Evidence for surface heating of wire plasmas using laser irradiated cone geometries

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Introduction

Cone-guided compression offers a number of advantages for the fast ignition approach to inertial fusion energy[1,2]. The path of the PW laser pulse is kept free of plasma, by-passing the growth of plasma instabilities that could, potentially, prevent energy transfer to the compressed dense core plasma. The deuterium-tritium fuel is assembled close to the tip of the cone so that the fast electron beam does not have far to propagate, maximising the energy coupling from the petawatt laser pulse to the thermal energy of the compressed plasma[3,4]. Recent three dimensional particle-in-cell simulations have indicated that this energy coupling may be increased by self-generated magnetic fields that act to guide lower energy electrons (that are generated spatially in the wings of the focused laser pulse) into the compressed core[5]. Indeed, recent experiments have shown that the optical emission from rear surface in the 400 nm - 600 nm wavelength range for 10 μm - thick Al foils decreased in size but increased in intensity with cone attached targets[6].

In addition to these advantages for fast ignition, cone-wire geometries potentially offer other important applications for high energy density plasma science. Plasma pressures in the Gbar regime may be generated when the coupling efficiency is high and temperatures reach 2 - 4 keV, making them an interesting source for equation of state studies[7]. On the other hand, these plasmas may also be subject to magnetohydrodynamic instabilities over longer timescales[8].

Experiments are reported here for cone-attached target geometries that have intensities on target of 5×10^{20} Wcm^{-2}, an order of magnitude higher than any previously reported study. Different cone-wire assemblies were studied to compare their performance, particularly the energy coupling between the high intensity laser pulse and the wire-plasma. A number of complementary measurement techniques were used to diagnose the interaction, including shadowgraphy, interferometry, and a number of X-ray imaging techniques, including K_α X-ray imaging. Density

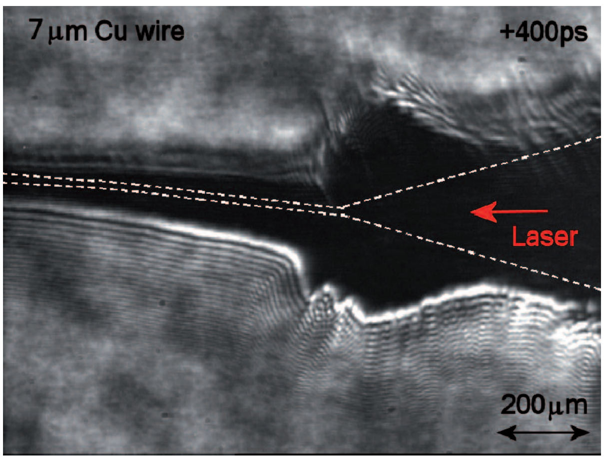

Figure 1. Shadowgram of a cone-wire target irradiated with 290 J on target.

profiles, unfolded from the interferometric measurements, indicate that a 7 μm copper wire plasma reaches a maximum initial temperature of 350 eV, by comparison with hydrodynamic simulations. It is found that the density profiles can only be reproduced provided that there is an initial non-uniform temperature profile on the wire, with the hottest region located on the outer region of the wire.

Experiment

The experiment was conducted on the Vulcan petawatt laser system at the Rutherford Appleton Laboratory. The Vulcan petawatt is an Nd:glass laser that is capable of delivering intensities of up to 5×10^{20} Wcm^{-2} on target at an operating wavelength of 1.054 μm. Typically 300J of laser energy was delivered in a pulse of 0.7 ps duration, and was focused onto target using an f/3 parabola to a spot size of 7 μm. Approximately 30% of the incident laser energy was contained within the central focal spot.

The expansion profile of the heated targets was diagnosed using an optical probe that was passed transversely across the target surface. The probe beam was created from a small part of the main beam that was frequency doubled to $2\omega_0$ (527nm). A polariser was also used to give the probe beam a 45° linear polarisation. The probe had a duration of 0.7 ps and was timed to cross the target 400 ps after the main interaction pulse.

