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TITLE: MAGNETIZED TARGET FUSION - AN ULTRA HIGH ENERGY APPROACH IN AN UNEXPLORED PARAMETER SPACE

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@CTITLE-MAGNETIZED TARGET FUSION:
An Ultrahigh Energy Approach in an Unexplored Parameter Space

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Abstract

Magnetized target fusion is a concept that may lead to practical fusion applications in a variety of settings. However, the crucial first step is to demonstrate that it works as advertised. Among the possibilities for doing this is an ultrahigh energy approach to magnetized target fusion, one powered by explosive pulsed power generators that have become available for application to thermonuclear fusion research. In a collaborative effort between Los Alamos and the All-Russian Scientific Institute for Experimental Physics (VNIIEF) a very powerful helical generator with explosive power switching has been used to produce an energetic magnetized plasma. Several diagnostics have been fielded to ascertain the properties of this plasma. We are intensively studying the results of the experiments and calculationally analyzing the performance of this experiment.

@H1-INTRODUCTION

The physical characteristics of inertial confinement fusion and magnetic confinement fusion differ by about ten orders of magnitude. The approach to creating the fusion plasma by these two methods are equally different. Because of the extreme differences and the vast parameter space that separates these two approaches, it is logical to consider the possibility of an intermediate approach to fusion. We believe that an idea suggested many years ago, and sporadically investigated over the past 20 years may provide an approach to fusion energy that avoids the difficulties of the previous extremes, if one is able and willing to accomplish a requisite first step to accommodate this intermediate approach. We are now studying one attempt to accomplish such a first step. The MAGO experiment fielded jointly by Los Alamos and the All-Russian Scientific Institute for Experimental Physics (VNIIEF) promises to provide the necessary components for that first step. In fact, VNIIEF has fielded many experiments, and Los Alamos has joined the effort only lately, but has also brought to the effort advanced diagnostic and computational capabilities that should greatly improve our understanding of the plasma creation process and the properties of the plasma created.

This intermediate approach to thermonuclear fusion is called magnetized target fusion (MTF). We coined this phrase only about two years ago, but in the past the same concept has been called variously magnetized fuel, fast liner fusion, and magnetothermally insulated fusion. Below we will present the salient facts for MTF and describe the US/Russian joint effort to take the first step toward realizing magnetized target fusion.

@H1-WHAT IS MAGNETIZED TARGET FUSION?

MTF is a relatively untried approach to fusion ignition, requiring two elements: a) a means of preheating and magnetizing the thermonuclear fuel and b) a compression system. The key aspects are 1) an embedded magnetic field is used to reduce the thermal conductivity of a hot plasma, not to confine the plasma, and 2) the ignition conditions are achieved.

For ICF, compression of the fusion fuel is called implosion and involves very strong shocks to accelerate a shell (or "pusher" that contains the fusion fuel) to high implosion velocity. This is because as fusion ignition conditions are approached the energy loss rates become high, and a high work rate is necessary to overcome them until fusion energy production is sufficient to overcome them. The major energy loss process for typical ICF targets is thermal conduction, but for targets with high fuel density the bremsstrahlung radiative loss from the fusion fuel can be more important. The details of ICF targets are discussed in a previous paper in this symposium [1].

The strategy of MTF is to suppress the losses from the fusion fuel, first by reducing the density of the fuel to reduce radiative losses, making the conduction losses dominant, and then by using a magnetic field to suppress the conduction losses. We think that this reduction of thermal conductivity should be classical [2].
This strategy drastically reduces the overall losses, which means that the work rate necessary to overcome the reduced losses can be much smaller, greatly relaxing the need for high implosion velocity.

Because at high temperature the plasma electrical conductivity is high, the embedded magnetic field is effectively frozen into the plasma, so that they move together, and as the plasma is compressed, so is the magnetic field. This means that the magnetic field will be amplified by a factor of about 100 in the course of about a thousand fold compression, which corresponds to a convergence of a factor of ten for a spherical target.

The MTF parameter space is shown in Figure 1. It is presented as an initial condition parameter space, that is, contours of unity gain plotted in the initial density, initial implosion velocity space. Three sets of contours are plotted in this initial condition space: Bo = 16, 40 and 100 KG. The plots are made for specified DT mass, initial temperature, and implosion energy [3].
@FIGURE-Fig 1 The initial condition space for MTF based on results
derived from a "zero-dimensional survey code that follows
the dynamics of an imploded magnetized fusion target [3].
The target plasma starts at 50 ev.
It is clear that MTF region in the lower left lies far from the ICF region in the upper right hand corner of the plot. This survey result suggests that MTF allows extremely low implosion velocities. Also, as the initial magnetic field is increased, the two fusion regions connect, so that there is a continuum between the two. The survey code used to produce Figure 1 did not allow for fusion energy deposition, so that fusion ignition was not possible. However, ignition is a possibility for MTF. What Figure 1 shows is that even without ignition MTF still provides a net gain in an accessible part of parameter space.

Because MTF does not need high implosion velocities, there are no strong shocks involved that serve to raise the temperature of the fusion fuel prior to continued compression by the pusher or liner. This means that it is necessary to heat the fusion fuel by an auxiliary means before compression.
In Figure 1 the initial temperature of 50 ev was used. Ohmic heating is a convenient choice because it is also desired to have a magnetic field in the plasma. However, ohmic heating alone may not suffice, because as the plasma temperature rises, the resistivity falls. There is a limit to the temperature attainable by simple ohmic heating. It is also possible to employ an MHD means of shock heating the fusion fuel, which is done in the case of the MAGO experiment. This will be

@H1-ACCESS TO THE MTF PARAMETER SPACE

Because the MTF target plasma is low density, for the same mass target, an MTF target must be larger than its ICF counterpart. This coupled with the fact that the MTF fusion region is accessible with lower implosion velocities means that the implosion times for MTF are much longer than for ICF. This means that the power and intensity on target for MTF are much lower than for ICF.
@FIGURE-Fig 2 Lines of constant power in the MTF initial condition space.
@FIGURE-Fig 3 Lines of constant intensity in the MTF initial condition space.
This is shown in Figures 2 and 3 as lines of constant values of power and intensity in the same initial condition space as Figure 1. It should be noted that the ICF region is extended to lower density in this diagram than would be the case for B = 0. In fact fully two or more orders of magnitude separate the extremes of the two regions in power, and four in intensity. These are significant factors that should make a substantial difference in the requirements for realizing fusion energy. The MTF fusion region is much more easily accessed than ICF. At the same time it avoids many of the classical magnetic confinement instabilities.
@FIGURE-Fig 4 The MTF parameter space for a small target (20 ug), requiring 100 K J implosion energy.
@FIGURE-Fig 4 The MTF parameter space for a larger target (200 ug), requiring 1 MJ implosion energy. Notice the expansion of the initial conditions that provide significant MTF gain.
Figures 4 and 5 show how the size of the MTF fusion region changes as the DT mass and implosion energy are increased. The solid contour is the unity gain contour. It should be noted that for all these initial condition space plots that there is no DT alpha energy deposition (i.e., no "self heating" in the plasma). This means that for these survey calculations, ignition was not allowed to occur. Therefore, the gains calculated were a lower limits, and the sizes of the MTF fusion regions should be larger. The details of the survey calculations from which these figures were derived are given in the 1983 paper [3].

It should be clear that MTF is not a simple matter of just adding a magnetic field to a conventional ICF target. The magnetic field necessitates target plasma preparation, in a lower initial density fusion fuel, which means a larger target. This coupled with the fact result that the target can be imploded much slower means that the target can operate at much lower power and intensity on target. The lower implosion velocities mean more massive pushers and longer dwell times near maximum compression that matches the longer fusion burn time due to the lower density. No pulse shaping should be required, but there is a requirement for plasma preparation before implosion.

