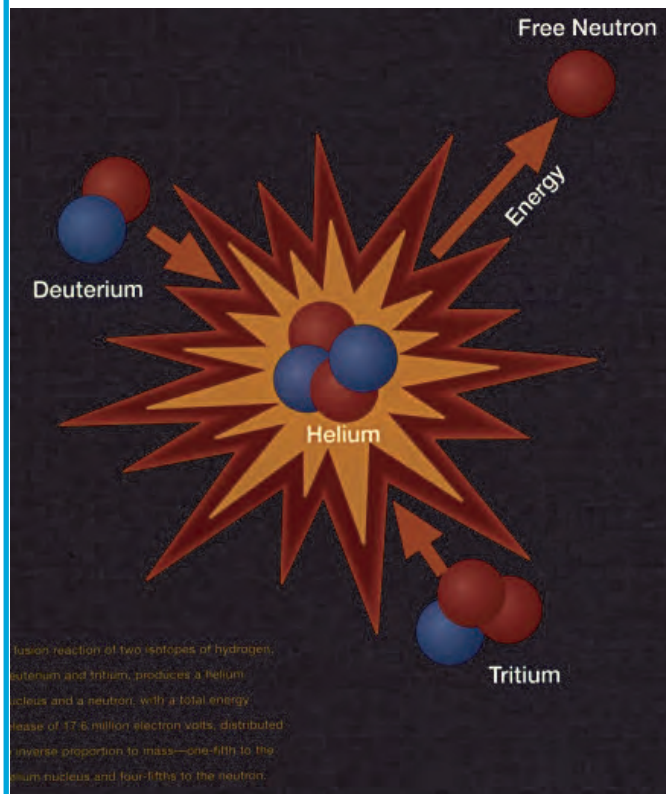


The Case for Magnetized Target Fusion (MTF) a.k.a Magneto-Inertial Fusion (MIF)



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Presented to
Nat'l Academy of Sciences
Committee on the Prospects for
Inertial Confinement Fusion Energy Systems
Albuquerque NM, March 31, 2011

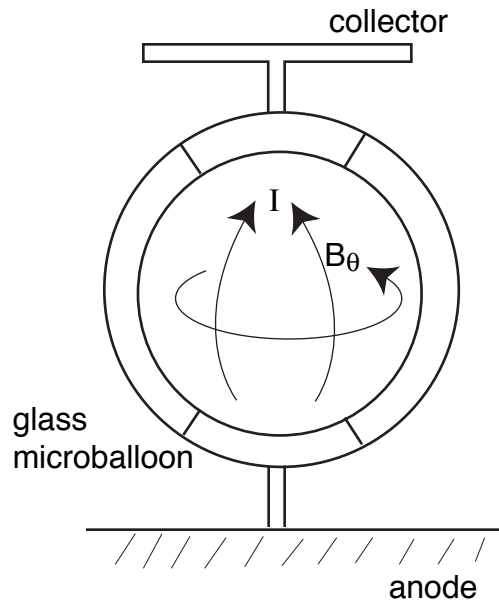
Acknowledgement: much of this presentation is due to the
original insight of Prof. Richard E. Siemon, UNR

MTF is a potential IFE game-changer

MTF is IFE--the primary heating mechanism is compressional heating by an imploding pusher/liner.

- **With significantly reduced power requirements, MTF potentially**
 - (a) opens up the very heavily constrained density space of conventional unmagnetized targets by orders of magnitude;**
 - (b) makes fusion “easier” for any driver;**
 - (c) makes existing (e.g., fast and slow pulsed power machines) and prematurely abandoned (e.g., e-beam, light ion) drivers feasible;**
 - (d) allows experimentation at much higher energy (e.g., 20 MJ implosion kinetic energy demonstrated with liners).**
- **MTF’s two-step process--magnetized plasma formation followed by target implosion--provides new parameters (“knobs”) to facilitate optimization, e.g., a sufficiently high initial plasma temperature can reduce the required radial convergence to < 10 .**
- **Low-cost MTF drivers can lead to a new fusion research paradigm: NIF-equivalent yields at multiple facilities using multiple approaches rather than at one multi-billion \$ national user facility**

The first neutrons ever produced by the US particle beam fusion program came from a magnetized target driven by an electron beam (REHYD, 1 MeV, 250 kA, 100 ns, 0.04 TW); see Phys. Today 8/77



The Sandia "Φ" Target

- **A non-relativistic precursor (5-15 kA, 1 μ s) was stopped by the collector, creating a voltage which induced an electrical discharge in the fuel.**
- **The 3-mm-diameter targets imploded at 4 cm/ μ s.**
- **10^6 - 10^7 neutrons were observed in CD₂ wire and D-T gas filled (6×10^{18} /cm²) targets.**
- **No neutrons were observed without the precursor or in a variety of "null" targets.**
- **Two-dimensional MHD computations indicated a 5-20 eV preheat, 300-500 eV final temperature, consistent with the observed neutron yield (Lindemuth and Widner, Phys. Flu. 24, 1981, p. 746).**
- **Sandia computations predicted high gain for ion and electron magnetized targets at low intensity (Sweeney and Farnsworth, Nuc. Fus., 1981, p. 41).**

“Ballpark” conditions for energy gain (Lindemuth and Siemon, American Journal of Physics Vol. 77, pp. 407-416, May 2009)

- $\dot{Q}_{loss} = \phi \dot{Q}_{FUS}$; find n_i, T, B so that $\phi < 1$; $\dot{Q}_{loss} = \dot{Q}_{TC} + \dot{Q}_{RAD}$
 $\dot{Q}_{RAD} = C_{RAD} n_i^2 T^{1/2}$ (Bremsstrahlung) $\dot{Q}_{TC} = -\nabla \cdot (K \nabla T)$ (K = thermal conductivity)

- Approximations to $\dot{Q}_{TC}, \nabla T$ make it possible to get simple expressions for physical quantities of interest:

$$\dot{Q}_{TC} \approx -\frac{1}{V} \int \nabla \cdot (K \nabla T) dV = -\frac{1}{V} \oint_S K \nabla T \cdot d\vec{S} \approx -\frac{S}{V} K \nabla T \approx \frac{KT}{\gamma \alpha a^2}$$

$$a = \text{characteristic dimension, } V = \epsilon a^3, \quad \frac{V}{S} = \gamma a, \quad \nabla T \approx -\frac{T}{\alpha a}$$

