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Detailed Modeling of Proposed Liner-on-Plasma Fusion Experiments

Peter T. Sheehey, Rickey J. Faehl,
Ronald C. Kirkpatrick, and Irvin R. Lindemuth
Los Alamos National Laboratory
Los Alamos, NM 87545 USA

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Magnetized Target Fusion (MTF) is a potentially inexpensive approach to controlled fusion in which a preheated and magnetized target plasma is hydrodynamically compressed by an imploding liner. If electron thermal conduction losses are magnetically suppressed, relatively slow O(1 cm/microsecond) "liner-on-plasma" compressions, magnetically driven using inexpensive electrical pulsed power, may be practical. Target plasmas in the range 10^{18} cm^{-3}, 100 eV, 100 kG need to remain relatively free of potentially cooling contaminants during formation and compression. Magnetohydrodynamic (MHD) calculations including detailed effects of radiation, heat conduction, and resistive field diffusion have been used to model separate static target plasma (Russian MAGO, Z-pinch, Field Reversed Configuration) and liner implosion (without plasma fill) experiments. Using several different codes, liner-on-plasma compression experiments are now being modeled in one and two dimensions to investigate important issues for the design of proposed liner-on-plasma MTF experiments. The competing processes of implosion, heating, mixing, and cooling will determine the potential for such liner-on-plasma experiments to achieve fusion conditions.

A US/RUSSIAN COLLABORATION

The experiments modeled here are the subject of a US/Russian collaboration, between the All-Russian Institute of Experimental Physics (VNIIEF) and Los Alamos National Laboratory. Participants include:

V. K. Chernyshev, V. N. Dolin, S. F. Garanin, V. P. Korchagin,

V. N. Mokhov, I. V. Morozov, S. V. Pak, E. S. Pavlovskii, G. I. Volkov, V. B. Yakubov

All-Russian Scientific Research Institute of Experimental Physics, Arzamas-16

and

I. Lindemuth, B. Anderson, J. Canada, R. Chrien, C. Ekdahl, C. Findley, J. Goforth, R. Kirkpatrick,

H. Oona, R. Reinovsky, P. Rodriguez, P. Sheehey, J. Shlachter, R. Smith, G. Stradling, R. Thurston

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J. Eddleman and C. Hartman of Lawrence Livermore National Laboratory have also collaborated with us in the modeling of these experiments.

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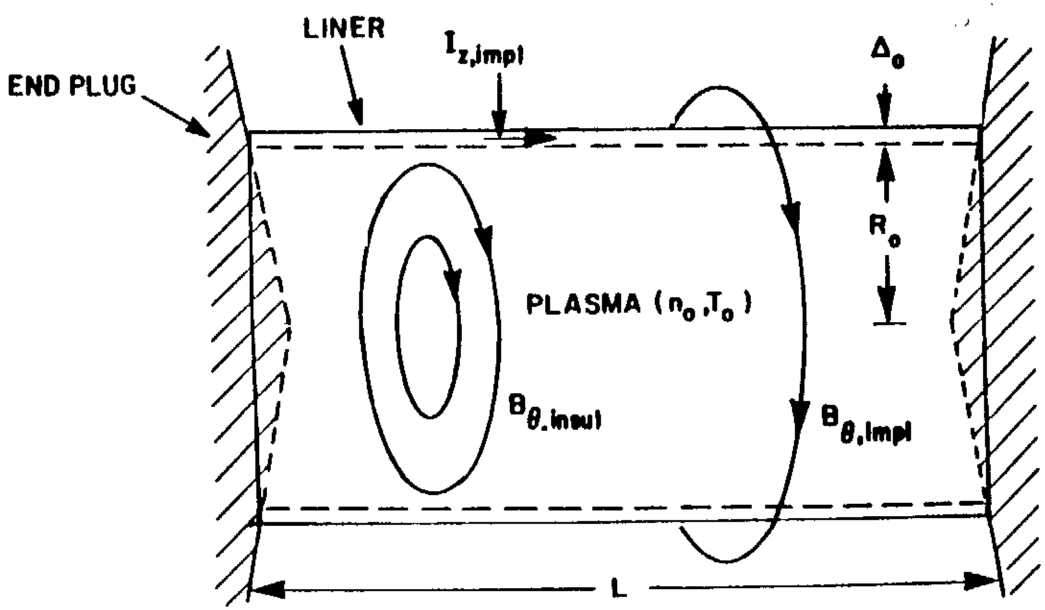
WHAT IS MAGNETIZED TARGET FUSION?

- MTF uses a magnetic field within a fusion plasma to suppress thermal conduction.
- Implosion heating and inertial confinement are similar to conventional ICF; however, compression can be near-adiabatic.



- An MTF system requires two elements:
  - (a) a preheated and magnetized initial plasma
  - (b) a target implosion driver.

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MTF is NOT ICF with a magnetic field

- Magnetic field must be closed to avoid "end losses".
- Thermal conduction is one energy loss that is reduced.
- MTF allows much lower density (down by 10^4), reducing radiation losses (down by 10^8).
- Lower density allows bigger targets.
- Reduced losses allow much slower implosions (down by 30).
- Slower implosions mean no strong shocks, no special pulse shaping, and volume ignition, but require a preheat to set the proper adiabat.
- Slower implosion and larger targets substantially reduce driver requirements!!!
- Canonical conditions: density of 10^{18} cm^{-3}, timescale of μsec, and size of cm.

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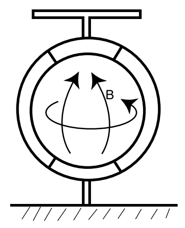
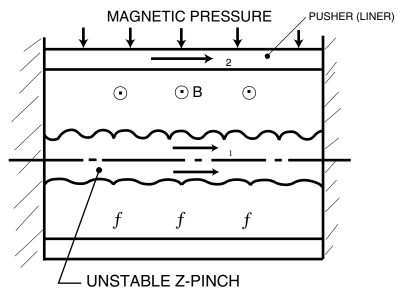
Magnetized Targets--some possible configurations

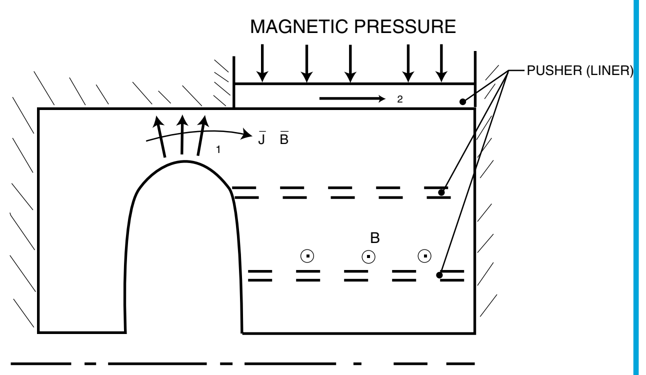
SNLA -target – a low-energy prepulse provided preheat and magnetization; a relativistic e-beam imploded the target; 1e6-1e7 neutrons produced in 1978.



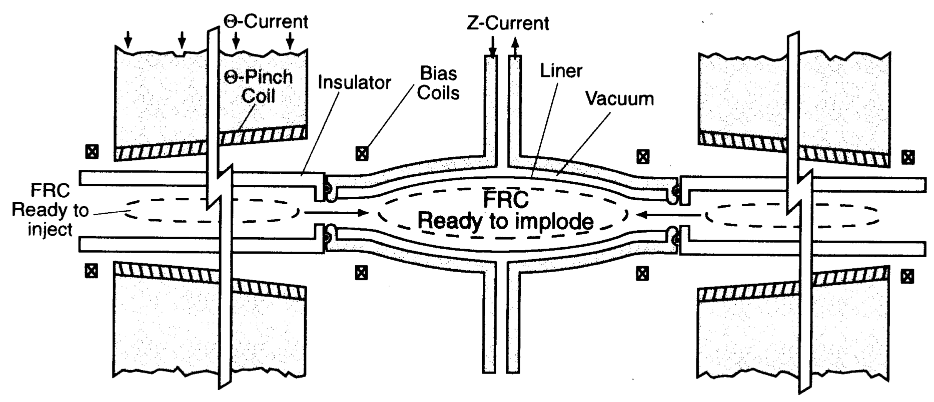
Z-pinch plasma/Z-pinch liner – an unstable gas-fill or cryogenic fiber z-pinch expands to fill the magnetically driven pusher; plasma formation experiments in progress at LANL



Russian "MAGO" – a hot magnetized plasma is formed within a magnetically driven pusher; 6e13 D-T neutrons formed in formation stage only; LANL computations predict 1e20 on subsequent implosion of quasi-spherical variant.



Field-reversed configuration (FRC)--purely inductive, electrodeless discharge forms plasma, which is injected into liner; early explorations by Kurtmullaev in Russia; LANL proposing to extend FRC operation into MTF density regime.



Critical Issues for MTF:

- A magnetized plasma suitable as an MTF target must have:
  Temperature > 50 eV
  Density between 10^{-6} and 10^{-3} g/cm^3
  Magnetic field > 50 kG
  and sufficient lifetime (e.g. several microseconds) for implosion.

- Reduction of thermal conductivity must be demonstrated for a dense, wall-supported plasma.

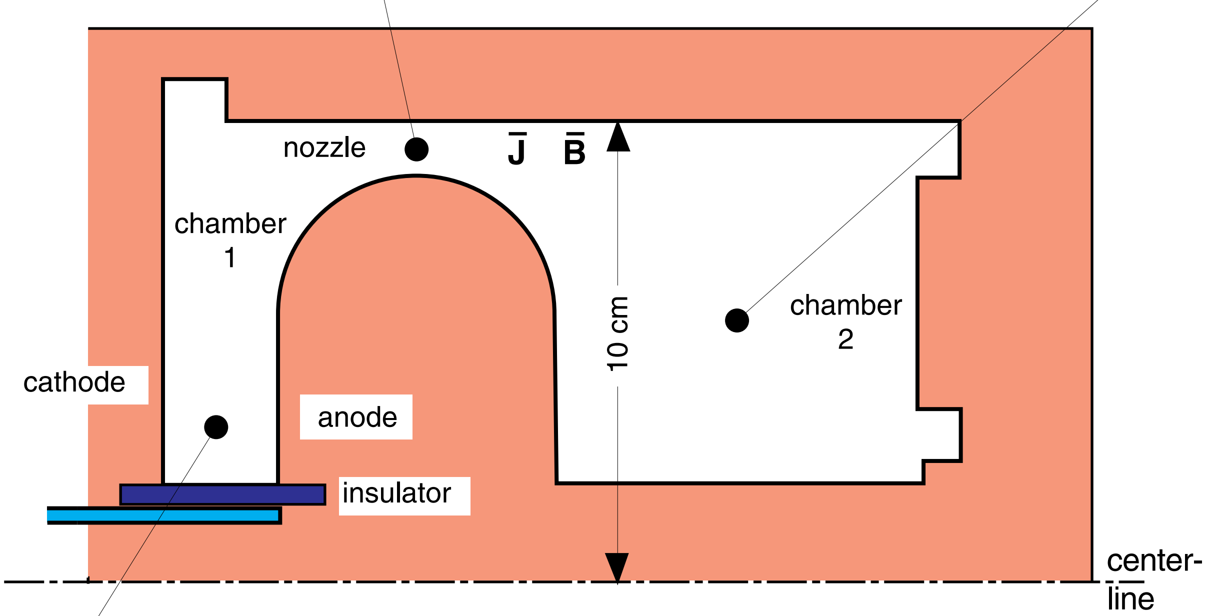
- Plasma-wall interaction must not create dynamical effects or excessive introduction of impurities, which could lead to rapid cooling of the plasma.

