Armando System Measurements at R-306 FY 2003 Report

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Armando System Measurements at R-306

FY 2003 Report

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Introduction

This report details some of the measurements made by Bechtel Nevada (BN) to characterize the Armando radiographic detection system and marks the completion of the R-306 Armando System Characterization milestone.

The measurements, made in July 2003, utilized the Cygnus pulse power machine, which was assembled at the Los Alamos National Laboratory (LANL) Firing Site R-306. This report describes the test configuration used and the findings concerning the following Armando radiographic detection system issues for

- source spot size,
- mirror vs. pellicle performance,
- scintillator configuration evaluation,
- resolution and reproducibility,
- off-axis scatter contribution, and
- source spectra reproducibility.

Test Configuration

The test configuration used at R-306 (Figure 1) was identical to the one initially envisioned for the U1a experiments at the Nevada Test Site; however, as a decision was made to use containment vessels for the subcritical experiments, the actual Armando configuration will be different. In the R-306 setup, the as-built radiographic magnification was 1.3 to 1 between the scintillator and the experimental package.

Source Spot Size

For the source spot size measurements, two tungsten rolled-edge targets were arranged in an L-shaped layout and placed on the source side of the first collimator block. Spot magnifications were arrived at by direct measurement. The source location was assumed to be 0.5 cm forward of the cathode ring.

Figure 1. Test configuration for measurements at R-306

Figure 2 shows the radiographic image of this target arrangement. The regions of interest (ROIs) that were analyzed for spot size determination are shown as shaded areas in the image. The spot sizes were determined with an algorithm, described below.

Figure 2. Radiograph of rolled edge showing ROIs for spot size calculations

First, the data was averaged perpendicular to the edge target. This averaged edge-spread function was then differentiated to obtain the line-spread function. The line-spread function was then transformed, using IDL Fourier fit transform (FFT) routines to obtain a modulation transfer function (MTF). The 50% modulation point (F_c) of the absolute value of the complex FFT was then determined. The equivalent diameter of a uniformly filled circular spot was then computed as:

$$\text{Spot Size} = 1/(\sqrt{2} * F_c).$$

Spot size measurements were made for a blunt rod and for a standard taper as a function of rod position. All rods were made of tungsten and had a diameter of 0.75 mm. The taper extended over a distance of 10 mm, with the taper running from full diameter down to 0.25 mm at the tip.

Table 1 shows a compilation of this data. The regions of interest start with ROI-1 (uppermost) and proceed counterclockwise to ROI-4.

By design, the Armando configuration is slightly off axis. The field of view (FOV) of the central vertical cord ranges from ~100 to 280 milliradians. In general, the off-axis spot size, as measured with the horizontal bar, shows a minor enlargement when compared with measurements taken from the vertical bar aligned along an on-axis chord. The tapered rod in the normal position indicated the smallest X-ray source spot size; there is some shot-to-shot variability detected in spot size. The remainder of the Cygnus data was recorded with a tapered rod in the normal position.

Table 1. Spot size data as a function of position and rod location

Shot #	Rod Configuration	Calculated Spot Size (mm)			
		ROI-1	ROI-2	ROI-3	ROI-4
159	10-cm tapered rod, normal position	1.17	1.16	1.24	1.23
160	10-cm tapered rod, normal position	1.13	1.11	1.15	1.14
161	9.75-cm tapered rod	1.16	1.15	1.17	1.17
162	9.5-cm tapered rod	1.17	1.15	1.22	1.22
164	Swap rod end-for-end (blunt)	1.21	1.05	1.32	1.33

Mirror vs. Pellicle Evaluation

System measurements were made to determine relative merits of using a mirror versus a pellicle. Degradation in image quality and/or increase in radiation scatter noise would indicate preference for one or another optical element.

Concerns were raised about the camera line of sight turning mirror as both a limitation to optical performance and a potential source of scattered radiation. Mirror dimensions are approximately 27.5 cm on the major axis. If the mirror is to be thick enough (~1 cm) that optical performance limitations are not a concern, Monte Carlo N-Particle (MCNP) calculations indicated that we could see a slightly elevated x-ray scatter dose at the U1a camera shown in Figure 1 due to the additional material in the beam path.

A solution to this problem is the use of a pellicle, a reflective thin-film membrane stretched over a flat frame. But the pellicle's extreme microphonic sensitivity, difficulty in cleaning, and delicacy could be drawbacks.

Radiation scatter noise was compared by measuring the number of star defects present in an un-illuminated portion of the imagery of shots 115 and 116. Shot 115 used a front surface glass mirror, 6.35 mm thick. Shot 116 used an essentially massless pellicle.

