CONTROL OF INTERNAL TRANSPORT BARRIERS IN DIII-D*

C.M. Greenfield, E.J. Doyle,[1] E.J. Synakowski,[2] K.H. Burrell, J.C. DeBoo, P. Gohil, G.L. Jackson, J.E. Kinsey,[3] G.R. McKee,[4] M. Murakami,[5] R.I. Pinsker, R. Prater, C.L. Rettig,[1] T.L. Rhodes,[1] G.M. Staebler, B.W. Stallard[6]

General Atomics
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1 UCLA 2 PPPL PRINCETON PLASMA PHYSICS LABORATORY 3 LEHIGH University 4 UNIVERSITY OF WISCONSIN MADISON 5 ornl 6

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GENERAL ATOMICS

OVERVIEW

- E×B shear is leading effect in creating internal transport barriers (ITB).
  - 1999: ITBs broader with counter-NBI than in similar discharges with co-NBI.
    - Co–NBI: Rotation dominates and opposes pressure gradient contribution to E×B shearing rate; increased or broadened pressure profile is *destabilizing* to turbulence.
    - Counter-NBI: Pressure gradient term dominates; increased or broadened pressure profile is *stabilizing* to turbulence.
  - 2000: Quiescent Double-Barrier regime (with sustained $\beta_N H^{89} \leq 7$) combines counter-injected ITB and steady-state ELM-free H-mode edge condition.
    - Separation between core and edge barriers provided by null in E×B shearing rate.
- 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 identify α-stabilization (also known as Shafranov shift stabilization) as trigger mechanism for electron ITB.

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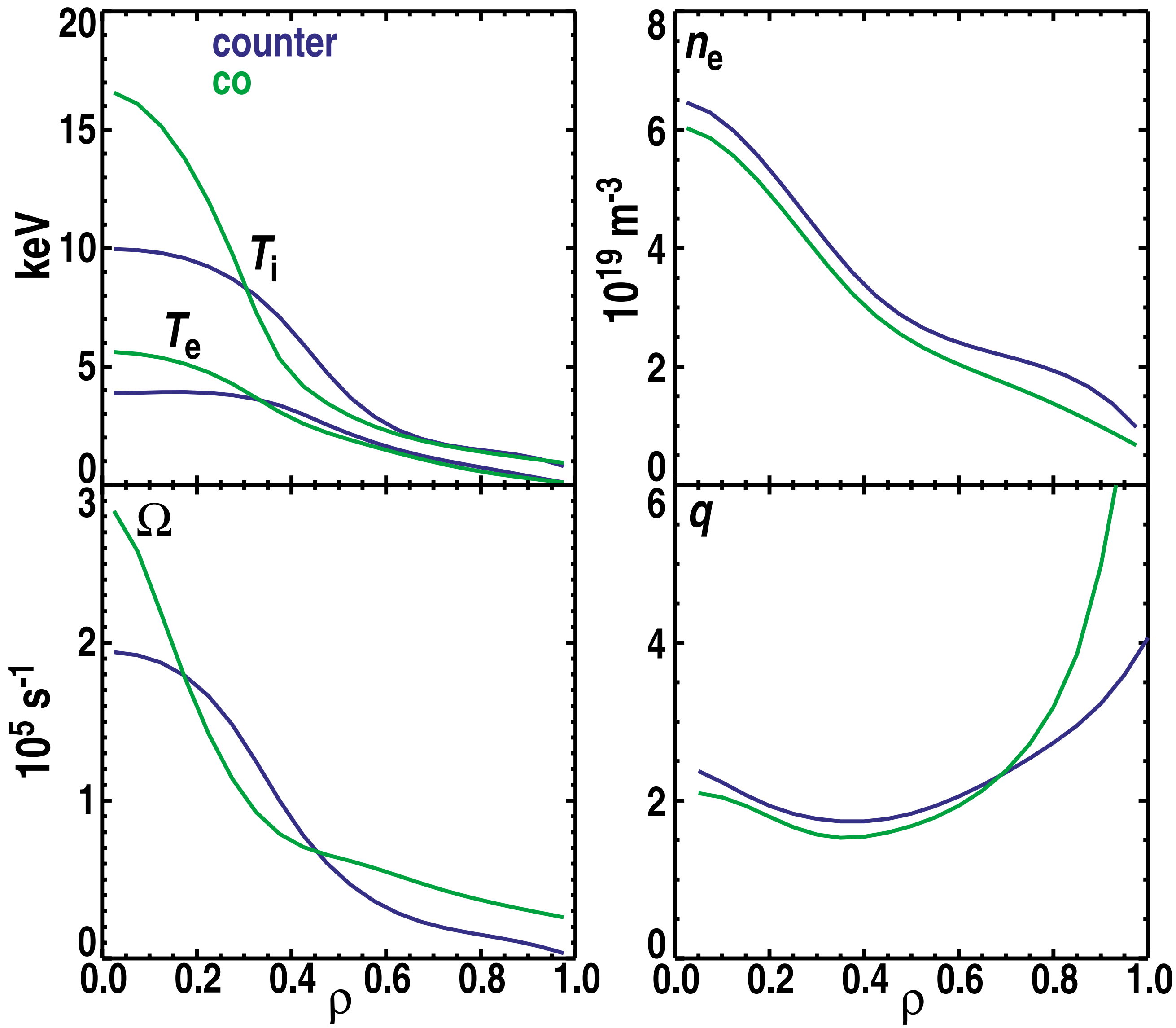
COUNTER-NBI RESULTS IN BROADER PROFILES

