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Fusion driven gamma and fast neutron radiography test-bed at Lawrence Livermore National Laboratory

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Accelerator Driven Gamma and Fast Neutron Radiography Test-bed At Lawrence Livermore National Laboratory

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Abstract. Accelerator driven fusion gammas and fast neutrons could provide unique radiography capabilities due to their ability to produce both high and low energy mono-energetic gammas and neutrons compared with broadband bremsstrahlung based x-ray sources. The possibility of simultaneously obtaining both gamma and neutron radiographs using one source could allow complex objects composed of a large range of low to high Z materials to be imaged. In this paper we review a 4 MV RFQ accelerator driven radiography test-bed at LLNL designed to study the physics involved in applying these dual output fusion reactions for radiography applications. First experimental neutron images from a carbon target are presented.

Keywords: fusion gammas, neutrons, radiography, NDE, imaging
PACS: 28.20.Pr, 07.05.Pj, 87.59.B-

INTRODUCTION

Accelerator driven fusion gammas and fast neutrons could provide unique radiography capabilities due to their ability to produce both high and low energy mono-energetic gammas and neutrons compared with broadband bremsstrahlung based x-ray sources. The possibility of simultaneously obtaining both gamma and neutron radiographs using one source could allow complex objects composed of a large range of low to high Z materials to be imaged. Prior work in neutron imaging has already shown it to provide significant complementary information to traditional x-ray or gamma radiography [1]. In this paper we review a 4 MV RFQ accelerator driven radiography test-bed currently being setup at LLNL designed to study the physics involved in applying these dual output fusion reactions for radiography applications. First experimental neutron images using a carbon target are presented.

The focus of our work is on the development of portable imaging systems, illustrated in Figure 1, which can serve a variety of needs such as isotope source replacement. The work entails: 1) Understanding the physics of gamma and neutron radiography with setups that have very close source to detector distances which result in uncollimated imaging. This result in significantly higher flux onto the detector which minimizes the integration time or source strength required. However, because the source is divergent this causes significant image blurring and distortion due to both the object and, especially for MeV level sources, the finite thickness of the detector. Figure 2 illustrates the effect schematically. We are working on mitigating some of these effects through post-processing software as shown in Figure 3 and discussed in detail by Wang [2]. If the deleterious effects on the image of thicker detectors can be mitigated, thicker, more efficient detectors could be used to further reduce the source strength, and thus the size of the accelerator or source, required for all applications. Lastly, the source spot-size must be small enough to prevent additional blurring at these close source-to-detector distances. 2) For isotope replacement [3], developing replacement sources that replicate the source spectrum and/or providing the same or improved functionality of the replaced source. Although in general it is extremely difficult to match the yield of isotope sources while maintaining portability using accelerator based systems, accelerator systems can match brightness and offer additional capabilities such as dual photon and neutron imaging.

To achieve these goals, we pursue a coupled simulation and experimental approach. For example, in a source replacement application focused in the non-destructive evaluation (NDE) space, we start with MCNP simulations of the radiography process for a proposed replacement source. Next, we validate the simulations via experiments. After validation, we can use the same models to examine different concepts of operation with simulations and determine the viability of the proposed source against established isotope sources currently used for NDE. In the next Sections we briefly review the experimental test-bed we have assembled for these validation experiments and the simulation approach we are taking to compare fusion based sources against isotope sources in the NDE space.

