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COMPUTATIONAL AND EXPERIMENTAL INVESTIGATION OF MAGNETIZED TARGET FUSION

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ABSTRACT

In Magnetized Target Fusion (MTF), a preheated and magnetized target plasma is hydrodynamically compressed to fusion conditions.[1,2] Because the magnetic field suppresses losses by electron thermal conduction in the fuel during the target implosion heating process, the compression may be over a much longer time scale than in traditional inertial confinement fusion (ICF). Bigger targets and much lower initial target densities than in ICF can be used, reducing radiative energy losses. Therefore, "liner-on-plasma" compressions, driven by relatively inexpensive electrical pulsed power, may be practical. Potential MTF target plasmas must meet minimum temperature, density, and magnetic field starting conditions, and must remain relatively free of high-Z radiation-cooling-enhancing contaminants. At Los Alamos National Laboratory, computational and experimental research is being pursued into MTF target plasmas, such as deuterium-fiber-initiated Z-pinches,[3] and the Russian-originated "MAGO" plasma.[4] In addition, liner-on-plasma compressions of such target plasmas to fusion conditions are being computationally modeled, and experimental investigation of such heavy liner implosions has begun. The status of the research will be presented.

INTRODUCTION

Magnetized Target Fusion is an approach to controlled fusion that is intermediate between magnetic confinement and inertial confinement fusion in time and density scales. This concept has been pursued independently in Russia as MAGO (MAGnitnoye Obzhatiye, or magnetic compression) [5-9] and in the US,[1,2] and more recently, as a US/Russian collaboration.[4] 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. Bigger targets and much lower initial target densities than in ICF can be used; the lower densities reduce radiative energy losses. 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 ($r_{initial}/r_{final}$) 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.

An MTF system requires two elements: (1) a preheated and magnetized initial "target" plasma; (2) a target implosion driver. The target plasma for such a system might be nearly as small as a typical ICF target, such as in the electron-beam-driven "ϕ-target"[1,2] experiments (Figure 1) done at Sandia National Laboratories, or as large as the 10-cm-radius explosive-pulsed-power-driven "MAGO"[4,8] experiments (Figure 2) originated at the All-Russian Scientific Research Institute of Experimental Physics (VNIIEF). Because the reduced energy losses in MTF relax the power and intensity requirements for an implosion driver, a ϕ-target might be driven to ignition by an electron or ion beam, or laser system, much less powerful than that required for a traditional ICF target. Relatively inexpensive electrical pulsed power to drive a liner-on-plasma implosion may be an optimal driver source for MTF. 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 Russian 200-MJ-class disk flux compression generators.[5,6] Such energy-rich sources might allow a demonstration of fusion ignition via MTF, without a major capital investment in driver technology.

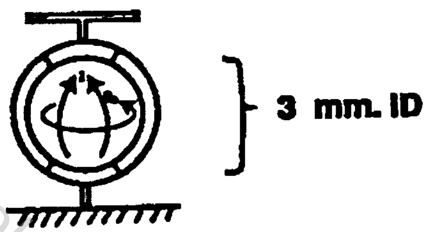

Figure 1. "Φ-target": A low-energy prepulse provided preheat and magnetization; main relativistic electron beam imploded the target.

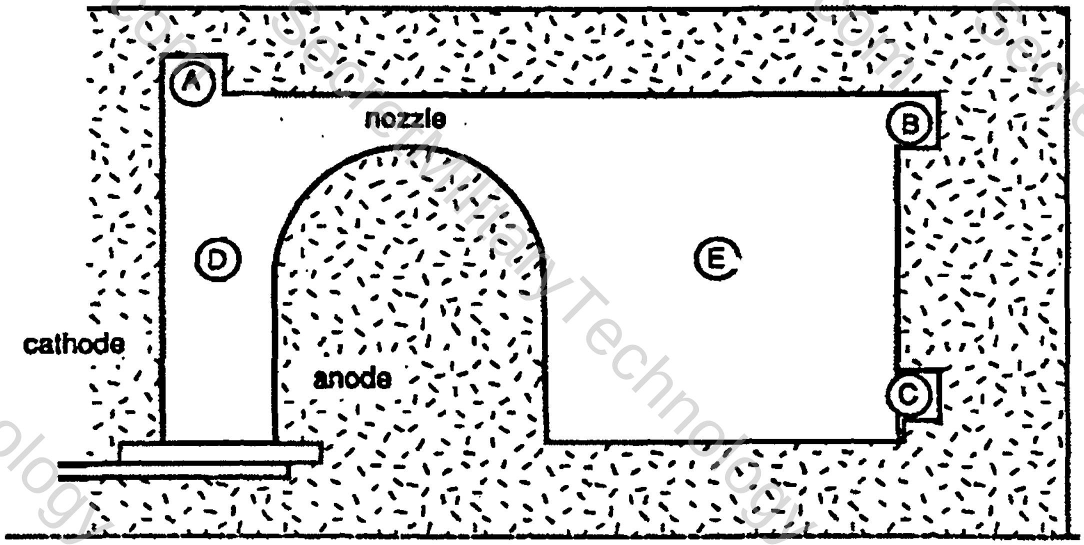

Figure 2. MAGO cylindrical plasma formation chamber (axis of symmetry at bottom): points A, B, and C contain inductive probes; points D and E indicate chordal lines of sight for interferometry and radiation measurements; chamber is electrically conducting, except for the insulator below point D.

