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TITLE: THE LOS ALAMOS SOLID-DEUTERIUM-FIBER Z PINCH, EXPERIMENT AND THEORY

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THE LOS ALAMOS SOLID-DEUTERIUM-FIBER Z PINCH; EXPERIMENT AND THEORY

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I. Introduction

The linear z pinch is among the simplest plasma configurations and was one of the first considered for controlled fusion applications. After an initial period of investigation, however, this research was largely abandoned because of observations and theoretical predictions of instabilities. Research on z pinches as radiation sources has continued.

Despite the troubled history of linear z pinches, they offer some great advantages, if ways can be found to tame their unstable nature. Since an unstabilized pinch in equilibrium is inherently a $\beta = 1$ plasma, it can be ohmically heated to fusion temperatures and thus requires no auxiliary heating sources. Since the heating current also provides the confining field, no magnetic field coils are required. Hence the two most expensive and complicated subsystems of a fusion reactor are eliminated. In addition, practical systems are expected to be inherently compact and small, involving only about 200 kJ of stored energy.

The greatest issue in making a practical z pinch is thus how to achieve sufficient stability. Present experiments aim to tackle this problem in at least two ways.

The first approach is that of the equilibrium pinch. Most z pinches have been formed by a discharge initiated on the cylindrical boundary of a comparatively low density gas, either on a wall, the outside of a gas puff, or in a wire array. The pinch effect then drives an implosion, culminating in assembly to high density on axis where the implosion kinetic energy is converted into thermal energy. Such a pinch has the current flowing in a current sheath on its edge. An equilibrium pinch, in contrast, is formed in a dense channel on the axis of the device, and the current rate of rise is programmed to keep that channel at or near radial pressure equilibrium at all times. Figure 1 illustrates the current profile theoretically required to maintain this equilibrium.

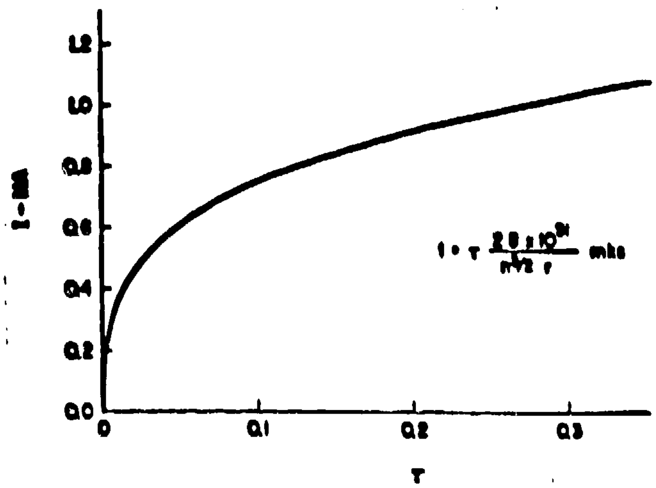

Figure 1

In an equilibrium pinch all of the heating is ohmic, and the current has the opportunity to penetrate into the center of the column. Kadomtsev[1] and Suydam[2] have shown that a z pinch can be stable to $m = 0$ modes if the plasma beta falls of with radius at a sufficiently slow rate. Thus an equilibrium pinch would be expected to form a more nearly stable configuration than an implosion pinch.

The second technique for achieving sufficient stability is to make the density of the column as high as possible. The rate at which the fastest growing instabilities grow is typically $\sim v_{therm}/r$. However, the radially integrated reaction rate is $\propto n^2 \pi r^2 \propto N^2/r^2$ where N is the density integrated across the column cross section. Thus if a given N is heated at smaller radius and hence higher density, more reactions will be generated before instabilities can grow to disruptive amplitudes. This approach amounts to reducing to a minimum the time that the magnetic fields must hold the plasma beyond the inertial confinement time. The experiments described here are performed at solid density, which is a practical limit for an equilibrium pinch.

This paper describes experiments that have been performed on a high density z pinch a Los Alamos National Laboratory over the last two years with plasma currents of 250 kA. Also described is an experiment under construction which will increase the plasma current to over 1 MA and several theoretical efforts to understand its behavior.