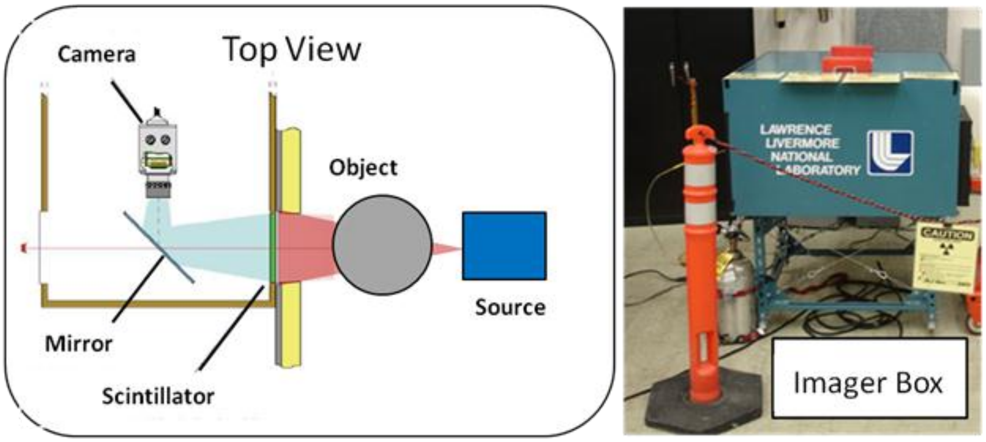

FIGURE 1. Portable imaging system concept, and test imager [10].

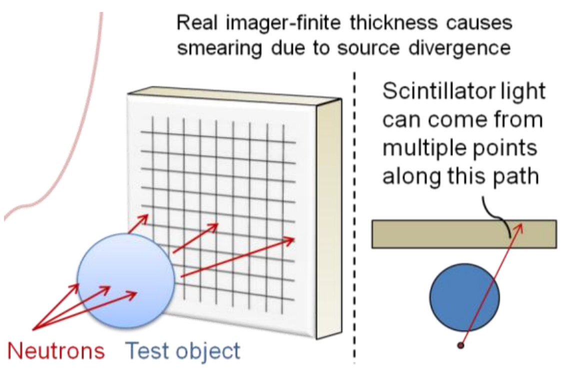

FIGURE 2. Smearing and blurring effects due to finite thickness detector.

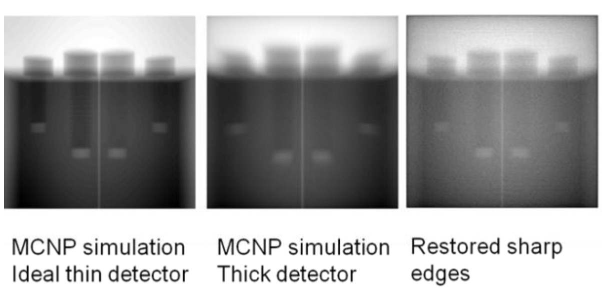

FIGURE 3. Numerical test of reconstruction routine to eliminate the blurring effect from thick detectors. The radiography setup simulated consisted of a Cf-252 source placed against a test object made of a 1" thick lead shield and a 1" thick polycarbonate blocks with nylon and steel screws. A 2 cm thick BC400 scintillator detector was place 2 cm behind the polycarbonate block.

RADIOGRAPHY SETUP AND FIRST RESULTS

The experimental test-bed consists of a 4 MV D^+ DL-4 RFQ from AccSys [4], shown in Figure 4, and has characteristics described in Table 1. Initial radiography tests of the RFQ started with a simple carbon target, which produces broadband MeV neutrons and mono-energetic gammas via primarily the following reactions, with the gamma output typically greater than the neutron output [5-7]:

$^{12}C(d,p\gamma\ (3.1\ MeV))\ ^{13}C$, Threshold=0.368 MeV [6]

$^{12}C(d,n)^{13}N$, Threshold=0.281 MeV[6]

The target is installed at the end of the RFQ and shown in Figure 5; it has a 20 degree tilt to increase the area receiving the beam power. 95% of the beam is on approximately a 2.5 mm spot on the target. The target has been tested up to 15 uA average current and no damage was observed. For 4 MeV D^+ beams previous experiments indicate total neutron yields of ~6 x 10^8 n/s per uA of deuteron current [5]. We have confirmed these yields to approximately a factor of two by dosimeter measurements of the forward neutron emission. The conversion between measured dose and neutron yield was calculated by MCNP simulations of our entire radiography setup, and estimated at ~40 mrem/hour=10^9 n/s for our dosimeter at its location. The primary uncertainty in this conversion factor involves the neutron spectra used in MCNP since the spectra is not mono-energetic nor is it isotropic: the complete neutron spectrum is difficult to model and is currently a work in progress. Based on the available cross-section data there is some forward directionality in the output [6, 8] and the mean neutron energy of the spectra should be around 1-2 MeV [9].

