Magnetized Target Fusion: Prospects for low-cost fusion energy

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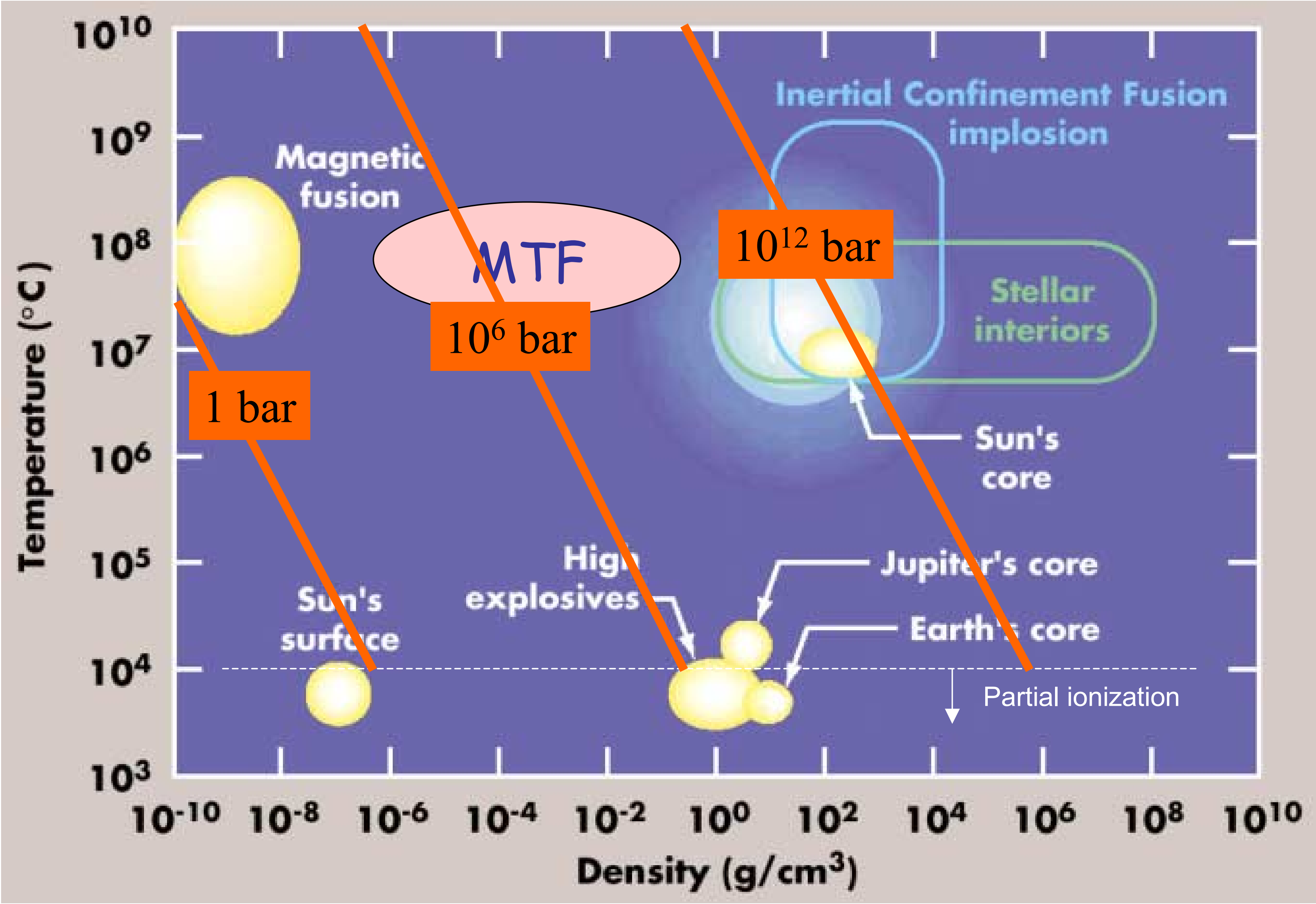
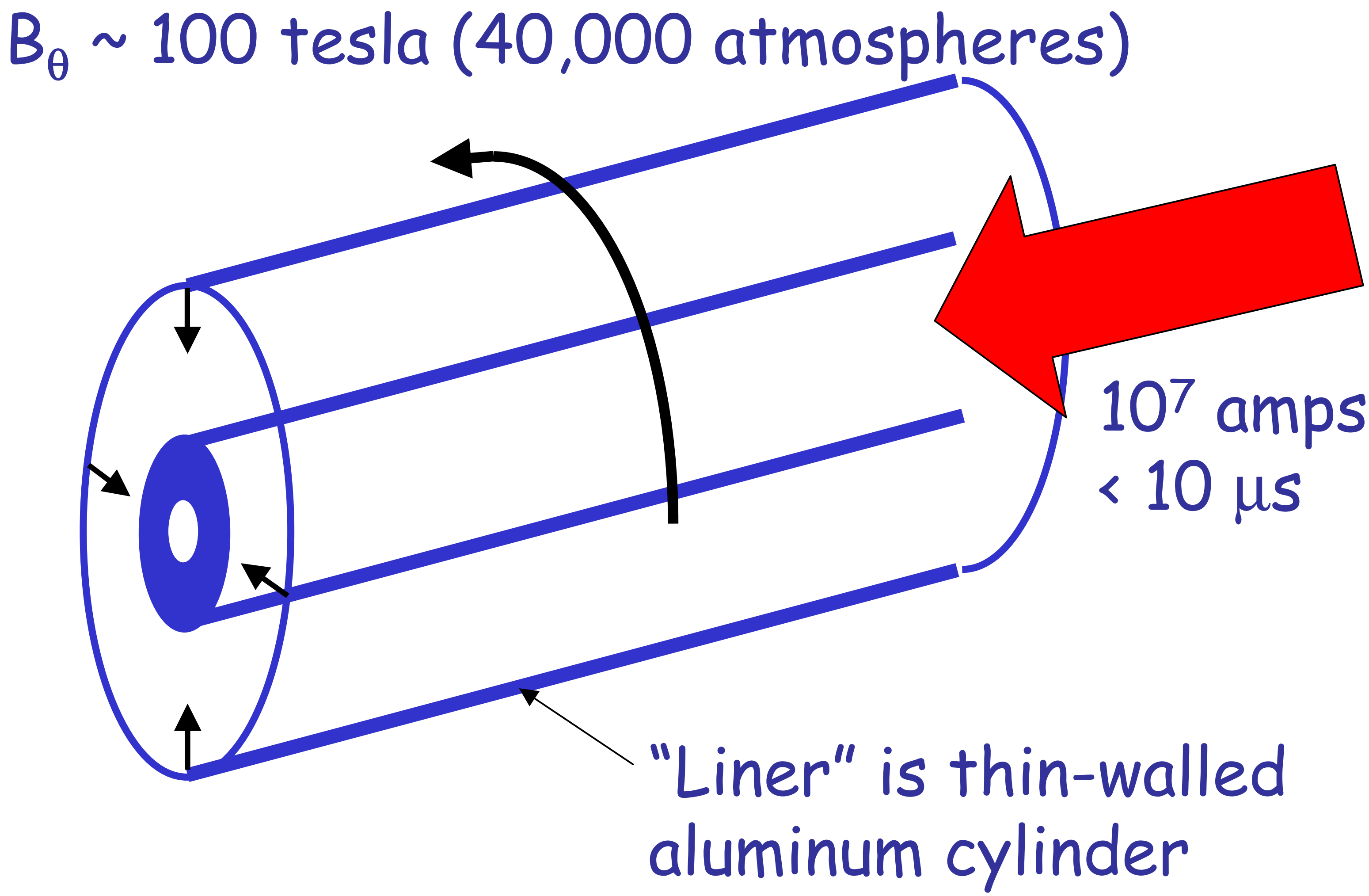
Fusion physics: 10^7 - 10^8 ^oC



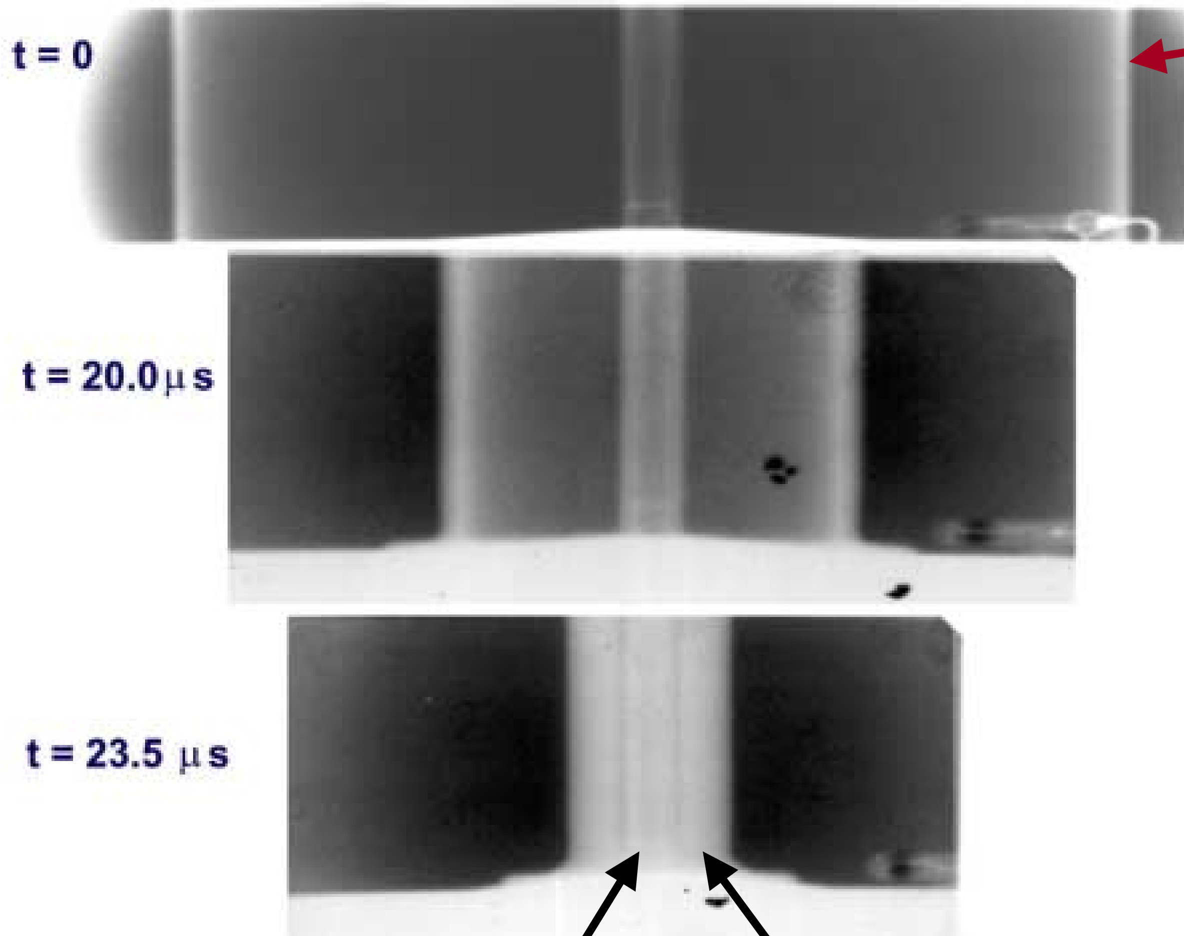
Maximum pressure depends upon technology

