IMPROVEMENT OF CORE BARRIERS WITH ECH AND COUNTER-NBI IN DIII–D

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Additional tools have been brought to bear on the challenge of core transport barrier control in the DIII–D Tokamak. An ECH/ECCD (electron cyclotron heating and current drive) preheat method has been developed to tailor the target current profile prior to formation of a beam-heated barrier, with resulting *q* profiles similar to those produced by neutral beam preheat. The flexibility of this method allows better control of the early current profile development to better optimize the final barrier characteristics. An interesting feature observed during the ECH preheat phase is the appearance of a strong, highly localized transport barrier in the electron temperature profile ($T_e(0) \leq 6$ keV) when a low density (1×10^{19} m^{-3}), low current (≥500 kA) plasma is heated with P_{ECH} = 0.5 MW (launched for counter-ECCD) and P_{NBI} = 0.5 MW. The upper limit to the electron thermal diffusivity in this barrier is calculated as $\chi_e \leq 0.2$ m^2/s. Later in these discharges, application of high power counter neutral beam injection (counter-NBI) can trigger formation of a core barrier evident in the thermal (both electron and ion), momentum and particle diffusivities. These barriers tend to be broader than those created in similar conditions with co-NBI. This is attributed to a favorable combination of the rotation and pressure gradient contributions to the E×B shearing rate $\omega_{E\times B}$. Increasing or broadening the pressure profile results in larger $\omega_{E\times B}$, allowing access to reduced transport over a broader region. In similar co-NBI discharges, these two terms oppose so that $\omega_{E\times B}$ may become small at large radii, thereby retarding barrier expansion. Another feature of the counter-NBI discharges is the appearance of a finite power threshold for barrier formation, in contrast to the negligible threshold previously reported with co-injection. This also appears to be a consequence of the modified $\omega_{E\times B}$ shear dynamics with reversal of the toroidal rotation.

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GENERAL ATOMICS

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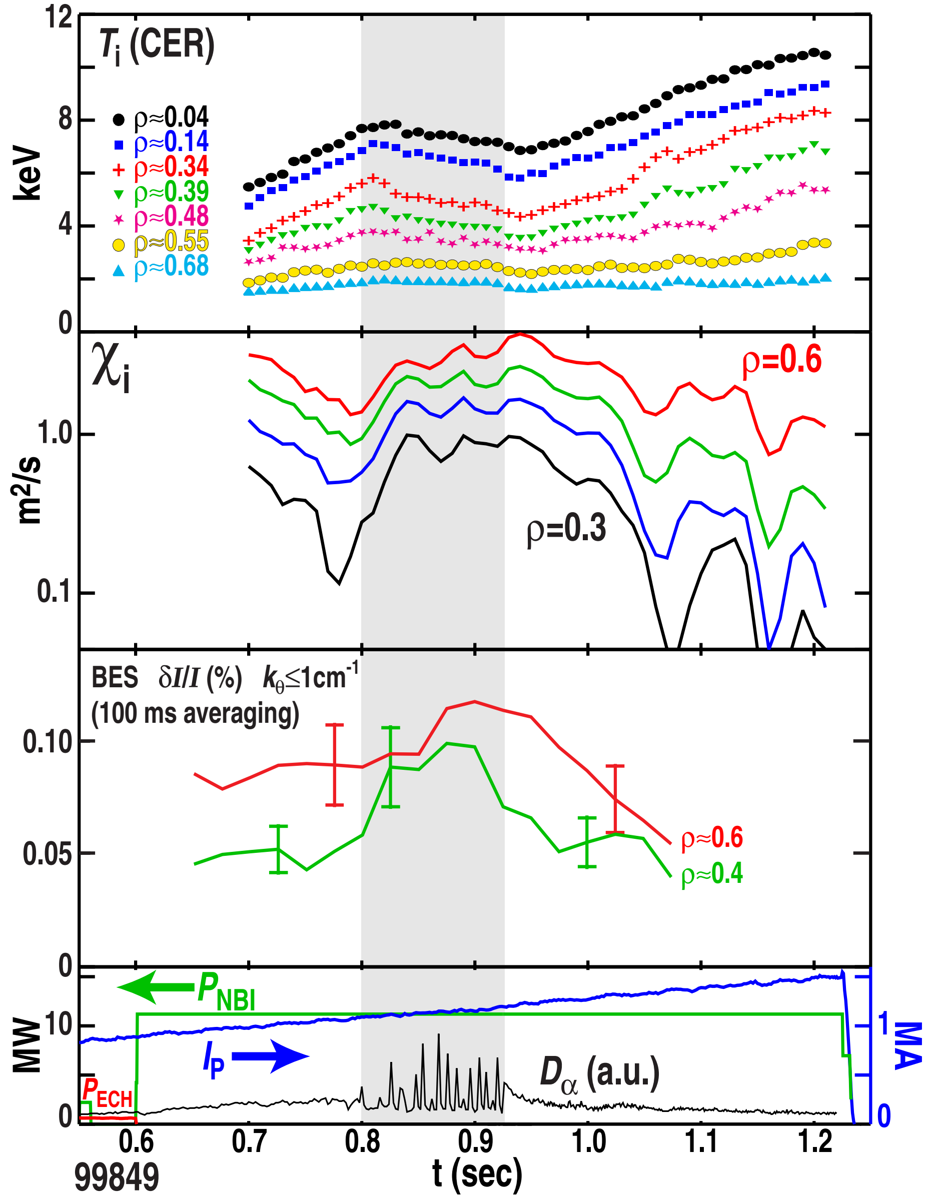
OVERVIEW

- E∝B shear is the leading effect in reducing ion thermal transport internal transport barriers (ITB).
  - ITBs are broader with counter-NBI than in similar discharges with co-NBI.
  - Due to modification of E∝B dynamics with counter-NBI.
    - Rotation and pressure gradient terms of E∝B shearing rate compete with co-NBI, but add to one-another with counter-NBI.
    - Region where E∝B shearing rate exceeds calculated linear growth rates for long wavelength drift instabilities (ITG, TEM) is larger with counter-NBI.
- Electron thermal transport is more difficult to reduce.
  - Strong electron ITB generated with localized direct electron heating (ECH).
  - Believed to require stabilization of both low-*k* (same as requirement for ion ITB) and high-*k* (ETG; an additional requirement) turbulence.
    - E∝B shear too weak an effect to reduce high-*k* turbulence.
    - Simulations point to α-stabilization as trigger mechanism for electron ITB.

INTERNAL TRANSPORT BARRIER PRODUCED WITH COUNTER-NEUTRAL BEAM INJECTION

- Normal ITB recipe in DIII–D with co-NBI:
  - Early co-NBI heats electrons, freezes in reversed *q* profile.
  - Slow ITB formation usually begins during this phase, even at low power.
- Counter-NBI recipe:
  - Early NBI not an option due to beam ion losses.
    - Both ohmic and ECH preheat successful.
  - ITB forms only if $P_{NBI} \geq 9$ MW.
  - ELMing H–mode phase interrupts ITB after MHD activity releases energy from core.
  - Core fluctuations drop following H–L transition, in conjunction with ITB reformation.
    - Profiles indicate resumption of ITB development.



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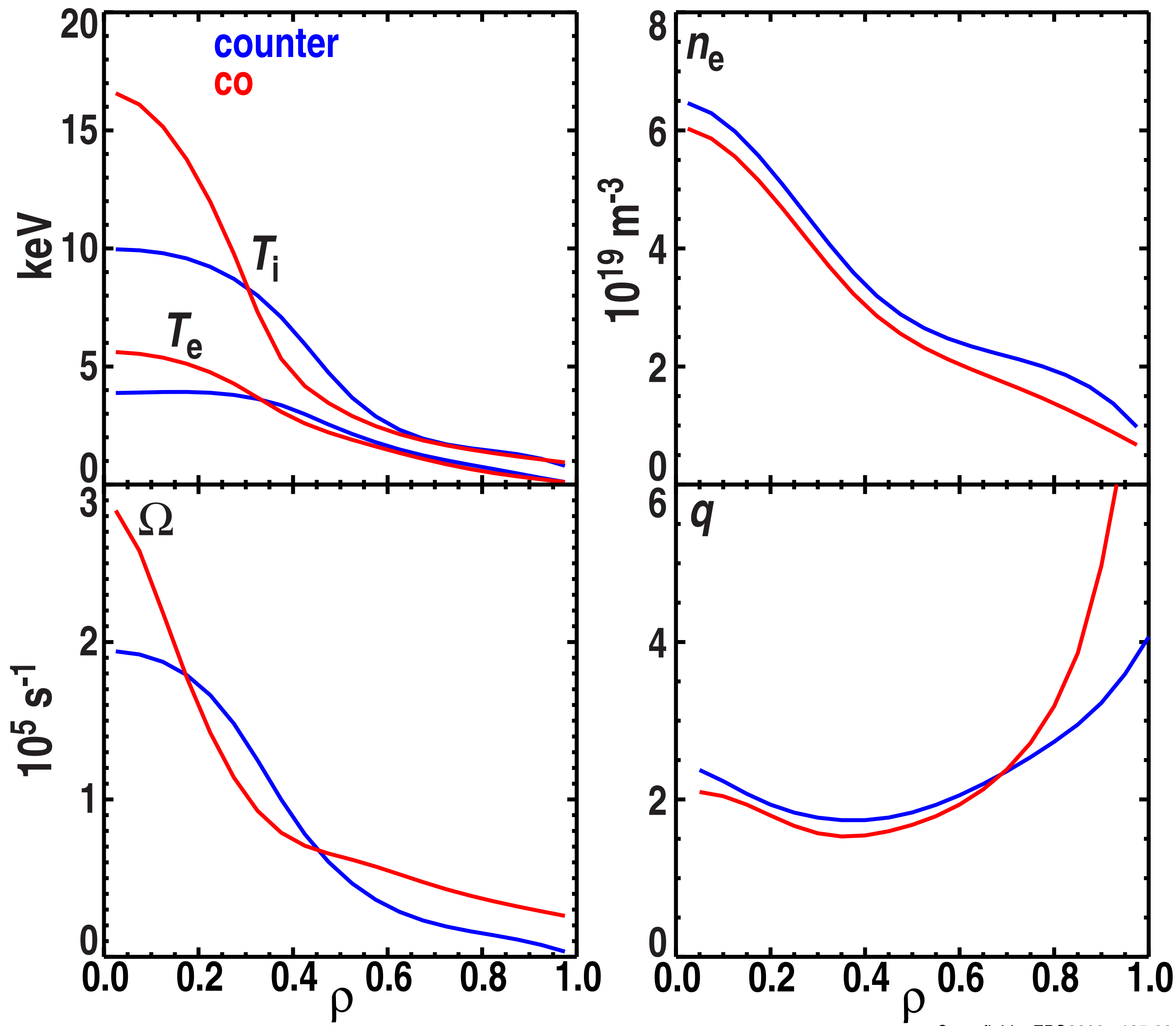
COUNTER-NBI RESULTS IN BROADER PROFILES

- **99849 (1.17s):**
  - Counter-NBI
  - W_{MHD} = 0.9 MJ
  - P_{NBI} = 11.2 MW (6.5 MW absorbed).

