

Production of Internal Transport Barriers by Intrinsic Flow Drive in Alcator C-Mod

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Abstract

New results suggest that changes observed in the intrinsic toroidal rotation influence the internal transport barrier (ITB) formation in the Alcator C-Mod tokamak. The ITBs arise when the resonance for ICRF minority heating is positioned off-axis at or outside of the plasma half-radius. These ITBs form in a reactor relevant regime, without particle or momentum injection, with $T_i \approx T_e$, and with monotonic q profiles ($q_{\min} < 1$). C-Mod H-mode plasmas exhibit strong intrinsic co-current rotation that increases with increasing stored energy without external drive. When the resonance position is moved off-axis, the rotation decreases in the center of the plasma resulting in a radial toroidal rotation profile with a central well, which then deepens and moves farther off-axis when the ICRF resonance location reaches the plasma half-radius. This profile results in strong $E \times B$ shear ($> 1.5 \times 10^5$ Rad/sec) in the region where the ITB foot is observed. Gyrokinetic analyses indicate that this spontaneous shearing rate is comparable to the linear ion temperature gradient (ITG) growth rate at the ITB location and is sufficient to reduce the turbulent particle and energy transport. Detailed measurement of the ion temperature demonstrates that the radial profile flattens as the ICRF resonance position moves off axis, which reduces the drive for ITG instability. These results are the first evidence that intrinsic rotation can affect confinement in ITB plasmas, and suggest that this regime could be achievable on ITER and future reactor experiments.

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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, $E \times B$ shear, and the ion temperature gradient influence the transport in the C-Mod ITB plasmas?

Features of C-Mod ITBs

C-Mod plasmas provide reactor relevant platforms for ITB study:

- No particle or momentum input
- Monotonic q profiles
- Tightly collisionally coupled ions and electrons with $T_i \approx T_e$

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

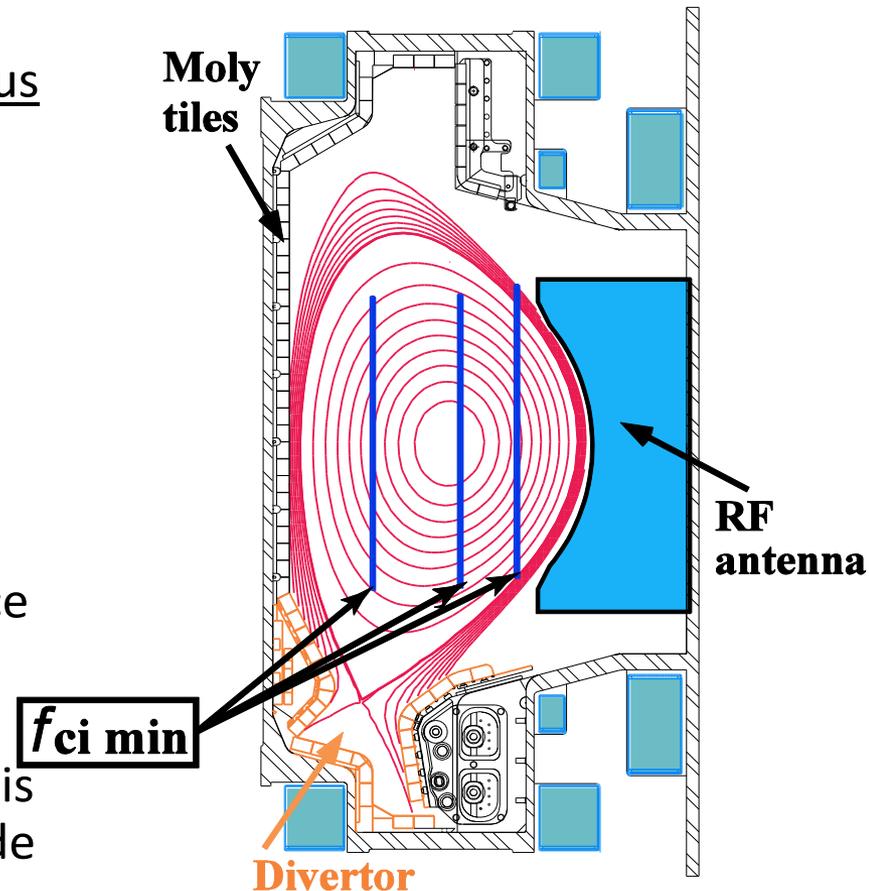
- Initially co-going after the H-mode, the self generated rotation at the plasma center decreases (sometimes reverses) throughout the ITB phase of the plasma.
- Rotation at the half radius does not change significantly.
- Significant $E \times B$ shearing rate is observed off-axis

Production of C-Mod ITBs

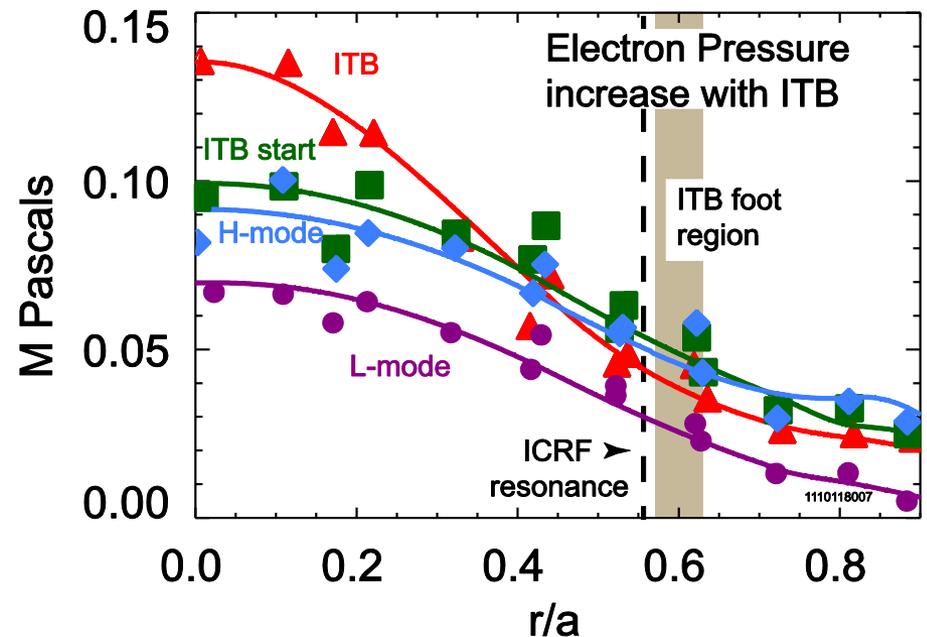
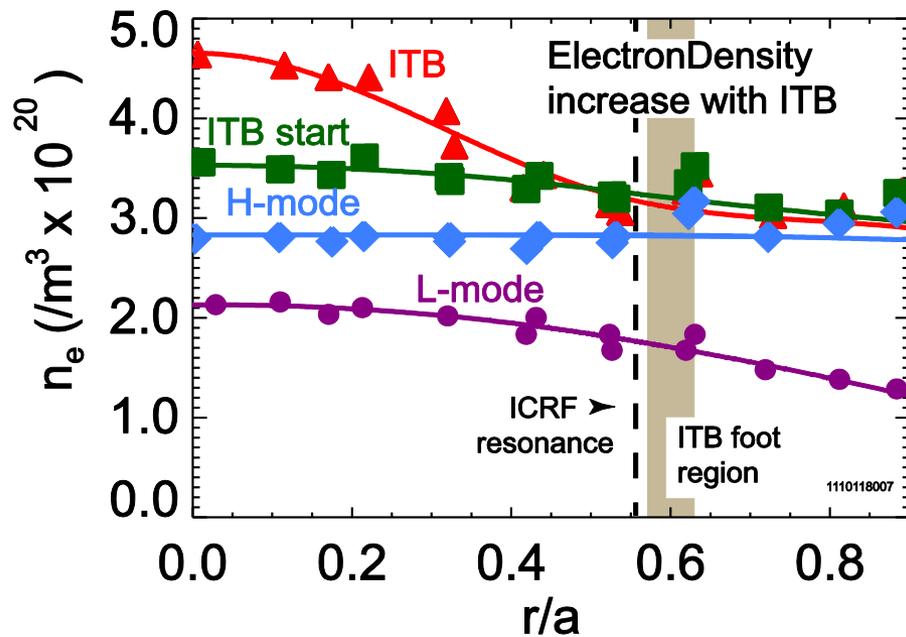
Ohmic EDA H-modes give rise to spontaneous ITB development