- Superconducting magnets (steady state)
  $B < 15$ Tesla
  $p < \beta B^2 \sim 100$ atmospheres
- Liner technology (pulsed)
  $B \sim 200$ Tesla
  $p \sim \beta B^2 \sim 10^6$ atmospheres
- Laser compression (pulsed)
  $p \sim 10^{11}$ atmospheres

Liner technology



Radiograph of liner implosion



Initial 1-mm thick Aluminum liner

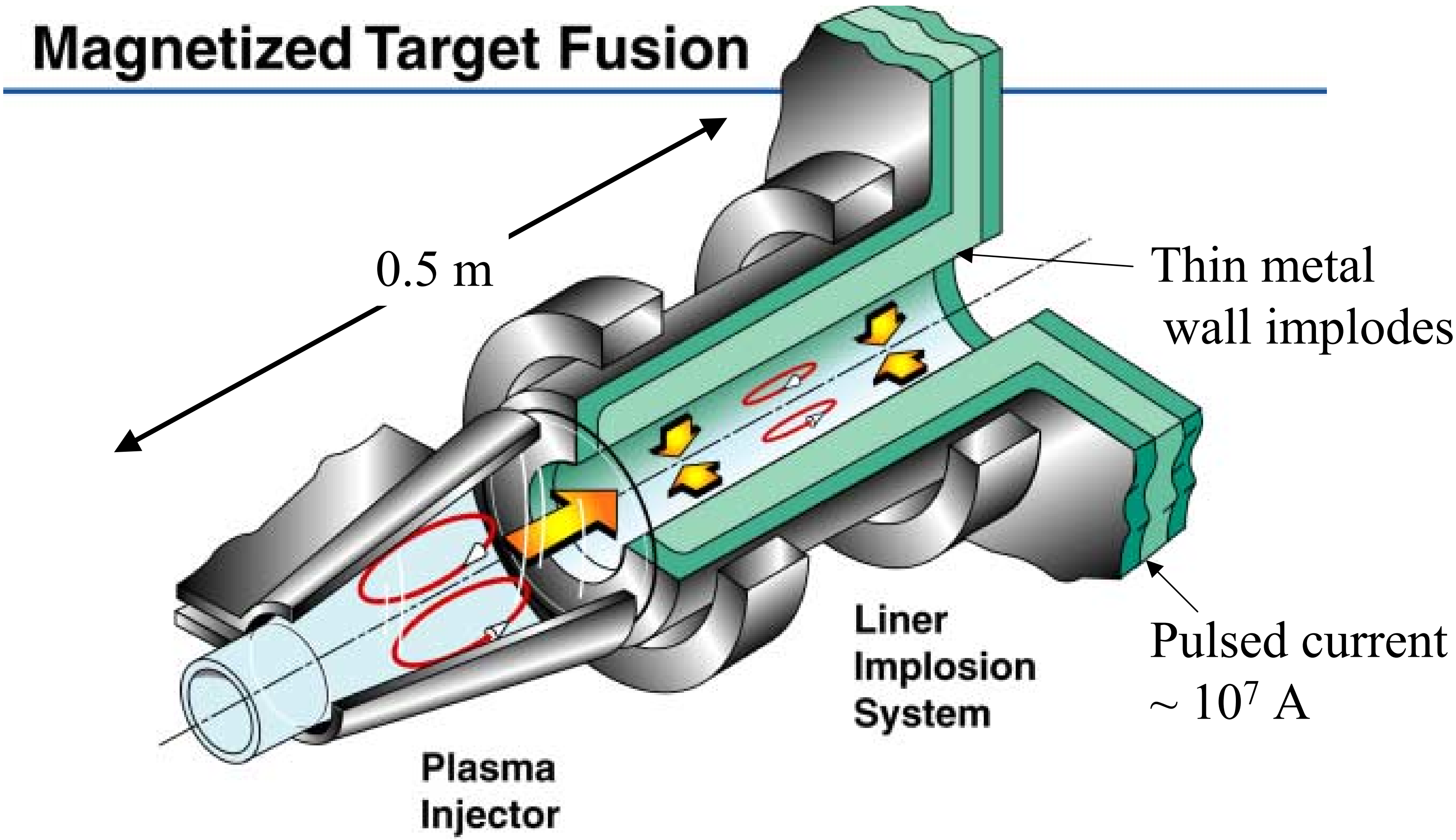
Flash xrays

Side-on view of liner moving 4 mm/µs

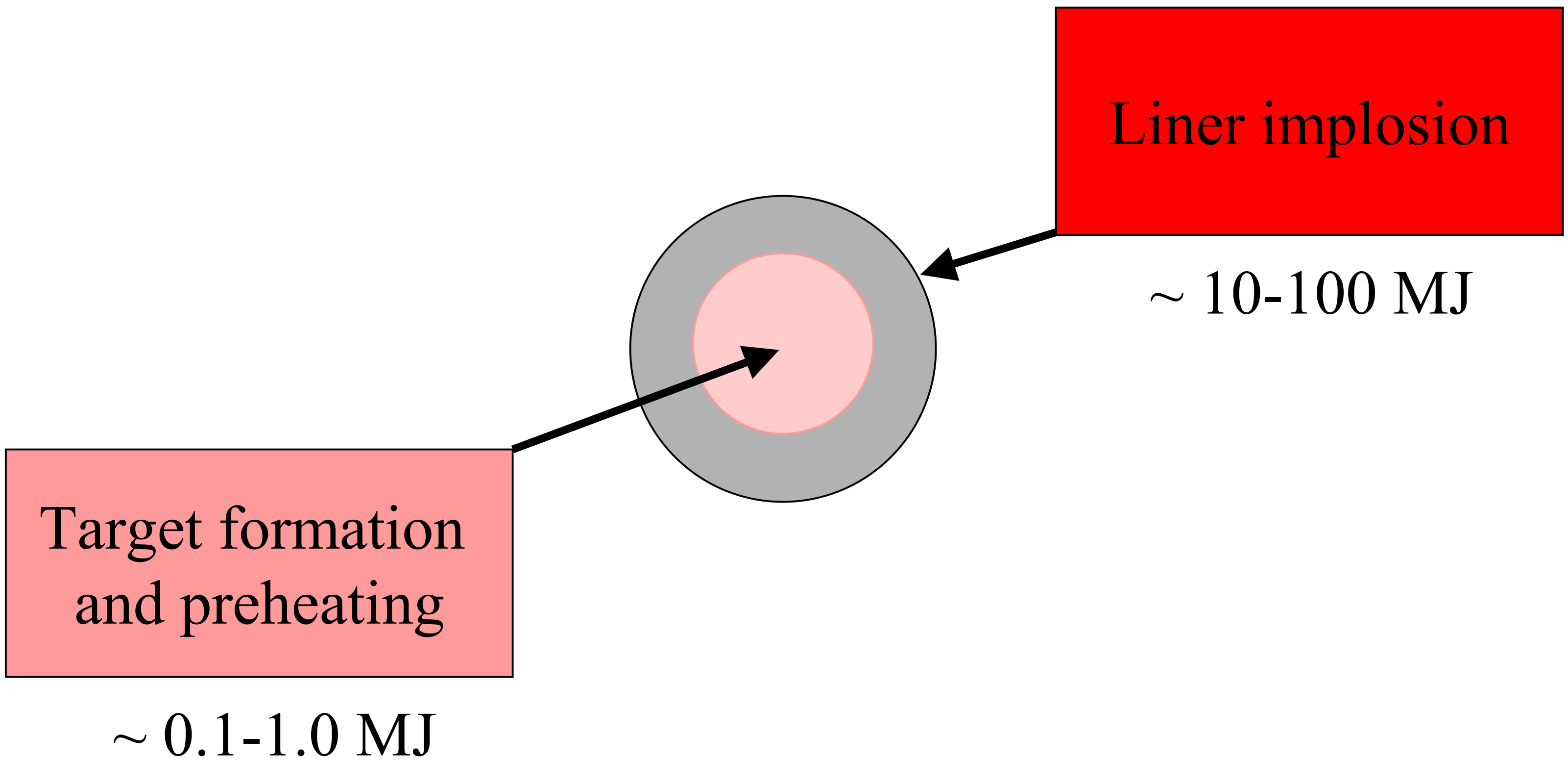
Stationary 6-mm probe jacket

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

How might MTF be done?

