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Investigation of the possibility of gamma-ray diagnostic imaging of target compression at NIF

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Abstract

The National Ignition Facility at Lawrence Livermore National Laboratory is the world's leading facility to study the physics of igniting plasmas. Plasmas of hot deuterium and tritium, undergo $d(t,n)\alpha$ reactions that produce a 14.1 MeV neutron and 3.5 MeV α particle, in the center of mass. As these neutrons pass through the materials surrounding the hot core, they may undergo subsequent (n,x) reactions. For example, $^{12}\text{C}(n,n'\gamma)^{12}\text{C}$ reactions occur in remnant debris from the polymer ablator resulting in a significant fluence of 4.44 MeV gamma-rays. Imaging of these gammas will enable the determination of the volumetric size and symmetry of the ablation; large size and high asymmetry is expected to correlate with poor compression and lower fusion yield. Results from a gamma-ray imaging system are expected to be complimentary to a neutron imaging diagnostic system already in place at the NIF. This paper describes initial efforts to design a gamma-ray imaging system for the NIF using the existing neutron imaging system as a baseline for study. Due to the cross-section and expected range of ablator areal densities, the gamma flux should be approximately 10^{-3} of the neutron flux. For this reason, care must be taken to maximize the efficiency of the gamma-ray imaging system because it will be gamma starved. As with the neutron imager, use of pinholes and/or coded apertures are anticipated. Along with aperture and detector design, the selection of an appropriate scintillator is discussed. The volume of energy deposition of the interacting 4.44 MeV gamma-rays is a critical parameter limiting the imaging system spatial resolution. The volume of energy deposition is simulated with GEANT4, and plans to measure the volume of energy deposition experimentally are described. Results of tests on a pixellated LYSO scintillator are also presented.

Keywords

NIF; gamma; scintillator; GEANT4; energy deposition; ignition; fusion

1. Introduction

The National Ignition Facility (NIF) at Lawrence Livermore National Laboratories is planning to achieve breakeven in inertial confinement fusion in the next few years. At the NIF, inertial confinement fusion is accomplished by using 192 high-energy laser beams to illuminate a gold hohlraum containing a small pellet of deuterium and tritium encased in a polymer shell. The interaction of the lasers with the gold cylinder of the hohlraum creates x-

rays that bathe the pellet. The x-rays ablate the outer polymer shell of the pellet, causing a shockwave to propagate inward, resulting in compression of the D-T material at the center of the pellet. The compression generates pressures and temperatures high enough to initiate fusion burning in D-T. The D-T reaction releases 14.1 MeV neutrons as part of this nuclear reaction. As the neutrons leave the compressed pellet, they may undergo nuclear reactions within the remnant materials, as illustrated in Fig. 1. These neutrons may scatter off hydrogen isotopes, generally in the dense cold fuel region (red), undergoing (n,n') reactions producing lower energy neutrons that may be detected and diagnosed. Typically neutrons within the energy band from 10-12 MeV are of greatest interest due to backgrounds from T +T fusion. In addition reactions within the carbon ablator debris will result in lower energy neutrons along with 4.44 MeV gammas via $^{12}\text{C}(n,n'\gamma)^{12}\text{C}$ reactions.

The output yield of the fusion reaction is very sensitive to the size and spherical symmetry of the compression. For this reason diagnostic equipment with spatial sensitivity is required. Los Alamos National Laboratory has developed a neutron-imaging detector as one of the tools to diagnose DT fuel geometry [1]. In the left panel of Fig. 2, a conceptual layout of the neutron imaging system is illustrated. Neutrons produced by the implosion are imaged through a 20 cm long occluder having pinholes and coded apertures capable of 10 μm resolution. The oblique nature of the pinholes, result in an object distance typically in excess of 10 cm. For the NIF neutron imaging system this distance varies from 22.5 cm to 32.5 cm. At 14.1 MeV, neutrons are efficiently detected in organic scintillators, but with a spatial resolution of close to 1 mm, requiring a system magnification approaching 100. At the NIF, the camera system, as illustrated in the right panel of Fig. 2 is located 2800 cm from the implosion, in a shielded structure outside the NIF building. To facilitate imaging more than one band of neutron kinetic energies, the pixellated scintillator is viewed by two gated imaging systems; one optically relayed by coherent optics directly coupled to the fluor and one relayed by a large, F/3.3 compound lens. Gating is accomplished using 75 mm microchannel plate image intensifiers manufactured by Photek Limited. The photocathode of the MCP is manufactured with a metallic mesh to facilitate rapid gating. Light from the image intensifiers is digitized by 16M pixel, SI-1000 CCD cameras. Gating is used to isolate neutrons with different arrival times, and therefore different kinetic energies. Typically images are taken with a gate width of ~60-70 ns 500 ns and 600 ns after the burn, corresponding to the energy gates from 17 MeV to 13 MeV, and 12 MeV to 10 MeV, and more than 400 ns after any photons produced in the burn arrive at the detector. The neutron-imaging diagnostic system gives valuable information on the neutron yield of the shot, ranging from 10^{14} to 10^{18} , as well as information on the symmetry of the implosion.