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



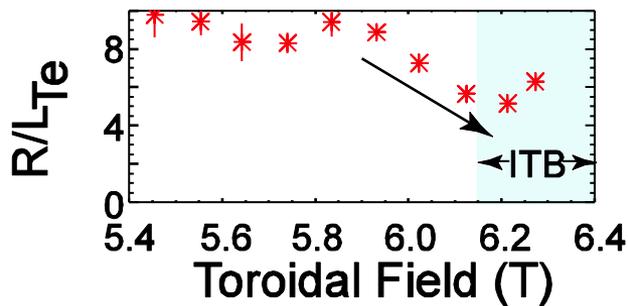
Internal Transport Barriers (ITBs) observed in Alcator C-Mod have strongly peaked pressure and density profiles



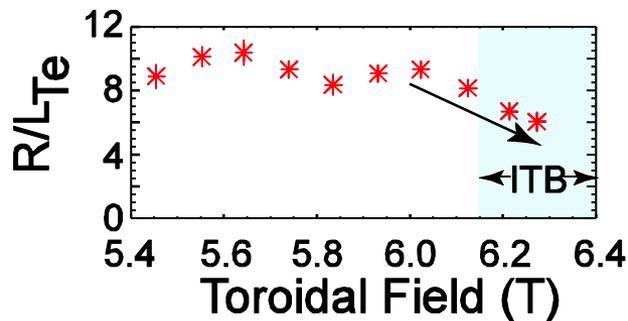
The electron density profile peaks gradually shortly after the transition to EDA H-mode. It continues peaking until a back transition occurs. The electron pressure is also quite peaked.

Early study using limited diagnostics showed temperature profiles flattening as ICRF resonance moves off axis.

R/L_{Te} decreases in the region near the ITB foot at the time of onset.

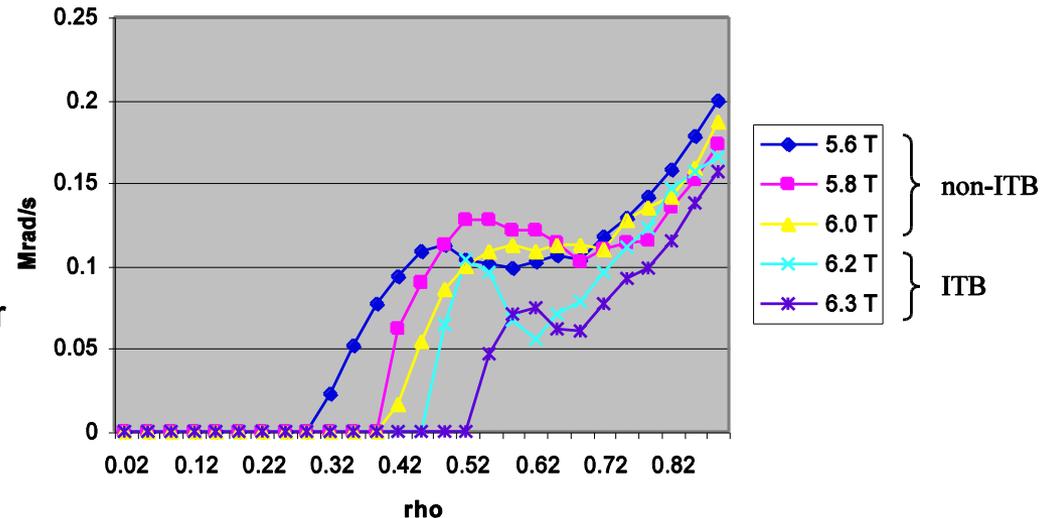


$R=0.78$ m
(near barrier foot, inside)



$R=0.80$ m
(barrier foot)

