Scintillator efficiency study with MeV x-rays

Stuart Baker,*,a Kristina Brown,a Alden Curtis,a Stephen S. Lutz,b Russell Howe,c Robert Malone,a Stephen Mitchell,c Jeremy Danielson,d Todd Haines,d Kris Kwiatkowski

aNational Security Technologies, LLC, Los Alamos Operations, P.O. Box 809, Los Alamos, NM 87544
bNational Security Technologies, LLC, Special Technologies Laboratory, 5520 Ekwill St., Suite B, Santa Barbara, CA 93111-2352
cNational Security Technologies, LLC, P.O. Box 98521, Las Vegas, NV 89193-8521
dLos Alamos National Laboratory, P. O. Box 1663, Los Alamos, NM 87545

ABSTRACT

We have investigated scintillator efficiency for MeV radiographic imaging. This paper discusses the modeled detection efficiency and measured brightness of a number of scintillator materials. An optical imaging camera records images of scintillator emission excited by a pulsed x-ray machine. The efficiency of various thicknesses of monolithic LYSO:Ce (cerium-doped lutetium yttrium orthosilicate) are being studied to understand brightness and resolution trade-offs compared with a range of micro-columnar CsI:Tl (thallium-doped cesium iodide) scintillator screens. The micro-columnar scintillator structure apparently provides an optical gain mechanism that results in brighter signals from thinner samples. The trade-offs for brightness versus resolution in monolithic scintillators is straightforward. For higher-energy x-rays, thicker materials generally produce brighter signal due to x-ray absorption and the optical emission properties of the material. However, as scintillator thickness is increased, detector blur begins to dominate imaging system resolution due to the volume image generated in the scintillator thickness and the depth of field of the imaging system. We employ a telecentric optical relay lens to image the scintillator onto a recording CCD camera. The telecentric lens helps provide sharp focus through thicker-volume emitting scintillators. Stray light from scintillator emission can also affect the image scene contrast. We have applied an optical light scatter model to the imaging system to minimize scatter sources and maximize scene contrasts.

Keywords: scintillator, radiography, CCD camera, hard x-ray, imaging

1. INTRODUCTION

This study investigates detector efficiency of imaging scintillators for radiography applications with hard x-ray sources in the MeV range. The source for this data set is the Cygnus x-ray machine1 with a tungsten rod-pinch bremsstrahlung diode, operating at approximately 2.25 MeV. Fig. 1 illustrates the experimental layout of the Cygnus dual-axis radiographic facility at the Nevada National Security Site. Explosive shock physics material studies are conducted at the facility, which places special constraints on the radiographic system. Experiments are conducted in a vessel to contain the experiment material. The scintillator provides the x-ray-to-visible photon light conversion; the scintillator image is then recorded with a camera. We have interest to study system sensitivity and resolution for the x-ray range from 0.4 MeV to 20 MeV. Scintillators used in these imaging applications are relatively thin with thickness of a few millimeters to maintain good resolution characteristics. Thin scintillator thickness results in poor stopping power in this MeV range and inefficient x-ray-to-light conversion.

*bakersa@nv.doe.gov, phone 1 505 663-2040; fax 1 505 553-2003

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The discussion focuses on scintillators suitable for single-pulse and static object applications. We are studying three cerium-doped lutetium yttrium orthosilicate (LYSO:Ce) panels 3, 5, and 10 mm thick, and 0.15, 0.4, and 0.6 mm thick micro-columnar thallium-doped cesium iodide (CsI:Tl) screen.\(^2\) The LYSO studied is PreLude\textsuperscript{TM} 420 (Lu\(_{1.8}Y.2\)SiO\(_5\):Ce)\(^3\) cut and polished in monolithic single-crystal panels. With a 41 ns decay time, it is a good fit for fast multi-pulse radiography with pulse separation as short as 100 ns. CsI:Tl, with a few microseconds decay, is better suited to single-pulse or static-object imaging; the increased photon conversion can benefit the radiography signal-to-noise ratio (SNR). Based on material cross sections and thickness, the thicker LYSO samples will absorb significantly more x-ray energy.\(^4\) However, the photon conversion efficiency and wavelength of CsI:Tl can provide an advantage over LYSO: the micro-columnar CsI has shown better detection efficiency over monolithic crystals. The LYSO has better SNR than CsI:Tl, and LYSO’s SNR improves as its thickness is increased. However, the signal gain must be balanced with resolution trade-off correlated with scintillator thickness.

