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Dynamic Radiographic Imaging

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ABSTRACT

A radiographic system recently developed by American and Russian collaborators is designed to capture multiple images of a dynamic event lasting less than 10 microseconds. Various optical and electro-optical components were considered and their performance compared. The final system employed a solid crystal of lutetium oxyorthosilicate doped with cerium (LSO:Ce or LSO) for X-ray-to-light conversion with a coherent fiber optic bundle to relay the scintillator image to a streak camera with charge coupled device (CCD) readout. Resolution and sensitivity studies were carried out for this system on two different sources of X-rays: a 20 MeV microtron and a 70 MeV betatron.

1.0 INTRODUCTION

A radiographic system capable of resolving the time evolution of an explosive-driven implosion of a tungsten cylinder has recently been developed by American and Russian collaborators[1]. The system consists of a pulsed X-ray source, a radiation-to-light converter (scintillator crystal) in the X-ray beam, an electronic optical camera to record the scintillator signal, and optics to carry the light from the scintillator to the camera (Figure 1).

Two radiographic Bremsstrahlung sources, a 20 MeV microtron at Los Alamos National Laboratory (LANL) and a 70 MeV betatron at the Russian Federal Nuclear Center[2], were used for these experiments. Preliminary system evaluations were conducted using the LANL microtron, while final systems evaluation and actual radiography of explosive events were conducted using the Russian betatron.

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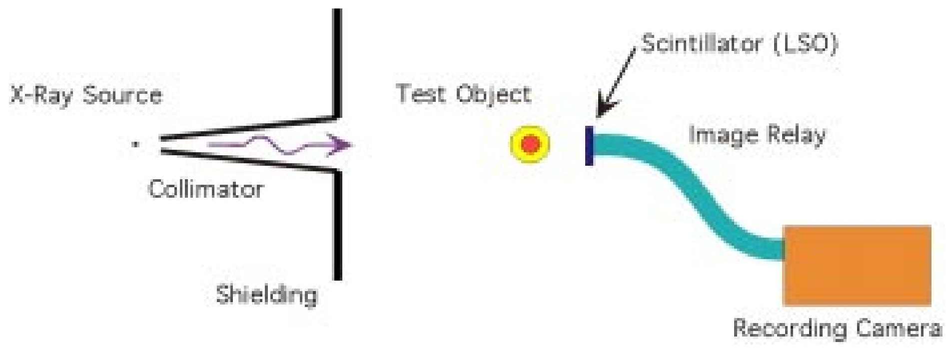

Figure 1. Simple Radiographic System

A key development in this study was the use of a coherent fiber-optic bundle rather than a conventional lens and mirror system to relay the scintillator image to the camera photocathode. Results of laboratory and actual explosive-driven experiments are summarized in this report.

Optical images of radiographed objects were created using the radiation-to-light converter LSO. Several thicknesses of LSO were investigated to determine the effect of thickness on system resolution and sensitivity. The primary recording system was a Bechtel Nevada (BN) streak camera designed around a blue-sensitive electro-optic streak tube with a measured peak quantum efficiency of approximately 18% at 390 nm. We imaged a 10 x 40 mm region of the scintillator onto the photocathode without a camera slit. For multi-pulse betatron experiments, the resulting image of the scintillator appeared much like a frame on a framing camera, each 100-ns-wide betatron pulse freezing the image in time on a 10 µs sweep. This sweep speed, combined with appropriate masking of the scintillator, prevented overwriting of the adjacent pulses for the 1.5 µs pulse interval required for the experiment. The readout system for the streak camera was an intensified, cooled, Photometrics 300 series 1024 x 1024 CCD camera. The performance of a BN framing camera, designed around a fiber-optic-coupled, blue-sensitive electro-optic image tube with a peak quantum efficiency of approximately 10% at 440 nm was also investigated.

2.0 SYSTEM EVALUATION

2.1 Microtron Specifications

For this evaluation, a lens and mirror relay system was assembled at the microtron. Streak camera images of different thicknesses of LSO crystals were recorded. The bulk optical system was then replaced with a coherent fiber-optic bundle to compare optical performance between the two image relay systems. The optical relay system and fiber-optic bundle are described in the Bechtel Nevada Memorandum "A Comparison of Optical Systems for the Argon Compression Experiment"[3].

