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Improved Stability & Confinement in a High-β Relaxed Plasma State

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Introduction

- **Taylor relaxed state – force free ($\beta = 0$)**
  - Minimum magnetic energy: $W_m = \int B^2/2\mu_o \, d\tau$
  - Conserving magnetic helicity: $K = \int \mathbf{A}\cdot\mathbf{B} \, d\tau$
  - $\Rightarrow$ **"Beltrami condition":** $\nabla\times\mathbf{B} = \lambda\mathbf{B}$, *$\lambda$ is a global constant*
- **Modern relaxation principle /two fluid theory (finite β)***
  - Minimizing total magnetofluid energy: $W_{mf} = \int (B^2/2\mu_o + mn\mathbf{u}^2/2) d\tau$
  - Conserving generalized helicities: $K_{e,i} = \int \mathbf{P}_{e,i}\cdot\nabla\times\mathbf{P}_{e,i} \, d\tau$, $\mathbf{P} = m\mathbf{u} + q\mathbf{A}$
  - Two distinct sets of surfaces in axisymmetric two-fluid equilibria:

    electron fluid: $\psi = const$ (*magnetic surfaces*)

    ion fluid: $\Psi = \psi + \varepsilon r \mathbf{u}_\theta = const$; $\varepsilon = \ell_i / r_s$

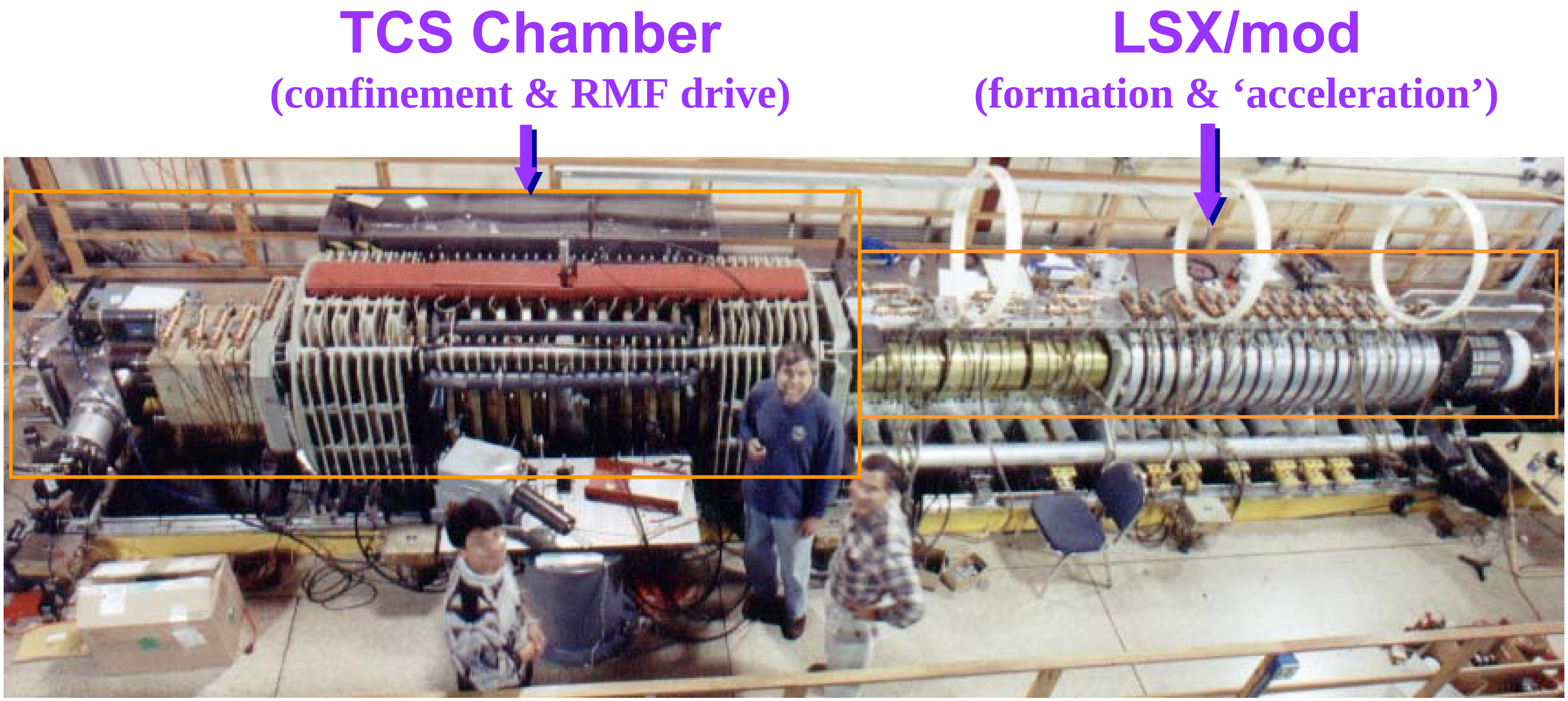
$\Rightarrow$ **In a two-fluid Minimum Energy State (MES), ion and electron stream functions characterizing poloidal flows are linear functions:** $\psi_e \sim \psi$, $\psi_i \sim \Psi$. **This is analogous to constant λ in a Taylor state.**

