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**Oblate FRC concept with NBI for
experimental studies of large-s FRC
formation, stability, current drive and
transport**

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Main Features¹

- Formation by counter-helicity spheromak merging.
- Flexibility to study FRC stability properties by
 - Varying the plasma shape and kinetic parameter
 - Using passive stabilizers and external field shaping
 - NBI stabilization
 - NBI induced rotation
- Sustainment of the FRC using a central Ohmic-transformer stack and/or NBI.

[1] Yamada et al., Plasma and Fusion Research (2007).

Oblate FRC-NBI experiment can address several major FRC issues (TAP report)

- Large-s stability
- Confinement
- Fast particle effects
- Current drive

- Eliminates the $n=1$ tilt stability issue due to the stabilization by conducting shell/external field shaping.
- An Ohmic transformer used to sustain and amplify poloidal flux in the initial phase, allowing flux build up to confine the NBI ions.
 - Separate FRC sustainment from stability and transport studies.
- The experimental design and data analysis benefit from computational support => Validation of codes and further improvement of the predictive models.

Oblate FRC vs prolate FRC stability

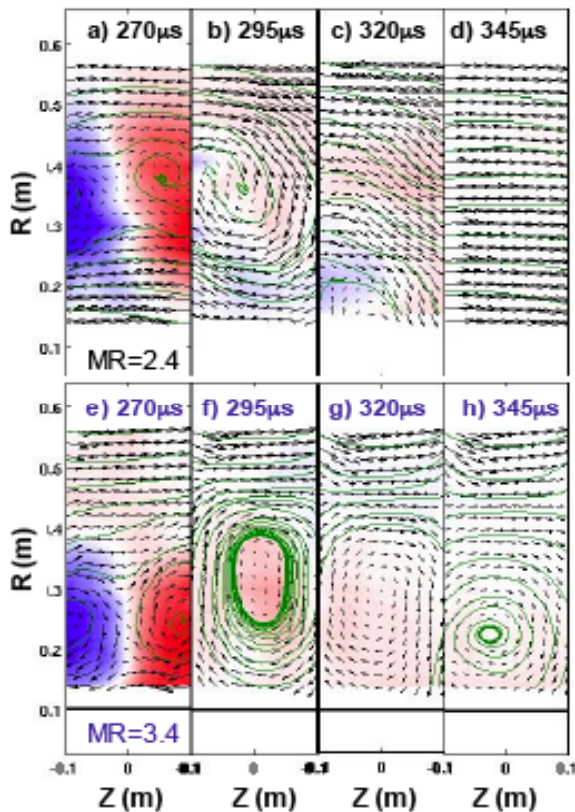
Prolate FRCs ($E \gg 1$)

- All unstable modes ($n \geq 1$) are internal.
- Conducting shell has little effect on stability.
- Low S^*/E are needed for kinetic/two-fluid stabilization.
- Strong beams may be needed to stabilize the $n=1$ tilt mode.

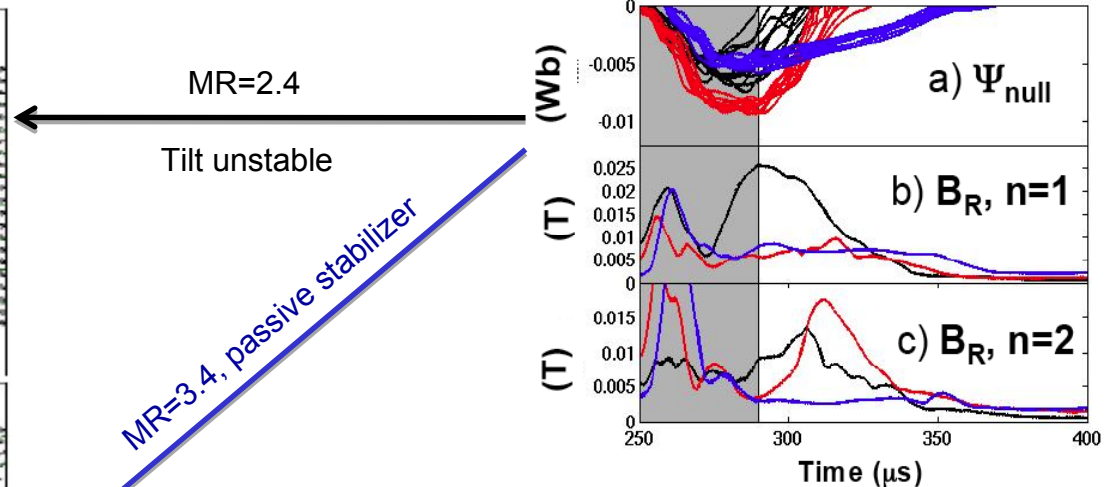
Oblate FRCs ($E < 1$)

- $n=1$ *tilt and radial shift* modes can be stabilized by conducting shells.
- $S^*/E \gg 1 \rightarrow$ FLR stabilization is weak.
- *Interchange modes* ($n \geq 1$) can be stabilized by profile effects.
- $n > 1$ *co-interchange* modes are internal modes, and they remain unstable in the presence of a close-fitting conducting shell.
- Residual modes can be stabilized by NBI.

