LA-UR- 96-3715

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CONF-9608132--16

Author(s):

Submitted to: Megagauss Magnetic Field Generation & Related Topics
August, 1996
Sarov, Russia

Los Alamos
NATIONAL LABORATORY

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October 15, 1996

This is the text of a paper to be published in the Proceedings of the Seventh International Conference on Megagauss Magnetic Field Generation and Related Topics, Sarov (Arzamas-16), Russia, August 5-10, 1996.

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36.

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Introduction

The end of the Cold War has made possible some remarkable scientific adventures--joint research projects between scientific institutions of the United States and the Russian Federation. Perhaps most unprecedented of the new partnerships is a formal collaboration which has been established between the All-Russian Scientific Research Institute of Experimental Physics (VNIIEF) and the Los Alamos National Laboratory (LANL), the two institutes which designed the first nuclear weapons for their respective countries.

In early 1992, emerging governmental policy in the US and Russia began to encourage "lab-to-lab" interactions between the nuclear weapons design laboratories of the two countries. Each government recognized that as nuclear weapons stockpiles and design activities were being reduced, highly qualified scientists were becoming available to use their considerable skills in fundamental scientific research of interest to both nations. VNIIEF and LANL quickly recognized a common interest in the technology and applications of magnetic flux compression, the technique for converting the chemical energy released by high-explosives into intense electrical pulses and intensely concentrated magnetic energy.

Magnetic flux compression technology had been pioneered in the Soviet Union at VNIIEF by a team originally lead by Nobel Peace Laureate Andre D. Sakharov and pioneered in the US at LANL by a team lead by C. M. Fowler. V. K. Chernyshev and the late A. I. Pavlovskii were early members of Sakharov's team. Motivated originally to evaluate any possible defense applications of flux compression technology, the two teams worked independently for many years, essentially unaware of the others' accomplishments. However, an early US publication[1] stimulated Soviet work, and the Soviets followed with a report of the achievement of 25 MG[2].

Throughout the cold war, the series of conferences on Megagauss Magnetic Field Generation and Related Topics became a forum for scientific exchange of ideas and accomplishments in this area. Fowler is the only scientist to attend all seven conferences.

Because of collegial relationships and friendships established at the Megagauss conferences, VNIIEF and LANL were able to respond quickly to the initiatives of their respective governments. In late 1992, following the Megagauss VI conference, the two institutions agreed to combine resources to perform a series of experiments that essentially could not be performed by each institution independently. Beginning in September, 1993, the two institutions have performed eleven joint experimental campaigns, either at VNIIEF or at LANL.

Hence, because of the relationships established at previous conferences, Megagauss-VII has become the first of the series to include papers with joint US and Russian authorship. An overview of the historic LANL/VNIIEF collaboration appears separately in these proceedings[3], and various aspects of the joint experimental campaigns are described in several additional papers also appearing in these proceedings.

In this paper, we review the joint LANL/VNIIEF experimental work that has relevance to a relatively unexplored approach to controlled thermonuclear fusion.

MAGO/MTF: A promising approach to controlled thermonuclear fusion

For more than four decades, controlled thermonuclear fusion has been one of the most exciting, and most frustrating, applications of pulsed power technology. Fusion research has evolved into two mainline approaches, Magnetic Fusion Energy (MFE) and Inertial Confinement Fusion (ICF), and pulsed power has played a major role in the progress made by both approaches. Controlled fusion has also been a major motivating force for the development of today's modern magnetic flux compression generators[4], but, for the most part, the approaches for which flux compression generators have been considered as drivers differ substantially from the two mainline approaches.

At VNIIEF, controlled fusion is often referred to as "Sakharov's fondest dream." Building on ideas originally proposed by Sakharov, VNIIEF has made major advances in a novel approach to controlled fusion known in Russia as MAGO (MAGnitnoye Obzhatiye, or "magnetic compression") and in the US as MTF (Magnetized Target Fusion). 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. The high initial adiabat of the preheated, magnetized fuel and the quasi-adiabatic compression of the fuel make it possible in principle to reach ignition temperatures at modest implosion velocity and at modest convergence ratios without strong, precisely timed shocks as required for unmagnetized fuel. 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, 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 contrast to direct, hydrodynamic compression of initially ambient-temperature fuel, 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. The magneto-thermal insulation of the fuel permits lower implosion velocities than are required for unmagnetized fuel. 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. 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.

