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NRL CAPILLARY Z-PINCH EXPERIMENT†

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I. INTRODUCTION

The dense linear z-pinch has been considered as the basis for a very simple fusion system since the earliest days of CTR. The current renewed interest is due in large part to a recent Los Alamos Study [1] which concluded that a z-pinch based reactor could produce 4.4 MJ of fusion energy per pulse for the modest input of 140 kJ per pulse, if a straight pinch could be maintained for 2 μsec.

Early attempts to achieve suitable high density z-pinches were of the implosion type [2] which produced hollow pressure profiles that quickly resulted in disruptive $m = 0$ instabilities. These instabilities are not found in the gas embedded pinch [3, 4, 5] in which an initially small diameter plasma (typically 100-200 μ) is kept in radial equilibrium by following a prescribed current waveform [3]. Unfortunately, these pinches are prone to a rapid accretion of the surrounding gas during the early stages of formation. This increases the line density N, and since the Bennett relation $I^2 = 4\ NkT$ applies, prevents attainment of high temperatures. This configuration is also subject to an $m = 1$ instability which turns the linear pinch into a helix, but which is not necessarily disruptive.

Our approach is to form the pinch inside small diameter quartz capillaries filled with neutral hydrogen. This fixes the line density. By driving currents through the pinch at a rate that exceeds that necessary for radial equilibrium, we expect the pinch to contract away from the walls and be subject to compressional, as well as ohmic heating. This contraction will, of course, produce a plasma between the pinch and the capillary wall, but we

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anticipate this "corona" will be kept at a low temperature (i.e., high resistance) by radiation and hence shunt only a small fraction of the pinch current. We also expect negligible impurities in the pinch as the classical mixing time will be much longer than the pinch duration at the densities (10^{21}-10^{22} ions/cm^3) and magnetic fields (1 - 10 MG) involved. However, we do expect the presence of the dense corona to reduce the growth rate of the m = 1 instability [7].

II. EXPERIMENTAL RESULTS

We have produced both gas embedded and capillary pinches using the 1.2 MV POSEIDON [8] generator as shown in Fig. 1. The present water insulated self-break output switch proved to be both very inductive and resistive, and limited our maximum current to 100 kA for 200 nsec with a rate of rise of only 3 kA/nsec.

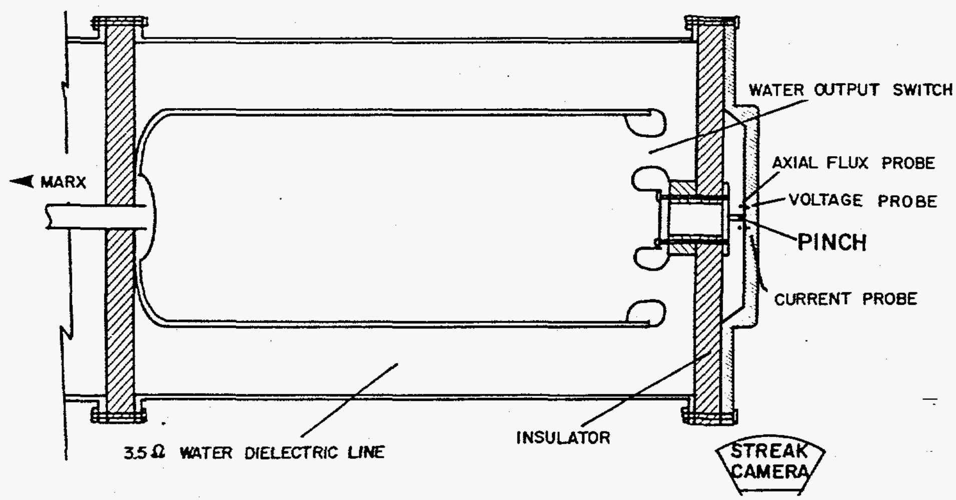

Fig. 1. The NRL Z-Pinch Facility

Gas Embedded Pinch

We formed the gas embedded pinch by filling the entire volume between the insulator and ground plane with D_2 at pressures up to 3 atm. Tungsten pins placed in the peak field region of both electrodes provided enough enhancement to designate a single initially straight channel according to both N_2 laser shadowgraphs and streak photography.

