The Parameter Space of Magnetized Target Fusion (MTF), aka Magneto-Inertial Fusion (MIF)

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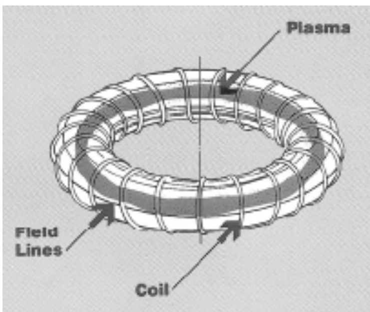
- Richard E. (Dick) Siemon (LANL & UNR, retired)—original analytic work showing key role of density in fusion, attractiveness of intermediate density (1995); organized workshops and seminars (1995-2003) that, at least in part, stimulated current interest in magnetized targets.

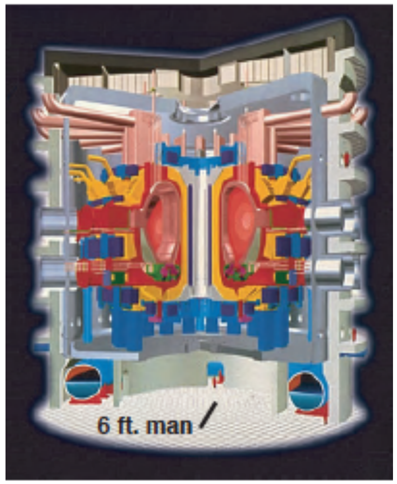
Abstract

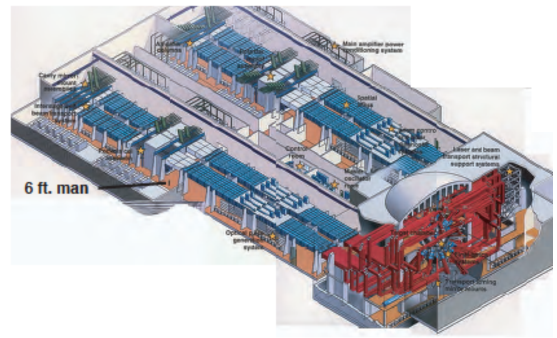
Magnetized Target Fusion (MTF), aka Magneto-Inertial Fusion (MIF), is an approach to fusion that compresses a preformed, magnetized (but not necessarily magnetically confined) plasma with an imploding liner or pusher. MTF/MIF operates in a density regime in between the eleven orders of magnitude (10^{11}) in density that separate inertial confinement fusion (ICF) from magnetic confinement fusion MCF. Compared to MCF, the higher density, shorter confinement times, and compressional heating as the dominant heating mechanism potentially reduce the impact of magnetic instabilities. Compared to ICF, the magnetically reduced thermal transport and lower density leads to orders-of-magnitude reduction in the difficult-to-achieve areal-density parameter and a significant reduction in required implosion velocity and radial convergence, potentially reducing the deleterious effects of implosion hydrodynamic instabilities. This tutorial presents fundamental analysis [1,2] and simple time-dependent modeling [2] to show where significant fusion gain might be achieved in the intermediate-density regime. The analysis shows that the fusion design space is potentially a continuum between ICF and MCF but practical considerations limit the space in which ignition might be obtained. Generic time-dependent modeling addresses the key physics requirements and defines "ball-park" values needed for target-plasma initial density, temperature, and magnetic field and implosion system size, energy, and velocity. The modeling shows energy gains greater than 30 can potentially be achieved and that high gain may be obtained at low convergence ratios, e.g., less than 15. A non-exhaustive review of past and present MTF/MIF efforts is presented and the renewed interest in MTF/MIF within the US (e.g., ARPA-E's ALPHA program) and abroad is noted.

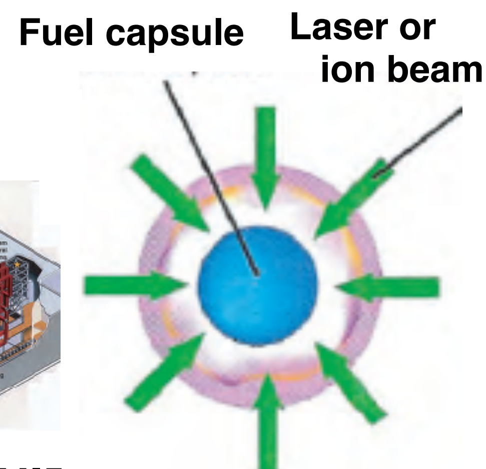
[1] I. Lindemuth & R. Siemon, "The fundamental parameter space of controlled thermonuclear fusion," Amer. J. Phys. 77, 407 (2009). [2] I. Lindemuth, "The ignition design space of magnetized target fusion," Phys. Plas. 22, 122712 (2015).

The fuel density (volume) of Magnetic Confinement Fusion (MCF) differs from the fuel density (volume) of Inertial Confinement Fusion (ICF) by a factor of more than 10^{11} (10^{16})









ITER

n=10^{14}/cm^3, $V \approx 10^3$/m^3
p=2.6 atm, E=320 MJ

NIF

n=1.4 x 10^{25}/cm^3, $V \approx 10^{-13}$/m^3
p=3.6 x 10^{11} atm, P=10^{14} W

\$$10^{11}$—stack 6250 miles high
10^{11} seconds—3171 years

\$$10^{16}$—stack > 3 round trips to sun
10^{16} seconds—300 million years

Is there anything in between?

Reference: I. Lindemuth & R. Siemon, “The fundamental parameter space of controlled thermonuclear fusion,” Amer. J. Phys. 77, 407 (2009).

OBJECTIVE: use analysis and time-dependent modeling to show that fusion energy might be possible in the 10^{11} density range intermediate between conventional ICF and MCF

OUTLINE

I. Necessary (but not sufficient) condition for fusion: $P_{loss} < P_{fus}$

- **a. $B=0$ (ICF): why ICF must operate at high density, pulsed**
- **b. steady state (MCF); why magnetization required, operate at low density**
- **c. attractiveness of intermediate density**
- **d. magnetized targets to access intermediate density**

II. Ignition condition: $P_{abs} = P_{loss}$

- **a. ignition possible at ρR << 0.4 g/cm^2 (ICF)**

III. Characteristics of magnetized targets

- **a. use ignition condition to define target plasma n_o-T_o-B_o-R_o**
- **b. simple implosion model: time-dependent calculations to define driver E_o, v_o and determine gain**
- **c. accessible space depends upon geometry**

IV. Past and present MTF—selected examples

V. Concluding remarks

Energy loss and fusion rates can be used to estimate minimum size, energy, etc., for energy gain at any *n-T-B* combination

For gain: $\dfrac{P_{loss}}{P_{fus}} = f_{loss} < 1, \quad P_{fus} = \dfrac{dE_{fus}}{dt} = \int Q_{fus} dV, \quad P_{loss} = \dfrac{dE_{loss}}{dt} = \int Q_{loss}\, dV$

Classical: $\quad Q_{loss} = Q_{rad} + Q_{tc}, \qquad \mathrm{Q}_{rad} = C_{rad} n^2 T^{1/2}, \qquad \mathrm{Q}_{tc} = -\nabla \bullet K \nabla T$

Approximate Q_{tc}:

$$Q_{tc} \approx -\frac{1}{V}\int_V (\nabla \bullet K\nabla T)dV = -\frac{1}{V}\oint_S K\nabla T \bullet dS \approx -\frac{S}{V}K\nabla T \approx \frac{KT}{g_1 g_{tc} a^2}$$

where a = characteristic dimension, $\quad \nabla T \approx -\dfrac{T}{g_{tc} a}, \qquad \dfrac{V}{S} = g_1 a, \qquad \mathrm{V} = \mathrm{g}_2 a^3$

g_1, g_2 are geometric quantities, e.g., sphere $g_1 = \dfrac{1}{3}, \quad \mathrm{g}_2 = \dfrac{4\pi}{3}$

Estimate g_{tc}:

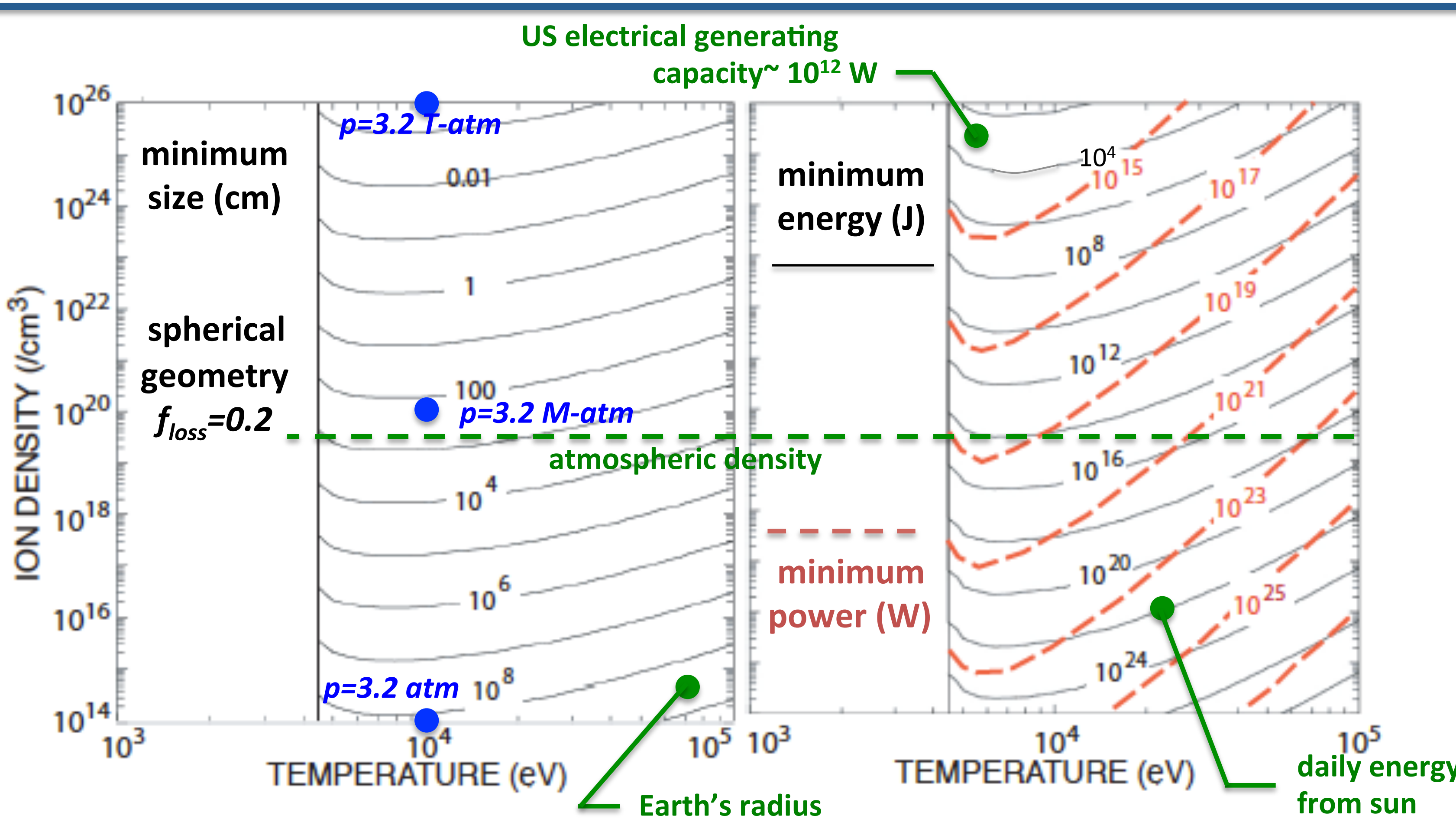
$$\frac{1}{r^n}\frac{\partial}{\partial r}\left(r^n K \frac{\partial T}{\partial r}\right) = c_1, \quad K = c_2 T^m \rightarrow T^{m+1} = T_o^{m+1}\left(1 - \left(\frac{r}{R}\right)^2\right) \rightarrow \left(K\frac{\partial T}{\partial r}\right)_{r=R} = -K_o \frac{T_o}{0.5 \bullet (m+1)}$$

$$B = 0 \rightarrow m = \frac{5}{2} \rightarrow g_{tc} = \frac{7}{4}, \qquad \text{Strong B } (\omega\tau >> 1) \rightarrow m = -\frac{1}{2} \rightarrow g_{tc} = \frac{1}{4}$$

Energy loss and fusion rates can be used to estimate minimum size, energy, etc., for energy gain at any *n-T-B-f_{loss}* combination

- **From approximation of Q_{tc}:** $a_{\min}^2 = \dfrac{KT}{g_1 g_{tc}} \dfrac{1}{f_{loss} Q_{fus} - Q_{rad}}$
- **Fuel mass:** $M_{\min} = n_i \left(m_i + m_e\right) g_2 a_{\min}^3$
- **Fuel thermal energy:** $E_{\min}^{plas} = 3 n_i T g_2 a_{\min}^3$
- **Required heating power:** $P_{heat} = \left(Q_{tc} + Q_{rad}\right) g_2 a_{\min}^3$
- **Required surface heating (intensity):** $I_{heat} = \dfrac{P_{heat}}{S} = \left(Q_{tc} + Q_{rad}\right) g_1 a_{\min}$
- **Implosion velocity for pdV heating:** $v_{imp} = \dfrac{I_{heat}}{(p_i + p_e)} = \dfrac{I_{heat}}{2 n_i T}$

B=0, D-T fuel: minimum size, power, energy, and pressure of unmagnetized fuel are strong functions of density, temperature.



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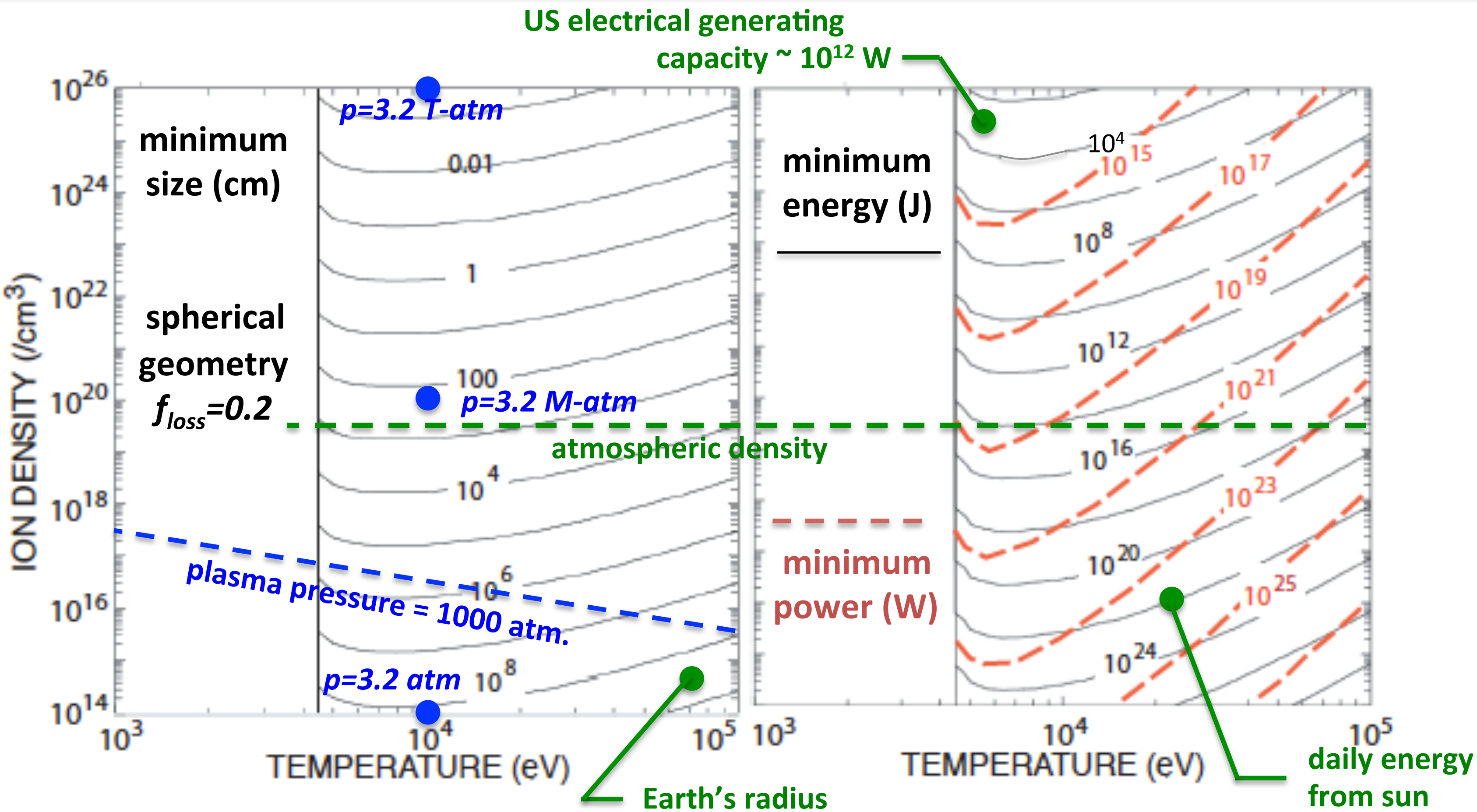

- "Steady state" requires pressure << e.g., 1000 atm, is not possible for B=0 (Y_{steel} = 2500 atm).

