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Mechanisms for ITB Formation and Control in Alcator C-Mod Identified through Gyrokinetic Simulations of TEM Turbulence

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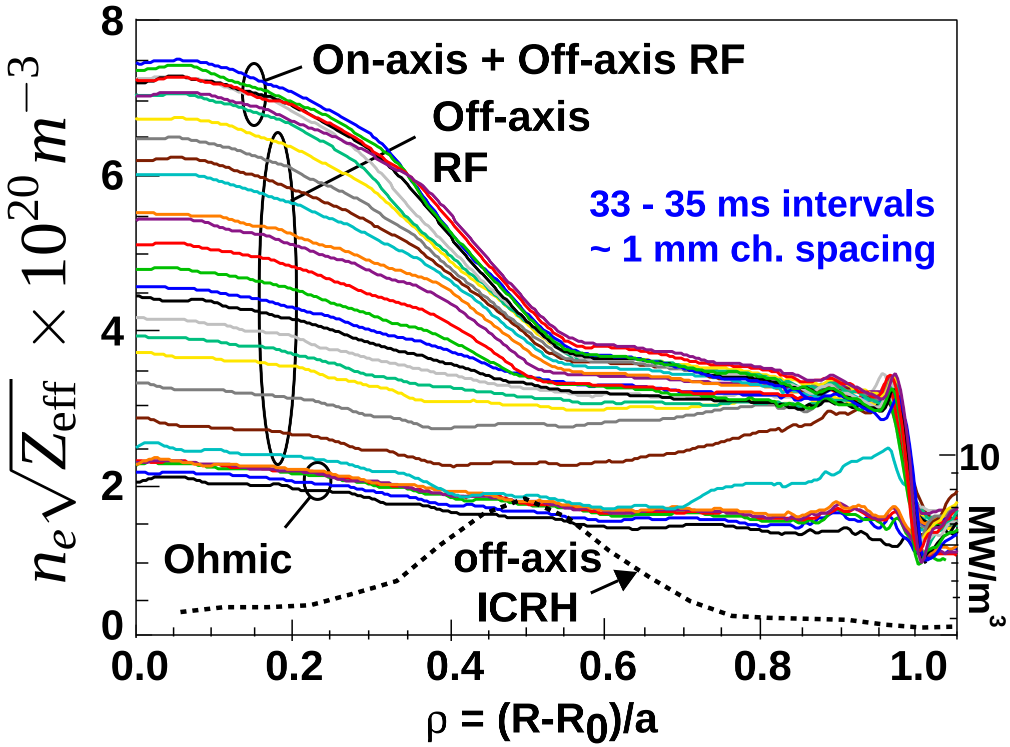
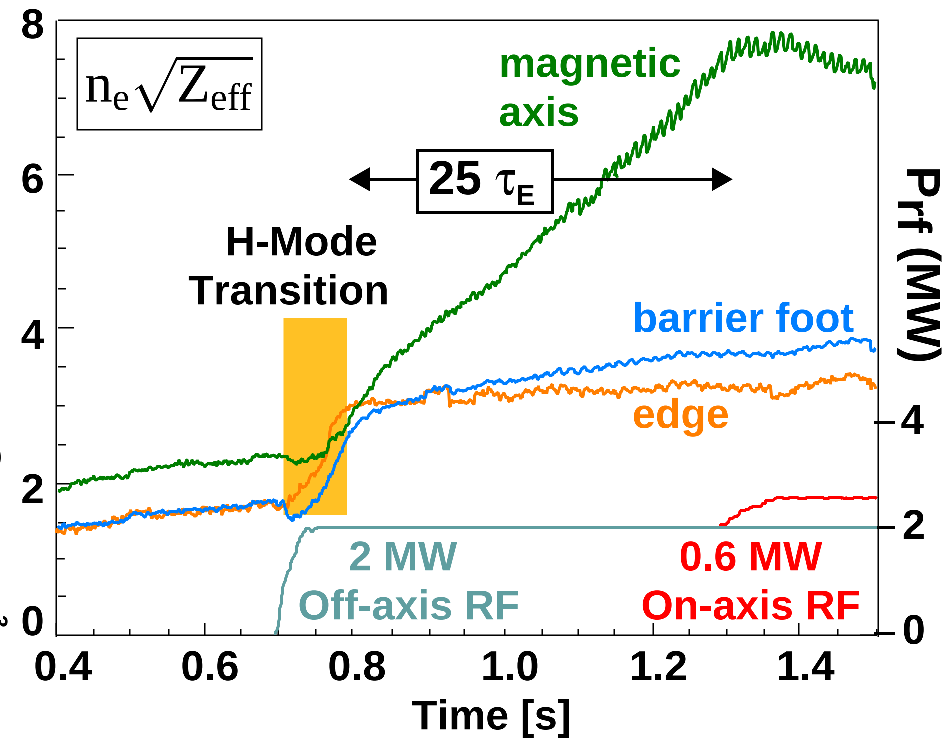
Internal Transport Barrier Produced by Moving ICRH Off-Axis