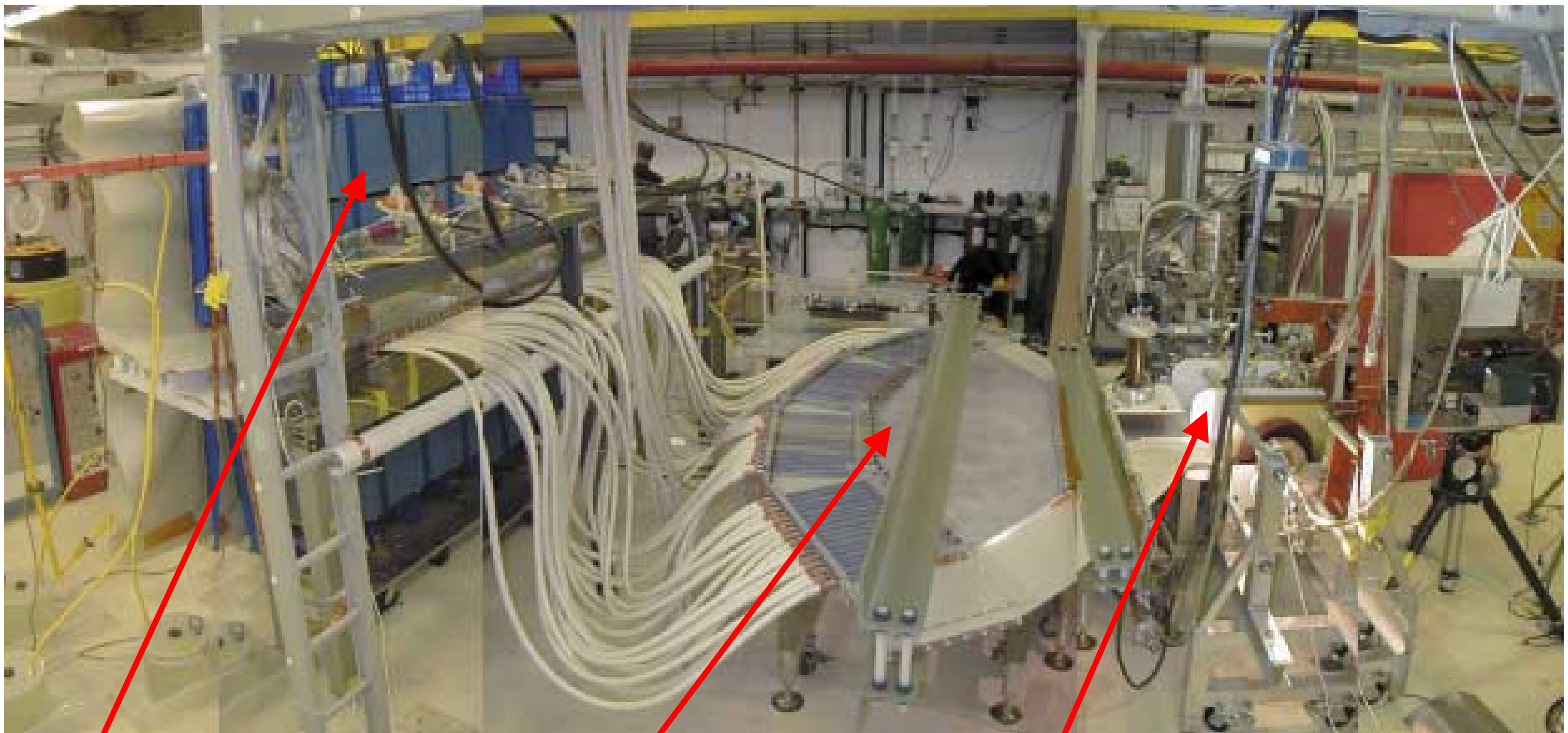


MTF requires energy to preheat the target and separately to implode the liner



Los Alamos FRX-L experiment

← 3 meters →



100-kV, 200-kJ
Capacitor bank

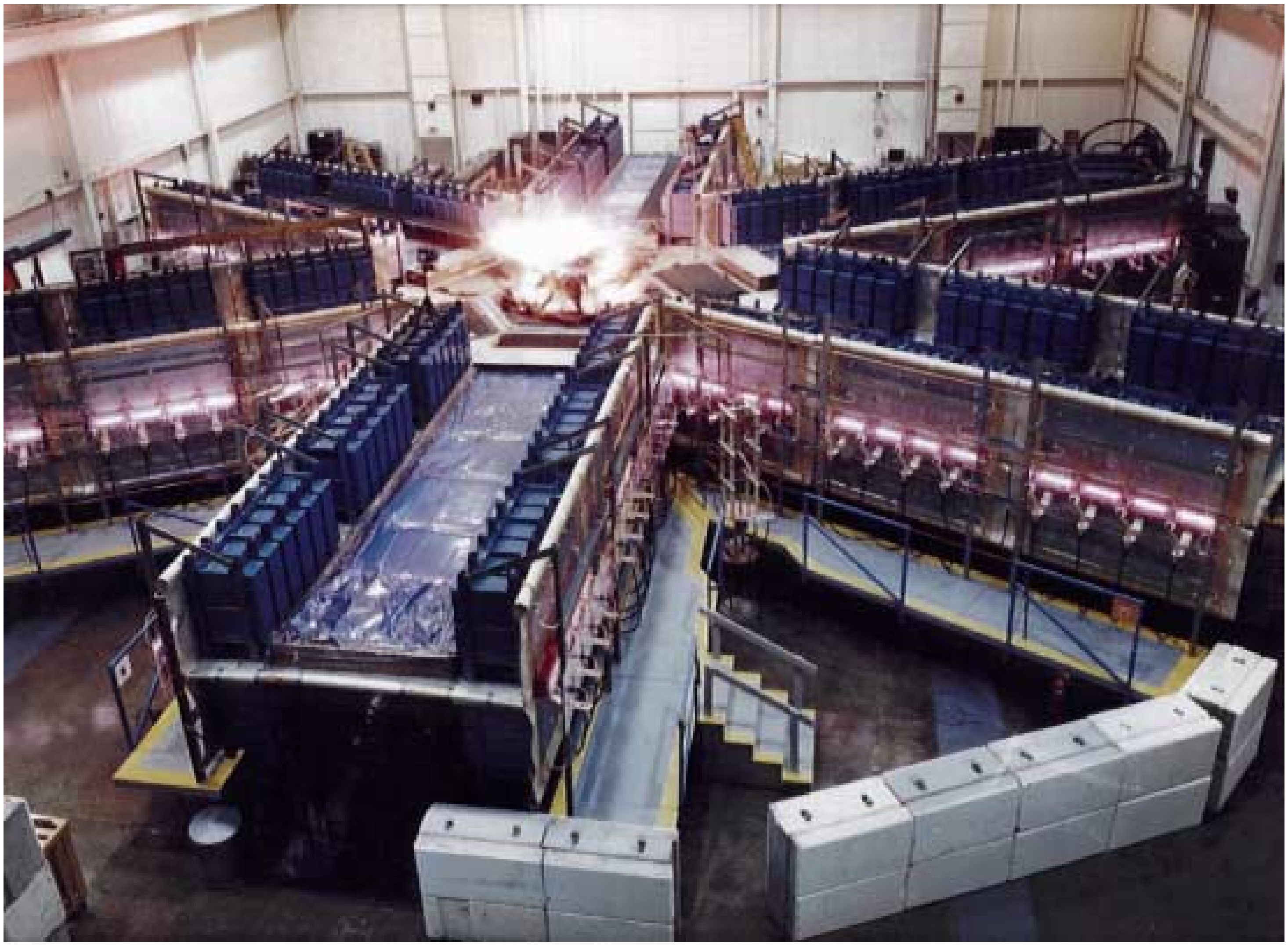
Current collector
plate

Theta-pinch coil
36-cm long;
12-cm diameter

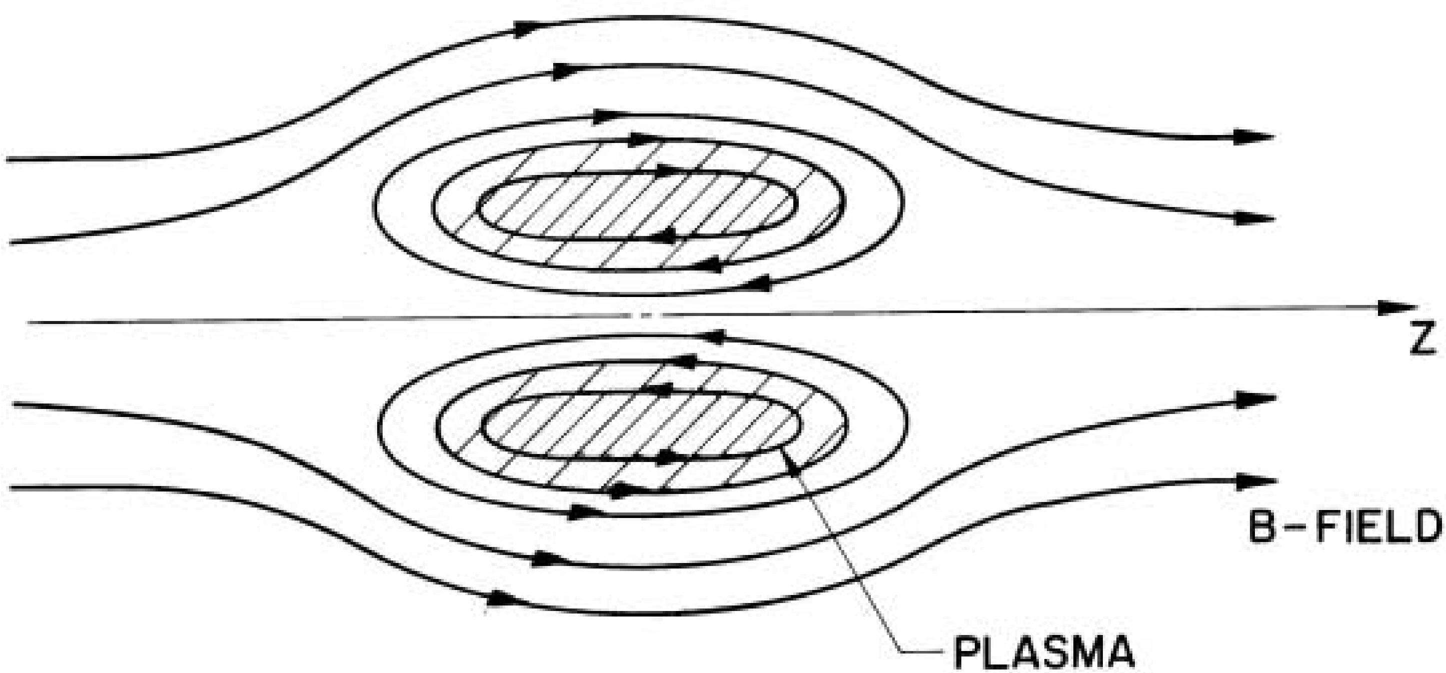
Predict
$n \sim 10^{17}$ cm^{-3}
$T \sim 300$ eV

Shiva Star liner implosion ($Q_{eff} \sim .01$)

