

Modeling a 1-D Bremsstrahlung and Neutron Imaging Array For Use On Sandia's Z Machine

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JUN 08 1998

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Abstract

Inertial confinement fusion is being studied on the Z facility at Sandia National Laboratories. Z is a large z-pinch machine which can provide 20 MA of current to z-pinch loads producing ~1.8 MJ of soft x-rays in less than 10 ns. Within the pinch region, decelerated electrons produce a strong source of bremsstrahlung radiation which varies from shot to shot. Additionally, a variety of ICF targets produce fusion neutrons whose intensity and distribution depend on the temperature and density of the target compression in the pinch. This paper describes the computer modeling behind the shielding design of a simple time-resolved, 1-D imaging array which can provide a time history of both the bremsstrahlung and neutron production as a function of height within the target region. It is demonstrated that by building an array of scintillator fibers separated by long, thin tungsten collimator plates, a spatial resolution of 0.254 mm at the target can be achieved. The corresponding channel-to-channel discrimination for such a design is shown to be better than 1000::1 for < 4 MeV photons and 100::1 for 2.45 MeV neutrons. By coupling scintillator fibers to a fiber-optic streak camera system, the signal can also be given as a function of time with a temporal resolution of about 1.2 ns.

1. Introduction

The Z machine at Sandia National Laboratories uses z-pinch principles to study, among other things, inertial confinement fusion (ICF)^{1,2}. In this approach, ICF targets are driven by strong magnetic fields, symmetric around the z-axis of the machine, which are created

by high currents within the target region. Currents are nominally 18 MA on Z, and with the large numbers of electrons accelerated throughout the pinch, high amounts of bremsstrahlung radiation are created. As changes are made in the diode configuration (height, mass, internal target, etc.), the direction of electron flow will vary. This can alter the magnitude and distribution of the bremsstrahlung radiation considerably between shots. Understanding this distribution can lend some insight into the electron source and acceleration mechanisms necessary for understanding the associated pinch physics.

In addition to the bremsstrahlung environment produced in z-pinches, deuterium fueled ICF targets may produce fusion neutrons with an energy of 2.45 MeV. These fusion schemes may be directly or indirectly driven, but in either approach, compression asymmetries can cause the distribution of neutrons to vary throughout the target length. The intensity of the neutron production in ICF targets is a function of temperature and density, so understanding the distribution of the neutron production can lend insight into the shape and uniformity of the target compression.

This paper outlines the shielding design of a diagnostic which is intended to image both the bremsstrahlung radiation and the neutron emission from z-pinch target regions on Z. This diagnostic is termed the Time Resolved Bremsstrahlung and Neutron (TRBN) Camera. The design of the TRBN consists of two main components: design of the collimation array, and design of the array's external shielding. Figure 1 shows a cross-sectional view of the TRBN as placed in the Z target chamber.

II. Array Design

The active element of the TRBN is an array of scintillator fibers separated by tungsten collimator plates. The design of the array must reflect the requirements of the problem. Namely, the pulse width of the pinch is about 5 ns. Thus, we need a system which can resolve time elements within this 5 ns window. This is addressed by using Bicron-422 scintillator fibers coupled to a fiber-optic streak camera system. With this system, a

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minimal signal loss with about a 1.2 ns temporal resolution can be achieved. Additionally, because important Raleigh-Taylor wavelengths are on the order of 1 mm, a spatial sampling of about 0.25 mm at the source is required to resolve the appropriate modes. The actual achievable resolution is determined by the scintillator and collimation plate thicknesses.

The thicknesses and spacing of the collimation plates is dependent on the desired signal discrimination between channels. That is, each scintillator is intended to measure a single source element which lies directly across from it. This only works if the collimation plates attenuate the cross signal enough that each channel detects only an insignificant amount of flux from any other channel's designated source element. The defining parameter is the determination of what constitutes an insignificant cross signal. The chosen figure-of-merit for the imaging system was a minimal channel-to-channel discrimination of 100::1. If 4 MeV is greater than the maximum significant bremsstrahlung energy, the dimensions of the collimator plates must provide better than a 100::1 channel-to-channel discrimination for both 2.45 MeV neutrons and 4 MeV photons.

