Enhanced Energy Localization and Heating in High Contrast Ultra-Intense Laser Produced Plasmas via Novel Conical Micro-Target Design

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Abstract. We report new experiments showing enhanced laser-target coupling and energy localization using nano-fabricated micro-conical Cu targets performed at the 100 TW CPA laser at LULI. A comparison was made between 1ω (λ = 1.057 µm, I = 10^19 W/cm²) and 2ω (λ = 0.53 µm, I = 4-8 x 10^18 W/cm²) irradiation to determine the effect of ASE induced pre-formed plasma filling the cone, using as principal diagnostics 2D Cu Kα imaging (transverse and rear-side), and high-resolution conical crystal spectroscopy of the Cu Kα bands. The 2ω irradiation exhibits laser absorption up to 50 µm deeper into the cone tip (versus at 1ω), with a commensurately smaller Kα emission zone. Spectroscopy indicates a higher average charge state for the Cu emission at 2ω, with some shots exhibiting up to at least O-like emission. We deduce that micro-cone targets have similar performance in terms of material heating as a 50 µm diameter reduced mass target, despite a 900-fold larger mass. The observed enhancement in energy localization and heating in the cone geometry is supported by 2D collisional PIC simulations which indicate the presence of self-generated resistive magnetic field structures (≥ 10 MG) which confine the energetic electrons to the tip region.
1. Introduction

Ultra-intense short pulse laser irradiation of solid targets has shown promising potential for creating strongly coupled plasmas [1], with the prospect for isochoric heating to high temperatures. However, due to the rapid diffusion of hot electrons away from the laser absorption region, the heating appears to be transient (~1-5 ps), resulting in large temperature and density gradients within the target. Various techniques have been suggested to confine these energetic electrons to a small target volume to improve the uniformity of the heating [1-5]. In addition, sharp-tip conical targets have been proposed to increase laser-target coupling efficiencies via optical guiding and enhanced absorption of the laser light and electron surface flow toward the cone tip [6]. With respect to the Fast Ignition fusion scheme, reentrant cone geometries are being utilized to improve energy transport closer to the imploded compressed core about the cone tip [7]. However, recently Baton et al. [8] showed that preformed plasma due to the amplified spontaneous emission (ASE) prior to the main pulse, fills the cone and degrades the respective coupling efficiencies.

2. Experimental set up and results

We perform experiments at high contrast laser irradiation using the 100 TW CPA laser at LULI. Free-standing funnel-shaped micro-conical Cu targets as well 50-300 μm diameter multi-layered reduced mass targets (RMTs) are tested at both 1ω (contrast ~10^{-6}, λ = 1.057 μm, I = 10^{19} W/cm^2) and at high-contrast 2ω (contrast ~10^{-12}, λ = 0.53 μm, I = 4-8 x 10^{18} W/cm^2). The hot electron propagation and target heating are inferred via x-ray emission from Cu Kα, which is spatially resolved in a narrow x-ray energy range by two spherically-bent Bragg crystal imagers [9] and spectrally resolved by a time-integrated high resolution conical crystal spectrometer [10].

Figure 1 shows the transverse and rear-side Kα images and the x-ray spectra for two funnel-cone targets irradiated with respectively 1ω (figure 1a), and 2ω (figure 1b) light. The imagers demonstrate focused emission from deeper (~50 μm) within the cone with a reduced radial extent at 2ω versus 1ω. The 1ω cone spectra exhibits cold Kα emission with a large diffuse background (grey curve), which is consistent with a large-scale preplasma at 1ω irradiation, which fills the cone [8] and resonantly accelerates electrons to several of MeV energies [11]. In comparison, the 2ω spectra shows a shift in the ionization balance to higher charge states of the Kα emission (≥ O-like Cu), indicating peak temperatures near ~400 eV at or near solid density. At high contrast, the laser light is able to propagate toward the cone tip while directly interacting and heating the solid density Cu cone wall along its path. We did consider whether the increased heating at 2ω was due to the lower mean energy of the hot electrons [12] by reducing the laser intensity (pulse energy) at 1ω a factor of 8, to correspond with the
predicted $T_{\text{hot}}$ at $2\omega$. We observe reduced heating and conclude that the enhanced heating at $2\omega$ is a result of improved laser penetration and coupling to the conical targets.

