ADVANCEMENT OF AN ACCELERATOR-DRIVEN HIGH-BRIGHTNESS SOURCE FOR FAST NEUTRON IMAGING*

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Abstract

Lawrence Livermore National Laboratory (LLNL) is building an intense, high-brightness fast neutron source to create sub-millimeter-scale neutron radiographs and images. An intense source (10^{11} n/s/sr at 0 degrees) of fast neutrons (10 MeV) allows for penetrating very thick, dense objects while preserving the ability to create good image contrast in low density features within the object and maintaining high detector response efficiency. 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 (absolute) deuterium gas cell target to produce neutrons by the D(d,n)^{3}He reaction. Due to the high-power density of such a tightly focused, modest-energy ion beam, the transport, controls, diagnostics, and in particular the neutron production gas target and beam stop approaches present significant engineering challenges. Progress and status on the building of the lab-scale demonstration machine shall be presented.

INTRODUCTION

Fast neutrons are highly effective for producing radiographic images of thick, dense objects that are difficult to penetrate with X-rays. In objects with 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]. Fast neutron radiography/imaging is being developed at LLNL as an advanced, compact non-destructive evaluation (NDE) technique for dense objects [2]. A current obstacle in advancing fast neutron imaging is the inconvenience of having to do measurements at a large-scale nuclear reactor or at a spallation neutron source. The LLNL system under development is intended to be a smaller lab-scale instrument instead of a facility-scale (nuclear reactor or accelerator-driven spallation) machine. This configuration should facilitate easier access, reduce capital and operating cost, and improve deployment opportunities for potential users.

NEUTRON IMAGING

Creating radiographs with fast neutrons for imaging internal detail in objects is fundamentally analogous to X-ray imaging. In X-ray imaging, a small, bright source of X-ray photons is produced by bremsstrahlung (impinging an electron beam on a tungsten target). The X-rays then illuminate an object and create a shadow radiograph on an X-ray sensitive material for creating a light image. Besides the technology differences in creating a bright source of neutrons for radiographs instead of X-rays, the other main difference is the detection of neutrons to create the radiograph is more challenging. A schematic representation of the imaging approach is shown in Figure 1.

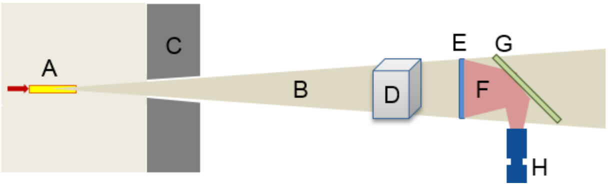

Figure 1: Schematic of neutron imaging approach showing the source (A), neutrons (B), collimators (C), object (D), scintillator (E), light from scintillator (F), turning mirror (G), and CCD camera (H). The location of the object between the source and scintillator sets the magnification of the system.

After extensive evaluation and study over the past decade, a deuteron linear-accelerator-driven neutron source approach was chosen to produce the neutrons needed for high-resolution imaging via a D(d,n)^{3}He reaction in deuterium gas target, the details of which have been reported on previously [3][4]. This combination of technologies results in a demonstration system that is comprised largely of commercially available equipment, fits in a reasonably sized shielded radiography vault, and is straightforward enough to enable operation by trained operators.

The use of a windowless deuterium transmission gas target is being pursued to create a quasi-monoenergetic neutron beam, as we believe this gives an optimum combination of high penetrability, higher contrast in internal lower Z materials in an object, higher detector response, lower dose to the object, and minimal air activation resulting in lower background gamma radiation levels that increases the scatter noise on the captured image.

To create radiographs of a given resolution using fast neutrons, it is necessary to balance a number of variables that include the source spot size, the image formation limitations in the radiation-to-light conversion medium, the pixel size in the digital camera, the source intensity, the object size, the magnification desired, the image formation technique, and the desired nominal imaging time. For the LLNL system using a lens coupled imaging capture approach, a list of some of the important system and imaging performance parameters are shown in Table 1.

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Table 1: Overall LLNL Neutron Imaging Machine Parameters

D+ energy (MeV)	7
D+ average current (microamps)	300
Accelerator duty factor (%)	2
Neutron energy (MeV)	10
Neutron intensity (n/s/sr @ 0 deg)	$1\text{x}10^{11}$
Scintillator type	Bicron 400
Scintillator size (cm)	60 x 60
Source to scintillator distance (m)	5
Nominal magnification	1.25
Source spot diameter (mm) FW0.1M	1.5
Source spot length (mm)	40
Scintillator light spot (mm)	1
CCD pixels count	4096 x 4096
CCD pixel size (microns)	15

ACCELERATOR AND BEAMLINE

To facilitate the development of fast neutron imaging, a neutron imaging test bed is being created at LLNL. Comprised of two deuteron accelerators, the test bed is being configured to allow research with two different deuteron ion beam sources. The beams from each accelerator are conveyed to a common target through a dipole magnet (not simultaneously), followed by a final focus beam transport line that shall also be used to thoroughly characterize the beam produced from the accelerators. A layout of the system is shown in Figure 2.