@H1-DT ALPHA ENERGY DEPOSITION

Because the magnetic field is compressed along with the fusion fuel, the gyro radius of the charged fusion reaction products decreases. For DT the one charged reaction product is the DT alpha with an initial energy of 3.5 Mev, an atomic mass of 4 and a charge of 2. If the gyro radius is much smaller than the distance from where the DT alpha is born to the pusher, or if the mean free path is sufficiently short, then most of the fusion energy carried by that reaction product will be deposited in the fusion fuel. However, most of the fusion energy escapes with the DT 14 Mev neutron. If sufficient fusion energy is redeposited in in the fusion fuel, it can ignite, meaning that the temperature will keep on increasing even after the implosion has reversed and expansion cooling now aids the energy loss processes in the fusion fuel.

plasma with uniform current density. During the implosion, the field in the target can be amplified, and possibly sufficiently to reduce the Larmor radius of the DT alpha and thereby significantly enhance the fusion energy "self-heating".

An example of the complex trajectory of a DT alpha in a magnetized DT fusion fuel is shown in Figure 6. Figure 7 shows the region in the rhoR, temperature plane where DT ignition is possible for MTF. Notice that it is greatly extended to lower values of areal density rhoR form the ICF region on the far right. This figure shows the fusion regions for several values of target plasma masses.

For a magnetic field of 5 MG, the MTF ignition region disappears for DT mass below about 1 ug. This sets a lower limit on the energy necessary for MTF ignition.

@FIGURE-Fig 7 Mass dependence of the new MTF region in a Lindl-Widner diagram. The specific heat of DT is 100 J/ug.Kev, so about 5 MJ is required to to drive 1 mg of DT to fusion temperature.

@H1-PREVIOUS EXPERIENCE WITH MTF

The basic ideas for MTF seem to have had their origins both in the US and in Russia. Because both Edward Teller and Andrei Sakharov were engaged in nuclear weapons work, the genesis of the ideas are not completely documented. It is clear that the basic ideas came from the groups they worked with during those secret times. The first published work on this topic did not appear until the late 1970's, and probably independently of the secret sources of information. Sandia National Laboratory published an early report on th Phi-target work in 1977 [4,5]. Two years later Mokhov and his colleagues published a very sketchy paper on a device intended to realize fusion with a magnetic implosion [6]. Because the actual fusion target was not discussed, many doubted it could work. Years later, we deduced that this scheme could not work without a magnetized fusion fuel. When the Soviet Union dissolved, we learned that this conclusion was correct. Indeed, we now know that Mokhov had worked with Sakharov at the premier Soviet nuclear weapons laboratory from the earliest days of their nuclear weapons work. Since the late 1970's there have been several advances in our understanding, but the Sandia Phi-targets have remained the single best example of an integrated MTF experiment. Figure 8 shows various geometries for MTF, including the Phi-target. These drawings are not to scale.

@FIGURE-Fig 8 Examples of possible magnetized fusion targets. The scales range from a few millimeters to several centimeters, and the geometries from cylindrical to spherical.

The Phi-target had a diameter of 3 mm. The MAGO experiment has a radius of 10 cm. No dimensions were given for the Mokhov device.

We believe that developments in the last decade warrant a renewed examination of MTF. First, modeling of Sandia Phi-target provided a better understanding of the essential physics. Second, survey code results put the MTF into a perspective against the back-drop of other fusion concepts [3]. In addition, there are now many new plasma diagnostics, pulsed power facilities, and improved computational tools. We think that one item that may be most important is the development of new methods for producing a hot, magnetized target plasma. The high density Z-pinch is one, and the Russian MAGO experiment is another. We are also considering other methods for creating a target plasma.

The acronym MAGO is properly translated magnetic compression. It has become the acronym used for a variety of related activities which include explosive pulsed power and the creation of a hot, magnetized target plasma. VNIIEF has demonstrated 200 MJ high explosive pulsed power (HEPP) drivers, and has coupled 25 MJ into a magnetically driven implosion. With their unique target plasma they have produced up to 5×10^{13} neutrons (without implosion). Now an unprecidented US/Russian collaboration in ultrahigh magnetic fields and pulsed power is familiarizing US scientists with Russia's remarkable accomplishments.

In September of 1993 the first joint experiment involving the scientists from the US and Russian nuclear weapons design laboratories was performed at VNIIEF in Arzamas-16 (Sorova), Russia. The experiment was the first tangible result of an unprecidented scientific collaboration established through the support and encouragement of the highest levels of the governments of both nations. That first joint experiment was followed by a series of joint high magnetic field experiments in December 1993 and August 1994, and also a series of MAGO experiments in April 1994 and October 1994.

@H1=EXPLOSIVE PULSED POWER

The magnetic flux compression technique for converting the chemical energy of high explosives to intense electrical pulses that can provide intensely concentrated magnetic energy, is one of the legacies of Andrei Sakharov, father of the Soviet H-bomb and winner of the Nobel Peace Prize. Beginning with his leadership, VNIIEF has created unmatched magnetic flux compression capability: 200 MJ at 200 MA, to produce fields in excess of 10 MG (1000 T). This advanced capability was not entirely unknown to the US, but rather unbelieved until recently in the US, so US researchers are just now pondering possible applications. Through the LANL/VNIIEF collaboration, VNIIEF is familiarizing US scientists with its unique capabilities.

The principle of magnetic flux compression is based on Lenz's Law. Electrical current in an inductive circuit stores energy in the form of a magnetic field in the inductance of the circuit. By decreasing the inductance in the circuit, the inductively stored energy can be amplified:

$$Lo.Io = Lf.If$$

$$If = Lo.Io / Lf$$

$$1/2\ Lf.If^{2} = 1/2\ Lo.Io^{2}\ .Lo/Lf$$

This can also be viewed from the standpoint of flux conservation in a resistanceless current loop. The magnetic energy density is increased by decreasing the area of the current loop. This is the principle has been applied to two general types of magnetic flux compression generators.

@FIGURE=Fig 9 A 3-module disk explosive magnetic generator (DEMG). Each module consists of a disk shaped explosive sandwiched between two cavities that feed a low inductance transmission line along the outer periphery of the modules. The disk explosives are initiated at the center.

The helical explosive magnetic generator (HEMG) is the one pursued most extensively in this country, but VNIIEF has also developed the disk explosive magnetic generator (DEMG), which has several advantages over former generators. Figure 9 illustrates a DEMG. These generators are modular. Each module consists of a shaped disk of high explosive sandwiched between two inductive cavities. The high explosive is initiated on axis and feeds a transmission line at the periphery. This makes a very low inductance transmission line possible. The modules can be stacked to increase the energy supplied without significantly effecting the delivery time. Systems using as many as 25 modules have been developed at VNIIEF, and a 3 module, 1 meter diameter VNIIEF system has delivered 100 MJ at 256 MA into a 3.3 nH load. Scaling directly to a 10 module 1 meter diameter system would produce 269 MJ at 196 MA into a 14 nH load.

In September of 1993 the first joint US/Russian experiment involoved implosion of a thin liner using explosive pulsed power.

@FIGURE-Fig 10 Configuration for the DEMG liner implosion experiment. An equivalent circuit for the system is shown as well. The capacitor bank shown in the equivalent was remotely located (not shown in the experiment configuration).

A DEMG was coupled to a liner load through an electro-exploded foil (fuse) opening switch. The experimental configuration and equivalent circuit are shown in Figure 10. It consists of (1) a capacitor bank (not shown in the configuration, but shown in the circuit) that provides an initial current for (2) a helical generator (HEMG), which provides an initial current for (3) the DEMG, which is coupled through (4) switches to (5) the liner load at the top of the configuration. 35 MA was supplied to the load in 1 us.

