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Imaging properties of pixellated scintillators with deep pixels

H. Bradford Barber¹, David Fastje¹, Daniel Lemieux^{1,2}, Gary P. Grim², Lars R. Furenlid¹, Brian W. Miller³, Philip Parkhurst⁴, and Vivek V. Nagarkar⁵

¹Center for Gamma-Ray Imaging, University of Arizona, Tucson, AZ

²Los Alamos National Laboratories, Los Alamos, NM

³Pacific Northwest National Laboratories, Richland, WA

⁴Proteus, Inc., Chagrin Falls, OH

⁵ Radiation Monitoring Devices, Inc. Watertown, MA, USA.

Abstract

We have investigated the light-transport properties of scintillator arrays with long, thin pixels (deep pixels) for use in high-energy gamma-ray imaging. We compared 10×10 pixel arrays of YSO:Ce, LYSO:Ce and BGO (1mm × 1mm × 20 mm pixels) made by Proteus, Inc. with similar 10×10 arrays of LSO:Ce and BGO (1mm × 1mm × 15mm pixels) loaned to us by Saint-Gobain. The imaging and spectroscopic behaviors of these scintillator arrays are strongly affected by the choice of a reflector used as an inter-pixel spacer (3M ESR in the case of the Proteus arrays and white, diffuse-reflector for the Saint-Gobain arrays). We have constructed a 3700-pixel LYSO:Ce Prototype NIF Gamma-Ray Imager for use in diagnosing target compression in inertial confinement fusion. This system was tested at the OMEGA Laser and exhibited significant optical, inter-pixel cross-talk that was traced to the use of a single-layer of ESR film as an inter-pixel spacer. We show how the optical cross-talk can be mapped, and discuss correction procedures. We demonstrate a 10×10 YSO:Ce array as part of an iQID (formerly BazookaSPECT) imager and discuss issues related to the internal activity of ¹⁷⁶Lu in LSO:Ce and LYSO:Ce detectors.

Keywords

scintillators; LSO; LYSO; high-energy gamma-ray imaging; pixellated scintillators; internal radioactivity

1. INTRODUCTION

We have constructed a Prototype NIF Gamma-Ray Imager shown in Figure 1. The Prototype Imager is made of 37 sub-arrays, each a 10×10 array of 1 mm × 1 mm × 20 mm LYSO:Ce pixels. It was developed as part of a program to demonstrate the possibility of gamma-ray imaging as a diagnostic tool to monitor target compression in inertial confinement fusion at the National Ignition Facility (NIF). The Prototype Imager has been described elsewhere [1], as has its initial testing at the OMEGA Laser Facility at the University of Rochester [1]. Figure 2 shows a 200 μm-pinhole image of a compressed ³He

target pellet taken at the OMEGA Laser; the bright central spot corresponds to thermal x-rays at a few tens of keV, while the surrounding extended emission is from hard x-rays (a few hundred keV) produced by Bremsstrahlung from energetic electrons due to the laser interaction with the plastic shell of the pellet. Figure 3(left) discloses a potential problem with the Prototype Imager, this is an image of a 6-cm-thick tungsten block backlit by the hard x-rays from another shot at OMEGA. It is expected that the tungsten block should completely attenuate the hard x-rays, but there is clear evidence of optical cross-talk between the pixels in the sub-arrays, but apparently not between the sub-arrays. It turns out that Figure 3(left) corresponds to a somewhat pathological example, the cross-talk is at the few percent level. However, this could still be a problem for NIF applications, because coded-apertures such as the penumbral aperture will be used to image targets, and optical cross-talk could interfere with the reconstruction process. Figure 3(right) shows the result off an attempt to correct the cross-talk in the image of Figure 3(left) using a heuristic algorithm. While this attempt was partially successful, and it gives us confidence that complete correction should be possible, we will need to map the optical cross-talk directly in the LYSO sub-arrays to make such a complete correction. This paper describes measurements of the optical cross-talk for that purpose, as well as various bench tests and calibration tests of LYSO sub-arrays, similar pixel arrays made of other scintillators and scintillators of other configurations that should help elucidate the causes of inter-pixel cross-talk and other properties of deep-pixel scintillator arrays. Because deep-pixel scintillator arrays should be useful for many high-energy gamma-ray imaging tasks, we also tested their properties for a wide range of applications including and iQID imager and with EMCCD readout.

