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COMPUTATIONAL MODELING OF PULSED-POWER-DRIVEN MAGNETIZED TARGET FUSION EXPERIMENTS

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ABSTRACT

Direct magnetic drive using electrical pulsed power has been considered impractically slow for traditional inertial confinement implosion of fusion targets. However, if the target contains a preheated, magnetized plasma, magnetothermal insulation may allow the near-adiabatic compression of such a target to fusion conditions on a much slower time scale. 100-MJ-class explosive flux compression generators [1,2], with implosion kinetic energies far beyond those available with conventional fusion drivers, are an inexpensive means to investigate such magnetized target fusion (MTF) systems [3,4].

One means of obtaining the preheated and magnetized plasma required for an MTF system is the recently reported "MAGO" concept [5,6]. MAGO is a unique, explosive-pulsed-power driven discharge in two cylindrical chambers joined by an annular nozzle. Joint Russian-American MAGO experiments have reported D-T neutron yields in excess of 10^{13} from this plasma preparation stage alone, without going on to the proposed separately driven MTF implosion of the main plasma chamber.

Two-dimensional MHD computational modeling of MAGO discharges shows good agreement to experiment. The calculations suggest that after the observed neutron pulse, a diffuse Z-pinch plasma with temperature in excess of 100 eV is created, which may be suitable for subsequent MTF implosion, in a heavy liner magnetically driven by explosive pulsed power. Other MTF concepts, such as fiber-initiated Z-pinch target plasmas, are also being computationally and theoretically evaluated. The status of our modeling efforts will be reported.

INTRODUCTION

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. This concept has been pursued independently in Russia as MAGO (MAGnitnoye Obzhatiye, or magnetic compression) [1-3] and in the US [4,7], and more recently, as a US/Russian collaboration. Magnetized target fusion 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. In MTF, the convergence ratio of the pusher in quasi-spherical geometries may potentially be less than 10, depending upon the initial temperature of the fuel and the adiabaticity of the implosion. Previous work relevant to MTF includes, but is not limited to, work in imploding liner fusion, impact fusion and electron-beam driven "phi" targets [4,7].

An MTF system requires two elements: (1) a target implosion system (2) a means of preheating and magnetizing the thermonuclear fuel prior to implosion. The advent of 200-MJ-class disk flux compression generators [1,2] make it possible to consider direct magnetic implosion [3] of fusion targets to ignition conditions in an energy-velocity space simply inaccessible by any other laboratory means [8]. Such energy-rich sources appear ideal for MTF and, consequently, for a demonstration of fusion ignition, without a major capital investment in driver technology.

MAGO COMPUTATIONS

One Russian-originated scheme [5,6] for forming a hot, magnetized plasma possibly suited for subsequent implosion is referred to here as "MAGO," the Russian abbreviation for MTF. The MAGO experiment utilizes a cylindrical plasma formation chamber shown in Fig. 1. One such experiment, performed jointly by Los Alamos National Laboratory and the All-Russian Scientific Research Institute of Experimental Physics (VNIIEF, at Arzamas-16) in 1994, is described in detail in the paper at this meeting, "Joint US/Russian Plasma Formation Experiments for Magnetized Target Fusion (MTF)," by Lindemuth, Chernyshev, et al.

