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I. Introduction

Intermediate between magnetic confinement (MFE) and inertial confinement (ICF) in time and density scales is an area of research now known in the US as magnetized target fusion (MTF) and in Russia as MAGO (MAGnitnoye Obzhatiye--magnetic compression). MAGO/MTF uses a magnetic field and a preheated, wall-confined plasma fusion fuel within an implodable fusion target. The magnetic field suppresses thermal conduction losses in the fuel during the target implosion and hydrodynamic compression heating process.

In contrast to direct, hydrodynamic compression of initially ambient-temperature fuel (i.e., ICF), MAGO/MTF involves two steps: (a) formation of a warm (e.g., 100 eV or higher), magnetized (e.g., 100 kG) plasma within a fusion target prior to implosion; (b) subsequent quasi-adiabatic compression by an imploding pusher, of which a magnetically driven imploding liner is one example. A number of computational models have been used previously to explore the potential parameter space of MAGO/MTF. A simple survey model enabled an extensive exploration by permitting thousands of target computations [1]. As summarized in Fig. 1, the survey computations identified new islands in parameter space where substantial fusion energy release could be obtained.

As shown in Fig. 1, the magneto-thermal insulation of the fuel permits lower implosion velocities and lower initial densities than are required for unmagnetized fuel. In gas target implosions, the rate, in watts, at which the implosion driver must deliver energy to the target is proportional to $\rho_0^{1/2}v_0$ and the intensity, in watts/cm^2, to which the energy must be focused is proportional to $\rho_0 v_0$, where ρ_0 is the initial density of the gas (plasma) fill and v_0 is the implosion velocity. Hence, in the new MAGO/MTF space, the driver requirements most difficult to achieve can potentially be reduced by orders of magnitude.

Furthermore, because the implosion process is quasi-adiabatic, the radial convergence ratio of a MAGO/MTF target may be lower than 10:1, depending upon the temperature achieved in the formation stage. Also, because of the adiabaticity of the process, precisely timed shocks, such as required for unmagnetized fuel, are not necessary. Because the magnetic field is amplified under implosion conditions, it may become large enough to trap charged fusion products and enhance fuel self-heating. Therefore, the areal density required to achieve fusion ignition potentially is substantially reduced. Because the implosion process substantially reduces the fuel burn time, when compared to non-imploded configurations, simple plasma formation and magnetization schemes can be considered.

Many of the basic principles of MAGO/MTF have been demonstrated previously. Experiments at Columbia University demonstrated classical reduction of thermal conduction in a wall-confined, magnetized plasma [2]. Experiments at Los Alamos demonstrated good symmetry in a liner driven magnetically to a velocity of 1 cm/μs and a radial convergence of ten [3]. The 3-mm-diameter "phi" target experiments at Sandia National Laboratory produced 10^6 neutrons at an implosion velocity of 4 cm/μs and provide a "soft proof of principle" of MAGO/MTF [4]; two-dimensional magnetohydrodynamic computations predicted that essentially no neutrons would have been produced at such low implosion velocity without the preheating and magnetization of the fuel [5].

Although the possible benefit of a magnetic field in a fusion target was recognized in the 40's by Fermi at Los Alamos and at approximately the same time by Sakharov in the former Soviet Union, it is only in light of recent advancements in plasma formation techniques, implosion system drivers, plasma diagnostics, and large-scale numerical simulation capabilities that the prospects for fusion ignition using this approach can be evaluated. In this paper, we present ongoing activities and potential future activities in this relatively unexplored area of controlled thermonuclear fusion.

II. Plasma Formation Schemes

Any potential candidate for forming the pre-implosion plasma must be readily able to be integrated with a target implosion driver. Although liner compression of magnetically confined plasmas, e.g., plasma separated from the imploding pusher by a vacuum magnetic field, can be considered (see, for example, [6]), plasmas in contact with the pusher appear to be more readily attainable and more readily mated with an implosion system and appear to put less stringent requirements on the symmetry and stability of the imploding pusher. Note, however, that the local plasma β, defined as the ratio of local plasma pressure to magnetic pressure, does not necessarily have to be greater than unity, although $\beta>1$ is advantageous from an efficiency-of-compression perspective. The actual plasma parameters, e.g., density, temperature, and magnetic field, depend in part upon the implosion parameters, such as velocity, radial convergence, and geometry (i.e., cylindrical vs. spherical), and there are tradeoffs between formation system and implosion system requirements. For example, high volumetric compression reduces the temperature required in the formation phase. Conversely, a high temperature achieved in the formation process can substantially reduce the compression needed in the second phase.