2. SCINTILLATOR PROPERTIES

2.1 Test scintillators

The scintillator samples tested in this work are described in Table 1. Table 2, gives some relevant properties of the scintillator materials used in the test samples. The overall goal of this effort is to image high-energy gamma-rays (i.e. 4.44 MeV gamma rays at NIF), so high-density scintillators such as BGO, LSO:Ce and LYSO:Ce are attractive candidate materials. The 4.44 MeV gammas are produced when the 14.6 MeV fusion neutrons interact with carbon in the plastic shell of the pellet via the $^{12}\text{C}(n,n'\gamma)^{12}\text{C}$ reaction. The symmetry of the target compression can be monitored by imaging the size and shape of the residual shell. For gamma-ray imaging at NIF, the gamma-ray fluence is typically 500 times smaller than the neutron fluence. Fortunately the imaging path is long (typically ~ 30 m) [2], so time-of-flight methods can be used to separate neutron and gamma-ray signals. The gamma rays arrive about 100 ns after the fusion burn, the 14.6 MeV fusion neutrons ($v \sim 0.18$ c) arrive about 470 ns later. Thus the imager will use a gated image intensifier and a CCD camera to integrate the gamma-ray signal and then shut off the imager before the fusion neutrons arrive. For this reason, the scintillator should have a fast decay time (< 100 ns). The decay time of BGO is too long to be optimal for our task. For an imaging array, the pixel size should be similar to, but smaller than the lateral spread of the energy deposition of the expected gamma ray, in this case 4.44 MeV. That is, the pixel size should not be the dominant contribution to the spatial resolution of the resulting imager. Also, the pixel depth

along the gamma-ray propagation direction should be long enough to stop, and detect a large fraction of the gamma rays. For LYSO:Ce, 20 mm is sufficient for 40% of the 4.44 MeV gamma rays to interact. At 4.44 MeV, a GEANT4 simulation [2] showed a lateral spread of energy deposition of 1.1 mm FWHM for BGO and 1.09 mm FWHM for LYSO:Ce, which is consistent with the choice of a 1 mm pixel size [1].

The Prototype NIF Gamma-Ray Imaging System is constructed of 37 10×10 LYSO:Ce (see Figure 1), each constructed of 100 pixels of size 1 mm × 1 mm × 20 mm. The test scintillators enumerated in Table 1 include 10×10 sub-arrays of 1 mm × 1 mm × 20 mm pixels of BGO, LYSO:Ce and YSO:Ce made by Proteus, Inc.[3]. Two additional 10×10 arrays of 1 mm × 1 mm × 15 mm pixels made of LSO:Ce and BGO were loaned to us by Saint-Gobain [4]. The Proteus arrays used a pixel separator made of a highly-reflective film called Vikuiti™ ESR {Enhanced Spectral Reflector} [5]. The Saint-Gobain pixel arrays use a white diffuse reflector for pixel separation. The properties of the inter-pixel reflector turn out to be important for imaging function. Other test scintillators in Table 1 include two monolithic BGO crystals, one with the same overall size as the Proteus 10×10 BGO sub-array and the other a thin slab.

Among the properties of the scintillators described in Table 2 are two, trapped light and internal radioactivity, that are usually not included in such tables. Both phenomena turn out to be important limitations for imaging use. Trapping of light in scintillators occurs when internally-emitted light suffers total internal reflection at all exit faces. Such trapping is most severe when the scintillator has a high index of refraction, all faces are polished and perpendicular (as for a rectilinear parallelepiped) and most, or all surfaces, have air interfaces. The numbers quoted for trapped light in Table 2 are for these conditions. In the actual case, all of our pixel arrays will have glass on the exit face and either ESR film or white reflector on the other faces. Since these materials have higher indices of refraction than air, the actual trapped fraction will be, in general, less than in Table 2. However, trapped light is a ubiquitous phenomenon for high-index scintillators, and it provides a limitation to performance, because not all of the light produced is generally extracted. If one of the constituent elements of the scintillator has a naturally-occurring radioactive isotope, the scintillator will typically have a background counting rate that is unavoidable. The presence of ^{176}Lu (2.59 % of natural Lu) gives rise to such a background in LSO:Ce and LYSO:Ce detectors. Even though the ^{176}Lu has a very long half-life (3.59×10^{10} yr.), the background counting rate is high enough to render LSO/LYSO detectors unsuitable for low-background counting, for applications such as SPECT imaging and to make it difficult to do common pixel calibration tests.

