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

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Alcator C-Mod

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
- $q_{min} \leq 1$
- 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

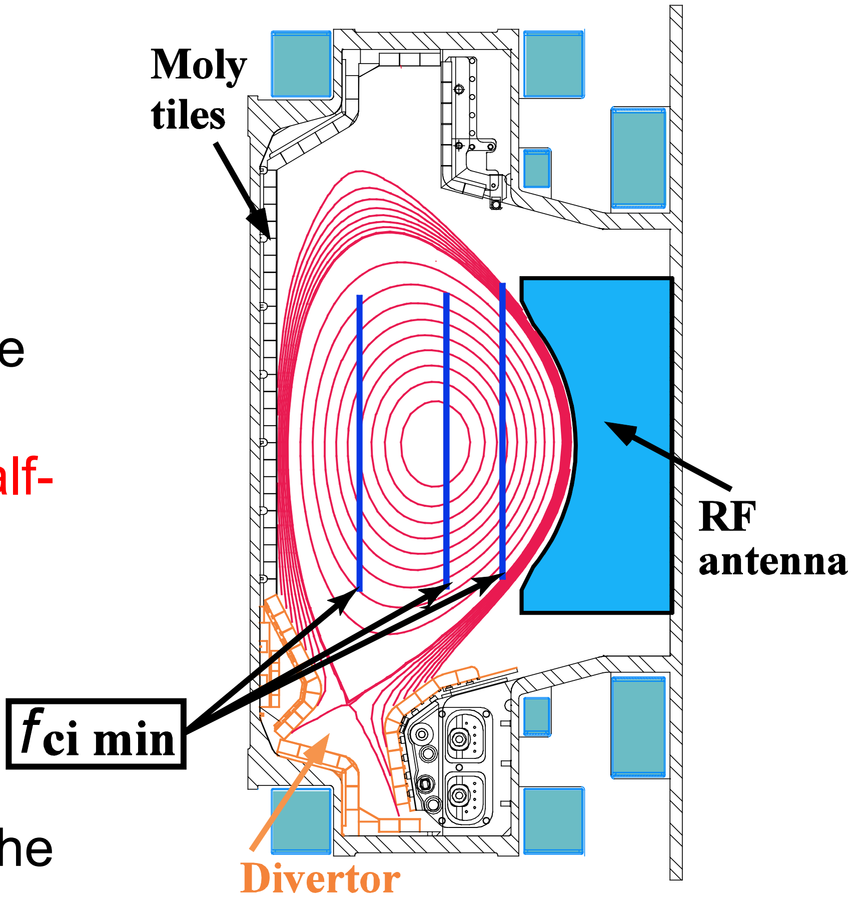
Question: How do the rotation, E×B shear, and the ion temperature gradient influence the transport in the C-Mod ITB plasmas?

Production of C-Mod ITBs

Ohmic EDA H-modes give rise to spontaneous ITB development

Off-axis ICRF heating gives rise to ITB

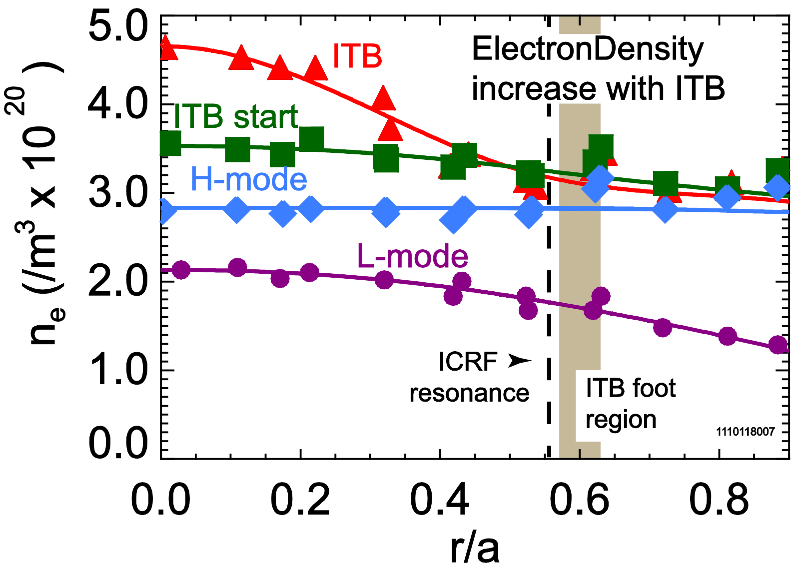
- ITBs are only seen in EDA H-mode plasmas
- ICRF resonance must be at the half-radius or greater
- ICRF frequency is fixed, the resonance position is moved by adjusting the toroidal field
- ITBs occur when the ICRF resonance is on either the low or the high field side of the plasma

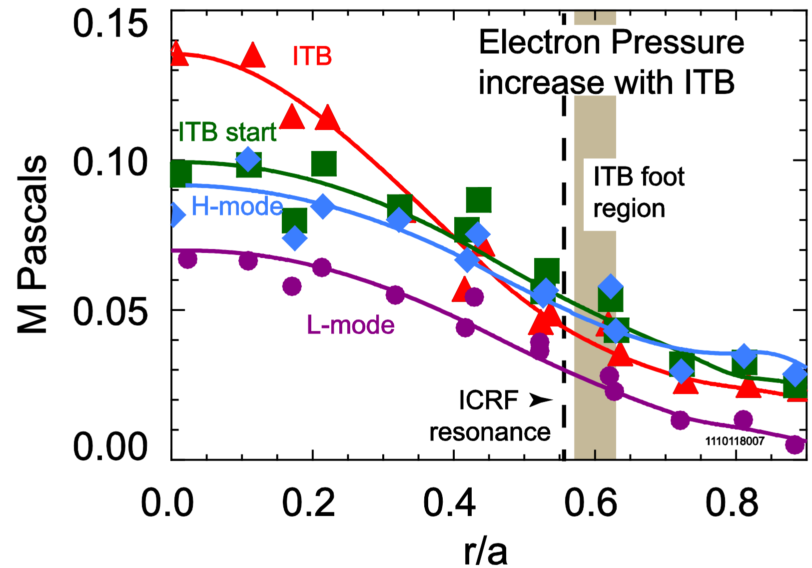


Features of C-Mod ITBs

<u>Reduction in particle and thermal transport is found in the barrier region</u>

