Magnetized Target Fusion: Prospects for low-cost fusion energy

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Fusion physics: $10^7 - 10^8 \, ^\circ C$
Maximum pressure depends upon technology

• Superconducting magnets (steady state)
  \[ B < 15 \text{ Tesla} \]
  \[ p < \beta B^2 \sim 100 \text{ atmospheres} \]

• Liner technology (pulsed)
  \[ B \sim 200 \text{ Tesla} \]
  \[ p \sim \beta B^2 \sim 10^6 \text{ atmospheres} \]

• Laser compression (pulsed)
  \[ p \sim 10^{11} \text{ atmospheres} \]
**Liner technology**

\[ B_\theta \sim 100 \text{ tesla (40,000 atmospheres)} \]

"Liner" is thin-walled aluminum cylinder
Radiograph of liner implosion

Initial 1-mm thick Aluminum liner

Flash xrays

Stationary 6-mm probe jacket

Elastic-plastic deformed 7-mm thick liner at 12:1 radial compression

Side-on view of liner moving 4 mm/µs
How might MTF be done?

Magnetized Target Fusion

- Pulsed current \( \sim 10^7 \text{ A} \)
- Thin metal wall implodes
- 0.5 m

Plasma Injector

Liner Implosion System
MTF requires energy to preheat the target and separately to implode the liner. 

- Target formation and preheating: \(\sim 0.1-1.0 \text{ MJ}\)
- Liner implosion: \(\sim 10-100 \text{ MJ}\)
Los Alamos FRX-L experiment

100-kV, 200-kJ Capacitor bank
Current collector plate
Theta-pinch coil 36-cm long; 12-cm diameter
Predict $n \sim 10^{17} \text{ cm}^{-3}$ $T \sim 300 \text{ eV}$
Shiva Star liner implosion \( (Q_{\text{eff}} \sim .01) \)

80 kV, 5 MJ
The Field Reversed Configuration
End-on FRC interferogram

R. Siemon et al.,
Fusion Tech. 9, 13 (1986)

M. Tuszewski,
with 416 references.
Time history of interferograms
Equilibrium theory up to $E \sim 5$

\[ \langle \beta \rangle = 1 - x_s^2 / 2 \]

\[ x_s = r_s / R_{\text{wall}} \]

\[ E = L / 2r_s \]
Stability appears to depend upon elongation

\[ S^* = \frac{r_s}{(c/\omega_{pi})} \sim \frac{r_s}{\rho_i} \quad E = \frac{L_s}{2r_s} \]
Profile of long FRC determined by equilibrium alone

D.C. Barnes, Phys. Plasmas 8, 4864 (2001)

Combining $p = p(\psi)$ with uniform elongation ($\partial/\partial z \ll \partial/\partial r$) gives solution

$$p = p_0[\psi; p_{op}] + \varepsilon^2 p_1[\psi; r_s(\hat{z})]$$

Depends on: open $p$; elongation; shape

Universal closed pressure

25:1 2D solution
Stability with Hall terms agrees with empirical good parameter regime*

Empirical analysis (Tuszewski) shows \( S^*/E < 3.5 \) for good plasma flux confinement.

Theory shows \( S^*/E < 2 - 4 \) for stability

\[ S^* = \frac{r_s}{(c/\omega_{pi})} \]
\[ E = \frac{l_s}{d_s} \]

*D. C. Barnes, Phys. Plasmas, accepted Nov. 2001
Los Alamos FRX-L team

Goal: Compress an FRC inside a liner to achieve $T \sim 10$ keV
Los Alamos Atlas facility ($Q_{\text{eff}} \sim 1$)

240 KV
25 MJ
Summary of introductory points

• The field-reversed configuration provides one method to position 300-eV plasma inside a conducting cylinder.

• Recent theoretical work suggests that the long-standing paradox of FRC stability might now be resolved.

• Liner implosions with 10:1 radial compression are feasible:
  \[ B \sim 50 \text{ kG} \rightarrow \sim 5 \times 10^6 \text{ G} \]
  \[ P \sim 100 \text{ bar} \rightarrow \sim 10^6 \text{ bar} \quad (1 \text{ bar} = 1 \text{ atmosphere}) \]

• One should ask: Why is this important to fusion research?
\[ \alpha = \frac{dR}{R} \]

10 keV plasma mixed with magnetic field

Pusher material with density \( \rho \)

High pressure cavity

\[ B \quad nT \]

\[ r \]
Lawson triple product requirement

\[ \frac{1}{2} n^2 \langle \sigma v \rangle E_f \geq 3nT/\tau_E ; \rho = n m_i \]

\[ nT\tau_E \geq 6T^2/\langle \sigma v \rangle E_f \]

Temperature and fusion cross section \( \sigma \) determine required product of pressure and energy confinement time
System size tends to decrease as pressure increases

Suppose $\tau_E$ is determined by thermal diffusivity; then size must be large enough to meet Lawson condition:

$$\tau_E = a^2/\chi$$

Define an engineering $\beta = nT / P$

$$a = \sqrt{\tau_E \chi} = \sqrt{nT \tau_E \chi / \beta} / \sqrt{P}$$
Variation of size with pressure depends upon specific loss processes.

