Accelerator-Driven Neutron Source for Cargo Screening[1]

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Abstract

Advanced neutron interrogation systems for screening sea-land cargo containers for shielded special nuclear materials (SNM) require a high-yield neutron source to achieve the desired detection probability, false alarm rate, and throughput. The design of an accelerator-driven neutron source is described that utilizes the $D(d,n)^3He$ reaction to produce a forward directed beam of up to 8.5 MeV neutrons. The key components of the neutron source are a high-current Radio Frequency Quadrupole (RFQ) accelerator and a neutron production gas target. The 5.1 m long, 200 MHz RFQ accelerates a 40 mA deuteron beam from a microwave-driven ion source coupled to an electrostatic Low Energy Beam Transport (LEBT) system to 6 MeV. At a 5% duty factor, the time-average D^+ beam current on target is 1.5 mA. A thin entrance window has been designed for the deuterium gas target that can withstand the high beam power and the 2-3 atm gas pressure. The source will be capable of delivering a flux $>1\cdot10^7$ n/(cm$^2\cdot$s) at a distance of 2.5 m from the target and will allow full testing and demonstration of a cargo screening system based on neutron stimulated SNM signatures.

I. INTRODUCTION

New technologies are currently being developed to address the threat of a nuclear weapon or improvised nuclear device being smuggled into the United Sates. Special Nuclear Materials (SNM), which may be shielded and deeply buried in cargo, can be detected by probing the cargo container with a beam of fast neutrons and stimulating characteristic fission signatures. In the so called “Nuclear Car Wash” concept [1] a cargo container is scanned with a neutron beam and the presence of SNM is signaled by the detection of β-delayed gammas with energies above ~3 MeV

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and β-delayed neutrons from fission products [2]. An upper neutron energy limit is set by activation of cargo and other materials leading to the emission of gammas that interfere with the SNM signal. The $^{16}O(n,p)^{16}N$ reaction leading to the emission of 6.1 MeV gammas with a 7.1 s half-life has been identified as an important interference [2] that must be avoided by keeping the maximum neutron energy below the 10.2 MeV reaction threshold. Other, weaker interferences are possible at lower neutron energies, and the optimal neutron energy range is a tradeoff between penetration and the likelihood of interferences. The required neutron flux depends on cargo and shielding to be penetrated, inspection times, required detection and false alarm probabilities and, importantly, the background count rate in the detectors and its variability. Furthermore, a forward directed neutron beam is desired, and the source must be suitable for deployment in the field and operation by non-experts.

Active neutron interrogation is currently being viewed as a secondary, alarm-resolving screening method to be employed after a primary, radiographic method has identified suspicious regions in a container. While a 40 ft container could be screened in minutes, it may be sufficient to interrogate regions of interest. Our goal is to design and build a neutron source that can provide the range of neutron energies and fluxes required for the comprehensive testing and demonstration of the full capabilities of a neutron interrogation system.

II. NEUTRON SOURCE SYSTEM

Among the nuclear reactions that are suitable for producing high neutron yields, the $D(d,n)^3He$ reaction was chosen for its large cross section in the forward direction, its positive Q-value of 3.269 MeV [3], and the absence of a low energy neutron contribution. Neutrons with energies below ~2 MeV are less penetrating than higher energetic ones and thus produce significantly fewer fission events per unit radiation dose to the container. Furthermore, this reaction allows the selection of an optimal neutron energy range. The upper energy limit is determined by the deuteron beam energy, the kinematics of the reaction, and the energy loss in the target window. The lower limit can be raised by choosing an appropriate target thickness that does not stop the deuteron beam. As an example, figure 1 shows the neutron energy spectrum at 0º for a 6 MeV d^+ beam that is fully stopped in a deuterium target and a spectrum for a thinner, 3 MeV energy loss target.

