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

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Invited tutorial presented at annual meeting of American Physical Society Division of Plasma Physics, San Jose, CA, October 31-November 4, 2016.
Acknowledgements

◆ Scott Hsu (LANL), Dan Sinars (SNL)—nominators

◆ Farhat Beg (UCSD), Bruno Bauer (UNR)—nomination support

◆ Ronald C. (Ron) Kirkpatrick (LANL, retired)—formulated original simplified implosion model of unmagnetized targets (1981); collaborated on original model of magnetized targets (1983); technical discussions ever since.

◆ 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.

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

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

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

$10^{11}$—stack > 3 round trips to sun
$10^{16}$ seconds—300 million years

NIF

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

Is there anything in between?

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: $P_{\text{loss}} < P_{\text{fus}}$
   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: $P_{\text{abs}} = P_{\text{loss}}$
   a. ignition possible at $\rho R \ll 0.4 \text{ g/cm}^2$ (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: \[ \frac{P_{\text{loss}}}{P_{\text{fus}}} = f_{\text{loss}} < 1, \quad P_{\text{fus}} = \frac{dE_{\text{fus}}}{dt} = \int Q_{\text{fus}} \, dV, \quad P_{\text{loss}} = \frac{dE_{\text{loss}}}{dt} = \int Q_{\text{loss}} \, dV \]

Classical: \[ Q_{\text{loss}} = Q_{\text{rad}} + Q_{\text{tc}}, \quad Q_{\text{rad}} = C_{\text{rad}} n^2 T^{1/2}, \quad Q_{\text{tc}} = -\nabla \cdot K \nabla T \]

Approximate \( Q_{\text{tc}} \):

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

where \( a \) = characteristic dimension, \[ \nabla T \approx -\frac{T}{g_{\text{tc}} a}, \quad \frac{V}{S} = g_1 a, \quad V = g_2 a^3 \]

\( g_1, g_2 \) are geometric quantities, e.g., sphere \( g_1 = \frac{1}{3}, \quad g_2 = \frac{4\pi}{3} \)

Estimate \( g_{\text{tc}} \):

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

\[ B = 0 \rightarrow m = \frac{5}{2} \rightarrow g_{\text{tc}} = \frac{7}{4}, \quad \text{Strong } B (\omega \tau >> 1) \rightarrow m = -\frac{1}{2} \rightarrow g_{\text{tc}} = \frac{1}{4} \]
Energy loss and fusion rates can be used to estimate minimum size, energy, etc., for energy gain at any $n$-$T$-$B$-$f_{\text{loss}}$ combination.

- From approximation of $Q_{tc}$:
  \[ a_{\text{min}}^2 = \frac{K T}{g_1 g_{tc}} \frac{1}{f_{\text{loss}} Q_{\text{fus}} - Q_{\text{rad}}} \]

- Fuel mass:
  \[ M_{\text{min}} = n_i (m_i + m_e) g_2 a_{\text{min}}^3 \]

- Fuel thermal energy:
  \[ E_{\text{plas}}^{\text{min}} = 3n_i T g_2 a_{\text{min}}^3 \]

- Required heating power:
  \[ P_{\text{heat}} = (Q_{tc} + Q_{\text{rad}}) g_2 a_{\text{min}}^3 \]

- Required surface heating (intensity):
  \[ I_{\text{heat}} = \frac{P_{\text{heat}}}{S} = (Q_{tc} + Q_{\text{rad}}) g_1 a_{\text{min}} \]

- Implosion velocity for pdV heating:
  \[ v_{\text{imp}} = \frac{I_{\text{heat}}}{(p_i + p_e)} = \frac{I_{\text{heat}}}{2n_i T} \]
$B=0$, D-T fuel: minimum size, power, energy, and pressure of unmagnetized fuel are strong functions of density, temperature.

