# High-Intensity-Laser-Driven *Z* Pinches

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Experiments were performed in which ultrahigh intensity laser pulses ($I > 5 \times 10^{19}$ W cm$^{-2}$) were used to irradiate thin wire targets. It was observed that such interactions generate a large number of relativistic electrons which escape the target and induce multimega ampere return currents within the wire. MHD instabilities can subsequently be observed in the pinching plasma along with field emission of electrons from nearby objects. Coherent optical transition radiation from adjacent objects was also observed.

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Since the technique of chirped pulse amplification [1] was first used in high power laser systems, peak powers have increased dramatically, and it is now possible to perform experiments at intensities approaching $10^{21}$ W cm$^{-2}$. One of the important characteristics of interactions at such intensities is the efficient conversion of laser energy into hot electrons and the consequent generation of beams of relativistic electrons [2], protons [3], and gamma rays [4]. The average energy of the hot electron population can exceed 1 MeV, and this also leads to the generation of significant return currents in the plasma.

Return currents can be produced as the laser-generated beam of hot electrons penetrates the plasma. For beams with currents greater than the Alfvén limit, a large neutralizing current of cold plasma electrons moving in the opposite direction is required for propagation. These return currents can cause Ohmic heating in the region of the plasma which is close to the interaction zone.

Another related source of return current is that due to the population of very energetic electrons which "escape" the plasma and which, consequently, create a large electrostatic potential on the target due to charge separation. In general, the number of electrons which can escape in this way is much less than those in the neutralized electron beam which penetrates into the plasma. The voltage which can be produced on the target is dependent on the target geometry but the peak potential is approximately the ponderomotive potential of the focused laser pulse since this corresponds to the electrostatic potential in the plasma due to the charge separation which can be maintained by the light pressure. When these fast electrons escape the target and establish this potential, a number of phenomena can be observed because of the generation of return currents in response to the resulting large scale electric fields.

There have been several previous experiments using nanosecond duration $CO_2$ laser pulses ($\lambda = 10.6\ \mu$m), which have studied the effect of return currents generated in this way. Benjamin *et al.* [5] reported the heating of thin fibers from the production of return currents and Hauer and Mason [6] used laser-produced return currents ($\sim$0.8 MA) to implode thin cylindrical liners. These experiments were performed with laser irradiance ($I\lambda^2$) up to $10^{18}$ W cm$^{-2}$ $\mu$m$^2$.

In this Letter, we present the first observations of the effect of return currents generated during much higher intensity laser plasma interactions (up to $5 \times 10^{19}$ W/cm$^2$) and, crucially, from interactions using much shorter pulse duration ($\sim$1 ps). Return currents and target charging effects are especially important in our experiments since these greatly influence the propagation and energy deposition of the generated hot electron beams. Consequently, such experiments have implications for applications of laser-produced proton and electron beams [7]. Our results suggest that the fast rising currents associated with petawatt laser interactions may be sufficient to make detailed studies of the physics of radiative collapse in *Z*-pinch-like targets, which is presently not possible using modern pulsed power generators.

The first series of experiments observed the Ohmic heating and subsequent rapid expansion of thin wire targets due to the generation of these laser-generated return currents. An MHD $m = 0$ instability similar to that seen in *Z*-pinch discharge experiments was observed. The second observation was the measurement of intense well-localized optical emission at the second harmonic of the laser frequency from nearby grounded objects. This

  

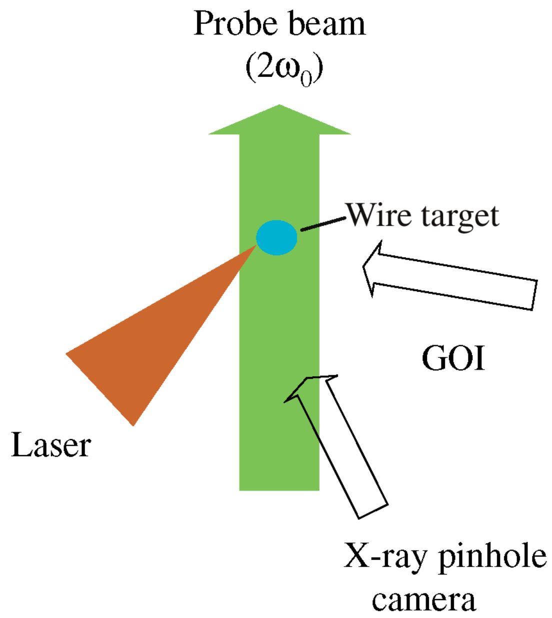


FIG. 1 (color online). Schematic diagram of experimental setup.

was likely due to significant field emission of electrons from these objects because of the large electrostatic potential generated. Aspects of the interaction were modeled using particle-in-cell (PIC) simulations.