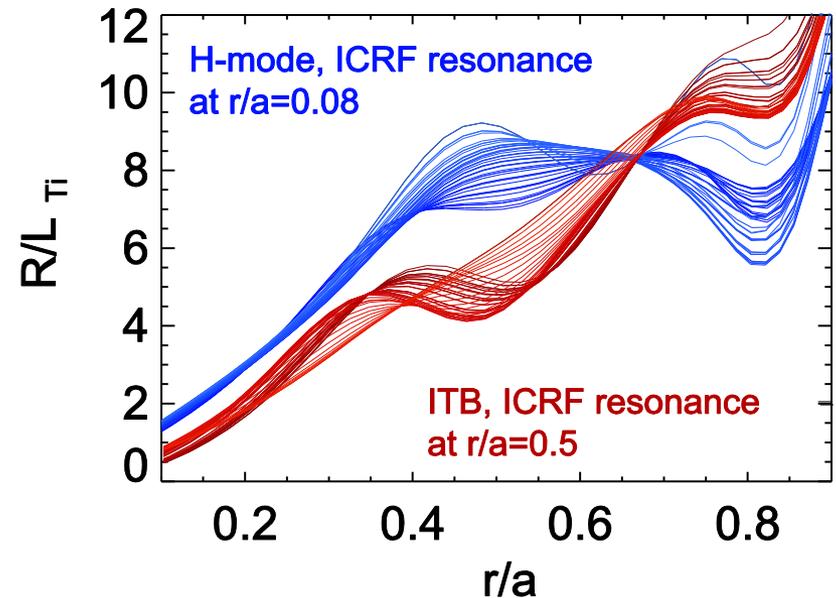
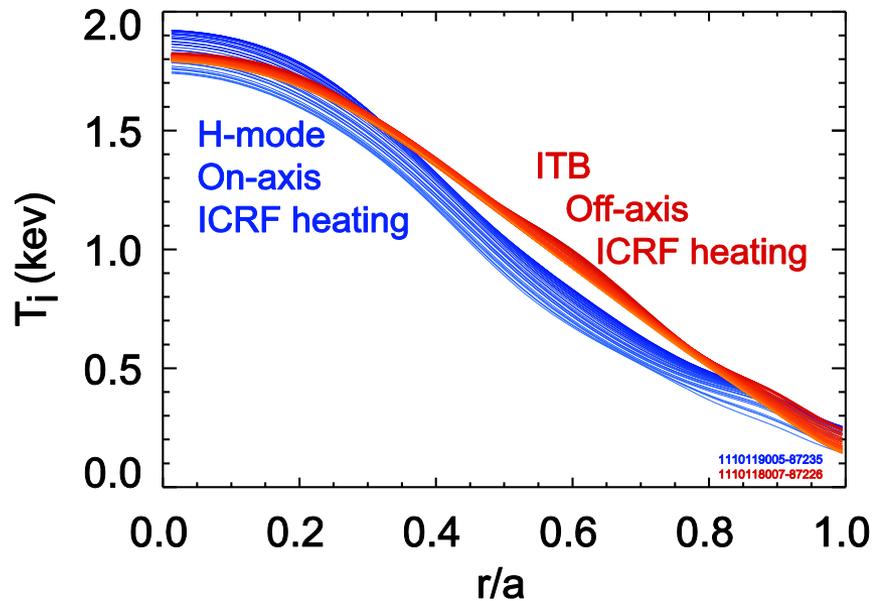
ITG growth rate profiles



The region of linear stability to ITG modes widens with increasing magnetic field.

Ion temperature profiles are broader with ICRF heating off-axis than on-axis; R/L_{Ti} is lower in core with off-axis heating

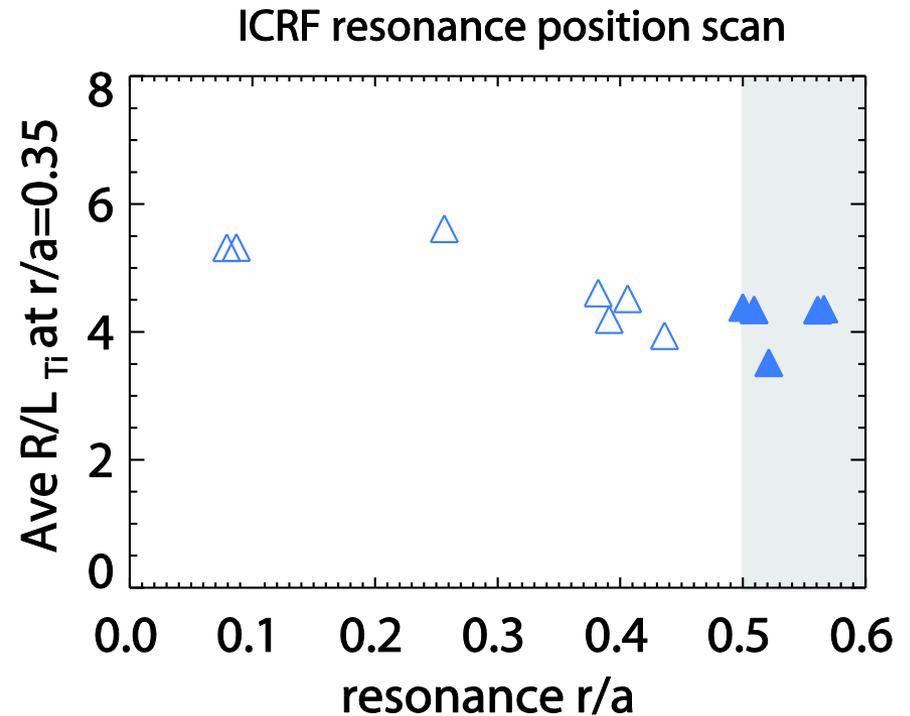
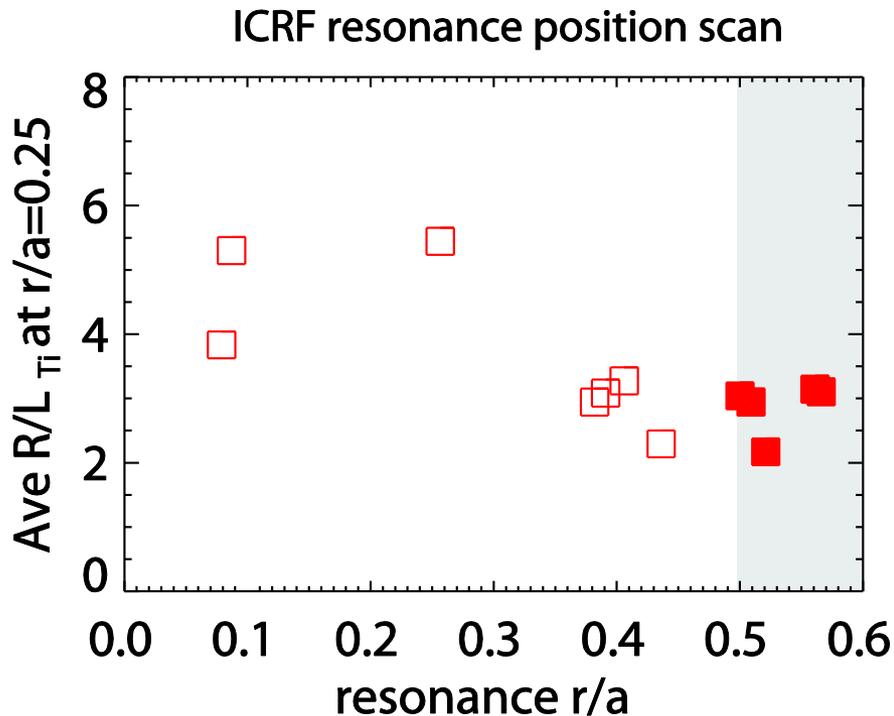
The ion temperature profile with central ICRF heating, standard H-mode (blue), is compared to the off-axis, ICRF resonance at half radius with ITB plasma (red).



