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# Identification of TEM Turbulence through Direct Comparison of Nonlinear Gyrokinetic Simulations with Phase Contrast Imaging Density Fluctuation Measurements

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Alcator C-Mod

# Outline

**Introduction**

- C-Mod ITB: Control with on-axis ICRH
- Previous work on role of TEM

**Stability Analysis**

- Including classical collisional diffusion in GS2
- Effect of on-axis ICRH

**Fluctuations and Nonlinear GS2 Simulations**

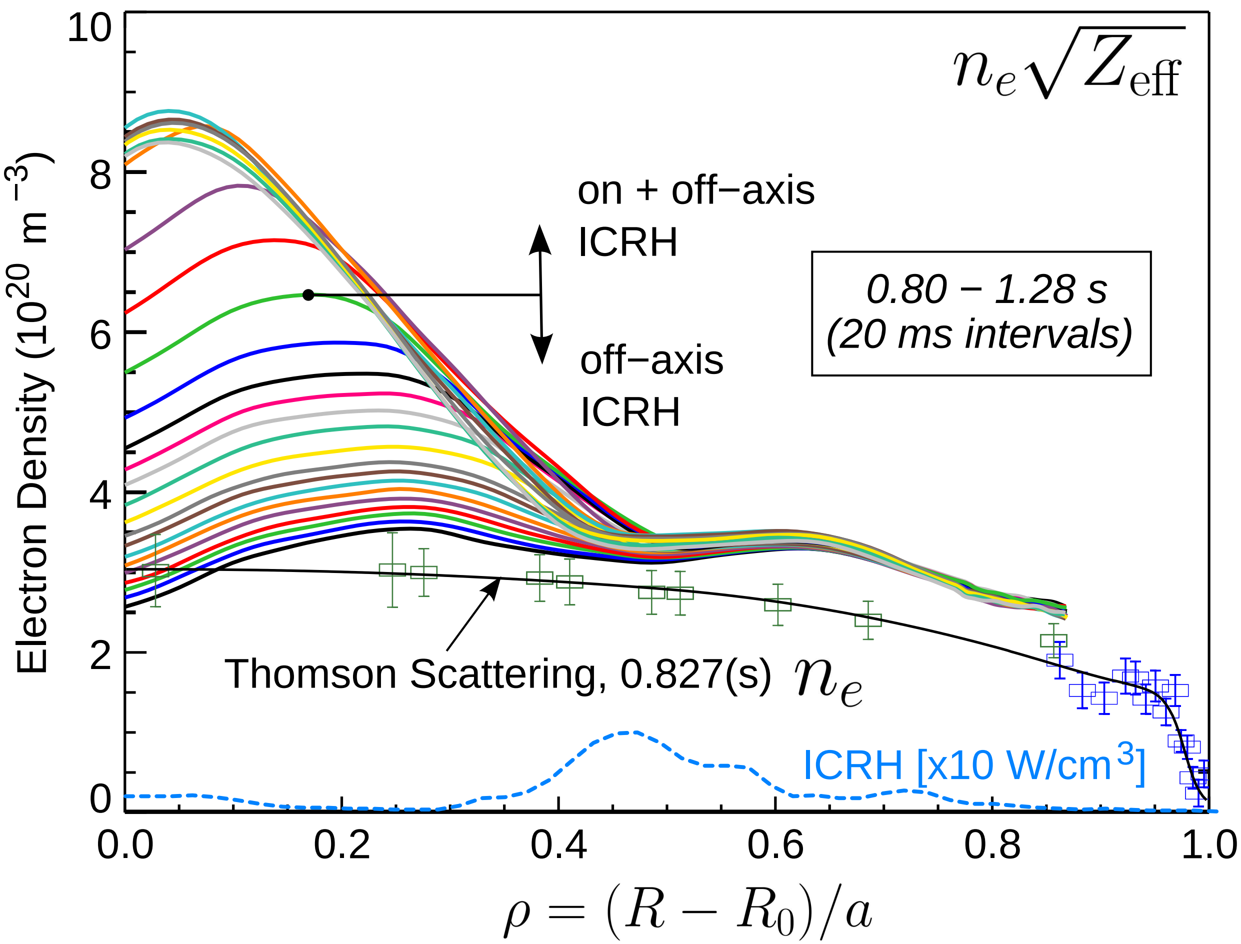
- Phase Contrast Imaging
- Increase in density fluctuation level with on-axis ICRH
- Comparison of wavelength spectra: TEM

**Nonlinear Upshift of TEM Threshold**

- Favorable collisionality dependence
- Role of secondaries

**Conclusions**

# C-Mod ITB formed with off-axis ICRH, controlled with on-axis ICRH




- CCD-based visible Bremsstrahlung:
  - $\Delta R \sim 1$ mm
  - sampled $>1$ kHz
- Densities $> 10^{21}$ m$^{-3}$
- Temperatures $T_i \simeq T_e \sim$const.
- Peaking over tens of $\tau_E$

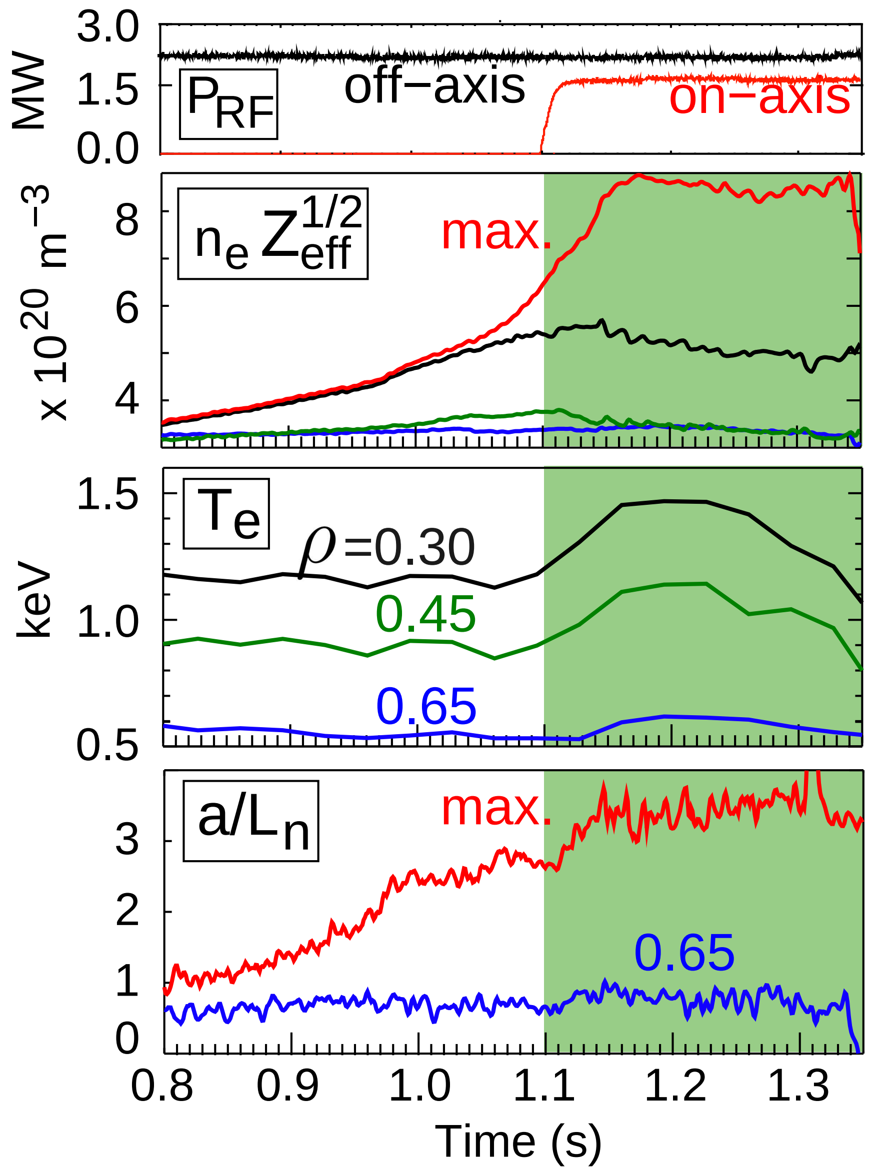
- Off-axis heating broadens temperature, reducing ITG drive
- Ware pinch peaks density (further suppressing ITG)
- Peaking continues until density gradient clamped by TEM