Designing shielding like this is a process of tradeoffs. That is, if the collimation plates are made thinner, the tradeoff is that they must also be longer. As a result, the design of the array is sensitive to where the detection element is placed with respect to the source. The array is designed to view the target region directly side-on with a 1::1 magnification. To achieve this, the TRBN must rest on the sloped surface of the upper anode within the target chamber on Z (see figure 1). However, within this chamber there is a background of scattered radiation which must be shielded against from all directions.

As shown in figure 2, backscattered bremsstrahlung inside the target chamber is a significant issue³. But, because the TRBN rests on the sloped surface of the upper anode, a source to detector distance of 750 mm is required to provide 40 mm of space below the scintillator fibers for shielding. Also, the maximum target height to be shot on Z is below 17 mm. The total array height must correspond to this value in order to ensure an image of the entire target length. Finally, because the array must be made of long, thin plates, we

must consider availability of materials in order to minimize costs. Both tungsten plates and scintillator fibers are commercially available off the shelf at thicknesses of 0.127 mm (0.005 in.). Therefore, we concentrated on developing array plates with both a thickness and spacing of 0.127 mm which combine to a total height of at least 17 mm. The scintillator fibers were additionally chosen to have a width and height of 0.127 mm in 10 mm of length. This corresponds to 68 tungsten plates and 67 scintillator fibers making up an imaging height of just over 17 mm and an optimal spatial resolution of 0.254 mm.

Calculating the proper length of these collimation plates in order to provide a suitable channel-to-channel discrimination requires the use of detailed shielding calculations. We utilized COG (a monte carlo particle transport code) to model the photon and neutron attenuation and scattering within the imaging array⁵. The computer model consists of a point source directly across (and 750 mm away) from what is defined as channel 1. Then, channel numbers 2 - 7 are defined as those channels adjacent to the previous number. In order to avoid modeling the remaining channels, the tungsten plates were replaced with a slab of tungsten which matched the appropriate array height, but whose density was scaled to account for the empty spaces that would otherwise exist. A rough schematic of the modeled geometry is shown in figure 3. (Note the space behind the scintillator fibers before the end of the array. This space is there to reduce backscatter induced by the external shielding discussed in the following section.)

Because 2.45 MeV neutrons are much more penetrating than 4 MeV photons, the array parameters were based on neutron attenuation. After a number of iterations, an array length of 400 mm was determined to provide the proper collimation. According to COG, the maximum channel-to-channel discrimination for 2.45 MeV neutrons corresponding to these parameters is over 500::1, and that for 4 MeV photons is over 5000::1 (see figure 4). This exceeds the original figure-of-merit, but as is described in the next section, adding an external shield can bring the neutron signal-to-noise ratio up to 100::1.

III. External Shielding Design

As was discussed in the previous section, there is a significant amount of seemingly isotropic backscattered radiation which exists in the target chamber of Z. Because such radiation can confuse the signal obtained by the TRBN, it is important that the array is shielded from all directions. This shielding must be robust enough to sufficiently attenuate the backscattered radiation, but at the same time induce minimal scattering in order to maintain a minimum 100:1 signal to noise ratio.

Currently, it is unclear what constitutes a good shield in the intense radiation environment produced by Z. However, due to previous experience in fielding instruments on this machine, it was decided that the array should be shielded by two inches of tungsten on all sides with the exception of the bottom and front. The bottom of the shield is limited by the slope of the upper anode surface on which the TRBN rests. Keeping the TRBN directly side-on with respect to the pinch and following the curvature of the anode, 40 mm of tungsten can be placed below the scintillator fibers and 20 mm below the front edge of the array. The front of the external shield is collimated to allow for a 10 mm wide field of view on either side of the machine axis, and only the 17 mm height discussed in the previous section. A schematic of the full TRBN design is shown in figure 5.