Reduction of R/L_{Ti} in core increases stability to ITG modes and reduces turbulent driven transport

R: position in major radius ; L_{Ti} : temperature gradient scale length $\left| \frac{1}{T_i} \frac{\partial T_i}{\partial r} \right|^{-1}$

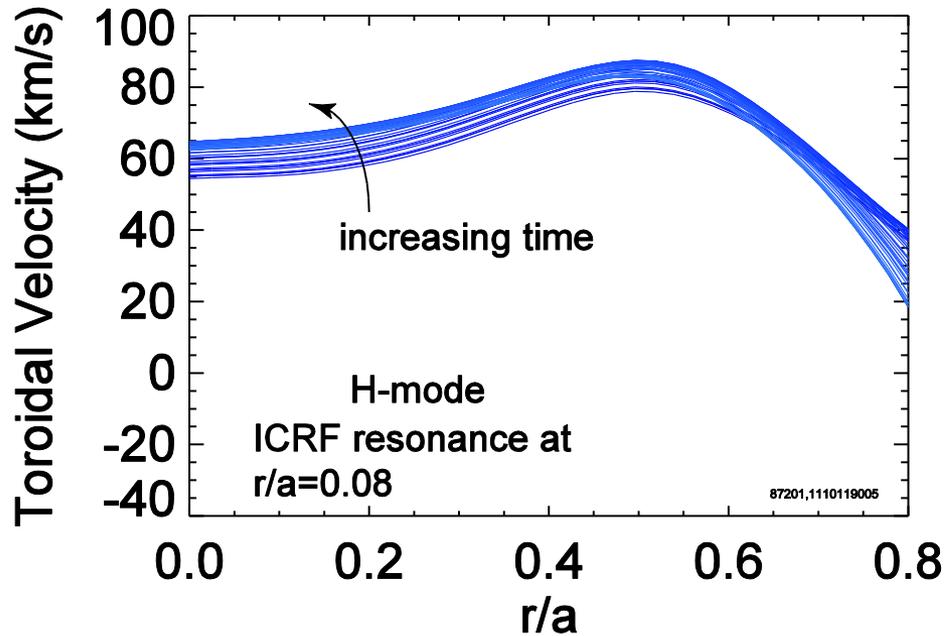
Temperature gradients are lower in core with off-axis ICRF heating



R/L_{Ti} decreases with the ICRF resonance position near the plasma center ($r/a=0.25$, red squares and $r/a=0.35$, blue triangles.)

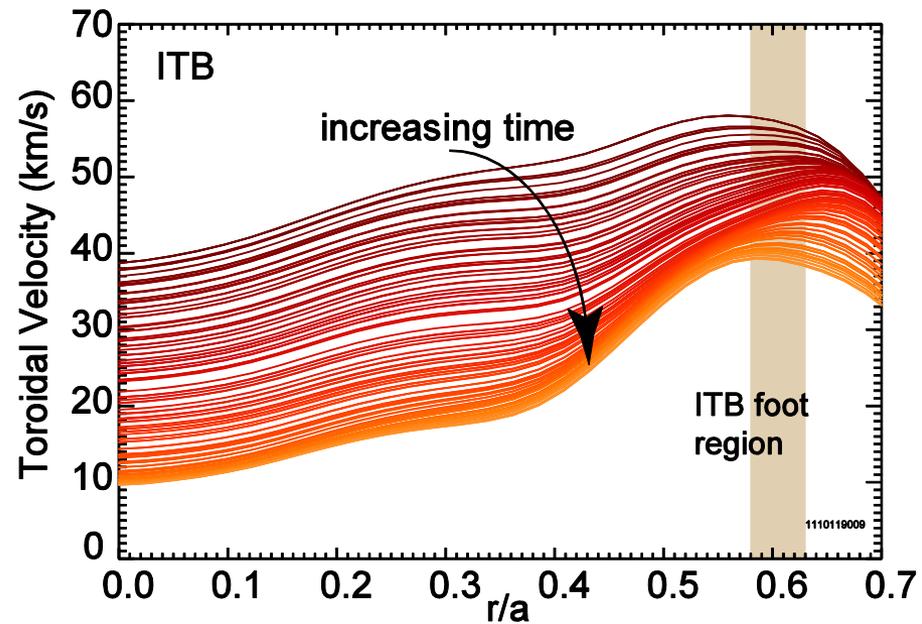
Solid symbols indicate that an ITB formed.

Toroidal rotation profiles and time history show difference in core region between on- and off-axis ICRF heating