# On-axis heating increases temperature, halting density rise

- Full available source power utilized to form and maintain ITB
- $T_e$ increases 40% with on-axis ICRH
- Density rise halts after $T_e$ increase
- TEM driving factor,

$$\frac{a}{L_n} = -\frac{1}{n}\frac{dn}{d\rho},$$

reaches large values



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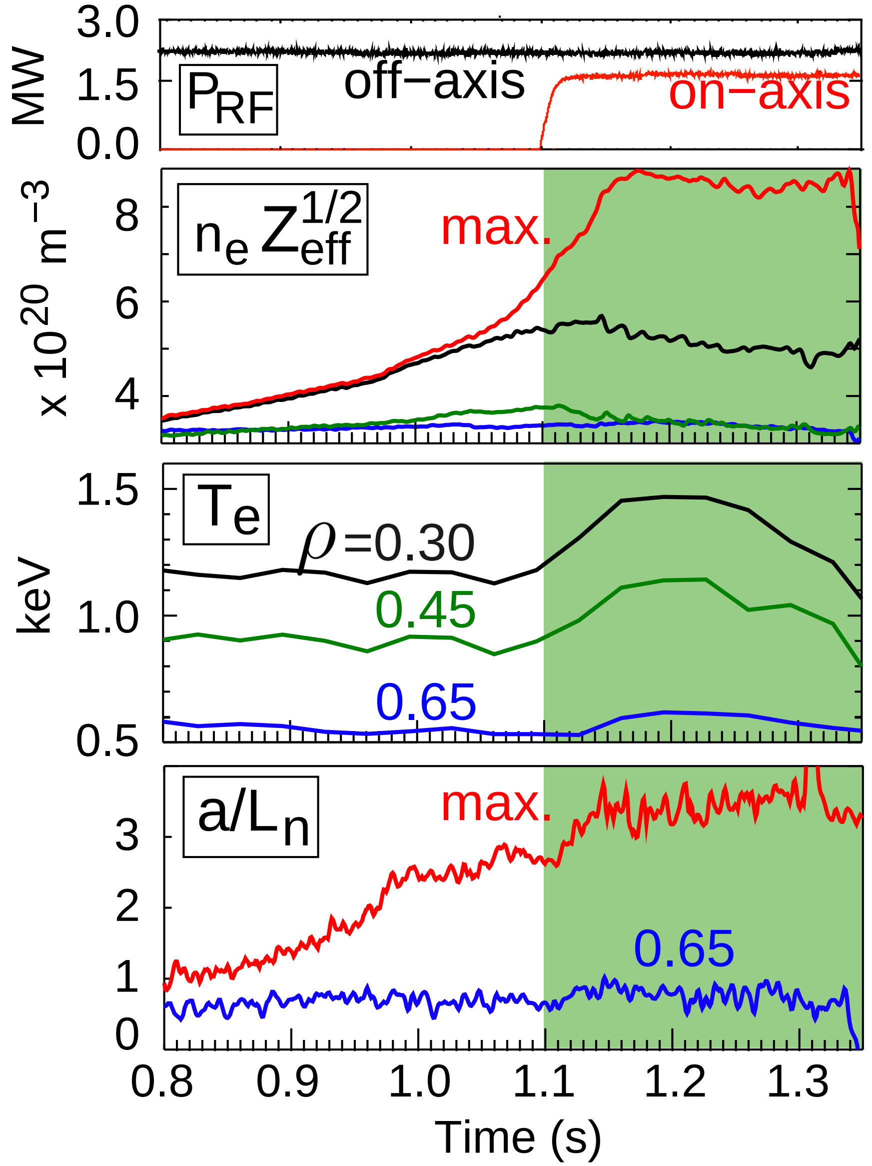
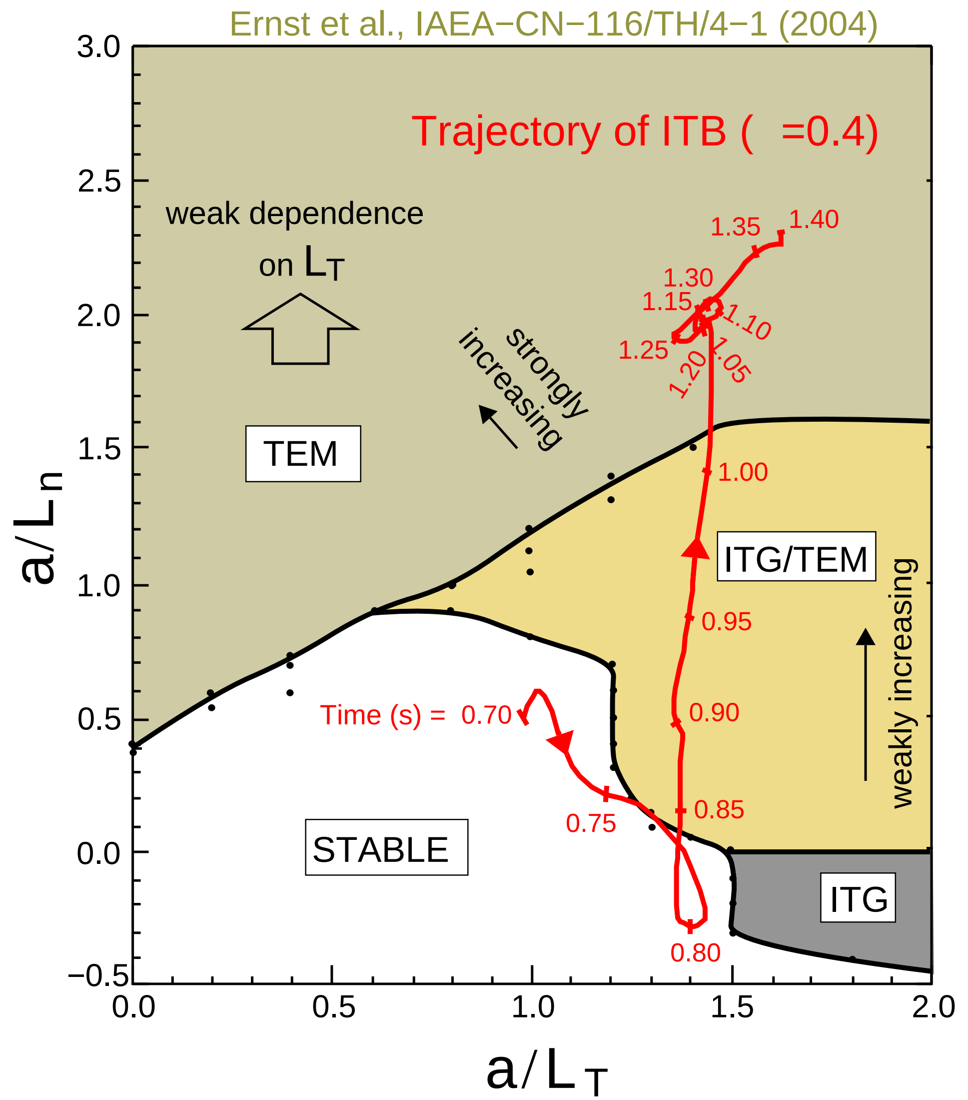


# Previous work explored role of TEM in control of ITB with on-axis heating




- Trajectory of ITB stagnates upon crossing TEM stability boundary
- Ware pinch balanced by TEM outflow
- Nonlinear GS2 simulations match measured fluxes
- Gyro-Bohm scaling of TEM transport
  - $T_e^{3/2}$ controls TEM flux
  - Collisionality dependence saturated

[Phys. Plasmas (2004) 2637]

- Limiting value of $a/L_n$ controlled by $T_e$ (on-axis ICRH)