The 10-cm-radius chamber, filled with 50-50 D-T gas, is powered by an explosive flux-compression generator. During the early operation of the generator, a slowly rising pulse of electrical current is delivered to the chamber, magnetizing the gas with a "bias" current through the center conductor of approximately 2 MA. At a prescribed time, an explosively operated opening switch rapidly increases its resistance, causing a rapidly increasing electrical current pulse up to about 8 MA in 3 μsec; this drives a plasma discharge in the chamber.
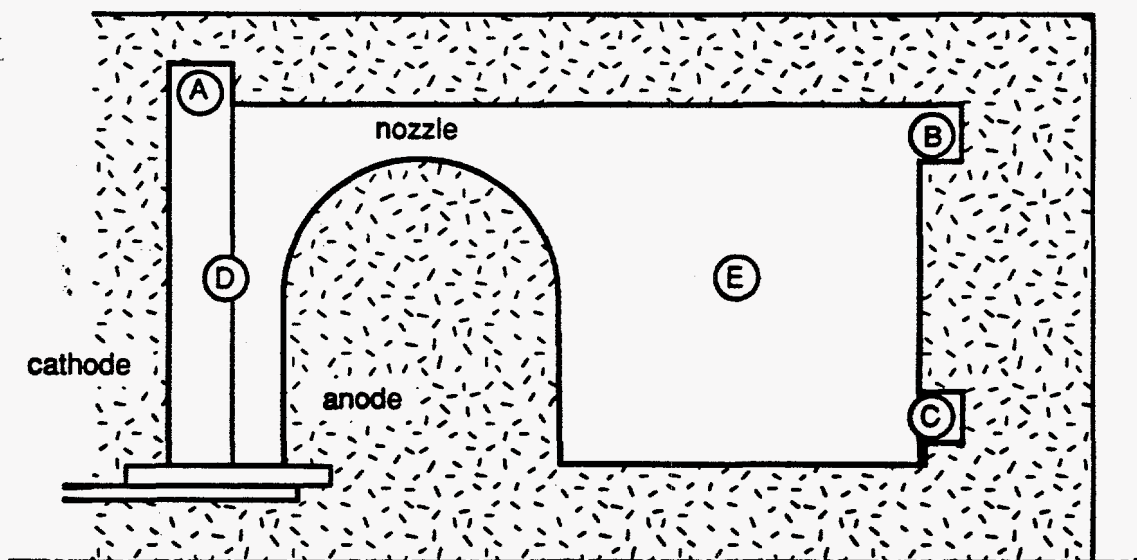

Fig. 1. The cylindrical plasma formation chamber: points A, B, and C contain inductive probes; points D and E indicate chordal lines of sight for interferometry and radiation measurements; chamber is electrically conducting, except for the insulator below point D.

At its average densities, $O(10^{18} \text{ cm}^{-3})$, the MAGO plasma will have an ion thermal transit time much greater than its ion-ion collision time, for temperatures below 1 keV; therefore, one

can expect a collisional magnetohydrodynamic (MHD) fluid model to hold. Plasma behavior was computationally modeled using the two-dimensional magnetohydrodynamics code MHRDR (Magneto-, Hydro-, Radiative-, Dynamics Research). MHRDR has been used to do detailed modeling of numerous plasma experiments, such as deuterium-fiber-initiated Z-pinches [9,10].

Because MHRDR at present cannot compute curved boundaries, the calculations employ a squared-off anode adjacent to the nozzle area. In single-temperature MHD calculations, MHRDR employs realistic equation of state and resistivity information from the SESAME database, from room temperature to hot plasma. However, room-temperature D-T is so resistive that the MAGO chamber, subject to the measured load current, would computationally simply act like a large, fixed inductance (with no current through the interior gas), in contrast to the experimentally evident plasma discharge in the chamber. To establish initial conducting paths resembling those presumably resulting from breakdown inside the chamber, small regions of D-T at the nozzle and adjacent to the insulator are set to 2 eV initial temperature, while the rest of the D-T gas starts at room temperature. This gives computational results in substantial agreement with plasma and current flow as measured by inductive probes and plasma interferometry (see the accompanying "Plasma Formation" paper for more detailed discussion).

The computations indicate that the gas that was originally in the left-hand section is compressed by an inverse pinch and accelerated through the nozzle. Upon exiting the nozzle, the fast-moving (20-100 cm/μs) plasma contacts the compressed plasma of the right-hand section and its kinetic energy is converted to thermal energy. Some plasma (< 5%) reaches temperatures higher than 1 keV, and it is from this plasma that the thermonuclear neutrons (in excess of 10^{13}) originate. One-temperature ($T_i=T_e$) computations give a neutron peak at approximately the same time as experiment, with a similar pulse width (Fig. 2, curve b). However, the total neutron yield is approximately two orders of magnitude too low. Two-temperature ideal gas computations (separate T_i, T_e; initially $T_i=T_e=2$ eV) more closely match the observed yield, but do not well match the plasma and current flow measurements, because of the high initial electrical conductivity of the entire gas within the chamber.
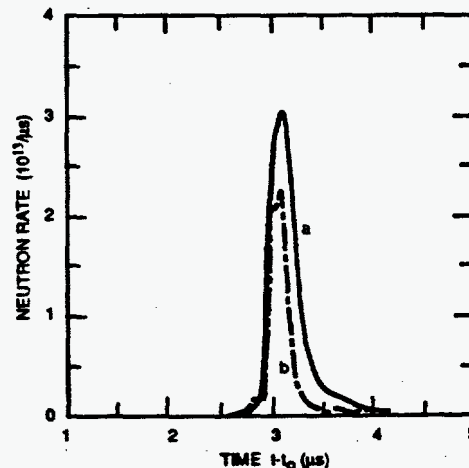

Fig. 2 Neutron emission rate vs. time: (a) measured; (b) computed x 50, one-temperature computation, cutoff density 10^{-2} times fill density.

