Hot Electron Generation for Fast Ignition

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Abstract. Fast ignition (FI) inertial confinement fusion, by separating the compression and ignition steps, offers high gain compared to the central hot spot concept with less stringent requirements on the symmetric compression of the fuel. For electron ignition the efficient conversion of laser energy into fast electrons and effective transport to the compressed fuel are the critical issues. The Titan laser facility at LLNL has been used to investigate two critical aspects of this process: electron divergence in a cone structure in the presence of pre-plasma, and propagation through materials of various *Z*. New diagnostics and target types were developed to allow more precise characterization of divergence than previously possible. First measurements indicate that the fluorescence-measured electron divergence in aluminum is smaller than previously reported (~30°), that within the confined area of a 30 μm diameter cone tip this divergence increases to 50-60°, and that the addition of pre-plasma sufficient to shift the critical surface ~50 μm has no discernable effect on these results but the insertion of mid- to high-*Z* layers reduces transported current to half its previous value. Hybrid PIC modeling has been performed to understand the underlying physics that plays an important role in these processes.

1. Introduction

The basic idea for the Fast Ignition (FI) approach to Inertial Confinement Fusion (ICF) is straightforward in concept: The fuel capsule is imploded onto the outer tip of a hollow cone; a short pulse laser is focused through the cone to produce relativistic electrons; these electrons travel through the cone tip and into the assembled DT to heat it to ignition [1]. However, the actual realization of the technique, and particularly the creation of the hot electrons, involves laser-plasma interactions at an extreme of intensity (I~10^{20} Wcm^{-2}) and resulting currents (~1 GA) only recently accessible, and their complexities not completely understood. Early analysis [2] of the process using laser generated hot electrons concluded that one must deposit hot electron energy, E_{ign} ~ 10-20 kJ, within τ_{ign}~ 30 ps into the compressed DT fuel. More recent, detailed simulations [3] show strong sensitivity of the energy requirement on details of the laser-generated electrons: laser-to-hot-electron conversion efficiency, electron energy spectrum, and most critically their divergence. These parameters depend sensitively on details of the laser-plasma interface (LPI), but the connection between interface and the resulting electrons, let alone control of their parameters, is not well understood because of both the influence of the laser pulse on the interface, and the inherent difficulty of making electron measurements inside dense plasmas.

Experimental campaigns to rectify this situation have been recently carried out at the Titan laser facility at Lawrence Livermore National Laboratory (LLNL) to study electron divergence and the effects on it due to a confined volume, and electron generation and transport as a function of the Z of the interface material. The experimental setup is described in Section 2. Sections 3 and 4 describe those campaigns and their preliminary results. Section 5 discusses these results and their implications for the design of a fast ignition target.

2. Experimental Setup

The Titan short pulse beam delivered $\tau \sim 1$ ps pulses of $E_{1\omega} \sim 150$ J at the fundamental , $\lambda = 1$ µm, and $E_{2\omega} \sim 40$ J at the second harmonic. In the former case the pulse is preceded by a mixture of a few ns amplified spontaneous emission (ASE) plateau and pre-pulse amounting to $E_{prepulse}$ <10 mJ. That early energy is essentially absent in the frequency doubled pulse in the latter case. The vacuum focus and preplasma were accurately characterized and monitored for every shot [4], in addition to the usual pulse energy and length. This gave assurance that conditions were unchanging in a shot series, and critical information for analyzing the results of those shots.

The targets were constructed of Al. The laser/plasma interface was either a 'flat', a 1 mm x 1 mm flat plane, or a 'buried cone', a 30 µm diameter flat at the tip of a 1 mm deep conical cavity with 30° opening angle. (This structure emulates the condition of an FI cone at the arrival of the ignition pulse, when it is surrounded by blow-off plasma from the compressed shell.) Each target contained a ~20 µm thick Cu layer buried at some distance from the front surface, to indicate by its fluorescence the spread of laser-generated electrons, backed up by ~ 1 mm thick C to assure the electrons did not reflux through the Cu. A spherically bent Bragg mirror relayed an image of the 8.05 keV Cu-K_α fluorescence to an x-ray ccd camera [5]. For z-dependence studies, each target also contained a surface or near-surface layer (Au, Mo, Al, or CH) to test electron transport. In that case, the integrated fluorescence signal was detected with a highly oriented-pyrolytic-graphite (HOPG) spectrometer [6].