Although some theoretical [7] and computational [8] studies of the interaction of a magnetized plasma with a cold wall have been performed, the behavior of wall-confined plasmas is not well understood. Computational work by Dawson [9] suggests that the thermal conduction of energy from the plasma should be "classical," but experimental verification is needed. Impurities in the plasma can potentially lead to radiative quenching of the adiabatic heating during implosion, so the plasma formation scheme must form a plasma of sufficient purity. As suggested by Fig. 1, the densities of interest in MAGO/MTF are sufficiently high that magnetohydrodynamic models of the plasma should describe many of the basic features.

Perhaps the simplest plasma formation candidate is a cryogenic fiber z-pinch, as illustrated in Fig. 2. The cryogenic fiber z-pinch has, in the past, been of interest as a fusion energy source when early experiments appeared to show "anomalous stability" [10]. With such anomalous stability, it appeared possible to directly heat a fiber-formed z-pinch to fusion temperatures through an electrical discharge using modest energy, modern pulsed power facilities. Unfortunately, subsequent second generation experiments and detailed two-dimensional computations [11] showed that m=0 instabilities prevented such a z-pinch from reaching fusion conditions directly. However, more recent computations using the same computational methodology suggest that the m=0 instabilities actually provide a mechanism for the pinch to fill an implosion vessel by forming a Kadomtsev-stable, wall-confined plasma suitable for subsequent implosion. Fiber-formed z-pinch experiments are underway on the COLT capacitor bank (100 kV, 2 MA, 200 kJ) at the Los Alamos National Laboratory (LANL) to confirm these predictions [12].

Building on ideas originally proposed by Nobel Peace Prize laureate A. D. Sakharov, the All-Russian Scientific Research Institute of Experimental Physics (VNIIEF) has made major progress in forming a plasma suitable for subsequent implosion [13]. Several variants of plasma formation chambers and pulsed power drivers have been used. Up to 4×10^{13} fusion reactions have been observed [14] as an "accidental" by-product of the formation process. The plasma formation chamber shown in Fig. 3 has been tested in three joint LANL/VNIIEF experiments. Because explosively driven electrical generators have matured more rapidly than stationary, capacitor bank technology in the former Soviet Union, the VNIIEF chamber is powered by a helical flux compression generator and explosively operated opening and closing switches, although there is no fundamental reason why the chamber could not be powered by a suitable capacitor bank (e.g., the SHIVA-STAR facility at Phillips Laboratory).

The current waveforms from the three joint experiments are shown in Fig. 4. Data from one experiment have been previously reported [15]. VNIIEF variable-width duct flow computations [13] and two-dimensional magnetohydrodynamic (MHD) computations performed at LANL [15], Lawrence Livermore National Laboratory (LLNL) [16], and the Phillips Laboratory [17] are consistent with many of the experimental observations. The computations suggest that the small variation in chamber current shown in Fig. 4 can make significant changes in event timing and plasma parameters. For example, computations using the waveform of Fig. 4a predict an average late-time average temperature of approximately 260 eV, more than 60% higher than the 160 eV predicted for the waveform of Fig. 4b [18].

The combination of experimental observations and detailed computations provide an reasonably complete understanding of the chamber operation. An initial slowly rising bias current magnetizes the gas volume but, because of its low voltage, does not cause an electrical breakdown of the initially neutral, room-temperature gas. The operation of the opening switch, however, generates a voltage large enough to lead to an electrical breakdown of the gas.