Data for the gas embedded pinch at 1 atm. D_2 is shown in Fig. 2. From the streak photo (Fig. 2a) we observe the pinch to expand rapidly with a velocity of 10^6 cm/sec, which we take as evidence of the accretion. Soft x-ray measurements (Fig. 2b) showed the electron temperature to reach 950 eV within the first 10 nsec, but decrease rapidly afterwards. This again is a manifestation of the accretion. While we were able to calculate from the absolute x-ray signal magnitudes that the radiation was emanating from the entire plasma (within the accuracy of our measurements) and hence conclude that the pinch was uniformly heated, we were not able to account for the 950 eV temperature by classical ohmic heating alone. This suggested to us the pinch was anomalously resistive, and as we calculated the drift velocity to exceed the sound speed, we presume that the ion acoustic instability was the likely mechanism.

In Fig. 2c we show oscilloscope traces of the pinch current and the axial flux produced by the m = 1 instability. The latter was detected by a simple one turn loop and appears to occur 40 nsec after the start of the discharge.

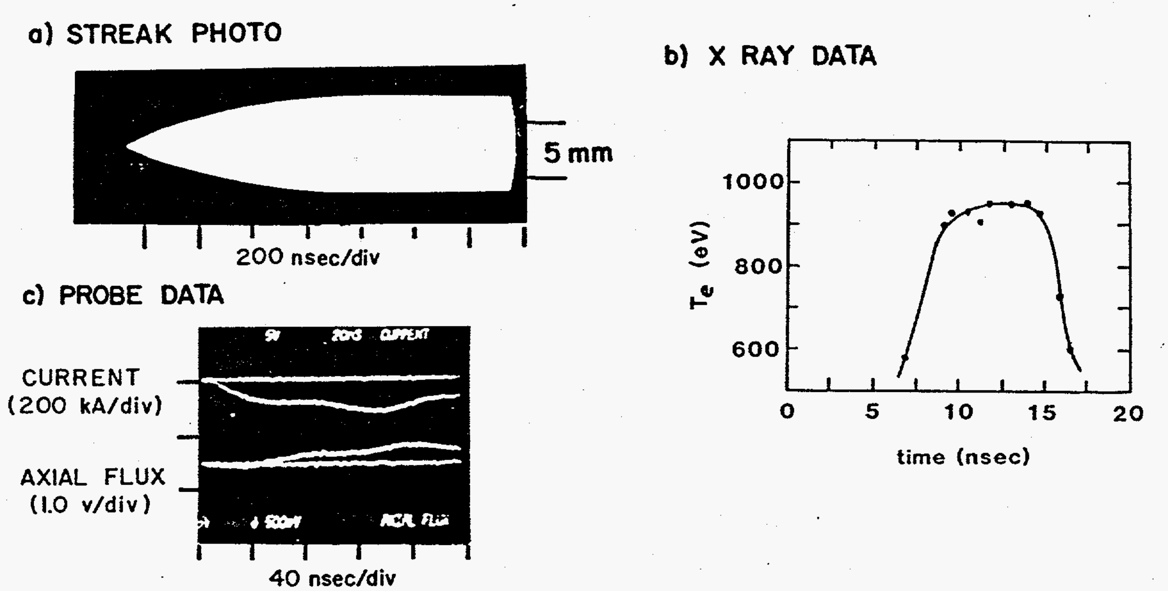

Fig. 2. Gas Embedded pinch data: a) Streak photograph. b) Electron temperature determined by soft x-ray measurements. Three pin diodes with Be foil filters .5 mil, 5 mil and 10 mil thick were used. Although only two detectors are needed to determine T, all three were used to verify the electrons were in a thermal distribution. c) Oscillograms of the pinch current (upper trace) and axial flux (lower trace).

From this data we can calculate the number of "turns" n of the helical plasma. For example, at t = 80 nsec (when the probe signals have stabilized) the axial signal is .25 V, the current 100 kA, and the pinch radius is (from the streak photo) .1 cm. Using these values and the calculated mutual inductance between the pinch and the loop, we have estimated n = 0.4. This is somewhat surprising, as it shows the pinch has not really wound up into a helix, but has instead adopted a lazy "twist" with a wavelength $\lambda = 125\ r$. This observation is in contrast to simple MHD theory [9] which predicts the most unstable mode to have $\lambda = 4\ r$.