- Target plasma must be readily integrated with drivers for liner-on-plasma compression to fusion conditions, in a future program.

The Russian VNIIEF MAGO plasma formation scheme is a leading candidate for MTF's pre-implosion plasma.

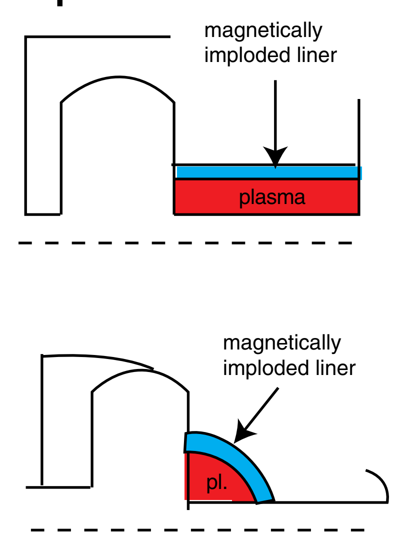
1. After a 1-2 MA "bias" current, a 6-8 MA current initiates in pre-magnetized cold 10-torr D-T gas, driving a z-pinch into chamber 2.

3. After a 3-4   s dynamic phase, a Kadomtsev-stable, wall-confined "hard core z-pinch" is formed at T =100-300 eV, n > 10^{18} /cm^3.

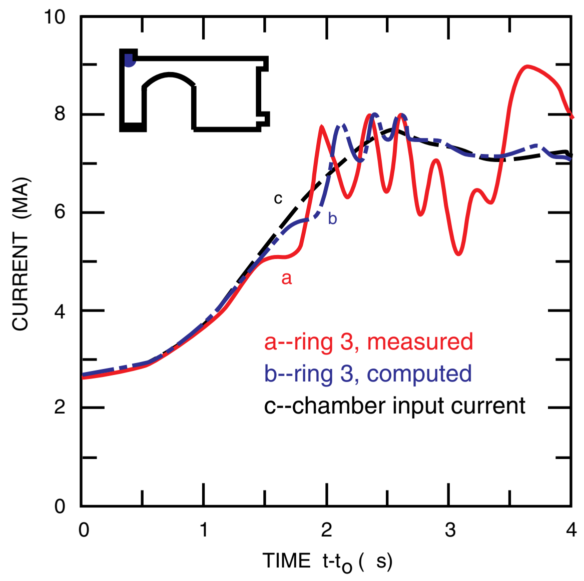


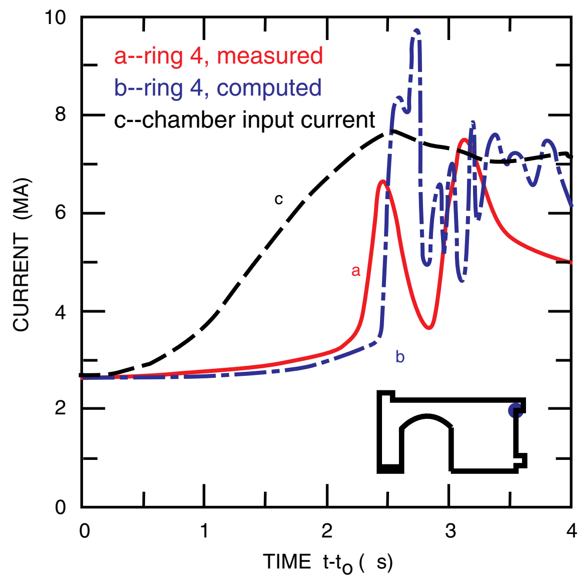
2. At 1   s, an "inverse z-pinch" forms at or near the insulator, accelerates plasma through the nozzle.

Implosion scenarios



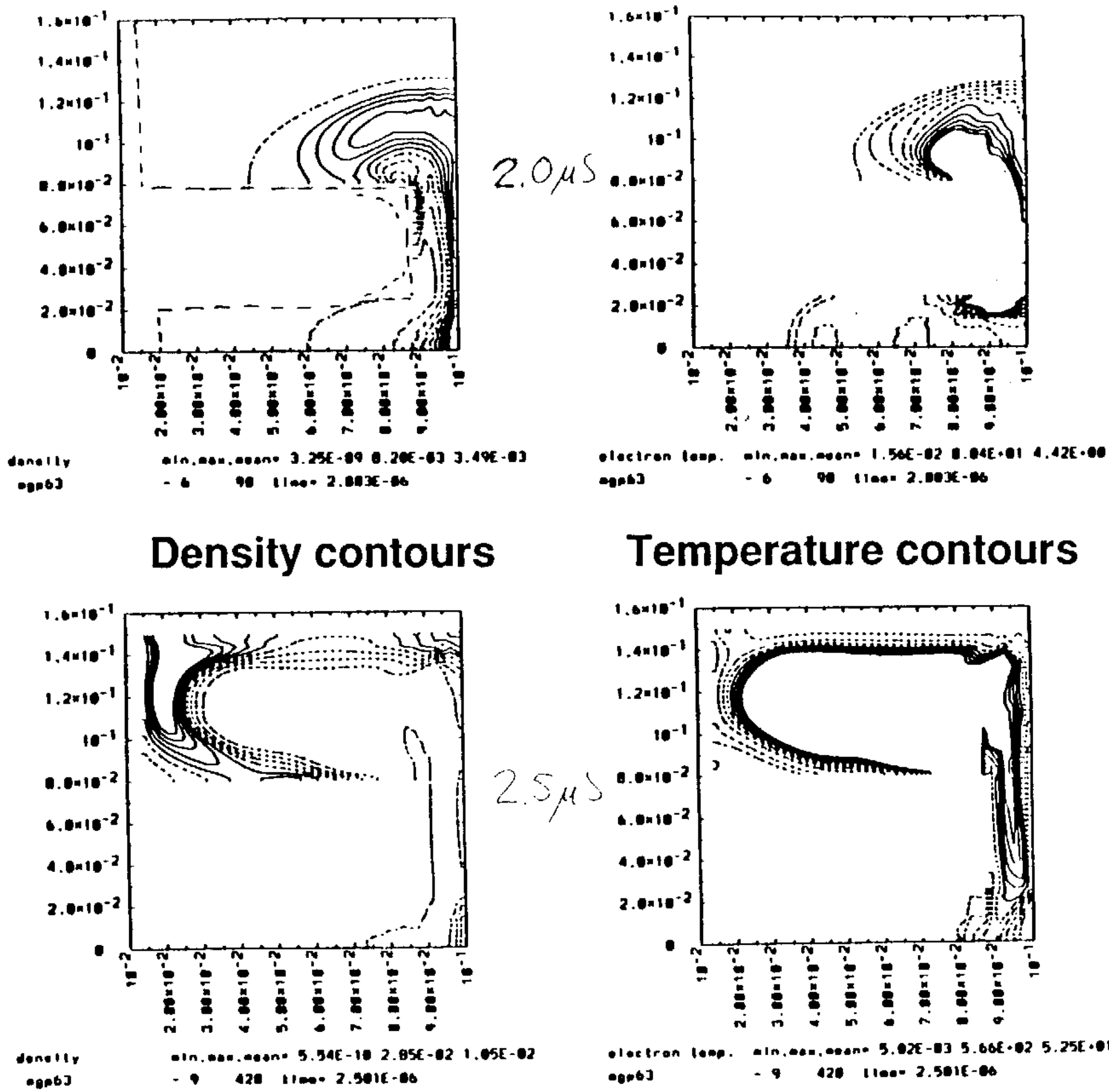
Computational modeling of MAGO and MTF systems requires detailed, time-dependent, non-linear computations from t=0.





- **LANL two-dimensional MHD computations include partial ionization, resistive diffusion, thermal conduction, radiation.**
- **By computing plasma flow, the computations include the effects convective heat losses to chamber walls.**
- **The computations predict observed MAGO inductive probe signals, a sensitive plasma dynamic diagnostic.**

Gross plasma behavior: Rapid sweeping of plasma through the annular nozzle, followed by radial convergence in the second chamber.



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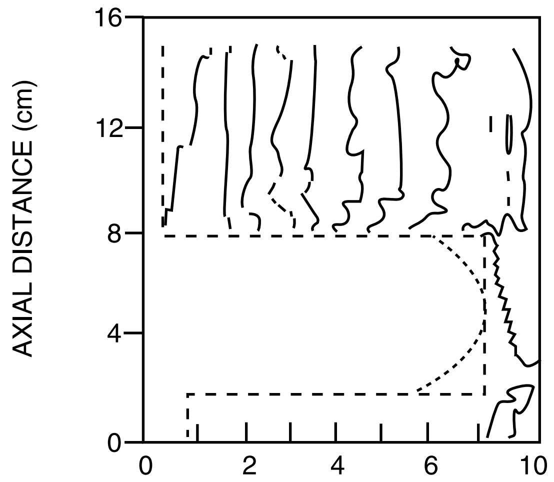
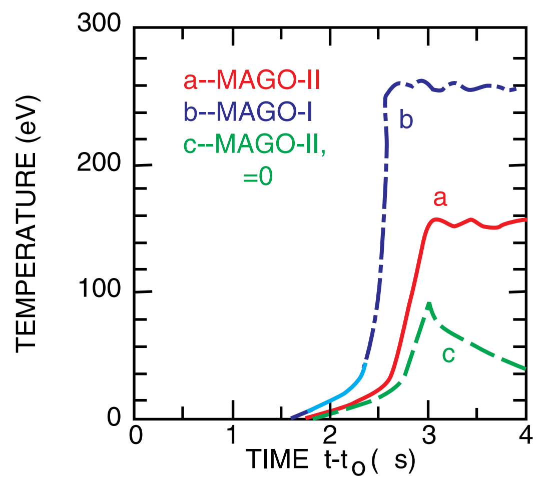
LANL computations predict a plasma suitable for implosion.

