Ultradense reproducible Z-pinch suitable for CO_2 laser-pellet simulation experiments

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The design and operating characteristics of a unique reproducible linear, high-density ($> 10^{19}$ e^-/cm^3), low-temperature ($17 < T_e < 30$ eV) helium Z-pinch are presented in this paper. It is shown that the temperature and critical density scale length (70–200 μm) of the pinched plasma are favorable for simulating CO_2 laser-pellet experiments. Focused CO_2 laser intensities of 10^{12} W/cm^2 result in $v_0/v_{\text{th}} \simeq 2.8$ at the critical layer, where v_0 is the quiver velocity of an electron in the laser electric field and v_{th} is the electron thermal velocity.

This article presents the results of a research effort to design and build a small linear Z-pinch, which generates a highly reproducible, low-temperature, steep gradient helium plasma with electron densities well above 10^{19} electrons/cm^3. Such a plasma is expected to be of importance in experiments simulating CO_2 laser-pellet interactions in laser-fusion[1] since the critical density for the CO_2 laser ($\lambda = 10.6$ μm) is 10^{19} electrons/cm^3. In our own CO_2 laser experiments, our focused intensity is 10^{12} W/cm^2, providing a ratio of electric field energy density to plasma kinetic energy density close to 3. Such a regime is necessary in order to study the possible existence of profile modification and other critical surface coupling mechanisms[2,3] as we have reported elsewhere.[4] The plasma is produced independently of the laser and hence, unlike laser produced plasmas, can be fully diagnosed without the laser. This allows for more quantitative studies of the laser-plasma interaction.

While the most important characteristic of this plasma device is its ability to produce a critical surface for the CO_2 laser (if the laser is incident in the radial direction), there are other approaches to achieve that single objective. In particular, the Mather-type plasma focus[5] is known to produce these electron densities along with long critical scale lengths ($L \simeq 1000$ μ) and hot electron–ion temperatures ($T_e \sim T_i \sim 1$ keV). Exploding wires,[6] imploding liners,[7] and vacuum arcs[8] have also produced electron densities over 10^{19} cm^{-3}. The plasma densities depend sensitively on the amount of initial material, thus making reproducibility a serious problem. Further, complete ionization is difficult to achieve in high Z plasmas. Laser breakdown plasmas can have densities over 10^{19} cm^{-3}, but are necessarily three-dimensional, making unambiguous diagnostics difficult and computer simulation impossible.

The Z-pinch as designed by our laboratory lends itself quite nicely to laser-plasma interaction experiments, if the CO_2 laser is incident in the radial direction. Since there is no azimuthal dependence, holographic interferometry may be used to extract radial density profiles. In addition, no z-dependence has been observed in the column at peak compression, permitting numerical modelling of the plasma in the absence of the laser for comparison with our diagnostics.

To simulate laser-pellet experiments, it is necessary to have $v_0/v_{\text{th}} \geq 1$, where $v_0 = eE/(m_e w_0)$ and $v_{\text{th}} = \sqrt{kT_e/m_e}$. The significance arises from the predicted existence of profile modification in this range which affects laser-plasma coupling.[2,3] The critical scale length L, is defined to be

$$L = \left.\frac{N_c}{\nabla N_e}\right|_{r=x_c},$$

where x_c is the radius at $N_e = N_c$ and N_c is the critical density for the incident laser. In the absence of profile modifications, this scale length for CO_2 irradiated plasmas is a few tens of microns. From this, one can maximize v_0/v_{th} with respect to temperature, given L and the incident intensity. Assuming a linear density gradient with scale length L, it is easily shown that the intensity incident on the critical surface ($x = x_c$) is (accounting for collisional absorption)

$$I(x = x_c) = I_0 \exp\left(\frac{16}{15}\frac{L}{c}\nu_{\text{ei}}\right),$$

where ν_{ei} is the electron–ion collision frequency. The electric field found from $I(r = x_c)$ must be adjusted for electric field swelling resulting from the usual Airy enhancement, namely (in MKS units)

$$E(x = x_c) = 2\left(\frac{\omega_0 L}{c}\right)^{1/16} \sqrt{\frac{2I(x = x_c)}{\epsilon_0 C}}.$$