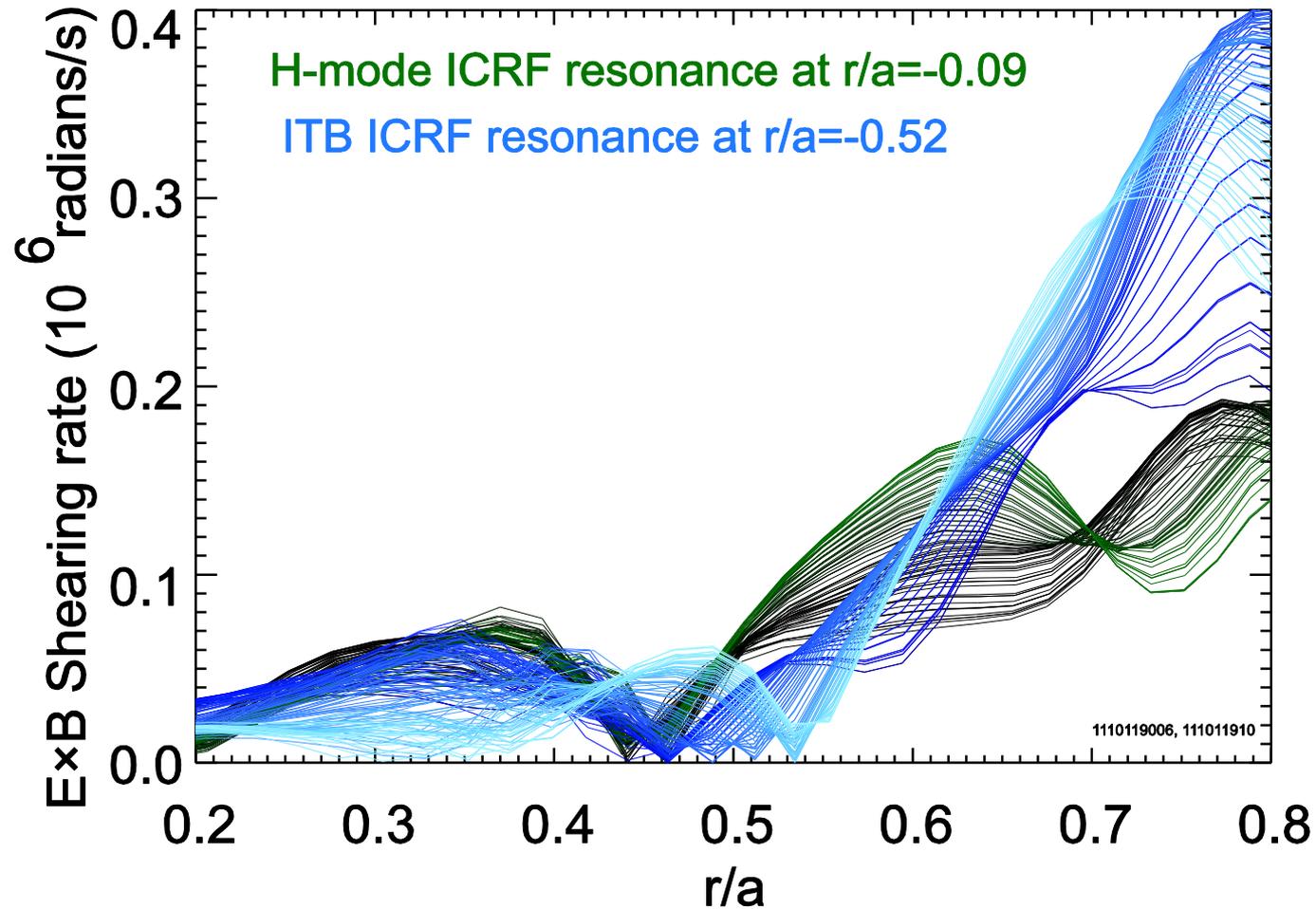


All rotation profiles in this data set were slightly hollow in H-mode; central value increases with time with on-axis heating

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



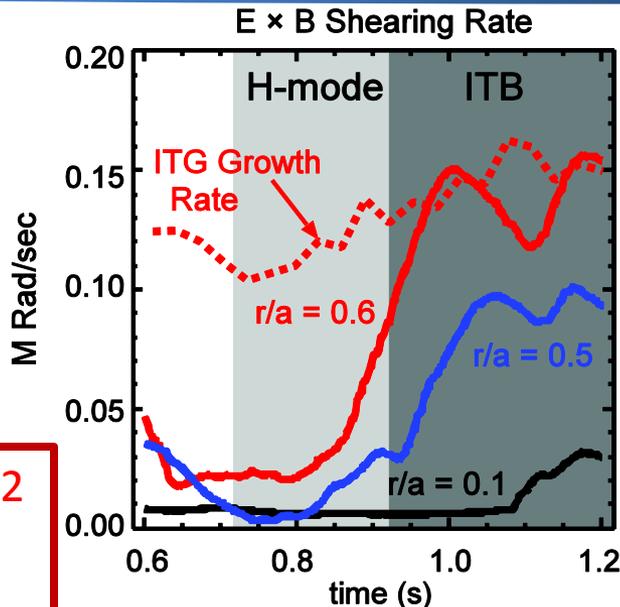
$E \times B$ shearing rate is higher for ITB cases than centrally heated H-mode, outside of the ITB region



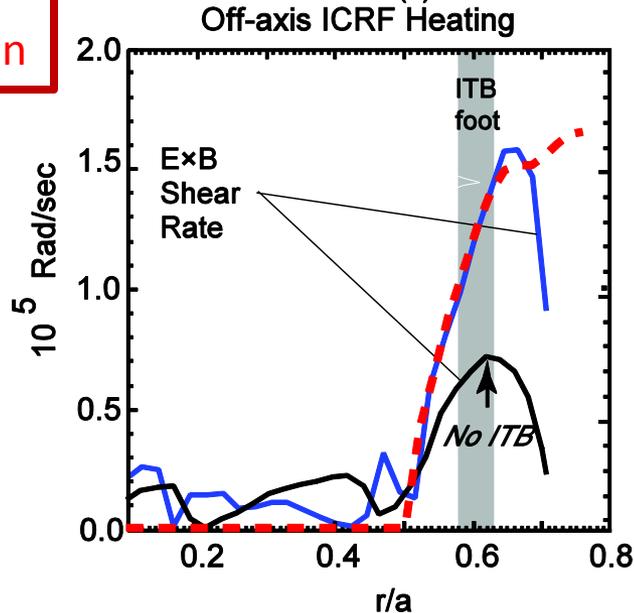
Linear Stability

- Goal: to determine how changes in the ion temperature profiles affect the drive term for the unstable ion temperature gradient (ITG) modes that typically cause diffusion in high density C-Mod plasmas.
- Question: What is the effect of spontaneous rotational shear that is seen in off-axis heated plasmas on the turbulent diffusion driven by the ITG?
- Linear stability is simulated using both the initial value gyro-kinetic code GS2 and also the linear GYRO code.
- The maximum linear growth rate in the range of $0 < k_{\theta} \rho_s < 1$ for the ITG instability shows that in the on-axis heated standard H-mode plasma, the linear ITG growth rate exceeds the experimental $E \times B$ shearing rate by a factor of 3.
- ITG growth rate is comparable to the $E \times B$ shearing rate in the off-axis heated plasma that formed an ITB.

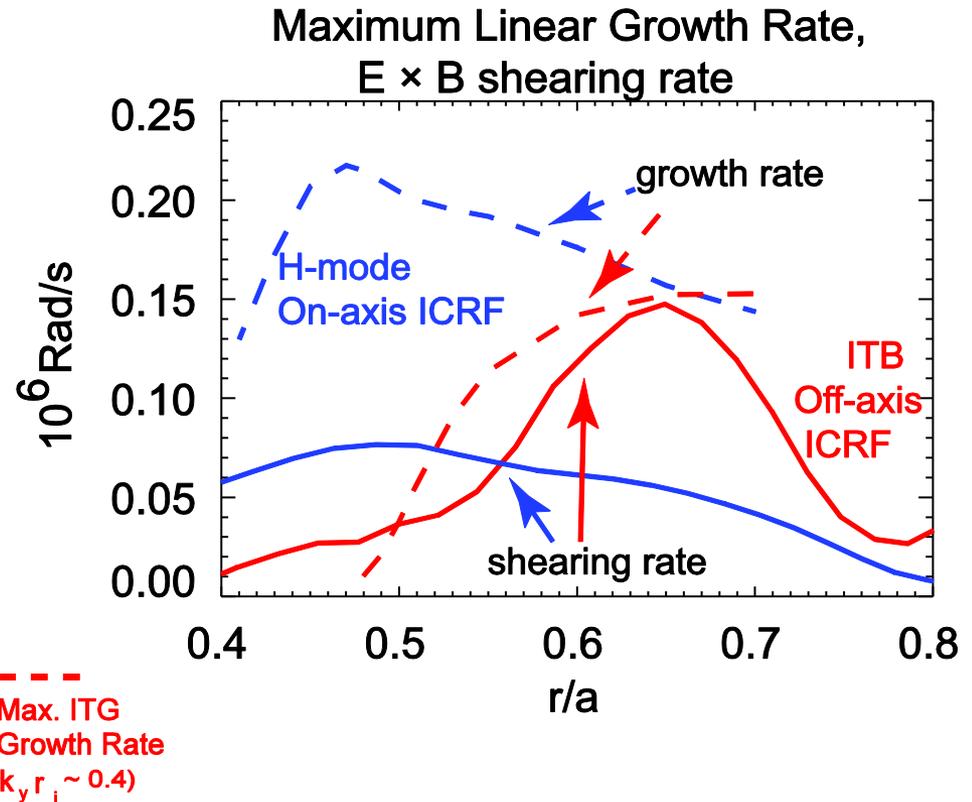
ITG growth rate is comparable to E×B shearing rate in the ITB foot region



