Electron Transport and Barriers in Reversed Shear Plasmas in TFTR

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Motivation & Outline

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- Core Ion thermal transport suppression demonstrated on many machines with reversed or weak magnetic shear (Internal Transport Barriers)
  – in some cases particle transport also suppressed
  – likely due to ExB flow-shear suppression of long-wavelength turbulence

→ basis for Advanced Tokamak and
Compact Stellarator Configurations

- Electron thermal transport is sometimes reduced, sometimes ~unchanged; always anomalous.

  – need to develop predictive understanding
  – need to understand to try to suppress

- Brief review of Enhanced Reversed Shear (ERS) transport and profiles

- Detailed structure of T_e profile, transport

- Comparisons with theoretical predictions

Two Confinement Regimes Observed with Reversed Core Magnetic Shear

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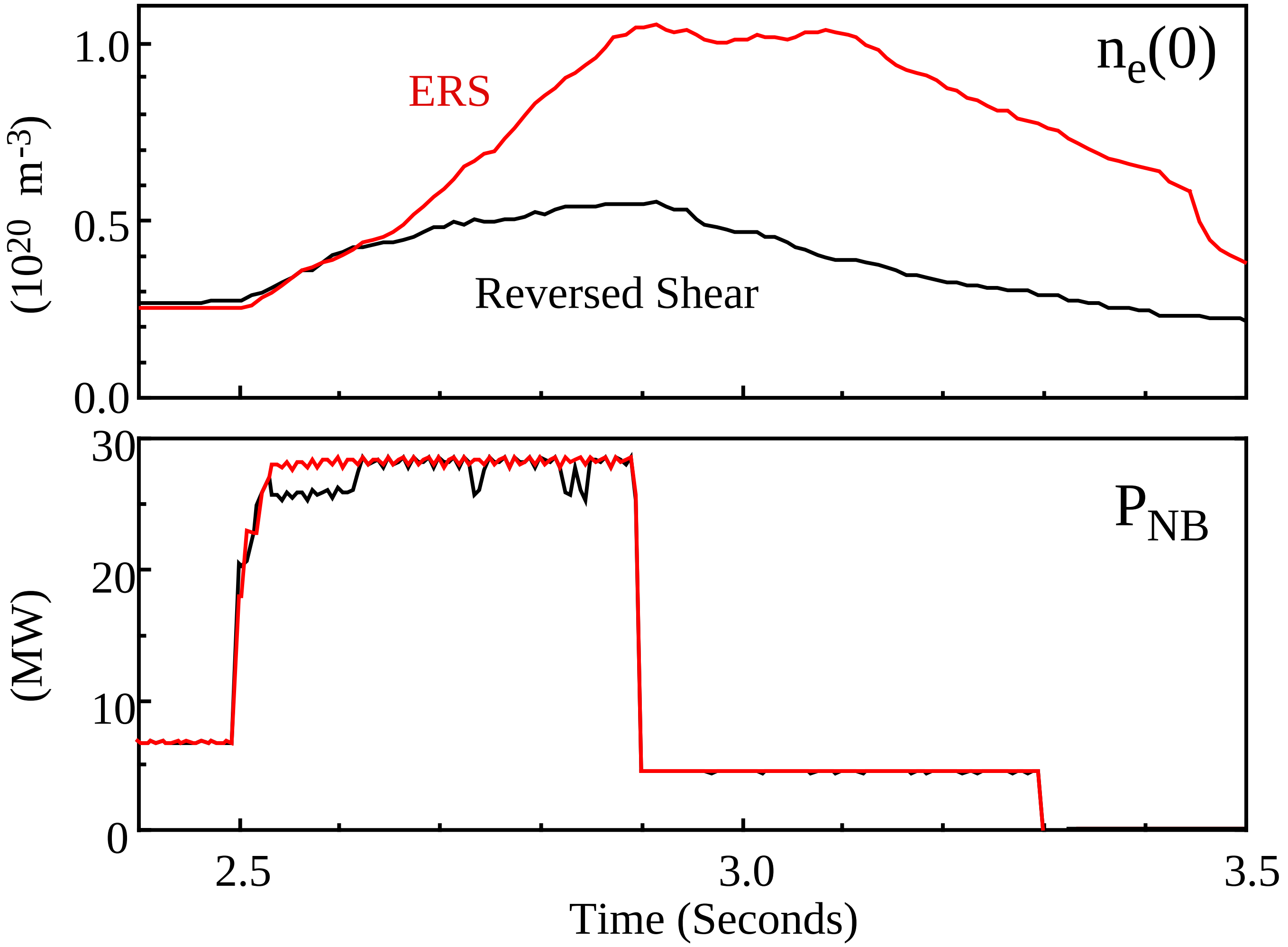

- Plasmas with reversed or weak magnetic shear can show a sudden transition to reduced core transport of particles and energy (ERS mode – Enhanced Reversed Shear)

- ERS plasmas develop extremely peaked profiles
  – $n_e(0) / \langle n_e \rangle \sim 5$, $p(0) / \langle p \rangle \sim 8$
  p(0) up to ~6 atmospheres

- ERS plasmas show extreme hysteresis
  High central density can be maintained with ~5 MW of NBI

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χ_i and De are Sharply Reduced after Transition to below neoclassical level

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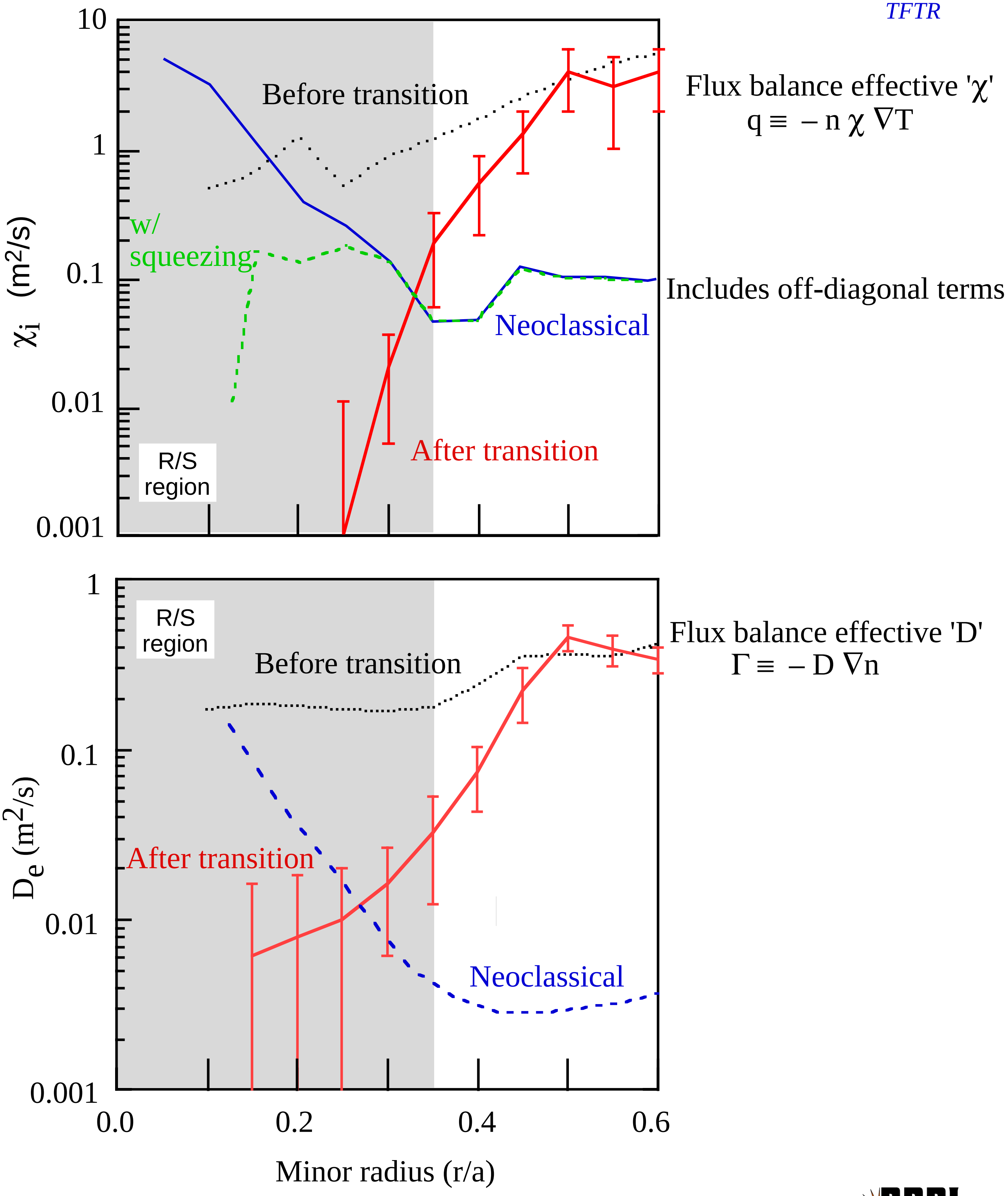