The experiments were carried out with the VULCAN laser system at the Rutherford Appleton Laboratory. The laser wavelength was 1.054 $\mu$m, the pulse length was 0.9–1.3 ps, and the energy incident on target was between 60 and 80 J. The laser was focused using a parabolic mirror with a 60 cm focal length. The peak intensity was $5 \times 10^{19}$ W cm$^{-2}$ (focal spot diameter $\sim$15 $\mu$m). The target configurations were one, two, or three parallel wires assembled on top of a 3 mm diameter grounded brass stalk. The wires were typically 20 $\mu$m diameter hard tempered copper of length 3–5 mm. Gold and glass wires were also used. For multiple wire target assemblies, a second wire was placed away from the laser propagation direction to avoid any transmitted or scattered energy from the interaction of the laser with the target wire. The targets were probed at 45° to the interaction laser beam using shadowgraphy with a picosecond duration, frequency doubled probe beam (see Fig. 1). In addition, plasma self-emission was measured using a four frame optical gated imaging system. The framing time was 1 ns. The timing of the frames was adjusted to obtain "prompt" images at the time of interaction and at 1 ns intervals subsequent to the interaction. Notch filters were used to reduce the intensity of scattered laser radiation on the detector. A time integrated x-ray pinhole camera measured the x-ray emission region with high spatial resolution.

Shots with single wire targets showed intense optical emission (see Fig. 2). This emission was observed to be a maximum near the laser spot but could also be observed along the wire for distances of several hundred microns. It was most intense along the wire in the direction connected to ground, and there was little emission towards the free end of the wire more than a few tens of microns from the interaction region. The wire was observed to expand with an average velocity of $5 \times 10^4$ m/s—reaching a diameter of 124 $\mu$m in the first nanosecond. This optical emission and expansion of the wire is due to Ohmic heating by the return current generated by fast electrons leaving the target. These electrons from ground will move to compensate for the charge imbalance generated during the interaction. For picosecond laser pulses, the rate of rise of the return current is limited by the wire inductance $L$ and the hot electron temperature $T_H$, i.e., $L[(\partial I)/(\partial t)] \sim (k_B T_H)/e$ (i.e., tens of ps).

The expansion velocity of the wire during these experiments is similar to that routinely observed in single wire $Z$-pinch discharge, with currents of 100 kA–1 MA. As in $Z$-pinch experiments, an $m = 0$ MHD instability was observed in the wire as shown in Fig. 2(e). The observed instability has an average wavelength of 110 $\mu$m (although it varied between 270 and 40 $\mu$m). The theoretical wavelength for this instability can be estimated [8] and is $\sim$100 $\mu$m, for the likely parameters of these plasmas.

In single wire $Z$-pinch discharges (peak currents $>$100 kA), the wavelength of the observed instability typically increases during the current rise. At early times in the discharge, the instability has a wavelength of about 100 $\mu$m which increases to 1 mm at later stages of the current pulse. The wavelength of the $m = 0$ instability

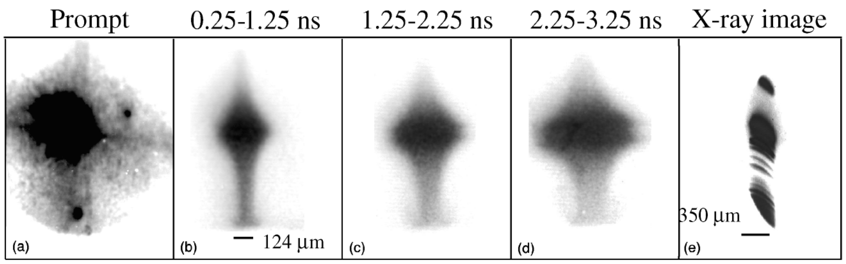


FIG. 2. A sequence of optical frames showing emission and expansion of the wire target. (e) Time integrated x-ray image showing $m = 0$ perturbations ($h\nu > 400$ eV). Optical and x-ray images have different magnifications.

in our experiment is relatively short compared to that observable on $Z$-pinch discharge experiments since the total energy in the current is much lower than in discharge experiments with long current pulses. Consequently, it is natural to expect that the background plasma temperature in a laser-driven $Z$ pinch ($<100$ eV) is lower than in pulsed power discharges—agreeing with the temperature dependence of the instability wavelength [8].