- 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

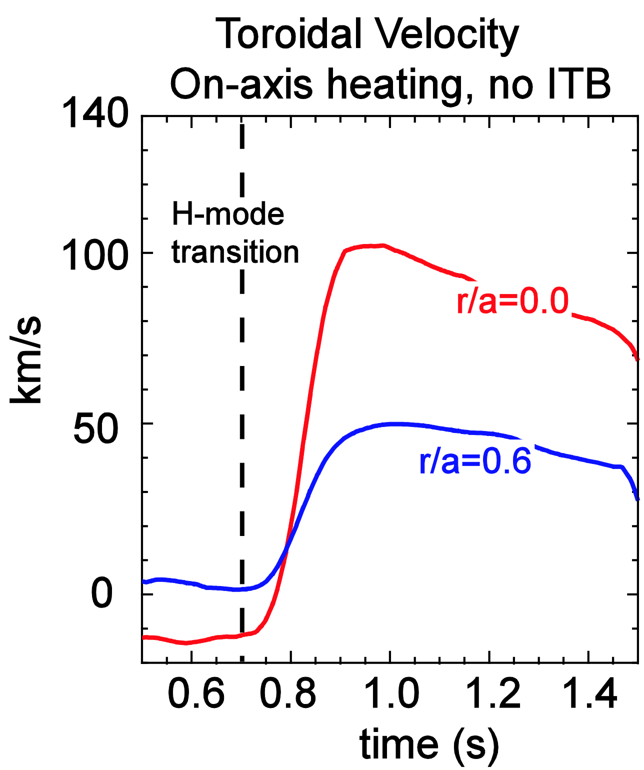


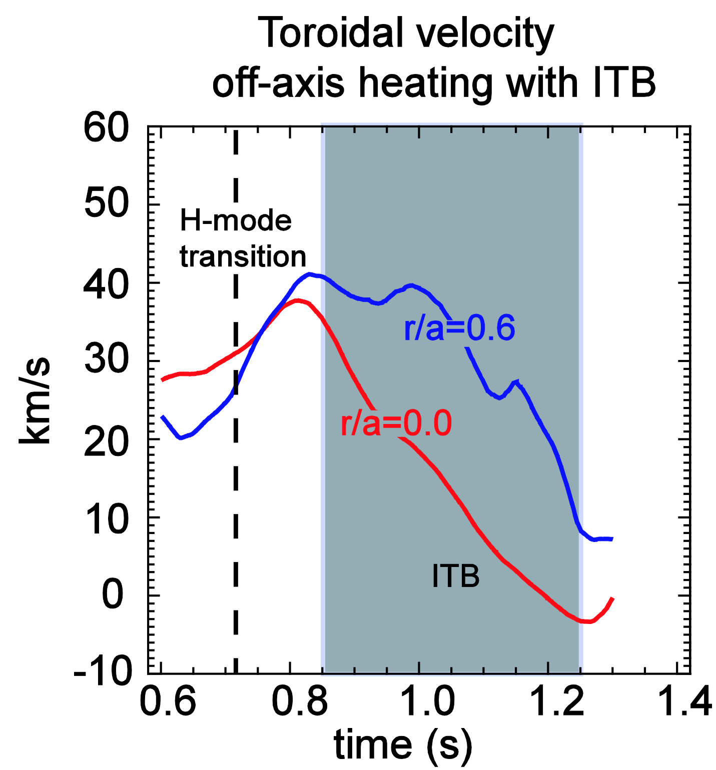


Features of C-Mod ITBs

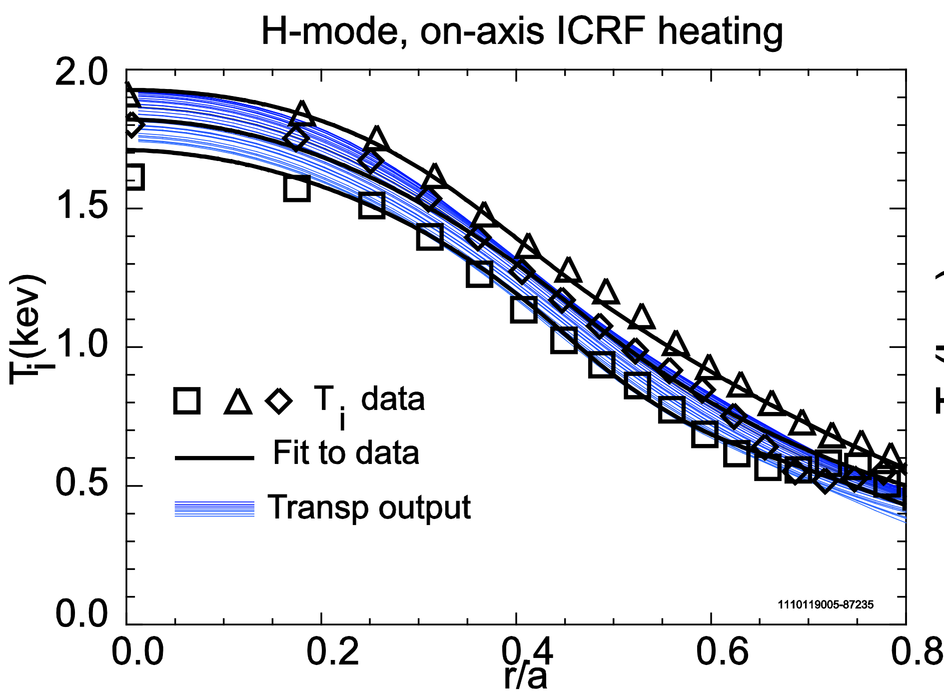
<u>Intrinsic toroidal rotation in the core of the plasma decreases with ITB</u>