2.2 Investigations of scintillator light output

The light output of a pixellated scintillator depends on the energy deposition in the scintillator, its light yield, the configuration of the pixel bars and what reflector surrounds the non-exit faces (i.e. white reflector, ESR,...etc.). The three Proteus BGO scintillators from Table 1 were mounted on a 3" diameter Hamamatsu R-6233-100 SBA PMT. The $18 \times 18 \times 3$ mm and $10 \text{ mm} \times 10 \text{ mm} \times 20 \text{ mm}$ detectors were covered with white reflector (Teflon tape) on all non-exit faces, and all three detectors were mounted on the PMT face

using optical coupling compound. The Proteus 10×10 BGO array had pixels separated by ESR film and all non-exit faces were covered with additional ESR plus Teflon tape. A collimated ^{57}Co (122 keV) gamma source was used to irradiate each detector individually. Pulse-height spectra were taken using an ORTEC PCI-MCA (PMT bias = −1000V, Canberra 2005BT preamplifier, Tc-243 spectroscopy amplifier). The normalized spectra of the three scintillators are compared in Figure 4. The main peak in each spectrum is the photopeak for the 122 keV gamma rays. A smaller peak below this is due to K x-rays from the Pb collimator. The lowest peak is due to Bi K-x-ray escape from the BGO scintillator. The shifts in the similar spectra of the three scintillators are due to the relative light collection efficiency in each configuration. The photopeak with the highest pulse height corresponds to the thin-slab BGO detector with its 18 mm × 18 mm side against the PMT face, a condition that allows nearly maximum light-collection efficiency. The use of a white diffuse reflector (Teflon) tends to minimize the amount of trapped light, because this type of reflection randomizes trajectory. The next lower peak is due to the 10 mm × 10 mm × 20 mm BGO; here the area of the exit face (1 cm²) is low compared to the surface area of the scintillator (10 cm²). The lowest photopeak pulse height in Figure 4, corresponding to the lowest light collection efficiency, is for the Proteus 10×10 BGO pixel array. When compared to the thin slab, the light loss is about 45%, but the reasons for this low light-collection efficiency are complex. First, the long, thin scintillator bars are viewed end on, which should make for low light collection efficiency. But the ends and sides of the pixel bars are covered with ESR film which has far better reflectivity than Teflon. However, ESR is a specular reflector that does not randomize trajectories on reflection. Consequently, we expect that the majority of light losses in the Proteus pixel array are actually due to light trapping effects.

3. USE OF A DEEP-PIXEL ARRAY WITH AN IQID DETECTOR

3.1 IQID imaging studies

A Proteus 10×10 YSO:Ce array was mounted on the fiber-optic input face of an intensifier as part of the iQID (Intensified Quantum Imaging Device) imaging system shown in Figure 5. This type of imaging device was formerly called BazookaSPECT [6,7]. The iQID of Figure 5 is composed of a Proxivision 2564 BZ-V 2-stage image intensifier [8] with a bialkali photocathode and a P47 output phosphor, optically coupled via a 6 mm-focal length lens to a Point Grey Grasshopper CCD camera [9]. The scintillator was exposed to a weak ^{22}Na source, and one frame of an iQID image is shown in Figure 6. The bright squares in Figure 6 are due to individual gamma rays interacting in single pixels in the 10×10 YSO array. The brighter squares are due to 1270 keV gamma rays, the less-bright squares to 511 keV gammas from positron annihilation. There are about 200 CCD pixels for each scintillator pixel in this configuration, and the square-shape of each interaction indicates that light illumination is quite uniform over the pixel face.

The main task envisioned for our Prototype NIF Gamma-Ray Imaging System assumes integrating the light produced by many interacting gamma rays in each detector pixel. Typically, the gamma rays will all be produced in under a nanosecond, so photon counting would be impractical. However, since other high-energy gamma-ray applications might

make use of a detector system such as ours, we have not limited the calibration testing to integrating applications. For instance, Miller and co-workers have pioneered the use of iQID/BazookaSPECT imagers for small-animal SPECT imaging and other applications [6,7].