*** Steinhauer & Ishida, PRL 79, 3423 (1997)**

Outline

- **Evidence of relaxation in an extremely high-β plasma state**
  - **Flux conversion** from toroidal to poloidal after super-Alfvénic translation
  - **Helicity preservation** inferred by an interpretive model
- **Discovery of a new relaxed ST-like FRC state**
  - Large q and strong magnetic shear
  - A broad core conforming to a Minimum Energy State
- **Confinement & stability of FRC-ST**
- **Summary & conclusions**

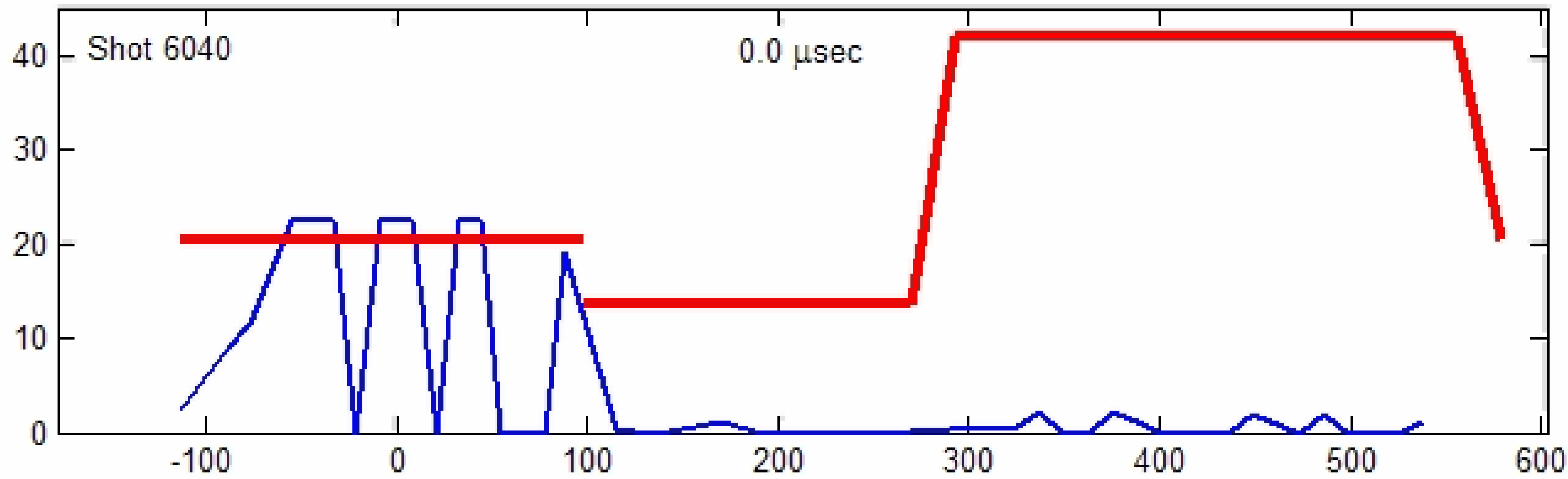
TCS facility at UW was built to investigate FRC formation and sustainment



- **Translation of high-β energetic plasmoids formed by LSX/mod θ-Pinch.**
- **FRC formation and sustainment by Rotating Magnetic Fields (*Hoffman*, *Milroy*, this meeting).**

FRC translation demonstrates extreme robustness

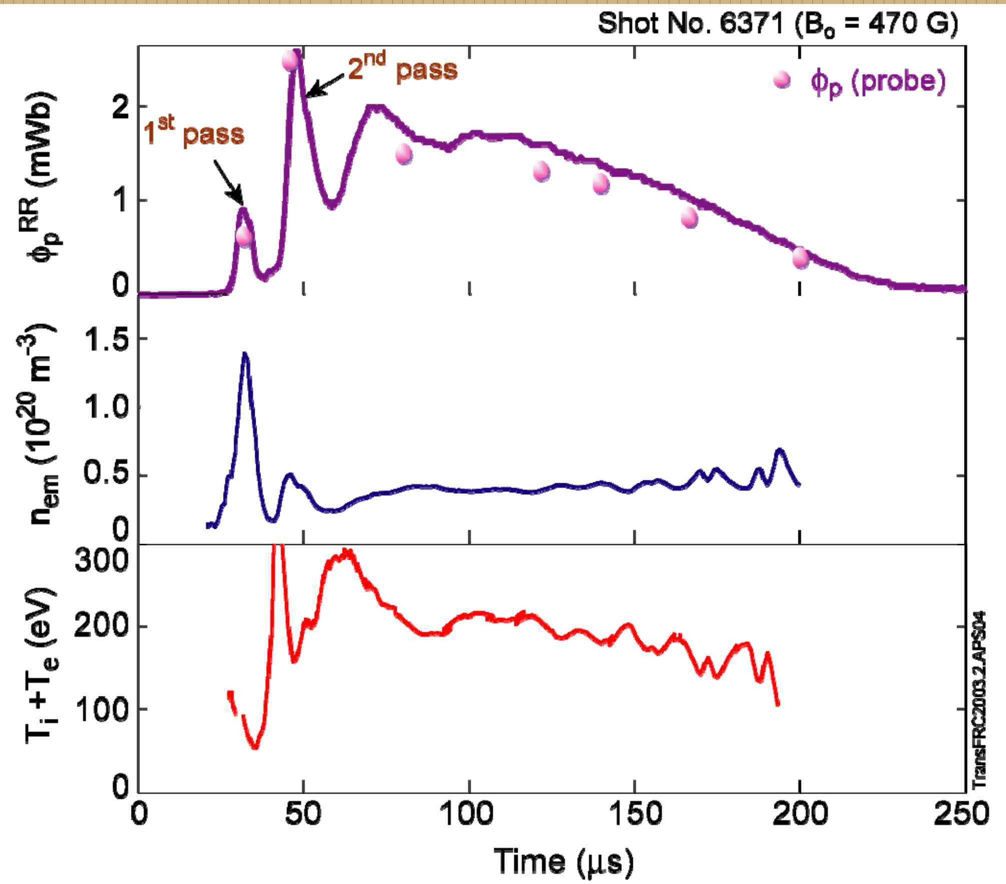
Evolution of $r_{\Delta\phi}$ (Z)