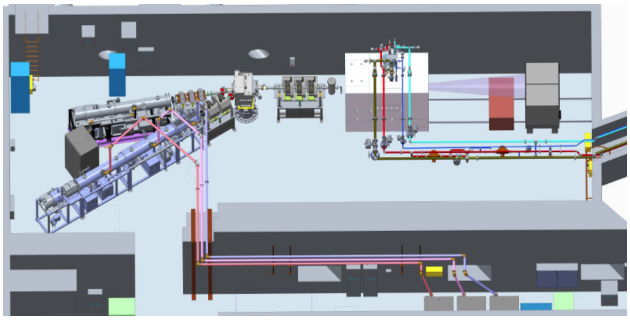

Figure 2: Graphic showing machine configuration being built, with the DL4 accelerator (top left), DL7 accelerator (bottom left), beamline, differential pump line, and gas target. Main electronics and the RF amplifiers are located outside the accelerator vault to protect electronics from radiation damage. The accelerator vault size is 70 x 40 feet.

A lower average power beam of 400 Watts will be provided by a 4 MeV, 100 microamp average current RFQ linac system, a DL4, built by Accsys Technology in Pleasanton, CA which is ready for installation; and a 2100 Watt average power, 7 MeV, 300 microamp average current DL7 system which is a combination of 2 RFQs and 1 DTL is in final production to be delivered later this year.

The one dipole and nine quadrupole transport magnets for the system built by Stangenes Industries in Palo Alto, CA have been received and are undergoing final inspection. A photo of the quadrupole magnets is shown in figure 3. Beamline diagnostics shall include beam position monitors, Faraday cups, and beam profile monitors based on residual gas fluorescence. The quad and dipole magnet parameters are shown in Table 2.

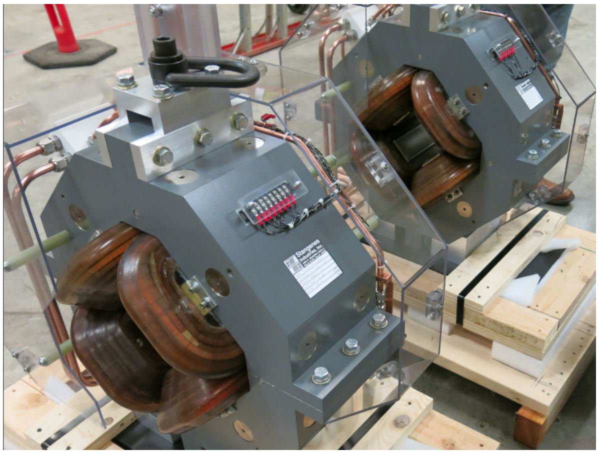

Figure 3: Photo of two quadrupole beamline magnets.

Table 2: Summary of Beamline Magnet Parameters

Dipole gap (cm)	6.6
Dipole operating current (A)	270
Dipole field strength (T)	1.27
Quadrupole bore (cm)	10.1
Quadrupole operating current (A)	240
Quadrupole field gradient (T/m)	11

NEUTRON PRODUCTION TARGET

Creating a high brightness neutron source using a 7 MeV deuteron beam in deuterium gas for a 2.1 kW average, and 115 kW peak power beam presents significant technical challenges. The current approach being pursued is to use a windowless deuterium gas cell at 3 bar-a where only a fraction of the deuteron beam reacts in the deuterium gas. While this target approach enables producing high resolution radiographs, technical solutions are being developed to address the associated challenges of rarefaction of the deuterium gas due to beam heating, of stopping the unreacted beam reliably in a way that doesn't contaminate the neutron spectrum, and of containing, controlling and recovering the gas leakage through the windowless aperture system.

To minimize the impacts of the beam heating the deuterium gas which causes a reduction in gas density, and hence neutron output, the deuterium gas shall be conveyed across the beam at upwards of 400-600 m/s. This high-volume gas flow will be realized by using a large-volume diaphragm pump in coordination with a rotary valving system to meter gas that will result in a pulsed gas jet to be produced corresponding to each beam macrobunch.

With only about 10% of the beam power being used to make quasi-monoenergetic neutrons, the remaining 90% of the beam needs to be stopped in a way that is robust, doesn't result in primary and knock-on neutrons from implanted deuterium over time, and won't create shadows and non-uniformities in the neutron illumination field for imaging.

