ROTATING APERTURE DEUTERIUM GAS CELL DEVELOPMENT FOR HIGH BRIGHTNESS NEUTRON PRODUCTION*

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Abstract

Work is underway at LLNL to design and build a high-brightness mono-energetic source for fast neutron imaging. The approach being pursued will use a 7-MeV deuterium linac for producing high-energy neutrons via a $D(d,n)^3He$ reaction. To achieve a high-brightness neutron source, a windowless rotating aperture gas cell approach is being employed. Using a series of close-tolerance rotor and stator plates, a differential pumping assembly was designed and built that contains up to 3 atmospheres of deuterium gas in a 40-mm-long gas cell. Rarefaction of the gas due to beam-induced heating will be addressed by rapidly moving the gas across the beam channel in a cross flow tube. The design and fabrication process was guided by extensive 3D modeling of the hydrodynamic gas flow and structural dynamics of the assembly. Summaries of the modeling results, the fabrication of the rotating aperture system, and initial measurements of gas leakage are presented.

INTRODUCTION

Over the past seven years, research and design work has been ongoing to develop a fast neutron imaging system. This machine would be used to image detail in low-Z materials that are heavily shielded behind high-Z materials. Substantial work has been completed that shows mono-energetic 10-MeV neutrons are highly effective for producing such images [1]. As this is intended to be a working imaging machine, extensive system engineering and parameter optimization studies were completed to achieve a design that can reliably run approximately 1750 hours per year.

Generating 10-MeV neutrons with a 1-2% energy bandwidth can be accomplished by passing a 7-MeV deuteron beam through a 40-mm-long deuterium gas cell pressurized to 3 atm. As a gas cell with these operating parameters only reduces the beam energy by 230 keV, the neutrons resulting from the $D(d,n)^3He$ reaction at 0^o will be 10.15 MeV +/- 150 keV. To achieve an imaging resolution on the order of ~1 mm^3, the beam in the gas cell volume needs to be focused to less than a 1.5 mm diameter. To achieve images of overall dense objects (ρl~100 g/cm^2) in time scales on the order of 8-10 hours, a neutron fluence of ~10^{11} n/sec/st at 0^o is required, which necessitates average deuteron beam currents on the order of 300 μA. The extreme energy deposition such a low-energy, high-intensity, tightly focused light-ion beam would make on a windowed gas cell approach is highly problematic. For any material that can handle the 3 atm load against vacuum over 1-2 mm diameter, the extreme energy deposition leads to near-immediate melting or vaporization. For this reason, a “windowless” rotating aperture system is being designed.

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ACCELERATOR, BEAM TRANSPORT, AND IMAGING OPTICS

Since 7-MeV deuterons are needed in a pulsed beam to facilitate use of a rotating aperture system , an evaluation was done on beam parameter, transport, and other system-related issues [2]. Based on this evaluation, a linear accelerator was determined to be the best solution, and a conceptual design study was commissioned.

Accelerator System

The linac envisioned for this machine is the DL-7 model deuteron linac produced by Accsys Technology. The RF structures are 425-MHz resonators that run at up to 2% duty factor. The machine is comprised of two radio frequency quadrupoles (RFQs) followed by one drift tube linac (DTL), where each resonator is connected to its own planar triode 350-kW-peak-power RF generator. Part of the design effort was focused on optimizing the beam physics design to achieve the highest beam current per structure at an emittance less than 3.3 mmmrad (5 x RMS, un-normalized) within the constraints of the RF amplifiers. The accelerator coupled to the high-energy beam transport (HEBT) is shown in Figure 1.

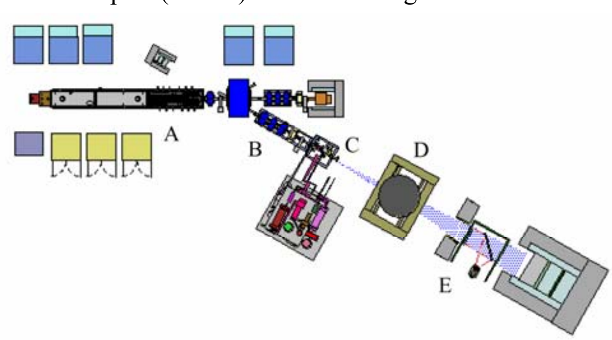

Figure 1: Drawing of a 7-MeV deuteron linac (A) coupled to the high energy beam transport (B). The beam makes neutrons in the gas cell (C), which then pass through the object (D) and produce an image on a plastic scintillator that is transported through an optics system to a CCD camera (E).

High Energy Beam Transport

To transport the deuteron beam from the end of the linac to the gas cell, a high-energy beam transport has been designed that bends the beam through 30^o to reduce activation to the linac due to backstreaming neutrons from the neutron source. As this is a developmental machine, a tune-up beam line is added to qualify the beam before it is turned toward the gas cell production target. This beamline will also be useful for optimizing the tune on the linac.

