Novel Gas Embedded Compressional Z-Pinch Configuration

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Experimental results are presented of a novel Z-pinch configuration in which two concentric columns of an initial, partially ionized plasma are compressed. Experimental comparison with the laser initiated gas embedded Z pinch and with the microdischarge initiated dense Z pinch performed on the same generator shows that the new configuration exhibits axial compression and no macroscopic instabilities are observed. A maximum current of 130 kA is obtained for a discharge in hydrogen at 0.33 atm. On axis electron density, n_e of 3×10^{25} m^{-3}, is observed 110 ns after the initiation of the discharge, 20 times larger than the laser initiated gas embedded Z pinch.

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Since the early days of plasma physics experiments the Z pinch has been considered an ideal candidate for fusion studies, in view of its inherent simplicity. After its propensity to ideal magnetohydrodynamics (MHD) instabilities was confirmed [1], work largely ceased on the Z pinch until the development of pulsed power generators. The resurgence of interest in this class of discharge has been due to the widely held belief that by sufficient heating, in conjunction with a sufficiently rapid compression, the plasma compression time could be made less than the instability growth time scale [2]. Generators capable of delivering driving currents well in excess of $I > 10^5$ A with values of $dI/dt > 10^{12}$ A/s are now in common use. The search for optimization of stability at high densities has led to the development of many variants for use on these generators. Among the variants tried are the gas embedded Z pinch and the fiber pinch (dense Z pinch). In the former case, $m=1$ instabilities leading to a helix [3,4] occur on a time scale of a few tens of nanoseconds. In the latter configuration $m=0$ instabilities appear [5,6], strangling the plasma column at different points. The formation of this class of instability is also found in a compressional Z pinch [7,8] using a pulsed power driver. In gas embedded Z pinches in which $m=1$ instabilities appear [3,4], as well as in a compressional pinch driven by a pulsed power generator [7,8], results show that the stability growth time scale is significantly slower than predictions using ideal MHD theory. Recently it has been shown that fiber pinches show instability growth time scale in accordance with linear MHD theory [9], provided the complete temporal evolution of the discharge is included in the calculations. The fiber pinch has been favored in recent years, and a new variant has been reported recently [10] showing a yet greater degree of enhanced stability. In this discharge a fiber is embedded within a low density aluminum plasma. This enhanced stability is apparently due to the fact that energy, supplied to the aluminum shell, is transferred efficiently to the fiber. The fiber is also preionized efficiently by radiation from the imploding shell. This result follows from the observation of enhanced stability on solid fibers coated with a higher Z material such as Cu or Ni [11]. At early times fiber Z pinches have an optically thick core which does not allow the measurement of electron density in this region. From indirect evidence it is concluded that the fiber is completely ionized, but no compression of the resulting plasma has been reported.

The increased stability observed has stimulated considerable progress in the theory of instabilities for the Z pinch. Among these developments, the more relevant ones are finite Larmor radius effects [12], resistive effects [13], and viscoresistive effects [14]. An attempt to integrate the accumulated theoretical knowledge has resulted in a two-dimensional diagram in terms of line density and pinch current to the fourth power times pinch radius [15].

In the present Letter we present a new configuration consisting of two concentric plasma columns embedded in a neutral gas (hydrogen). Previous work [16] on a microdischarge initiated gas embedded Z pinch has been used successfully to form dense Z pinches with no evidence of macroscopic instability but it remains to establish the degree of real compression. The initial plasma column is formed by a continuous μA discharge between fine-tipped tungsten electrodes.

In the new configuration a microdischarge is set up between two stainless steel conical hollow electrodes with a 2 mm diameter. The edges are formed with a 50 μm radius of curvature. With the microdischarge set up a few nanoseconds before the application of the main voltage from the driver, a pulsed laser is focused through the anode onto the cathode. A schematic of the electrode arrangement with the different stages of the pinch evolution is shown in Fig. 1. By these means two parallel concentric conductive paths are established for the current. The dynamic current evolution during the first part of the rising voltage ramp will depend on both the increasing conductivities of the concentric plasmas as well as the inductance of each path.

