Characterization of an ultradense reproducible Z pinch[a)]

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The apparent complexity of the laser-plasma coupling in laser fusion target irradiation has stimulated the need for carefully controlled experimental studies of the laser-plasma interaction at the critical surface. A helium Z pinch has been constructed which produces a high density plasma, independent of the laser, enabling the separation of the laser-plasma interaction physics from the plasma formation mechanism. Its peak electron density (4×10^{19} cm^{-3}), critical density scale length (70–200 μ), and temperature ($\sim$25 eV) make it suitable for simulating and studying laser-pellet interaction mechanisms at CO_2 laser wavelengths. Detailed numerical modelling of these experiments was employed as a check against our diagnostics, as well as providing physical insight in those ranges of experimental parameters where measurements were not made.

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Early experiments in laser fusion quickly demonstrated that the relevant laser-plasma coupling physics was more complex than originally expected. To guide theoretical thinking, valuable simulation experiments were performed at microwave frequencies, using low-density plasmas. Independent production of the plasma allowed separation of plasma physics from the plasma formation process and permitted detailed comparisons with numerical simulation. Furthermore, diagnostics on these plasmas were well developed. Similar experiments using high-powered lasers (CO_2 or Nd-glass) have not yet been reported due to the lack of a suitable plasma. Reproducible overdense plasmas produced independently of the laser with appropriate critical scale lengths ($L = n_c/\nabla n_e \sim 50\ \mu$) and electron temperatures ($v_0/v_e \gtrsim 1$ where v_0 is the electron quiver velocity in the oscillating laser electric field and v_e is the thermal velocity) were not available. Since there is a need to study the nonlinear laser-plasma interaction directly,[1] we designed *a* Z-pinch plasma with the above characteristics allowing independent plasma production of a laser-pellet-like plasma. The laser-plasma interaction experiments with a CO_2 laser incident in the radial direction are being presented elsewhere.[2] This letter presents the experimentally determined plasma characteristics along with the results of our numerical model.

The design details of the device itself have been previously reported.[3] Figure 1 shows a schematic of the Z pinch and Fig. 2 is a photograph of the actual four-port target chamber. The pulsed energy source was a 14-μF 40-nH Sangamo capacitor charged from 10 to 18 kV. To maximize discharge speed, a coaxial design was chosen similar to other efforts.[4,5] The ringing period in this configuration was 8 μsec as determined by a pickup coil. Triggering was provided by a pin biased at one-half the charging voltaging switched via a 5C22 to −16 kV. The jitter was less than 40 nsec and could be improved by switching at higher voltages (e.g., −50 kV). The data presented in this letter were taken at a charging voltage of 12.75 kV. Peak current was 140 kA with time to pinch occurring at 900 nsec after discharge initiation. This precedes peak current by 1.1 μsec. The current at pinch time is 90 kA.

The electron density profile was determined using ruby doubled holographic interferometry at $\lambda = 347.2$ nm. The holograms were made perpendicular to the Z axis, and the radial profiles were extracted from the raw data by Abel inversion. Figure 3(a) shows the radial density profile of the pinch column taken at the midplane of the Z axis. The critical radius scale length

$$L = \left[\frac{1}{n_c}\left.\frac{\partial n_e}{\partial r}\right|_{r=x_c}\right]^{-1}, \qquad (1)$$

where x_c is the critical radius and n_c is the critical density ($n_c = 10^{19}$ cm^{-3}), is measured to be 70 μ for CO_2 laser illumination. The critical radius is measured to be 800 μ. Confirmation of the densities was made assuming conservation of particles and measuring compression from streak photographs. Furthermore,

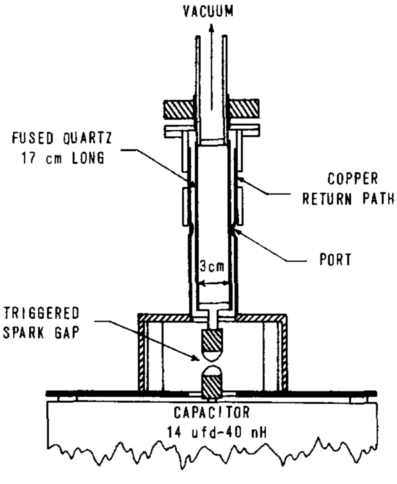

FIG. 1. Z-pinch design (the four beam port arms not shown).

