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Shot-to-shot comparison of the first Li-beam driven hohlraum experiments.

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Shot-to-shot comparison of the first Li-beam hohlraum experiments on PBFA II provides an opportunity to measure and determine the factors that affect on-axis reproducibility of the Li ion beam. Both inner shell and thermal x-ray emission are used to estimate the relative beam power on target from shot to shot. The M- and L-shell Au x-ray yield measurements were made with an array of 11 filtered PIN detectors, and the thermal emission measurements were made with an array of three filtered bolometers. The analysis shows that the beam intensity on target varied by more than a factor of ten during the shot series. By correlating the results of the beam on target with other diagnostics and events, we have identified some potential causes for these variations. A slight difference in top-to-bottom timing appears critical in affecting relative peak power on target.

I. Introduction

PBFA II is a pulsed-power-driven accelerator designed to study the generation of light ion beams for Inertial Confinement Fusion (ICF).^{1,2} Recent experiments have provided the first Li ion beam to heat hohlraum configuration targets. The primary purpose of the experiment was to compare the soft x-ray emission with simulations in order to demonstrate a predictive capability. We attempted to do these experiments while operating the accelerator under constant conditions. The beam performance on target was observed to vary. In this paper, however, we explore the factors affecting the reproducibility of the beam power on target. The target included either a 0.5- μm - or a 1.0- μm -thick gold cone 8 mm in diameter at the top and 4 mm in diameter at the bottom, centered in

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the machine. The gold serves as a source of inner-shell (M- and L-band) x-rays generated by ion impact excitation and of thermal emission from the target. We use both the inner shell and the thermal emission from the target to determine the relative power on target from shot to shot. Two companion papers to this one are included in these proceedings and illustrate diagnostic issues.^{3,4}

Many aspects of the target and the beam transport differed from the normal operating conditions of PBFA II. Routine PBFA II experiments are performed to better understand ion source development and these experiments are performed with a different target type and diagnostic set than is used for these thermal x-ray experiments.²

The differences included use of an on-axis azimuthally symmetric target. The target design required a nominal 2 cm radius vacuum region before the beam impacted the target as well as requiring us to load the target and associated hardware from the top of the machine. The top loading of the hardware introduced some differences; when loaded from the top, the transmission lines carrying power to the diode from the bottom were not cleaned between shots. This was because the extra work would have decreased the shot rate from about 2 shots/week to about 1 shot/week.

Fig. 1a shows the machine configuration, highlighting the power flow regions (Marx banks, intermediate store/pulse shaping and triggering, parallel plate, vacuum section) and target area locations. In PBFA II the power flows from a Marx bank to an intermediate store and pulse sharpening switch, to a water filled transmission line, through a vacuum interface into vacuum transmission lines, and finally into the diode region where the power is converted into an ion beam.

Four target configurations were fielded during these experiments. These configurations allowed us to test our predictive capability of the thermal x-ray emission by observing the effects of wall thickness and hole size on x-ray emission. Unfortunately, large variations in the power on target obscured the target-design-induced differences in target performance. Figure 1b shows the basic target including the gold cone which, by ion-impact interactions, emits L-shell gold radiation, thereby allowing an interpretation of the beam energy and power striking the target. The bolometers were located on the top of the target and the PIN detectors were located below the target.

II. Beam Power On target and Soft x-ray Emission

The diagnostics used to characterize the beam on target show that the beam parameters changed from shot to shot. The primary diagnostic for obtaining the relative power on target was an array of PIN detectors filtered to obtain broad-band x-ray spectral characteristics from 1 to 20 keV. These PINs observed the inner-shell x-rays generated by ion impact excitation. The PIN detectors, manufactured by Quantrad Corp., had a nominally 0.7 μm thick dead layer and a 22 μm active thickness. One of these detectors was filtered to act as a sensor for L-shell Au x-rays.

There are large uncertainties in the inner shell x-ray production cross sections with incident angle and incident ion energy. In the analysis presented we assume that the beam has the same voltage history and angular distribution for all of the shots. The voltage is known to vary between shots, however, the correction for this voltage variation is not known. Under the assumption that voltage is constant and given the thin gold target, the inner shell x-ray emission from the targets is roughly proportional to the power into the target times the thickness. The targets are of different thicknesses and these thicknesses must be taken into account in estimating the relative power into each target, based on the L-shell emission.⁵ Because the PIN detectors were uncalibrated, we present only the relative peak amplitude of the signals from shot to shot. In Fig. 2 we show the ratio of the peak in the PIN response divided by the Au cone thickness and normalized to the PIN response on shot 6000. This represents our best estimate of the relative peak power into the target.

Figure 2 also shows the normalized soft x-ray emission from the target as measured by filtered bolometers. Shot 6000 was chosen for the normalization because it had the most complete set of diagnostic results for the high intensity shots. Shot 6017 was a machine failure with reduced energy coupled to the diode, as shown in fig. 3. There was greater than a factor of 10 variation in the L-shell emission and more than a factor of 5 variation in thermal emission during the shot series, excepting shot 6017.

