Gyrokinetic Simulations of Trapped Electron Mode Turbulence in Alcator C-Mod Internal Particle Transport Barriers

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in collaboration with

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Alcator C-Mod

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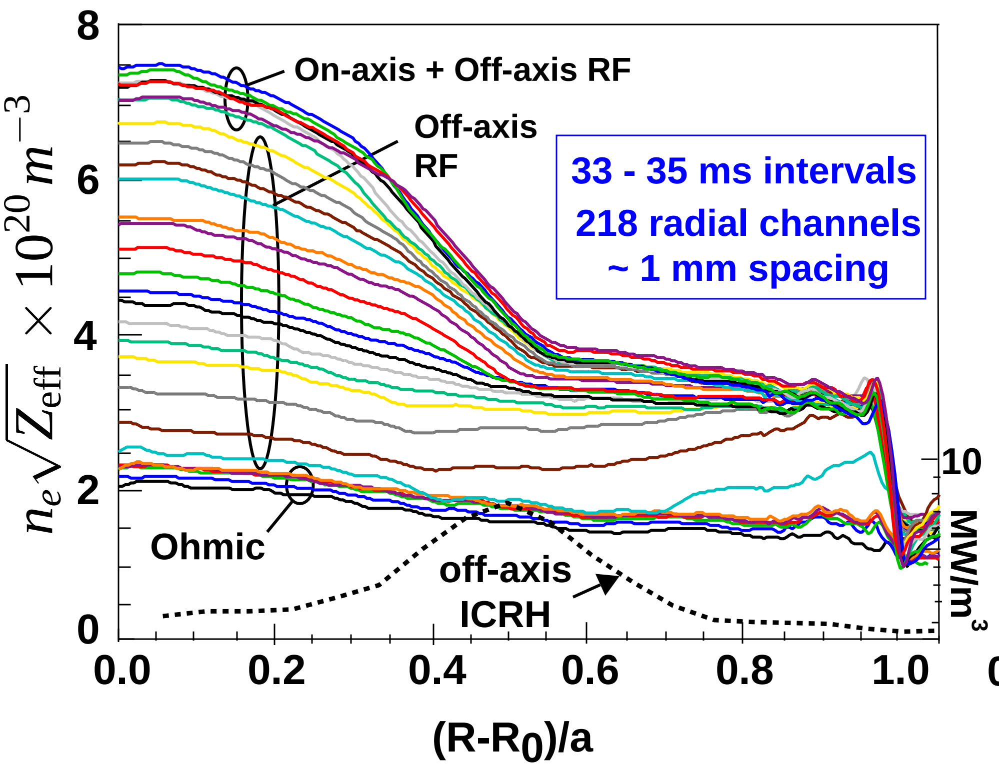
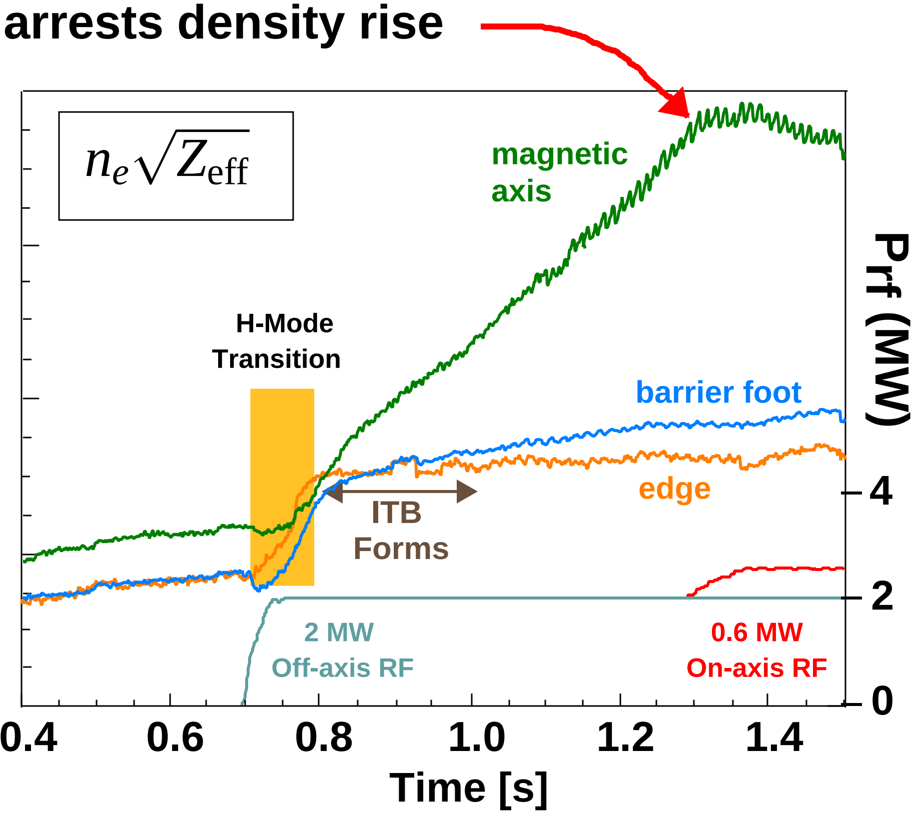
Internal Transport Barrier Produced by Moving ICRH Resonance Off-axis

- **Broadened temperature profile remains nearly unchanged while density peaks**
- **Electron and impurity densities rise inside the heating radius until radiative collapse, unless controlled (here $Z_{eff} < 1.8$)**
- **Modest on-axis ICRF heating (< 0.6 MW) arrests density rise**





- **Recent result: ITB threshold very sensitive to B_T, reproducible, no hysteresis**

S. J. Wukitch *et al.*, Phys. Plasmas (2001)
C. L. Fiore *et al.*, Phys. Plasmas (2004)

C-Mod ITBs Provide Test Bed for Particle Transport Studies

- **Density slowly peaks while temperature profile remains ~fixed.**

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

Absence of central fueling
(no particle sources or sinks)

- **TEM is dominant mode; particle transport remains diagonal**
- **Very high core densities ~ 6 x 10^{20} m^{-3}**
- **No net momentum input**
- **$T_i = T_e$**
- **Monotonic q-profiles, small Shafranov shift (no precession drift reversal)**
- **Impurity accumulation controlled with on-axis ICRH (Z_{eff}<1.8)**
- **Varying on-axis ICRH power varies core density rate of rise.**