For very short current pulses, MHD instabilities will not have sufficient time to grow as the current rise is shorter than a typical MHD time. In our experiments, an MHD instability growth time is of the order of 0.1–1 ns (i.e., the Alfvén transit time across the pinch). The curved emission regions visible in the x-ray image are likely caused by the motion of the plasma after the current has ended and after such instabilities have stopped growing.

Experiments were performed with a second grounded wire adjacent to the wire target. Optical images clearly show well-localized second harmonic emission from the second wire. In Fig. 3, a second wire was placed 300 $\mu$m from the main wire target and a bandpass interference filter was used to measure only emission at the second harmonic frequency of the laser. The first optical frame is synchronous with the laser pulse. Intense second harmonic emission can be seen both at the laser spot position and from the second wire. The observed emission is due to the optical transition radiation [9]. The second wire expands to a diameter of 50 $\mu$m and the emission from the plasma lasts much longer than that from the target wire. The emission from the target wire is less and is of shorter duration than that from target wire when there was no second wire in the vicinity of the interaction. This is likely due to intense field emission from the second wire—which subsequently provides much of the return current for the hot electrons which escape during the interaction. Structured x-ray emission patterns due to MHD instabilities could also be observed on both wires in x-ray pinhole images of the interaction. In comparison, when two additional wires were used, second harmonic emission and plasma formation due to the generation of return current was observed only from one of the additional wires—that which was closest to the target wire.

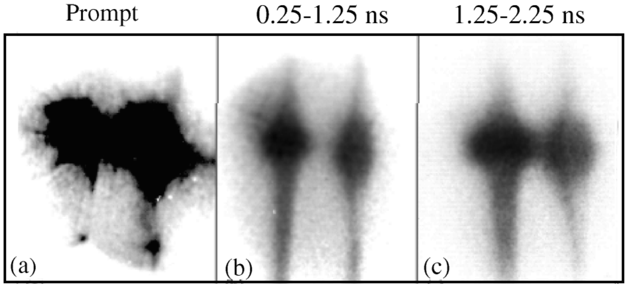


FIG. 3. Optical emission from two wire targets. The laser is incident on the wire on the right. The second wire shows more emission and faster expansion.

The total hot electron current can be estimated using a simple energy balance equation [6], $fIA = (J_H/e)kT_{\rm hot}$, where $f$ is the fraction of the absorbed energy into hot electrons, $I$ is the intensity of the laser in W/cm$^2$, and $A$ is the area of the laser spot. This suggests that the hot electron current in the vicinity of the interaction is approximately 4 MA, using an intensity of $5 \times 10^{19}$ W cm$^{-2}$, a spot size $\sim$15 $\mu$m, and 10% laser energy in hot electrons with an electron temperature of 2.0 MeV. This, consequently, would correspond to the magnitude of the return current in the wire near the interaction region. The target potential can also be simply estimated by assuming a Boltzmann distribution of energies for the escaping hot electrons and is given by $\phi = [(Ne)/(4\pi\varepsilon_o r)]\exp\{[-(k_B T_{\rm hot} - e\phi)]/(k_B T_{\rm hot})\}$, where $N$ is the total number of electrons which escape the plasma and $T_{\rm hot}$ is the ponderomotive potential of the focused laser pulse. Consequently, an electrostatic potential up to 10 MV can be generated for interactions at $10^{21}$ W/cm$^2$ and can extend for several centimeters around the target.

We have performed 2-1/2 D PIC simulations using the OSIRIS code [10]. In the simulations, a laser pulse ($I = 10^{20}$ W cm$^{-2}$) with a focal spot of 5 $\mu$m diameter is incident in the positive $x1$ direction on a flat target of about 4 $\mu$m thickness with a square "wire" placed 4 $\mu$m behind the foil. The electron density in the foil and the wire is 20 times the critical density. The dimensions of the target and the separation between the secondary wire and the target are less than that used in the experiments because of the computational cost. In the simulations, the electrons in the foil and in the wire are treated as distinct species and may be plotted separately. It is not possible to model the full range of collisional and collisionless behavior of this complex system but a 2D PIC model shows the essential features of the creation of a return current across the vacuum which can partially neutralize energetic electrons driven out of the primary target.