Experimental results regarding oblate FRC



(a-d) Time evolution of discharge with large $n=1$ tilt mode ($MR=2.4$); (e-h) A very oblate plasma with a center-column ($MR=3.4$), which displays more robust stability. Helium FRCs.

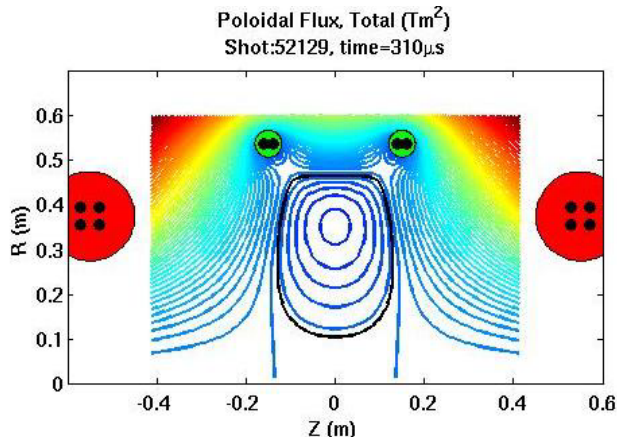


MRX-FRC results

- Poloidal flux up to 10mWb, $E=0.35-0.6$
- Co-interchange modes with $n \geq 2$ have been observed for the first time.
- Studied effects of central conductor and external field shaping on stability.
- Demonstrated FRC sustainment by Ohmic transformer.

[Gerhardt et al, PRL (2006)]

MRX FRC experiments show improved stability for large mirror ratio, small elongation ($E < 0.5$) cases.



MRX-FRC equilibrium [S. Gerhardt, 2006]

- Two types of co-interchange modes are observed:
 - radially-polarized modes,
 - axially-polarized modes.[For $n=1$ these are the radial shift mode and tilt mode, respectively.]
- Strong equilibrium field shaping (large mirror ratio) can stabilize the $n=1$ modes, and improve stability of $n=2$ modes.
- Effects of external field shaping are much weaker for higher- n modes ($n \geq 3$) due to more localized structure of these modes.
- Energetic beam ions can provide additional stabilizing mechanism for $n \geq 3$ modes.

Injection of energetic ion beams may provide additional stabilizing mechanism, as well as plasma heating and current drive

Issues related to NBI stabilization of low- n modes in FRCs:

- Optimal injection parameters: I_b/I_{tot} , n_b , V_0 , and injection angle.
- Dependence on the FRC elongation, shape and S^* .
- Stability of the $n=1$ tilt mode and $n>1$ co-interchange modes with NBI.

These issues can be addressed by oblate FRC-NBI experiment. Experimental data can also be used to validate/improve codes.

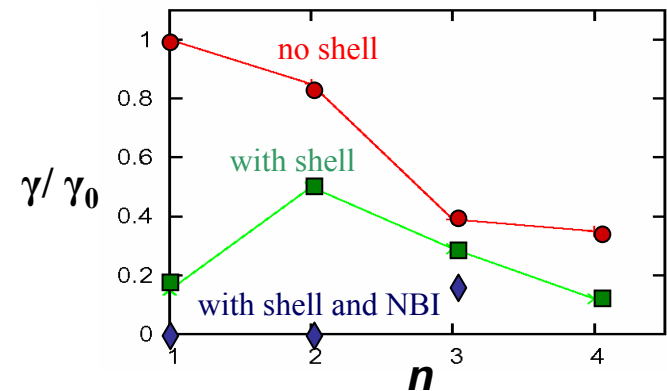
Energetic ion beams effects: oblate vs prolate FRC

- Self-consistent equilibrium calculations show that the beam ions tend to coalesce between the magnetic null and the separatrix near the midplane; stronger beams are more localized [Barnes`91, Nishimura`99, Lifschitz`02].
- The beam ion contribution is stabilizing provided: $n|\Omega| > \omega_\beta$, where Ω is average toroidal rotation frequency of the beam ions, and ω_β is the betatron frequency [Lovelace`75, Finn and Sudan`93].