3. Electron Divergence and the Effect of a Confined Volume

Experimental data on electron divergence from imaging buried fluorescence layers below flat surfaces, has historically had sufficient scatter in the data that characterization of their divergence is difficult at the ~100 µm distances of interest to FI [7]. Careful surface preparation and shot-by-shot monitoring of the laser pulses substantially reduced that scatter [Fig. 1(a)]; this data has a straight-line expansion with distance, following the bottom edge of previous data. The initial fluorescence fwhm spot diameter is ~60 µm and the slope ~30°; both are noticeably smaller than previous determinations. Subsequent measurements using frequency-doubled pulses ($\lambda = 0.5$ µm) show very similar divergence [Fig. 1(b)]. In that case, measurements were made both without prepulse (a consequence of the non-linear doubling crystal),

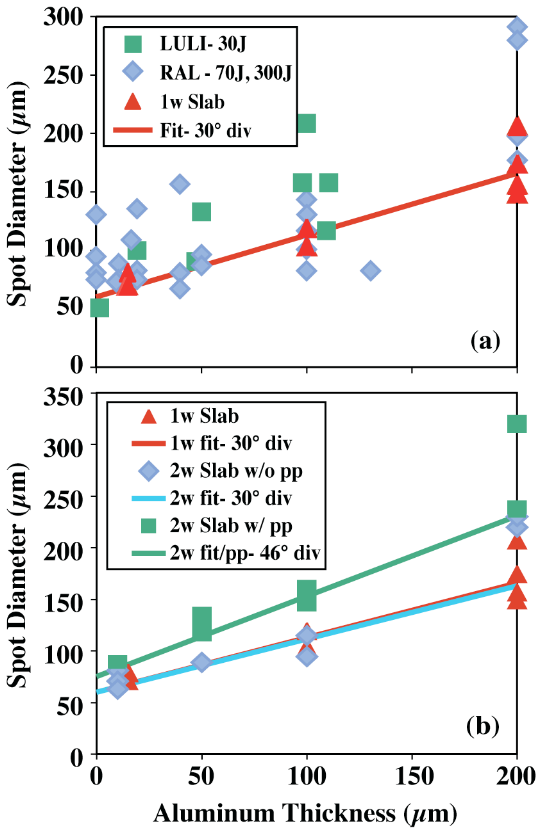

FIG. 1. fwhm of K_α fluorescence from Cu layers buried in Al beneath the laser/plasma interface. (a) shows data at 1ω and nominal prepulse overlain on historical divergence data [5]. (b) shows data at 2ω with a prepulse added equivalent to that present in (a) and without prepulse. Lines and their slopes are guides to the eye, not fits.

and with added 1ω equivalent prepulse. The 2ω shots with added prepulse show slightly increased divergence [also in cone geometry Fig. 2(d)], but the small difference and limited data preclude drawing conclusions from that.

