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SAND--92-2754C

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AUG 24 1993
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Development and characterization of a time-, position- and energy-resolved x-ray diagnostic
for PBFA II target experiments

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ABSTRACT

A time-, position- and energy-resolved soft x-ray (100-500 eV) diagnostic is being developed for PBFA II target experiments. The diagnostic provides measurements of hydrodynamic motion and thermal gradients in light-ion fusion targets. A slit-image of the source is imprinted onto thin sheets (20 μ m) of organic scintillator to create a one-dimensional image. The scintillator light is then proximity-coupled to a linear array of fiber-optics that transports the light to a streak camera that is operated without an intensifier. The streak camera output is recorded on a charge-coupled-device (CCD) camera. We are characterizing the spatial and temporal resolutions of the systems. This is done by collecting data from as many as 90 individual fibers and correcting for variations in throughput and the effects of spatial resolution to roughly 5% standard deviation in their relative throughput. Spatial resolution of these systems at the source is approximately 0.4 mm. Timing resolution is nominally 2 ns and it is limited primarily by the scintillator response and dispersion in the 50-m-long fiber array. We describe the measurement techniques and the results of the characterization.

1. INTRODUCTION

1.1 Target experiment description

We are beginning experiments at the Particle Beam Fusion Accelerator II (PBFA II)^{1,2,3} to study the potential of light ion beams to drive inertial confinement fusion targets. This paper discusses development work on a diagnostic to measure the spatial and temporal soft x-ray emission from these targets in the energy range 100-500 eV. The diagnostic will be used to study x-ray opacity and target hydrodynamics.

We will compare raw data and analyzed data to simulated results from recent experiments in order to illustrate the features of the diagnostic. In the experiments, Li-ions converged radially in a cylindrical geometry, on a target that consisted of a gold-cone filled with low density CH foam. A sketch of a target is illustrated in Fig. 1 using relative dimensions. The gold wall serves as a hohlraum and as a source of inner-shell diagnostic x-rays. The bulk of the energy is deposited in the foam and causes the foam to heat. As the beam deposits its energy and heats the target, x-rays are emitted. The x-ray emission pattern depends upon the beam energy deposition, target opacity and time. The purpose of this diagnostic is to measure the changing x-ray emission pattern from the target.

Fig.1 Radially incident ion beam on Au and foam filled target.

In order to measure this, the diagnostic uses a slit-aperture to image the emission onto a coated sheet of scintillator (20 μm of Bicron Corp. 418⁴) that is placed against a linear array of optical fibers. The thickness of the scintillator and the light-tight, x-ray filter over the scintillator determine the broadband x-ray energy resolution. The light exiting the fiber optics is focused onto a streak camera photocathode slit, and the streak camera output is lens-coupled to a CCD camera.

1.2 Example of a single x-ray image output

The output of the diagnostic is an image containing three separate spatially resolved images. Each image has a unique spectral response determined by the scintillator x-ray filter. Each of these images is integrated in one dimension, spatially-resolved in the other, and continuous in time. To explain how the diagnostic works and the type of output expected, we show a comparison of measured and modeled responses for a single image. An example of the raw data, a flat field corrected image, and a simulated diagnostic response are shown in Fig. 2. The simulated response is generated by modeling the beam energy deposition and radiation transport with LASNEX.⁵

The soft x-ray primary data acquired by the diagnostic is preceded by optical light generated in the fibers by bremsstrahlung. The bremsstrahlung is due to electron losses during diode operation; the electron energy distribution is continuous in energy up to 10-MeV.⁶ The bremsstrahlung acts as a timing fiducial and because it is the same in each fiber we use it to provide an approximate flat-field response. This is adequate for a quick qualitative look at the data as shown in fig.2. We used a 2 ns-wide lineout through the bremsstrahlung signal for a quick qualitative look at the data as shown in Fig. 2. It is clear from the data that there are quantitative differences between the simulations and the experiment. The intensity decay times clearly differ significantly, and the spatial extent of the emission features differ by ~25% from the simulation. However, the features are qualitatively similar; there are two clearly separated lobes of similar duration with comparable contrast between the center and lobe emissions in the data and simulations. At present one of our goals is to determine if the differences are due to problems with the diagnostic or inadequacies in the modeling.

