LA-UR 97-2714
CONF-9705120--

TITLE:

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SUBMITTED TO:

Dense Z-Pinches: Proceedings of the 4th International Conference on Dense Z-Pinches, May 28-30, 1997, Vancouver, B.C., Canada

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Computational Modeling of Wall-Supported Dense Z-Pinches

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Abstract. In our previous computational modeling of deuterium-fiber-initiated Z-pinches intended for ohmic self-heating to fusion conditions, instability-driven expansion caused densities to drop far below those desired for fusion applications; such behavior has been observed on experiments such as Los Alamos' HDZP-II. A new application for deuterium-fiber-initiated Z-pinches is Magnetized Target Fusion (MTF), in which a preheated and magnetized target plasma is hydrodynamically compressed, by a separately driven liner, to fusion conditions. Although the conditions necessary for a suitable target plasma--density $O(10^{18}\ cm^{-3})$, temperature O(100 eV), magnetic field O(100 kG)--are less extreme than those required for the previous ohmically heated fusion scheme, the plasma must remain magnetically insulated and clean long enough to be compressed by the imploding liner to fusion conditions, e.g., several microseconds. A fiber-initiated Z-pinch in a 2-cm-radius, 2-cm long conducting liner has been built at Los Alamos to investigate its suitability as an MTF target plasma. Two-dimensional magnetohydrodynamic modeling of this experiment shows early instability similar to that seen on HDZP-II; however, when plasma finds support and stabilization at the outer radial wall, a relatively stable profile forms and persists. Comparison of experimental results and computations, and computational inclusion of additional experimental details is being done. Analytic and computational investigation is also being done on possible instability-driven cooling of the plasma by Benard-like convective cells adjacent to the cold wall.

INTRODUCTION

Fast-current-rise Z-pinches initiated from frozen deuterium fibers appeared to show anomalous stability at current peaks up to 600 kA, leading to hopes that fusion conditions could be reached in machines designed for peak currents in excess of 1 MA. However, pinches produced on high-current machines, such as Los Alamos' HDZP-II, showed instability-driven plasma column expansion, dropping densities far below those desired for fusion applications. We developed a detailed two-dimensional computational magnetohydrodynamic (MHD) model for such discharges, which showed good agreement to experimental results (1,2). A new application for such dense Z-pinches is as a preheated and magnetized tar-

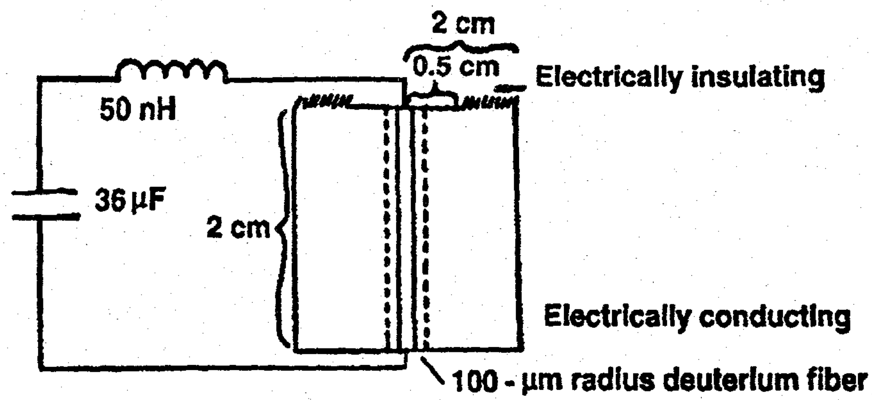

FIGURE 1. LANL Z-pinch target plasma: a 2-cm radius, 2-cm long, electrically conducting plasma chamber, containing a deuterium-fiber-initiated Z-pinch, driven by a capacitor bank (200 kJ, 100 kV, 2.2 µs risetime).

get plasma for subsequent hydrodynamic compression, by a separately driven liner, to fusion conditions, in a scheme known as "Magnetized Target Fusion."

Magnetized Target Fusion (MTF) is an approach to controlled fusion that is intermediate between magnetic confinement and inertial confinement fusion (ICF) in time and density scales (3,4). MTF uses a pusher-confined, magnetized, preheated plasma fuel within a fusion target. The magnetic field suppresses losses by electron thermal conduction in the fuel during the target implosion heating process. Reduced losses permit near-adiabatic compression of the fuel to ignition temperatures, even at low (e.g., 1 cm/µs) implosion velocities. An MTF system requires two elements: (1) a target implosion system (2) a means of preheating and magnetizing the thermonuclear fuel prior to implosion. An optimal driver source for MTF may be relatively inexpensive electrical pulsed power. This could utilize either fixed pulsed-power facilities, such as Los Alamos' Pegasus or Atlas, or explosive-flux-compression generators, such as Los Alamos' Procyon or the 200-MJ-class disk flux compression generators developed by the All-Russian Scientific Research Institute of Experimental Physics (VNIIEF) (5,6). Such energy-rich sources might allow a demonstration of fusion ignition via MTF, without a major capital investment in driver technology; evaluation of such implosion systems is ongoing at Los Alamos.