3.2 iQID spectroscopy studies

We tested the YSO:Ce 10×10 array with the iQID readout with various gamma-ray sources, ^{125}I (26–31 keV, 35 keV), ^{241}Am (60 keV), ^{57}Co (122 keV) and $^{99\text{m}}\text{Tc}$ (140 keV). The results for single-photon spectroscopic performance are shown in Figure 7. In each case, a large number of frames were taken for each source with, typically, only a few individual hits per frame. The light signal from each hit pixel was summed and the background from a dark-field (no source) frame was subtracted. Each spectrum was a histogram of a few thousand such events. The spectra indicate that individual gamma-ray events can be detected down to ~ 30 keV with such a deep-pixel iQID device, but the energy resolution is poor compared to scintillators on PMT's. There are a number of reasons for this. The high gain noise in the image intensifier [10] is likely the most limiting factor, followed by the summed readout noise from the large number of CCD pixels corresponding to each scintillator pixel. Microchannel-saturation effects [11] might also make a minor contribution to the limited energy resolution. One phenomenon that probably does not limit energy resolution in this case, is the variation in light transmission with interaction depth along the long, thin pixels as we shall see in the next section.

4. LIGHT TRANSMISSION IN DEEP PIXEL ARRAYS

For this experiment, we mounted various 10×10 deep pixel scintillator arrays on a Hamamatsu R3998-100 SBA PMT (Bias = -1000V, Canberra 2003BT preamplifier, Tc-243 spectroscopy amplifier and ORTEC PCI-MCA). A highly-collimated ^{57}Co source (250 μm -square beam) was scanned along the scintillator perpendicular to the pixel axis from the PMT to the distal end. Spectra were taken every 0.5 mm along the long pixel axis. The counts in the photopeak in each spectrum indicated whether the beam was on or off the scintillator, and the photopeak position (peak channel) was a measure of the light-collection efficiency of the pixel for interactions in that position. Results are shown for the Proteus 10×10 BGO array and the Saint-Gobain 10×10 BGO array in Figure 8, and for the Proteus 10×10 LYSO:Ce array and Saint-Gobain 10×10 LSO array in Figure 9. In each case, the plot of counts in the photopeak agrees well with the physical length of the individual pixel array (the Proteus arrays are 20 mm long and the Saint-Gobain arrays are 15 mm long). The light-collection efficiency is very uniform for the Proteus arrays that use ESR films on the sides and distal ends, the variation is, at most, a few percent. The variation in light-collection efficiency is much more significant for the Saint-Gobain arrays, despite their shorter length, which is likely a consequence of the use of a white diffuse reflector in these arrays. The mechanisms of light reflection are quite different in the two reflector materials. The 3M-ESR Vikuiti™ films have very good reflectivity near normal incidence (> 98 % [5].), and the reflection is specular. For larger angles to the normal for the polished surfaces of these high-index scintillators, total internal reflection should dominate. So, overall, reflection is specular and very efficient for the Proteus arrays. The white reflector used in the Saint-

Gobain arrays is expected to have an approximately Lambertian angular response and thus is randomizing. For such a reflector, the probability of light absorption during a somewhat random transport down the long, thin pixel bar is expected to be higher. Interestingly, the variation in light-collection efficiency is more severe for the Saint-Gobain LSO than for the Saint-Gobain BGO. The index of refraction of BGO ($n=2.15$) is greater than that of LSO ($n=1.82$), so more of the LSO light will penetrate into the white reflector (i.e. not suffer total internal reflection) where it can suffer absorption. The LSO emissions are shorter wavelength than those of BGO (420 nm vs. 480 nm), which could also enhance absorption.

The lower variations in light collection efficiency in the Proteus arrays make this design very attractive for single-photon spectroscopy applications, where such variations would contribute to degradation of the energy resolution. In our application, in which the light of many interacting gamma rays is integrated, such considerations are less significant.

5. DEEP-PIXEL IMAGING USING AN EMCCD CAMERA

5.1 Spatial distribution of light from pixels

We mounted each of our 10×10 BGO arrays directly on the fiber optic coupler of a custom-designed EMCCD camera developed by Radiation Monitoring Devices, Inc.[12] In this case the $8\text{ mm} \times 8\text{ mm}$ CCD footprint contained 512×512 CCD pixels, so each 1 mm-square scintillator pixel corresponded to approximately 4000 CCD pixels. We used a ^{57}Co (122 keV) source for flood illumination, and summed about 10,000 frames to get the EMCCD camera images of Figures 10(left) and 11(left). As expected from the single-photon studies with the iQID camera (Figure 5), the light output is quite uniform across each pixel, save for a stochastic variation due to counting statistics. There is some small variation from scintillator pixel to scintillator pixel. This is probably due to light coupling effects. The pixel arrays are not perfectly flat, and the individual pixels can protrude or be recessed by as much as a few tens of microns. Despite the use of optical coupling grease, this could account for slight differences in overall brightness.