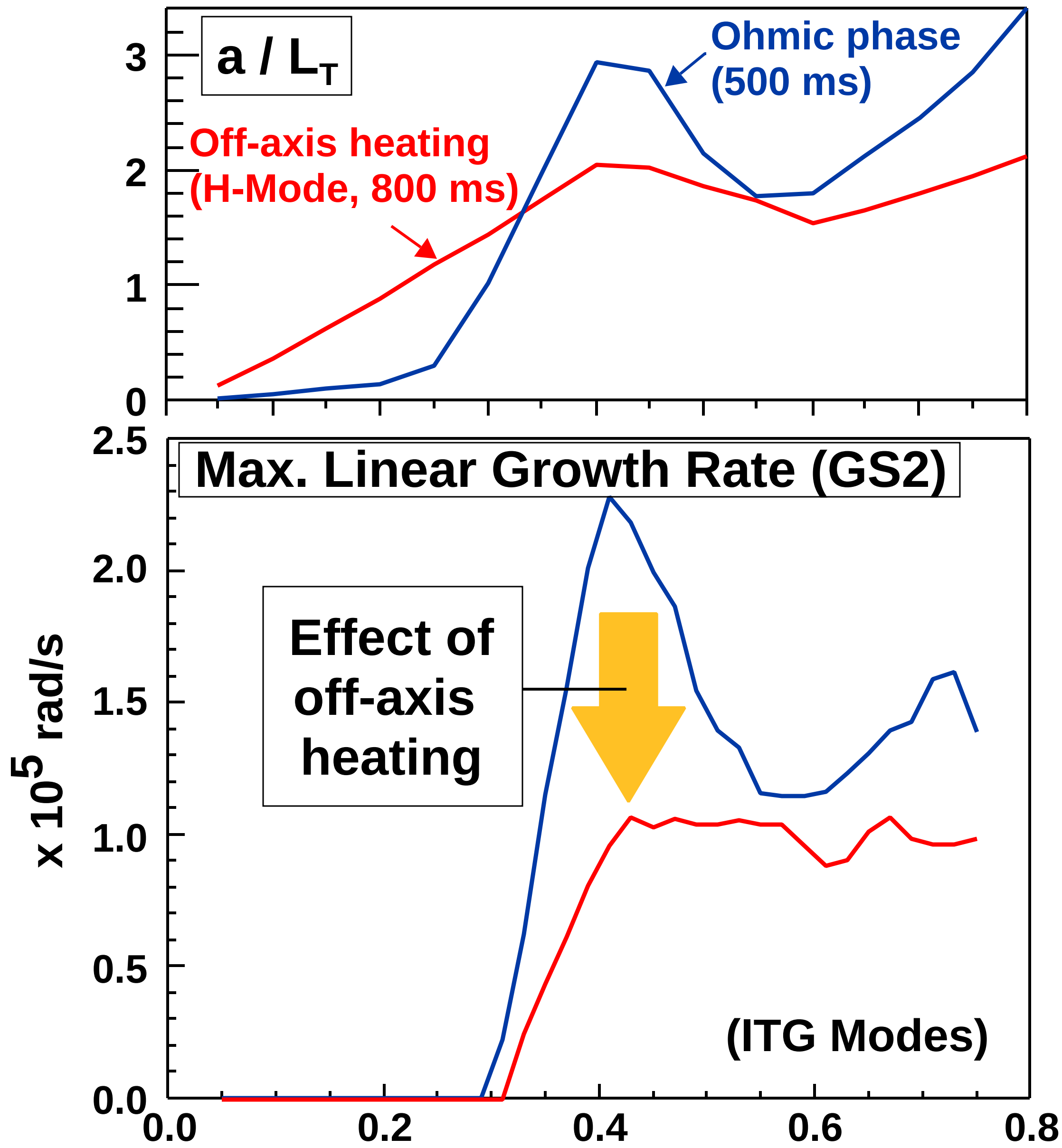
- Densities > 10^{21} m^{-3}
- No core particle sources or sinks
- $T_i(r) = T_e(r)$ unchanged while density peaks
- Monotonic q-profile, small Shafranov shift
- No external torques, significant fast ions, or impurity content

- Sharp magnetic field threshold for ITB, no hysteresis
- On-axis ICRH arrests density rise

Quantitative Simulations of TEM Turbulence in C-Mod ITB

- no adjustable parameters
- GS2 nonlinear gyrokinetic code [Dorland, Kotschenreuther, Liu]
  - Gyrokinetic Vlasov, time advancing
  - Local flux-tube, cross-section 30-60 ρ_i
  - General magnetic geometry
  - Spectral in $\perp$ direction
  - Lorentz collisions
  - All species fully gyrokinetic
- Our general interface to experiments [GS2_PREP] used for several years at TFTR, JET, DIII-D, JT60-U, C-Mod
- Collection of runs prepared automatically, viewed as profile
- Linear and non-Linear (electrostatic) results benchmarked
- Detailed comparisons with experiments performed toward understanding ITB formation and control with RF heating

Toroidal ITG Modes Suppressed by Off-Axis Heating



$$\rho = \sqrt{\text{norm. tor. flux}} \sim r/a$$

- C-Mod has no core particle sources:

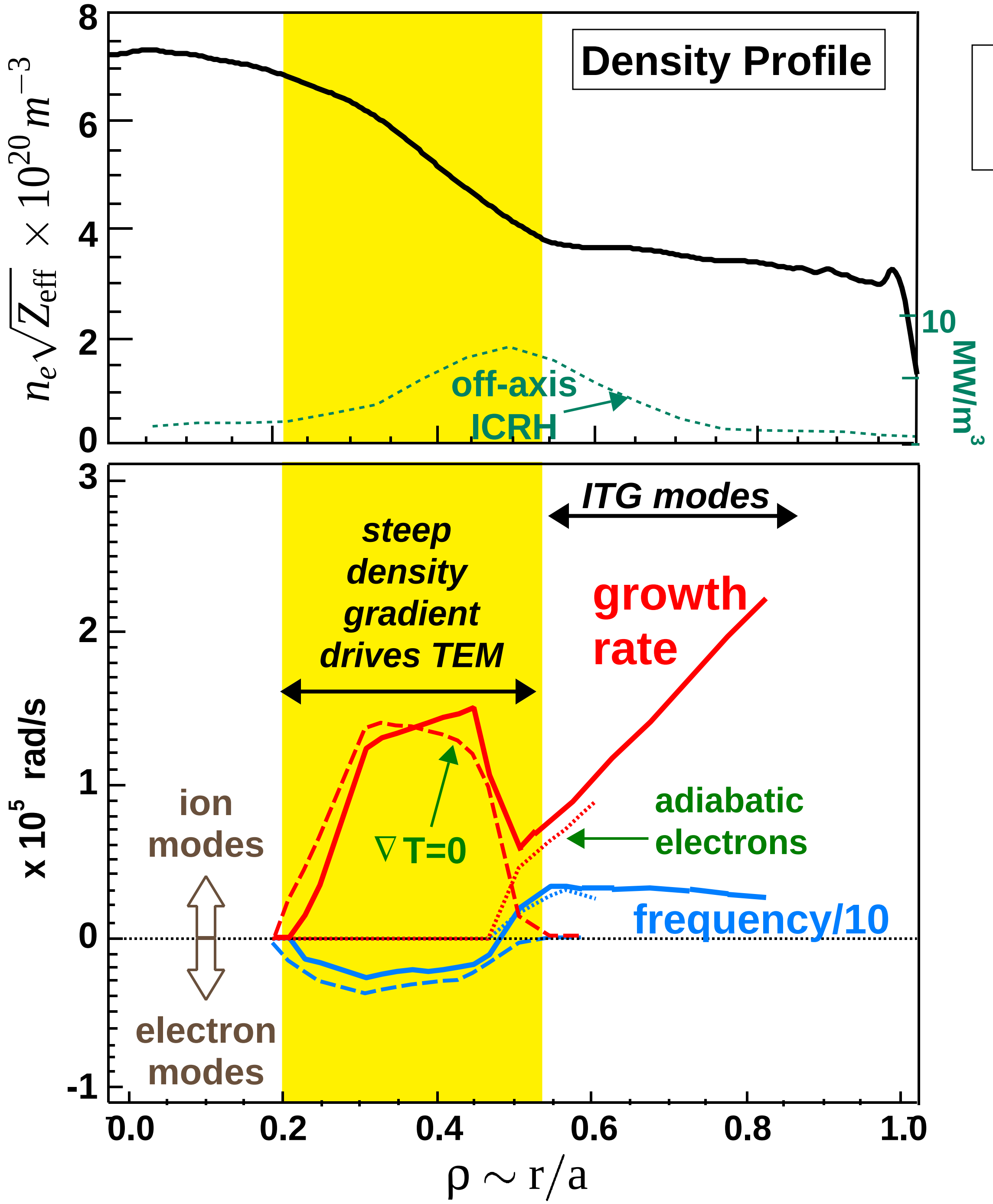
$$\frac{\partial n_e}{\partial t} + \nabla \cdot (\Gamma_{\text{Ware}} + \Gamma_{\text{turb}}) = 0$$

initially small, outward flux

- Ware pinch peaks density where ITG modes suppressed
- Nonlinear turbulence simulations show negligible turbulent pinch
- Ware pinch alone accounts for twice observed rate of density rise

MIT PSFC Alcator C-Mod

As Density Gradient Steepens, TEM forms in Barrier



2 MW off-axis + 0.6 MW on-axis ICRH, Double Barrier, 1.34 sec (late in time)

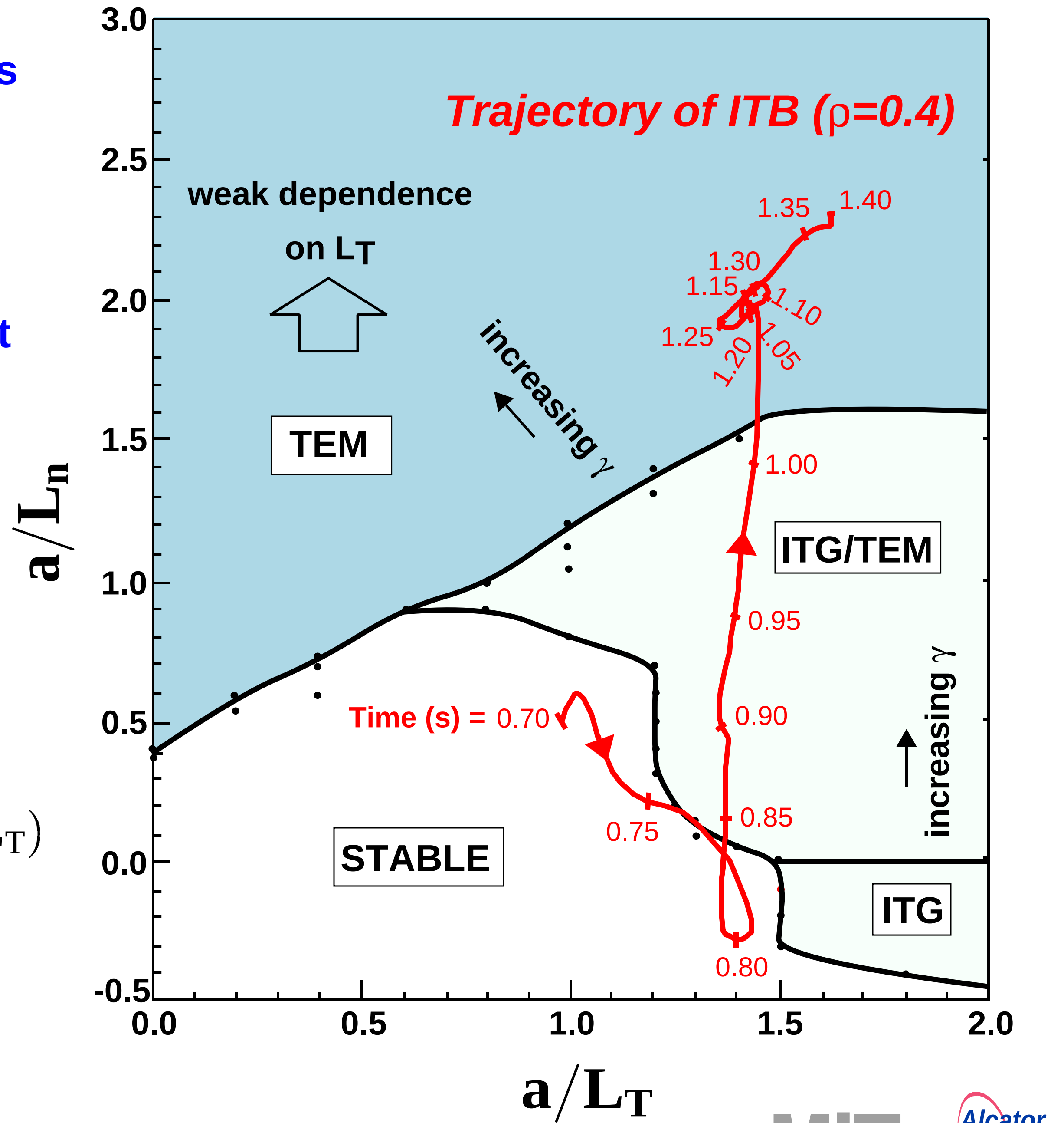
- Phase velocity in electron direction
- Vanishes with adiabatic electrons
- Driven solely by density gradient
- Usual toroidal ITG modes outside ITB foot