An extensive system of diagnostics were fielded to measure the liner motion. There were four B-dot probes in the glide plane, thirty contact (shorting) pins, configured as columns of 5 probes each at six azimuthal locations, thirty-six fiber optics probes with four probes monitoring light from the inner surface and 32 probes monitoring liner transit along 8 radial spokes of 4 recessed probes.

@FIGURE-Fig 11 The liner assembly for the DEMG liner implosion experiment. Two cross sections of the assembly show the diagnostic arrangements.

The configuration and equivalent circuit are illustrated in Figure 11. The HEMG, DEMG, fuse and closing switch operated as expected, but a transmission line insulation breakdown limited the current to the liner and led to some asymmetry in the implosion. Los Alamos optical current measurement confirmed the DEMG performance, and the joint experiment provided the first opportunity for VNIIEF to familiarize Los Alamos personnel with their assembly and operating procedures. This experiment has led to significant improvement in the Los Alamos theoretical and computational models.

@H1-THE MAGO EXPERIMENT

The MAGO experiment is an approach to creating a hot, magnetized target plasma that has been under development at VNIIEF for several years, but was first announced as a contributed paper at an IEEE pulsed power conference in 1991. However, the paper was not presented at that meeting, but rather was first presented 7 months later at the Zababakin Scientific Talks in Russia. Since then we have learned a lot about this complex and interesting experiment. It employs the VNIIEF HEPP capabilities to produce a transient wall confined plasma. The geometry of this experiment is shown in Figure 12 together with a circuit diagram.

@FIGURE-Fig 12 The MAGO target plasma creation experiment chamber with an equivalent circuit for the HEMG, switches, and chamber.

The experiment consists of an HEPP system that drives the MAGO experiment chamber through a complex explosive switching module. No DEMG is used for this experiment, since the energy and current needed to create the plasma are not very high. The HEPP system works thus: A capacitor is discharged through the entire system, including the experiment chamber. This puts a seed current in the helical generator. Then, the capacitor is isolated by closing switch S1. Next, the high explosives are initiated to operate the HEMG, thus amplifying the current through the chamber. Then, the switch S2 is operated to isolate the experiment chamber while the HEMG continues to operate, achieving a very much higher current (approaching 9 MA). Because the time constant for the isolated chamber is long, the current continues to flow there with little or no decay. At maximum current the explosively operated opening switch indicated as a variable resistor in series with with S2 is triggered. This suddenly introduces the very high current to the experiment chamber, causing a breakdown and next paragraph. One might consider the sudden introduction of the approximately ten times higher current to the experiment chamber as an inductive kick. The dynamic behavior of the plasma in the chamber is important is determining the continued time history of the current.

The experiment chamber is divided into two chambers by a barrier mounted on a rod along the axis of the chamber. The early current through the rod and walls of the chamber sets up a magnetic field in the 10 torr DT gas in the chamber. No ionization occurs because the voltage across the insulator is not very high and is changing only slowly with time. When the high current is suddenly switched into the chamber, breakdowns occur in the chamber, first across the gap (or "nozzle") between the barrier and the cylinder wall. The current path broadens and the heated plasma expansion sends a shock into the second chamber. The process is not fully understood, but we see from the B-dot probes that the breakdown across the insulator occurs some time later. As the dynamics develop, the current across the nozzle provides a ponderamotive force on the plasma in the nozzle, accelerating the plasma in the gap to high velocity. This high velocity plasma runs into the previously shocked (and thereby ionized) gas in the second chamber, producing a stationary second shock. The temperature rises to high values in hot spots in the region between these two shocks. The temperature of the bulk plasma is much lower, but it is the hot spots that are mainly responsible for the neutron output of up to 5 x 10^13.

The MAGO IIP experiment was a pure deuterium experiment, fielded in the same way as other MAGO experiments. Because there were no primary 14 Mev neutrons, this experiment afforded an opportunity to make a neutron ratio measurement that provided a rough lower limit for the bulk electron temperature in the plasma. That is because the tritons produced in the DD reaction are energetic, and while being slowed down in the plasma (mainly by electrons), they can undergo fusion reactions with the deuterium nuclei, thus producing a 14 Mev neutron. The ratio of these 14 Mev neutrons with the DD neutrons from the branch of the DD reaction that has one neutron and a light helium nucleus as its products is greater for higher electron temperatures because the range of the triton is longer for hotter electrons. It is a lower limit because the less reactions than otherwise will occur if the range is longer than the distance to the wall, or the ions substantially slow the tritons. A rough measurement was made by using activation detectors for the 14 Mev neutrons. A lower limit of 110 ev seemed to be indicated for the electron temperature.

On the basis of computations done for our most recent experiment (MAGO II), it appears that the performance of the MAGO experiment is somewhat sensitive to the ratio of the early current to the later high current. In that experiment, the two currents had a smaller difference, so the neutron output was some what down (~ 10^13) and the computed bulk temperature was only about half that of a previous DT experiment (MAGO I). The computed bulk temperatures were about 270 ev in MAGO I and 160 ev in MAGO II.

In the MAGO I experiment we made time resolved neutron measurements, obtained neutron activation, did optical interferometry for electron density, obtained time resolved visible spectroscopy, did time integrated near-UV spectroscopy, and many obtained current and field measurements. Much of this data is still being analyzed, but we know that about 8 x 10^12 neutrons were produced, the activation agreed with the time of flight measurements, the interferometry saw electron densities up to about 8 x 10^16, and the spectroscopy saw mostly continuum. While the analysis of the data is still in progress, the results so far are reasonably consistent with computations.

We obtained extensive diagnostics form MAGO II as well as insured

to correctly correlate features in the various measurements.
In the MAGO II experiment we also got a similar neutron yield to that of MAGO I (about 10^13). The visible spectroscopy in correlation with the interferometry and features in the B-dot probes looks very interesting. We now see more than continuum. Time resolved, filtered X-ray measurements were made, which should contain spectral information on the emission from the plasma.
The data reduction will take some time.

@H1-A PROOF-OF-PRINCIPLE EXPERIMENT

The reasonably high bulk temperature in the MAGO experiments makes it interesting as a vehicle for a proof-of-principle experiment. We are currently examining the measurements made on MAGO II and analyzing them with our MHRDR code to ascertain whether or not this plasma is suitable for subsequent implosion. To be suitable, the bulk plasma thermal time scale must be greater than the time required for compression. For MAGO with an implosion velocity on the order of 1 cm/us, the time scale must be about 10 us. Yakubov has pointed out that any impurities in the bulk plasma will reduce this time scale, especially as the plasma density increases [7].

@FIGURE- Fig 13 Adiabatic compression of the hot, magnetized plasma to fusion conditions requires only a modest convergence.

VNIIEF has from the very beginning of this collaboration suggested methods of accomplishing a compression of the second chamber of the MAGO experiment. Two such methods are illustrated in Figure 13. Depending on dimensionality of the compression and the temperature of the bulk plasma, it may take only a modest convergence to reach fusion ignition temperatures. However, the temperature, field, and rhoR of the MAGO plasma are too low for fusion ignition if cylindrical compression used. If the plasma life time is in accord with the calculations, a cylindrical compression of the existing design of the MAGO second chamber should provide a very convincing proof-of-principle experiment. If the bulk plasma were compressed from about 6 cm down to about 1.5 cm, with the central rod unchanged in diameter, then neglecting losses, the plasma would be driven from 300 ev to 2.7 Kev, and the field would be pumped to tens of megagauss. Computations predict a plasma suitable for implosion cylindrically compressed should settle into a Kadomtsev stable wall-confined Z-pinch profile.