Source Acceleration Confinement

- **High-β plasmoid was formed by LSX/mod θ-pinch, then ejected into confinement chamber at highly super-Alfvénic speed (~400 km/s).**
- **FRC survived the extremely violent reflections, and retained a long lifetime.**

High-β relaxation is evidenced by a poloidal flux amplification of the translated CT*



- Poloidal flux ϕ_p appears to increase significantly after 1st reflection, as inferred from external magnetic measurements:

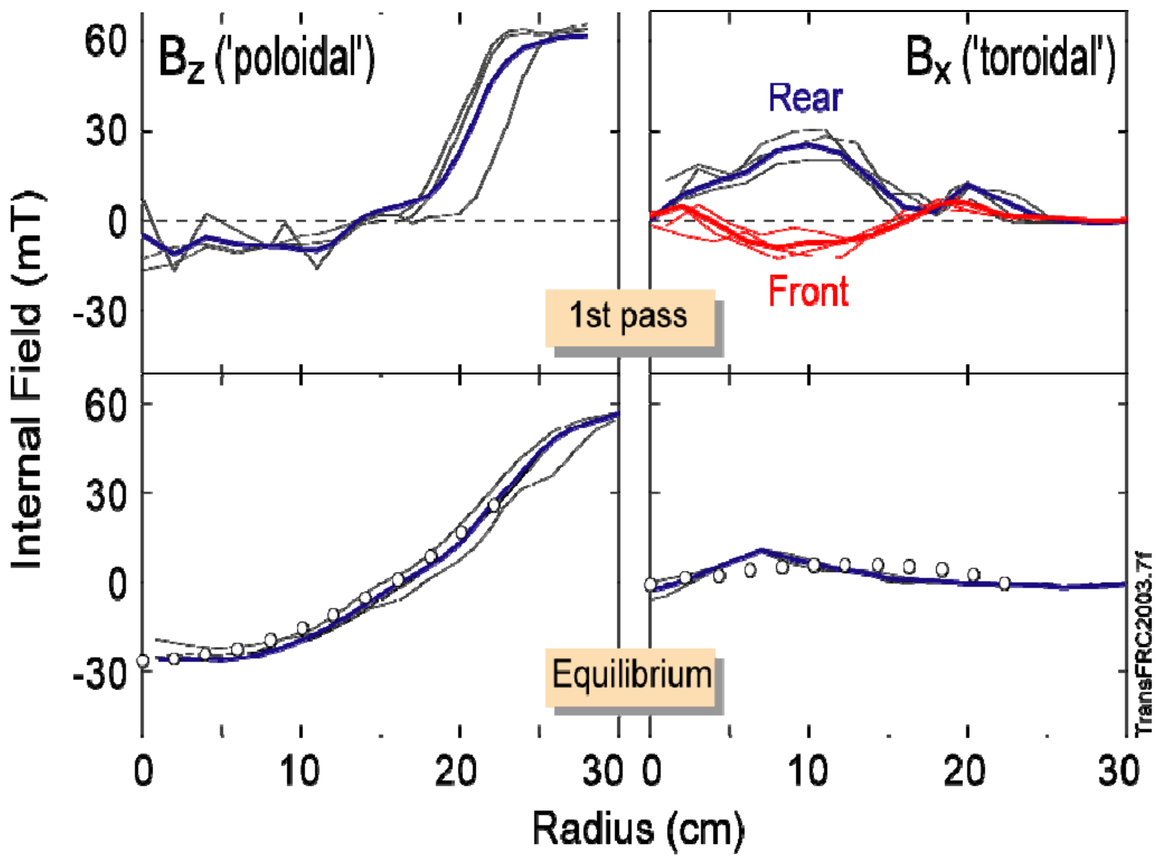
  $\phi_p^{RR} = 0.31\ x_s\ \Delta\Phi$

- This has been verified, for the 1st time, by detailed internal probing.