We have thus assumed for our conversion factor calculations that the flux hitting our dosimeter is two times higher than the isotropic flux. We have also calculated the variation in the factor based on using different mono-energetic neutron energies; this appears to be a +/-30% effect and for our current factor we have simply averaged the dose response for 1.5 MeV and 4 MeV neutrons. Overall, the dosimeter derived yields using this conversion factor are typically ~80% of the expected yields based on measured RFQ current output in the 5-15 uA range where initial operations took place. We thus expect yields of ~7 x 10^{10} n/s when we operate the accelerator at the full operating current of 110 uA.

We have begun preliminary neutron radiography tests using this carbon target as part of the shakedown process. Figure 6 shows an initial radiography setup and a test object composed of polycarbonate blocks with nylon and metal screws shielded by 1 inch of lead. The lead shield was placed to test the effectiveness of neutron radiography of low-Z materials shielded by higher-Z slabs. Figure 7 shows the recorded neutron radiograph after an integrated fluence of ~10^9 n/cm^2 on the lead shield of the test object. Images were taken over 45 s intervals and summed to form the final image; each image was processed with a filtering routine to eliminate high intensities "spikes" caused by direct neutron interaction with the CCD pixels. A background image with no test object, processed with the background learner described in [2], was used for background subtraction. In the final image, the screws in the test object can be seen behind the lead shield along with the C-clamp holding the test object together, but the blind holes in the bottom test block were not easily visible. The imager used is described in [10] and is currently equipped with a 4 cm thick BC-400 scintillator, which is significantly more sensitive to neutrons than gammas.

We have now installed a transport beamline with four quadrupole magnets which will allow us to change the spot size of the beam to test the effect of different source brightness and to increase the test-bed capabilities. The quadrupoles came from the Advanced Test Accelerator experiment and can be operated up to ~5 T/m. Figure 8 shows these quads along with beam images from preliminary tuning tests.

TABLE 1. DL-4 Performance Specifications (adapted from DL-4 Manual)

Operating Frequency	425	MHz
RFQ output energy (nominal)	4.0	MeV
Linac maximum output current (marco-bunch, pulsed)	12	mA
Total linac length	3.62	m
Beam pulse width range	15-150	μsec
Beam pulse repetition rate range	15-150	Hz
Pulsed rf power requirement	290	kW
Maximum rf duty factor	1.2	%
Calculated normalized output beam emittance (90%)	<=1.0	π mm-mrad