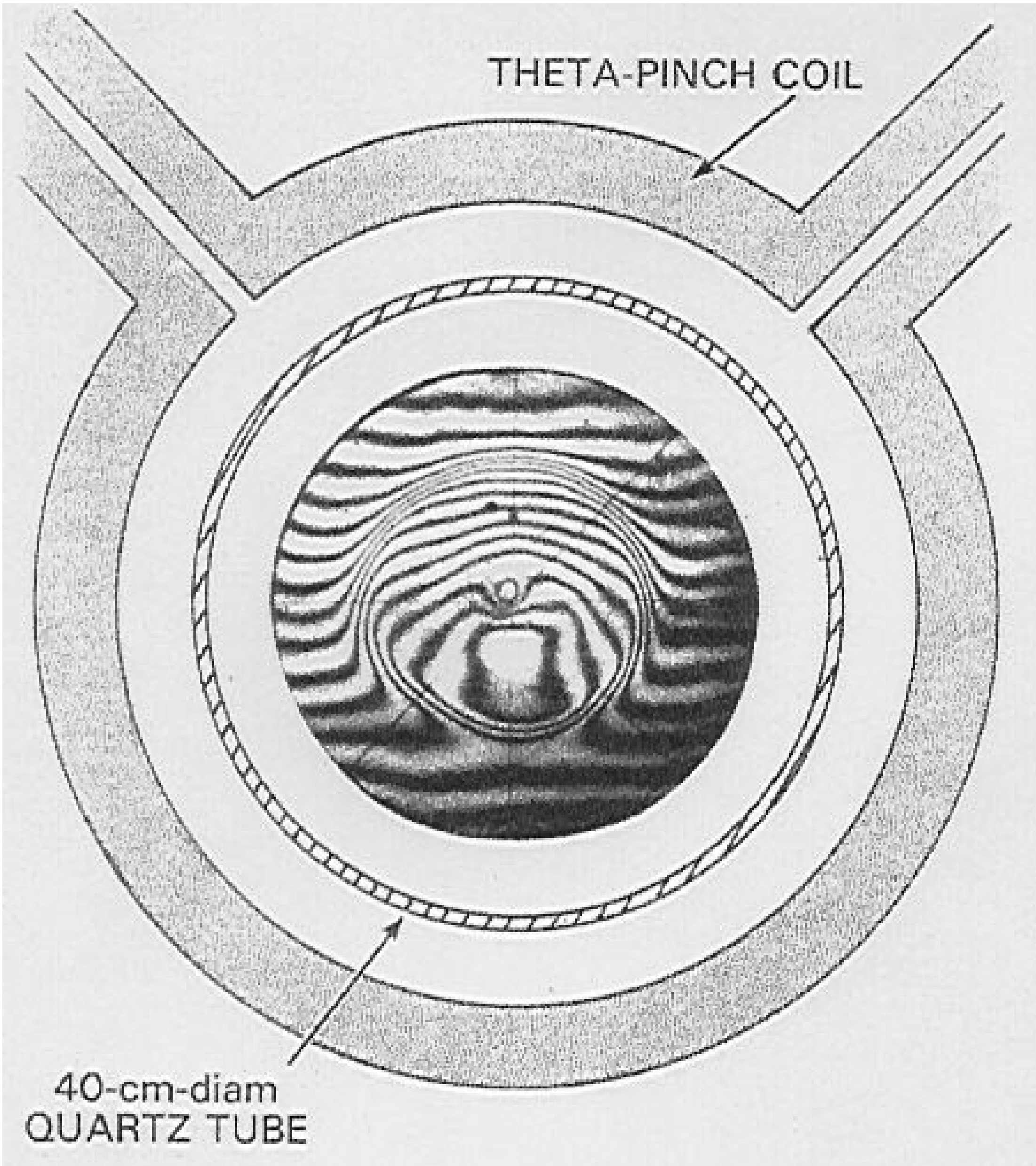
80 kV, 5 MJ



The Field Reversed Configuration



End-on FRC interferogram

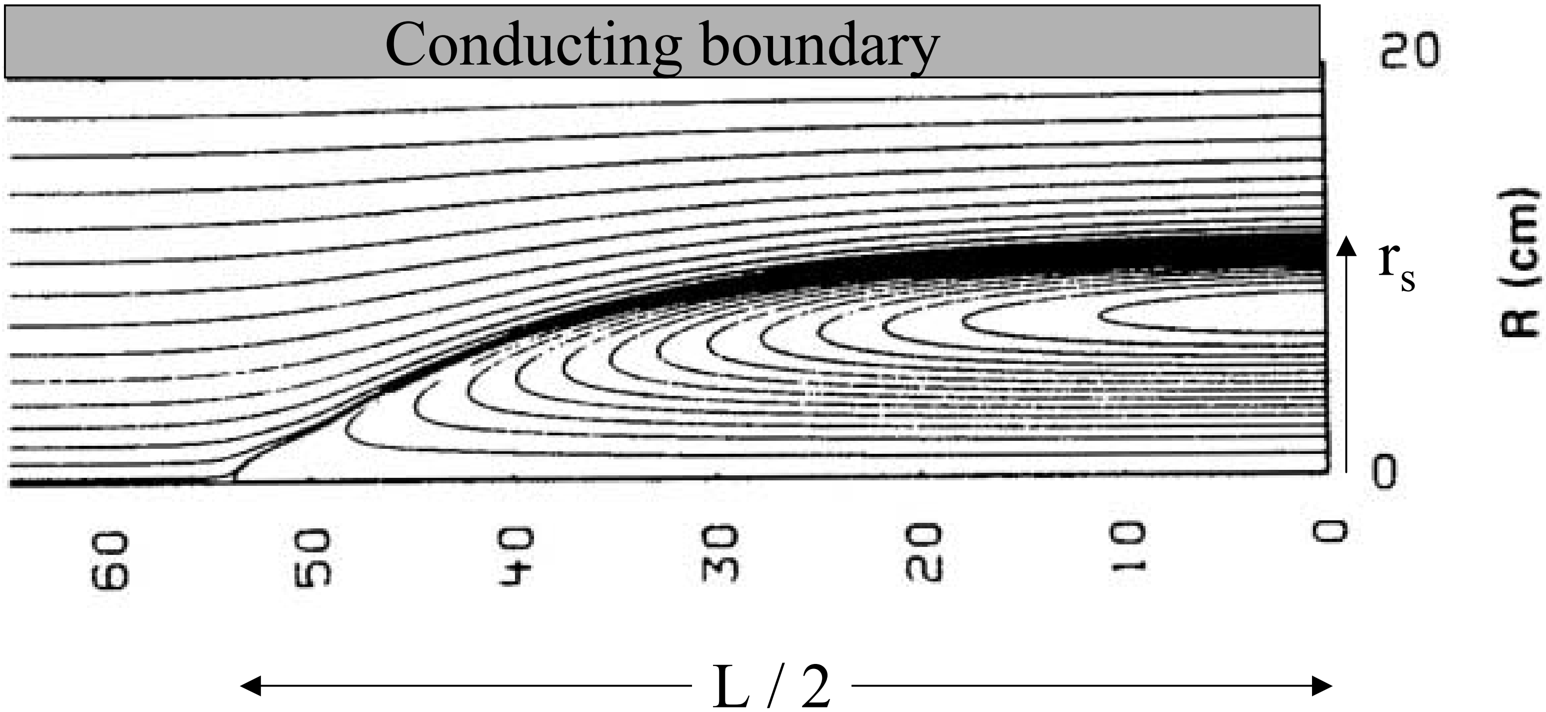


R. Siemon et al.,
Fusion Tech. **9**, 13 (1986)

M. Tuszewski,
Nuc. Fusion **28**, 2033 (1988)
with 416 references.

Time history of interferograms

Equilibrium theory up to E ~ 5

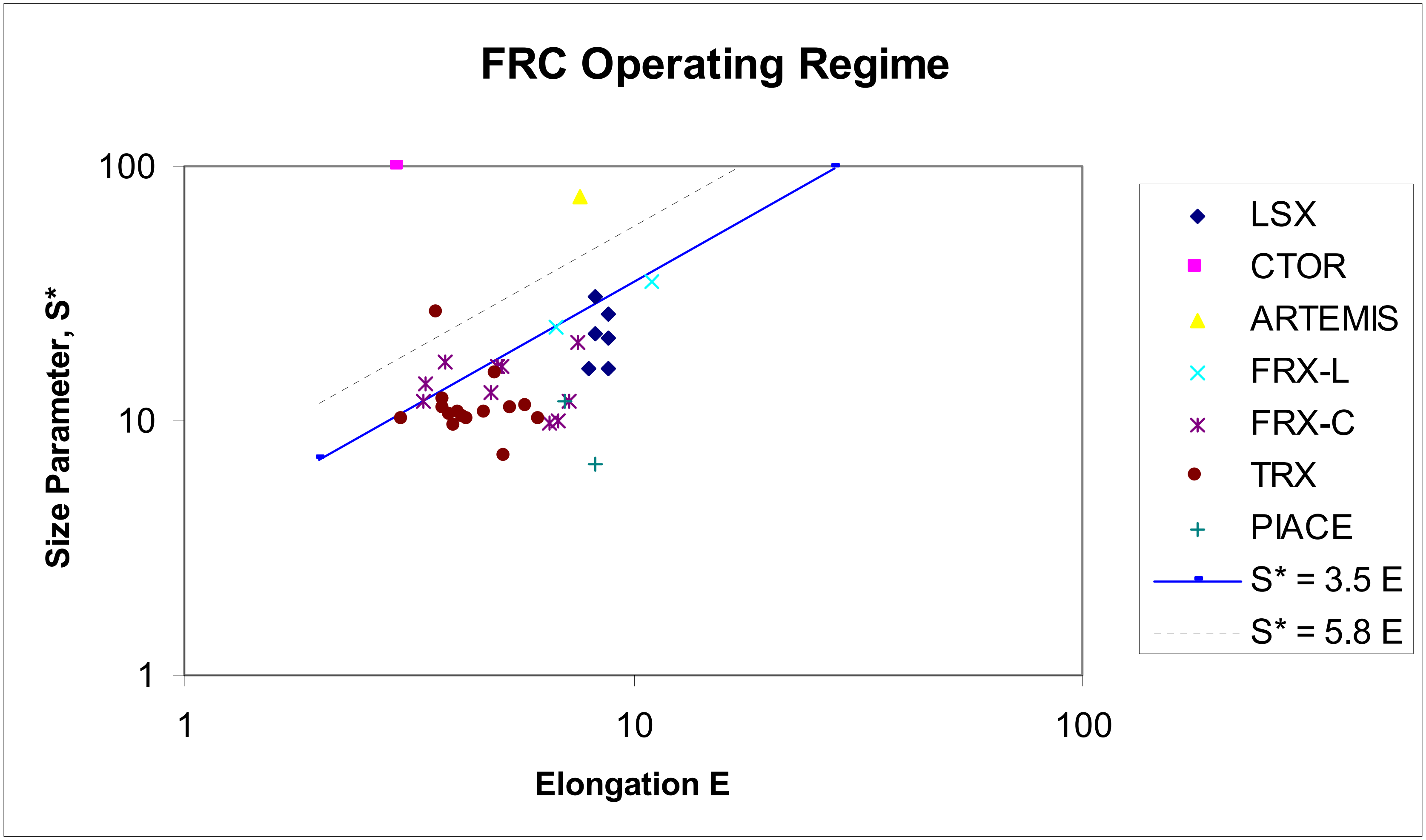


$\langle\beta\rangle = 1 - x_s^2/2$

$E = L / 2r_s$

$x_s = r_s / R_{wall}$

Stability appears to depend upon elongation



$S^* = r_s / (c/\omega_{pi}) \sim r_s / \rho_i$ $\quad$ $E = L_s / 2\, r_s$

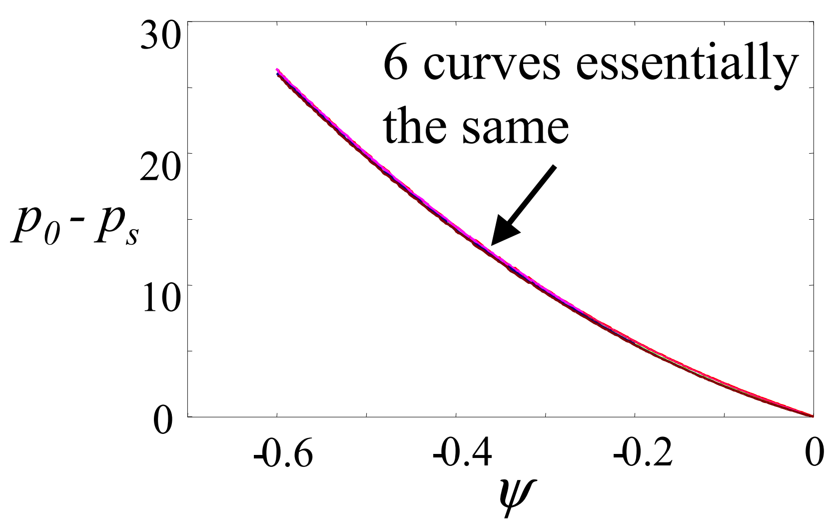
Profile of long FRC determined by equilibrium alone