Breakdown occurs initially in the nozzle region (Fig. 3), and the Lorentz J x B force drives an ionizing shock wave into the right hand side of the chamber (region 2). A weaker breakdown following about 1 μs later at or near the insulator (region 1) carries a small fraction of the current, resulting in an inverse z-pinch directed radially outward. The inverse z-pinch drives plasma that was formed in the left-hand chamber through the nozzle. The plasma that exits the nozzle has high velocity and low density. When the fast moving plasma collides with the shock-wave-formed bulk plasma already in the right-hand chamber, the kinetic energy is converted to thermal energy, a small fraction (<10%) of the total plasma mass reaches a temperature of several keV, and a burst of neutrons is produced.

After a 3-4 μs dynamic phase, a "warm" (100-300 eV) target plasma remains in the right hand chamber (region 2). The plasma is in contact with the chamber walls, but heat losses to the wall are substantially reduced because of the magneto-thermal insulation due to the embedded magnetic field. It is this relatively quiescent, late-time plasma that is of interest in an MTF context as a plasma suitable for subsequent compression. The computations based upon an assumption of a purely hydrogenic plasma predict that the late-time plasma indeed has the proper density, temperature, and magnetization for proceeding to the subsequent compression stage and could give a fusion yield of 1 GJ at an implosion velocity of 2 cm/μs [15]. However, some observations are not yet satisfactorily explained by the computations, and definitive measurements of plasma purity and late-time density and temperature have not yet been made.

Other plasma formation schemes, e.g., plasma guns (either gas filled or gas "puff"), field-reversed configurations (FRC), spheromaks and other compact tori, are potential candidates for the pre-implosion plasma required in MAGO/MTF. At this point in time, only the chamber of Fig. 3 has both experimental data and detailed computational modeling to suggest that the plasma formed is suitable for subsequent compression. With the exception of the fiber z-pinch discussed above, essentially all other configurations have traditionally operated at much lower densities than the optimum in Fig. 1 and research has focused on configurations prevented by the magnetic field from contacting the containment vessel. No reasonably credible computations have yet been performed to suggest that these configurations can reach suitable plasma parameters. Furthermore, the various configurations may have topological constraints that substantially reduce the available parameter space and possible gain. For example, Armstrong found that excessive length excursions and liner/plasma contact limited the fusion gain and operating space in liner compression of magnetically-confined, FRC plasmas [19].

III. Liner Implosion Drivers

Although a variety of target implosion drivers such as lasers and particle beams can be considered as candidates for powering MAGO/MTF's second stage, a major attraction of MAGO/MTF is the fact that the lower velocity required according to Fig. 1 for MAGO/MTF is readily achievable by magnetically driven liners powered by existing pulsed power facilities. Furthermore, the kinetic energy that can be imparted to an imploding liner is orders of magnitude higher than possible with other existing target drivers. The energy available with existing magnetic flux compression generators appears to be more than adequate to achieve fusion ignition via MAGO/MTF.

Since magnetically driven liners can be solid, liquid, or plasma, some consideration must be given to determining the most appropriate liner state based upon stability concerns and velocity requirements.

Magnetically driven imploding liner experimental campaigns are already in progress on LANL's Pegasus capacitor bank facility (4 MJ, 12 MA) [20]. These investigations are aimed primarily at investigation of the stability properties of imploding liners. Use of imploding liners as impactors to develop strong shocks for material studies is also under investigation. A typical aluminum cylindrical liner has a diameter of 4.8 cm, a length of 2 cm, and a thickness of 0.4 mm.

A new "slow mode" of operation for the SATURN accelerator at Sandia National Laboratories has made solid liner implosions a possibility. In the slow mode of operation presently being implemented, the current will rise to 11 MA in 200 ns, followed by a flat top period lasting about 1 μs. One-dimensional MHD calculations of cylindrical implosions indicate that a composite aluminum-tantalum (or tungsten) liner with a total mass of 3.5 g, length of 2 cm, and an inner (outer) diameter of 0.8 cm (1.12 cm) should reach 10-fold radial compressions with the tantalum inner liner unmelted, peak liner velocities of 1.45 cm/μs and no evidence of spallation during the initial pressure pulse. The inner liner kinetic energy is 60 kJ at 10-fold compression. Interestingly, one advantage of comparatively small liners such as this example is the high energy density achieved at reasonable compression ratios. The stagnation of the liner in the one-dimensional calculations leads to pressures in excess of 100 MB. Slightly after stagnation, with the inner liner within a radius of 1/10 the initial radius, the pressure in the tantalum liner is a fairly uniform 60 MB. These conditions are more than adequate to produce substantial adiabatic heating of a magnetized plasma. Empty liner experiments and further calculations would optimize the liner design for MTF applications.

