Large Format Radiographic Imaging

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ABSTRACT

Radiographic imaging continues to be a key diagnostic in many areas at Los Alamos National Laboratory. Radiographic recording systems have taken on many forms, from high repetition-rate, gated systems to film recording and storage phosphors. Some systems are designed for synchronization to an accelerator while others may be single shot or may record a frame sequence in a dynamic radiographic experiment. While film recording remains a reliable standby in the radiographic community, there is growing interest in investigating electronic recording for many applications. The advantages of real time access to remote data acquisition are highly attractive. Cooled charge-coupled (CCD) camera systems are capable of providing greater sensitivity with improved signal-to-noise ratio. This paper begins with a review of performance characteristics of the Bechtel Nevada large format imaging system, a gated system capable of viewing scintillators up to 300 mm in diameter. We then examine configuration alternatives in lens coupled and fiber optically coupled electro-optical recording systems. Areas of investigation include tradeoffs between fiber optic and lens coupling, methods of image magnification, and spectral matching from scintillator to CCD camera. Key performance features discussed include field of view, resolution, sensitivity, dynamic range, and system noise characteristics.

Keywords: radiography, imaging, electro-optics, CCD camera, scintillator, image intensifier.

1. INTRODUCTION

A radiographic imaging system consists of a radiation source, a radiation-to-light converter and a camera system or detector. We are investigating ways to optimize radiographic image recording. With today's high resolution image tubes and large charge coupled device (CCD) arrays, it is possible to configure a camera system with tens of line pairs per millimeter (lp/mm), resolution. In this application, system performance is restricted by the radiation source and scintillator combination. High resolution imaging systems typically have a small field of view but are useful in evaluating the radiation source/scintillator combination. A high-resolution detector may be used to evaluate various scintillators with a given radiation source to determine the best system configuration. Many experiments require a large field of view while maintaining the highest possible resolution with good sensitivity. In some instances a resolution requirement may restrict the overall field of view. Other experiments may require maximizing sensitivity at the expense of resolution. Bechtel Nevada (BN), in collaboration with Los Alamos National Laboratory (LANL), has developed a set of radiographic imaging systems. One system under development is the large format imaging (LFI) system. This system is capable of viewing scintillators up to 300 mm in diameter and has variable gate width and gain. Other systems couple electro-optical components to record a scintillator image. We will review the LFI system then examine performance tradeoffs in various electro-optical component configurations.

2. LARGE FORMAT IMAGING SYSTEM

This is a brief review of a system proposed in the paper, "Large Format Imaging System."¹ This system was designed to record large field of view radiographic images with an accelerator neutron, gamma ray, or X-ray source. The system is currently configured to integrate long exposures of stationary objects. It is housed in a light tight enclosure which contains a scintillator screen excited by a radiographic object illuminated by a radiation beam (figure 1). The scintillator, provided by Scott Watson from LANL, was a 300-mm diameter, 10-mm thick NaI fluor with a reflective covering upstream, which was mounted on the side panel of the light tight enclosure. Scintillator images are viewed through a Spindler and Hoyer 146-mm

f/0.9 lens with a mirror to keep the lens and camera out of the radiation path. The Spindler and Hoyer lens operates at a fixed conjugate with magnification $M = 0.25$, which reduces the 300-mm fluor image to 75 mm. This image is further reduced by the first electro-optical component, the 80:40 electrostatic minifier. This minifier tube from Photek² has variable magnification, an S-20 photocathode, and a P-43 phosphor screen. The magnification factor in our application was preset to two selectable settings, 0.25 and 0.44. During normal operation, the entire fluor area is visible at the $M = 0.25$ setting. This produces a 19-mm sized image on the output of the 80:40 minifier. This image size is enlarged with a 20 mm to 40 mm fiber optic taper. The taper output couples to a 40 mm micro-channel plate image intensifier (MCP II) tube. The fiber taper expands the image size so that the system resolution is not limited by the MCP II. The MCP II image is then readout with a 1024 x 1024, fiber-coupled, cooled CCD camera. Except for the Spindler and Hoyer lens, all of the components are fiber optically butt-coupled. The image tubes are mounted in fixtures that provide spring loaded coupling, to allow flush coupling of the fiber optic surfaces with no mechanical focusing between electro-optical components. The spring loaded coupling supports the individual components in place on an optical rail system while allowing a few millimeters of flotation in the optical axis. The flotation allows the multiple large diameter fiber face plates to make a flush coupling. Any tilt in the coupling surfaces will result in severe loss of resolution and sensitivity.