- **87031 (1.82s):**
  - Co-NBI
  - W_{MHD} = 1.2 MJ
  - P_{NBI} = 9.6 MW (7.6 MW absorbed).



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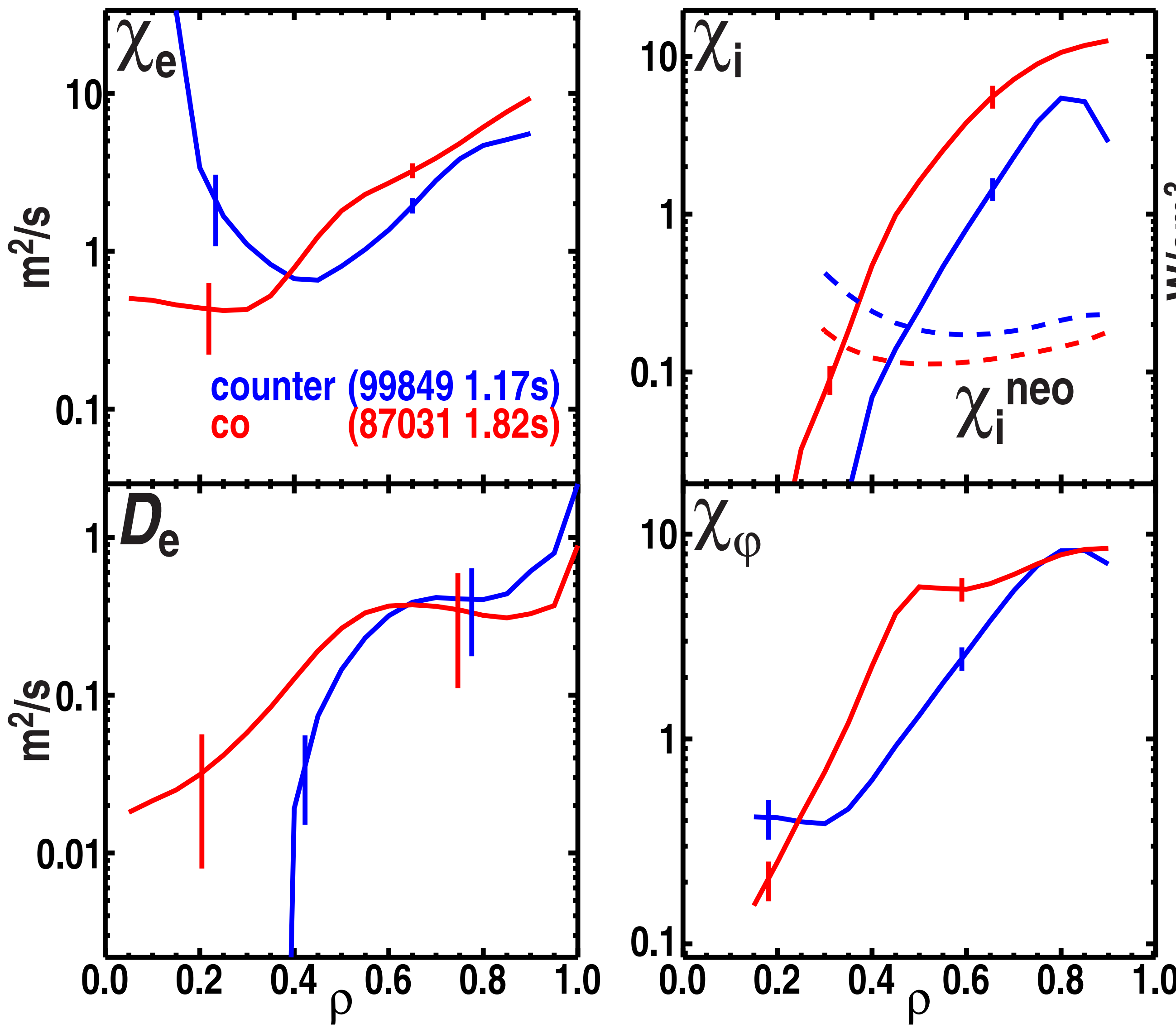
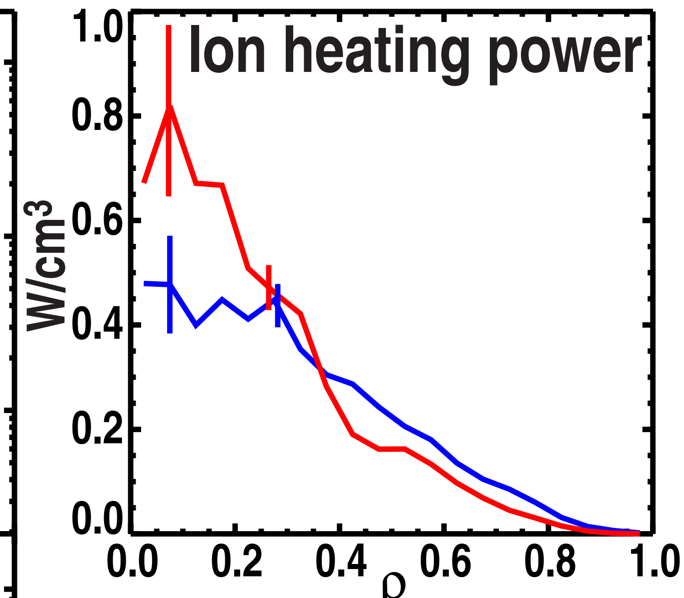
THE REDUCED TRANSPORT REGION IS BROADER IN ALL CHANNELS WITH COUNTER-NBI





- **Possible causes of ITB broadening:**
  - **Broader heating profile**
  - **Enhanced E×B shear**

E∝B SHEAR AND ITS COMPONENTS

- The E∝B shearing rate is usually calculated from charge exchange recombination measurements of the carbon impurity density, temperature and rotation:

$$\omega_{E\times B} = \frac{(RB_\theta)^2}{B}\frac{\partial}{\partial\psi}\frac{E_r}{RB_\theta}$$

  where

$$E_r = (Z_i e n_i)^{-1}\nabla p_i - v_{\theta i}B_\varphi + v_{\varphi i}B_\theta$$

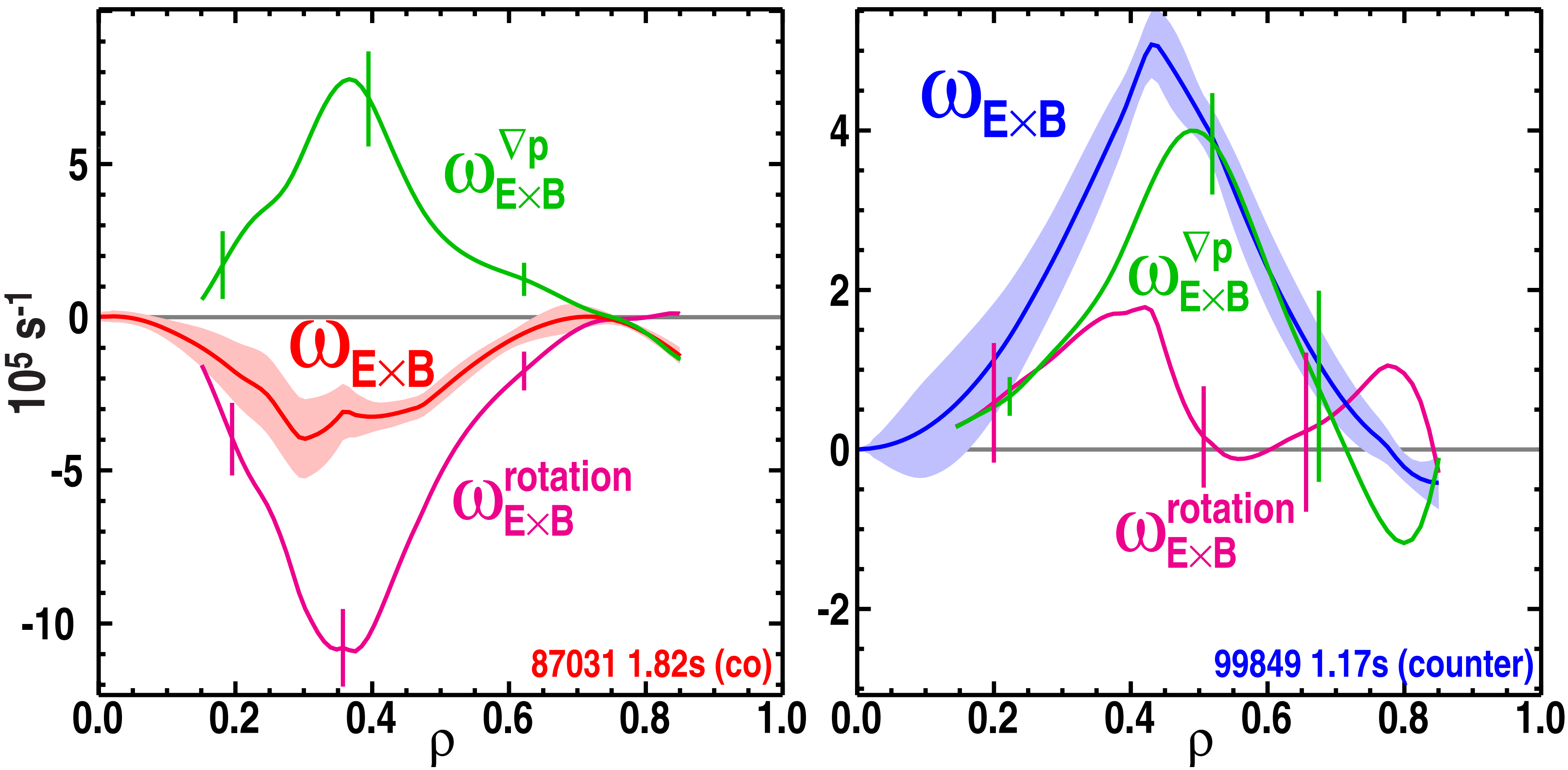
  and i can denote any ion species.

