Tomographic Observation of FRC Rotational Modes and Stabilization by Various RMF Antenna Geometries in TCS

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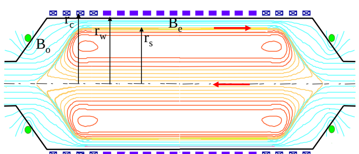
Abstract

The most common instability observed in FRCs is a fluting instability driven by centrifugal forces related to toroidal ion rotation. In theta-pinch formed FRCs this rotation is due to preferential ion losses, while in Rotating Magnetic Field (RMF) driven FRCs it is due to the torque applied by the RMF. In order to study this effect and determine its mode structure, a visible light tomographic system was built and employed at the FRC midplane. The primary unstable mode was the n=2, but both n=1 and higher modes were also observed. The fluting modes were observed to rotate at the same speed as the bulk plasma (determined from Doppler shifts of impurity ions), and could be correlated with internal magnetic probe measurements. Interestingly, the instability could be stabilized by the RMF radial pressure under some antenna geometries. Simple models were developed to explain this stabilization, which can also have application to other, quasi-linear devices such as symmetric mirrors.

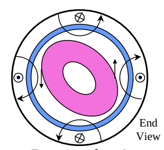
The FRC and Rotational Instability



$x_s \equiv r_s/r_c$

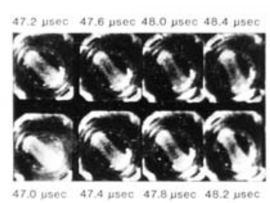
- The Field Reversed Configuration (FRC) is a compact toroid (CT) with little or no toroidal field
- Inherently high beta: $\langle\beta\rangle = 1 - \frac{1}{2}x_s^2$
- Flux conservation: $B_e = B_o/(1 - x_s^2)$
- Simple radial pressure balance: $p + B^2/2\mu_o = B_e^2/2\mu_o$
- Field null at $R = r_s/\sqrt{2}$
- RFTP formation: ionized gas embedded in axial field, then external axial field is reversed, end reconnection forms a CT
- RMF formation: electrons driven azimuthally by RMF create azimuthal current, which produces the poloidal field.

- In traditionally RFTP formed FRCs, centrifugal forces due to ion diamagnetic rotation drive a rotationally unstable mode n=2

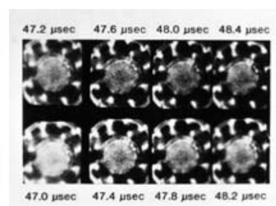


Rotational n=2

- It has been proven to be stabilized by weak multipoles with $B_m^2/2m_o$ > centrifugal pressure.

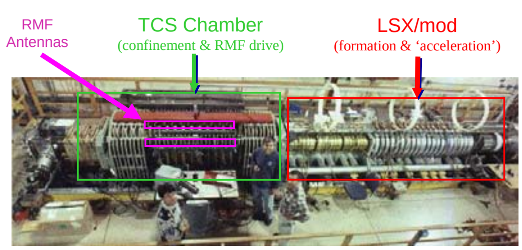


No Stabilization



Octopole Stabilization

The TCS Machine and RMF Current Drive



- The TCS experiment consist of 2 main sections:
  - LSX/mod that can be used to form and translate FRCs
  - TCS chamber in which a rotating magnetic field can be applied to a pre-formed FRC, or generate a FRC from a pre-ionized plasma
- The TCS chamber is constructed of a 40-cm radius quartz vacuum chamber. An axial field is produced by solenoidal magnets. 2-pair of Helmholtz-type coils that are driven 90° out of phase create a rotating field transverse to the axial field.