Linear GS2 growth rate calculation



Linear GYRO calculation

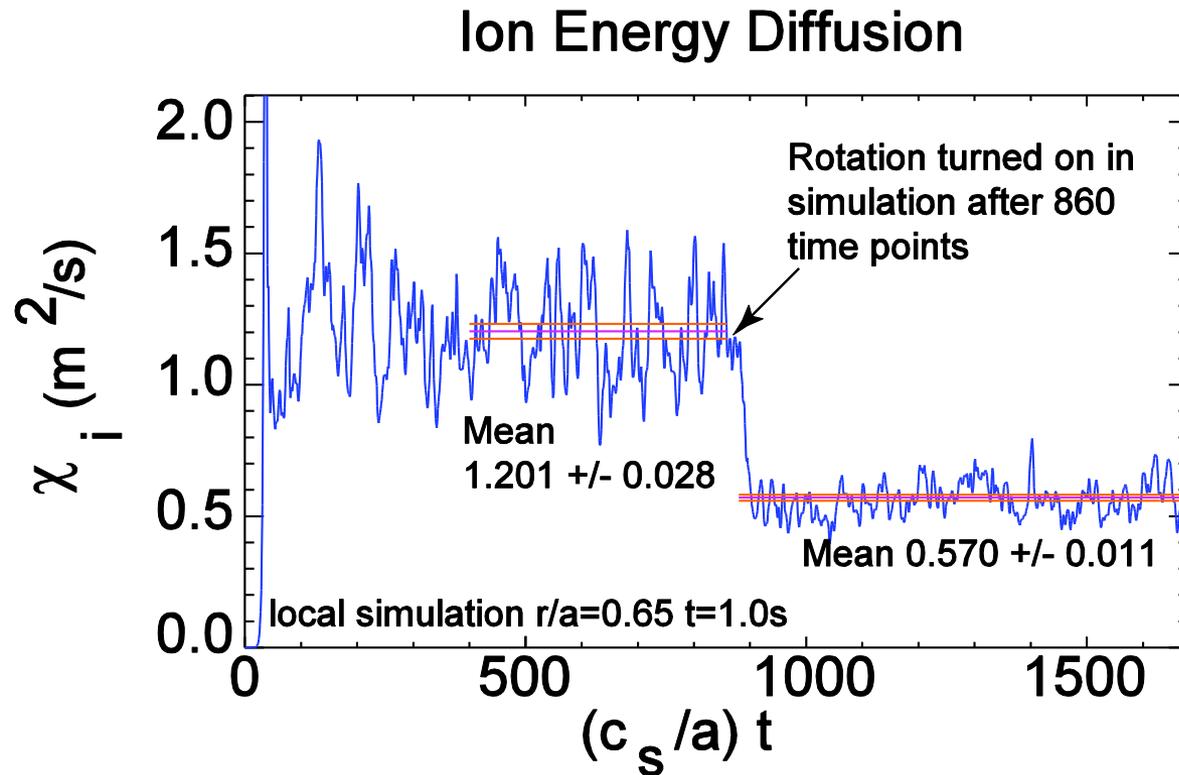


Maximum ITG growth rate in off-axis ICRF ITB is 1.5×10^5 Rad/s at $k_{\perp} \rho_i = 0.4$.

Non-linear GYRO simulation

- Non-linear (local) simulation using the GYRO code for the off-axis heated ITB was initially carried out using the experimental parameters but with the plasma rotation input disabled.
- The results, have no rotation included in the simulation in the first 880 time steps.
- Once the fluctuation level calculation converged, the plasma rotation was enabled at the experimentally measured value. A substantial decrease in the simulated χ_i was seen in the simulation after the addition of rotation.
- The mean value of χ_i decreased from 1.2 m²/s to 0.57 m²/s, more than a factor of 2 when the rotation was turned on after 800 time steps. The simulated value without rotation included is above the experimental value of $\chi_i = 0.4$ m²/s and $\chi_{\text{eff}} = 0.8$ m²/s at t=1.0 s but agreement is obtained with the inclusion of the rotation in the simulation.

