A HIGH-INTENSITY NEUTRON PRODUCTION SOURCE BASED ON ROTARY VALVING*

B. Rusnak, P. Fitsos, J. M. Hall, R. Souza, P. Peaslee, LLNL, Livermore, CA 94550

Abstract

As part of the effort to develop a fast neutron imaging capability at LLNL, a novel windowless deuterium gas target was developed for use with high-intensity pulse deuteron beams to generate neutrons via the D(d,n)^{3}He reaction. The system was designed to create high-velocity, cross-flowing gas to minimize rarefaction due to beam heating in the target gas. The system also employs a unique gas beam stop to minimize knock-on neutrons from implanted deuterons over time. A prototype system employing rotary valving to generate and modulate gas flow, and a rotating aperture to minimize gas back streaming into the beamline vacuum system, was designed and built. Design details and supporting analyses of the gas dynamics of the system are presented.

INTRODUCTION

Investigating low-density features and materials that are heavily shielded within high-density materials is a challenge for x-ray techniques due to the attenuation of the x rays in the high-Z outer materials. Using the high penetrability of fast neutrons to create radiographic images is an alternative technique demonstrated to be very effective at creating cubic-millimeter-scale resolution images in heavily shielded low-Z test objects [1]. Technology development in the pursuit of creating a fast neutron imaging capability as a complimentary non-destructive evaluation (NDE) diagnostic to x rays has been on going at LLNL for the last decade [2].

Neutron Source Requirements

To achieve high penetrability in a variety of potential high Z materials, a 10-MeV neutron energy was chosen. In addition, this energy would not create short-lived activation products in air due to the ^{16}O(n,p)^{16}N reaction, which has a threshold above 10 MeV. The rapid decay of ^{16}N produces a background of high-energy gammas that are not only a radiological hazard but can degrade image resolution. To minimize image degradation due to an excess of scattered lower energy neutrons, the source neutrons also needed to be quasi-monoenergetic. For this application, having the energy width be approximately 10% was acceptable. To achieve nominal cubic-millimeter resolution, the source spot size needed to be at most 1.5 mm in diameter. These requirements placed significant constraints on the system and have strongly influenced the technology development path.

*This work performed under the auspices of the U. S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344.

Production Target Resolution Requirements

Production of quasi-monoenergetic high-energy neutrons can be readily achieved by impinging a deuteron ion beam onto a fixed length of high-pressure deuterium gas via the D(d,n)^{3}He reaction. The maximum final neutron energy is determined by the incoming beam kinetic energy plus the Q value of the fusion reaction of 3.3 MeV, and the energy width of the neutron beam is directly related to the ion beam energy loss as the beam subtends the length gas cell. For this application, the deuterium gas cell is nominally 1.5 mm in diameter and 40 mm long. A deuteron beam of 7 MeV will be used to create ~10 MeV neutrons with a nominal 1 MeV energy width with 90% of the beam being in a forward directed.

Production Target Intensity Requirements

The neutron source intensity desired is 10^{11} n/sec/st at zero degrees. This was set by the goal of realizing a full 256-image computed tomographic (CT) reconstruction of a heavily shielded object in a nominal work shift. To achieve this intensity, 300 uA of average beam current will need to interact with nominally 3-bar deuterium gas at ambient temperature in the gas cell volume.

The small source spot size required for high-resolution imaging will create very high deposited power densities on any materials the beam interacts with, including any solid-material window typically used for making deuterium-gas neutron targets. This is due to the high energy loss of ion beams in solids at these low energies. Operating such a windowed source lends itself to DC accelerators as these provide the lowest possible average power for a given spot size in the window compared to pulsed beam structures. A great deal of experimentation over the years has shown that most windowed gas cells with millimeter-scale focal spots only achieve ~20–30 uA of average current before failure [3]. Given the factor of 10 higher beam currents needed to make the intensity requirements, an alternate approach to windowed gas cells was needed.

Another significant challenge due to the small spot size was stopping and disposing of the unreacted beam after the gas cell. For any solid high-Z stop, since the beam loses only 10% of its energy and does not appreciably enlarge when interacting with the deuterium gas, the beam stop needs to absorb 90% of the beam power over a stopping range of tens of microns. While grazing incident and rotating stop ideas were considered to prevent melting, there was concern that the density variations produced for the neutron beam would result in unwanted shadows on the radiographs, that the solid material would be damaged over time due to the pulsed nature of the

ISBN 978-3-95450-138-0

beam and subsequent cyclic heating and cooling, and that the build-up of implanted deuterium over time would lead to "knock-on" neutrons that broaden and soften the desired fast-neutron spectrum and degrade the resolution; therefore, such a solid stop was not pursued.