Figure 1. Large format imaging system. Beam path is off of the page.

2.1. Remote Control

The active components of this system are remote controlled. The minifier controller can be set for gated or DC operation; the gate width control has five ranges with continuous variable adjustment on each. The MCP II controller has adjustable gain and gate width and may be operated in gated or DC mode. The CCD camera readout is computer controlled, and exposure time, full or partial frame readout, and externally triggered exposure are among the settings available. The component triggering sequence is configured in the external control room and cabled into the camera system. The component remote control allows the detector system to be positioned in a radiation environment while the control modules, image acquisition computer and system operators are located at a safe distance.

2.2. System Setup

The 80:40 minifier tube is gated with an adjustable gate width ranging from 50 nanoseconds (ns) to 5 milliseconds (ms) and is triggerable up to a 100-kHz repetition rate. The primary shuttering is done with the 80:40 minifier to minimize background noise level. The trigger rate on the minifier may be synchronized to an accelerator pulse. This allows the CCD camera to integrate multiple scintillator exposures while minimizing the buildup of background noise. The MCP tube is gated for longer time periods to record the slow decay (~ 1.2 ms) of the P-43 phosphor on the minifier. The CCD camera integrates the exposure, then the gate triggers are inhibited while the CCD camera reads out. Exposure times may be as long as seconds or tens of seconds to register a good signal level from a low intensity image. The mirror, Spindler and Hoyer lens, and readout camera system are mounted on a rail system. The readout camera position on the rail is adjusted remotely to adjust

mechanical focus and sharpen the Spindler and Hoyer image. Initial focus position is set on the fluor surface nearest the lens using a back-lit target taped to the fluor. As radiographic images are viewed, the focus is adjusted to locate several planes inside the fluor material until the sharpest focus is achieved. The focus process is simplified using the larger 0.44 minifier magnification value during adjustment of mechanical focus. This technique makes it easier to distinguish small changes in image detail. Then the minifier is switched to the $M = 0.25$ setting get a full view of larger objects, or used in the $M = 0.44$ setting to examine finer detail. The minifier tube has variable magnification, however the operating voltages vary with magnification;¹ therefore, only two different magnifications have been preset.

2.3. System Performance

Sensitivity and resolution have been measured at different locations in the system. Using a film target applied to the minifier photocathode or the face of the fluor, the limiting resolution was measured for both magnification settings. System resolution was also measured at the object plane using a 6 MeV X-ray beam to radiograph a tantalum resolution target. Table 1 shows the resolution measurements, along with sensitivity measurements. The sensitivity measurements are referenced to the fluor output. They were recorded using a DC lamp with a 450 nm by 10 nm spectral filter positioned at the fluor plane. The last column gives the photons per resolution element at the dark current level. Numbers less than one indicate that the minimum detectable signal is photon statistic limited.

Table 1. Large Format Imaging System Performance

Magnification	Minifier Input (lp/mm)	Fluor Output (lp/mm)	Object Plane (lp/mm)	Sensitivity (J/cm ² /sr)	Photons/resolution element
$M = 0.25$	9	1.26	1	3.17×10^{-17}	0.044852
$M = 0.44$	16	4.0	2	8.05×10^{-18}	0.114752

The transfer curve in figure 2 illustrates the dynamic range of the LFI recording camera. The data was taken with a DC lamp illuminating the photocathode of the minifier with white light. Neutral density filters were used to attenuate the light level over the camera's detectable range. An energy meter with a radiometric filter was used to monitor the input light level. Gated images were taken of the DC light. A 330-microsecond minifier gate recorded the input energy shown in figure 2. Camera signal indicates average counts per pixel.

Figure 2. Large format imaging system dynamic range.