The microtron is a 20-MeV pulsed electron source operated with a pulse repetition rate of 60 Hz and an individual macro pulse width on the order of 4 µs. The electron beam is converted to a Bremsstrahlung source in a 1-mm-thick sheet of tungsten. The nominal beam size is reported to be 0.729 mm in diameter, and the experimental geometry was selected to produce a source blur no greater than 150 μm at the scintillator.

2.2 Experiment 1 – Lens vs. Fiber Coupling Efficiency (week of April 20, 1998)

Lens Coupling. The key components of the optical relay system were two single-element quartz lenses, shown in Figure 2 as L1 and L2. The light was collimated between them. Four mirrors in a periscope configuration directed the light to the camera out of the radiation beam. The working f/number of the system was slower than f/2, and the magnification was 0.35. Ideal collection efficiency between the Lambertian-emitting scintillator and the camera photocathode was calculated to be 0.4 %.

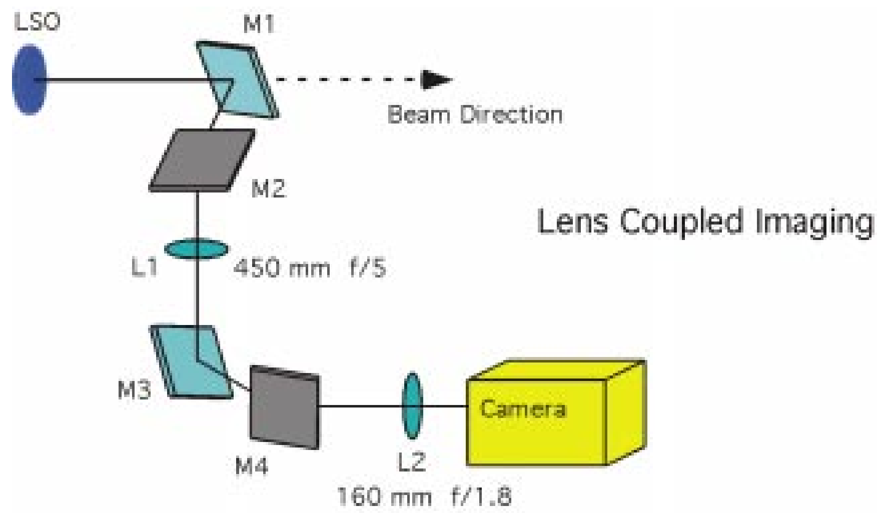

Figure 2. Lens Diagram

Fiber Coupling. The collection efficiency for a high numerical aperture (NA) coherent fiber-optic bundle was expected to be significantly higher than that of the lens system. To test this hypothesis, a 900-mm long x 18 mm x 18 mm, square-faced coherent bundle made of Schott[4] standard material (NA = 0.6) was selected. This bundle was fabricated using 10 μm fibers, and its resolution is advertised to be 50 lp/mm.

Light from a tungsten lamp was passed through an optical bandpass filter (425 nm x 70 nm) and an opal glass diffuser. Light from the surface of the diffuser was directly coupled into the bundle. This configuration simulated emission, both in color and angle, from an LSO sample. Using this laboratory configuration, the bundle collection and transmission efficiency was measured to be 14%, a 35-fold improvement over the calculated performance of the lens system.

2.3 Results of Microtron Experiment 1

2.3.1 Conventional Lens and Mirror System

The lens relay system described above was used to collect images produced by one of four different LSO crystalline disks, polished on both faces. Sample thicknesses were 0.79 mm, 3 mm, 5 mm, and 10 mm. Each sample was approximately 45 mm in diameter. To limit the streak camera time response, the scintillator was mounted in a fixture that allowed X-ray-generated light to be emitted only from a slit region 3 mm wide by 40 mm long. A background image was generated in the readout camera from scattered radiation with the X-ray beam on and the camera gated on, with a mask over the photocathode to block optical signal. This background was subtracted from each signal image. Signal levels were then measured using a 200-pixel-wide window to calculate the average signal level produced for each LSO thickness. The relative signal levels are shown as the dashed line in Figure 3. The signal from the 0.79 mm sample was too low to record measurable data with lens coupling. For lens and fiber optic coupling, the dependence of scintillator light generated vs. scintillator thickness is linear. This result indicates minimal “self-absorption” of light emitted by LSO. Depth of focus effects in samples up to 1 cm thick were smaller than the system resolution.