@H1-THE PROSPECT FOR FUSION IGNITION

Besides offering a vehicle for an MTF proof-of-principle experiment, the MAGO experiment may also provide a route to demonstrating fusion ignition. An attempt to achieve fusion ignition would require a redesign of the MAGO second chamber so that convergence along the axis as well as radially occurred. Assuming hemispherical compression, a convergence of ten would more than suffice for ignition if the initial temperature were 300 ev and the compression was reasonably adiabatic. We must emphasize that this discussion is very speculative at this stage, because neither the bulk plasma temperature or the life time of the bulk plasma has been established with certainty yet.

@H1-THE VNIIEF PIECES

VNIIEF high explosive pulsed power and ultrahigh magnetic field capability works as advertised. This capability significantly exceeds existing US capability. The three experimental campaigns completed to date simply could not have been performed using off-the-shelf US technology. VNIIEF high field generators have a variety of potential physics applications, beyond their successful use to determine the high temperature superconductor critical a higher energy alternative source for present and future US pulsed power applications. The September 1994 DEMG/liner experiment coupled with the MAGO series of experiments suggest that VNIIEF may have all the pieces required to achieve thermonuclear fusion ignition, but almost certainly provide the essentials for an unambiguous MTF proof-of-principle experiment. If ignition is possible, then it can be demonstrated without a billion dollar capital investment.

@H1-FUSION SYSTEM CONFIGURATION

While the beam on target configuration is appealing for a fusion research program and possibly for other applications, it does put a very touchy high technology component between the necessary pulsed power supply and the target. MTF using the high explosive pulsed power capabilities of VNIIEF would eliminate the "middlemen".

MTF permits a complete rethinking of the entire driver/target configuration. Conventional target drivers (lasers, light ions, etc.) are optimized for conventional targets and are probably not appropriate for MTF in its extremes. For sufficiently strong magnetic fields, there is a continuum between conventional ICF target space and MTF space, suggesting a possible role for existing drivers. If the MAGO experiments confirm our calculations, the VNNIEF 200 MJ HEPP systems should allow a fusion ignition experiment to be attempted in the near future with a minimal capital outlay.

@H1-AN MTF PROGRAM

An MTF program should focus on three major goals:
We must have a convencing proof-of-principle demonstration of quasi-adiabatic heating (Tf > 2 To) of a magnetized plasma by a magnetically driven liner. Achievement of fusion ignition temperatures (> 4 Kev) and high neutron yield (> 10^14) should be the next step. Finally, it is necessary to demonstrate thermonuclear fusion ignition and a significant burn-up fraction.

Each goal requires both a hot, magnetized target plasma and a target implosion system. The obvious target plasma formation candidates are the VNIIEF MAGO plasma for which characterization is in progress, and the Los Alamos cryogenic fiber Z-pinch for which only the early stages are characterized. There are two reasonable candidates for an implosion system: Both Los Alamos and VNIIEF have had extensive experience with cylindrical liners magnetically driven to velocities in the range of 0.3 to 1.0 cm/us with convergences up to about 10. In addition, A quasi-spherical implosion at 0.5 cm/us with a convergence of about 3 has been demonstrated by VNIIEF (?) and Phillips Lab (?).
This could satisfy conditions necessary for a proof-of-principle experiment. Each goal requires extensive computations to evaluate the trade-offs between initial temperature of the target plasma, the convergence required, the liner (or pusher) velocity, and the energy required.

We believe that a six year program costing about $ 3-6 M per year may suffice to demonstrate fusion ignition for MTF.
For this program each of the goals would require about three years with a computational effort defining each of the necessary experiments and providing analysis of their results. The tasks for each goal can be overlapped to some degree, so that three years is a reasonable estimate of the time needed to accomplish all three goals.
With more resources the time to demonstration could be shortened.

@H1-PROSPECTS FOR A FUSION REACTOR

What are the prospects for an MTF reactor?
We recognize that the magnetic flux compression generators cannot be

is to demonstrate fusion ignition. Ruby lasers first demonstrated lasing, but they are rarely used today. Nor do transoceanic airlines still use internal combustion engines. Based on our present knowledge, existing 200 MJ DEMG capabilities are more than adequate to achieve thermonuclear fusion ignition via MTF. MTF does not require a major capital equipment investment before the very first ignition experiment can even be attempted. Only when a large fusion burn-up fraction has been achieved can we truly say that controlled fusion is just an engineering problem. Just as the myriad of laser applications could not have been predicted long before lasing was demonstrated, the potential of MTF (or any other fusion concept) cannot be realistically evaluated until ignition is demonstrated.

@H1=SUMMARY

Magnetized target fusion has many attractive features. These include low implosion velocities, low convergence ratios, enhanced self-heating, the use of existing drivers with excess energy, and the possibility of demonstrating fusion ignition at low operating cost and no capital cost. All these features make MTF very attractive as a future research direction in our quest for controlled fusion. They also point toward the possibility of a very economical fusion power technology. However, the first major step is to demonstrate fusion ignition. Depending on the resources committed to this effort, that first major step could be accomplished at a much earlier date than is currently projected for the mainline fusion efforts and at a much lower cost.

@H1=ACKNOWLEDGEMENTS

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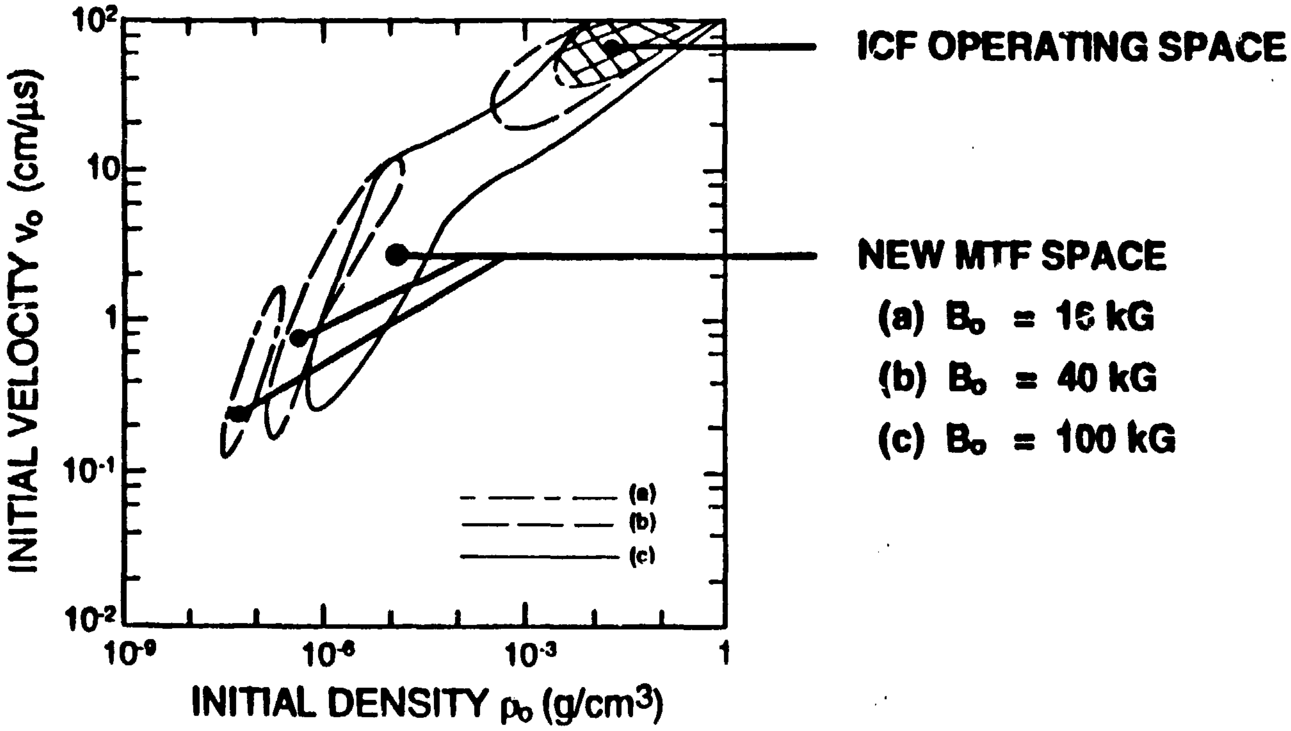