The temperature dependence of v_0 enters in the electron–ion collision frequency. Hence, the maximum of v_0/v_{th} may be found at $T_e = T_{\text{crit}}$ where

$$T_{\text{crit}} = (1.65\ L)^{2/3}(\text{eV}) \quad \text{and}$$

L is in microns. For a scale length $L = 70$ μm, and $T_{\text{crit}} = 22$ eV. Hence, for plasmas found in the plasma focus or vacuum arcs, significantly higher laser intensities would be needed to study effects at $v_0/v_{\text{th}} \gtrsim 1$.

We were guided in our Z-pinch design by investigations performed by three other laboratories.[9–11] Hashino

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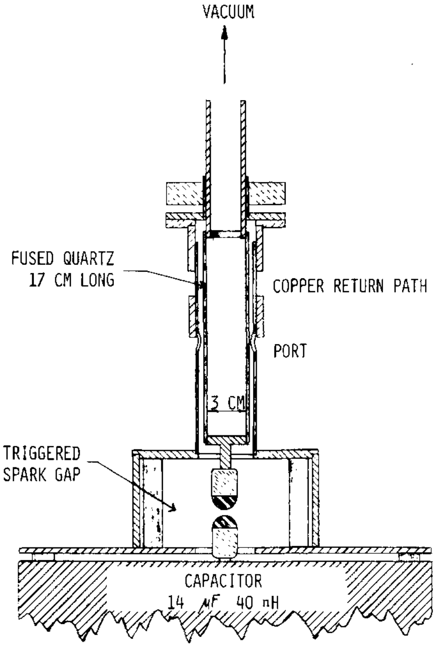

FIG. 1. *Z*-pinch design (the four beam port arms are not shown).

et al.[11] indicated possible density scaling based on a model proposed by Leontovitch and Osovets.[12] In particular, Hashino defined a parameter

$$\eta = (\text{const})1/\omega I_0,$$

where ω is the ringing frequency and I_0 is the peak current. This parameter follows from the assumption that there is no coupling of the plasma inductance and plasma resistance to the circuit parameters. They gave evidence that the peak density increased as η decreased. While this conclusion was substantiated by their experiments, our own model (which included a modified Leontovitch–Osovets equation coupled with the circuit equations) showed possible scaling with a parameter θ^2, where

$$\theta^2 = (\text{const}')(C_0V_0)^2/(\rho_0 r_0{}^4),$$

where C_0 is the capacitance, V_0 the charging voltage, ρ_0 the initial mass fill density, and r_0 is the initial plasma radius. The peak electron densities in the previous experiments were found to increase as θ^2 increased. Rather than design the plasma device based on possible density scaling laws, we chose to let η and θ^2 indicate the direction of design. Given a charging voltage V_0, we felt we could maximize the electron density and minimize scale lengths by keeping r_0 small and maximizing $dI/dt = \dot{I}$.

The design chosen is shown schematically in Figs. 1 and 2; the completed target chamber appears in Fig. 3. To minimize cost, a medium inductance high-capacitance energy storage capacitor was chosen having a peak voltage rating of 20 kV, capacitance C_0 = 14 μF, and inductance L_c = 40 nH. The coaxial feed was chosen to avoid more complicated feeds and yet minimize circuit inductance. In this configuration the ringing frequency was 8 μs. The *Z*-pinch was fired by a triggered spark gap. The gap itself was enclosed in a copper collar to suppress electrical and acoustic noise.