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χ_e is Not Reduced after Transition

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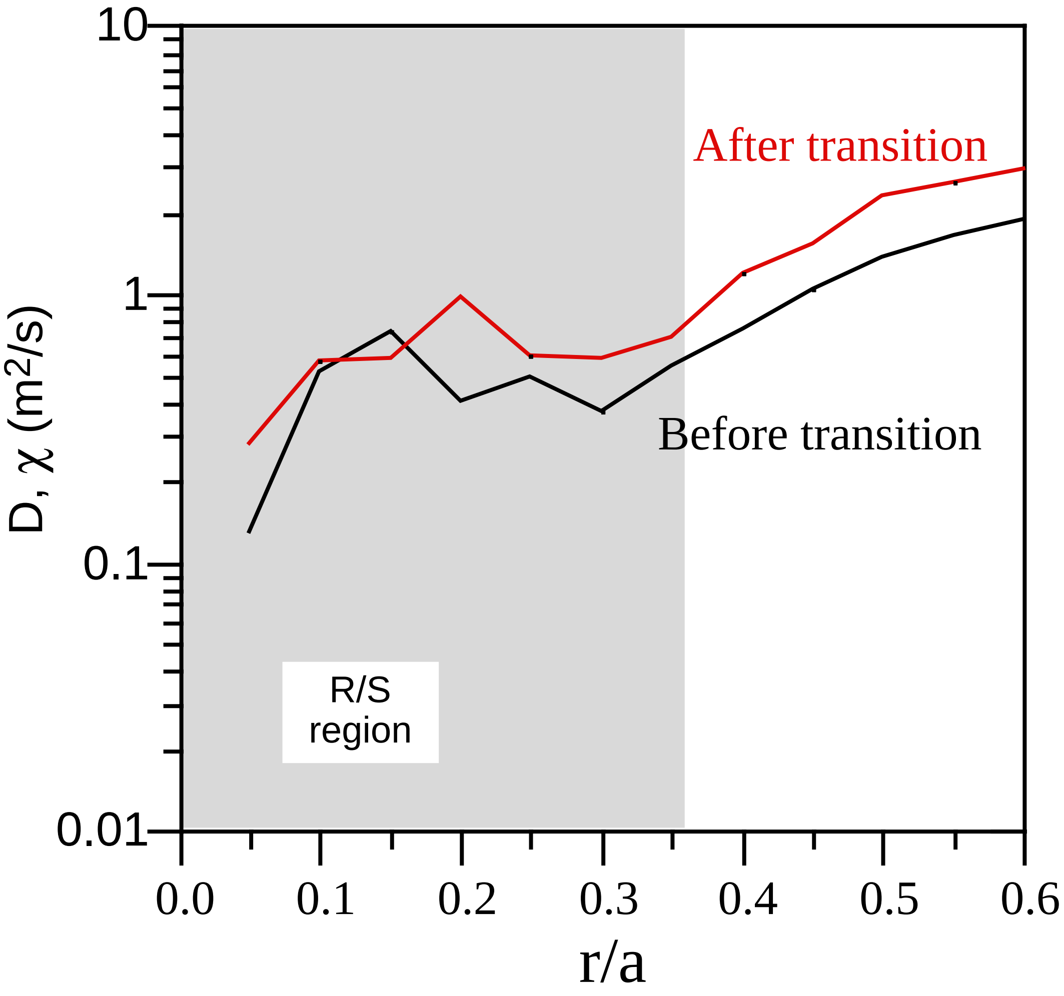
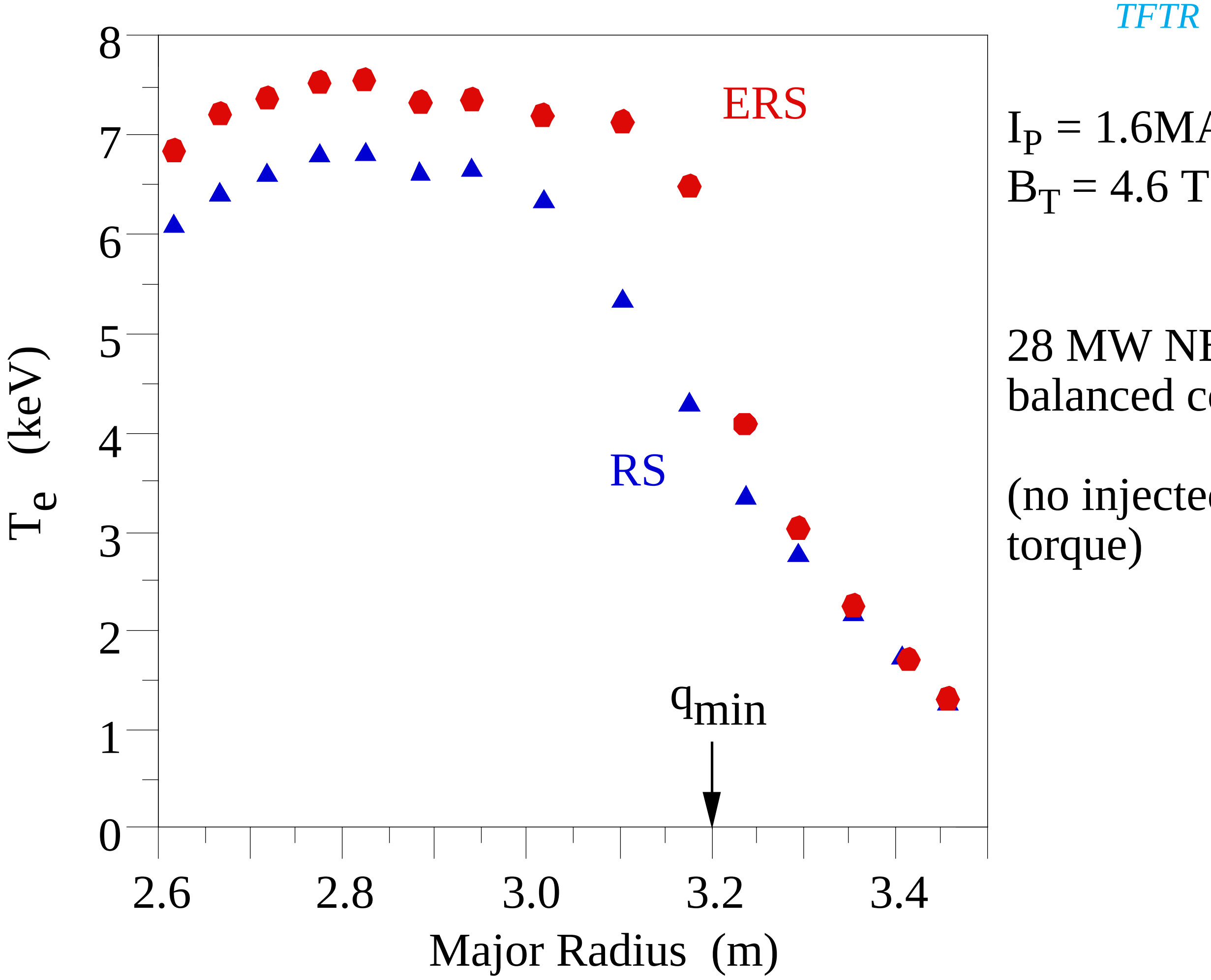


- Is χ_e larger in ERS?

  or ~ equal within the uncertainties
  - uncertainties due to large time derivatives and profile measurements of ∇T

- Why?