- **The plasma settles into a diffuse (Kadomtsev stable??), wall-confined z-pinch**
- **Beginning with an average temperature of ~ 300 eV, fusion temperatures can be achieved at modest compression ratios**
- **A plasma without magnetothermal insulation (=0) is not suitable for implosion.**



DENSITY CONTOURS (t=7.5   sec)

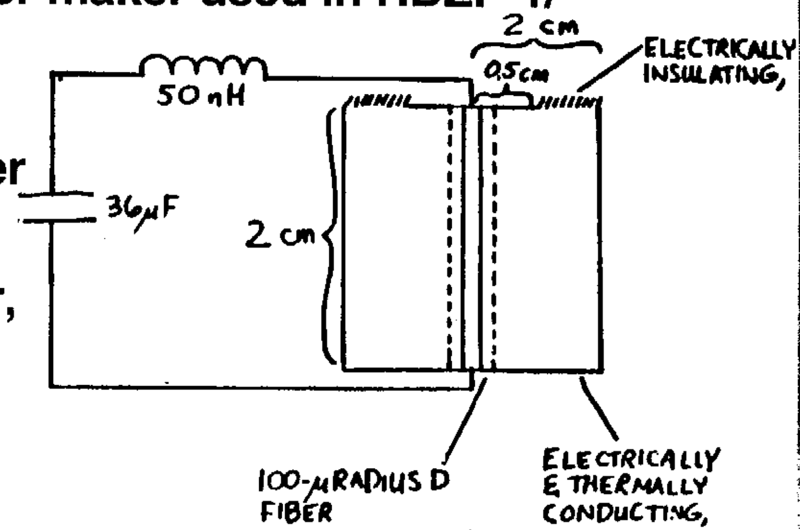


VNIIEF/LANL

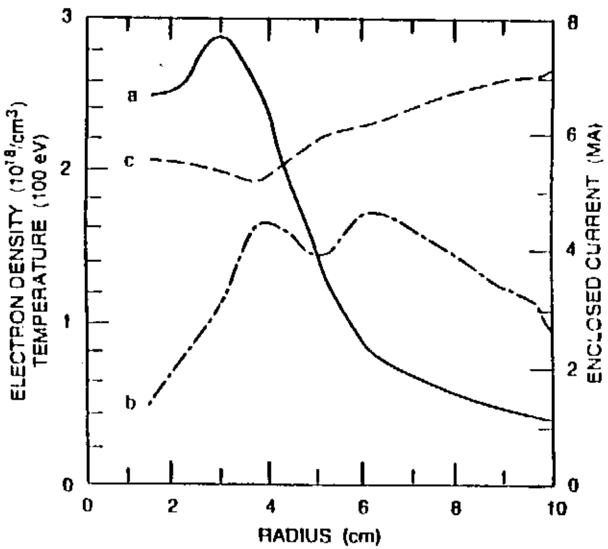
IL-6/95-45

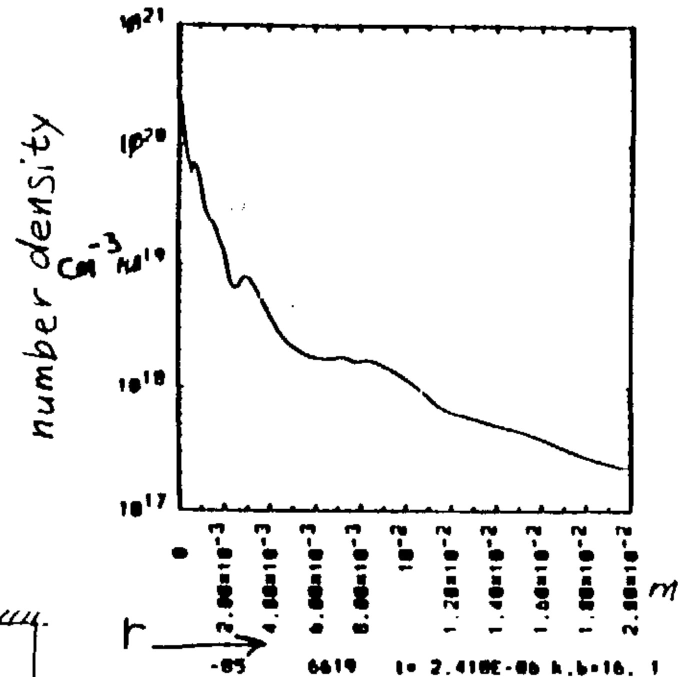
An attempt was made to demonstrate a Z-pinch target plasma for MTF, adapted from existing LANL pulsed-power facilities.

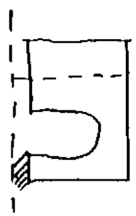
- Detailed two-dimensional MHD computational modeling suggests a deuterium-fiber-initiated Z-pinch, driven by the Colt capacitor bank, could produce the desired plasma conditions.
- Colt bank (0.18 MJ, up to 100 kV, 2 MA with 2.2 μs rise time) was adapted to drive the Z-pinch load.
- Intent was to employ the deuterium fiber maker used in HDZP-1/ HDZP -2 dense Z-pinch experiments.
- A two-centimeter radius, two-centimeter long, electrically conducting plasma chamber, incorporating the fiber maker, was to be mated to the Colt bank.

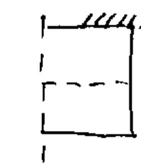


Comparison: dense Z-pinch vs. late-time MAGO plasmas as candidates for subsequent MTF compression. Both meet average density, temperature, magnetization requirements.









MAGO (computed radial profiles)
more uniform ρ, T, B
center conductor

Dense Z-pinch
pinched ρ, T, B
no center conductor

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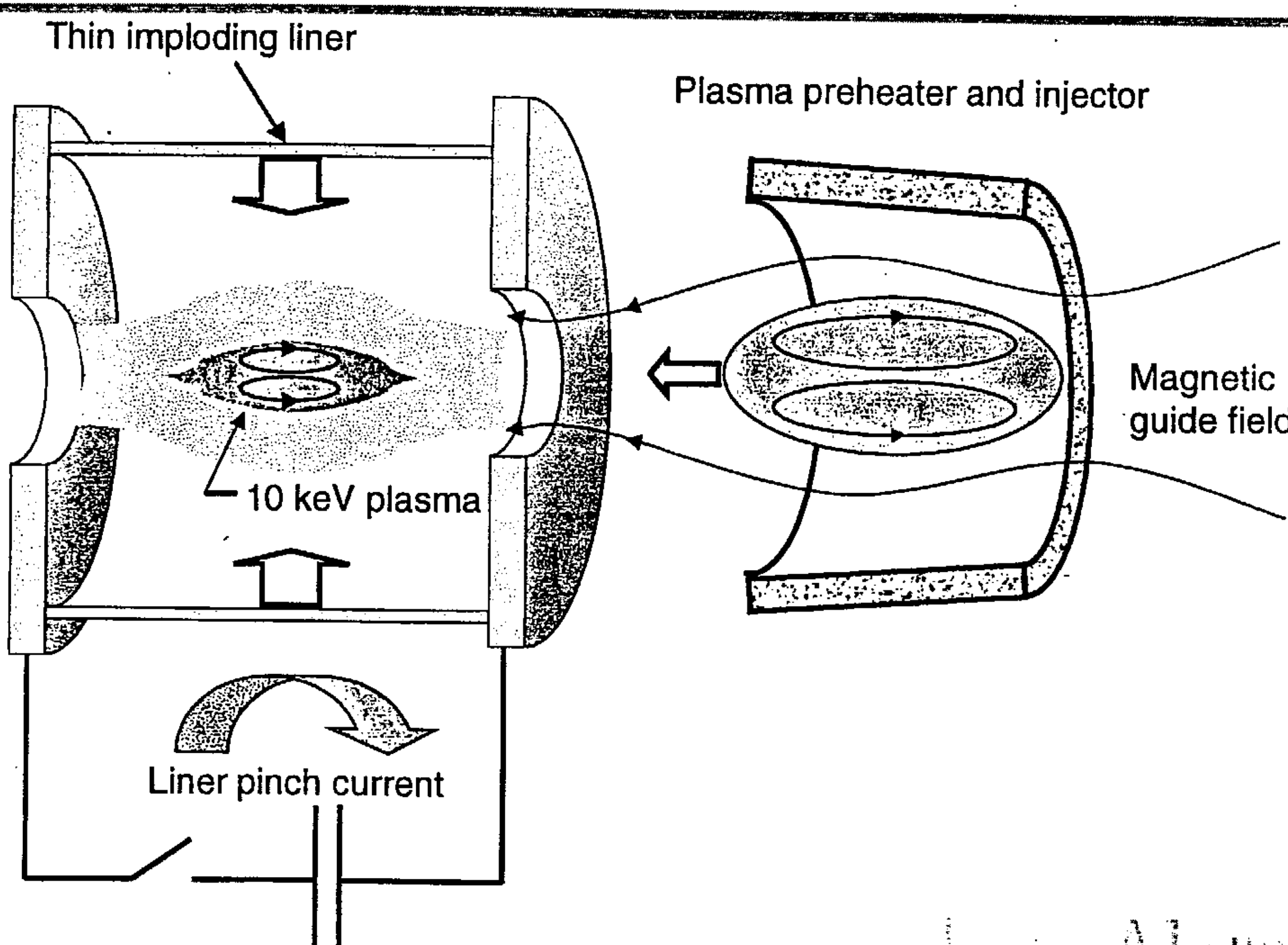
A new program at Los Alamos National Laboratory aims to develop a Field Reversed Configuration (FRC) plasma as a target for a proof-of-principle MTF plasma compression experiment, with collaboration from the Air Force Research Laboratory and other laboratories and universities.