The experiments were carried out on GEPOPU, a generator delivering currents up to 200 kA at 1.5 Ω impedance for 120 ns. The value of dI/dt of the current ramp was approximately 2×10^{12} A/s [17]. The central plasma column was initiated with a 6 ns, 200 mJ

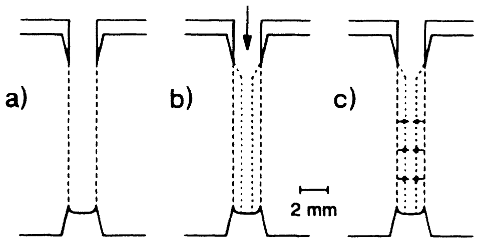

FIG. 1. Schematic diagram of electrode configuration and pinch evolution. The anode is on top. (a) $t < 0$, annular microdischarge; (b) $t = 0$, the laser is applied and the central current channel is initiated; and (c) $t > 0$, the plasma channel is compressed by the pinch current.

Nd:YAG laser pulse at 1.06 μm. A frequency doubled 6 ns pulse from the same laser was split up into eight beams, each delayed by 10 ns with respect to each other, to allow the observation of the discharge with up to eight frames of holographic interferograms per shot [18]. In this way the evolution of the electron density profile $n_e(r)$, the electron line density N, and the external Z-pinch radius a are obtained with good temporal resolution. The total current $I(t)$ was measured with a 25 mm radius, single turn Rogowskii coil, located in the base of the earth electrode, with an estimated accuracy of 5%. The external voltage was measured with a capacitive divider at the end of the transmission line, just before the live electrode. All the discharges shown in this Letter were performed in hydrogen at 0.33 atm. In order to highlight the particular features of the double column pinch, we present observations of the conventional laser initiated gas embedded Z pinch with flat electrodes as a reference. On applying the driver voltage, it was observed that, in both cases, the initial current rise was slow until a value of about 3.6 kA was attained, at which time the dI/dt increased dramatically. In the gas embedded Z pinch this value of current was attained after 5 ns, whereas in the new configuration a markedly longer interval of 40 ns was observed. In Fig. 2 we present two sequences of holographic interferograms; the upper one corresponds to the reference discharge, whereas the lower sequence presents results for the new configuration in an otherwise identical experimental arrangement. Near the cathode of the discharges (bottom) a region of nonuniformity is observed. This is caused by the initiating laser spark on the cathode electrode in addition to diffraction effects. At the anode end in the new configuration the upper fringe shift observed at its maximum deviation is obscured by the conical protrusion. The discharge is uniform over 6 out of the total 10 mm length. Using the half density radius obtained in Table I this corresponds to an aspect ratio of 120 at times as late as 110 ns. For the reference pinch the laser spark is partially obscured by the instability at later times. In both cases the left hand interferogram corresponds to the time at which the current reaches a few kA. This explains the apparent discrepancy in the time scales. In both cases the line charging voltage was 160 kV with a maximum current of 110 kA for the reference discharge and 130 kA in the new configuration. In the gas embedded Z pinch the development of the pinch may be seen after 25 ns but the