- $\omega_{E\propto B}$ can be expressed as the sum of separate rotation and pressure gradient terms:

$$\omega_{E\times B}^{rotation} = \frac{(RB_\theta)^2}{B}\frac{\partial}{\partial\psi}\left[\frac{1}{R}\left(v_{\varphi i} - v_{\theta i}\,{B_\varphi}/{B_\theta}\right)\right] \qquad \omega_{E\times B}^{\nabla p} = \frac{(RB_\theta)^2}{Z_i e B}\frac{\partial}{\partial\psi}\left[\frac{1}{n_i R B_\theta}\nabla p_i\right]$$

- Since the shearing rate is independent of the species, it is also valid for the main deuterium ions.
  - Pressure gradient term calculated using main ion density from TRANSP.
  - Rotation term calculated by subtracting pressure gradient term from total shearing rate.
- Criterion for stabilization of turbulence: $|\omega_{E\propto B}| > \gamma_{max}$, where γ_{max} is the calculated linear growth rate.

COMBINATION OF ∇p AND ROTATION EFFECTS IN $\omega_{E \times B}$ NATURALLY BROADENS COUNTER BARRIERS



- Shearing rate $\omega_{E \times B}$ separated into *thermal main ion* rotation and pressure gradient terms.
  - Total calculated from CER impurity measurements.
  - Main ion pressure term from profile measurements.
  - Rotation term by subtraction.

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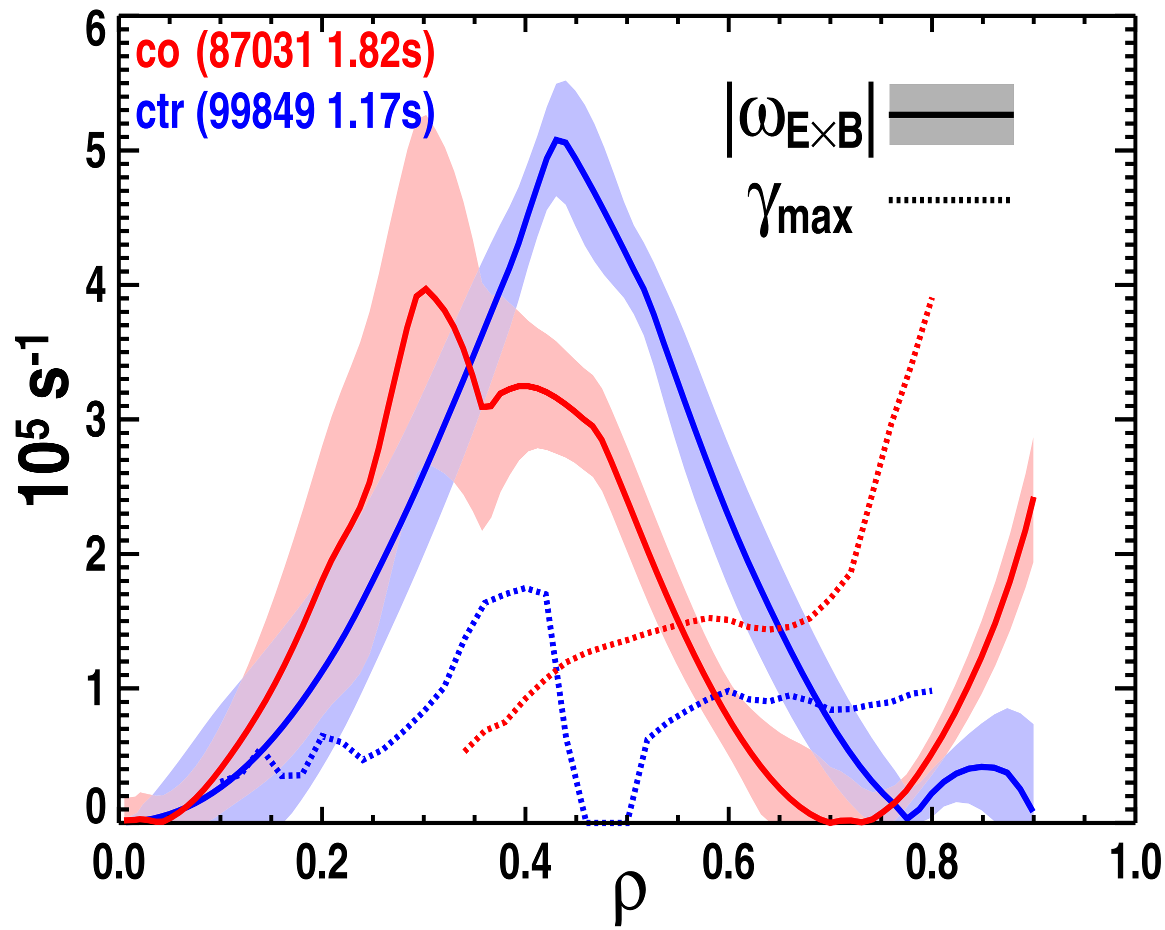
E×B SHEAR SUPPRESSION OF LOW-*k* TURBULENCE IS DOMINANT OVER A LARGER AREA WITH COUNTER-NBI

- Stability to drift ballooning modes calculated using a linear gyrokinetic stability (GKS) code.
  - Non-circular, finite aspect ratio equilibria with fully electromagnetic dynamics.
- With counter-NBI:
  - Linear growth rates smaller at at large r, possibly due to higher Zeff near edge (core Zeff ≈ 2.5 in both cases).
  - The shearing rate profile extends to larger radius.



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ELECTRON ITB PRODUCED BY ECH

- **An electron thermal transport barrier has been obtained in a discharge heated with low-power ECH (0.5 MW) and counter-neutral-beam injection (0.5 MW).**
  - **Central electron temperature approaches 6 keV with $T_e/T_i \geq 10$.**
  - **Electron thermal transport essentially eliminated in a narrow barrier region.**

- **The electron transport barrier appears under conditions where we would normally expect any barrier to be impeded by turbulence.**
  - **Low- and high-*k* turbulence growth rates calculated too large to be suppressed by E∞B shear alone.**
    - **E∞B shear may still have an important effect on low-*k* stability.**
  - **Growth rates are very sensitive to α (normalized pressure gradient).**

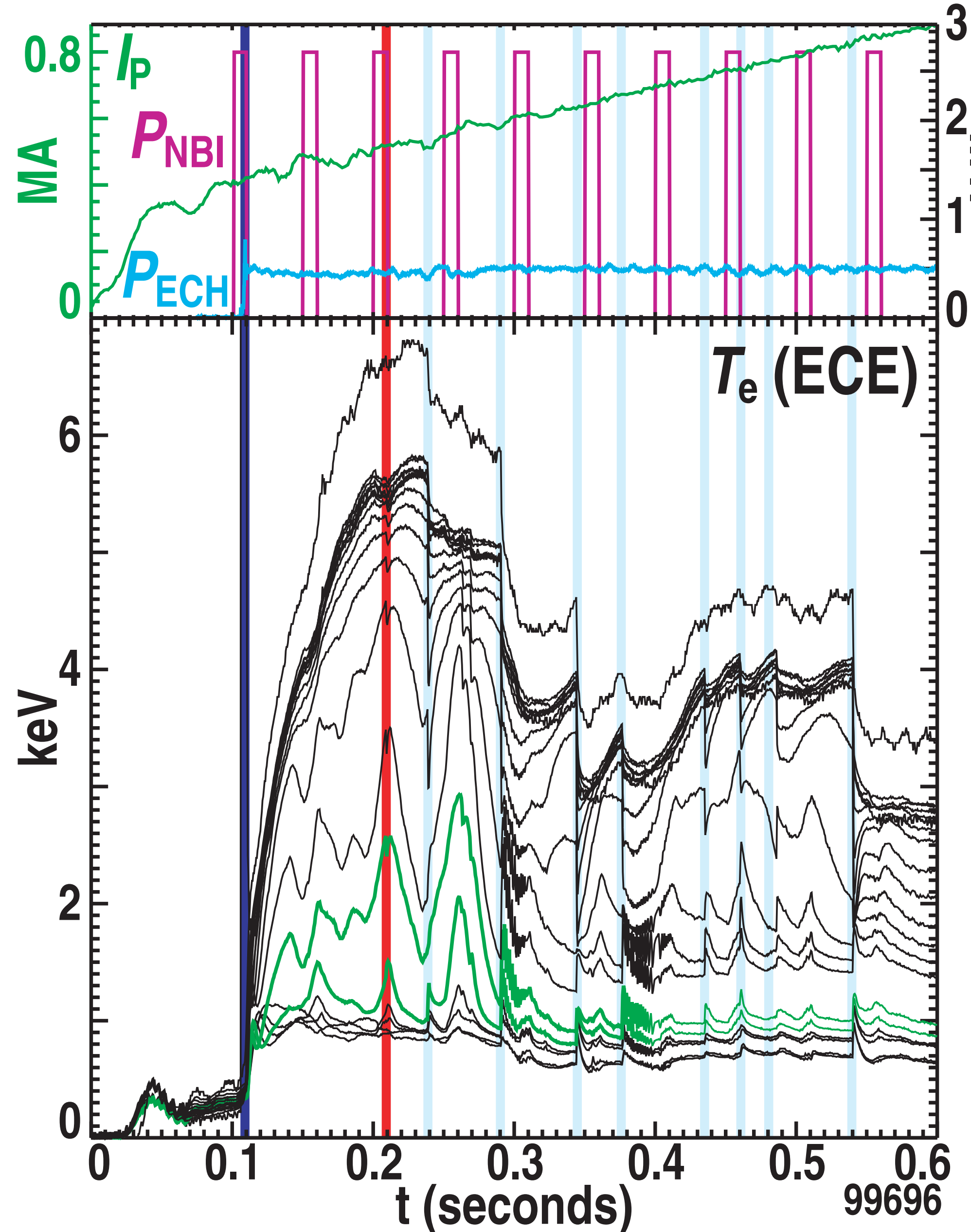
- **Predictive simulation with the GLF23 model reproduces the development of the electron transport barrier with sufficiently large α.**

- **α-stabilization appears to be a requirement in order to enter this regime.**

ECH PREHEAT GENERATES AN ELECTRON INTERNAL TRANSPORT BARRIER

- Beam blips for MSE and CER, time averaged $P_{NBI} \approx 0.5$ MW (counter).
  - Poor beam ion confinement at low current and counter-NBI... most of this power is lost.

