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 $\mu$m) 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 $v_0/v_{th} \approx 2.8$ 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 since the critical density for the CO$_2$ laser ($\lambda = 10.6$ $\mu$m) is $10^{18}$ electrons/cm$^3$. In our own CO$_2$ laser experiments, our focused intensity is $10^{14}$ 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 as we have reported elsewhere. 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 is known to produce these electron densities along with long critical scale lengths ($L \approx 1000$ $\mu$m) and hot electron--ion temperatures ($T_e \sim T_i \sim 1$ keV). Exploding wires, imploding liners, and vacuum arcs 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 modeling of the plasma in the absence of the laser for comparison with our diagnostics.

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

$$ L = \frac{N_e}{\nabla N_e} \left|_{x = x_c} \right. $$

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)

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

where $v_{ei}$ 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)

$$ E(x = x_c) = 2 \left( \frac{a_0 L}{c} \right)^{1/16} \sqrt{\frac{2I(x = x_c)}{e_0 C}}. $$

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 $T_r = T_{crit}$ where

$$ T_{crit} = (1.65 L)^{2/3}(eV) $$

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

We were guided in our Z-pinch design by investigations performed by three other laboratories.
plasma resistance to the circuit parameters. They gave
evidence that the peak density increased as \( \eta \) decreased.
While this conclusion was substantiated by their experi-
ments, our own model (which included a modified Leo-
tovitch–Osovets equation coupled with the circuit equa-
tions) showed possible scaling with a parameter \( \theta' \),
where
\[
\theta' = (\text{const}')\left( C_0 V_0^3 / (\rho_0 r_0^4) \right),
\]
where \( C_0 \) is the capacitance, \( V_0 \) the charging voltage,
\( \rho_0 \) the initial mass fill density, and \( r_0 \) is the initial plasma
radius. The peak electron densities in the previous ex-
periments were found to increase as \( \theta' \) increased. Rather
than design the plasma device based on possible density
scaling laws, we chose to let \( \eta \) and \( \theta' \) indicate the
direction of design. Given a charging voltage \( V_0 \), we
felt we could maximize the electron density and mini-
imize scale lengths by keeping \( r_0 \) small and maximizing
\( dl/dt = 1 \).

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-capaci-
tance energy storage capacitor was chosen having a
peak voltage rating of 20 kV, capacitance \( C_0 = 14 \, \mu\text{F} \),
and inductance \( L_c = 40 \, \text{nH} \). The coaxial feed was
chosen to avoid more complicated feeds and yet mini-
mize circuit inductance. In this configuration the ring-
ing frequency was 8 \( \mu \text{s} \). The Z-pincli 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

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

**Fig. 2.** Top view of Z-pinch. Cross-section showing the four viewing port arms.
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, 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 CO₂ experiments, the optical windows needed to be transparent at λ = 10.6 μm. 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 CO₂ 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. 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 λ = 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 $N_e = 10^{10}$ electrons/cm² is 70 μm.

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

$$T_e = \frac{2 \mu_0 I^2}{3 \gamma T_N N_e},$$

where $I$ is the current at pinch time and $N_e$ 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. Furthermore, the level of x-ray emission indicates that the temperature is below 40 eV. Note that this temperature is in close proximity to $T_{crit}$ which maximizes $v_0/v_{th}$ as shown above.

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

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

Fields shown here are close to 20 T.

![Streak photograph. $t_0$ is time of current initiation.](image)
For CO₂ 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 \( \frac{dI}{dt} \) from a pickup coil or a magnetic probe. It is found that a pronounced dip in \( \frac{dI}{dt} \) 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 thyatron. The charging voltage, \( V_0 \), is typically 12–20 kV and \(-V\) is \(-16 \text{ kV} \). We feel the jitter should be reduced when switching at \(-50 \text{ kV} \).

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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