- Strong beams are highly localized and can be destabilizing: $\Omega < \omega_\beta$.
- Due to localization, the peak NBI current density J_b can be comparable to the local thermal plasma current density, even when the fraction of the total current carried by the NBI ions is small – beneficial for oblate FRC.
- The $n=1$ tilt mode is hardest to stabilize - oblate FRC avoids this issue.

FRC stability including close-fitting conducting shell and energetic beam ion effects: I. Linear simulation results

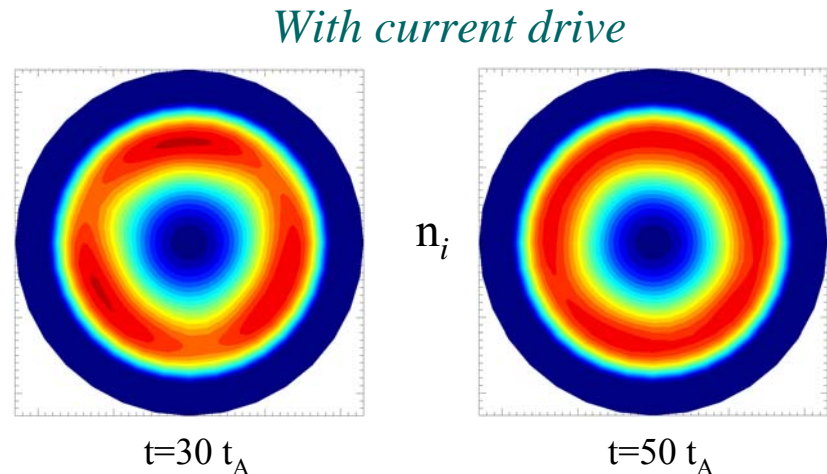
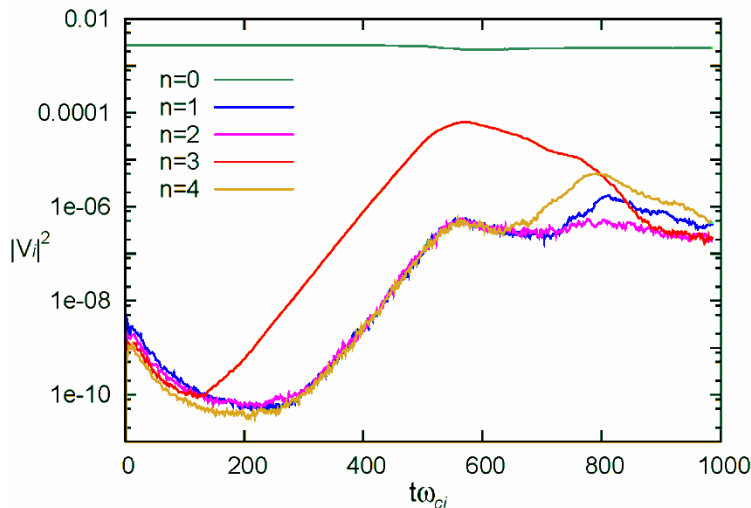
- Close-fitting conducting shell stabilizes all low- n radially-polarized modes.
- Due to localization, the ion beams are effective in stabilizing the residual low- n instabilities.
- The $n=1$ tilt mode and the $n=2$ mode are stabilized, and the growth rate of the $n=3$ mode is reduced.



Normalized growth rates of the $n=1-4$ modes from 3D hybrid simulations including the effects of conducting shell and NBI stabilization. $E \sim 1$, $n_b/n_i=0.03$, and $V_0=6V_A$.

FRC stability including close-fitting conducting shell and energetic beam ion effects: II. Nonlinear simulations

- Nonlinear 3D simulations show that the residual instabilities (n=3 mode) saturate at small amplitudes.
- FRC remains stable with respect to **all MHD modes**, if FRC is sustained.



Nonlinear hybrid simulations of an FRC with $E=1.1$, including the effects of the beam ions and the close-fitting conducting shell. (a) Time evolution of $n=0-4$ modes kinetic energy; and (b) contour plots of plasma density in the toroidal cross sections.

Basic Study of the FRC Transport

Critical issues:

- Dependence of the flux dissipation rate in FRC on collisionality, kinetic parameter s , and toroidal flow.
- Excitation of electrostatic/electromagnetic lower hybrid waves and other high frequency instabilities, which can enhance flux dissipation rate.
- Close collaboration between experiments/theory is needed.