Although, the neutron image of the burning region of the target provides useful information about quality of the implosion, information on the outer boundary of the fuel assembly provides key information on the compression of the fuel not participating in the burn, both its size and symmetry. Due to the kinematics of the (n,n') scattering process, and acceptance of the neutron imaging system, the 10-12 MeV, cold-fuel image does not provide information on the outer radius of the nuclear fuel in the target. This information may be determined by imaging the polymer shell, which does not move far during the time of the burn (~100 ps). It should be possible to image the ablation debris by looking at the 4.44 MeV gammas given off by the neutron interaction with the carbon in the debris. The

symmetry by which the X-rays ablate the polymer shell directly influences the compression shockwave. We expect to use decomposition of the gamma-ray images into sums of Legendre Polynomials to analyze the image for asymmetry. In general, asymmetries correspond to large coefficients for the higher order polynomials. This knowledge can be used to help steer the NIF towards its goal of higher yields and ultimately nuclear ignition.

2. Imaging System

The purpose of this paper is to investigate the feasibility of developing a gamma-ray imaging diagnostic system for the NIF and to describe initial efforts to design such a system.

The neutron-imaging system can be used as a starting point for designing the gamma imaging system. This system uses both optical imaging and a fiber-taper to read out an array of plastic scintillator pixels. Both of these approaches are under consideration for the gamma imaging system. The neutron system uses a pixellated scintillator, but monolithic scintillators, as well as Cherenkov radiators, are also under consideration for the gamma-ray imaging system.

The mean free path of 14.1 MeV neutrons (3.26 cm) in the Au collimator material is similar to, but larger than that of 4.44 MeV gamma rays in Au (1.24 cm). In fact, the neutron collimator is overdesigned for gamma-ray use. This leads to the possibility of using the same collimator for both systems, or at least a collimator of similar design, an approach that has significant logistical and cost advantages. Thus, we will use the design of the neutron system collimator for feasibility studies, and as a guide to gamma-ray system design.

The neutron system is designed for neutron yields of 10^{14} to 10^{18} into 4π steradians. Only a small fraction of these are imaged through the 8- μm pinholes onto the scintillator. The gamma-rays produced are a thousand times fewer and consequently yields of 10^{11} to 10^{15} are assumed. Figure 3A shows that for a desired SNR of 25 dB (black dotted line) and the distances of the above neutron system, only the highest yields of 10^{14} gamma rays and above can be imaged with one pinhole and 10^{13} gammas with 5 pinholes.

Figure 3B shows that moving the pinholes closer opens up the ability to image smaller yields. Consequently, using more pinholes and a pinhole closer to the target should allow improved detection efficiency for the gamma ray imager; imaging with gamma yields of better than 10^{12} should be possible. NIF is currently achieving neutron yields $> 10^{14}$, corresponding to gamma yields of $> 10^{11}$. Additional counting efficiency improvements should be possible using coded-aperture collimators. In fact, a penumbral coded aperture collimator is already in use in the neutron-imaging system. It should be noted that these calculations assume 100% detection efficiency for the gamma-ray imaging system, where as a detector efficiency of 40% can be reasonably obtained. Figure 3 shows that the two largest contributors towards SNR are the number of pinholes and aperture distance from the emitting pellet, both of which increase the number of gammas imaged. Both of these two parameters will be adjusted to optimize the gamma imaging system design. The current gamma yields at NIF are sufficiently high enough for a pinhole aperture placed at 11 cm from chamber center to image.