INITIAL VELOCITY v_o (cm/μs)
10^2
10
1
10^{-1}
10^{-2}
10^{-9}
10^{-6}
10^{-3}
1
INITIAL DENSITY ρ_o (g/cm^3)
(a)
(b)
(c)
ICF OPERATING SPACE
NEW MTF SPACE
(a) B_o = 16 kG
(b) B_o = 40 kG
(c) B_o = 100 kG

Fig. 1

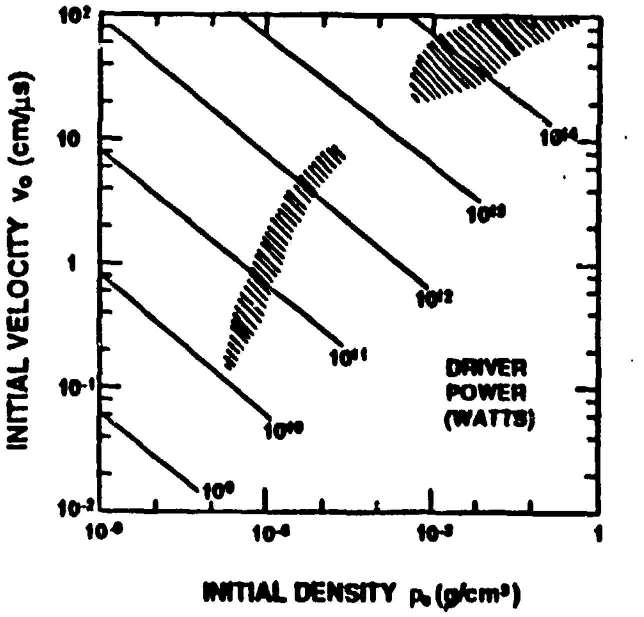
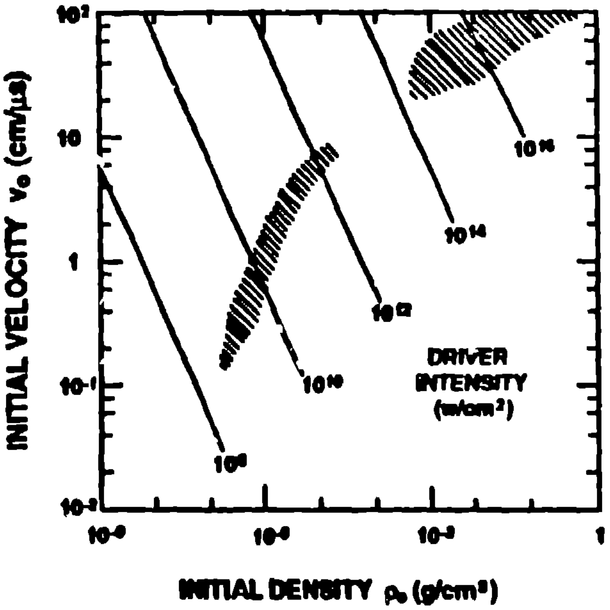
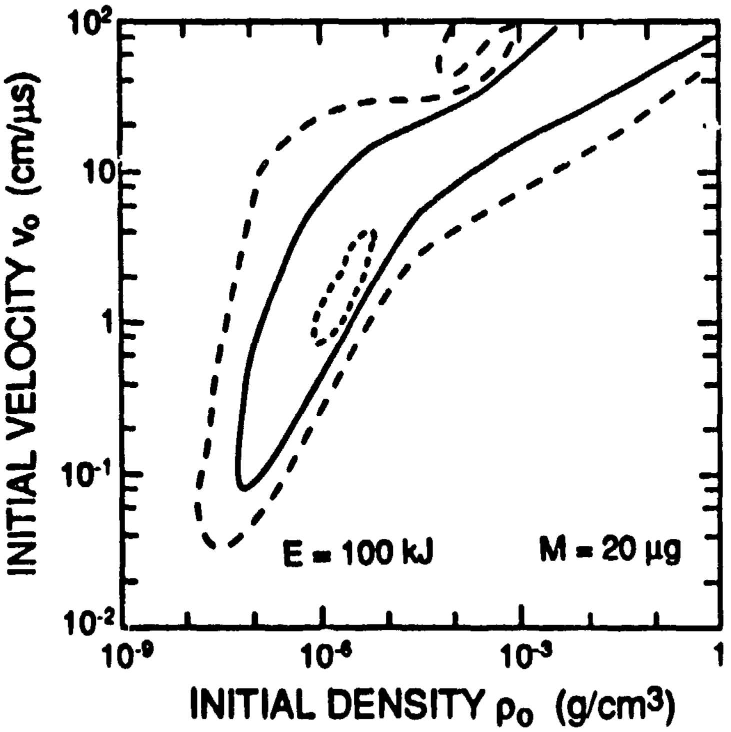
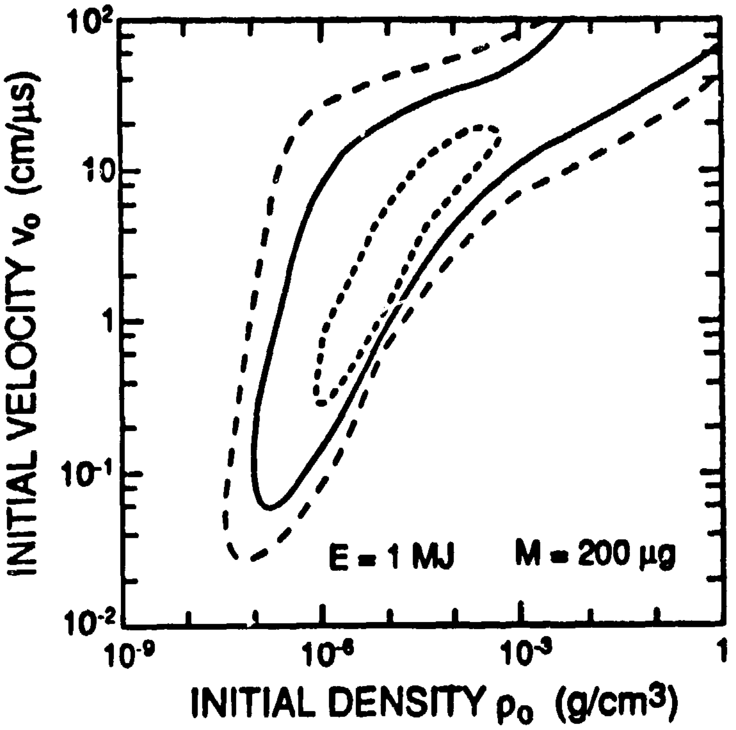

INITIAL VELOCITY v_0 (cm/μs)
10^2
10
1
10^{-1}
10^{-2}
10^{-6}
10^{-4}
10^{-2}
1
INITIAL DENSITY ρ_0 (g/cm^3)
10^9
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
DRIVER POWER (WATTS)

