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Experimental observations of transport of picosecond laser generated electrons in a nail-like target

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The transport of relativistic electrons, generated by the interaction of a high intensity (2×10^{20} W/cm^2) laser, has been studied in a nail-like target comprised of a 20 μm diameter solid copper wire, coated with ~2 μm of titanium, with an 80 μm diameter hemispherical termination. A ~500 fs, ~200 J pulse of 1.053 μm laser light produced by the Titan Laser at Lawrence Livermore National Laboratory was focused to a ~20 μm diameter spot centered on the flat face of the hemisphere. K_α fluorescence from the Cu and Ti regions was imaged together with extreme ultraviolet (XUV) emission at 68 and 256 eV. Results showed a quasiexponential decline in K_α emission along the wire over a distance of a few hundred microns from the laser focus, consistent with bulk Ohmic inhibition of the relativistic electron transport. Weaker K_α and XUV emission on a longer scale length showed limb brightening suggesting a transition to enhanced transport at the surface of the wire. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2815790]

The transport of laser generated relativistic electrons in solid materials is critical to the development of fast ignition (FI) schemes[1] for inertial confinement fusion,[2] particularly that variant in which the igniter laser is incident into a re-entrant gold cone,[3] and also for the creation of laser generated ultraintense x-ray sources.[4,5] Electron driven x-ray fluorescence measurements have proven a useful tool for measuring the penetration of energetic electrons within a variety of solid targets.[6,7] Ohmic inhibition of electron transport occurs when the Ohmic potential from the return current stops forward propagation of the relativistic electrons.[8] While studies have been carried out in both cold and heated dense plasmas,[9,10] experimental data establishing the extent to which Ohmic inhibition limits the flow of energy into a solid target, or dense plasma, remains limited. It is also an open question as to what extent high energy electrons will tend to flow along the surface of a conductor. Both of these issues are of importance in understanding the behavior of hot electrons in a re-entrant cone guided FI target.

The observation of relativistic electron transport in intermediate and high atomic number (Z) metallic targets, relevant to fast ignition and x-ray backlighting, is problematic due to the opacity of the materials to their own K-shell fluorescence. Furthermore the ability to model the transport with particle-in-cell (PIC) and hybrid PIC codes is limited by the computer power currently available. The time required to solve a given problem is roughly proportional to the size of the computational mesh. In such particle simulations, it is necessary to resolve the Debye length, in order to avoid unphysical self-heating. Consequently it is immensely computationally demanding to model large solid density targets, at appropriately low temperatures. Thin wires afford a low mass geometry for experiments that allow ready diagnostic observation and numerical modeling. It is practically challenging to irradiate the end of a sub-50 μm diameter wire with a high intensity short pulse laser. Employing a cone interface with the wire, such as described in Ref. 9, adds substantial additional mass and unwanted complexity.

We present an experimental study using "nail" targets. These are 20 μm diameter Cu wires with an approximately 80 μm diameter, roughly hemispherical termination, formed by melting the wire end and subsequent machining. These targets were also coated with 2 μm of Ti (before machining). In addition, 50 μm Ti wire targets (without nail head) were also shot. Results for these Ti wires were compromised by the target being of comparable diameter to the pointing accuracy of the laser.

The targets were illuminated by an ~500 fs, ~200 J pulse of 1.053 μm laser light from the Titan laser[11] in a ~20 μm diameter spot centered with ~20 μm pointing accuracy[12] on the flat face of the nail head.

The diagnostic layout is shown in Fig. 1. Two spherically bent Bragg crystal monochromatic 2D x-ray imagers, one set up to view Ti K_α radiation at 4.5 keV (resolution ~20 μm, magnification 11×) and the other to observe Cu K_α emission at 8 keV (resolution ~20 μm, magnification 7×) were employed to record the fluorescent emission from

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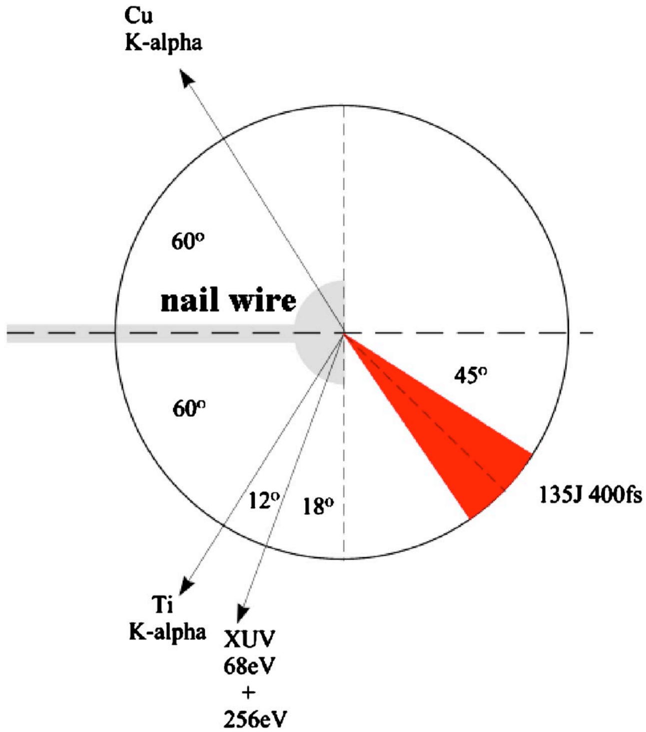

FIG. 1. (Color online) Schematic of the experimental arrangement.

