DEVELOPMENT OF A HIGH BRIGHTNESS SOURCE FOR FAST NEUTRON IMAGING*

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Abstract

Lawrence Livermore National Lab is developing an intense, high-brightness fast neutron source to create high resolution neutron radiographs and images. An intense source (10^{11} n/s/sr at 0 degrees) of fast neutrons (10 MeV) allows: penetrating very thick, dense objects; maintaining high scintillator response efficiency; and being just below the air activation threshold for (n,p) reactions. Fast neutrons will be produced using a pulsed 7 MeV, 300 microamp average-current commercial ion accelerator that will deliver deuteron bunches to a 3 atmosphere deuterium gas cell target. To achieve high resolution, a small (1.5 mm diameter) beam spot size will be used, and to reduce scattering from lower energy neutrons, a transmission gas cell will be used to produce a quasi-monoenergetic neutron beam in the forward direction. Because of the high power density of such a tightly focused, modest-energy ion beam, the gas target is a major engineering challenge that combines a "windowless" rotating aperture, a rotary valve to meter cross-flowing high pressure gases, a novel gas beam stop, and recirculating gas compressor systems. A summary of the progress of the system design and building effort shall be presented.

INTRODUCTION

Using fast neutrons for radiography enables producing radiographic images of thick, dense objects that are difficult to penetrate with X-rays. For objects with ρ*l areal densities greater than approximately 100-150 g/cm^2, fast neutrons are more effective than X-rays for producing sub millimeter-scale images with less absorbed dose to the interrogated object than would occur with X-rays [1]. For this reason, fast neutron radiography/imaging is being developed as an advanced non-destructive evaluation (NDE) technique. Areas of potential application include radiographing large assemblies like car engines and heavy machinery that are optically too thick for X-rays to produce images of interior details [2]. A major challenge in advancing the technique for more uses is the inconvenience of having to do the measurements at a large-scale nuclear reactor or at a spallation neutron source. The LLNL system being developed is intended to be a much smaller lab-scale instrument instead of a facility-scale machine. This should facilitate not only easier access, but improve deployment opportunities for potential users.

NEUTRON PRODUCTION FOR IMAGING

Fast neutron imaging is accomplished in the same fashion as X-ray shadow radiography, except that an intense, bright source of fast neutrons is used instead of a bright source of bremsstrahlung X-ray photons, shown schematically in Fig. 1.

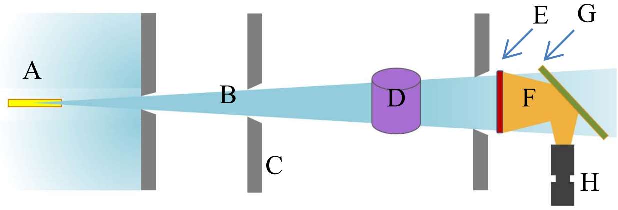

Figure 1: Schematic of neutron imaging approach showing the source (A), neutrons (B), collimators (C), object (D), scintillator (E), light from scintillator (F), turning mirror (G), and CCD camera (H). The location of the object between the source and scintillator sets the magnification of the system.

Achieving high resolution requires a small, bright source spot as the source spot size fundamentally sets the resolution for the system. The LLNL neutron imaging machine is being designed to have a neutron source spot size that is 1.5 mm in diameter and 40 mm in length. Viewed end on, this establishes sub-millimeter image resolution out to 30 cm from the axis 5 m from the source. System resolution is also influenced by the light generation physics in the scintillator, by the scintillator thickness, and the CCD imaging camera. The design has been optimized such that all these elements are consistent with sub-millimeter resolution, and no one element has been over-engineered only to be limited by other elements.

For penetrability, it was determined that the neutron total cross section for most elements drops to the relatively low value of a few barns for neutron energies of 10 MeV and higher. In addition, many heavy elements have a dip in the cross section between 10-15 MeV, suggesting this is a near ideal energy range for fast neutron imaging. Neutrons in this energy range have the added benefits of still having relatively high interaction cross sections with low Z materials inside heavily shielded assemblies, and with the scintillator to produce light that generates the radiograph.