Fig 2

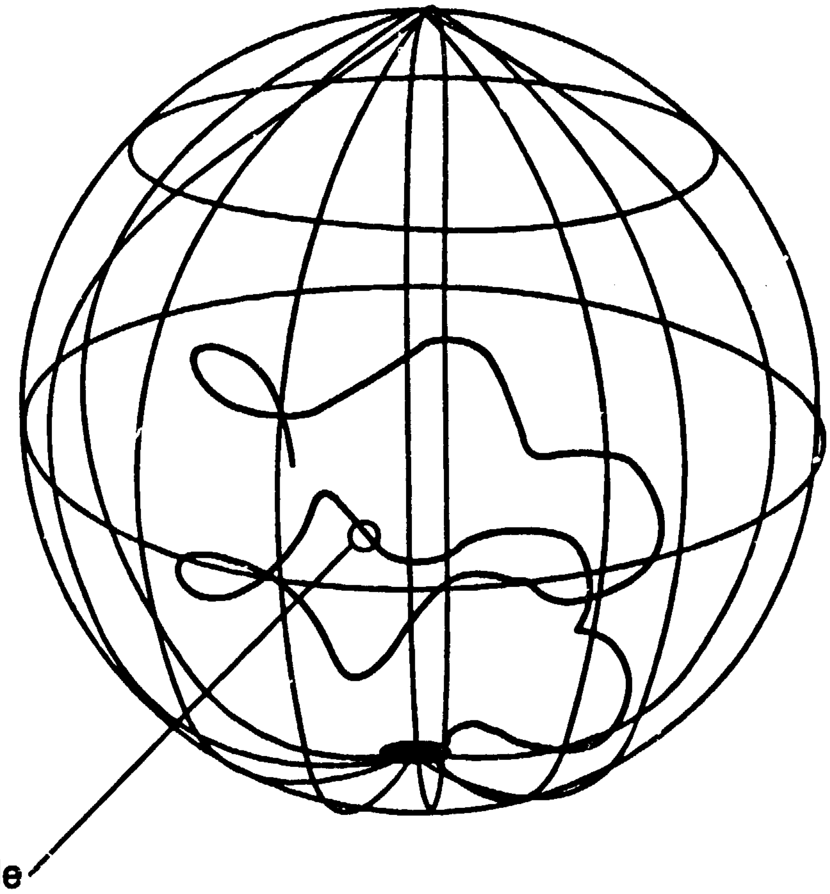

10^2
10
1
10^{-1}
10^{-2}
INITIAL VELOCITY v_o (cm/μs)
10^{-9}
10^{-6}
10^{-3}
1
INITIAL DENSITY ρ_o (g/cm^3)
10^{8}
10^{10}
10^{12}
10^{14}
10^{16}
DRIVER
INTENSITY
(w/cm^2)

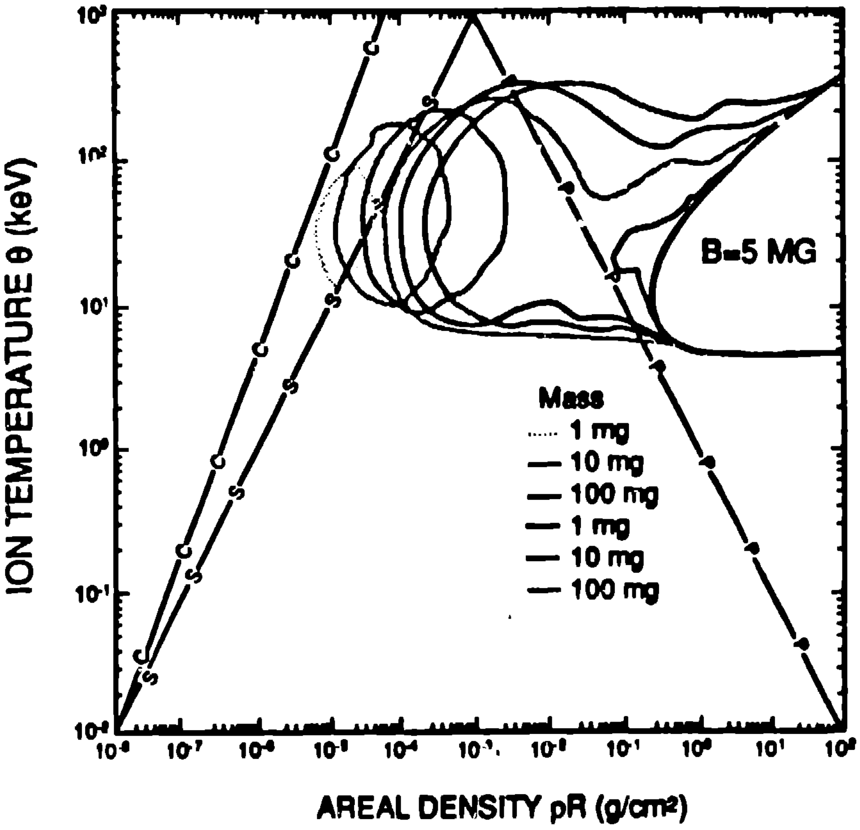


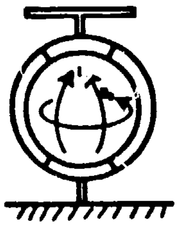
10²
10
1
10⁻¹
10⁻²
10⁻⁹
10⁻⁶
10⁻³
1
INITIAL VELOCITY v₀ (cm/µs)
INITIAL DENSITY ρ₀ (g/cm³)
E = 100 kJ
M = 20 µg



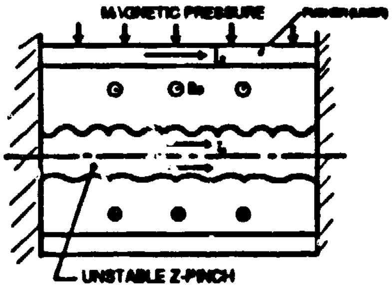
10^2
10
1
10^{-1}
10^{-2}
10^{-9}
10^{-6}
10^{-3}
1
INITIAL VELOCITY v_o (cm/μs)
INITIAL DENSITY ρ_0 (g/cm^3)
E = 1 MJ
M = 200 μg


alpha particle
in uniform J

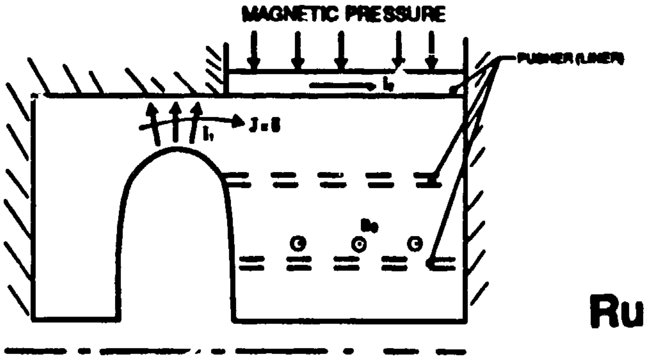

ION TEMPERATURE θ (keV)
AREAL DENSITY ρR (g/cm²)
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
C
S
B=5 MG
Mass
1 mg
10 mg
100 mg
1 mg
10 mg
100 mg