The SHIVA-STAR facility at the Phillips Laboratory has been used to drive solid and quasi-spherical liners. The quasi-spherical liner experiments have shown reasonable symmetry and stability at a radial convergence of 6:1 [21].

Other existing pulsed power facilities such as the PBFA-Z (14 MJ, 25 MA) facility at SNLA are, in principle, useful tools for studying the physics of liner implosions. The ATLAS facility under design at Los Alamos should prove a very powerful tool for MAGO/MTF studies, as illustrated in Table I.

The Los Alamos PROCYON system couples a helical magnetic flux compression generator with an explosively operated opening switch to develop approximately 20 MJ of inductively stored energy [22]. PROCYON has been used to deliver a 16 MA, 3-μs-rise pulse to a 2-cm-long, 8-cm-diameter, 1-mm-thick cylindrical aluminum liner, which reached a velocity greater than 1 cm/μs.

VNIIEF-developed magnetic flux compression generators provide a means for driving target implosions at energy levels more than an order of magnitude higher than any other existing or near-term target driver and appear to provide sufficient energy for tests of the MAGO/MTF concept at the scale required for significant fusion gain. Generators delivering over 200 MJ of electrical energy have been demonstrated [23]. A recent VNIIEF/LANL experiment used a VNIIEF 5-module, 1-m-diameter disk explosive magnetic generator (DEMG) to drive a massive, cylindrical aluminum liner that had an initial diameter of 48 cm, a thickness of 4 mm, and an initial length of 10 cm. Because the z-pinch electrodes had a 6 degree slope, the length of the liner was 6 cm when it contacted a central measuring unit located at a radius of 6 cm. The DEMG delivered a current pulse in excess of 100 MA to the liner. Preliminary post-shot computations suggest that the liner had a velocity of 0.65 cm/μs and a kinetic energy greater than 25 MJ when it contacted the measuring unit. The large body of experimental data obtained will provide an important basis for projecting the utility of such ultrahigh energy liners in a MAGO/MTF context.

IV. Integrated Liner-on-plasma implosions

If MAGO/MTF is to achieve the goal of controlled fusion ignition, a suitable plasma formation system must be mated with an implosion driver. All of the pulsed power facilities discussed in the previous sections can be considered drivers for integrated experiments, although some modification may be necessary to incorporate the chosen plasma formation scheme. The survey model [1] suggests that the pulsed power driver must provide 5-20 MJ for each mg of plasma fuel. Hence, for a given facility, the energy available limits the mass of the plasma, and correspondingly, the size of the target. During the compression stage, the liner must retain adequate symmetry and stability.

Effects such as the liner material strength and Ohmic heating of the liner must be taken into consideration. Contaminants introduced into the fuel during the liner acceleration and implosion process are of concern, although most contaminants "burn through" at relatively low temperatures. Even without volume mixing, impurity-induced radiation at an edge layer may cause accretion of plasma at the liner/plasma interface and limit adiabatic heating.

Three major goals can provide the focus of research in this area. First would be a "proof-of-principle" demonstration of quasi-adiabatic heating of magnetized plasma by a magnetically driven pusher by, for example, doubling the plasma temperature under implosion conditions. The second goal would be to reach and measure the achievement of a fusion temperature (e.g., 4 keV). Third would be to actually demonstrate thermonuclear fusion ignition and large fuel burn-up.

Possible implosion scenarios for the cryogenic fiber z-pinch and the VNIIEF plasma formation schemes are illustrated in Figures 2 and 3, respectively. For the same initial temperature and the same radial convergence, the cylindrical schemes will not reach as high temperature as the corresponding spherical convergence, as noted in Table II. However, cylindrical systems provide greater diagnostic access and would appear preferable for initial confirmation of the implosion heating principle of MAGO/MTF.