Magnetized target fusion faces some critical issues. The initial target plasma must meet minimum temperature (~50 eV), density (between 10^{-3} and 10^{-6} g/cm^3), and magnetic field (>50 kG) requirements, and must have a lifetime, adjacent to the supporting wall, greater than the implosion time (typically several µsec for a pulsed-power-driven implosion). Plasma-wall interaction must not create dynamical effects or excessive introduction of impurities, which might lead to rapid cooling of the plasma. The target plasma must be readily integrable with drivers for compression to fusion conditions.

MTF-related research at Los Alamos National Laboratory (LANL) presently involves two candidate target plasmas: the Russian-originated MAGO plasma formation scheme, and the high-density Z-pinch. The MAGO work includes ongoing joint US-Russian experiment and theory aimed at determining the suitability of the plasma created for MTF compression, and evaluation of Russian explosive-flux-compression generators as MTF drivers. A partially wall-supported deuterium-fiber-initiated Z-pinch experiment at LANL will allow investigation of this plasma for MTF applications, in a laboratory environment.

MAGO: EXPERIMENT AND COMPUTATION

The Russian-originated MAGO plasma formation experiments are now the subject of a US-Russian collaboration involving LANL and VNIIEF. Four joint explosive-pulsed-power-driven MAGO shots have been performed to date, aimed at characterizing the dynamics and lifetime of the plasma created. MAGO is a unique discharge in two cylindrical chambers joined by an annular nozzle (Figure 2). The 10-cm-radius chamber, usually filled with 10 torr of 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.

At its average densities, O(10^{18} 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. MHD modeling of MAGO has been done at LANL 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.[3] 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.

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 a pulse of thermonuclear neutrons (in excess of 10^{13}) originates. One-temperature (T_i=T_e) computations give a neutron peak at approximately the same time as experiment, with a similar pulse width. 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 everywhere) 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. The two-temperature computations suggest that the ion temperature of the shock-heated neutron-producing plasma becomes significantly higher than the electron temperature, during the time of peak neutron production. Because the high-temperature, relatively low-density neutron-producing plasma is collisionless, it can hardly be expected that a collisional fluid model will reproduce the details of neutron production exactly; to the evident extent that the dynamics of the plasma is dominated by the collisional bulk fluid, however, the MHD model does give good results.

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 (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 x 10^{18}/cm^3, ρ=6.7 x 10^{-6} g/cm^3, T=130 eV, B=240 kG, β=0.3, $(\omega\tau)_e$=140. Depending upon driving current, average 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 ωτ'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.

A "0-d" spherical magnetized target survey model[1] 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.[4] The computations were based upon the experimental mass (8.9 mg, pure 50-50 D-T), 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 260 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.

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[5,6] are sufficient to provide the 65 MJ of energy used in the survey computations. A joint LANL-VNIIEF experiment planned for mid-1996 will attempt to put at least 20 MJ of kinetic energy into a heavy imploding cylindrical liner, which could be used in a MAGO liner-on-plasma compression experiment. Calculations have been begun to predict the two-dimensional behavior of such an imploding liner, for liner-on-plasma applications.