We also compare the spectra and rear-side $K_\alpha$ emission of the Cu cones to 50 and 300 $\mu$m planar RMTs at $2\omega$ irradiation (figure 2). The 300 $\mu$m target (black curve) shows a typical “cold” $K_\alpha$ doublet; whereas, the 50 $\mu$m and funnel cone targets (blue and red curves) exhibit “hot” $K_\alpha$ emission from highly ionized Cu ions as well as an intense continuum of what appears to be L-shell and/or $K_\beta$ emission. In fact, if we overlay the spectra from the funnel cone to the 50 $\mu$m RMT, we notice a remarkable similarity. This suggests, at least empirically, comparable peak temperatures are achieved. The enhanced heating with decreasing RMT volume is similar with other works [4] and demonstrates the effect of the ambipolar confinement of the hot electrons. This, along with the presence of the ionic Cu $K_\alpha$ emission, confirms that the relative intensity of the L-shell and/or $K_\alpha$ emission is associated with hot emission. Furthermore, the rear-side images (figure 2a,b) indicate that the cone emission is similar in radial extent to the 50 $\mu$m RMT. Conversely, the 300 $\mu$m RMT target (figure 2c) shows emission throughout the entire foil from the lateral transport of hot electrons and a brighter central region representing the laser focal spot. Taking into account the 900-fold larger total mass of the cone foil versus the 50 $\mu$m RMT, there must be an additional confinement mechanism, which focuses and confines the energetic electrons to heat the cone tip region to high thermal temperatures.

3. Simulations

We perform 2D collisional Particle-In-Cell (PICLS) simulations of high intensity laser-target interactions at high contrast irradiation to determine the topology of the resistive magnetic field structures and heating of the target by lower energy electrons ($\lesssim 100$ keV) circulating in the return current. The code PICLS [see, e.g., Ref. 5] employs a binary collision module, extended to include both relativistic collisions and collisions between weighted macro-particles. Simulations are carried out with an $P$-polarized incident Gaussian laser pulse of 1 $\mu$m wavelength, 350 fs duration and a spot size of 10 $\mu$m FWHM on a target with a density of $\rho = 10_n$. The plasma is initially fully ionized with 4 Cu ions and 116 electrons per cell on a mesh size of $\Delta x = \Delta y = 80$ nm. The target is initially cold (i.e., electron temperature is zero) and progresses with a time step equal to 0.26 fs.

Figure 3 shows the magnetic field topology of a 10 $\mu$m thick funnel cone and a 50 $\mu$m diameter by 27 $\mu$m thick Cu RMT foil at 2 ps after the arrival of the laser pulse. Compared to the RMT foil, the funnel cone exhibits strong resistive (bulk) magnetic fields of up to ~10 MG, particularly in the flared region. Lasting for several of ps, this magnetic field initially arises as electrons are forced into the resistive wall around the laser absorption region, where it is driven by the gradient in resistivity between the heated tip region and the colder flared region of the cone. Figure 3 also plots the respective electron energy density (i.e., average energy times average density), which consists of the...
small fraction of very energetic electrons (responsible for producing Kα emission), and the thermal electrons which heat the bulk (responsible for the Cu ionization state and L-shell emission). The funnel cone demonstrates more uniform heating throughout a reduced volume at the cone tip than the 50 μm foil (coupling efficiencies are ~87% for the cone and 22% for the RMT), which appears to be due to the magnetic confinement of the energetic electrons within the cone walls.

4. Conclusions
We have shown that conically shaped targets irradiated with high-contrast ultra-intense laser pulses, exhibit enhanced material heating due to strong self-generated resistive magnetic fields within the target bulk, which localize the hot electrons to a reduce volume at the tip region. Moreover, these fields degrade with large-scale length pre-formed plasma filling the cone tip, which inhibits laser light propagation, absorption and heating at solid density. We deduce that at high contrast, funnel-shaped micro-conical targets exhibit similar performance, in terms of material heating, as a 50 μm diameter reduced mass target, and therefore, similar high peak electron temperatures are inferred.

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