On the 30° beamline, a quad triplet will be used to focus the beam into a beam focus channel in the gas that is 1.5 mm in diameter over the 40-mm length of the gas cell. This focusing requirement sets the acceptance of the HEBT optics and hence, the emittance needed out of the linac.

Imaging System

To create an image, neutrons that come through an object go into a plastic scintillator (e.g., Bicron BC408) producing a light track along the neutron flight path. Images of the object are created by integrating the capture of light off the scintillator with a CCD camera suitably shielded from scattered radiation.

NEUTRON PRODUCTION

Neutron production by $D(d,n)^3He$ is a common technique in nuclear physics. The three main benefits to the reaction are: it has a positive Q value of 3.3 MeV, which beneficially adds to the deuteron energy to give high-energy neutrons; it has a good total cross section of 90-95 millibarns; and it generates a kinematically focused neutron beam peaked in the forward direction. The downside to using deuterium in a neutron production target is that it is a gas. The rarefaction created in the beam channel due to beam-induced heating will lead to a rapid fall-off of neutron intensity within a beam macrobunch.

Modeling results from the LLNL hydrodynamic code ALE3D [3] shows the density rarefaction of the beam channel that leads to a corresponding roll off in neutron production. Figure 2 shows the density rarefaction in the beam channel as a function of peak beam current.

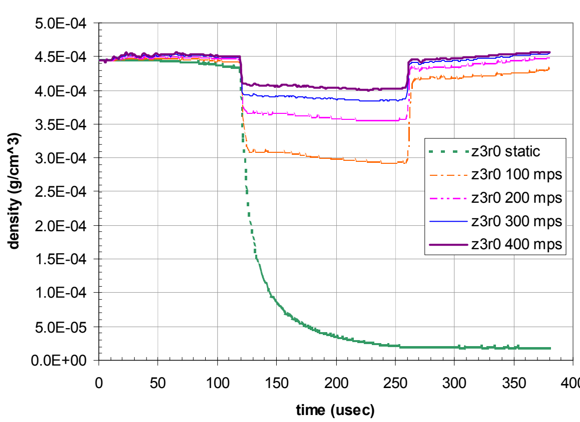

Figure 2: Density rarefaction due to beam heating in beam channel as predicted by hydrodynamic modeling. The step is the width of a macrobunch. The traces show the difference between static and moving gas.

To overcome rarefaction, cross-flowing deuterium gas is being pursued [4]. By passing deuterium gas in front of the beam, the beam-heated gas is rapidly replaced by colder, higher-density gas. Figure 3 shows the roll-off of neutron intensity as a function of peak beam current and the consequent recovery of intensity due to cross-flowing deuterium.

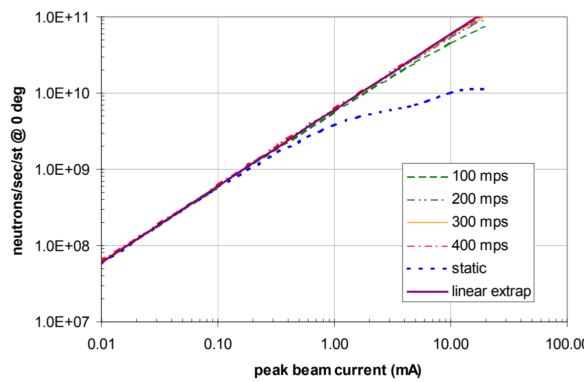

Figure 3: Predicted neutron intensity roll off as a function of peak beam current. Moving the gas from 100-400 m/sec in front of the beam decreases rarefaction.

ROTATING APERTURE GAS CELL

To contain the high-pressure deuterium gas while maintaining a good vacuum in the beamline for transporting the beam, a windowless aperture is being employed. By using two rapidly rotating disks with holes near the outer circumference, high-pressure deuterium gas in a cross-flow tube can be well contained against vacuum. When the holes in the rotor and cross-flow tube align, the beam is fired and interacts with the deuterium gas to produce a burst of mono-energetic neutrons. When the holes are not aligned, the gas flow out of the cross-flow tube is greatly impeded by the close-tolerance gap between the rotor and cross-flow tube faces. Figure 4 shows a simplified drawing of the rotors and cross-flow tube, where the gap between the rotor and tube faces needs to be 1-2 mils (0.001”-0.002”).

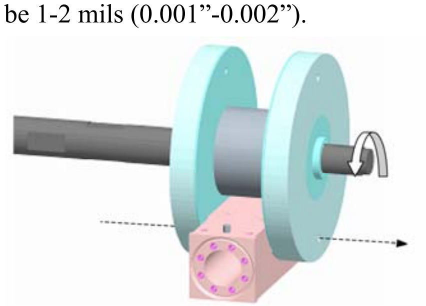

Figure 4: Two rotating aperture disks surrounding a cross-flow tube that contains pressurized deuterium gas. The beam path is shown by the dashed arrow.