II. Experimental Techniques

The current generator for the 250 kA experiments is a 12 kJ, 600 kV Marx bank charging a 1.6 Ω, 100 ns water transmission line switched to the load by a self-breaking multipont water switch. The plasma chamber is maintained at a vacuum of $10^{-6} - 10^{-7}$ Torr. The plasmas are created from fibers of cryogenic deuterium with diameters ranging from 20 to 40 μm and a length of 5 cm. The fibers hang in the vertical anode-cathode gap of the plasma chamber (see figure 2), and are ionized, heated, and confined

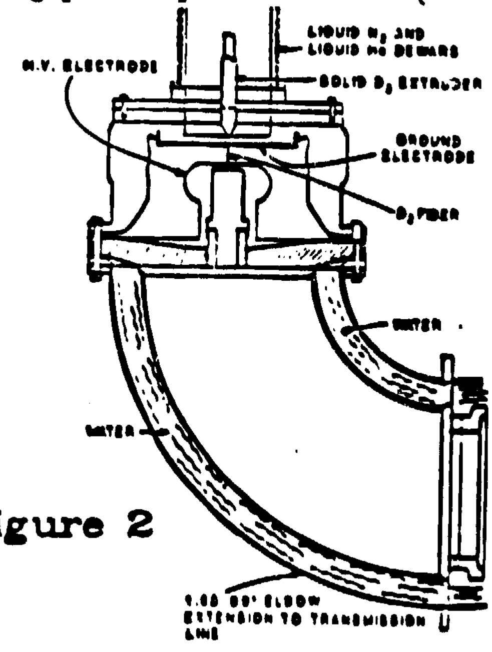

Figure 2

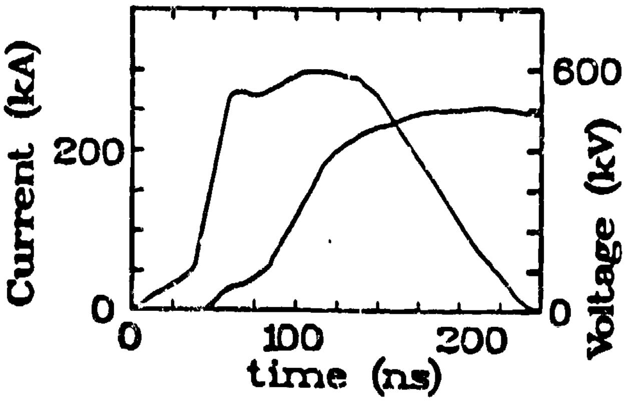

Figure 3

by application of the 600 kV voltage pulse. The resulting voltage and current profiles are shown in figure 3.

Diagnostics of the pinch include a multi-frame fast schlieren camera giving seven images, one every ten nanoseconds, neutron counting with a silver counter, and neutron time history using a scintillator/photomultiplier tube arrangement, differential absorber XRD soft x-ray detectors, and an x-ray pinhole camera.

III. Results at 250 kA

The fibers are observed to begin current conduction typically at the peak of the voltage pulse, although the time of initial conduction can vary by up to 50 ns. The resulting plasma columns expand at a velocity less than 1/10 of thermal velocity despite the fact that the current rate of rise is well below what figure 1 would imply is necessary to maintain radial equilibrium. The columns are free from visible instabilities for typically 80 ns into the current discharge, at which time the instability growth times would be expected to be ≈ 1 ns. After approximately 80 ns $m = 0$ modes become apparent, which ultimately disrupt the column. However, $m = 1$ modes are not observed.

Plasma parameters are inferred from a number of diagnostics. Since the initial fiber diameters are known, the average plasma density can be obtained from measurements of the column diameter. The initial solid density is 5×10^{28} m^{-3}, which drops to 2×10^{27} m^{-3} before the onset of instability.