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

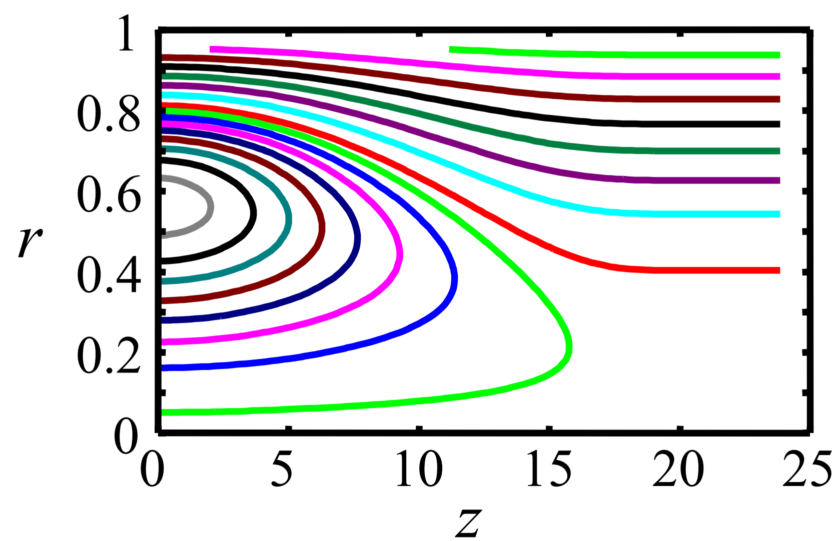
Combining $p = p(\psi)$ with uniform elongation ($\partial/\partial z << \partial/\partial r$) gives solution

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

Depends on: open *p* ; elongation ; shape

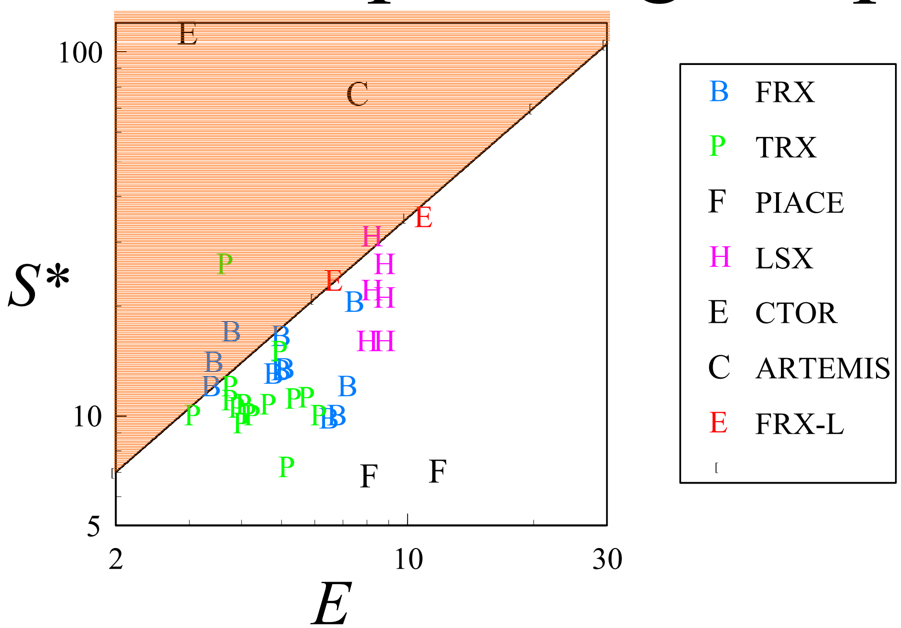


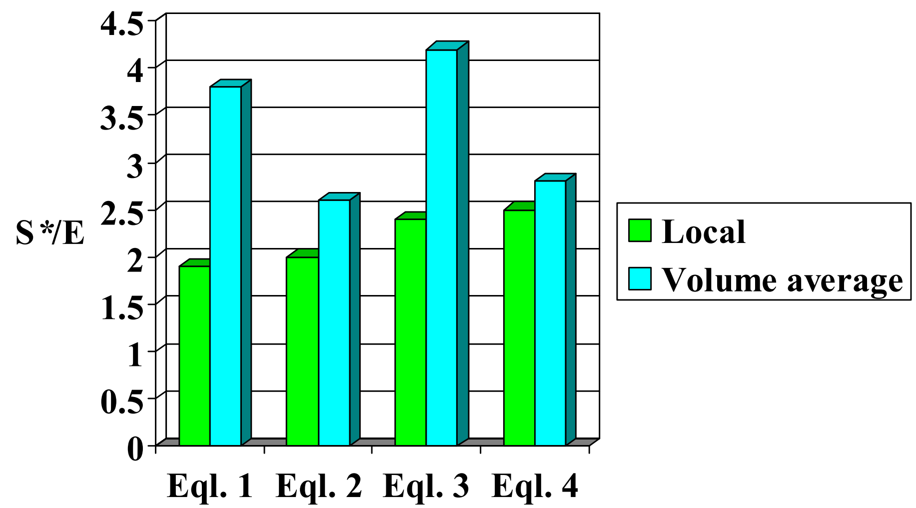
Universal closed pressure



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

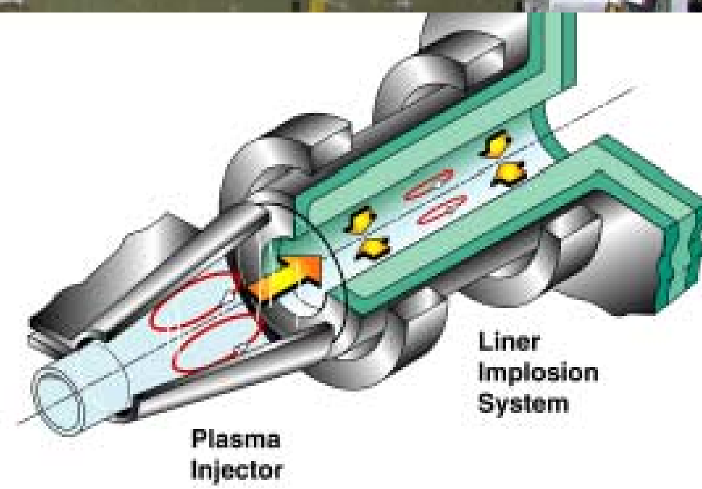
$$S^* = r_s/(c/\omega_{pi})$$

$$E = l_s/d_s$$

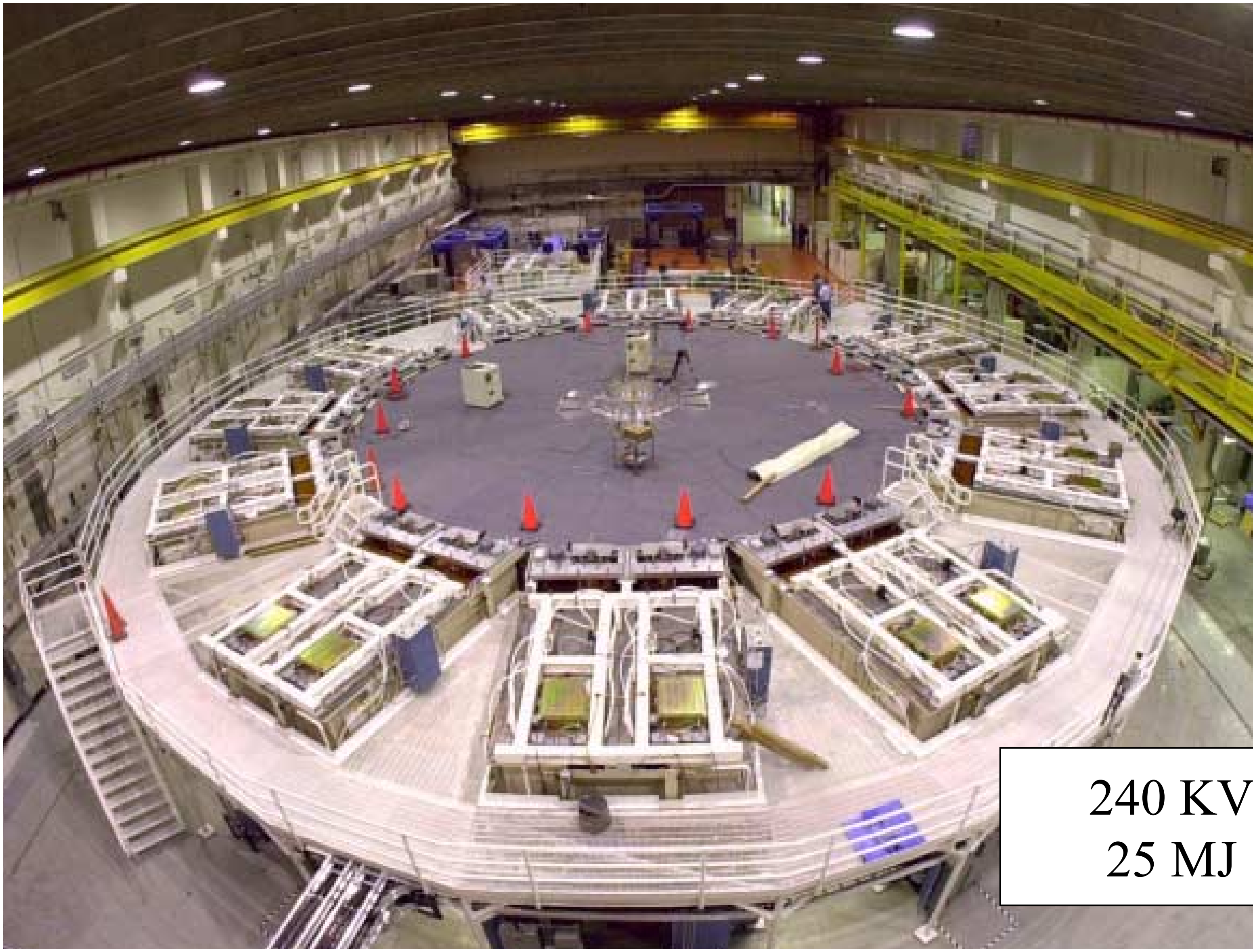
*D. C. Barnes, Phys. Plasmas, accepted Nov. 2001

Los Alamos FRX-L team

Goal: Compress an FRC inside a liner to achieve T ~ 10 keV



Los Alamos Atlas facility ($Q_{eff} \sim 1$)