Reasons for ITB formation? **What is mechanism for control?**

- **Similar density profile control with external ICRH or ECH:**

reverse shear ITBs

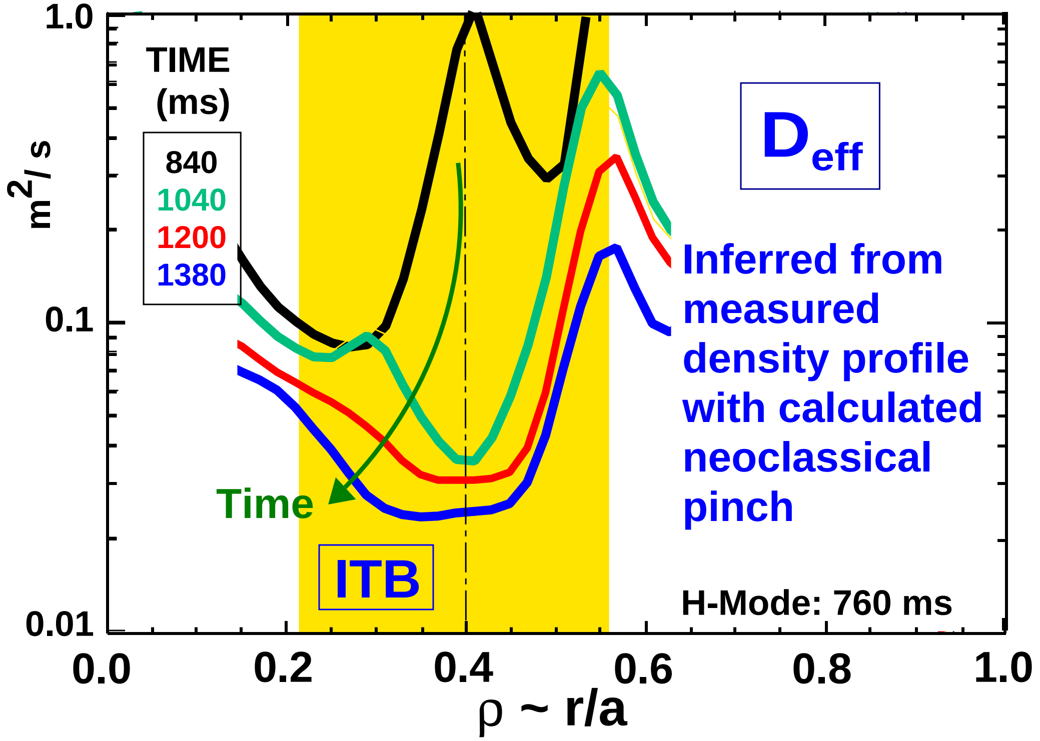
DIII-D [E. J. Doyle *et al.*, BAPS (2002)]
JT60-U [S. Ishida et al., Phys. Plasmas (2004)]

spontaneous peaking H-Modes (find $D_{eff} \sim \chi_{eff}/4$)

ASDEX-U [Stober *et al.*, Nucl. Fusion (2001)]
JET [Suttrop *et al.*, Phys. Plasmas (2002)]

Neoclassical Pinch together with Reduced Turbulent Transport Sufficient for Barrier Formation

TRANSPORT ANALYSIS



- **Including Ware pinch keeps $D_{eff} > 0$, allowing margin for turbulent diffusion**

c.f. Bonoli, APS (2001)

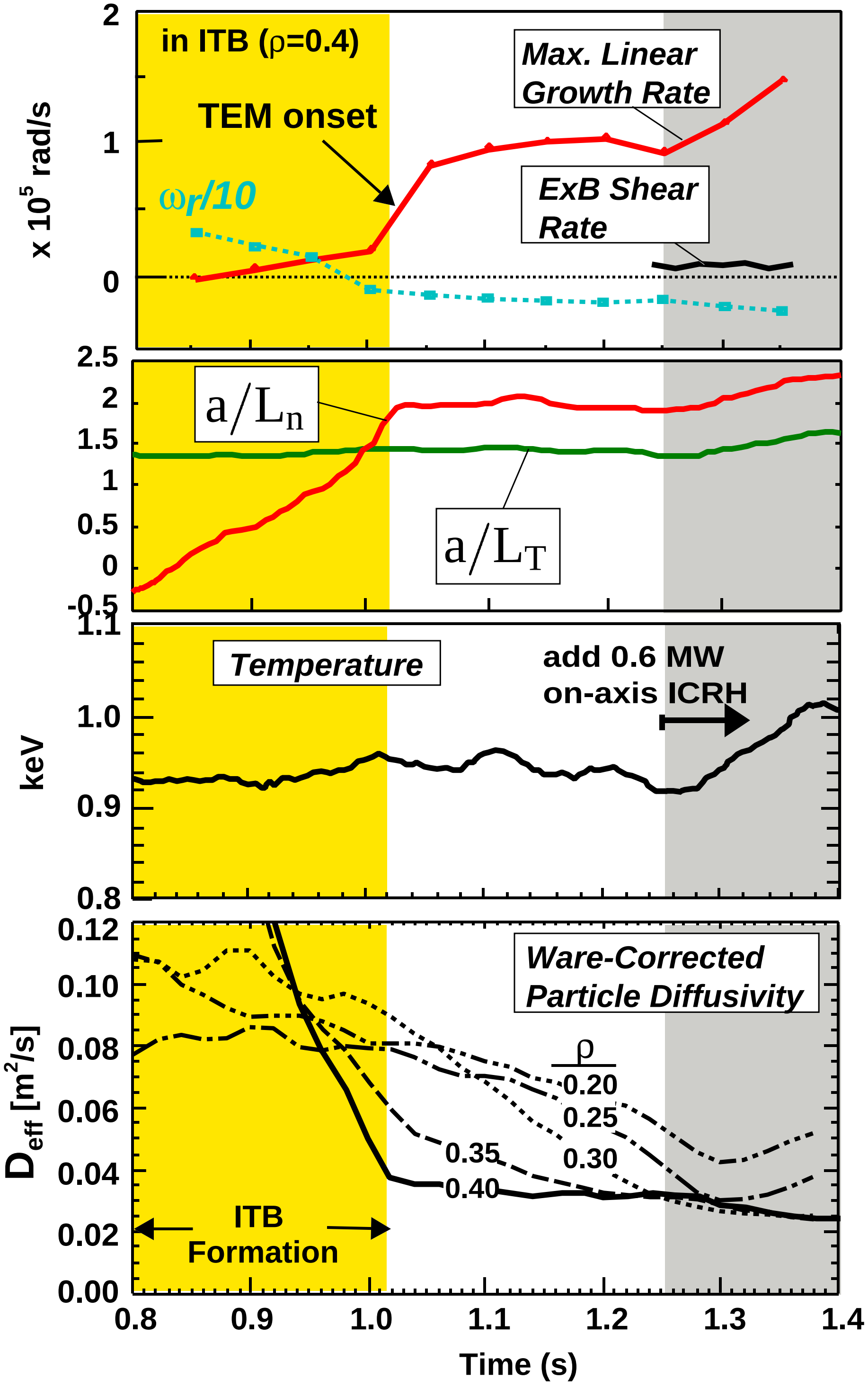
Ware-Corrected Particle Diffusivity

$$\frac{\partial n_e}{\partial t} + \nabla \cdot \left(\mathbf{\Gamma}_{\mathrm{Ware}} - D_{\mathrm{eff}} \nabla n_e\right) = 0$$

$$D_{\mathrm{eff}} = \frac{\Gamma_{\mathrm{neo}} \langle |\nabla \rho| \rangle + \frac{1}{V'} \int d\rho \, V' \frac{\partial n_e}{\partial t}}{\langle |\nabla \rho|^2 \rangle \frac{d n_e}{d\rho}}$$