For radiographic applications we have several restrictions on the scintillator performance and dimensions that limit our options. The material needs to be of good optical quality and free of blemishes and inclusions. Spectral emission in the blue to green wavelength range matches well to camera sensitivity. Thinner scintillator thickness is often desired for sharp edge resolution and better scene contrast. Large-area imaging, up to 20 cm by 20 cm, limits options available due to material fabrication capabilities. LYSO is tiled in three panels to accommodate this full area. For static-object imaging or single-pulse x-ray machines, decay time requirements are not severe; the camera can use a long exposure to integrate the longer time decay scintillator image. Other applications supporting multi-pulse radiography in explosive tests need to acquire multiple images from a single scintillator within a few microseconds. In these cases, decay time and image latency become important concerns. Ultra-fast applications in high-energy-density physics needing nanosecond or sub-nanosecond decay times are not discussed.

A telecentric zoom lens system (ZLS) designed at National Security Technologies, LLC for the Cygnus x-ray machine\(^5\) is used to relay the scintillator image to the CCD camera. The telecentric lens better accommodates focusing in thicker scintillators by tracing the focus trajectory of the ray-bundles through the scintillators back to the x-ray point source. Light is continuously produced along each x-ray track as it passes through the scintillator. For optimal light collection, emission from a thick scintillator should be viewed along the x-ray track generating the light. The 1 mm x-ray point source is 2.4 m away from the scintillator, so the primary rays of light emitted will diverge as they exit the scintillator. We found it difficult to collect these ray bundles in an optical model, so a
compromise was to make the zoom lens telecentric, meaning that the center rays of each ray bundle emanating from each field point of the scintillator must be parallel to the optical axis.

The ZLS used on Cygnus allows radiographic and imaging magnification to be optimized for different physics experiment object sizes. The ZLS accommodates a larger field of view than the previous lens system and can be zoomed with remote motor control to optimize field of view, scene contrast, and resolution for smaller objects. Camera focusing also is controlled remotely, positioning the camera with micron resolution. The ZLS is optically designed to focus with either blue or green light, which allows use of high-efficiency green scintillators that may perform better on certain experiments.

2. METHODOLOGY

For this study we examine radiographic signal brightness. Detection is accomplished with scintillators in the beam line and a camera viewing the scintillator through a lens and thin film pellicle mirror. The pellicle is used to deflect the scintillator image by 90° so that no direct x-rays hit the optical transport, lens, system or the CCD camera. The pellicle mount is designed to have no metal in the x-ray line of sight. Care is taken to minimize x-ray scatter that would produce stars in the CCD camera image. The rod-pinch diode of the Cygnus machine provides a bremsstrahlung point source for cone beam radiographic geometry.6 The x-ray beam is collimated to the object extent to reduce scatter background and starring in the radiograph. We record a series of open-beam, no-object, images to measure dose normalized7 signal levels associated with each scintillator tested. Components of a radiographic model8 are illustrated in Fig. 2. Source x-rays are attenuated by the object, creating an x-ray shadowgraph in energy deposition in the scintillator. Visible scintillator light is relayed through the optical transport to the electronic camera to record the radiograph. Image processing is then applied to remove background, fixed pattern noise, and beam profile to produce a corrected image.

X-ray energy absorbed in the scintillator is modeled on the rod-pinch diode flux and radiographic geometry. The absorbed scintillator dose produces the visible photon emission to be measured. The Cygnus optical lens system numerical aperture collects a fractional amount of the scintillator emission and relays the scintillator image to the...
recording camera. The lens system blue wavelength light transmission has been measured and applied in the model; spectral transmission curves over the visible range for the anti-reflective coatings have been measured. The camera photon transfer curve is calibrated in laboratory tests to characterize the camera gain factor K (e~/count). Photon sensitivity (counts per Joule/cm²) is calibrated radiometrically. A measure of detective quantum efficiency (DQE) of the system can be calculated based on observed SNR and modeled x-ray photons incident on the scintillator per resolution element.