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

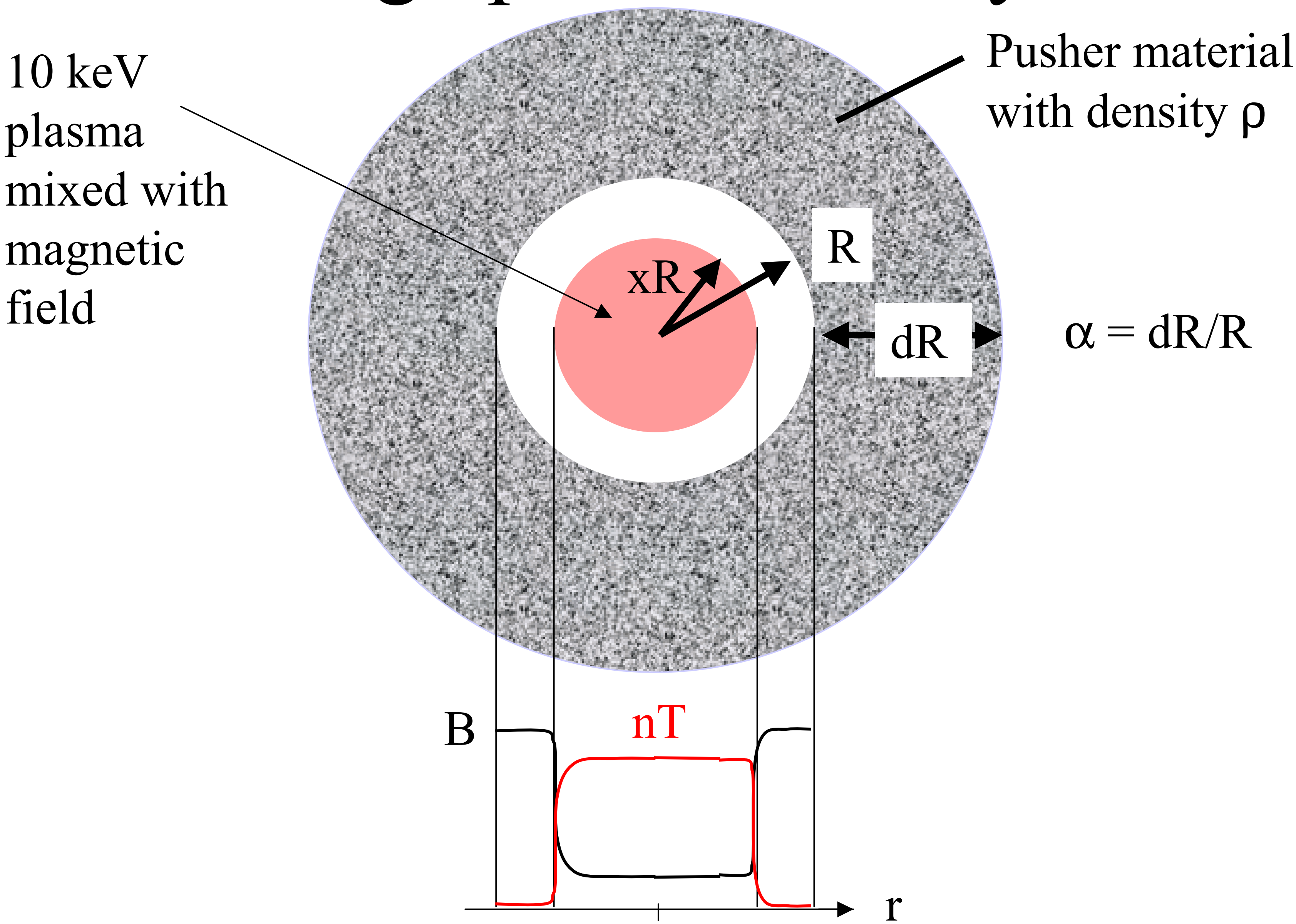
•Liner implosions with 10:1 radial compression are feasible

$B \sim 50$ kG $\rightarrow$ $\sim 5 \times 10^6$ G

$P \sim 100$ bar $\rightarrow$ $\sim 10^6$ bar (1 bar = 1 atmosphere)

•One should ask: Why is this important to fusion research?

High pressure cavity



Lawson triple product requirement

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

$$nT\tau_E \geq \; 6T^2/ \langle\sigma v\rangle E_f$$

Temperature and fusion cross section σ determine required product of pressure and energy confinement time

System size tends to decrease as pressure increases

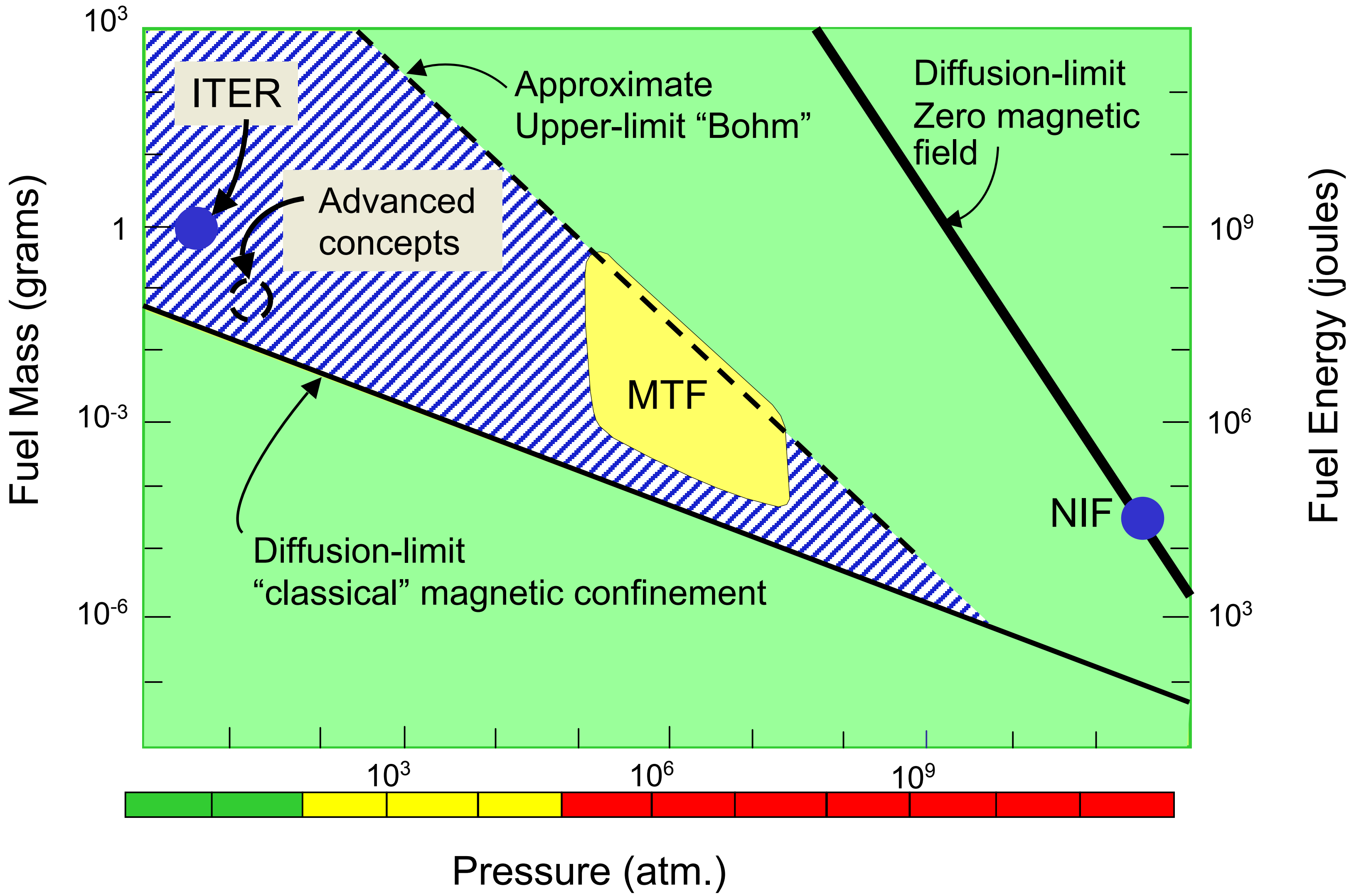
Suppose τ_E is determined by thermal diffusivity; then size must be large enough to meet Lawson condition:

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

Define an engineering $\beta = nT / P$

$$a = \mathrm{sqrt}(\tau_E\,\chi) = \mathrm{sqrt}(nT\tau_E\,\chi/\beta) / \mathrm{sqrt}(P)$$

Variation of size with pressure depends upon specific loss processes



Dwell time

Pressure (P) lasts for a pulse time τ limited by inertia of liner (density ρ).

$$\tau = dR / (P/\rho)^{1/2}$$

Pulse duration τ must separately satisfy the Lawson condition.

Liner kinetic energy and power

Can show:

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

Kinetic Energy is related to E by an efficiency ε

$KE = E/\ \varepsilon$

Characteristic Power = $E\ /\ \tau$

Cost estimate

State-of-the-art pulsed power devices:

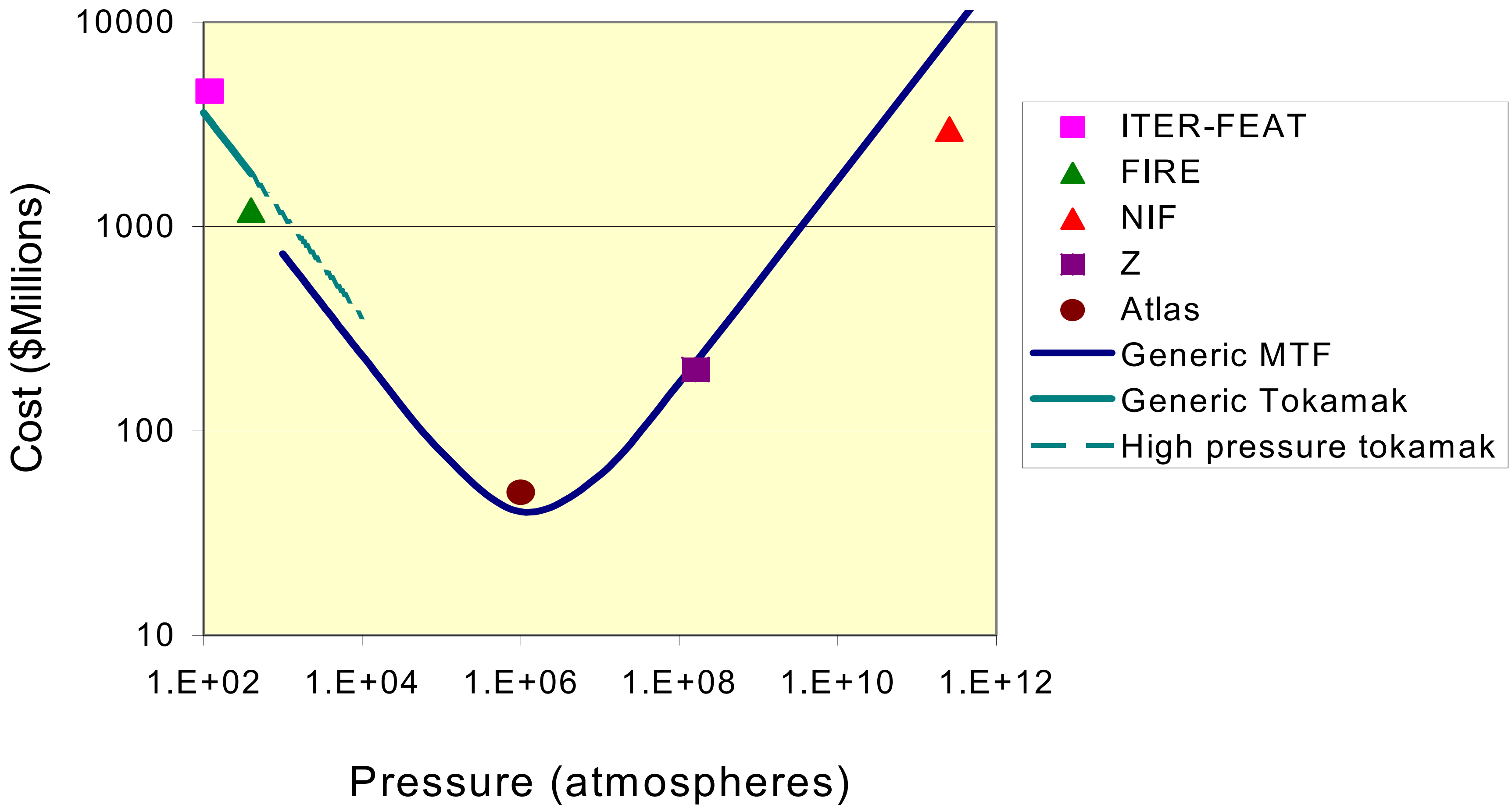
NIF	\$6 / megawatt
Z machine	\$3 / megawatt
Atlas	\$12 / megawatt