- **Ware pinch is sufficient, but is there also a turbulent pinch?**

ITB formation ceases at each radius with TEM onset



- In late phase of discharge, toroidal rotation is small, ExB shear unimportant

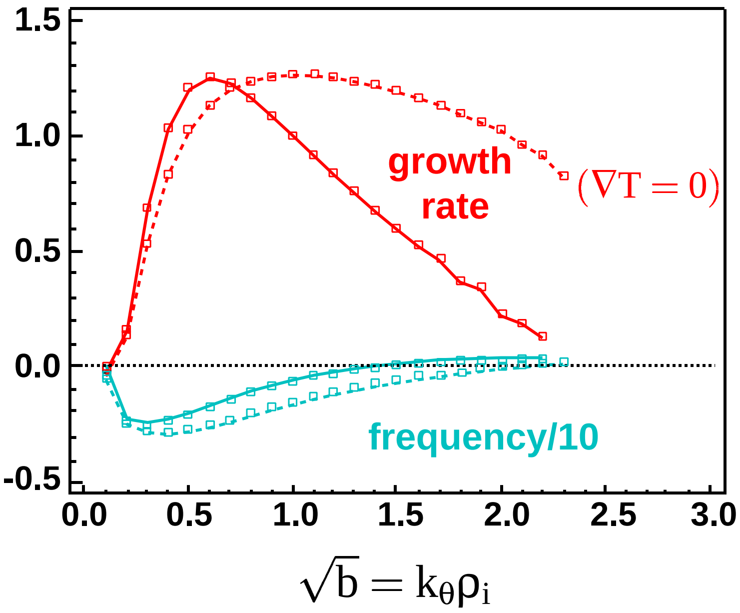
- Density gradient scale length comes to steady state with TEM onset (~ 1.0 sec)

- On-axis ICRH increases temperature starting 1.25 sec

- D_{eff} ceases to drop when TEM goes unstable (~ 1.0 sec)

Gyrokinetic Simulations Using GS2[1,2] Code

- Nonlinear, gyrokinetic Vlasov, initial-value, flux-tube representation
- General magnetic geometry, multiple species, electromagnetic, Lorentz collisions
- Linearly benchmarked, electrostatic nonlinear benchmarks completed
- We have developed tools[3] to interface to experiments, automate runs, plot results
- GS2 runs prepared & run automatically for each radius and time of interest, reassembled into profiles
- Linear stability analysis, data preparation, results plotting benchmarked against FULL and GKS codes, for TEM in JT60-U and DIII-D ITBs



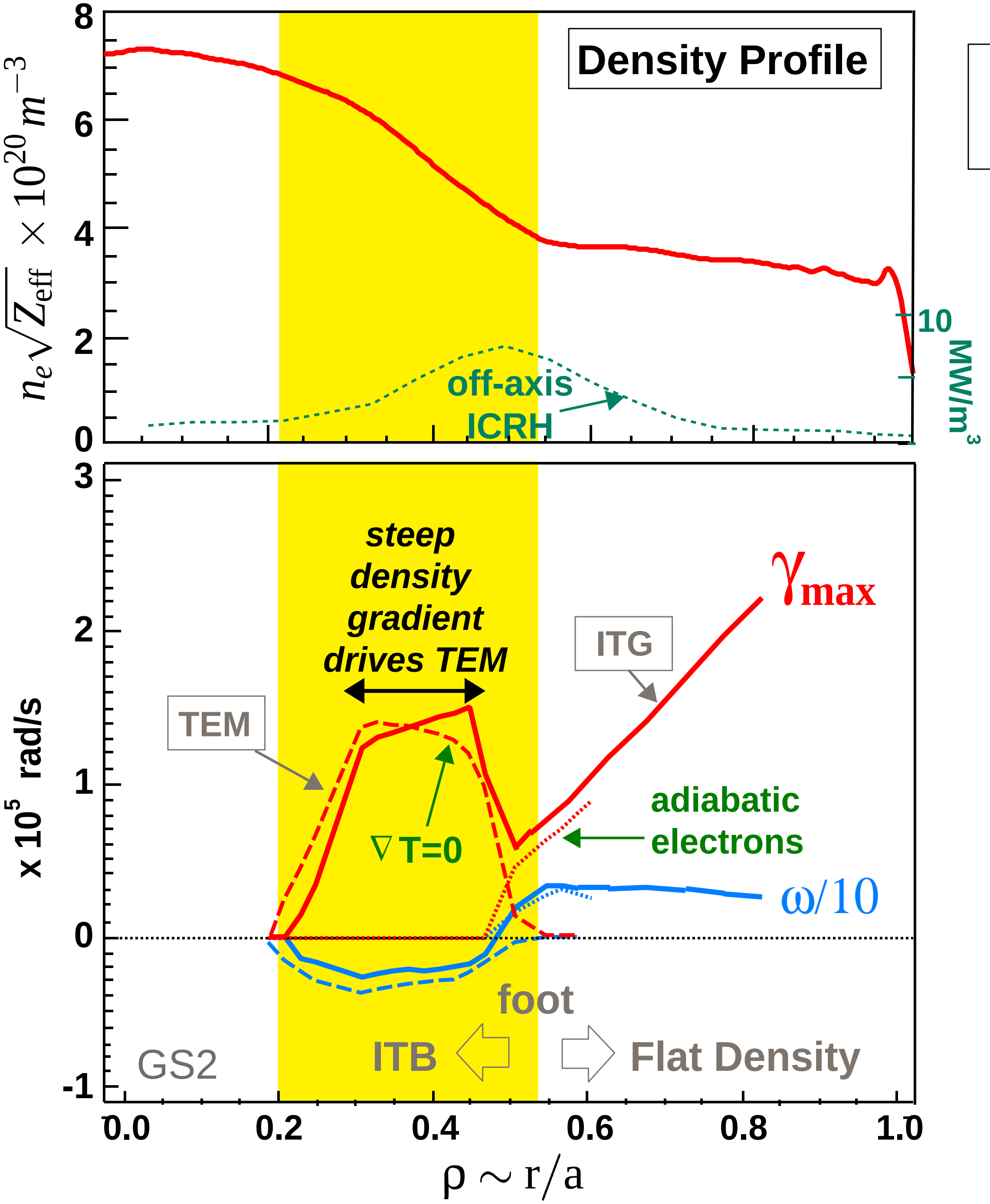
Growth Rate Spectrum in ITB (one radius)

This talk:

3 species
16 energies
10 circ. pitch angles
32 trapped pitch angles
periodic B.C.

[1] W. M. Dorland et al., Phys. Rev. Lett. **85** (2000) 5579.
[2] M. Kotschenreuther et al., Comp. Phys. Comm. **88** (1995) 128.
[3] D. R. Ernst et al., Phys. Plasmas (2000) 615