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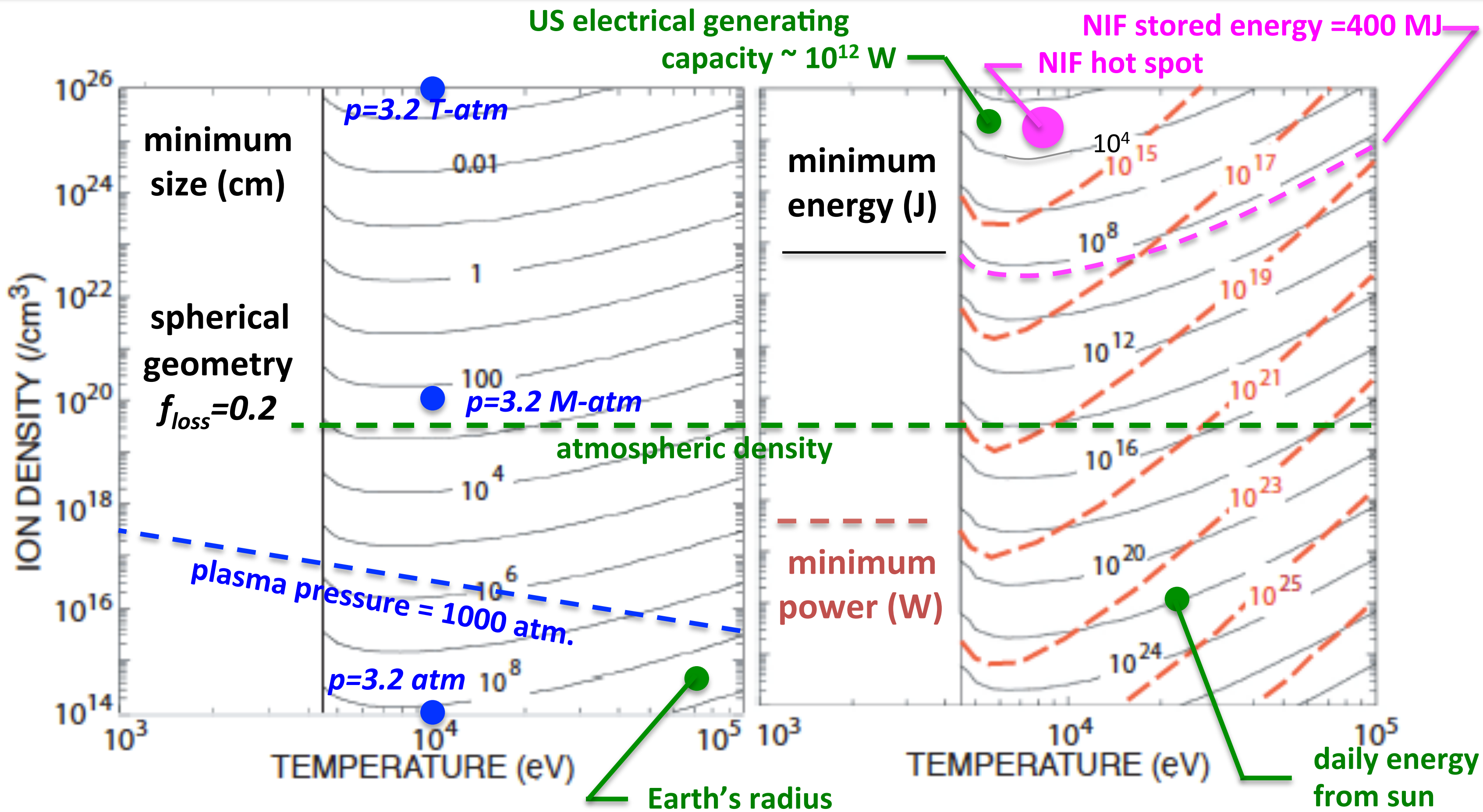
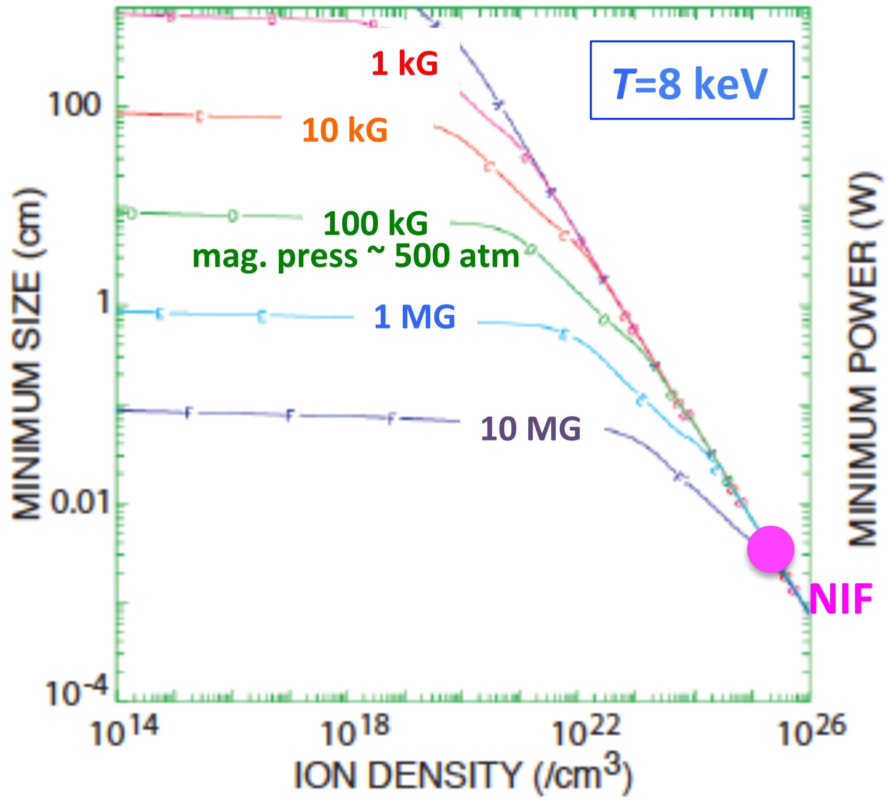
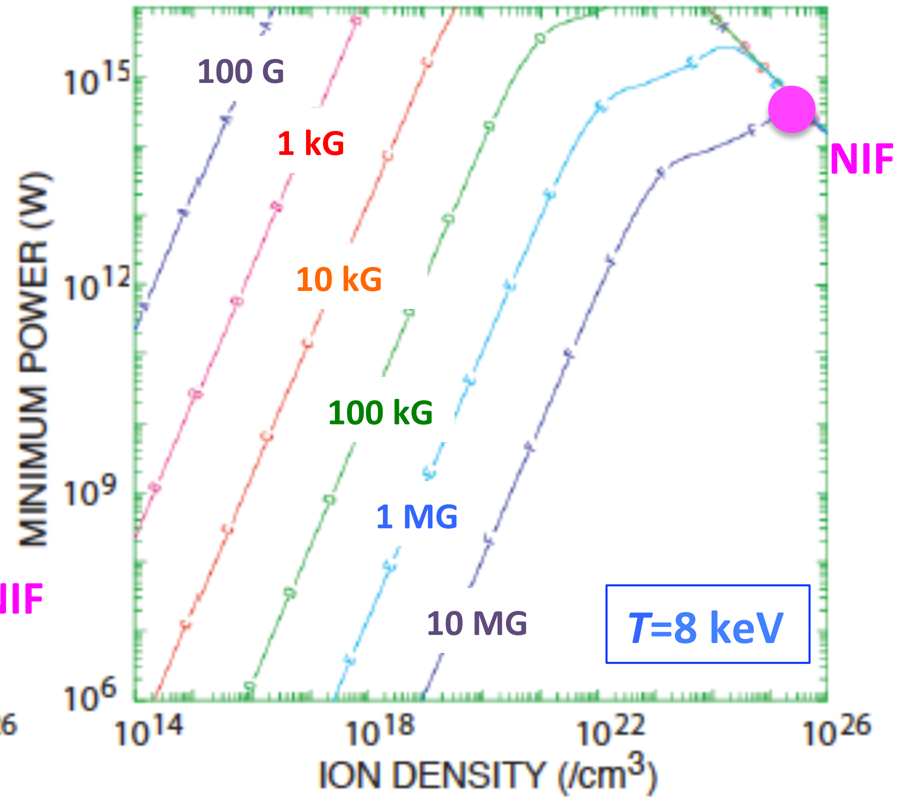


- "Steady state" requires pressure << e.g., 1000 atm, is not possible for B=0 (Y_{steel} = 2500 atm). If B=0 (i.e., ICF), high fuel pressure (~ 1 T-atm) means fusion must be "pulsed."

A magnetic field significantly reduces the size, power, and energy, potentially opening up the density space between ICF and MCF.





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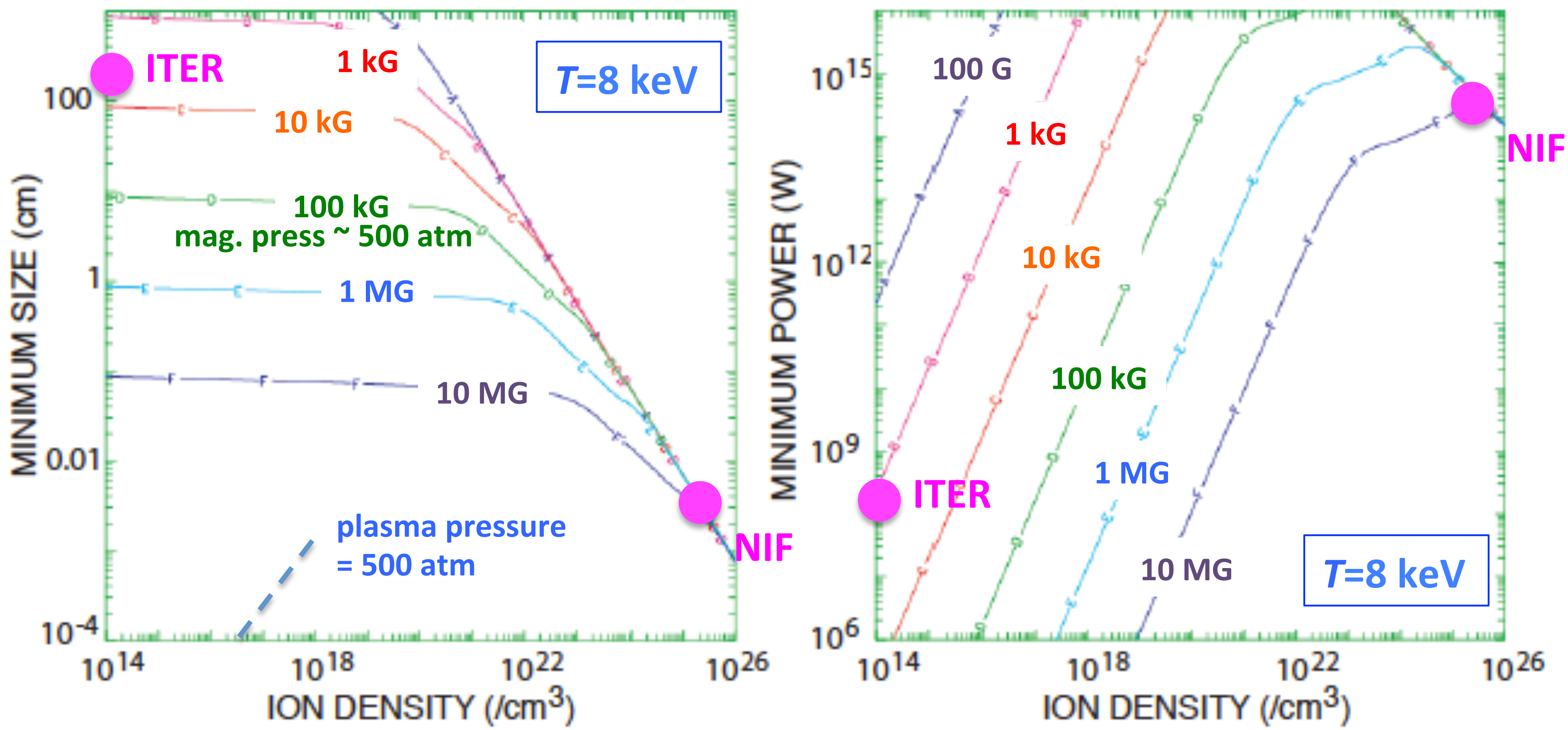
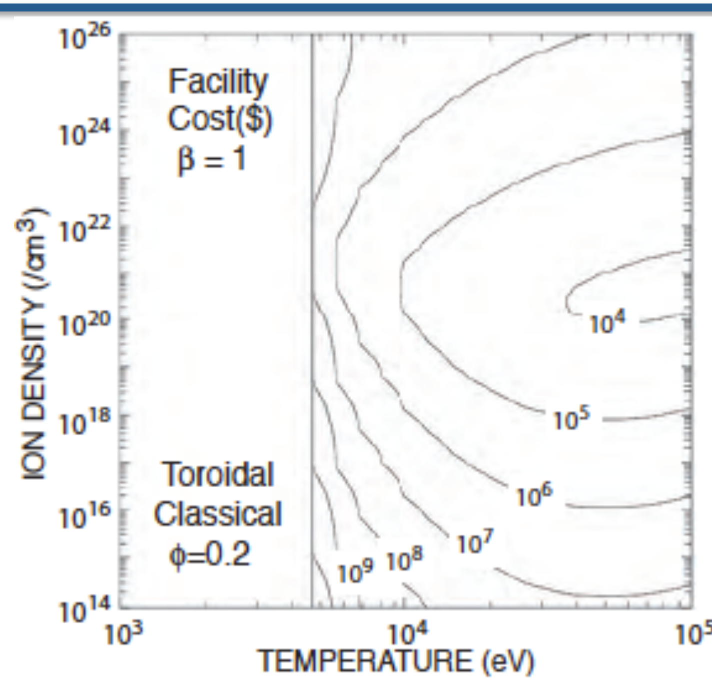


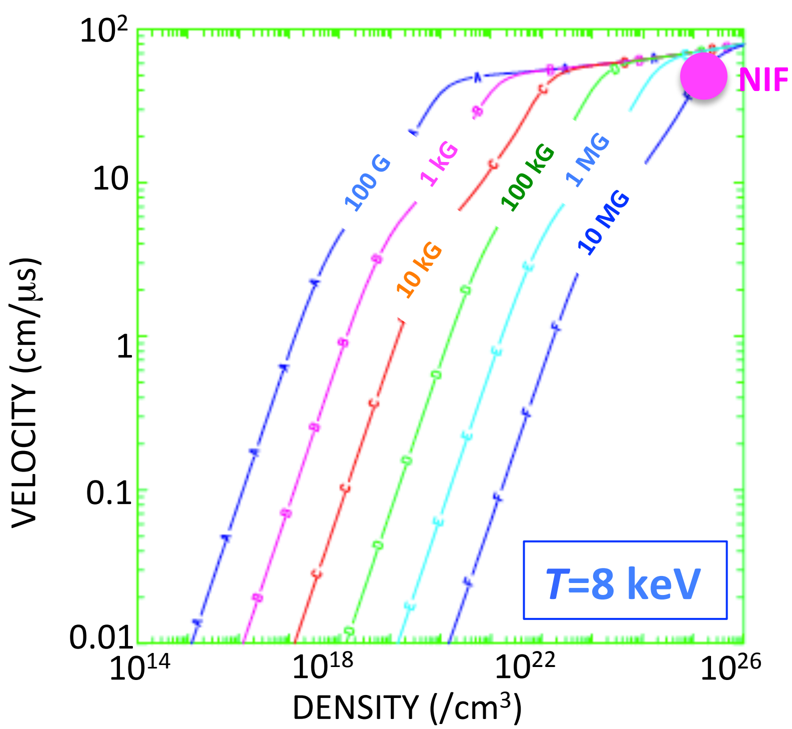
- **A magnetic field potentially makes "steady state" possible.**
- **ITER's poloidal field is 10 kG; size (minor radius) and required heating power are larger than the "classical" values because of higher-than-classical "transport" and impurity radiation.**

Power is reduced at density lower than ICF, energy is reduced at density higher than MCF, leading to lower cost & implosion velocity

- **The potential for significantly lower cost makes the intermediate density regime attractive.**

$$Cost = C_1 E_{plas} + C_2 P_{heat} \approx \frac{Cost_{ITER}}{E_{ITER}} E_{plas} + \frac{Cost_{NIF}}{P_{NIF}} P_{heat}$$





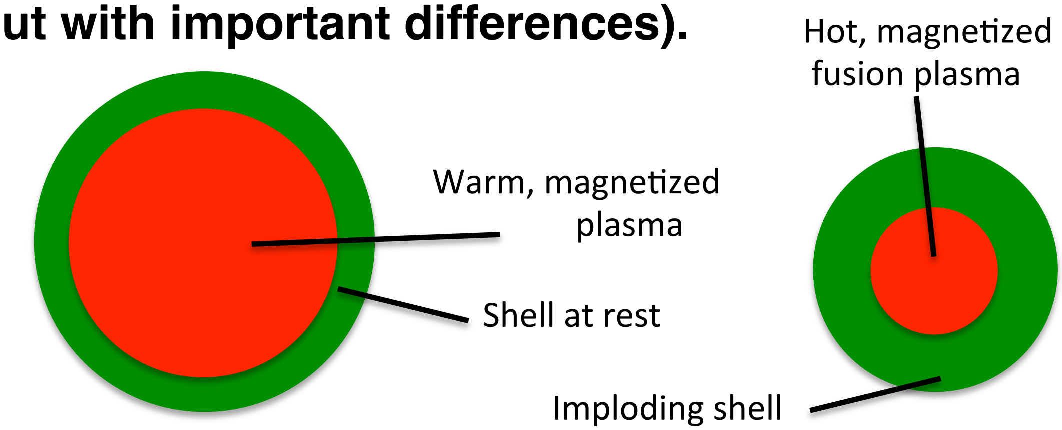
- **"The optimal velocity ... is the primary determinant of the minimum size driver for ignition," J. D. Lindl, UCRL-119015, 11/95.**

- **0.1-10 cm/μs velocity is range of magnetically driven liners and other possible drivers.**

Because the required velocity is within reach of magnetically driven liners & other drivers, magnetized targets have been proposed as a way to access the intermediate density.