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Codes such as MOQUI and MACH-2 will be used to model the formation, evolution, and compression of FRC plasmas:

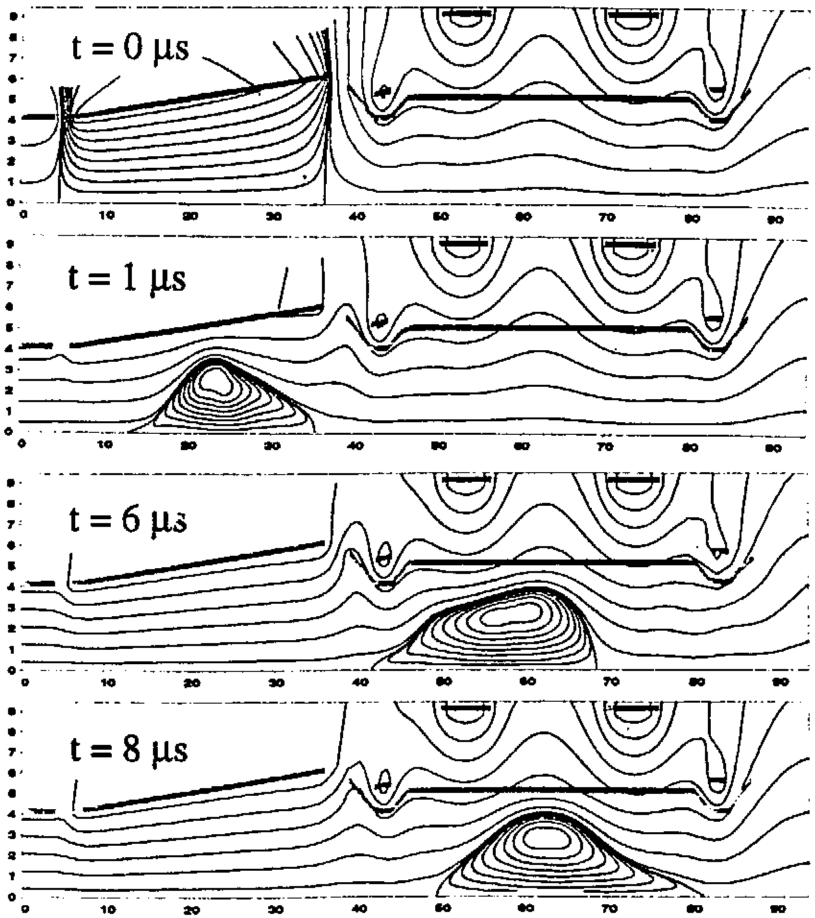


Fig. 5. MOQUI Calculation of FRC formation and injection into liner-compatible geometry. The conical theta pinch is on the left, and the liner is on the right.

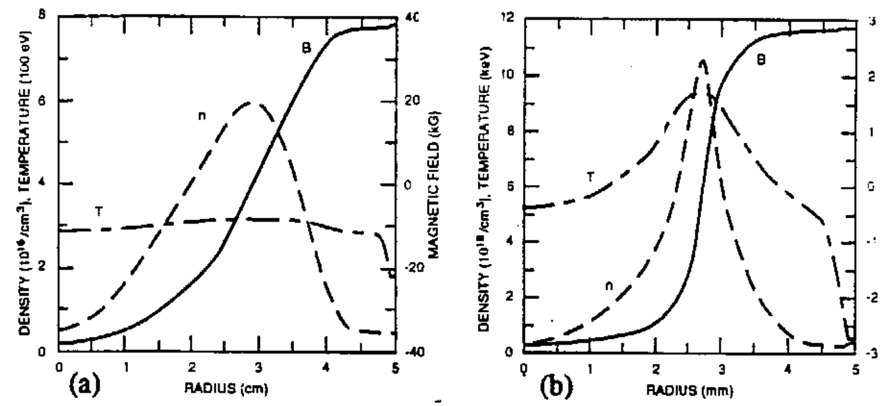
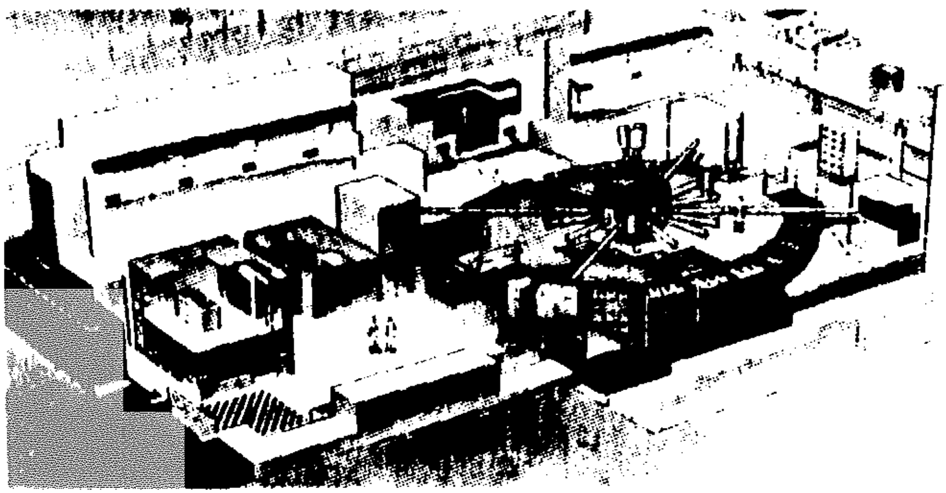


Fig. 6. FRC profiles of density (n), temperature (T), and poloidal magnetic field (B) at: (a) t=2 μs, immediately prior to implosion at 3 mm/μs; (b) t=17 μs, when liner has reached a radial convergence of 10.

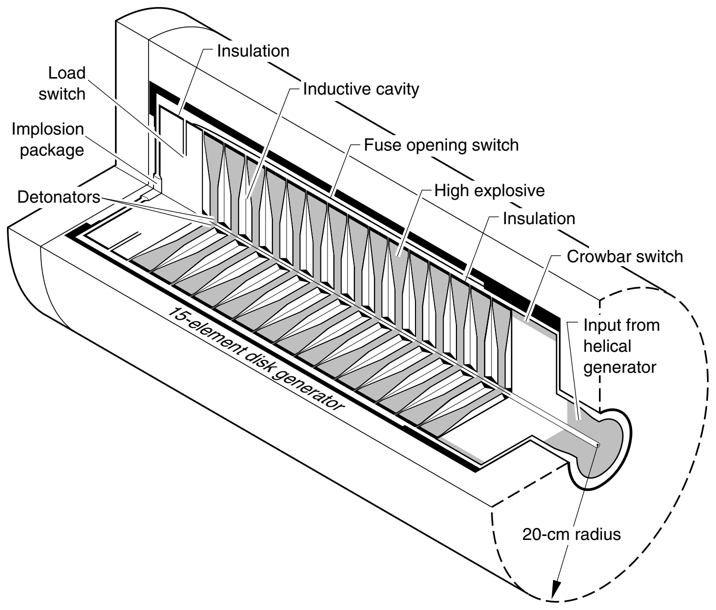
The 36 MJ ATLAS capacitor bank will be able to implode solid liners for MTF to > 1cm/μs, > 7 MJ.



r (cm)	10	6	3
len (cm)	8	5.6	2.9
δ (mm)	1	1.5	3
v (cm/μs)	1	1.6	1.8
E (MJ)	6.7	10.4	7.4
I (MA)	60	45	39

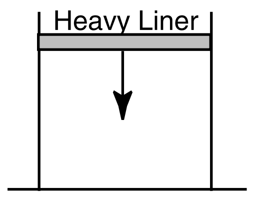
- **Higher velocities are possible for liquid and plasma liners.**
- **At 5 MJ/mg, ATLAS can drive MTF targets with 1.4 mg D-T fuel.**

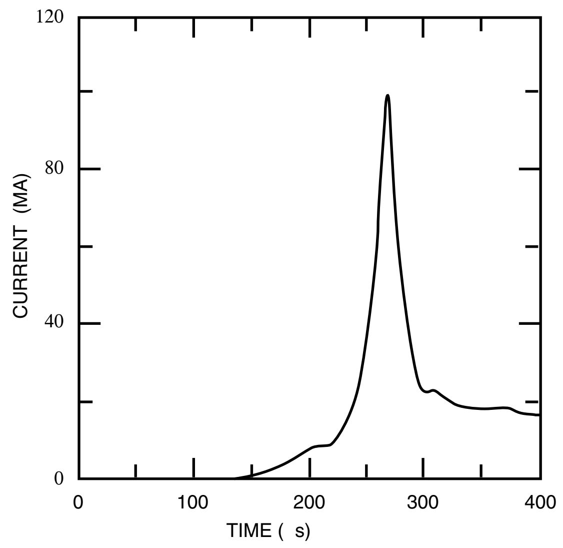
VNIIEF's extensively developed Disk Explosive Magnetic Generator (DEMG) provides an intense electrical pulse to drive the magnetically accelerated liner-on-plasma implosion.



- **3 sizes available (25, 40, 100-cm-dia.).**
- **modular (up to 25 demonstrated).**
- **100 MJ @ 256 MA demonstrated (100-cm, 3-module).**
- **> 1 GJ plausible.**

- **An August 1996 VNIIEF/LANL experiment delivered 100 MA, > 20 MJ of kinetic energy to a liner, represents a step toward an ultrahigh energy MTF driver.**





VNIIEF/LANL

IL-10/96-6

Russian Lagrangian and Eulerian 2-d hydrodynamic calculations (driven by magnetic pressure calculated with 1-d MHD) and Los Alamos Eulerian 2-d full magnetohydrodynamic calculations gave similar, outwardly bowed liner behavior at late times; detailed glide plane-liner interaction still questionable.

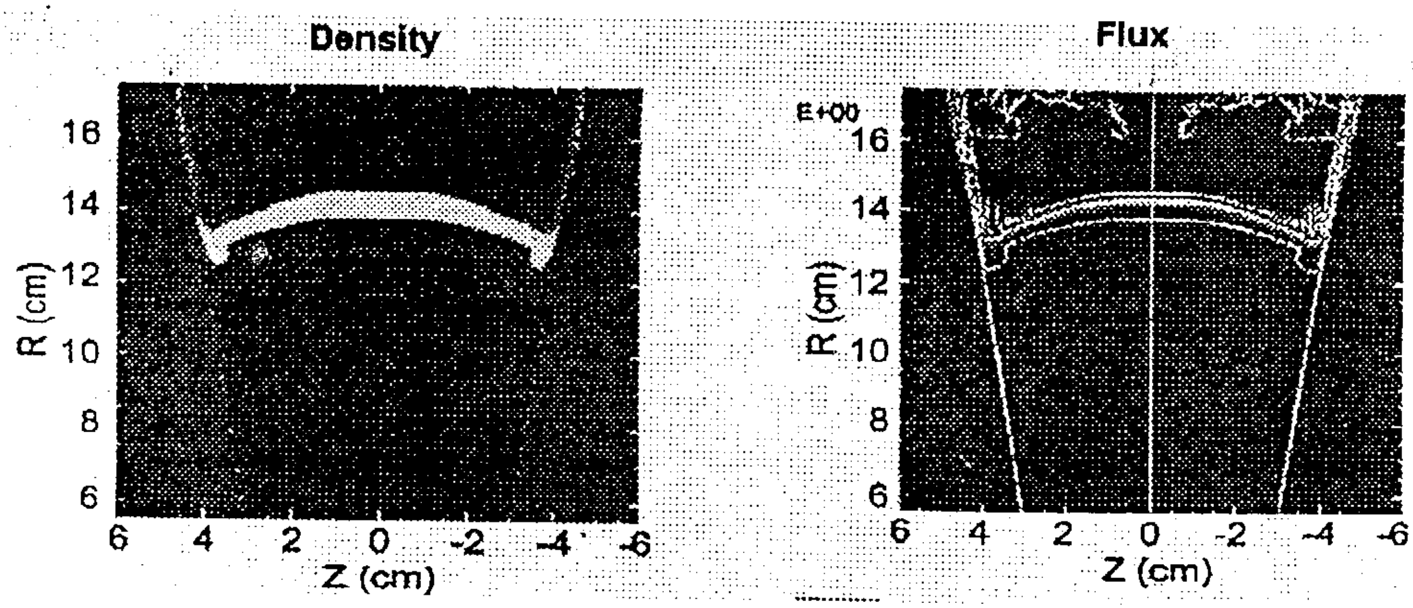


Figure 7. Two dimensional calculations showing liner bowing and glide plane run ahead

Los Alamos 2-d Eulerian magnetohydrodynamic results

Computational modeling of the liner-on-plasma compression of Z-pinch and other potential MTFtarget plasmas is being d one. Modest compression ratios appear sufficient for fusion goals.