Given this ideal energy range, DT tubes were initially considered for this application given their relative simplicity, modest cost, and ability to produce quasi-monoenergetic neutrons at 14 MeV via the D(t,p)^{4}He

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reaction. After evaluation, it was determined that while the DT tube provided isotropic 14 MeV neutrons, the commercial tubes available were not able to produce a small source spot size of neutrons at the desired intensities. DT tubes with nominal ~2 mm spot sizes typically run in the 10^7 n/s range [3]. While the highly penetrating nature of neutrons is desirable for imaging through thick, dense objects, it also makes them difficult to detect for producing an image. To obtain reasonable imaging times on the order of hours, a neutron intensity of 10^{11} n/s/sr is desired. At this intensity range, the diameter of the source for DT tubes approaches 1 cm or larger to prevent prematurely depleting or damaging the target, which greatly reduces resolution. For this reason, a different technical direction was pursued.

It was determined that the desired neutron intensity can be achieved via the $D(d,n)^3He$ reaction using a suitably sized deuteron accelerator. To limit the cost and size of the accelerator, a 10 MeV neutron energy was chosen as adequately penetrating. This energy has the added benefit of being just below the $^{16}O(n,p)^{16}N$ reaction threshold which decays with the release of a number of high energy (6.15 and 7 MeV) gammas that can create unwanted noise in the imaging optics.

Using a 4 cm long transmission gas cell filled with deuterium gas at 3 atm-gauge is sufficient to produce the desired neutron intensity when illuminated with a 7 MeV, 300 micro-amp average-current deuteron ion beam. This reaction has the added benefit of being kinematically collimated, providing more than an order of magnitude increase in neutron flux within a ± 10 degree cone in the forward direction compared to an isotropic source. The corresponding neutron energies, which peak at 0 degrees, also decrease monotonically as the laboratory angle increases, reaching a minimum at 180 degrees. This increases the production efficiency for useful neutrons, and decreases the shielding required for operating the machine.

TECHNOLOGY APPROACH

The small spot size needed for imaging combined with the high average current needed for reasonable imaging times presents a major technical challenge in designing a production target for a lab-scale neutron imaging machine. Since 7 MeV deuterons have a nominal range of tens of microns in most metals, it has historically been impossible to achieve average beam currents above approximately 20 micro-amps in traditional thin-windowed gas cells with small (<5 mm) spot sizes [4].

To operate at the desired current, a windowless gas cell is being developed that is being used in conjunction with a pulsed ion linac that builds upon earlier work in windowless apertures [5]. The gas cell uses close tolerances and high rotation speeds to not only impede gas leakage down the beam line, but also to meter gas flow into the gas cell such that gas is moving at over 400 m/s in front of the beam to prevent rarefaction due to beam-induced heating [6]. The gas cell also employs a novel gas beam stop to capture the unreacted beam that passes through the deuterium gas. Both the deuterium and beam stop gases will be recirculated and delivered at pressure to the gas cell by two commercial diaphragm pumps.

The beam is conveyed to the target via a beamline system comprised of magnetic quadrupole doublets and triplets separated by a dipole bend magnet so the accelerator is not directly in the backward-directed neutron fluence from the target.

To handle the gas leaking from the target, a differential pumping line is being developed to efficiently remove the gas load from the target to allow the accelerators to operate properly and to minimize radiation along the beamline due to beam interactions with the background gas.

Downstream of the production target, collimators may be used to further shape the neutron beam. A rotation translation stage will be used to place and rotate objects of interest for imaging and computed tomography. In the imaging optics system, a plastic scintillator will be used to convert a portion of the neutrons to light that will be turned by a mirror and focused by a custom-designed fast lens onto a cooled CCD chip to capture the image.

As the system being developed is intended first and foremost to be an imaging instrument, commercial solutions and vendors have been sought out for as many major subsystems as possible. Using a 7 MeV linac readily allows creating a lab-scale (3000-4000 sq. ft.) machine, shown schematically in Fig. 2.