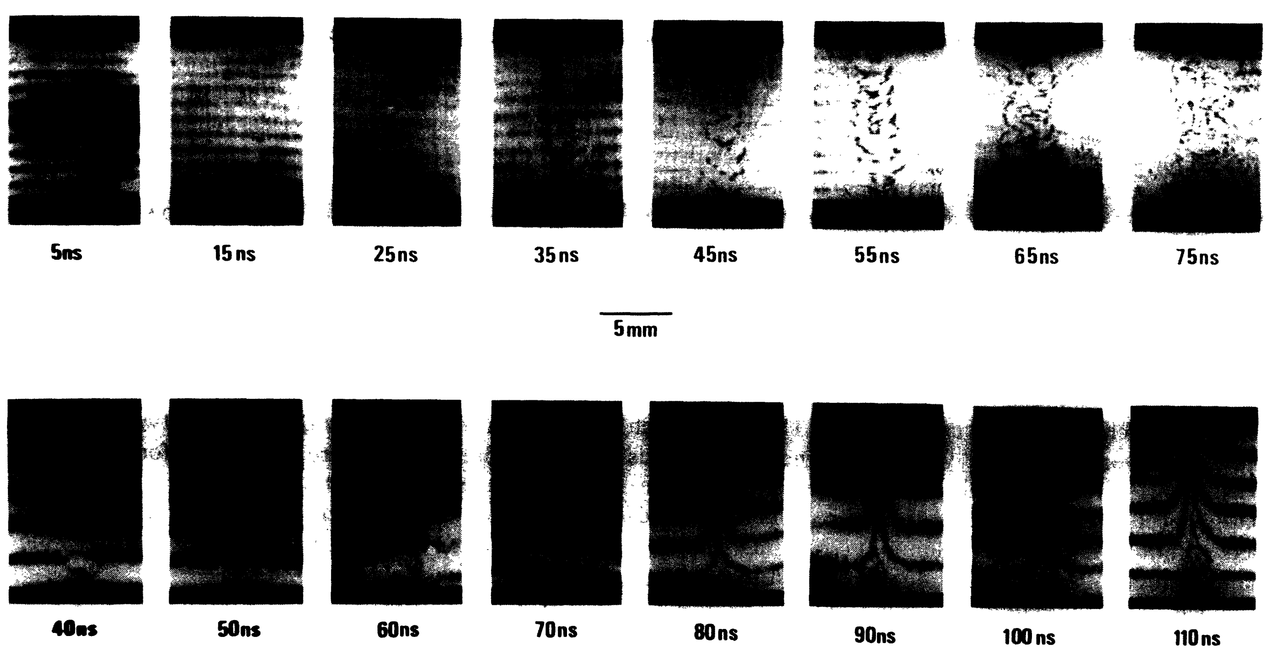

FIG. 2. Sequences of single shot multiframe interferograms. Upper series corresponds to the reference discharge, and the lower series to the double column Z pinch. The cathode is at the bottom. A metallic plasma and diffraction effects are observed near the cathode. The left-hand frame corresponds to a current of 4 kA.

TABLE I. Values of line density N, obtained directly from interferograms, estimates of Bennett temperature T_B, and half-height maximum-density radii $a_{1/2}$, at different times for the new configuration. Estimates of error are given for the different parameters.

t (ns)	$N(\pm 10\%)$ (10^{19} m^{-1})	$T_B(\pm 20\%)$ (eV)	$a_{1/2}(\pm 10\%)$ (mm)
50	0.26	20	0.98
70	0.60	118	0.18
80	0.89	128	0.09
90	0.79	190	0.07
100	1.1	152	0.05
110	1.3	140	0.046

onset of the $m=1$ instability occurs at 35 ns, with a characteristic expansion in the pinch radius. In clear contrast, in the double column configuration, the two columns coalesce into one, with the density confined to the central region.

In order to establish whether the central current channel is important in the new configuration, tests were carried out with a hollow cylindrical microdischarge but with no preionizing laser. In this case only an annular column is established. Expansion was observed in this case and, indeed, in the main current discharge phase, the interferograms, which are not presented in this Letter, show no significant ionization in the central column. For the case of the laser initiated double column Z pinch we find that, during the main phase of the discharge, the external radius is defined at 50 ns and is maintained until at least 110 ns, which corresponds to the last frame available. This final value of the pinch radius is attained about 20 ns after the end of the initial current ramp.

An important criterion in assessing ideal MHD pinch stability is the radial Alfvén transit time, $\tau_A = a/\bar{v}_A$, where $\bar{v}_A$ is the mean Alfvén speed and a is the pinch radius. For a Z pinch in hydrogen, $\tau_A = 2.6 \times 10^{-10} a N^{1/2} I^{-1}$ [15], where N is the pinch line density and I the pinch current, both in SI units. For the reference pinch, τ_A is estimated to be 3.5 ns at the end of the stable phase, whereas in the double column pinch, $\tau_A = 14$ ns for the conditions corresponding to the last frame in Fig. 2.