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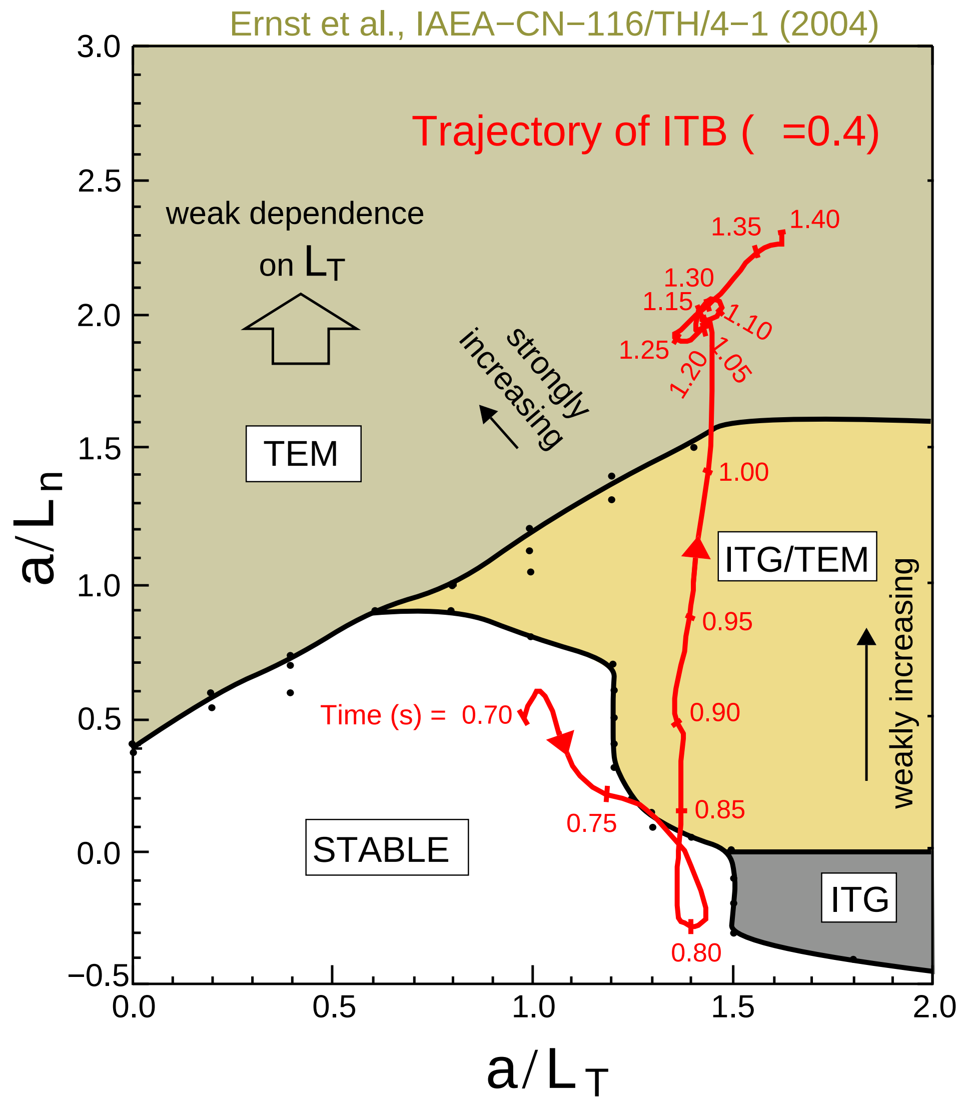


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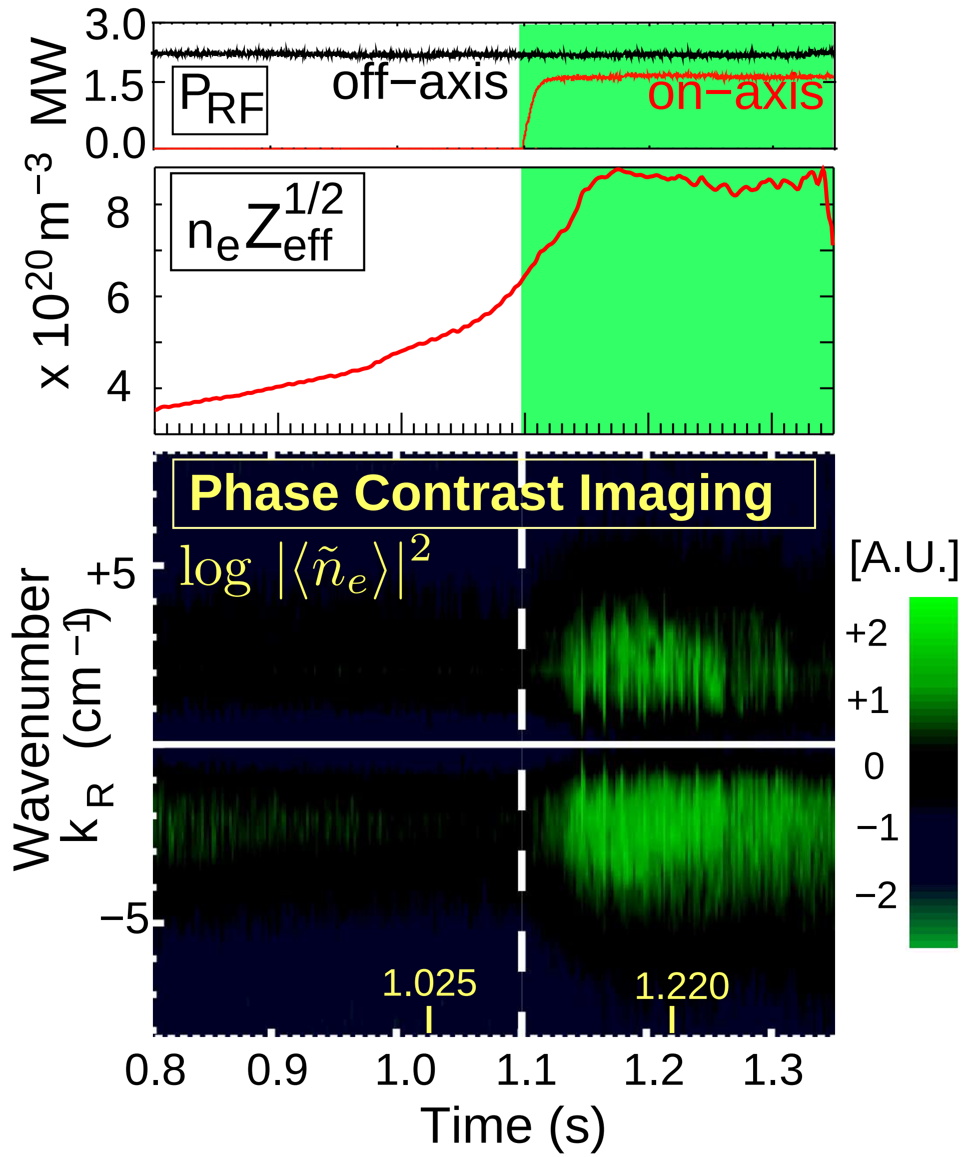
# Strong density fluctuations observed during on-axis heating




- Phase Contrast Imaging (PCI) measures line-integrated density fluctuations
- Wavenumber $k_R$ in major radius direction
- Onset of strong turbulence in the range $1 \lesssim k_R \lesssim 5$ $cm^{-1}$
- Is this TEM turbulence?
- Begin with stability analysis at two times shown ...

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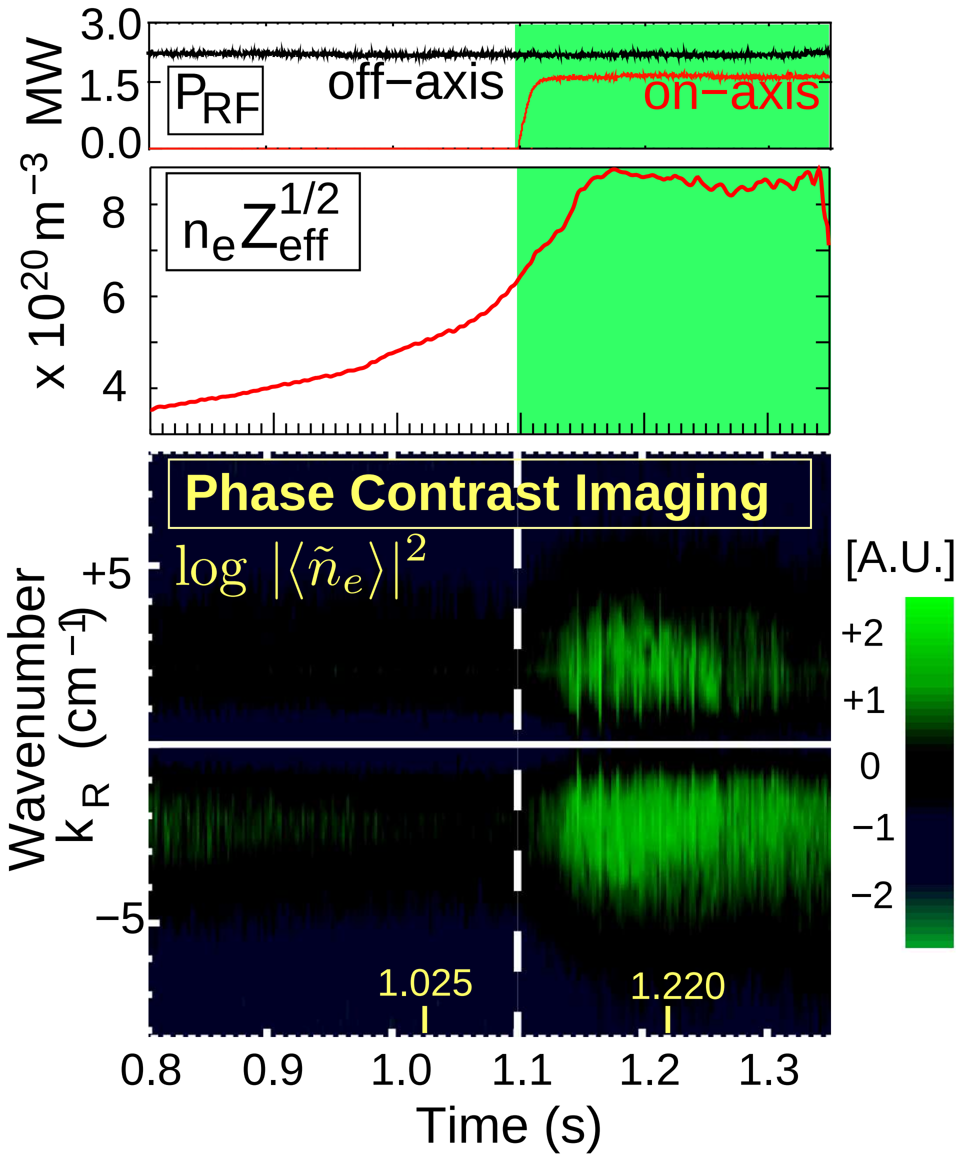