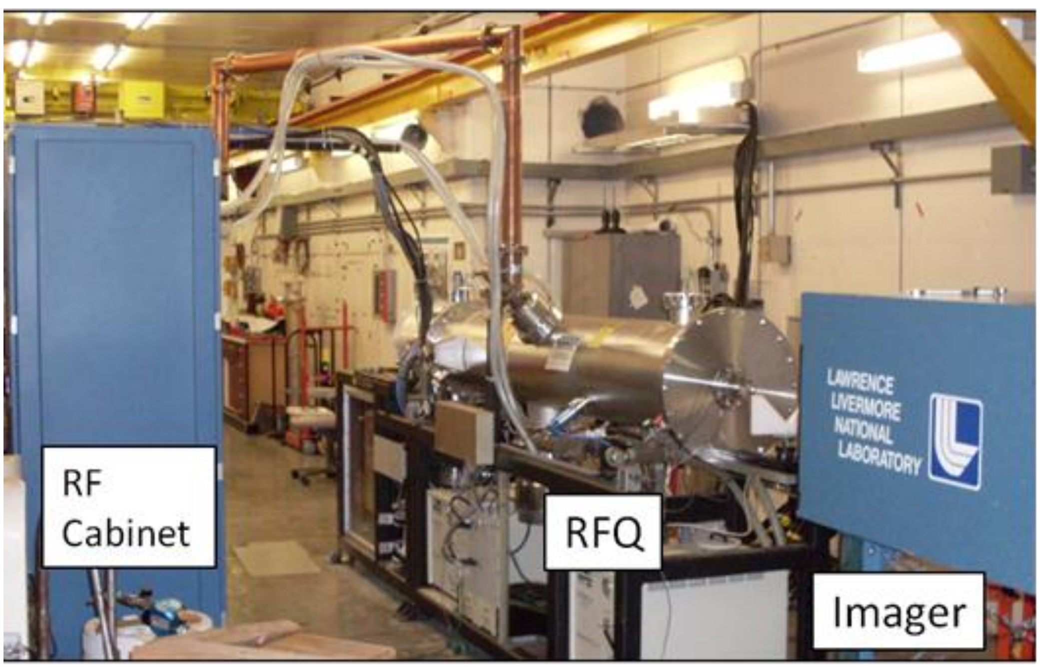

FIGURE 4. 4 MV D^+ AccSys DL-4 RFQ Accelerator with test imager

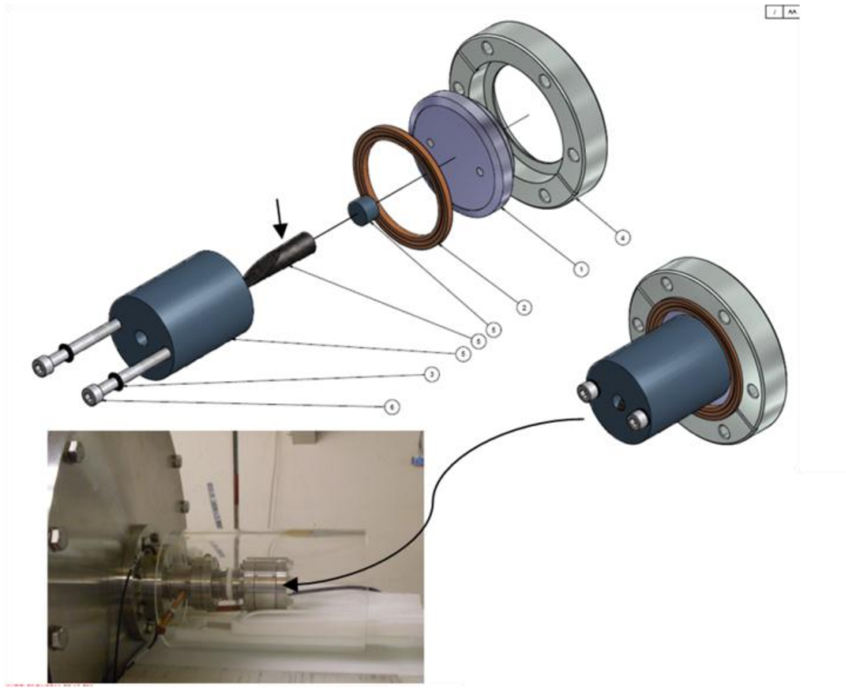

FIGURE 5. Carbon Target for neutron radiography. The carbon target, indicated by the arrow in the exploded assembly, is slanted at 20 degrees. The assembly is mounted on a 2 ¾ ConFlat flange and mounted to the RFQ via a short ceramic break. The break allows the current on the target assembly to be measured.

