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Gas-puff Z pinches with D_2 and D_2-Ar mixtures

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Results obtained with the University of California, Irvine gas-puff Z-pinch experiment are described for deuterium and deuterium-argon mixtures. This experiment utilizes a hollow cylindrical gas puff injected between electrodes driven by a 4.8-kJ capacitor bank. Various gas compositions have been tested, including pure deuterium, 90% D_2-10% Ar, and up to 10% D_2-90% Ar. We have observed the stages of collapse and its rate, electron density at the pinch, neutron yield, and the time dependence of x-ray and neutron emission. When a 90% D_2-10% Ar mixture is injected, the plasma annulus is observed to separate into two columns which implode concentrically.

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In the present study of Z-pinch dynamics with pure deuterium and deuterium-argon mixtures, we have utilized the basic experimental setup described in Refs. 1 and 2. A hollow cylindrical gas puff is injected between two electrodes driven by a capacitor bank ($12\,\mu f$, 4.8 kJ). The initial gas density is controlled by a delay between injection of the gas and application of the high voltage. The delay can be adjusted so that the pinch occurs when the current is a maximum.

With pure deuterium two regimes have been observed, each characterized by its relatively high or low density at the pinch. The regime of operation is determined by the initial gas density. A summary of the main parameters measured is presented in Table I.

In the high density regime the pinch occurs at current maximum, resulting in an average ion density of $\bar{n}_D \sim 2\times 10^{19}\ \text{cm}^{-3}$. The pinched column radius is $r_p \sim 1.5$ mm with some plasma left in an anode cloud [Fig. 1(a)]. The maximum neutron yield was $Y \sim 5\times 10^7$ N/pulse; hard x-rays ($E > 75$ keV) were also emitted from most shots. However, in 20% of the high density discharges no hard x-rays were observed. The neutron yield in these cases was substantially lower: $Y \sim 10^6$ N/pulse. The absence of hard x-rays from these shots suggests that the neutrons were of thermal origin rather than due to beam-target interactions.

In the low density regime the column pinches to a minimum radius of about $r_p \sim 2$ mm slightly before (~ 50 ns) the current reaches its maximum. The ion density is $n_D \sim 2\times 10^{18}\ \text{cm}^{-3}$. More plasma is left in the anode cloud than in the high density regime [Fig. 1(b)]. The maximum neutron yield was $Y \sim 2\times 10^8$ N/pulse. Hard x-rays were observed from all shots, indicating that probably most of the neutron emission is due to beam-target interactions. The enhanced neutron yield in the low density mode is consistent with previous work,[3] where it was found that higher potentials for beam acceleration exist when the density is lower.

TABLE I. Pinch parameters.

	Pure D_2		90% D_2/10% Ar	
	Low density	High density	Inner column	Outer column
$\bar{n}_e$ (cm^{-3})	2×10^{18}	2×10^{19}	6×10^{19}	1×10^{20}
τ (ns)		10 ± 5	40 ± 10	25 ± 5
$R_{\min}$ (cm)	0.2	0.15	5×10^{-2}	8×10^{-2}
$\dot{R}_{\text{AVE}}$ (cm s^{-1})		0.7×10^7	0.4×10^7	1.2×10^7
$Y_{\max}$ (N/pulse)	2×10^8	5×10^7	5×10^7	

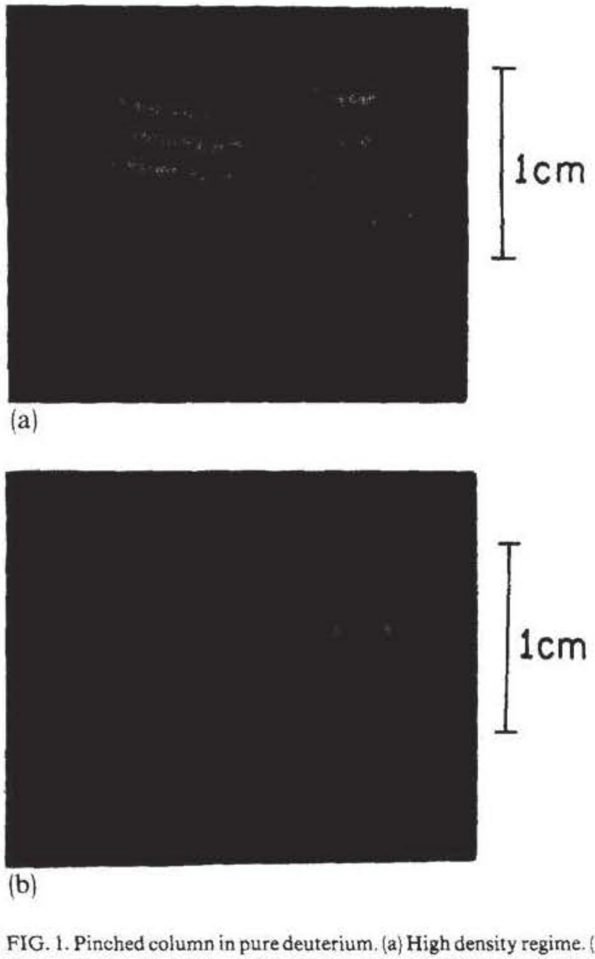

FIG. 1. Pinched column in pure deuterium. (a) High density regime. (b) Low density regime. A dispersed cloud of plasma near the anode (bottom of interferogram) is present in both cases.