Gyrokinetic Stability Analysis: TEM forms in Barrier



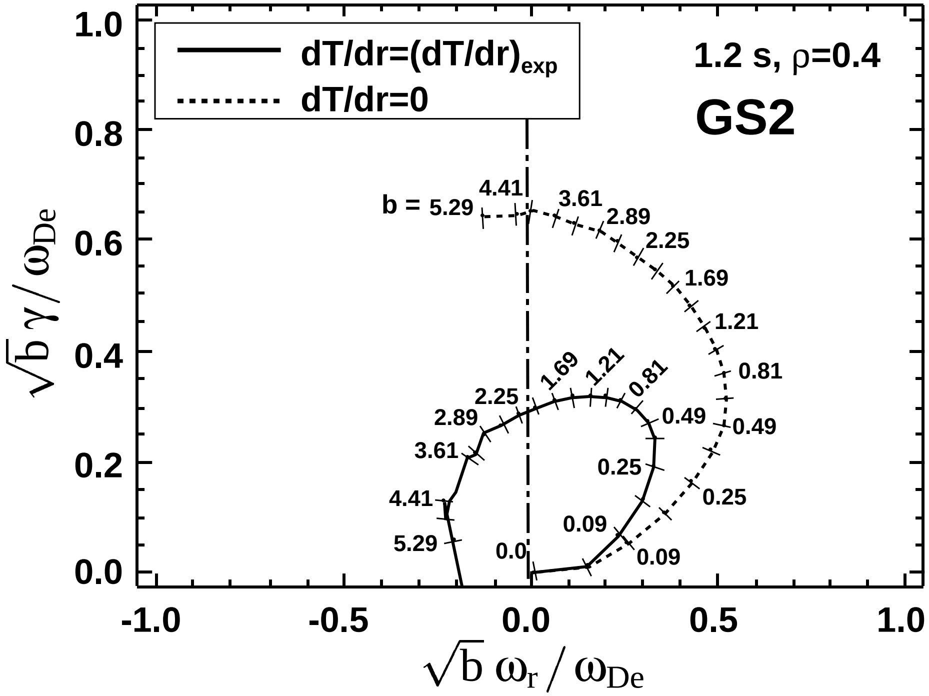
2 MW off-axis + 0.6 MW on-axis ICRH,
Double Barrier, 1.34 sec (late in time)

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

GS2 in Qualitative Agreement with Existing Linear Theory for TEM

- **Simplest dispersion relation**

$$1-\frac{\omega_{*e}}{\omega}+\frac{\eta_i\omega_{*e}\,\omega_{De}}{\omega^2}+\frac{n_T}{n}\frac{2}{\sqrt{\pi}}\int_0^\infty dx\sqrt{x}\,\frac{\omega-\omega_{*e}[1+\eta_e(x-3/2)]}{\omega-\bar{\omega}_{De}(x)}\Big|_{x=E/T}=0$$



keep resonance

$$\gamma \simeq \omega_{*e}\frac{n_T}{n}\,2\sqrt{\pi}\,\eta_e\left(x_0-3/2\right)x_0^{3/2}\,e^{-x_0}$$

$$x_0 = R/L_n$$

note threshold

expand integral in fluid limit $\omega_{De} \ll \omega$

$$\gamma \simeq k_\theta\rho_i\sqrt{\frac{\frac{g_\mathrm{eff}}{L_n}\left(\frac{n_{eT}}{n}+\eta_i\right)}{1-n_{eT}/n+b_i}}$$

TEM

Toroidal ITG

$$g_\mathrm{eff} = v_\mathrm{thi}^2/R$$

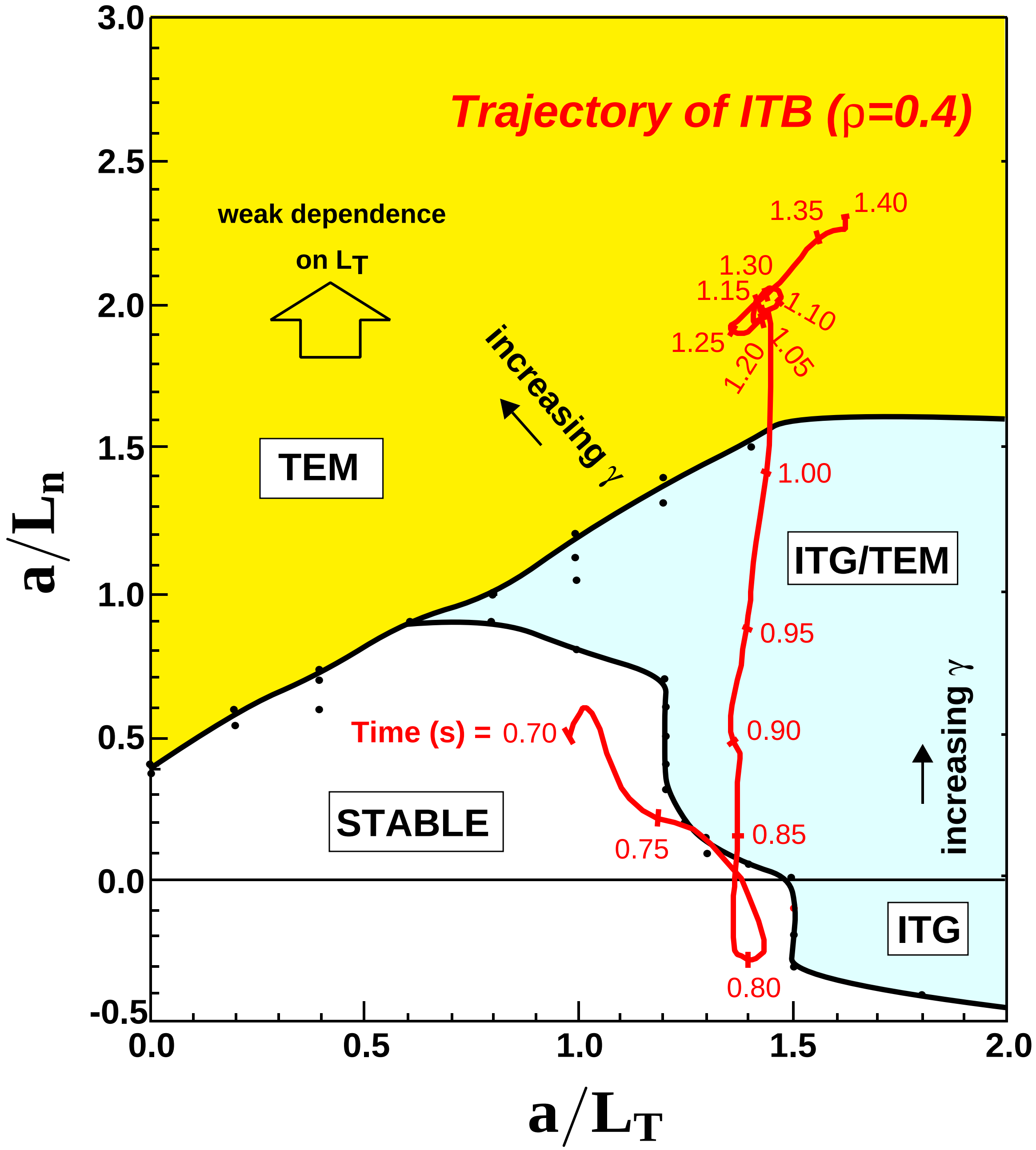
Refs for most basic theory:
B. B. Kadomstev and O. P. Pogutse, Sov. Phys.-JETP 24, 1172 (1967).
B. Coppi and G. Rewoldt, PRL 33 (1974) 1329.
J.C. Adam, W. M. Tang, P.H. Rutherford, Phys. Fluids 19 (1976) 561.
C. S. Lui, M.N. Rosenbluth, W.M. Tang, Phys. Fluids 19 (1976) 1040.
B. Coppi and F. Pegoraro, Nuc. Fus. 17 (1977) 969.
W. M. Tang, G. Rewoldt, Liu Chen, Phys. Fluids 29 (1986) 3715.
B. Coppi, S. Migliuolo, Y.-K. Pu. Phys. Fluids B 2 (1990) 2322.
D. W. Ross, J. C. Adam, W. M. Tang, Phys. Fluids 20, 613 (1977).
C. Z. Cheng and L. Chen, Nucl. Fusion 21, 403 (1981).