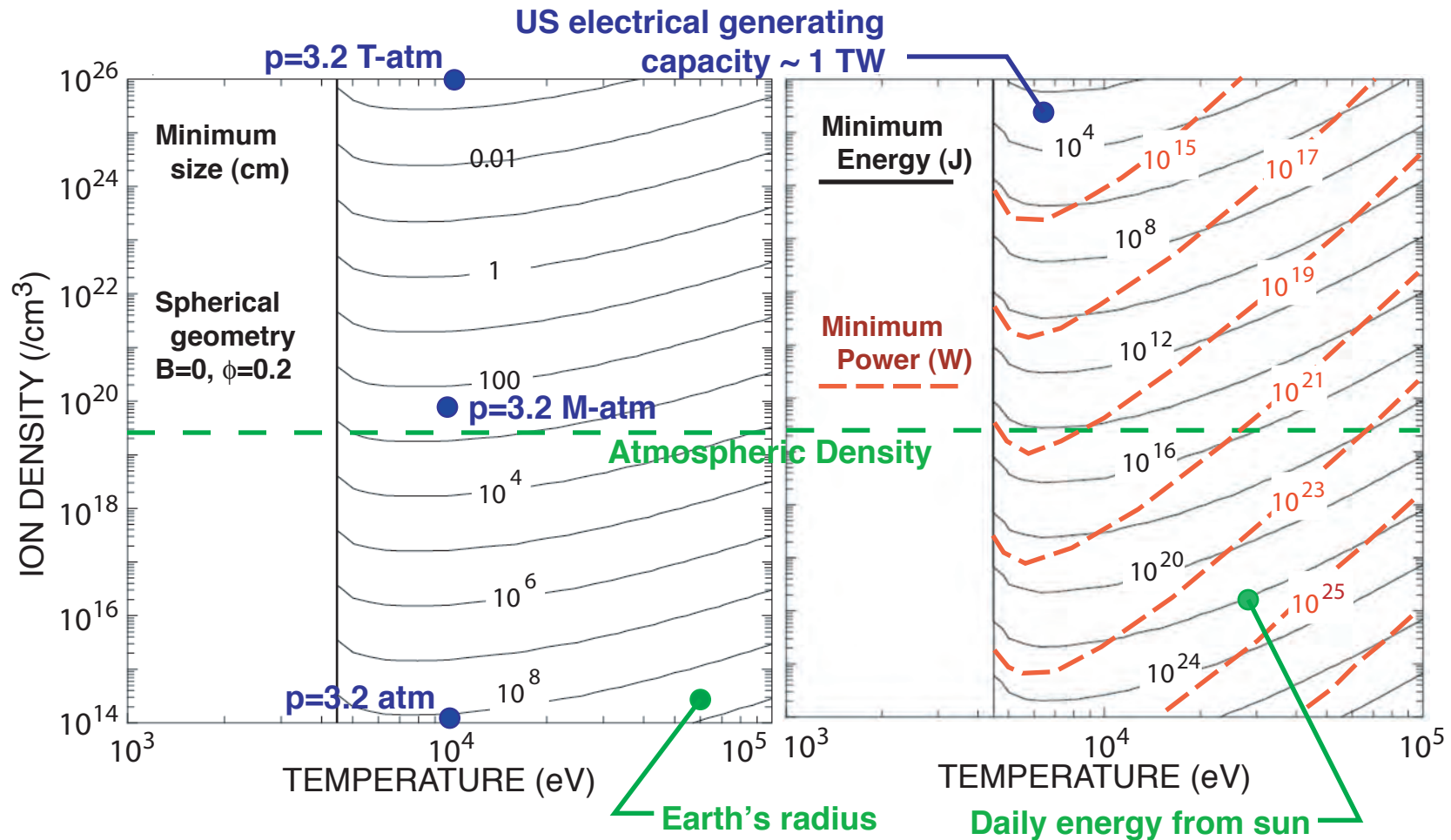
- ϵ, γ are geometric quantities, e.g., for spheres $\epsilon=4\pi/3, \gamma=1/3$.
- Loss rates depend upon n_i, T, a , model for $K=K_i+K_e$, geometry (ϵ, γ), profile details (α). In the simplest, “classical,” form, the thermal conductivity for an unmagnetized plasma depends only on temperature: $K_o=C_o T^{5/2}$; with magnetization, the conductivity is reduced by a factor of $1+(\omega\tau)^2$.

The conduction rate approximation can be used to determine the minimum size, other relevant parameters for a desired loss ratio ϕ .

- **Minimum size:** $a_{\min}^2 = \frac{KT}{\gamma\alpha\phi\dot{Q}_{FUS'S} - \dot{Q}_{RAD}}$, $a_{\min} = a_{\min}(n_i, T, B)$
- **Minimum fuel mass:** $M = n_i(m_i + m_e)\epsilon a_{\min}^3$
- **Minimum fuel thermal energy:** $E_{PLAS} = 3n_i T \epsilon a_{\min}^3$
- **Required heating power:** $P_{HEAT} = (\dot{Q}_{TC} + \dot{Q}_{RAD})\epsilon a_{\min}^3$
- **Required surface heating (intensity):** $I_{HEAT} = \frac{P_{HEAT}}{S}$
- **Minimum implosion velocity:** $v_{IMP} = \frac{I_{HEAT}}{p} = \frac{I_{HEAT}}{2n_i T}$

Unmagnetized fuel must operate at very small size, very high density & pressure

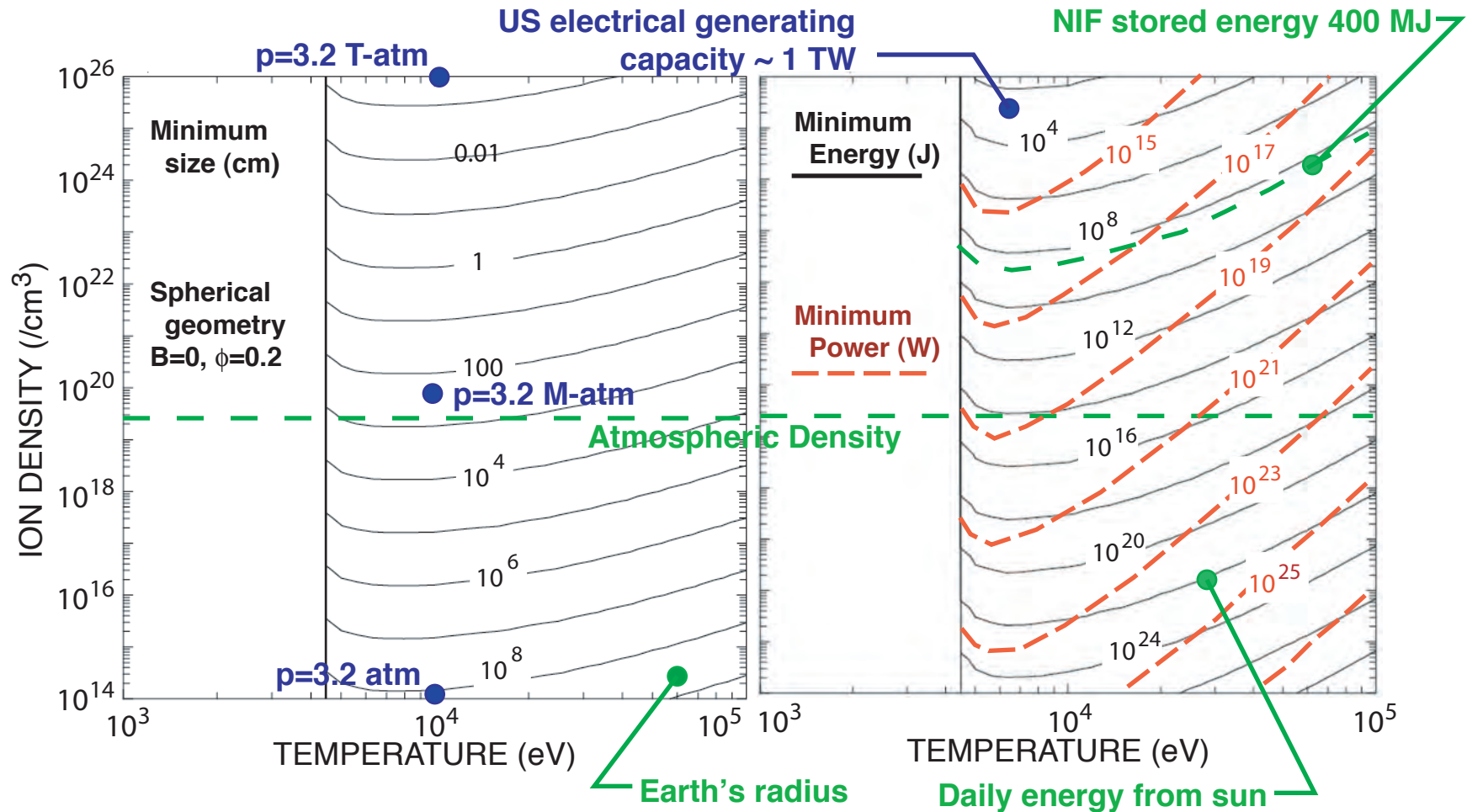
$$p_{atm} = 3.2 \times 10^{-15} n_i T_{keV}$$