- 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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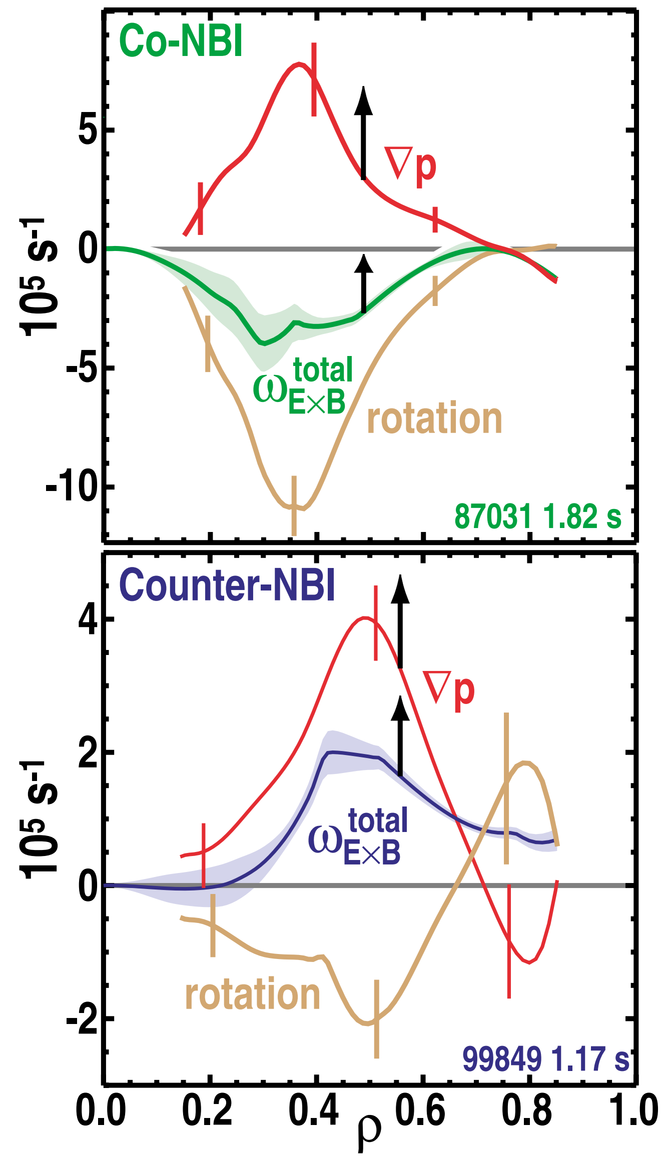
COUNTER-NBI IS FAVORABLE FOR ITB EXPANSION DUE TO INTERPLAY OF TERMS IN E×B SHEARING RATE

- Shearing rate $\omega_{E\times B}$ can be separated into pressure gradient and rotation terms.
  - Total shearing rate is species independent, but individual terms depend on species.
  - Calculation shown is for main (deuterium) ions:
    - Total $\omega_{E\times B}$ from CER carbon impurity measurements.
    - ∇p term uses TRANSP calculation of main ion thermal density.
    - Rotation term by subtraction.
- Counter-NBI is more favorable than co-NBI for barrier expansion:
  - Co: rotation term dominates $\Rightarrow \omega_{E\times B}$ *decreases* with increased or broadened pressure profile $\Rightarrow$ *turbulence is destabilized.*
  - Counter: ∇p term dominates $\Rightarrow \omega_{E\times B}$ *increases* with increased or broadened pressure profile $\Rightarrow$ *turbulence is stabilized.*



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DISTINCT CORE AND EDGE BOUNDARIES COEXIST IN THE QUIESCENT DOUBLE-BARRIER REGIME

- Distinct barriers coexist in larger devices, but only with degradation of the ITB in co-injected discharges in DIII–D:
  - With ELMs: ELMs penetrate plasma and impede core barrier.
  - ELM-free: Core and edge barriers merge.
    - Ion thermal transport can become neoclassical throughout entire plasma, but cannot be sustained.