SNLA ϕ-target

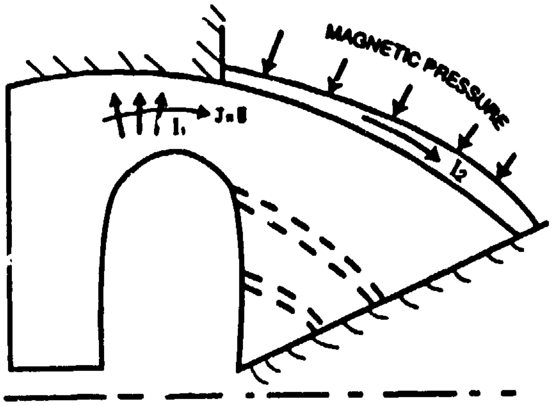


Z-pinch plasma/Z-pinch liner

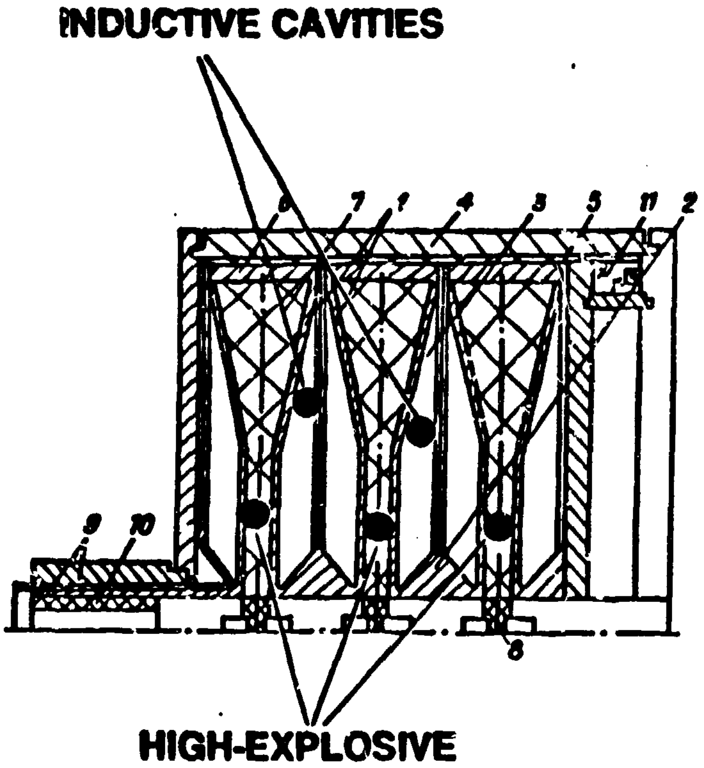


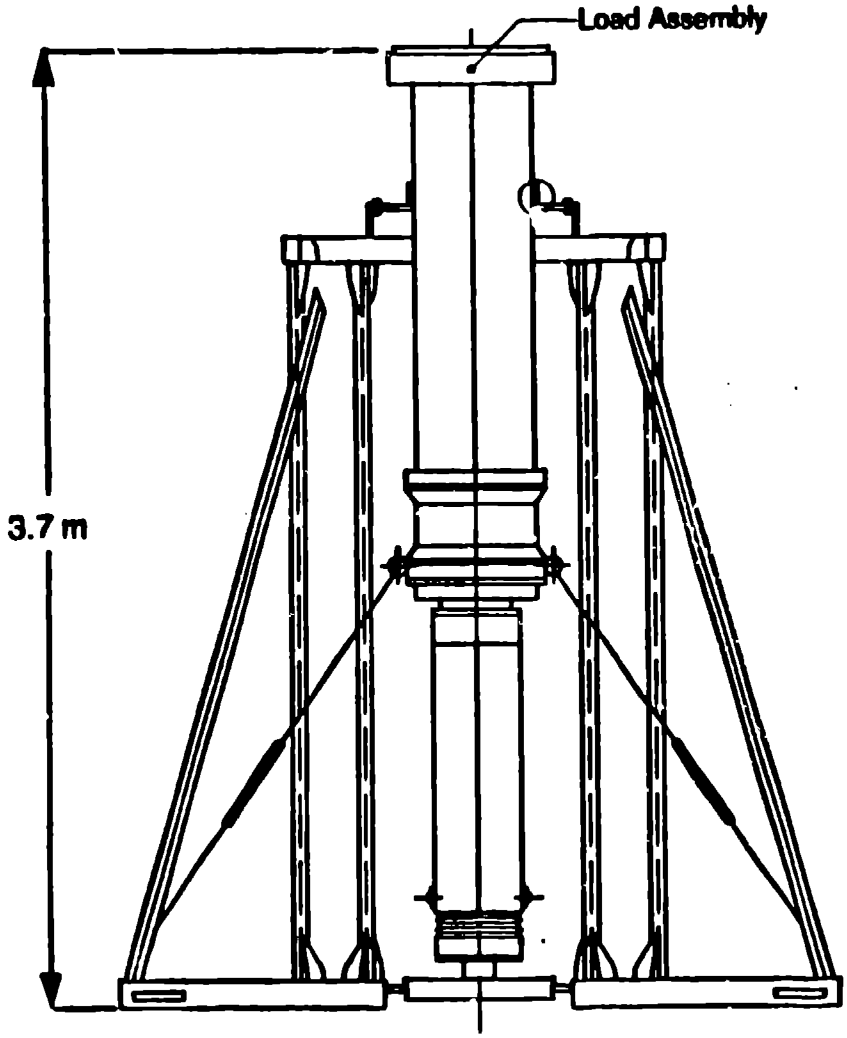
CYLINDRICAL

Russian "MAGO"

