Using Dynamic Radiography to Determine the Volume of an Imploding Cylinder

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ABSTRACT

Experiments have been conducted in Sarov, Russia, with a dynamic radiographic system designed to establish the volume of an imploding 14-mm-diameter tungsten cylinder. Images were formed using a 65-MeV gamma source, lutetium oxyorthosilicate doped with cerium (LSO:Ce) radiation-to-light converter, and a fiber optic imaging bundle. Three radiographs were recorded in the course of approximately 2 microseconds using an electronic streak camera with intensified charge-coupled device (CCD) readout. Significant improvements in system performance were achieved over lens coupling of components by the introduction of coherent fiber optics.

Keywords: radiography, fiber optics, streak camera, lutetium oxyorthosilicate, CCD camera, gamma radiation, coherent bundle

1. INTRODUCTION

A series of experiments, conducted at Los Alamos National Laboratory (LANL) and at the All Russian Scientific Research Institute of Experimental Physics (VNIIEF) at Sarov, Russia has led to the evolution of a dynamic radiographic recording system designed to measure the compression of a tungsten-lined cylinder containing a solidified rare gas (argon or krypton). These experiments were carried out to determine if argon or krypton would become conductive when compressed isentropically to megabar pressures.^{1,2,3} The radiographic recording system employed for these experiments consisted of a LSO:Ce scintillator with a 1-mm-thick Ta Compton converter, a Bechtel Nevada streak camera, a microchannel plate image intensifier (MCP II), and a commercial charge-coupled device (CCD) readout camera. The image was oriented on the streak photocathode so that a 4 mm by 24 mm cross-sectional view of the target cylinder (5 mm by 30 mm at the scintillator with radiographic magnification) was aligned with the camera's spatial axis. Three separate images, depicting the cylinder diameter at different times during the compression were sufficiently spaced along the camera's temporal axis to avoid overlapping. The isentropic compression was assumed to be radial, *i.e.*, the cylinder length remained constant in volume calculations, and compression was calculated from the ratio of the compressed vs. uncompressed volumes.

Over the course of several years, the radiographic recording system evolved to become more rugged, more easily fielded, more sensitive and to have better resolution.⁴ Most of these improvements were the direct result of successively replacing more and more of the discrete optical components of the original system with fiber optic components.

2. IMPROVEMENTS REALIZED BY FIBER OPTICS

There are many compelling reasons for considering fiber optics in lieu of discrete optics for coupling images into and out of electro-optic components in a radiographic system, especially one that is used as a diagnostic on an explosively driven

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experiment. The salient features and geometric constraints of the argon compression experiment are shown in Figure 1. The radiographic object (1), a 20-mm-diameter copper tube with tungsten lining for improved radiographic contrast, was nested inside an imploding device comprised of copper, epoxy, foam and high explosives. It was desired that the volume of the copper tube be ascertained at the time, or as close as possible to the time, of peak compression when the above-mentioned materials are the most dense (i.e. most attenuating to gammas). The recording system (3) was, therefore, located in a blast-mitigating enclosure (2) as close to the object as could be expected to survive the explosion. The tight physical confines of the enclosure made installation and alignment of lenses and mirrors difficult and time consuming. Particulates settled on the optical surfaces during the course of set-up and alignment, and especially during the experiments, which meant that the optics needed cleaning and realignment after each experiment.

Figure 1. Experimental set-up. The distance from the betatron (4) to the target cylinder (1) is 5 meters, and the distance from the target to the scintillator (3) is about 1 meter.

2.1. Sensitivity Improvements

Perhaps the strongest argument for using coherent fiber optics in the coupling of various radiographic system components is the potential for improved sensitivity. Using a solid angle approximation for the collection efficiency of a lens, it can be determined that the angle subtended by a lens Ω_{lens} can be written in terms of its $f/\#$ and the system magnification, M :

$$\Omega_{\text{lens}} = \frac{\pi}{4(F/\#)^2 (1 + 1/M)^2} \quad (1)$$

In our application, the lenses needed to be relatively impervious to radiation-induced fluorescence and transmissive to the scintillator emission (390 to 440 nm). The first system was fielded in 1997 and used a pair of quartz singlets. The ratio of the solid angle subtended by this system ($f/\# = f/1.4$ and $M = 0.35$) to that of a Lambertian emitter (2π radians), shows that our first system collected less than one-half percent of the light emitted by the scintillator on axis. It should be recalled that this collection efficiency rolls off with $\cos^4 \theta$, where θ is the angle formed between the optical axis and an off-axis point on the streak camera photocathode.

The solid angle subtended by a fiber optic system can be shown to be given by:

$$\Omega_{\text{f.o.}} = 2\pi(1 - \cos(\sin^{-1}(NA))) \quad (2)$$

In 1998, we tested a radiographic system that employed a three-foot long coherent fiber optic bundle. The fiber that was used to fabricate this bundle had a numerical aperture (NA) of 0.6. Using the same solid angle arguments, the collection efficiency for light emitted by the scintillator was calculated to be approximately 20 percent. Unlike the lens system, this collection efficiency applies equally to emission both on and off the optical axis, resulting in a much "flatter" field.⁴ Transmission through the optical fiber plays an important role in the efficiency of coupling the scintillator transmission through to the camera photocathode. Figure 2 shows the measured transmission through a three-foot length of a coherent fiber optic bundle as a function of wavelength before and after radiation darkening. It can be seen from the graph, that the transmission of 410 nm light through an undamaged three foot long bundle (top curve) is expected to be about 43 percent. When this transmission efficiency is brought into consideration, the coupling efficiency from scintillator to photocathode through three feet of coherent bundle was expected to be approximately 8.6 percent, or about 20 times more efficient at collecting scintillator emission and transmitting it to the streak camera than the lens system. A measurement of the signal strengths of the two systems proved consistent with this calculation and showed that the fiber optic system was more efficient by about 18 times.