- Double-barrier mode predicted with counter-NBI in DIII–D:
  - E_r strongly negative both in core and at edge (H–mode) barriers.
    - Flattening of E_r profile inside H–mode edge locally removes E×B shear stabilization.
  - Inherent low confinement region expected to separate core and edge.

- Quiescent H-mode edge allows core barrier to exist without ELM degradation:
  - Quiescent Double-Barrier (QDB) regime allows sustained high performance.

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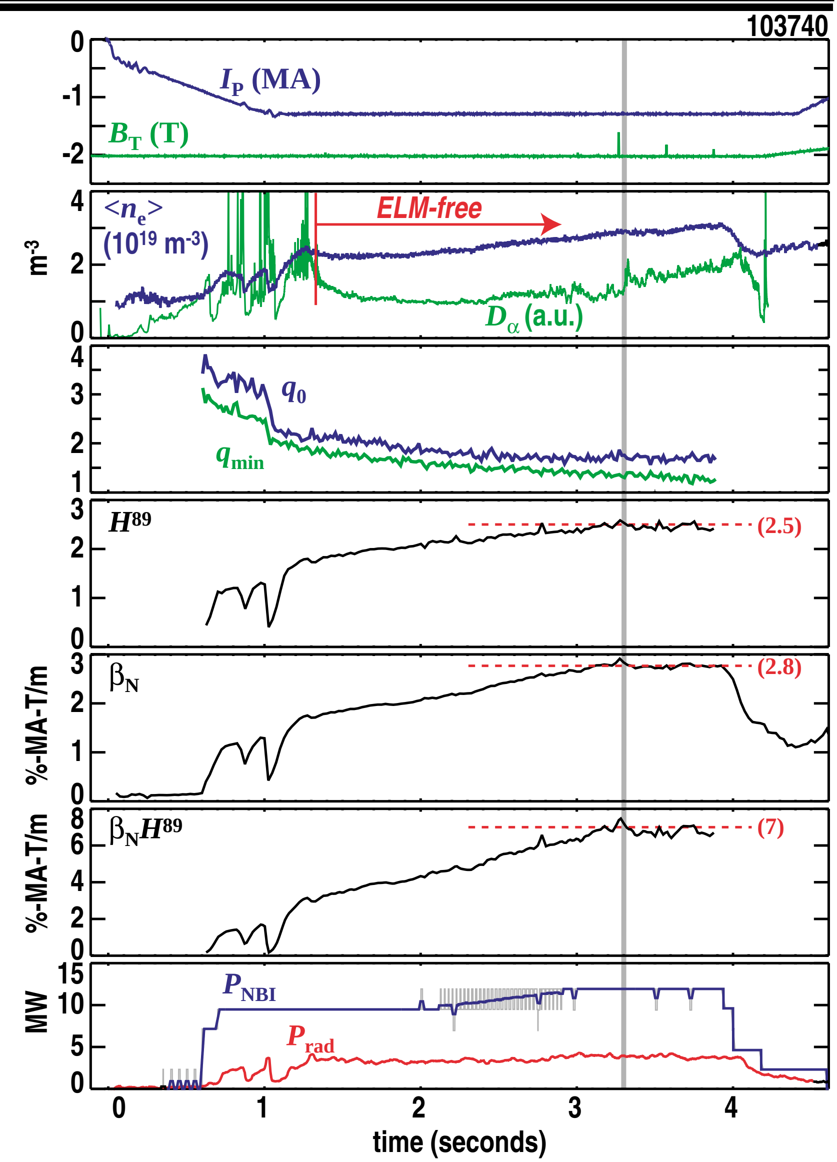
SUSTAINED HIGH PERFORMANCE IN THE QUIESCENT DOUBLE-BARRIER REGIME

- Quiescent double-barrier (QDB) regime combines:
  - Quiescent H-mode edge barrier:
    - Only observed with counter-NBI.
    - Edge Harmonic Oscillation (EHO): a benign replacement for ELMs.
    - Density control achieved through divertor cryopumping.
      - Particle flux enhanced by EHO.
  - Core barrier:
    - Characteristics similar to L-mode edge ITB with a pedestal.
    - Constant over lifetime of QDB regime.
- Counter-NBCD maintains $q_{min} > 1$.
- Parameters obtained to date (all with I_P=1.3MA, B_T=1.8-2.1T):
  $\beta_N \le 2.9$, $H^{89} \le 2.5$, $\beta_N H^{89} \le 7$, $S_N \le 4 \times 10^{15}$ neutrons/s
- Sustained for length of beam pulse.