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In both regimes the duration of the neutron pulse is ~ 50 ns; the pulse due to x-rays with $h\nu > 4$ keV lasted for ~ 35 ns, while interferograms show that the column disrupted ~ 10 ns after the pinch.

The behavior of the Z pinch with deuterium-argon mixtures has been investigated. The addition of argon should affect the principal characteristics of the pinch, e.g., electron concentration, temperature, stability, and radiation. Several mixtures have been tested. The results obtained for the 90% D_2-10% Ar mixture are reported in detail. A summary of the main parameters is given in Table I.

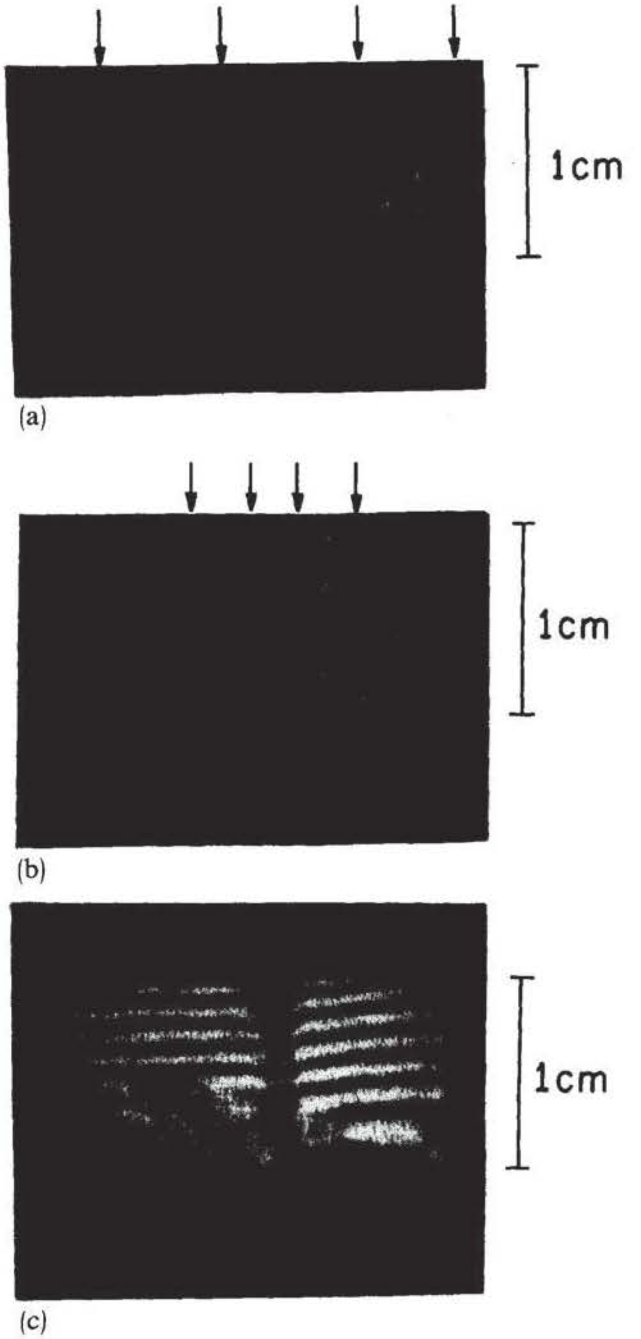

FIG. 2. Interferograms showing the compression of the 90% D_2-10% Ar mixture. The arrows indicate the regions of highest density (The direction of the fringe shift is reversed compared to Figs. 1 and 3). The separation of the plasma into two concentric columns is evident in (a) and (b). (a) 125-ns before pinch. (b) 50-ns before pinch. (c) Pinch.

In the 90% D_2-10% Ar mixture the interferograms show a separation of the cylindrical plasma into two distinct concentric columns. Figure 2 shows the compression of the two columns. Since the discharge is highly reproducible, taking an interferogram on a few successive shots allows us to determine the radial progression of the implosion. The radial velocities given in Table I correspond to a time ~ 70 ns before the final pinch. The actual maximum velocities may be much higher. The inner column pinches about 20 ns before the outer; the final result is a uniform column over virtually the entire gap length, as shown in Fig. 2(c). This is in contrast to the dispersed cloud of plasma present near the anode in a pure D_2 pinch.

Sufficient data has been obtained with mixtures containing 95% D_2-5% Ar, 90% D_2-10% Ar, and 75% D_2-25% Ar to determine that as the relative amount of argon is increased, the density of the inner column decreases (Fig. 3). Previous experiments[4] showed that during an implosion of pure argon very little plasma is found inside the main plasma annulus. Therefore, we can postulate that the inner column is composed mostly of deuterium while the outer is mostly argon. The mechanism for the separation of the discharge into two columns is not clear. However, factors which should be contained in a model describing this effect include the e/M ratio, temperature, and collision rate for each species.

