Stabilization of Interchange Modes by Rotating Magnetic Fields (RMF)

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High-\(\beta\) linear confinement configurations are intrinsically unstable to interchange or fluting modes due to unfavorable field line curvature.

In FRCs, the ions generally carry much of the diamagnetic current, and the concomitant plasma rotation produces a much more dominant instability drive force.

The dominant instability under these conditions is the rotational \(n=2\) instability, which is nearly ubiquitous in the \(\theta\)-pinch formed FRCs.
Outline

- Rotational instabilities in $\theta$-pinch formed FRCs
- Ion rotation and structure of rotational modes in RMF driven FRCs in TCS
- Evidence of stabilizing effects from RMF
- Influence of RMF antenna geometries
- Summary and conclusions
FRC stability

- **Internal tilt starts out as an axial n=1 shift mode**
  - Highly unstable, predicted by MHD
  - But has not been observed experimentally

- **Rotational n=2 mode is the dominant global instability observed experimentally**
  - Driven by centrifugal force due to plasma rotation
  - Leading to Rayleigh-Taylor type instability
Rotational instabilities in $\theta$-pinch formed FRCs

- Simple Rayleigh-Taylor analysis:
  \[ \omega^2 = -g/[\delta_\rho(1/4 \delta_\rho^2 + (n\pi/\hbar)^2 + k^2)] < 0, \]
  \[ g = \Omega^2 r, \ k = n/r \]
  Growth rate: \( \gamma \approx (g/\delta_\rho)^{1/2} \)

- MHD with FLR corrections \( \Rightarrow \)
  Instability threshold: \( \alpha = \Omega/\Omega_i^* > 1 \)

- Static multipole stabilization:
  \[ B_m^2/2\mu_o > \langle \rho \rangle \Omega^2 r_s^2 \]
Ion rotation in RMF driven FRCs

- Plasma spins up in electron diamagnetic direction due to the RMF applied torque, contrary to θ-pinches formed FRCs.
- $\omega_i \geq \Omega^*$ for most FRCs except at high $\omega$ due to reduced RMF torque.

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Rotational instabilities in $\theta$-pinch & RMF formed FRCs

- **$\theta$-pinch FRC**: $n=2$ is destructive
- **Usually stabilized by multipole fields**

- **RMF FRC**: $n=2$ is non-destructive
- **Stable when RMF antennas cover central portion**
n=2 mode seen by tomography

- n=2 mode rotates in the electron diamagnetic direction, in the same direction as RMF.
Internal structure of n=2 modes

- **n=2 distortions** are localized outside the field null, \( \omega_{n=2} = \omega_i, k_z = 0 \).
- **Driven by ion rotation outside field null** where centrifugal force is in the same direction as the pressure gradient force.
RMF stabilization

- Oscillations are significantly reduced at edge where RMF is strong.
- Can be completely suppressed by keeping the separatrix radius $r_s$ sufficiently close to the wall.

➢ We surmise that the radial force imposed by RMF provides stability to rotational modes by counteracting centrifugal force due to plasma rotation.
Simple theory for RMF stabilization
(applicable to any plasma column)

- Rayleigh-Taylor analysis
  \[ \gamma \approx \left( \frac{g}{\delta_\rho} \right)^{1/2} \]

- Radial force due to RMF
  \[ F_r = 2B_\omega^2 / (\mu_0^*) (r_s/r) e^{-2[(rs-r)/\delta^*]} \]

- Effective growth rate
  \[ \gamma = (\Omega r / \delta_\rho - F_{r1} / \rho_\|)^{1/2}, \quad F_{r1} = F_r / r_s \]

- Stability threshold
  \[ \Rightarrow B_-^2 / \rho_\| \geq 1.3 \left( \rho_\| \right) \Omega^2 r_s^2 \]
2D \((r, \_\_)\) simulation – with fixed stipulated elliptical distortion

- Inward force due to RMF \(\langle j_B \rangle\) changes as FRC column distorts exerting stronger force as plasma column extends outwards.
RMF Stabilization criterion is satisfied for most FRCs except for the lowest $\omega$, which produced the highest densities, pushing the centrifugal force beyond the instability threshold.

RMF stabilization also has significant implications for other quasi-linear confinement configurations, such as mirrors, which are intrinsically unstable to interchange/fluting modes.
Localized central RMF drive

- Operation with shorter antennas was less prone to n=2 mode.
- Plasma at ends rotates at a slower rate with a strong flow shear: \( \frac{dV_\theta}{dz} \sim 10^5 \text{ s}^{-1} \sim 0.4 \, kV_A \), which may be stabilizing.

Stabilization threshold for a sheared flow Z-Pinch is 0.1 \( kV_A \).
Effect of anti-// RMF configuration

- Anti-// RMF proposed by Cohen-Milroy as means of keeping even the edge fields closed.
- Also appeared to be even more stabilizing to rotational instabilities.
Quadrupole RMF proposed as even better stabilization geometry – *it wasn’t!*

- Quadrupole RMF formed FRCs and drove currents just as well as normal dipole antennas (*R.D. Milroy, this meeting*).
- But, less efficient in stabilizing the n=2 mode, possibly due to insufficient RMF near the field null where centrifugal force is strong.
Possible effect on tilt mode

- No tilt modes have been observed for FRCs lasting over 500 tilt growth times:
  \[ \frac{1}{\gamma_{\text{tilt}}} \sim \frac{\lambda_s}{2V_A} \sim 20 \, \mu s \]
- RMF may also have some influence on tilt stability since it can act somewhat inside the separatrix.
- Axial variation in RMF fields seem to be beneficial in experiments with both shorter antenna lengths and anti-parallel antennas.

**Kinetic effects are not important as \( T_i \) is low.**
As in conventional $\theta$-pinch formed FRCs, rotational modes have been observed in RMF formed FRCs with $\omega_{n=2} = \omega_i$.

Rotational instabilities are localized near the field null, significantly reduced at the edge where RMF is strong.

Can be further reduced by the use of either anti-// or centralized RMF current drive.

In contrast, FRCs produced by the quadrupole RMF are more prone to rotational instabilities.

No tilt instability has been observed in RMF driven FRCs with the configuration time lasting over 500 $\tau_{\text{tilt}}$. RMF may be also stabilizing to the tilt instability.