(H^{89} corrected for beam ion orbit losses: increased by ~10%)

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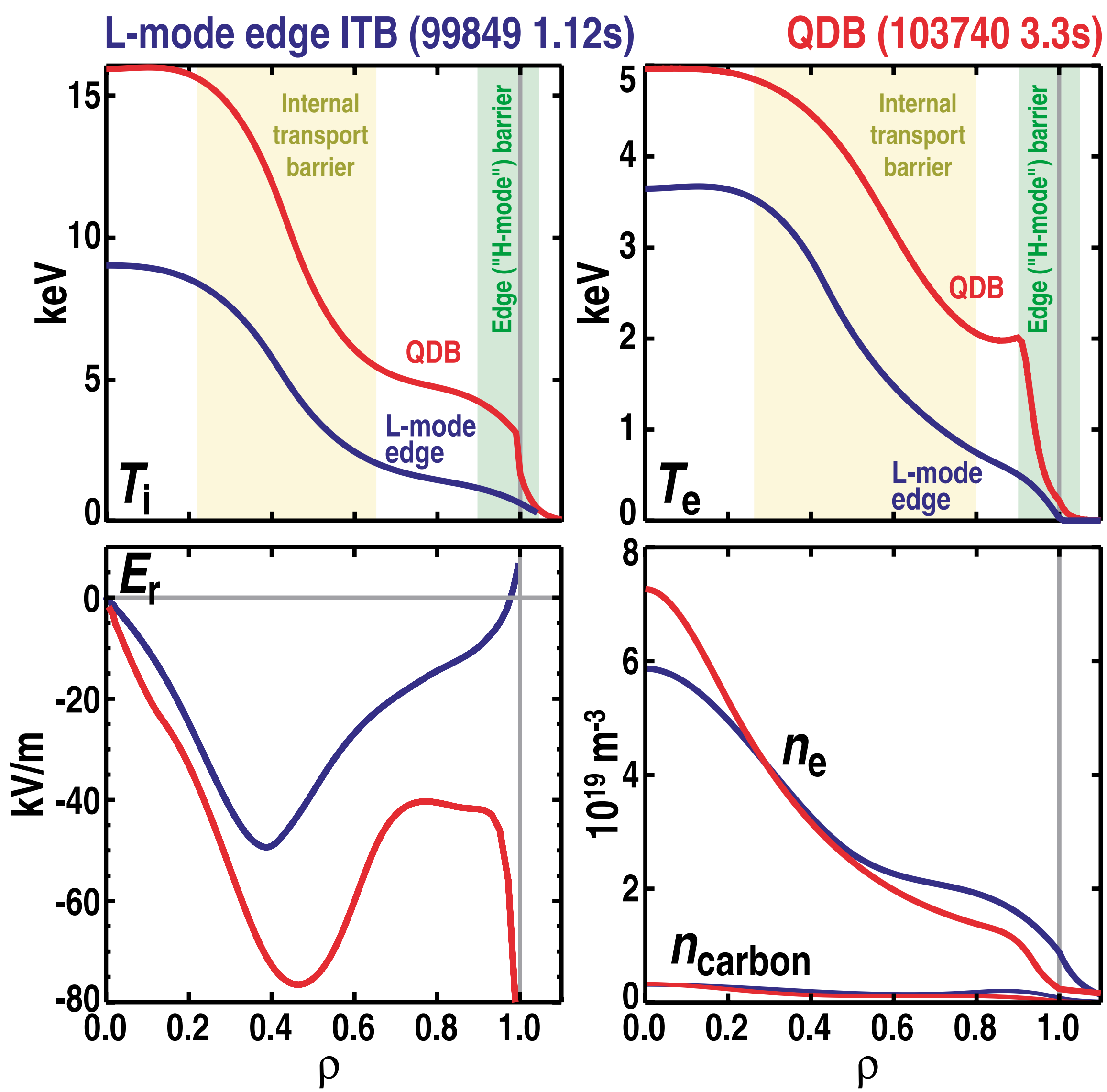
Doyle, M01.007

COUNTER-NBI HEATED CORE BARRIER PERSISTS WITH THE ADDITION OF AN H-MODE EDGE

- Core profiles similar to L-mode edge ITB with additional edge pedestal.
- Flat region in E_r profile corresponds to separation between core and edge barriers.
  - Note that the barriers frequently merge in co-NBI discharges in DIII-D.