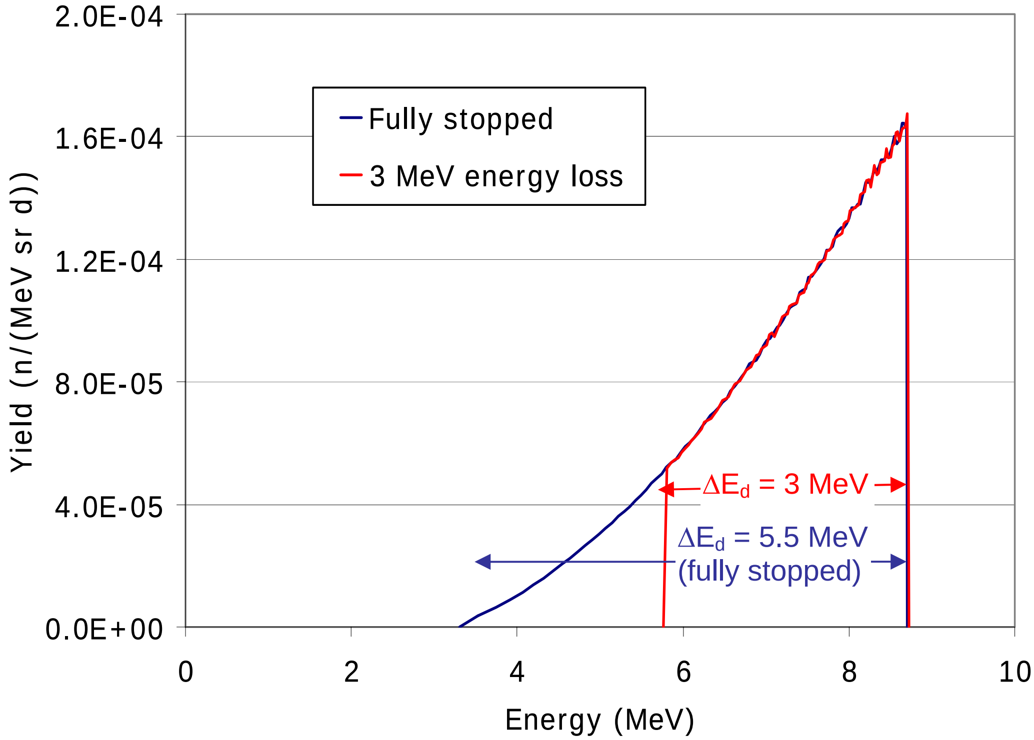

Figure 1. Energy spectra of neutrons produced in the gas target at 0º for a 6 MeV deuteron beam, a 0.5 MeV energy loss in the window, and two target thicknesses. The spectrum for beam fully stopped in the deuterium gas is indicated in blue and the spectrum for a 3 MeV energy loss in red.

A 3D model of the neutron source configured for installation in a pit is shown in Fig. 2. In this design a D^+ beam is extracted from a microwave ion source and injected by a low energy beam transport system (LEBT) into an RFQ that accelerates the ions to an energy of 6 MeV. The beam is transported from the RFQ to the target by a set of bending and focusing magnets. Energy degrading foils mounted near the target window can be inserted into the beam for lowering the maximum neutron energy. A thin-window deuterium gas target has been chosen for the neutron production. It provides a significantly higher conversion efficiency than, for example, a heavy water or a deuterium loaded titanium target because the deuterium area density seen by the beam is lowered in these targets by the other atoms bonded to the deuterium. Estimates based on stopping power calculations [4] and D(d,n)^{3}He cross sections [3] indicate that the neutron yields of these composite materials are one third or less of the gas target yield.

The neutron source is being designed to deliver a high neutron flux up at neutron energies up to 8.7 MeV. The maximum energy can be lowered in a stepwise fashion by inserting degrader foils. A D^+ beam current exceeding 1 mA is required to produce the desired neutron flux of more than $1 \cdot 10^7$ n/(cm^2·s) at 2.5 m from the neutron production target.