Gradients in ITB Initially Follow ITG Stability Boundary, Allowing Ware Pinch to Peak Density

- Several hundred linear GS2 runs trace out stability boundaries
- Following H-Mode transition, "Trapped Electron-ITG" modes weakly grow as density gradient steepens
- Shortly after TEM stability boundary is crossed, trajectory stagnates
- Fit to TEM critical density gradient:

$$(a/L_n)_{crit} = \max\begin{cases} 0.4 + 0.83(a/L_T) \\ 1.6 \end{cases}$$

$$R_0/a = 3.3$$



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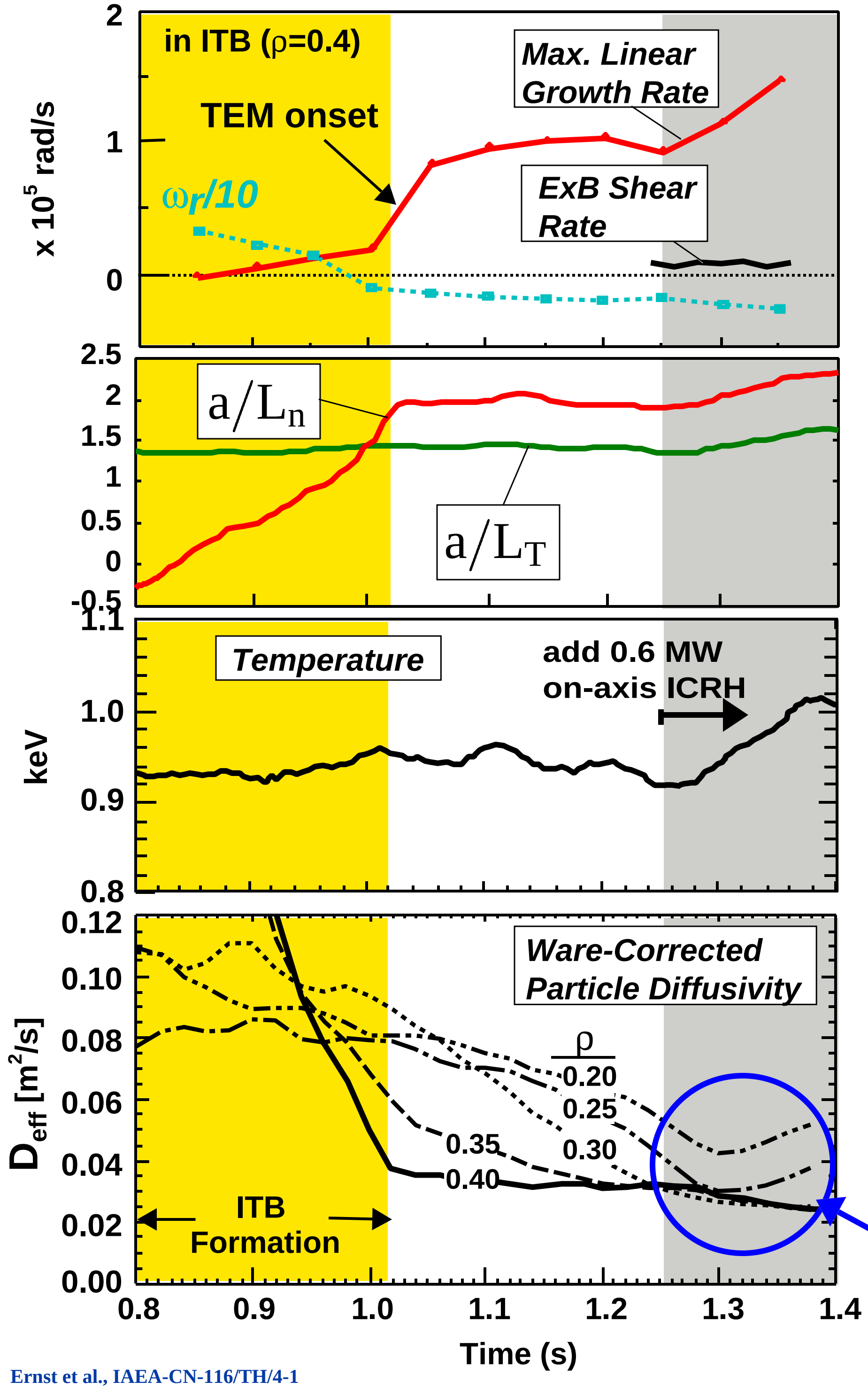
ITB Formation Ceases at Each Radius with TEM Onset