- **Temperature gradient suppresses short wavelength modes**
- **Critical density gradient increases with temperature gradient**

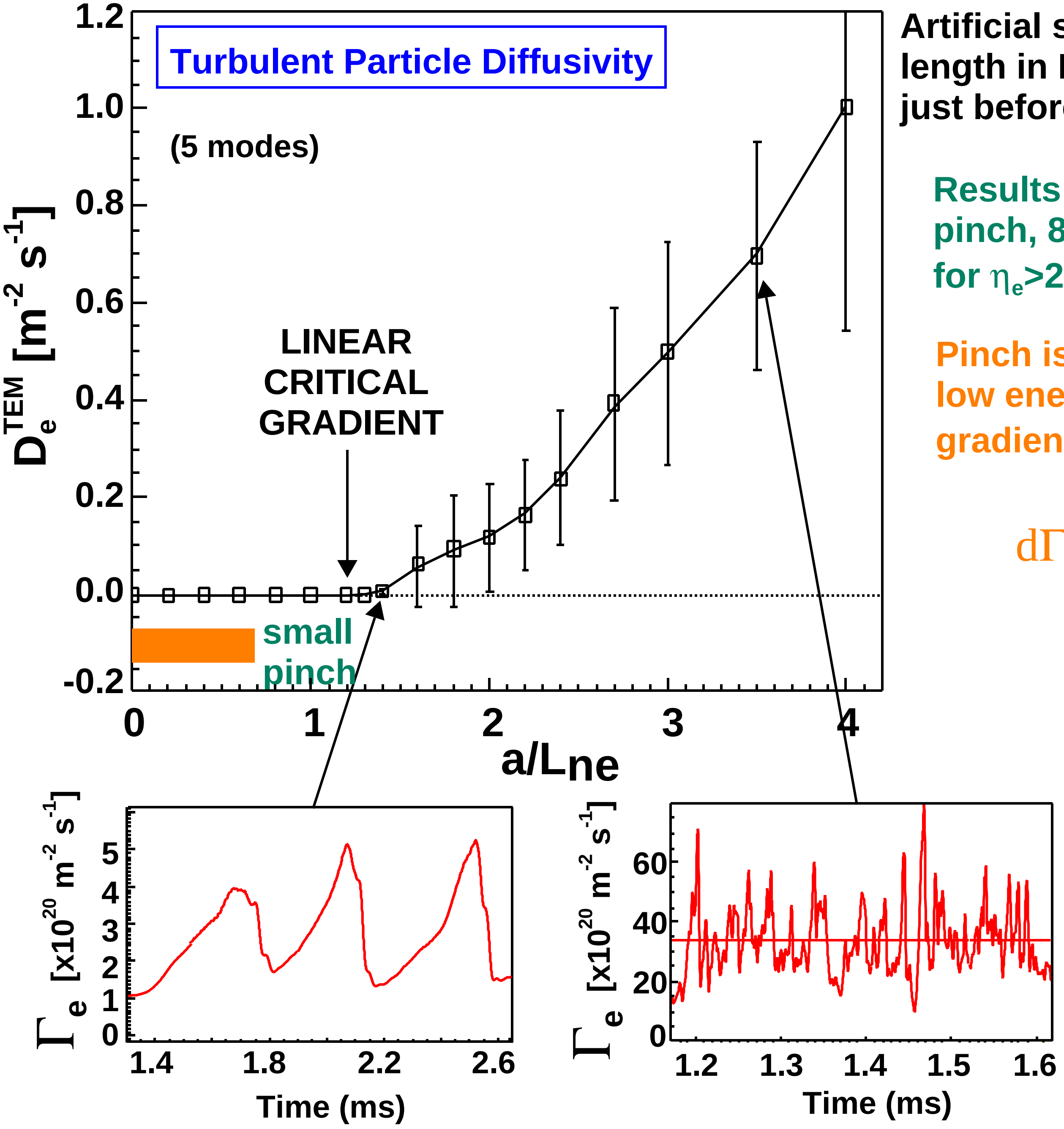
Gradients in ITB Initially Follow ITG Stability Boundary, Allowing Ware Pinch to Peak Density

- **Several hundred linear GS2 runs trace out stability boundaries (holding Z_{eff} = const.)**
- **Initially, ITB marginally stable to toroidal ITG modes (L→H 0.75-0.80 s)**
- **As L_n shortens (< 1 sec), "Trapped-Electron-ITG" modes weakly grow**
- **When pure TEM stability boundary is crossed, trajectory stagnates near**

  a/L_n~ 2.0



Nonlinear simulations show early pinch in ITB is negligible



Artificial scan of density gradient scale length in ITB, freezing all other parameters just before onset of central ICRH.

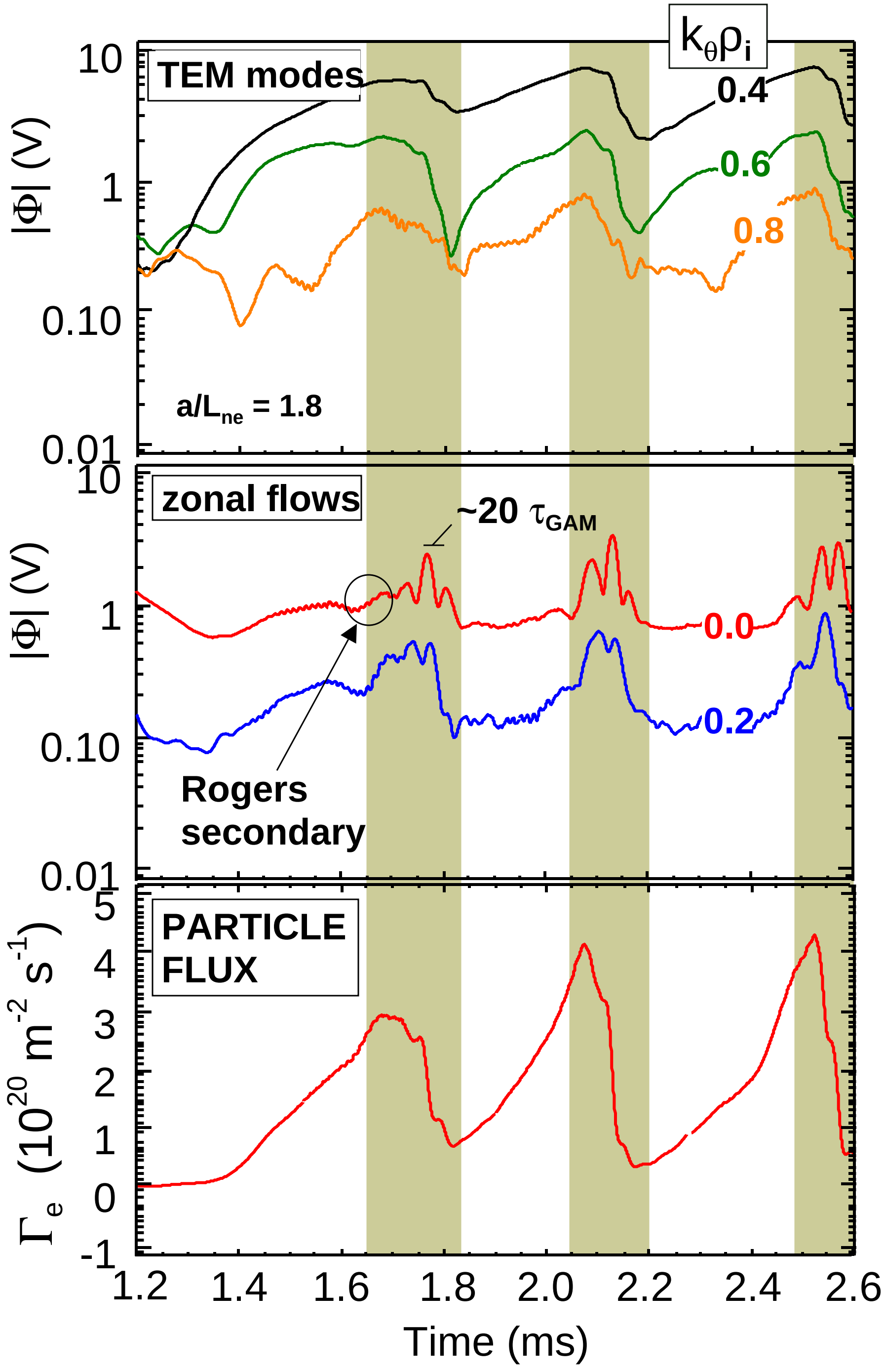
Results show small anomalous pinch, 80% due to circulating particles, for η_e>2 [K. Hallatschek, APS (2002)]