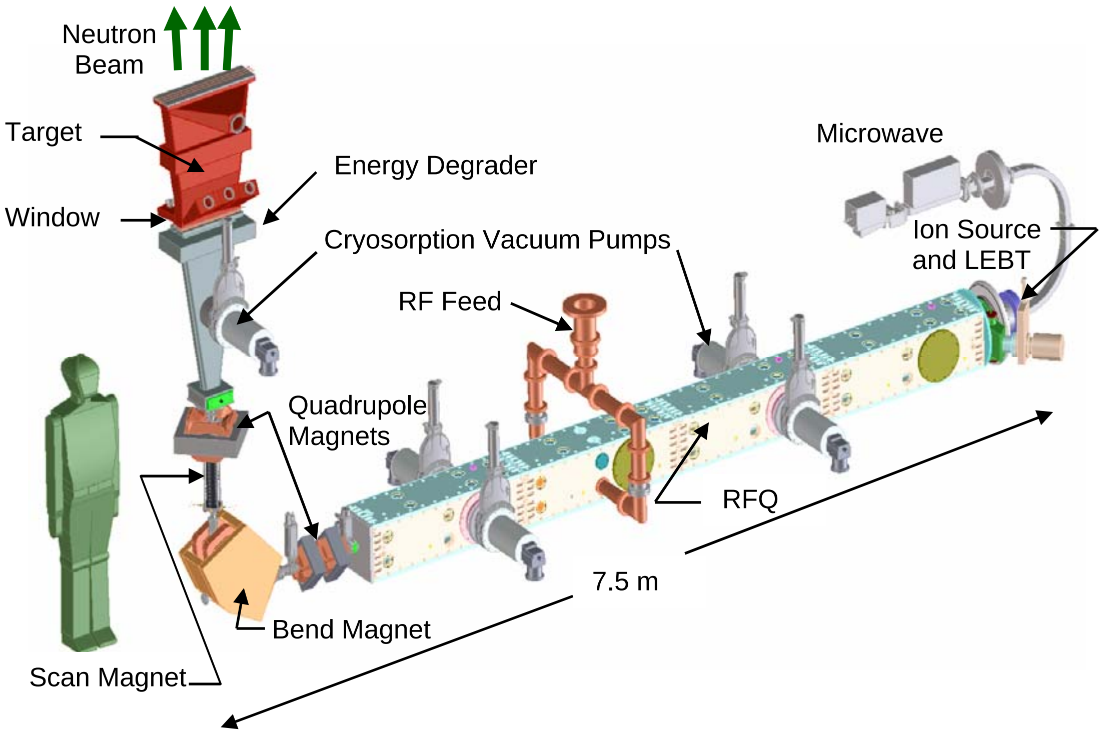

Figure 2. Neutron source model.

ACCELERATOR DESIGN

The microwave-driven ion source [5] is well suited for this application. It can run at high power and high duty factor for long periods of time without requiring maintenance since it has no consumable parts such as a filament. In first tests [6] such a source has produced a 40 mA beam current with an 85% atomic fraction for efficient RFQ operation. The beam is shaped by an electrostatic LEBT with two Einzel lenses and two pairs of steering electrodes embedded in the center and injected into the RFQ at 60 keV [6].

The largest and costliest component of the neutron source is the 6 MeV RFQ-accelerator. The design goal was to achieve good beam capture and transmission efficiencies while keeping the RFQ compact. A 200 MHz RFQ design was chosen over a 400 MHz design and a “kickbunch" beam dynamics design [7] has been selected to optimize for high peak current. While the 200 MHz RFQ is ~1 m longer than the 400 MHz one and has twice the cross section, the larger feature size offers the advantages of looser mechanical tolerances and, most importantly, of operating at twice the peak current, or half the duty factor, with greatly lower RF power consumption. Further, at 200 MHz the amplifier for the RF drive can be based on gridded-tubes and is therefore significantly less costly and more compact than a klystron-based 400 MHz system.

In our design the RFQ is divided into 4 modules. Each module consists of four vanes that are bolted together as indicated in Fig. 3. The vacuum seal is achieved with a unique, custom 3D "O"-ring shaped like the edges of a cube. The RF power is pulsed at 180 Hz. With an injected current of 40 mA, 85% atomic fraction, and 90% transmission the peak accelerated current is 30 mA resulting in a time averaged beam current of 1.5 mA for a 5% duty factor. The peak RFQ power is estimated as ~830 kW with ~650 kW for cavity excitation, i.e., the thermal power is ~33 kW at a 5% duty factor.