- “Steady state” operation requires pressure $< 1000 \text{ atm.}$, is not possible, so unmagnetized fuel must be “pulsed,” i.e., a small nuclear explosion.

Unmagnetized fuel must operate at very small size, very high density & pressure

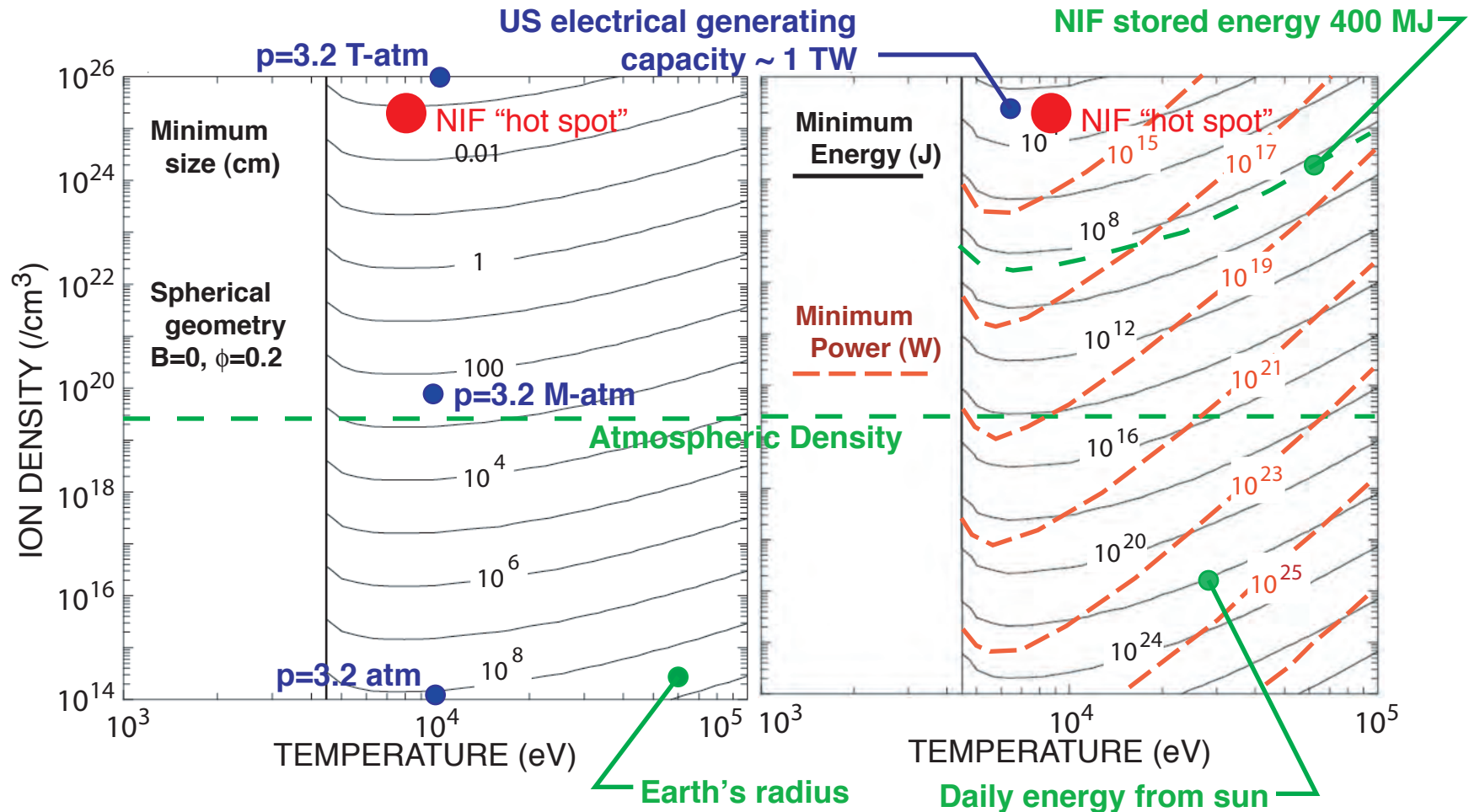
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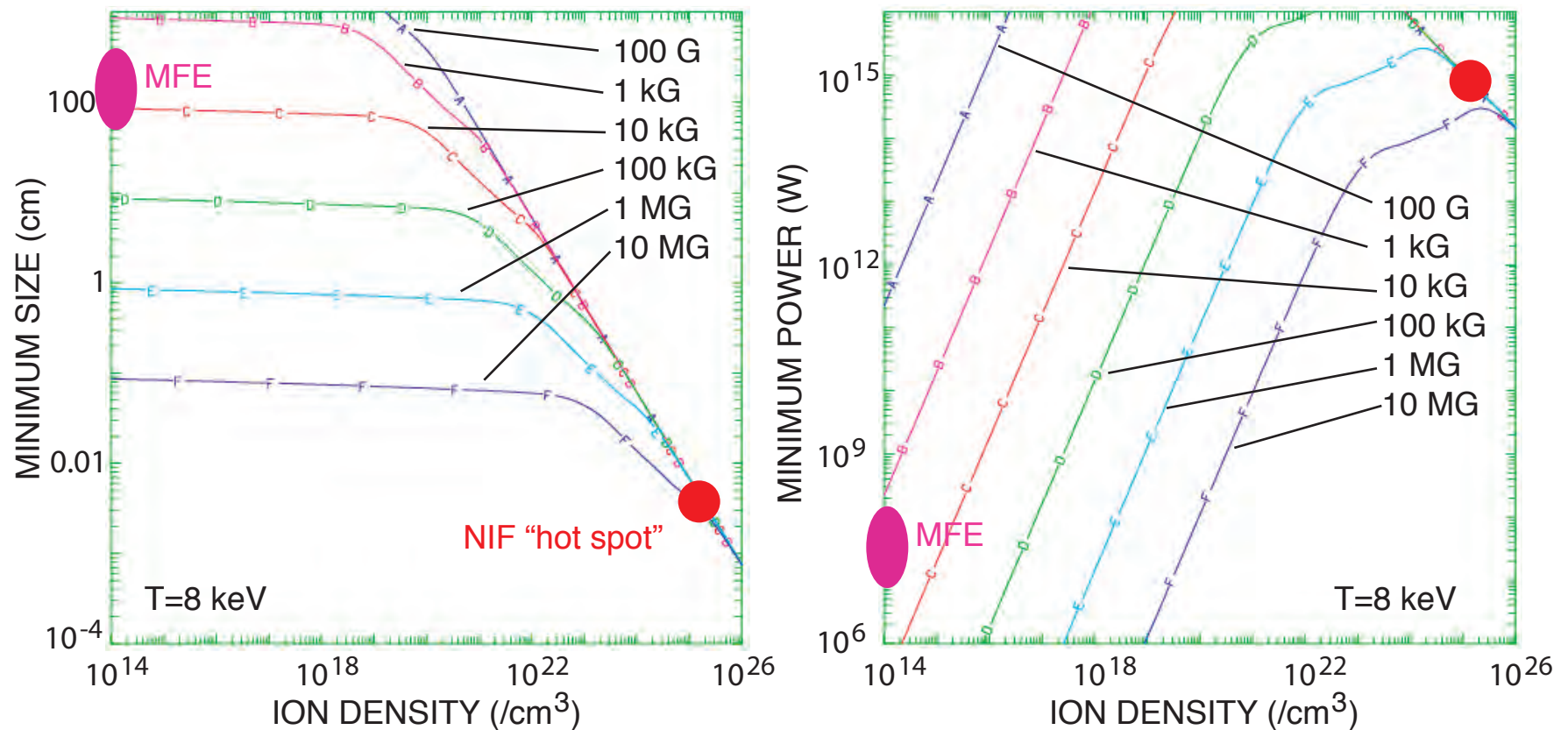
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Electron thermal conductivity establishes the density lower limit; the dominant role of thermal conductivity was recognized early.