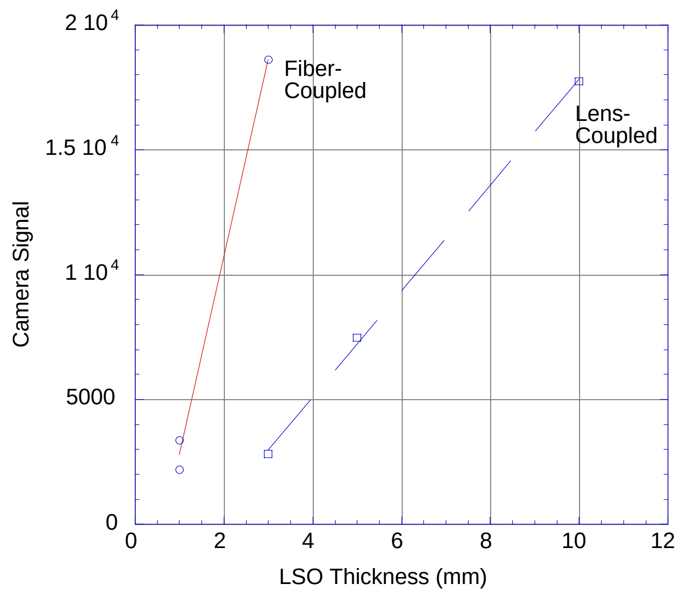

Figure 3. Signal vs. LSO:Ce Thickness

2.3.2 Fiber-Optic Coherent Bundle System

Similar experiments were performed using a coherent bundle in place of the conventional lens and mirror system. In this configuration, the 0.79-mm LSO sample produced measurable signal levels at an image intensifier gain 23-fold lower than that used with the lens system. Processed signals from 0.79-mm and 3-mm thick samples are shown in Figure 3. Thicker samples were not studied because their output saturated the camera. The same image processing was performed as had been for the lens system. In the fiber bundle coupling it was impossible to mask the scintillator without a loss of resolution. The fiber optic bundle coupling has magnification M = 1 from the scintillator to the camera and records a 18-mm-wide square region of the scintillator. The lens system, with magnification M = 0.35, sampled a region 3 mm by 40 mm.

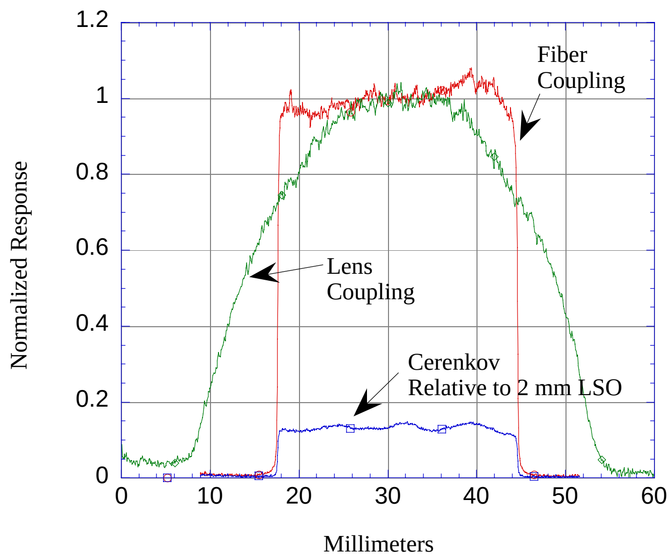

Figure 4. 2-mm LSO scaled to fiber coupling signal

In addition to average collection efficiency, the flat field response is an important indicator of optical performance. Flat field response is used to describe the uniformity of the optical system across the entire field of view (FOV). Variations in response with position across the field are very difficult to correct properly. Figure 4 shows the relative flat field response of fiber coupling and lens coupling systems normalized to the center of the field of view. The bundle signal is very flat, while there is significant “roll-off” in the lens coupling system. As mentioned earlier the field of view with the two optical systems is slightly different. The sharp variations in the fiber bundle flat field profile are caused by light scattering from defects in the LSO crystal. These defects are not resolvable by the lens system.

