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Title: Neutron Radiography of Thick Dynamic Systems

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Neutron Radiography of Thick Dynamic Systems

Relatively low energy neutrons (14 MeV) are excellent probes for thick systems, due to their penetrating capabilities. As fast pulses sources, such as the dense plasma focus (DPF) and laser driven sources, are developed the potential for using neutrons for flash radiography of thick systems is becoming feasible.

One way to determine the range of object thicknesses accessible to a particular probe is through comparisons of a radiographic figure of merit (FOM). One common figure of merit is the contrast to noise ratio normalized by the fractional thickness variation. In practice this is the change in transmission for a given change in object thickness divided by the noise level. A probe is optimized to an object when it provides the largest change in transmission for a small change in object thickness. For probes which follow Beer's law for transmission (shown in equation 1) this figure of merit can be determined analytically and is shown in equation 2.

$$N = N_o e^{-\frac{l}{\lambda}} \qquad \text{eq. 1}$$

$$FOM = \frac{\Delta N / \sqrt{N}}{\Delta l / l} = \frac{1}{\sqrt{N}} \frac{dN}{dl} = \sqrt{N_o} \frac{l}{\lambda} e^{-l/2\lambda} \qquad \text{eq. 2}$$

Where N_o is the incident flux, N is the flux exiting the object of thickness l and λ is the interaction length for the radiographic probe. This figure of merit is designed to be largest when the contrast is large relative to the measurement noise near a small density variation within an object. An illustration of this FOM for various contrast to noise ratios is shown in figure 1.

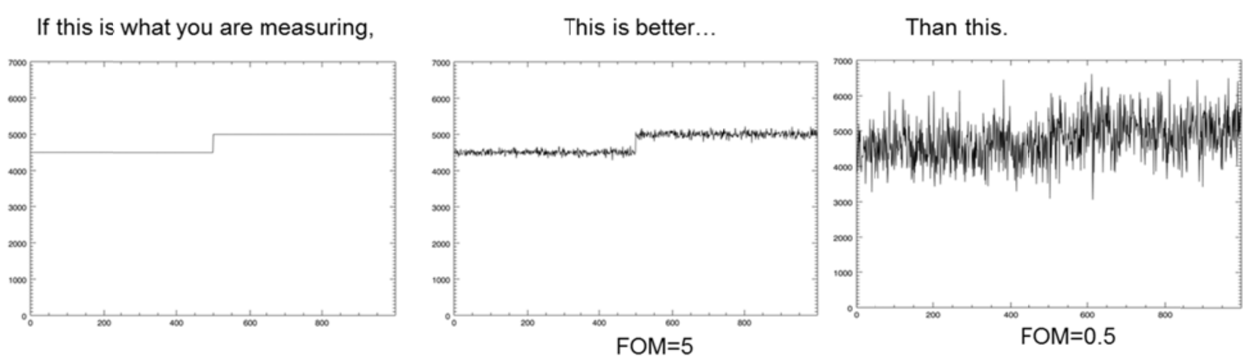

Figure 1: Left: the radiographic probe flux across a small variation in density within the object. Middle: a measurement of this difference with a high FOM probe. Right: a measure of this same difference with a low FOM probe.

The interaction lengths in uranium for 1 MeV x-rays (~Cygnus), 4 MeV x-rays (~DARHT) and 14 MeV neutrons are 10 g/cm^2, 25 g/cm^2 and 65 g/cm^2, respectively. With these parameters this figure of merit is shown in figure 1 as a function of uranium object thickness, assuming the same number of incident particles, N_o, for each of these radiographic probes.

From this graph it is clear that 14 MeV neutrons are the optimal probes for objects >100 g/cm^2. The reason that neutrons have not been used in the past for flash radiography is that it is difficult to generate a sufficient number of neutrons in a short period of time (N_o has been small) to provide a high statistics radiograph of thick, dynamic objects. Because of this limitation, x-rays have become the work horse for flash radiography applications, driving the development of high intensity x-ray sources. The high intensity is required to increase the FOM to a useful range for thick objects by increasing the incident flux, N_o. However, if a small fraction of the bright x-ray source is scattered into the detection system, the signal can be easily lost in the scatter background. Decades of optimization to reduce this scattered background have resulted in the remarkable capabilities of the DARHT and Cygnus x-ray sources that are operational today.