➢ *In an axisymmetric plasma, ϕ_p decays at a rate that depends on resistivity – it can never increase. The only way to amplify ϕ_p is by a topology-breaking, which is a marker of a turbulent relaxation.*

* Guo, Hoffman, Miller, Steinhauer, PRL 92, 245001 (2004)

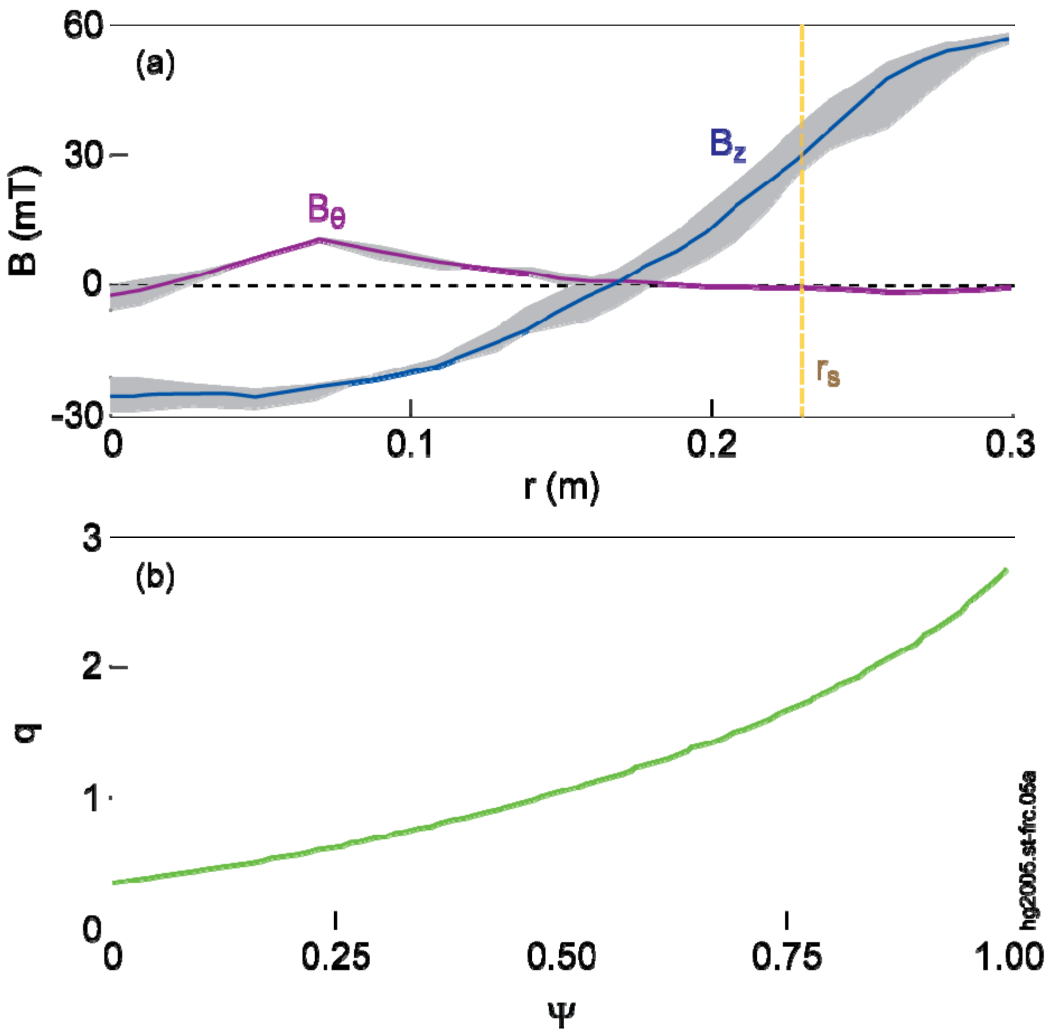
Significant flux conversion occurs with magnetic helicity roughly conserved



- Initial plasmoid has little ϕ_p, strong ϕ_T at the ends.
- After violent reflections, it settles into a near-FRC state with ϕ_p increased significantly.
- Most of the oppositely directed ϕ_T annihilated, with only a reduced uni-directional ϕ_T remaining.
- Magnetic helicity was approximately conserved.

➤ *Significant toroidal rotation has been observed, but flow measurements are incomplete to determine whether the ion helicity is conserved.*