A significant challenge in designing such a rotating aperture system is maintaining close geometric tolerances between the rotors spinning at ~4000 rpm and the cross-flow tube surfaces. As the objective is to impede gas flow when the holes are out of alignment, maintaining close tolerances over a broad area of the tube/rotor interface is

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important. To maintain these tolerances, substantial design effort went into creating the rotating aperture assembly, shown in Figure 5. The rationale for using a rotating aperture system over a simple orificed differential pumping system is this approach requires a much smaller and less expensive gas pumping system, and it takes substantially less beamline length.

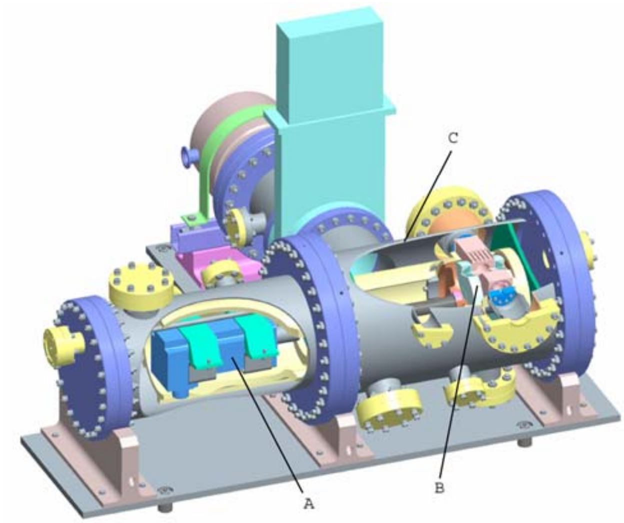

Figure 5: Details of the rotating aperture assembly including the motor (A), the cross flow tube and rotors (B), and the vacuum vessel (C). The overall length of the system shown is 1.2 m.

PRELIMINARY SEALING RESULTS

To avoid the added complication of using flammable deuterium gas during development, helium was used as a surrogate gas since the majority of its physical and flow dynamic properties are similar to deuterium. Initial measurements show the extent to which the system could contain the deuterium gas. Dynamic sealing results with helium gas are shown as the points in Figure 6, with static leakage shown in Figure 7. Results were obtained using three 600 l/min scroll pumps in parallel on the vacuum chamber for pumping.

As the data shows, the dynamic pressure drop across the rotating apertures during operation was a factor of 33. For the estimated gap spacing of 1-2 mils at 2280 Torr in the gas cell, about 18% of the gas load is due to static leakage when the apertures are closed. While this result was encouraging, a pressure drop on the order of 400 is needed to keep the spectrum of lower-energy neutrons less than 5% of the desired energy, which can be obtained by increased pumping capacity on the vacuum volume.

Work also has progressed on modeling the gas-vacuum behavior of the rotor and cross-flow system. Gas flow through the aligned holes has been modeled as choked flow, while leakage through the non-aligned holes was modeled using a pressure-dependent viscous flow through gap. As shown in Figures 6 and 7, good agreement between the model and the data was achieved.

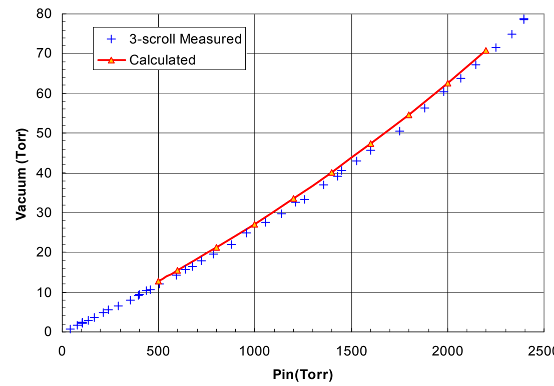

Figure 6: Plot showing the dynamic leakage of gas through the rotating aperture system compared to modeling (red line) Data is for helium gas and apertures set for a 2% duty factor beam.

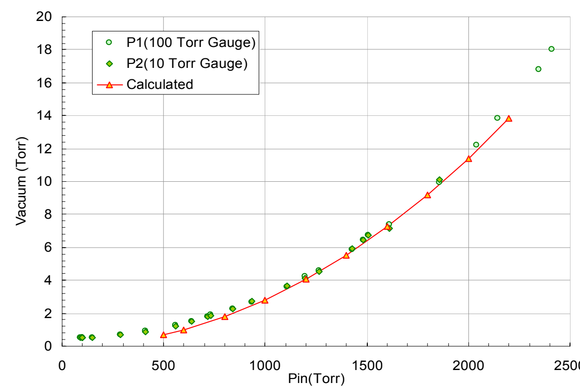

Figure 7: Static leakage results with the holes not aligned indicate the extent of leakage through the rotor-cross-flow gap compared to model (red line).

CONCLUSION

Ongoing work on developing a rotating aperture system for fast neutron radiography has yielded encouraging initial results. Gas leakage models have been developed that will be applied to improving the design.

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