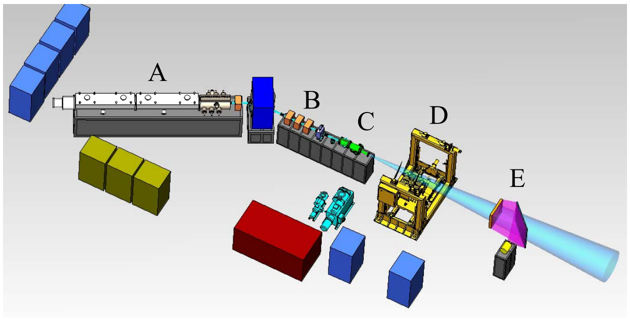

Figure 2: Schematic layout of the 7 MeV accelerator (A), the beam transport line (B), the gas target and pumps (C), the rotation/translation stage (D), and the imaging optics system (E).

DEUTERON ACCELERATORS

To achieve the desired neutron intensity, a 7 MeV pulsed deuteron linac has been purchased from Accsys Technology in Pleasanton, California, and is currently under construction with delivery set for the April 2017 time frame. This DL7 machine will be capable of delivering up to 16 mA of peak current at a 2% duty factor, which provides the required 300 micro-amp average current needed with margin. The machine will be comprised of two radio frequency quadrupole (RFQ) sections and one drift tube linac (DTL) section. The resonators will be driven by three 350 kW peak power RF amplifiers at 425 MHz based on a 12 tube resonant combiner approach. The ion beam will be provided by a pulsed electroncyclotron-resonance driven ion source. A graphic of the DL7 being built is shown in Fig. 3.

To provide for earlier testing potential, and to serve as a hedge against possible schedule delays, a second already available linac system will also be installed. This machine is an Accsys Technology DL4 system. This accelerator can provide up to a 4 MeV deuteron ion beam at 1% duty factor and can in principle deliver 100 micro-amps of average current. It is comprised of a single 425 MHz RFQ resonator and has a duoplasmatron filament-based ion source. A picture of the DL4 system is shown in Fig. 4.

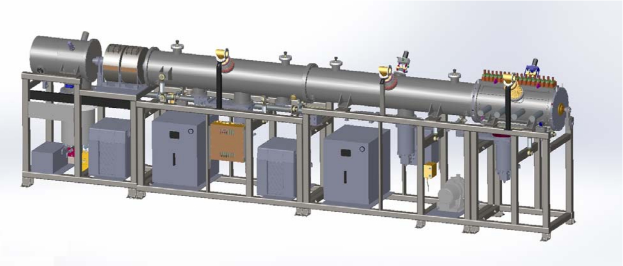

Figure 3: Graphic of Accsys DL7 7 MeV deuteron accelerator currently being fabricated showing (starting at left) the ion source, the low energy beam transport, the two RFQ resonators, and the DTL in their respective vacuum chambers.

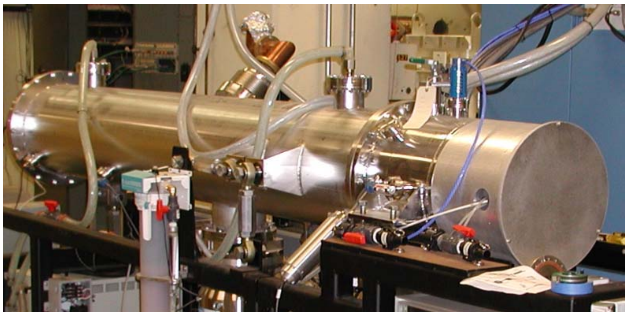

Figure 4: Photo of the DL4 4 MeV deuteron accelerator made by Accsys, showing (starting from right) the ion source, low energy beam transport, and RFQ resonator in its vacuum chamber.

The 4 MeV accelerator delivers approximately half the peak beam power of the DL7 machine, but only one fifth the average beam power, making it a useful tool for performing early testing on the target system and beam line diagnostics and components. Early testing is important because of the small source spot sizes and the high peak power – nominally 100-120 kW – in the beam macrobunch. Diagnosing the beam and understanding its impact on the target are critical considerations that need to be addressed to realize a successful and reliable machine given the damage such a high beam powers can inflict on materials.