If in both cases the pinch is assumed to be fully established at the end of the initial slow rising current ramp, the reference pinch becomes macroscopically unstable after seven radial Alfvén transit times, which is of the same order as the five radial Alfvén transit times corresponding to the last available frame in the double column pinch. In Fig. 3 we show results of an Abel inversion for the radial density in the central region of the pinch from 50 to 110 ns. The central density continues to increase on axis without significant expansion. A maximum on axis density is measured at 3×10^{25} m^{-3}, that is, some 20 times the reference gas embedded Z-pinch value [19] and nearly twice the expected value from filling pressure. The

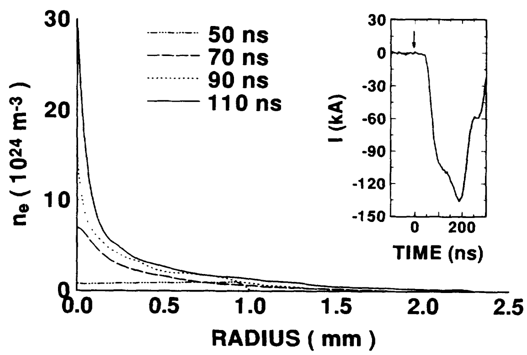

FIG. 3. Radial electron density distribution of the new configuration from the interferogram sequence of Fig. 2. Inset shows the time evolution of the current on the same shot; the arrow indicates the laser pulse.

line density obtained directly from the interferograms [6], N, increases early on in the discharge, but then has a modest increase as shown in Table I. This is in contrast to the gas embedded Z pinch where the value increases substantially throughout the discharge. From this difference, it may be inferred that the neutral gas does not cross the pinch boundary. Also shown in Table I are values of radii defined at half maximum density obtained from Abel inversion. It is apparent that the radius so defined is continually decreasing.

The difference in the current behavior in the predischarge phase, that is, until a value of 3.6 kA is reached, requires explanation. In the case of the double column pinch, the 40 ns required to reach the main discharge regime occurs when there is a substantial voltage applied. This voltage is capable of extracting electrons from the laser plasma formed on the center of the cathode electrode and, simultaneously, increase the conductivity of the annular plasma. The total energy delivered during the predischarge phase is about 8 J, which is consistent with the energy needed to ionize the whole volume of gas which carries the current (2 mm diameter by 10 mm length). Immediately on transition to full conduction, a larger fraction is thought to pass in the annulus owing to its smaller inductance. A stronger compression is to be expected in the other pinch, as it experiences the B_θ field associated with the total current. For the conditions at the end of the initial driver current ramp, the current diffusion time is estimated to be less than 1 ns; hence it can be inferred that a substantial fraction of the current flows in the inner region. The precise role of any trapped magnetic field is not clear, but we expect it to favor a centrally peaked density distribution. Measurements to clarify this point are planned for the near future. The shorter initial slow rising current ramp observed in the reference pinch could be ascribed to the much smaller initial pinch radius, which reduces by more than 1 order of magnitude the neutral gas volume to be ionized and heated by the current at early times.

The Bennett equilibrium does not depend on the current density profile $J(r)$, which means that the two concentric plasma columns, either initially separate or later coalesced, may be considered as only one Z pinch with a total current $I(t)$. A further condition is that the radial velocity be less than the Alfvén velocity, which is easily satisified in the double column pinch at all times in the discharge. Thus the Bennett relation can be used to estimate the pinch temperature. Using the measured pinch current and the line density obtained from interferograms the temperature is estimated from the Bennett relation and is shown in Table I. A maximum value of over 150 eV is found at 90 and 100 ns. This is a substantially higher value than that found under similar assumptions for the laser initiated gas embedded pinch and for the microdischarge initiated gas embedded Z pinch reported earlier [4,16,19]. The difference is presumably due to the fact that the line density increases in these discharges, but remains nearly constant in the double column pinch.

The fact that no gross instabilities are observed in the new configuration could be due to resistive effects at early times. At later times the discharge becomes hotter. The most significant difference between the two cases is that the ratio of the ion Larmor radius, a_i, to the pinch radius, a, is significantly lower for the double column pinch. This may be seen on comparing the value with that found for the gas embedded laser initiated Z pinch which is used as the reference. The estimated value is fairly close to $a_i/a = 0.1$. There exists both experimental and theoretical evidence indicating that greater stability is found for values of this ratio close to 0.1 [16,20,21].