To better understand system throughput any given combination of input spectra, window filtration, object, and detector can be characterized with a single mono-energetic equivalent energy number (effective energy). that is, the single energy, based on tabulated absorption cross section values of the object under study, required to produce the observed total attenuation. Total scintillator attenuation or energy absorption is comprised of photoelectric absorption, Compton scattering, and pair production. Each of the interactions contributes to the scintillator photon emission. For typical configurations, using these input spectra, this effective energy is found to range from 50 to 800 keV. The two examples presented in Fig. 3 have effective energies of 130 keV for 0.15 mm CsI:Tl, and 395 keV for 10 mm LYSO:Ce. These spectra represent an empty field, or very low test object mass response. As the beam is further filtered, or hardened, by a dense object, this effective energy number will increase. Conversely, if the amount of window filtration is reduced, the equivalent energy is further decreased. Exploiting this fact, one can, using detector geometry, effectively tune the performance and contrast for a wide range of experimental requirements.

Fig. 3. Normalized photon spectrum from rod-pinched diode source. The graph shows system input spectra through vessel nose cone attenuation and spectra absorbed in the thinnest CsI:Tl sample and the thickest LYSO:Ce scintillator sample.

The solid line in Fig. 3 shows a peak normalized input photon spectra, propagated through 50 mm of Al, to simulate the vessel x-ray windows shown in Fig. 4. Also shown in Fig. 3 are the absorbed photon spectra for two of the scintillators considered in this paper. These spectra have been normalized by the peak intensity of the input spectra. The two examples, 10 mm thick LYSO:Ce and 0.15 mm thick CsI:Tl, represent the extremes in range of thickness and areal density considered. Differences in spectral content of these two absorptions are striking.
3. SYSTEM MODEL

The Cygnus bremsstrahlung spectra used for these calculations is derived from a result presented by T. Kwan et al. Kwan’s source model utilizes pulse power parameters and diode geometry, a 2-D particle-in-cell code model (Merlin), and an electron-photon Monte Carlo code to produce a simulated source spectra. These spectra are then re-binned to roughly 100 energy bins, filtered by experimental window geometries, and the peaks normalized.

Monte Carlo particle transport codes are used to model the energy spectra transmission through the systems. We have a construct being configured in MCNP6, but results are pending at the time of this publication. To facilitate this scintillator discussion, we model system performance as described below.

Results presented here use a polychromatic spectral transmission model based upon NIST-tabulated XCOM x-ray cross section tables. The input spectra, in photon units, are propagated through an experimental configuration. These said spectra are attenuated as a function of energy using the total attenuation coefficient. This procedure is repeated for the series of components defined by the experimental geometry presented in Figs. 2 and 4. The resulting spectra are then absorbed in the scintillator based on absorption models derived from the energy absorption cross section tables, also contained in the above reference. Absorbed scintillator energy is calculated by the summed product of the absorbed photon spectra times the given energy bin. Object transmission values are defined as the ratio of scintillator energy absorbed by a target plus window attenuated beam to that of a beam attenuated only by window filtration. Observed scintillator brightness is assumed to be linearly proportional to energy fluence absorbed in the material for these energy ranges.

The optical portion of this detection system is a key component for detection efficiency and image quality. Maximizing optical photon collection, while minimizing system blur through a volume emitter, is of great concern in this system design. The telecentric performance of the ZLS, mentioned earlier in this paper, provides substantial improvement over previous designs that had limitations in wavelength and image size.
Table 1 indicates some of the scintillator and camera key parameters. The scintillator efficiency is shown in thousands of photons per MeV energy absorbed. Only a fractional amount of the scintillator emission is collected by the optical system.\textsuperscript{14} Interest in the micro-columnar CsI:Tl stems partly from this concern. In principle, the light-guiding structure of this scintillator will spatially contain the brightness through the volume of the scintillators, effectively presenting a volume-deposited x-ray image on the surface of the scintillator, and thereby mitigating depth of field concerns. In practice, over the 600-micron thickness currently available in this material, depth of field of the optical system is not a system resolution limitation. However, for the thickest monolith 10 mm LYSO:Ce, depth of field is a significant concern.