The 4 MeV machine shall be installed on the beamline first, and, depending on production schedules, testing may begin using this machine to commission the beamline and to test beamline diagnostics before the DL7 machine is installed. A graphic showing the overall machine configuration with both accelerators, the beamline, the differential pumping line, and the target is shown in Fig. 5.

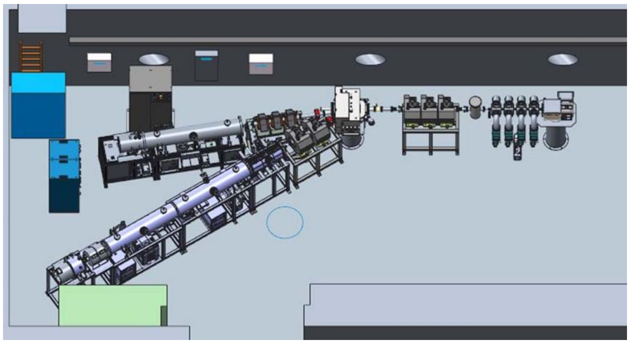

Figure 5: Graphic showing machine configuration being built, with the DL4 accelerator (top left), DL7 accelerator (bottom left), beamline, differential pump line, and gas target.

DEVELOPMENTAL BEAM LINE

To convey the beam from the end of the linacs to the target, a developmental beamline is being constructed. To save space and cost, a simple beam transport with a non-achromatic bend will be used. Part of the work in commissioning the system will be to carefully measure the beam properties to ensure such a transport line is sufficient for propagating the beam cleanly to the target.

The magnetic dipole and quadrupoles for the beamline were designed and fabricated by Stangenes Industries Inc. of Palo Alto, California. Pictures of the dipole and quadrupole are shown in Figs. 6 and 7. The dipole is a water-cooled magnet capable of producing up to 1.27 T fields at the mid plane with a gap of 6.6 cm, to enable bending deuteron ions through up to 66 degrees bend with a bend radius of 45.7 cm. The quadrupole magnets were designed with a 10.1 cm bore, have an effective length of 24.8 cm, and are capable of producing up to 11 T/m field gradients. All the magnets were designed with ample margin to allow maximum tuning capability and performing a wide variety of beam measurements.

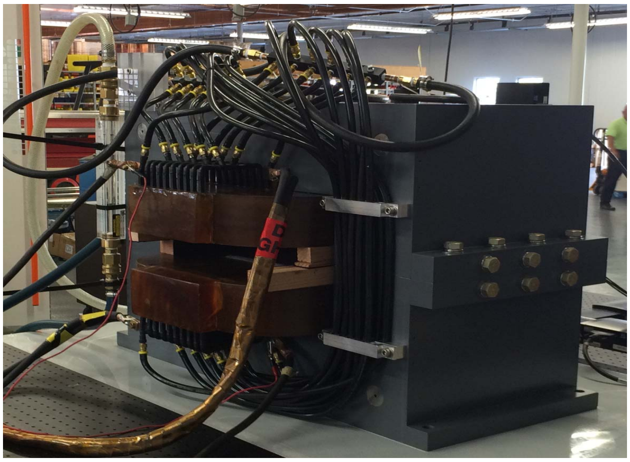

Figure 6: Production photo of the dipole being built by Stangenes Industries, Inc., that is capable of creating 1.27 T fields at the midplane of the 6.6 cm gap.

Figure 7: Production photo of one of the nine quadrupole magnets being manufactured by Stangenes. The quadrupole magnets are capable of creating 11 T/m field gradients over 24.8 cm effective length.

GAS TARGET

The windowless aperture, rotary valve gas target being developed employs rotating machinery to reduce gas flow down the beamline and to create and meter high velocity gas flow in front of the beam. The target was mechanically designed to accommodate the 2% duty factor pulsed beam from the linac and has been described in detail previously [6].