US electrical generating capacity $\sim 10^{12} \text{ W}$

Minimum size (cm) $f_{\text{loss}}=0.2$

Minimum energy (J)

Minimum power (W)

Daily energy from sun

Ion density (cm$^{-3}$)

Temperature (ev)

Atmospheric density

Earth’s radius

P = 3.2 M-atm

P = 3.2 atm
**B=0, D-T fuel:** minimum size, power, energy, and pressure of unmagnetized fuel are strong functions of density, temperature.

- **spherical geometry** \( f_{\text{loss}} = 0.2 \)
- **minimum size** (cm)
- **minimum energy** (J)
- **minimum power** (W)

\[ p = 3.2 \text{ atm} \]

**US electrical generating capacity** \( \sim 10^{12} \text{ W} \)

- **plasma pressure** \( = 1000 \text{ atm} \)
- **atmospheric density**
- **Earth's radius**
- **daily energy from sun**

- **"Steady state"** requires pressure \(< <\) e.g., 1000 atm, is not possible for B=0 \((Y_{\text{steel}} = 2500 \text{ atm})\).
B=0, D-T fuel: minimum size, power, energy, and pressure of unmagnetized fuel are strong functions of density, temperature.

**Spherical geometry:**

- Minimum size (cm)
- Power (W)
- Energy (J)
- Pressure (atm)

- US electrical generating capacity: \(~10^{12}\) W
- NIF stored energy: 400 MJ
- NIF hot spot

**Plasma pressure = 1000 atm.**

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

- Daily energy from sun
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.

\[
Cost = C_1E_{plas} + C_2P_{heat} \approx \frac{Cost_{ITER}}{E_{ITER}} E_{plas} + \frac{Cost_{NIF}}{P_{NIF}} P_{heat}
\]

- "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/\mu s 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:
  
<table>
<thead>
<tr>
<th>Cylindrical</th>
<th>Cylindrical</th>
<th>Spherical</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_z$</td>
<td>$B_\Phi$</td>
<td>$B_\Phi$</td>
</tr>
<tr>
<td>Shell at rest</td>
<td>Imploding shell</td>
<td></td>
</tr>
<tr>
<td>Hot, magnetized plasma</td>
<td>Warm, magnetized plasma</td>
<td></td>
</tr>
</tbody>
</table>
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

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II. Ignition condition: \( P_{\text{abs}} = P_{\text{loss}} \)
   a. ignition possible at \( \rho R \ll 0.4 \text{ g/cm}^2 \) (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 magnetization of the D-T fusion fuel enhances alpha particle deposition and fuel self heating, potentially leading to ignition at a lower $\rho R$ 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:
  \[
  f_d = \frac{1}{1 + \frac{f_{\rho R}}{f_{RB}}} \quad f_{RB} = 0.0843 \left( \frac{RB}{0.2703} \right)^2
  \]
  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 $B_\phi$, $\beta=1$ at ignition

<table>
<thead>
<tr>
<th>$\rho$</th>
<th>$R$</th>
<th>$RB$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{14}$</td>
<td>$10^2$</td>
<td>1</td>
</tr>
<tr>
<td>$10^{16}$</td>
<td>$10^4$</td>
<td>$10^2$</td>
</tr>
<tr>
<td>$10^{18}$</td>
<td>$10^5$</td>
<td>$10^4$</td>
</tr>
<tr>
<td>$10^{20}$</td>
<td>$10^7$</td>
<td>$10^6$</td>
</tr>
<tr>
<td>$10^{22}$</td>
<td>$10^9$</td>
<td>$10^8$</td>
</tr>
<tr>
<td>$10^{24}$</td>
<td>$10^11$</td>
<td>$10^{10}$</td>
</tr>
<tr>
<td>$10^{26}$</td>
<td>$10^{13}$</td>
<td>$10^{12}$</td>
</tr>
</tbody>
</table>

- The $\rho R$ can be orders of magnitude less than the 0.4 g/cm$^2$ 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 $B_\phi$, $\beta=1$ & $L/R=15$ at ignition—-the parameter space is similar to spherical $B_\phi$.