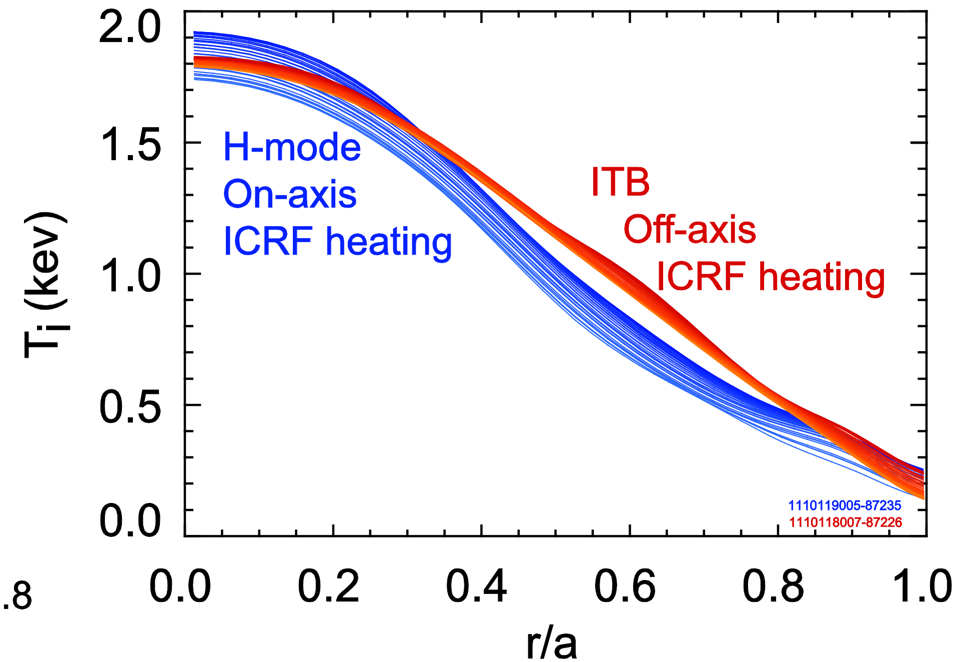
- Initially co-going after the H-mode, the self generated rotation at the plasma center decreases throughout the ITB phase of the plasma.
- Rotation at the half radius does not change significantly.
- There is significant E×B shearing rate is off-axis when the ITB forms





Ion temperature profile data from Doppler broadened argon X-ray emission are used as input for TRANSP to examine ion temperature gradient effects