Neglecting any radiation scattered into the detector from the target chamber itself, COG predicts the TRBN external shielding will induce a signal-to-noise ratio of about 100:1 for 2.45 MeV neutrons (see figure 4) while not significantly affecting the bremsstrahlung signal. Additionally, COG predicts a good time-of-flight separation between the bremsstrahlung radiation and the neutrons. This indicates that even if the magnitude of the bremsstrahlung source is much larger than the neutron signal, the scintillator decay time is sufficient to allow for an observable neutron pulse. To further define the total time-of-flight effects inside this tungsten shield, a computer model was constructed replacing the imaging array with a single scintillator block 10 mm wide on all sides and centered at 750 mm from the source. Inputting both the 2.45 MeV neutron source and the measured

bremsstrahlung spectrum shown in figure 2 as a delta function in time at $t = 0$, figure 7 demonstrates how COG predicts the photon flux to fall off by 5 orders of magnitude in less than 400 ps with the peak of the neutron signal arriving 32 ns after the initial bremsstrahlung pulse.

IV. Summary

We have completed the initial calculations for the shielding design of a time resolved, 1-D bremsstrahlung and neutron (TRBN) imaging camera for use on the Z facility at Sandia National Laboratories. The imaging array is collimated to view 10 mm on either side of the machine axis over a total height of about 17 mm. Computer modeling indicates that the TRBN has a spatial resolution of 0.254 mm with a channel-to-channel discrimination better than 100::1 for 2.45 MeV neutrons and better than 1000::1 for < 4 MeV photons. Additionally, using Bicron-422 scintillator fibers coupled to a fiber-optic streak camera system, a temporal resolution on the order of 1.2 ns should also be achievable. Although there is some uncertainty surrounding shielding parameters for diagnostics on Z, current calculations suggest that neglecting any backscattered radiation from the Z target chamber, the TRBN should obtain good time of flight separation between bremsstrahlung and neutrons with the neutron pulse arriving 32 ns after the initial bremsstrahlung pulse.

This work supported by the U.S. Department of Energy under Contract DE-AC04-94AL85000. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed-Martin Company, for the United States Department of Energy.

V. References

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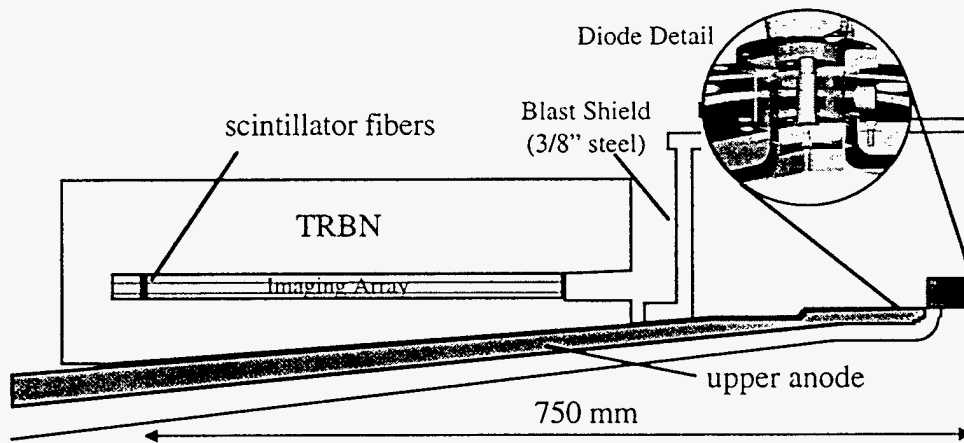


Figure 1. Cross-sectional schematic of TRBN positioning as it would be in the Z target chamber (not to scale). Placement of the imaging array is determined by available space for shielding below and in front of the array. Based on these considerations, the source to detector distance is 750 mm.

