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Energy Injection for Fast Ignition*)

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In the fast ignition concept, assembled fuel is ignited through a separate high intensity laser pulse. Fast Ignition targets facilitate this ignition using a reentrant cone. It provides clear access through the overlaying coronal plasma, and controls the laser plasma interaction to optimize hot-electron production and transport into the compressed plasma. Recent results suggest that the cone does not play any role in guiding light or electrons to its tip, and coupling to electrons can be reduced by a small amount of preplasma. This puts stringent requirements on the ignition laser focusing, pointing, and prepulse.

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1. Introduction

The Fast Ignition (FI) concept originally envisaged the laser ignition pulse having a precursor that would channel and hole-bore through the corona to create electrons near the core [1]. The apparent complexity in and the stochastic nature of that process (see recent work by Ren *et al.* [2]) led to the suggestion that a reentrant cone would provide a more efficient, deterministic ignition channel. Testing of the cone concept in integrated experiments [3–5], showed promise, with ~20% of the incident laser energy transferred to the condensed target. These integrated experiments were not instrumented to reveal the physics involved in the energy transfer; the integrated core heating efficiency is a convolution of the conversion efficiency to electrons, their energy spectrum, and their direction. Detailed analysis was needed.

We review here a selected work on cone-relevant physics that our group has been developing over the last few years, and look at the resulting requirements for the target and the ignition laser. The problem was addressed using surrogate targets that eased characterization of specific aspects of the integrated task.

We discuss in the following sections the role of the flat cone tip in generating electrons, that of the cone wall in mediating the laser-plasma interaction and finally the directionality of the resulting hot electrons toward the assembled fuel. We bring those considerations together to suggest a strategy for optimizing a fast ignition cone.

2. Laser-Plasma Interaction

Cone-wire assemblies allowed easy analysis of the electrons generated in the cone (Fig. 1 (a)). Hot electron production was measured in these experiments using the fluorescence emission from the Cu wire by combining the absolute measurement of a single hit spectrometer [6] with the good signal to noise of a highly oriented pyrolitic graphite (HOPG) spectrometer [7] and the spatial discrimination of Bragg-mirror imaging of the K_α fluorescence. Analysis of the $1/e$ length of fluorescence intensity [8] in the wire using an analysis developed by Bell *et al.* [9] sug-

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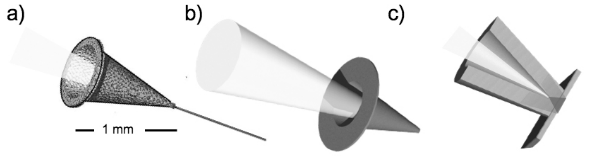

Fig. 1 Surrogate targets enable observation of hot electrons from CuK_α fluorescence a) coupled to the wire on the tip of a cone, b) generated in the thin wall of a Cu cone, and c) propagated to a buried Cu layer beyond the tip of the cone.

gested a much colder electron spectrum (~670 eV) than anticipated from the usually invoked ponderomotive scaling [10] for $I \sim 10^{20}$ W/cm^2.

Recent simulations, [11–13] and analyses [14] explain the lower temperature as to be expected from laser plasma interfaces with relatively short scale lengths, and experimental work at ILE [15] showed that e-spectrometers of the sort that had established the ponderomotive scaling [16] were sampling only the very earliest generated hot electrons,[1] so do not necessarily represent the whole population.

A technique for *in situ* electron temperature, T_{hot}, measurement is being developed using bremsstrahlung radiation from the hot electrons [17]. Preliminary analysis from recent Titan campaigns using flat foils suggest the hot electron spectrum is indeed much colder than expected from ponderomotive scaling [18] approximating the $T_{\mathrm{hot}} \propto I^{1/3}$ Beg scaling seen at lower intensities [19].

Such scaling allows the desired electron energies (1-3 MeV) to be optimally produced with much higher intensities ($I \sim 6 \times 10^{20}$ W/cm^2), reducing the required tip area and/or pulse length required to produce the ignition energy (100 kJ in 20 ps on 3×10^{-4} cm^2).

3. Laser-Cone Wall Interaction

Simulations had suggested that the cone walls were instrumental in increasing the light and electron intensity at the cone tip [20, 21]. Recent Titan experimental campaigns directed toward that question used flat foils as surrogates for the inside cone wall [22]. Light reflectivity and electron generation was measured as a function of polarization and angle of incidence using laser pulses up to 150 J and 10^{19} W/cm^2. We observed small angle scattering (an $f/3$ incident beam was reflected as $\sim f/2$) that was polarization independent, a near-normal reflectivity ~2% and a glancing angle reflectivity ~50%. These instruments showed that glancing incidence beams converted ~1/10 as much of their energy into hot electrons, and that those electrons were mostly localized to the focal spot of the laser. In short, light hitting cone walls suffers unacceptable losses and generates only a minimal number of electrons.