The electrodes used at the top and bottom of the

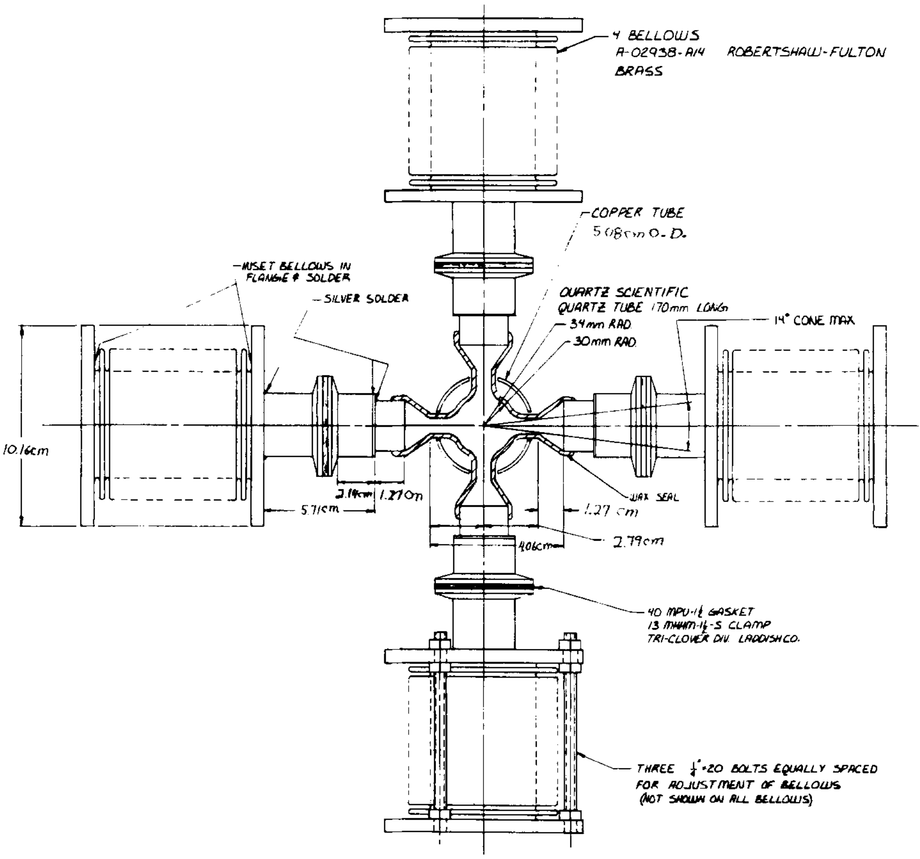

FIG. 2. Top view of *Z*-pinch. Cross-section showing the four viewing port arms.

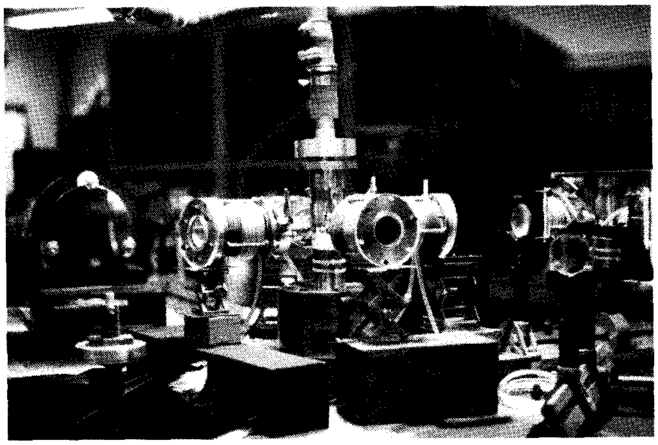

FIG. 3. *Z*-pinch target chamber.

quartz chamber were copper with sand blasted surfaces. The top electrodes had several holes as a gas and vacuum inlet. The electrodes were bonded to the chamber with Glass Blower's Wax,[13] a hard, brittle, low-temperature wax. The chamber itself was blown from fused quartz. While quartz is difficult to work, Pyrex would not withstand the shock heating at its surface, and Vycor deteriorated after several shots. Quartz retained its integrity for nearly one hundred shots at which point the quartz arms would weaken and break. If the chamber were removed before that point, the quartz could be reheated and annealed. This would also burn away deposited impurities.