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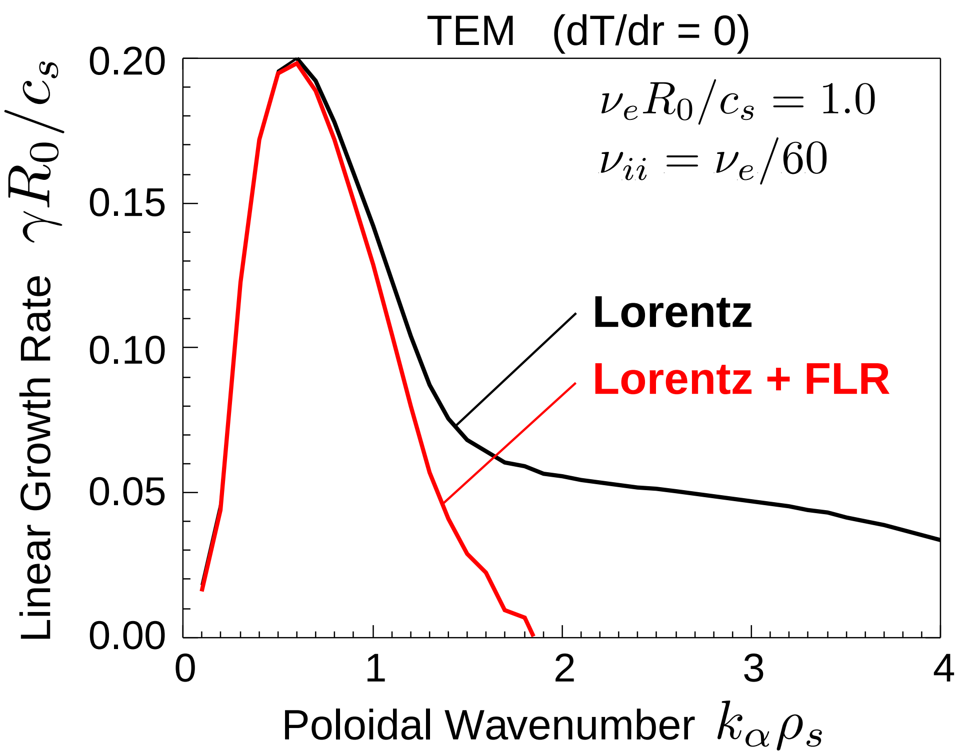
# Classical collisional diffusion damps shorter wavelength TEMs

$$\left\langle e^{i\mathbf{k}\cdot\rho}\left[\mathcal{C}(he^{-i\mathbf{k}\cdot\rho})\right]\right\rangle = \mathcal{C}_{\mathrm{Lorentz}}(h) + (k_\perp^2\rho_i^2)\,\mathcal{F}(v^2, v_\parallel/v)\,h$$

[GK Collision Operator: Catto & Tsang, Phys. Fluids (1977)]




- Implemented FLR terms in GS2
  - "FLR Krook" operator
  - Augments usual GS2 Lorentz
  - Conserving terms implemented
- Damps TEM for $k_\theta \rho_i > 2$, for C-Mod collisionalities

- TEMs extended along field lines, with higher $k_\theta = nq/r$: $k_\perp^2 = k_\theta^2(1 + \hat{s}^2(\theta-\theta_0)^2)$ damps tails of eigenfunction $\phi(\theta)$
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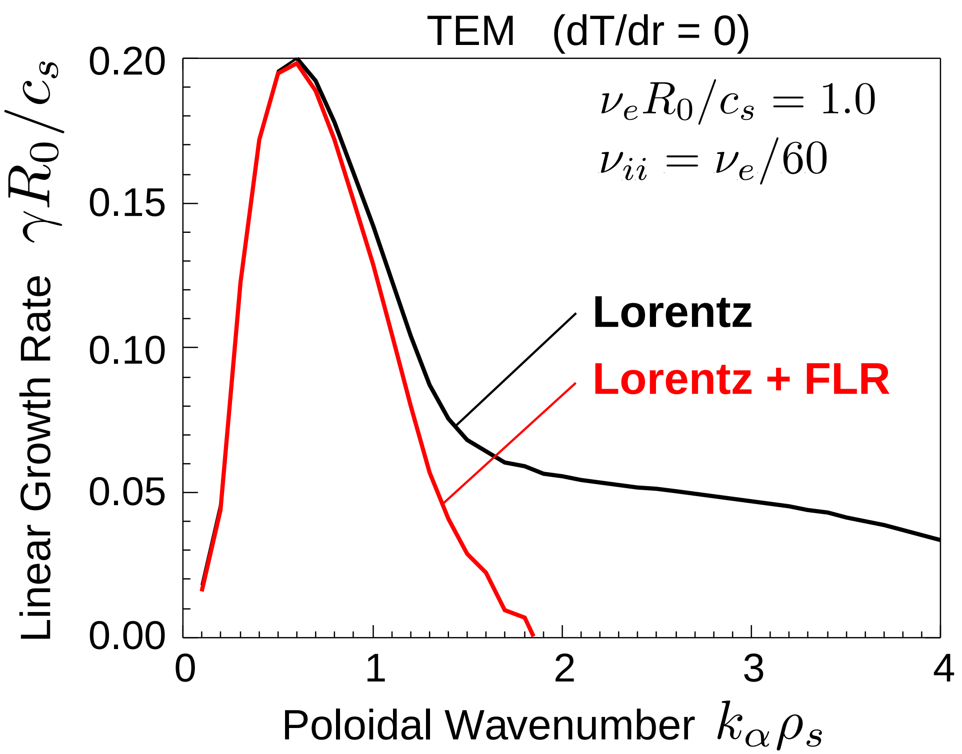


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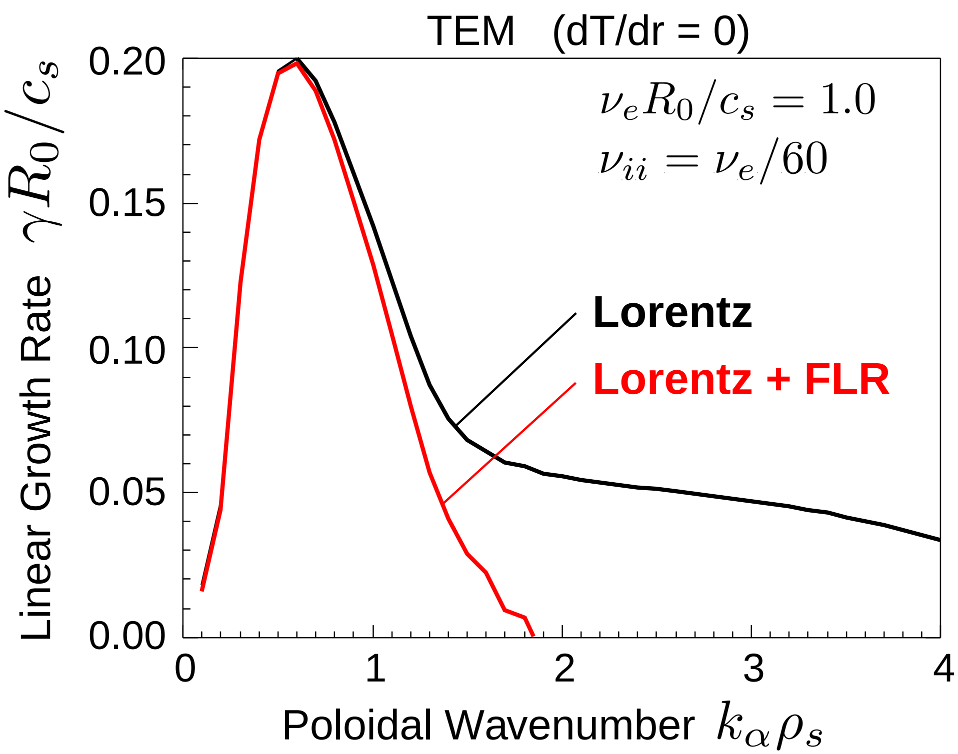