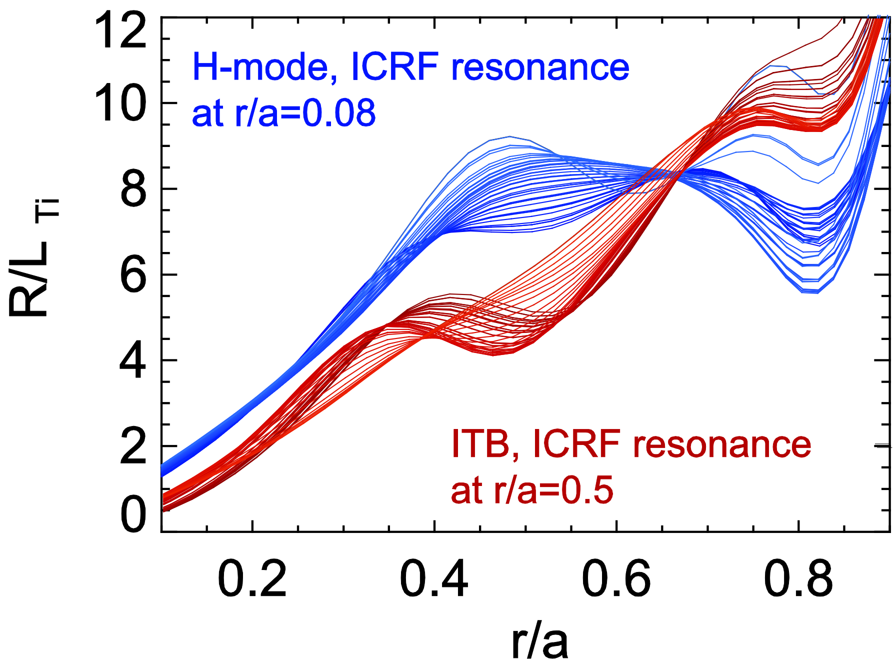


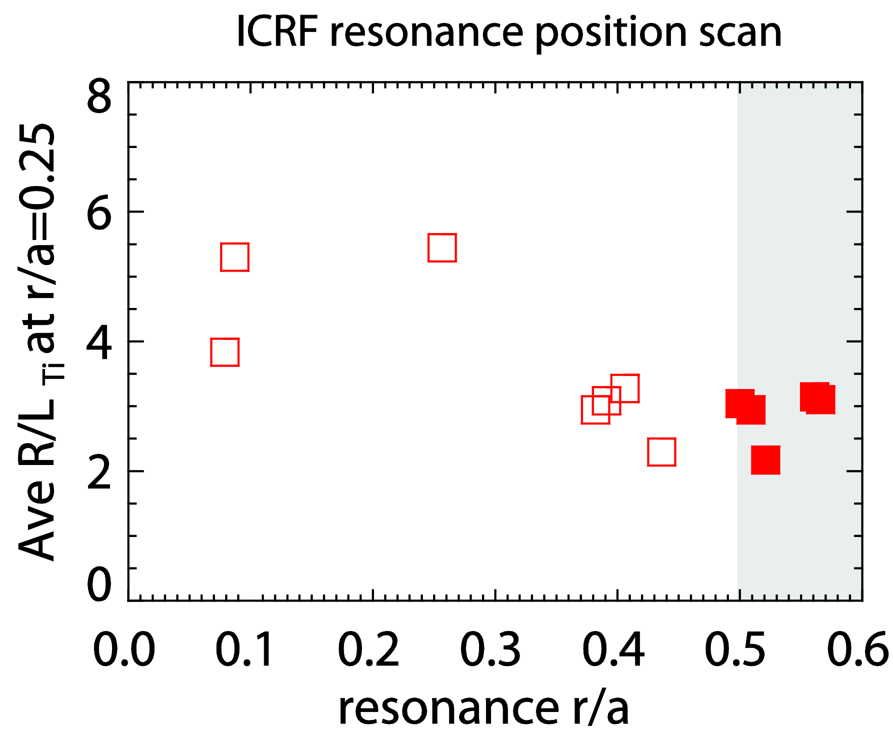


Data (symbols) from Doppler broadened impurity x-ray lines with fit are compared to TRANSP Ti output (blue) used for stability analysis

Ion temperature is typically lower, broader in off-axis heated discharges, ITB case

Temperature gradients are lower in core with off-axis ICRF heating

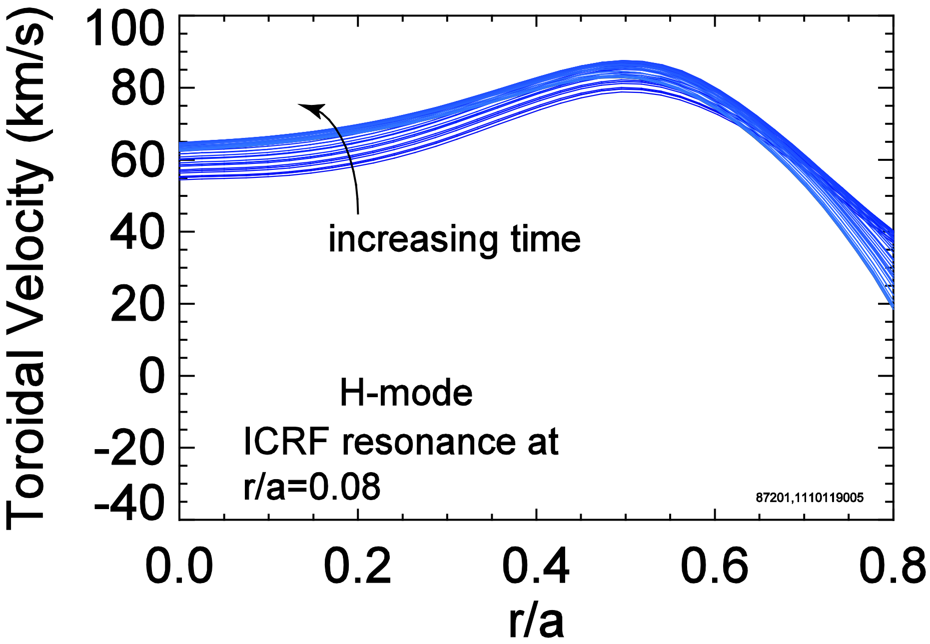




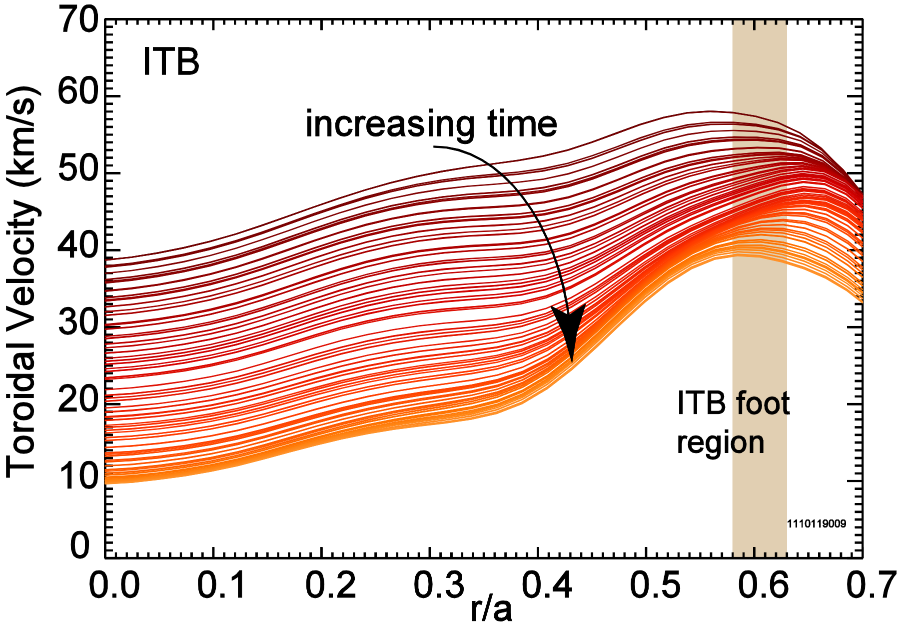
Ion temperature gradient, R/L_{Ti} is typically lower in off-axis heated discharges inside of the region where the ITB foot forms than in on-axis heated plasmas.