In this experiment, a 7-cm diameter, 40-cm focal length achromatic lens was used to collect the probe light after the target. The image was relayed outside of the target chamber where the beam was split, providing a shadowgraphy channel and a Nomarski interferometer. An eight-bit Charge Coupled Device (CCD) recorded the shadowgrams onto a personal computer, whereas a 16-bit Andor Technology CCD was used for the interferometry measurements. The total f-number of the imaging system was f/12 and the magnification was ×5. The spatial resolution was 12 μm for both diagnostic channels.

The first gold cone target, manufactured at Osaka University, had an opening angle of 30° and had a 7 μm-thick gold end wall. The 1 mm wire targets were attached to the cone tip by a glue joint of <5 μm. For comparison, identical opening angle gold cone targets, manufactured at General Atomics, were irradiated. In these cases, the 1 mm wire targets were embedded mechanically so that the wire itself formed the end wall of the cone and the end wall around the wire was sealed with a glue joint. In that case, the electrons had to traverse 5 μm of glue and 10 μm of copper before emerging from the end of the cone. The copper wires were 10 μm and 20 μm diameter.

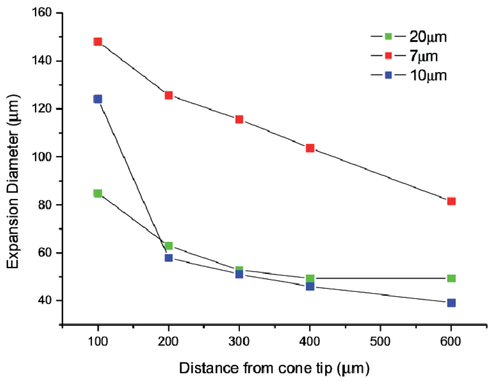

Figure 2. Measurements of the inaccessible region as a function of distance from the cone tip for different wire diameters.

Figure 1 shows the cone-wire shadowgram of the Osaka University cone-wire target that had an initial wire diameter of 7 μm. Similar shadowgrams were obtained for the other targets that were irradiated. The initial target position is included as a dotted line to aid the eye. These shadowgrams all showed that the tip of cone has exploded radially much faster than the attached wires. The differences in the glue joints, which strongly affect the energy coupling to the wire plasma, are too small to affect the overall expansion profile around the cone tip. The size of the inaccessible region along the wire length is shown in Figure 2 for the different cone-wire attached targets. Clearly, the energy coupling is maximized for the Osaka University cone-wire target as this shows the largest radial expansion compared with the other assemblies.

The amount of energy transferred to the attached targets was inferred from the expansion profiles extracted from the interferometric data. Figure 3 shows an interferogram of the same laser-irradiated cone-wire target that had an initial wire diameter of 7 μm. This data was used to create a two-dimensional (2D) density map, assuming that the plasma expansion is approximately cylindrically symmetric. The image was loaded into the IDEA (Interferometrical Data Evaluation Algorithms) software package. The 2D phase maps that were generated were used to obtain density profiles as a function of position by selecting line across the phase map perpendicular to the original wire position. Each line drawn at a certain distance from the cone tip gave a radial density profile. In order to generate a complete 2D density map $n(r,z)$, a program called BASIS was used. BASIS took the phase information generated by IDEA and performed a series of Abel inversions (based on the BASEX method[9]) to produce a 2D density map. Figure 4 shows the 2D density profile extracted from the phase map information. The maximum electron density that can be obtained from this measurement is limited to 5×10^{19} cm^{-3} due to refraction of the probe light out of the collecting optics.

To model the expansion of the plasma, the one-dimensional Lagrangian hydrodynamic code MEDUSA was used in cylindrical geometry. The initial electron temperature was set and the expansion profile calculated as a function of time. The 3.5 μm radius Cu plasma was divided into 80 zones and the flux-limit set at 0.1. The simulation was terminated at 400 ps to match the probe