- Reference: Enrico Fermi, "Super Lecture No. 5--Thermal Conduction as Affected by a Magnetic Field," Los Alamos Report 344, Sept. 17, 1945.

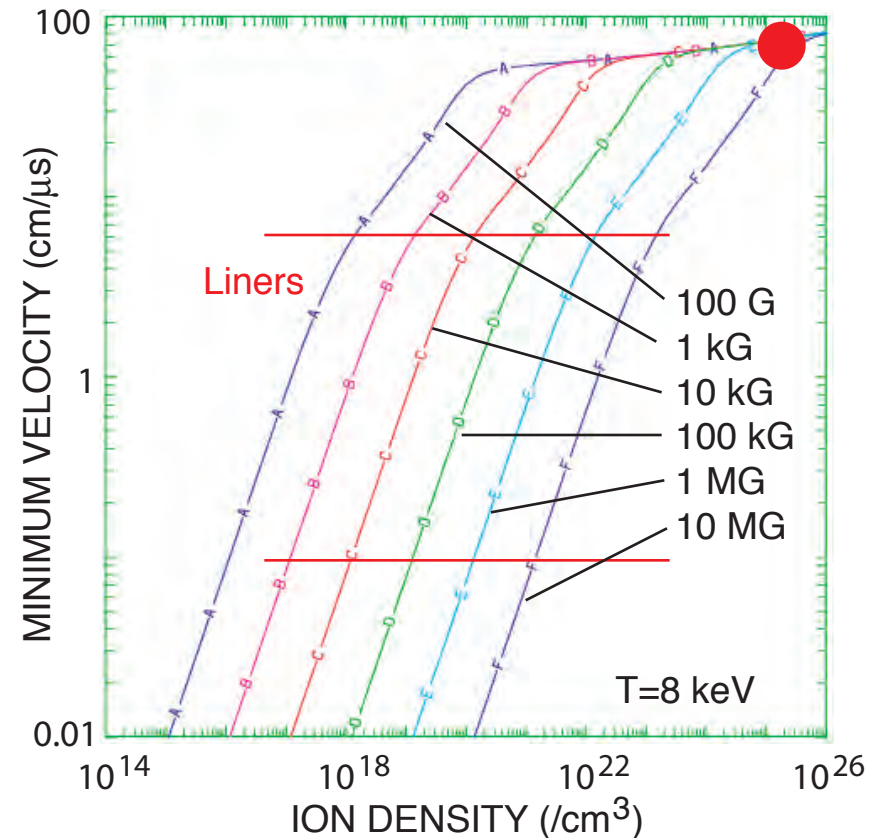
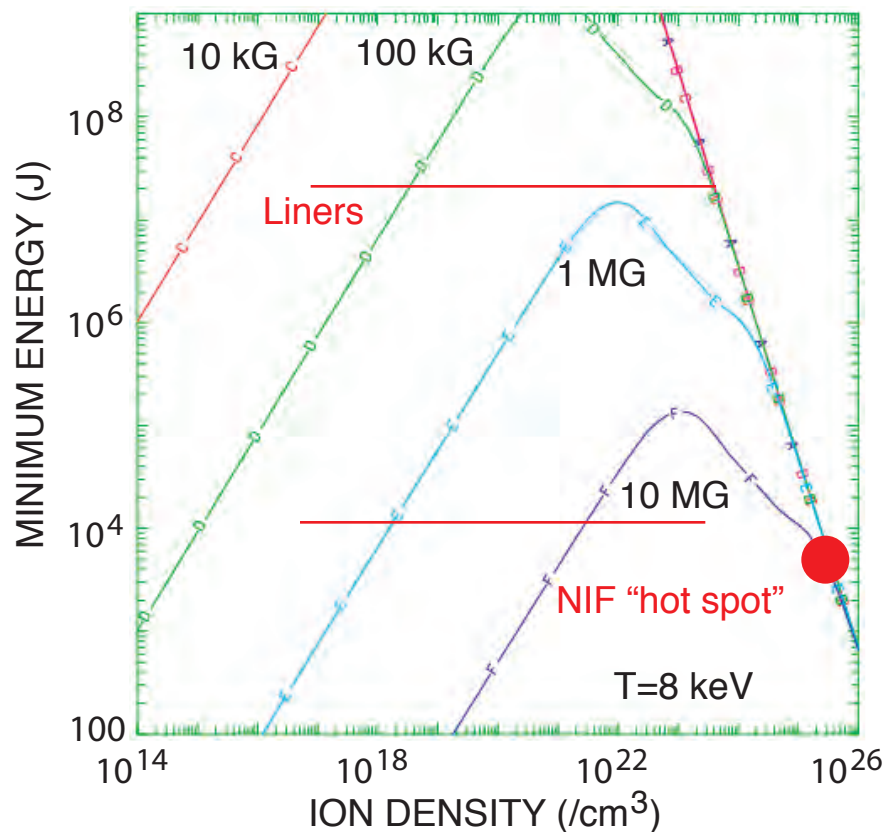
"A possible method of cutting down the conduction to the walls would be the application of a strong magnetic field, H . This tends to make the electrons go in circles between collisions, so impedes their mobility. Actually, it makes them go in spirals, and does not reduce the conductivity parallel to H but only to the other two dimensions, so one would probably want to design the container elongated in the direction of H , or even toroidal...with the lines of force never leaving the deuterium...rather large fields will be required...thus a field in excess of 20,000 gauss would help reduce conduction loss. While it would not be possible to produce such fields in a large volume in a steady state, the technical problem of making the field is much aided by the fact that the time during which the field is needed is much shorter than the usual relaxation time of magnetic fields, so it need be applied only instantaneously."