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

Make estimate:

MTF cost (\$) = \$1 * KE(J) + \$10 * Pwr(MW)

Generic MTF facility cost vs. pressure



Energy confinement – specific targets

ICF: electron thermal conduction

$$\chi = \lambda v_e$$

λ = m.f.p.,
v_e = elec. thermal speed

Field Reversed Configuration: empirical scaling

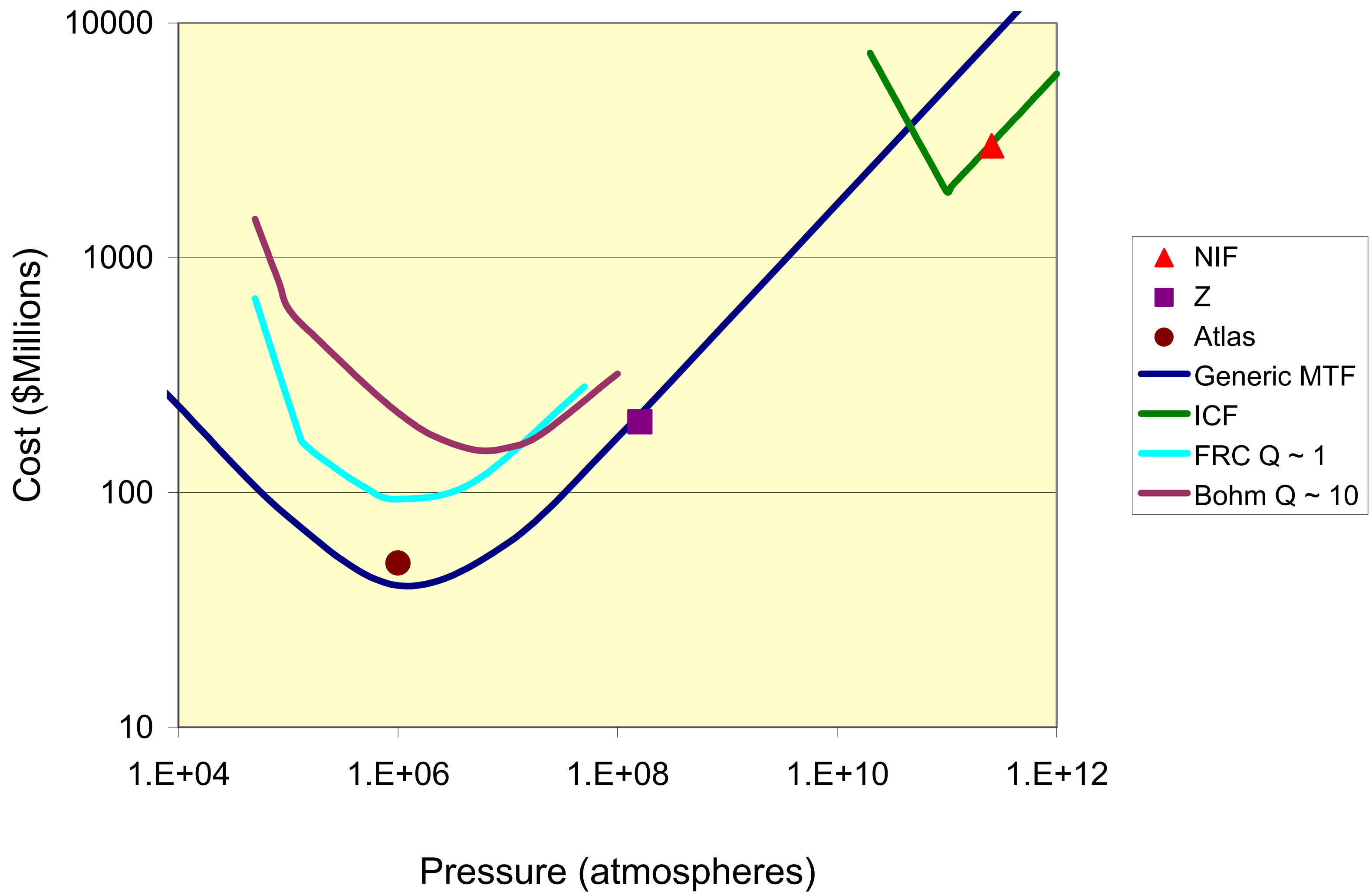
$$\chi = \rho_i v_o$$

ρ_i = ion gyro radius
$v_o = 4 \times 10^6$ cm/s

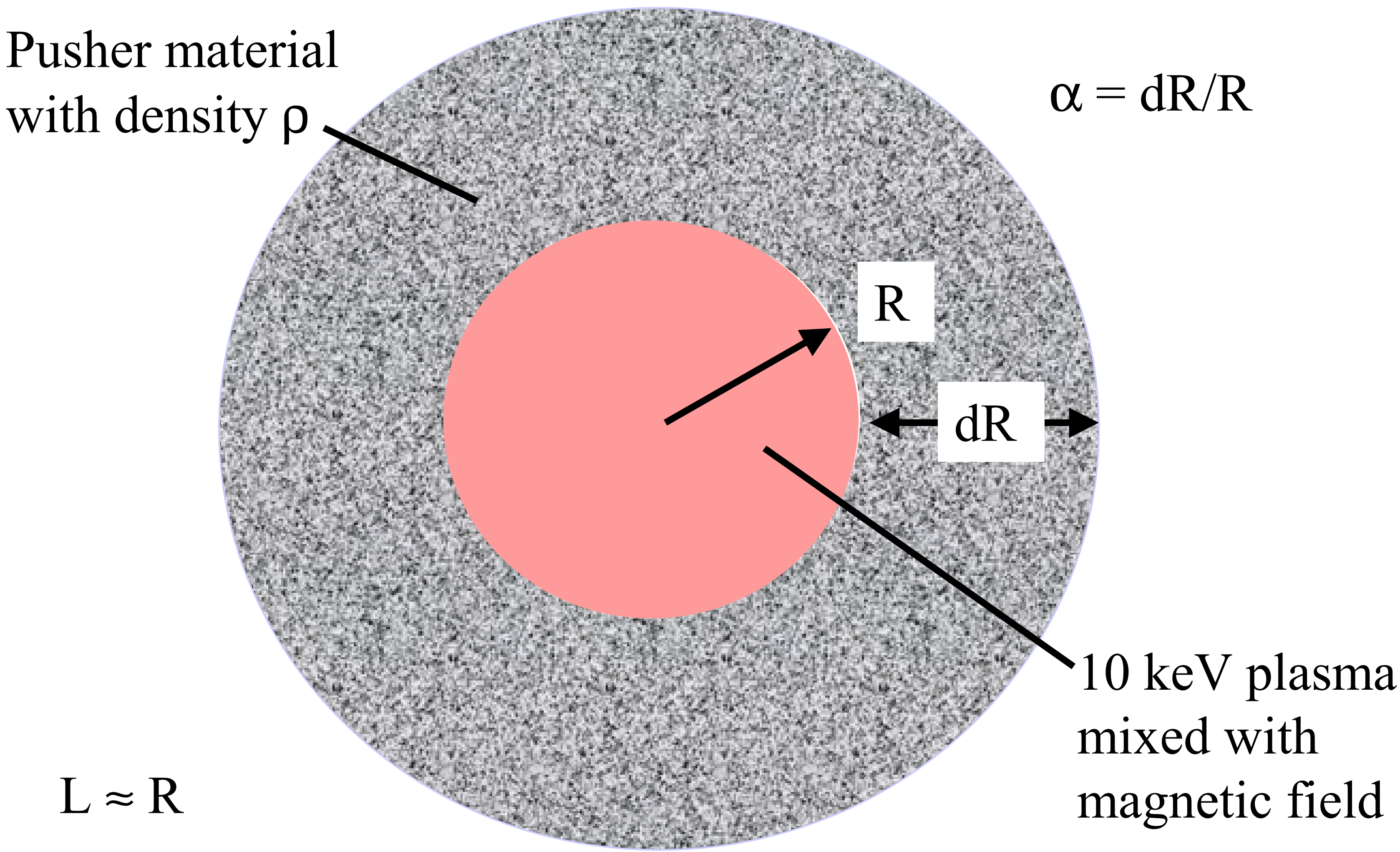
