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Osaka University
Effect of Laser Intensity on Fast-Electron-Beam Divergence in Solid-Density Plasmas

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Metal foil targets were irradiated with 1 μm wavelength (λ) laser pulses of 5 ps duration and focused intensities (I) of up to 4 × 1019 W cm−2, giving values of both IA2 and pulse duration comparable to those required for fast ignition inertial fusion. The divergence of the electrons accelerated into the target was determined from spatially resolved measurements of x-ray Kα emission and from transverse probing of the plasma formed on the back of the foils. Comparison of the divergence with other published data shows that it increases with IA2 and is independent of pulse duration. Two-dimensional particle-in-cell simulations reproduce these results, indicating that it is a fundamental property of the laser-plasma interaction.

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The fast ignition concept proposed in 1994 [1] has attracted extensive experimental and theoretical interest due to the reduced requirements for irradiation symmetry and drive energy compared with conventional inertial confinement fusion. In the fast ignitor scheme a separate laser is used to focus on target at an angle of 40°. The targets were 2 mm × 2 mm Ti or Cu foils of thickness and layered targets consisting of 25 μm Cu foils sandwiched between Al foils. Since the electron stopping due to electric field generation is more...
directly related to the distance traveled, rather than the target's areal density, it is reasonable to include these
different target types in one combined data set. The main
diagnostics employed to measure the electron beam diver-
gence were Cu and Ti \(K_\alpha\) imagers and transverse optical
probing, as these have been shown to provide complementary
information \([5]\). The Cu \(K_\alpha\) imager, used to spatially
resolve the 8.05 keV Cu \(K_\alpha\) emission from the target \([6]\),
consisted of a spherically bent Bragg crystal coupled to an
image plate. The quartz (2131) crystal focused the
8.05 keV Cu \(K_\alpha\) photons from the rear of the target onto
the image plane where FujiFilm BAS-SR2040 image plate
was placed. The Ti \(K_\alpha\) imager consisted of a similar setup
using a quartz (2023) crystal optimized to focus 4.5 keV Ti
\(K_\alpha\) emission.

A probe beam was created from a small part of the main
beam that was frequency doubled to 2\(\omega\) (527 nm). The
probe was timed to cross the target 200 ps after the main
interaction pulse so as to image the plasma expansion on
the front and rear surfaces. A 7-cm diameter, 30-cm focal
length achromatic lens was used to collect the probe light
after the target. The image was relayed outside of the target
chamber to an eight-bit charge coupled device. The
\(f/\) number of the imaging system was \(f/5\) and the magnifi-
cation was \(\times8.5\). The spatial resolution was 5 \(\mu\)m. The
maximum density probed was limited to roughly \(5 \times 10^{19}\) \(\text{cm}^{-3}\) due to refraction in the steep density
gradients.

Two sets of laser parameters were used to obtain data
sets A and B. Data set A was obtained using a laser pulse
duration of 5 ps. The target was displaced 180 \(\mu\)m from
best focus towards the parabolic mirror to provide a nomi-
nal defocused spot size of 50 \(\mu\)m. In practice, the spot was
made up of a central 10 \(\mu\)m full width half maximum
(FWHM) spot, within which resided 20\% of the energy,
along with a \(= 50 \mu\)m diameter lower intensity outer
region. The focused laser intensity was calculated using
the central high-intensity spot to be \(1.5 \times 10^{19}\) \(\text{W cm}^{-2}\).
Data set B was obtained with the target placed at the
optimum focus position. This provided a 7 \(\mu\)m FWHM
central peak and, with 5 ps pulse duration, an intensity on
target of \(4 \times 10^{19}\) \(\text{W cm}^{-2}\).

The \(K_\alpha\) emission spot size was measured by taking a
FWHM along the vertical axis of the target rear surface as
the target and crystal were on the same horizontal plane.
The \(K_\alpha\) emission depth for each target was calculated
using the method described by Lancaster et al. \([5]\).

Figure 1 shows a plot of target depth vs \(K_\alpha\) spot size for
data set A. The electron beam divergence was inferred from
the slope of the plotted \(\alpha\) vs target depth as \(2 \times
\arctan(m)\), where \(m\) is the slope. The straight line was fitted
to the data using the least squares method weighted by the
individual spot radii errors. These were governed primarily
by fitting Gaussian profiles to the measured spot sizes,
taking into account the measured signal-to-noise ratio.
The divergence angle was calculated to be 29(\(\pm 7\))\(^\circ\). The
divergence angle was also inferred by measuring the
FWHM of the plasma expansion on the rear surface of the
targets from the shadowgrams for this data set. Fewer
data points are included as most targets were too thick to
exhibit a clear rear surface expansion. From the slope in
Fig. 1 the divergence angle was measured as being
32(\(\pm 18\))\(^\circ\). Data set B is also plotted in Fig. 1. The diver-
gence angle for this data set was seen to increase to
35(\(\pm 13\))\(^\circ\).

