The Effect of Intrinsic Flow Drive in the Production of C-Mod Internal Transport Barriers

Catherine Fiore
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With contributions from:
D. R. Ernst*, Y. Podpaly*, D. Mikkelsen #, N. T. Howard*, J. Lee*,
M.L. Reinke*, J.E. Rice*, J. W. Hughes*, Y. Ma*, W. L. Rowan†, I. Bespamyatnov†,

*MIT-PSFC
†FRC-UTA
#PPPL
Motivation

Spontaneous internal transport barriers develop in Alcator C-Mod without the triggers seen in other devices:

- There are no external momentum or particle sources
- \( q_{\text{min}} \leq 1 \)
- \( T_i = T_e \) through tight collisional coupling

The C-Mod plasmas present reactor-like conditions for the study of ITBs relevant to ITER and to future machines.

Spontaneous self-generated mean toroidal flows are a hallmark of C-Mod plasmas in all operating regimes.

Question: How do the rotation, \( E \times B \) shear, and the ion temperature gradient influence the transport in the C-Mod ITB plasmas?
Ohmic EDA H-modes give rise to spontaneous ITB development

Off-axis ICRF heating gives rise to ITB

- ITBs are only seen in EDA H-mode plasmas
- ICRF resonance must be at the half-radius or greater
- ICRF frequency is fixed, the resonance position is moved by adjusting the toroidal field
- ITBs occur when the ICRF resonance is on either the low or the high field side of the plasma
Features of C-Mod ITBs

Reduction in particle and thermal transport is found in the barrier region
- The Ware pinch is sufficient to peak the density profile.
- Strongly peaked pressure and density profiles arise.
- Ion thermal transport is reduced to neoclassical levels
Intrinsic toroidal rotation in the core of the plasma decreases with ITB

- Initially co-going after the H-mode, the self generated rotation at the plasma center decreases throughout the ITB phase of the plasma.
- Rotation at the half radius does not change significantly.
- There is significant $E\times B$ shearing rate is off-axis when the ITB forms.
Ion temperature profile data from Doppler broadened argon X-ray emission are used as input for TRANSP to examine ion temperature gradient effects. Ion temperature is typically lower, broader in off-axis heated discharges, ITB case.

Data (symbols) from Doppler broadened impurity x-ray lines with fit are compared to TRANSP Ti output (blue) used for stability analysis.
Temperature gradients are lower in core with off-axis ICRF heating. Ion temperature gradient, $R/L_{Ti}$, is typically lower in off-axis heated discharges inside of the region where the ITB foot forms than in on-axis heated plasmas. $R/L_{Ti}$ decreases with the ICRF resonance position near the plasma center ($r/a=0.25$).
Toroidal rotation profiles and time history show difference in core region between on- and off-axis ICRF heating.

With off axis-heating the central rotation decreases steadily as the ITB forms.

All rotation profiles in this data set were slightly hollow in H-mode; central value increases with time with on-axis heating.
$E \times B$ shearing rate is higher for ITB cases than centrally heated H-mode, outside of the ITB region.
E×B shearing rate is 2-3 times higher in ITB foot region in plasmas where ITB develops.

Standard H-mode has shearing rate peaked off-axis; the magnitude is lower than in the ITB case.

In the case of off-axis heated H-mode the shearing rate is peaked outside of r/a=0.6 where the ITB foot is observed.

The shearing rate is lower at r/a=0.6 if an ITB does not form.
ITG growth rate is comparable to $E \times B$ shearing rate in the ITB foot region.

Maximum ITG growth rate in off-axis ICRF ITB is $1.5 \times 10^5$ Rad/s at $k_r \rho_i = 0.4$. 

Maximum linear growth rate, $E \times B$ shearing rate.

Linear GYRO calculation.
Including rotation in the simulations shows a strong decrease in the ion energy diffusion!

**Ion Energy Diffusion**

- Experimental R/L$_{Ti}$ at t=1.0s
- Rotation turned on after 880 time steps
- Experimental Value of Rotation used
Simulated $\chi_i$ shows dependence on strength of toroidal rotation used.

The scaling factor for the rotation was increased from 0.5 (red) to 1.2 (blue), compared to 1.0 (purple).
Simulated $\chi_i$ including rotation is reduced to the experimental value of $\chi_{\text{eff}}$ in the ITB case.

A range of $\chi_{\text{eff}}$ obtained by changing experimental values within expected error is shown.

The diamonds show simulated $\chi_i$ values with varying rotation scaling from a factor of 0 (top point) to 1.2 (lowest point).
Conclusions

Intrinsic, self generated mean toroidal flows are an important feature of C-Mod ITB plasmas
- Toroidal rotation is centrally peaked with on-axis ICRF heating
- Off-axis ICRF heating leads to off-axis peaking and formation of a central well in the rotation profile
- The rotation profile results in strong E×B shear in the ITB foot region

Ion temperature profile broadens with off-axis ICRF
- R/L_{Ti} is somewhat reduced from on-axis ICRF heated plasmas when the ICRF resonance reaches r/a ≈0.4
- Reduction in R/L_{Ti} lessens the drive for ITG turbulence

Gyrokinetic simulation supports importance of E×B shear in reduction of fluctuation driven transport in C-Mod ITB plasmas
- The linear ITG growth rate is comparable to EXB shearing rate near the ITB foot
- Non linear gyrokinetic simulation indicates that the spontaneous rotation is sufficient to reduce the ion energy diffusion to the experimental values.
Future Work

Experiment (JRT2012):

- Use pulsed central ICRF to study TEM in off-axis heated ICRF ITBs (Ernst), validate gyro-kinetic codes
- ITBs in I-mode: Use off-axis ICRF be used to produce ITB in an I-mode plasma, contribute to understanding of the transition physics
- High power ITBs: Do TEM modes become unstable driven by density gradient alone?
- Ohmic H-mode ITBs with added central heating: study of role of TEM development in Ohmic ITBs.

Simulations:

- Continue both non-linear and linear analysis of complete data sets for toroidal field scans
- Examine stability of discharges that were expected to have ITBs but fell short.
- Expand analysis to include Ohmic H-mode ITBs
- Analysis of any new experimental data, JRT2012 ITB results