- Existing US and Russian explosive pulsed power generators, and fixed facilities such as ATLAS, are capable of magnetically imploding metallic liners to compress such plasmas at implosion velocities O(2 cm/μsec).

- One-dimensional MHD modeling of such compressions has been begun, with realistic (cold, heat conducting) boundary conditions and radiative energy losses. A clean DT plasma of conditions believed obtainable in Z-pinch or other experiments (~300 eV) could reach keV temperatures with only modest--i.e. <10:1--compression ratios.

- More detailed one- and two-dimensional modeling of such compressions is planned, to include realistic drive of the liner, plasma-wall interactions, and so on; experimental normalization of such work is vital.

Los Alamos

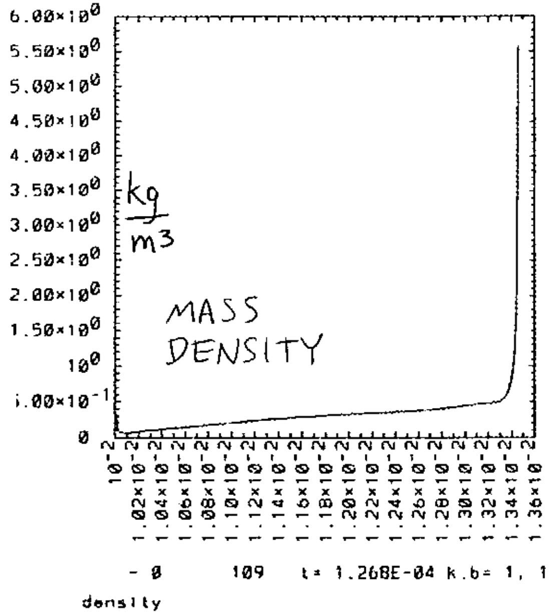
Two Los Alamos MHD codes have been employed in modeling MTF experiments. The MHRDR code has been used extensively in modeling the MAGO and fiber-initiated Z-pinch target plasma experiments (13). Because MHRDR is fully implicit and has a generalized Eulerian structure, in which zonal quantities such as velocity are computed relative to a pre-programmable grid velocity, the code can run liner-on-plasma calculations relatively quickly. However, it can only compute a single material (e.g., the target plasma DT); the outer radial boundary of the computational mesh is programmed to implode at the expected liner velocity. Boundary conditions are idealized: perfectly electrically conducting and zero-temperature, infinitely heat-conducting walls (hence the heat conductivity of the magnetized plasma is the only impediment to heat flow out the boundary). In these cases MHRDR uses cylindrical r-z geometry with a single B_θ magnetic field component. The plasma radiative energy losses and electrical resistivity are taken from Los Alamos "Sesame" data tables. Heat conduction is full (arbitrary $\omega_\alpha \tau_\alpha$) Braginskii, unless we override this for comparison to other models.

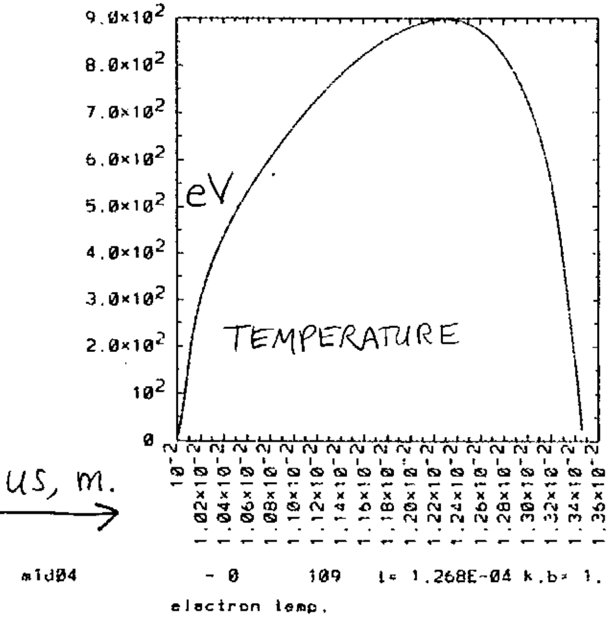
A second Los Alamos Eulerian MHD code [14] was used to model the HEL-1 and Shiva-Star liner experiments. This code can compute multiple materials, such as an aluminum liner imploding onto a DT plasma. However, it runs much slower than MHRDR because it is not fully implicit and must use a fixed grid; to date it has only been possible to do one-dimensional liner-on-plasma calculations (two-dimensional runs are planned). At present, Braginskii heat conduction is only included for the electron fluid (ion fluid has the non-magnetized conductivity value); however, it has been possible to estimate the Braginskii effect on the ions and include a constant factor times the non-magnetized value (1/15) to approximate the full Braginskii magnetoinsulation effect. Braginskii ion heat conduction is being added to this code. The diffusion of magnetic field, heat, and radiation between liner and plasma is computed, but the boundary between liner and plasma remains sharp (i.e., no intermixing takes place).

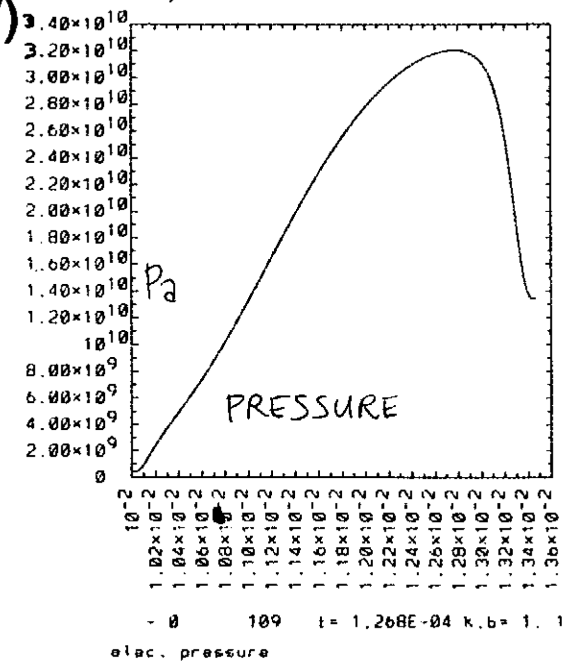
A one-dimensional liner-on-plasma problem based on demonstrated target plasma and liner drive quantities was run with both codes. The target plasma resembled a late-time (smaller chamber) MAGO plasma: 100 eV, 10^{-5} g/cm^3, with 3.0 MA on the 1.0 cm-radius copper inner conductor, with the outer aluminum liner starting at 5.4 cm inner radius (0.6 cm thick). The current driving this liner was based on a portion of the measured HEL-1 current, which would implode this liner from 5.4 cm to 1.36 cm in 7.5 μsec, with a final implosion velocity of 1.6 cm/μsec (computed liner inner radius vs. time values were used in the MHRDR calculation). Such a liner implosion is not an optimized choice for an experiment intended to achieve fusion conditions, but it represents something clearly achievable, and which could serve as a useful step in demonstrating compression heating of an MTF plasma.

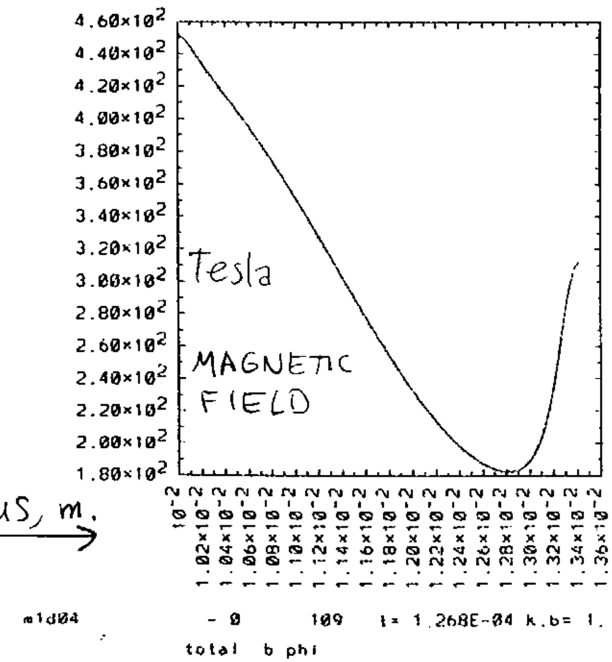
MHRDR 1-D MHD Liner-on-Plasma Results

Final Radial Profiles →

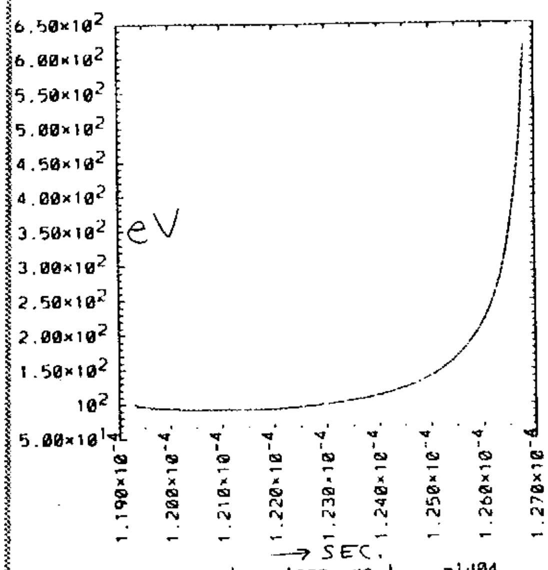








Mass-Weighted Average Temperature vs. Time (T_{Final}=1.03 keV) (adiabatic)



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Los Alamos MHD code #2 liner-on-plasma results (1-d): radial profiles of temperature and current. Note diffusion of heat and magnetic field into walls.