ERS Te Profiles Are Broader, Squarer than RS



I_P = 1.6MA
B_T = 4.6 T

28 MW NBI
balanced co/ctr

(no injected
torque)

- Te measured by ECE grating polychromator, each channel cross calibrated to Michelson interferometer
- Adjacent identical shots, except one transitions to ERS
- ERS Te profile shape develops ~ 0.1 sec after transition
- Observed on all ERS, Type I transitions
  Not observed on Type II transitions
- Gradient in reversed shear region is within systematic uncertainty of diagnostic calibration

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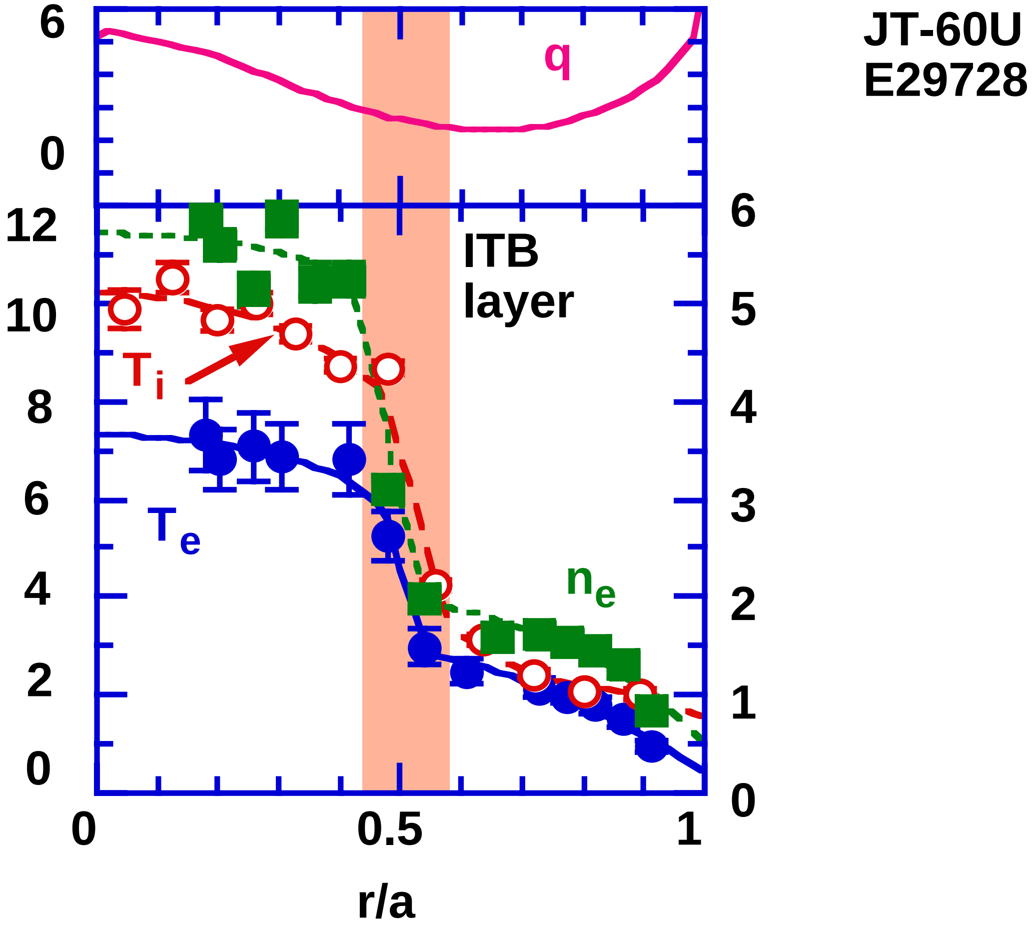
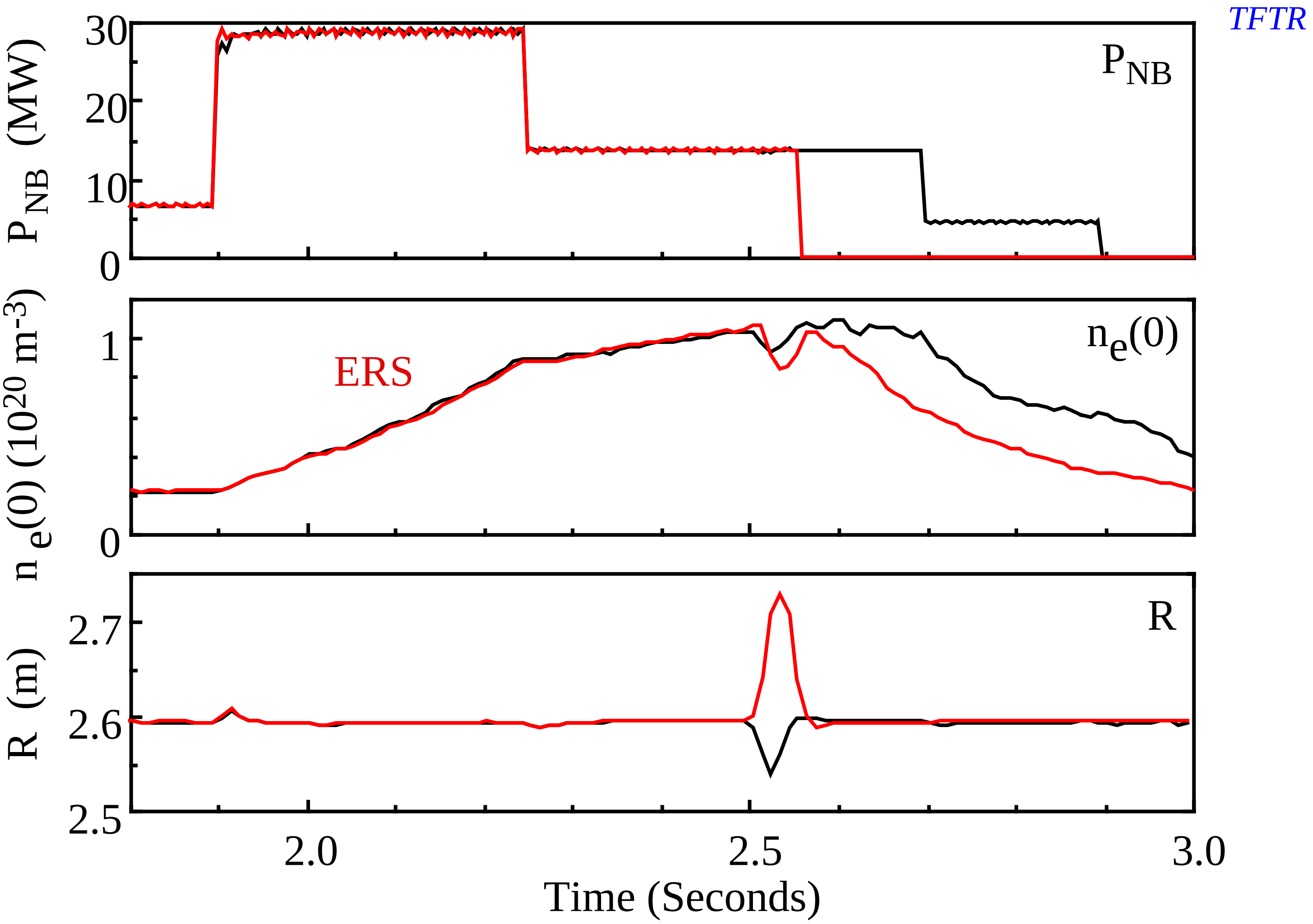
Similar flattening is Observed on JT-60U & AUG



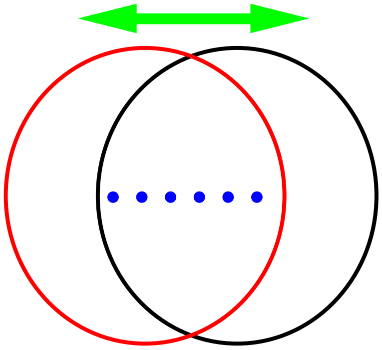
- see H. Shirai et al, Phys. Plasmas 5, 1712 (1998)
  and 1998 IAEA, Yokahama, Japan.