- **MTF is a two-step process:**
  - **(a) formation of a preheated, magnetized plasma (similar to MCF, but with important differences);**
  - **(b) compression of the plasma by an imploding higher density shell (similar to ICF, but with important differences).**

- **The optimum plasma formation/driver combination has not been determined.**



- **The parameter space for 3 types of targets will be considered:**

cylindrical B_Z

cylindrical B_Φ

spherical B_Φ

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The magnetization of the D-T fusion fuel enhances alpha particle deposition and fuel self heating, potentially leading to ignition at a lower ρR than ICF's 0.4 g/cm^2.

- **Ignition is required in both ICF and MCF; gain may be possible without ignition in MTF.**

- **Magnetization enhances alpha deposition:**

$$f_d = \frac{1}{1 + \frac{1}{f_{\rho R} + f_{RB}}}\ , f_{RB} = 0.0843 * \left(\frac{RB}{0.2703}\right)^2$$

Similar to Basko et al., Nuc. Fus. 40, 59 (2000)

- **The "ignition condition:"** $\frac{3.5}{17.6} f_d P_{fus} = P_{loss}$

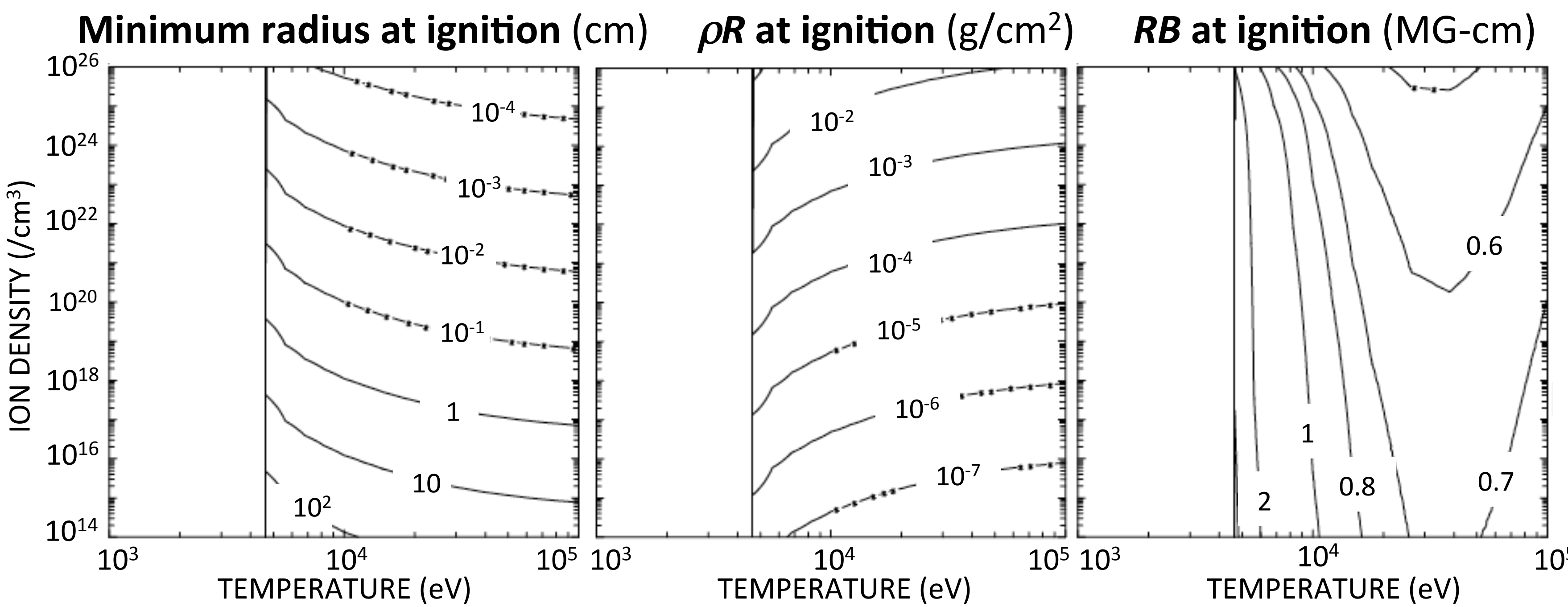
$$P_{ae} + P_{ai} = P_{ec} + P_{ic} + P_{er} + P_{eN} + P_{eE} + P_{iE}$$

P_{ae}, P_{ai} --- alpha deposition to electrons, ions
P_{ec}, P_{ic} --- thermal conduction to outer wall
P_{eE}, P_{iE} --- thermal conduction to end caps
P_{er} --- radiation
P_{eN} --- Ettinghausen effect

- **Have to find minimum *R* at ignition from *n-T-B* by iteration.**

Magnetization makes ignition possible over the full range of density between MCF and ICF.

- **Example: Spherical B_ϕ, β=1 at ignition**



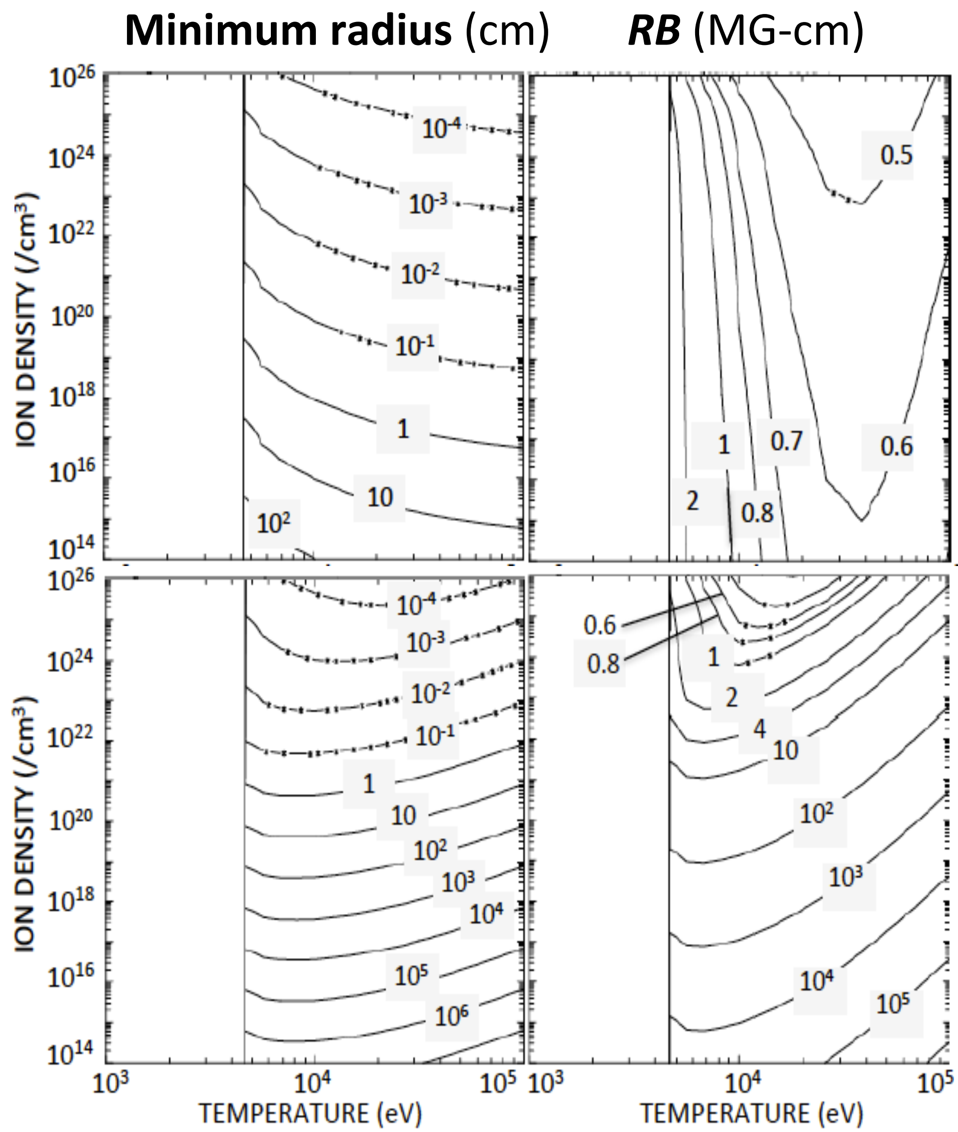
- **The *ρR* can be orders of magnitude less than the 0.4 g/cm² required in ICF.**

- **Over most of the intermediate density space, 0.5 MG-cm < *RB* at ignition < 2 MG-cm.**

Magnetization allows cylindrical targets to reach ignition at densities much lower than ICF

- **Top: Cylindrical B_ϕ, β=1 & L/R=15 at ignition)--the parameter space is similar to spherical B_ϕ.**

- **Bottom: Cylindrical B_z, β=1 & L/R=50 at ignition--at low density, thermal conduction to the end caps determines the length (ρL > 0.08 g/cm²), which in turn determines R ($R=L/50$), hence the large RB.**



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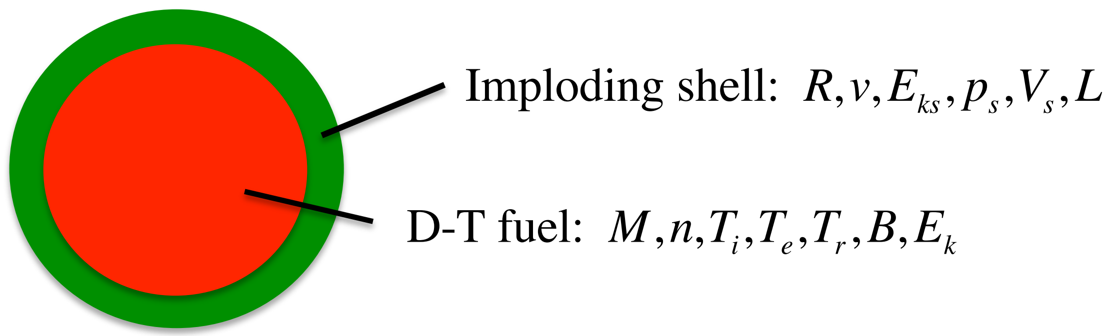
Time-dependent modeling is required to delineate characteristics of magnetized targets.

- The ignition condition is an equilibrium condition: $dT/dt=0$.
- The ignition *n-T-B-R* combinations give approximate conditions that must be achieved during implosion.
- Even when the ignition condition is exceeded, i.e., $dT/dt > 0$, the heating rate may be small compared with cooling processes.
- Reaching ignition conditions does not necessarily lead to high gain.
- Time-dependent calculations are required to determine the gain that can be achieved with an imploding system
- Time-dependent modeling requires:

  A mathematical model

  Initial conditions
- A desired ignition condition can be projected back to define appropriate initial conditions.

A simple target implosion model



- Ordinary differential equations, 6 dependent variables: R, v, T_i, T_e, T_r, B
- Analytic formulas relate E_{ks}, E_k, p_s, V_s, n to dependent variables
- Model includes: Magnetic reduction of ion, electron thermal conductivity
  Magnetic pressure, diffusion, Ohmic heating, flux annilation
  Magnetic enhancement of alpha deposition
  Hydro processes   Nernst, Ettinghausen effects

A simple target implosion model: solve six ordinary differential eqns

$$\frac{d}{dt}\left(E_i + \frac{p_i}{p}E_k\right) = P_{wi} + P_{ai} - P_{ie} - P_{ic} - P_{iE}$$

$$\frac{dR}{dt} = v$$

$$\frac{d}{dt}\left(E_e + \frac{p_e}{p}E_k\right) = P_{we} + P_{ae} + P_{ie} - P_{ec} - P_{eE} - P_{eN} + P_o - P_{er}$$

$$\frac{d\Phi}{dt} = -V_L - V_N$$

$$\frac{d}{dt}\left(E_r + \frac{p_r}{p}E_k\right) = P_{wr} + P_{er} - P_{rc} - P_{rE}$$

$$\frac{d}{dt}\left(E_{ks} + E_s + E_B + \frac{p_B}{p}E_k\right) = -P_{wi} - P_{we} - P_{wr} - P_o$$

- **Problem specification: target plasma--n_o, T_o, B_o, R_o (+ L for cylinders)**
  imploding shell--v_o, E_o

- **Model limitations include: "Volume burn"—no burn waves**
  No energy added during implosion, full velocity at t=0
  No shocks—total pressure a constant
  No radial/axial profile effects (except $\nabla T = -T/(g_1 a)$)
  Thermal and radiation losses not absorbed by shell
  No magnetic flux containment by shell

A simple target implosion model (cont'd)

- A set of coupled ordinary differential equations is solved to:
  - --rapidly scan parameter space
  - --provide a starting point for more detailed investigations by defining "ballpark" system parameters
  - --give insight into the many competing process
  - --provide a learning tool
  - --help build an "intuition" about the "trade-offs"
    - driver complexity <---> initial plasma formation
    - initial temperature <---> radial convergence
  - --increase confidence in large-scale computations

Because MTF is a quasi-adiabatic, quasi-flux conserving process, ignition conditions can be projected back to define initial conditions that can potentially lead to ignition at a desired convergence C_R.

- For spheres, if adiabatic and flux-conserving:

$$C_R=R_o/R \qquad T=T_o(C_R)^2 \qquad n=n_o(C_R)^3 \qquad B=B_o(C_R)^2 \qquad \beta=\beta_o C_R$$

- Step 1: choose T_{ig}, C_{ig}, n_o, and β_o or $B_o=(4\mu_o n_o T_o/\beta_o)^{1/2}$

$$T_o=T_{ig}(C_{ig})^{-2} \qquad n_{ig}=n_o(C_{ig})^3 \qquad B_{ig}=B_o(C_{ig})^2$$

- In MTF, there is a tradeoff between initial temperature and convergence.

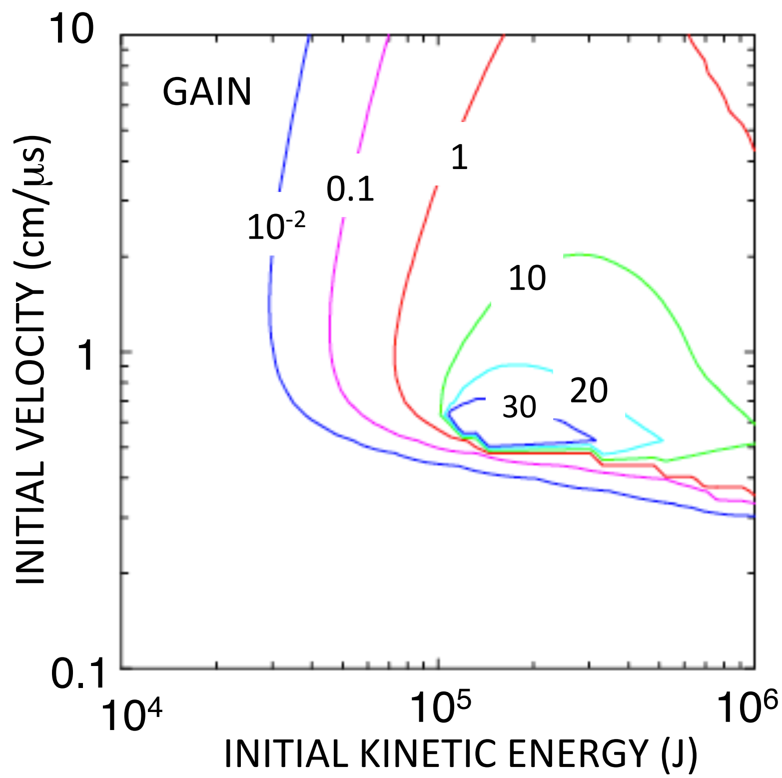
- Step 2: calculate R_{ig} based on T_{ig}, n_{ig}, B_{ig}, then calculate $R_o=R_{ig}C_{ig}$, i.e.,

$$R_o=\frac{(RB)_{ig}\,\beta_o^{1/2}}{T_{ig}^{1/2}\,n_o^{1/2}\,(4\mu_o)^{1/2}}$$

- To limit overall $C_R < 20$-30, ignition conditions should be reached at $C_R <$ 10-15.

For specified initial conditions, the optimum implosion velocity and kinetic energy that maximize gain can only be determined by a series of calculations.