- Electron thermal ITB develops rapidly after onset of ECH.
  - Barrier grows in strength while remaining nearly stationary in position.
  - Little or no barrier appears in ion thermal, particle or angular momentum channels.
    - *But the sources for these channels are very small.*



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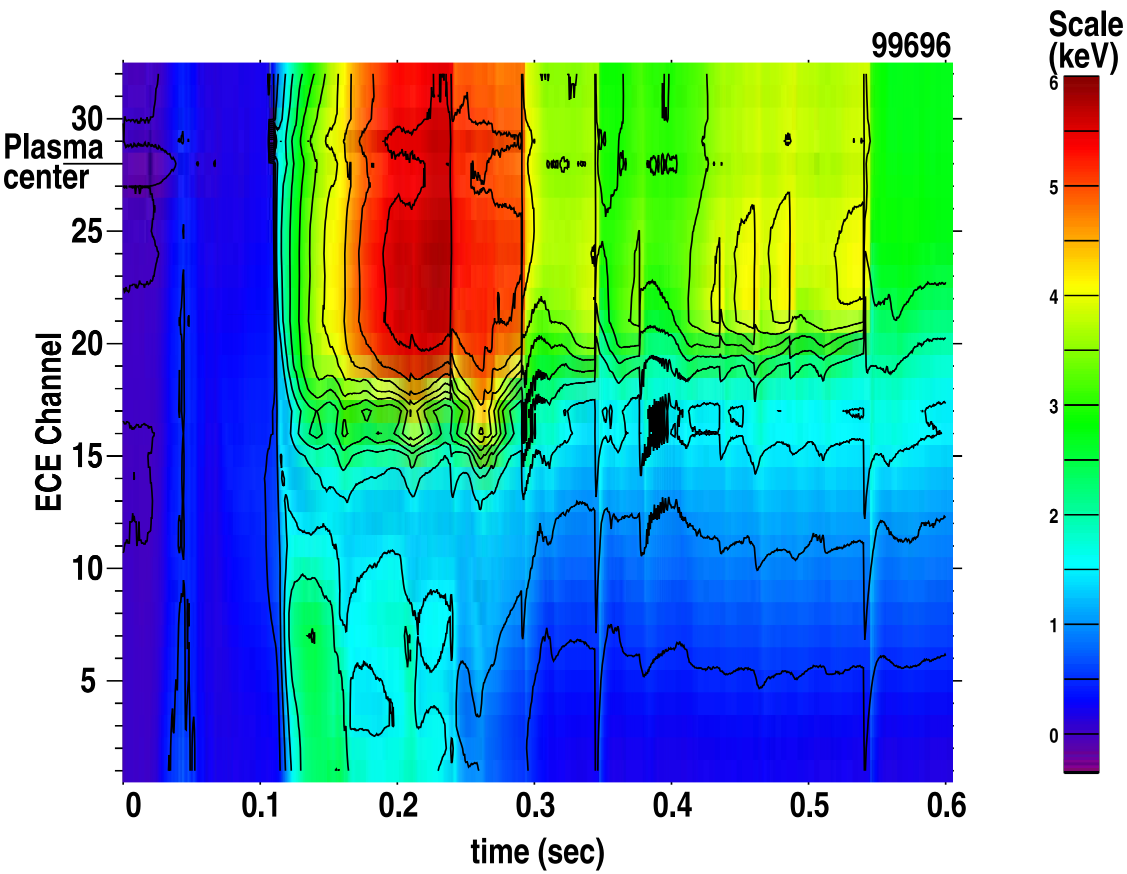
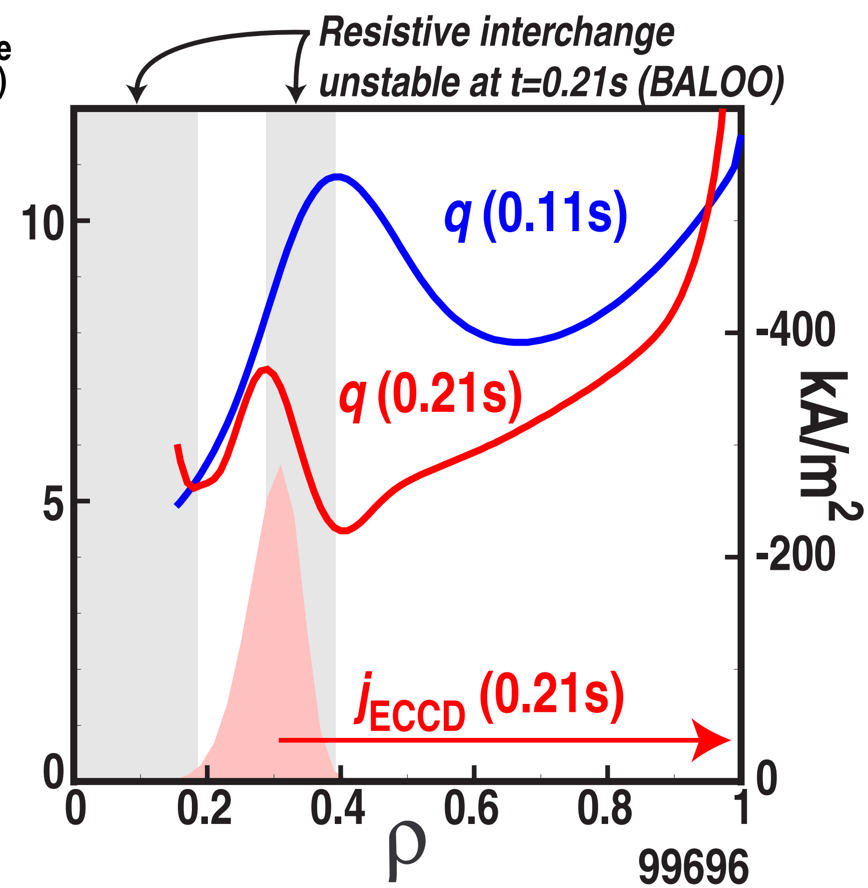
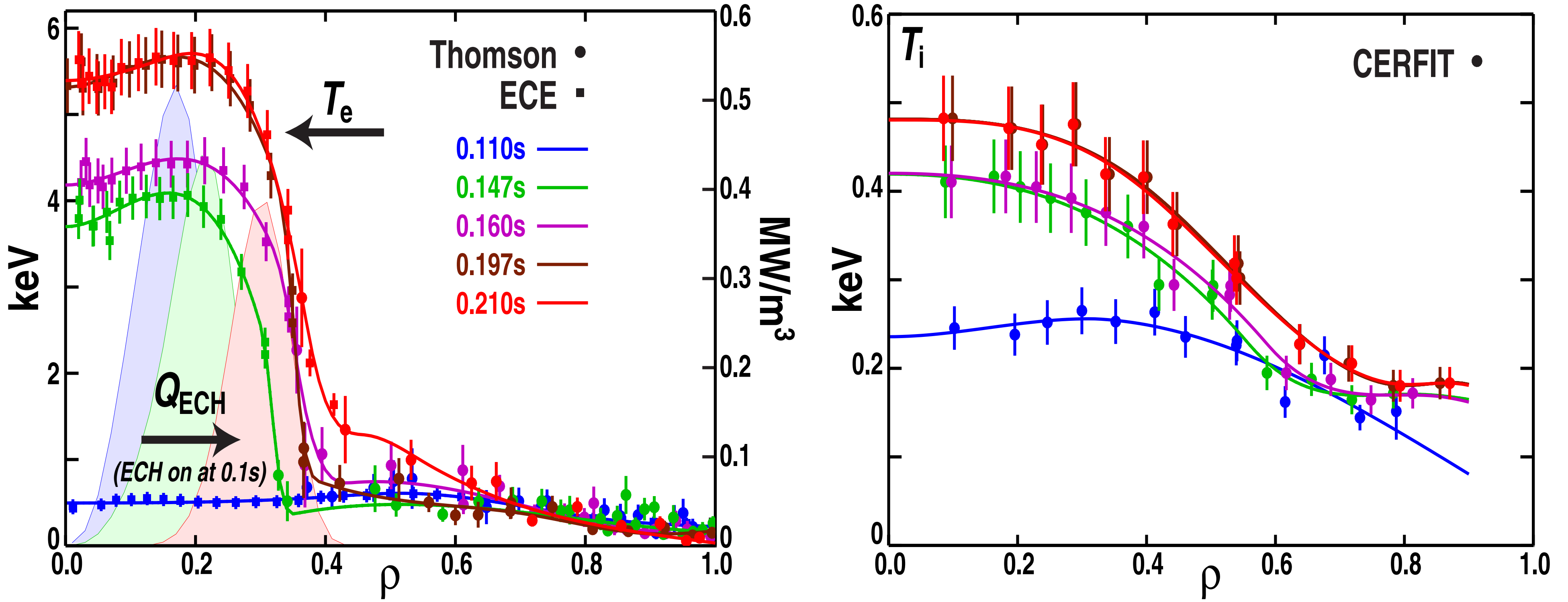
STRONG PERIODIC CONTRACTIONS OF ELECTRON TEMPERATURE PROFILE MAY BE DUE TO RESISTIVE INTERCHANGE MODE





- Calculated unstable to resistive interchange in negative shear region by BALOO at *t*=0.21s.