- also observed on T_e only in Asdex-Upgrade,
  see paper by R. Wolf et al, 1998 IAEA, Yokahama, Japan.

Plasma 'Jog' Used to Improve Radial Resolution



- Sweep plasma past fixed detectors to improve radial resolution
  both inward and outward motions used



- Maximum velocity ~ 3 m/sec;
  sample rate up to 500 kHz

- Jog during reduced power 'postlude'
  plasma near steady state

- Gives single detector measurement of gradients
  ⇒ reduced systematic uncertainty

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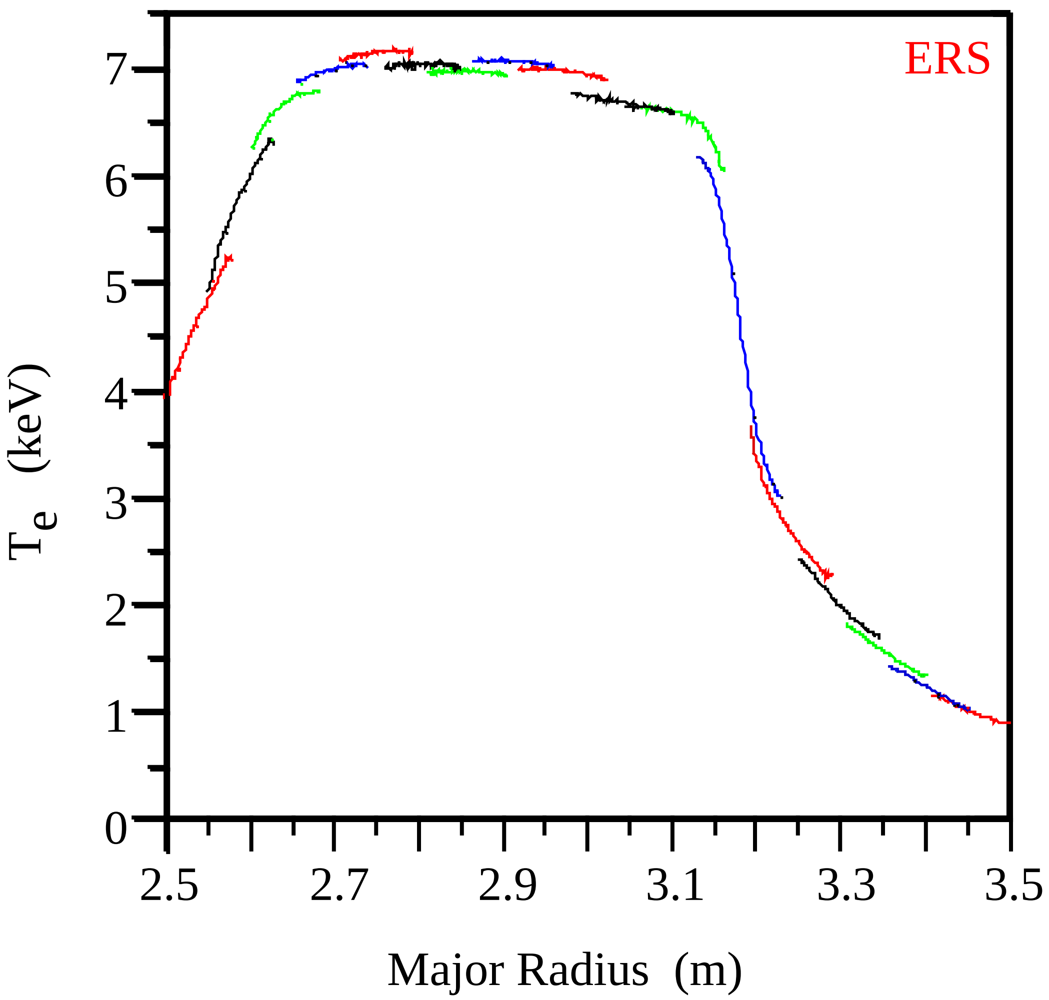
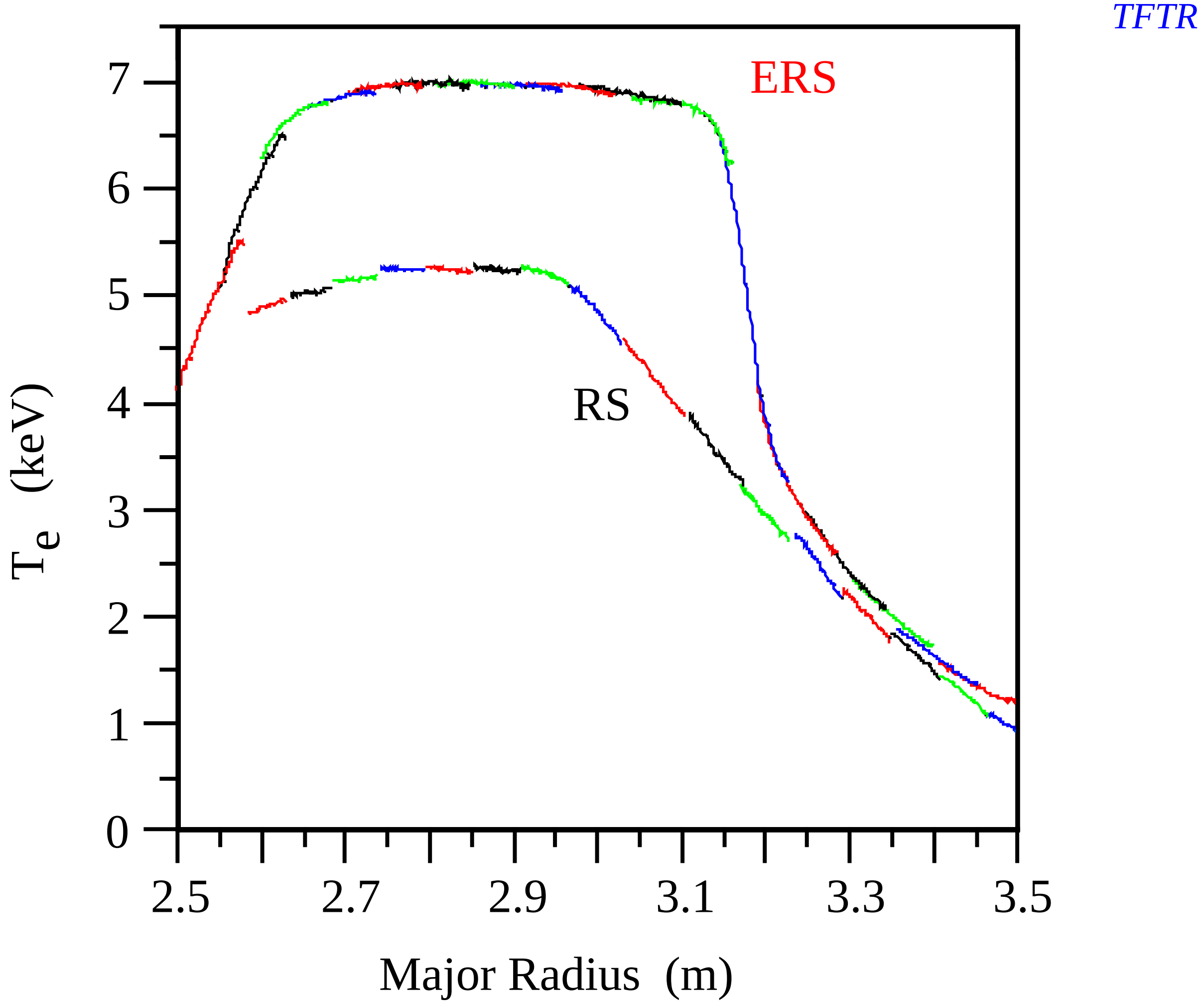
Jog'd ECE Shows Core T_e is Flat in ERS !



- Each colored segment shows the trajectory of a single detector during the plasma motion, mapped to the pre-motion position
- Similar profiles obtained at low and high B ERS shots
- Note corner in T_e profile near shear-reversal point

Jog'd ECE Shows Core Te is Flat in ERS !



- Detector calibrations corrected
  correction factors averaged over 4 shots
  in core-region < 4 % corrections, typ. ~ 2%

- ERS Not profile consistent !!