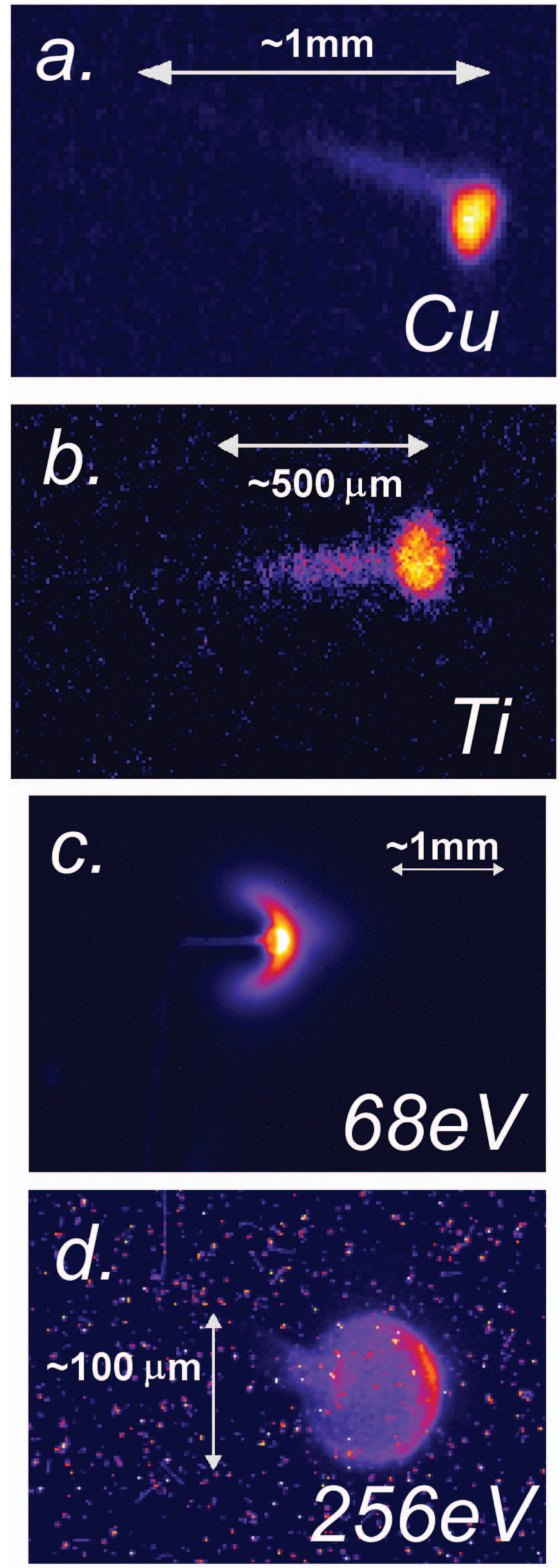

FIG. 2. (Color) Results from a single shot onto a nail target. (a) Cu K_α emission; (b) Ti K_α emission; (c) 68 eV XUV emission; (d) 256 eV XUV emission. Similar data were collected for each of the four targets fielded.

the targets.[13] XUV emission at 68 eV (resolution ~12 μm, magnification 11×) and 256 eV (resolution ~10 μm, magnification 11×) was also collected by multilayer mirror imagers.[14] These time integrated records show the thermal emission from the plasma in contrast to the K_α diagnostics, which only record emission generated by the hot electrons. Simultaneous measurements taken with both a highly oriented pyrolytic graphite (HOPG) spectrometer and a single photon counting camera, both looking at Cu *K*-shell emission allow for absolute brightness to be inferred from the K_α channels.

Figure 2 illustrates typical data from a single shot. In this figure, scale bars have been corrected for the angle of view to show distances along the horizontal wire, with the exception of the 256 eV image (d) in which the scale is correct for measurements in the vertical direction.