- **Bottom:** Cylindrical $B_z$, $\beta=1$ & $L/R=50$ at ignition—-at low density, thermal conduction to the end caps determines the length ($\rho L > 0.08$ g/cm$^2$), which in turn determines $R$ ($R=L/50$), hence the large $RB$. 
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   d. magnetized targets to access intermediate density

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

III. Characteristics of magnetized targets
   a. use ignition condition to define target plasma \( n_0-T_0-B_0-R_0 \)
   b. simple implosion model: time-dependent calculations to define driver \( E_0, v_0 \) and determine gain
   c. accessible space depends upon geometry

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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

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

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

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

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

◆ 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 \(\nabla T = -T / (g_i a)\))
Thermal and radiation losses not absorbed by shell
No magnetic flux containment by shell
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 processes
-- provide a learning tool
-- help build an “intuition” about the “trade-offs”
  driver complexity $\longleftrightarrow$ initial plasma formation
  initial temperature $\longleftrightarrow$ 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:
  \[
  C_R = \frac{R_o}{R} \quad T = T_o(C_R)^2 \quad n = n_o(C_R)^3 \quad B = B_o(C_R)^2 \quad \beta = \beta_o C_R
  \]

- Step 1: choose $T_{ig}$, $C_{ig}$, $n_o$, and $\beta_o$ or $B_o = (4\mu_o n_o T_o / \beta_o)^{1/2}$
  \[
  T_o = T_{ig}(C_{ig})^2 \quad n_{ig} = n_o(C_{ig})^3 \quad B_{ig} = B_o(C_{ig})^2
  \]

- 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, \( n_o=10^{18}, \beta_o=1, T_o=70 \text{ eV}, B_o=75 \text{ kG}, R_o=1.6 \text{ cm} \) (initial conditions projected back from ignition at 7 keV, \( C_R=10 \)):

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

Maximum \( C_R < 25 \).

A maximum gain of 48 occurs at 0.56 cm/\( \mu \text{s} \), 145 kJ; burn fraction--29%
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, $n_o=10^{18}$, $\beta_o=1$, $T_o=70$ 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, $n_o=10^{18}$, $\beta_o=1$, $T_o=70$ 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):

<table>
<thead>
<tr>
<th>$R_o$ (cm)</th>
<th>$E_o$ (kJ)</th>
<th>Gain</th>
<th>$C_R@ig$</th>
<th>$T_i@ig$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.8</td>
<td>17.9</td>
<td>1e-4</td>
<td>--</td>
</tr>
<tr>
<td>B</td>
<td>1.01</td>
<td>35.7</td>
<td>3e-3</td>
<td>--</td>
</tr>
<tr>
<td>C</td>
<td>1.27</td>
<td>71.5</td>
<td>0.2</td>
<td>--</td>
</tr>
<tr>
<td>D</td>
<td>1.6</td>
<td>143</td>
<td>48</td>
<td>20</td>
</tr>
<tr>
<td>E</td>
<td>2.02</td>
<td>286</td>
<td>41</td>
<td>15</td>
</tr>
<tr>
<td>F</td>
<td>2.54</td>
<td>572</td>
<td>40</td>
<td>13</td>
</tr>
<tr>
<td>G</td>
<td>3.2</td>
<td>1144</td>
<td>40</td>
<td>11.3</td>
</tr>
</tbody>
</table>

- 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 $\beta_o > 1$.

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

$$\beta_o: A--0.001, B--0.01, C--0.1, D--1, E--10, F--100, G--1000$$
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, $C_R=10$)

<table>
<thead>
<tr>
<th>$\beta_o$</th>
<th>A 0.001</th>
<th>B 0.01</th>
<th>C 0.1</th>
<th>D 1</th>
<th>E 10</th>
<th>F 100</th>
<th>G 1000</th>
</tr>
</thead>
</table>

![Graph showing the relationship between initial radius, magnetic field, kinetic energy, and initial density.](image)
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 $\beta_o=1$, $n_o > 10^{17}$/cm$^3$ & $v_o > 1$ cm/$\mu$s for $\beta_o=100$
Although MTF operating space potentially covers whole MCF-ICF range, practical considerations (size, energy, etc.) can limit space.