ELECTRON TRANSPORT BARRIER DEVELOPS RAPIDLY FOLLOWING ECH ONSET



- Profiles flat or slightly hollow inside barrier.
- Barrier location expands ahead of ECH heating location.
- Smaller response in ion channel.

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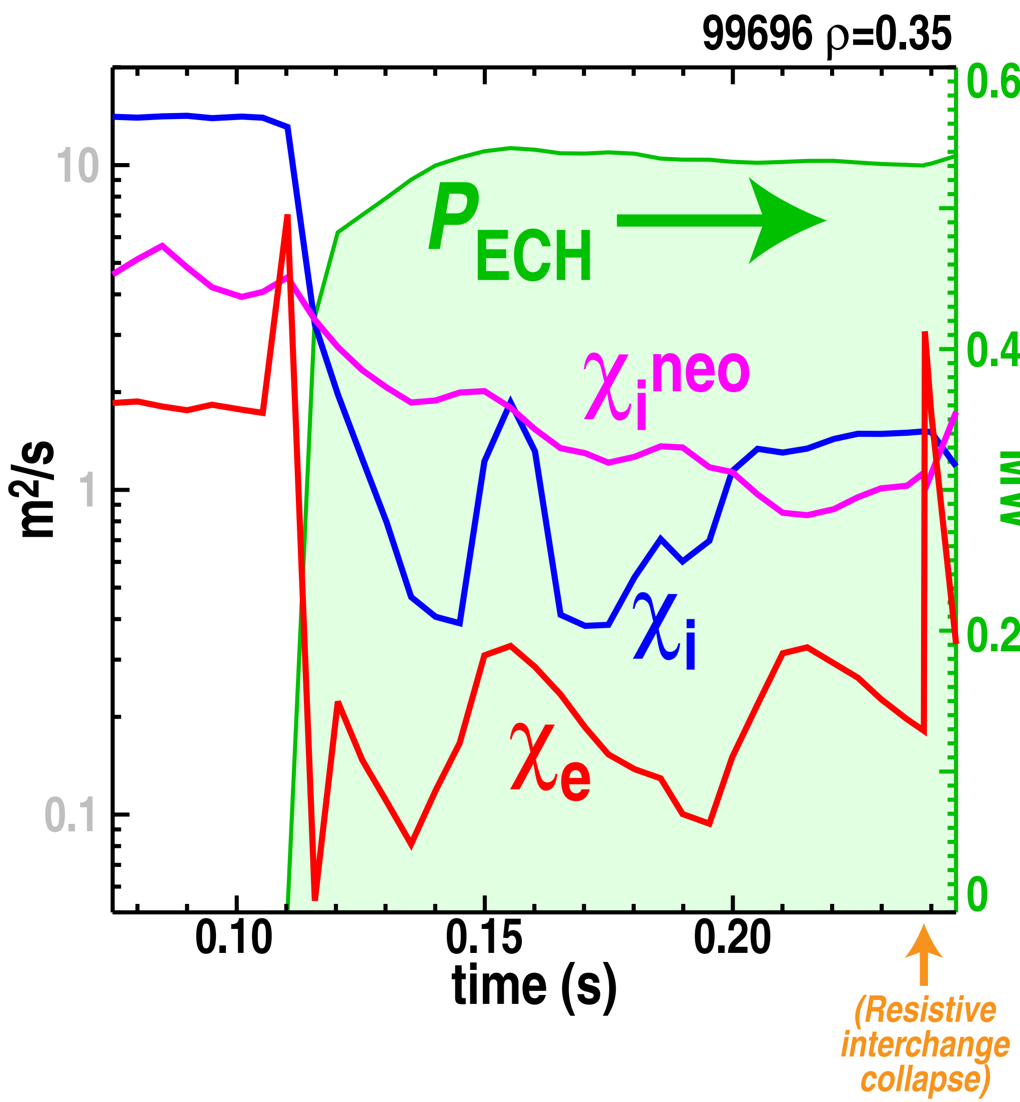
TRANSPORT DECREASES IN BOTH THE ION AND ELECTRON CHANNELS AT THE ECH TURNON

- Large uncertainties in *quantitative* transport values.
  - Uncertainty in *q* profiles.
    - Predicts large ohmic power near axis.
  - Large, localized source appears at e-ITB location due to ECH.

- *Relative change in χ profiles are more accurately determined.*

- Both ion and electron thermal transport respond to ITB formation.



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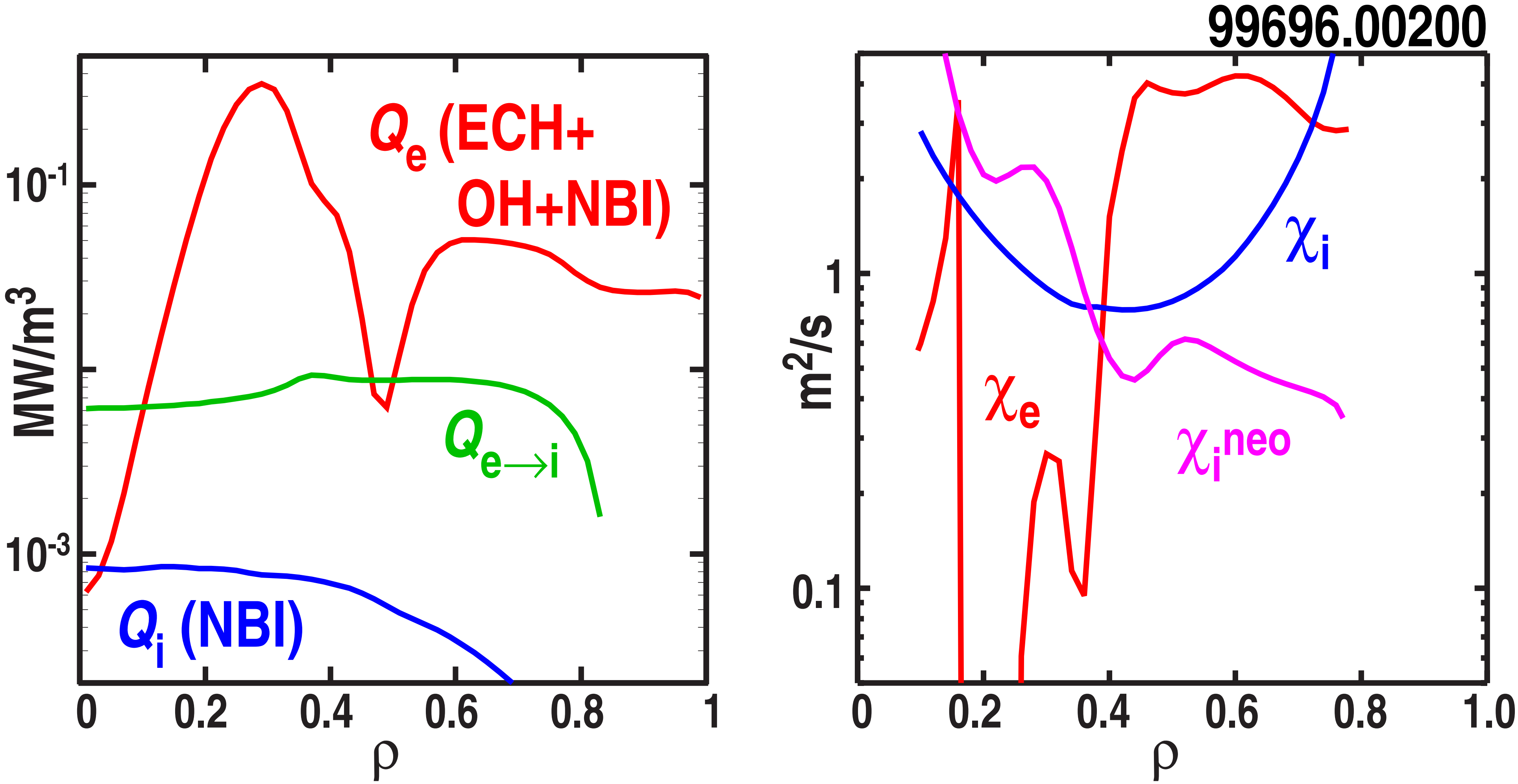
ELECTRON THERMAL TRANSPORT IS ESSENTIALLY ELIMINATED IN BARRIER REGION



- Power heating ions is very small.
  - T_i remains small despite reduced transport.