- Most of the ERS core ∇Te in the standard analysis is from systematic errors in detector calibration

- RS profile similar to jog-measured T_e profile for supershots
  profile shape ~ similar to other regimes
  L-mode, supershot, ohmic,...

Forward/Back Jog Shows Plasma is not Damaged

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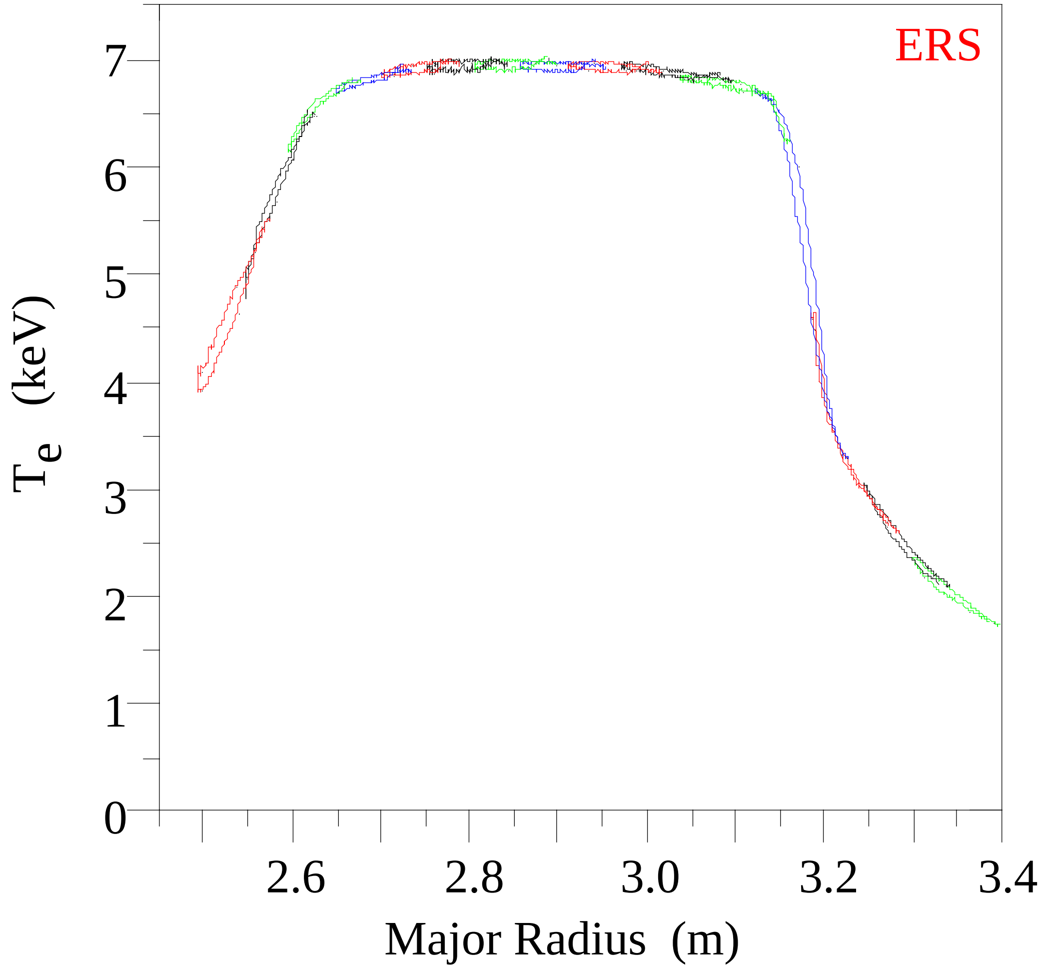

- Shows full jog, moving out and then back to original position
  elapsed time: 70 msec

- Individual detectors trace loops, height ~50 eV in core

- Loops close
  ⇒ likely residual problems with plasma position measurement

Jog'd Interferometetry: Core n_e is Peaked

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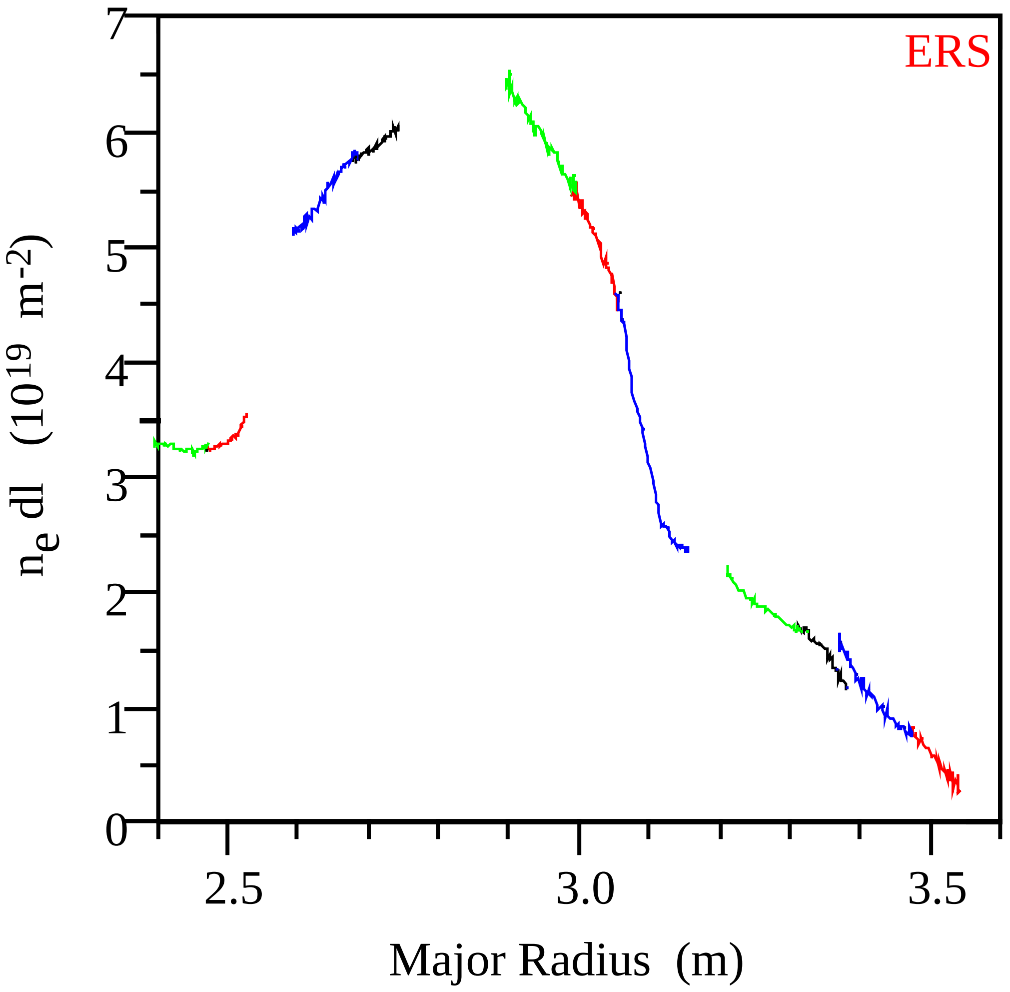
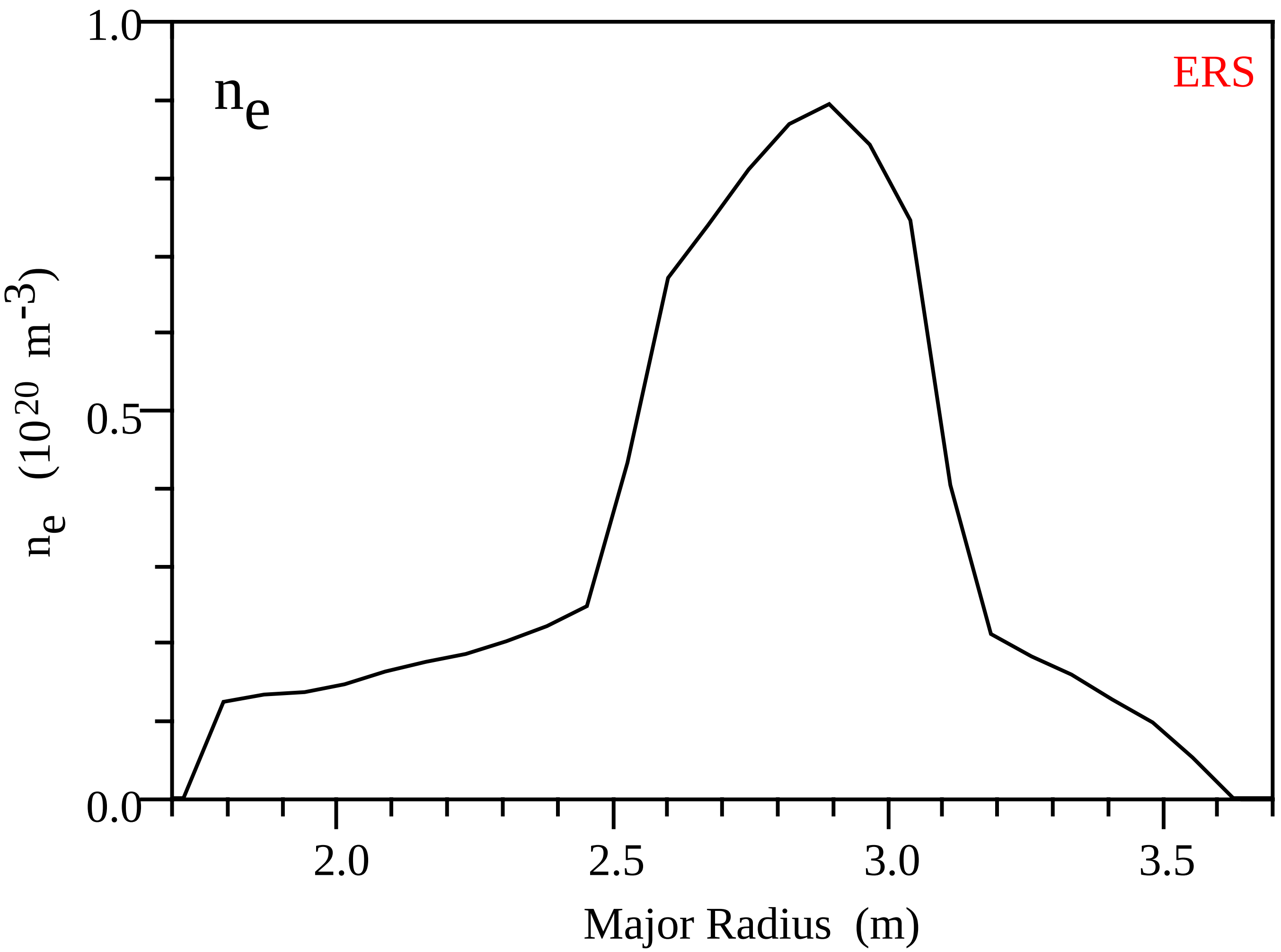