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- If, e.g., $R_o < 50$ cm, $n_o > 10^{15}$/cm$^3$ for $\beta_o=1$, $n_o > 10^{17}$/cm$^3$ & $v_o > 1$ cm/$\mu$s for $\beta_o=100$

- If, e.g., $E_o<10$ MJ, $n_o > 10^{19}$/cm$^3$ and $v_o > 3$ cm/$\mu$s for $\beta_o=100$
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: $0.1 \text{ cm} < R_o < 50 \text{ cm}, E_o < 50 \text{ MJ}$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>1</th>
<th>10</th>
<th>100</th>
<th>1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_o$ ($/\text{cm}^3$) for $R_o&lt;50 \text{ cm}$</td>
<td>$&gt;10^{15}$</td>
<td>$&gt;10^{16}$</td>
<td>$&gt;10^{17}$</td>
<td>$&gt;10^{18}$</td>
</tr>
<tr>
<td>$n_o$ ($/\text{cm}^3$) for $R_o&gt;0.1 \text{ cm}$</td>
<td>$&lt;2 \times 10^{20}$</td>
<td>$&lt;10^{21}$</td>
<td>$&lt;2 \times 10^{21}$</td>
<td>$&lt;4 \times 10^{21}$</td>
</tr>
<tr>
<td>$n_o$ ($/\text{cm}^3$) for $E_o&lt;50 \text{ MJ}$</td>
<td>$&gt;10^{14}$</td>
<td>$&gt;5 \times 10^{15}$</td>
<td>$&gt;3 \times 10^{18}$</td>
<td>$&gt;5 \times 10^{19}$</td>
</tr>
<tr>
<td>Practical $n_o$ range ($/\text{cm}^3$)</td>
<td>$10^{15}-2 \times 10^{20}$</td>
<td>$10^{16}-10^{21}$</td>
<td>$3 \times 10^{18}-2 \times 10^{21}$</td>
<td>$5 \times 10^{19}-4 \times 10^{21}$</td>
</tr>
<tr>
<td>Practical $R_o$ range (cm)</td>
<td>50-0.1</td>
<td>50-0.1</td>
<td>9-0.1</td>
<td>3-0.1</td>
</tr>
<tr>
<td>Practical $E_o$ range (J)</td>
<td>$5 \times 10^6-10^4$</td>
<td>$3 \times 10^7-3 \times 10^4$</td>
<td>$5 \times 10^7-10^5$</td>
<td>$5 \times 10^7-10^5$</td>
</tr>
<tr>
<td>Velocity $v_o$ range (cm/µs)</td>
<td>0.03-5</td>
<td>0.2-10</td>
<td>3-20</td>
<td>10-25</td>
</tr>
<tr>
<td>Fusion yield range (J)</td>
<td>$10^8-3 \times 10^5$</td>
<td>$10^9-2 \times 10^6$</td>
<td>$4 \times 10^9-8 \times 10^6$</td>
<td>$2 \times 10^9-8 \times 10^6$</td>
</tr>
</tbody>
</table>

Subject to these limits, the practical operating space for spherical targets covers six orders of magnitude in density ($10^{15}/\text{cm}^3—4 \times 10^{21}/\text{cm}^3$) 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 $T_{ig}$, $n_o$, $\beta_o$ 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:
<table>
<thead>
<tr>
<th>$C_R$</th>
<th>Sphere</th>
<th>Cylinder</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.5</td>
<td>125</td>
<td>470</td>
</tr>
<tr>
<td>10</td>
<td>70</td>
<td>324</td>
</tr>
<tr>
<td>15</td>
<td>31</td>
<td>189</td>
</tr>
</tbody>
</table>

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

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

- For $n_o < 10^{19}/\text{cm}^3$, $(RB)^{cylz}_{ig}$ can be significantly larger than $(RB)^{cyl\phi}_{ig}$ 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: $n_o=4.45 \times 10^{20}/cm^3$, $T_o=250$ eV, $B_o=330$ kG, $\beta_o=82$

$R_o=0.21$ 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 $B_\phi$, $L=0.71$ cm, $E=670$ KJ: max $C_R=\infty$, $G=0$

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 $B_\phi$ targets is similar to spherical targets; the gain for cylindrical $B_z$ targets is different due to end losses.