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



ITB

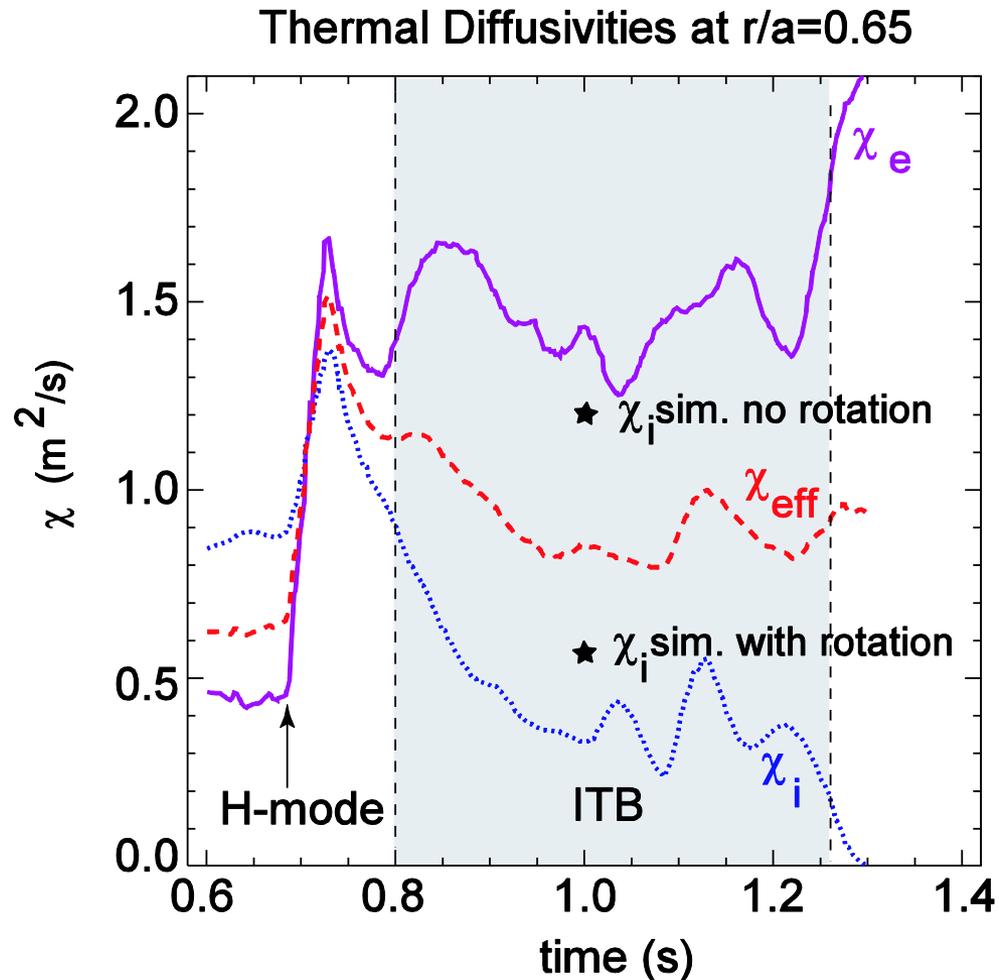
HFS off-axis ICRF

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

Rotation turned on after 860 time steps

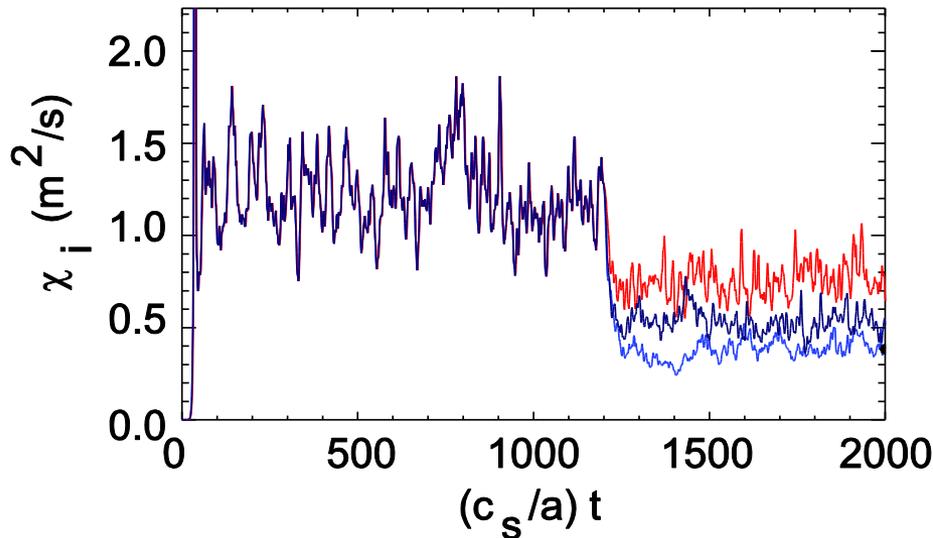
Experimental Value of Rotation used

Simulated χ_i including rotation reduced to near the experimental value in the ITB case



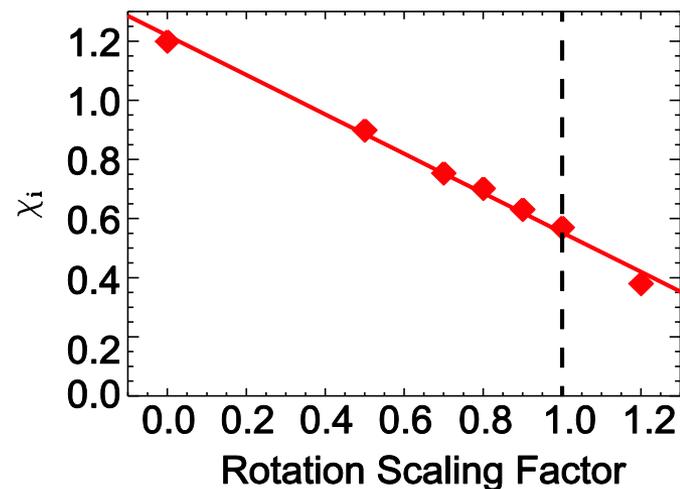
GYRO Simulation: Increasing the rotation scaling factor decreases diffusive transport