The uncertainties in the L-shell data have been determined by adding the relative uncertainty due to the noise and the estimated shot-to-shot scope amplitude jitter in quadrature. For low level signals, the uncertainty is dominated by the noise. The filters were not changed between shots and the detector sensitivity was assumed not to vary. The relative bolometer uncertainties were estimated based on the noise characteristics of the input signals for shot 6000 and a scope relative amplitude reproducibility of 5%.

A simple model for the soft x-ray fluence predicts the thermal emission to be nearly proportional to the incident beam power⁶ and the bolometer measurements are presented as a crude verification of the trends observed in the estimated relative power on target based on the L-shell signal. There is clearly a correlation between the thermal emission and the inner shell emission, however, the discrepancies between the peak power as determined by the two methods are as yet unexplained. In the continuing analysis of these experiments we plan to correct for diode voltage in the inner shell yields as well as thermal emission variation due to the target configurations.

The other detectors in the PIN array provided background and x-ray spectral information such as the bremsstrahlung generated by the machine. From the analysis of the spectrum, we have determined that the background effect in the L-shell channel is small. On shot 5936 the entire 11-channel array used filters of similar materials on all detectors to determine what variations in sensitivity existed between detectors. The standard deviation of the peak amplitude was 10%. Because the filter used was optimized for Au M-band, there was no data available in the L-shell. The point plotted in fig. 2 for shot 5936 is an estimate of the relative power as extrapolated from the M-shell yield based on the other shots. This point is used in subsequent estimates of the power on target. The uncertainty shown represents the uncertainty based on our estimates of the thick target yield differences between M- and L-shell emission. The bolometer data from shot 5936 is not shown because the soft x-ray cameras indicated that the target was obscured by debris. On shot 6022 there was no L-shell x-ray data because a gate valve did not open. Because there is no inner shell data on this shot the relative soft x-ray emission between shots 6000 and 6022 is used to estimate the power on target for shot 6022. For shot 6022 the magnetic field used to transport and focus the ion beam

was adjusted to improve performance over the prior shots. This is what we believe accounts for the improved performance on this shot.

III. Comparison of beam on target with machine performance.

We have analyzed the power flow in the machine in order to determine the reasons for the differences in the power on target. The total energy to the diode region on the vacuum side of the vacuum interface, as estimated by a power flow model from current and voltage waveforms, is not correlated with the energy delivered to the target. This is shown in fig. 3. Given that the amplitude of the current and voltage waveforms was fairly constant throughout the series of shots, the cause of the greater than a factor of 10 variation in the estimated beam power on target is most likely due to timing variations in the voltage and current flow to the diode.

The timing at the intermediate store (IS), measured at the capacitive voltage monitor, is not correlated with the power on target. The earliest (in the power flow chain) that timing differences correlate with the power on target is at the parallel plates. The correlation is shown in fig. 4. The exception to the correlation is shot 6022, which will be discussed in greater detail later.

To find the causes of the losses, we assessed the correlation among variables that changed during the experimental series. The three variables that correlated most strongly with the power on target were adjustments to switch timing, stack cleaning of the magnetically insulated transmission lines (MITL's), and changing of the ion diode cathode magnets. Fig. 4 shows that increased power on target is correlated with the occurrence of timing differences between the top and the bottom forward going voltage waveforms. These measurements of the pulse timing are made with the capacitive voltage monitors located after the gas switches in the parallel plate section.⁷ Shot 6022 does not show evidence of this asymmetry. On this shot the magnetic field configuration in the diode was deliberately changed to improve beam focusing. This may be the reason this point does not correlate with the others.

After shot 5984, some damage was observed in the magnetic field components. These magnets, which were encased in Inconel, were replaced with new magnet coils cased in titanium. There is a correlation between shot sequence and the estimated power on target and the cathode type. The correlation shows that power on target decreases with shot number after cleaning and resetting the switch timing, see fig. 5.

IV. Summary and conclusions

We have shown that, with the exception of shot 6022, the best estimate for the power on target is correlated with either stack cleaning or a timing asymmetry between the top and the bottom of the accelerator at the parallel plate location. There also appears to be a correlation with the cathode hardware and the associated magnetic field profiles.

The timing asymmetry results in a small current flowing through the diode, with the exception of shot 6022. The correlation implies that some timing asymmetry, or more current through the diode, leads to improved performance. The direction of this current flow does not seem important. Presently the conventional wisdom is that B_θ , the azimuthal magnetic field, should be zero because a non-zero B_θ will steer the beam off target up or down. The data presented that either current flowing through the diode has a positive effect on the beam transport. It is also possible that the B_θ is compensating for a vertical offset in the beam focusing. Additional work is necessary to understand and verify these conclusions.

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FIG. 1. Schematic representations of PBFA-II cross section (1a) and target configuration (1b).

FIG. 2. Relative L-shell yield and soft x-ray fluence as measured with a filtered PIN detector and with a filtered bolometer, respectively.

FIG. 3. Power on target as compared to energy into the diode.

FIG 4. Top and bottom variations in timing at the intermediate store and the parallel plates, compared to the estimated peak power at the target.

FIG 5. Correlation of power on target with shot number after stack cleaning and with Inconel versus titanium encased magnets.

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