The target is designed to create a stream of deuterium gas at 3 atm-g and 40 mm long moving at over 400 m/s in front of the deuterium beam to produce the 10^{11} n/s/sr at 0-degree fluence of neutrons needed for imaging. As only about 8-9% of the beam interacts with the deuterium gas, the remaining portion of the beam needs to be stopped and discarded. To do this, a novel gas beam stop is being developed in which argon gas at 1-2 atm-g moving at nominally 300 m/s in front of the beam will stop and absorb the beam energy without producing neutrons, and without suffering from mechanical damage and implanted deuterium that can lead to knock-on neutron production over time. A schematic of the rotating aperture and valving approach is shown in Fig. 8.

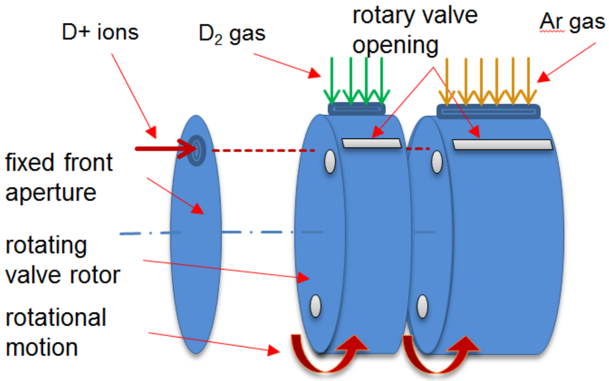

Figure 8: Schematic showing the rotating volumes that create the windowless aperture and rotary valve actions.

This "generation 4" target system is a significant technical challenge, as modelling calculations have not been capable of adequately capturing all the complex beam interaction and gas dynamic behaviours, so extensive testing is required. In addition, analysis has indicated that, while 7 MeV deuteron ions impinging on argon nuclei are classically below the Coulomb barrier, there will nevertheless be sufficient activation of the argon via the direct ^{40}Ar(d,p)^{41}Ar reaction, in which ^{41}Ar with its 1.83 hour half-life and 1.3 MeV gamma presents a significant radiation source during and shortly after beam operation.

The pursuit of such a complicated design is driven by the potential this target has to produce the near ideal quasi-monoenergetic neutron fluence needed for high resolution imaging while avoiding many of the known engineering issues related to using solid beam targets and stops and/or using magnetic optics to steer the unreacted beam away to a separate beam stop, both viable fallback positions in the event the generation 4 target proves unworkable.

PROCESS GAS PUMPING SYSTEM

To move the deuterium and argon gases through the target, two diaphragm pumps were procured from PDC Machines in Philadelphia, Pennsylvania. The pumps are ideal for deuterium service because they use 316L stainless steel diaphragms and the process gas side of the systems are hermetically sealed to outside contamination. The pumps were purchased with over 200% margin to ensure adequate gas is delivered to the target so the neutron intensity requirement is met.

The pumps will be connected to the target through a 316L piping system that will allow for supplying both process gasses continuously through the target. An important part of the gas piping system is the pending design of the gas recovery portion of the system. This portion of the system will be required to scavenge as much process gas as possible from the differential pump line and vacuum beam line to allow minimum topping up of the process gas inventory.

DIFFERENTIAL PUMPING LINE

A differential pumping section is being developed to pump the high gas loads expected from the windowless gas target. The target will be releasing copious gas when the rotating aperture and rotary valve aspects of the target are open roughly 6% of the time, and will be releasing a lesser "leaked" amount for the remaining time through the gaps between the rotor assembly and the stationary parts. System modelling and supportive testing is underway in order to design an efficient, compact differential pumping system to minimize gas loading in the beamline from released gases, and to limit the effective neutron production volume length consistent with the resolution requirements for the overall system. A picture of the experimental setup for developing the differential pumping line coupled to the gas target is shown in Fig. 9.

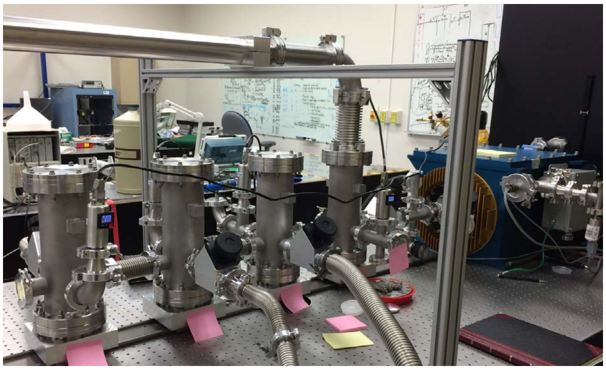

Figure 9: Photo showing a 4 stage differential pumping line being used to develop a model for further optimizing the design. The gas target is shown on the right of the photo as the blue and gold assembly.