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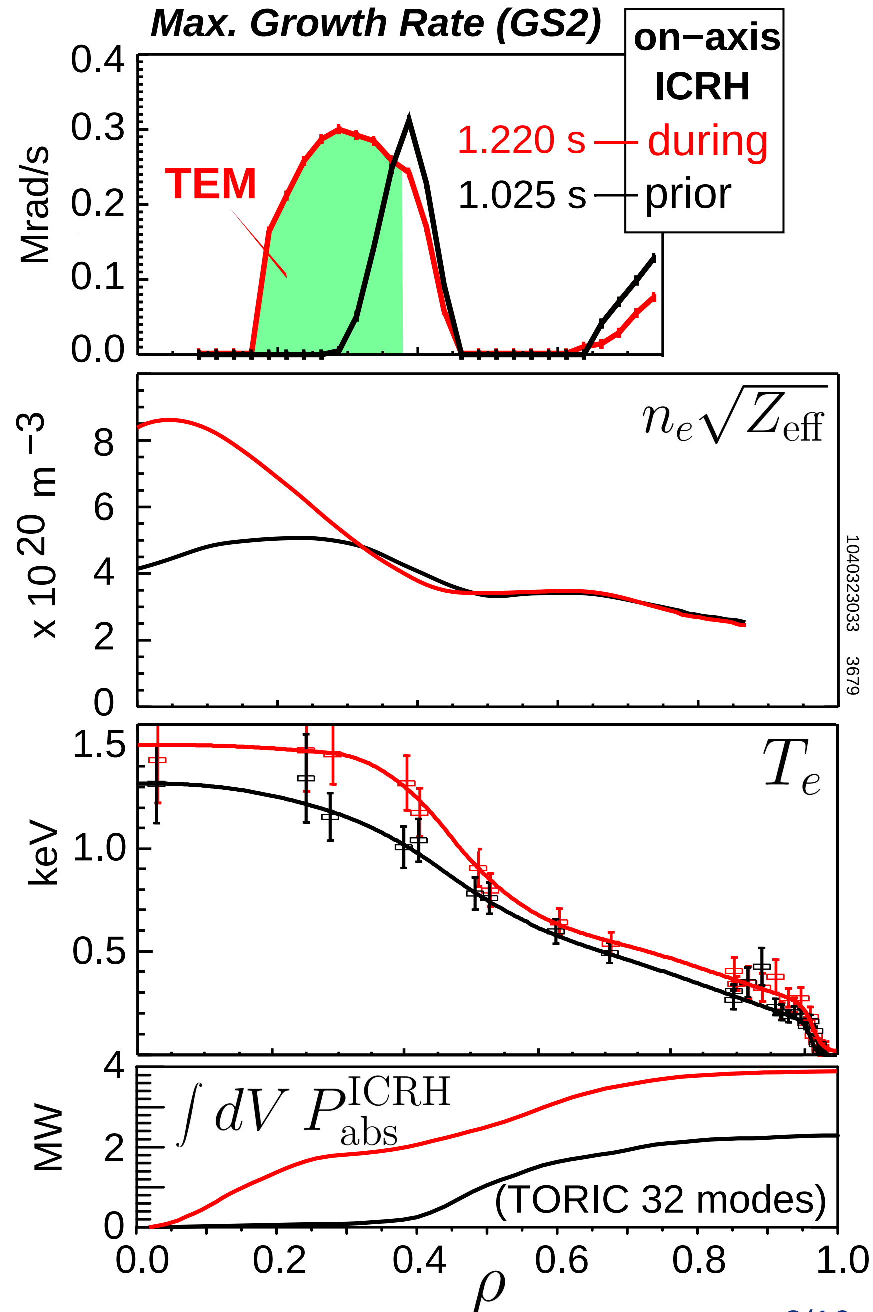
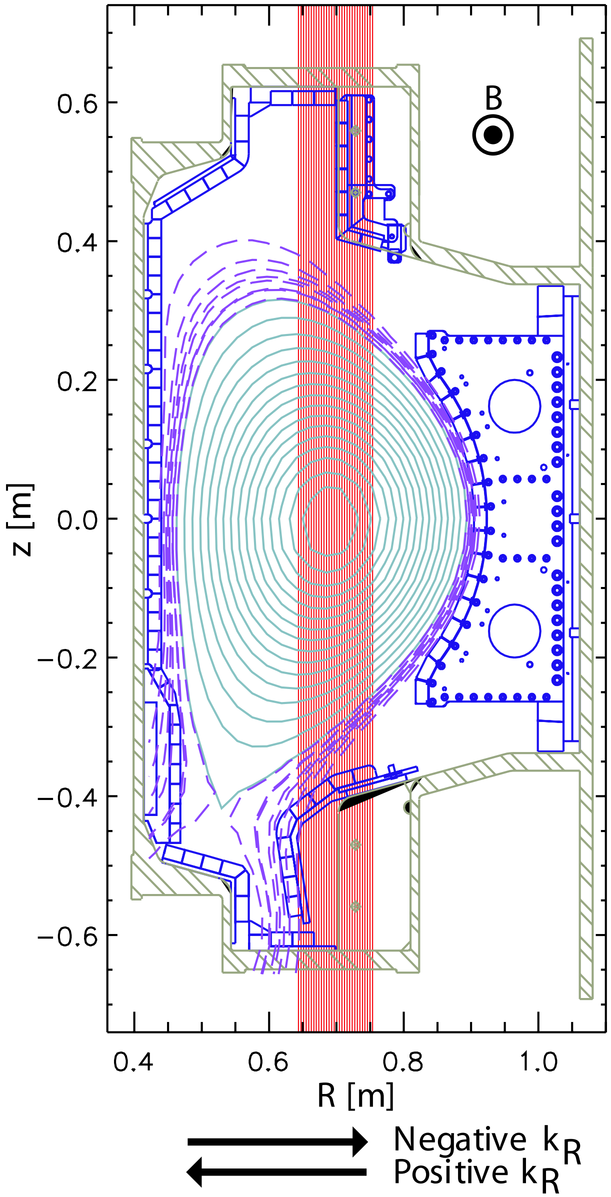
# On-axis heating increases temperature, destabilizing TEM inside ITB foot

- Gyrokinetic stability analysis before/during on-axis heating
- Before on-axis heating:
  - Toroidal ITG modes dominant
- During on-axis heating:
  - Strong TEM for $\rho < 0.4$
  - Density gradient driven
  - Little change for $\rho > 0.4$
- ITB used to localize chordal PCI measurement



# Phase Contrast Imaging




- Electron density fluctuations along 32 vertical chords ⇨ (f, $k_R$ ) spectra
- Phase plate shifts scattered beam, recombined with reference beam on detector