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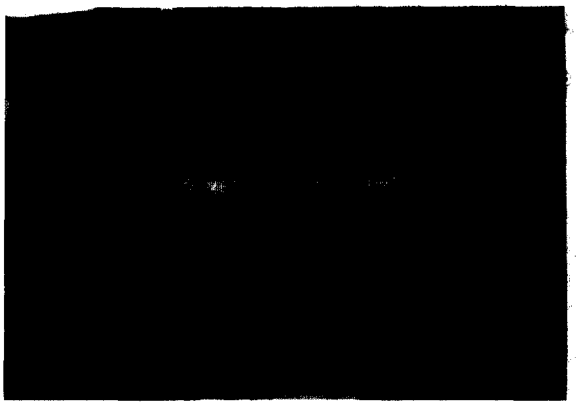

FIG. 2. Z-pinch target chamber.

spectroscopic streak photographs show complete continuum radiation at the pinch with no observable lines. Stark profiles of the He I 5876-Å line before and after the pinch indicated electron densities in excess of 6×10^{18} cm^{-3}. From the interferograms one can determine the effective charge Z_{eff} by comparing the integrated electron number to the available electrons in the tube prior to the discharge. We measure a $Z_{eff}=2$ implying full ionization.

Measurement of the electron temperature has proved to be quite difficult. Stark broadening of He I lines at these densities exceeds 1000 Å. This along with full ionization has precluded line ratio measurements. Saha calculations at these densities indicate a lower bound estimate of 10 eV to achieve $Z_{eff}=2$. The level of free-free x-ray emission has been too low to allow continuum ratio measurements, but an upper bound of 40 eV has been established. However, from a knowledge of the current, the temperature can be estimated from the Bennett pinch model[6] (in mks units),

$$T=\tfrac{2}{3}\,\mu_0 I^2/8\pi N_{el}, \qquad (2)$$

where I is the current at pinch time and N_{el} is the number of electrons per unit length; this suggests $T_e=25\pm5$ eV. While this measurement is not a direct one, it has given good agreement in previous Z-pinch research.[5] With $T_e=25$ eV and $L=70$ μ laser intensities as low as 10^{11} W/cm^2 may be utilized to achieve $V_0/V_{th}\cong1$.

The theoretical analysis of the dense helium Z-pinch experiment employed a one-dimensional two-temperature Lagrangian single-fluid MHD computer code.[7] The momentum equation is solved explicitly and the ion temperature and magnetic field diffusion equations are solved implicitly, while the electron temperature equation is solved using a modified predictor-corrector algorithm. Shock waves are handled using the usual artificial viscosity terms. The set of MHD equations is solved in one-dimensional cylindrical geometry (assuming θ and Z symmetry), allowing for radial and temporal variations of plasma parameters only.

The effective charge of the plasma is calculated using a set of equilibrium rate equations (slowly varying in time) based on a model which includes collisional ionization and collisional and radiative recombination. The ionization state rate equations model ground states of helium only, and the population densities of the states are calculated as functions of electron density and temperature. The effective charge is then implemented in the various transport coefficients, such as resistivity and thermal conductivity, which occur in the MHD equations. In addition, a radiation loss term is included in the electron temperature equation to account for bremsstrahlung and radiative recombination processes (integrated over frequency).

The simulation begins 0.1 μsec after the current discharge is initiated, and particle temperatures and effective charge are initialized at 3.0 eV and 1.0, respectively, although the plasma dynamics are rather insensitive to these initial conditions. All other input parameters are set so as to duplicate experimental conditions as accurately as possible. The simulation predicts that the first plasma pinch occurs at 0.74 μsec with a radius of slightly less than 1 mm at the pinch and magnetic fields of ~150 kG. The plasma is totally ionized at this time. Direct comparison of theory and experiment can be made by analyzing the density profile predicted by the computer simulation at the time of the first pinch [Fig. 3(b)]. The holography and computer simulation are in excellent agreement in terms of the

