



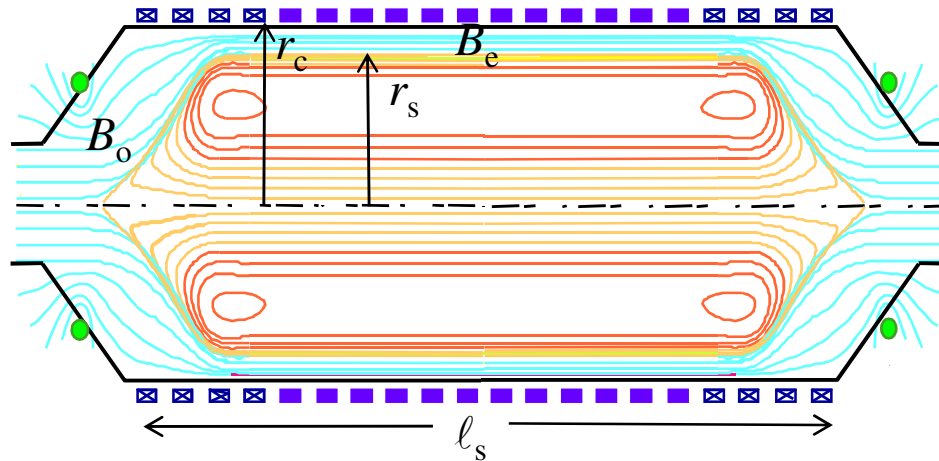
FRC Issues, Needs, and Gaps

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Field Reversed Configurations (FRC)



- ◆ Compact toroid with little or no toroidal field.
- ◆ Can be prolate (elongated), or oblate.
- ◆ Very High $\langle \beta \rangle$ (always > 0.5 for prolate FRCs).
- ◆ Diamagnetic, cross-field toroidal currents.
- ◆ Unstable in ideal MHD.



The FRC Kinetic Parameter

- ◆ The number of gyroradii for a thermal ion between the null and the separatrix

$$S = \int_R^{r_s} \frac{r dr}{r_s \rho_i} \sim RB/T_i^{1/2}$$

- ◆ The parameter $S^* = r_s/\delta$, where $\delta = c/\omega_{pi}$ is often used, and is a measure of the importance of the Hall term in the Generalized Ohm's law.
- ◆ $S^* \sim 5 - 10$ for an FRC, depending on the magnetic profile.



FRC Achievements

- ◆ θ -pinch formed FRCs (pulsed)
 - In LSX, $n \sim 5 \times 10^{21} \text{ m}^{-3}$, $T_e \sim 500 \text{ eV}$, $T_i \sim 1000 \text{ eV}$, $\tau \sim 1 \text{ ms}$
 $\phi \sim 10 \text{ mWb}$, $s \sim 4$
- ◆ Rotating Magnetic Field (RMF)
 - Steady state FRCs ($\sim 10 \text{ ms}$ sustainment)
 - Formed and sustained with $\sim 2 \text{ MW}$ power
 - $n \sim 1 \times 10^{19} \text{ m}^{-3}$, $T_e + T_i \sim 300 \text{ eV}$, $\phi \sim 5 \text{ mWb}$, $s \sim 1 - 2$
- ◆ Merging Spheromak
 - Formed by merging two opposite helicity spheromaks, so toroidal field cancels
 - Potential to form high flux, large s FRC ($> 5 \text{ mWb}$ achieved in modest facilities)

FRC Issues – Unchanged from TAP report



◆ Tier 1:

- Stability at large s . (Achieve global stability at large s in low collisionality plasma.)

◆ Tier 2:

- Transport (Establish transport scaling.)
- Current drive and sustainment

◆ Tier 3:

- Fast particles (Understand effects on current drive, stability and confinement.)
- Heating (Demonstrate efficient heating methods)