Fig. 2. Comparison of raw data, flat-field corrected image and simulated detector output. 2a) Raw data from array 3 on shot 5942, the image shows comb time-axis and impulse calibration signals. 2b) Image after correcting with flat-field data taken from early time bremsstrahlung. 2c) Camera response predicted using LASNEX.

The raw data, shown in Fig. 2, needs to be corrected for variations in intensity along both the spatial and temporal axes due to non-linearity in camera gain, fiber-to-fiber variations in throughput, and non-uniformities in fiber position. Fibers which have broken and do not transmit measurable light need to be taken into account. The most important concern in the quantitative analysis of the diagnostics results is this flat-field correcting of the intensity as a function of the space and time where the signal is acquired on the CCD.

1.3 The coupled fiber optic array and streak camera system

We fielded the diagnostic as three linear arrays with distinct spectral responses. Two of these systems were fielded simultaneously on our experiments for a total of six energy bands with peak sensitivities below 500 eV. The configuration of the fibers is shown in fig. 3a. The fiber bundle is made of 100 μm diameter multimode polyamide fiber. Each system's bundle is coupled to its own streak camera/CCD camera system. At the top and bottom of the streak camera input bundle are two fibers that can carry calibration information. The three imaging arrays are in the center of the bundle.

In this paper we will describe our characterization work with just one of these systems. The schematic for the camera system used is shown in Fig. 3b. An EGG streak camera⁷ with 50 mm S-20 photocathode, a fiber optic faceplate input window, and better than 40 lp/mm static output resolution was used with a a Tinsley^{8,9} f/0.58 lens and a CCD camera¹⁰ to acquire the data.

Fig. 3. Components of the time-, space-, and energy-resolved x-ray diagnostic. 3a) Cartoon of diagnostic showing target as seen through slit and detector. Three different energy sensitivities are obtained by using different filters over the 3-fiber arrays. Light is integrated along the slit and spatial information is provided normal to the slit. 3b) Block diagram of system components showing streak camera input, streak camera, output lens and CCD.

The features of the diagnostic system are shown on the uniform source image of Fig. 4. An approximately uniform source was generated by placing a strobe (output 2.5 cm in diameter) 60 cm from the diagnostic input. The acquired image was rotated 88.5 degrees with software to allow the time and pixel axis to be oriented to the right because the alignment hardware mechanism does not allow this rotation. The image shows the three separate fiber arrays, fiber-to-fiber variations in transmission, a slight tendency for gain variations with time, and two timing calibration features¹¹ (a 250 MHz comb signal and an optical pulse to time-tie the electrical operation of the machine with the x-ray emission).

Fig. 4. Uniform field image showing the timing and output features of the diagnostic. Comb and impulse timing marks calibrate the timing scale. Brightness illustrates gain variations over the field of view.

1.4 Critical parameters for the diagnostic

Basic considerations of the target experiments determined the system requirements. For the initial proof of concept of this diagnostic, we desired 10-resolution elements over the target area which reduces to ~ 0.8 mm in spatial resolution at the source, and 10-temporal resolution elements over the 20 ns power pulse or approximately 2ns resolution.

Major advantages of this diagnostic are potential excellent reproducibility and easier calibration as compared to other time resolved imaging techniques. Good reproducibility is expected because the diagnostic does not use image intensifiers or gated microchannel plates (time-dependent gain) and film (background problems and development). Shot-to-shot variations of less than $\pm 5\%$ in absolute sensitivity is desired. Beginning with this work we introduce this diagnostic and preliminary aspects of its operation. We plan to develop this as an absolutely calibrated diagnostic. Although the spatial resolution will remain poor, this diagnostic should provide excellent cross-calibration of other higher-resolution systems and allow uniformity measurements of the emission field correctable to 1% at a 1-sigma uncertainty. The stringent uniformity specification is due to our ultimate need to perform radiation field uniformity measurements with nominally 1% uniformity.