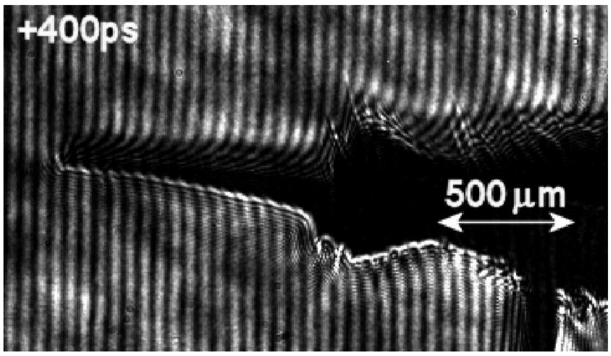

Figure 3. Interferogram for the 7 μm diameter copper wire.

timing. Both the size of the inaccessible region seen in the shadowgrams in Figure 3 and the density profiles in Figure 4 were used to infer the initial plasma conditions. It is interesting to note that a single temperature in the wire produced an expansion profile that remained sharp edged and overdense to the probe light (i.e. above 5×10^{19} cm^{-3}) at 400 ps. The experimental data could only be reproduced when the outer surface of the wire plasma was heated to a higher temperature than the core during the interaction. The radial expansion profile was found to be insensitive to core temperatures in the range of 20 eV - 100 eV. In Figure 5 the experimental derived radial density profile is shown at 400 µm along the wire surface from the cone tip. Also shown in the simulated density profile where the outer 0.5 µm of the wire was heated to 350 eV.

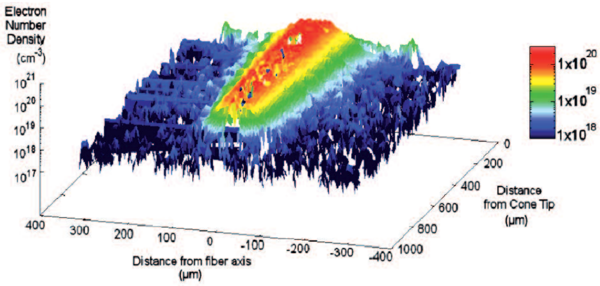

Figure 4. 2D density profile for 7 µm diameter copper wire.

These observations support the particle-in-cell energy transport calculations presented in reference[7] where the radial electric field generated to balance the azimuthal magnetic field and confine the fast electron flow to the wire was maximized close to the wire surface.

Information about the temperature gradient along the wire-plasma length cannot be obtained in an unambiguous manner from the optical probe data alone, as it is likely that the expansion of the cone tip plasma obscures the heated region closer to the cone tip where the temperature gradient is expected to be greatest. An unambiguous temperature gradient profile was obtained by analysis of the X-ray images and these are reported elsewhere in this report[10].

When one integrates the total energy required to heat the Cu wire target along the total length one finds that approximately 1% of the total laser energy was transferred to the wire during the interaction. This compares with approximately 4% energy coupling for 5 µm diameter carbon wires irradiated with the petawatt laser at Osaka University, reported in reference[7]. There the intensity on target was 1×10^{19} Wcm^{-2} It may be possible to increase the energy coupling substantially under the experimental conditions reported here by increasing the diameter of the wire provided, as we have demonstrated, that the glue joint is minimized.

In conclusion, different cone-wire assemblies have been compared experimentally. The energy coupling was optimised for targets with a small <5 µm glue joint attaching the wire to the cone. Information obtained from shadowgraphy has confirmed that the energy absorption is maximized close to the cone tip. Interferometric measurements have confirmed that the energy is transported along the wire surface, by comparison of the radial expansion profiles with hydrodynamic simulations.

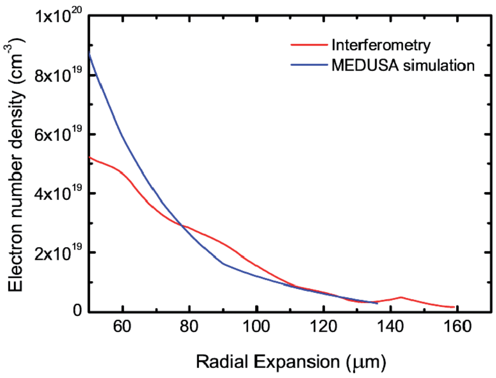

Figure 5. Experimental and computational radial density profiles for 7 µm diameter copper wire 400 µm from the cone tip.

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