In Fig. 4(a), we plot the longitudinal phase space (momentum, $p1$ vs coordinate, $x1$) of the "foil" electrons at 120 fs. The electrons in the foil target are strongly bunched at a frequency of $2\omega$ due to the $\mathbf{J} \times \mathbf{B}$ force of the laser. Most of the foil electrons are reflected at a Debye sheath on the rear of the foil, but some escape the foil leaving a large positive charge on the foil. Figure 4(b) shows the $p1$-$x1$ phase space of the wire electrons at 180 fs. The electrons from the wire are accelerated towards the foil and reach energies of more than 4 MeV ($\gamma = 8$). The white lines drawn in Fig. 4(b) emphasize the bunching of the electrons leaving the wire which show a similar periodicity as the laser accelerated electrons. This may give rise to the emission of second harmonic (green) light from the unirradiated wire due to optical transition radiation. Indeed, this agrees with

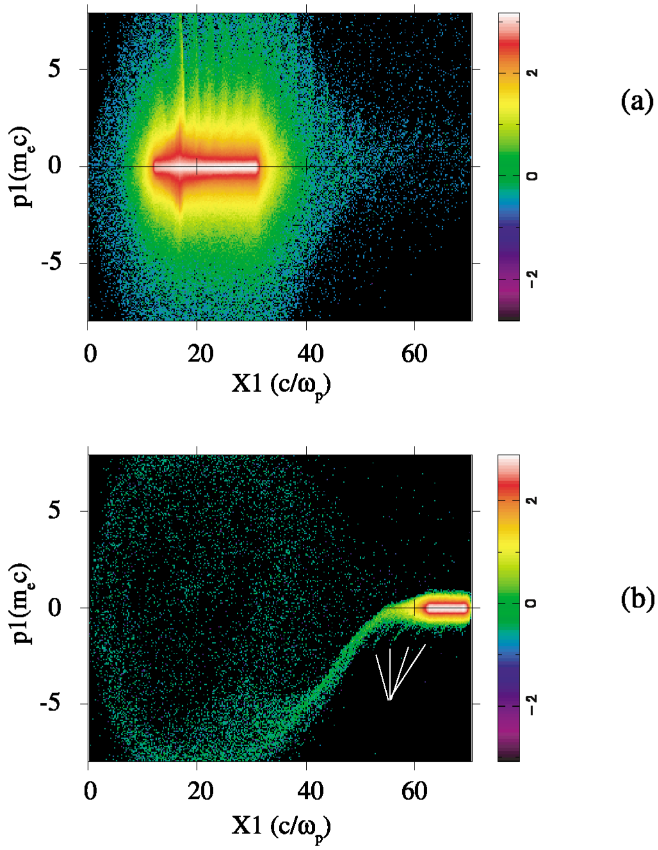


FIG. 4 (color). The longitudinal phase space of electrons from (a) a foil target at 120 fs and (b) secondary wire target at 180 fs using 2-1/2 D PIC simulations with OSIRIS code. White lines indicate the bunching of electrons at $2\omega$.

experimental observations where well-localized second harmonic emission is observed from the second wire.

In conclusion, we have shown the first results of Ohmic heating of thin wire targets due to the return current in short pulse laser-solid interactions, i.e., laser-driven $Z$ pinch. This current is produced by the escape of fast electrons from the target. We have also observed well-localized optical emission from the additional wire due to electron emission. In addition, we have observed growth of short wavelength modes of the $m = 0$ "sausage" instability which is indicative of relatively slower growth due to shorter current pulses. This result may have important implications for future $Z$-pinch experiments. $Z$ pinches were previously considered a good candidate for thermonuclear fusion experiments—since it was theoretically possible to radiatively "collapse" plasmas to high density. Such experiments using pulsed power drivers showed that the pinch becomes unstable early in the discharge if the current is slowly rising (many nanoseconds). Short wavelength MHD instabilities grow and eventually destroy the pinch before uniform collapse. However, for a laser-driven $Z$ pinch using a laser intensity approaching $10^{21}$ W cm$^{-2}$, it may be possible to increase dramatically the energy and number of fast electrons that escape the target. As a result, return currents produced by escaping fast electrons can exceed multi-MA levels and may have a current rise time which is significantly less than the growth time for unstable MHD modes. Hence, such fast rising currents may be sufficient to make detailed studies of radiative collapse which are presently not possible using pulsed power generators.

Finally, it may also be possible to enhance the x-ray power levels from laser-driven $Z$ pinches using wire array and x-pinch configurations—similar to present $Z$-pinch research using pulse-power drivers [11]. With a fast rising current such as that in the experiments described here, more uniform plasmas and, consequently, higher x-ray powers may be generated.

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