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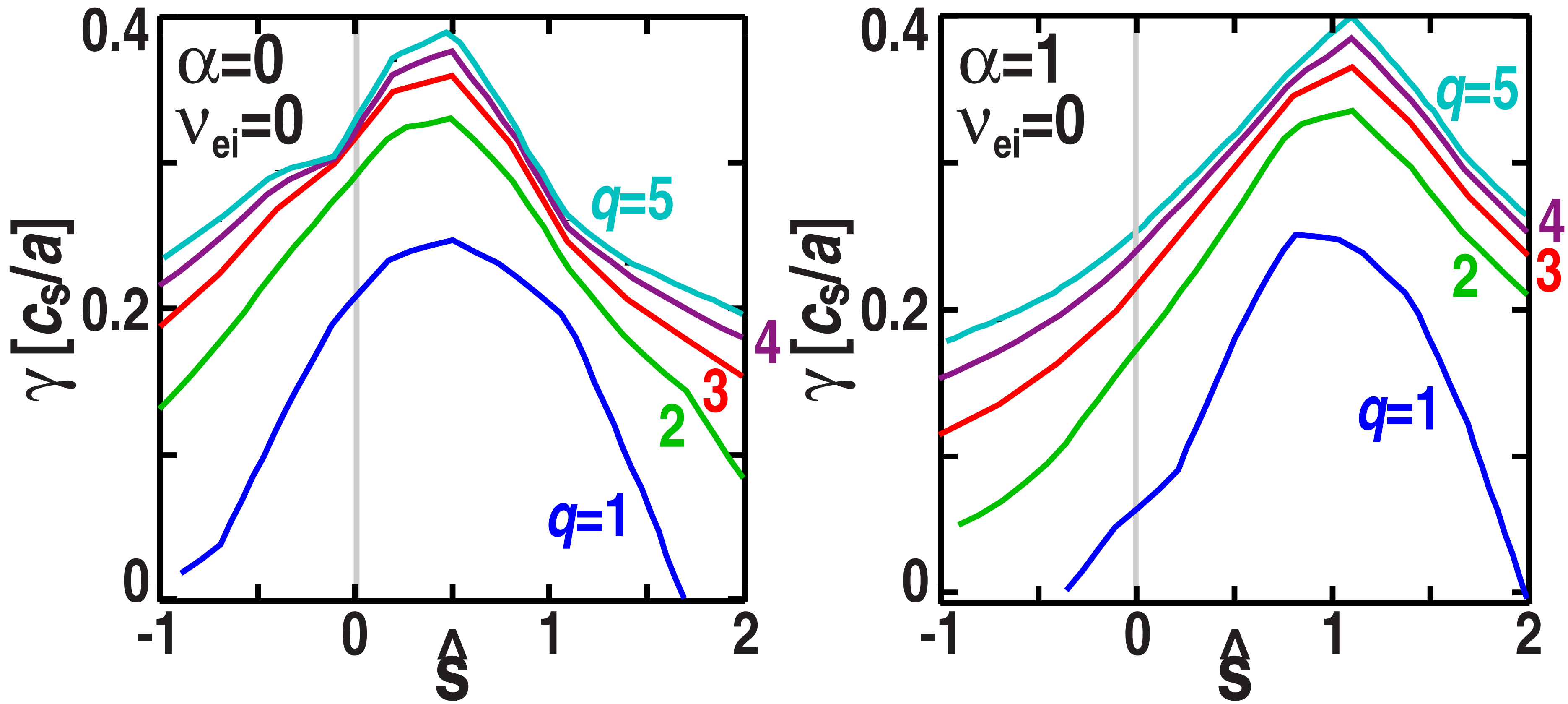
SHAFRANOV SHIFT CAN BE STRONGLY STABILIZING WITH NEGATIVE MAGNETIC SHEAR



- **Growth rate spectrum from GKS code is reduced for negative magnetic shear in the collisionless limit [Waltz, *et al.* , Phys. Plasmas 4, 2482 (1997)].**
- **Shafranov shift stabilization and α stabilization, both commonly used terms, are synonymous.**
  - $\alpha = -\mu_0 P'(\Psi) V'(\Psi) (V/4\pi R_0)^{1/2}$ **[normalized pressure gradient]**

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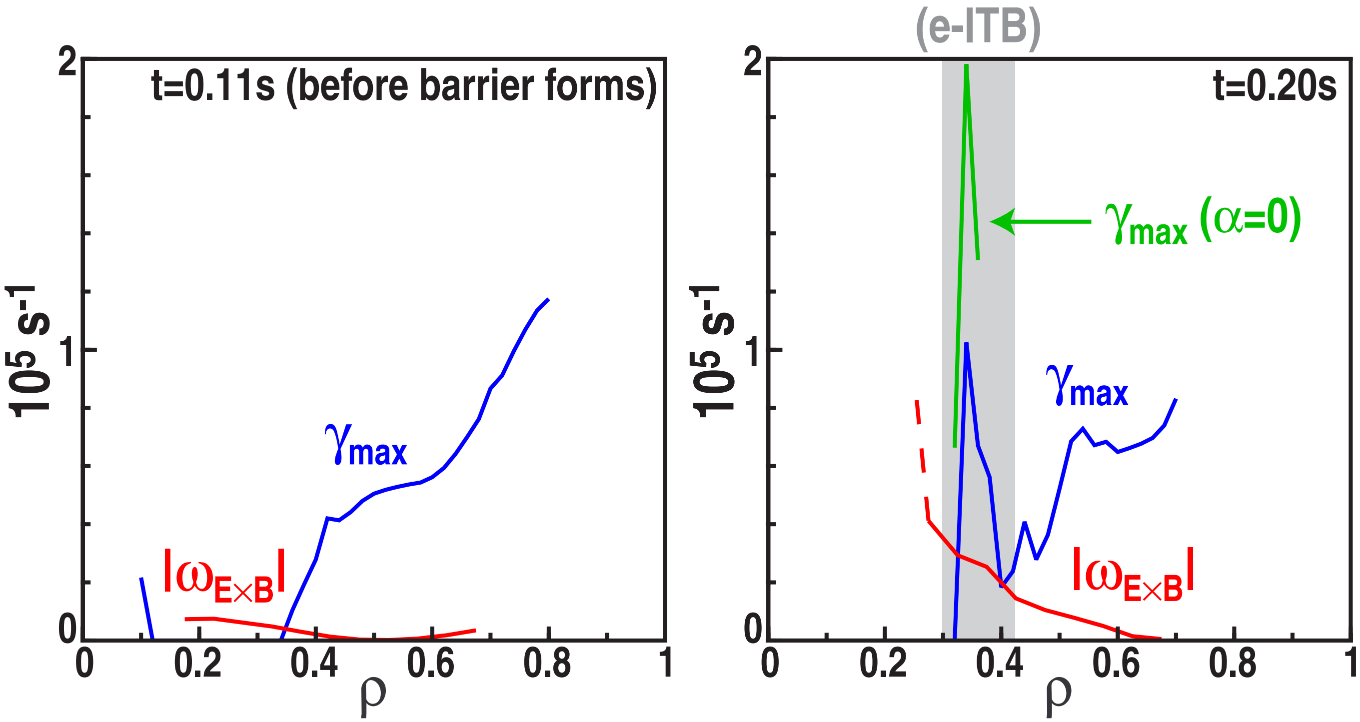
ESTIMATED E∞B SHEAR IS NOT LARGE ENOUGH TO SUPPRESS LOW-*k* MODES



- E∞B shearing rate estimated using neoclassical (NCLASS) poloidal rotation.
  - No measurement available for this discharge, but v_θ is small contribution.
  - Error bars probably significant: typically ~25% with measured v_θ.
- Growth rate for low-*k* modes somewhat exceeds shearing rate .
  - ITG and/or TEM predicted unstable... should prevent ion or electron ITB.
- Growth rate increases when α 0 (β set to zero in code).

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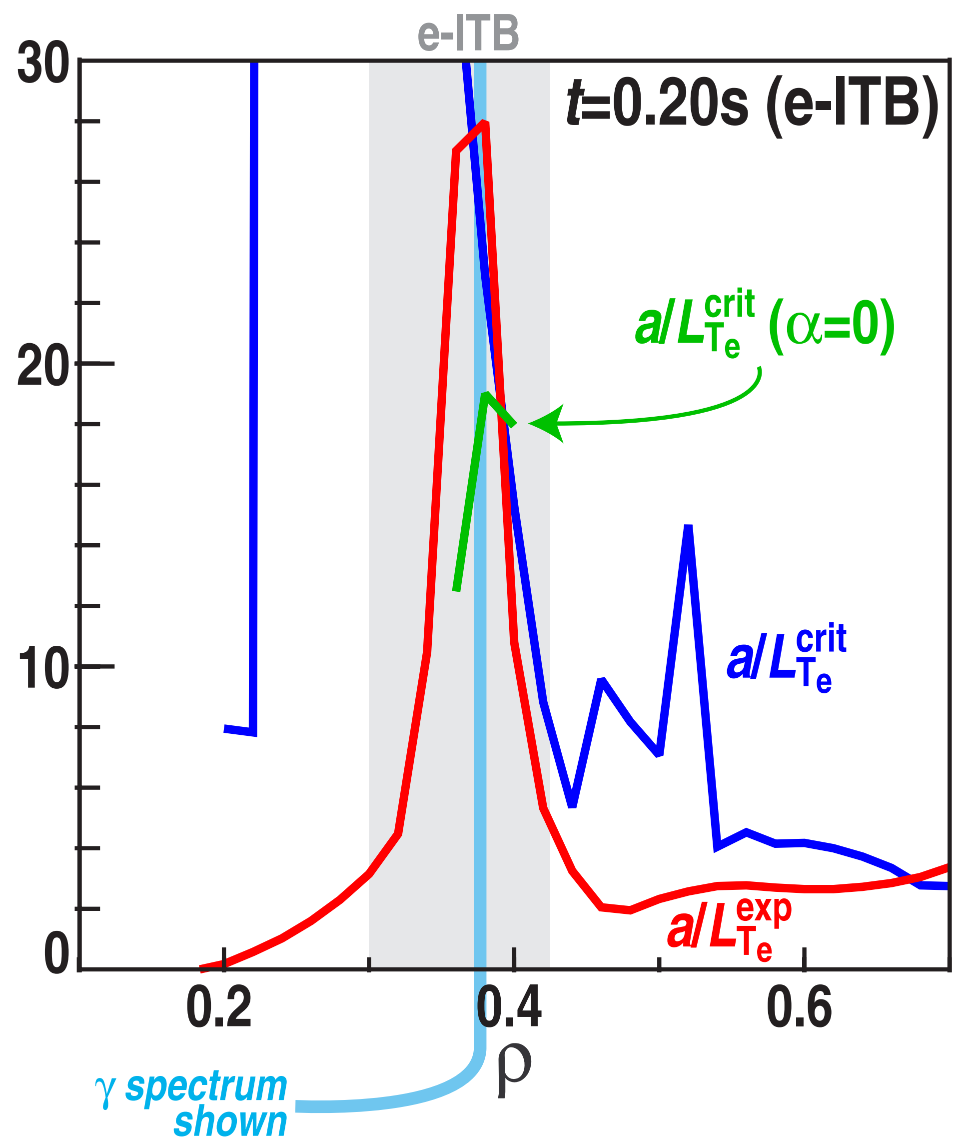
ELECTRON TEMPERATURE GRADIENT IS MARGINAL FOR STABILITY TO ETG MODES IN THE BARRIER