2.3.3 Lens System vs. Fiber System

Data from the 3-mm-thick LSO samples were recorded with both image relay systems. Experimental results and data analysis are described in the Bechtel Nevada memoradum "Radiographic Imaging Sensitivity—Argon Compression Lens vs. Fiber Coupling."[5] For the lens coupled images with a 3-mm-wide FOV on the scintillator, total signal was measured to be 3.67×10^6 counts. For the fiber bundle coupling, which had an 18-mm FOV, a 3-mm portion of the signal was extracted. The fiber bundle signal was 2.89×10^6 counts with a microchannel plate (MCP) gain factor of 23 less. The lens coupled magnification factor of 0.35 compresses the spatial energy density from the scintillator viewed per pixel. The relative efficiency between the fiber and lens systems is measured as:

$$(2.89 \times 10^6 \times 23) : (3.67 \times 10^6 \times 0.35) = 18 : 1 \text{ (Fiber : Lens)}$$

This result is close to best case predictions from the laboratory simulation and calculations. With the fiber bundle collection and transmission measured to be 14% at 425 nm, and lens efficiency estimated to be 0.4 %, the ratio predicted was 14 : 0.4 = 35:1.

2.4 Microtron Experiment 2 – Fiber Bundle Resolution (week of May 25, 1998)

The results of the first microtron experiment with the fiber optic bundle indicated a substantial improvement, both in ease of installation and optical collection efficiency. However, characterization of the spatial resolution of this radiographic system remained to be determined. The principal objective of the second microtron experiment was to determine the optimum radiographic resolution of selected scintillator/camera systems using a coherent bundle for image relay.

The microtron was operated as it had been in the earlier experiment. The system resolution was determined by varying the scintillator thickness and evaluating images of a 35-mm-thick tantalum resolution target. The resolution target was assembled using sheets of tantalum, spaced by air, and assembled in groupings with element thicknesses of 2 mm, 1 mm, 0.5 mm and 0.25 mm. Four tantalum sheets and four equally thick spaces comprised the elements of each grouping. (See Figure 5.)

The target, scintillator, and source were spaced so as to produce a source blur[6] of less than 150 microns. The Schott 1220-mm long x 18 mm x 18 mm square-faced coherent bundle was directly coupled to the scintillator and the input photocathode of a BN streak or framing camera. The cameras were triggered to capture one or more microtron pulses. The same four scintillator thicknesses were evaluated.

2.4.1 Results of Experiment 2

For the streak camera, an image of the resolution target was captured for each scintillator thickness using the fiber optic bundle. The camera operated in the focus mode to simplify alignment requirements. Image resolution improved incrementally as the scintillator thickness was reduced. With scintillator thicknesses of 0.79 mm and 2 mm, the 0.25 mm group in the

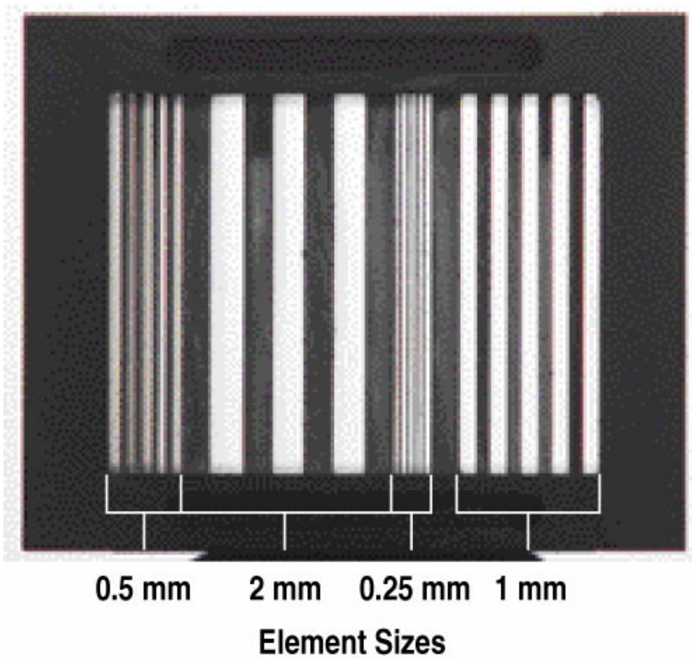

Figure 5. Target

resolution block was easily resolved (Figure 6). This is a significant improvement over previous lens-coupled experiments, which required a 10-mm-thick scintillator to obtain sufficient signal. With lens coupling, 0.5 mm resolution block elements were nearly unresolvable. With fiber coupling, modulation in the 0.5 mm group was resolved at 60 % with the 0.79 mm scintillator. This modulation dropped to 17 % with 5 mm LSO. The Cerenkov signal in the coherent bundle was approximately 25% of the signal produced in the 0.79-mm-thick LSO scintillator. No optical filtering of the scintillator signal was attempted. However, 100-µm-thick bandpass filters have been acquired and should be tested to evaluate the effect on system contrast and resolution. Next, a 2:1 (40:20 mm) fiber reducer was placed between the scintillator and the bundle to increase the field of view. Using the reducer and the 2-mm-thick LSO sample, signal level remained significant and the 0.25-mm group was resolved.

