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DENSE Z-PINCH PLASMAS

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Introduction

Early researchers recognized the desirable features of the linear Z-pinch configuration as a magnetic fusion scheme. In particular, a Z-pinch reactor might not require auxiliary heating or external field coils, and could constitute an uncomplicated, high plasma β geometry. The simple Z pinch, however, exhibited gross MHD instabilities that disrupted the plasma, and the linear Z pinch was abandoned in favor of more stable configurations. Recent advances in pulsed-power technology and an appreciation of the dynamic behavior of an ohmically heated Z pinch have led to a reexamination of the Z pinch as a workable fusion concept.

Analytical work by Haines [1] and Hammel [2] has revealed the necessity for rapid current rise rates during the formation and heating phases of a quasi-equilibrium pinch, and this in turn has indicated the need for high voltage discharges across the inductive plasma load. To prevent the collapse of an annular, high impurity-fraction plasma formed off the walls of the discharge chamber, the concept of an isolated Z pinch was developed. A comparison of the heating time scale and canonical instability growth time (Alfvén transit time across the plasma column) with the burn time required by the Lawson criterion has demonstrated the advantages of high plasma density operation. Preliminary reactor calculations [3] suggest that a pulsed dense Z pinch could produce 4.4 MJ_t for an input energy of only 140 kJ in a single, 2-µs burn. This represents an extremely attractive scheme in spite of the many present physics uncertainties. Our group at Los Alamos has been investigating isolated high density Z pinches in three distinct embodiments: gas-embedded pinches, wall-limited pinches, and solid fiber pinches.

Gas-Embedded Z Pinches

The first series of experiments in our program involved the formation of a plasma channel down the axis of a large (30-cm radius) chamber filled with high pressure gas (1/3 - 3 atmosphere H_2). The gas between the electrodes in the chamber forms the load for the 12-kJ pulsed power system (Fig. 1). The Bennett equation describing the balance between plasma internal pressure and magnetic field pressure,

$$I^2(\text{Amps}) = 6.4 \times 10^{-12}\ N(\text{m}^{-1})\ T(\text{eV}),$$

indicates the need for manageable plasma line density, N, in order to achieve a high plasma temperature, T, at an acceptable driving current, I. At high pressure, one must therefore initiate a narrow channel to avoid an overly large plasma inventory or line density. Our experiments incorporate a

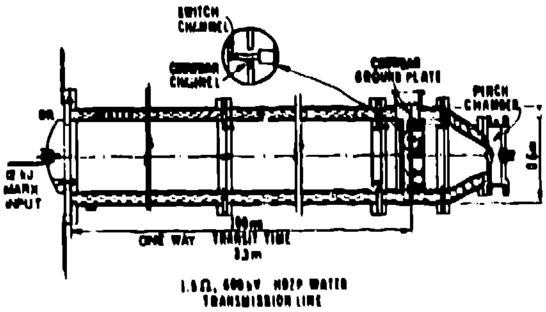

Fig. 1. Schematic of dense Z-pinch apparatus.

high power, pulsed, solid state laser focused through an entrance hole in the ground electrode and dumped in a cavity in the high voltage electrode. The 30-ns Q-switched laser is operated <u>below</u> the threshold for laser-induced breakdown in the hydrogen and is fired 100 ns before voltage is applied across the 5-cm long electrode gap. Schlieren photographs reveal the successful designation of a narrow (100-μm diameter), straight, stable, channel carrying 50 kA. Time resolved x-ray measurements using multiple thickness metallic foils and scintillator-photomultiplier combinations show the plasma temperature rising to 1000 eV in 10 ns in agreement with simple ohmic heating estimates, and then falling rapidly. No violent MHD activity is observed during the 200-ns current pulse; after approximately 50 ns there is a three dimensional surface structure evident in the schlieren photographs which, while possibly related to m = 1 kinking, is not at all disruptive.

We have conclusively established that the drop in plasma temperature is the result of an increase in the plasma line density (measured using a new quantitative moiré-schlieren technique) [4]. The initial plasma column accretes new plasma from the neutral gas blanket and cools through rapid equilibration. Accretion is undesirable because it prevents the sustainment of high temperatures, and we have examined the problem both analytically and computationally [5], in some depth.

Our present explanation for the observed accretion is a bootstrap or two-phase process. Initial overheating of the plasma column (Bennett equilibrium cannot be achieved in the first few nanoseconds) launches a radially propagating, weakly ionizing cylindrical shock into the neutral gas. Current continues to rise in the column because the high voltage is still applied across the electrode gap, and the incoming flux combined with Townsend avalanching raises the ionization level of the blanket surrounding the plasma core.

The accretion problem observed in gas-embedded Z pinches may be surmountable with proper attention to the applied voltage waveform. There are practical difficulties associated with the necessary pulsed power switching modifications, however, and we have concentrated our recent efforts on two alternative configurations, wall-limited pinches and solid fiber pinches. Both schemes eliminate accretion by physically limiting the amount of material available for ionization.

<u>Wall-limited Z Pinches</u>

Wall-limited Z pinches are simply gas-embedded experiments conducted inside insulating tubes of sufficiently small diameter that full ionization of the contained gas does not constitute an unacceptably high plasma line density [6]. To prevent classical wall formation of the plasma, we are continuing to use our laser initiation process. We have successfully produced narrow plasma channels inside 3-mm diameter polycarbonate tubes which still allow transverse optical diagnostic access, and the next experiments will be performed inside 1-mm diameter tubes. In connection with these laser-initiated experiments we have observed self-focused channels produced by a 12-J Nd-glass laser when operated above the laser-induced breakdown threshold. The single mode, low-divergence laser interacts with the neutral gas (3 atmospheres of H_2), and schlieren photographs reveal channels which are several centimeters long and have diameters less than 50 μm (Fig. 2). This unexpected phenomenon may increase the

Fig. 2. Schlieren photograph of channel produced by self-focused laser.

possibility of initiating plasma channels in submillimeter diameter chambers. The obvious potential problem of wall interaction and accompanying impurities remains, and we are attempting to model this process with numerical simulations.

Solid Fiber Pinches

The ultimate density for uncompressed magnetically confined fusion experiments is that of solid D_2 ($\sim 5 \times 10^{22}$ cm^{-3}) and our line density limitations place severe restrictions on fiber diameters. Operating at 2 MA, a 40-μm diameter solid fiber could be ohmically heated to 10 keV in Bennett equilibrium. At this high density the required plasma energy confinement time is only a few nanoseconds.

Using a liquid He cooled cryostat, we have extruded solid D_2 fibers 40 μm in diameter and 20-cm long into a vacuum chamber [7]. These fibers are straight, uniform, and remain at nearly constant diameters for several minutes (Fig. 3). In the solid fiber pinch program, a fiber will be dropped vertically between the electrodes in the discharge chamber; the gravity feed system for the fibers has necessitated construction of a 90° elbow in the water transmission line. Experiments performed with our 350-kA machine will determine the importance of gross MHD modes, and we will require a higher current pulsed power system to carry the plasma temperature up to the kilovolt regime.

Fig. 3. Solid D_2 fiber.

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