2. SPATIAL CHARACTERIZATION OF THE IMAGING SYSTEM

2.1 Resolution of the slit-imaging systems and alignment characteristics

The diagnostic was designed to have a magnification of 2.1:1 detector element to source size and was intended to be alignable to better than 1 mm. The magnification was determined by the ratio of the distance of the slit to the source to the distance of the slit to the detector. The thirty fibers were located

nominally 0.66 mm apart, center-to-center. The slit width, τ , used for most of the shots was 300 μm . Using $2\tau^{1/2}$ as the resolution and adding the fiber position error ($<300\text{ }\mu\text{m}$ center-to-center) to give a spatial resolution at the detector of 670 μm and $\sim 320\text{ }\mu\text{m}$ at the source. This is better than the initial 800 μm design criteria.

There were three problems observed with the mechanical setup as fielded. Two were related to installation and bracketing. First, we found that the alignment hardware was consistently off by approximately 2 mm. This is the reason that the images are offset from the center of each array's image. This is not shown in figure 2, there were 10-fibers not shown that have no relevant signal because of this alignment problem. Second, the bracketing of the instrument that resulted in a 12% error in the magnification of the diagnostic as fielded versus the design criteria. The third problem was that the slit was 8 mm long - the same size as the target. The alignment error then means that the target emission was not sampled appropriately and that from one side of the target to the other there may be as much as a 25% effect on the intensity across the image. These will be fixed before the diagnostic is fielded again.

2.2 Spatial effects of scintillator coupling to the fiber bundle

The scintillator (20 μm of BC 418) is vapor deposited with various x-ray filters that act as a light tight seal between the target and the fibers. The scintillator is held against the fiber arrays with a steel gasket. One concern we have regarding the spatial resolution of the system is that the light that is accepted by any single fiber be generated within one resolution element. A simple calculation shows that unless there is a large separation ($>200\text{ }\mu\text{m}$) of the scintillator from the fiber, light generated near one fiber will be totally internally reflected in the scintillator and will not contribute noticeably to the resolution. We are attempting to measure this contribution to the resolution directly. The results are not available at this time.

2.3 Correcting for background and time-dependent variations in camera gain

There are two independent steps to the appropriate processing of this data. The first is to perform the a simple background subtraction. This is done by acquiring a background image immediately after the real data shot, this corrects for the CCD amplifier noise and dark current.

The second step is to test for time-dependent or time-axis changes in gain. We have measured the non-uniformity's in the phosphor, they show up in the data as time-dependent variation in system gain, at the back of the streak tube (time- and space- dependent camera gain) by both injecting laser light (a single point measurement with a constant light source) and using a strobe setup as a far-field source (uniform-field entire-photocathode illumination). Based on the laser measurement across the center of the photocathode, there is no point over which this variation is greater than $\pm 10\%$ and the standard deviation of intensity with time is 3.5% during a window from -25 ns to 125 ns. The variation in system gain over the entire time window with a nominal 400 ns sweep setting on the camera is shown in figure 5. Time zero is chosen to correspond to the peak in the bremsstrahlung signal (channel 400). The selected portion in the figure represents the time for which data was acquired on our recent experiments. The strobe based measurements, see fig. 4, also show a slight variation in gain over the portion of the image that contains data. At present we are not attempting to correct for the time-dependent gain effects in the data analysis.

Figure 5. Gain variation versus time based on laser input to a single fiber through the center of the photocathode. Shaded region represents time of signal acquisition.

2.4 Correcting for fiber-to-fiber variations in scintillator coupling and fiber throughput.

The next step in the data analysis is to correct for variation in the combined axial sensitivity of the photocathode, the fiber-to-fiber transmission effects and any spatial effects in the coupling of the scintillator to the fibers. We are studying two different means to correct for these variations. The first method is to take a vertical lineout through either a far-field uniform irradiation of the fibers or the bremsstrahlung portion of the image. Then we normalize the data of interest by dividing by the value of the far-field image. This method blurs the image because it simply smoothes the tails of the emission from individual fibers into the emission of its neighbors. The advantage is that it is straightforward and it allows a simple comparison to the continuous image generated by the modeling. An example of this method was shown in fig. 2. We use this method for quick qualitative looks at the data.