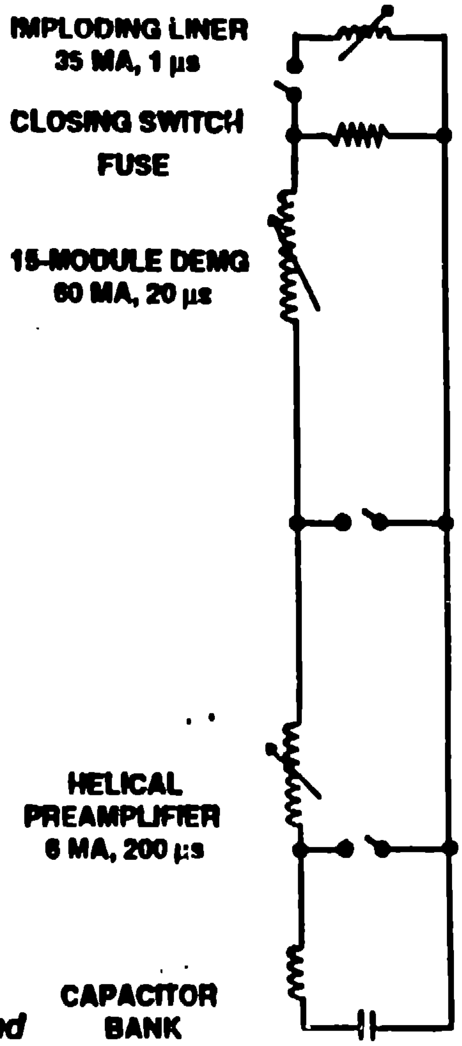


QUASI-SPHERICAL


INDUCTIVE CAVITIES
6
7
1
4
3
5
11
2
9
10
8
HIGH-EXPLOSIVE



Disk Electromagnetic Generator Experiment in shot stand



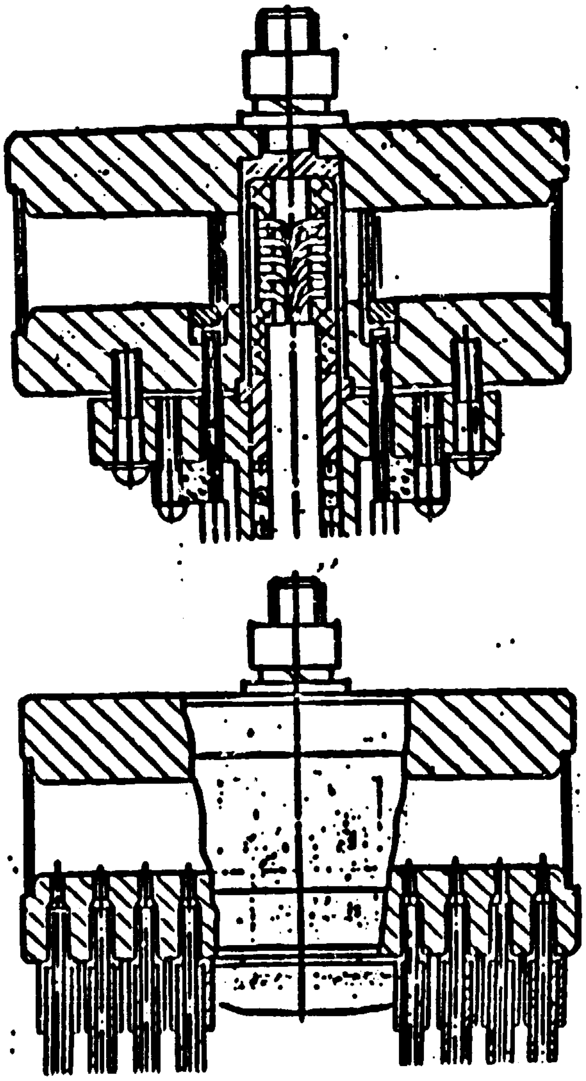
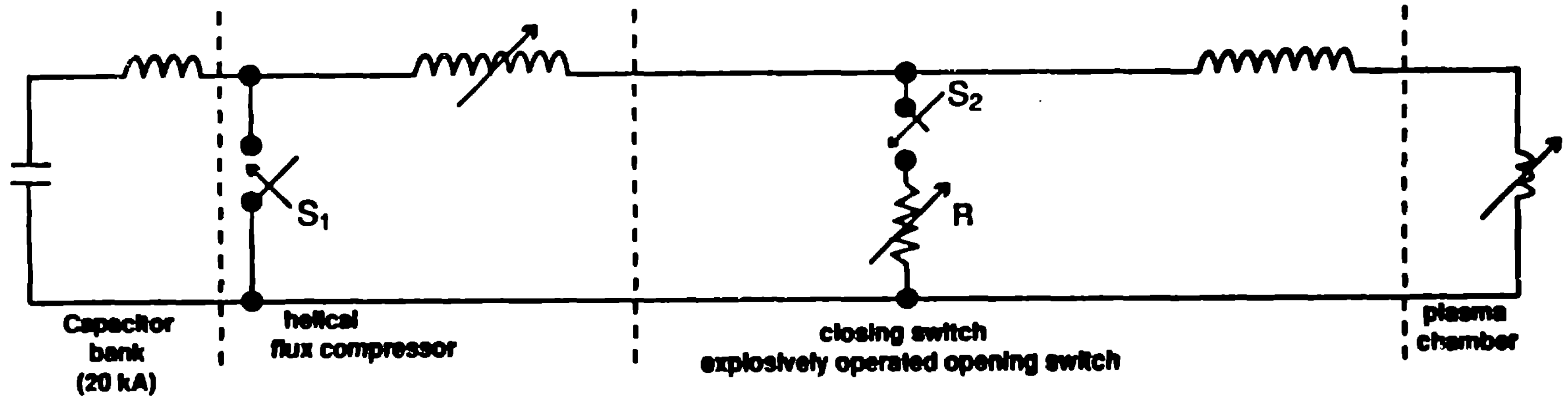
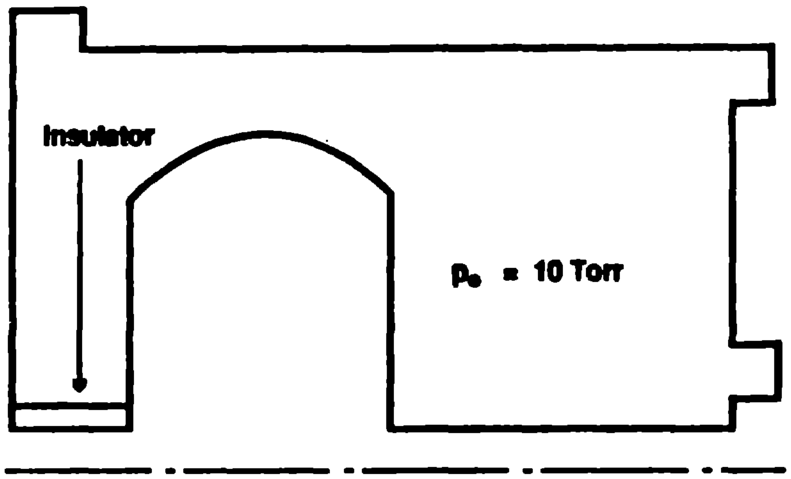


Fig. 11





Reference: "Investigation into the Possibility of Obtaining Thermonuclear Magnetized Plasma in a System with Magnetic Compression - - Mago," A. Buyko et al., Zababakhin Scientific Talks, Kishtym, Russia (January 1992).

Fig. 12

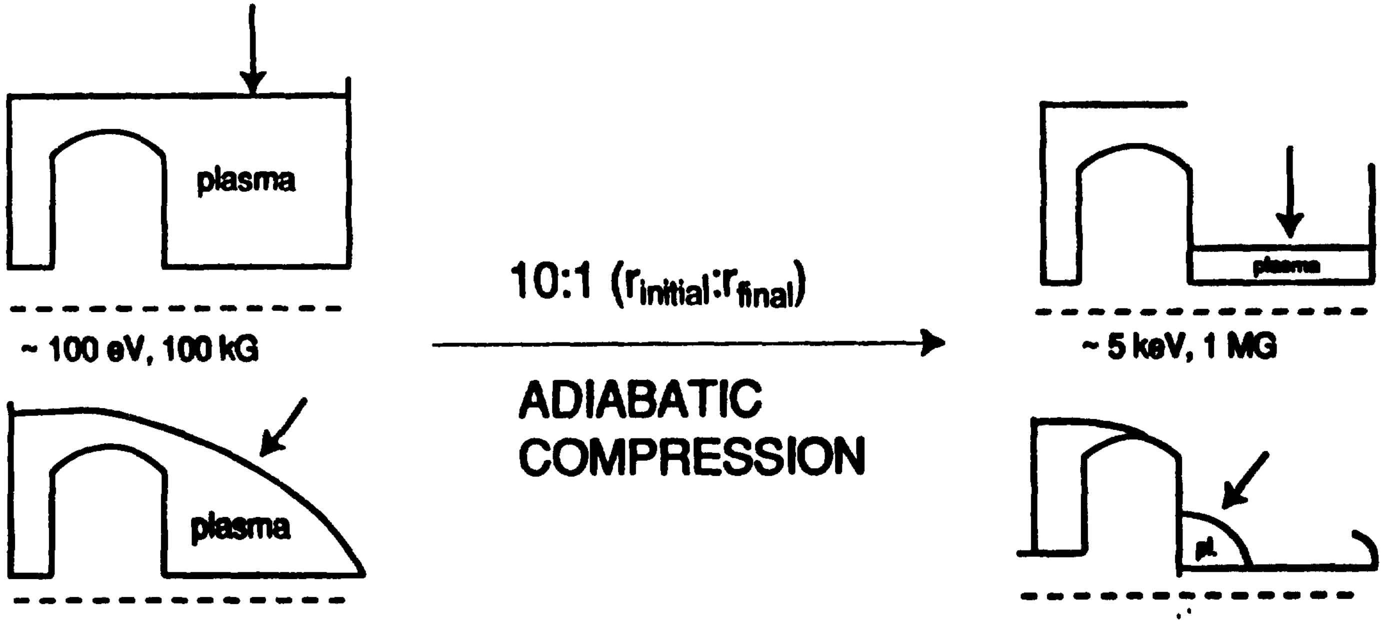

plasma
~ 100 eV, 100 kG
plasma
10:1 ($r_{initial}$:r_{final})
ADIABATIC
COMPRESSION
plasma
~ 5 keV, 1 MG
pl.

Fig. 13