- To provide current drive, the RMF provides a torque on the electrons:

$$T_{RMF} = 2\pi r_s \delta^* B_\omega^2 / \mu_o$$

where δ^* is the penetration depth of the RMF given by $\delta^* = (2\eta_{//}/\mu_o\varpi)^{1/2}$
- The origin of the azimuthal force on the electrons is from axial oscillations of electrons interacting with the radial component of the RMF field, producing a $F_\theta = \langle j_z B_r \rangle$ force
- Ion-electron collisions provide a resistive torque:

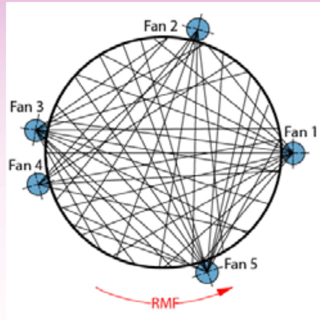
$$T_\eta = 0.5\pi\eta_\perp \left\langle n_e e^2 (\omega_e - \omega_i) \right\rangle r_s^4$$

- Flux and density are increased until an equilibrium is reached where T_{RMF} equals T_η
- The RMF also generates a strong radially inward force, $F_r = \langle j_z B_\theta \rangle$

Tomography Setup

- Tomgraphic fans arranged near the midplane of the TCS confinement chamber
- Filtered Si-diode array responsive from 510-580nm between the D_α and D_β emission lines to view Bremsstrahlung radiation
- Light collected by 7.62cm (3") diameter ball lens, focused into 3mm plastic fiber optics, and transferred to Si-PD
- Data is multiplexed 8:1, and read by an 8-bit, 10M sample/sec digitizer, giving time resolution of 1μsec

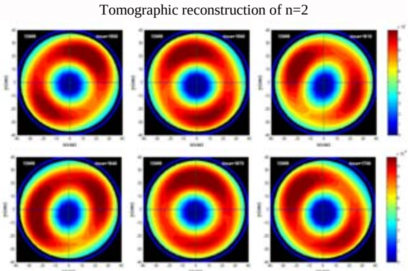
Visible Light Tomography System

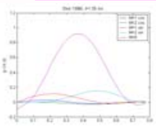


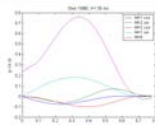
- The algorithm used is based on papers written by A.M. Cormack and later improved by R.S. Granetz. Much of the code used was originally implemented on the TCV experiment in Switzerland, and modified for use with TCS data.
- The method is based on expanding the chordal measurements and the solution function in harmonic constituents, where the azimuthal component is expressed in sine and cosines, and the radial component is expanded in terms of Zernicke polynomials

n=2 and n=1 Observed on TCS

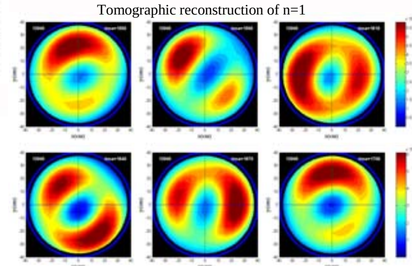
Tomographic reconstruction of n=2





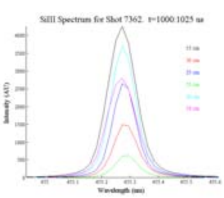


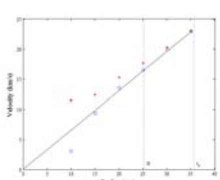
Tomographic reconstruction of n=1



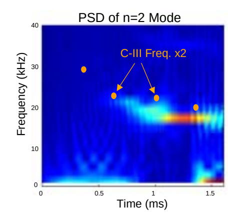
- Tomographic reconstructions of the TCS plasmas show evidence of n=1 and n=2 rotational instabilities
- Shown to the left is one period of an n=2, and to the right an n=1. Above are the 5 most prominent harmonics used in the reconstruction

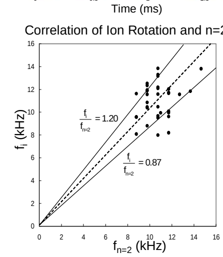
Rotation Frequency Correlated with Ion Rotation





- Impurity line radiation is measured with a 6 chord ICCD spectrometer, with data collected over 25-100μs
- (Upper left) By measuring the Doppler shift of emission lines, the ion azimuthal velocity can be derived
- (Lower left) The chordal data (red stars) is then Abel inverted to give the ion velocity profile (blue, open circles)
- (Upper right) Velocity of ions rigidly rotating is translated into a frequency that corresponds to the frequency of the n=2
- (Lower right) Ion rotation frequency is within ~20% of n=2 frequency





