Characterization of Fast Electron Source Using Copper $K_{\alpha}$ and Proton Emission from Cone-Wire Targets

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The Fast Ignition (FI) Concept for Inertial Confinement Fusion (ICF) has the potential to provide a significant advance in the technical attractiveness of Inertial Fusion Energy (IFE) reactors. FI is different from conventional “central hot spot” (CHS) target ignition due to separate compression and ignition phases. In this concept, laser (or heavy ion or Z pinch) drive pulses (10’s of ns) are used to assemble a dense fuel mass and a much shorter (~10 ps) high intensity pulse is used to ignite a small region of it. FI could significantly reduce the driver energy (and cost) required for an IFE power plant. FI targets can burn with ~3X lower fuel density than CHS targets, resulting in (all other things being equal) lower required compression energy and relaxed drive symmetry/target smoothness requirements at a higher gain. Experiments in this area provide some of the most extreme High Energy Density (HED) conditions accessible. Here, we report results from experiments carried out using the OMEGA EP laser with ~ 1 kJ and 10 picosecond pulses. We used a gold cone attached to a copper wire to characterize the electrons generated by the laser by observing copper $K_{\alpha}$ and proton emission from the wire. Results show that the copper $K_{\alpha}$ yield increases with the laser energy, and proton emission is mainly due to three factors: i) the divergence of the fast electrons’ beam entering into the wire ii) the collisional scattering of fast electrons and iii) formation of a cloud of electrons around the wire due to the refluxing of electrons from the far end of the wire.

Key Words: Laser plasma interaction, Fast ignition, Fast electron transport

1. Introduction

High Energy Density Science\(^1\) is entering a new era of opportunity with a next-generation class of high power lasers coming on line throughout the world. Two such examples are the OMEGA EP laser\(^2\) at the Laboratory for Laser Energetics and the LFEX laser at Osaka University.\(^3\) Both lasers deliver more than 1 kJ energy in 10 ps pulses. These facilities provide excellent opportunities to study laser plasma interactions in unexplored High Energy Density (HED) regimes. Particularly, this regime is appropriate for studying Fast Ignition (FI) of inertial confinement fusion which will require 10 s of kJ laser pulses with duration of order 10 ps. The FI concept involves extremely complex HED physics: ultra-intense laser fields that generate extremely high intensities (> $10^{19}$ W/cm$^2$). These laser fields produce massive currents (~ giga-Ampere in 10’s μm diameter) at the critical surface that are required to propagate through hot (keV), dense (> 10$^5$ n$_c$) plasma. Investigating this regime both experimentally and numerically with multi-kilojoule lasers is challenging and offers an outstanding scientific opportunity.

The FI concept was proposed\(^4\) upon the emergence of ultra-high-intensity, ultra-short pulse lasers using chirped pulse amplification.\(^5\) The concept is different from conventional central hot spot (CHS) ignition\(^6\) due to separate compression and ignition phases. It was immediately recognized as an attractive concept that will be compatible with any fuel compression driver (i.e. laser, z-pinch, and ion beams) and have the potential for higher gains and smaller energy requirements than the CHS approach. In the original FI concept, after the spherical fuel shell is compressed by an external driver, a powerful precursor laser pulse of about $10^{19}$ s duration is focused to a small spot on the compressed fuel. This laser creates a channel through the ~ 1 mm of coronal plasma, at densities up to the critical, that surrounds the compressed fuel by expelling the plasma via its ponderomotive forces. Then, a subsequent main ignitor pulse (10 ps, > $10^{19}$ Wcm$^{-2}$) is propagated through the channel to the critical surface where a stream of energetic (~ 1 MeV) electrons are produced and deposit their energy in the compressed core to heat it to 10 keV temperature.

Early research showed that channeling through the coronal plasma was a major challenge in this original concept termed the channeling approach, thus motivating an alternative design using a hollow Au cone inserted in the spherical shell.\(^7\) The fuel compression/produces dense plasma at the outside tip of the cone, while the hollow cone permits the short-pulse ignition laser to be transported inside without interference, and enables the generation of hot electrons at its inner tip, very close to the dense plasma.

Understanding the electron source characteristics (conversion efficiency and spectrum) and transport is a challenging issue, which can be discussed independently from the implosion physics to avoid complexities of implosion physics with...
the cone. One of the crucial issues for cone-guided fast ignition is to properly characterize the fast electrons generated due to the interaction of short pulse laser with the cone. Particularly, the information about the energy of generated fast electrons (typically characterized by a slope temperature, \( T_{\text{hot}} \)) and the conversion efficiency, from laser to fast electrons is required. Cone-wire targets provide a simple way to study the generation of fast electrons inside the cone. Typically both \( T_{\text{hot}} \) and conversion efficiency are inferred by analyzing the experimentally measured \( K_{\alpha} \) x-ray emission from the wire. However, alternate experimental methods to estimate parameters such as the \( T_{\text{hot}} \) and conversion efficiency would help improve the level of confidence in the present measurements. One such example is measurement of proton emission from the wire.

In this paper, we describe results from an experiment carried out on the OMEGA EP laser to study the fast electron source, conversion efficiency and proton production from cone wire targets. Modeling using the Large Scale Plasma (LSP) code was carried out to understand the underlying physics of proton production.