- Combination of two identical shots, one jog'd inward, one jog'd outwards

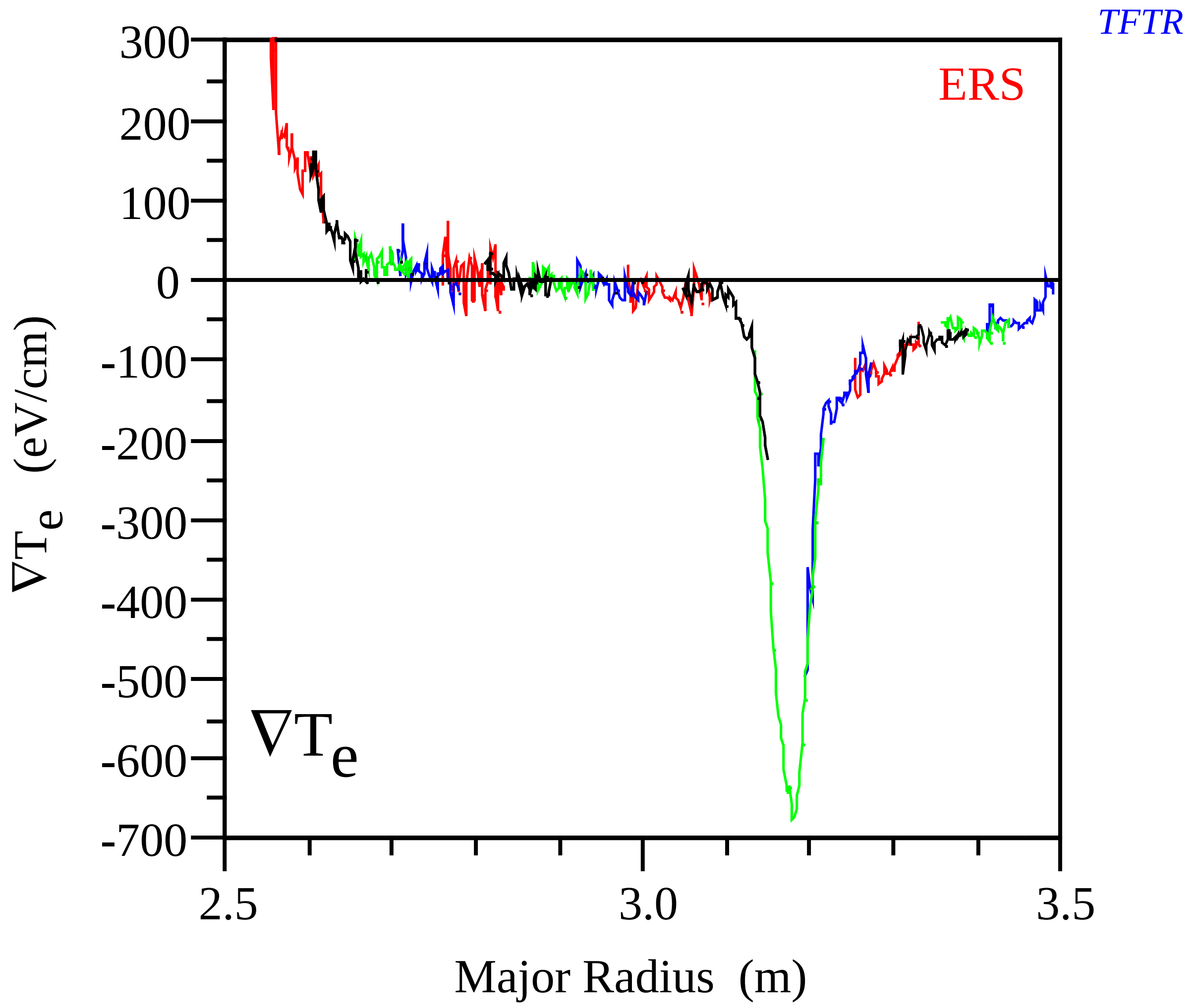
- Also: jog'd core Visible Bremstrahlung emission $\propto n_e^2\, T_e^{1/2}\, Z_{eff}$ very peaked, consistent with peaked n_e