The dynamic range, shown in figure 2, was measured to be at least 5250 : 1 at a MCP II gain of 450 V. The CCD background had a standard deviation of 2 counts. The MCP II gain adjustment provides range of greater than 2000:1.

A sample radiographic image of a cylindrical test object viewed axially is shown in figure 3. This image was taken with the minifier in the $M = 0.25$ setting. The minifier had a gate width of 3 ms and was triggered at a 60-Hz repetition rate for one second. The MCP II was operated at a gain of 20 in DC mode. The image was background subtracted and flat field corrected. It is displayed in pseudo color to highlight the various rings in the test object.

Figure 3. LFI radiographic image. False color image of cylindrical test object.

2.4. Proposed Upgrades

Some radiographic experiments may require integration times of minutes or tens of minutes in order to build up the signal level from a dim fluor or low contrast image. In this case, replacing the MCP II with a diode intensifier would help in producing high-resolution, low-noise images. MCP II shot noise would become a problem with long exposures or high gain, reducing system dynamic range. The LFI system could be used to take several single snapshots in dynamic recording experiments. A more interesting approach would be to use an 80:40 minifier with a P-47 100-ns phosphor used in combination with a framing camera readout to record a series of X-ray snapshots. The best resolution may be from a pixelated scintillator. This would produce an image at the surface of the fluor and not within the volume. Thus, the lens depth of field would not produce image blur.

3. LARGE FORMAT IMAGING II SYSTEM

The large format imaging II (LFI II) system was specifically designed to record dynamic radiographic experiments. This imaging system was designed around a custom built lens with a 3.4 meter standoff distance. This lens was designed and built by Industrial Research³ of New Zealand. It has an effective focal length of 394 mm, a T/# of 0.9, and magnification of 0.24. The lens incorporates reflective optics, and is optimized for blue light. Curvature of the focal plane is corrected by positioning a fiber-optic taper with a curved input surface in the image plane. The output of the taper is coupled to a gated intensified CCD readout camera. The taper output is 38 mm in diameter and over fills a 1 inch square CCD area with 1:1 coupling. The readout camera is a proximity focused diode intensifier fiber optically coupled with spring loading to the CCD camera. The diode intensifier provides shuttering for the CCD camera; it has an S-20 photocathode and a P-43 phosphor. The readout camera is coupled to the lens using a gimble mount, which allows the camera head to pivot and obtain a flush coupling to the fiber optic output window.

A schematic of the LFI II system is shown below in figure 4. A radiographic image of the object under examination is generated on a fluor. The Kiwi Star lens views the fluor image through a mirror to keep the lens and recording camera out of

the radiation path. For this imaging system to be used in a dynamic radiographic experiment, a blast shield to protect the Kiwi Star lens and recording camera system would be necessary.

Figure 4. Large format imaging II system. The front of the lens is positioned 3.4 meters from the fluor.

3.1. System Performance

Sensitivity and resolution measurements were made using a strobe lamp with a blue, P-47 filter to illuminate either an aperture or resolution target at the fluor plane mounted on opal glass. The P-47 filter is used to match the spectral output of some of the fast scintillators typically used in dynamic radiography experiments. Scintillator types include lutetium oxyorthosilicate doped with cerium (LSO:Ce or LSO), and yttrium oxyorthosilicate. The resolution at the fluor plane was measured to be 4 lp/mm. Sensitivity measured has been referenced to the energy density at the lens input 3.4 meters from the fluor. For an energy density of 6.6 pJ/cm^2 at the lens input, 1.15×10^9 counts were measured.

3.2. Readout Options

A number of different readout options can be used with the Kiwi Star lens. With its fiber optic output window, the most efficient readout coupling is to a CCD camera with a fiber optic input window. Most fiber optically coupled CCD cameras require an external shutter. The shutter typically used is a fiber optically coupled image intensifier, which include MCP's and proximity focused diodes. Diode intensifiers have better resolution and lower shot noise than a MCP intensifier, and can improve system signal to noise ratio. It is easier to obtain shorter gate widths using MCP image intensifiers, which also can provide higher signal gain at the expense of increased noise. Gated intensified CCD cameras are light enough to mount directly to the Kiwi Star lens frame. A framing camera is too bulky to practically allow direct mechanical coupling to the fiber optic output, but this could be accomplished by employing a fiber optic bundle as an image relay system. The bundle coupling allows some flexibility in mechanical positioning while eliminating focusing requirements of lens coupling.