However, in the cone geometry (Fig. 1 (b)) we found that a beam focused to the cone tip produced fluorescence spreading up the cone wall a distance that depended on the energy in the laser prepulse. At the lowest feasible prepulse energy (~5 mJ) the spread wasn't much larger than seen in flat targets; 300 mJ spread the fluorescence ~300 µm up the wall, and 1 J extended the fluorescence all the way to the top of the ~750 µm long cone [22]. This large spread in fluorescence maps out the extent of the conducting region available to the hot electrons; the plasma generated by the prepulse and confined to ~1-D expansion by the cone walls. The electrons, trapped in the cone by sheath fields as noted above, can move much more freely throughout the internal plasma than diffuse along the thin cone wall.

The ultra-intense, short-pulse ignitor beam, in traveling through this plasma, could generate transverse electrons or filament, and the laser plasma interaction at the tip could be substantially modified. We had preliminary evidence of that in the increased fluorescence observed with cone geometry as noted above. But that did not tell us whether the extra electron energy was forward directed; the sheath electric fields around our cone targets redirected the electrons.

4. Hot Electron Coupling toward the Core

A cone used in an ignition target would be surrounded, when the ignition pulse arrives, by plasma blow-off from assembling the fuel. That plasma, estimated to have $\rho \sim 5$ g/cc and $T_{\mathrm{ee}} \gg 100$ eV near the cone tip [23] for a low adiabat implosion [24], has very good conductivity. It would eliminate the sheath fields present in our previous cone experiments and remove any electron guiding effect they may cause [25]. This electron-core coupling situation was modeled using thick-walled aluminum cone targets coupled to Cu wires or to fluorescing layers (Fig. 1 (c)). Initial results show that indeed many of the electrons generated in these experiments are traveling at large angles to the cone axis; the coupling to the wire goes down an order of magnitude as the cone wall thickness increases from 12 to 250 µm. Addition of a prepulse above the intrinsic 5 mJ level only makes that worse. Imaging the electrons using a buried fluorescent layer proved difficult, and the results somewhat scattered, but the best spots, 50 µm from the cone tip, had fwhm diameter of ~200 µm; that is at least 50% larger diameter than comparable buried layer measurement in a flat foil target. A large prepulse ($E \sim 400$ mJ) increased that diameter nearly a factor of 2.

5. Target Consequences

Our work suggests that the only function of the reentrant cone in a fast ignition target is to maintain a clear path

[1] For a typical 150 J Titan laser pulse, the capacitance, C, of a typical 1/2 mm diameter target, limits the energy E of escaping $V \sim$MeV electrons to $E < V^2/C \sim 10$'s mJ.

to a point near the compressed fuel. Light reflected off the cone walls loses half its energy and is somewhat diffused; hence the ignitor laser must be focused to the cone tip requiring a focussed spot diameter $\leq 40\,\mu$m, and a pointing accuracy $\ll 40\,\mu$m. Moreover, any detectable preplasma noticeably reduces the forward coupling of electrons indicating a requirement for the ignitor laser prepulse $\ll 1$ J.

Although the sidewalls do not improve electron coupling, added cone structures at the cone tip might. The wall/vacuum with its associated electrostatic sheath field, has been shown in cone-wire experiments [25] and simulations [26] to focus electrons more into the forward direction. That approach has been developed into a double walled hohlraum [27] that, in simulations, considerably improves coupling of hot electrons into the target. Another approach generates confining electric fields using material resistive differences [28].

6. Future Work

The consequences discussed above rest on preliminary indications from still unpublished data; full analysis may modify these conclusions. But several critical issues are raised here that need detailed investigation, regardless.

Electrons generated from the tip of a cone spread more than from a flat surface, and fluorescence is larger. That is surprising if we have done the experiment we intended. The laser can be focused and pointed to the center of the cone tip, clear of the cone walls, preplasma resulting from Titan's intrinsic prepulse should not be large enough to modify that, and reflected laser intensity, (~2%) should not be sufficient to increase fluorescence from 2nd and 3rd bounces. We need, and are developing, more thoroughly instrumented experiments for clarification.

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