Ion Energy Diffusion

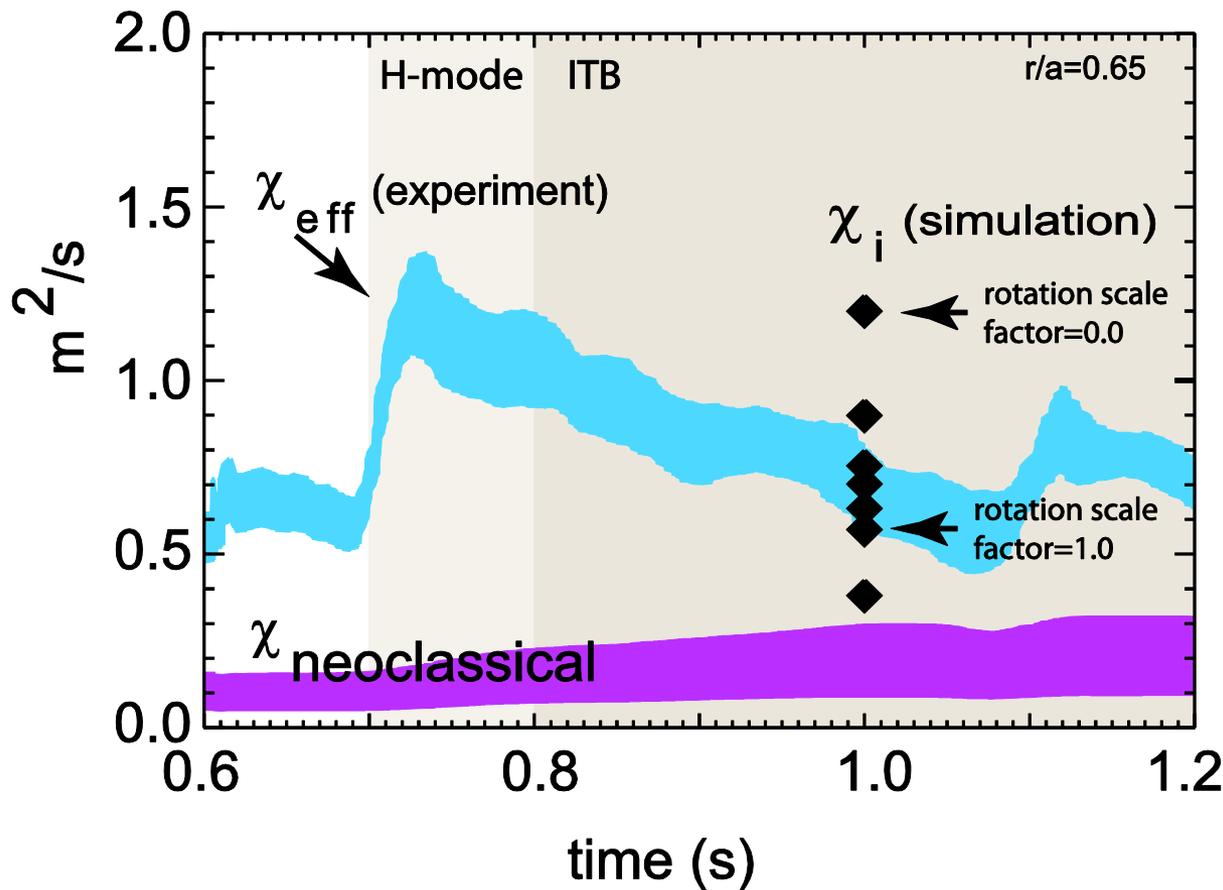


Simulated ion energy diffusion coefficient is shown for 3 values of rotational scaling factor, 0.5 (red), 1.0 (black) and 1.2 (blue), after rotation is turned on at 1200 time steps. The rotation scaling is 0 in first 1200 time steps.

The mean χ_i values after 1200 time steps in the simulation with increasing levels of rotational scaling factor are compared, from 0 to 1.2



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

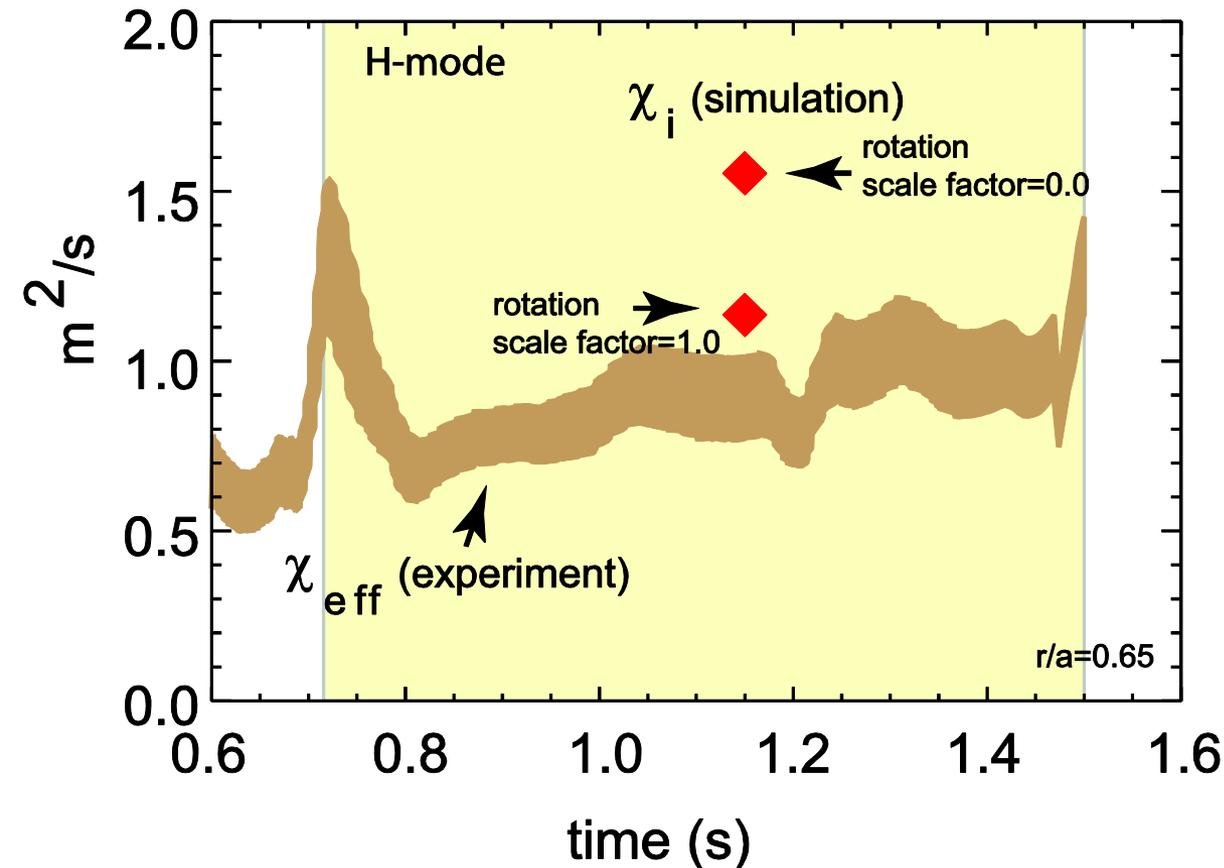


A range of χ_{eff} obtained by changing experimental values within expected error is shown (cyan).

$\chi_{\text{neoclassical}}$ is shown (purple) for comparison

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

Simulated χ_i is above experimental value of χ_{eff} in the standard on axis EDA H-mode plasmas; including rotation in the simulation has χ_i near experimental χ_{eff}



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

The diamonds show simulated χ_i values with varying rotation scaling from a factor of 0 (top point) to 1.0 (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 $E \times B$ 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 $E \times B$ shear in reduction of fluctuation driven transport in C-Mod ITB plasmas

- The linear ITG growth rate is comparable to $E \times B$ 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.

Research Status and Future Work

Experiment (JRT2012):

- Use pulsed central ICRF to study TEM in off-axis heated ICRF ITBs (Ernst), validate gyro-kinetic codes (data obtained in I-mode w/o ITB 10/2/2012, analysis to be done)
- 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 (data obtained 8/30/2012, analysis to be done.)
- High power ITBs: Do TEM modes become unstable driven by density gradient alone? (data obtained 7/19, 7/20/2012, analysis in process.)
- Ohmic H-mode ITBs with added central heating: study of role of TEM development in Ohmic ITBs (not completed).

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