A star removal algorithm was used in which an ROI, typically 10 x 10 pixels, was moved through the image. Statistics were calculated on each ROI. If a pixel value exceeded a set number of standard deviations calculated for each ROI, the pixel value was replaced with the ROI median value, and its initial

intensity was logged into a histogram array. To obtain the total number of star defects in the image, the histogram was totaled.

Table 2 shows the totaled histogram results for these two images, expressed as the fractional number of pixels contaminated by radiation-induced star defects. Also shown in Table 2, for comparison, is a typical star density for the SABRE and STALL-1 experimental configurations. As seen in the table, there is a slim (~10 percent) reduction in the radiation-induced camera noise with the use of the pellicle. However, the blast house configuration (see Figure 1) is a major improvement in terms of radiation shielding of the camera system over either of the two previously fielded experimental geometries.

Table 2. Star count for various Armando systems

Shot #	<Stars/pixel>	Comments
115	0.0019	Mirror
116	0.0017	Pellicle
SABRE #407	0.0083	SABRE configuration
STALL-1 #17	0.0136	Mini-B/Stall-1

Figure 3 shows a graphical comparison of the MTF for mirror-based and pellicle-based systems. As one can see, the pellicle-based system has a somewhat better MTF than that of the mirror-based one. This is consistent with independent bench tests of the two optics. However, the differences observed in this measurement are small and within shot-to-shot variations of the Cygnus machine.

Given that the pellicle did exhibit a minor improvement in both resolution and radiation-induced detector noise, a pellicle was used for all following measurements.

Figure 3. MTF comparison of mirror and pellicle-based systems

Scintillator Configuration—Dynamic Range and Minimum Detectable Material

Four different options were evaluated in this series of tests.

The first two options addressed the form factor of the lutecium oxyorthosilicate (LSO)-tiled matrix. One configuration used a series of identical 50 x 50 x 2.7-mm LSO tiles arranged in two three-tile mosaics per line of sight. The second configuration used a central 80 x 50 x 2.7-mm LSO tile with a single 30 x 50 x 2.7-mm LSO tile at either end of the larger, central tile. The larger central tile's function was to move the tile seams further from the more interesting central region.

The third and fourth options addressed the decision to coat the sides and back of the tiles with black paint, which was assumed would reduce tile glow. Two sets of tiles, cut to a thickness of 2.7 mm and polished on all sides, were prepared. One set was painted black on the back and side, the other was coated on the edges using the conventional 'India ink' method.

The 80 x 50 x 2.7 mm tiles were cut longitudinally from a specially oriented boule that had been purchased several years ago by BN as a part of initial efforts within the Armando project to harvest larger LSO tiles. The seed crystal was also specifically oriented in an attempt to reduce the stress that is a by-product of the growth process, but that promotes cracking when the boule is cut lengthwise. The experiment was successful, in that the boule was successfully cut and polished by Ken McClellan (LANL). Four high-quality tiles were produced.

Figures 4a and 4b show zoomed-in views and contrast-enhanced images of raw radiographic data for the longitudinally and laterally cut scintillators. The notable fixed patterns are presumably associated with the growth process, while the variation in scintillator sensitivity, on the order of a few percent, is mostly removed by flat field corrections. However, as shown in table 3, there were minor differences noted in system performance between these two scintillator options.

Figure 4a. Fixed pattern in longitudinally cut LSO

Figure 4b. Fixed pattern in laterally cut LSO

Resolution measurements were also made with the four different scintillator options. Figure 5 shows a typical target scenario for system characterization studies. This image has been flat-field corrected, and radiation-induced stars have been removed.

Figure 5. Typical radiograph of calibration targets

To compare the relative merits of the two scintillator crosscuts, statistical comparisons were made of the flat-field corrected images. Table 3 is a compilation of variance values taken for the background in a region behind the W rolled edge and in the unattenuated region above the rolled edge (Figure 5). The minimum detectable amount of Pu (Table 3, column 5) was determined by relating the 1 sigma value of the noise in the unattenuated region to a calculated amount of material required to produce an equivalent absorption.

The dynamic range was calculated as the reciprocal of noise in the totally attenuated region of a normalized (peak intensity = 1.0) radiograph.

Table 3. Detection statistics of various scintillator configurations

Shot #	Scintillator	Coating	Sigma 100% region (normalize units)	Minimum detectable areal density Pu (mg/cm ²)	Sigma in 0 % region (normalized units)	Dynamic Range (1/sigma)
120	50x50x2.7	No paint	0.00737	~7	0.00141	708
123	80x50x2.7	No paint	0.0077	~6	0.00166	602
125	50x50x2.7	Paint	0.00647	~6	0.00137	731
130	80x50x2.7	Paint	0.00754	~7	0.00202	495

Scintillator Configuration—Resolution

Figure 6 is a graph of the MTFs associated with the four scintillator options. The 50 percent modulation point (F_c) for the four shots range from 1.15 to 1.2 per millimeter and does not appear to be correlated with scintillator type or coating. It was also interesting that there appeared to be no improvement in low frequency modulation that one might have expected with a reduction of ‘tile glow’ in the painted tiles. This observation is consistent with the assumption that the trapped light is completely uncorrelated spatially. The long-range blur, therefore, must not be caused by trapped light, but by some other mechanism, such as radiation scatter.