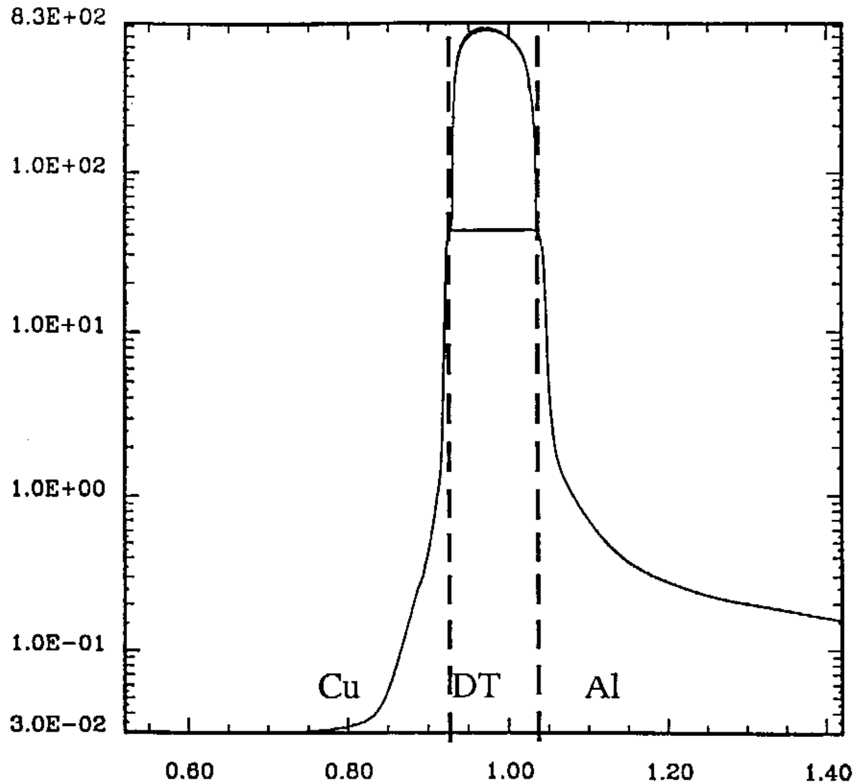


Figure 2. Temperature (eV) vs. radius (cm.), 1-d calculation.

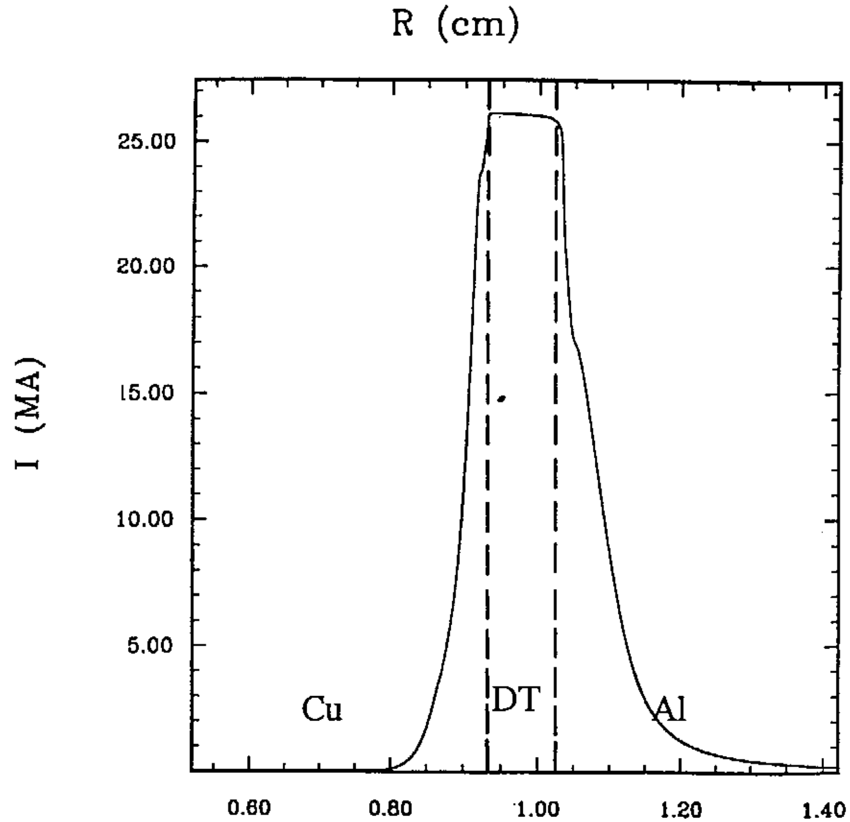
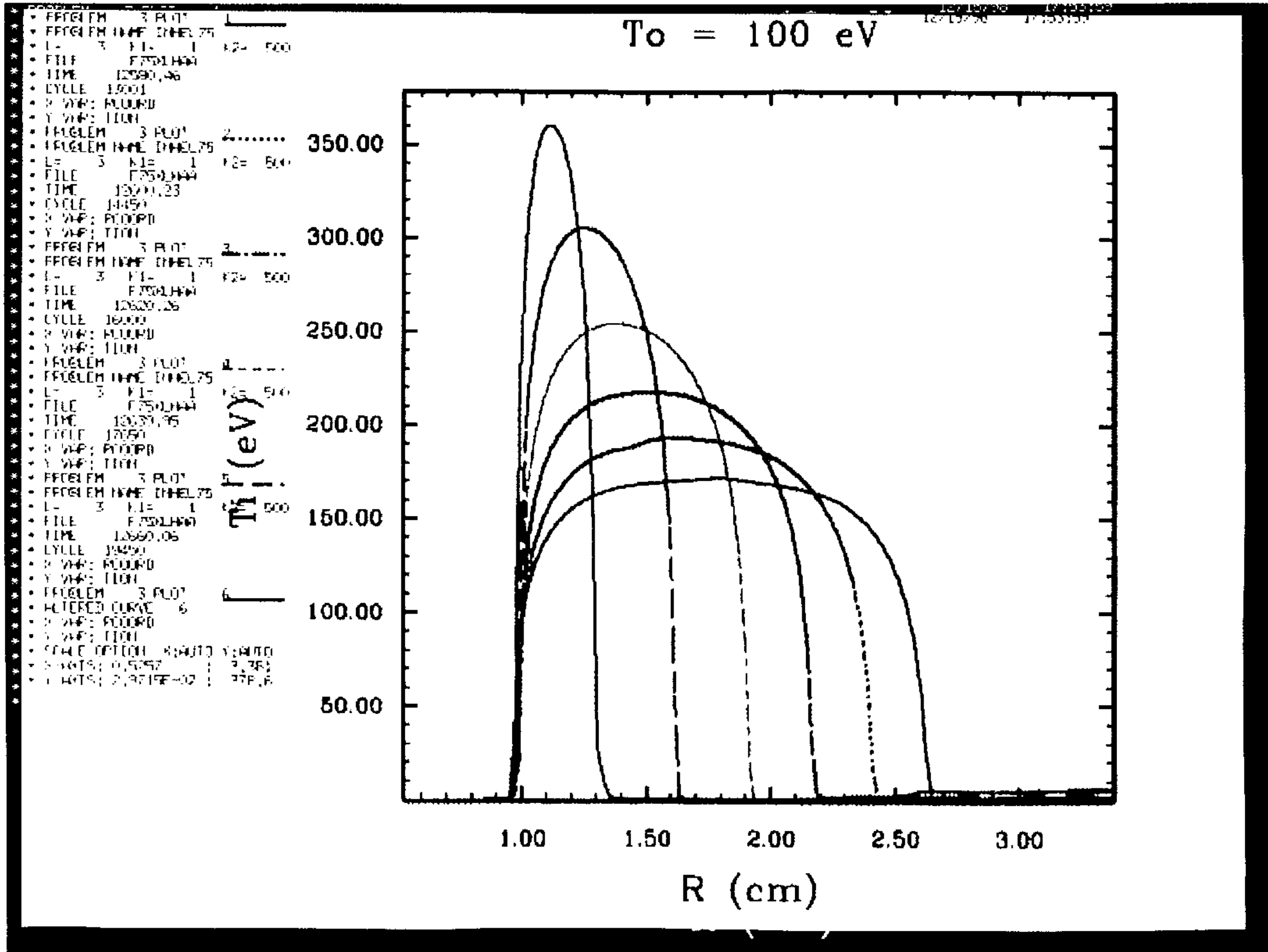
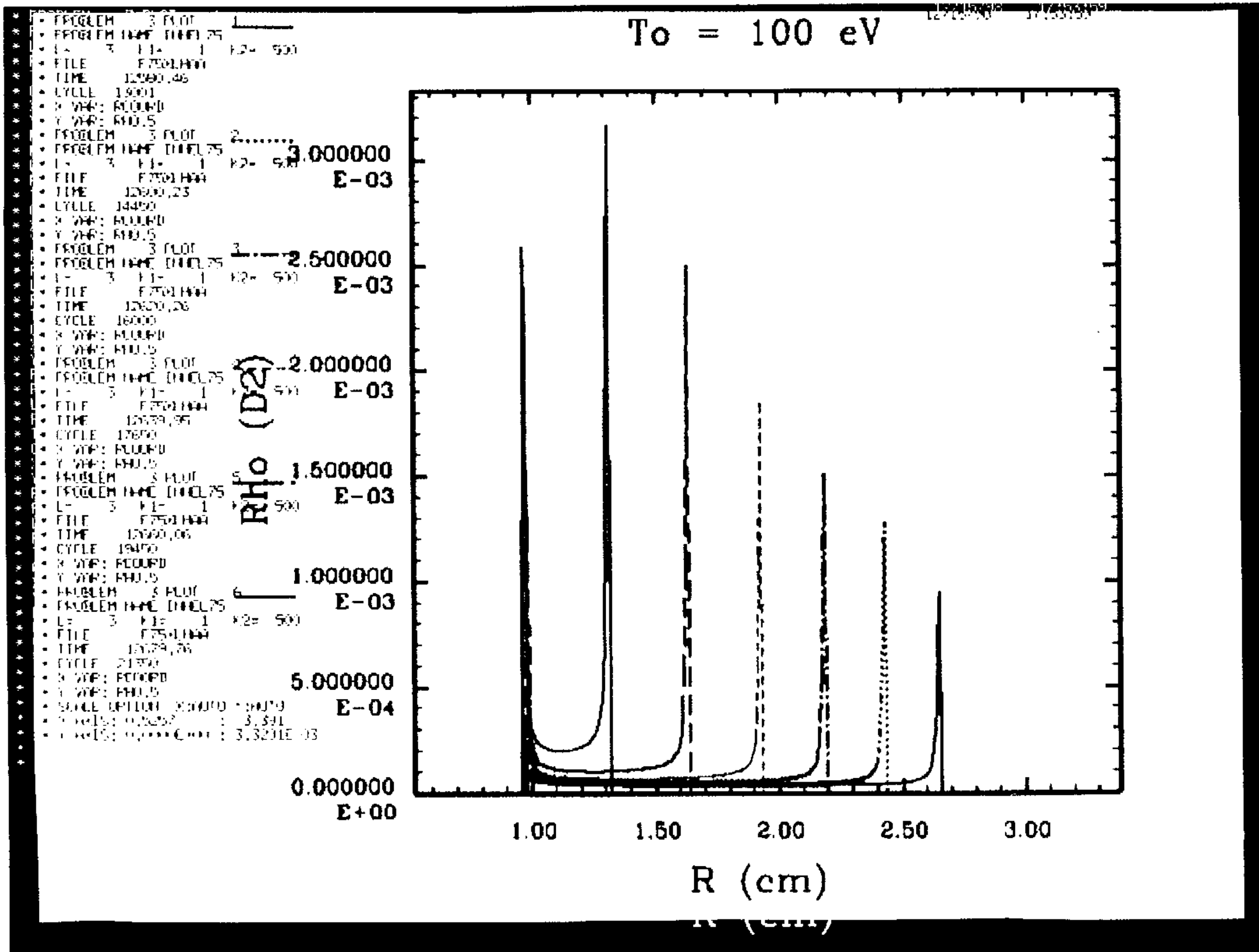