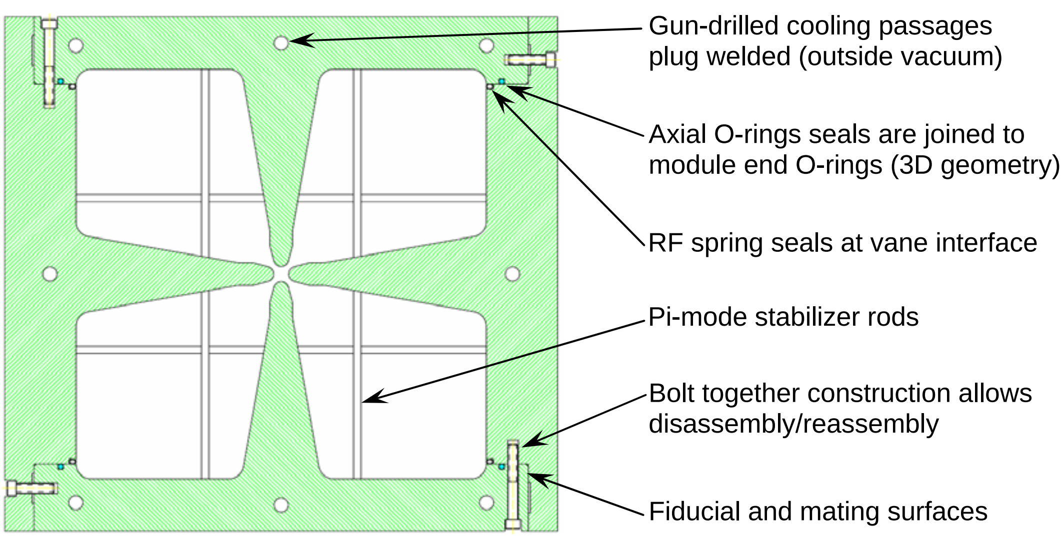

Figure 3: RFQ cross section.

BEAM TRANSPORT AND TARGET DESIGN

The beam is transported and directed towards the target by a pair of focusing quadrupoles and a 90° bend magnet. The beam is spread across an elongated target window by a combination of an air-core scan magnet producing a small deflection and a following defocusing quadrupole magnet that amplifies the deflection. The beam is swept ± 6° across the target once every 0.278 ms long beam pulse.

The neutron production gas target must be designed to withstand the beam power and pressure loads. The beam entrance window must be thin to minimize the beam's energy loss, must withstand the gas pressure in the target (~2.5 atm), and must be efficiently cooled to dissipate the heat from the ion's energy loss in the window foil. In our design the window is 4 cm x 35 cm in size and consists of a 10 μm thick Havar foil that is supported by a molybdenum backer with 1mm wide ribs aligned parallel to the short side of the window. The ribs are slightly bent so that they flex in a predictable way at elevated temperatures. The gap size between the ribs and therefore the transmission of the window depends on the gas pressure; at 2.5 atm the transmission is ~75%.

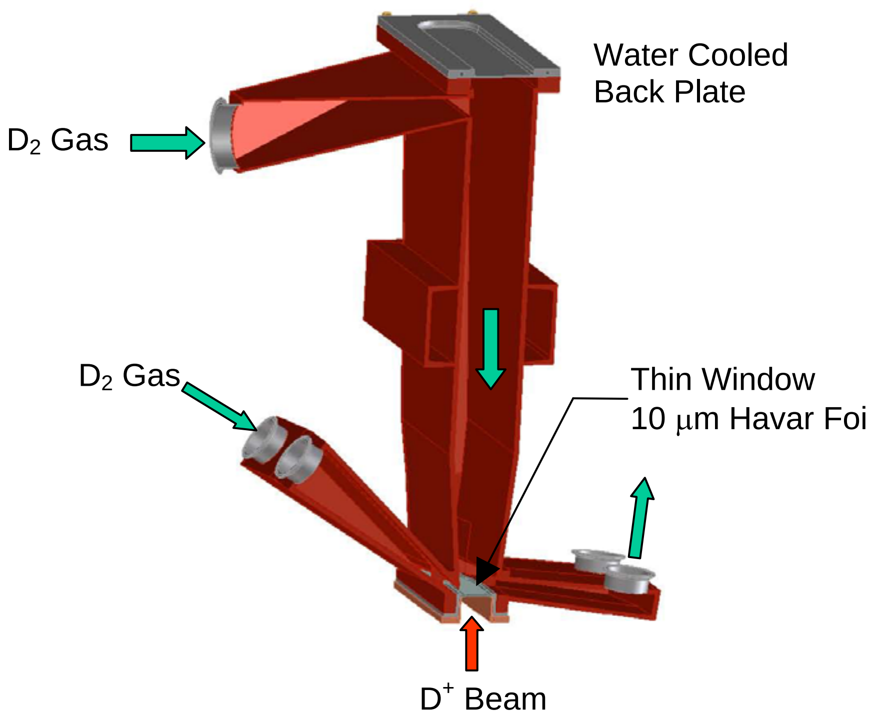

Figure 4: Deuterium Gas Target in Cross Section.