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

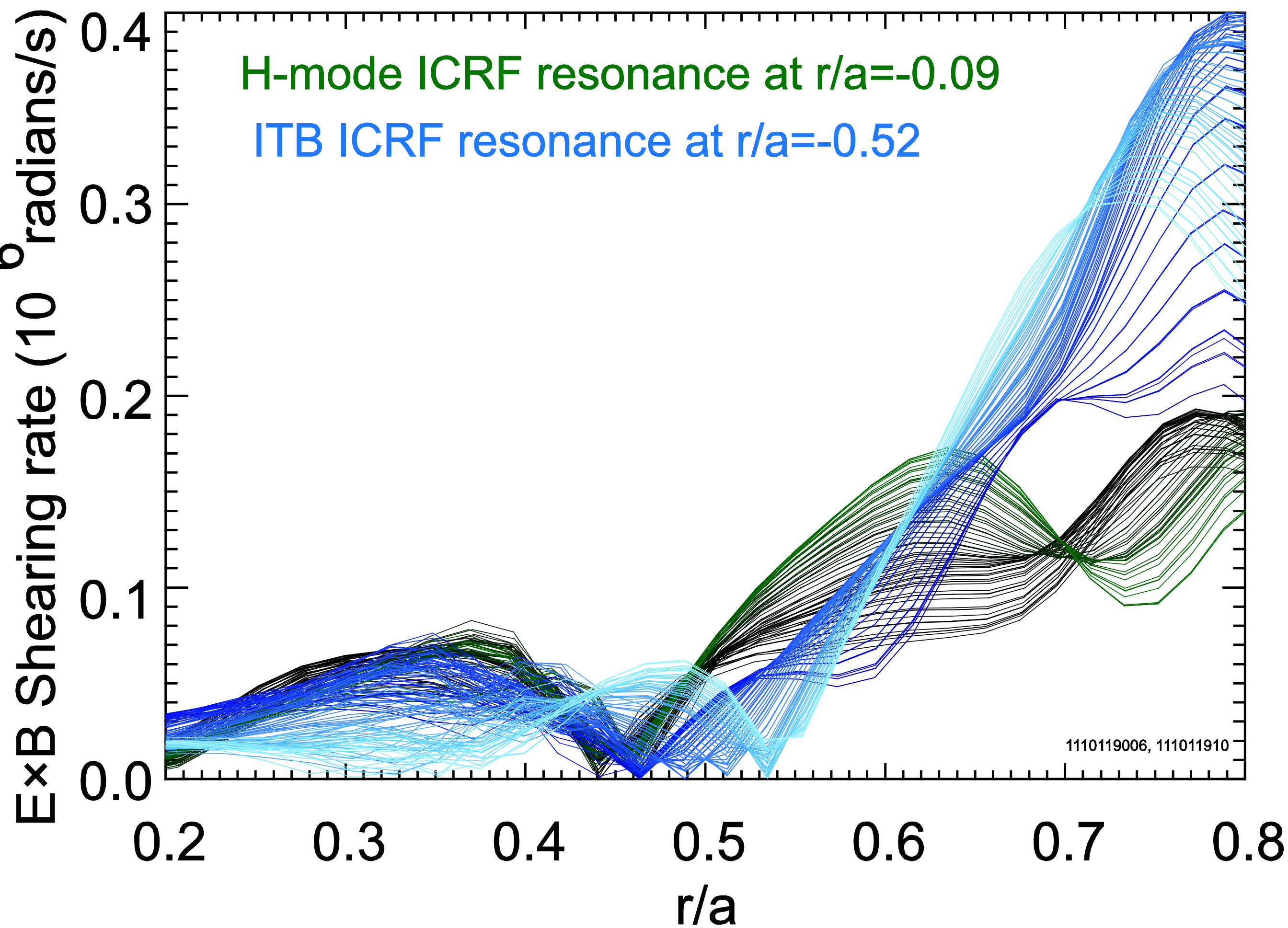


With off axis-heating the central rotation decreases steadily as the ITB forms



All rotation profiles in this data set were slightly hollow in H-mode; central value increases with time with on-axis heating

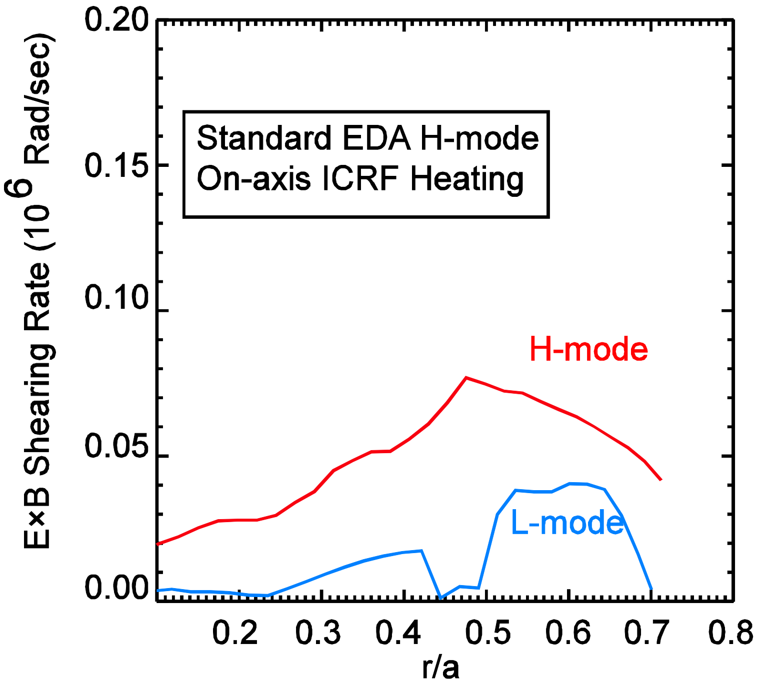
E×B shearing rate is higher for ITB cases than centrally heated H-mode, outside of the ITB region