The two-temperature computations suggest that the ion temperature of the neutron producing plasma becomes significantly higher than the electron temperature, during the time of peak neutron production. Computational neutron yield is sensitive to the "cutoff density," a density below which plasma heating is turned off, in order to avoid unrealistic heating of low-density areas which are effectively vacuum. Neutron yield increases as cutoff density is lowered to about 10^{-3} of the fill density, then saturates, at a value slightly higher than typical measurements. At this cutoff density, a small portion of the plasma reaches rather absurd temperatures, on the order of 100 keV; a cutoff density about 10^{-2} of the fill density gives neutron yields quite close to those measured, without any plasma at such extremely high temperatures.

For times later than about 4 μsec, i.e., after the very complex early-time plasma formation process, the computations show a surprisingly stationary plasma in the right-hand section of the chamber. The plasma can be roughly described as a diffuse, wall-confined z-pinch (see Fig. 3a). The plasma is approximately one-dimensional, with plasma parameters such as density, temperature, and magnetic field varying only with radius. Average computed late-time (10 μs) plasma parameters are $n_e=1.6 \times 10^{18}/cm^3$, $\rho=6.7 \times 10^{-6}$ g/cm^3, T=130 eV, B=240 kG, $\beta=0.3$, $(\omega\tau)_e=140$. Depending upon driving current, average plasma temperatures as high as 300 eV are possible (Fig. 3b).

Like other high-energy-density gas discharge configurations, it would be expected that the plasma would at some time show contamination by wall material (e.g., copper) and that insulator constituents could enter the chamber behind the plasma and possibly mix with the hot plasma during the late times. If a substantial amount of high-Z material entered the plasma, enhanced radiative cooling could drop the high late-time plasma temperatures rapidly. A similarly enhanced cooling is shown in the computational experiment of curve c, Figure 3b, in which we completely removed the magnetothermal insulation of the plasma, by holding all $\omega\tau$'s equal to 0. One can begin to investigate the effects of wall material interaction with the plasma computationally, but full two-dimensional multi-material MHD computation of such a system is a very difficult task. Measurement of late-time temperature and composition of the MAGO plasma is a major focus of continuing experiments.

The spherical magnetized target survey model [4] has been used to predict the fusion yield which could potentially be achieved if the plasma formed in the experiment reported here were subsequently imploded [11]. The computations were based upon the experimental mass (8.9 mg), average computed temperature and magnetic field, and an implosion kinetic energy of 65 MJ. The computations show that unity gain can occur for initial densities above about 10^{-6} g/cm^3 and initial velocities above approximately 0.2 cm/μs. Gains in excess of ten can occur for densities and velocities approximately 2-3 times higher. A gain of 16, and a thermonuclear yield of 1 GJ, is predicted for a density of 6.7 x 10^{-6} g/cm^3, a pusher implosion velocity of 2 cm/μs and a maximum radial convergence of less than 20. The survey computations show that the 290 eV average temperature (Fig. 3b, curve b) computed for an earlier, lesser diagnosed experiment can significantly reduce the convergence required, and that approximately adiabatic compression can be expected for initial magnetic fields as low as 75 kG.