The fiber z-pinch and the VNIIEF chamber are sufficiently different as to place differing demands on the implosion system. Each must address the closing and sealing of a gap in the system, for the fiber pinch the power flow entrance and for the VNIIEF chamber the plasma injection gap. Under implosion conditions, the fiber z-pinch plasma must carry all magnetization current, whereas, in the chamber, the central conductor may carry substantial current, if, for example, instabilities increase the resistance of the plasma. Although the chamber central conductor is clearly necessary for the magnetization that takes place before electrical breakdown, the conductor may be disadvantageous from an implosion perspective.

In a MAGO/MTF context, the "phi" targets [4] provide the only available integrated liner-on-plasma data. The phi-targets were powered by an electron beam, and the beam's low-energy precursor provided the voltage that drove a diffuse z-pinch that provided preheat and magnetization. Hence, the phi-targets do not necessarily demonstrate that modern pulsed-power driven formation systems can be satisfactorily mated with an imploding liner system.

However, in another context, the Phillips Laboratory has mated a plasma formation system with the quasi-spherical liner implosion system discussed in the previous section. A coaxial plasma gun was used to form a magnetized plasma, and magnetic acceleration of the plasma provided the means for injecting the plasma into a quasi-spherical liner. Since the goal was to use the plasma as a "working fluid," radial vanes at the injection port "stripped" the magnetic field from the plasma, and the liner was filled with essentially unmagnetized plasma. The imploding liner then compressed the working fluid, which in turn compressed an inner metallic rod [24]. Radiographs suggest that the liner moved across the injection ports without the introduction of substantial perturbations and sealed the working fluid volume. Although the plasma temperature was much lower than desired for MAGO/MTF, the Phillips experience provides confidence that plasma formation systems can be satisfactorily mated with an imploding liner driver.

V. Concluding Remarks

A number of advanced plasma diagnostic capabilities developed in other contexts, e.g., time- and space- resolved x-ray spectroscopy, x-radiography, etc., can be used to characterize the plasma and the liner behavior for MAGO/MTF. These diagnostics provide a means of validating the several large-scale computer codes already being used to simulate liner implosions and magnetized plasmas. The potential for a very strong synergism between experimentation and time-dependent, multidimensional computer modeling enhances the prospect for understanding in this area.

Existing and near-term modern pulsed power capabilities, plasma formation techniques, diagnostics, and computer codes provide the necessary tools for an evaluation of MAGO/MTF without a major capital investment and with relatively low operating costs. Near-term experiments with laboratory pulsed power devices and magnetic flux compression generators will benchmark calculations and test critical issues such as the mix of wall/insulator material with the fuel. These experiments would be at the appropriate plasma conditions to allow proof-of-principal tests of MTF as a path to fusion.

For fusion reactor scenarios based on MAGO/MTF, major engineering design and major capital expenditures to replace the one-shot electrical sources with a fixed, repetitive pulsed power facility would occur only after ignition and substantial fuel burn-up have been demonstrated. Magnetized targets may prove to be ideal for reactors using heavy ion beams as target implosion drivers.

VI. Acknowledgments

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The remaining authors regret the loss of their colleague, Jim Eddleman, who died in October, 1996. His technical expertise and his never-ending sense of humor are deeply missed.

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radius (cm)	10	6	3
length(cm)	8	5.6	2.9
thickness (mm)	1	1.5	3
velocity (cm/μs)	1	1.6	1.8
energy (MJ)	6.7	10.4	7.4
current (MA)	60	45	39

Table I. Projected ATLAS performance for aluminum cylindrical liners.

initial temperature (eV)	0.025	10	50	300
final temperature (keV)	5	5	5	5
spherical convergence (r_o/r_f)	447	22.3	10	4.1
cylindrical convergence (r_o/r_f)	946	106	31.6	8.3

Table II. Ideal gas law convergence required to reach fusion temperatures.