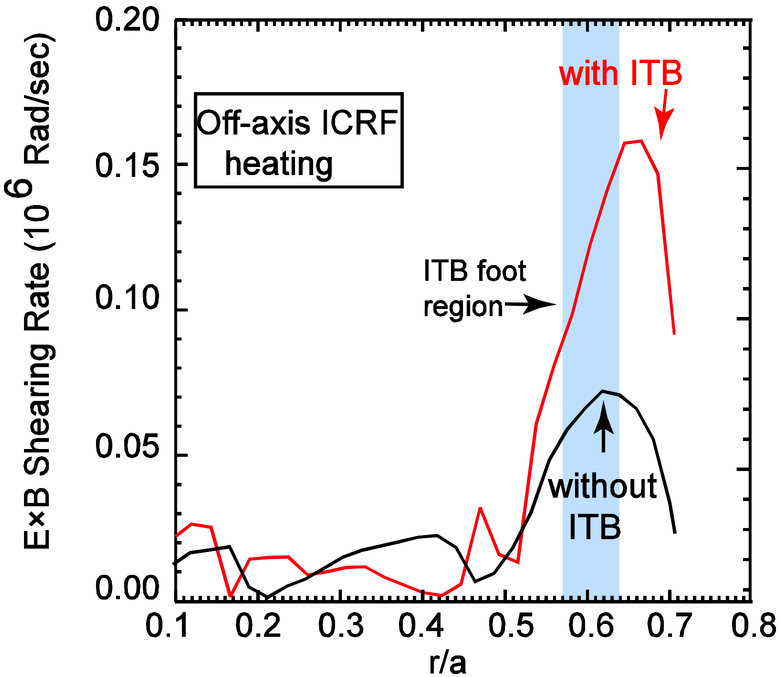


E×B shearing rate is 2-3 times higher in ITB foot region in plasmas where ITB develops

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.

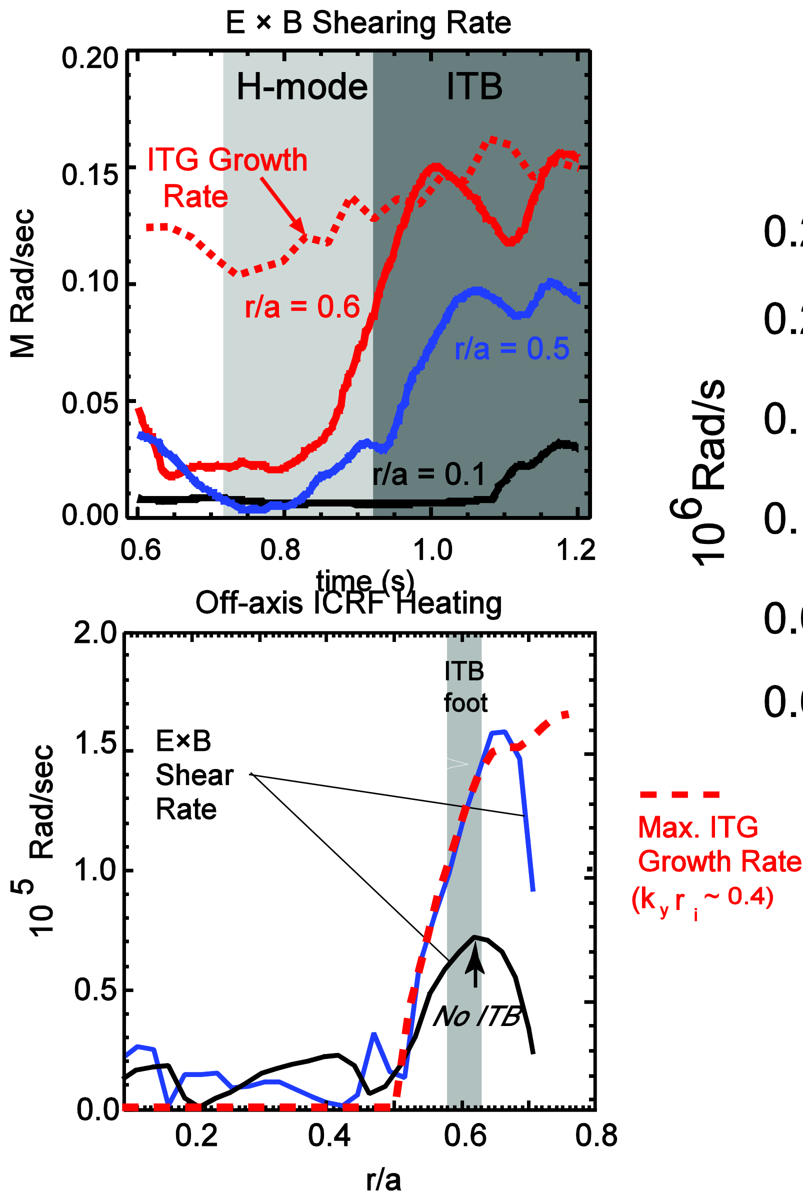




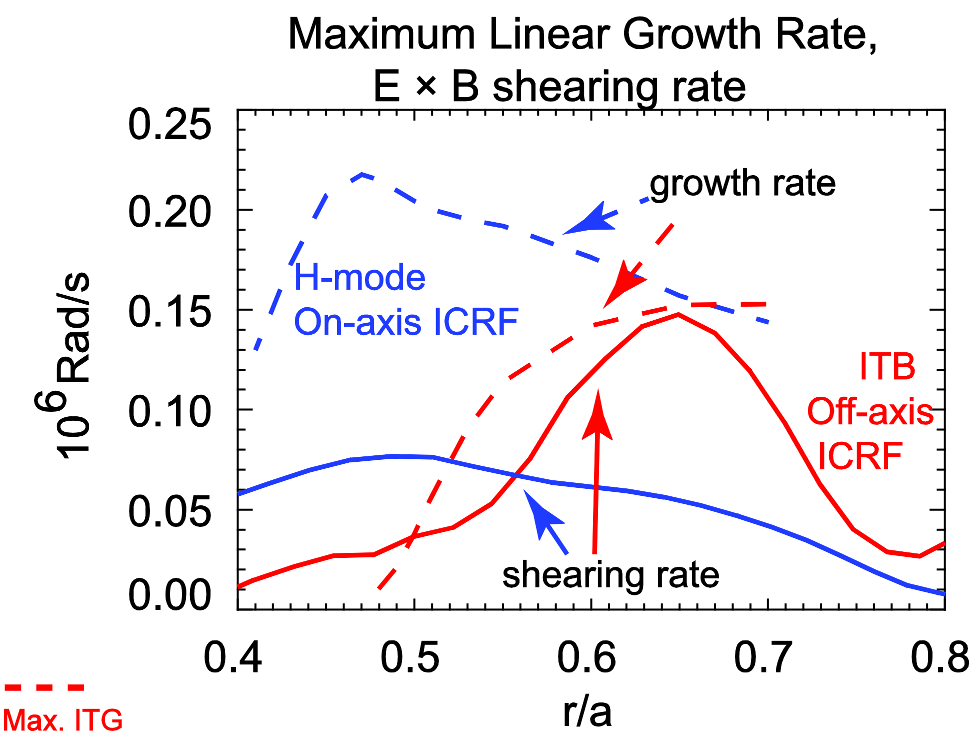
The shearing rate is lower at r/a=0.6 if an ITB does not form