A magnetic field can significantly reduce the size of the burning plasma and the heating power required.



- Reduced size, power make “steady-state” fusion (MFE; $n \sim 1\text{e}14$) feasible; the low power heating requirements can be met with RF and neutral beams.

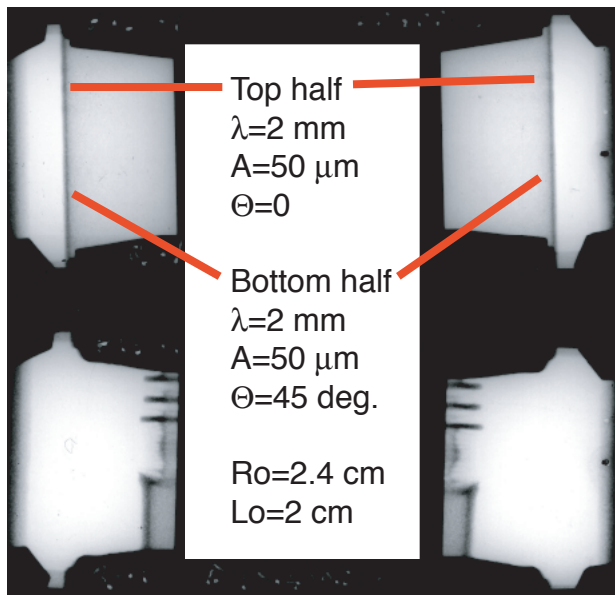
Most importantly, the magnetic field reduces the required energy and implosion velocity to the range demonstrated by modern high-current pulsed power machines (Atlas, Shiva-Star, Z, DEMG)



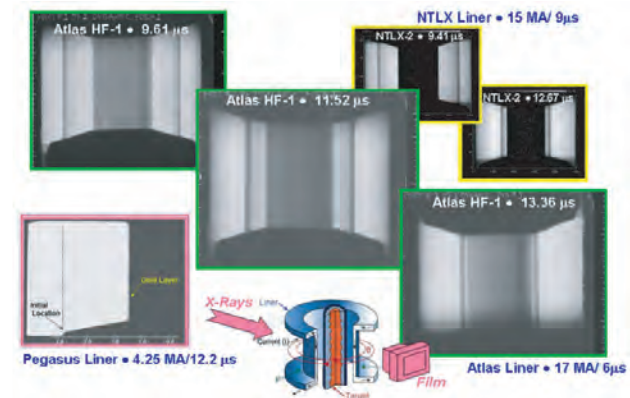
- For conventional targets, "the optimal velocity...is the primary determinant of the minimum size driver for ignition..."(J. D. Lindl, UCRL-119015, 11/95), i.e., reduced velocity means reduced costs.

Magnetically driven liner technology is relatively mature, offers highest efficiency coupling from “wall” to target plasma; the magnetically driven Rayleigh-Taylor instability is a concern.

- LANL has demonstrated high-precision implosions on a variety of facilities; two-dimensional MHD computations agree well with observations and offer insight into design considerations for stability (Reinovsky et al., IEEE Trans. Plas. Sci. 36, p. 112, 2008).



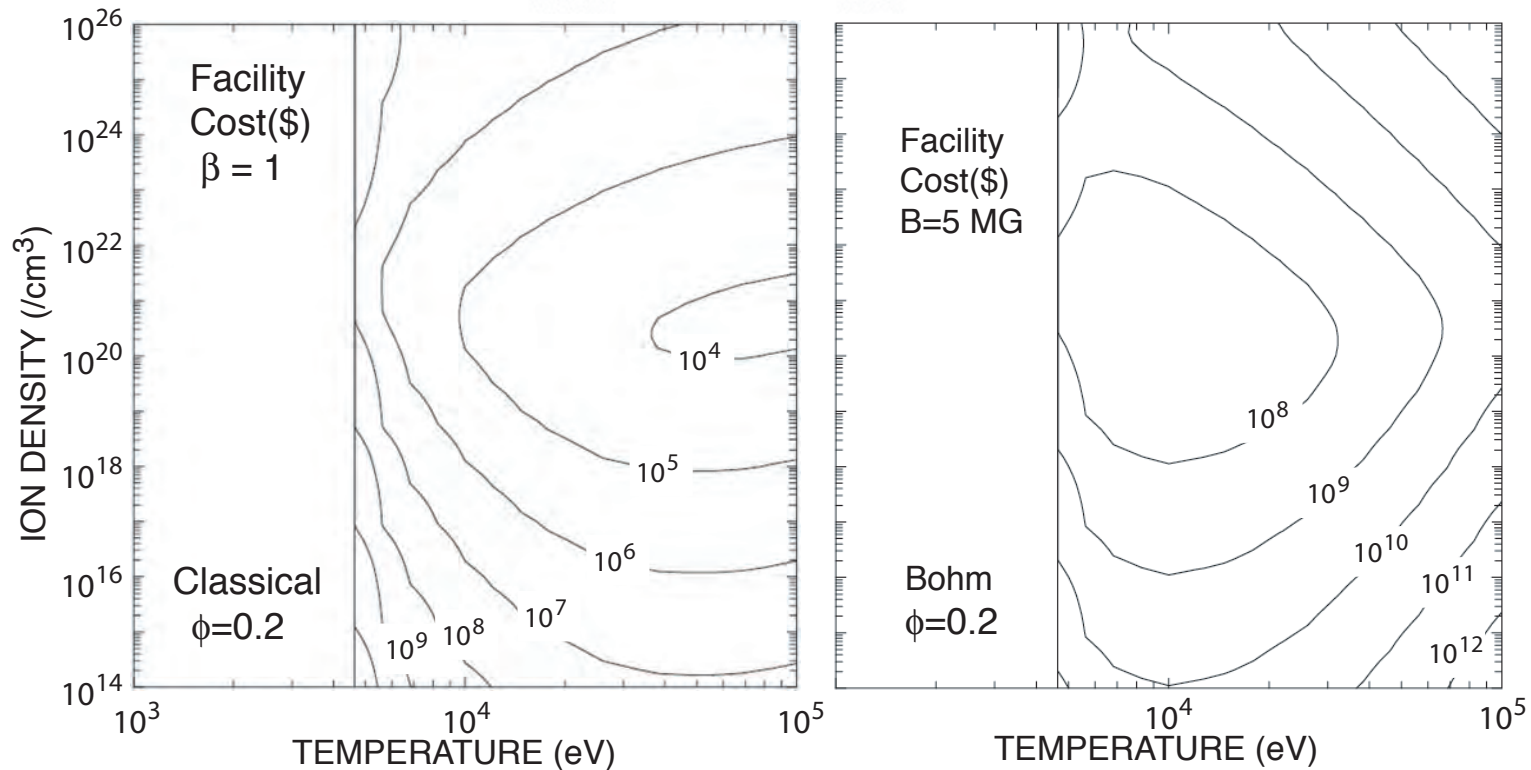
LANL/VNIIIEF



- A joint AFRL/LANL liner experiment showed good stability at a radial convergence of ~ 17 (Degnan et al., IEEE TPS 36, p. 80, 2008).
- A joint LANL/VNIIIEF experiment (left) showed that imposed screw perturbations lead to a stable implosion (Anderson et al., 2001 IEEE Pulsed Power Conf. Digest of Papers, p. 354); the generality of this technique has yet to be explored.