Optimal target plasma conditions for MTF are temperature O(100 eV), density O(10^{18} cm^{-3}), and magnetic fields O(100 kG). Sufficient plasma lifetime to allow implosion is necessary (on the order of several microseconds), and plasma-wall interactions must not lead to excessive introduction of impurities, which could result in rapid cooling of the plasma. A deuterium-fiber-initiated Z-pinch might well produce an acceptably hot, dense, magnetized target plasma for subsequent MTF compression. Using the same computational tool--a version of Lindemuth's MHRDR code (7,8)--with which the Los Alamos HDZP-I and HDZP-II fiber Z-pinches were modeled (obtaining excellent agreement with experiment (1,2,8)), a fiber Z-pinch target plasma experiment has been designed and modeled. This experiment has been built and is now operating at Los Alamos.

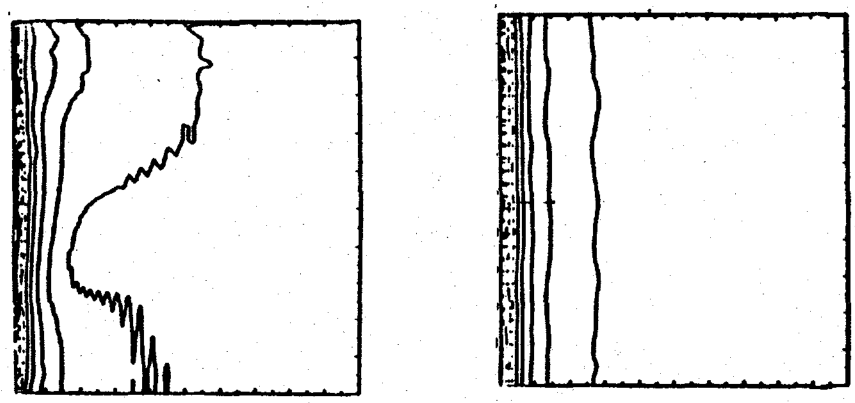

FIGURE 2. Computed axial current contours (*r-z* 2 cm by 2 cm): (left) early (1.1 μsec) unstable, expanding phase; (right) later (2.4 μsec) stable, wall-supported phase.

FIBER Z-PINCH TARGET PLASMA EXPERIMENT

The Z-pinch target plasma experiment (Figure 1) will be driven by the Colt capacitor bank at Los Alamos (200 kJ, 100 kV, up to 2 MA with a 2.2 μsec risetime), which is considerably lower voltage and slower than the original Los Alamos HDZP experiments. In addition, the plasma will be contained inside a 2-cm-radius conducting wall; the HDZP experiments were in a chamber with tens-of-centimeter distant walls.

Detailed two-dimensional MHD modeling of such an experiment predicts early behavior similar to the HDZP experiments: the fiber-initiated plasma becomes unstable and expands explosively. However, when the plasma finds support and stabilization at the conducting wall, it appears to settle into a dense, hot, Kadomtsev-stable state, capable of carrying megamp-plus currents in a few-mm-radius column, over several microseconds (Figure 2). The pinch varies from temperatures near 1 eV, and densities near 10^{17} cm^{-3} at the 2-cm-radial wall, to near 1 keV and 10^{20} cm^{-3} at r=0. To the extent that such an experiment lives up to these predictions and remains free of contaminants, it would certainly be an acceptable MTF target plasma, and would be of considerable research interest, even without MTF liner-on-plasma compression.

Of course, such predictions must be verified experimentally. Such problems as insulator flashover and wall-plasma interactions must be investigated. Three-dimensional effects will have more time to develop than in the HDZP experiments, although the relatively close conducting wall should have some stabilizing effect. Since these are issues critical to many MTF liner/plasma schemes, experimental investigations on such a device can be extremely useful parts of an MTF research program.

As an MTF target plasma, such a dense Z-pinch has advantages and disadvantages when compared to other possible target plasmas, such as compact toroids or the Russian-originated "MAGO" plasma (9). MAGO plasmas, in their late-time relatively steady state, are calculated to be much more uniform in temperature, density, and field, and to load the electrodes with smaller current per unit area. Hence a more nearly adiabatic compression of such plasmas by wall implosion might be possible; on the other hand, dense hot plasma may spend more time in contact with the walls, which could lead to deleterious wall-plasma interactions. Compact toroids have the potential advantage of being electrically detached from the electrodes after formation, avoiding current-driven electrode material influx; but it remains to be seen whether or not the necessary plasma densities can be achieved in a compact toroid. Detailed experimental and computational analysis will have to be continued to sort out these differences and evaluate the best target plasma for MTF. The Colt Z-pinch facility will not only allow the development of diagnostics and detailed computational models for evaluating the Z-pinch as an MTF target plasma, but should be adaptable to other configurations if they appear advantageous.

Dense magnetized plasmas in contact with a cold wall (fixed or imploding) may form Benard-like convective cooling cells. The MHD code being used for these Z-pinch simulations has been employed to study such convective processes (10,11). Semi-analytic models are being developed in conjunction with computational work to predict the occurrence and consequences of such phenomena.

CONCLUSIONS

Deuterium-fiber-initiated Z-pinches may provide a suitably hot, dense, magnetized target plasma for compression inside a heavy metallic liner to fusion conditions in a Magnetized Target Fusion (MTF) scheme. Modeling of such a target plasma inside a 2-cm-radius conducting liner predicts that, after initial explosive instability-driven expansion, the plasma may find a state stabilized by wall support of the plasma and magnetic field. An experiment to investigate these plasmas, and allow development of target plasmas for MTF, is beginning operation at Los Alamos National Laboratory.

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