- **E.g., spherical, n_o=10^{18}, β_o=1, T_o=70 eV, B_o=75 kG, R_o=1.6 cm (initial conditions projected back from ignition at 7 keV, C_R=10):**



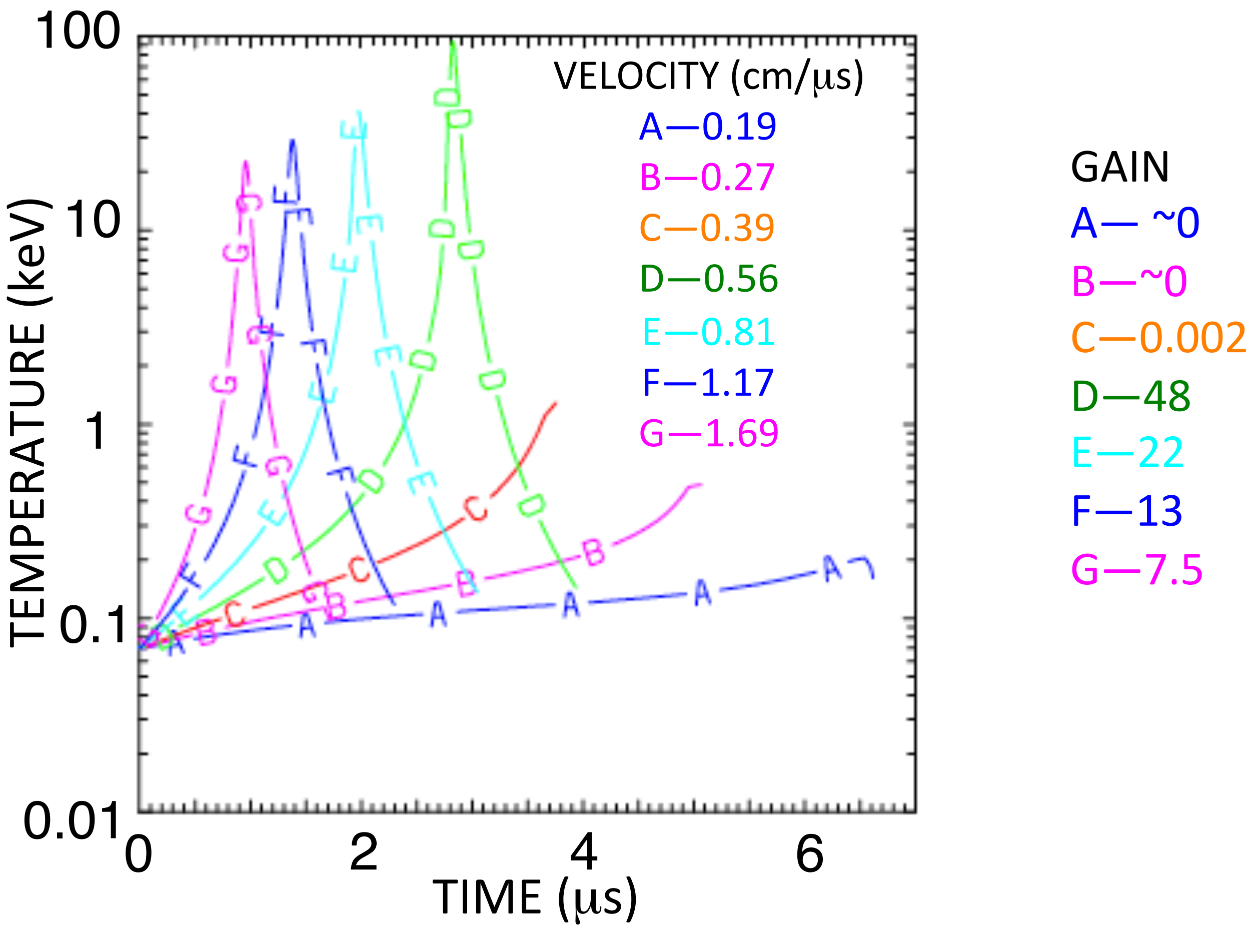
Maximum C_R < 25.

A maximum gain of 48 occurs at 0.56 cm/μs, 145 kJ; burn fraction--29%

- **Magnetized targets are not as sensitive to initial and drive conditions as conventional, unmagnetized targets**

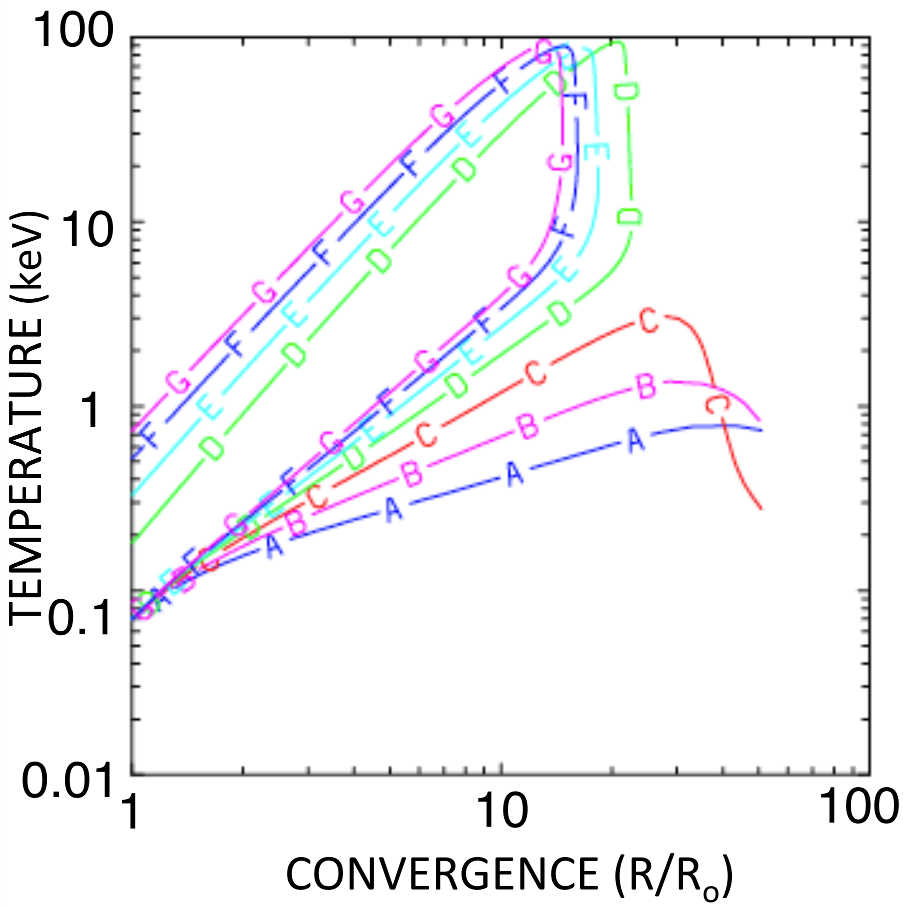
A velocity lower than optimum does not overcome cooling mechanisms; a velocity higher than optimum reduces the "dwell" time, leading to lower gain

- E.g., spherical, n_o=10^{18}, β_o=1, T_o=70 eV, B_o=75 kG, R_o=1.6 cm, E_o=145 kJ, E_O/M=2 KJ/μg (ignition projected at 7 keV, C_R=10):



The R_o determined by projecting back from ignition conditions leads to the minimum size and energy required for high gain

- **E.g., spherical, n_o=10^{18}, β_o=1, T_o=70 eV, B_o=75 kG, v=0.56 cm/μs, E_O/M=2 KJ/μg (ignition projected at 7 keV, C_R=10 for R$_o$=1.6 cm):**



	R_o(cm)	E_O(kJ)	Gain	C_R@ig	T_i@ig
A	0.8	17.9	1e-4	--	--
B	1.01	35.7	3e-3	--	--
C	1.27	71.5	0.2	--	--
D	1.6	143	48	20	5.6
E	2.02	286	41	15	5.6
F	2.54	572	40	13	5.6
G	3.2	1144	40	11.3	5.2

- **Due to losses during the implosion, ignition, i.e., when P_{abs}=P_{loss}, occurs at higher C_R, higher density, and lower T_i than projected.**

Using initial conditions projected back from ignition conditions, gains greater than 10 can be obtained over the full range of density between MCF and ICF, with maximum $C_R < 25$, for $\beta_o > 1$.

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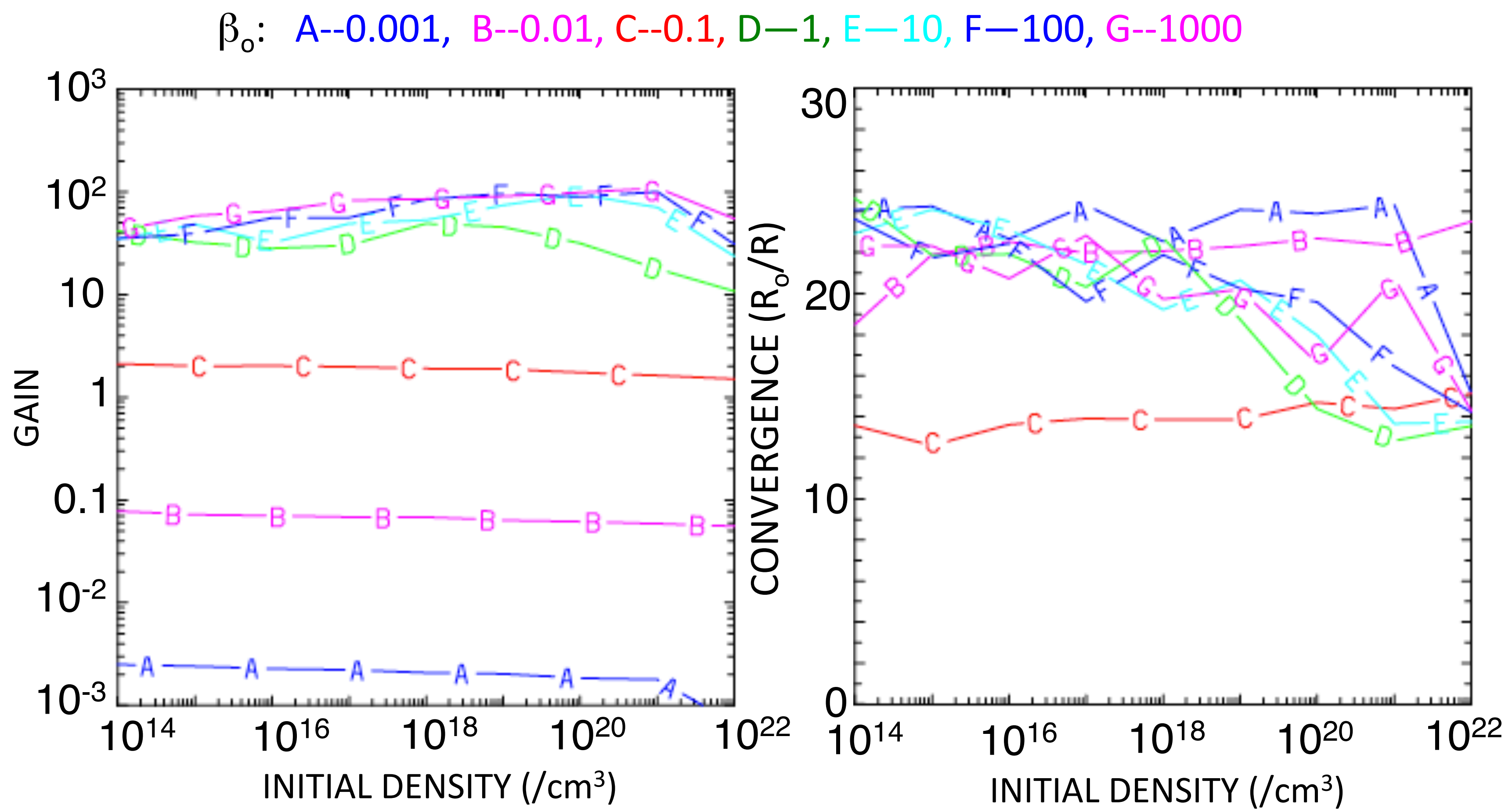
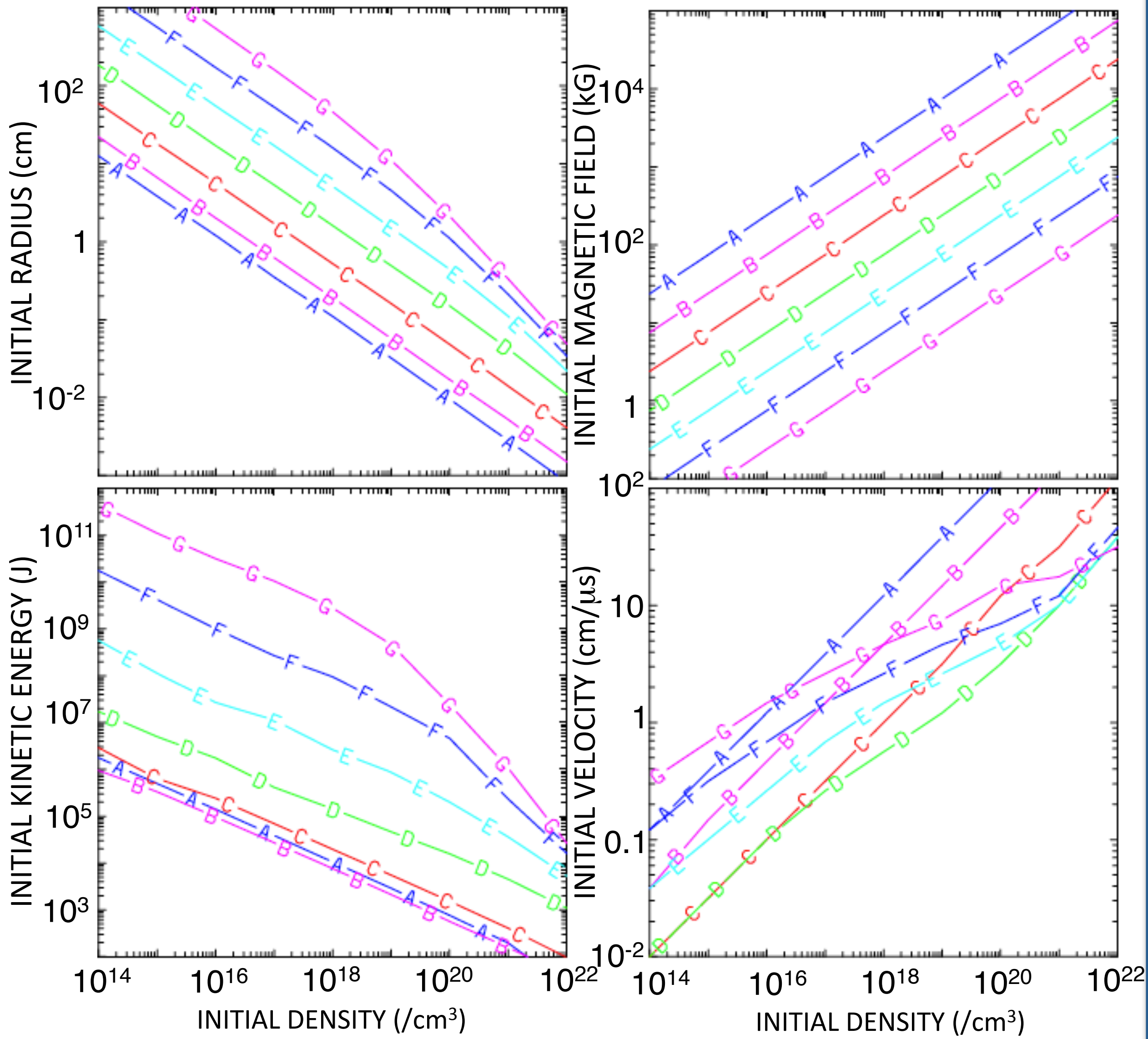


Although MTF operating space potentially covers whole MCF-ICF range, practical considerations (size, energy, etc.) can limit space.