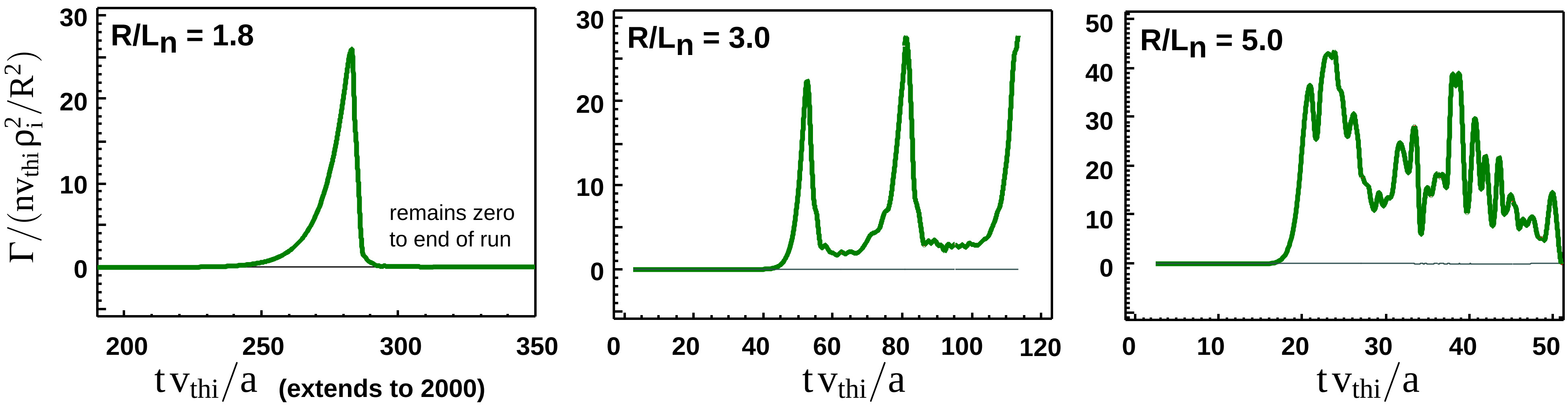
- In late phase of discharge, toroidal rotation is small, ExB shear unimportant
- Density gradient scale length comes to steady state with TEM onset (~ 1.0 sec)
- On-axis ICRH increases temperature starting 1.25 sec
- D_{eff} ceases to drop when TEM goes unstable (~ 1.0 sec)
- One-fluid χ_{eff} reaches neoclassical values in inner core
- D_{eff} increases during on-axis heating

Ernst et al., IAEA-CN-116/TH/4-1

Nonlinear simulations reveal new upshift in TEM critical density gradient

Modified "Cyclone Base Case"
$\nu_{ei}\, a/v_{thi}$ = 0.01 R/L_T = 0
Linear TEM threshold R/L_n = 1.44

increasing density gradient

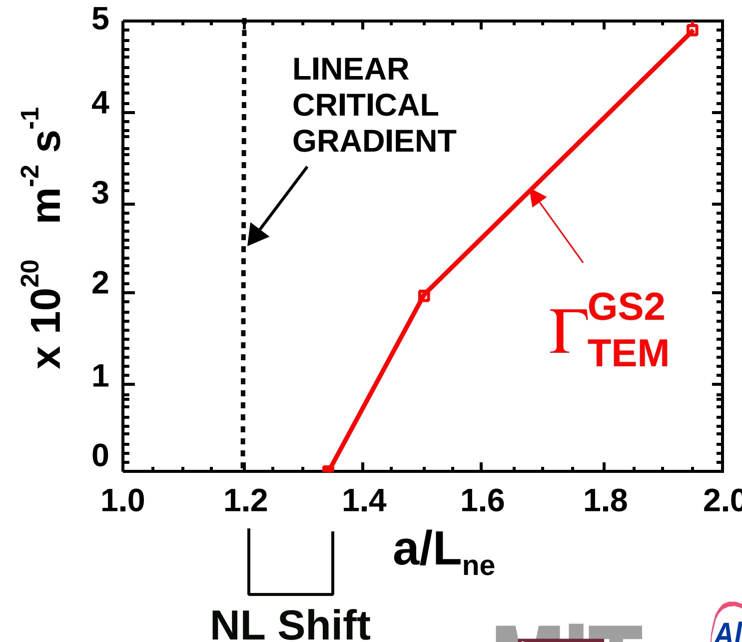


- **Pure TEM linearly unstable, but nonlinearly quasi-stable, for a range of density gradients**
- **Analogous to Dimits shift in temperature gradient for ITG turbulence**
  [A. M. Dimits et al., *Phys Plasmas* (2000)]
- **Results from explosive growth of zonal flows, which are weakly damped**

$$\gamma_{ZF} \propto \delta\phi_{primary} \quad \Rightarrow \quad \phi_{ZF} \propto \exp(\exp \gamma t)$$