ITG growth rate is comparable to E×B shearing rate in the ITB foot region

Linear GS2 growth rate calculat ion

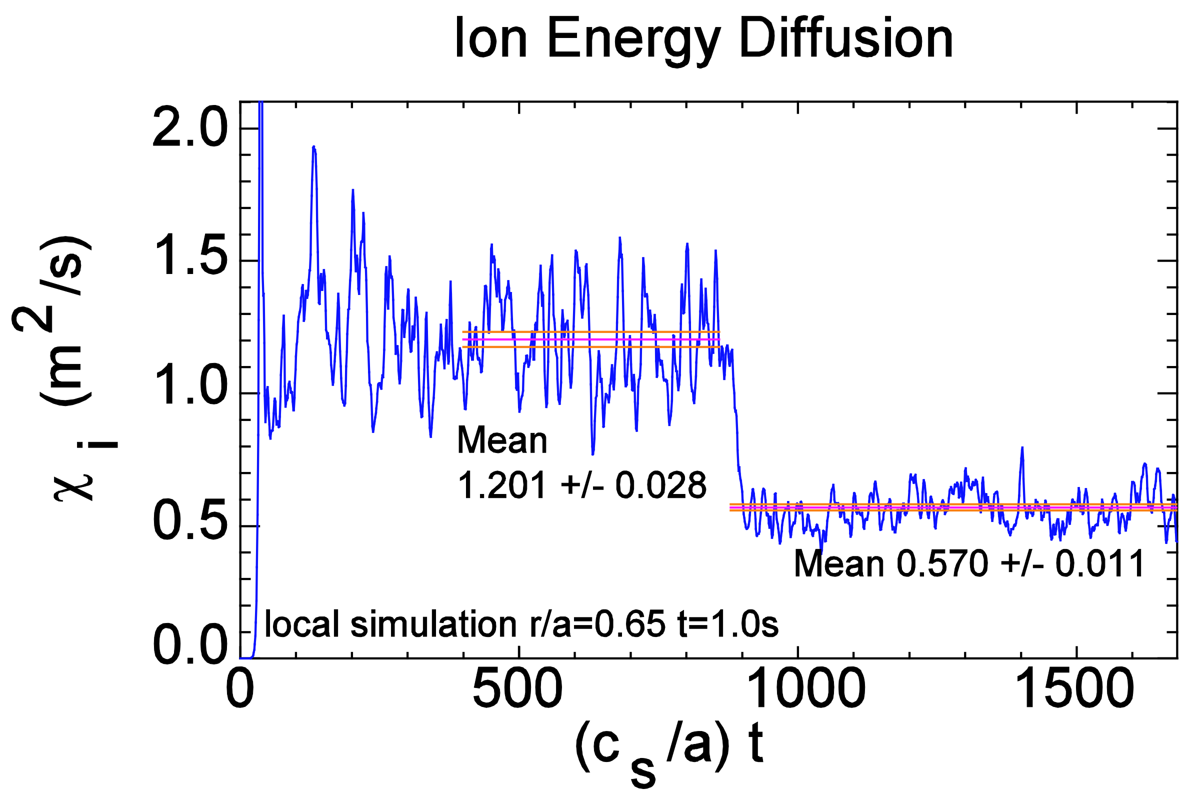


Linear GYRO calculation



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

Including rotation in the simulations shows a strong decrease in the ion energy diffusion!