2. Experimental Details

We have carried out experiments on the OMEGA EP laser facility to understand the interaction of kilojoule, 10 ps laser pulses with a gold cone. The experiments were performed at the Laboratory for Laser Energetics at the University of Rochester. The EP short pulse beam was focused into the Au cone target with 80% of the beam energy within a \( \sim 25 \mu \text{m} \) radius spot. The energy of the beam was varied from 250 J to 810 J with a full width half maximum pulse duration of \( \sim 10 \text{ ps} \). The average laser intensity within the spot was \( 5 \times 10^{16} \text{ W/cm}^2 \), and the peak intensity was \( \sim 10^{19} \text{ W/cm}^2 \) for the 810 J shot, with \( \sim 500 \text{ mJ} \) in the pedestal (3 ns long). Fast electron generation and the transport through the cone tip were studied using a Cu wire attached to the cone tip. The cone-wire target schematic is shown in Fig. 1. The target consisted of a 1.0 mm long, 40 \( \mu \text{m} \) diameter Cu wire attached to a Au cone with 40° full opening angle, 51 \( \mu \text{m} \) tip outer diameter, and 5 ~ 10 \( \mu \text{m} \) tip thickness. The interaction of the laser and the cone tip produced energetic electrons, of which a fraction transported through the cone tip into the attached wire inducing the 8.0 keV Cu \( K_{\alpha} \) x-rays. The Cu \( K_{\alpha} \) yield was measured with a highly oriented pyrolytic graphite (HOPG) crystal spectrometer,\(^{12} \) which was absolutely calibrated with a single-photon counting camera. The spectrometer was oriented perpendicular to the wire axis. X-ray attenuation in the Cu wire was taken into account in analysis of the data. In addition, thermal plasma emission inside the cone was monitored with a time-integrated x-ray pinhole camera, and the spectrum of electrons escaping along the wire axis was measured with an electron spectrometer.\(^{13} \)

In this experiment, we also observed emission of energetic protons from the wire in the radial direction i.e. in the direction transverse to the length of the wire. The details are given in ref. 14. Detailed numerical modeling with hybrid PIC code LSP\(^{15} \) showed that transport of fast electrons from the source excites a radial electric field around the wire which in turn leads to emission of protons.

3. Experimental Results

For these shots, the OMEGA EP laser had a significant laser prepulse as mentioned above, which created substantial preplasma filling up the cone as discussed by Ma et al.\(^{10} \) The main pulse interacted with the preplasma and laser energy was absorbed producing the fast electrons. Then, these fast electrons from the gold cone moved into the wire through the cone tip, where they made binary collisions, producing copper \( K_{\alpha} \) photons. Fig. 2 shows increase in copper \( K_{\alpha} \) yield with the OMEGA EP laser energy. Although the copper \( K_{\alpha} \) increases with the laser energy, the overall conversion efficiency to \( K_{\alpha} \) photons is low at about 1% as discussed by Yabuuchi et al.\(^{16} \)

We also recorded the proton emission from the wire to extract information about the fast electrons in the wire. Fig. 3 shows the proton spectrum. Protons with maximum energy of 18 MeV were emitted from the wire in the radial direction. Also, the two-temperature fitting (black line) of the proton spectrum gives cold temperature, \( T_{\text{cold}} = 0.72 \text{ MeV} \) and hot temperature, \( T_{\text{hot}} = 3.38 \text{ MeV} \). The proton spectrum was used to constrain the energy spectrum of fast electrons that were injected into the wire in numerical modeling.

4. LSP Simulations

The simulations were performed with the hybrid PIC code LSP in 2-D RZ cylindrical geometry for the experimental conditions described above. The proton emission was modeled by adding a contaminant proton layer on the surface of the wire (40 \( \mu \text{m} \) diameter, 1 mm long). Due to long scale-lengths (~ mm) and time-scales (~ 10 ps) of the problem, simulating laser-plasma interaction (LPI) inside the cone is extremely computationally expensive. Instead of LPI, we performed a series of simulations by injecting fast electrons with different

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**Fig. 1** Schematic of cone wire target showing the OMEGA EP laser incident inside the hollow cone.

**Fig. 2** Plot showing increase in copper \( K_{\alpha} \) yield from wire as a function of laser energy.
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The beam was injected for the duration of 10 ps, consistent with the laser duration described above. The axially escaped electrons were calculated by counting the fast electrons crossing through an extraction plane placed 200 \( \mu \)m away from the other end of the wire. We performed simulations for three different cases: i) fast electron temperature of 8 MeV and laser to fast electrons conversion efficiency of 10%. ii) fast electron temperature of 8 MeV and conversion efficiency of 1% and iii) fast electron temperature of 1 MeV and conversion efficiency of 10%. The transverse temperature of the electrons’ beam was initialized at 1 MeV for all three cases. The spectra of radially emitted protons (Fig. 4 (a)) and axially escaped electrons (Fig. 4 (b)) for these different input fast electron beams are shown below.

As can be seen from figure 4, the proton spectrum (Fig. 4 (a)) was sensitive to both \( T_{\text{hot}} \) and \( \eta \). For example, with 1 MeV fast electron temperature the spectrum (solid blue line) fell off sharply compared to the 8 MeV cases. Similarly, for the same fast electron temperature of 8 MeV, the numbers of protons emitted with 1% conversion efficiency (dotted line) was found to be proportionately less than those with the 10% conversion efficiency (black line with ‘+’ marks). Also, the escaped electron spectrum (Fig. 4 (b)) was found to be proportional to the temperature of injected fast electrons. Thus, we demonstrate that simultaneous measurement of escaped electron spectrum and radial proton spectrum can provide useful information to characterize the fast electron spectrum generated inside the cone.

5. Summary

Experimental and hybrid PIC modeling results using copper K\textsubscript{α} and proton emission from a wire attached to the gold cone show that the conversion efficiency increases with the laser energy and protons are produced primarily due to three factors: i) the divergence of the fast electrons’ beam entering into the wire ii) the collisional scattering of fast electrons and iii) formation of a cloud of electrons around the wire due to the refluxing of electrons from the far end of the wire.

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