Pinch is essentially non-adiabatic, low energy electrons, subject to reversed gradient for η_e > 2:

$$d\Gamma \propto \frac{1}{L_n}(1-\eta_e/2)\frac{dv_\parallel}{v_\parallel}$$

Pinch significant in collisionless cases, but collisions should kill it here.

Flux Near Marginal Stability Characterized by Explosive Zonal Flow Bursts



- **Zonal flows initially driven by Reynolds stress until K-H parasitic instabilities develop with explosive growth rates (Rogers secondaries)**

[Rogers, Dorland, Hammett, PRL (2000)].

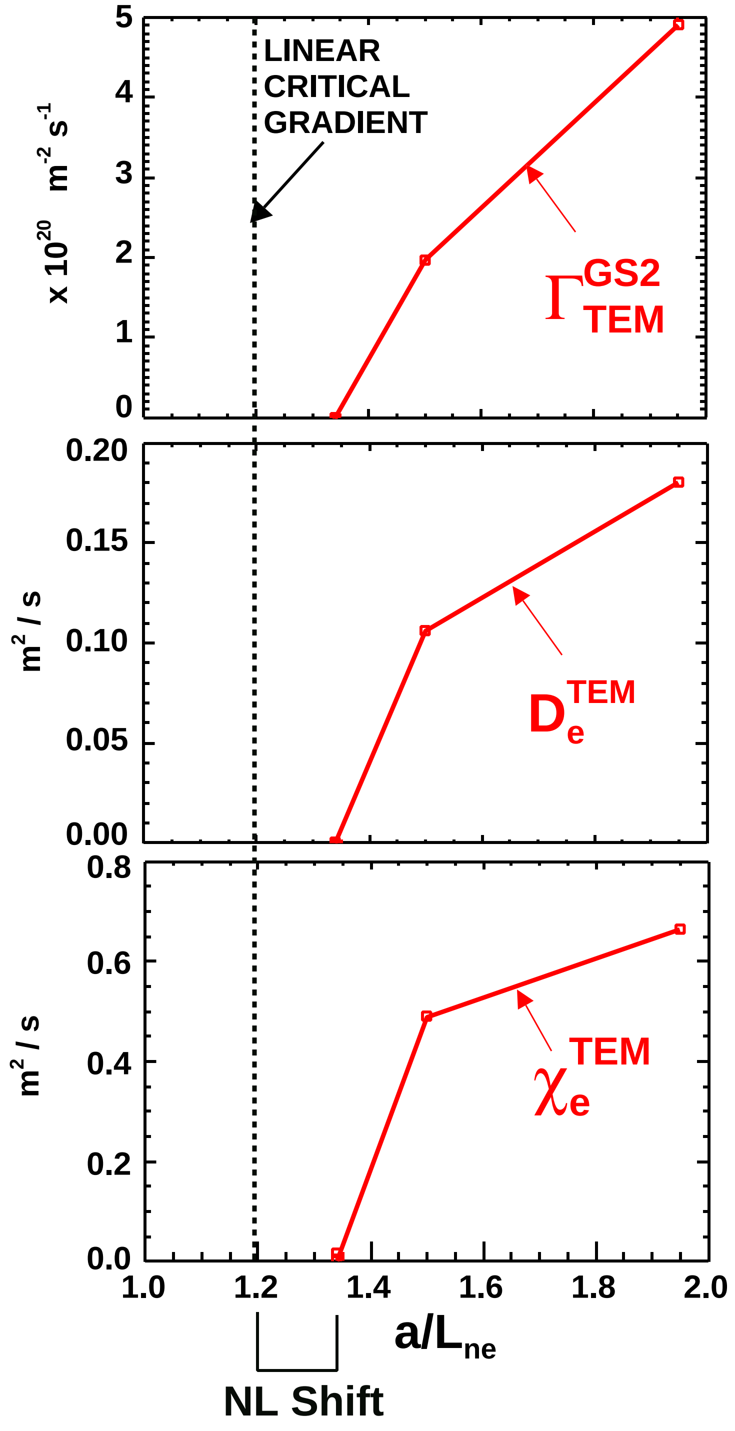
$$\gamma_{ZF} \propto |\Phi|_{TEM}$$

$$|\Phi|_{ZF} \propto \exp\left[e^{\gamma_{TEM} t}\right]$$

- **Following explosive growth of zonal flows, primary modes are stabilized and then re-grow**

- **Details of zonal flow dynamics with non-adiabatic electrons under current investigation**