For the Saint-Gobain 10×10 BGO array of Figure 10(left), the yellow arrows indicate the location of a vertical profile through the image, which is plotted in Figure 10(right). The signal variation across the image is quite uniform and drops between the pixels as expected, because the white reflector is not expected to transmit light for any significant distance. The results for the Proteus 10×10 BGO array are quite different. Again the vertical profile of Figure 11(right) seems quite uniform within the pixel, but the light output per unit area between the pixels is higher than within the pixel. A similar bright-gap response was noticed by Baudet [2,13] for the Proteus 10×10 YSO:Ce array of Table 1. We have identified two possible causes for the excess light at pixel boundaries. One is that the light exiting the high-index scintillator and entering the lower index ESR film, bends away from the normal at the interface due to refraction and then propagates down the ESR film as if it were a light guide (ESR films are used to backlight LCD displays in smart phones using a variant of this mechanism [5]). When the light reaches the edge of the film at the pixel exit face, it can escape from the film. Because this mechanism can extract light that might otherwise be trapped, the film edge can be brighter than the pixel face. Another possibility is that the edges of the scintillator pixel are not perfectly sharp, but have some crazing and cracking

due to the nature of the polishing process, and these imperfections allow trapped light to escape. Baudet observed a Proteus 10×10 YSO array in the dark under a microscope with a strongly radioactive source stimulating the scintillator, and concluded that most of the light was coming from the ESR film [14]. Thus the former mechanism appears to be the main source of the excess light, but we cannot exclude small contributions from the latter mechanism. Quantitatively, the portion of the total pixel light attributable to these ESR/edge effects for the Proteus 10×10 BGO array of Figure 11 is 6.25%, taking into account the different areas involved.

5.2 Angular distribution of light from pixels

Baudet [2,13] also developed an instrument to measure the angular distribution of light (radiance) coming from scintillators under stimulation by gamma-ray sources. For many scintillators, including columnar CsI(Tl), the light-output distribution approximates a Lambertian. The result for the angular distribution of the light output from a 10×10 YSO:Ce array stimulated by a ^{57}Co source is shown in Figure 12. The solid curve in Figure 12 is a Lambertian, the data points represent measurements of light intensity of the YSO array. There is a deficit of light emitted along the pixel axis (0°) but an excess of light around 40° as compared with a Lambertian response. The fact that the light exiting the pixel face bends away from the normal (hence the deficit) and a more complex exit pattern from the irregular ends of the ESR film, might account for such a pattern, but in the absence of a comprehensive model, the angular distribution of Figure 12 must remain somewhat mysterious.

6. INTERNAL RADIOACTIVITY IN SCINTILLATORS

Two of our 10×10 scintillator arrays (Proteus LYSO:Ce and Saint-Gobain LSO:Ce) contain Lutetium; 2.59 % of natural Lu is ^{176}Lu , a naturally-occurring radioisotope with a half-life of 3.59×10^{10} yr. The internal counting rate of the two detector arrays is 500–600 c/s as indicated in Table 2. This counting rate is high enough to make many calibration tests difficult. Both the Proteus 10×10 LYSO array and the Saint-Gobain 10×10 LSO array were separately mounted on a Hamamatsu R3998-100 SBA PMT. The spectra shown in Figure 13 were obtained without a source. Spectra of internal emission sources can be hard to interpret, because any sequence of events in a decay that each deposits energy can sum in the spectra. Consider, first the LSO spectrum of Figure 13(left). The ^{176}Lu decays with a β^- transition to ^{176}Hf , greater than 99% of these decays are to a 0.597 MeV excited state in the ^{176}Hf nucleus. This excited state decays by three successive electromagnetic transitions, emitting three gamma rays in cascade: 0.307 MeV(93%), 0.202 MeV(84%) and 0.088 MeV(13%). The gamma-ray yields are less than 100% because there is a competing process, isomeric transition, that de-excites the level by ejecting an inner-shell atomic electron. A simplified energy-level diagram for the decay is shown in Figure 14. The maximum amount of energy that can be deposited in the scintillator by a ^{176}Lu decay is the maximum beta energy, 0.565 MeV, plus the total energy in electromagnetic transitions in the residual nucleus, 0.597 MeV or a total of 1.162 MeV. Beta decay is a three-body process with a portion of the energy carried away by an undetectable neutrino, consequently we should expect the spectrum to exhibit a broad peak between 0.597 MeV and 1.162 MeV. However,