The reduced size/energy (when compared to ITER) and reduced power (when compared to NIF) lead to a much lower cost for MTF.

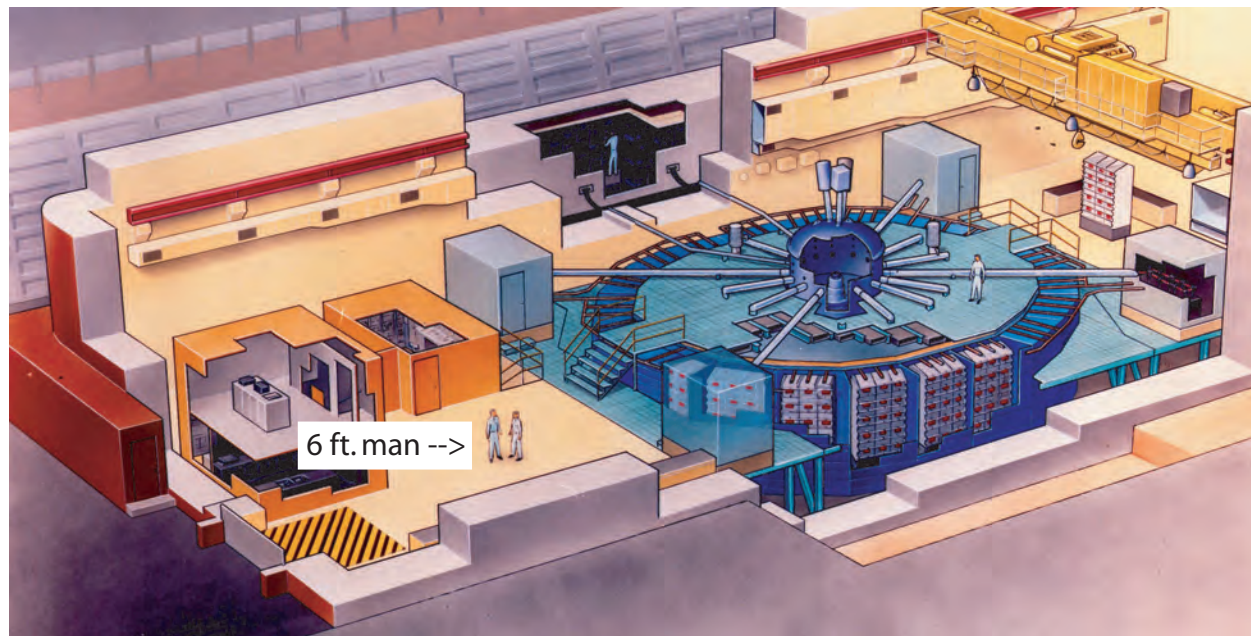
$$Cost = c_1 E_{PLAS} + c_2 P_{HEAT} \approx \frac{\$10B}{E_{ITER}} E_{PLAS} + \frac{\$3B}{P_{NIF}} P_{HEAT} \quad (\text{Am. J. Phys. 77, p. 407, 2009})$$



- Computations by Dawson and experiments at Columbia U. suggest that the losses should be classical, but even if the losses are Bohm, there is a large intermediate space where MTF should be lower cost than ICF, MCF

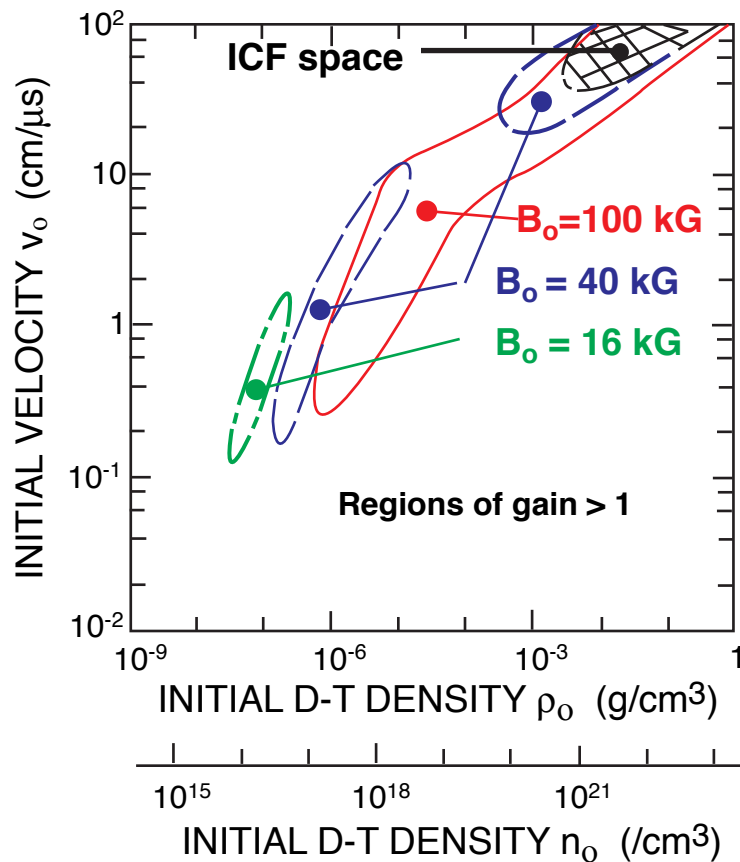
The Atlas capacitor bank (23 MJ, 30 MA, 6 μ s) at NTS was designed to drive imploding liners in the range of 1-10 MJ, 0.1-1 cm/ μ s to create high energy density environments.