- **Electron temperature gradient in barrier region at marginal stability level for ETG mode.**
  - **Consistent with previous observations [B.W. Stallard, *et al.*, Phys. Plasmas 6, 1978 (1999)]**
- **α=0 (β set to zero in code) reduces critical gradient below experimental profile.**
- **Large calculated critical gradient inside barrier suspicious.**
  - **May be numerical consequence of resistive interchange instability.**



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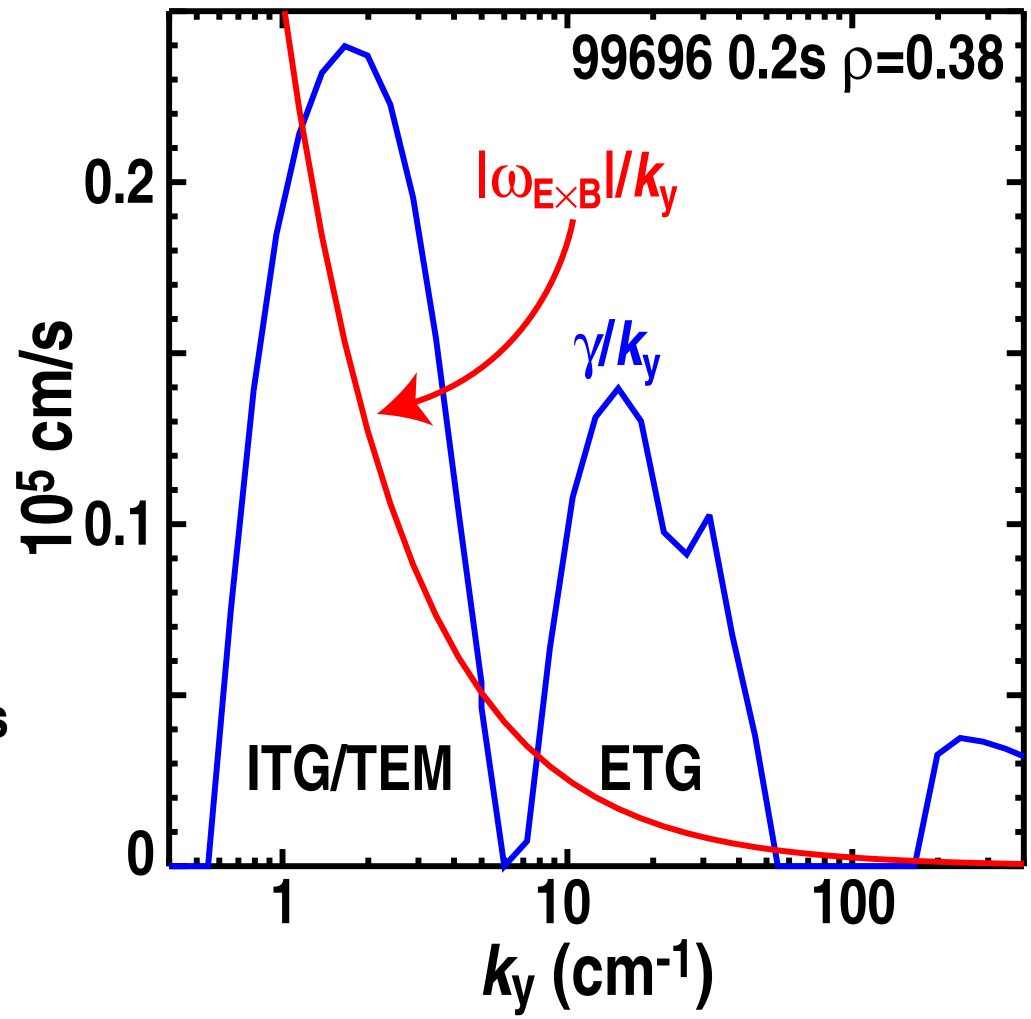
TRAPPED ELECTRON AND ELECTRON TEMPERATURE GRADIENT MODES BOTH HAVE SIGNIFICANT CALCULATED GROWTH RATES

- Spectra shown at point with peak a/L_{te}, where gradient slightly exceeds marginal level for ETG.
  - ETG feature vanishes at critical level.
  - Increases rapidly above critical level.
  - This condition can enforce marginality.



- Estimated E∞B shearing rate appears too small to suppress turbulence in either range by itself.
  - May be large enough to have an effect on low-*k* range.

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SIMULATIONS USING THE GLF23 MODEL

- The GLF23 model, which contains both heat flux and momentum bifurcation mechanisms, is used to dynamically follow bifurcations leading to the formation of ITBs.
  - Includes ITG (ion temperature gradient mode), TEM (trapped electron mode), ETG (electron temperature gradient mode).

- The simulations are carried out taking the density profile, *q*-profile, sources, sinks, and equilibrium from a power balance analysis (TRANSP).

- The temperature and toroidal velocity profiles are initialized at pre-barrier levels and are evolved while computing the effects of E∝B shear stabilization using the predicted profiles.
  - E∝B shear computed with all three terms including predicted T and v_φ.

- Boundary conditions are enforced at ρ=0.9 using experimental data.

- GLF23 model has been parallelized using MPI and is exercised In the XPTOR code which typically runs with 10 processors on the GA Luna Linux cluster.

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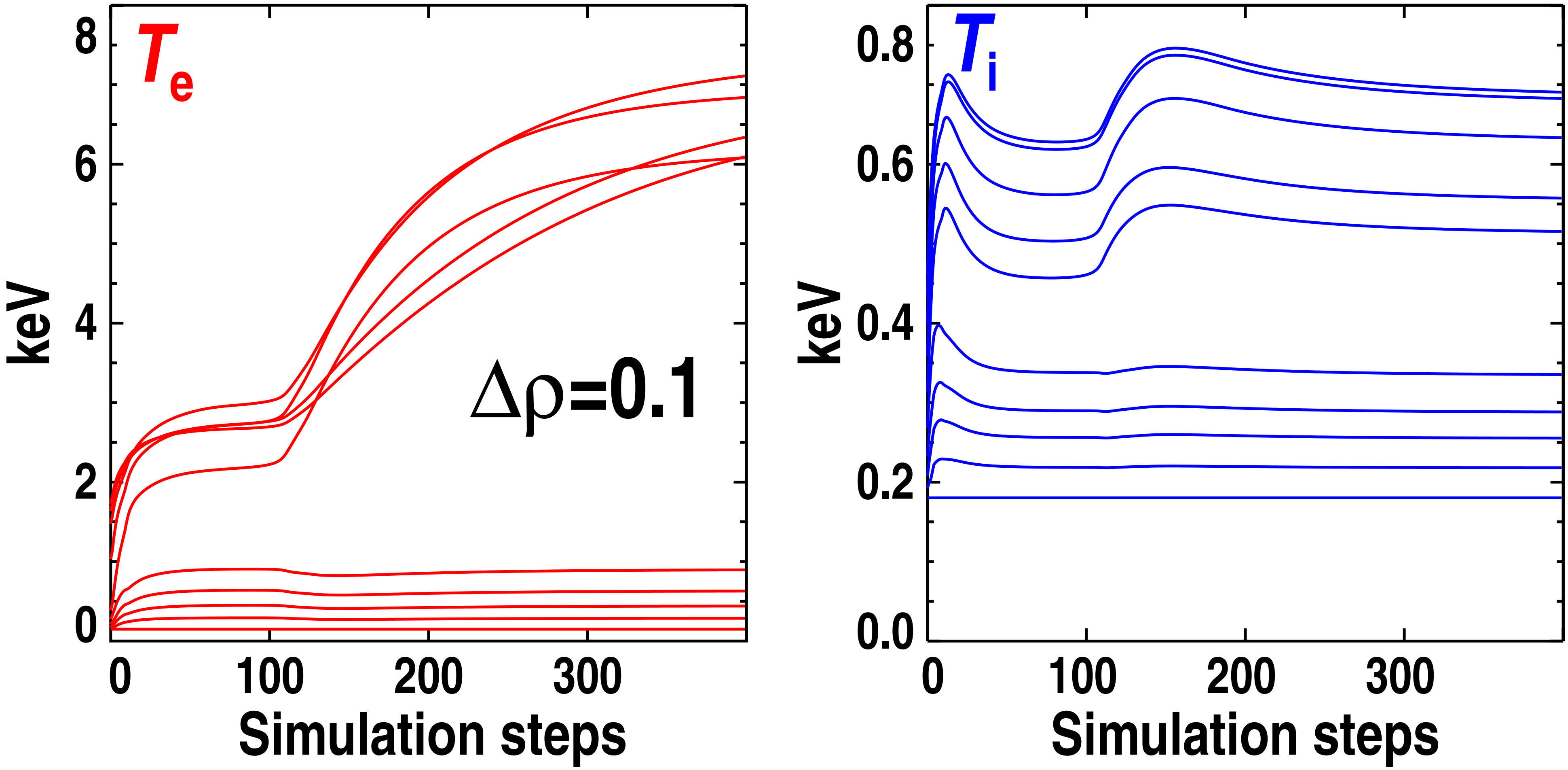
BIFURCATION IN ELECTRON TEMPERATURE PROFILE IS PREDICTED BY GLF23 MODEL



- Simulated evolution predicts barrier formation in T_e profile.
- Dynamic formation requires α to be increased by a factor of 1.35 above that calculated directly from the simulated profiles.
  - Well within experimental or numerical uncertainty.