A number of computational models have been used previously to explore the potential parameter space of MAGO/MTF. A simple survey model developed at LANL enabled an extensive exploration by permitting thousands of target computations[5]. As summarized in Fig. 1, the survey commutations identified new islands in parameter space where substantial fusion energy release could be obtained. In gas target implosions, the rate (W) at which the implosion driver must deliver energy to the target is proportional to $\rho_0^{1/2}v_0$ and the intensity (W/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.

As noted in several papers in these proceedings and in the proceedings of previous Megagauss conferences[6], the lower velocity required according to Fig. 1 for MAGO/MTF is readily achievable by magnetically driven liners, and, of course, 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 MTF. However, additional work is required to determine the optimal implosion velocity and optimal imploding liner, or pusher, shape for an ignition demonstration experiment.

US work in the mid-1970's and early 1980's demonstrated some of the basic principles of MAGO/MTF. Experiments at Columbia University demonstrated classical reduction of thermal conduction in a wall-confined, magnetized plasma[7]. 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[8]. 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[9]; 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[10]. More recently, the Phillips Laboratory has demonstrated a quasi-spherical magnetically driven shell implosion, conceptually appropriate for a MAGO/MTF target pusher[11] and has demonstrated that an unmagnetized plasma can be compressed by the imploding quasi-spherical liner [12].

The VNIIEF MAGO Plasma Formation Scheme

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 x 10^{13} fusion reactions have been observed[14]. The history of the development of VNIIEF's unique chamber is reviewed in these proceedings[15], and a number of other papers address various aspects of the MAGO/MTF approach to controlled thermonuclear fusion.

Three joint experiments designated MAGO-I, MAGO-II, and MAGO-III were performed at VNIIEF in April 1994, at LANL in October 1994 and at VNIIEF in September 1995, respectively, and were aimed at characterizing the deuterium-tritium (D-T) plasma produced in one chamber design. The chamber used is shown in Fig. 2. The chamber is powered by a helical flux compression generator and explosively operated opening and closing switches, shown schematically in Fig. 3. A preliminary experiment designated MAGO-IIP and using deuterium was also performed at LANL in October, 1994, to confirm the operation of the helical generator and switches using US explosives.

A wide variety of advanced plasma diagnostic techniques have been attempted, with varying degrees of success, to characterize the system performance. The diagnostics include time-resolved neutron measurements, neutron activation, time-resolved visible spectroscopy (350-650 nm), time-integrated near-uv spectroscopy (220-300 nm), inductive probe current measurements, faraday-rotation chamber input current measurements, fiber-optic visible emission probes (700-1000 nm), neutron imaging, x-ray filtered silicon photodiode arrays, time-resolved x-ray streak spectroscopy, chamber input voltage probes, vuv gated optical multichannel analyzer (OMA), and chordal density interferometry.

The sequential operation of the closing switch and opening switch (Fig. 3) of the pulsed power system results in the delivery to the plasma chamber of a slowly rising "bias" current followed by a rapidly rising discharge current. The bias current is established during the early operation of the helical generator. When the closing switch closes, the chamber is "crowbarred" and the current delivered to it remains approximately constant in time. In the meantime, the helical generator continues to operate and the current through the closing switch/opening switch branch of the circuit increases to approximately 15 MA. At a predetermined time, the opening switch is operated and a high voltage is delivered to the chamber.

The current waveforms from the three D-T experiments are shown in Fig. 4. Data from the MAGO-II experiment have been previously reported[16]. The MAGO-II experiment performed at LANL produced 10^{13} neutrons, the most ever achieved at LANL.

VNIIEF variable-width duct flow computations[13] and two-dimensional computations performed at LANL[17], Lawrence Livermore National Laboratory[18], and the Phillips Laboratory[19] are consistent with many of the experimental observations. A detailed comparison of LANL's two-dimensional computations with inductive probe, interferometry, and x-ray emission shows excellent agreement[16].

The initial conditions for LANL's two-dimensional computations are a gas at room temperature, except for two small regions at an elevated temperature to give initial conducting paths[17]. The computations suggest that the chamber operation is somewhat more complex than the model of simple nozzle operation with all gas initially ionized, i.e., a plasma, and strongly coupled to the magnetic field because of its initially high electrical conductivity. Models that assume full ionization and high electrical conductivity simply do not accurately describe the plasma dynamics reflected in inductive probe and interferometry measurements[16].