The thin window foil is convectively cooled by flowing deuterium gas across it as indicated in figure 4. In addition, the gas in the target chamber is heated by the beam and must be cooled by circulating it through a heat exchanger. The target is designed to handle 1 mA of D^+ beam at 6

MeV or 1.5 mA at 4 MeV. The beam power is limited by the thermal stresses generated in the support grid. Other target geometries, a round beam for example, are possible but require a more complex backer design.

III. NEUTRON SOURCE PERFORMANCE

The neutron beam has been modeled using angle and energy dependent cross sections for the $D(d,n)^3He$ reaction [3] and stopping power calculations [4]. Figure 5 shows the neutron flux distribution at a distance of 2.5 m from the target, i.e., at about the distance to the center of a cargo container, for a 6 MeV D^+ beam. The beam is spread out in one direction for covering the container height but more collimated in the transverse direction. The neutron flux at the center is $1.8 \cdot 10^7$ n/(cm$^2\cdot$mC) for a 6 MeV D^+ beam and $6 \cdot 10^6$ n/(cm$^2\cdot$mC) for a 4 MeV D^+ beam.

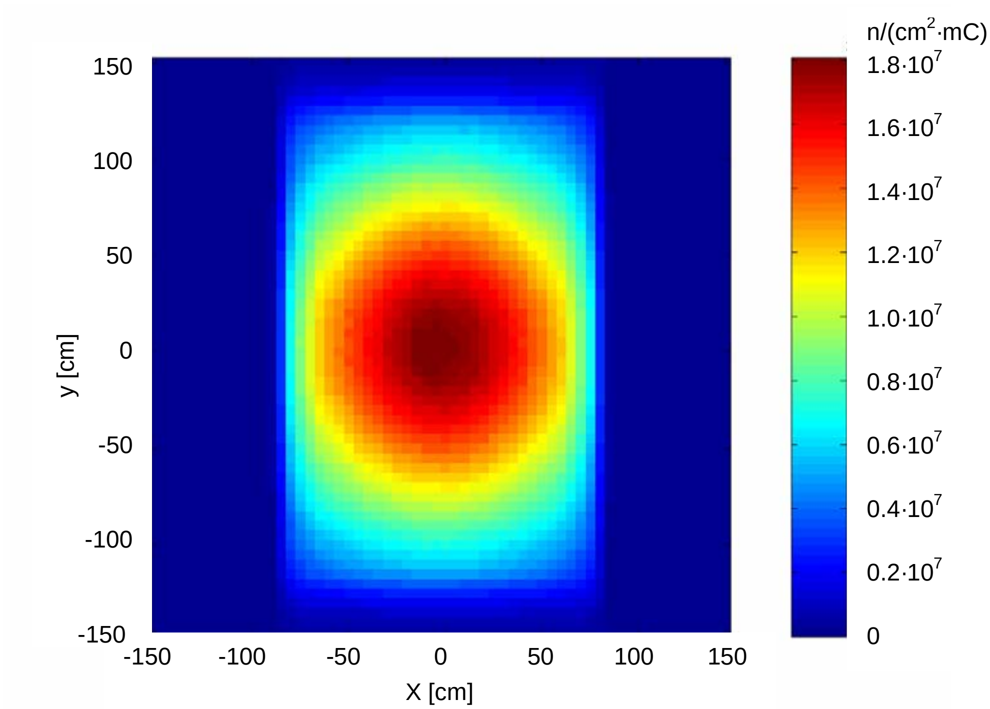

Figure 5: Neutron flux distribution for a 6 MeV d^+ beam, 3 MeV thick target at a 2.5 m distance.

IV. SUMMARY

A neutron source has been designed based on an RFQ accelerating a high-current deuteron beam and a high-power deuterium gas target. The source will provide a forward directed neutron beam with neutron energies up to 8.7 MeV and fluxes up to $2 \cdot 10^7$ n/(cm$^2\cdot$s) at a distance of 2.5 m from the target that will allow the comprehensive testing and demonstration of active neutron interrogation with realistic cargo and shielding configurations.

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