- **NIF**
  - Diffusion-limit
  - Zero magnetic field
- **Approximate Upper-limit “Bohm”**
- **Iter**
- **Advanced concepts**
- **MTF**
  - Diffusion-limit
  - “classical” magnetic confinement

Graph showing the relationship between Fuel Mass (grams), Fuel Energy (joules), and Pressure (atm.).
Dwell time

Pressure \( (P) \) lasts for a pulse time \( \tau \) limited by inertia of liner (density \( \rho \)).

\[
\tau = \frac{dR}{(P/\rho)^{1/2}}
\]

Pulse duration \( \tau \) must separately satisfy the Lawson condition.
Liner kinetic energy and power

Can show:

\[ E = E_{\text{plasma}} + E_{\text{field}} = (1+\beta x^2/2) PV \]

Kinetic Energy is related to \( E \) by an efficiency \( \varepsilon \)

\[ KE = E / \varepsilon \]

Characteristic Power = \( E / \tau \)
Cost estimate

State-of-the-art pulsed power devices:
  NIF $6 / megawatt
  Z machine $3 / megawatt
  Atlas $12 / megawatt

Adopt $1/joule and $10 / megawatt for this type of pulsed-power supply

Make estimate:

\[ \text{MTF cost (\$)} = 1 \times \text{KE (J)} + 10 \times \text{Pwr (MW)} \]
Generic MTF facility cost vs. pressure

- Iter-FEAT
- FIRE
- NIF
- Z
- Atlas
- Generic MTF
- Generic Tokamak
- High pressure tokamak

Pressure (atmospheres)

Cost ($Millions)
Energy confinement – specific targets

ICF: electron thermal conduction
\[ \chi = \lambda \, v_e \]
\[ \lambda = \text{m.f.p.,} \]
\[ v_e = \text{elec. thermal speed} \]

Field Reversed Configuration: empirical scaling
\[ \chi = \rho_i \, v_o \]
\[ \rho_i = \text{ion gyro radius} \]
\[ v_o = 4 \times 10^6 \, \text{cm/s} \]

Wall-confined Bohm thermal conduction
\[ \chi = \rho_i \, v_i / 16 \]
Facility costs - specific plasma targets
Wall-confined Bohm-like plasma

Pusher material with density $\rho$

$\alpha = \frac{dR}{R}$

$L \approx R$

10 keV plasma mixed with magnetic field
Computations show wall-confined plasma cools at acceptable rate

5x10^{19} \text{ cm}^{-3}

1 \text{ keV}

50 \text{ T}

2 \times 10^4 \text{ bar}

\begin{align*}
n & \quad \begin{array}{c}
\text{Z pinch } B_\theta \\
\theta \text{ pinch } B_z
\end{array} \\
\text{Z} & \quad \theta
\end{align*}

\begin{align*}
\text{r} & \quad 3 \text{ cm} \\
3 \text{ cm} & \quad 3 \text{ cm}
\end{align*}
Russian MAGO has wall-confined plasma

Inverse pinch acceleration

Nozzle action
Conceptual experiment to study wall-confined plasma

- Insulator
- Ground
- Aluminum
- Inverse pinch current sheet
- $T \sim 0.5 \text{ keV}$
- $n \sim 10^{17} \text{ cm}^{-3}$

- 1 MA
- $\sim 0.1 \mu s$
- 5 cm
- Center-line
Program plans

DOE Office of Fusion Energy Sciences Exploratory Research

- Develop FRC target plasma    FY 2002-2003    $2-4 M / year

Proposed:

- Liner implosion Shiva Star    FY 2003-2004    $4-6 M / year
- Liner implosion Atlas        FY 2005-2008    $10-20 M / year

NASA Marshall Space Flight Center

- Plasma-gun implosion system  FY 2002 – 2004    $2-3 M / year

Actual budgets in black
Anticipated budgets being proposed in red
Technical issues

• Plasma target formation, stability, and energy confinement at high density
• Wall-plasma interactions and impurity mixing with fusion fuel
• Gain limitations using batch-burn mode
• Practicality of pulsed operation
Conclusions

- MTF warrants exploration given its potential as a low-cost approach to fusion
- The cost results are derived from simple considerations and experience with pulsed-power facilities; not plasma physics.
- Plasma physics will determine the detailed behavior and ultimate optimization of an MTF system.
- Experimental facilities already exist that allow testing of many critical MTF issues.
- This research is just beginning; interested scientists are encouraged to contact any of the authors (more information at http://fusionenergy.lanl.gov).