Capillary Pinch

In this case one end of a 200 μ ID quartz capillary was sealed with a short length of tungsten wire and placed in contact with the high voltage electrode. The other end was left open and bonded to a hollow screw in the ground electrode. Through the open end we first evacuated the capillary and then filled it with D_2 at the pressure of our choice (up to 80 atmospheres). We then filled the remaining volume between the electrodes with SF_6 at 50 psi to prevent breakdown outside the capillary.

A streak photo of a typical capillary pinch at 2 atm. D_2 is shown in Fig. 3a. In Fig. 3b we have sketched the prominent features of this photo. The drawing is compensated for the focussing effect of the capillary. While it is a bit premature for us to give a precise explanation of all the features of this picture, we can offer a reasonable explanation of the main events. At the beginning, the very bright flash of 4 nsec duration (unresolved due to the slit being used) shows the initial discharge is being formed totally inside the capillary. (When we compare these streaks with those in evacuated capillaries, it is clear that this is a volume discharge, and not surface breakdown along the capillary wall). The 18 nsec long dark region that follows is probably due to full ionization of the D_2 plasma so that all the strong line emission is "burned through." Immediately afterwards a diffuse expanding luminous front can be seen which propagates outwards from the capillary bore at a speed of 2.35 mm/μsec (about 40% of the bulk sound speed in quartz). At about 210 nsec after the start of the discharge, the outer wall of the capillary becomes suddenly luminous (before the luminous front arrives) and almost simultaneously the free (outside surface) begins to move outward at a constant speed.

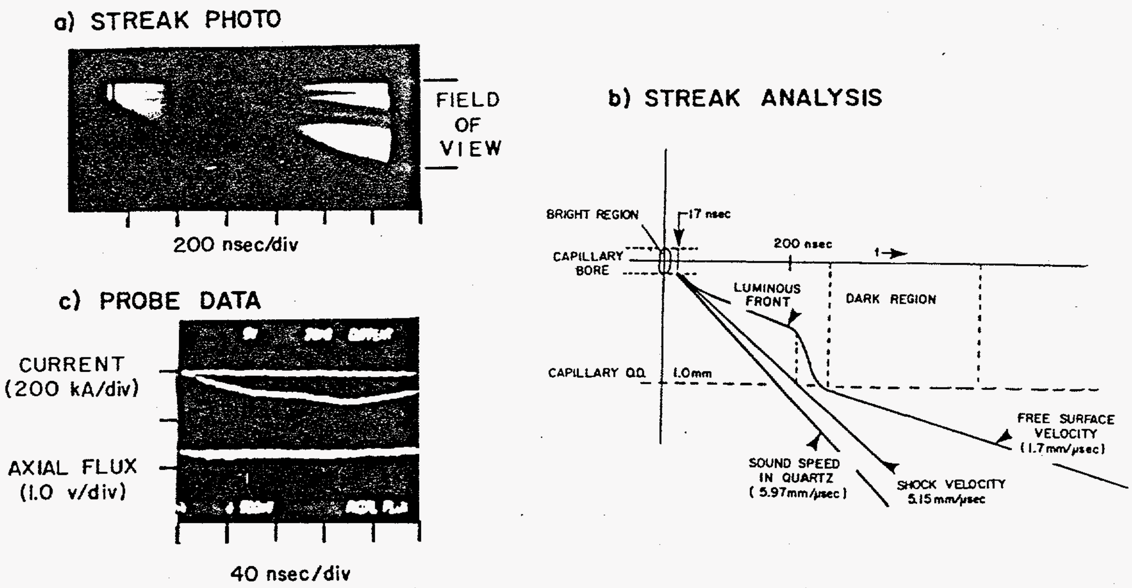

Fig. 3. Capillary pinch data: a) Streak photograph. b) Analysis of the streak photograph compensated for focussing in quartz capillary. c) Oscillograms of the pinch current (upper trace) and axial flux (lower trace).

