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SUBJECT: Divergence of E beam in 100-TW Trident Experiments

Determination of the divergence of the relativistic electron beam is critical to estimation of the total electron current arising from thin-foil targets at the Trident Laser Facility. This has relevance for electron fast ignition, as well as for other possible uses of this short-pulse technology such as ion acceleration. We have collected data to answer this question with the scheme drawn in Fig. 1. The 370-nm TPX target, illuminated with a FWHM power of 75 TW for shot 23750, saw a nominal irradiance of $1.9 \times 10^{20} \text{ W/cm}^2$.

Figure 1. Cartoon of divergence measurement, Trident shot #23750

Because the image-plate detector (IP) is sensitive to x-ray, electron, and ion impact, steps were taken to remove the ambiguity of the origin of the exposure on our IP. A 0.125-in Al plate removes all ion flux below 25 MeV in energy. The blocked proton fraction, assuming an exponential energy distribution, $f(E) = 1 - \exp(-E/E_0)$, is 63% for $E = E_0$. It is justified to neglect the proton flux as is discussed below. All remaining radiation passes through a pepper pot¹, a simple array of holes, shown in Fig. 2, commonly used to measure beam emittance on accelerators. The so-called eWasp magnet used behind the pepper pot disperses the radiation according to charge. Electrons are directed upward by the magnetic field, ions downward, and x rays pass straight through. The eWasp has non-parallel pole pieces to allow a lateral expansion of the radiation through the angular array of pepper-pot holes.

Geometrically, the pepper pot has an axial hole and hexagonal rings of holes at 15° and 30° off axis. Each 0.125-in hole is tilted and pointed at the appropriate angle toward

Figure 2. Side, front, and back details of the 5/16" W pepper pot.

Figure 3. IP data, photo-stimulated luminescence (PSL), from shot 23750 with the pepper pot – PSL is proportional to energy deposited by radiation in the IP.

the target center. Some of the holes are blocked by the top, bottom, and pole pieces of the eWasp magnet, but for 23750, signal from seven apertures reach the IP (Fig. 3). We see exposure from the central hole, five of the 15° holes, and a single 30° hole. While the six-fold symmetry of the inner ring is obvious, subtle perturbations are apparent. One might expect energy dispersion in the vertical direction perpendicular to the magnetic field of the eWasp. Because of the field geometry, one expects particles off the vertical midplane to sample higher field on average. Similarly, the field is not symmetric in the vertical direction either. Adding to the complications, e-beam emittance is not necessarily uniform for each hole and likely depends on bunch energy, which may be a function of angle. We notice immediately that the exposure is not exactly centered on the axial hole – an experimental detail. The illustrated origin of the horizontal and vertical axes is derived from a least-squares best fit to an assumed Gaussian exposure model:

$$J(r) = J_0 \exp(-((x - x_0)^2 + (y - y_0)^2)/r_0^2)$$

where r_0 is the e-folding radius in the image plane, and x_0 and y_0 indicate the center of the Gaussian. The origin adjustment in the fit shifts the value of r for each of the seven data samples – holes. This dependence, made without regard to the magnet and energy disturbances just mentioned, is shown in Fig. 4. The fit parameters are the peak exposure

on axis, J_0 , r_0 , x_0 , and y_0 . The modest errors, as manifested by $r_0 = 109 \pm 7$ mm, are the square roots of the product of the χ^2 and the diagonal of the inversion matrix.² For reference, the plane of the IP was 216 mm behind the target.

Figure 4. Best-fit Gaussian to the center of the pepper-pot data.

Before continuing with the analysis, we consider the possibility that IP exposure is due in some part to ions or x rays. The effect of the magnetic field – that electrons do not travel in straight lines – is also taken into account. The Al shield blocks more than ions. According to <http://henke.lbl.gov/cgi-bin/filter.pl>, the transmission through this material is lower than 10% for photon energies ≤ 22 keV. Though turning on quickly for higher energies, we know from observations of IP data in magnetic electron spectrographs that the IP is much more sensitive to electrons than to x rays in the Trident environment. Similarly, there is no evidence of ion disturbances in the central hole of Fig. 3 – something one would expect were both protons and electrons passing through this hole and magnetic field. See Fig. 5 for an expanded view of this feature. If anything, the hole radius is elongated in the direction parallel to the magnetic field. This idea is verified with a second least squares fit – an elliptical fit, also in Fig. 5, that shows the horizontal radius is 26.6 mm versus 24.7 mm in the vertical (cross-field) direction. Ordinarily, with less deflection than electrons, protons would create an asymmetric bright bottom edge of the images of Fig. 3. This is not seen, implying a paucity of protons. As an aside, the horizontal broadening in Fig. 5 could be evidence of electron emittance. We conclude that the data are sufficiently robust to derive the electron divergence.

As for the field effects on the electrons, from the magnetic spectrometry data, we know there exists a broad range of electron energies. The geometric projection of the axial hole in the plane of the IP would have a diameter of ~ 34 mm; the fit contour in Fig. 5 is $\sim 47\%$ larger, consistent with some electron energy dispersion. Regardless, from the

Fig.4 fit for r_0 , we can calibrate the divergence of the electron beam. We already have suspicion that the magnetic field screws up the geometry somewhat, but we know the hole pattern in the image plane of the IP. We can do another elliptical fit to the hexagonal ring of holes at 15° to calibrate the divergence angle. This hexagonal fit is shown in Fig. 6 with the result that the radius of this ring is 80 ± 1 mm (The major and minor radii are 81.4 and 79.2 mm respectively.)

Figure 5. Zoomed in view of the central hole of the pepper-pot exposure – This shows that the beamlet width as deflected by the eWasp magnet is less than the width parallel the magnetic field. The elliptical fit (white curve) is based on the 12 boxed points.

Figure 6. Elliptical fit to the inner pepper-pot ring at 15°

Therefore, a little bit of math gives us the calibration. The e-folding angle θ_0 is to 15° in Fig. 6 as the e-folding radius r_0 in Fig. 4 (109 mm) is to 80 mm (Fig. 6):

$$\theta_0/15^\circ = 109 \text{ mm}/80 \text{ mm}.$$

Therefore, the e-folding angle divergence θ_0 is 20.4° . The half-width at half maximum, or half-angle divergence, would be 14.2° , less by $\ln 2$. This is a critical measurement for determining the total charge emitted from the target and consequently, the total electron current – the connection to fast ignition.

Parallels to ion divergence in short-pulse experiments must be considered. The cause and effect is different, for electron departure from the target is what sets up the electric fields that accelerate the ions. For the TNSA process, Schollmeier has written the definitive paper on proton divergence³. His Figure 5 is copied here to show that ion divergence for this family of TNSA experiments is extremely similar to the integrated electron divergence model described in this memo. There is a remarkable similarity to the present electron result. Using a 3D *p-i-c* simulation based on proton divergence, Fuchs⁴ concludes that the electron divergence is 25° , due mainly, he says, to multiple Coulomb scattering in the target. He neglects electron recirculation. The observation of ‘effect’ to determine the ‘cause’ is a bit self-serving, especially given the neglect of electron reflux, which repeatedly reheats the electrons to higher and higher energy as the laser irradiance increases on the leading edge of the pulse. Nevertheless, it is interesting that neither Fuch’s estimate and the present measurement indicate divergence $> 30^\circ$.

Figure 7. Schollmeier’s proton divergence data, Ref. 3.

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