Stability Model Developed

- RMF provides a steady radial force, $<j_\theta B_z>$, that supports the plasma pressure, and can provide stabilization.
- The radial inward force due to RMF, $F_r=<j_z B_\theta>$, is derived from the RMF fields and driven currents within the FRC, $r < r_s$:

$$B_r = \sqrt{\frac{2r_s}{r}\frac{\delta^*}{r}} B_\omega e^{-\left(\frac{r_s-r}{\delta^*}\right)} e^{i\left(\omega t-\theta-\frac{\pi}{4}-\left(\frac{r_s-r}{\delta^*}\right)\right)}$$

$$B_\theta = 2\sqrt{\frac{r_s}{r}} B_\omega e^{-\left(\frac{r_s-r}{\delta^*}\right)} e^{i\left(\omega t-\theta-\frac{\pi}{2}-\left(\frac{r_s-r}{\delta^*}\right)\right)}$$

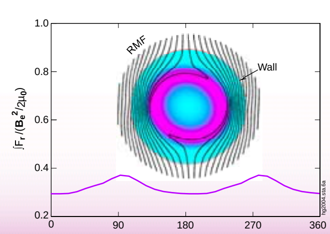
$$j_z = \varpi E_z/\omega\eta_{//} = \varpi r B_r/\eta_{//}$$

- Averaging over an RMF period, the radial force due to RMF is:

$$F_r = -\left\langle j_Z B_\theta \right\rangle = -\frac{2B_\omega^2}{\mu_o \delta^*}\frac{r_s}{r} e^{-2\left(\frac{r_s-r}{\delta^*}\right)}$$

- Stability criteria can be derived by examining how the radial force responds to a radial distortion $\xi(r,\theta)$.
- Radial stability is provided by an increased curvature of the RMFlines
- If the peak B_θ is distorted to vary as $B_\omega(2+\xi/r_s)$, the first order correction to the RMF radial force is:

$$F_{r1} = -\frac{2B_\omega^2}{\mu_o \delta^*}\frac{r_s}{r} e^{-2\left(\frac{r_s-r}{\delta^*}\right)} \frac{\xi}{r_s}$$



- Evidence of this 1st order force is shown in the RMF penetration calculation to the left with $\xi_{max} = 0.1r_s$

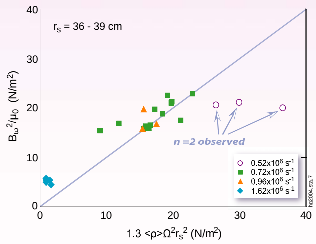
Simple Rayleigh-Taylor Analysis

- Simple Rayleigh-Taylor analysis, like in Goldston and Rutherford's Plasma Physics, shows an instability growth rate of $('g'/\delta_\rho)^{1/2}$, where for the case of the rotating FRC, $'g' \sim \Omega^2 r - (F_{r1}\delta_\rho/\rho\xi)$ and δ_ρ the density gradient scale length
- From this a radial stability criteria can be derived by integrating from the field null to the separatrix radius
- Stability requires:

$$B_\omega^2/\mu_o > \langle\rho\rangle\Omega^2 r_s^3/4\delta_\rho$$

- For a typical FRC density profile, $\delta_\rho = (2/3)(r_s - R)$, so the stability criteria simplifies to:

$$B_\omega^2/\mu_o > 1.3\langle\rho\rangle\Omega^2 r_s^2$$

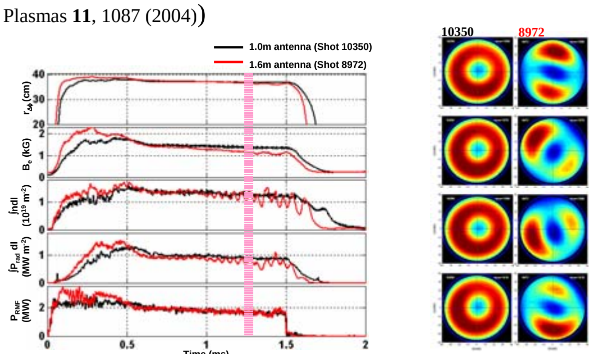


n=2 Dependence on Antenna Geometry

- TCS's RMF antenna was modified in order to study the effect of antenna design on RMF current drive
- A strong dependence of the n=2 instability on the antenna design was found