The K_α channels both show bright emission from the nail head and a quasiexponential fall off of brightness along the wire from the nail head with a scale length of about 150 μm. Figure 3 shows a lineout taken from the Cu imager for a typical shot which has been calibrated using the single photon counting diagnostic. This latter diagnostic had a direct view of the laser spot meaning that the calibration, which assumes isotropic emission from the target, is likely to be out by a factor of a few, given that the hot electron current is nonuniform within the nail head and the attenuation length of the K_α photons within the nail head is 22 μm. In addition to this error in the absolute magnitude, small changes are to be expected in the reflectivity of the imager to the K_α emission in the brightest regions, due to the thermal shifting and broadening of the emission line at high temperatures, and the limited bandwidth of the imager.[15] This effect modifies the scale length of the falloff of the emission, however, most of the K_α production, and the highest temperatures, occur in the nail head. Related analyses of other experiments show that this effect should be small in the wire itself (on the order of 1%–2%).[16] The laser-K_α coupling efficiency to the target as a

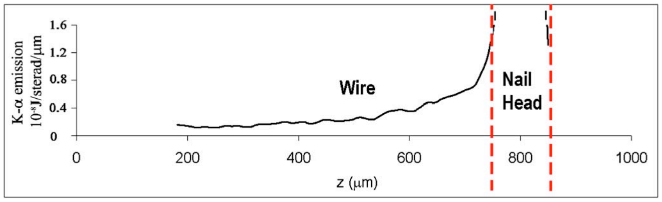

FIG. 3. (Color online) Lineout showing Cu K_α emission along a nail wire.

whole, also determined from the single hit photon counting diagnostic, is on the order of 10^{-5}. The wires are transparent to their K_α fluorescence (attenuation lengths, calculated using the Los Alamos TOPS code[17] are 22 and 20 μm for Cu and Ti, respectively), and opacity effects must be taken into account in inferring the K_α emissivity from such data. The decay of the emission observed is, however, consistent with bulk Ohmic inhibition of the hot electron transport.[8,18] If we consider the ponderomotive potential of the laser is given by $\Phi_{\text{pond}}=[(1+a_0^2)^{1/2}-1]mc^2$, where $a_0=e\varepsilon/m_e c\omega$ is the dimensionless vector potential of the laser field, and assume $T_{\text{hot}} \simeq \Phi_{\text{pond}}$, then we would expect $T_{\text{hot}} \sim 5$ MeV and a corresponding mean penetration depth, considering only collisional effects, of greater than 500 μm. Conversely, taking the model of Ohmic inhibition given by Bell *et al.*,[8] and assuming the conductivity of Cu to be $\sim 1\times 10^7\ \Omega^{-1}\ \text{m}^{-1}$, which is consistent with that expected in the laser spot, we obtain a hot electron density scale length of ~ 150 μm, agreeing well with the emission scale length observed in the experiment, which is of the same order.

A 50 μm solid Ti wire with no nail head irradiated on its flat end showed limb brightened Ti K_α emission extending around the 90° bend in the wire (which was mounted in a similar fashion to the nail targets, as described earlier); see Fig. 4. The scale for the main image is corrected for the view angle such that length along the horizontal wire is correct. The scale in the plot below is appropriate to measurements in the radial direction of the vertical portion of the wire. The observation of this limb brightening in the fluorescent emission, from a source that is somewhat transparent to its fluorescence at 4.5 keV, implies preferential hot electron current flow along the surface of the wire. The fact that this limb brightening is not observed in the horizontal portion of the wire suggests that the trend to enhanced transport at the surface increases at greater distances from the nail head. Note that, given the limited resolution of the fluorescence imagers, it is not possible to establish whether K_α limb brightening is present in the nail targets due to their smaller diameter.

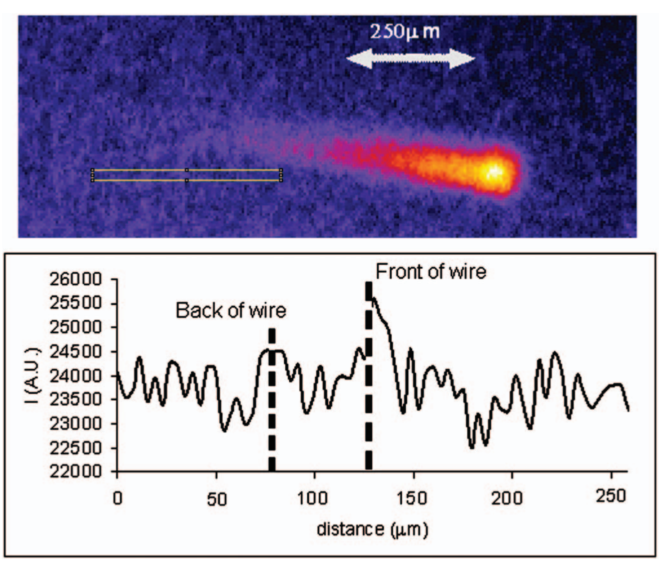

FIG. 4. (Color) K_α emission image from a 50 μm diameter solid Ti wire shows limb-brightened emission extending around a 90° bend. The plot below shows a lineout taken at the position of the yellow box in the main image.