ITB

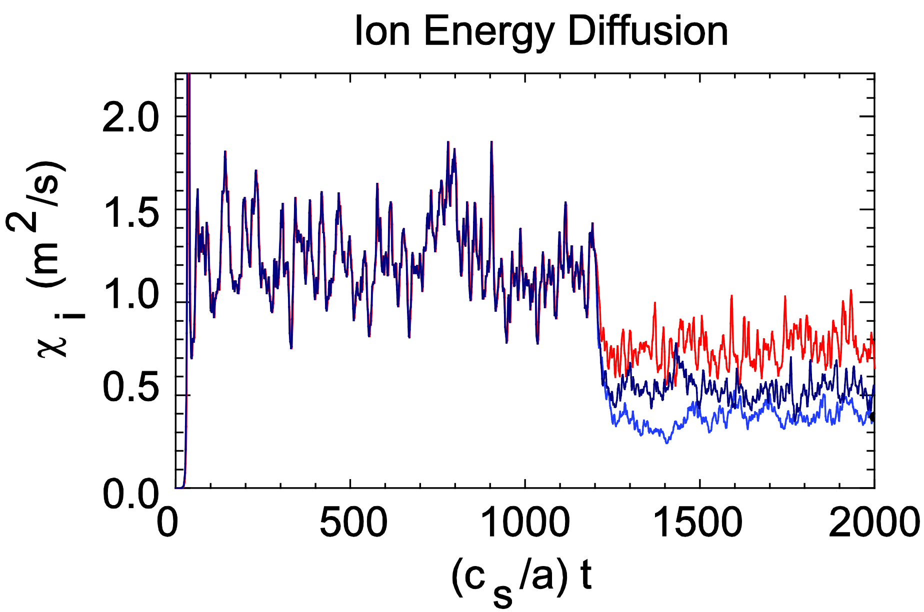
HFS off-axis ICRF

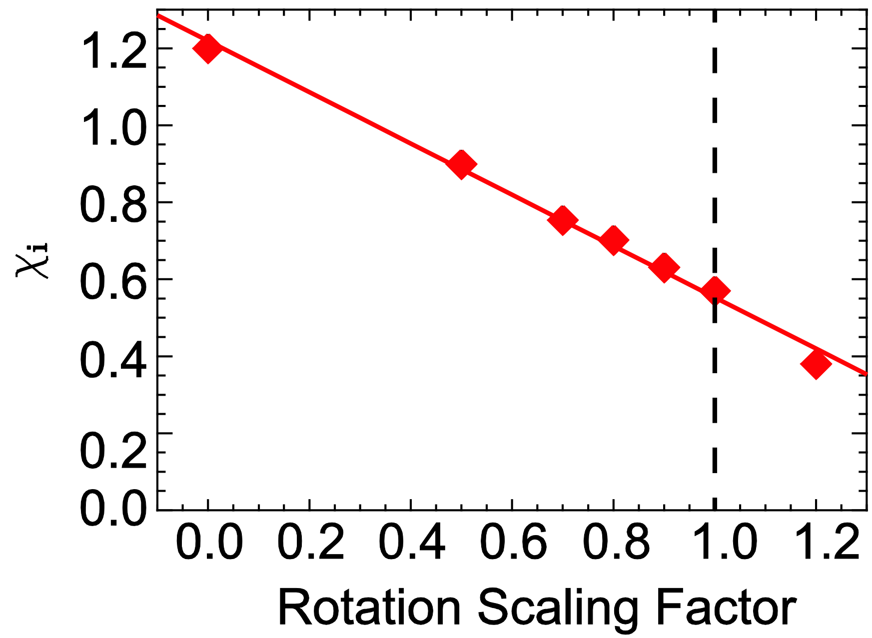
Experimental R/L_{Ti} at t=1.0s

Rotation turned on after 880 time steps

Experimental Value of Rotation used

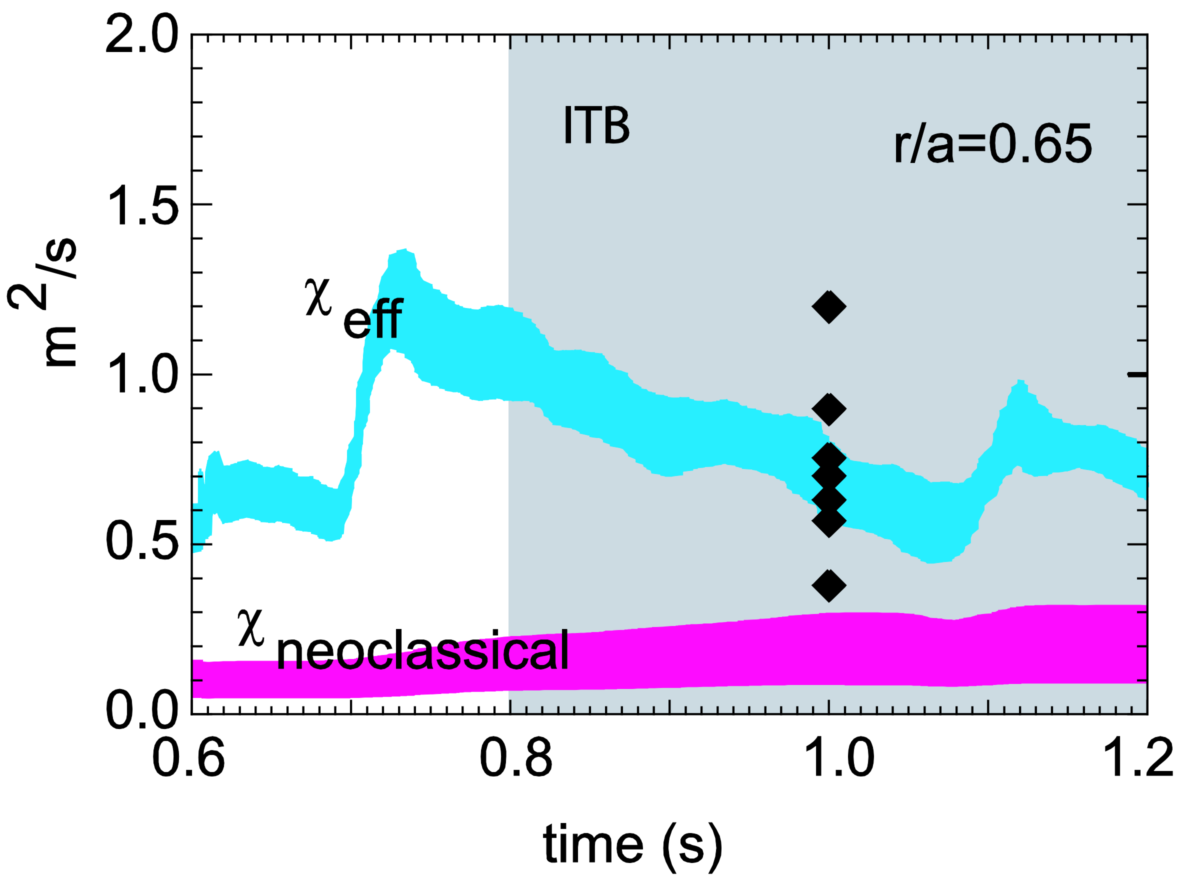
Simulated χ_i shows dependence on strength of toroidal rotation used





The scaling factor for the rotation was increased from 0.5 (red) to 1.2 (blue), compared to 1.0 (purple)

Simulated χ_i including rotation is reduced to the experimental value of χ_{eff} in the ITB case



A range of χ_{eff} obtained by changing experimental values within expected error is shown.

The diamonds show simulated χ_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 $r/a \approx 0.4$
- 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