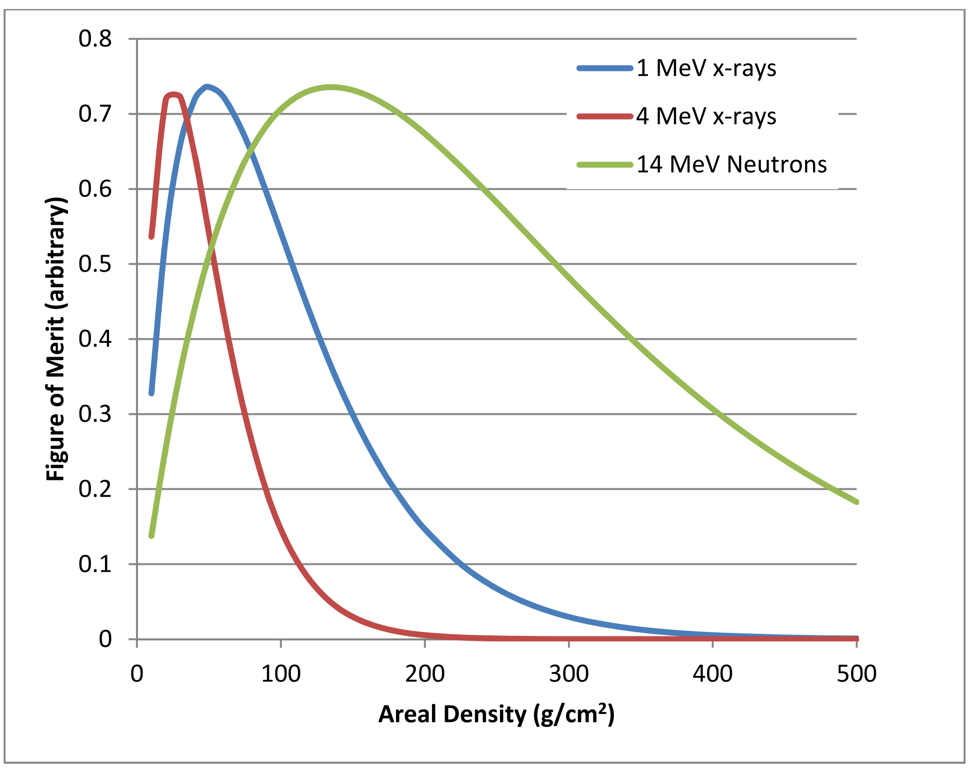

Figure 2: Figure of Merit as a function of areal density for 1 MeV x-rays (~Cygnus), 4 MeV x-rays (~ DARHT) and 14 MeV neutrons.

Recent advances in dense plasma focus (DPF) neutron sources have reinvigorated interest in flash neutron radiography of thick systems. In order to be a useful radiographic source a large number of neutrons must be generated in a small area and in a short time period. The DPF presently being upgraded by NSTec at the NNSS is expected to generate 10^{14} neutrons within a ~1 mm source and ~50 ns duration.

The figure of merit shown in figure 1 does not incorporate resolution, which is considered separately here. Figure 2 shows how the detector resolution and the source size are combined through geometry of the radiography system to determine the radiographic resolution. With a 1 mm diameter source and 1 mm detector resolution, which is typical of 14 MeV neutron detection, this system can provide 0.8 mm resolution in an optimized geometry. This resolution is large when compared with Cygnus resolution (~0.1 mm FWHM), but comparable to DARHT resolution (~1 mm). As with DARHT radiography, this is the uncorrected resolution, which can be improved through reconstruction techniques, such as those incorporated in the BIE.