RADIUS (cm)
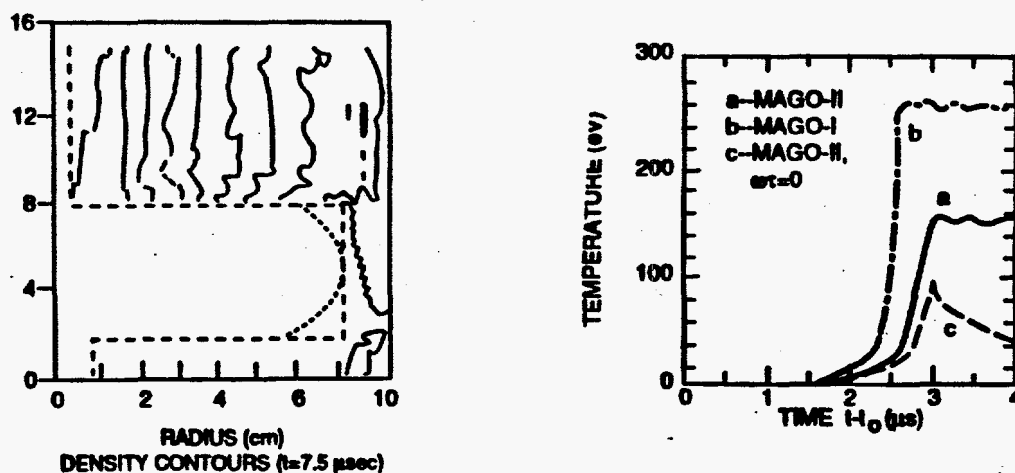DENSITY CONTOURS (t=7.5 μsec)

Fig. 3 Computed late-time MAGO plasma: (a) plasma axial current contours; (b) average plasma temperature vs. time, three separate MAGO computations.

The survey results coupled with the two-dimensional computations suggest that a plasma suitable for subsequent implosion in a MTF context can be produced in a MAGO experiment. Further plasma formation experiments are required before the present plasma chamber can be confidently mated with an implosion system. Future experiments will emphasize characterization of the late time plasma behavior and will search for wall and insulator impurities which would degrade the implosion heating process by enhancing the radiation energy losses from the plasma. Although it is quite plausible that the present plasma chamber could be scaled to a smaller size, reducing the implosion energy required, existing high-explosive pulsed power devices [1,2,8] are sufficient to provide the 65 MJ of energy used in the survey computations.

FIBER Z-PINCH TARGET PLASMAS

Numerous existing pulsed power facilities at Los Alamos National Laboratory and elsewhere may be useful for development of MTF target plasmas, liner compression drivers, and full liner-on-plasma compression experiments. However, plasma research, motivated by the goals of magnetic confinement or inertial confinement fusion, has typically concentrated on plasma densities and driver implosion time scales orders of magnitude away from those which may be optimal for magnetized target fusion. Nevertheless, plasma configurations investigated in magnetic confinement research, and drivers developed for inertial confinement, may be adaptable to MTF, and they certainly provide some well-grounded starting points for research.

One such magnetized plasma configuration on which there is extensive experience at Los Alamos National Laboratory is the deuterium-fiber-initiated Z-pinch. It was once hoped that such an approach could lead to very dense, anomalously stable Z-pinch fusion plasmas, but plasmas generated on machines scaled up to potentially reach fusion conditions, such as Los Alamos' HDZP-2, displayed explosive instability as currents and temperatures were increased, dropping densities far below those desired for fusion applications [9,10]. However, a deuterium-fiber-initiated Z-pinch might well produce an acceptably hot, dense, magnetized target plasma for subsequent MTF compression to fusion conditions.

Using the same computational tool--a version of the MHRDR code--with which the HDZP-1 and HDZP-2 fiber Z-pinches were modeled (obtaining excellent agreement with experiment [9,10]), a fiber Z-pinch target plasma experiment has been designed and modeled. It would 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 fiber Z-pinch target plasma would 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, relatively stable state, capable of carrying megamp-plus currents in a few-mm-radius column, over several microseconds. To the extent that such an experiment lives up to these predictions, it would certainly be an acceptable MTF target plasma, and would be of considerable 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. Since these are issues critical to many MTF liner/plasma schemes, experimental investigations on such a device would be extremely useful parts of an MTF research program. This experiment will be pursued as funding permits.

CONCLUSIONS

Magnetized Target Fusion (MTF) is an approach to controlled fusion which potentially avoids the difficulties of the traditional magnetic and inertial confinement appoaches. It appears possible to investigate the critical issues for MTF at low cost, relative to traditional fusion programs, utilizing pulsed power drivers much less expensive than ICF drivers, and plasma configurations much less expensive than those needed for full magnetic confinement. Computational modeling, such as reported here on MAGO and fiber Z-pinch plasmas, can enhance the development of target plasmas and plasma compression schemes for MTF.

ACKNOWLEDGMENTS

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