- **Atlas is, serendipitously, an ideal machine for accessing the intermediate density regime by compressing magnetized fuel with a magnetically driven liner.**



- **Atlas' cost of \$50M confirms the simple cost estimates for fusion facilities.**

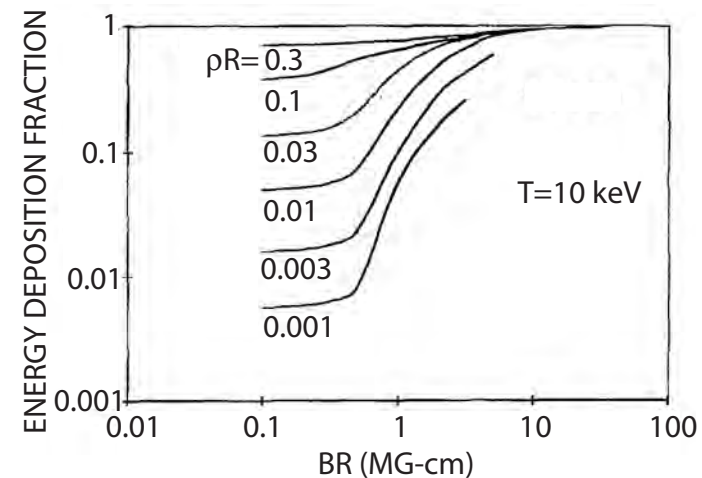
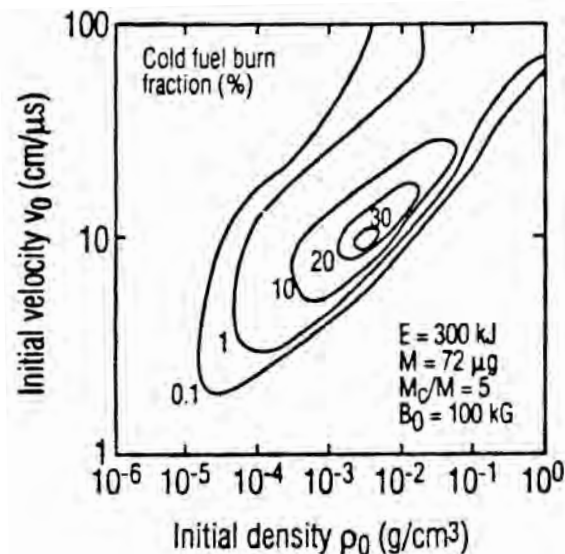
To fully determine the initial parameters (or final conditions), detailed implosion computations are needed.



- Lindemuth and Kirkpatrick (Nuc. Fus. 23, p. 263, 1983) formulated a simple implosion model and found a surprisingly broad parameter space.
- The results were confirmed by LASNEX and other computations.
- The simple model continues to serve as a guide for more detailed, multi-dimensional MHD computations.
- At the time the model was formulated, lasers were considered the most likely drivers, and plasma creation was considered a challenge (so use implosion $E=10$ kJ, $T_o=50$ eV).

A magnetic field can trap alpha particles and enhance self-heating (ignition); a magnetized “hot spot” can ignite “cold fuel” to achieve high gain

- The parameter BR , rather than ρR , determines the deposition fraction; ignition is possible for very low ρR (Kirkpatrick & Lindemuth, in *Current Trends in International Fusion Research*, NRC Canada, p. 261, 1999).



- An extension of the L-K model showed high gain at low velocity (Lindemuth and Kirkpatrick, *Fus. Tech.* 20, p. 829, 1991); LASNEX calculations give similar results.
- But, the high efficiency of MTF drivers may mean that high gain is not as critical for magnetized targets.

The L-K model showed that MTF implosions are quasi-adiabatic and approximately flux conserving

- If adiabatic compression and flux conservation, the initial plasma n_o , T_o , B_o required to reach a specified final n , T , B can be estimated

$$\begin{array}{l}
 \text{Quasi-spherical} \quad \frac{n}{n_o} = \left(\frac{r_o}{r}\right)^3 \quad \frac{T}{T_o} = \left(\frac{r_o}{r}\right)^2 \quad \frac{B}{B_o} = \left(\frac{r_o}{r}\right)^2 \quad \frac{\beta}{\beta_o} = \frac{r_o}{r} \quad \frac{\omega\tau}{(\omega\tau)_o} = \left(\frac{r_o}{r}\right)^2 \\
 \text{Cylindrical} \quad \frac{n}{n_o} = \left(\frac{r_o}{r}\right)^2 \quad \frac{T}{T_o} = \left(\frac{r_o}{r}\right)^{4/3} \quad \frac{B}{B_o} = \frac{r_o}{r} \quad \frac{\beta}{\beta_o} = \left(\frac{r_o}{r}\right)^{4/3} \quad \frac{\omega\tau}{(\omega\tau)_o} = \frac{r_o}{r}
 \end{array}$$

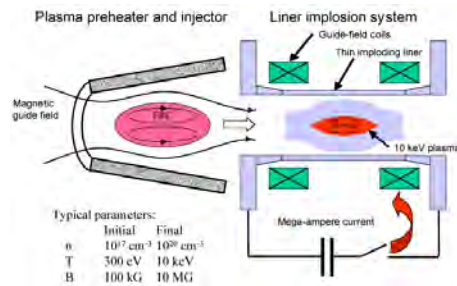
- **Example: to limit $r_o/r=10$, but reach $n=1e20/cm^3$, $T=10$ keV, $B=1$ MG:**

Quasi-spherical--initial $n, T, B = 1e17/cm^3, 100$ eV, 10 kG

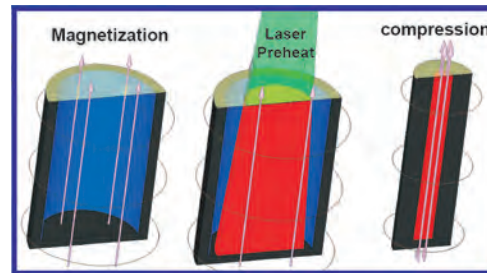
Cylindrical--initial $n, T, B = 1e18/cm^3, 464$ eV, 100 kG

- In MTF, there is a trade-off between convergence r_o/r and initial n , T , B .
- MTF does not need the high convergence ($r_o/r \sim 30$) that makes ICF difficult.

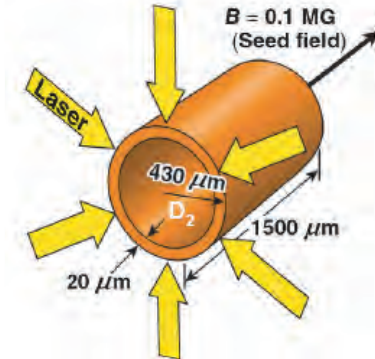
The $> 1e4$ density, $> 1e2$ velocity range of MTF admits many plasma/driver combinations; plasma may be magnetically or wall confined with simple magnetic topology; pulse-shaping is not needed



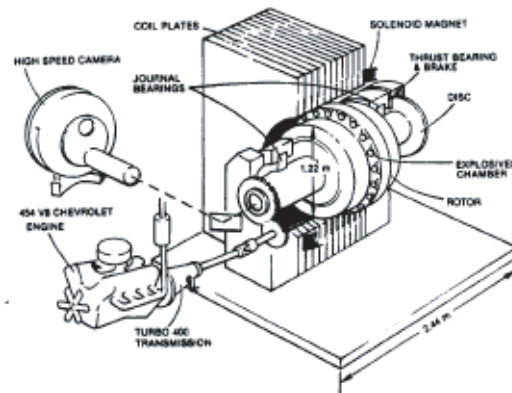
AFRL/LANL/UNR FRC/Shiva-Star
(J. Degnan, G. Wurden et al.)