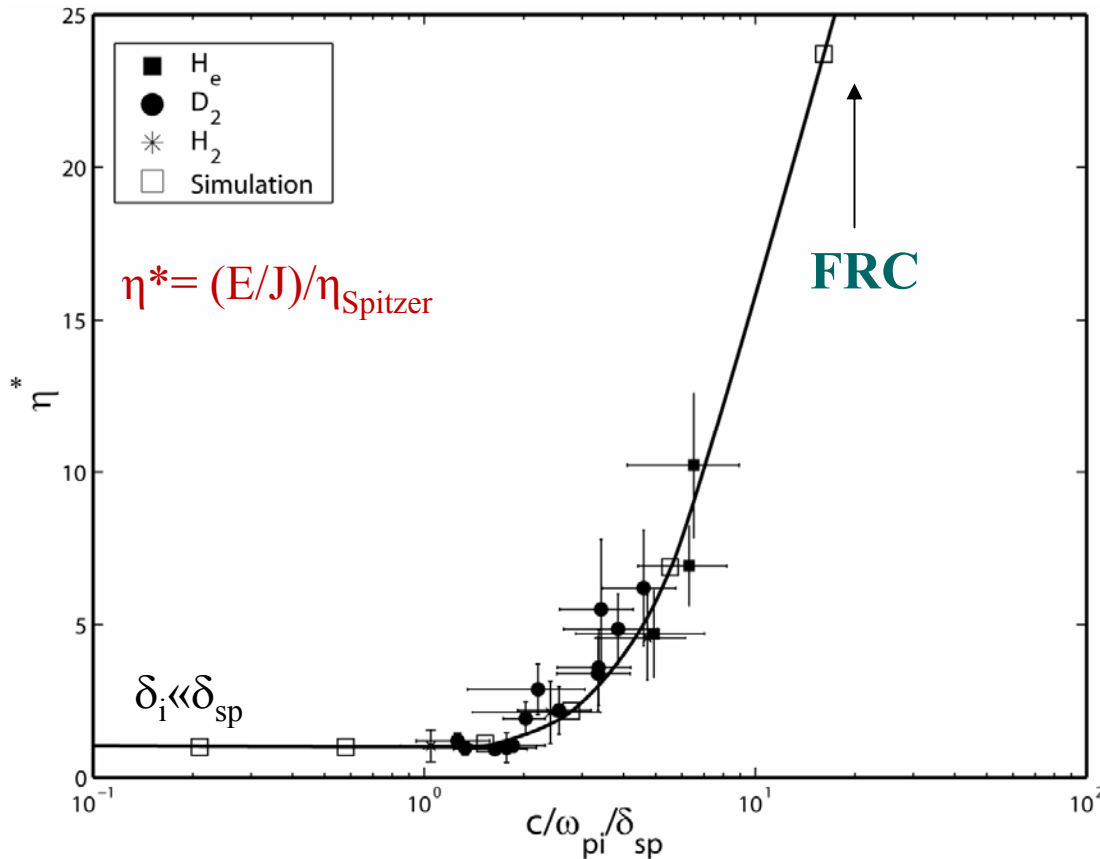
Magnetic Energy Dissipation in FRC

- For collisional MHD regime: $\lambda_{\text{mfp}} \ll L$
 - ⇒ Magnetic dissipation occurs through collisional dissipation
 $E = \eta_{\text{c}} j$
- For collisionless regime: $\lambda_{\text{mfp}} > L$
 - ⇒ Two-fluid effects are important
 - ⇒ $E_{\text{Hall}} / \eta_{\text{c}} j \sim (\lambda_{\text{mfp}} / L) (m_i / m_e)^{1/2} \gg 1$

Fast Reconnection \Leftrightarrow Enhanced Resistivity

- Cause of the observed enhanced resistivity?
- FRC current center \sim reconnection current sheet
- Hall MHD Effects create a large E field
- Electrostatic Turbulence
- Electromagnetic Fluctuations
 - » All Observed in MRX

MRX Scaling: η^* (Effective resistivity) vs $(c/\omega_{pi})/\delta_{sp}$



$$\delta_i / \delta_{sp} \sim 5 (\lambda_{mfp} / L)^{1/2}$$

$\delta_i = c/\omega_{pi}$ – ion skin depth

$\delta_{sp} = L/S^{1/2}$ – Sweet-Parker width

MRX scaling shows transition from the MHD (collisional) to two-fluid regime based on normalized ion skin depth

A linkage between reconnection rate and B dissipation