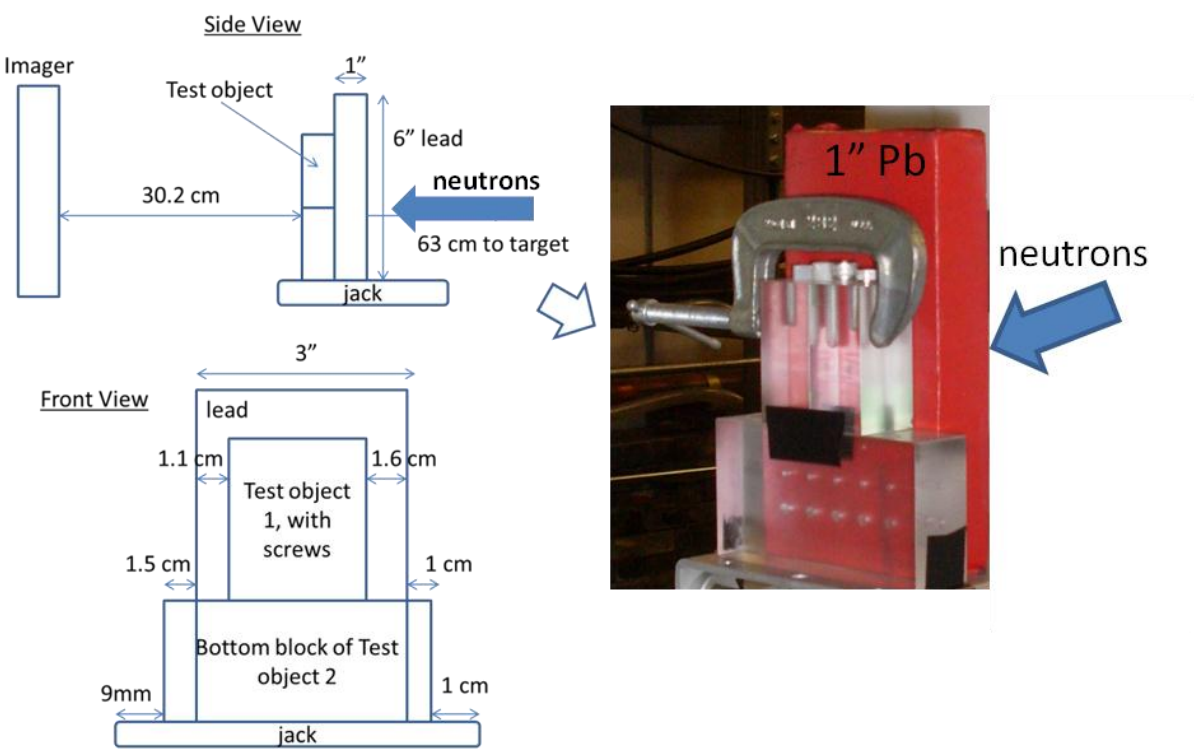

FIGURE 6. Experimental imaging setup with test objects behind a lead shield.