Shortened Antenna

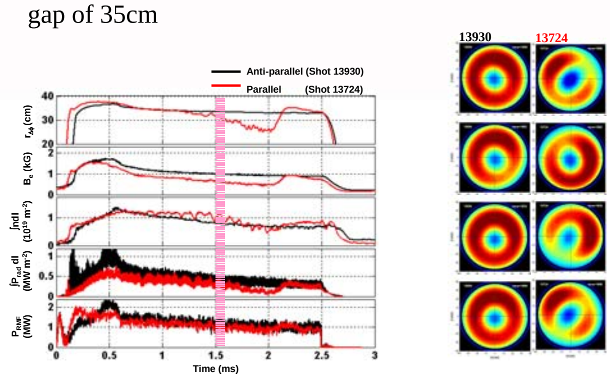
- The original RMF antenna spanned the axial length of the TCS chamber, 1.6m
- The antenna was shortened by 0.3m on each side of the TCS midplane, resulting in 1.0m antenna
- It was found that in general the shorter antenna configuration provided even better stabilization of the n=2 rotational instability
- Stability is attributed to a low ion rotation rate in the area at the end of the FRC outside the shortened antenna where no RMF current drive exists (Guo and Hoffman, Phys. Plasmas **11**, 1087 (2004))



Comparison of similar shots with different antenna length, with corresponding tomographic reconstruction.

Anti-Parallel Antenna

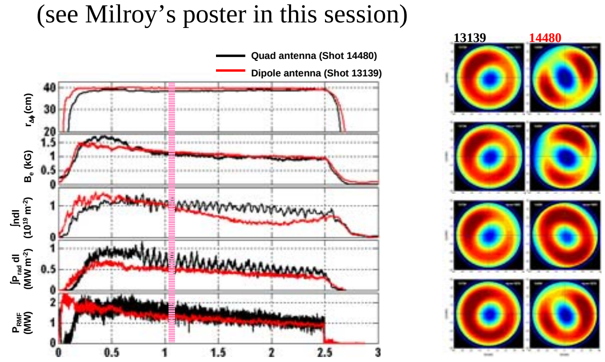
- For anti-parallel current drive, the RMF antenna were reconnected across the midplane of the TCS chamber, and each section driven 180° out of phase with its corresponding neighbor
- Calculations show that anti-parallel current drive can promote a closed-field line topology whereas parallel current drive tends to open the field lines (Cohen and Milroy, *Phys. Plasmas*, **7**, 2539.)
- Anti-parallel current drive results in a more stable FRC provided that the gap between the antenna at the midplane is small
- For the anti-parallel shot shown below, the central gap was 5cm and performed much better than shots with a gap of 35cm



Comparison of similar shots with parallel and anti-parallel current drive

Quadrupole Antenna

- The dipole antenna was replaced with a quadrupole configuration
- FRCs driven with this configuration were recognized to be prone to n=2 modes due to Edge-Driven Modes (Milroy and Miller, Phys. Plasmas **11**, 633 (2004))
- This is likely due to RMF not penetrating to the field null (see Milroy's poster in this session)



Comparison of similar shots with dipole and quadrupole antenna

Summary

- A method to tomographically invert chordal visible light emissions has been implemented on TCS which has been used to investigate FRC plasma stability
- In RMF driven plasmas, the n=2 instability is most common, and is found to rotate at the same velocity as the ion species, which was ascertained from making spectroscopic ion Doppler measurements
- It is found that inward radial pressure from the RMF provides a stabilizing force as predicted by a simple model
- RMF stabilizing effects are dependent on RMF antenna geometries; in particular, the quadruple RMF provides less stablization to an n=2, possibly due to insufficient RMF present near the field null