Field-reversed configurations (FRCs) are created and sustained using a rotating magnetic field (RMF) in the Translation Confinement and Sustainment (TCS) experiment. Normally this experiment is operated in a manner where the RMF only partially penetrates the plasma column. Recently, it has been shown with numerical simulations that if the resistivity profile is sharply peaked near the plasma edge, an inner magnetic structure forms and co-rotates with the current carrying electrons at a much lower frequency than the RMF. When this happens, a tearing and reconnection process produces a torque transfer from the outer RMF to the inner structure, allowing it to act as an RMF downshifted to a lower frequency, and thus provides current drive to the inner region of the FRC. This mode of RMF current drive is being called “edge-driven mode”. This mode has a clear spectral signature in both the internal and external magnetic fields, and it is clearly evident over much of the normal TCS operating range. The oscillating fields associated with edge-driven mode are very strong when TCS is operated with a large separatrix radius, and decrease when parameters are changed to reduce the separatrix radius. In its milder form, edge-driven mode appears to help current drive on the inner field lines, leading to stronger reversal field, but the oscillations associated with its stronger form appear to adversely affect current drive. In recent TCS operations that employ a rotating quadrupole field, rather than the usual rotating dipole field, a clear and strong edge-driven mode is observed. These observations, combined with the numerical modeling, suggest that a significant fraction of the RMF power is absorbed in a thin high resistivity region near the edge of the plasma.

Abstract

RMF penetrates just far enough, \( \Delta r \approx \frac{(B_e/\mu_0)/n_e \omega}{\eta \omega_{rs}} \), to maintain the diamagnetic current. Poloidal flux will increase as long as the RMF torque on the electrons exceeds the torque due to electron-ion drag (resistivity)

\[
E_\theta = n_e j_x + \left( -v_x B_\| \right) + V_z B_\| - V_\| B_z,
\]

Under Antenna

Outer: + + +
Inner: - - -

FRC Ends

Outer: + + +
Inner: - - -

Experimental

Numerical

Typical Observations:

1. The RMF does not penetrate to the magnetic field null.
2. There is no tendency for the \( B_z \) profile to flatten near the null.
3. The external axial field \( B_e \) and the internal axial field \( B_i \) have strong oscillation at a frequency of approximately 30 kHz below the RMF frequency.
4. The internal transverse field \( B_\theta \) has a strong oscillation at approximately 30 kHz.
5. Sometimes, near the field null, the internal axial field \( B_i \) has a strong oscillation at approximately 30 kHz.

For many experimental pulses:

Time dependent frequency spectra

Numerical simulations with a sharply peaked resistivity profile lead to similar predictions including the same spectral signatures and similar B_z profiles.

An internal magnetic structure forms which co-rotates with the electrons. A continuous reconnection and tearing process takes place, transferring some torque from the outer principal RMF to the inner structure. The inner structure then drives current in the inner low resistivity region.

The tearing and reconnection process leads to an oscillatory torque transfer, with a positive pull each time the inner and outer fields line up. Thus the frequency of the oscillation is \( f_{\text{RMF}} - f_{\text{struct}} \), where \( f_{\text{struct}} \) is the rotation frequency of the inner structure. This model explains most of the observed discrepancies with the standard model.

What experimental conditions lead to edge-driven mode?

- Low \( \xi \) (Inner electrons rotate relatively slow compared to the RMF).
- Separatrix radius must be close to the quartz wall. Never observe edge-driven mode for smaller separatrix radius FRCs.
- Stronger \( B_{\text{RMF}} \) leads to stronger oscillations associated with edge driven mode.

- External \( B_z \) loop extends azimuthally around the chamber wall. This produces a clean spectral response consisting of \( f_{\text{RMF}} \) and \( f_{\text{RMF}} - f_{\text{strain}} \).
- Internal \( B_z \) probe sees this plus some pickup of an amplitude modulated \( B_z \) signal.
- Internal \( B_z \) probe sees strong signal at frequency \( f_{\text{ref}} \).
- Some \( B_z \) oscillation around the field null at frequency \( f_{\text{ref}} \).
Long pulse operation & higher performance mode

• TCS has been operated with long (10 msec) RMF pulses
• A higher performance was observed as the separatrix radius decreased, during long pulse operation.
• This jump in performance was preceded by edge-driven mode.
• A significant decrease in $B_z$ fluctuations, especially inside the field null, coincides with the higher performance mode
• There is an even shallower RMF penetration at this time
• It is accompanied by the spontaneous generation of toroidal fields.

Edge-driven mode with rotating quadrupole current drive

• TCS has been operated with a quadrupole antenna set.
• Overall performance is comparable to the normal dipole antenna operation.
• Strong oscillations appear for quadrupole drive when machine parameters lead to a large $r_s$. These oscillations have the spectral signature of edge-driven mode.
• The strong oscillations can be prevented by keeping $r_s$ away from the wall.

Conclusions

• When the FRC is close to the plasma tube wall a distinct mode is found where an inner RMF structure rotates at a downshifted frequency close to average electron rotation rate.
• The inner structure is sustained by a tearing-reconnection process to the main high frequency RMF.
• This leads to an oscillating overall RMF torque that produces distinct features on many diagnostics.
• Numerical calculations show that this feature is almost certainly due to a highly non-uniform resistivity profile, which is sharply peaked near the FRC separatrix.
• Almost all of the RMF power is deposited in this edge region.
• The undesirable features of this mode can be somewhat mitigated by compressing the FRC further from the tube wall, which produces higher overall performance (higher magnetic fields).