Limb brightening is also observed in the XUV emission from the wire in the data presented in Figs. 2(c) and 2(d). Here the situation is more complicated because the wires are highly opaque at XUV wavelengths. The intensity of the emission observed at a particular location at the image plane corresponds to the temperature of the plasma ~1 radiation mean free path depth into the target. If the electron driven heating is nonuniform, such that the wire forms a relatively cold core, surrounded by a hot, optically thin, corona, then the radiation emanating from the limb will be more intense. This is a consequence of the greater thickness of hot plasma being subtended by rays extending from the limb region, at the target plane, toward the camera. If the heated layer were optically thick, then limb brightening would not be observed, since all rays would emanate from similarly hot plasma. In this case the brightness would be uniform except at the extremities, where less than a mean free path of plasma is presented along the ray to the camera. Figure 5 presents a graphical illustration of the anisotropic heating induced limb brightening effect alongside an enhanced view of the horizontal portion of the wire shown in Fig. 2(c). It can be seen that limb brightening is present, suggesting the presence of an optically thin hot coronal layer, and furthermore, this limb brightening becomes more pronounced with increasing distance from the nail head. The most likely explanation for this is that the hot coronal region near the nail head is thicker, approaching the case where the emission comes entirely from a hot optically thick layer, which, as just described, would result in a uniform pattern of emission from the bulk of the wire. The preferential surface heating implied by the observations may in part be a result of a tendency of the hot forward going electrons to flow along the surface, as evidenced by the results from the fluorescent imager. However, the more collisional cold return current, which is expected to flow within a skin-depth of the surface of the wire, is thought to drive the majority of this surface heating.

In summary, the observation of limb brightening in the fluorescent emission from thin wire targets implies preferential hot electron current flow at the surface of the wire. Measurements of thermal emission from the same targets suggest enhanced surface heating, which, though it is expected to be largely a consequence of the cold return current, may be exacerbated by any tendency of the hot forward current to flow near the surface. The presence of an Ohmic barrier to relativistic electron transport is suggested by the quasiexponential decay, over a distance of ~ 150 μm, of the fluorescent emission along the length of the wires. These data are being used to test hybrid PIC and PIC numerical models of

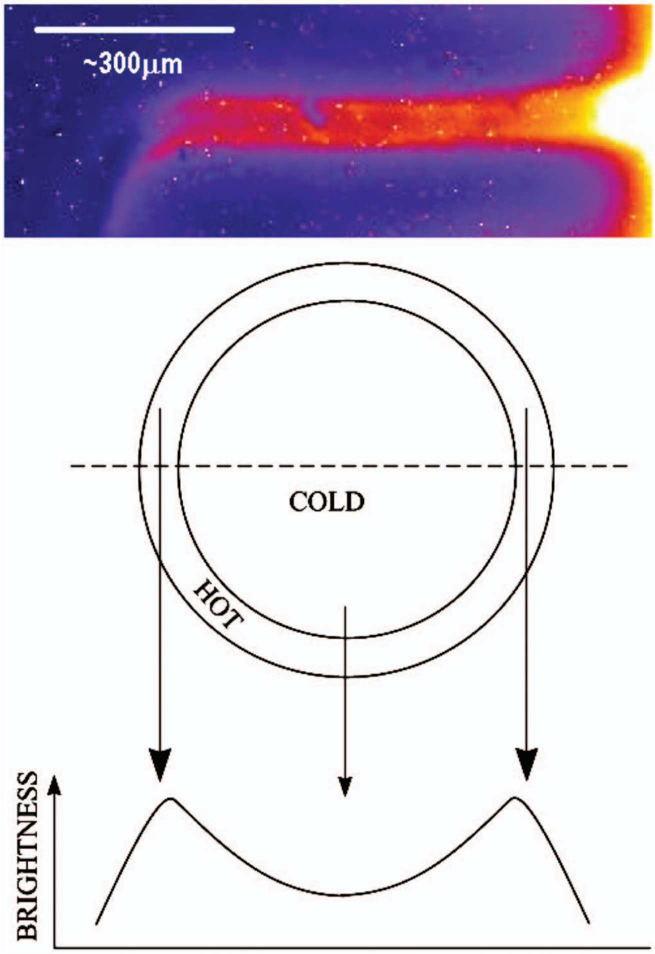

FIG. 5. (Color) Enhanced view of the horizontal portion of the wire shown in Fig. 2(c) shown above an illustration of the limb brightening effect.

the electron transport, in particular e-PLAS,[19] LSP,[20] and PICLS.[21] Future publications will compare more detailed quantitative results of the experiment with this numerical modeling.

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