Figure 3. Current (MA) vs. radius (cm.), second code 1-d calculation.

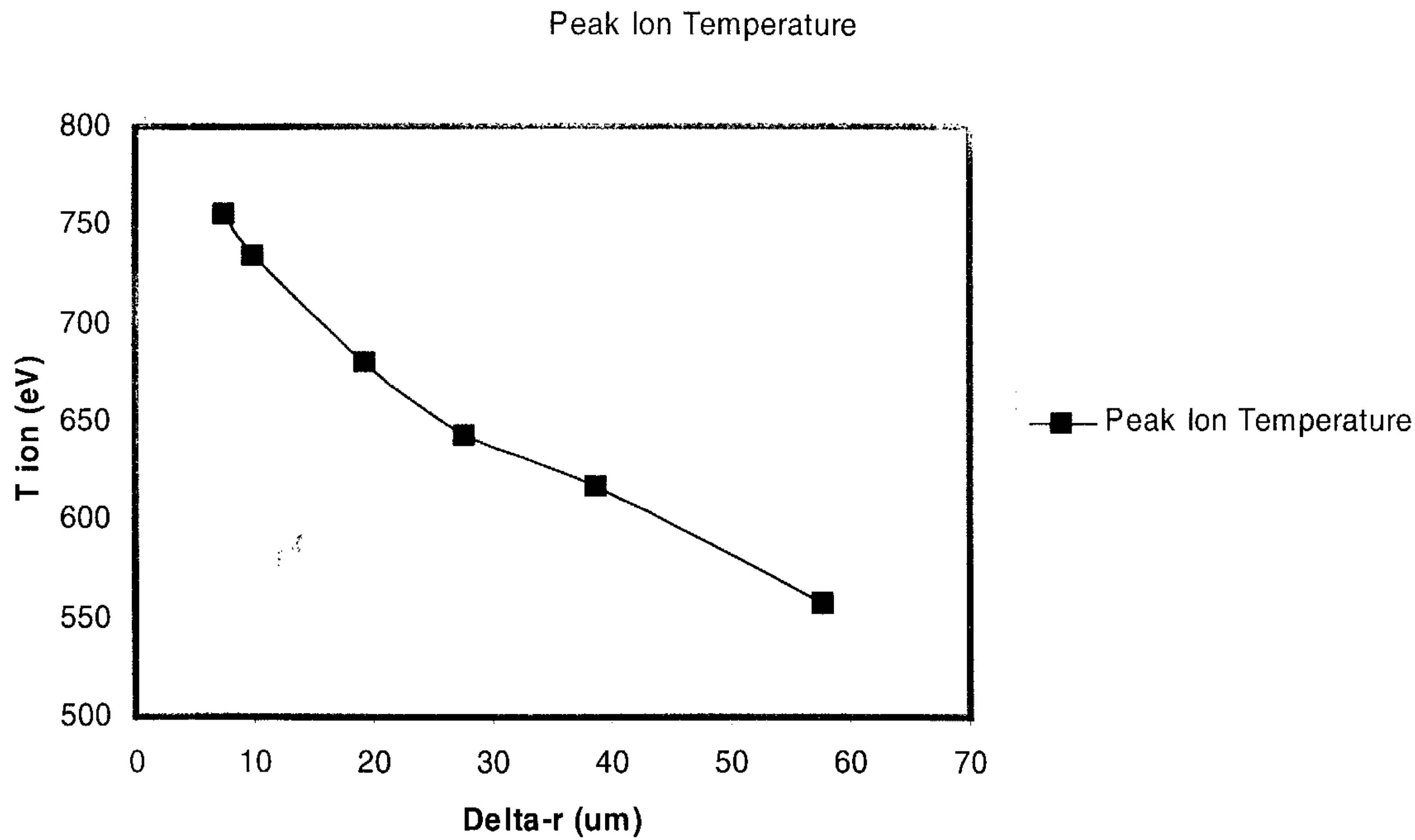
Temperature Distributions Corresponding to the Liner Positions.



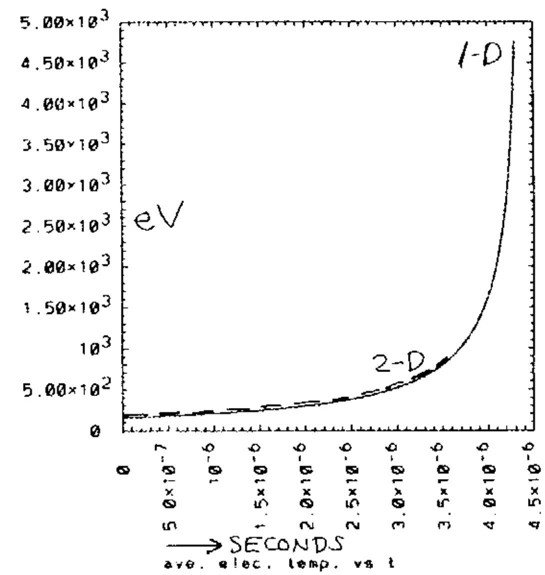
D$_2$ Density Distribution Is Sharply Peaked Near the Walls.



Calculating Correct Conditions at the End of the Implosion Can Be Sensitive to Zone Resolution.



MHRDR has also been used to compute one- and two-dimensional compressions of computed late-time MAGO target plasmas at 2 cm/μsec. The starting conditions for these calculations were computed second-chamber plasmas at 12 μsec in the LANL-VNIIEF MAGO-2 target plasma experiment; the MAGO-2 target plasma calculations showed good agreement to the earlier time experimental measurements available [7-11]. The computed late-time MAGO plasma profiles are diffuse, wall-supported Z-pinch equilibria which show Kadomtsev stability to m=0 perturbations. In liner-on-plasma calculations, the 10-cm outer wall was imploded at 2 cm/μsec to a final radius of 1.4 cm (inner wall was 1.2 cm). One-dimensional calculations reached a peak mass-weighted average temperature of 4.75 keV, with a peak profile temperature of 7 keV. Two-dimensional calculations have been run as far as 3.5 μsec to date, with the <T> the same as in the one-dimensional result (800 eV). An interesting feature can be seen in the two-dimensional calculation: formation of convective cooling cells close to the imploding outer boundary (Figure 4). The MHRDR code has previously been used in studies of such cells [15-17]. Since the bulk temperature reached has not changed compared to the one-dimensional case, this appears (to the time calculated to date) to be a localized effect countered by stronger heating and insulating processes.



MASS-WEIGHTED <TEMPERATURE> VS. TIME, 1-D AND 2-D RUNS

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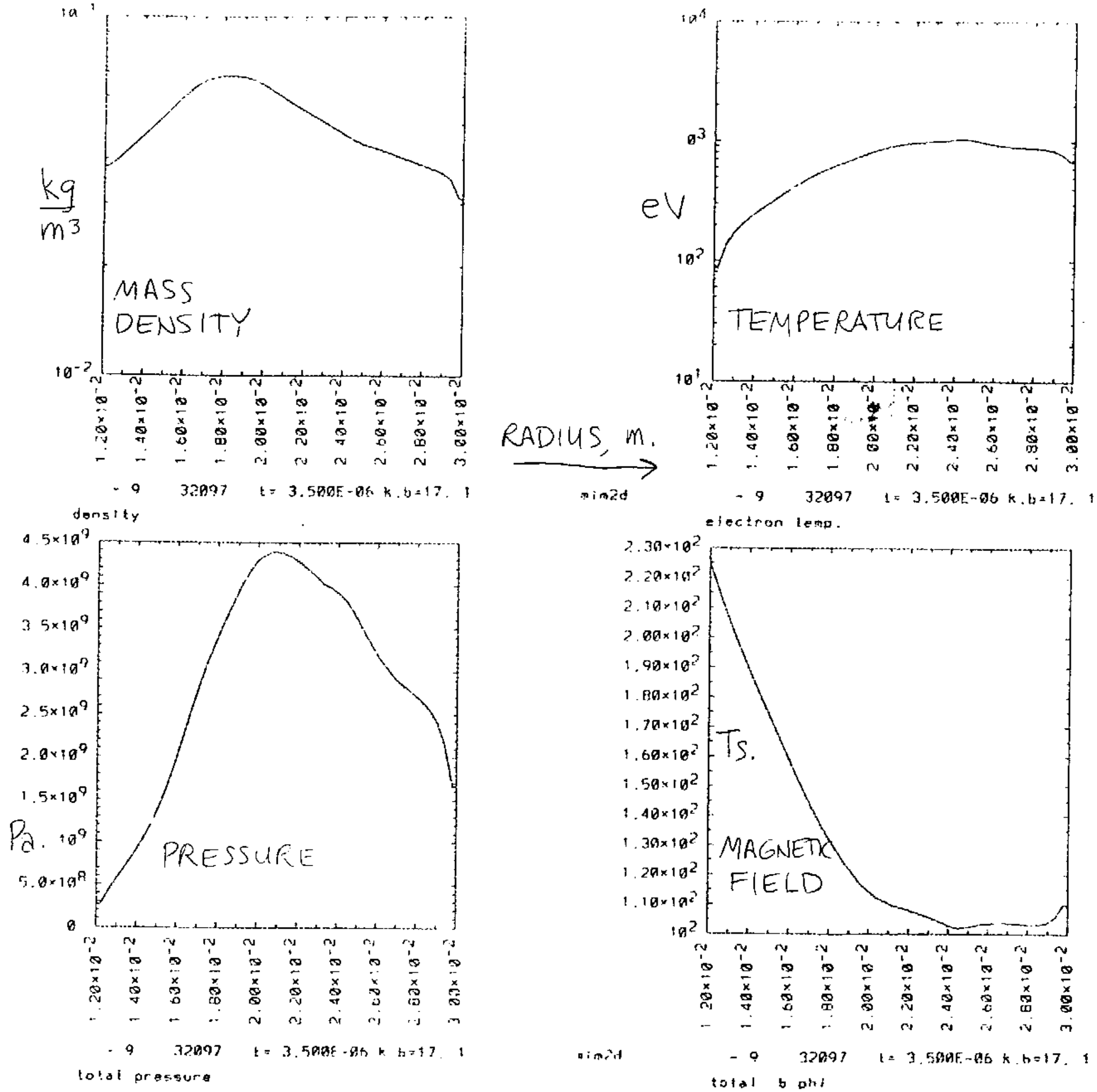
MHRDR 2-D MHD Liner-on-Plasma Results: Mid-Axial Radial Profiles, 3.5 μsec