- **E.g.,spherical, T_o=70 eV (ignition projected at 7 keV, C_R=10)**

β_o

A 0.001
B 0.01
C 0.1
D 1
E 10
F 100
G 1000



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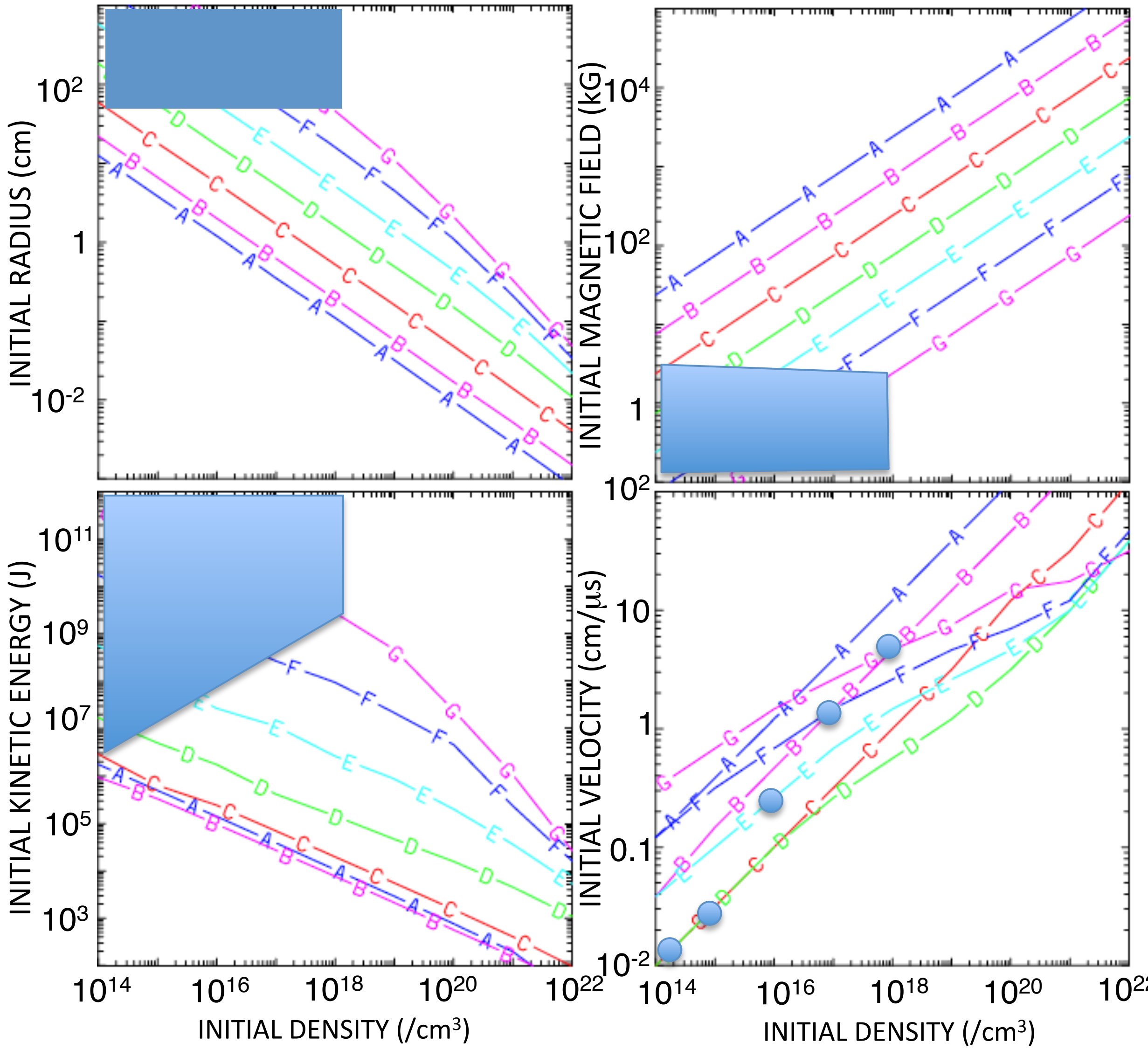
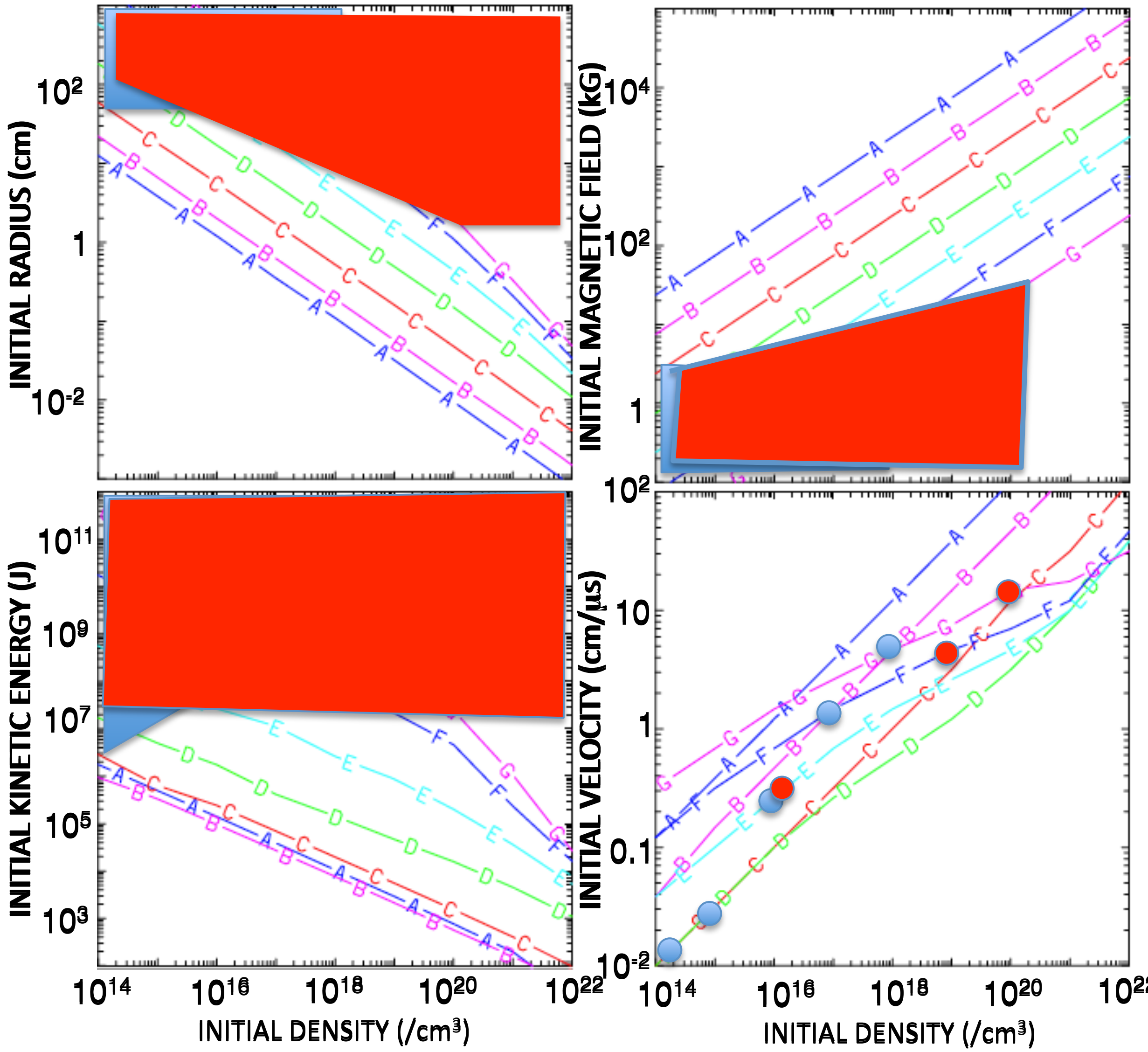
- **E.g.,spherical, T_o=70 eV (ignition projected at 7 keV, C_R=10)**
- **If, e.g., $R_o < 50$ cm, $n_o > 10^{15}$/cm^3 for β_o=1, $n_o > 10^{17}$/cm^3 & $v_o > 1$ cm/μs for β_o=100**



Although MTF operating space potentially covers whole MCF-ICF range, practical considerations (size, energy, etc.) can limit space.

- E.g.,spherical, T_o=70 eV (ignition projected at 7 keV, C_R=10)
- If, e.g., $R_o < 50$ cm, $n_o > 10^{15}$/cm^3 for β_o=1, $n_o > 10^{17}$/cm^3 & $v_o > 1$ cm/μs for β_o=100
- If, e.g., E_o<10 MJ, $n_o > 10^{19}$/cm^3 and $v_o > 3$ cm/μs for β_o=100



Practical considerations (size, energy, etc.) can limit space.

- **Upper bounds on initial radius and kinetic energy set a lower bound on practical density range; lower bound on initial radius sets upper bound on density.**

Example: 0.1 cm < R_o < 50 cm, E_o < 50 MJ

β_0	1	10	100	1000
n_0 (/cm^3) for R_0<50 cm	$>10^{15}$	$>10^{16}$	$>10^{17}$	$>10^{18}$
n_0 (/cm^3) for R_0>0.1 cm	$<2 \times 10^{20}$	$<10^{21}$	$<2 \times 10^{21}$	$<4 \times 10^{21}$
n_0 (/cm^3) for E_0<50 MJ	$>10^{14}$	$>5 \times 10^{15}$	$>3 \times 10^{18}$	$>5 \times 10^{19}$
Practical n_0 range (/cm^3)	10^{15}-2×10^{20}	10^{16}-10^{21}	3×10^{18}-2×10^{21}	5×10^{19}-4×10^{21}
Practical R_0 range (cm)	50-0.1	50-0.1	9-0.1	3-0.1
Practical E_0 range (J)	5×10^6-10^4	3×10^7-3×10^4	5×10^7-10^5	5×10^7-10^5
Velocity v_0 range(cm/μs)	0.03-5	0.2-10	3-20	10-25
Fusion yield range (J)	10^8-3×10^5	10^9-2×10^6	4×10^9-8×10^6	2×10^9-8×10^6

- **Subject to these limits, the practical operating space for spherical targets covers six orders of magnitude in density (10^{15}/cm^3—4×10^{21}/cm^3) and three orders of magnitude in velocity (0.03 cm/μs—25 cm/μs).**

- **Lower upper bounds on R_o, E_o or higher lower bound on R_o can reduce the practical operating space.**

- **Yields > 10^9 J are possible, leading to the possibility of low rep rate fusion reactors.**

Because the dependence on C_R is different for cylindrical geometries, a different T_o, B_o, and R_o is required for a specified T_{ig}, n_o, β_o *and* C_R

- Cyl: $C_R = R_o/R$ $\quad T = T_o(C_R)^{4/3}$ $\quad n = n_o(C_R)^2$ $\quad B_\phi = B_o C_R$ $\quad B_z = B_o(C_R)^2$

- T_o(eV) to reach 7 keV if adiabatic:

C_R	Sphere	Cylinder
7.5	125	470
10	70	324
15	31	189

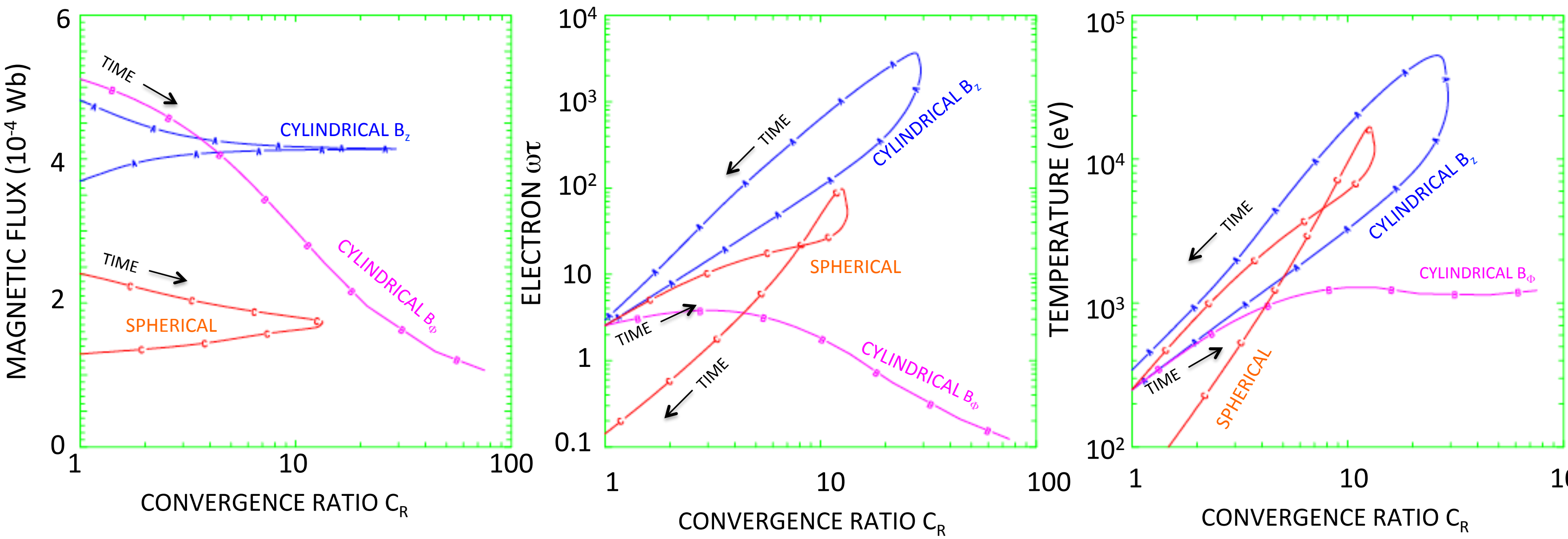
- As with spheres, minimum R_o can be calculated from T_{ig}, C_{ig}, n_o, and β_o.

$$R_o^{cyl\phi} = \frac{(RB)_{ig}^{cyl\phi}\,\beta_o^{1/2} C_{ig}^{2/3}}{T_{ig}^{1/2} n_o^{1/2} (4\mu_o)^{1/2}}; \qquad \frac{R_o^{cylz}}{R_o^{cyl\phi}} = \frac{(RB)_{ig}^{cylz}}{(RB)_{ig}^{cyl\phi}} \frac{1}{C_{ig}}$$

- For $n_o < 10^{19}/\mathrm{cm}^3$, $(RB)_{ig}^{cylz}$ can be significantly larger than $(RB)_{ig}^{cyl\phi}$ due to open field line end losses.

Because the dependence on C_R is different, a set of initial conditions may not lead to the same gain for each geometry

Example: n_o=4.45 x 10^{20}/cm^3, T_o=250 eV, B_o=330 kG, β_o=82
R_o=0.21 cm, v_o=7.5 cm/µs, E/M=3.52 kJ/µg

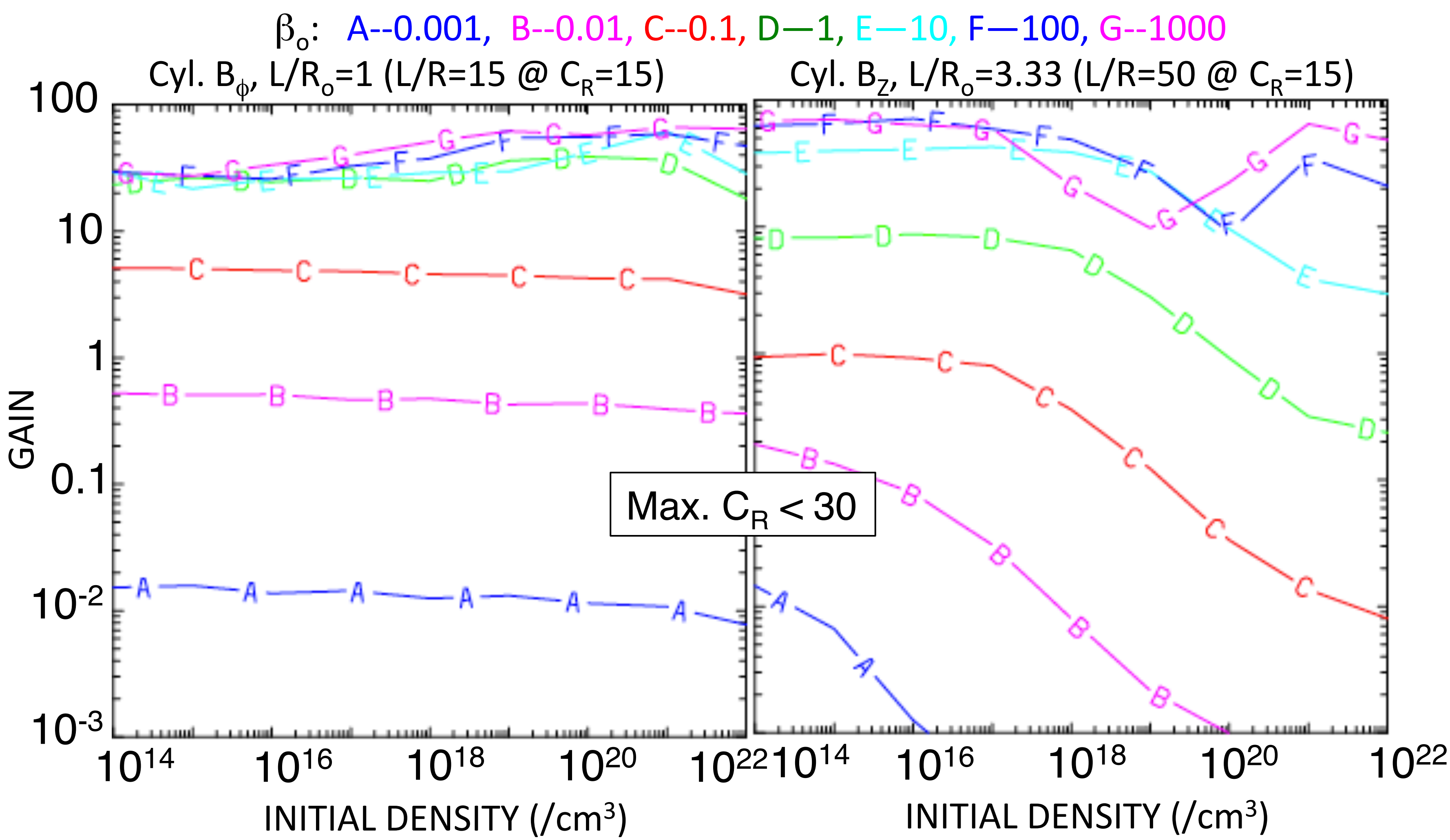


A. cylinder B_z, L=0.71 cm, E=670 KJ: max C_R=29.2, G=16.4
B. cylinder B_Φ, L=0.71 cm, E=670 KJ: max C_R=infinity, G=0
C. sphere, E=268 kJ: max C_R=13.3, G=20.2

- **Case B: slower increase in $\omega\tau$ leads to limited increase in temperature, increased Nernst voltage, further reducing magnetic flux and $\omega\tau$.**

The gain for cylindrical B_ϕ targets is similar to spherical targets; the gain for cylindrical B_z targets is different due to end losses.