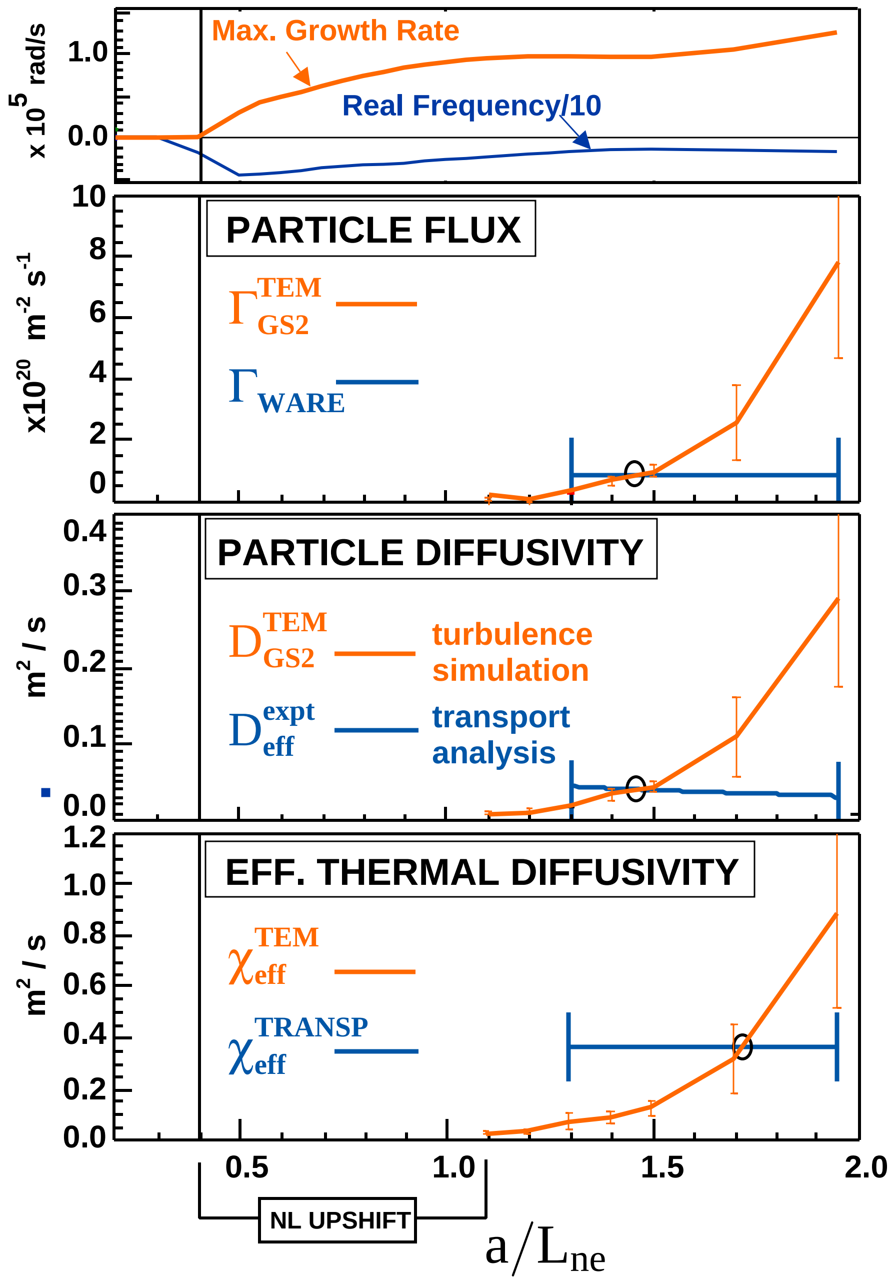
[Rogers, Dorland, Kotschenreuther, *Phys. Rev. Lett.* (2000)]

Simulated Particle Flux in ITB



MIT PSFC Alcator C-Mod

Ultimately, TEM outflow balances Ware Pinch: Locally stable equilibrium



- Upon exceeding nonlinear critical density gradient, turbulent outflow strongly increases until

$$\Gamma^{TEM}_{GS2} + \Gamma_{WARE} \simeq 0$$

- Error bars represent uncertainty in Z_{eff} gradient

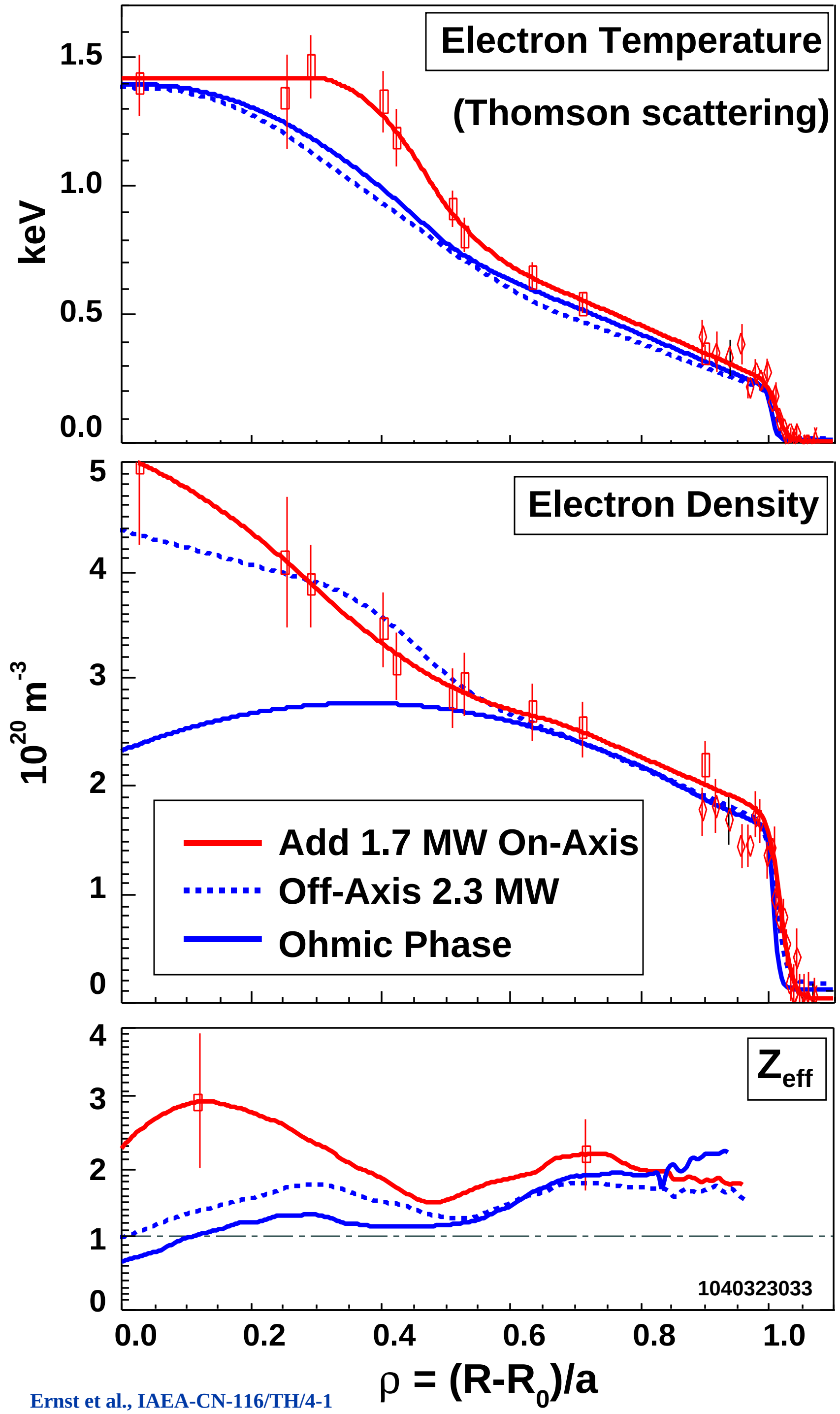
- $n_e Z_{eff}^{1/2}$ gradient measured via 218 channel visible brehmstraahlung