Jog'd Interferometetry: Core n_e is Peaked



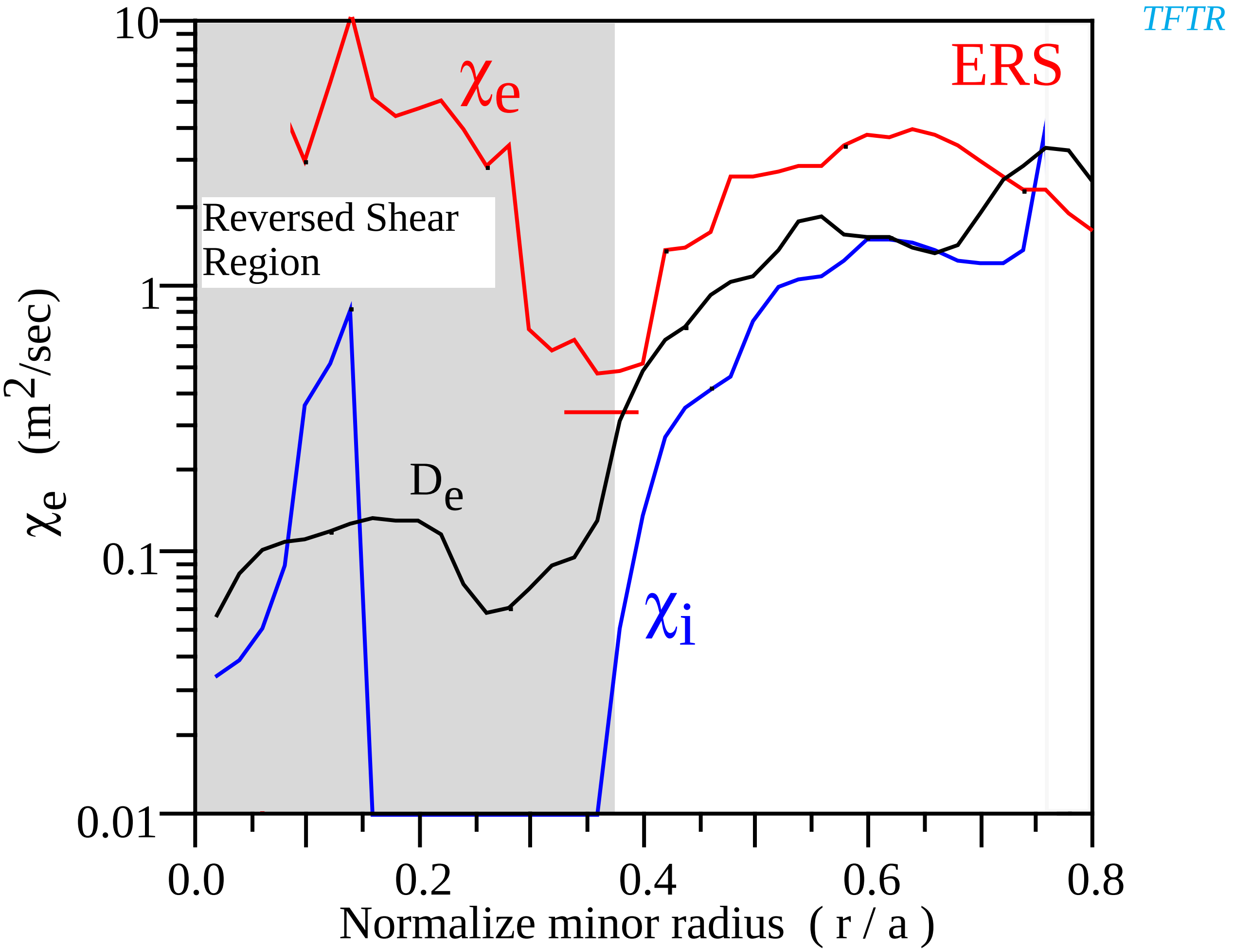
- From Abel Inversion of jog'd $n_e l$ profile
- Peak n_e is ~10% lower than non-jog standard analysis
- Outer edge of steep gradient is at same location as for T_e
- T_i and v_φ measurment averaging time too long for jog-technique
  - – however, those profiles are peaked outside the error bars

Core ∇Te is Extremely Low in ERS



- ∇T$_e$ measuremented by a single detector in each spatial region, from change in T$_e$ during plasma motion
  – minimize systematic uncertainty
- ∇T$_e$ ~ 15 eV/cm in core, averaged over one cm.
- Very high ∇T$_e$ near shear-reversal surface
- transition from ~ 60 eV/cm to > 300 eV/cm with <2 cm separation !
  At the limit of instrumental spatial (frequency) resolution

ERS χ_e is Increased in Core, Reduced in Barrier



- Power balance analysis of jog'd profiles for T_e and n_e

- Analysis during near-steady-state 'postlude'
  Reduced uncertainties relative to earlier analysis with large time-derivatives. Largest uncertainty now, for thermal transport, is due to Ti and the ripple modeling.

- χ_e / D_e ~ 50 in the core !!
  ~ 4 in the barrier

  χ_e / χ_i ~ 100 in the core

Most Plausible Explanation:
Stochastic B !

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In core: $\chi_e / D_e \sim 50$, $\chi_e / \chi_i > 100$

- Difficult to understand how electrostatic modes could give such large χ_e / D_e
  - Rechester-Rosenbluth: $\chi_e / D_e \sim m^{1/2} = 67$ would require $\tilde{B}_r/B \sim 3 \times 10^{-4}$

- Must be high $k_\perp \rho_i$ turbulence to avoid ion transport via ion orbit averaging.
  - $\rho_i = 0.3 - 0.5$ cm

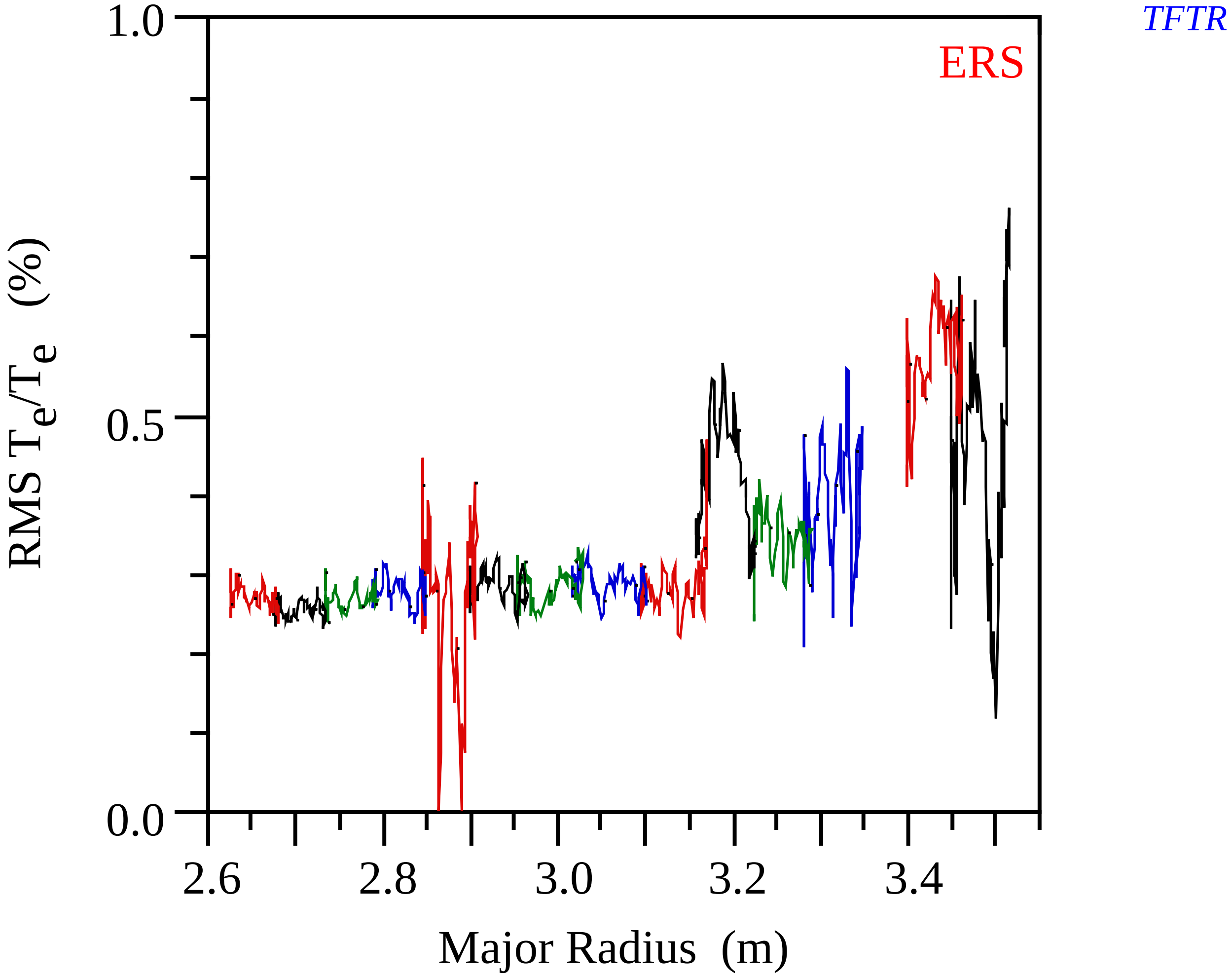
What Instability?