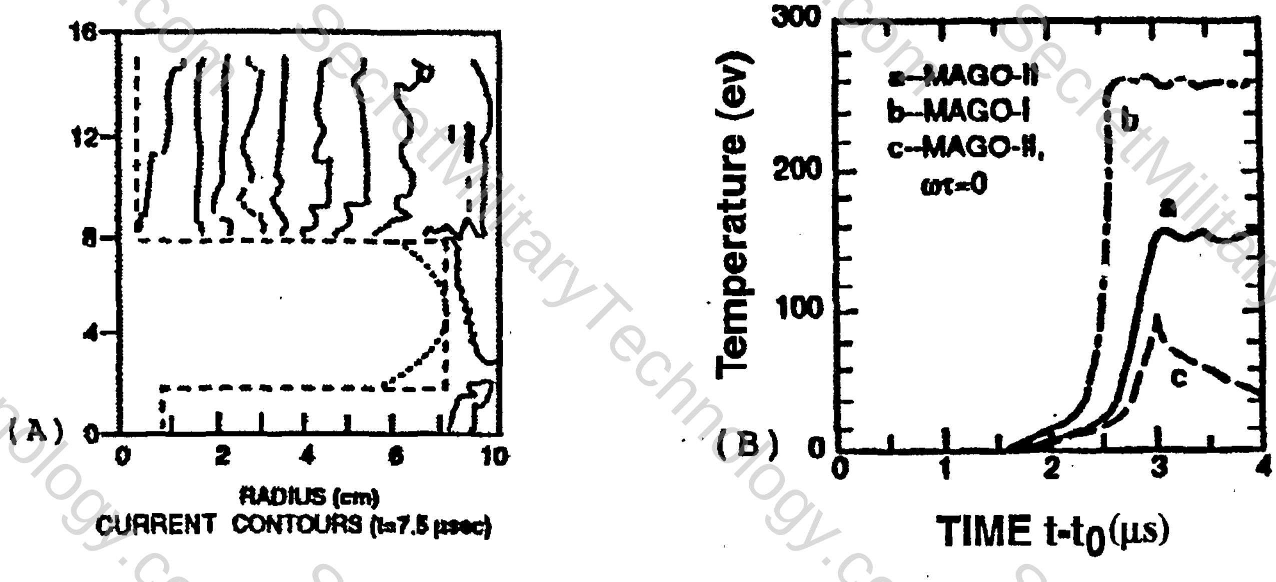

Figure 3. Computed late-time MAGO plasma: (a) MAGO-2 plasma axial current contours; (b) average plasma temperature vs. time, three separate MAGO computations (a-MAGO-2, I_{bias}=2.6 MA, I_{peak}=8.0 MA; b-MAGO-1, I_{bias}=1.6 MA, I_{peak}=8.5 MA; c-MAGO-2 with $\omega\tau_{i,e}$=0, i.e. no magnetothermal insulation).

FIBER-INITIATED Z-PINCH TARGET PLASMA

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 developed for magnetic confinement, 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.[3] 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[3]), a fiber Z-pinch target plasma experiment has been designed and modeled (Figure 4). 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. Because a smaller quantity of D-T would be contained in such a chamber, compared to the MAGO experiments, substantially smaller implosion driver energies should be required to reach fusion conditions. Hence implosions driven by fixed (non-explosive) pulsed power facilities, such as Los Alamos' Pegasus or Atlas, might well demonstrate substantial MTF compression heating. On the other hand, this smaller configuration would have a larger surface-to-volume ratio, which could lead to relatively larger deleterious wall interactions.

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. Average plasma temperatures of several hundred eV are possible, densities in the 10^{18} cm^{-3} range, and magnetic fields of order 200 kG. 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. Of course,

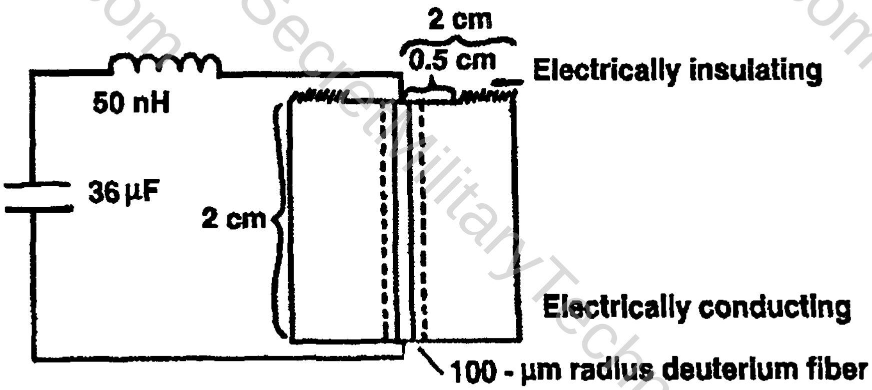

Figure 4. LANL Z-pinch target plasma: a 2-cm radius, 2-cm long, electrically conducting plasma chamber, containing a deuterium-fiber-initiated Z-pinch, driven by a capacitor bank (200 kJ, 100 kV, 2.2 μs risetime).

such predictions must be verified experimentally. Such problems as insulator flashover and wall-plasma interactions must be investigated. Three-dimensional effects might have undesirable consequences. Since these are issues critical to many MTF liner/plasma schemes, experimental investigations on such a machine would be extremely useful parts of an MTF research program. This experiment is now beginning operation at Los Alamos.

MTF REACTORS

The present focus of the research is toward "proof of principle" experiments, which should be possible (including ignition) without a large capital investment. Given proof of the concept, there are two approaches that come to mind for an MTF power reactor. One is to utilize ICF-like beam-driven "ϕ-targets," incorporated in an ICF-like pulsed reactor system. The other approach would be to aim for the maximum energy output per shot, allowing the use of a lower repetition rate. If inexpensive electrical pulsed power could be used as the implosion driver, smaller, more economically viable reactors might be possible. Because of MTF's qualitative differences from the inertial or magnetic confinement approaches to fusion, MTF reactors will have different characteristics and trade-offs, enhancing the prospects for practical fusion power.

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 and experimental research into MTF is proceeding at Los Alamos, VNIIEF, and other laboratories.

ACKNOWLEDGMENTS

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