We can interpret these observations with the aid of shock compression studies made in quartz by Wackerle [10]. He found that for driving pressures above 40 kbar a strong shockwave is seen traveling at 5.15 mm/μsec. It is preceeded by a faster, but weaker, precursor wave which propagates at the sound speed (5.97 mm/μsec) but which produces little motion when it arrives at the free surface. When the strong shock arrives, however, the surface moves outward at a constant speed that depends on the magnitude of the driving pressure. In addition, for driving pressures above 160 kbar, a second shockwave is generated. This one propagates even slower than the first, and causes a further step increase in the free surface speed when it arrives. Both the strength and speed of this second shock are dependent on the initial pressure.

Applying these results to our capillary, we observe the outer surface to begin to move outwards at about 210 nsec, in agreement with a shock speed of 5.15 mm/μsec (see Fig. 3b). From the observed velocity of the free surface (1.7 mm/μsec) and from Wackerle's data, we estimate the driving pressure to be above 100 kbar, but as no evidence of a second shock is seen on the free surface, we conclude it is less than 160 kbar. This is not unrealistic, as the generator has delivered more than enough energy by $t = 20$ nsec to account for this pressure.

The streak photo goes suddenly dark soon after the free surface starts moving. This is probably due to increased scattering of light from inside the capillary by the now shattered outer surface. The light reappears after about 500 nsec, which is close to the time at which the original luminous front would reach the capillary wall. Needless to say, in the end the quartz is returned to its initial state ....sand.

Oscilloscope traces for this shot are shown in Fig. 3c. We observed virtually the same current as in the gas embedded pinch (Fig. 2c), which is not surprising since the current waveform was determined more by the switch than the pinch behavior, yet we saw no axial flux signal. If the pinch had curled up with the same unstable mode as we saw earlier ($\lambda = 125$ r) then with a radius of 100 μ (the capillary radius) this would have produced a signal of .026 volts, which we easily could have detected. (A more conventional $\lambda = 4$ r would have resulted in a 2 volt signal). As the 200 psec magnetic diffusion time through the wall plasma, (assuming 10 eV and an effective Z of 1) is too fast to affect our magnetic measurement, we can only conclude that the capillary has indeed prevented the $m = 1$ instability.

III. CAPILLARY PINCH MODEL

We have developed a simple zero dimensional model to describe the dynamic evolution of a capillary pinch driven by a 3.5 ohm pulseline. We assume the pinch radius r cannot exceed the capillary radius r_t, but it can be less, in which case the vacated volume is filled with a plasma consisting of the capillary material. The temperature of this corona will be kept quite low by radiation, but nevertheless it can still shunt some of the current from the pinch. As we have not yet developed a model of the corona, its temperature is treated as an input parameter.

The equation for the total current I is

$$L \frac{dI}{dt} = V_0 - I(Z+R) \quad , \qquad (1)$$

where L is the total (switch plus load) inductance, R the total resistance, V_0 the voltage and Z the line impedance.

The equation for the temperature T is

$$\frac{dT}{dt} = T\left(\frac{1}{t_1} - \frac{1}{t_2} - \frac{1}{t_3}\right) , \qquad (2)$$

where t_1, t_2, t_3 are, respectively, the characteristic times for ohmic heating, radial conduction loss and bremsstrahlung loss. Since the model is zero-dimensional, we have allowed for an adjustable factor α to give the radial conduction loss time for various radial temperature profiles. Thus

$$\alpha t_2 = \frac{3\ NkT}{2\pi r\ C(n,B,T)} \cdot \frac{r}{T} ,$$

where C(n,B,T) is the thermal conductivity, $B = 2I_p/r$, is the magnetic field at the edge of the pinch, and n is the density.

At each time step of the calculation the pinch radius is adjusted so that the temperature is brought, either by adiabatic compression or expansion, to that required for the Bennett equilibrium ($I_p^2 = 4\ NkT$). As we assume the total current I is divided resistively between the pinch current, I_p and the corona current I_c, we can write

$$\frac{I_p}{I_c} = \frac{\eta_c}{r_t^2 - r^2} \cdot \frac{r^2}{\eta_\rho} ,$$

where η_ρ and η_c are the resistivities of the pinch and corona, respectively.