The second and more accurate method is to correct for individual fiber-to-fiber variations in throughput. We fit each peak in the streak, obtained from a vertical lineout, to a gaussian distribution and determine relative amplitudes. This method allows for what we feel is the better interpretation of the data because each fiber is treated as an individual diagnostic and any large variation in output from fiber-fiber is accounted for. The results of testing the fit method by comparing the fitted data to the raw data is shown in fig. 6. The data shown in the figure shows the raw data overlaid with the fitted gaussians. Only 10 of the fibers are shown so that the quality of the fits would be clearer. The quality of the fits can be determined quantitatively by comparing the applying the fits to the far field data. We have done this at three different times across the far-field image for one of the three arrays. The variation in the mean relative fitted amplitudes is shown in, Fig. 7. These fits were performed assuming the same full-width at half maximum resolution for each fiber. The appropriate figures of merit are the mean and relative standard deviations of the fitted amplitudes. These are given in table 1. The most important conclusions are that the fits will provide corrections adequate to about 5% and that time dependence is comparable to the amount the phosphor gain variations and can be corrected for.

Figure 6. Superposed lineout of fiber-fiber variations in system gain for 10-fibers and the gaussian fits to each peak. The crosses show the estimated peak signal for each fiber.

Figure 7. Variation in the mean relative fitted amplitudes at three different times in the streak record (early, middle, late).

Mean Relative Amplitude	Standard Deviation
0.89	3.9
0.97	4.4
1.00	4.3

Table 1. Summary of Amplitude and uncertainty analysis of the relative amplitude correction for array 3.

3. DETECTOR TEMPORAL RESPONSE

Each fiber optic bundle includes two fibers at each end of the streak camera input for timing calibration and test purposes. We inject a visible input to the streak camera system, both an impulse and an optical comb. The impulse is a single pulse of visible light <500 ps FWHM, the comb is continuous train of these pulses with peaks separated by 4 ns. These inputs allow us to compare absolute timing with regard to the PBFA II operation and they allow us to calibrate the time scale of the diagnostic. These calibration signals are acquired on each data acquisition. An example of these outputs is given in fig. 4. The example shows a comb trace, seen as the dotted line, and an impulse, seen as the bright point.

3.1 Timing scale linearity.

During the PBFA experiments either a 100 MHz or 250 MHz optical pulse is provided to the streak camera, located physically above and below the data carrying fibers. This comb pulse allows us to determine the linearity of the streak camera sweep. The linear fit of the time to peak intensity (every 4ns) in pixels has a correlation fit of $R=0.9997$. This can be observed graphically in fig. 8, where the pixel value at comb peak is plotted versus time based on the comb clock, believed accurate to 5 significant figures. The figure also shows the difference between the peak location and that predicted by the linear fit. The end result is that the sweep is linear to within no greater than a 1ns deviation over any portion of the sweep that contains usable data. The structure of the difference in time between the least squares fit and the pixel location is due to finite pixel size and the estimate of where the peak occurs; this is analogous to aliasing of the signal.

Figure 8. Illustration of the diagnostic time scale linearity. Pixel versus predicted time and the difference between the least squares linear fit and the peak intensity locations.

3.2 Relative and absolute timing uncertainty.

The absolute timing of the diagnostic with respect to the machine operation is determined by injecting a narrow (<500ps) optical pulse into the streak camera input end of the optical bundle, as shown in fig. 4. This pulse appears as a dot on the CCD output. The absolute position is what determines the timing. By comparing the electrical and optical time delays, due to cable lengths and electronics, we obtain the comparison of the diagnostics absolute timing. The jitter in this system is believed to be ~ 2 ns based upon the input trigger accuracy. The internal electronic delays have not been measured to better than 50ns. The promise for using the optical impulse for shot-to-shot accurate absolute timing has not yet been realized and as such its usefulness is limited to relative interpretation.

At present we are using the half-height rise of the bremsstrahlung signal to absolutely time-tie the x-ray emission signal with respect to the machine operation. Analysis of our earlier proton beam experiments gives us better than 3 ns uncertainty in the absolute timing with better than 1-sigma confidence. This confidence is based on the nominal 6 ns long (20-80 percent of peak) rise time of the various bremsstrahlung diagnostics. Additional work needs to go into improving the optical absolute timing marks to an adequate level, <1 ns uncertainty.