The team evaluated the option of placing quadrupoles and dipoles downstream of the gas cell to defocus and then divert the expanded beam to a solid beam stop further down stream and out of the imaging flight line. This approach was rejected due to the need to have massive steel electromagnets in a high-neutron-flux region for extended periods where they would become activated and produce unwanted scattered neutrons that degrade resolution. Permanent magnets were not seen as viable due to a large bore needed downstream of the gas cell to capture the beam (at least 3–4" diameter) and concerns over their sensitivity to high fluxes of neutron radiation and the longer lived activation products that would be produced.

In response to these issues, an argon gas beam stop was developed to use in conjunction with the deuterium gas cell. Stopping the beam in a high-pressure gas will remove the three main issues related to solid stops.

The array of target challenges due to the small source spot size and beam current needed also precluded using the 14-MeV neutrons from the D(t,n)^{4}He reaction. DT tubes are easily capable of achieving some combination of small-source spot sizes, high intensity, and long lifetimes but not simultaneously and reliably as is needed for neutron imaging.

WINDOWLESS APERTURE

As an alternative to a physical window separating the deuterium gas cell from the beamline vacuum, a rotating aperture system was studied that would allow passage of a low-duty-factor, pulsed beam into the cell but would then restrict gas flow back up the beamline. The rotating aperture approach exploits the pulsed nature of commercial accelerators that operate at ~1–2% duty factor and can reduce the gas load and the associated differential pumping system size and cost significantly [4]. The effectiveness of the technology is maximized by achieving precision tolerances of less than 0.001-0.002" in the gaps between sealing surfaces when closed.

To achieve accurate timing of the rotating aperture with the ion beam, a series of vignetting equations were created that modeled the aperture opening behavior as a function of overall diameter, rotational speed, hole size, and beam diameter [5]. These equations allowed designing the system to accommodate the operational range of the pulsed accelerator system.

Hydrodynamic modeling done as part of the analysis effort that looked at gas flow into the vacuum with and without the beam interaction showed that the large peak powers in the beam macrobunch (~110 kW) would significant rarefy the gas in the cell due to rapid heating. The team concluded that the gas in the gas cell could not remain static, as that would lead to a roll-off of neutron intensity for peak currents above ~1 mA. Cross-flowing deuterium gas moving at a minimum of 400 m/s in front of the beam was effective at maintaining the required gas density [6]. To achieve such high cross-flow velocities, various concepts were explored using either venturis or pulsed valves opening against a large pressure differential. The approach pursued was to extend the rotating aperture technique to be a rotating valve as well. By using a valve to modulate the gas, a smaller gas compressor could be used to circulate gas in the system than would be needed for a simple venturi.

The rarefaction predicted in the deuterium section of the gas cell will be even greater in the argon beam stop section, as 90% of the beam power is deposited there, and the energy deposition of the beam in the stopping gas per unit length is a factor of 9.1 greater. Calculations show that achieving high cross-flow velocities with argon will be more difficult than deuterium due to the lower sound speed in the heavier gas. The goal is to realize flow velocities in the 300 m/s range.

ROTARY VALVING APPROACH

Straightforward modifications were made to the rotating aperture vignetting equations to adapt them for rotary valving. These equations were then used to calculate the effective opening areas of the rotating aperture and the rotary valve, which can be compared to the beam pulse, as shown in Figure 1.

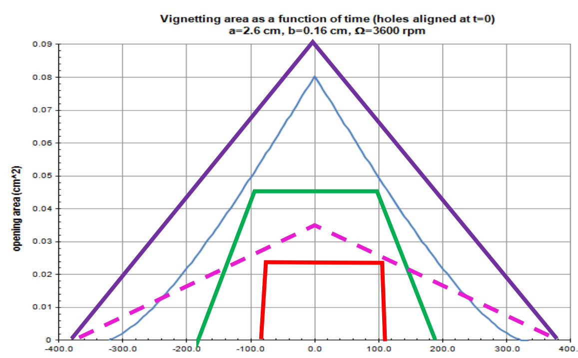

Figure 1: The plot shows the interrelation of the effective opening and the closing areas of the rotary valve gas inlet (purple), the aperture hole opening (light blue), the beam diameter opening (green), and representations of the gas pulse (purple dashed) and the deuteron beam (red).

Just as close tolerances were needed to reduce gas flow to the beamline when the aperture was closed, precision tolerances were also needed on the rotating valve portion of the assembly. The need to hold gap tolerances of less than 0.002" over the rotor length of nominally 14" drove many of the design choices. A system drawing is shown in Figure 2 and a finished system photo in Figure 3.