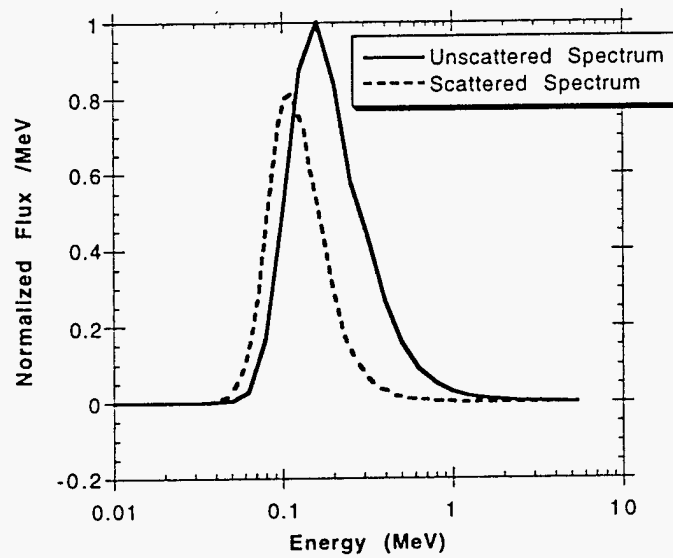


Figure 2. Measured bremsstrahlung spectrum (solid line) and sample COG modeled calculation of associated backscattered spectrum (dashed line) within the target chamber of Z. (The backscattered intensity changes at different locations within the chamber. This is an example of how intense it can be.)

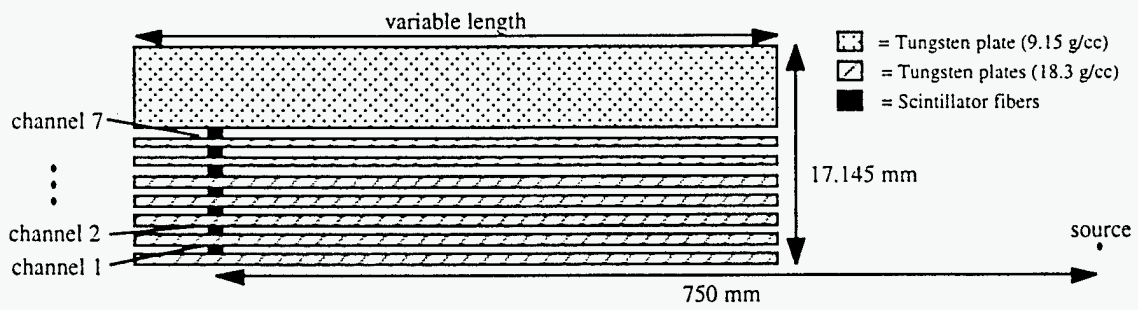


Figure 3. Side view of array geometry as modeled in COG (not to scale). The density of the upper tungsten plate is scaled to account for the empty space between plates that would exist in the real array.

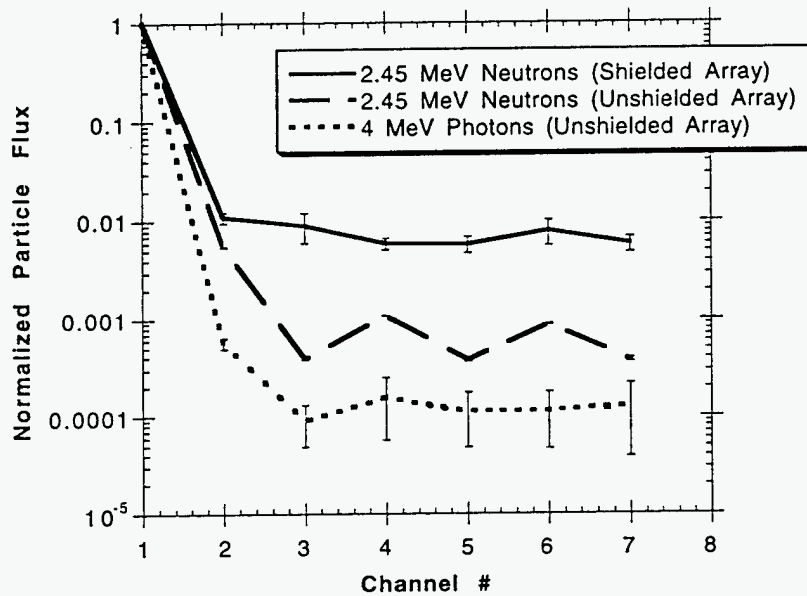


Figure 4. COG modeled channel-to-channel discriminations. Neutron signal-to-noise ratios go up considerably for a fully shielded array (solid line). (These calculations do not include the influence of scattered radiation from the target chamber walls.)