The Kinetic Parameter and FRC Stability

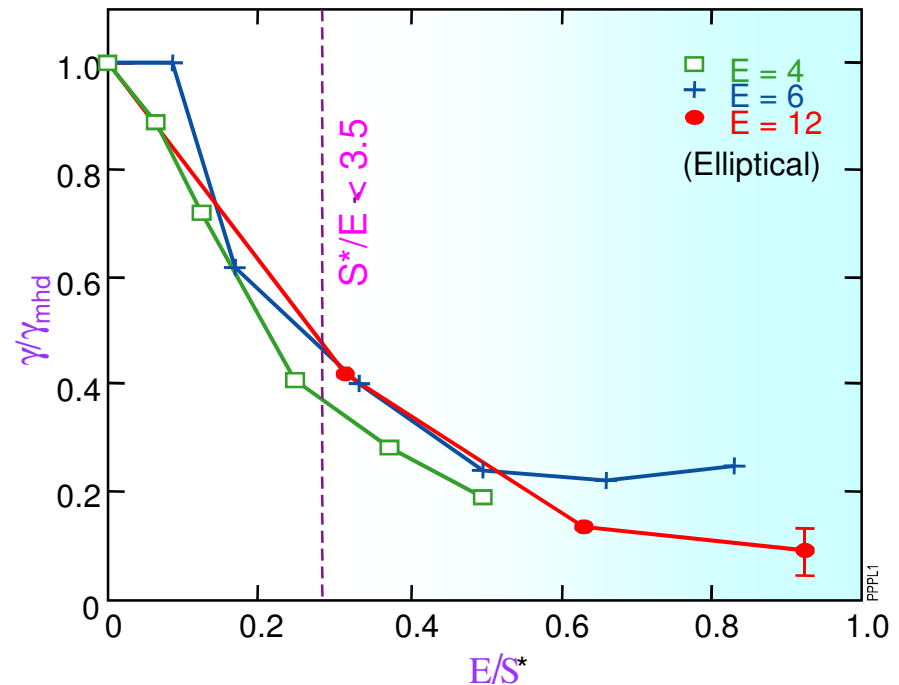


- ◆ FRCs have been observed to be robustly stable.
 - θ -pinch formed FRCs survive a violent formation process
 - May be translated into a different radius chamber at Alfvénic velocities
 - Bounce off strong mirror fields, or even collide and merge.
- ◆ RMF sustained FRCs can be sustained as long as the RMF power is on, without evidence of gross instabilities.
- ◆ However, these experiments are at relatively small s .
 $s < \sim 4.0$.

Tilt stability - Theory

◆ Stabilizing Effects

- Hall term leads to reduction in growth with increasing E/S^* .
- Nonlinear hybrid simulations show tilt can saturate nonlinearly, if linear growth rate is sufficiently small.
- Energetic beam can be stabilizing, depending on beam parameters
- Other stabilizing effects include sheared rotation, poloidal flows, gyroviscous effects, small toroidal field ...



Calculations by E. V. Belova et al.

FRC Research Needs and Gaps (Tier 1)



◆ Stability at large s

- Demonstrate stable, hot, collisionless, steady-state (or slowly decaying) FRCs at high s .
- Since $s \sim RB/T^{1/2}$, RB is a critical parameter that must be increased from recent experiments.
- Density in low 10^{19} m^{-3} range to keep sustainment powers reasonable
- Require neutral beam injection to study their stabilizing effects
- Require 20 – 50 mWb to confine 10-20 keV ions from neutral beam injection

FRC Research Needs and Gaps (Tier 1)



- ◆ Some progress can be made with existing facilities & codes, but upgrades are required to resolve the issue.
- ◆ Requirements
 - Large s device
 - Neutral Beam Injection to study fast ion stabilizing effects
 - 20 – 50 mWb poloidal flux
- ◆ Methods to form a large s , large flux FRCs
 - Rotating Magnetic Field
 - Merging spheromaks
 - θ -pinch (with possible inner coil)

FRC Research Needs and Gaps (Tier 2)



◆ Transport

- FRC resistivity (η_{\perp}) is anomalously high and is thought to be due to microinstabilities.
- Demonstrate reduced transport and establish confinement scaling.
- Anomalous resistivity may be reduced with low $\gamma_d \equiv v_{de}/v_{ti} \sim \rho_i/R \sim 1/s$
- Existing facilities, combined with a facility to address Tier 1 issues are appropriate, but additional diagnostics required.

FRC Research Needs and Gaps (Tier 2)



◆ Current drive and sustainment

- Demonstrate simultaneous efficient current drive and good energy confinement
- Methods under consideration for current drive and sustainment include:
 - » Fueling near the magnetic null
Since current is diamagnetic, flow from the field null can overcome resistive effect everywhere but the null. $\eta J_{\theta} \cong -u_r \times B_z$
 - » Rotating magnetic fields (RMF)
Formation and sustainment has been demonstrated
 - » Neutral beam injection
Axis encircling ions contribute to the toroidal current

FRC Research Needs and Gaps (Tier 3)



◆ Fast particles

- Understand effects of fast particles on current drive, stability and confinement

◆ Heating

- Demonstrate efficient heating to near burning plasma values
 - » RMF
 - » Compression
 - » Neutral Beam Injection



FRC Research Needs and Gaps

- ◆ Theory and modeling played a critical role in understanding present day FRCs, and is essential to move forward.
 - Hybrid kinetic stability studies
 - 2-D MHD θ -pinch formation / translation
 - 3D MHD and Hall MHD
- ◆ Need accurate simulations to better understand:
 - Formation (all methods)
 - Stability, including kinetic and beam effects
 - Transport mechanisms
 - Sustainment with RMF (including wave physics)
 - Sustainment with NBI
- ◆ Best codes available should be adapted and advanced.