Figure 6. Resolution of four different scintillator configurations

Off-axis Scatter Contribution

A second camera was setup in the normal position for the second Cygnus machine line of sight and used to collect data on the off-axis scatter contribution to the direct axis measurement.

The scatter field, in all cases, has measurable light intensity. Averaged intensity levels typically varied from 0.2 to 1 percent of the level in the main beam, depending on target configuration in the main beam.

Source Spectra Reproducibility

The thickness of the lead step wedge shown in the radiograph in Figure 5 varies from less than 1 to 52 mm in 10 steps. The transmission values of the lead steps can be used as an indicator of the source spectra. Calculations were made using a modified Peter Menge (formerly of Sandia National Laboratories) calculated source spectra and a modeling code based on a NIST x-ray attenuation table to address the reproducibility of the source spectra.

Figure 7. Transmittance verses lead (Pb) thickness for five shots

Figure 8. Shot 120 step wedge data overlaid with modeled result

Figure 7 shows the compilation of transmission values for five shots. The transmittance values overlay fairly well with the exception of the 26-mm point from shot 123. It is not known what happened to this point, and it was omitted in subsequent analyses.

Figure 8 shows a fit to the data for shot 120 using transmission values calculated with the modified Peter Menge spectra. This spectra was modified by degrading the energy axis by a multiplicative factor until agreement was obtained in the mid-range, wedge step 5. The model was then used to solve for the predicted transmission of step10, and an offset was added to the data to fit this highly attenuated point. This procedure was iterated until there was agreement between the calculated and measured data at the fifth and tenth lead step.

This fitting procedure was done for all five shots with the results shown in Figure 7. Table 4 presents the multiplier for each input spectra, the “implied endpoint,” and the peak erection voltage, as measured by machine diagnostics provided by John Smith.

Table 4. Calculated spectra endpoint compared with measured peak voltage

Shot #	End Point Multiplier	Calculated Endpoint (MeV)	Measured Peak Voltage (MeV)
120	0.75	1.76	2.20
123	0.79	1.86	2.40
125	0.80	1.88	2.25
127	0.81	1.90	2.40
130	0.82	1.93	2.70

As shown in Table 4, with the exception of shot 123, there is a monotonic correlation between the measured peak voltage and the calculated endpoint. More data needs to be analyzed to establish a predictable relationship.

Figure 9. Measured transmission of lead step 4 versus calculated end point

To ascertain the error in mass assignment induced by this spectral variance, transmission data for these five measurements were averaged and an error analysis done on the distribution of thickness assignments. Figure 9 shows a plot of the transmission of step 4 for shots 120, 123, 125, 127, and 130. These transmission values are shown plotted versus the calculated endpoint values given in Table 4. This shot-to-shot variance in transmission presumably is caused by variation in the Cygnus emittance spectrum. This uncertainty is far larger than the ~0.002 to 0.007 percent variance range quoted in Table 3. The values shown in the table are due to detection statistics and appear to be dominated, in an absolute sense, by shot-to-shot variation in beam spectra. Using the measured lead (Pb) mass vs. %T calibration curve of the system, one can transform these variations in transmission values to precision limitations on mass assignment. The results of these data are graphically shown in Figure 10.

Figure 10. Precision in mass thickness measurement vs. mass thickness

Conclusions

A series of tests were made to determine the performance of the Armando radiographic system.

The source spot-size, measured in the off-axis Armando FOV, is on the order of 1.1 to 1.2 mm, equivalent diameter of a uniformly filled spot.

System resolution, as measured at the 50% MTF, exceeds the 1 line pair/millimeter specification by nearly 20 percent. System dynamic range is on the order of 700:1.

The blast house configuration provides excellent shielding for the imaging camera. This configuration is substantially better than any other configuration fielded to date. Care should be taken to include camera shielding in the final Armando design.

The 6-mm turning mirror has only a slight effect on overall camera noise. Pellicles; however, do represent a superior solution, both in terms of camera noise and optical performance.

Shot-to-shot variation in beam spectra, based on step wedge transmission variations, appear to place between a 1.5 and 3 percent precision limitation on mass determination. Presumably, this error bar could be reduced with the addition of in-situ calibration targets, visible in the x-ray image at shot time.

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