The chamber had four optical quality beam ports. Bellows were originally a part of the design to allow accurate positioning of the windows. However, it was quickly discovered that after two shots, deposits on the windows rendered them useless. This problem was solved by wrapping Tygon tubing around the bellows and pumping liquid nitrogen through it, thus cooling the bellows to below 0 °C. In this manner, with the bellows serving as a getter, the windows remained clean for twenty shots. They were then removed for repolishing. The deposit appeared to be silicon with very little metal.

For CO_2 experiments, the optical windows needed to be transparent at $\lambda = 10.6\ \mu m$. While NaCl windows are usually quite satisfactory, it was found that even polycrystalline NaCl windows cracked when the discharge was fired at our typical fill pressure of 1.4 Torr He. While germanium windows were not damaged by the discharge, their CO_2 laser damage threshold was too low. This forced us to use expensive ZnSe windows which seem to be surviving the discharge and our repolishing techniques.

Detailed experimental results and comparison with theory are being presented elsewhere.[14,15] The results of our diagnostics, in particular, radial density profiles, critical scale lengths, temperatures, and magnetic fields are presented here. The data were taken for a charging voltage of 12.75 kV, yielding a peak current of 140 kA. The plasma was first studied using streak photography. Figure 4 shows the plasma in the compression phase occurring approximately 800 ns after triggering. Note the radiation present at the top of the streak photograph. This occurs at about 2.3 μs and has been diagnosed spectroscopically as impurity radiation believed to result from diffusion from the walls and electrodes. The density was measured using ruby-doubled holographic interferometry at $\lambda = 347.2$ nm. The holograms were made with the ruby laser perpendicular to the *Z*-axis of the plasma. The radial density profile follows from the Abel inversion of the raw data. A typical profile is shown in Fig. 5. The critical scale length measured from this profile with $N_c = 10^{19}$ electrons/cm^3 is 70 μm.

The electron temperature is inferred from the Bennett pinch relation.[16] Namely, if $T_e = T_i$ (a reasonable assumption at these densities) one finds for helium assuming full ionization (in MKS units)

$$T_e = \frac{2}{3} \frac{\mu_0 I^2}{\gamma \pi N_{el}},$$

where I is the current at pinch time and N_{el} is the number of electrons per unit length. For our plasma $17 < T_e < 30$ eV based on this relation. While this estimate is not a direct measurement, it has given good agreement in previous *Z*-pinch research.[9–11] Furthermore, the level of x-ray emission indicates that the temperature is below 40 eV. Note that this temperature is in close proximity to $T_{\rm crit}$ which maximizes $v_0/v_{\rm th}$ as shown above.

The critical radius magnetic field is estimated from (in MKS)

$$B = \frac{\mu_0 I}{2\pi X_c}\ \mathrm{T}.$$

Fields shown here are close to 20 T.

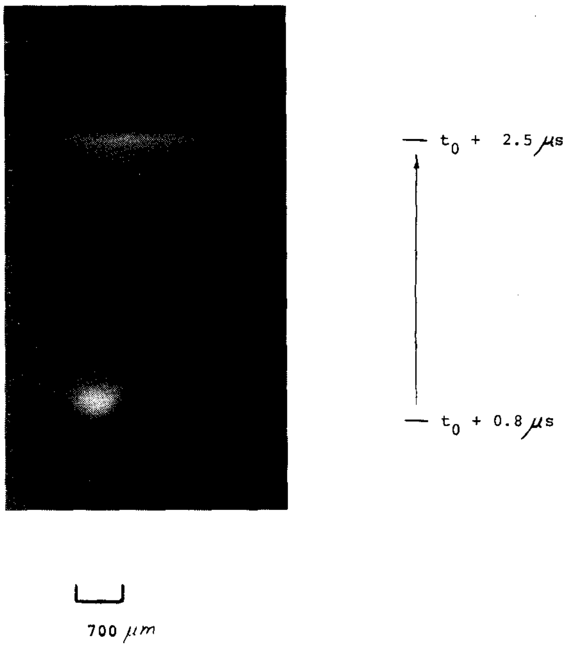

FIG. 4. Streak photograph. t_0 is time of current initiation.