LANL's computations also suggest that the small variation in chamber current shown in Fig. 4 can make significant changes in event timing and plasma parameters. For example, changing in the computations the input current from the waveform of Fig. 4b to a scaled waveform in which the rapidly changing part increases from 2.7 MA to about 8 MA, instead of 7.5 MA, moves features observed on inductive probes earlier by about 200 ns, thereby more precisely matching the observed timing[16]. As reported in these proceedings[20], 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.

The combination of experimental observations and detailed computations provide an reasonably complete understanding of the chamber operation. The 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 (Fig. 3), however, generates a voltage large enough to lead to an electrical breakdown of the gas.

Breakdown occurs initially in the nozzle region (Fig. 2), 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.

As previously reported[13,16,17], integrated inductive (dI/dt, dB/dt) signals provide valuable insight into the behavior of the plasma. The unintegrated signals appear to provide additional evidence of the plasma dynamics. For the two experiments performed at LANL (IIP, II), signals from four chamber input current dI/dt probes, located 90 degrees apart at four different azimuths, show excellent symmetry. However, some possibly significant asymmetries of the current feed were observed in the two experiments performed at VNIIEF. Some comparisons have been made between features observed on the inductive probes and the neutron production, but at this time there does not appear to be a close correlation between inductive probe features and neutron production dynamics. Recent VNIIEF[21] and LANL computational modeling efforts are leading to a satisfactory interpretation of the features observed in the input current signals.

The measurements of plasma radiation and particle emission are not yet well understood. Visible emission provides information about contaminants in the plasma and x-ray spectroscopy shows x-ray emission lasting more than 10 microseconds[22]. X-ray silicon diode measurements show signals lasting more than 30 μs, but unresolved questions about possible probe failure preclude a definitive conclusion about the plasma life-time[23]. The total neutron yield of all D-T experiments was approximately the same, but the pulse shapes and timing differed, perhaps due to discharge asymmetry. The neutron pulse shows evidence of a non-Maxwellian plasma particle distribution as might be expected from the high velocity, high temperature, and low density predicted for the neutron-producing component of the plasma[24].

For time later than about 4 μs, i.e., after the very complex early-time plasma formation process, the computations show a plasma having parameters suitable for subsequent implosion; characteristic computed late-time plasma parameters for the MAGO-II experiment 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, $\beta=0.3$, $(\omega\tau)_e=140$.

Survey spherical target computations[5] based upon the experimental plasma mass (8.9 mg), characteristic computed temperature and magnetic field, and an implosion kinetic energy of 65 MJ have been performed to evaluate the suitability, in a subsequent implosion context, of the plasma formed in the MAGO-II experiment[16]. A gain of 16, and a thermonuclear yield of 1 GJ, is predicted for a density of 6.7×10^{-6} g/cm^3 (the density predicted computationally to have been achieved experimentally), 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 computed for the MAGO-I experiment[20] 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 MAGO/MTF context has been produced in the joint plasma formation experiments. It is quite plausible that the present plasma chamber could be scaled to a smaller size, reducing the implosion energy required. However, existing VNIIEF Disk Explosive Magnetic Generators (DEMG) are sufficient[6] to provide the 65 MJ of energy used in the survey computations.

Concluding Remarks

The joint VNIIEF/LANL plasma formation experiments discussed in this paper represent major progress towards the achievement of controlled thermonuclear fusion via MAGO/MTF. Further plasma formation experiments are required before the 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.

After adequate confirmation that the plasma is suitable for subsequent implosion, a combined formation and implosion system will be designed. The recent Phillips Laboratory experience[11,12] suggests that any obstacles encountered in moving to the second step of MAGO/MTF can be overcome.

An attractive feature of MAGO/MTF is that the best available theoretical models suggest that fusion ignition is possible without a major capital investment in driver technology. Fusion reactor scenarios based on MAGO/MTF would replace the one-shot flux compression generators with expensive, capital-intensive, multi-year-construction, fixed, repetitive facilities only after ignition has been demonstrated.