T_o=189 eV → T=7 keV @ C_R=15 if adiabatic



Upper bounds on R_o, E_o set a lower bound on practical n_o; lower bound on R_o, upper bound on B_o set upper bound on practical n_o.

Example: 0.1 cm < R_o < 50 cm, E_o < 50 MJ, B_o < 500 kG

- **Cylindrical B_ϕ targets have very narrow n_o range that disappears with slight reduction in upper bounds on E_o, B_o for $\beta_o > 1$.**

β_o	1	10	100	1000
n_o (/cm^3) for R_o<50 cm	>4 x 10^{16}	>4 x 10^{17}	>3 x 10^{18}	>2 x 10^{19}
n_o (/cm^3) for R_o>0.1 cm	<4 x 10^{21}	<10^{22}	<10^{22}	<10^{22}
n_o (/cm^3) for E_o<50 MJ	> 10^{17}	> 5 x 10^{19}	> 6 x 10^{20}	>2 x 10^{21}
n_o (/cm^3) for B_o<500 kG	<2 x 10^{19}	<2 x 10^{20}	<2 x 10^{21}	<2 x 10^{22}
Practical n_o (/cm^3) range	10^{17}-2 x 10^{19}	5 x 10^{19}-2 x 10^{20}	6 x 10^{20}-2 x 10^{21}	2 x 10^{21}-10^{22}
Practical R_o range (cm)	30-2	3-1.5	1-0.7	1-0.1
Velocity v_o range (cm/μs)	0.2-1.5	8-10	20-20	30-40

- **Cylindrical B_z targets must operate at $\beta_o > 1$.**

β_o	1	10	100	1000
n_o (/cm^3) for R_o<50 cm	>7 x 10^{17}	>7 x 10^{17}	>7 x 10^{17}	>7 x 10^{17}
n_o (/cm^3) for R_o>0.1 cm	<3 x 10^{20}	<5 x 10^{20}	<2 x 10^{21}	< 10^{22}
n_o (/cm^3) for E_o<50 MJ	>2 x 10^{19}	>9 x 10^{18}	>7 x 10^{18}	>4 x 10^{19}
n_o (/cm^3) for B_o<500 kG	<2 x 10^{19}	<2 x 10^{20}	<2 x 10^{21}	<2 x 10^{22}
Practical n_o range (/cm^3)	--	9 x 10^{18}-2 x 10^{20}	7 x 10^{18}-2 x 10^{21}	4 x 10^{19}-10^{22}
Practical R_o range (cm)	--	4-0.2	5-0.1	3-0.1
Velocity v_o range(cm/μs)	--	1-4	2-10	7-20

- **Cylindrical B_ϕ targets will operate at larger R_o, lower β_o, and lower v_o.**

Under practical constraints of 1 mm < R_o < 10 cm, B_o < 500 kG, max C_R < 30, $(E_{fuel})_{ig}$ < 500 kJ, a recent paper concluded the following:

- **High gain is possible for each type of target, although each type operates in a different *n-B-R-v-E* range.**
- **Cylindrical B_z targets operate at a relatively high n_o (e.g., 10^{21}/cm^3), high β_o (>10) and velocity (e.g., 10 cm/μs), relatively small size (e.g., < 5 mm).**
- **Cylindrical B_Φ targets operate at a relatively low n_o (e.g., 10^{18}/cm^3), low β_o (< 1) and velocity (e.g., 0.5 cm/μs), relatively large size (e.g., 5 cm).**
- **The initial size, density, velocity of spherical targets spans the other types, but the initial temperature, magnetic field, energy can be lower; β_o is intermediate (0.1-10)**
- **Reaching the ignition condition does not necessarily lead to high gain.**
- **The operating range of each type of target can be extended somewhat by relaxing the practical constraints.**

Reference: I. Lindemuth, “The ignition design space of magnetized target fusion,” Phys. Plas. 22, 122712, 2015.

In spite of its simplifications, the model agrees reasonably with published, more complete calculations.

Slutz et al., Phys. Plas. 17, 056303 (2010): cylindrical B_z target

T_o=250 eV, n_o=4.45 x 10^{20}/cm^3, B_o= 300 kG, β_o=82, R_o=2.7 mm, L=5 mm

inferred: E_o=600 kJ, v_o=5 cm/μs

	Slutz	Full Model	Turn off endloss	Turn off endloss, Nernst	Turn off endloss, RB alpha dep.	Turn off endloss, all alpha dep.	B=0, turn off endloss
Yield (kJ)	500	449	516	891	308	260	8
$C_R=R_o/R_f$	25	24.4	24.7	22	36.4	36.6	50
Max. T_i (keV)	8	4.1	4.3	5.2	3.8	3.6	1.6
Max. B (MG)	130	147	137	143	269	273	---
Max. RB (MG-cm)	1.41	1.56	1.5	1.76	2	2.01	---

Knapp & Kirkpatrick, Phys. Plas. 21, 070701 (2014)

spherical B_Φ target

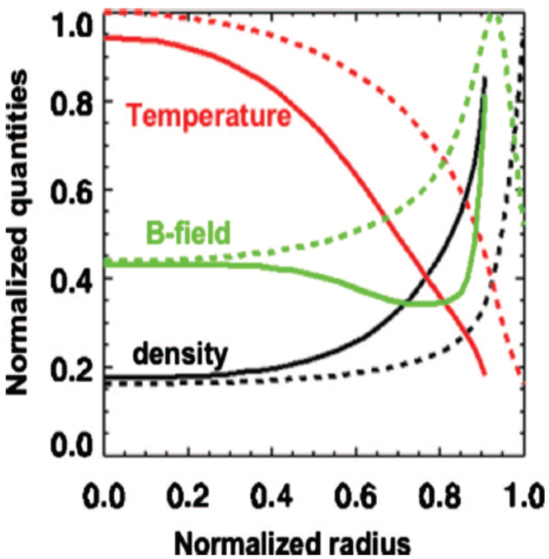
n_o= 4.26 x 10^{18}/cm^3, T_o= 80 eV, B_o=100 kG, β_o=162

R_o=4 cm, E_o=22 MJ, v_o=6 cm/μs

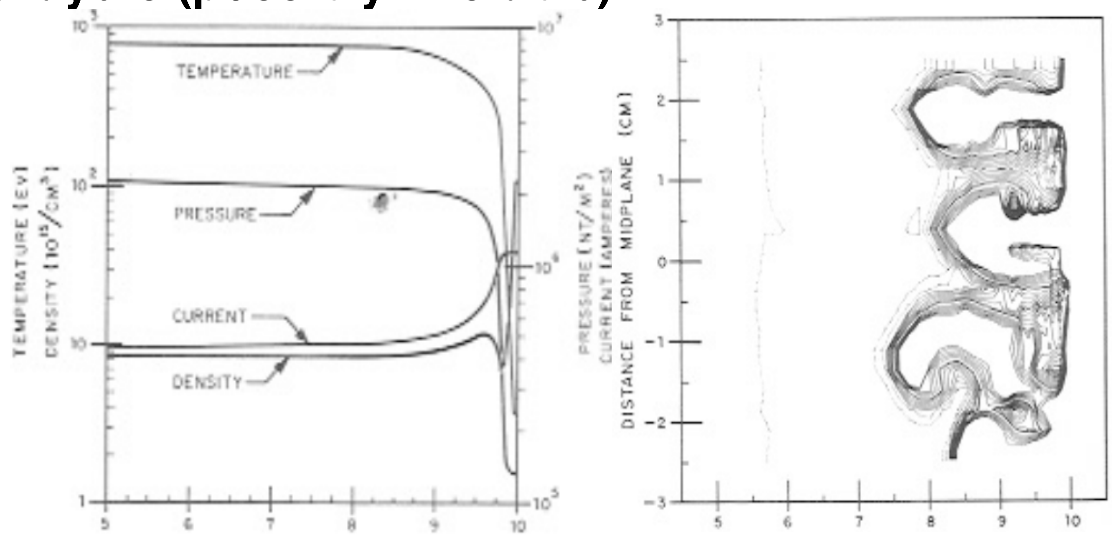
	K&K	Model
Gain	12.6	16
Max. $C_R=R_o/R_f$	~17	15.3
Max. T_i (keV)	> 80 keV	126

In spite of simplifications, the model agrees with more complete calculations, but ... has limitations, maybe (compensating?) errors.

- The density is always = $n_o(C_R)^b$ (b=2, cyl.; b=3, sph.), does not allow profile effects, boundary layers (possibly unstable):



Slutz et al., Phys. Plas. 17, 056303 (2010)



Lindemuth et al., Phys. Flu. 21, 1727 (1977) "Unstable behavior of hot, magnetized plasma in contact with a cold wall"

- "Volume burn;" no propagating burn waves.

- No "cold fuel" in cylindrical geometries for very high gain; initial results for sphere: "The promise of magnetized fuel: high gain in ICF," Lindemuth & Kirkpatrick, Fus. Tech. 20, 829 (1991) → optimum: n_o= 10^{21}/cm^3, v=10 cm/μs, B=100 kG. Similar to Slutz & Vesey, Phys. Rev. Lett. 108, 025003-1 (2012).

In spite of simplifications, the model agrees reasonably with more complete calculations, but ... has limitations, maybe (compensating?) errors.

- The shell model is intended to give "ballpark" velocity, energy
- No realistic shell EOS (pV^{γ}=const); no realistic drive conditions
- A total energy equation is used to determine v until abs(v) < 0.1*v_o, then replaced with a momentum equation that is not totally consistent.
- Pressure balance with fuel is imposed, i.e., $p_{shell}=p_i+p_e+p_B+p_{rad}$
- $V_o/V=(p_{sh}/p_o)^{1/g}$; shell volume decreases, internal energy increases if fuel pressure increases (e.g., ignition) even without motion
- Presumably, more equations describing the shell could increase the realism of the calculations (see McBride and Slutz, Phys. Plas. 22, 052708, 2015; also, Langendorf and Hsu, this conference)

OBJECTIVE: use analysis and time-dependent modeling to show that fusion energy might be possible in a density range intermediate between conventional ICF and MCF

OUTLINE

I. Necessary (but not sufficient) condition for fusion: $P_{loss} < P_{fus}$
   a. $B=0$ (ICF): why ICF must operate at high density, pulsed
   b. steady state (MCF); why magnetization required, operate at low density
   c. attractiveness of intermediate density
   d. magnetized targets to access intermediate density

II. Ignition condition: $P_{abs} = P_{loss}$
   a. ignition possible at ρR << 0.4 g/cm^2 (ICF)

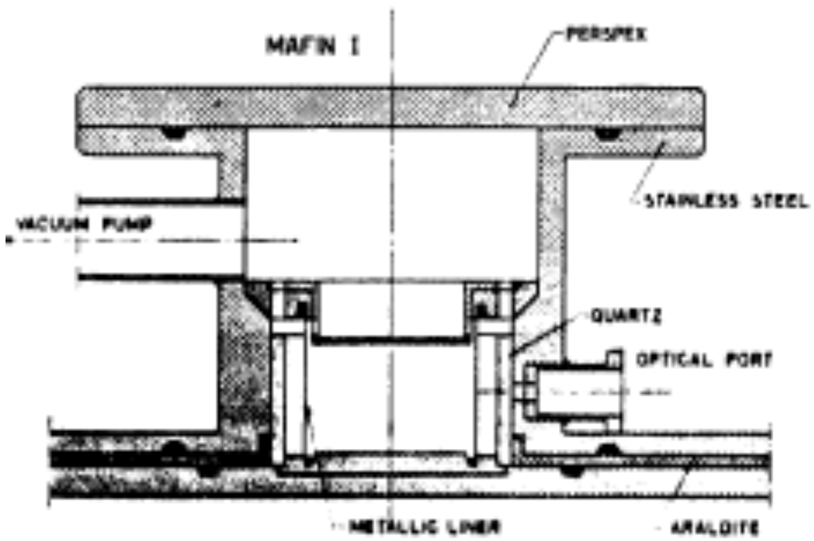
III. Characteristics of magnetized targets
   a. use ignition condition to define target plasma n_o-T_o-B_o-R_o
   b. simple implosion model: time-dependent calculations to define driver E_o, v_o and determine gain
   c. accessible space depends upon geometry

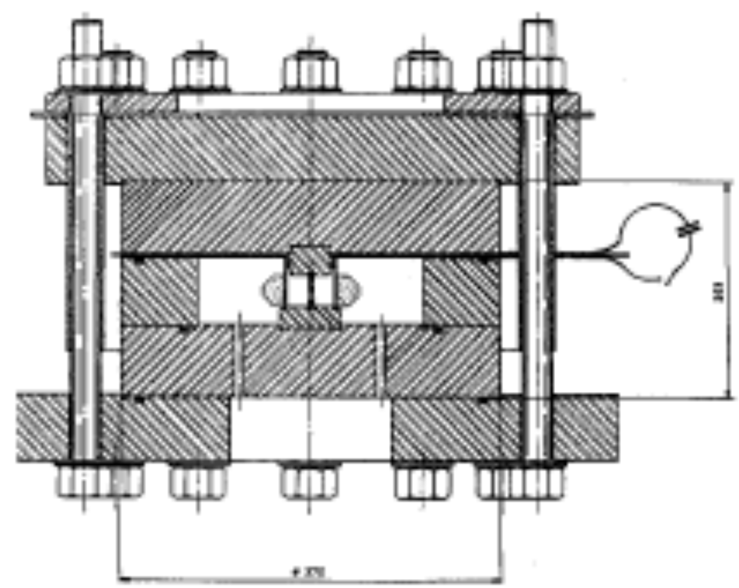
IV. Past and present MTF—selected examples

V. Concluding remarks

The group at Frascati, Italy was among the first to start down the pathway now known as Magnetized Target Fusion

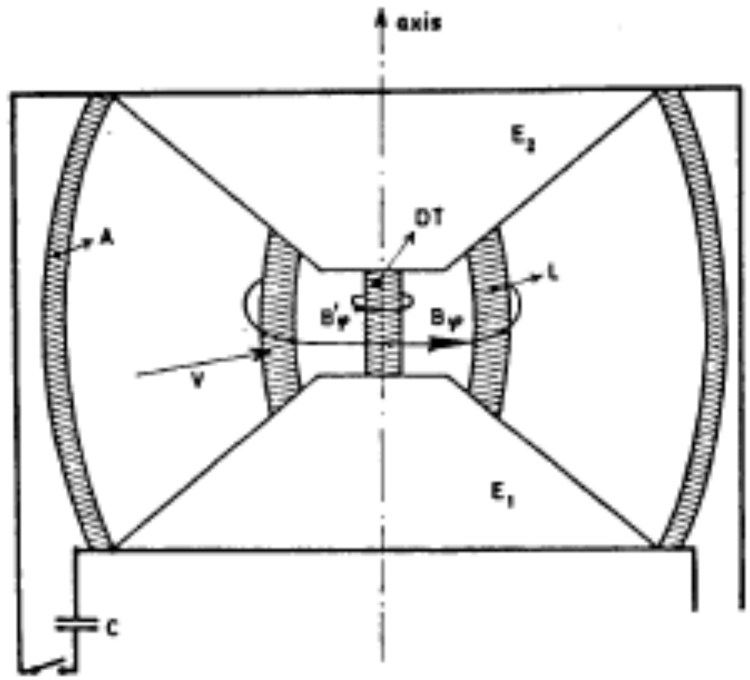
- "The principle is described of **inertial confinement of plasma** in which a cylindrical metallic shell compresses a magnetic field and plasma in a 'soft-core' geometry ... the source of the kinetic energy of the shell can be either a condenser bank or an annular explosive charge"—J. Linhart, H. Knoepfel, C. Gourlan, "Amplification of Magnetic Fields and Heating of a Plasma by a Collapsing Metallic Shell," Nuc. Fus. Supp. Pt. 2, p. 733 (1962).





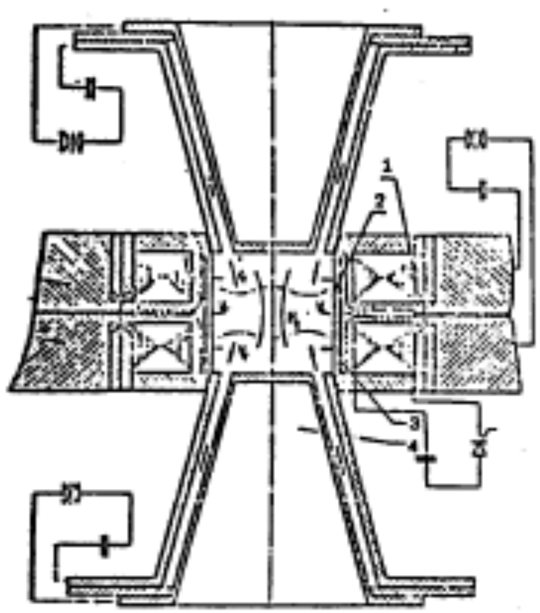
By 1970, the Frascatti group had delineated the fundamental challenges of MTF.