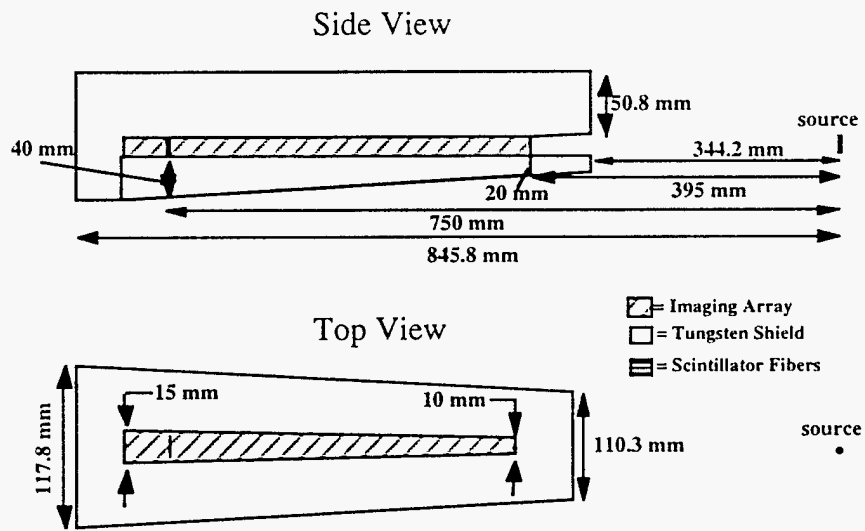


Figure 5. Schematic of TRBN shielding design. (not to scale)

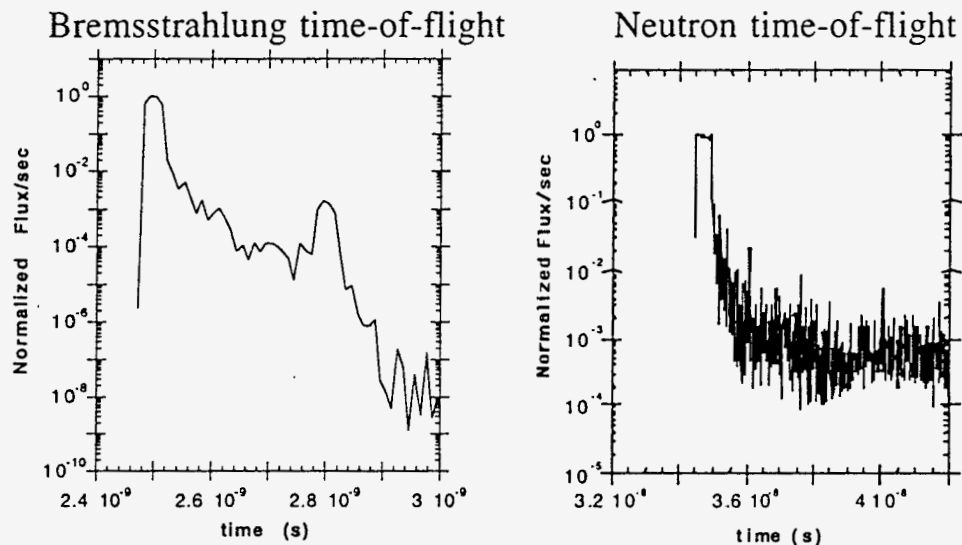


Figure 6. COG modeled bremsstrahlung and neutron time-of-flight distributions inside the TRBN external shield. The detection element is a scintillator block 10 mm wide on all sides and centered within the shield at 750 mm from the source. The bremsstrahlung source is modeled as the unscattered spectrum shown in figure 1 occurring as a delta function in time at $t = 0$ s. The neutron source is modeled as 2.45 MeV neutrons occurring also as a delta function in time.

M98005529



Report Number (14) SAND--98-0472C
CONF-980605--

Publ. Date (11) 199806
Sponsor Code (18) ^{DOE} DP, XF
UC Category (19) UC-712, DOE/ER

19980702 010

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