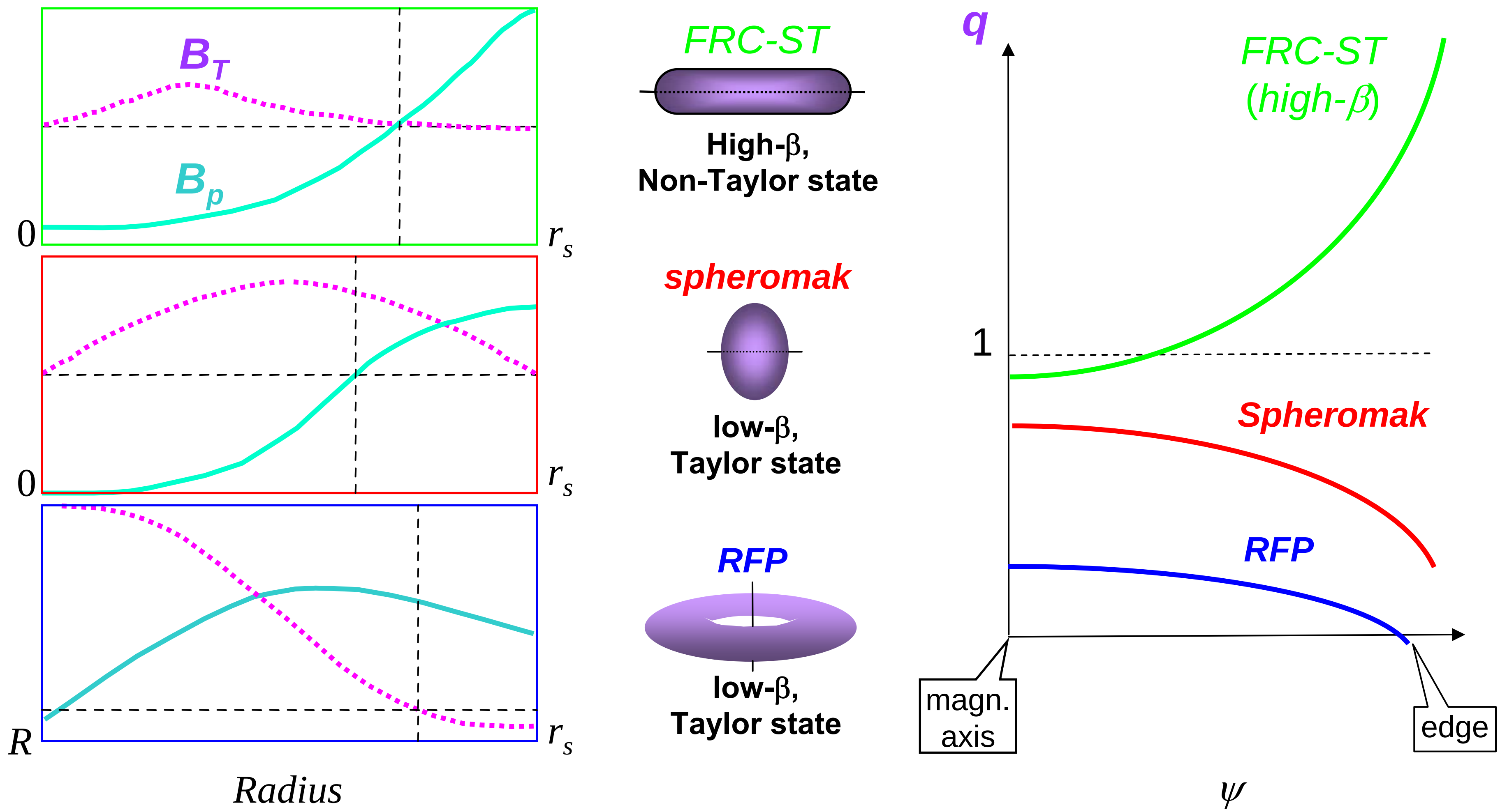
Relaxation leads to a ST-like FRC state with a large q and significant shear



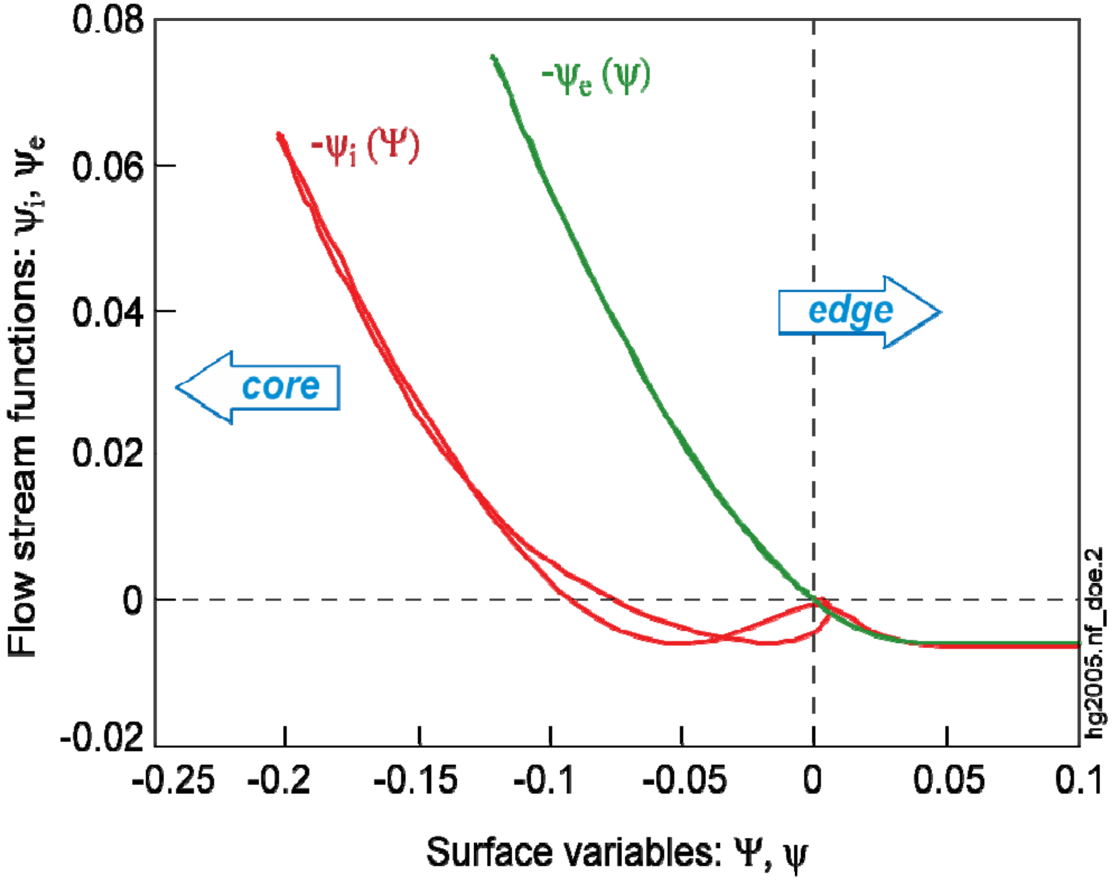
- High-β $\rightarrow B_{tor}/B_{pol}$ is small
- Large-q arises from high elongation, E, as first noted by Ryutov.
- Strong shear is due to highly localized B_θ.