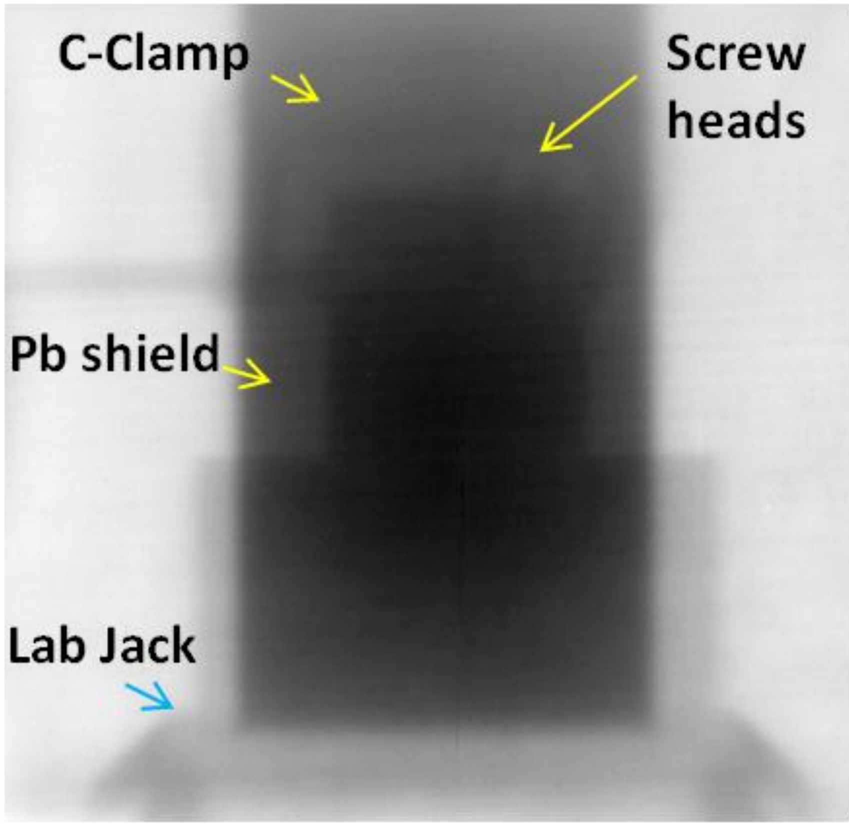

FIGURE 7. Processed radiograph from setup in Figure 6. The image has been rotated 1.4 degrees during the post-processing to correct for experimental tilt.

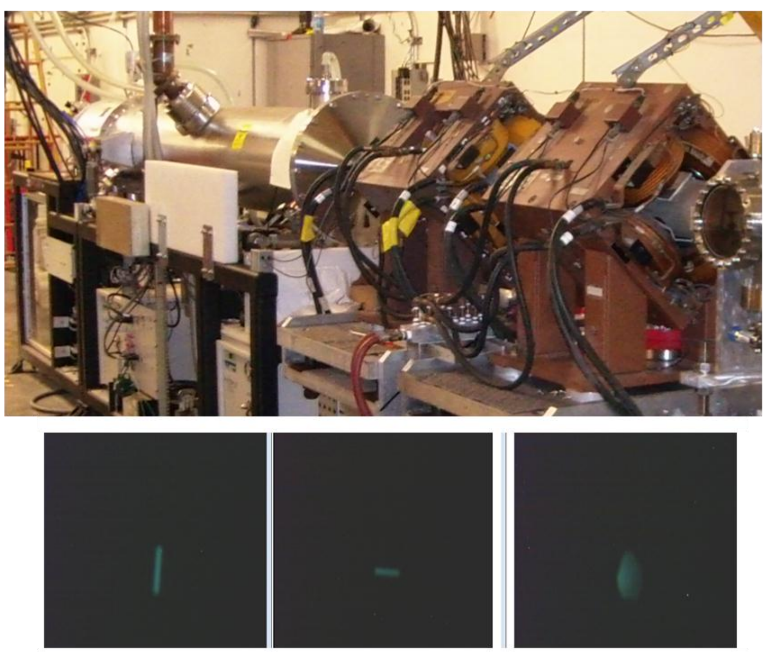

FIGURE 8. New beamline with 4 quads from the ATA accelerator, and preliminary beam profile imaging results using angled borosilicate glass foils.

NEXT STEPS: SOURCE COMPARISONS AND MODELING VALIDATION

With the test-bed established we will now proceed, for NDE source replacement, to test proposed dual gamma and neutron sources, using reactions such as D-C and D-Li sources and established ASTM standards [11,12]. These standards allow us to quantitatively compare the NDE capabilities, in terms of Equivalent Penetrameter Sensitivities (EPS), of the proposed sources against current industrial x-ray and isotope sources used for NDE. These tests will serve to validate MCNP simulations of the ASTM based processes that we are currently performing and thus will allow us to make a significant number of comparisons via simulations. Lastly, we plan to exercise the test-bed at the full 110 uA level which will allow neutron and gamma production rates up to ~10^{11}/s and permit the facility to be used for materials testing.

ACKNOWLEDGMENTS

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