Acknowledgments

This collaboration would not have been possible without the support and encouragement of many officials of the governments of Russia and the United States and many administrators and colleagues at the All-Russian Scientific Research Institute of Experimental Physics and the Los Alamos National Laboratory.

References

1. C. M. Fowler, W. B. Garn, and R. S. Caird, J. Appl. Phys. **31**, 588 (1960).
2. A. D. Sakharov *et al.*, Sov. Phys. Dokl. **10**, 1045 (1966).
3. C. A. Ekdahl *et al.*, these Proceedings.
4. C. M. Fowler, these Proceedings.
5. I. R. Lindemuth and R. C. Kirkpatrick, Nuclear Fusion **23**, 263 (1983).
6. For example, see R. Reinovsky *et al.*, these Proceedings.
7. B. Feinberg, Plasma Physics **18**, 265 (1978).
8. A. Sherwood *et al.*, in *Megagauss Physics and Technology*, edited by P. Turchi (Plenum Press, New York, 1980), p. 391.
9. J. Chang *et al.*, in *Proceedings of Second International Conference on High Power Electron and Ion Beam Research and Technology* (Cornell University, New York, 1977).
10. I. R. Lindemuth and M. M. Widner, Phys. Fluids **24**, 746 (1981).
11. J. H. Degnan *et al.*, Phys. Rev. Lett. **74**, 98 (1995).
12. J. H. Degnan *et al.*, these Proceedings.
13. A. M. Buyko *et al.*, in the *Digest of Technical Papers: Proc. IX IEEE Pulsed Power Conf.*, edited by K. Prestwich and W. Baker (Institute of Electrical and Electronics Engineers, New York, 1993).
14. V. K. Chernyshev, in *Megagauss Magnetic Field Generation and Pulsed Power Applications,* edited by M. Cowan and R. Spielman (Nova Science Publishers, New York, 1994), p. 557.
15. G. Volkov *et al.*, these Proceedings.
16. I. Lindemuth *et al.*, Phys. Rev. Lett. **75**, 1953 (1995).
17. I. Lindemuth *et al.*, ref. 14, p. 361.
18. J. Eddleman and C. Hartman, Lawrence Livermore National Laboratory report UCRL-JC-114685 (1993).
19. R. Peterkin, Jr., *et al.*, in *Proceedings of the 31st AIAA/ASME/SAE/ASEE Joint Propulsion Conference*, publication AIAA 95-2899 (American Institute of Aeronautics and Astronautics, Washington, DC, 1995).
20. P. Sheehey *et al.*, these Proceedings.
21. S. Garanin, these Proceedings.
22. H. Oona *et al.*, these Proceedings.
23. G. Idzorek and R. Kirkpatrick, these Proceedings.
24. O. Burenkov *et al.*, these Proceedings.

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[5].

Fig. 2. Artist's conception of the operation of the MAGO plasma formation chamber. The chamber diameter is 20 cm.

Fig. 3. Electrical schematic of the MAGO plasma formation system.

Fig. 4. Electrical current delivered to the MAGO plasma formation chamber: (a) MAGO-I, t_0=351 μs; (b) MAGO-II, t_0=347 μs; (c) MAGO-III, t_0=349 μs.

Fig. 1, Lindemuth et al., "The Plasma Formation Stage in Magnetic Compression/Magnetized Target Fusion (MAGO/MTF)."