A number of previous experiments with shorter pulse
durations have obtained results on the divergence of the hot
electrons. Early experiments using multiterawatt laser sys-
tems suggested a collimated fast electron flow in low Z
targets \([7–9]\). Simulations of these experiments indicated
that the magnetic field formed at the edge of an electron
beam inside the target resulted in beam collimation \([10]\).
Later experiments used imaging of \(K_\alpha\) emission from high
Z buried layer targets to measure electron beam divergence
\([11]\). Results indicated a fast-electron beam with a 40\(^\circ\)
spreading full angle. Santos et al. \([12]\) used time-resolved
optical diagnostics to measure the optical self-emission
generated either by incoherent transition or synchrotron
radiation (at the target rear surface) for different thickness
targets and found a fast-electron-beam divergence angle of
34\(^\circ\). Kodama \(K_\alpha\) \([13,14]\) inferred a 20\(^\circ\)–30\(^\circ\) beam diver-
gence using a similar technique at two different intensities.
Most recently, Lancaster et al. \([5]\) compared a range of
imaging techniques to diagnose electron energy transport
at the highest intensity range to date \((5 \times 10^{20}\) \(\text{W cm}^{-2}\)).
Shadowgraphy and \(K_\alpha\) imaging measurements revealed a
larger divergence angle of more than 50\(^\circ\).

Figure 2 shows the divergence angle as a function of
intensity on target for both newly obtained \(K_\alpha\) data sets, as
well as those in the published literature \([5,11–14]\) de-
scribed above. There is a clear trend of increasing beam
divergence with intensity on target and that the beam
divergence angle is most strongly influenced by this pa-
parameter, particularly as those measurements were taken with very different focal spot conditions ranging from a circular focal spot of 7 \( \mu \)m diameter [5] to an elongated spot of 30 \( \mu \)m \( \times \) 40 \( \mu \)m [14].

To test the validity of this conclusion, two-dimensional (2D) computer simulations were performed. The simulation of the whole process of the generation and transport of relativistic electrons by short, ultraintense laser pulses is an extremely difficult problem due to the large range of length scales that must be modeled. The process of electron acceleration in the laser focal spot is largely independent of the subsequent transport processes, although a rigorous treatment would have to allow for the fact that the large return current of “cold” electrons is an essential feature in maintaining the electron density in the interaction region. Any transport phenomena that hindered the return current, such as large magnetic fields or collision frequencies enhanced by strong plasma turbulence, would have a significant effect on the plasma environment in the acceleration region.

In the absence of fully self-consistent models for laser interactions with solid targets we have used the collisionless particle-in-cell (PIC) model OSIRIS [15] in 2D-3V geometry to model the data using as high a background density as is computationally feasible. The simulation grid covers 20 \( \mu \)m (axially) by 40 \( \mu \)m (transversely) with a 4000 by 8000 grid. There are 4 electrons and 4 ions per cell, equivalent to \( 1.6 \times 10^9 \) particles per square wavelength. This enables the solid density to be set to 100\( n_c \). The density rises linearly from zero to 100\( n_c \) over 2.5 \( \mu \)m, using a two step profile (0–30\( n_c \) in 2.5 \( \mu \)m and 30–100\( n_c \) in 1 \( \mu \)m). This increases the absorption of laser energy but does not markedly affect the temperature and divergence of the electrons. The laser rises linearly to its peak in 12 fs and remains constant. The electron parameters are measured at 100 fs. All electrons with a Lorentz factor greater than 1.5 are binned to give the distribution in energy and angle. A plot of the fast electron angular distribution \( n(\theta)d\theta \) for one simulation is shown in Fig. 3. The simulations use peak values of the vector potential of \( a_0 = 2, 5, \) and 10 and spot sizes of 4, 8, and 16 \( \mu \)m.

The results are summarized in Table I, the temperature is the slope of the logarithmic energy distribution, and the angular distribution is measured to 50% of the forward peak. The spot size has rather little effect on temperature or divergence apart from slightly lower temperatures for the smallest spot size.