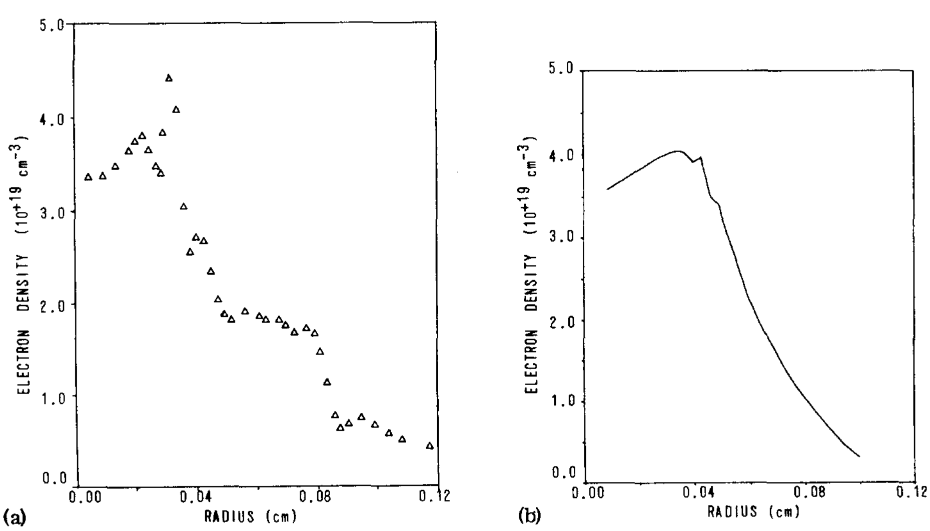

FIG. 3. (a) Measured radial electron density profile, obtained at peak compression from Abel inversion of a holographic interferogram ($\lambda=347.2$ nm). (b) Radial electron density profile at peak compression obtained from numerical simulation.

peak electron density attained and its radial position. Values of 4×10^{19} cm^{-3} for electron density at a radius of about 0.35 mm are typical for simulation experiments with input parameters adjusted for best agreement, within the limits of experimental uncertainty in these parameters. In addition, the agreement is also excellent in the radial position of the critical surface for 10.6-μ laser light ($n_e=10^{19}$ cm^{-3}), occurring at about 0.83 mm. It may be of interest to note that the location of this critical surface, as predicted in simulations, is relatively insensitive to variations in the peak plasma current (±20%).

The electron temperature distribution of the plasma during the pinch was calculated to be approximately 55 eV in the high-density regions, rising slightly to higher values (70 eV) near the plasma center and peripheral zones. The rise in electron temperature was quite marked during the pinch and increased from about 15–25 eV at a time 10 nsec earlier to the 55-eV temperature at the pinch, due, predominantly, to strong shock heating of the ions and collisional temperature equilibration between ions and electrons. The numerical model has also provided quantitative information (e.g., radial profiles of magnetic field and current density, and effective charge state) which is not readily available from experimental diagnostics.

In conclusion, we have demonstrated the ability to produce and successfully analyze an ultradense helium Z-pinch plasma which can be used in simulating laser-pellet interaction experiments at CO_2 wavelengths. Further experiments and theoretical studies should provide valuable information relevant to understanding the complexities of intense laser interaction with dense plasma.

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Light detection in dielectric waveguides by a photodiode through direct evanescent field coupling[a]

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Though $LiNbO_3$ and $LiTaO_3$ have excellent electro-optic properties, they are insulators and therefore do not lend themselves for the realization of an efficient photodetector scheme. Using the idea of evanescent coupling we propose and demonstrate a convenient and efficient light detection scheme to be used with a variety of dielectric waveguide devices. The scheme utilizes an etched mesa photodiode fabricated in silicon, evanescently coupled to a waveguide for light detection. The high detection sensitivity (0.3 mA/mW at $\lambda = 6328$ Å) and the possibility of incorporating integrated circuits on a common substrate (in Si or GaAs) make the scheme very attractive for hybrid integration of thin-film optical and electronic devices.

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Lithium niobate ($LiNbO_3$) is one of the most efficient electro-optic materials known and with the development of low-loss waveguides formed by Ti diffusion[1] many thin-film electro-optic devices have subsequently been realized. However, so far no suitable detection scheme has been found for use in conjunction with $LiNbO_3$ ($LiTaO_3$) devices in integrated optics. Usually light is first coupled out by means of a prism coupler[2] or a grating coupler[3] and then fed into a suitable detector (photodiode or photomultiplier). Waveguide detectors[4–7] fabricated to date all require that light be first fed into the detector waveguide to be detected, and therefore cannot be conveniently used for $LiNbO_3$ devices. In this paper we propose and demonstrate a new scheme, whereby a separately optimized photodetector can be conveniently used to reliably extract light from a separate waveguide for purposes of detection.

We demonstrate the scheme using an etched mesa photodiode (realized in Si) and detect the modulated light output from a $LiNbO_3$ branched waveguide modulator.[8–10] The modulator-detector assembly is schematically shown in Fig. 1. The operation of our scheme is similar to that of a prism coupler where the coupling out of energy from a waveguide is by means of the evanescent field extending outside the boundaries of the waveguide. Experimentally when the prism ($n_{prism} > n_{guide}$) and waveguide are placed in intimate contact,

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