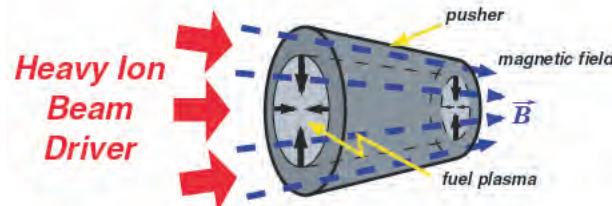
SNL "Z" MAGLIF (S. Slutz et al.)



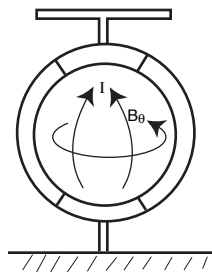
LLE Omega (Fiksel, Hohenberger et al.)



NRL LINUS (Turchi et al., 70s-80s)
Reciprocating 0.1 mm/ μs liquid liner



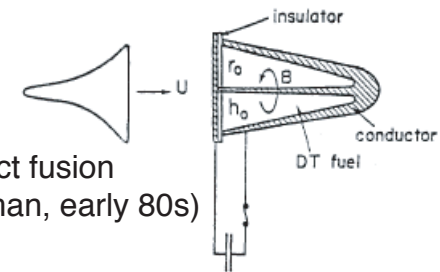
HIF (Kemp et al.)



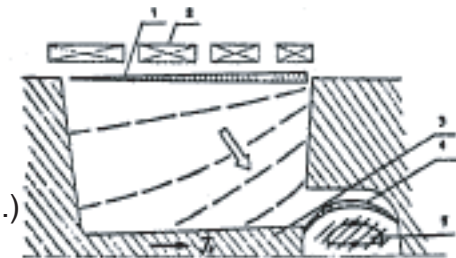
SNL e-beam Φ -target (late 70s)



Plasma-jet liner (Witherspoon et al.)

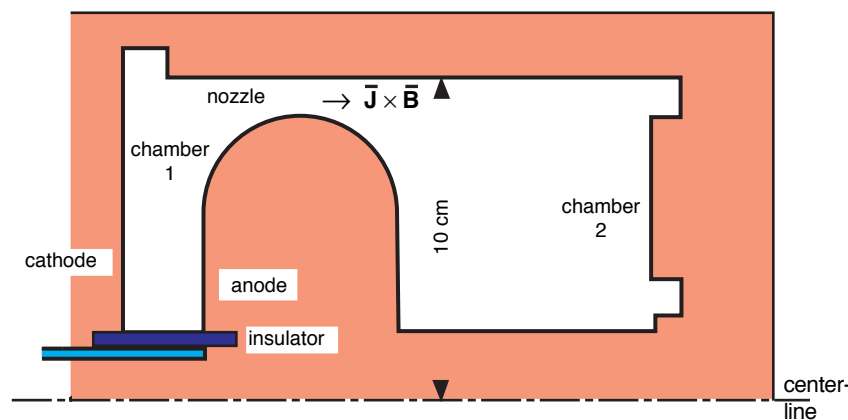


impact fusion
(Tidman, early 80s)

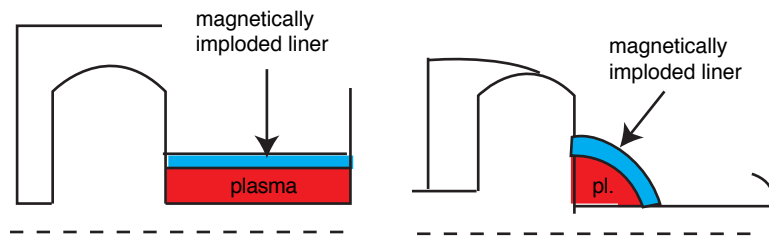


Russian (Kurtmullaev et al, 70s-80s)

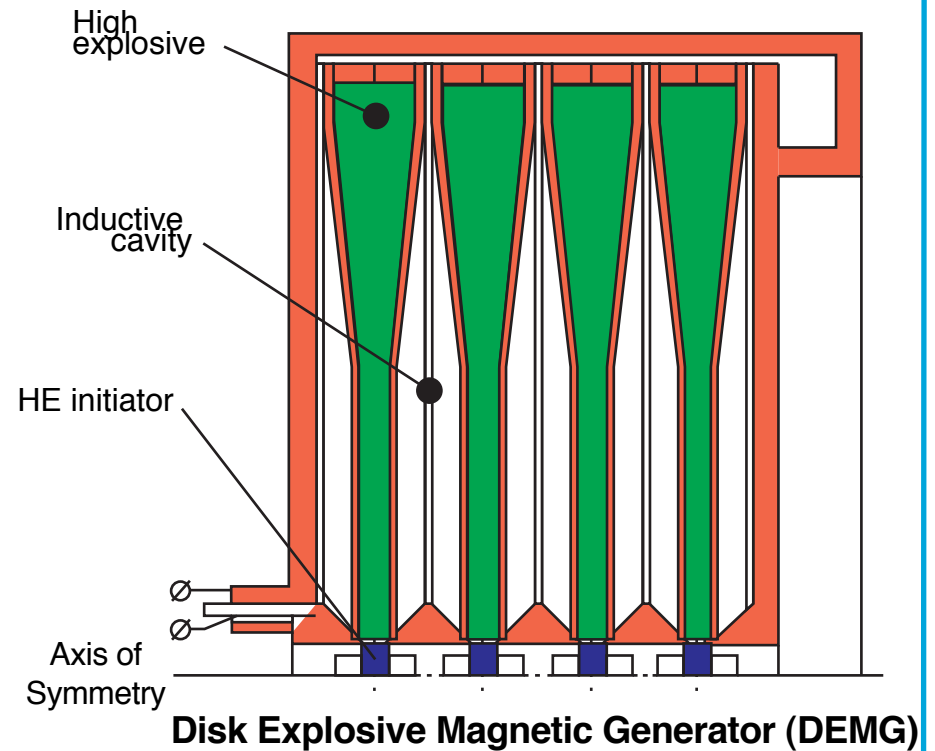
The Russian “MAGO” plasma has near-ideal density and temperature ($1e18/cm^3$, 300 eV) for MTF; $1e13$ D-T neutrons are produced in the formation stage.



MAGO (Magnitnoye Obzhatiye)



Implosion scenarios



- The All-Russian Institute of Experimental Physics (VNIIEF--the “Russian Los Alamos”), building on the work of Nobel Laureate Andre D. Sakharov (“father of Russian H-bomb”), has developed explosively powered generators that develop more electrical current (300 MA) and energy (200 MJ) than any US facility.

MTF is a potential IFE game-changer

- The potential benefit of combining magnetothermal insulation with compressional, implosion heating has been recognized for more than six decades (Fermi, 1945).
- Previous endeavors that would now be called MTF have been terminated before reaching any level of technical maturity; what is now "obvious" and "well known" to us was unknown or little understood by early researchers; the tools (machines, diagnostics, codes, etc.) with which the early researchers worked are quite primitive by our present standards.
- Using existing machines (e.g., Atlas) and modern diagnostics and codes, MTF's new paradigm will focus more on targets and less on drivers.
- MTF is an "orthogonal," complementary alternate to MFE and conventional IFE; because MTF is qualitatively different--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.
- MTF needs a chance to reach technical maturity.