Wall-confined Bohm thermal conduction

$$\chi = \rho_i v_i / 16$$

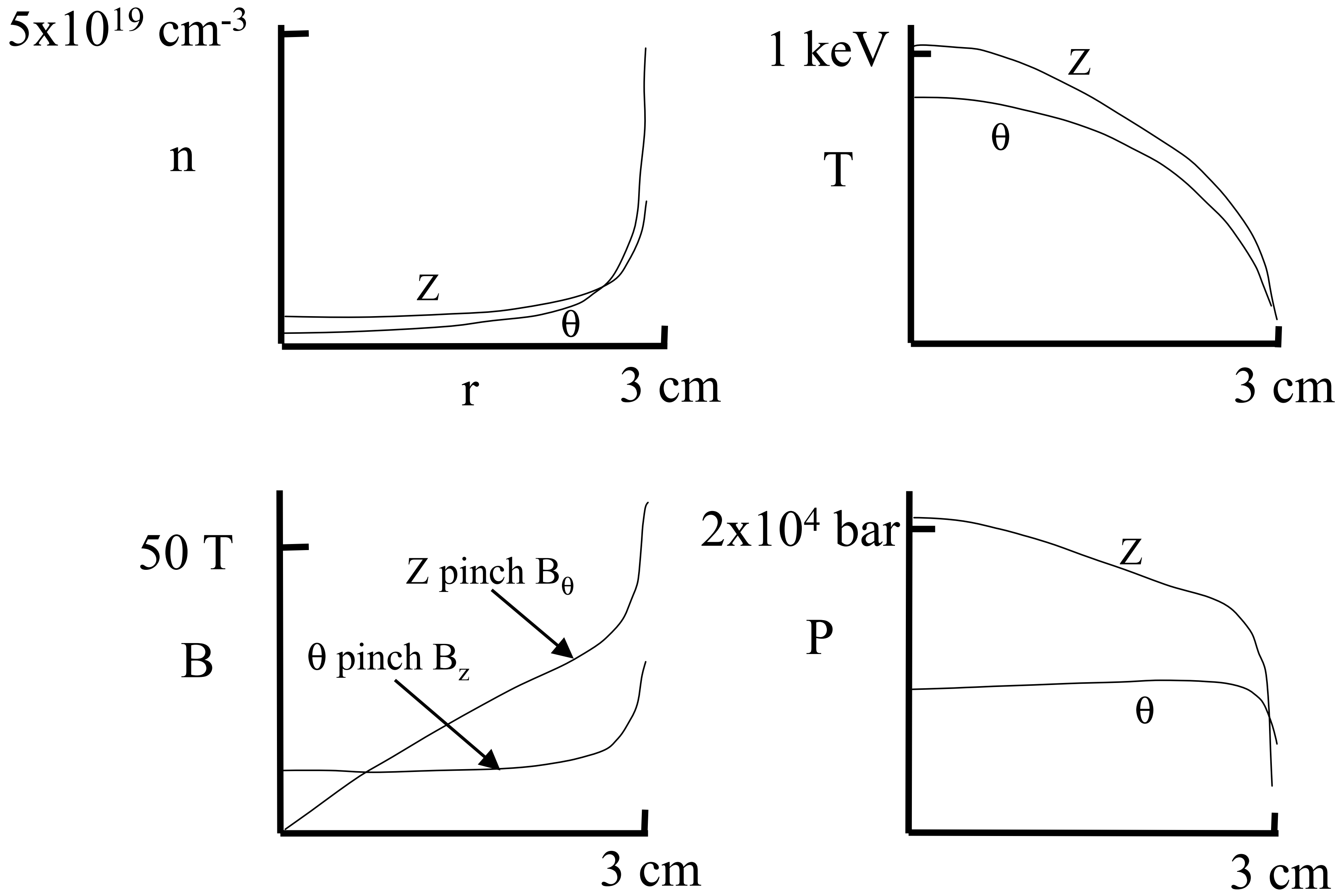
Facility costs - specific plasma targets



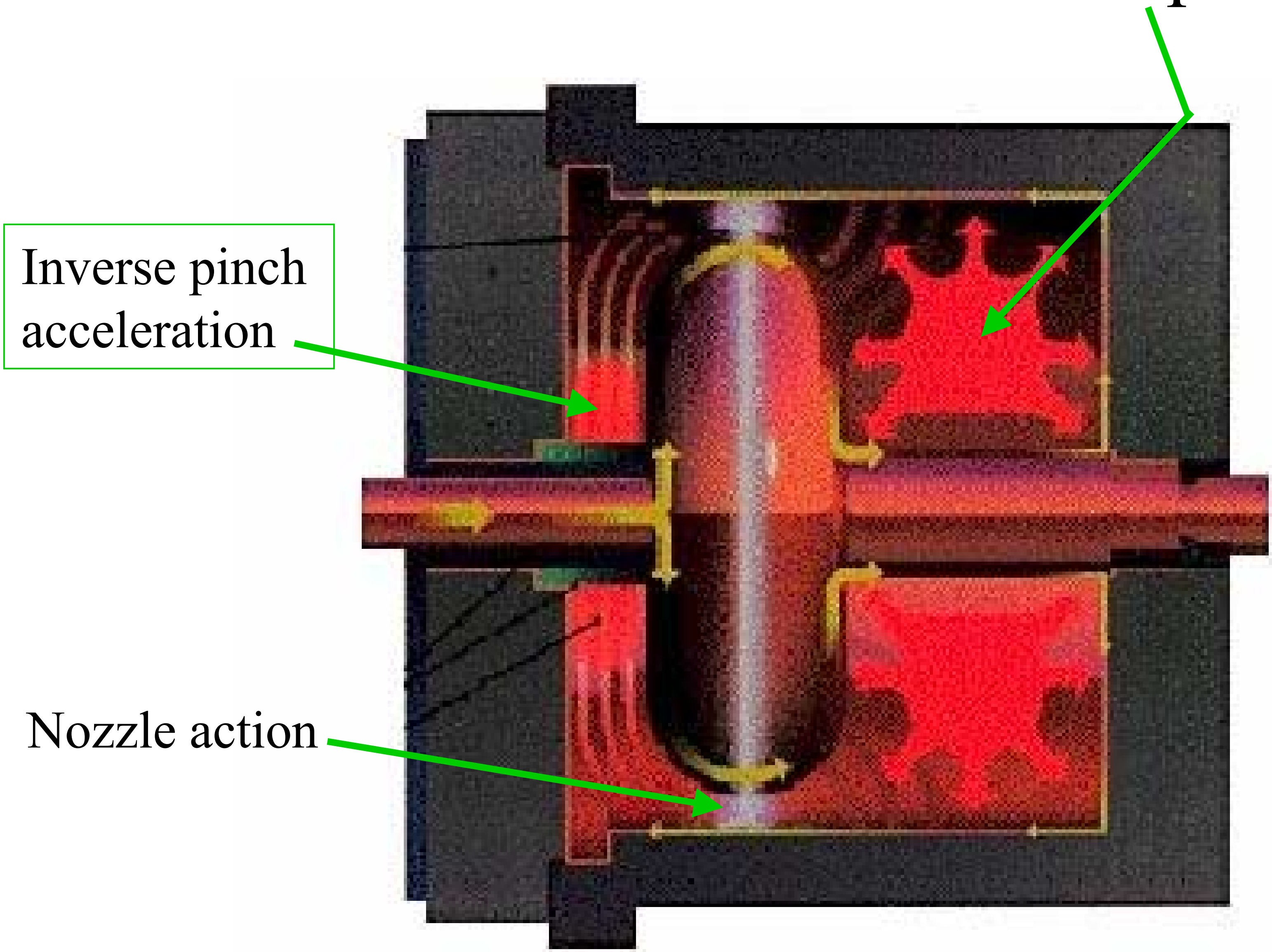
Wall-confined Bohm-like plasma



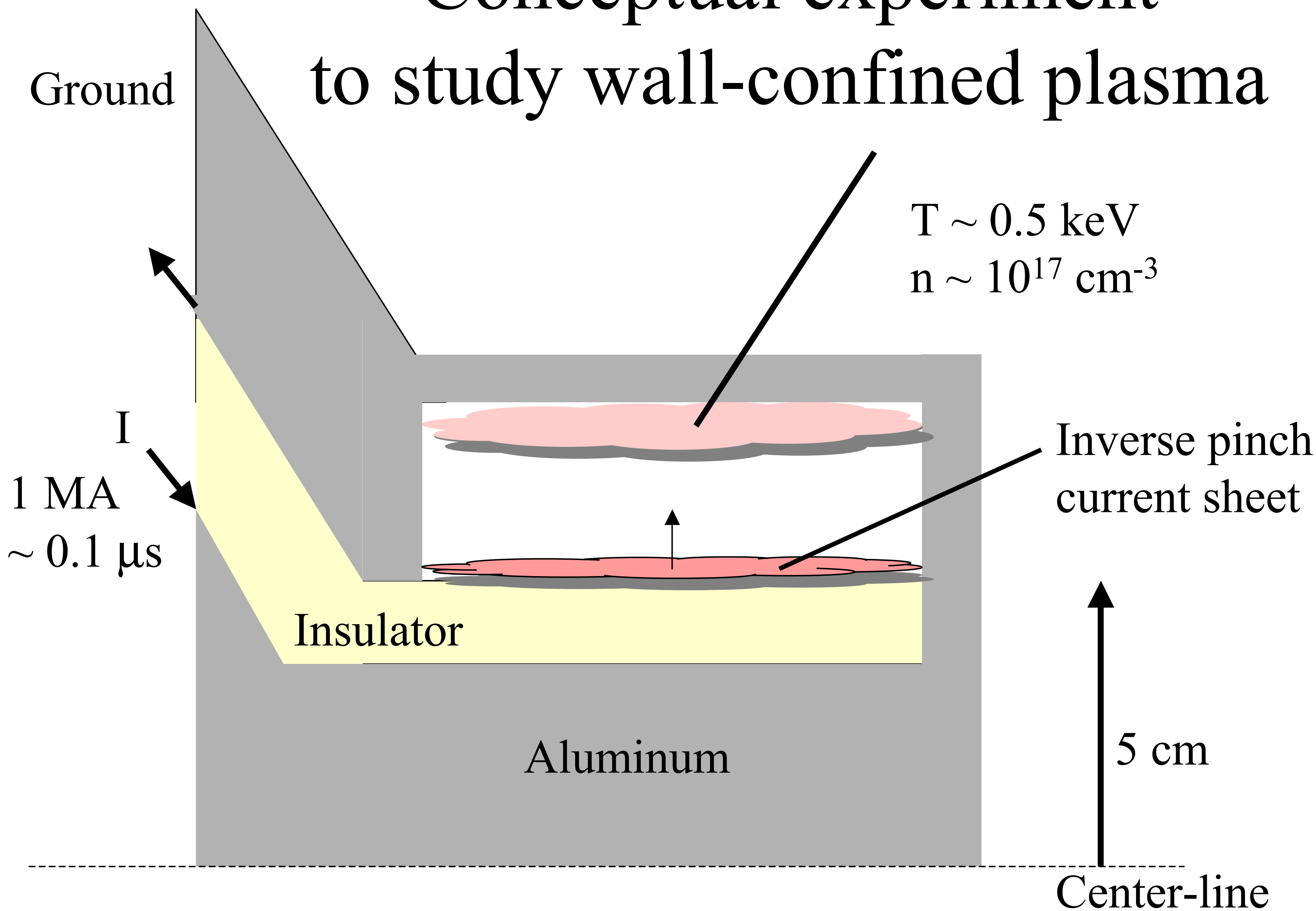
Computations show wall-confined plasma cools at acceptable rate



Russian MAGO has wall-confined plasma



Conceptual experiment to study wall-confined plasma



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).