Stabilization due to viscoresistive effects is not to be expected as $SR \sim 7800$, where SR is the product of the Lundquist and the Alfvén-Reynolds numbers [14].

A novel Z-pinch configuration has been presented, in which an initial coaxial current distribution gives rise to a well-confined and stable Z pinch. The interplay between the current flow along the axis and in the annular volume leads to an effective decoupling between the plasma and the background gas. Given an effective decoupling, the line density stops increasing and the pinch compresses, as is expected from calculations using a zero dimensional model [22,23]. At times at which the discharge reaches higher temperature and density values the FLR is estimated to be below 0.2 after 70 ns, in agreement with recent experimental and theoretical work which finds that the stability would be optimum for a value of 0.1 [16,20,21]. The results presented here show that it is possible to have a compressional gas embedded Z pinch. The results point the way to an alternative route to obtaining dense confined plasmas. To optimize the findings in this Letter, it would be advantageous to tailor the current pulse to increase the rate of rise of current at the time the discharge comes close to FLR values of 0.1. In this way the temperature of the plasma could be raised by better coupling of the generator to the plasma load.

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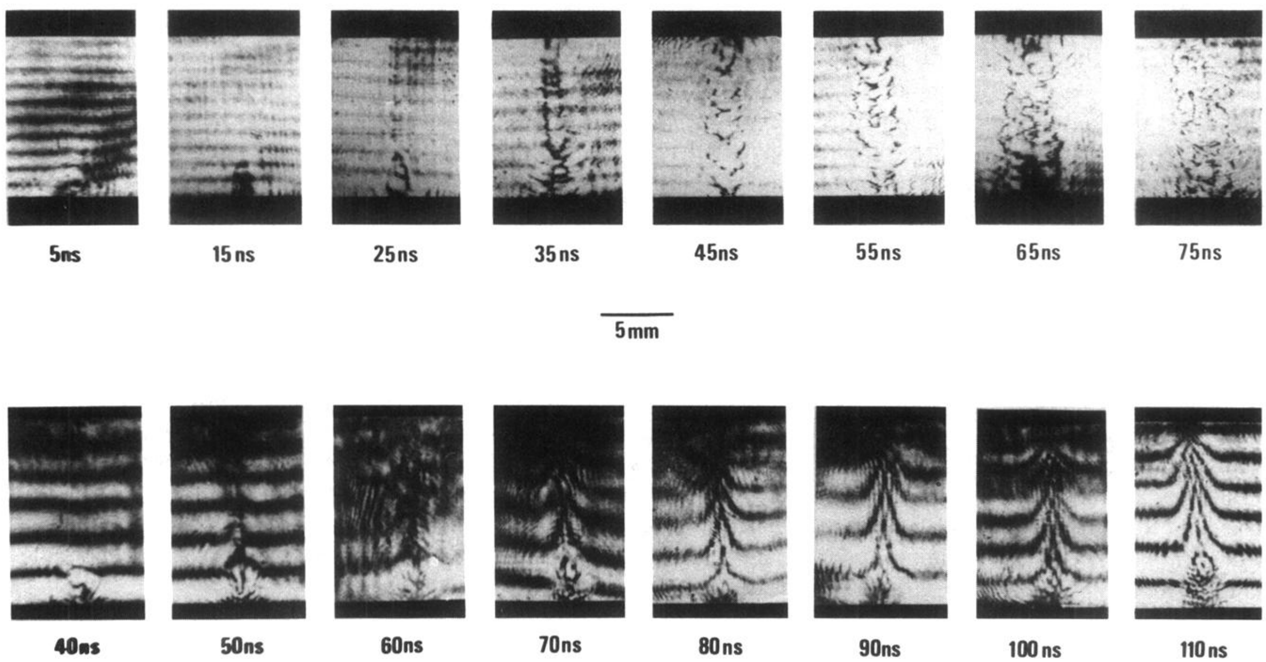

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