IMAGING OPTICS

To create the shadow radiographs, a lens-coupled imaging optics system was developed. The system is comprised of a 60 x 60 cm plastic scintillator sensitive to fast neutrons, but less sensitive to gammas, e.g., Bicron BC400, BC408, BC430, ZnS(Ag), or ZnS(Cu); a turning mirror; a fast (f~2) lens to efficiently capture light off the scintillator; and a Spectral Instruments 1100 Series cryo-cooled camera with a 4096 x 4096 pixel CCD chip. Integration, testing, and final modifications of this system is nearly complete. The designing of the radiation shielding for the system, especially for the camera electronics, is in progress. A picture of the imaging optics system is shown in Fig. 10.

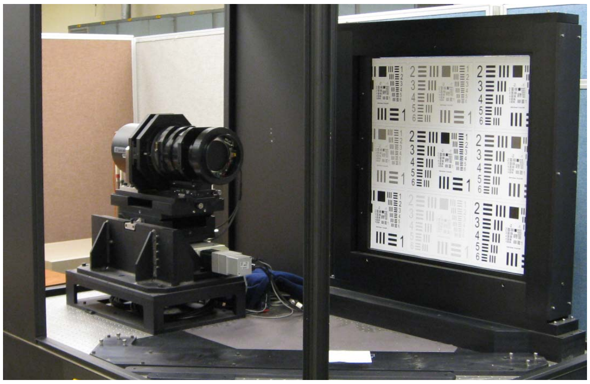

Figure 10: Photo showing the imaging optics system. The camera and lens, mounted on the translation stage, are shown on the left. The scintillator holder is shown on the right with a test pattern on it. The mirror is not installed.

SHIELDING CALCULATIONS

As part of the authorization basis process for operating the accelerators in the LLNL B194 facility, extensive Monte Carlo simulations using MCNP were performed to determine the radiation dose in the accelerator cave due to the neutron source, and how to shield the source to reduce dose to accelerator electronics that need to be co-located with the accelerators in the cave. The calculations show building a shielding assembly of steel and borated poly around the target can reduce radiation doses in the cave by approximately 3 orders of magnitude compared to the unshielded case. A predicted neutron flux map showing the efficacy of the source shielding is shown in Fig. 11.

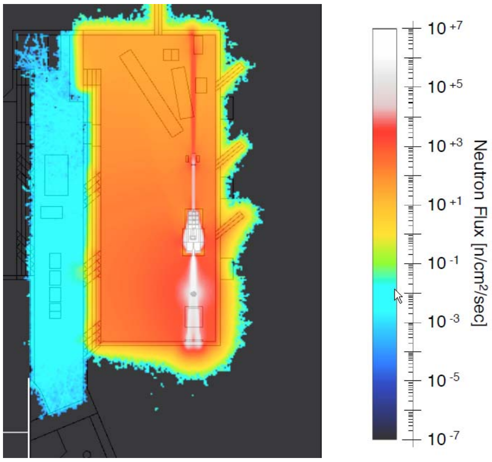

Figure 11: Predicted flux map showing the effectiveness of a localized iron and borated poly shield around the neutron production target.

CONCLUSION

A significant effort is underway at LLNL to complete the construction and installation of the accelerators, beamline, target, and imaging systems needed to demonstrate a lab-scale intense fast neutron source suitable for advancing fast neutron imaging of dense, thick objects that are inaccessible to X-rays for non-destructive evaluation. In the next 12 months, the plan is to commission the machine and carry out initial measurement on the ion beam characteristics and the neutron flux produced by the target. After that, initial imaging evaluations shall be done.

Given the intensity, energy, and spectral purity of the beam, it is anticipated that this source could also be useful to nuclear physicists for doing specialized cross section and reaction measurements.

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