Using the same bundle system and reducer, images were collected using the BN four-image framing camera with an unintensified CCD readout system. Without MCP intensification, sensitivity was significantly less than for the streak system. The framing system was at least a factor of 60 times less sensitive. Also, image quality appeared to be reduced relative to the streak system. Microtron run time was limited and the evaluation was discontinued.

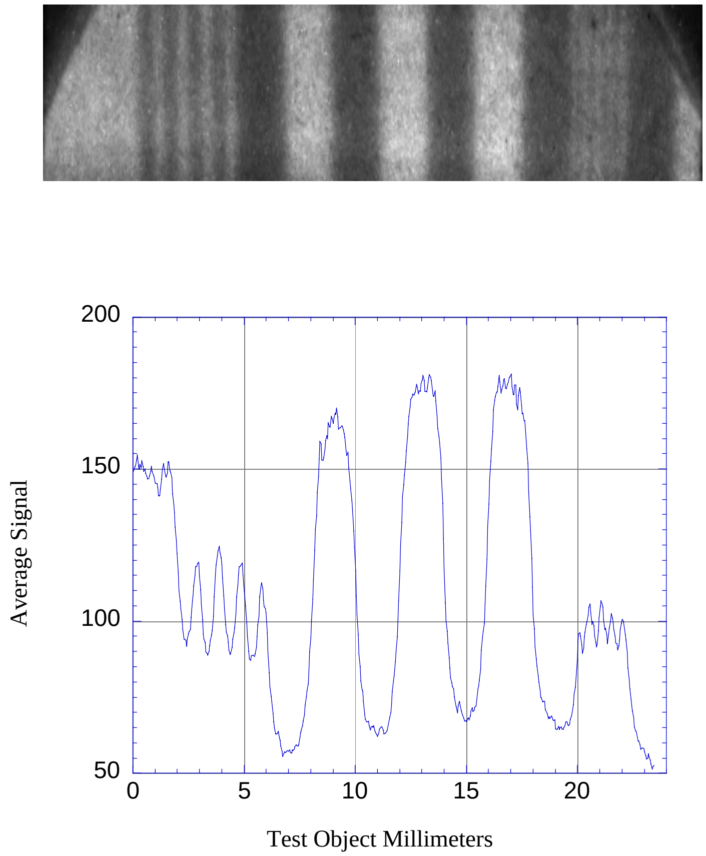

Figure 6. Image with Profile of Resolution Pattern (Image 2 mm LSO, 2 lp/mm)

2.4.2 Conclusion from Microtron Experiments

The improvements in collection efficiency and sensitivity due to fiber coupling and the new CCD readout camera suggest a potential gain of 50 over the bulk optics system used in November 1997 in Russia. Also, limited Cerenkov light generated in the coherent fiber optic bundle by the 20 MeV radiation reduces concerns about using this configuration. Ease of installation, a large collection efficiency increase, improved system resolution, and flatness of field made the fiber optic system more attractive than the lens system for dynamic radiography experiments. The BN framing camera sensitivity is 2% of that of the streak camera and was not sensitive enough for this application, as appealing at it would be to "frame" rather than "streak" the radiographic images.

2.5 Betatron Experiments

2.5.1 Betatron Specifications

The Russian betatron has an ironless core magnet which allows fast, flexible extraction of the beam. The X-ray pulse has a width of 100 to 200 ns. Up to three output pulses can be produced at an interval of 600 ns or longer. The fraction of the beam amplitude in each of the pulses can be adjusted to compensate for any changes in attenuation as the radiographic object implodes and its density changes. The electron energy is 70 MeV, the average current is 45 A, and the focal spot size of the beam is roughly 1 x 2 mm. Conversion of the electron beam to Bremsstrahlung radiation is in a 2-mm-thick tungsten target. For dynamic experiments, the camera system is protected in a tightly packed steel enclosure. (See Figure 7.)