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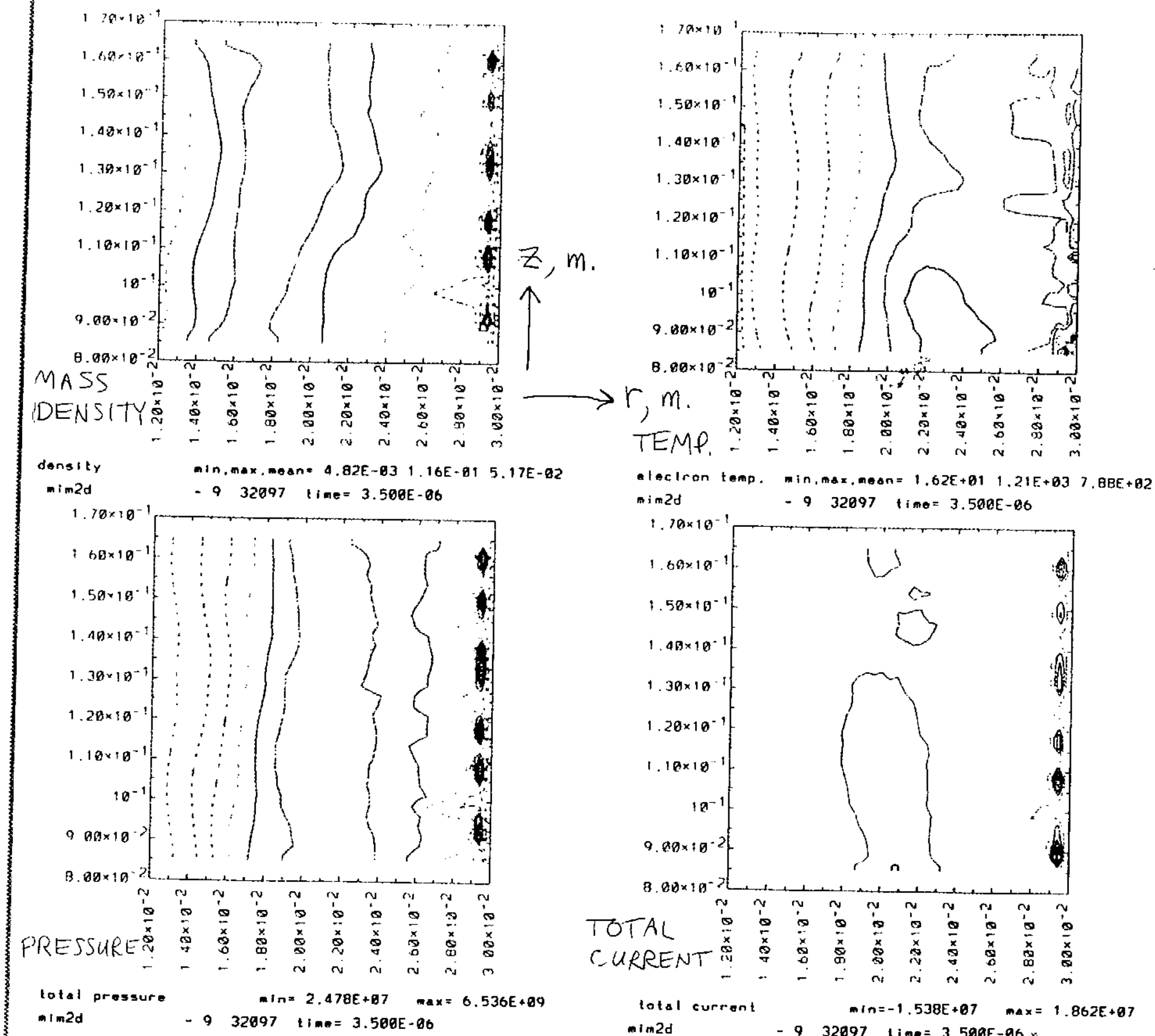
MHRDR 2-D MHD Liner-on-Plasma Results: Contour Plots, 3.5 μsec



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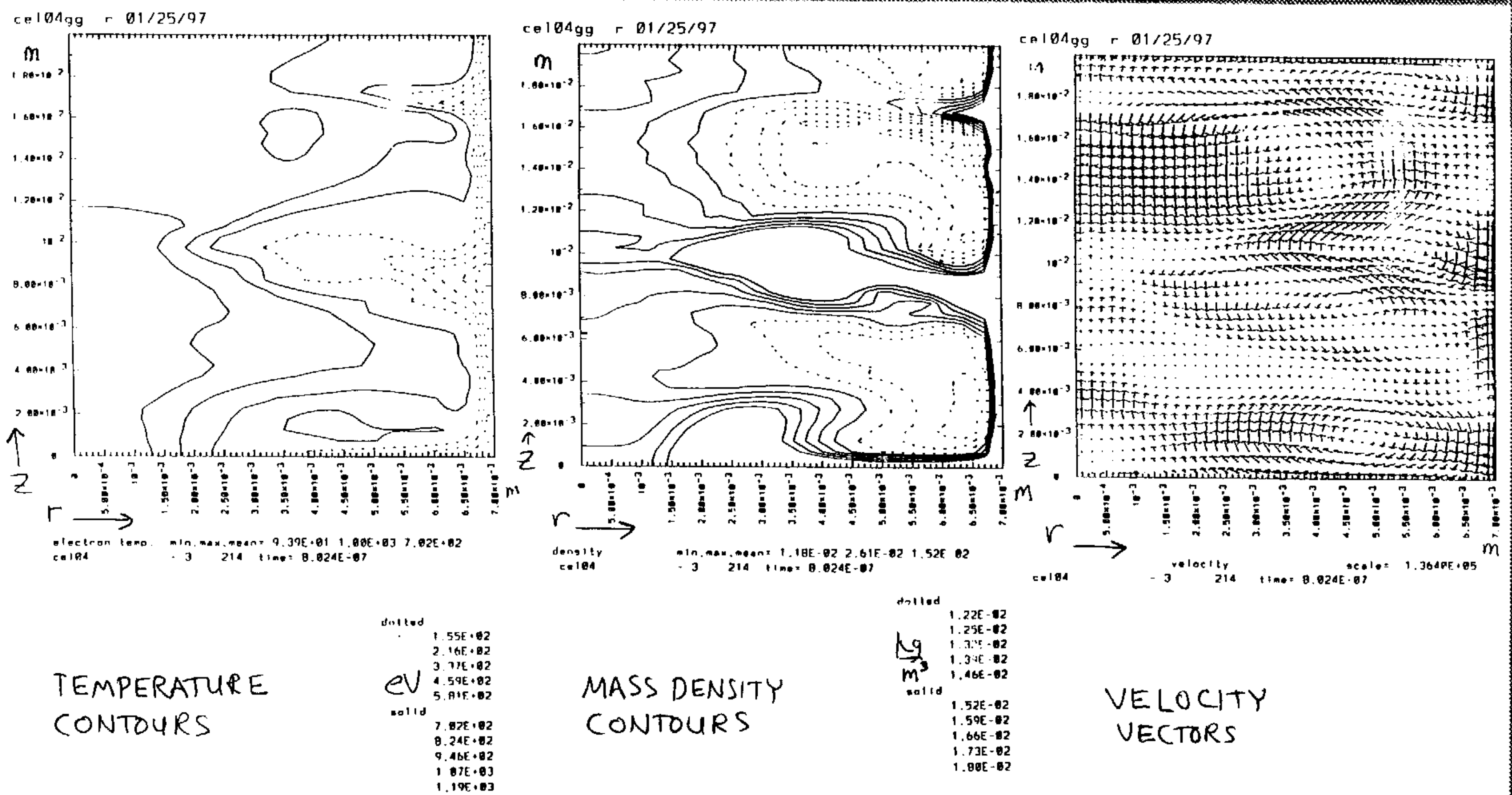
Dense magnetized plasmas in contact with a cold wall (fixed or imploding) may form Benard-like convective cooling cells. Computational and theoretical investigation of this is continuing.



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MTF Power Reactors

- Present focus of research is "proof-of-principle," which should be possible, up to and including ignition, without a large capital investment.

- Two reactor approaches come to mind:
  1) ICF-like beam-driven "ƒ-targets," in ICF-like pulsed reactor system.
  2) Maximized energy output per shot, with lower repetition rate.

- If relatively inexpensive electrical pulsed power could be used as the implosion driver, smaller, more economically viable reactors than for conventional fusion appoaches might be possible.

- Because MTF is qualitatively different from inertial or magnetic confinement fusion--different time, length, and density scales--MTF reactors will have different characteristics and trade-offs, increasing the chances that a practical fusion power scheme can be found.

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Conclusions:

- Magnetized Target Fusion (MTF) is an approach to controlled fusion which may avoid the difficulties of the traditional magnetic and inertial confinement approaches.

- It appears possible to investigate the critical issues for MTF at low cost by utilizing existing pulsed power facilities and explosive pulsed power.

- Whether or not wall material will mix with and cool DT plasma before it can be compressively heated to fusion conditions depends upon rates of competing processes of implosion, heating, mixing, and cooling.

- Los Alamos MHD codes contain substantial portions of the physics governing such competing processes, including 2-d effects. Guided by experimental data as it becomes available, these codes can be used to optimize the design of MTF liner-on-plasma demonstration experiments.

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