in practice, either or both of the 0.307 MeV and 0.202 MeV gamma rays can escape the detector crystal, these contribute to a complex of structures below the main peak in Figure 13(left). Figure 13(right) shows the background pulse height spectrum for the Proteus LYSO array. The horizontal axis in Figure 13(right) has higher gain than that of Figure 13(left), but otherwise the spectra are quite similar, as might be expected, since the main emissions come from the same source, ^{176}Lu . However, Figure 13(right) has a structure at highest pulse height that is not present in Figure 13(left). This activity does not appear to be associated with ^{176}Lu , but is due to some unknown constituent. Lanthanide ores are rich in other lanthanides, some of which have long-lived radioisotopes, as well as actinides such as U and Th, together with the radioactive daughters in their extensive decay chains. Because LSO is used in PET detectors, Saint-Gobain probably goes to some trouble with its purification. In our own extensive experience with lanthanide halide scintillators [15,16], we have found that low-level radioactive contaminants are not uncommon.

7. PIXEL CROSS-TALK IN DEEP-PIXEL DETECTORS WITH ESR FILM SEPARATION

7.1 Apparatus for measuring pixel cross-talk

We expect no optical cross-talk in the Saint-Gobain arrays because the white reflector should be opaque to optical photons, and no cross-talk is evident in Figure 10. However, the results of the Omega experiment clearly indicate optical cross-talk between pixels in the Proteus 10×10 LYSO sub-arrays but not between sub-arrays in the Prototype NIF Gamma-Ray Imager. It turns out that measuring the optical cross-talk between the Proteus LYSO sub-arrays is quite difficult, because of the internal ^{176}Lu radioactivity. The background counting rate in each LYSO sub-array is 556 counts per second, and the energetic gamma rays from the ^{176}Lu decay can escape one pixel to interact in another.

In order to measure the optical cross-talk in the LYSO sub-arrays, we constructed the apparatus shown in Figure 15. This device is similar to the iQID camera of Figure 5. Either the 10×10 LYSO sub-array or the full Prototype NIF Gamma-Ray Imager of Figure 1 is mounted on a 3:1 fiber optic taper which is coupled to a Proxivision 2564 BZ-V image intensifier, the output phosphor of which is imaged via a 6 mm-focal-length lens onto a Point Grey Grasshopper CCD camera. The frame at right in Figure 15 has a highly-collimated ^{57}Co source (500 μm -square beam) which can be positioned close enough to the detector that a single chosen pixel is illuminated. The detector array and the iQID camera are mounted on a 2-D translation stage [17], and control and data acquisition use software written in LabVIEW™. The camera is operated with a very short integration time (< 1 ms) so that in a given CCD frame the probability of a ^{176}Lu decay in that sub-array is less than 50%, such decays are easily visible. With the collimated ^{57}Co source beam centered on a selected scintillator pixel, a large number (> 10^6) frames are acquired. A data processing algorithm reviews each frame and accepts only those with a hit in the target pixel with a brightness corresponding to a 122 keV gamma-ray interaction (much less than for a ^{176}Lu decay) and no hits in other pixels of that sub-array (i.e. no other ^{176}Lu decays). All such frames are then summed. The weak optical cross-talk in neighbor pixels should then sum and, hopefully, be visible in the summed frame above any background noise sources. Most

of the optical cross-talk is expected to take place in the ESR film that separates the pixels in the sub-array, but the Proteus arrays also have an ESR film covering the distal end of the array (opposite the exit face). This film is tacked on with small spots of epoxy (to allow easy removal), so an air-gap is possible between the end of each pixel and the ESR, a feature that probably promotes inter-pixel optical cross-talk. Tests were performed with the distal ESR in place, and with it removed and replaced by either a white diffuse reflector (Teflon) or a black absorber. The results of optical cross-talk tests of a Proteus 10×10 LYSO array with a black distal absorber are shown in Figure 16. Figure 16(left) shows that the optical cross-talk is only a tiny fraction of the light in the target pixel, and there is a hint that the cross-talk may be asymmetric in orthogonal directions. Figure 16(right) shows a side profile view along the direction indicated by the arrow in Figure 16(left). The cross-talk in nearest-neighbor pixels is dramatically larger than that in more distant pixels, this is because a portion of the cross-talk in nearest-neighbor pixels is due to re-interaction of Compton scattered gamma rays and K x-rays from the target pixel, i.e. nearest-neighbor pixels can have gamma-ray cross-talk as well as optical cross-talk. The scattering to the right-side nearest-neighbor pixel is higher than to the left-side nearest neighbor in Figure 16(right), this is probably due to the beam being slightly offset to the right of the target pixel. Because of the good stopping power of LYSO and the low energy of the gamma rays there should be negligible gamma-ray cross-talk to non-nearest-neighbor pixels.