Peak plasma temperature measured with differential absorber XRDs is 150 eV. The Bennett relation

$$\mu_0 I^2 = 16\pi NkT$$

gives temperatures which range from 150 eV to 600 eV for fiber diameters of 40 μm down to 20 μm. The number of neutrons per shot varies from several 10^6 to 10^8. The larger neutron numbers would imply plasma temperatures of ≈ 300 eV. However, this number is very sensitive to any non-Maxwellian tail on the distribution function and is therefore a poor temperature diagnostic. Both the neutrons and the soft x-rays are observed to occur in pulses approximately 50 ns long about the current maximum.

The x-ray pinhole photographs are taken on Kodak type 101-01 film behind a 0.5 μm aluminum foil. They show emission from a narrow (resolution-limited), continuous column, although it is impossible to rule out structure in the pictures smaller than the 400 μm pinhole size.

IV. Future Experiment

Extension of these experiments to plasma currents of 1 MA and above is underway. To do so requires a substantially larger current generator with 200 kJ of stored energy and a voltage of 3 MV. The design we have used is based on a Sandia National Laboratories, Albuquerque generator, named MITE. It will consist of a 3.2 MV marx bank feeding a 32 nF intermediate store water capacitor which, in turn, charges a 1.9 Ω, 50 ns vertical transmission line to drive the same fiber load used in the present experiments. Our approach is to use conservative pulsed power design in order to maximize the probability of achieving the intended parameters.

The vertical tranmission line has been fabricated and tested with the existing MITE marx bank and intermediate store at Sandia. These tests achieved a current of 0.93 MA in a plastic fiber load. By optimizing the design of the intermediate store and the interconnections between stages, achievement of currents up to 1.2 MA is expected.

Bennett scaling of the plasma parameters predicts that a 20 μm diameter fiber at 1 MA would have a temperature of 10 keV. If such a plasma at or near solid density demonstrated the same stability properties as have been observed in present experiments, it would be capable of producing significant thermonuclear burn in a comparatively modest experiment.

V. Theory

Several numerical codes have been used to attempt to simulate the behavior of the high density z pinch. Glasser has written a 1-D adaptive mesh code which efficiently models this problem. These calculations and those discussed below all show that there is substantial current penetration into the core of the pinch despite the high conductivity of the plasma.

Nebel[3] has shown that a z pinch near equilibrium has self-similar time and space separable solutions. If the current has a time dependence of the form $I \propto t^{\alpha}$, then the radial profiles depend only on α. Using a 1-D radial MHD code he has shown that these solutions are attractors, i.e., a z pinch with arbitrary radial profile will rapidly relax to one of these solutions.

Lindman has used a laser fusion code LASNEX to calculate the transition of the fiber from a solid to a plasma. Preliminary results show the ionization process requiring up to 50 ns. However, there are substantial uncertainties about the correctness of the transport used in LASNEX at cryogenic temperatures, so that the correct ionization time may be shorter.

VI. Summary

Experiments in which 250 kA have been passed through a z-pinch column formed from a thin fiber of cryogenic solid deuterium have demonstrated unexpectedly stable behavior. It has been shown that it is possible to maintain a z pinch in near radial equilibrium while it is ohmically heated from 16° K to several hundred eV.

These encouraging results have motivated an effort to increase the plasma current to 1 MA and above, giving the potential of producing reactor-relevant plasmas capable of significant thermonuclear burn. Such a megamp experiment has been designed, partially fabricated, and successfully tested with an existing generator.

A variety of analytic and numerical tools have been used to study the behavior of these pinches. They have shown that the high density z pinch may be expected to have a pressure profile peaked on axis, which can contribute to stability; that the ionization of the fiber may require a time significant with respect to the duration of the experiment; and that the spatial behavior of these plasmas may frequently be described by simple, elegant analytic solutions.

[1] B. B. Kadomtsev, "Hydromagnetic Stability of a Plasma," in *Reviews of Plasma Physics* (Consultants Bureau, New York, 1965) Vol. 1, p. 205.
[2] B. R. Suydam, Los Alamos Scientific Laboratory Report No. LA-7809-MS, May 1979.
[3] R. A. Nebel, H. R. Lewis, J. E. Hammel, D. W. Scudder, 1987 Sherwood Controlled Fusion Theory Conference, April 6-8, San Diego, paper 2B1.