Fundamental problem: What gradient provides drive? T_e is being transported, but $\nabla T_e \sim 0$.

Substantial ∇T_i and ∇n_e, but they are not being dissipated.

- η_e or Electron Temperature Gradient-Mode (ETG) has no drive
  - $L_{Te} \sim 3.5$ m $> R=2.6$ m
  - $\eta_e < 0.1$

No Apparent Core T_e Fluctuations



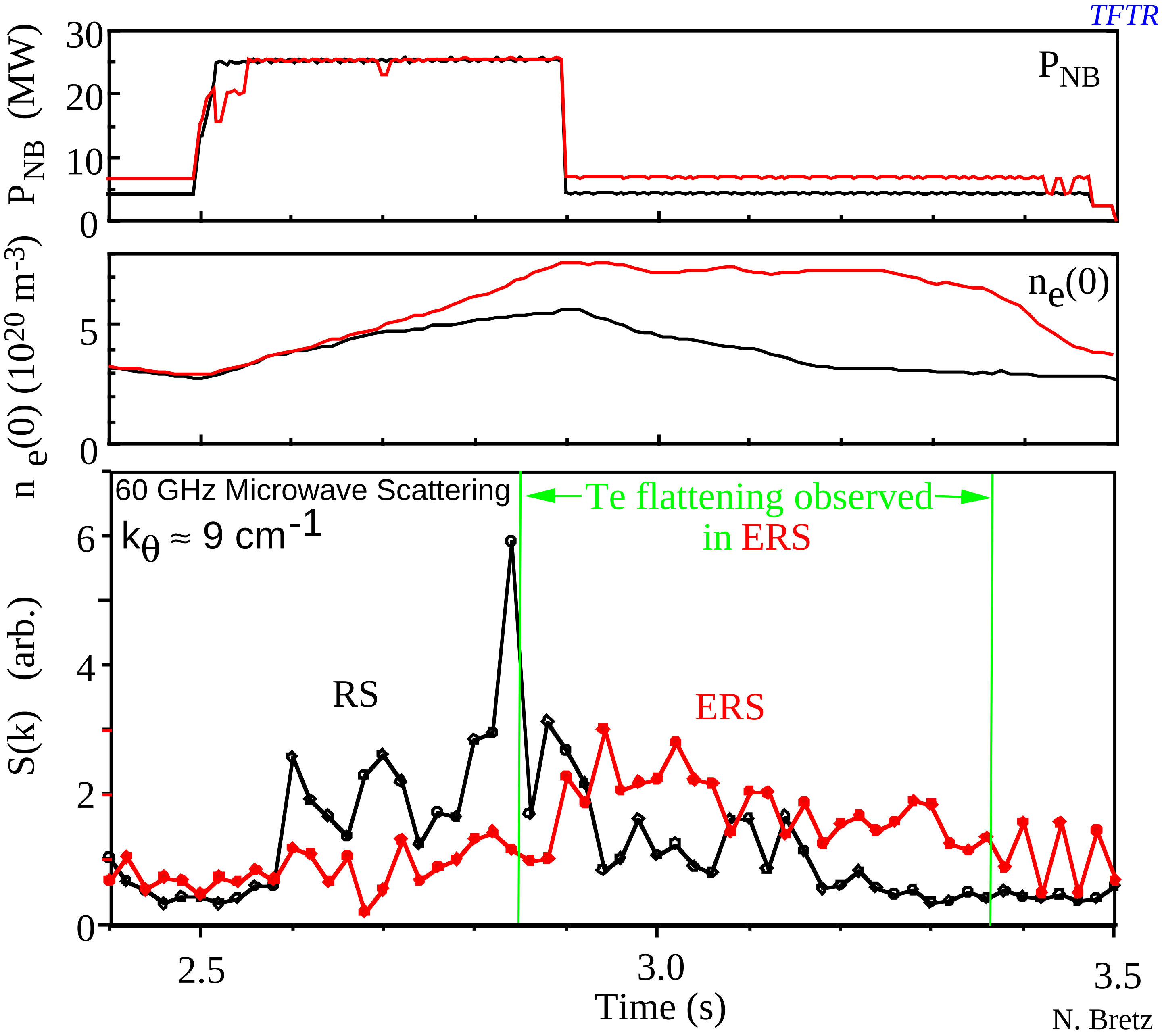
- RMS T_e fluctuation in 1ms intervals, mapped to pre-motion position

- Amplifier noise subtracted. Channel at R ~ 2.87m very noisy

- In core, measured T_e fluctuations consistent with expected ECE blackbody noise.
  – As expected for convective modes with $\nabla T_e \sim 0$.

- Very small 60 +/- 10 kHz fluctuations near shear reversal also observed on reflectometer, Mirnov array
  $n = -3$, $m = 5 - 7$ from Mirnov
  displacement ≤ 1 mm

No Strong High-k_θ Density Fluctuations



- Integrating shifted scattered spectrum, ignoring unshifted line center
- Core T_e flattening observed in ERS case from ~2.85 s thru ~3.37 s
- Scattered signal is proportional to density ⇒ fluctuations similar in postlude phase for ERS and RS
- For k_θ ~ 2 cm^{-1}, RS fluctuation level higher than in ERS, similar to reflectometer measurements

Core χ_e: Possible Models

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- No unstable ideal MHD modes found (J. Manickam)

- Electromagnetic skin-depth

$$\frac{c^2}{\omega_{pe}^2}\frac{v_{Te}}{R\,q} \sim 1\ \mathrm{m}^2/\mathrm{s} \ll \chi_e$$

- Resistive Interchange: $D_R \sim 1$ both ERS and RS (M. Hughes)
  - mode is barely unstable, easily stabilized kinetically
  - at higher β values, $D_R \sim 70$ has been calculated

    appears to be uncorrelated with transport

- Resistive pressure gradient turbulence

  [e.g. Carreras-Diamond, Phys. Fluids B1, 1017 (1989)]
  - predicts large enough transport,
  - Gives same level for ERS and RS: no discrimination.
  - Should be re-examined, including flow shear

- GS code by M. Kotschenreuther [CPC 88, 128 (1995)]
  - Comprehensive linear stability analysis of full gyrokinetic equations (Antonsen and Lane) in ballooning representation.
  - Should address all short wavelength electrostatic and electromagnetic modes, including resistive interchange, resistive ballooning, micro-tearing, ETG, ...

  - finds no linearly-unstable modes !!

Need to look at non-linear instabilities
and (possibly) tearing modes (below neoclassical stabilization)

Transport in the Barrier: ETG?

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The GS code has also analyzed the microstability of the electron transport barrier region, where χ_e is suppressed in ERS.

Preliminary results:
(some cross checking in progress)

- unstable mode with $k_\perp \rho_i \sim 100$, $k_\perp \rho_e \sim 1$
- ∇T_e is ~30% higher than the critical gradient for ETG

ETG is analogous to ITG (with i ↔ e), but with strictly adiabatic ions due to the very high $k_\perp \rho_i$
⇒ strong gyro-averaging.

From the analogous ITG calculation, can estimate

- $\chi_e(\mathrm{ETG}) > 30\, D_{mix} \sim 3\, \chi_e(\mathrm{Exp}) \sim 100\, \chi_i\, (\mathrm{ETG})$

where D_{mix} is the Kadomtsev mixing length estimate

$$D_{mix} \sim \gamma / k_\perp^2$$

⇒ ETG may be strong enough to enforce marginality
uncertainties need to be investigated

Summary

- T_e is <u>very flat</u> in the core of ERS plasmas (inside the shear reversal surface)

- χ_e in the ERS core is <u>much larger</u> than in RS
  - in contrast to D_e, χ_i, χ_φ

- χ_e ~ 50 D_e, ~ 100 χ_i in core!
  - may imply that the core magnetic field is stochastic, on a very fine scale
  - dissipating ∇T_e but no ∇T_e drive!

    what is driving the turbulence?
  - no instabilities found by comprehensive code

- ∇T_e is locally <u>very large</u> (~ 680 eV/cm) in ~5 cm layer near reversal surface

- χ_e is 4 times lower in ERS than RS in layer near reversal surface
  - clear electron thermal transport
  - may be limited by ETG