Wave number range

$0.5\ cm^{-1} < |k_R| < 8.3\ cm^{-1}$

Frequency Range

2 kHz ~ 5 MHz

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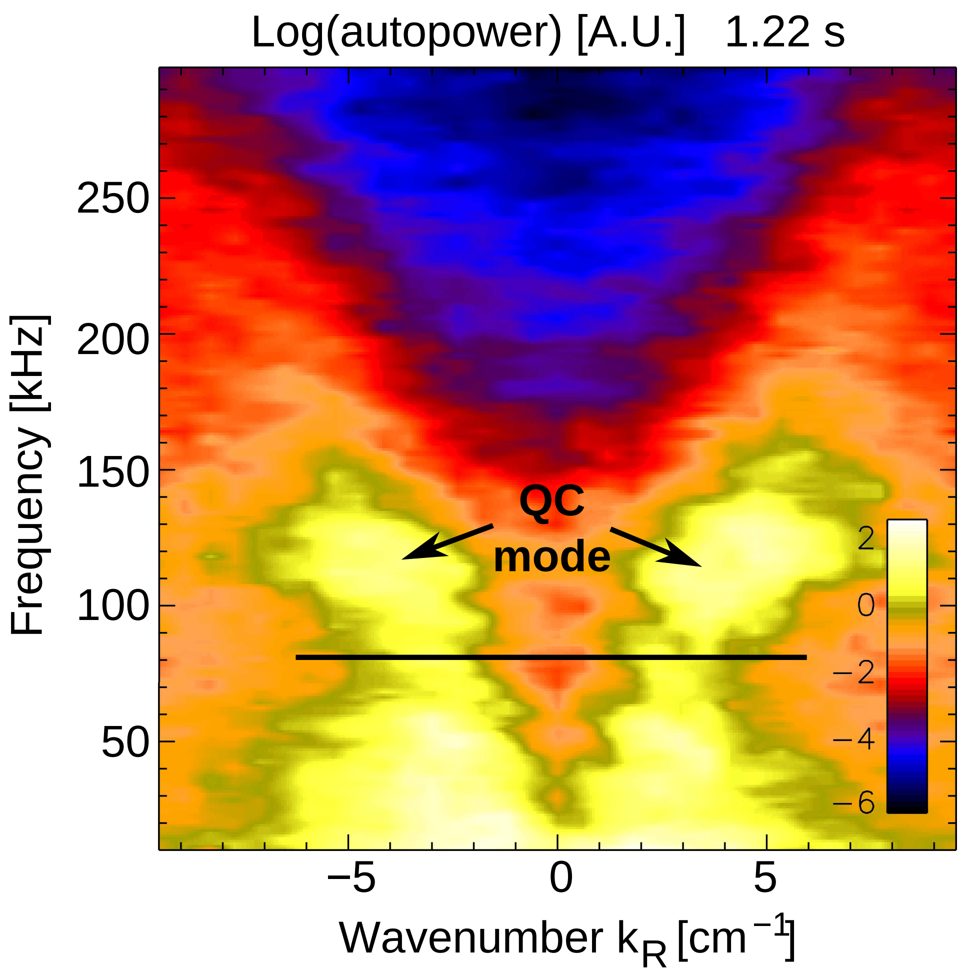
M. Porkolab et al., IEEE Trans. in Plasma Sci. **34** (2006) 229.

# Filtering the edge Quasi-Coherent Mode




QC Mode on PCI:

A. Mazurenko *et al.*, Phys. Rev. Lett. **89** (2002) 225004.

- QC mode regulates EDA H-Mode pedestal gradients
- QC <20% contribution to total fluctuation power (this case)
- Wavenumber spectrum insensitive to
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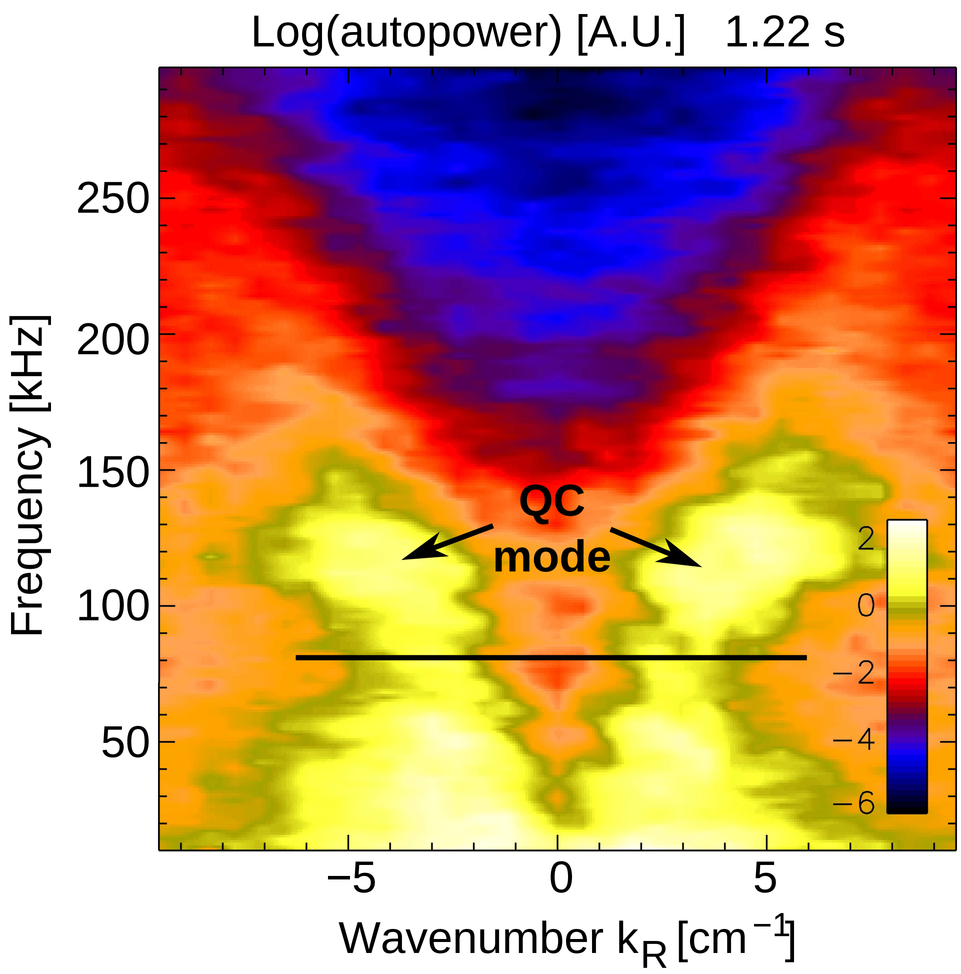


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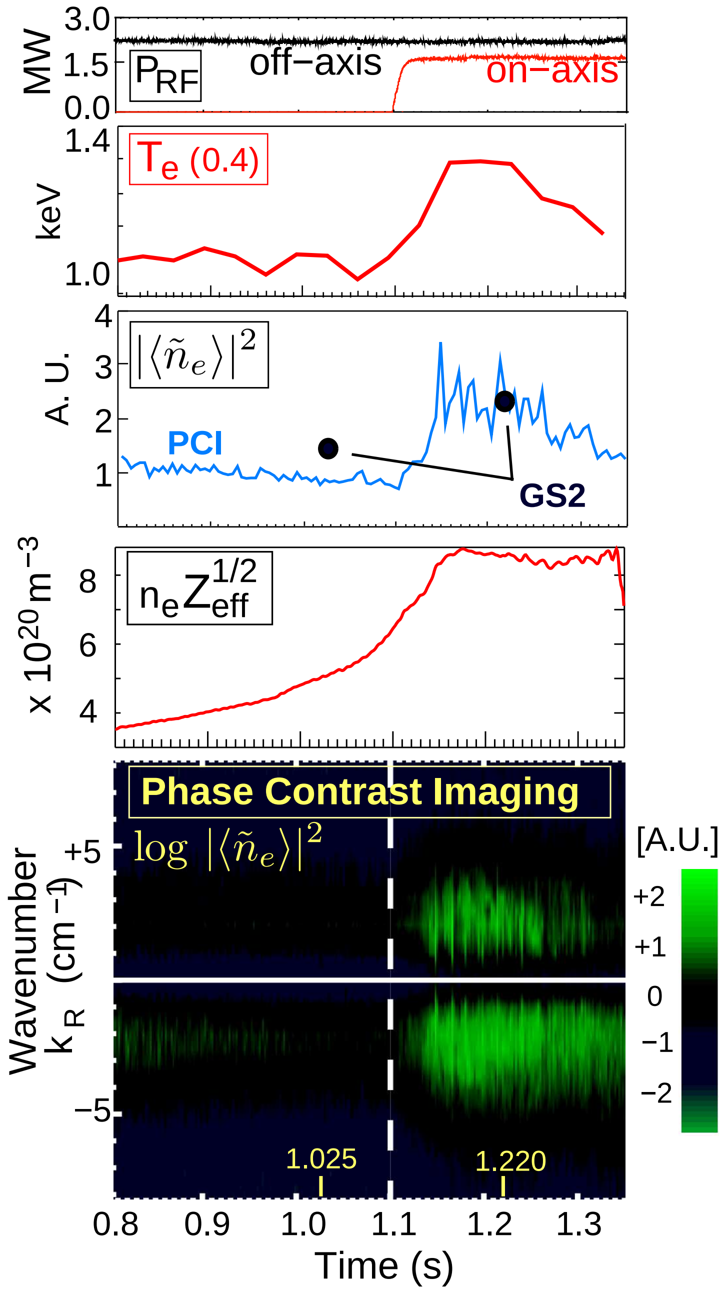
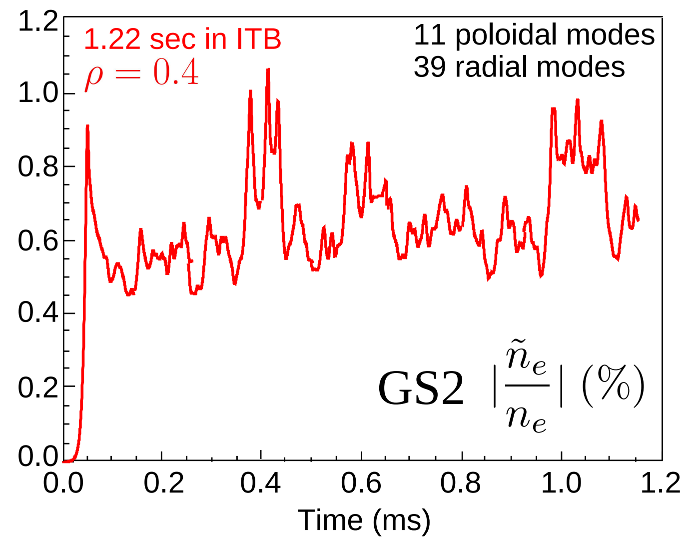
# Nonlinear GS2 simulations reproduce relative increase in density fluctuation level