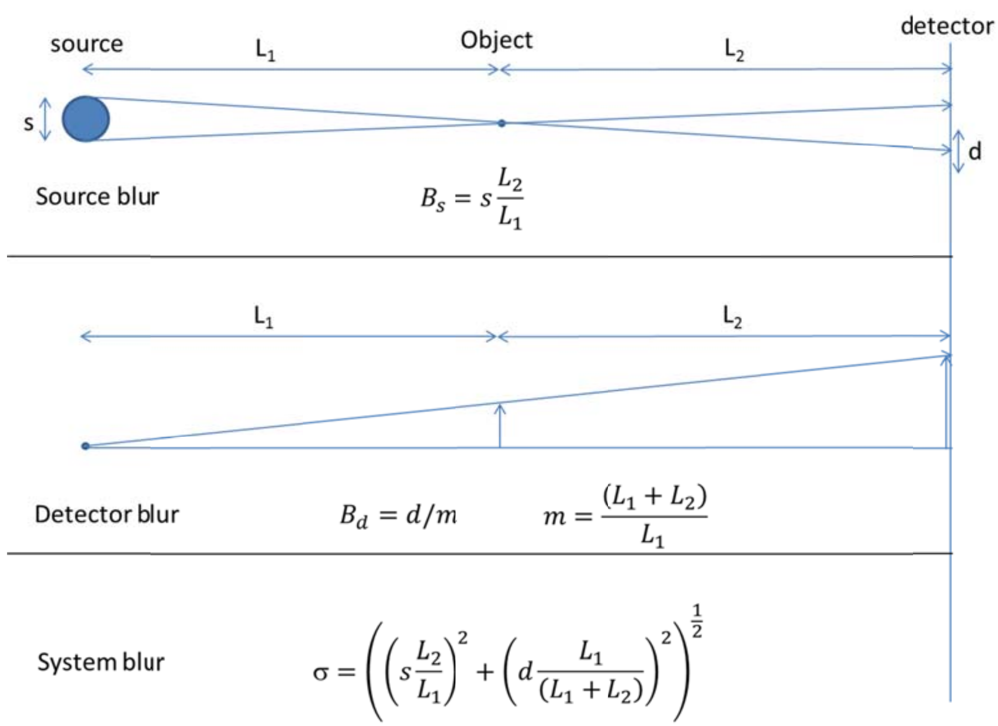

Figure 2: Top: The extent of the source size results in blur of the object at the detector position. L_1 is the distance from the source to the object, L_2 is the distance from object to detector, s is the source size and B_s is the blur from this source size. Middle: the blur due to the detection process is the detector blur divided by the magnification factor. d is the detector blur while B_d is the image blur due to this effect. Bottom: the two blurring processes are added in quadrature to estimate the system blur. With a 1 mm source and 1 mm detector blur the system blur is 0.8 mm in the optimized geometry.

Another consideration, beyond resolution and the FOM shown in figure 1, is if there is sufficient flux to make accurate density measurements within each resolution element (is N_o large enough?). This is determined by the neutron transmission through the object and the detection efficiency of the detector system. The upgraded DT DPF source is expected to provide 10^{14} neutrons per pulse. If the source is located at 1 m from the object, there is a flux of $8x10^6$ neutrons per square mm entering the object. Transmission through optimal object thickness (~135 g/cm^2), which is determined by the location of the maximum FOM shown in figure 1, is ~15%. This results in $1x10^6$ neutrons exiting the object. With a detection efficiency of 10%, which is achievable with thick, segmented plastic scintillators, the number of detected neutrons is $1x10^5$. If the noise in the detection system can be optimized so that counting statistics is the dominant noise source, this system can provide >1% density measurements within a resolution element.

Conclusion

The upgraded DT DPF source, generating 10^{14} neutrons per ~50 ns pulse in a 1 mm source, at the NNSS could provide a remarkable source for flash neutron radiography. This source could provide radiographs with 1 mm uncorrected spatial resolution and 2% density resolution within a spatial resolution element. Standard reconstruction algorithms, such as exist in the BIE, could be implemented to improve the resolution of the imaging system to sub-mm resolution.

Proposal

The upgraded source will be commissioned by NSTec in the spring of 2013. We propose to support the commissioning of this source as well as developing the imaging capability described above. The first step in this process will be to characterize the DPF source. The first characterization steps would be to measure the source distribution through pinhole imaging. The equipment and analysis techniques required to make these source measurements exist from the neutron imaging development effort at NIF. This equipment has been previously successfully fielded at the NNSS and could be re-installed quickly and inexpensively for these measurements. This effort would provide three useful data sets. First, it would provide an experience base for making neutron measurements in the DPF environment, providing information on background (both electromagnetic as well as neutron backgrounds). Second, it would provide a measure of the neutron source size for DPF commissioning and optimization and third it would provide an opportunity to collect the first DPF neutron radiographs of test objects for further development of this technique. This work would provide the experimental data set required to assess the feasibility of the radiographic performance expected from this analysis.

In addition we propose to use the structure of the BIE to develop simulation tools to forward model and reconstruct neutron images. This tool will provide the modeling capability required to assess radiographic performance as well as guide source and detector development activities.

This work would require 30k in travel to the NNSS for experiments, 20k in M&S for fabrication and procurement of equipment specific to the installation at the NNSS and 250k in labor to field the experiments and analyze the data. The development of the BIE simulation capability will require 100k of labor. This totals to $400k to begin investigations into the potential for this future radiographic capability.