New Nonlinear Upshift of TEM Critical Density Gradient



- **"High" resolution simulations at 1.20 sec, ρ=0.4 in ITB**

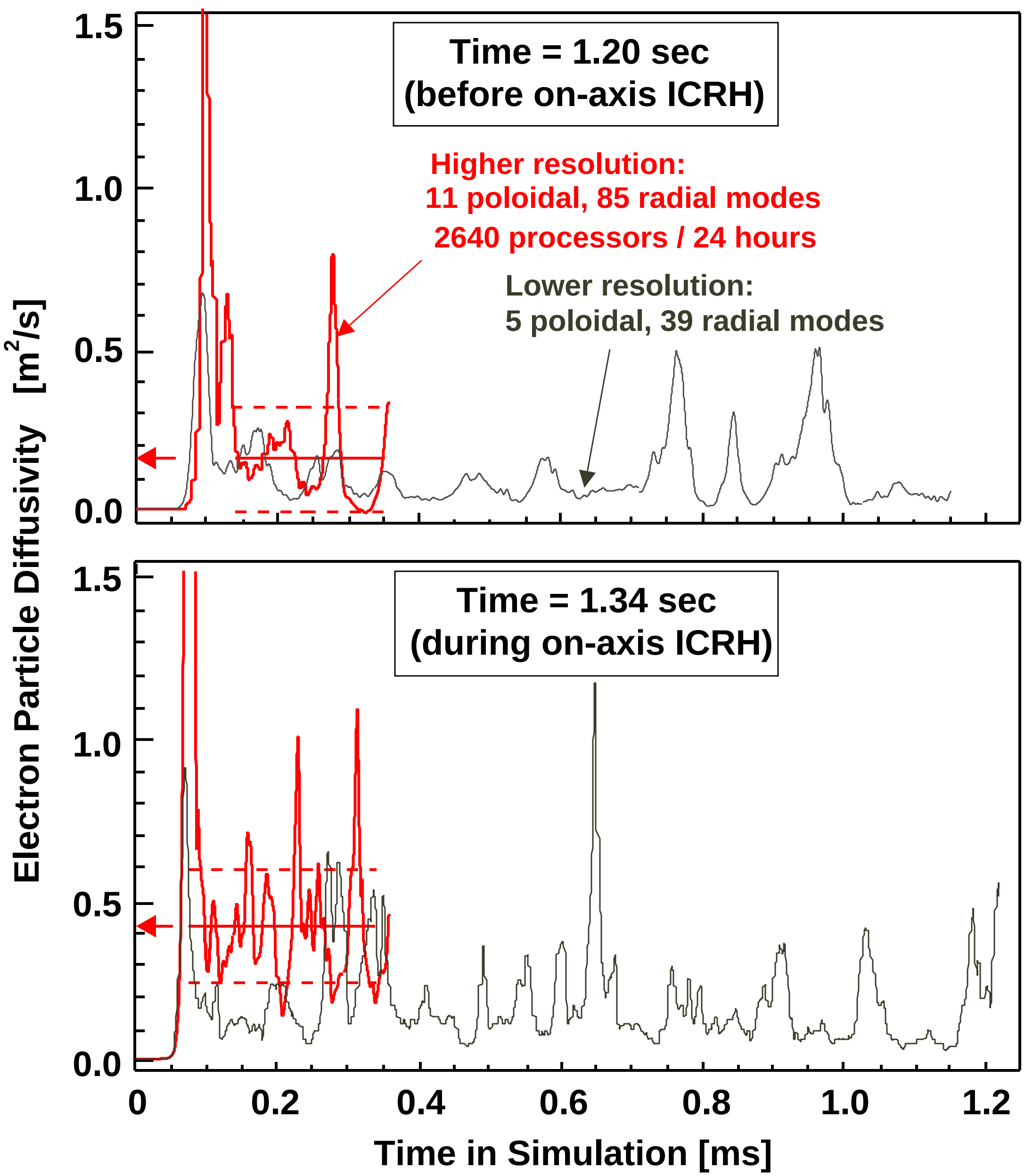
  11 poloidal modes
  85 radial modes

- **Analagous to Dimits shift of critical ion temperature gradient for toroidal ITG turbulence [A. M. Dimits *et al.*, PoP (2000)].**

- **Appears to result from being in a parameter regime where zonal flows are stable and undamped by collisions [Rogers, Dorland, Hammett, PRL (2000)].**

- **Shift persists with strong ion-ion collisions (as shown with ν_{*e} ~ 0.8)**

Nonlinear Gyrokinetic Simulations Using GS2 Show Increase in Particle Diffusivity During Central ICRH



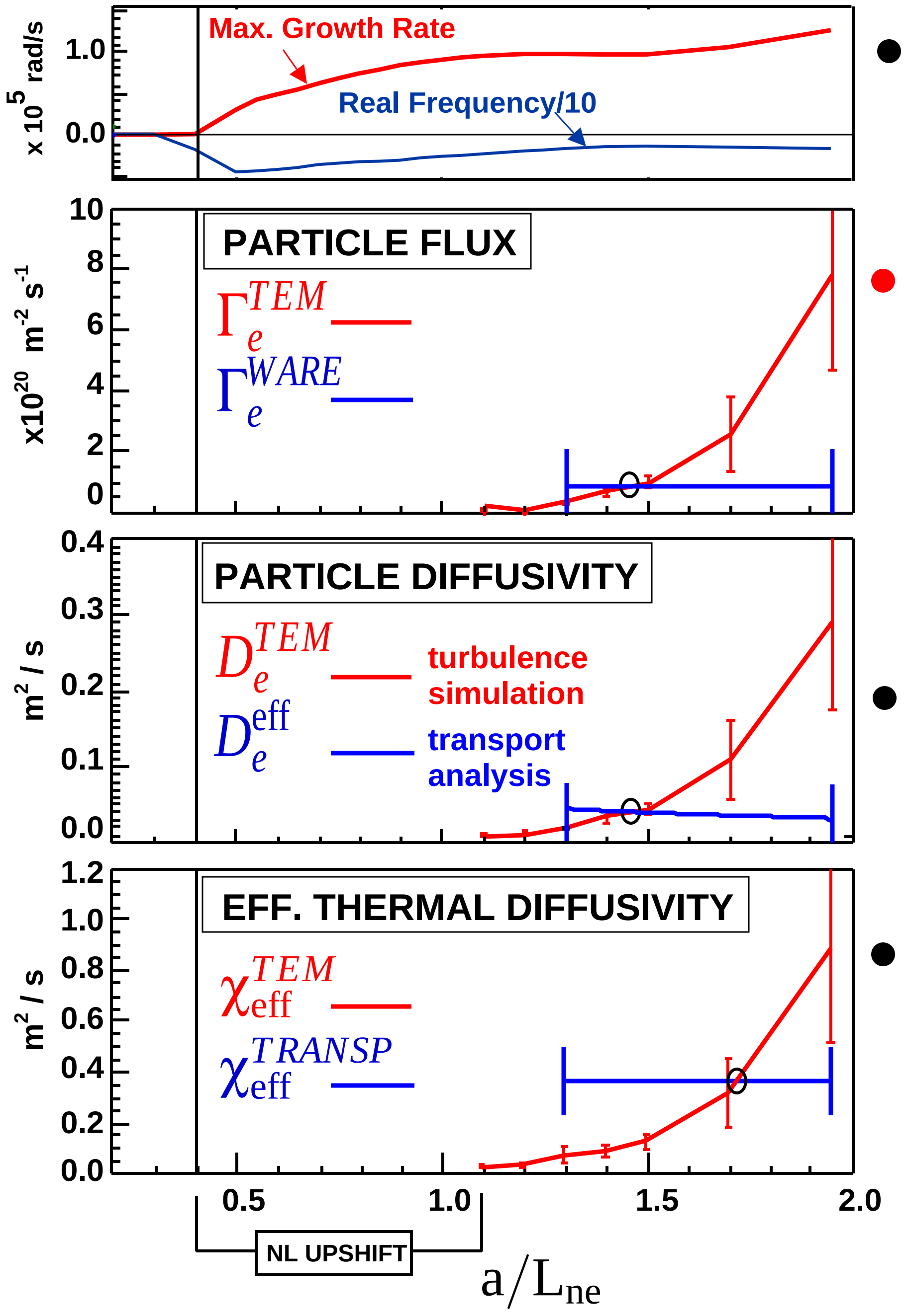
- TEM simulations require extended $k_y\rho_i$ spectrum, and weak shear causes extension along field line

$$k_x = \hat{s}\theta k_y$$

- Poloidal extension requires very high radial resolution
- Closer to marginal stability at 1.20 sec: bursty transport
- Long run shows no drift in average

Converged 11 mode run shows diffusivity doubles with central heating on.