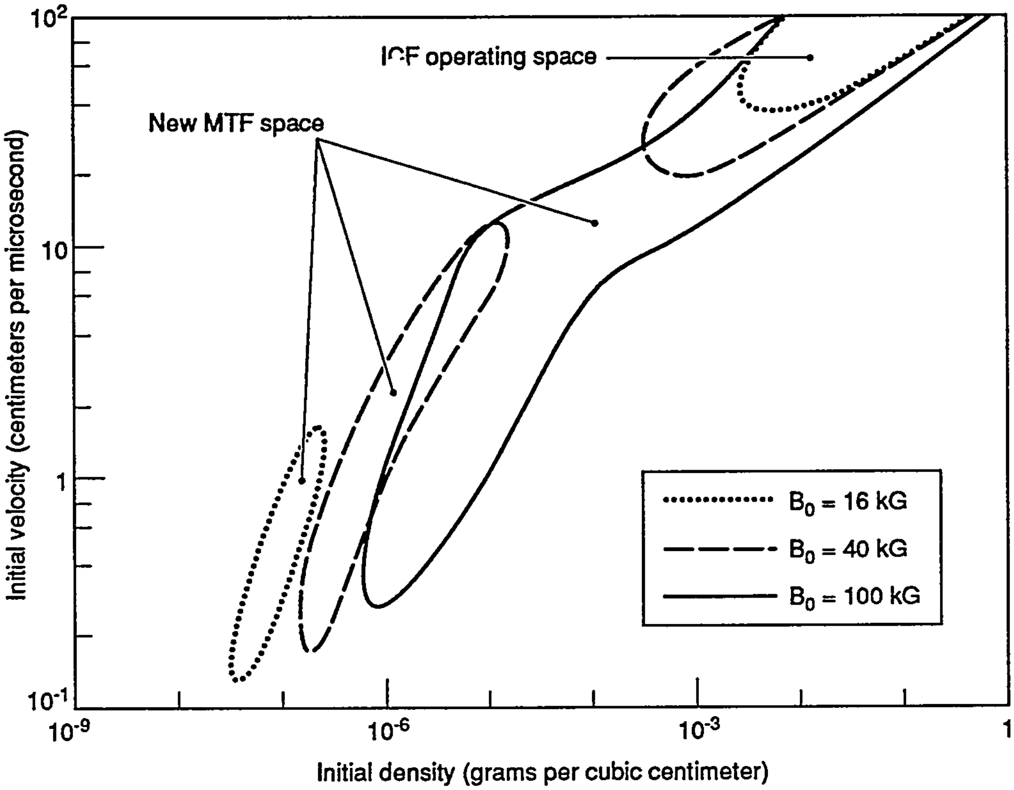
Figure Captions

Fig. 1. The parameter space for Magnetic Compression/Magnetized Target Fusion (MAGO/MTF). The actual extent of the parameter space depends on many parameters, including the pusher kinetic energy, the fuel mass, and the initial fuel temperature [1].

Fig. 2. The cryogenic fiber z-pinch . Left--plasma formation. Right--implosion of a cylindrical liner.

Fig. 3. Left--artist's conception of the operation of the VNIIEF plasma formation chamber. The chamber diameter is 20 cm. Right--possible implosion scenarios.

Fig. 4. Electrical current delivered to the VNIIEF plasma formation chamber: (a) t_0=351 μs; (b) t_0=347 μs; (c) t_0=349 μs.



10²
10
1
10⁻¹
10⁻⁹
10⁻⁶
10⁻³
1
I^F operating space
New MTF space
Initial velocity (centimeters per microsecond)
Initial density (grams per cubic centimeter)
B0 = 16 kG
B0 = 40 kG
B0 = 100 kG