Figure 2. Transmission data measured with a scanning monochromator, integrating sphere, and silicon detector.
Courtesy of Tim Schaefer, Bechtel Nevada, Los Alamos Operations.

A caveat is appropriate here. It must be noted that the image formed by the coherent fiber bundle on the streak camera photocathode is the same size as the image at the scintillator ($M = 1$). The formula for the lens collection efficiency manifests a functional dependence on magnification. In fact, when $M = 1$ is assumed, using the above thin lens approximation, the collection efficiency for an optical system based on discrete optics is predicted to be about 1.6 percent, or a little more than five times less efficient than the fiber-optic based equivalent.

Additional improvement in sensitivity was also realized by replacing the lens that imaged the intensified streak camera output onto the CCD chip of the readout camera with fiber optics. Figure 3 shows the two systems and the relative sensitivity improvements that were achieved by fiber optics. In 1997, an MCP II was directly coupled to the phosphor screen at the streak camera output and the MCP output was imaged by means of a pair of commercial Nikon photographic lenses onto a cooled CCD camera. As noted in Figure 3, a relative improvement in signal strength of about 20 times was achieved by substituting a direct fiber-coupled readout camera.

Fall 1997 Dynamic Radiographic System

Summer 1998 Dynamic Radiographic System

Figure 3. Component changes and relative sensitivity gains thereby achieved between the 1997 and 1998 dynamic radiographic systems. The 1997 system used a pair of quartz singlets and four mirrors to image the radiographic image formed at the scintillator onto the streak photocathode. All of these components were replaced in the 1998 system with a single, 5 mm by 30 mm coherent fiber optic bundle. The other change introduced in the 1998 system was the use of a fiber-optic-coupled readout camera.

2.2. Resolution Improvements

The aforementioned improvements in sensitivity caused an improvement in resolution. With an increase in sensitivity, acceptable signal strengths were achieved with thinner scintillators. A decrease in scintillator thickness decreased system susceptibility to two resolution-degrading effects: radiographic blur and defocusing. The increase in sensitivity achieved by introducing the changes noted in the 1998 system were sufficient to allow a decrease in scintillator thickness from 3 mm to 1 mm, which, in turn, resulted in an improvement in limiting resolution from 0.5 to 2 lp/mm. The significance of this achievement can be determined from a quick glance at Table 1, a compilation of the effect of resolution on realizable volumetric measurements. System resolution was determined by placing a tungsten resolution block at the location of the object (figure 1), irradiating it with a pulse of gamma radiation, then recording the resulting scintillator image. A factor of four improvement in the percent accuracy of volumetric measurements was achieved by the above-mentioned resolution improvements to our radiographic system. The calculated values for the percent error in volumetric measurement, which show an increase by about a factor of two for the compressed cylinder, is for an uncompressed cylinder having a radius of 7 mm.

Table 1. Precision of cylinder volume measurements as a function of radiometric system resolution, r , is 7 mm, and $\Delta V = 2\pi r l \Delta r$

Resolution (lp/mm)	Radial Resolution Δr (mm)	% Error $\Delta V/V$
0.5	1	28
1	0.5	14
2	0.25	7

2.3. Radiation Effects

The effects of radiation on performance of the fiber utilized in fabricating coherent bundles were studied in two different radiation environments; a continuously operated 20 MeV source that produced about 9 Krad per minute at one meter, and a pulsed 65 MeV source that produced about 2.5 rad per pulse at one meter. Prior to testing the coherent fiber optic bundle in a radiation environment, there was some concern expressed about the optical noise that would be introduced from Cerenkov radiation and radiation-induced fluorescence. The combined contributions of both fluorescence and Cerenkov radiation were measured by positioning the bundle directly in the radiation beam without a scintillator and measuring the strength of the signal thus generated using the same recording system as that used for the radiographic application. The results of this study, which are presented in an earlier paper,⁴ showed that the greatest levels of optical noise were less than 10 percent of the signal generated by a 1-mm-thick sample of LSO:Ce. The effect of this noise contribution decreased as the scintillator thickness increased.

Fiber performance was, however, affected by prolonged exposure to radiation. In the 20 MeV c-w environment, a 6- to 12-inch-long section of fiber was allowed to accumulate about 20 to 30 Krads. A pronounced yellowing of the transmission spectrum was readily observed by visual inspection. The effects of these radiation-induced color centers on the spectral transmission of a coherent bundle is shown in figure 2. It is obvious that the transmission in both long and short wavelengths of the visible spectrum is reduced by this effect. No such effect was observed in the sample that was subjected to less than 100 rads of 65 MeV pulsed radiation.

3. CONCLUSION

Improvements to the sensitivity of a dynamic radiographic system, resulting from the use of coherent fiber optic elements instead of discrete optics, made it possible to use thinner scintillator samples and improve radiographic resolution. This, in turn, yielded more accurate dynamic volumetric measurements. The resulting system was also more easily fielded, more rugged, and less susceptible to dirt and misalignment. Anticipated difficulties with radiation-induced fluorescence and Cerenkov radiation proved to be manageable, although some evidence exists of the formation of radiation-induced color centers in the bundles, which could lead to decreased system sensitivity over time and the necessity of periodically replacing fiber optic components.

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