3.3 Diagnostic bandwidth

We are beginning to quantify the contributions to the bandwidth of the diagnostic by measuring the response of the optical comb through both the short calibration fibers (2 m) and the longer x-ray data transmitting fibers (50 m). The output of the comb is at 830nm rather than the ~400 nm light of the scintillator.

We have done made these measurements at the 400 ns full-sweep setting of the camera and at the 100ns full-sweep setting of the streak camera. Note that up this point in the paper all of the work and data has been acquired at the 400 ns sweep setting. These comparisons will help us judge not only what we presently have in terms of bandwidth, but what we might obtain for the diagnostic time response.

To illustrate the effect of the sweep speed on the timing resolution we show a small portion of a lineout through the combs in fig 9. Fig. 9 illustrates the shape of the comb pulse through the short and long fiber runs at the two sweep speeds. There are obvious differences in the shape of the pulses and the sample size effect on the pulse fidelity of the comb with sweep speed and fiber length. By comparing the full width at half maximum (FWHM) under the different conditions some conclusions can be drawn as to the causes of the time broadening. These effects are quantified in table 2. The estimated FWHM of detected scintillation light is determined by adding the 1.2 ns FWHM of the scintillator response⁴ in quadrature with the measured comb-system response. The impulse response of the comb alone has been measured to be better than 500 ps FWHM.

Because the ratio of the FWHM (pixels) for short fibers with sweep speed is 3 rather than the 4 (the difference in sweep speeds) the lens is probably the limiting factor in the time resolution at that sweep speed. At the higher sweep speed (100 ns FS) because the pulse shape is more asymmetric and the comb width varies so much with fiber length, the distance induced broadening and the scintillator response will dominate the resolution. Even so, the magnitude of the estimated diagnostic response with 50 m cable varies little (500 ps) under any of these scenarios. Either response function unfolding at the higher sweep speeds or hardware redesigns allowing shorter fiber runs could be used to improve the system response.

Figure 9. Comparison of comb profiles for comb marker under different conditions.

9a) Comb response through 2m calibration fiber.

9b) Comb response through 50m fiber bundle.

Fiber Length (m)	Full Sweep (ns)	Comb FWHM (ns)	Comb FWHM (pixels)	Estimated Diagnostic FWHM (ns)
2	400	1.4 + 0.1	2.3	1.8
2	100	0.6 + 0.05	5	1.3
50	400	1.6 + 0.1	2.5	1.9
50	100	1.0 + 0.05	7	1.6

Table 2. Quantitative comparison of system under differing sweep speed and fiber length conditions.

4. FUTURE WORK - ABSOLUTE CALIBRATION and DYNAMIC RANGE MEASUREMENTS

For this diagnostic to meet the goals for which it is designed we need to perform absolute calibrations as a function of x-ray energy as well as PSF measurements. We are presently assembling some hardware and making some design improvements that will allow practical calibration of the diagnostic and better alignment. The systems' dynamic range, and limitations on the amplitude linearity need to be determined. In addition, we have not yet performed the measurements to verify the diagnostics reproducibility. Future work on this diagnostic will be in these areas.

5. SUMMARY

The diagnostic has worked on PBFA II to illustrate physical phenomenon occurring in the target experiments. This paper contains the results of our initial attempts to characterize the systems performance. At present we can correct for fiber-fiber variations to nominally 5% standard deviation after flat-fielding. Temporal variations in gain can be measured and accounted for without correction to about $\sigma = 5\%$. The ultimate goal of 1% standard deviation in uniformity has not been met but the data shows where improvements can be made.

The diagnostic exhibits excellent temporal linearity characteristics; better than 1/2 FWHM over the entire time record. The estimated FWHM of an x-ray impulse is 2.3 ns with a 400 ns full sweep. Overall

we feel that this is an excellent beginning in the development of this space-, time-, and energy-resolved diagnostic.

6. ACKNOWLEDGMENTS

This work is supported by the U.S. Department of Energy Contract No. DE-AC04-76DP00789.

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