Target development to date has pursued using a cross-flowing argon gas beam stop to arrest the remaining beam and remove its heat from the system. A gas beam stop was attractive as it was a fluid that didn't suffer from beam induced physical damage like a solid would, it readily carried away the heat in the moving fluid stream, and it minimized the mass and non-uniformities that would impact imaging. Argon was chosen as a stopping gas as it was minimally reactive chemically, was mostly monoisotopic, and was readily available and therefore economical.

While initial development work showed argon to be a potentially attractive option for the problems it solved, further nuclear physics evaluations done in part to support the development of the authorization basis showed the direct reaction ^{40}Ar(d,p)^{41}Ar has a substantial cross section at over 400 mb, and the resultant decay characteristics of ^{41}Ar would quickly make a short lived and highly radioactive source of the recirculating argon gas. This activation level is highly undesirable from an operations and safety basis standpoint, and alternative approaches are being evaluated.

TARGET SHIELDING ASSEMBLY

To collimate the 10 MeV fast neutron beam, and to minimize radiation levels in the accelerator vault, a specially designed beam collimator and target shielding assembly is being designed, shown in Figure 4. Monte Carlo simulations show the shield will reduce dose levels to equipment in the room approximately a factor of a thousand. The shield is comprised of a 14-inch-thick forward collimator plus a nominal 4-inch-thick side enclosure for the target made both of mild steel in order to moderate neutron energies above 5 MeV. The rest of the assembly will be made of 5% borated polyethylene.

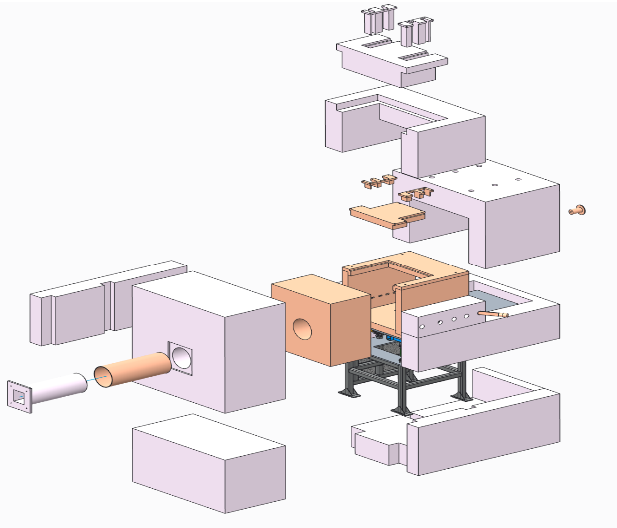

Figure 4: Graphic showing the latest design of the target collimator and shielding assembly, comprised of mild steel (orange), and 5% borated poly (pink). The overall shield will weigh around 40,000 lbs, and is nominally 66" x 120" x 96" high.

TARGET NUCLEAR PHYSICS

As part of the physics re-evaluation regarding the gas beam stop, a number of beam-stopping spectrum-weighted reaction cross sections were generated from the TENDL libraries, shown in Figure 5. As shown in the plot, for gases lighter than krypton, there are a number of potential (d,n) and (d,2n) reactions of greater magnitude than the D(d,n) baseline reaction. The published data also showed significant inconsistencies and gaps in the data that suggest more detailed evaluations are warranted. While the D(d,n) reaction remains the baseline due to the quasi-monoenergetic spectrum it provides, some of the other light gases offer intriguing potential as more poly-energetic neutron targets as an alternative to Be as a stopping medium.

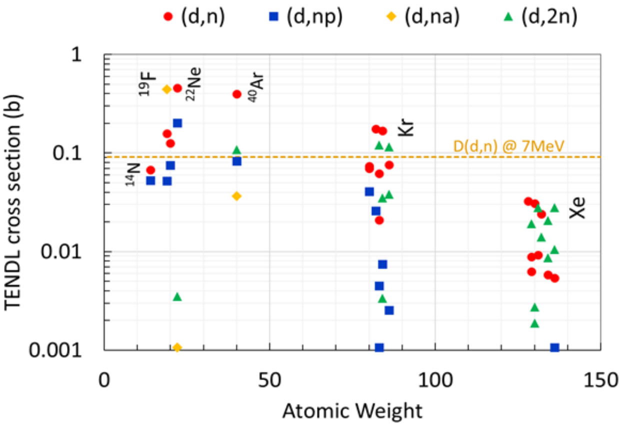

Figure 5: Plot shows cross sections for various light gas isotopes compared to D(d,n) shown as a dashed line.

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 coming 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 anticipated spectral purity of the beam, it is anticipated that this source could also be useful for nuclear physics, activation, calibration, and scintillator development measurements.

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