$T_o = 189 \text{ eV} \rightarrow T = 7 \text{ keV} @ C_R = 15 \text{ if adiabatic}$

$\beta_0$: A--0.001, B--0.01, C--0.1, D--1, E--10, F--100, G--1000

Cyl. $B_\phi$, $L/R_o = 1$ ($L/R = 15$ @ $C_R = 15$)

Cyl. $B_z$, $L/R_o = 3.33$ ($L/R = 50$ @ $C_R = 15$)

Max. $C_R < 30$
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 \( B_\phi \) targets have very narrow \( n_o \) range that disappears with slight reduction in upper bounds on \( E_o \), \( B_o \) for \( \beta_o > 1 \).**

<table>
<thead>
<tr>
<th>( \beta_o )</th>
<th>1</th>
<th>10</th>
<th>100</th>
<th>1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>( n_o ) (/cm(^3)) for ( R_o \leq 50 \text{ cm} )</td>
<td>&gt;4 \times 10^{16}</td>
<td>&gt;4 \times 10^{17}</td>
<td>&gt;3 \times 10^{18}</td>
<td>&gt;2 \times 10^{19}</td>
</tr>
<tr>
<td>( n_o ) (/cm(^3)) for ( R_o &gt; 0.1 \text{ cm} )</td>
<td>&lt;4 \times 10^{21}</td>
<td>&lt;10^{22}</td>
<td>&lt;10^{22}</td>
<td>&lt;10^{22}</td>
</tr>
<tr>
<td>( n_o ) (/cm(^3)) for ( E_o &lt; 50 \text{ MJ} )</td>
<td>&gt;10^{17}</td>
<td>&gt;5 \times 10^{19}</td>
<td>&gt;6 \times 10^{20}</td>
<td>&gt;2 \times 10^{21}</td>
</tr>
<tr>
<td>( n_o ) (/cm(^3)) for ( B_o &lt; 500 \text{ kG} )</td>
<td>&lt;2 \times 10^{19}</td>
<td>&lt;2 \times 10^{20}</td>
<td>&lt;2 \times 10^{21}</td>
<td>&lt;2 \times 10^{22}</td>
</tr>
<tr>
<td><strong>Practical ( n_o ) (/cm(^3)) range</strong></td>
<td>10^{17}-2 \times 10^{19}</td>
<td>5 \times 10^{19}-2 \times 10^{20}</td>
<td>6 \times 10^{20}-2 \times 10^{21}</td>
<td>2 \times 10^{21}-10^{22}</td>
</tr>
<tr>
<td><strong>Practical ( R_o ) range (cm)</strong></td>
<td>30-2</td>
<td>3-1.5</td>
<td>1-0.7</td>
<td>1-0.1</td>
</tr>
<tr>
<td><strong>Velocity ( v_o ) range (cm/µs)</strong></td>
<td>0.2-1.5</td>
<td>8-10</td>
<td>20-20</td>
<td>30-40</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>( \beta_o )</th>
<th>1</th>
<th>10</th>
<th>100</th>
<th>1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>( n_o ) (/cm(^3)) for ( R_o \leq 50 \text{ cm} )</td>
<td>&gt;7 \times 10^{17}</td>
<td>&gt;7 \times 10^{17}</td>
<td>&gt;7 \times 10^{17}</td>
<td>&gt;7 \times 10^{17}</td>
</tr>
<tr>
<td>( n_o ) (/cm(^3)) for ( R_o &gt; 0.1 \text{ cm} )</td>
<td>&lt;3 \times 10^{20}</td>
<td>&lt;5 \times 10^{20}</td>
<td>&lt;2 \times 10^{21}</td>
<td>&lt;10^{22}</td>
</tr>
<tr>
<td>( n_o ) (/cm(^3)) for ( E_o &lt; 50 \text{ MJ} )</td>
<td>&gt;2 \times 10^{19}</td>
<td>&gt;9 \times 10^{18}</td>
<td>&gt;7 \times 10^{18}</td>
<td>&gt;4 \times 10^{19}</td>
</tr>
<tr>
<td>( n_o ) (/cm(^3)) for ( B_o &lt; 500 \text{ kG} )</td>
<td>&lt;2 \times 10^{19}</td>
<td>&lt;2 \times 10^{20}</td>
<td>&lt;2 \times 10^{21}</td>
<td>&lt;2 \times 10^{22}</td>
</tr>
<tr>
<td><strong>Practical ( n_o ) range (/cm(^3))</strong></td>
<td>--</td>
<td>9 \times 10^{18}-2 \times 10^{20}</td>
<td>7 \times 10^{18}-2 \times 10^{21}</td>
<td>4 \times 10^{19}-10^{22}</td>
</tr>
<tr>
<td><strong>Practical ( R_o ) range (cm)</strong></td>
<td>--</td>
<td>4-0.2</td>
<td>5-0.1</td>
<td>3-0.1</td>
</tr>
<tr>
<td><strong>Velocity ( v_o ) range (cm/µs)</strong></td>
<td>--</td>
<td>1-4</td>
<td>2-10</td>
<td>7-20</td>
</tr>
</tbody>
</table>