There are two possible explanations for the increase of divergence with intensity. Simulations since those of Wilks [16] have shown a rippling of the density contours at the target front surface on the scale of the laser wavelength in addition to the larger scale hole boring [17]. The beam divergence could be determined by the laser fields around the ripples, which in the simulations grow more quickly at higher irradiance. One might then expect the beam divergence with very short laser pulses, say less than 50 fs, to be smaller than for pulses of 100 fs or more. Simulations performed by Ren et al. [18] and Adam et al. [19] have suggested that the electron divergence is set by deflection in magnetic fields generated by the filamentation instability of the electron beam as it propagates through the target.

In the analysis by Silva et al. [20] for the filamentation instability for electron beams with water bag distributions, the threshold for the instability can be written \( \theta^2 = \frac{n_{\text{hot}}}{\gamma n_{\text{bg}}} \) where \( \theta \) is the divergence of the hot component, \( n_{\text{hot}} \) and \( n_{\text{bg}} \) are the densities of the hot beam and background species, respectively, and \( \gamma \) is the Lorentz factor for the beam electrons. In this analysis the divergence is...
Table I. The slope temperature (MeV)/divergence half angle (degrees) for different intensities on target and focal spot diameter.

<table>
<thead>
<tr>
<th>$a_0$</th>
<th>Intensity</th>
<th>4 $\mu$m</th>
<th>8 $\mu$m</th>
<th>16 $\mu$m</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>$4 \times 10^{18}$ W cm$^{-2}$</td>
<td>0.46/17</td>
<td>0.61/19</td>
<td>0.64/19</td>
</tr>
<tr>
<td>5</td>
<td>$2 \times 10^{19}$ W cm$^{-2}$</td>
<td>1.3/35</td>
<td>1.8/35</td>
<td>1.8/35</td>
</tr>
<tr>
<td>10</td>
<td>$1 \times 10^{20}$ W cm$^{-2}$</td>
<td>2.7/38</td>
<td>3.4/47</td>
<td>3.6/45</td>
</tr>
</tbody>
</table>

approximately independent of intensity since $n_{\text{hot}}$ and $\gamma$ both increase approximately linearly with $a_0$ for relativistic laser intensities. However, the real situation with a large spread of beam energies is that there are many beam electrons with $\gamma \sim 1$ and a smaller number with large values of $\gamma$. Provided that the beam averaged $\gamma$ remains close to unity while $n_{\text{hot}}$ increases with intensity, then overall the beam divergence will increase with intensity as observed experimentally and in the simulations.

For the simulations with a background density of 100$n_{\text{p}}$, the divergence expected from this very simple model is around $8^\circ$ at $a_0 = 2$ and $17^\circ$ at $a_0 = 10$. This is about half of what is observed in the simulations, and some of the discrepancy may be due to differences between water bag and Maxwellian distributions for the transverse velocity components. In the situation of the experiments, it is difficult to know what value of background density to use in the presence of a largely unknown density gradient near the target surface.

The implications for fast ignition inertial fusion are significant. These results, together with the requirements detailed by Atzeni et al. [2], require the value of $I\lambda^2$ to be limited to $5 \times 10^{19}$ W cm$^{-2}$ $\mu$m$^2$ for realistic ignition beam energies (i.e., $\leq 100$ kJ) [3]. Higher intensities on target will require control of the beam divergence pattern [21]. A beam divergence that increases with $I\lambda^2$ and that is independent of the spot size and profile has also been predicted to occur as a result of the decreasing collimating strength of the magnetic field generated inside the solid target [22,23]. This means that we cannot clearly distinguish between the effects of generation and transport in the experimental results. However, the OSIRIS results indicate that the increase in divergence with $I\lambda^2$ is not purely a transport effect, which means that this result is not limited to solid targets, and therefore can be extrapolated to fast ignition using cone guided geometries.

In conclusion, the fast-electron-beam divergence has been measured for intensity and pulse duration conditions of those required for fast ignition inertial fusion for the first time. The divergence has been measured to be $29(\pm 7)^\circ$ and $32(\pm 18)^\circ$ by x-ray $K_\alpha$ imaging and optical shadowgraphy, respectively, at $1.5 \times 10^{19}$ W cm$^{-2}$. A divergence of $35(\pm 13)^\circ$ was found at $4 \times 10^{19}$ W cm$^{-2}$ by x-ray $K_\alpha$ imaging. An intensity dependence to the beam divergence has been revealed for the first time by comparing the new data with others published in the literature. The beam divergence appears to be independent of pulse duration. The intensity dependence on beam divergence is confirmed by 2D PIC simulations.

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