$$q \equiv \oint_\psi \frac{B_\theta d\ell}{2\pi r B_p} \sim \frac{2E}{\pi} \frac{B_{tor}}{B_{pol}}$$

FRC-ST is a new addition to relaxed states of magnetically confined plasmas



A broad core of FRC-ST conforms to a two-fluid Minimum Energy State (MES)



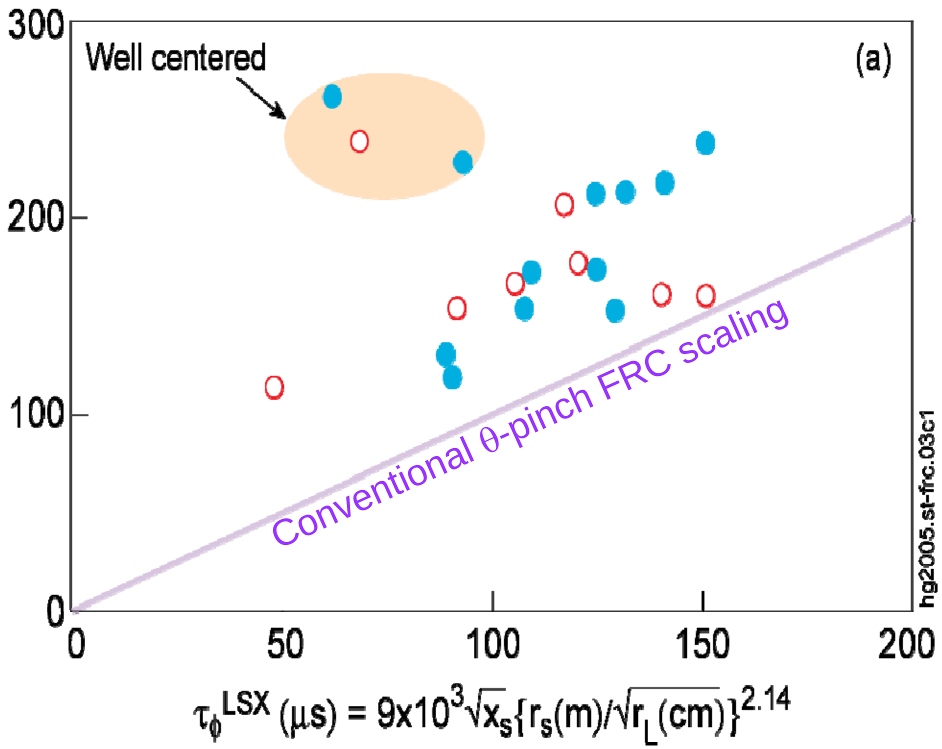
- **In a two-fluid MES, ion and electron stream functions are linear functions, i.e., $\psi_i \sim \Psi$, $\psi_e \sim \psi$** *(analogous to constant λ in Taylor-states).**
- **The inferred stream functions appear to be linear in a large core region, indicating that a broad core of FRC-ST is very close to a MES.**