- On-axis heating drives TEM unstable
- GS2 nonlinear simulations before/during on-axis ICRH
- Normalized to later time



# Synthetic PCI Diagnostic for GS2

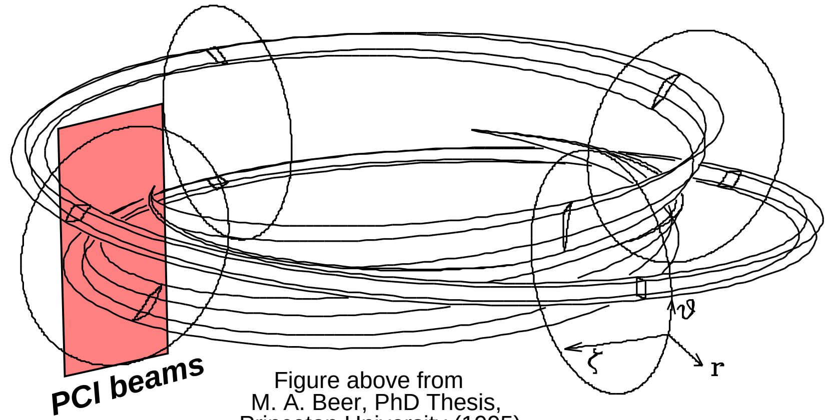
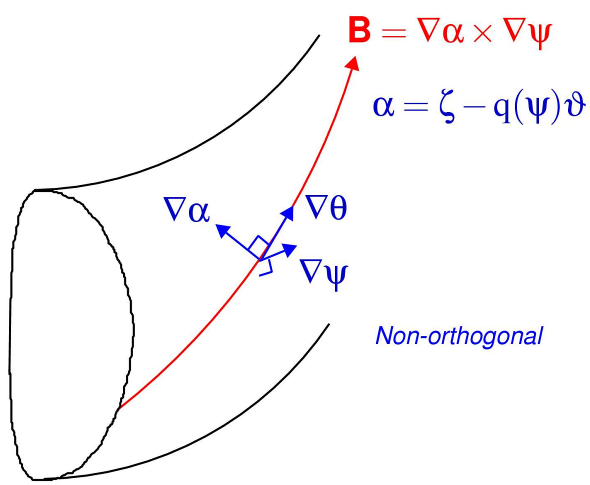
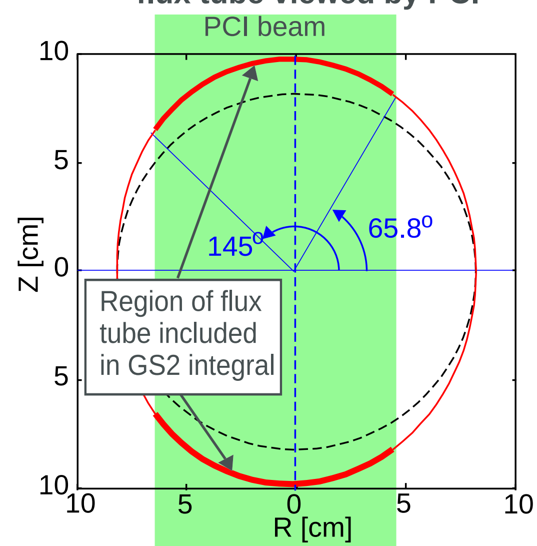



Figure above from
M. A. Beer, PhD Thesis,
Princeton University (1995).



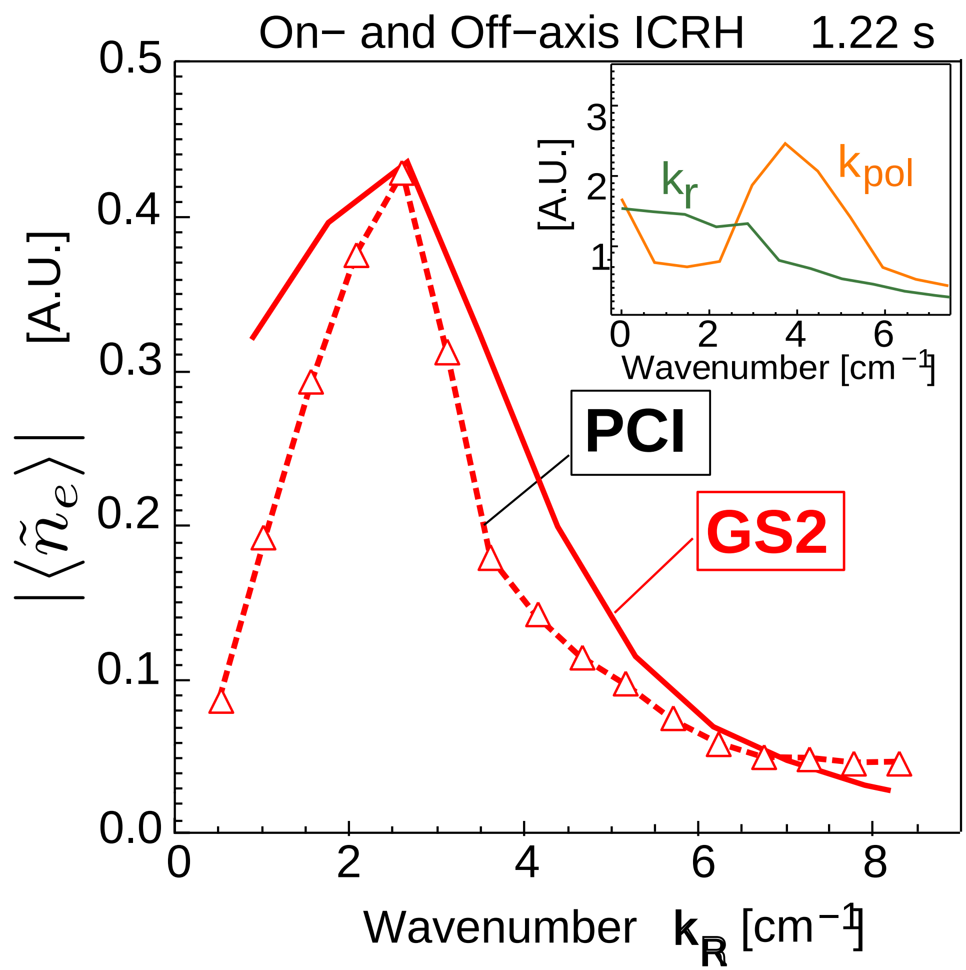

**Integration over parts of flux tube viewed by PCI**




**(Poloidal Projection)**

- Transform $k_R = (\nabla R \cdot \nabla\psi/|\nabla\psi|)k_\psi + (\nabla R \cdot \nabla\alpha/|\nabla\alpha|)k_\alpha$
- Integrate along GS2 flux tube over poloidal angles covered by PCI.
- Apply instrument function to account for Gaussian beam, finite aperture, reference beam at $k_R \simeq 0$