Figure 17(left) shows a magnified 5×5 pixel region about the target pixel of Figure 16(left) (LYSO 10×10 array, black distal absorber). Figure 17(right) shows the same data plotted with a logarithmic vertical scale to make the low-level optical cross-talk more visible. The orthogonal asymmetry in the optical cross-talk is now quite evident in Figure 17(right). Asymmetrical optical cross-talk is probably a consequence of the way the Proteus arrays are constructed. Scintillator-pixel bars ($1\text{ mm} \times 1\text{ mm} \times 20\text{ mm}$) were prepared with an ESR film glued to one long side. Then a $10\text{ mm} \times 20\text{ mm} \times 1\text{ mm}$ slab was prepared by gluing bars together with a single layer of ESR film now separating each pixel bar; a sheet of ESR film is the glued on top. Ten such slabs are then glued together to make a 10×10 pixel array, and ESR film is now glued to the sides and tacked to the distal surface. At this point all pixels are separated by a single layer of ESR; this method of assembly was chosen to keep the inter-pixel spacing as small as possible, so most of the detector array is active scintillator. Figure 18 shows a sketch of a Proteus 10×10 sub-array using the above construction scheme. It should be evident from Figure 18 that light travelling vertically must traverse multiple ESR layers to reach distant pixels, but light travelling horizontally within the ESR layer can access many pixels. It should be noted that the index of refraction of the ESR is much lower than that of the scintillator, so light entering the ESR from the scintillator will bend away from the normal and be more likely to travel along inside the ESR film. This is likely the reason for the asymmetrical optical cross-talk.

The Omega results of Figure 2 indicated that the optical cross-talk between sub-arrays was negligible. The Proteus sub-arrays are each surrounded by a single thickness of ESR film, so when mounted together, the sub-arrays are separated by two layers of ESR. Apparently two layers of ESR are sufficient to suppress optical cross-talk to negligible levels. In subsequent deep-pixel arrays, it should be possible to further suppress cross-talk by using two layers of ESR between each pixel, with some modest loss in fill-factor. Alternatively, diffuse white

reflector can be used, as in the Saint-Gobain arrays with some loss in light-transmission efficiency.

7.2 effect of distal termination

Figure 19 shows the effect on optical cross-talk of different distal coatings: ESR, diffuse white reflector or black absorber. Again, a vertical logarithmic scale is used to enhance the visibility of low-level effects. In the Fall of 2014, we plan to perform further tests on the Prototype NIF Gamma-Ray Imager at the High-Energy Gamma Source (HIGS/TUNL) at Duke University [18]. Prior to this effort, we expect to remove the distal ESR from each sub-array and replace it with black absorber. A discussion of the planned tests at HIGS is covered in a companion paper in another conference at this meeting [19]. We also expect to use the results of the optical cross-talk measurements (e.g. Figure 16(left)) to correct images such as Figure 3. We are in the process of implementing this for the Prototype NIF Gamma-Ray Imager. Because the optical cross-talk is asymmetric, it is necessary to measure the orientation of each of the 37 sub-arrays in the Prototype NIF Gamma-Ray Imager prior to correction, and this work is in progress. A full correction algorithm for optical cross-talk is expected to be available for the HIGS experiment.

8. CONCLUSION

As has been reported elsewhere [1], we have constructed a Prototype NIF Gamma-Ray Imager to demonstrate the possibility of gamma-ray imaging as a diagnostic tool for inertial-confinement fusion. Here, we report studies of deep pixel scintillators for use in high-energy gamma-ray imaging. Some of these studies were done as part of the design and development of the Prototype Imager, others to better understand its performance limitations and other possible uses of deep pixel imaging. We have described the light-collection efficiency of deep pixel scintillators and the roles of different types of reflectors and internal light trapping in the performance of such pixellated scintillators in both integrated imaging tasks and in single-photon spectroscopic imaging. We have presented detailed measurements of inter-pixel cross-talk in the Prototype NIF Gamma-Ray Imager, and elucidated its origins in the use of an ESR film as a pixel separator. We have also discussed possible design improvements to the Prototype Imager. We have demonstrated deep pixel detectors as part of an iQID imager and briefly considered the limitations of internal radioactivity from ^{176}Lu for calibration and testing of lutetium-based scintillators such as LSO:Ce and LYSO:Ce.