➢ ***MES core may promote good stability and confinement.***

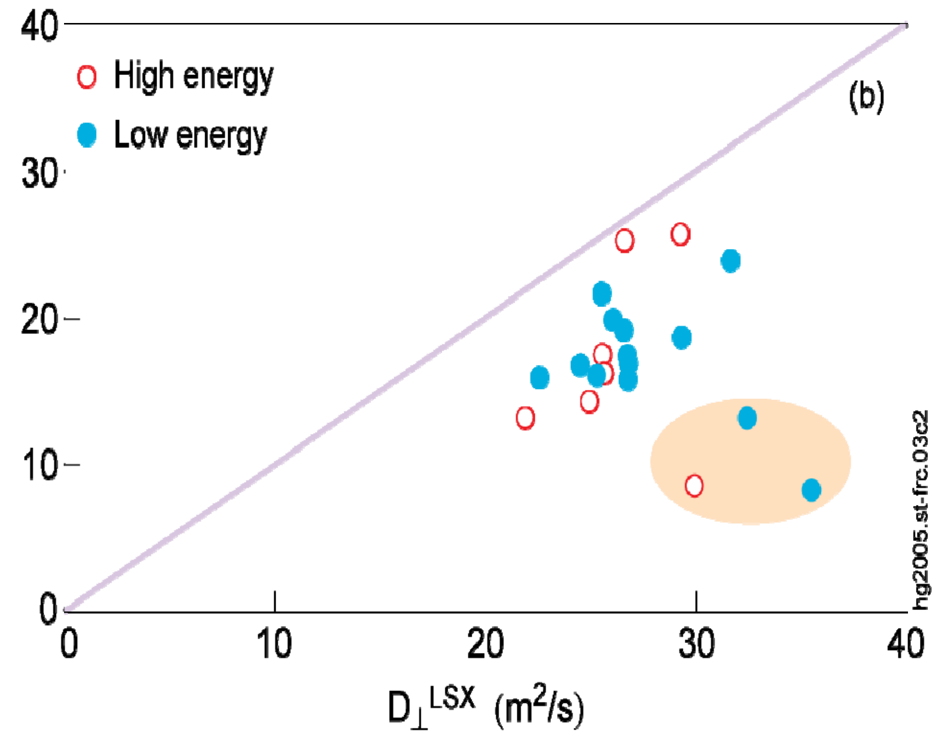
* **Steinhauer, this meeting**

FRC-ST exhibits up to 4x improvement in τ_ϕ with significantly reduced transport*

Flux confinement time, τ_ϕ



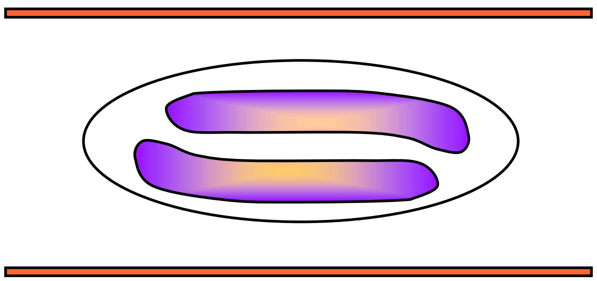
Diffusivity, $D_\perp = \eta_\perp/\mu_o$



* Guo, Hoffman, Steinhauer, Miller, PRL 95, 175001 (2005).

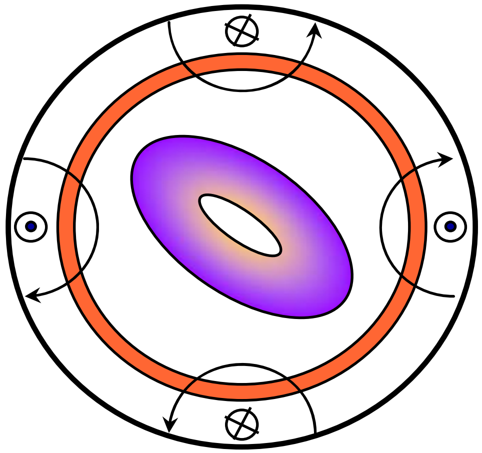
Dominant global instability observed in an FRC is n=2 rotating interchange mode

- n=1 tilt mode
  - MHD unstable, but
  - Not observed experimentally.



Side View

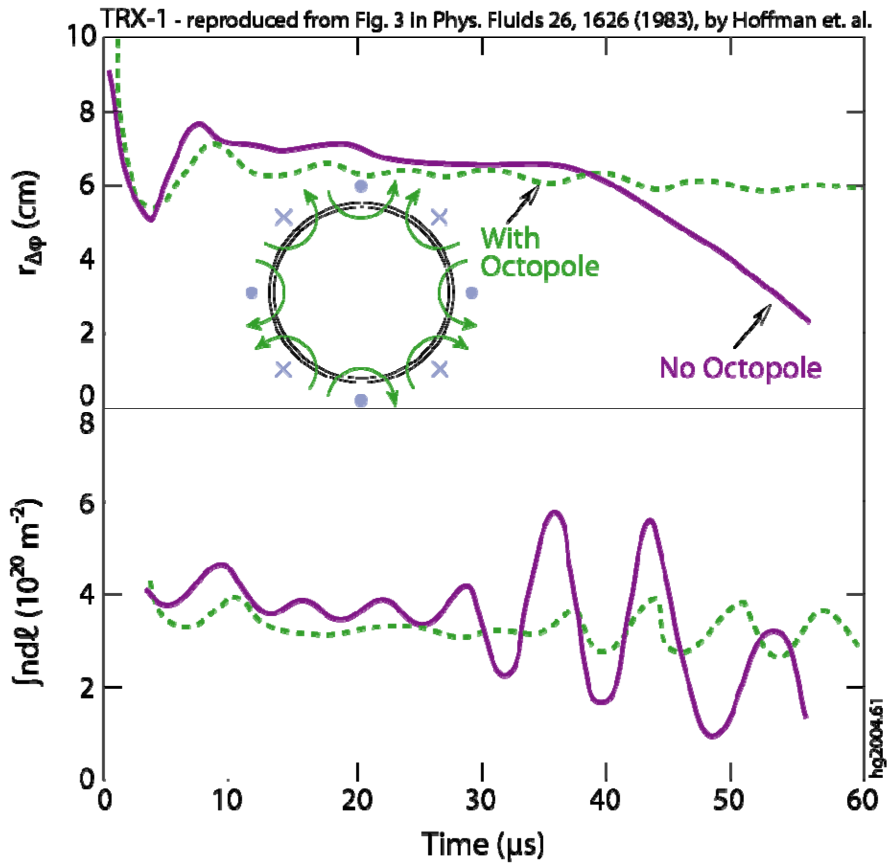
- n=2 rotating interchange
  - Driven by centrifugal force due to plasma rotation.
  - Usually stabilized by external static multipole fields in θ-pinch formed FRCs.
  - Rotating Magnetic Fields also provide strong stabilizing effects.*