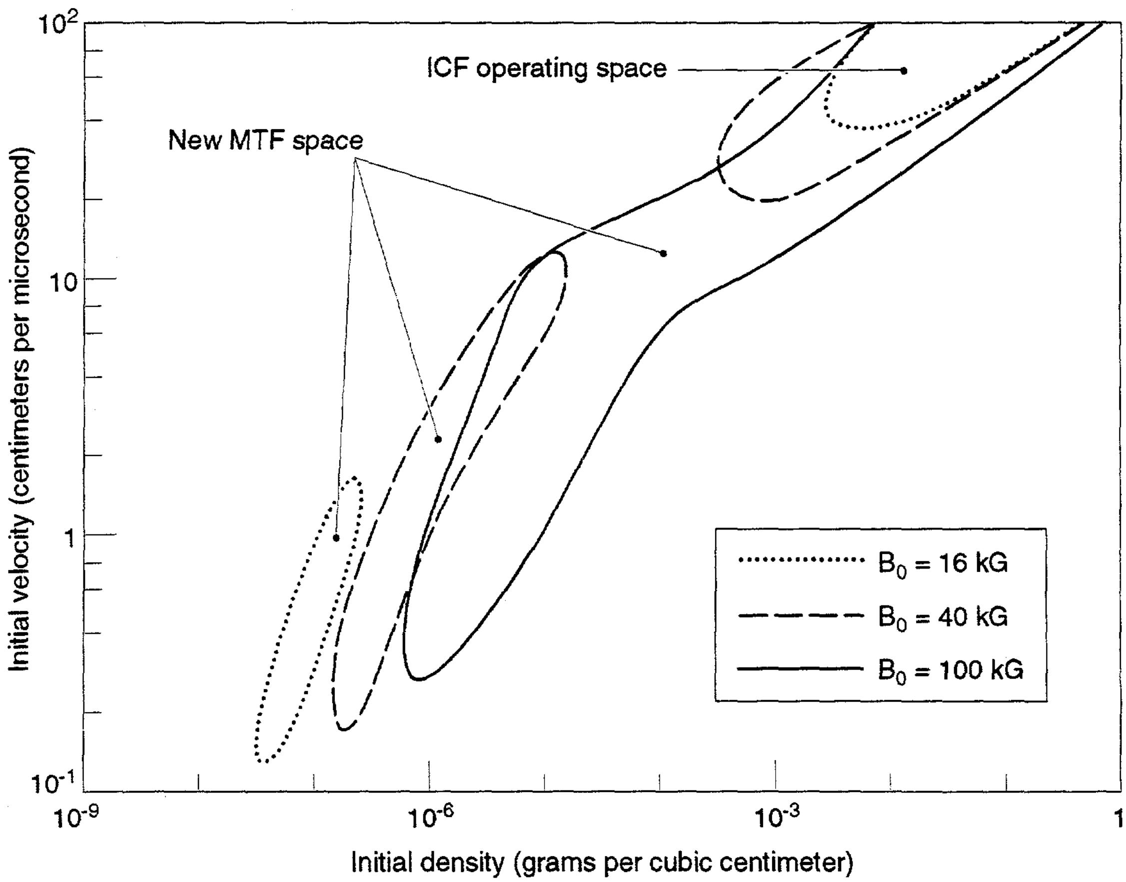

Fig. 2, Lindemuth et al., "The Plasma Formation Stage in Magnetic Compression/Magnetized Target Fusion (MAGO/MTF)."