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Figure 1.
Detector array for the Prototype NIF Gamma-Ray Imager[1].

Figure 2.

Image from OMEGA of a ^3He -pellet shot taken with the Prototype NIF Gamma-Ray Imager and a pinhole aperture.

Figure 3.

Image from OMEGA of a 6-cm-thick tungsten block, back-lit by a 3He-pellet shot: image shows unsharp edges due to inter-pixel optical cross-talk (left), with correction using a heuristic algorithm (right).

Figure 4.
Comparison spectra of BGO scintillators with collimated ^{57}Co source (122 keV).

Figure 5.
Photograph of iQID imager.

Figure 6.
Frame from the iQID imager with a 10×10 YSO:Ce array showing single gamma-ray interactions from a ^{22}Na source.

Figure 7. Gamma-Ray spectra taken with the 10×10 BGO array and the iQID imager: 125I source{26–35 keV}(upper left), 241Am source{60 keV} (upper right), 57Co source{122 keV} (lower left) and 99mTc source{140 keV} (lower right).

Figure 8.

Light transmission in 10×10 BGO arrays: Proteus (left), Saint-Gobain (right). Top frames show the counts in the photopeak (showing the length of the detector), bottom frames show the peak channel number (measure of light collection efficiency).

Figure 9.
 Light transmission in 10×10 arrays: Proteus LYSO:Ce (left), Saint-Gobain LSO:Ce (right).
 Top frames show the counts in the photopeak (showing the length of the detector), bottom
 frames show the peak channel number (measure of light collection)

Figure 10. Results for a Saint-Gobain 10×10 LSO:Ce array on an RMD EMCCD camera (left), and a vertical profile (right).

Figure 11. Results for a Proteus 10×10 BGO array on an RMD EMCCD camera (left) and a vertical profile (right).

Figure 12.
Angular distribution of light from a 10×10 YSO:Ce array from the work of Baudet [2,13].
Solid line is a Lambertian response.

Figure 13.
Pulse-height spectrum of the internal activity of a Saint-Gobain 10×10 LSO:Ce array (left)
and a Proteus 10×10 LYSO:Ce (right).

Figure 14.
Simplified energy-level diagram for ^{176}Lu decay (energies in MeV).

Figure 15.
Photograph of the apparatus used to measure optical inter-pixel cross-talk in pixel arrays.

Figure 16.
Optical cross-talk results from a Proteus 10×10 LYSO:Ce array with black distal backing:
oblique view (left), profile view (right).

Figure 17.
Optical cross-talk results from a Proteus 10×10 LYSO:Ce array with black distal backing:
magnified 5×5 pixel region (left), with logarithmic vertical scale (right).

Figure 18.
Sketch of the layout of a Proteus 10×10 pixel array.

Figure 19.

Optical cross-talk results from a Proteus 10×10 LYSO:Ce array, the effect of distal backing: white diffuse (left), ESR (center), black (right).

Table 1

Test Scintillators

Scintillator	Array	Pixel Size	Supplier
YSO:Ce	10×10	1×1×20 mm ³	Proteus
LYSO:Ce	10×10	1×1×20 mm ³	Proteus
BGO	10×10	1×1×20 mm ³	Proteus
BGO	10×10	1×1×15 mm ³	St. Gobain
LSO:Ce	10×10	1×1×15 mm ³	St. Gobain
BGO	monolithic	10×10×20 mm ³	Proteus
BGO	monolithic	18×18×3mm ³	Proteus

Table 2

Properties of Scintillators

		Density g/cm ³	Yield ph/MeV	Decay time ns	λ_m nm	n	Trapped light %	Internal activity d/s/cm ³
BGO	Bi ₄ Ge ₃ O ₁₂	7.13	8,200	300	480	2.15	66	--
LSO	Lu ₂ SiO ₅ :Ce	7.4	27,000	40	420	1.82	51	305
LYSO	Lu _{1.8} Y _{0.2} SiO ₅ :Ce	7.1	32,000	41	420	1.81	50	278
YSO	Y ₂ SiO ₅ :Ce	4.45	9,200	42	420	1.80	49	--