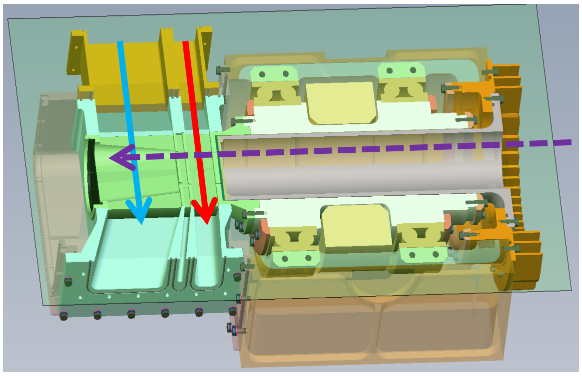

Figure 2: Cutaway of rotary valve system showing the ion beam (dashed) the cross-flowing deuterium gas (red), and the cross-flowing argon stopping gas (blue).

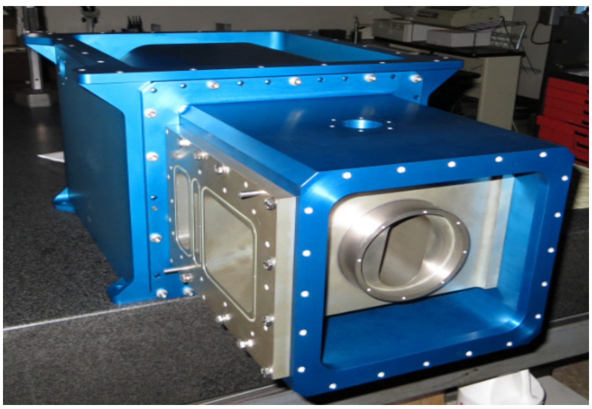

Figure 3: Photo of rotary valve being assembled, showing the central rotor inside the valve manifold (silver aluminium), and the outer aluminium case (blue anodized).

As the gas cell will ultimately need to operate in an intense neutron radiation field, design choices were made to improve reliability and ease disposal, including:

- Moving the motor ~12” away from the deuterium interaction point and being able to put in shielding
- Making as much of the assembly as possible out of 7075 aluminium to minimize longer lived activation products while maintaining good working strength and hardness
- Being able to use all metal seals on the assembly

GAS FLOW ANALYSIS

Extensive modeling allowed evaluation of the fluid flow of the gases in the cells. To simplify the studies and to better relate them to experiments, helium gas was used as a surrogate to deuterium, as it has comparable thermodynamic properties without the flammability hazard. Studies included:

- Helium (deuterium) cross-flow velocity and leakage with no beam
- Helium (deuterium) heating and density with beam energy present, shown in Figure 4
- Argon cross-flow velocity and leakage with no beam
- Argon heating and density with beam energy present
- Helium (deuterium) and argon intermixing with and without beam energy present
- Helium (deuterium) leakage down the beam line

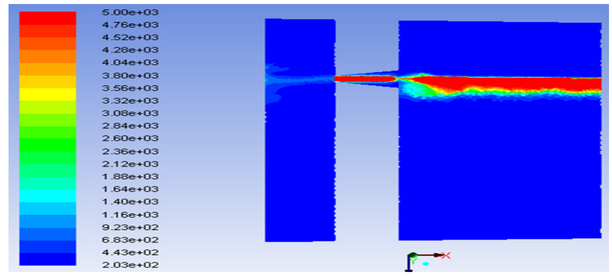

Figure 4: Temperature difference in Kelvin in the deuterium (left) and argon (right) streams due to variations in density and energy deposition with beam power present and the gases moving across the beam channel.

DESIGN DETAILS AND MACHINING

To sustain the tight tolerances needed to better seal the rotary aperture and valve sections, large-diameter bearing doublets were used successfully. To avoid the use of any type of rotary feed-through, which would be problematic at the 3600-rpm rotational speeds and the high radiation environment, a DC motor was installed in the chamber and attached to an aluminium heat sink. To reduce the risk of galling in the event the close-tolerance rotating surfaces contacted, those parts were coated with Ni-Lube, a nickel Teflon composite layer that significantly reduces friction.

ACKNOWLEDGEMENT

The authors would like to recognize the masterful machinist skills of Steve Reid and Peter Steinebrunner at the CHAMP Company, Campbell, CA, and their efforts to achieve the tight tolerances needed on this system.

REFERENCES

[1] J. M. Hall et al, “High-Energy Neutron Imaging Development at LLNL,” Proc. of the 8th World Conf. on Neutron Radiography, Gaithersburg, MD, May 2007.
[2] B. Rusnak, J. M. Hall, S. Shen, “Rotating Aperture Deuterium Gas Cell Development for High Brightness Neutron Production,” 2005 PAC, Knoxville, TN, May 2005.
[3] J. B. Marion, J. L. Fowler, Fast Neutron Physics, (New York: Interscience, 1960), Part I, 703.
[4] J. Guzek, “Elemental Radiography Using Fast Neutron Beams,” doctoral thesis, March 1999.
[5] B. Rusnak, loc. cit.
[6] Loc. cit.

ISBN 978-3-95450-138-0