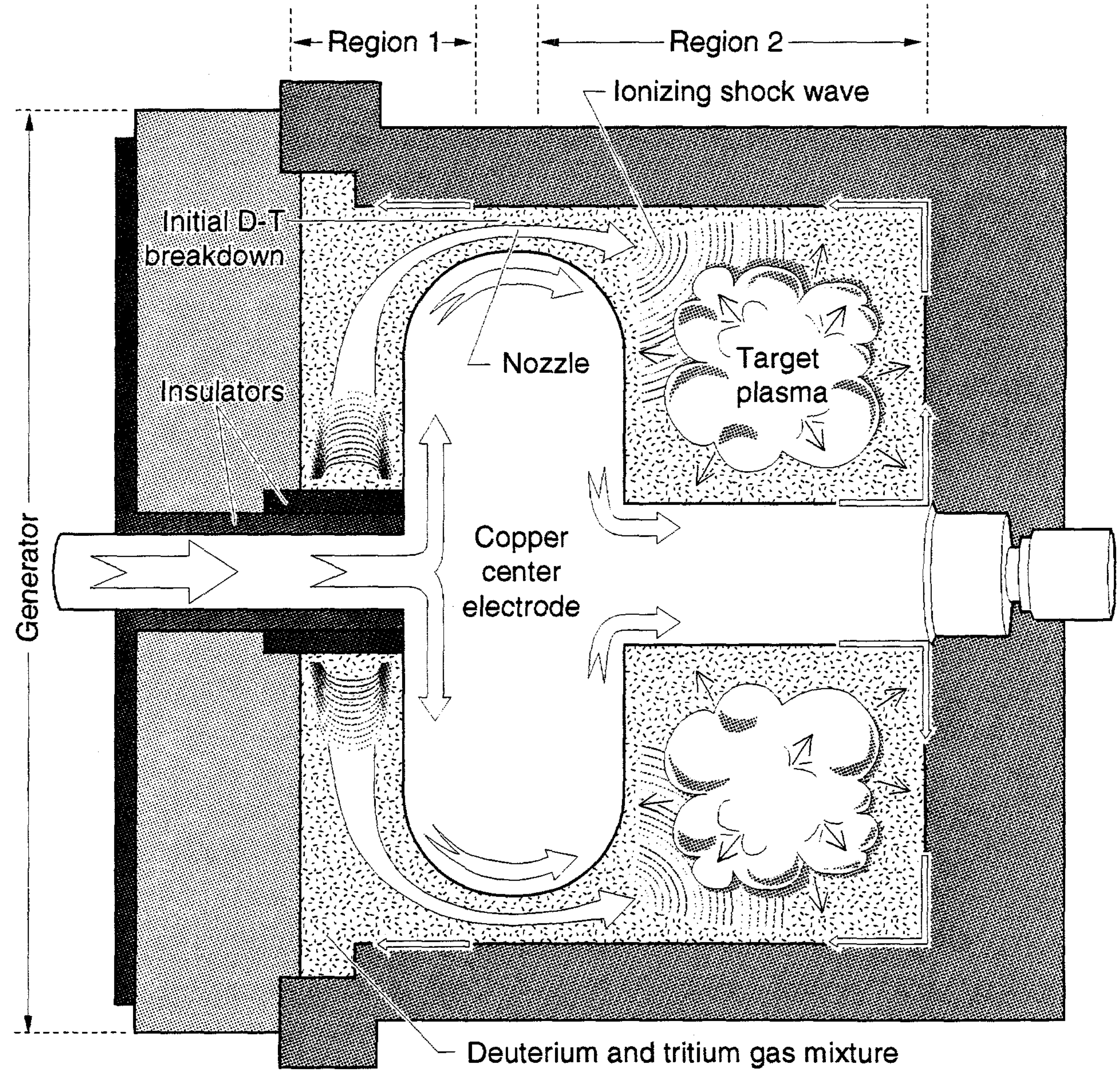

Fig. 3, Lindemuth et al., "The Plasma Formation Stage in Magnetic Compression/Magnetized Target Fusion (MAGO/MTF)."

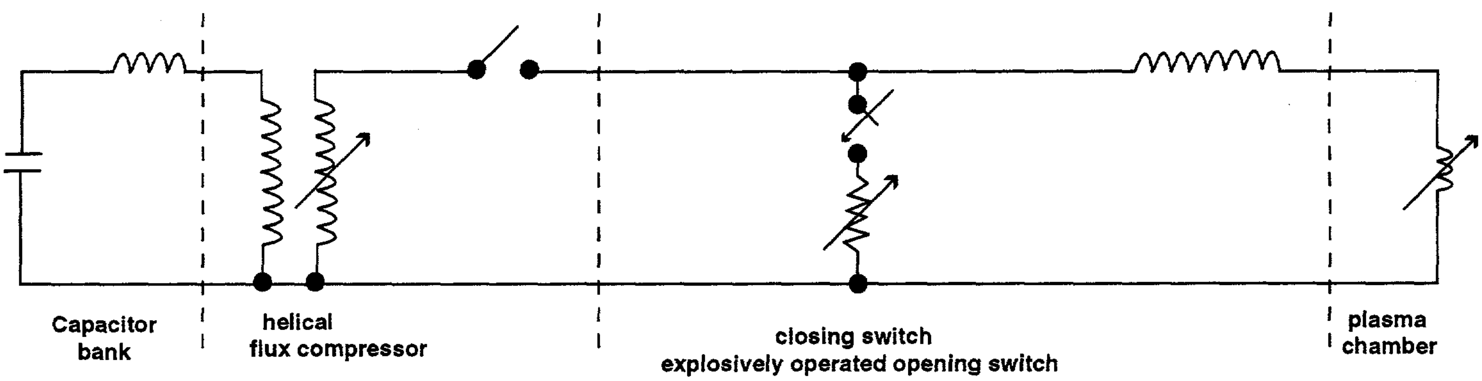

Fig. 4, Lindemuth et al., "The Plasma Formation Stage in Magnetic Compression/Magnetized Target Fusion (MAGO/MTF)."