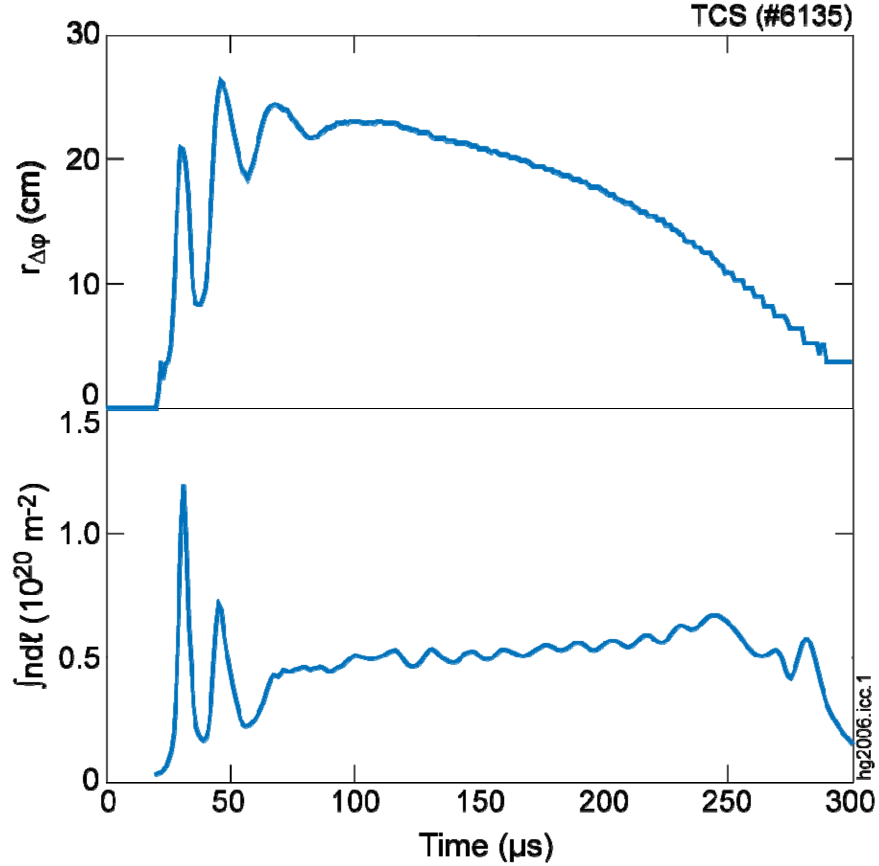


End View

* Guo, Hoffman, Milroy et al., PRL 94, 185001 (2005).

FRC-ST exhibits remarkable stabilizing effects for n=2 rotating interchange mode





- θ-pinch FRC: n=2 is destructive
- Usually stabilized by external static multipole fields.
- FRC-ST: n=2 mode does not develop despite the absence of multipoles.

This is explained by a simple model taking into account magnetic shear

- **Energy principle analysis (*Bellan*):**

$$\delta W \approx \frac{1}{4}\int dV \; \xi_{\perp}^{2}\left(B_{1\perp}^{2}/\mu_0 + \Omega^2 r \nabla \rho\right)$$

  – *neglecting $J_{//}$-drive & curvature-related ∇p-drive terms.*

- **Stability criterion:**

$$\left(\frac{dq}{d\Psi}\right)^2 > \frac{3R^2 Z_0 \Omega^2}{n^2 V_A^2}\left|\frac{\nabla\rho}{\rho_0}\right| \sim 1, \;\; \text{for } n = 2$$

- **From inferred *q* profile:**

$$\left(\frac{dq}{d\Psi}\right)^2 \sim 5$$

⇒ ***Sufficient to stabilize centrifugally driven n=2 mode.***

Summary & conclusions

- **Relaxation in an extremely high-β plasma has appeared in the TCS translation experiment, producing a new ST-like FRC state,** ***i.e., clearly not a Taylor state, strongly suggesting that a more general principle regulates the relaxation.***
- **Modeling using the newly developed nearby-fluids theory shows that a broad core of FRC-ST is very close to a** ***two-fluid Minimum Energy State (MES).***
- **This relaxed plasma state exhibits significantly reduced transport with up to** ***4x improvement in confinement.***
- **FRC-ST also exhibits a** ***remarkable stabilizing property*** **for the normally lifetime terminating n=2 centrifugally driven interchange modes in θ-pinch FRCs, which is attributed to the strong magnetic shear.**