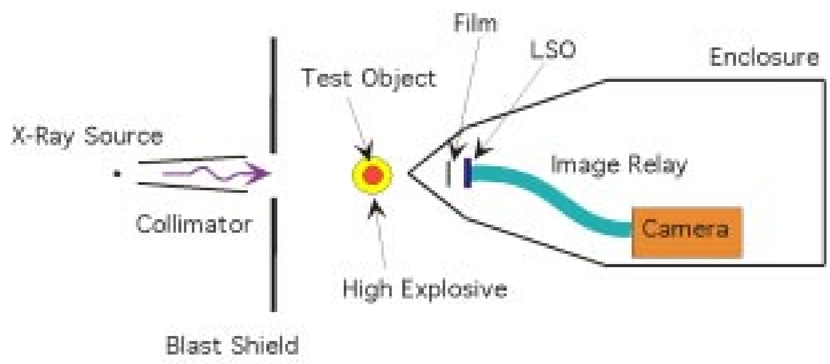

Figure 7. Betatron Experiment System

2.5.2 Camera Comparisons

The same two camera systems were fielded in a series of August 1998 experiments using the Russian betatron. The framing camera was used without MCP intensification, and readout was accomplished using the Photometrics 300 series 1024 x 1024 cooled CCD. It employed a framing tube with a blue-sensitive photocathode and a fiber-optic faceplate that was directly coupled to a 1220-mm long x 18 mm x 18 mm coherent bundle. The streak camera was fielded with a Varo MCP II and used the same Photometrics CCD camera readout. The streak tube had a blue-peaked photocathode with a fiber-optic faceplate. It was directly coupled to a 1220-mm long x 5 mm x 30 mm coherent bundle. As previously mentioned, the sensitivity of the framing camera system was significantly less than the streak camera system. This is attributable to five factors:

1) The sensitivity of the framing camera photocathode in the spectral region of LSO:Ce emission is 2.0 times less than the sensitivity of the streak camera photocathode. This is determined by integrating the QE area under the LSO curve. (See Figure 8.)
2) The framing tube has three mesh gating grids which reduce its optical gain.
3) Framing tube magnification is 1.7 as compared to 0.85 of the streak tube, reducing photo-electron density and phosphor brightness.
4) The readout for the streak camera has a MCP intensification which adds gain to the system.
5) Due to environmental conditions, the readout camera used during the experiment with the framing camera was only cooled to –15^{o}C, whereas

the readout camera on the streak system was cooled to –35°C, which resulted in a lower noise floor and more effective bits of signal.

Nonetheless, the results of the framing camera test were encouraging for future use. With the introduction of a proximity focused diode in front of the framing camera, we would increase system sensitivity. A diode intensifier in front of a framing camera requires a fast blue phosphor. The effective gain of the diode is reduced due to blue transmission through the fiber bundle. With the use of a shorter coherent bundle, we might realistically see an increase in framing camera sensitivity of 10 to 20 times for this application.

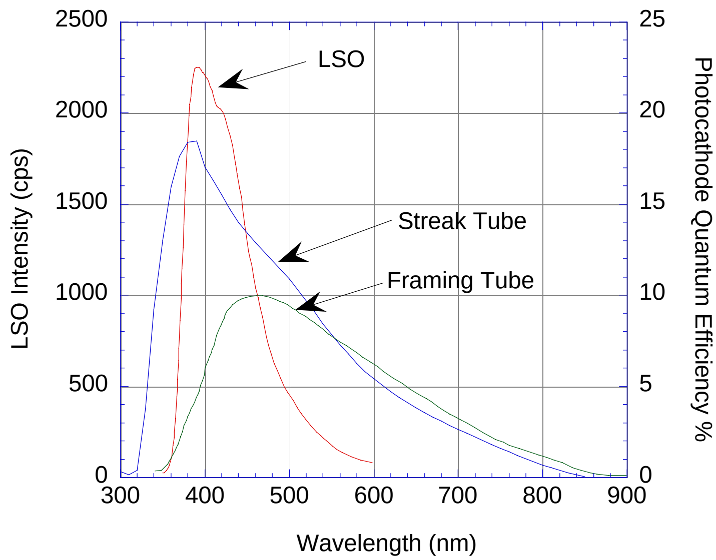

Figure 8. Spectral Emission of LSO with Image Tube Sensitivity
(LSO courtesy of Terry Boan, BN/STL)

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