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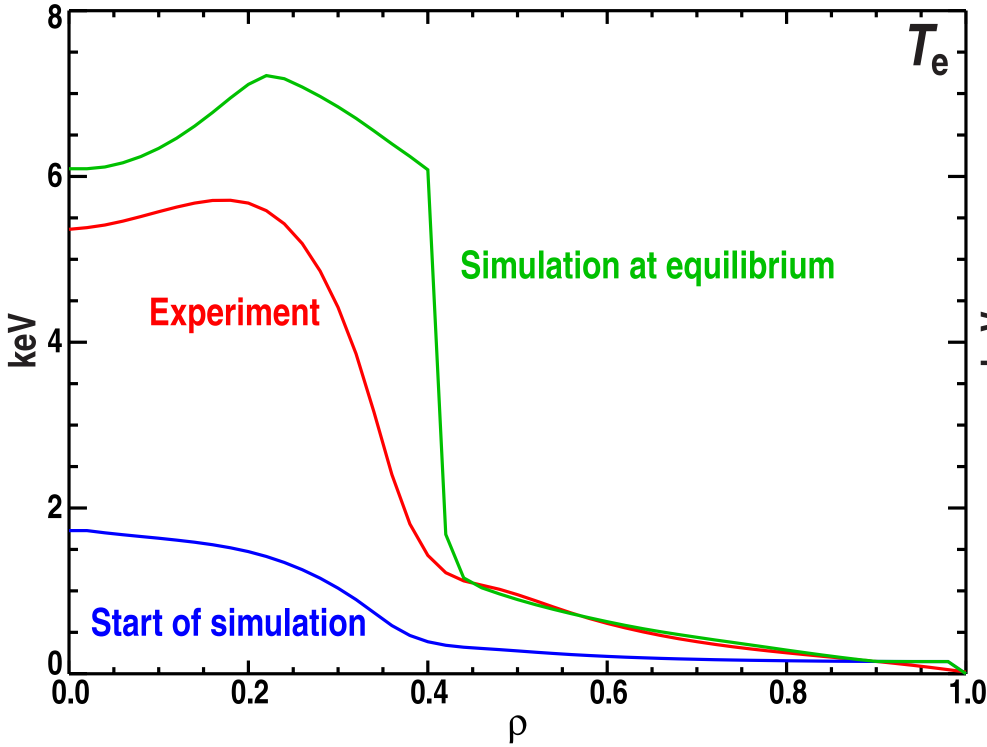
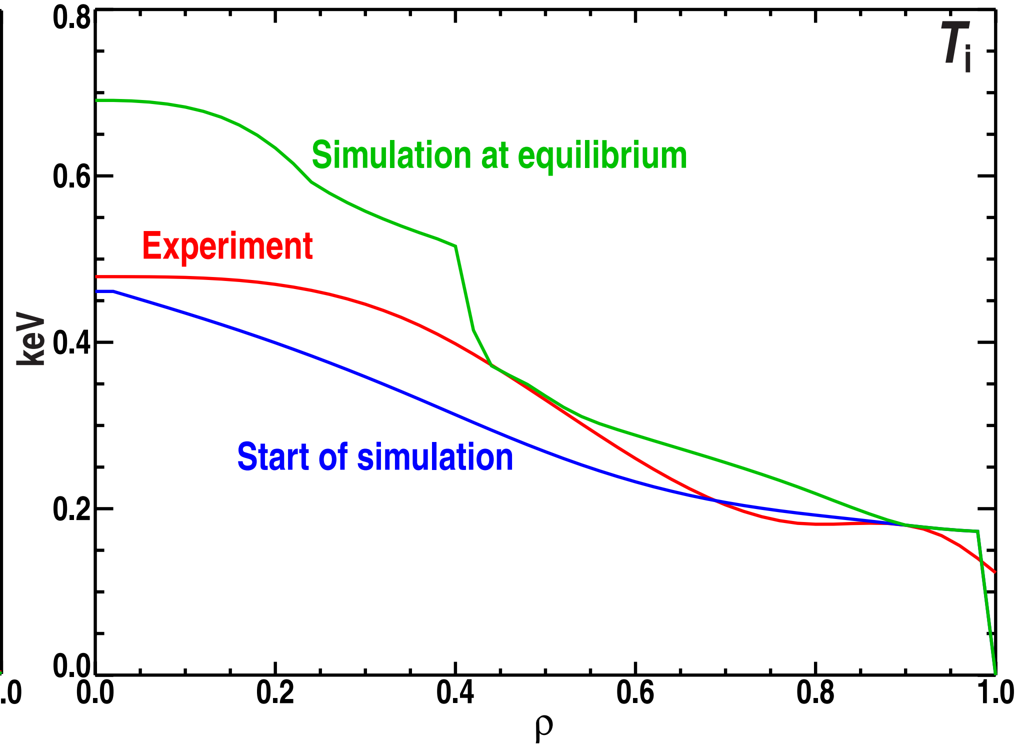
TIME DEPENDENT SIMULATION REPRODUCES ELECTRON THERMAL TRANSPORT BARRIER





- **Simulation begins with experimental profiles prior to barrier formation.**
- **Electron ITB forms if α is sufficiently large.**
  - **$\alpha = c_\alpha \alpha^{calc}$, where α^{calc} is the value of α calculated from the profiles used by the code, and c_α is an arbitrary coefficient.**
  - **No barrier forms when $c_\alpha < 1.35$.**
  - **Without $E \infty B$ shear, $c_\alpha \geq 1.7$ required for barrier formation.**

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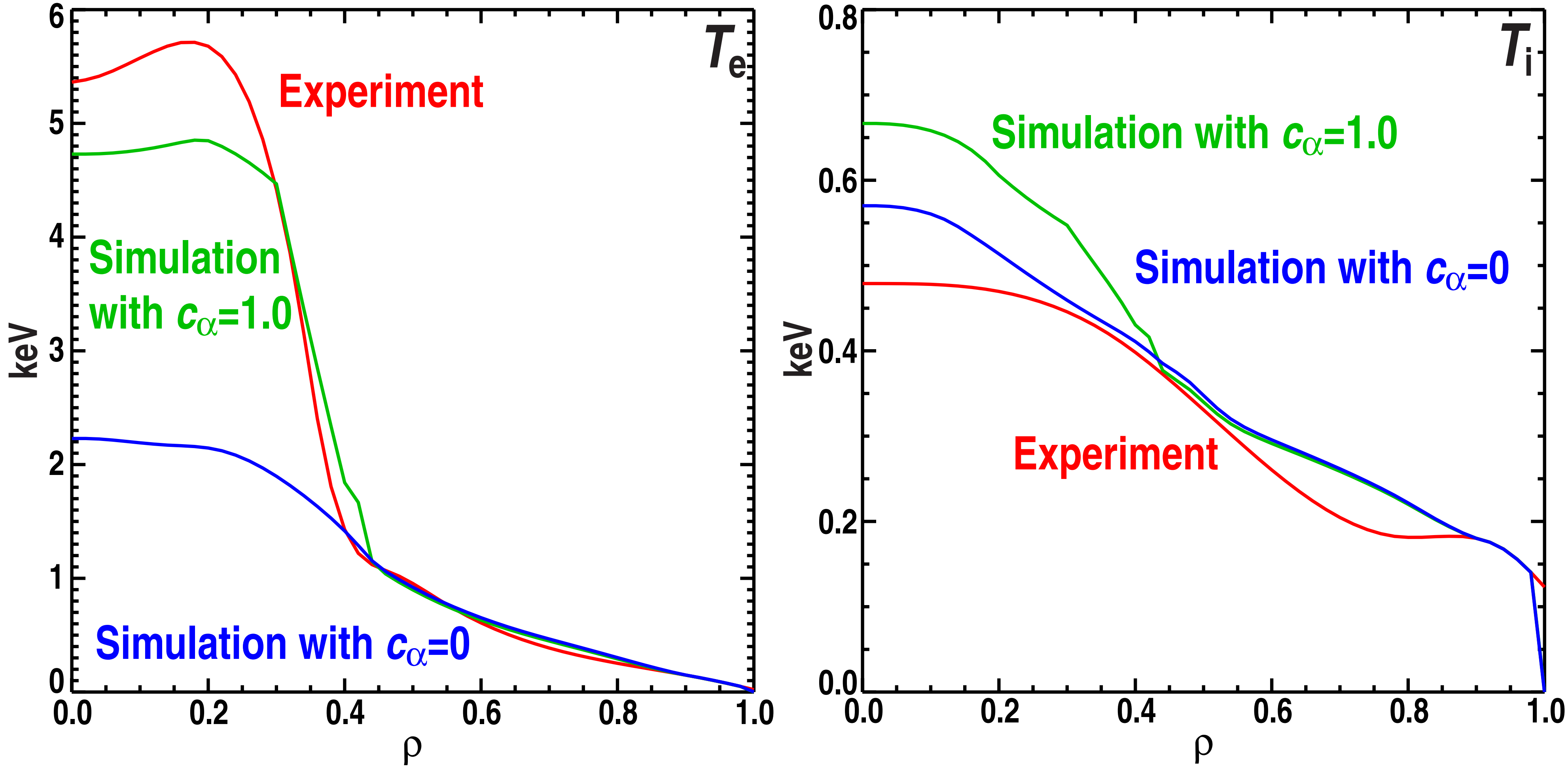
THE BARRIER IS ONLY MAINTAINED WHEN THE EFFECTS OF FINITE PRESSURE ARE INCLUDED



- Simulations start with experimental profiles of fully developed e-ITB and run to steady-state.

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PHYSICAL PROCESSES BELIEVED IMPORTANT FOR ITB FORMATION

- Our working model assumes that turbulence must be reduced or eliminated to form a core barrier.
  - Low-*k* turbulence (ITG, TEM):
    - Affect both ion and electron thermal transport.
    - Can be stabilized by E×B shear and/or finite α.
  - High-*k* turbulence (ETG):
    - Affects electron thermal transport only.
    - Not affected by E×B shear: small spatial scale and large growth rates.
    - α-stabilization can stabilize these modes.
- Both E×B shear and α-stabilization can trigger ion thermal ITB.
  - Modification of terms in E×B shearing rate can change barrier characteristics.
    - Barrier broader with counter-NBI.
- Electron thermal ITB requires additional stabilization.
  - Provided by α-stabilization.
  - Conditions for ion ITB necessary but not sufficient for electron ITB.
  - Implies electron ITB not possible in absence of ion ITB.
    - Exploitation of ion ITB requires additional ion heating power.

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