<table>
<thead>
<tr>
<th>Description</th>
<th>LYSO:Ce</th>
<th>CsI:Tl</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho$</td>
<td>7.4 g/cc</td>
<td>4.5 g/cc</td>
</tr>
<tr>
<td>$n_{\text{Scint}}$</td>
<td>1.81</td>
<td>1.74</td>
</tr>
<tr>
<td>Light output, photons per MeV\textsuperscript{15}</td>
<td>32,000</td>
<td>56,000</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>$420 \times 10^{-9}$ m</td>
<td>$550 \times 10^{-9}$ m</td>
</tr>
<tr>
<td>$K_{\text{CCD-C1-Cam106}}$</td>
<td>$2.12$ e$^{-}$/cnt</td>
<td>$2.12$ e$^{-}$/cnt</td>
</tr>
<tr>
<td>$K_{\text{CCD-C1-Cam192}}$</td>
<td>$1.79$ e$^{-}$/cnt</td>
<td>$1.79$ e$^{-}$/cnt</td>
</tr>
</tbody>
</table>

4. Results

For the purposes of this paper, modeling of the optical system is not considered, as all measurements presented utilize the same ZLS configuration. Measured signals, in units of counts, are converted to camera electrons, using measured knowledge of the sensitivity ($K_{\text{CCD}}$ Table 1)\textsuperscript{9} of each of two different cameras used in this study.

The graph in Fig. 5 is a plot of calculated energy absorption of the scintillators measured vs thickness. For this calculation, the energy spectra are defined by window material only, with no object present. These numbers represent the scaled, energy multiplied, summation of the two absorption spectra shown in Fig. 2. Consistent with Fig. 2, the CsI:Tl screens absorb much less energy than the thicker, denser LYSO:Ce. When plotted against thickness, the energy absorption lines do not intersect as the two different materials have substantially different densities.

It is striking that the CsI:Tl screen absorption is approaching a decade lower than the LYSO:Ce samples, but the detected signal of the CsI:Tl is slightly higher than that of the LYSO:Ce. The graph in Fig. 6 plots camera signal vs scintillator thickness. Two different imaging systems are used to record the series of scintillators. The 5 mm LYSO:Ce is the standard detector for the systems and is recorded on both systems. The other samples are only recorded on one of the systems. The two cameras have slightly different sensitivities (digital counts/photon), which resulted in a level shift when comparing signals in counts. We apply the camera gain $K$ (electrons per count) to the image digital count level to present signal levels in electrons. In these units, the sensitivity of the two systems agree to better than 10%.
Fig. 5. Calculated energy absorption of scintillators used; energy absorption increases proportion to areal density (g/cm²) of the scintillator detector.

Fig. 6. Plot of measured camera signal electrons detected versus scintillator thickness. Monolithic LYSO in blue, micro-columnar CsI:Tl in green. The 0.6 mm CsI:Tl appears as bright as the 10 mm LYSO:Ce.
The graph in Fig. 7 plots camera signal electrons per energy absorbed vs scintillator thickness. This measure of scintillator efficiency highlights the brightness of the CsI:Tl over the LYSO:Ce. Based on general scintillator efficiency, photons/MeV absorbed, predicts that signal per absorbed energy will be, to first order, a constant ratio independent of the scintillators thickness. Based on these results, this prediction clearly does not fit the results of the thin CsI:Tl samples.