- "All of these requirements point to an apparatus in which cylindrically or spherically collapsing dense plasma piston (liner) compresses a mixture of D-T plamsa and a magnetic field. Thus, one encounters principally two problems: (1) how to create a dense, rapidly converging plasma liner; (2) how to produce a suitable D-T plasma core with its magnetic field ... One may suspect that either plasma instabilities or heat conduction may not allow heating to thermonuclear temperatures."– J. G. Linhart, "Very-high-density Plasmas for Thermonuclear Fusion, Nuc. Fus. 10, p. 211 (1970).



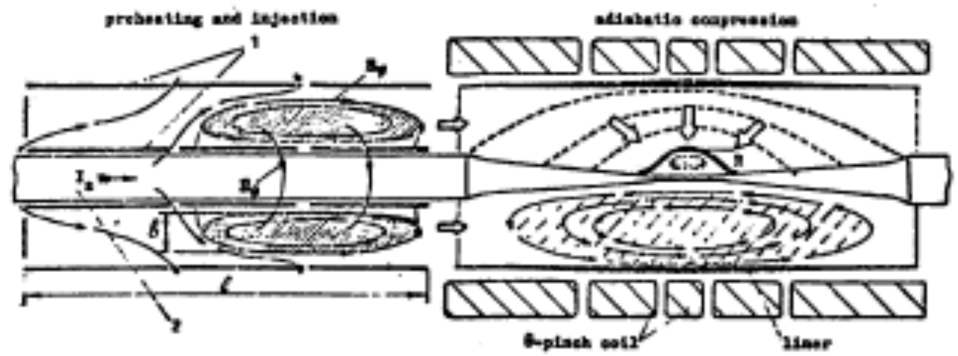
In the 1970's, the Soviet Union pursued a number of concepts that would now be called MTF

- **Poloidal magnetic fields (B_r-B_z) were used to shape an imploding liner; a number of plasma formation configurations were considered.**



1. MAGNETIC FIELD COIL 2. LINER 3. PROTECTIVE CYLINDER 4. PLASMA INJECTOR

Allkhanov et al.



Eskov, Kurtmullaev et al.

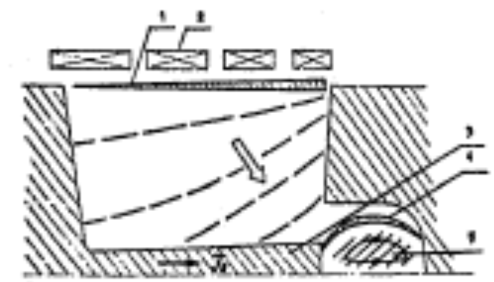
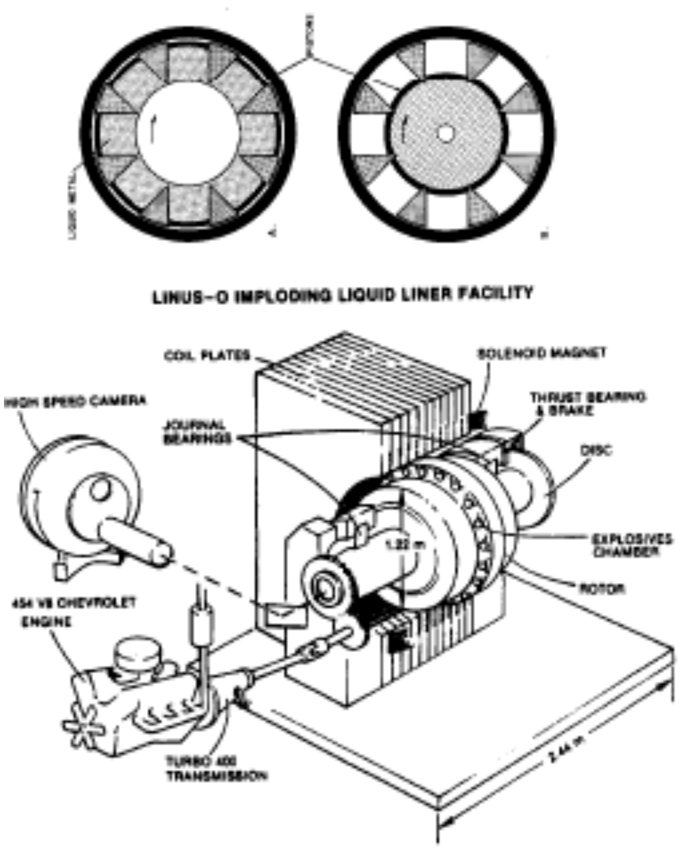


Diagram of the bursting of the shell using an MK-generator. 1 – liner of the MK-generator, 2 – pusher coil, 3 – central conductor, 4 – bursting shell, 5 – initial plasma with thermoinsulating fields.

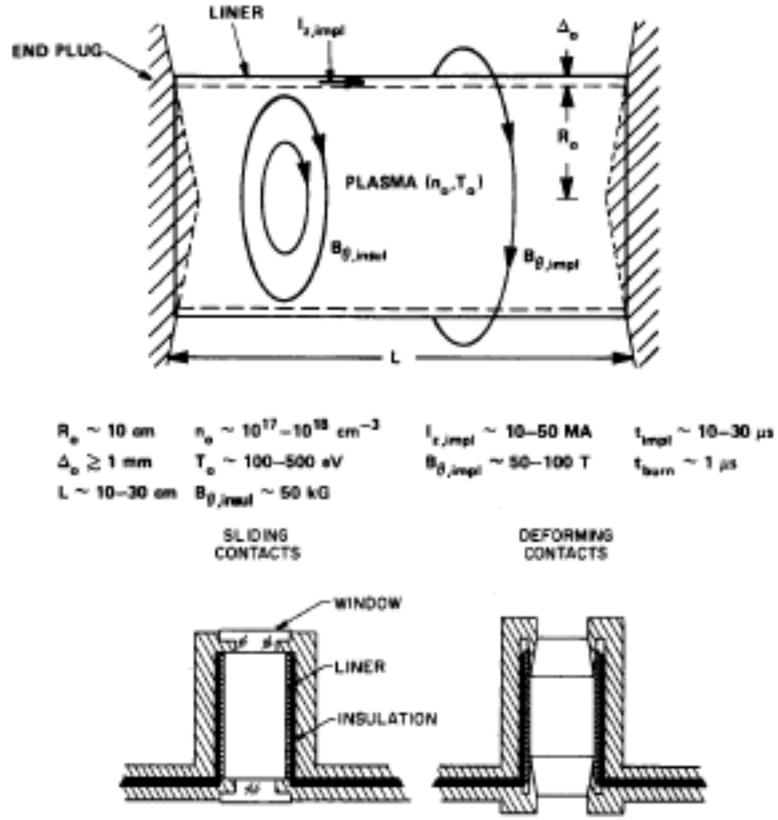
Kurtmullaev et al.

- **These efforts appear to be spearheded by E. Velikov, who would later become chairman of the ITER Council.**

The Soviet activities stimulated a number of fledgling efforts in the US

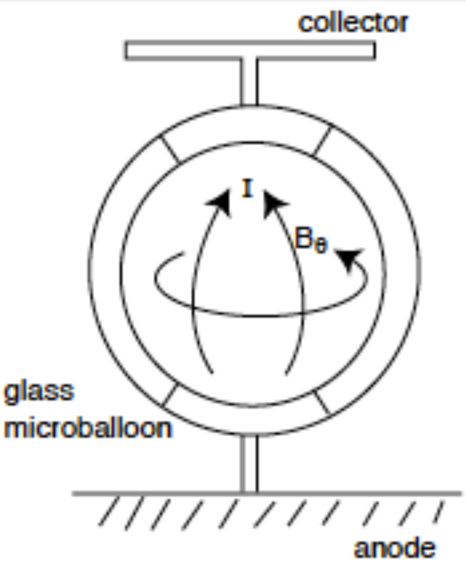


NRL LINUS (Turchi et al.)
v = 0.1 mm/μs
Θ-pinch plasma formation



LANL "Fast Liner" (Sherwood et al.)
v = 10 mm/μs
z-pinch plasma formation and liner driver

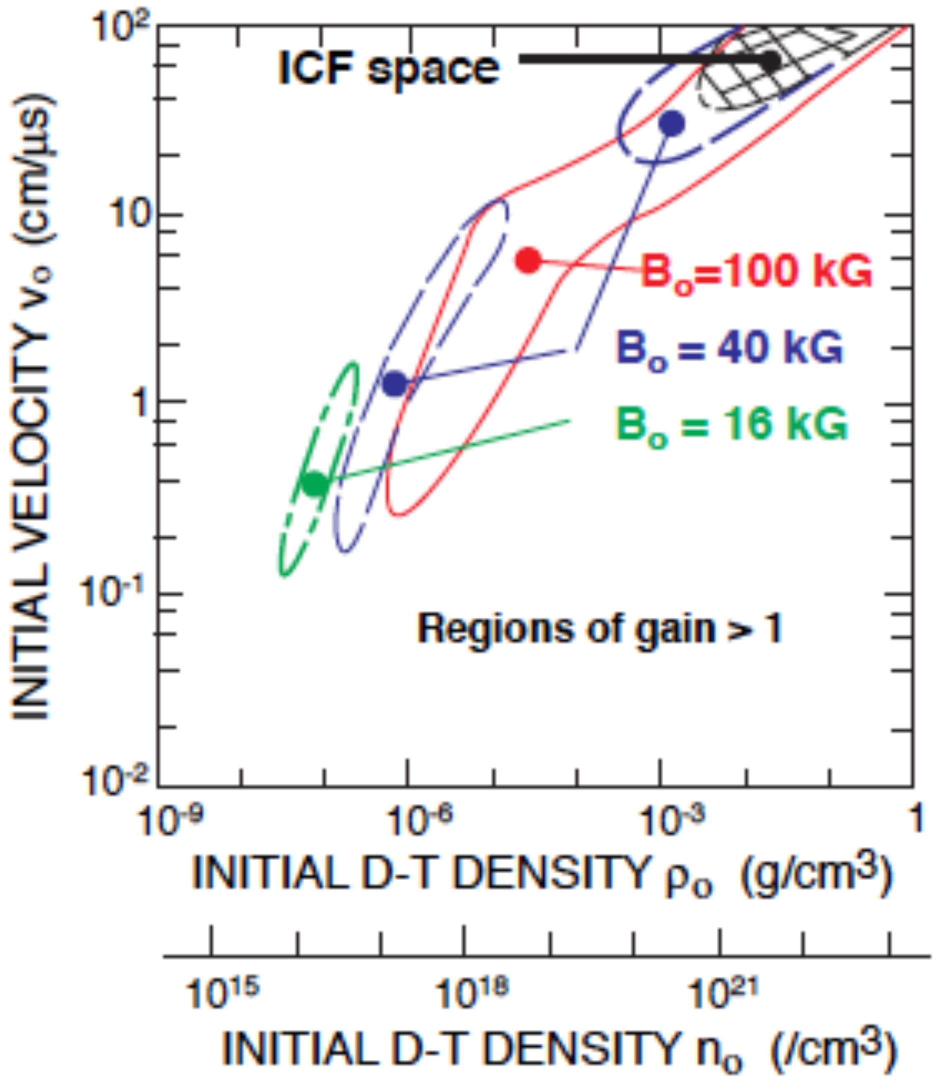
First neutrons ever produced by US particle beam fusion program came from a magnetized target (see Physics Today, August 1977).



The Sandia "Φ" Target

- Target was driven by Sandia electron beam (REHYD, 1 MeV, 250 kA, 100 ns, 0.04 TW).
- Collector stopped a non-relativistic precursor (5-15 kA, 1 μs), creating a voltage which induced an electrical discharge (diffuse z-pinch) in fuel.
- The 3-mm-dia. targets imploded at 4 cm/μs; 10^6-10^7 neutrons were observed in CD_2 wire and D-T gas filled ($6 \times 10^{18}/cm^3$) targets
- No neutrons observed without precursor or in variety of "null" targets.
- 2-D MHD computations indicated 5-20 eV preheat, 300-500 eV final temperature, consistent with observed yield--Lindemuth & Widner, Phys. Flu. 24, p. 746 (1981).
- Computations predicted high gain for ion & electron magnetized targets at low intensity—Sweeney & Farnsworth, Nuc. Fus. 21, p. 41 (1981).

Lindemuth and Kirkpatrick (Nuc. Fusion 23, p. 263, 1983) formulated a simple implosion model and showed gain was possible in a new (compared to ICF) region of parameter space

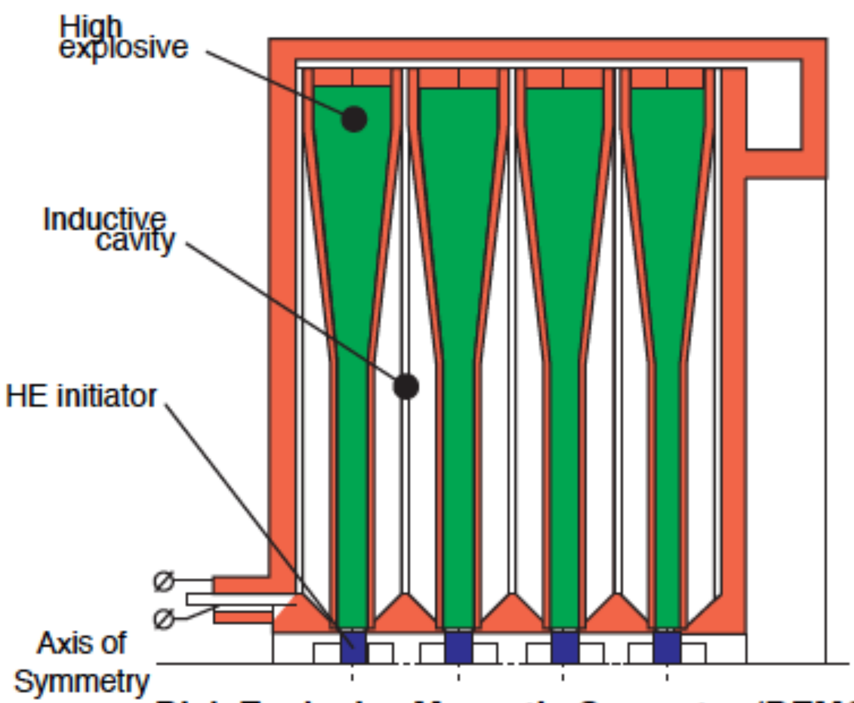


- The time-dependent calculations reported in this presentation and in a recent paper (Phys. Plas. 22, 122712, 2015) represent an extension of the 1983 model.

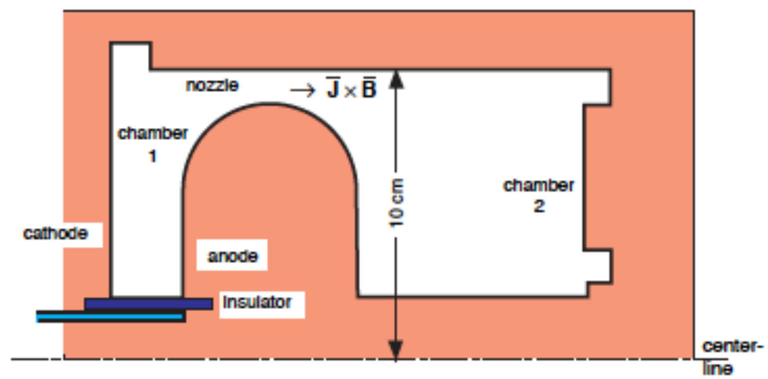
Much of the current US interest in MTF can be traced back, at least in part, to the Russian “MAGO” concept.