- Simulations match experimental particle and energy transport in ITB within the uncertainties

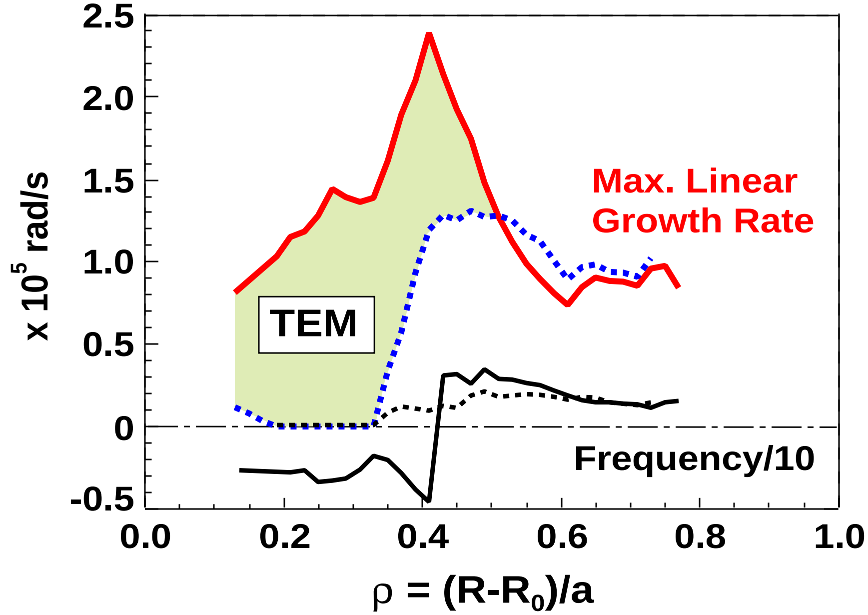
Ernst et al., IAEA-CN-116/TH/4-1

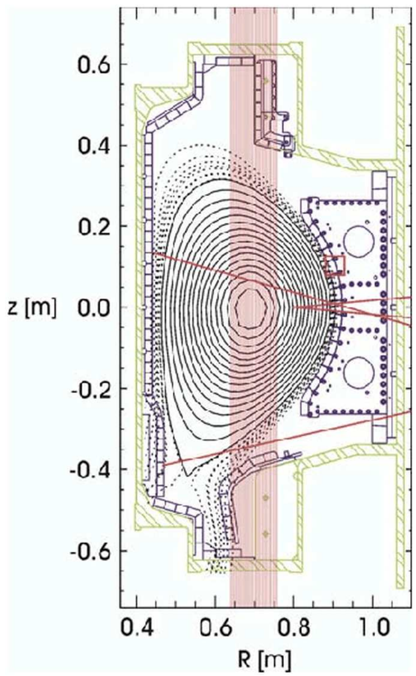
Alcator C-Mod

Recently, Full available source power maintained steady ITB



- Higher temperature again destabilizes TEM





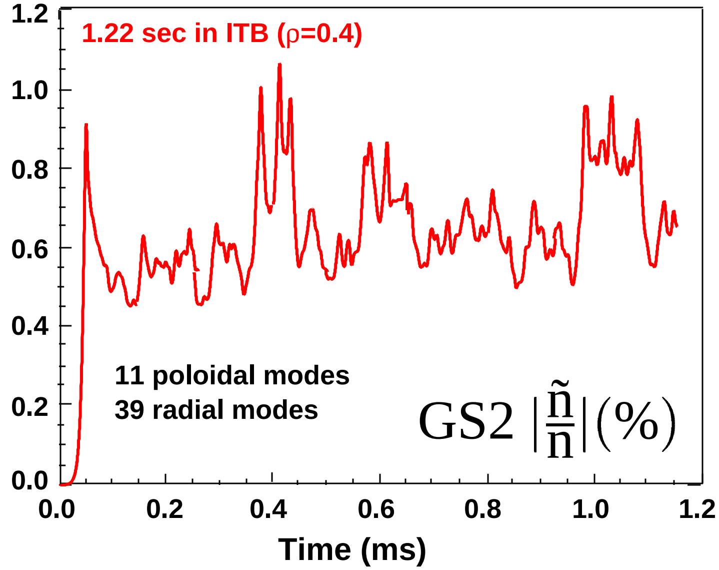
- Density fluctuation data available from improved Phase Contrast Imaging Diagnostic:

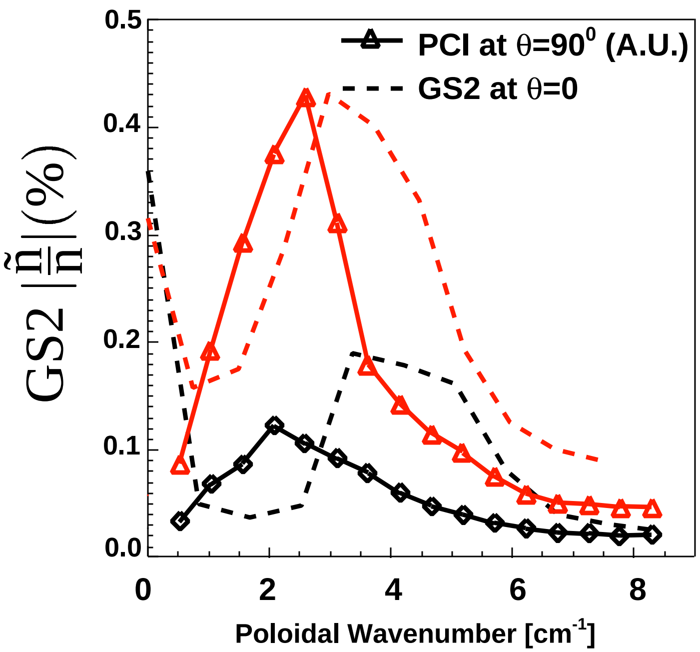
10 kHz - 5 MHz
0.5 - 12 cm^{-1}
line-integrated

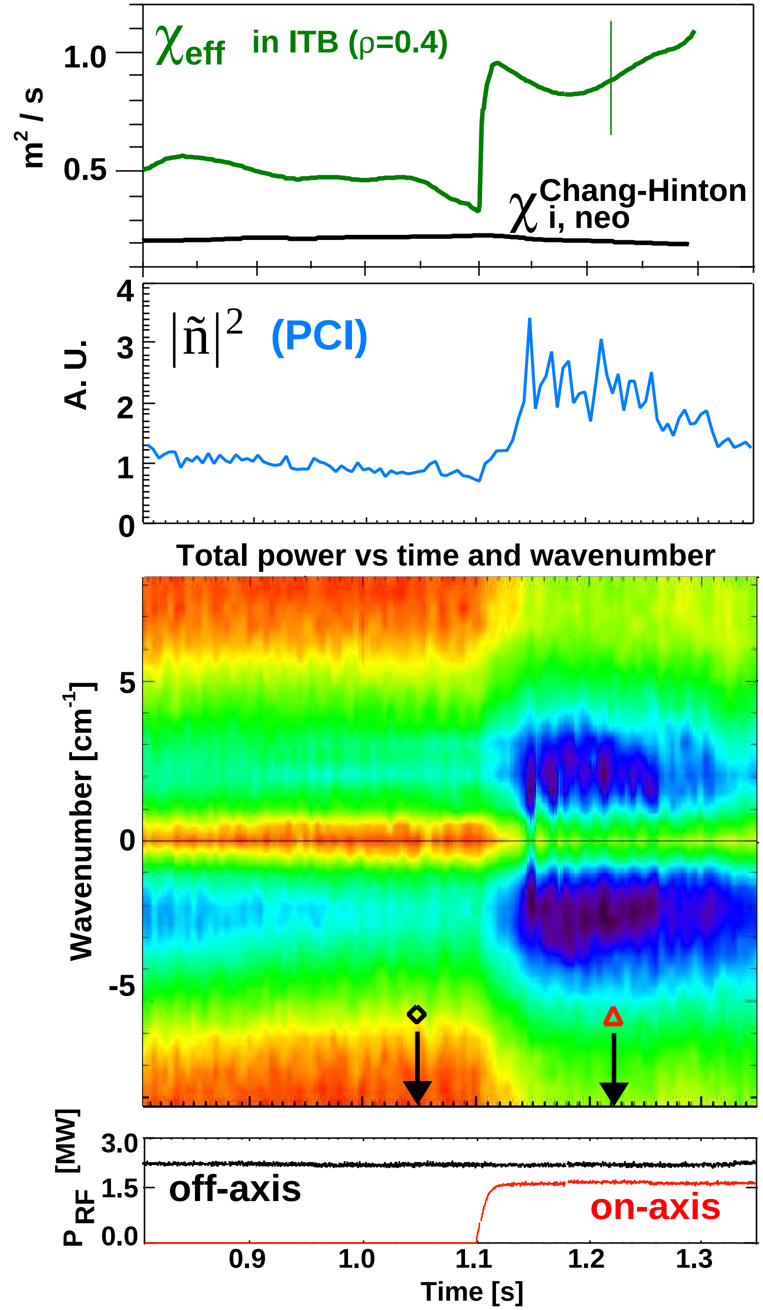
Ernst et al., IAEA-CN-116/TH/4-1

Encouraging preliminary comparison of GS2 and PCI in TEM frequency range

- PCI observes wavelengths and frequencies similar to GS2 prediction.
- GS2 nearly correct on increase of fluctuation power during on-axis ICRH.







Phase Contrast Imaging

20 - 80 kHz

Avoids edge QC mode

Ernst et al., IAEA-CN-116/TH/4-1

Alcator C-Mod

Conclusions

- **Ware pinch sufficient to account for C-Mod ITB formation when off-axis heating broadens T(r), suppressing ITG modes**
- **As density peaks, TEM driven unstable**
- **When TEM flux balances Ware pinch at each radius, stable equilibrium**
- **GS2 simulations of particle and energy flux in ITB match experiment**
- **On-axis heating increases temperature, increasing TEM particle flux consistent with gyrobohm scaling, collisionality plays 2nd order role**
- **At same time, Ware pinch decreases with temperature**

$$\boxed{\frac{\partial n_e}{\partial t} + \nabla \cdot \left\{ \Gamma_0^{TEM} \left(\frac{T}{T_0} \right)^{3/2} + \Gamma_{0\,Ware} \left(\frac{T}{T_0} \right)^{-1/2} \right\} = 0} \quad \textbf{(ITB control)}$$

- **New nonlinear upshift of TEM critical density gradient, due to zonal flows**
- **GS2 spectrum and increase in density fluctuations in rough agreement with Phase Contrast Imaging (preliminary)**

Alcator C-Mod