3. Selection of a Scintillator

There are three main conditions that govern the selection of a scintillator for use in the gamma-ray imaging system. First, the scintillator should have high density and high atomic number constituents in order to increase its efficiency for stopping 4.44 MeV gamma-rays. The dominant interactions at this energy are Compton scattering and pair production. Second, the scintillator should have high light yield in order to reduce noise; this is an integrating system so detective quantum efficiency (DQE) should be as high as possible. Finally, the scintillator should have a fast decay time. The yield of 4.44 MeV gamma rays is expected to be 10^{-3} of the neutron yield; for a 28 m distance from target to detector, the neutrons arrive about 400 ns after the gamma-rays. If an integration time of 400 ns were used, neutron counts would swamp the gamma-ray image. Since the neutrons and spurious gamma-rays do not provide information on the ablated shell, they constitute noise that can be suppressed by time-of-flight dispersion using a timing window. A gated image intensifier is used in the optics chain for this purpose. Because there are other objects close to the target in the field of view of the imaging system on which neutron interactions can produce spurious gamma-rays, we shall adapt a conservative time window for gamma-ray detection of 100 ns.

A total of 27 scintillator candidates, including conventional scintillators and new ones under development, were investigated. Table 1 lists the best candidate scintillators that are commercially available at the current time. Table 1 also shows the relevant properties of the candidate scintillators including the attenuation coefficients at 4.44 MeV, the percent of 4.44 MeV gamma-rays that would interact in a 2-cm-thick sample and the light yield within the 100 ns window. A thickness of 2 cm is reasonable for the gamma-ray imaging system; it is also the thickness we chose for the test detector arrays. Of these, BGO probably has too low a light yield, YSO:Ce has an unattractively low efficiency, and LaBr:Ce is very hygroscopic and thus would be difficult to work with. Two very similar scintillators, LSO:Ce and LYSO:Ce, appear to be the best candidates at this time. LYSO seems to be more readily available, so we chose it for a test array.

4. Scintillator Confinement

The most likely choice for the gamma-ray detector is a pixellated scintillator configured similarly to the pixellated plastic scintillator in the neutron-imaging system. 10×10 arrays of 1-mm pixel pitch and 2.0-cm pixel length were obtained from Proteus Inc. of three different scintillators: BGO, YSO:Ce, and LYSO:Ce. Monolithic scintillator blocks of each material of the same size (10 mm $\times$ 10 mm $\times$ 20 mm) were obtained for comparison purposes. The pixellated scintillators are similar to block detectors being developed for the next generation of PET scanners. Each pixel is wrapped on 5 of its 6 sides with a highly-reflective ESR coating. The YSO:Ce array was mounted on a Hamamatsu R7600U-200 PMT and scanned along the 2-cm length of the pixel bars with a collimated ^{57}Co source (122 keV); light output varied by less than 2%.

Each pixellated scintillator was mounted on a Proxitronic Detector Systems BV2533 BX-V 2-stage image intensifier coupled by a 6-mm-focal-length lens to a Point Grey Research

Grasshopper CCD Camera and tested with various radioactive sources. One CCD frame for the LYSO array irradiated with a $\sim 10 \mu\text{Ci}$ ^{60}Co source (1.17 MeV, 1.33 MeV) is shown in Figure 4. The pixels hit by individual gamma-rays are readily seen in Figure 4, and the $1 \text{ mm} \times 1 \text{ mm}$ square shape of the scintillator pixels is easily discerned. The energy deposition from the $\sim 1\text{-MeV}$ gamma rays is usually confined to one pixel, but we must determine if this is true for 4.44 MeV gamma rays as well.

The LYSO pixellated detector has internal radioactivity due to the emissions of naturally occurring ^{176}Lu . These emissions amount to 240 disintegrations per second per cubic centimeter of LYSO. For the experiments of Figure 4 it was necessary to shorten the integration time of the CCD camera to $80 \mu\text{s}$ to avoid imaging internal radioactivity events; at 150 frames per second for the CCD, the duty cycle was only 1.2%. This is an annoyance for single-gamma-ray imaging studies, but should not constitute a problem for building the final imager. If the final detector is $30 \text{ cm} \times 30 \text{ cm} \times 2 \text{ cm}$ of LYSO, and the integration time for the shot is 100 ns, there is only a 4% probability of a single disintegration occurring in the entire detector during the acquisition.