- **Building on the work of Nobel Laureate Andre D. Sakharov (“father of the Soviet H-bomb”), the All-Russian Institute of Experimental Physics (VNIIEF) developed explosively powered generators that produce more electrical current (200 MA) and energy (200 MJ) than any US capability.**

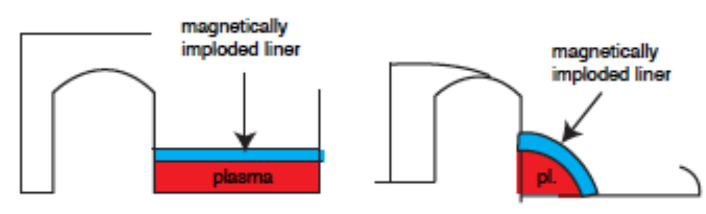
- **The major motivation for this capability was an MTF approach “MAGO.”**



Disk Explosive Magnetic Generator (DEMG)



MAGO (Magnitnoye Obzhatiye)



Implosion scenarios

Joint MAGO experiments were conducted by Los Alamos National Lab. (LANL) and VNIIEF ("the Russian Los Alamos")

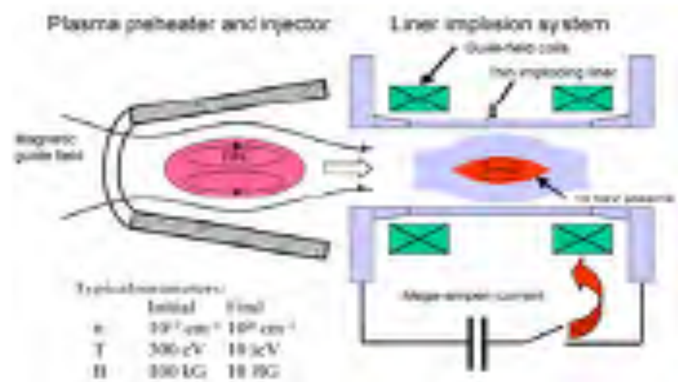
- **MAGO-II plasma formation experiment (i.e., no implosion) at LANL (October 1994) set LANL record for fusion neutrons in a single experiment (10^{13}).**

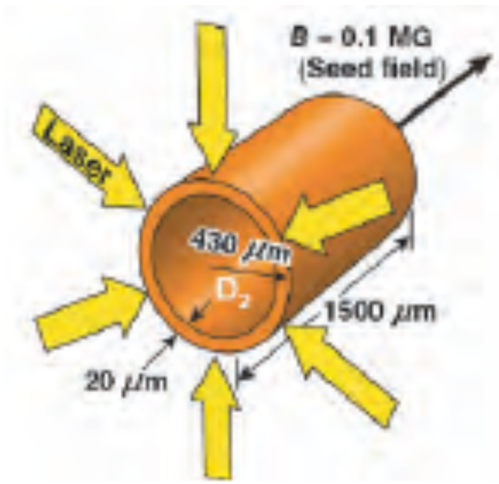
- **HEL-1 High Energy Liner experiment (i.e., no target plasma) at VNIIEF (October 1996) was highest kinetic energy liner experiment ever for US scientists (> 20 MJ).**

- **Experiments conducted as part of unprecendented post-Cold-War collaboration between institutes that designed their nation's first nuclear weapons.**

Promising experimental results have been obtained in the last decade

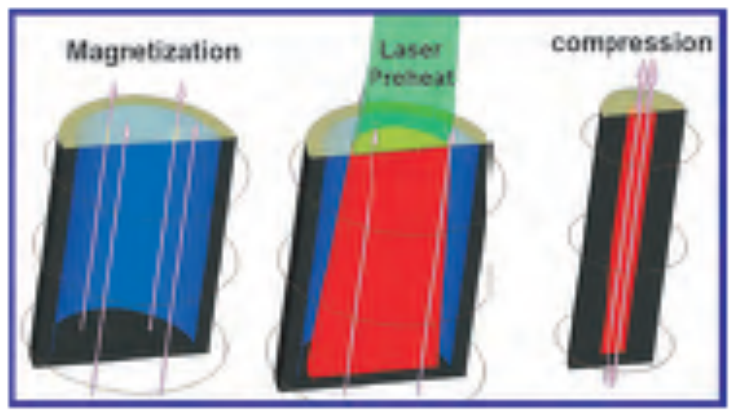
- **An AFRL/LANL/UNR team used a 12 MA, 10 μs current to implode a 10-cm-dia., 30-cm-long liner and compress an injected FRC plasma to a record $10^{18}/cm^3$.**





- **The U. of Rochester used a laser to compress a < 1 mm-dia. shell and observed record magnetic field (70 MG) and a 30% increase in neutron yield due to the magnetic field.**

- **SNL's MagLIF 20-MA, 100 ns implosion of a 5 mm-dia, 7.5 mm long laser-formed plasma lead to ~ 10^{12} D-D neutrons; secondary D-T neutrons indicated magnetization of the D-D-formed tritons.**



At 2012 APS-DPP (Providence), Velikovich discussed magnetic flux compression, high fields, and applications, including fusion

Magnetic Flux Compression in Plasmas

A. L. Velikovich[1], S. A. Chaikovsky[2], J. P. Chittenden[3],
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[2]High Current Electronics Institute, Tomsk, Rus
[3]Imperial College, London, UK
[4]Sandia National Laboratories, Albuquerque, N
[5]Starmark, Inc., San Diego, CA, USA
[6]Laboratory for Laser Energetics, University of
[7]Berkeley Research Associates, Beltsville, MD
[8]Icarus Research, Bethesda, MD, USA
[9]Russian Federal Nuclear Center, VNIIEF, Sar

Presented at the 54th Annual Meeting
October 31, 2012 • Pr

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Nuclear Security Administration u

Outline

- Why magnetic flux compression?
  - Because this is the only way to produce in the laboratory magnetic fields of ~100 MG on a nanosecond time scale
- Why would anyone need magnetic fields that high?
  - To explore new opportunities for inertial confinement fusion
  - Other MFC applications in the areas of Z-pinch physics & pulsed power
    - Stabilization of Z-pinch implosions
    - Increase peak current, shorten the rise time
    - K-shell production, neutron production, code validation
- Why plasma, which is a notoriously unreliable medium, needs to be used instead of solid conductors?
  - No condensed medium survives multi-Mbar pressures and keV temperatures
  - We need the field inside the plasma

Interest in MTF is increasing.

- In 2014, the US Dept. of Energy Advanced Research Projects Agency (ARPA-E) announced a $30M program ALPHA (Accelerating Low Cost Plasma Heating and Assembly) that "will focus on intermediate density fusion approaches between low-density, magnetically confined plasmas and high-density, inertially confined plasmas" and "seeks to create and demonstrate tools that aid in the development of new lower-cost pathways ... and enable more rapid progress in fusion research and development ." 7 of the 9 funded projects are related to MTF, either driver or target plasma; first fusion-energy oriented MTF "program" with "critical mass."

ALPHA-funded PLX @ LANL

- MTF activity in Russia, China, Germany, France, India

- Three MIF sessions (Monday BO8 & CO8, Tuesday GP10) and scattered papers at this conference.

OBJECTIVE: use analysis and time-dependent modeling to show that fusion energy might be possible in a density range intermediate between conventional ICF and MCF

OUTLINE

I. Necessary (but not sufficient) condition for fusion: $P_{loss} < P_{fus}$
   a. $B=0$ (ICF): why ICF must operate at high density, pulsed
   b. steady state (MCF); why magnetization required, operate at low density
   c. attractiveness of intermediate density
   d. magnetized targets to access intermediate density

II. Ignition condition: $P_{abs} = P_{loss}$
   a. ignition possible at $\rho R << 0.4$ g/cm^2 (ICF)

III. Characteristics of magnetized targets
   a. use ignition condition to define target plasma n_o-T_o-B_o-R_o
   b. simple implosion model: time-dependent calculations to define driver E_o, v_o and determine gain
   c. accessible space depends upon geometry

IV. Past and present MTF—selected examples

V. Concluding remarks

MTF scientific issues and related topics

- How to form high-β plasmas with the requisite n_o, T_o, B_o, and R_o that are also compatible with an implosion system (biggest MTF challenge?)
- Drivers with requisite E_o and v_o, capable of reaching the needed C_R, also compatible with plasma formation system (reactor compatibility?).
- Physics and stability of magnetically driven liners (cylindrical and quasi-spherical with “proof-of-principle” parameters and convergence have been demonstrated).
- Interaction of fuel with wall (impurities?)
- Magnetic reduction of thermal conduction (“Anomalous,” Bohm? only at low β?).
- Physics and stability of driver/fuel interface during deceleration and turn-around (dwell time).
- Magnetic enhancement of alpha particle deposition.
- Can high gain be achieved without ignition?
- High gain “cold fuel” layer compatible with plasma formation (formed by convection to cold wall?).

MTF is an emerging field rich in possibilities for physics discoveries and contributions to fundamental science and energy development.

- **The vast parameter space between MCF and ICF is relatively unexplored.**
- **In contrast to conventional ICF unmagnetized targets, magnetized targets**
  - **--can have varied geometries**
  - **--do not require precise driver pulse shaping**
  - **--do not require high convergences --have a wide design space**
  - **--are relatively insensitive to parameter variations**
  - **--have many driver candidates**
  - **--may reach "breakeven"and high gain with existing driver technology**
- **Because MTF has different time, length, and density scales, MTF reactors will have different characteristics and trade-offs, increasing chances that a practical fusion scheme can be found.**

MTF may be the shortest, least expensive path to ignition and high gain

"Producing an ignited plasma will be a truly notable achievement for mankind and will capture the public's imagination. Resembling a burning star, the ignited plasma will demonstrate a capability with intense potential to improve human well being. Ignition is analogous to the first airplane flight or the first vacuum-tube computer. As in those cases, the initial model need not resemble the one that is later commercialized." President's Council of Advisors on Science and Technology (PCAST), Report on Fusion Energy, p.22, July 1995.

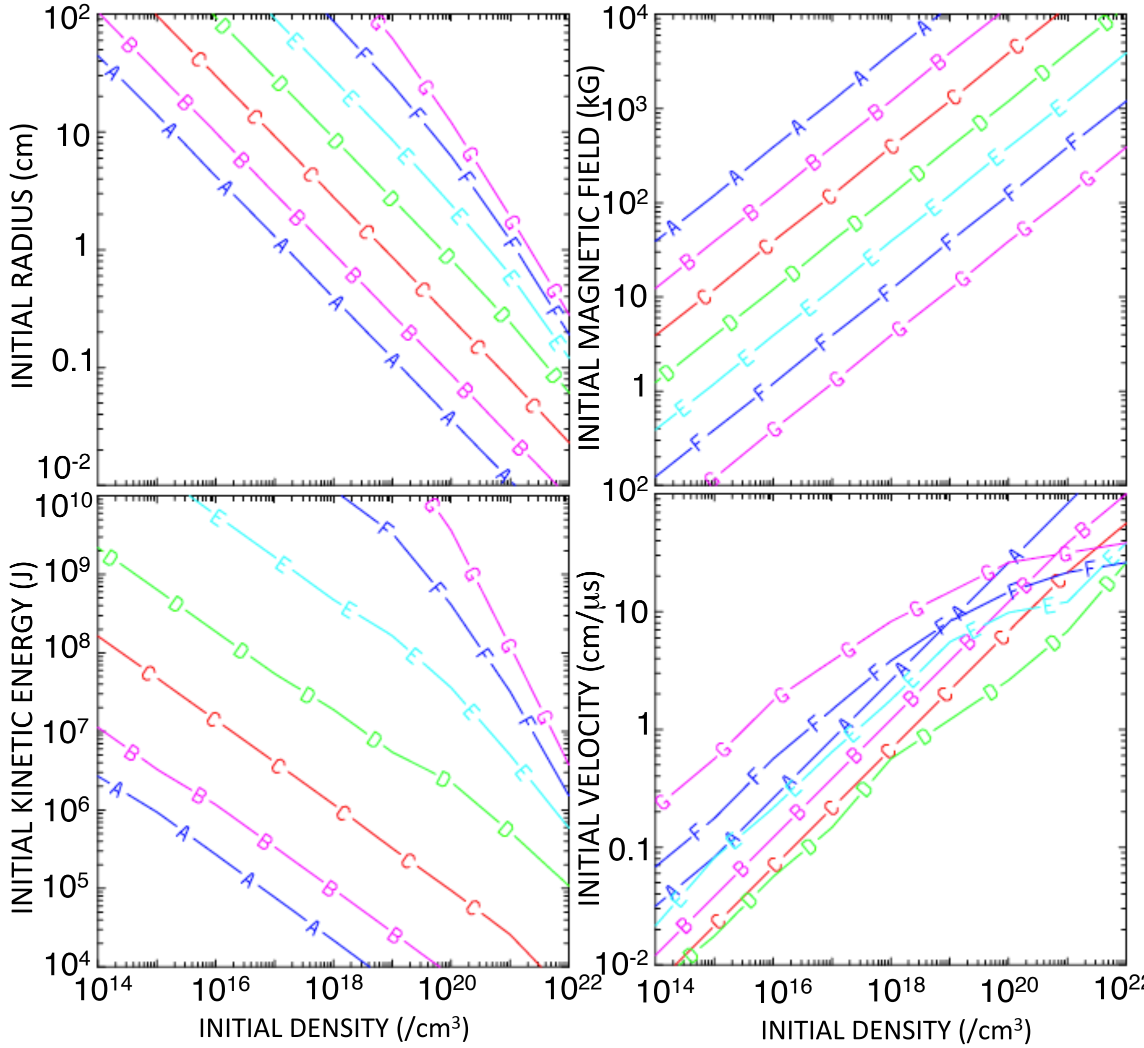
Practical considerations force cylindrical targets to operate at a higher density than spherical targets.

B_ϕ targets:

- if flux conserving, $B=B_oC_R$, so RB is constant and R_oB_o must equal $(RB)_{ig}$.
- The magnetic energy is also a constant: $E_B=(B^2/2\mu_o)(\pi R^2L)$, so no work is required to compress the magnetic field.
- Limitations on initial B magnitude may place upper bound on initial n.

β_o: A--0.001, B--0.01, C--0.1, D—1, E—10, F—100, G—1000

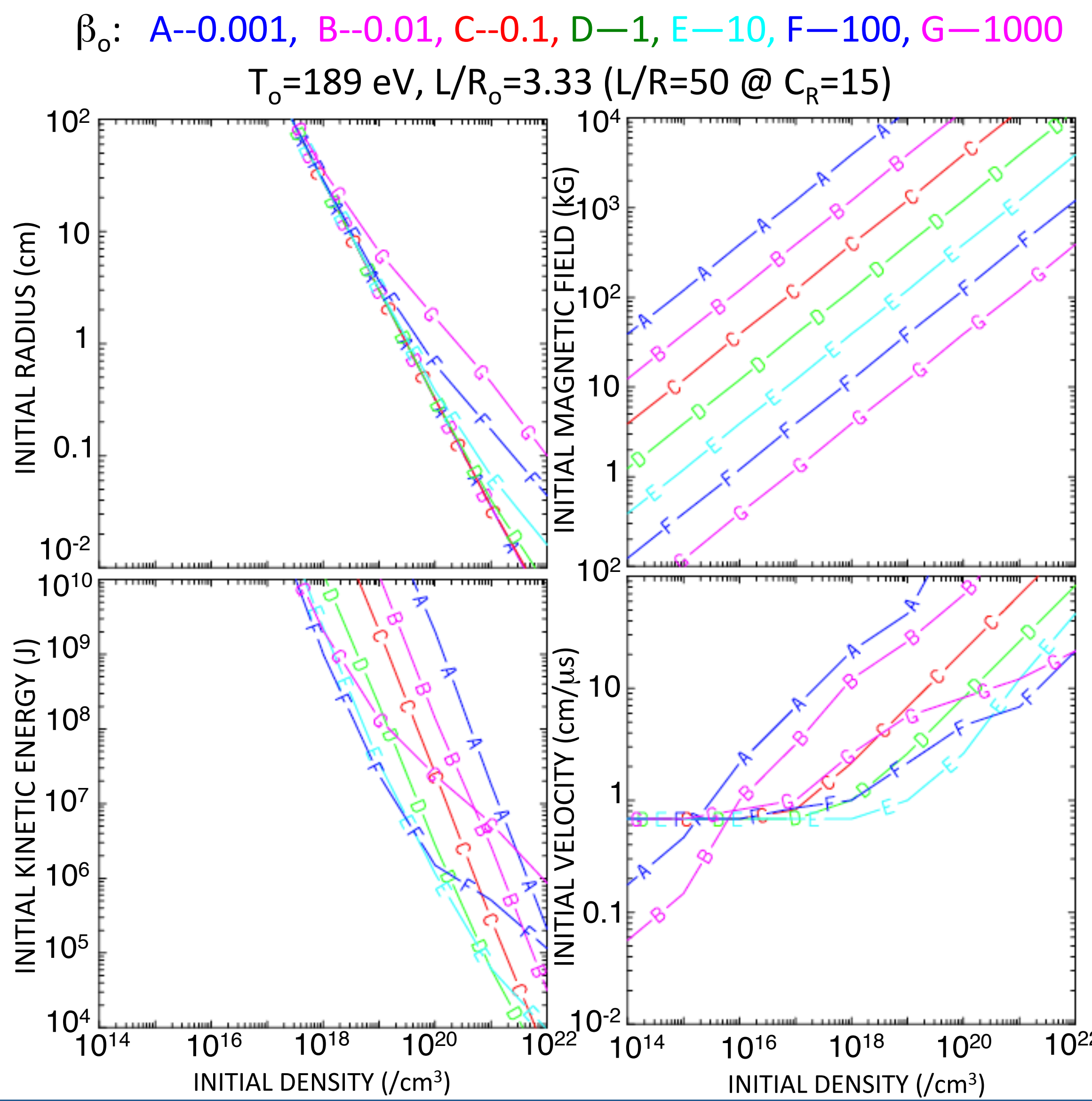
T_o=189 eV, L/R_o=1 (L/R=15 @ C_R=15)



Practical considerations force cylindrical targets to operate at a higher density than spherical targets.

B_z targets:

- **Must operate at high β_o (> 10), high n_o (> 10^{20}/cm^3), and high v_o (> 5 cm/μs)**



Practical considerations force cylindrical targets to operate at a higher density than spherical targets.

B_z targets:

- **Must operate at high β_o (> 10), high n_o (> 10^{20}/cm^3), and high v_o (> 5 cm/μs)**
- **Limitations on initial B magnitude may place upper bound on n_o, e.g., if B_o < 500 kG, n_o < 10^{19}/cm^3 for β_o=1 → E_o > 100 MJ.**