Gyrokinetic Turbulence Simulations Reproduce Inferred Particle/Heat Transport in C-Mod ITB



- Nonlinear GS2 simulations at 1.20 sec, preceding on-axis ICRH

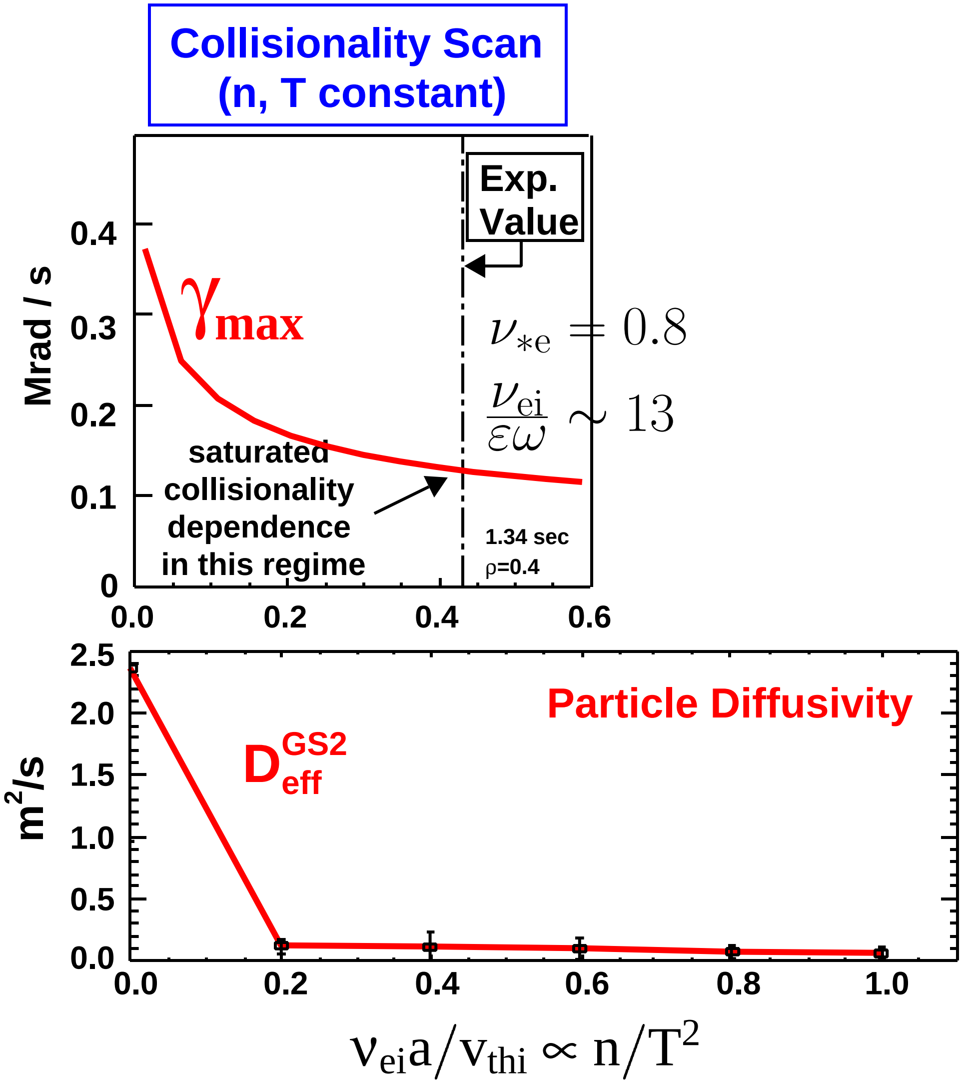
- Scan density and Z_{eff} scale lengths, subject to constraint:
  - $n_e Z_{eff}^{1/2}$ scale length fixed by measurement
  - Z_{eff} = const.

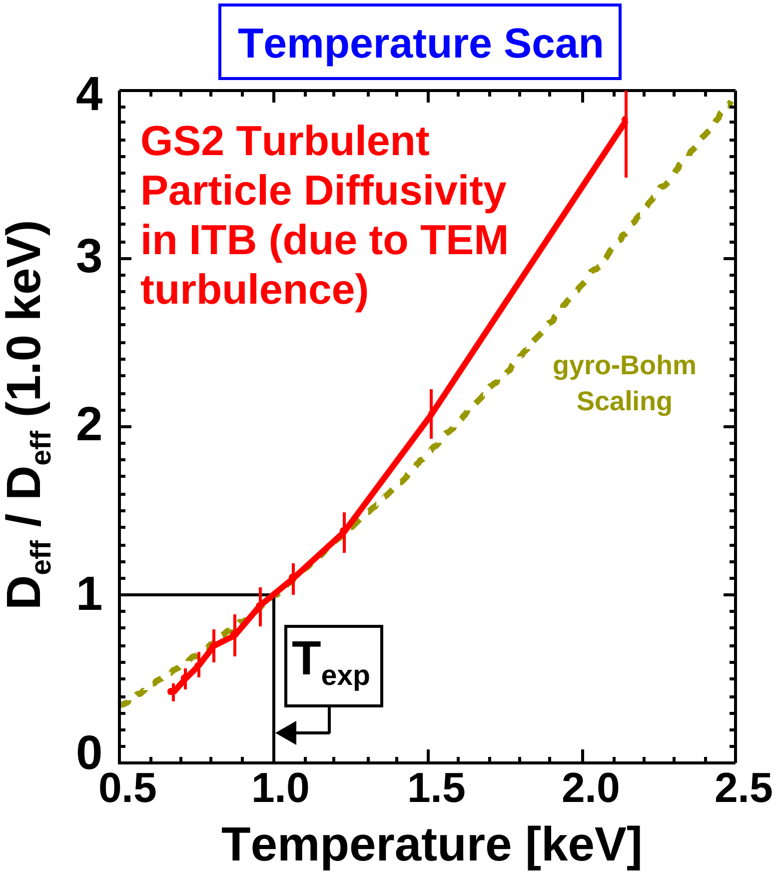
- Error bars on density gradient from uncertainty in Z_{eff} gradient

- New nonlinear upshift in TEM critical density gradient due to zonal flows

Gyro-Bohm Scaling Dominates Temperature Dependence of TEM Turbulent Transport in this Parameter Range

- **Central heating increases TEM driven flux through temperature.**
- **GS2 is flux-tube (radially local) ⇨ gyroBohm scaling.**
- **ρ_* =1/188 in C-Mod: local should be ok.** **[Candy, Waltz, Dorland, Phys. Plasmas (2004)]**





$$\boxed{D_{eff}^{TEM} \propto T^{3/2}}$$

Collisionality effects subdominant.

Conclusions

- **Ware pinch sufficient to account for C-Mod density peaking, and anomalous pinch is negligible**

- **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 agree with experiment**

- **On-axis heating increases temperature, increasing TEM particle flux consistent with gyrobohm scaling**

- **At same time, Ware pinch decreases with temperature**

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

- **Along the way, uncovered new nonlinear upshift of TEM critical density gradient**

For details, see D. R. Ernst et al., Phys. Plasmas, May (2004) Special Issue.