Another important property of the scintillator is its radiant intensity as a function of emission angle. This property will define the light transfer through a fiber-optic taper or through a lens imaging system, two candidate approaches for the gamma-ray-imaging system that are also used in the neutron imager. Figure 5 shows an optical-bench radiant-intensity testing stand on which the pixellated scintillators were tested [2]. This test stand was designed to provide uniform response for uniform radiant intensity at all angles. The scintillators were irradiated with a 10 mCi ^{57}Co source mounted about 1 cm from the end of the scintillators. The testing stand integrates light from many gamma-ray interactions, unlike the gamma-ray photon-counting experiments described earlier. The radiant-intensity pattern seen at different angles for the YSO scintillator is shown in Figure 6. The bright grid pattern was something of a surprise. It results from light escaping the scintillator at the rounded edges of the pixel bars, as can be clearly seen when the irradiated scintillator is viewed in the dark under a microscope. This is actually somewhat fortuitous, because most of the scintillation light would otherwise be trapped in the scintillator due to its perpendicular faces and high index of refraction ($n=1.8$). The measured angular distribution of emitted light for the pixellated YSO scintillator is shown in Figure 6B. The dip in the center is a consequence of Snell's Law: light exiting through the face of the scintillator at nearly normal incidence bends away from the normal, causing a depopulation of trajectories at closer-to-normal exit angles. The excess light at 45 degrees is due to the rounded edges of the pixel bars mentioned previously. Scintillators with rough surfaces and microcolumnar scintillators tend to have Lambertian distributions similar to the solid line in Figure 6. Monte Carlo simulations of scintillators with conical ends predicts angular distributions with light peaked more forward than Lambertian. Since a Lambertian distribution, or better yet, a forward-peaked distribution would improve light transfer, we intend to investigate modification of the pixel-exit faces experimentally in the future.

5. Simulations

The Monte Carlo program GEANT4 was used to study the spatial volume of energy deposition in the scintillator by 4.44 MeV gamma rays. This physics simulation program was originally written for the CERN particle accelerator and hence is capable of dealing with high-energy regimes and exotic particles. Various physics models can be implemented with GEANT4, and great care must be used when picking these. For this imaging system: ionization, Bremsstrahlung, scattering, and annihilation were simulated for electrons and positrons. For 4.44 MeV gamma rays interacting in BGO, Compton scattering is the most important physical process as it is responsible for 59% of the energy deposited. Pair production accounts for 38% of the deposited energy and the photoelectric effect is negligible at 3%. These proportions are similar for LSO and LYSO. It is important to take all of these effects into account as a single gamma can cause multiple physical interactions. The full width half max (FWHM) of the energy deposited is approximately 1.1 mm (Figure 7) in BGO with a system magnification of around 100, this translates to a source image resolution of 11 μm , provided that the imaging system contributes no additional degradation of spatial resolution. This resolution should be more than adequate to detect asymmetries in ablator debris.

6. Experimental Measurement of Light Emission Volume for 4.44 MeV Gamma Rays

In order to verify the GEANT4 simulations, and as a cross check, the light emission volume will be experimentally measured in both pixellated scintillators and monolithic crystals. The latter will model the light emission in a monolithic slab scintillator, one of the possible detector configurations to be investigated for the gamma-ray-imaging system.

Samples of BGO, LYSO:Ce, and YSO:Ce have been obtained for study. Pixellated Cherenkov radiators have also been obtained. All are 1 cm $\times$ 1 cm $\times$ 2 cm and half are pixellated with 1mm square pixels. An Americium-Beryllium source is used to obtain 4.44 MeV gamma rays for these tests. The excited state of ^{12}C in the AmBe neutron source is the same energy level as in the $^{12}\text{C}(n,n'\gamma)^{12}\text{C}$ 4.44 MeV gamma emission(see below); the gamma flux is 30% of the neutron flux with this source.

We have obtained the loan of a Campbell Pacific Nuclear DR503 soil moisture probe containing a 50 mCi AmBe neutron source. The neutron production rate with this probe is $\sim 10^5$ n/s into 4π steradians[4], the 4.44 MeV gamma ray rate is expected to be 30% of this. In order to measure the volume of energy deposition in the scintillators, we need to collimate the gamma rays and reduce the neutron flux as much as possible because their interactions in the scintillator are a source of noise and because they add to personnel dose. A housing was

constructed of lead and paraffin to hold the AmBe source and collimate its gamma emissions. The AmBe source is inserted into a 14-inch tube with 1.5 inches of paraffin at the front (Figure 5). The tube is surrounded with 4 inches of paraffin followed with 4 inches of lead bricks. At the end of the paraffin filled tube is a 1.5-mm-diameter pinhole. This pinhole provides a collimated source for use in testing the scintillator samples.

