates.

4. Initial Test Results

Ion source tests showed extracted current densities exceeding 25 mA/cm^2 and atomic species fraction exceeding 75% at 2-4 mTorr operating pressures. Ion beam current rise times of ~20 μs were measured indicating that the neutron generator can be operated in pulsed mode with pulses as short as 100 μs by pulsing the RF power of the ion source. However, during operation of the generator coating of the inside insulator surface of the plasma chamber occurred. Possible ion source design changes have been identified to prevent this and to achieve reliable operation in the future. The titanium-soot based pressure regulator performed well in the generator tests and the gas pressure could be regulated up to 10 mTorr with a fast response time.

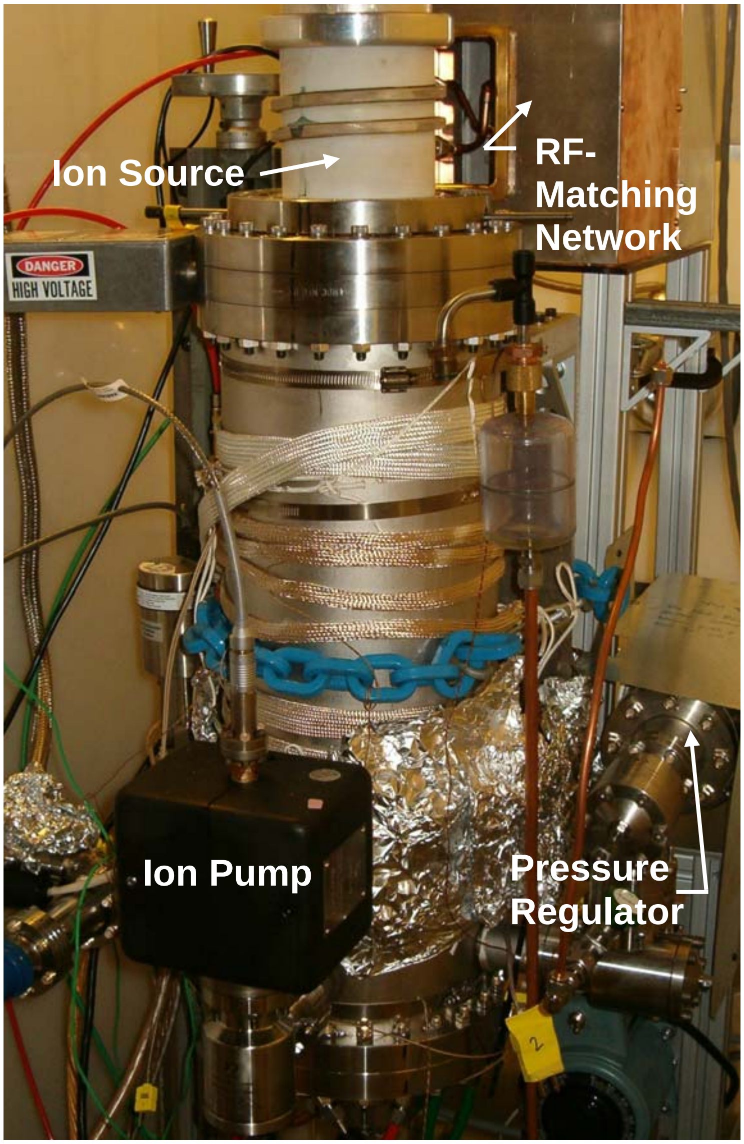

Figure 4: Neutron generator in test stand.

First operational testing of the neutron generator, shown in figure 4, in D-D mode demonstrated neutron production and basic functionality of the generator. However, the neutron production was hampered by a HV breakdown problem that limited operation to 70 kV acceleration voltage. The limited HV holding was not due to operation with beam but manifested itself during HV conditioning and was likely due to issues involving the neutron tube assembly. The required matching of plasma density and electric field at the extraction aperture made it necessary to operate the ion source at an RF power far below the design value. Consequently, only about half of the full beam current was extracted and the atomic fraction was likely significantly below 75%. Under these conditions a neutron yield of $3 \cdot 10^8$ n/s was measured. This result is consistent with a possible neutron production well above 10^{11} n/s when extrapolated to 100 kV, 1000 mA D-T operation of a fully functioning tube. The capabilities of the generator will be determined and demonstrated when the full HV holding capability has been restored.

5. Conclusion

A sealed tube, D-T neutron generator has been designed and built for high-yield operation. In particular, an RF-driven ion source has been developed that operates at the low gas pressure required for sealed source, produces a 100 mA beam current, and can be pulsed. The generator is operated with a D/T gas mixture and the target is beam-loaded for achieving a long lifetime at a high neutron output. Tests indicated that a molybdenum target can produce about half the neutron yield of a titanium target and thus offers the possibility of a thick, long-lifetime target. Initial generator tests at reduce HV showed roughly the expected neutron output.

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