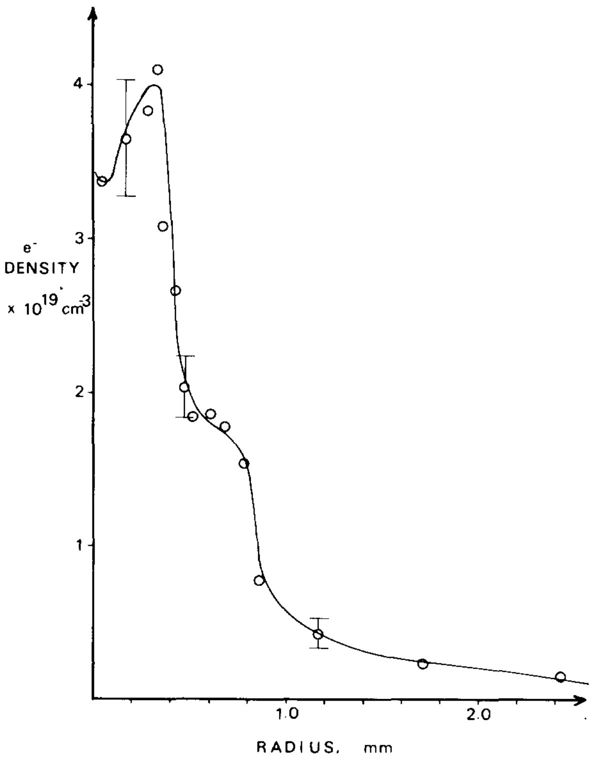

FIG. 5. Measured radial electron density profile. Obtained from Abel inversion of a holographic interferogram ($\lambda = 347.2$ nm) at peak compression.

For CO_2 laser interaction experiments, timing is extremely critical in order to obtain reproducible results. Our timing is performed with respect to one of two signals with jitter on the order of 40 ns arising from statistical fluctuations in the triggered gap and discharge breakdown. This jitter is marginally acceptable given a measured confinement time of 70 ns. Our primary timing signal is the burst of continuum radiation accompanying the peak compression. This signal is coincident with peak electron densities and provides a convenient reliable timing marker. The time from spark gap trigger to peak electron density is approximately 800 ns. Alternatively, one can monitor dI/dt from a pickup coil or a magnetic probe. It is found that a pronounced dip in dI/dt occurs near peak compression. However, for reasons that are not yet understood, this dip precedes peak compression by 150 ns.

Due to the peculiar static electric field distribution present in the charged state of the Z-pinch, it is worth commenting on the exact triggering procedure for reliable performance. In particular, the upper spark ball which forms the lower electrode of the Z-pinch discharge is grounded through a high resistance, thus placing that ball at zero potential. A tungsten trigger pin is biased through high resistance resistors at $V_0/2$ and positioned at $2V_0/3$ between the spark balls. To trigger the discharge, the pin is switched to $-V'$ through a trigger circuit, i.e., a 5C22 thyratron. The charging voltage, V_0, is typically 12–20 kV and $-V'$ is -16 kV. We feel the jitter should be reduced when switching at -50 kV.

In conclusion, we have built and tested a novel linear Z-pinch capable of producing a plasma similar to a laser-pellet plasma. This plasma has been operating in our laboratory for over a year now with no problems other than those mentioned above. It is a reproducible plasma and has resulted in our observation of important laser-plasma coupling phenomena.

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