4. INTENSIFIED CAMERA COUPLING OPTIONS

Many permutations of recording systems have been evaluated in an effort to achieve high radiographic resolution along with high sensitivity. The trade-off between signal level and resolution has been studied in thin scintillators.⁴ Interest in systems with high resolution, high sensitivity, low noise and wide dynamic range prompted this study.

4.1. Gain Study

Signal levels and resolution were compared for various combinations of electronic and electro-optic components, using an Optoliner strobe with a 420 nm bandpass filter. A 1:1 lens system was used to project the image of a 2-mm diameter aperture for sensitivity studies and a resolution target. Figure 5 illustrates the system configurations tested.

The first system studied was a shuttered CCD camera. The CCD camera used had a fiber optic input window, and was digitized to 16 bits and cooled to -39°C . Relative signal levels of the various configurations are compared relative to the detected CCD camera signal. All of the electro-optic components used were fiber optically coupled.

A 40-mm MCP II with an S-20 photocathode and a P-43 phosphor was then introduced as a gain stage, and the signal was measured. (Figure 6 shows the gain as a function of MCP voltage.) Additional components were then added in front of the MCP II. The relative gains, or losses, of these components were compared with the MCP II set at a gain voltage of 450 V. The introduction of a 40:20-mm coherent fiber optic taper resulted in a reduction of the measured signal level to approximately 51% of signal and changed the area of the image, affecting the energy density on the CCD. Relative signal strengths are therefor compared to each other in terms of total signal instead average signal per pixel. Two types of proximity focused diode intensifiers were also studied. Both of the diodes had an S-20 photocathode; one had a P-43 phosphor and the other had a P-47 phosphor. The P-47 and P-43 diodes in front of the MCP II resulted in an additional gain of approximately 7 and 23, respectively. The results of the component measurements with the MCP II are also shown in figure 6. The P-47 and P-43 diodes directly coupled to the CCD camera provided a relative gain of approximately 14 and 77, respectively. A 4-foot long, flexible, coherent fiber bundle was then added in front of the P-43 diode-intensified CCD camera. The fiber bundle showed transmission of approximately 44%. This matches well with spectral transmission curves of coherent fiber optic bundles.⁵ Coherent fiber bundles have been used to replace lens imaging systems entirely in small field of view applications.^{4,5} They can provide very efficient high resolution coupling directly to a scintillator. Standard deviation of the background level in all of the systems varied from 1.6 to 3.1 counts.

Figure 5. Coupling Diagram

Large gain differences were noted with the different intensifier combinations. The graph in figure 7 indicates the spectral matching issues that arise when combining image tubes in series. Typical P-43 and P-47 phosphor spectral emissions are shown along with quantum efficiency curves for a typical S-20 photocathode and a typical front side illuminated CCD chip. When viewing blue phosphors or scintillators, the use of a P-43 intensifier provides wavelength shifting to better match the CCD spectral response, resulting in the observed higher effective gain.

Figure 6. CCD gain plot, indicating relative gain of different intensifier combinations.

Figure 7. Phosphor spectral emission of P-43 and P-47 phosphors with spectral sensitivity of an S-20 photocathode and a CCD. Phosphor and photocathode measurements courtesy of Tim Schaefer, Bechtel Nevada, Los Alamos Operations, Photonics

5. CONCLUSION

Special lenses are very helpful when a large field of view or a large standoff distance is required in radiographic image recording systems. High light collection efficiency is the key to the successful performance of lens-coupled imaging systems. After the image has been collected, there are many options available in electro-optical imaging systems. This makes it possible to meet a wide variety of application requirements. Different methods of image intensification are required for different applications. The use of fiber optic coupled recording systems is an area of strong interest. Image tubes may be combined in series when additional intensification, fast shuttering or image magnification are required. Performance characteristics such as gain, resolution, dynamic range, and noise characteristics of various systems is an area of strong interest. Comparison of electro-optical image coupling to lens and fiber optic coupling is an area of continued investigation.

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