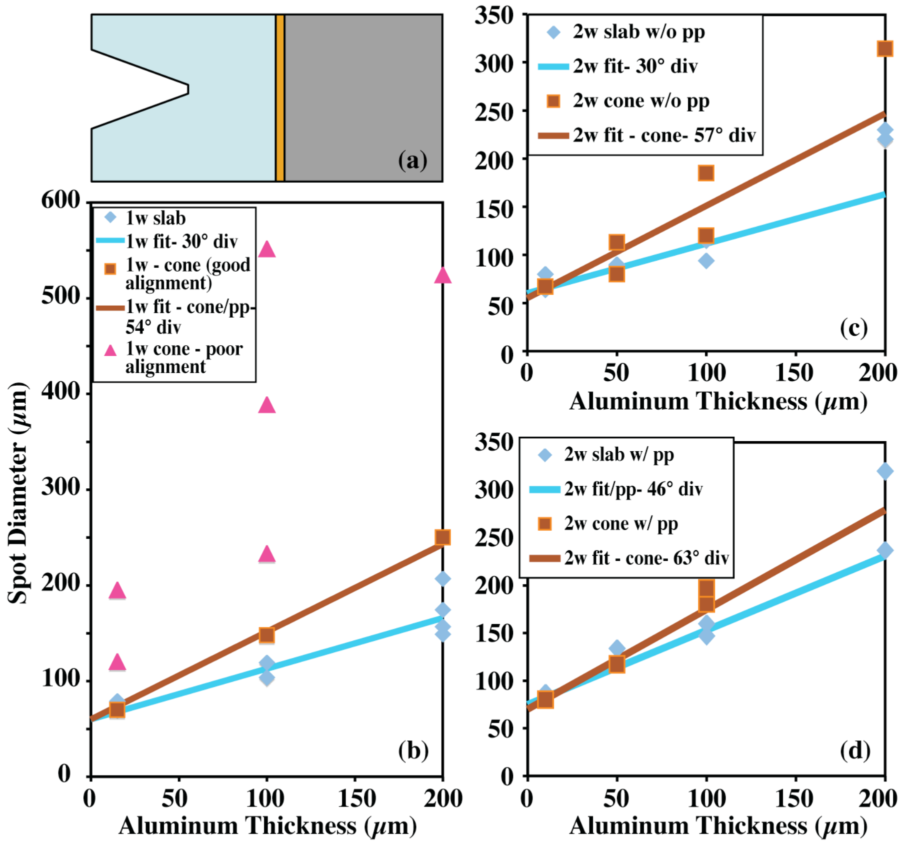

FIG. 2. (a) cross-section of 'buried cone' target. The cone has a 30 μm diameter flat at the bottom of a conical cavity in Al with 30° opening angle. The Cu layer is backed up by a 1 mm thick 'get-lost' layer of carbon or carbon-loaded plastic that ensures electrons make only one pass through the Cu. The graphs show fwhm fluorescent spot diameters for (b) 1ω laser pulses preceded by ~5 mJ pre-pulse, (c) 2ω laser pulses without prepulse, and (d) 2ω laser pulses with prepulse equivalent to that in (a). The blue diamonds are for flat laser/plama interfaces, the brown squares for buried cone geometry, the red triangles for poorly aligned shots.

This much improved reference data was compared to equivalent shots in 'buried cones' (Fig. 2), for which the volume around the laser/plasma interface was severely restricted causing substantial increase in the vertical extent of the preplasma [8]. That preplasma is expected to cause considerable restructuring of a focused laser beam, as shown in Fig. 3 (from Fig. 3 of MacPhee et al. [8]). The experimental data show an increase in electron divergence, but only from ~30° to ~60°, which, although a factor of 2 larger, is still much less than seen in preliminary experiments [9]; misalignment of the short-pulse beam with the cone tip results in much larger divergences [the red triangles in Fig. 2(b)]; such a problem could explain those earlier results.

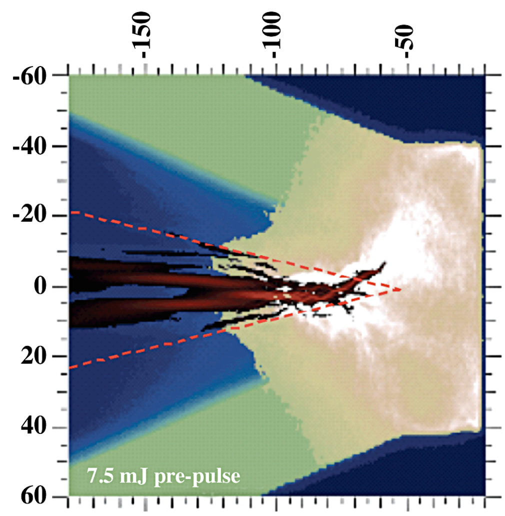

FIG. 3. Overlay of laser Poynting flux and electron density maps after 7.5 mJ of pre-pulse and 1 ps after nominal peak fluence on target (from Fig. 3 of MacPhee et al. [8]).

4. Electron Generation and Transport for Different *Z* Materials

In a real FI target, the cone wall and tip must be massive enough to keep the compressed plasma out of the cone and maintain an open path for the ignition pulse. The cone wall must be thick enough that the shock generated by imploding the shell does not break through the inner surface until after maximum fuel density is attained. Gold, with the highest density (ρ_{Au}~19.3 g/cm^3), permits the thinnest wall (~10-15 µm appears sufficient for implosions at OMEGA [10].). Using gold permits cone geometries with the smallest diameter tip making it easier to have the dense fuel close to that tip. Lower density materials would have to be thicker by the ratio of shock velocity speed (~ square root of 1/ρ). Scattering of electrons traversing the cone tip has been a concern for such a high *Z* material. Targets for this aspect of our campaign contained a *Z*-transport layer (Fig. 4) to investigate. The layer thickness was set to have approximately equal shock transit time (except CH which, at ~40 µm, would have caused fabrication problems), to allow comparison of materials giving equal shock protection. The results are shown in Fig. 5. The higher *Z* materials cause substantial reduction in transmitted electrons as seen by the reduced Cu-K_α fluorescence for those conditions. CH also causes substantial reduction; likely caused in this case by instabilities in the ionization front of the initially insulating plastic [11]; these results qualitatively agree with PIC simulations [12].