Figure 9 shows a test apparatus for measuring light-emission volume in monolithic scintillators. The scintillator is mounted in the scintillator housing and irradiated by the collimated 4.44 MeV beam produced by the collimation system (Figure 8). The light is collected by a fast f/0.5 lens and focused onto the fiber-optic input of a Proxitronic Detector Systems BV 2533 BX-V image intensifier that is coupled via a 6-mm lens to a Point Grey Research Grasshopper CCD Camera. For the pixellated scintillators, the detectors will be mounted directly in contact with the image intensifier as was done for the image of Figure 4.

7. Conclusion

We have performed simulations, calculations, and preliminary scintillator tests leading to the design of a gamma-ray-imaging diagnostic system for use at the NIF. This instrument is a candidate for use in conjunction with the LANL neutron-imaging system at NIF as a diagnostic tool for determining the pellet-compression asymmetry in NIF fusion experiments. Initial studies seem promising. After the next round of experiments using a 4.44 MeV gamma-ray source, we will design three candidate gamma-ray-imaging systems: a pixellated LYSO detector with ~1-mm pitch and either optical imaging or fiber-optic taper for readout, a slab LYSO scintillator with optical readout, and a Cherenkov radiator with an optical imaging readout. Using the results of these experiments we should be able to reliably predict the relative performances of these systems in order to select a candidate for development.

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9. References

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Figure 1.

Schematic of an imploding pellet, 4.44 MeV gamma rays are produced from neutron-carbon interactions in the ablator debris surrounding the pellet (blue region outside the red shell).

Figure 2.

Current neutron imaging system. The target and pinhole apertures are about 28 m away in the target chamber. The neutron imaging system shown has both fiber-optic taper leg (above with fiber optic light guide, in black) and an optical imaging leg (lower right with optical reflector at 45 degrees). The detector array is the gray object in the brown rectangle at center-left. The neutrons would enter from below through the reflector. The gated image intensifiers and imaging cameras are the black and white objects at the end of each imaging chain. [1]

A.

B.

Figure 3.

SNR comparison of 10^{11} (bottom line) to 10^{15} gamma-ray yields (top line) for multiple 8- μm pinholes. The horizontal line represents a SNR cutoff of 25 dB. A) Using neutron-imager configuration, B) Proposed aperture/detector distances for a gamma-ray imaging system.

Figure 4.
Light confinement in 1-mm-square pixels.

Figure 5.
Radiant intensity testing stand.

Figure 6. Results for angular distribution of emitted light from a pixellated YSO scintillator. At top are mages taken at different angles, at bottom is the derived relative radiant intensity as a function of angle. The solid line corresponds to a Lambertian emitter.[2]

Figure 7.

Results of a GEANT4 simulation of energy deposited into BGO scintillator. The plot shows the fraction of gamma-ray energy deposited outside of a cylinder of a given radius about an infinitesimally narrow beam of 4.44 MeV gamma rays in BGO. The radius at one-half maximum is 0.55 mm, so FWHM = 1.1 mm.

Figure 8.
Side-cut view(drawn in SolidWorks™)[3] of the paraffin and lead-brick collimator for the Americium-Beryllium source.

Figure 9.
Testing apparatus for determining the volume of 4.44 MeV gamma-ray energy deposition (light-emission volume) in scintillator samples.

Table 1

Candidate scintillator properties

Scintillator	Formula	Density (g/cm ³)	Light Yield (ph/MeV)	Decays (ns)	Emission Max(nm)	Refractive Index	Atten. @ 4.44MeV (cm ⁻¹)	%Int of 4.44MeV in (2cm)	Light Yield In 100ns (ph/MeV)
BGO	Bi ₄ Ge ₃ O ₁₂	7.13	8,200	300	480	2.15	0.276	42	2,300
LSO	Lu ₂ SiO ₅ :Ce	7.4	27,000	40	420	1.82	0.278	43	24,900
YSO	Y ₂ SiO ₅ :Ce	4.45	9,200	42	420	1.8	0.144	25	21,500
LYSO	Lu _{1.8} Y _{0.2} SiO ₅ :Ce	7.11	32,000	41	420	1.81	0.264	41	29,200
LaBr ₃	LaBr ₃ :Ce	5.08	70,300	16	380	1.9	0.173	29	70,000