The results of a run in which we attempted to simulate the experiment are shown in Fig. 4. We assumed a corona temperature of 10 eV which is most probably an overestimate. In this case we found about 35% of the total current was shunted by the corona, and the pinch reached about 450 eV. Total neutron yield was predicted to be 2.5×10^6 which was right at the threshold of our detector and probably explains why we detected none.

IV. FUTURE PLANS

While we have demonstrated that a z-pinch can be formed inside a capillary, we feel that the presently available current rise rates and peak current have prevented us from adequately testing this concept. In order to rectify this situation, we have replaced the present self-break water switch with an SF_6 insulated switch that is based on a multichannel, floating

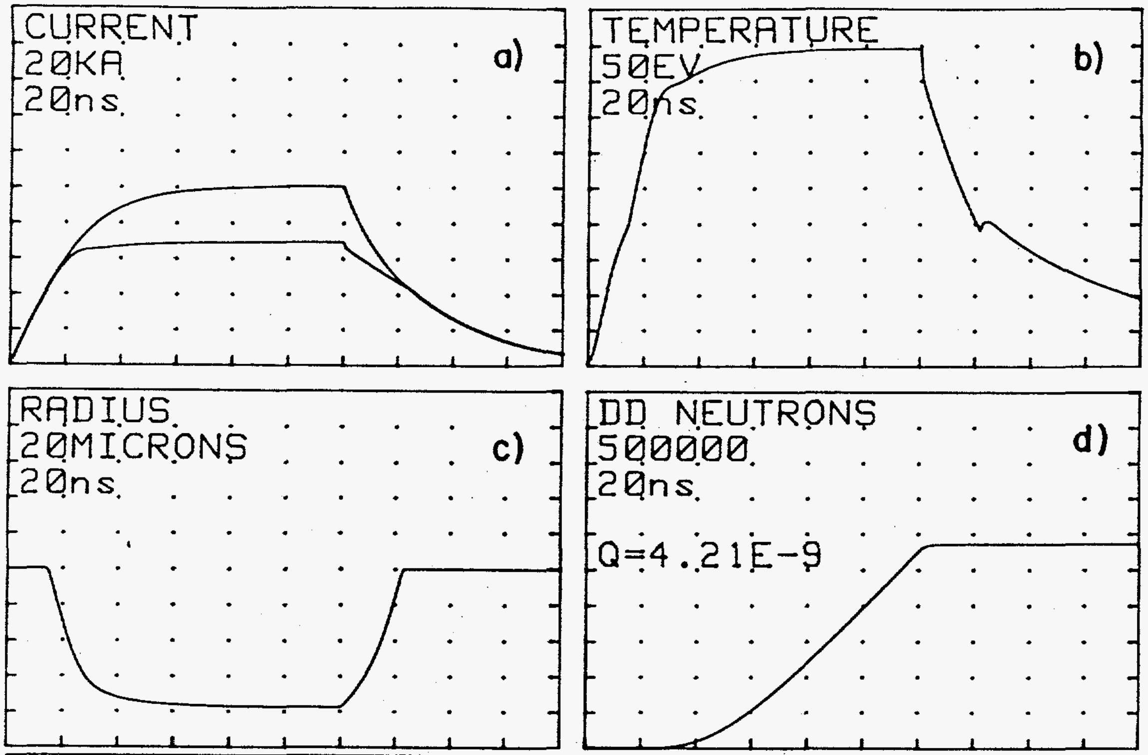

Fig. 4. Results of capillary pinch model: a) Total current through capillary (upper curve) and current through pinch (lower curve); b) electron temperature; c) pinch radius; d) neutron yield.

midplane, oil-insulated design of John Shipman [11]. To date, we have achieved currents of 380 kA with initial risetimes of 15 kA/nsec into a 41 nH short circuit. We fully expect 450 kA at full charge which, according to our model, predicts $T_e \sim 900$ eV and the neutron yield to be 10^9.

As described elsewhere in these preceedings [12], we have developed a reactor based on this concept in which the pinch is formed not in a capillary, but in a rapidly rotating vortex of cold water. We plan to develop this concept further if our high current experiments prove successful.

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