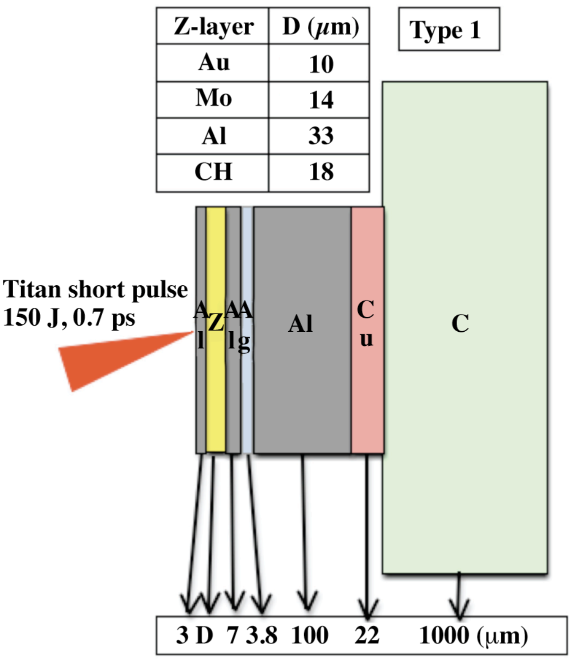

FIG. 4. Cross-section of targets used for testing *Z*-dependence. The front surface is Al to provide a consistent electron source. The thickness of the *Z* layer is approximately inverse with shock velocity to allow comparison between materials. Fluorescence from the Ag and Cu layers was used to measure the electron flux.

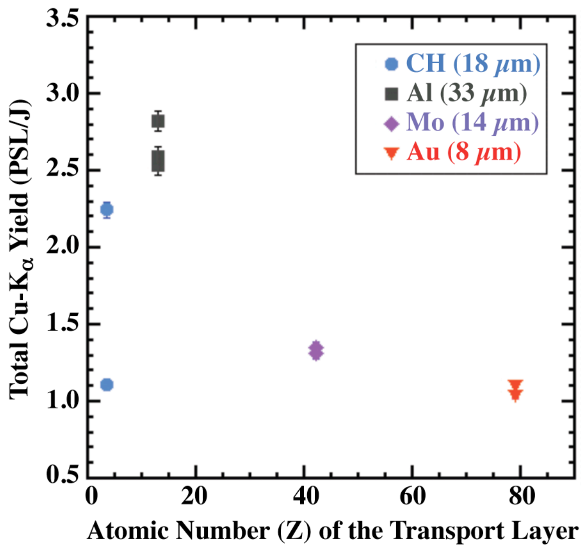

FIG. 5. Integrated K_α fluorescence from a Cu layer buried in an Al target shown in Fig. 4 under layers of various *Z* with thickness indicated in the insert.

5. Summary

Careful experimental design and execution have allowed accurate measurement of several laser-generated electron transport properties relevant to Fast Ignition. These results differ from those previously published, and as such are somewhat different than previously seen, so should be considered preliminary pending accumulation of a larger data set and detailed analysis.

Modeling suggests that divergence measured from a flat plane in an initially cold, therefore resistive, plasma is considerably smaller than the electron source due to focusing by resistance-gradient-induced magnetic fields [13]; electrons generated in lower resistance materials (a hot cone tip) would, from previous divergence data, diverge at ~100°. Nevertheless, our observation of a reduced divergence in aluminum, implies a smaller source divergence than previously considered.

The observed changes in divergence when that laser/plasma interface is confined to a 30 μm diameter cone tip, and overlain with a substantial plasma are surprisingly small. Not at all consistent with expectations derived from PIC models as shown in Fig. 3, which shows the laser beam, starting hundreds of microns above the cone tip, breaking into multiple filaments and spraying electrons into a very wide angle; the cone should have had a much larger effect that was relatively insensitive to alignment. The codes from which those simulations were generated are admittedly missing crucial physics; they assume a fixed ionization in the under-dense plasma and do not include radiation transport or scattering, for instance. It appears that inclusion of the missing parts is crucial for proper understanding of the laser/plasma interaction. The PICLS code [14] is currently being upgraded; dynamic ionization was added first to 1D [12] and now to PICLS. Improved modeling will be critical to a proper understanding of the role of preplasma.

The Z-dependence data show that scattering will be an important component of that improved modeling, and that there is considerable advantage to designing a cone with a reduced Z tip, consistent with creating a nearby core of dense fuel.

These measurements, while preliminary, imply a lower divergence of hot electrons and less sensitivity to preplasma than previously expected. They also show the necessity of adding more physics to simulations to properly capture the laser/plasma dynamics.

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