The average electron density of the pinched column is $\bar{n}_e \sim 1 \times 10^{20}\ \mathrm{cm}^{-3}$. Assuming all ions in the inner column are deuterium, our measurements indicate that the deuterium ion density is $\bar{n}_D \sim 6 \times 10^{19}\ \mathrm{cm}^{-3}$. Interferograms show that the plasma remains stable for 20 ns after the outer column has pinched. Since the inner column pinched 20 ns before the outer, the lifetime of the D_2 pinch is $\tau \sim 40$ ns. The enhancement of column stability may be due to argon acting as a gas blanket around a dense core consisting mostly of deuterium. The blanket would tend to damp out surface waves in the core plasma.[5]

Since the pinch occurs at current maximum, the voltage across the plasma column is zero and $LI =$ constant. Using this fact, the efficiency of converting energy stored in the magnetic field during implosion to plasma and radiation en-

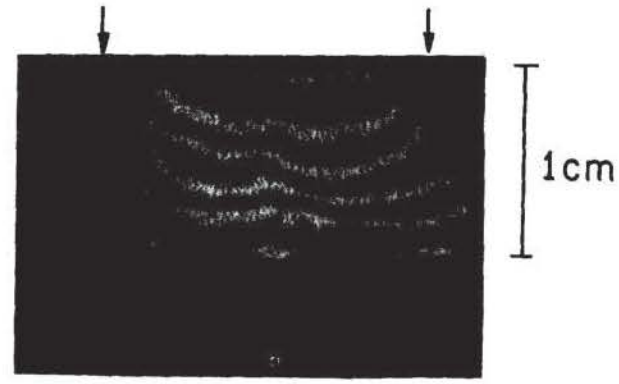

FIG. 3. Interferogram showing compression of 75% D_2-25% Ar mixture, 120 ns before pinch. Note greatly decreased density in region inside main plasma annulus compared to Figs. 2(a) and 2(b). The bulk of the plasma is located in the column indicated by the arrows.

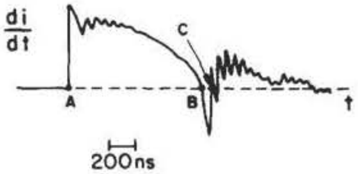

FIG. 4. Typical *di/dt* curve. Energy is transferred to the pinched plasma between B and C.

ergy is

$$\eta = \frac{\frac{1}{2}L_B I_B^2 - \frac{1}{2}L_c I_c^2}{\frac{1}{2}L_B I_B^2} = \frac{I_B - I_c}{I_B}.$$

Here, I_B is the current just before the pinch and I_c is the current just after the pinch. The efficiency can thus be deduced from the *di/dt* curve (Fig. 4). The efficiency for the 90% D_2-10% Ar mixture was $\eta_{D_2/Ar} \sim 6\%$ while for pure deuterium $\eta_{D_2} \sim 3\%$, a factor of 2 lower.

In conclusion, (1) the addition of a small percentage of argon results in a more uniform, efficient, and stable pinch. (2) The 90% D_2-10% Ar mixture results in $(N\tau)_D \sim 2\times 10^{12}$, an order of magnitude higher than for pure D_2. The optimum mixture has not yet been determined and further increase in $N\tau$ may be possible. (3) The neutron yield obtained with the present device compares favorably with the results obtained in a plasma focus. The yield from a plasma focus scales according to $Y \propto E^{2.5}$.[6,7] Typical yield for a plasma focus operating at 93 kJ is $Y \sim 3\times 10^{10}$ N/pulse.[6] Scaling this to an energy comparable to our device, we obtain $Y \sim 2\times 10^7$ N/pulse. However, in the low density regime the obtained neutron yield is an order of magnitude higher. (4) Further studies of the separation effect and a self-consistent model which will explain it, as well as several other mixtures and the resulting effects on column stability, temperature, $N\tau$, and neutron yield are under way.

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Shock dynamics and neutron production in an explosive generator driven dense plasma focus

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An explosive generator driven dense plasma focus is simulated numerically using a magnetohydrodynamic model which includes thermal conduction, resistive diffusion, and radiation in addition to the Lorentz force and shock hydrodynamics. It is shown that the dominant heating mechanism is shock heating. Neutron yield is shown to occur at the current minimum. The neutron yield is a result of the initial shock reflecting off the axis of symmetry, reflecting off the magnetic piston driving the focus, and reconverging on axis. Peak neutron production occurs when post-shock plasma converges on axis.

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The large scale numerical modeling of the dense plasma focus has been of interest since the pioneering work of Potter[1] and D'yachenko and Imshennik.[2] Potter's calculations demonstrated three features of the focus discharge: an anode cold source, a hot pinch region, and an axial shock. Most recently, Maxon and Eddleman[3] described the behavior of a focus with a rounded, hollow anode. Although D'yachenko and Imshennik and Maxon and Eddleman question the quantitative accuracy of Potter's results, the qualitative description provided by Potter remains valid. Neither Potter nor Maxon and Eddleman actually compute the neutron production rate and correlate it with the current waveform and the shock dynamics of the focus, although Potter gives an estimate.

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