- **Cylindrical \( B_\phi \) targets will operate at larger \( R_o \), lower \( \beta_o \), and lower \( v_o \).**
Under practical constraints of $1 \text{ mm} < R_0 < 10 \text{ cm}$, $B_0 < 500 \text{ kG}$, max $C_R < 30$, $(E_{\text{fuel}})_{\text{ig}} < 500 \text{ kJ}$, 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 $n_0$ (e.g., $10^{21}/\text{cm}^3$), high $\beta_0$ (>10) and velocity (e.g., 10 cm/$\mu$s), relatively small size (e.g., < 5 mm).

- Cylindrical $B_\phi$ targets operate at a relatively low $n_0$ (e.g., $10^{18}/\text{cm}^3$), low $\beta_0$ (< 1) and velocity (e.g., 0.5 cm/$\mu$s), 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; $\beta_0$ 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.

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, $n_o=4.45 \times 10^{20}/\text{cm}^3$, $B_o=300$ kG, $\beta_o=82$, $R_o=2.7$ mm, $L=5$ mm

inferred: $E_o=600$ kJ, $v_o=5$ cm/µs

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

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

spherical $B_\Phi$ target

$n_o=4.26 \times 10^{18}/\text{cm}^3$, $T_o=80$ eV, $B_o=100$ kG, $\beta_o=162$

$R_o=4$ cm, $E_o=22$ MJ, $v_o=6$ cm/µs

<table>
<thead>
<tr>
<th></th>
<th>K&amp;K</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gain</td>
<td>12.6</td>
<td>16</td>
</tr>
<tr>
<td>Max. $C_R=R_o/R_f$</td>
<td>~17</td>
<td>15.3</td>
</tr>
<tr>
<td>Max. $T_i$ (keV)</td>
<td>&gt; 80 keV</td>
<td>126</td>
</tr>
</tbody>
</table>
In spite of simplifications, the model agrees with more complete calculations, but ... has limitations, maybe (compensating?) errors.

- The density is always \( n_0(C_R)^b \) (b=2, cyl.; b=3, sph.), does not allow profile effects, boundary layers (possibly unstable):

- “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) \( \rightarrow \) optimum: \( n_0 = 10^{21}/\text{cm}^3 \), \( v=10 \text{ cm}/\mu\text{s} \), \( B=100 \text{ kG} \). 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 ($pV^n=$const); no realistic drive conditions
- A total energy equation is used to determine $v$ until $\text{abs}(v) < 0.1* v_o$, then replaced with a momentum equation that is not totally consistent.
- Pressure balance with fuel is imposed, i.e., $p_{\text{shell}} = p_i + p_e + p_B + p_{\text{rad}}$
- $V_o/V = (p_{\text{sh}}/p_o)^{1/g}$; 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: $P_{\text{loss}} < P_{\text{fus}}$
   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: $P_{\text{abs}} = P_{\text{loss}}$
   a. ignition possible at $\rho R << 0.4 \, \text{g/cm}^2$ (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 plasma 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.