FIG. 1

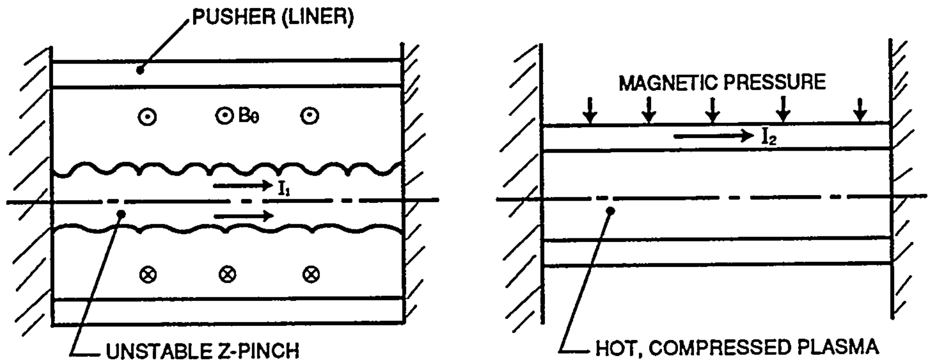

PUSHER (LINER)
Bθ
I₁
UNSTABLE Z-PINCH
MAGNETIC PRESSURE
I₂
HOT, COMPRESSED PLASMA

FIG. 2

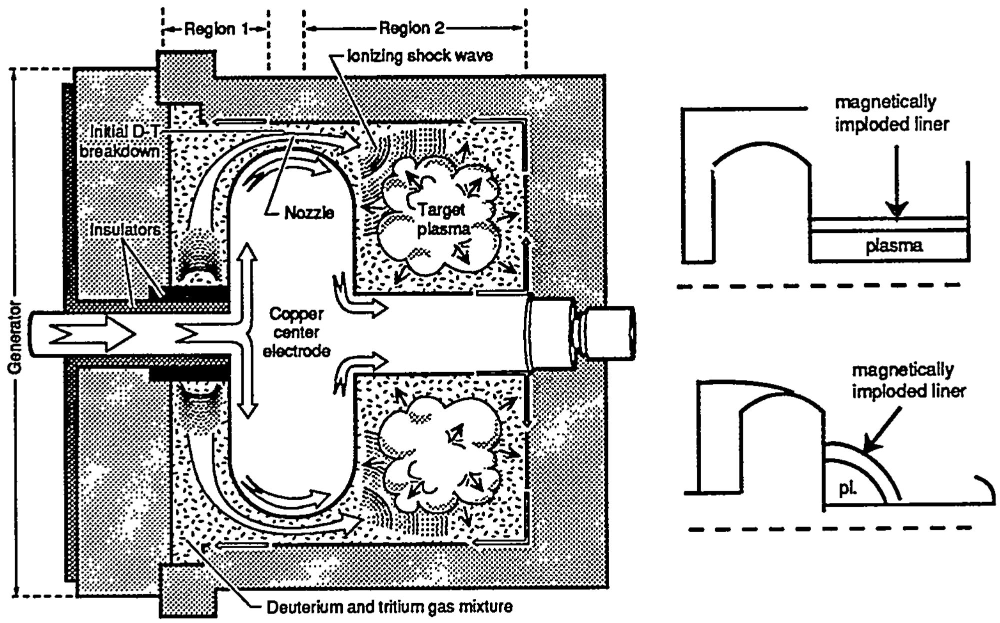

Region 1
Region 2
Ionizing shock wave
Initial D-T breakdown
Nozzle
Target plasma
Insulators
Copper center electrode
Generator
Deuterium and tritium gas mixture
magnetically imploded liner
plasma
magnetically imploded liner
pl.

FIG. 3

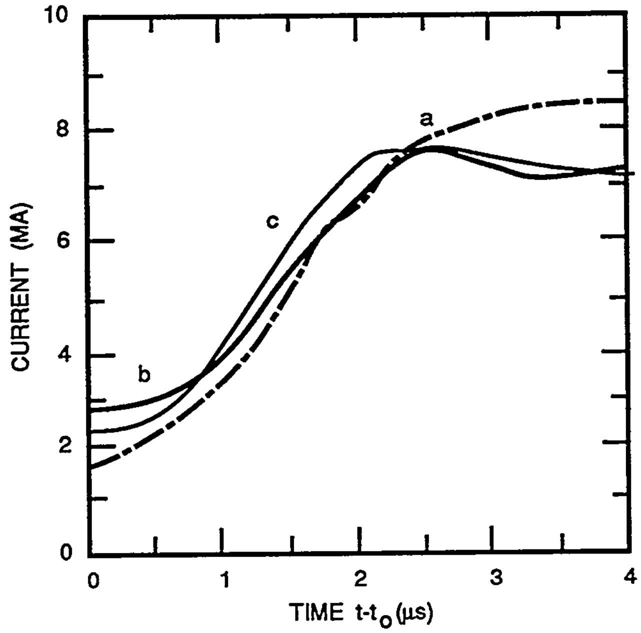


FIG. A

1A