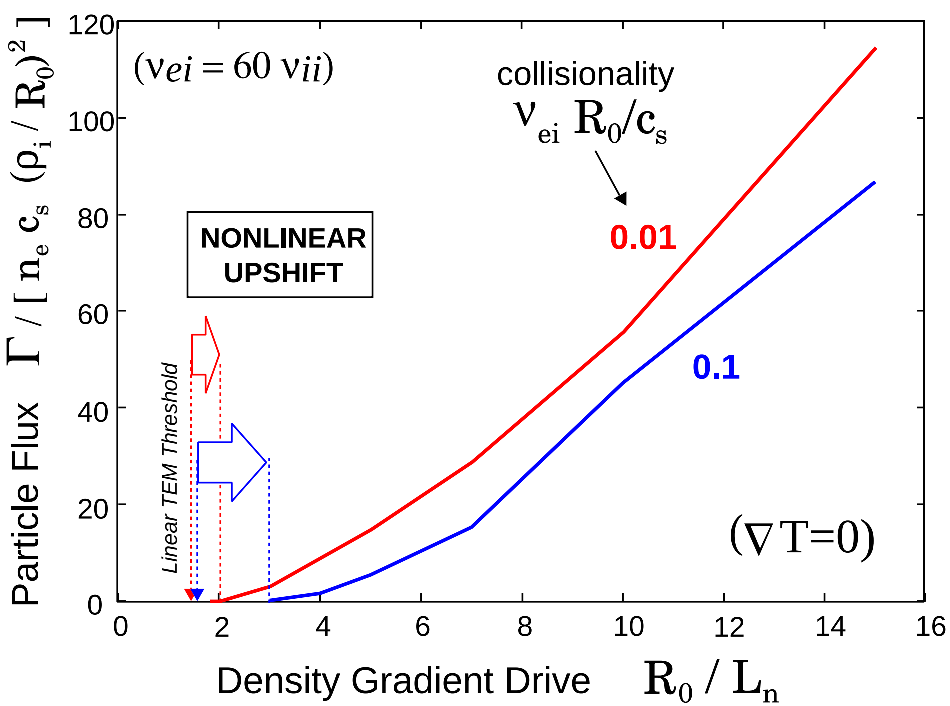
# Nonlinear gyrokinetic simulations reproduce measured wavelength spectrum of TEM density fluctuations in the ITB



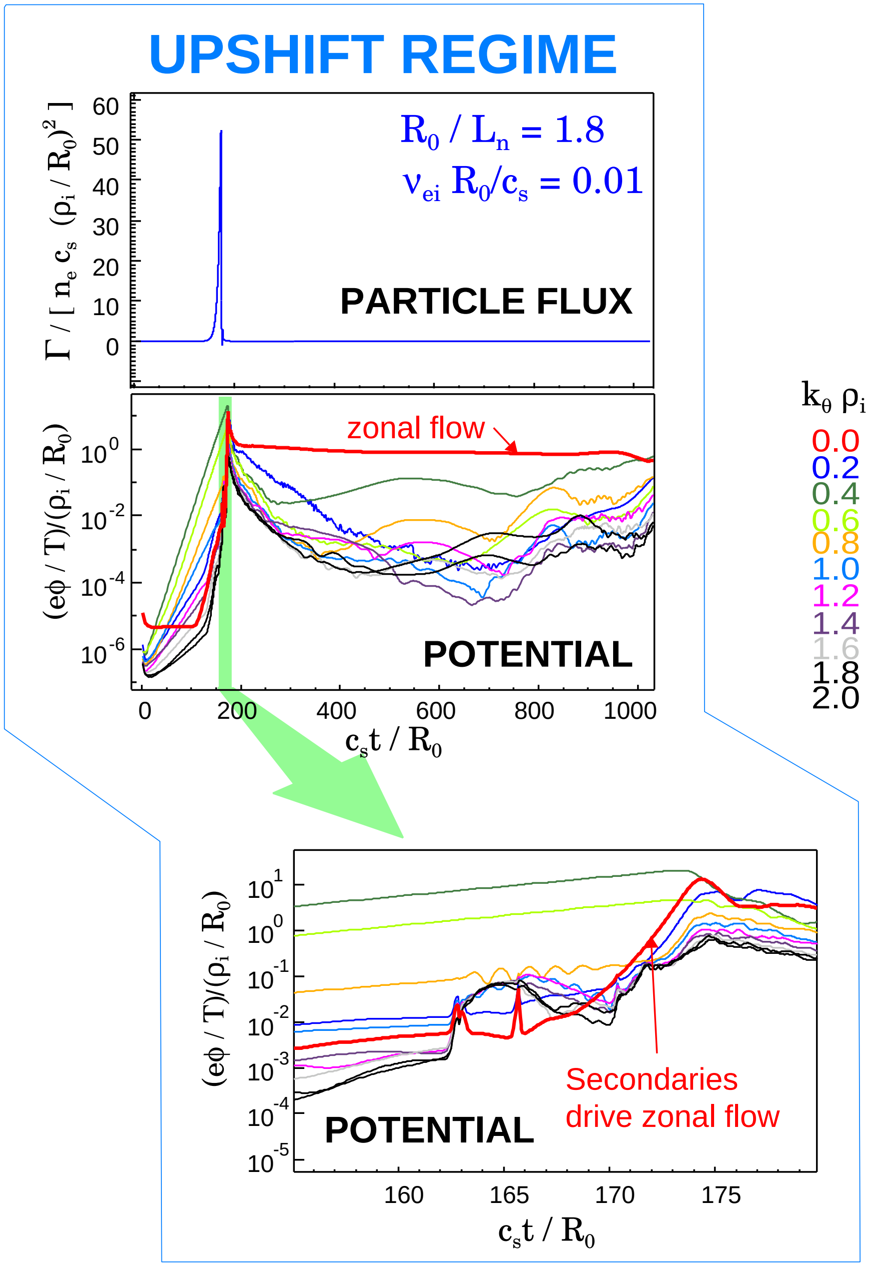

- GS2 with new synthetic PCI diagnostic
- Shape of $k_R$ spectrum reproduced
- Wavelength of peak in very close agreement
  - Linear combination of poloidal and radial spectra
  - Radial spectrum provides necessary 1 cm$^{-1}$ downshift
  - GS2 spectrum slightly more broad than PCI
- Observation of TEM turbulence

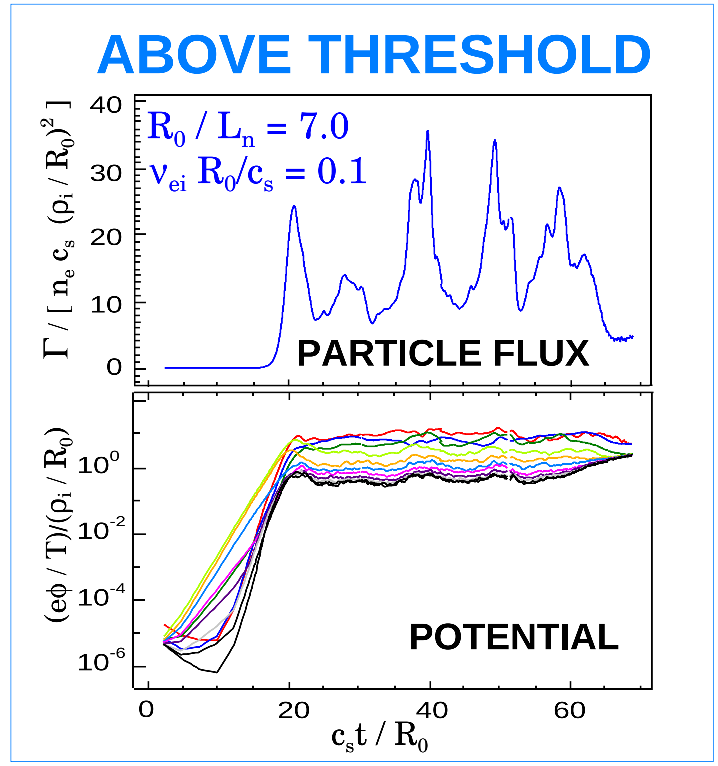
# Nonlinear Upshift of TEM Critical Density Gradient Increases with Collisionality

- TEM upshift [Phys. Plasmas (2004) 2637], analogous to Dimits shift for ITG.
- Linear threshold insensitive to collisionality
- TEM strongly damped by electron-ion collisions, $\propto (\nu_e/\varepsilon\omega)^{1/2}$
  [Connor *et al.*, PPCF (2006) 885].
- Zonal flows weakly damped by ion-ion collisions
- Nonlinear TEM threshold increases with density



# Secondary instability leads to zonal flow dominated states in the upshift regime




► **Secondary instability rapidly transfers energy from primaries (TEM) to zonal flows.**

$$\gamma_{ZF} \propto |\phi_{TEM}|$$

$$\phi_{ZF} \propto \exp(\exp \gamma_{TEM})$$

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

► **Zonal flows are slowly damped by ion-ion collisions.**

# Conclusions

- ITB localizes chord integrated fluctuations, isolates TEM
- Developed new synthetic PCI diagnostic for GS2, TEM simulations reproduce:
  - Relative increase in density fluctuations with on-axis heating
  - Meas. TEM wavelength spectrum, in first of kind comparison
- Basic TEM physics:
  - Classical diffusion suppresses shorter wavelength TEMs
  - Nonlinear upshift of TEM critical density gradient increases with collisionality