- These efforts appear to be spearheaded by E. Velikov, who would later become chairman of the ITER Council.
The Soviet activities stimulated a number of fledgling efforts in the US
First neutrons ever produced by US particle beam fusion program came from a magnetized target (see Physics Today, August 1977).

- 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 \(\mu\)s), creating a voltage which induced an electrical discharge (diffuse z-pinch) in fuel.
- The 3-mm-dia. targets imploded at 4 cm/\(\mu\)s; \(10^6\)–\(10^7\) neutrons were observed in CD\(_2\) wire and D-T gas filled (6 x \(10^{18}/\text{cm}^3\)) targets.

- No neutrons observed without precursor or in variety of “null” targets.


- 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.”
Joint MAGO experiments were conducted by Los Alamos National Lab. (LANL) and VNIEF (“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 VNIEF (October 1996) was highest kinetic energy liner experiment ever for US scientists (> 20 MJ).

- Experiments conducted as part of unprecedented 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. Velikovich¹, S. A. Chaikovsky², J. P. Chittenden³
M. E. Cuno³, F. S. Folber³, J. P. Knauer⁴, A. E. Robson⁷, A. V. Shishlov²

¹Plasma Physics Division, Naval Research Laboratory
²High Current Electronics Institute, Tomsk, Russia
³Imperial College, London, UK
⁴Sandia National Laboratories, Albuquerque, NM
⁵Starkrak, Inc., San Diego, CA, USA
⁶Laboratory for Laser Energetics, University of Rochester, NY
⁷Berkeley Research Associates, Beltsville, MD
⁸Icarus Research, Bethesda, MD, USA
⁹Russian Federal Nuclear Center, VNIIEF, Sarov

Presented at the 54th Annual Meeting of the APS
October 31, 2012 • Providence, RI

Supported by the U.S. Department of Energy
Sandia National Laboratories is a multi program laboratory owned wholly by the U.S. Department of Energy as part of the Nuclear Security Administration in the National Nuclear Security Administration.

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.”

◆ 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

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   d. magnetized targets to access intermediate density

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   a. ignition possible at \( \rho R \ll 0.4 \text{ g/cm}^2 \) (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-\(\beta\) 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 \(\nu_o\), 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 \(\beta\?)

- 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.

$B_\phi$ targets:

- If flux conserving, $B = B_0 C_R$, so $RB$ is constant and $R_0 B_0$ must equal $(RB)_{ig}$.
- The magnetic energy is also a constant: $E_B = (B^2/2\mu_0)(\pi R^2 L)$, so no work is required to compress the magnetic field.
- Limitations on initial $B$ magnitude may place upper bound on initial $n$. 

\begin{align*}
\beta_0: & \quad A - 0.001, \quad B - 0.01, \quad C - 0.1, \quad D - 1, \quad E - 10, \quad F - 100, \quad G - 1000 \\
T_0 = 189 \text{ eV}, \quad L/R_0 = 1 \quad (L/R = 15 @ C_R = 15)
\end{align*}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{chart.png}
\end{figure}
Practical considerations force cylindrical targets to operate at a higher density than spherical targets.

**$B_z$ targets:**

- Must operate at high $\beta_0$ (> 10), high $n_0$ (> $10^{20}$/cm$^3$), and high $v_0$ (> 5 cm/µs)
Practical considerations force cylindrical targets to operate at a higher density than spherical targets.

**B_z targets:**
- Must operate at high $\beta_o$ ( > 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 $\beta_o=1 \Rightarrow E_o > 100$ MJ.