The various micro-columnar CsI:Tl samples are from different manufacturer runs, but the brightness increase with thickness is dramatic on a log scale. The signals from the micro-columnar CsI:Tl are much brighter that predicted. We speculate that there may be some form of small aperture collimation of light emitted from the crystal fiber filaments, resulting in increased lens coupling efficiency over and above that of a lambertian emitter. Individual fibers are sub 10 microns in diameter. It is also interesting to note that at 140-micron thickness, the CsI scales nearly as expected, viz. the LYSO, using the quoted photon/MeV numbers presented in Table 2. That is, the 140-micron sample mimics performance of monolithic crystals. Further studies of angular emittance of these samples are planned. Table 2 list the scintillators tested with energy deposited, observed system signal and noise characteristics along with the system sensitivity to energy absorbed.
<table>
<thead>
<tr>
<th>Camera</th>
<th>Experiment</th>
<th>Scintillator Thickness (mm)</th>
<th>Observed Mean Signal (e⁻)</th>
<th>Energy Deposited (MeV/cm²)</th>
<th>Sensitivity e⁻/(MeV/pixel)</th>
<th>Photons Incident on Scintillator per Pixel</th>
<th>Observed SNR</th>
</tr>
</thead>
<tbody>
<tr>
<td>LYSO:Ce</td>
<td>C1-Cam166</td>
<td>2399</td>
<td>14208</td>
<td>1.35E+08</td>
<td>3.9</td>
<td>228095</td>
<td>65.1</td>
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<tr>
<td></td>
<td>C1-Cam166</td>
<td>2389</td>
<td>22218</td>
<td>1.87E+08</td>
<td>4.4</td>
<td>228095</td>
<td>97.3</td>
</tr>
<tr>
<td></td>
<td>C2-Cam192</td>
<td>2390</td>
<td>23854</td>
<td>1.87E+08</td>
<td>4.7</td>
<td>228095</td>
<td>96.3</td>
</tr>
<tr>
<td></td>
<td>C2-Cam192</td>
<td>2400</td>
<td>31997</td>
<td>2.77E+08</td>
<td>4.3</td>
<td>228095</td>
<td>124.4</td>
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<tr>
<td>µCol CsI:Tl</td>
<td>C1-Cam166</td>
<td>2431</td>
<td>2411</td>
<td>9.21E+06</td>
<td>9.7</td>
<td>228095</td>
<td>27.4</td>
</tr>
<tr>
<td></td>
<td>C1-Cam166</td>
<td>2419</td>
<td>15328</td>
<td>1.33E+07</td>
<td>42.8</td>
<td>228095</td>
<td>36.2</td>
</tr>
<tr>
<td></td>
<td>C2-Cam192</td>
<td>2410</td>
<td>33890</td>
<td>1.33E+07</td>
<td>94.6</td>
<td>228095</td>
<td>100.4</td>
</tr>
</tbody>
</table>

SNR levels are used to compare scintillator brightness and image clarity. SNR is measured after removal of fixed pattern noise. The high quality of the monolithic LYSO:Ce crystals with very few visible inclusions results in very good SNR readings. The thicker LYSO:Ce sample generates a bright signal level for the camera and with an SNR level that clearly outperform the micro-columnar CsI:Tl in this area. The structure of the CsI:Tl limits the clarity of the CsI:Tl images resulting in a generally lower SNR. The brightness of the 0.6 mm CsI:Tl outshines even the thickest, 10 mm, LYSO:Ce tested. This brightness allows the SNR to outperform the 5 mm LYSO:Ce, but is not as good as the 10 mm sample.

5. CONCLUSION

The scintillator efficiency discussed here is for open beam imaging with no test object in place. The simulations include x-ray beam filtering and spectral hardening from the vessel nose cones (Fig. 4). The nose cones are part of the system and are typically included in radiographs. The radiographic object introduced into the system will further harden and attenuate the beam energy. A new simulation is needed to account for the additional material.

Micro-columnar CsI:Tl brightness appears to increase dramatically with thickness. There are process limitations to producing thicker micro-columnar CsI:Tl than the 0.6 mm sample tested. It would be very interesting to discover how a 1 mm sample performs in regard to this trend. The brightness efficiency of the micro-columnar CsI:Tl strongly outgains the LYSO:Ce. Camera signal per energy absorbed shows unexpected results. We can hypothesize that the thinnest CsI:Tl, 0.15 mm, will absorb very little of the higher energy in the beam. As the thickness increases a few hundred microns, higher energies begin to contribute a larger percentage of energy absorption, thereby increasing photon generation.

There is concern that thicker micro-columnar screens will introduce significant blur due to channel crosstalk due to x-ray trajectories through the screen. One basic difference in the two scintillators is that the CsI:Tl optical focus plane is the output surface, while the monolithic LYSO:Ce crystal’s optical focal plan is within the volume of the LYSO. We will be investigating detector blur associated with these scintillator samples. Further efforts will combine detector blur and brightness information. These two detector characteristics, brightness and resolution, will be key parameters in determining requirements for future system designs to understand limiting requirements for optical transports and recording cameras.
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