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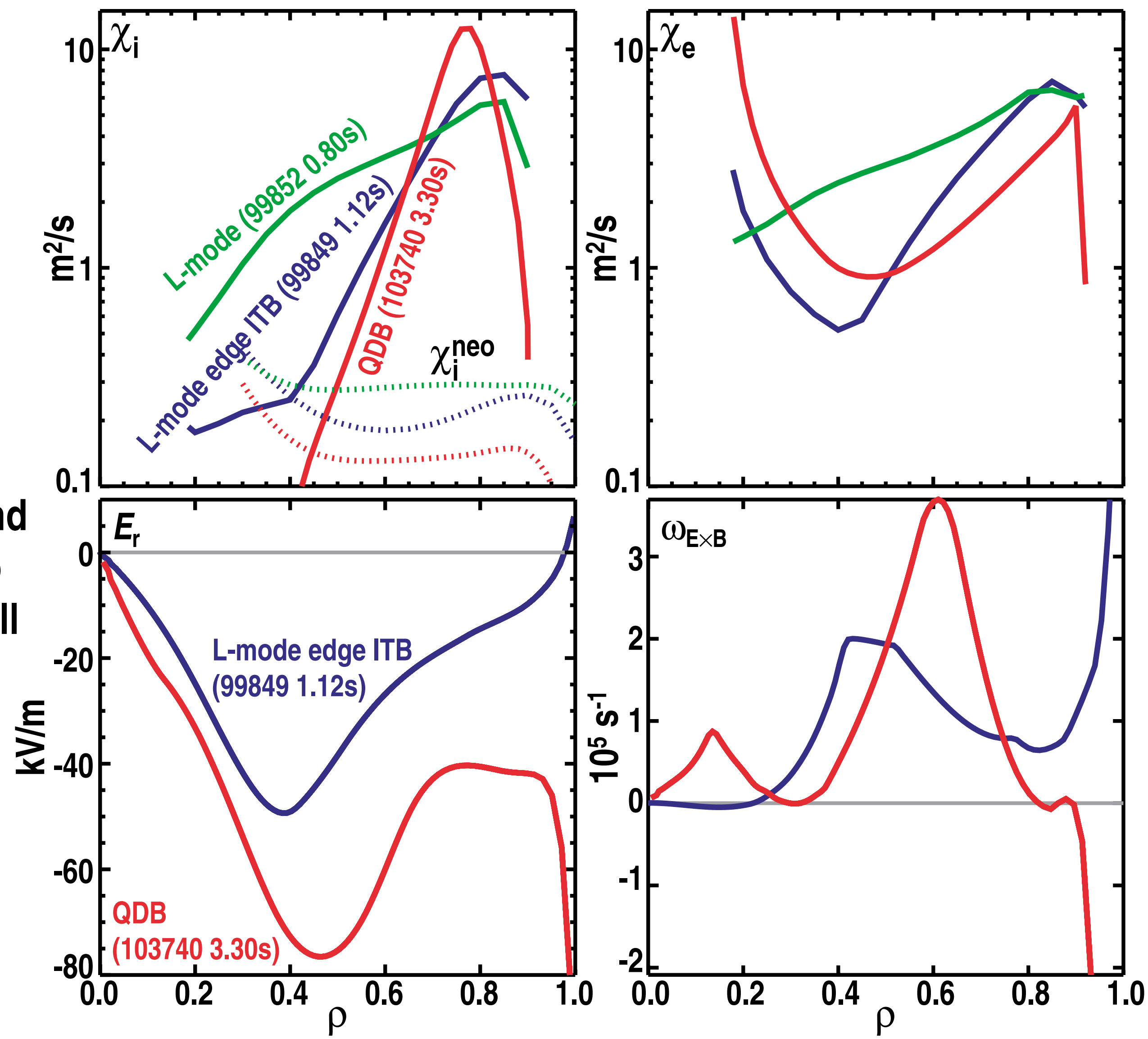
CORE TRANSPORT IN QDB REGIME SIMILAR TO L-MODE EDGE ITB

- **Core transport with ITB reduced to similar levels regardless of L- or H-mode (QDB) edge.**
  - **Second barrier appears near edge of QDB discharge.**

- **Separation between edge and core barriers corresponds to flattening of E_r profile and null in shearing rate $\omega_{E\times B}$.**

- ***All three discharges with counter-NBI.***



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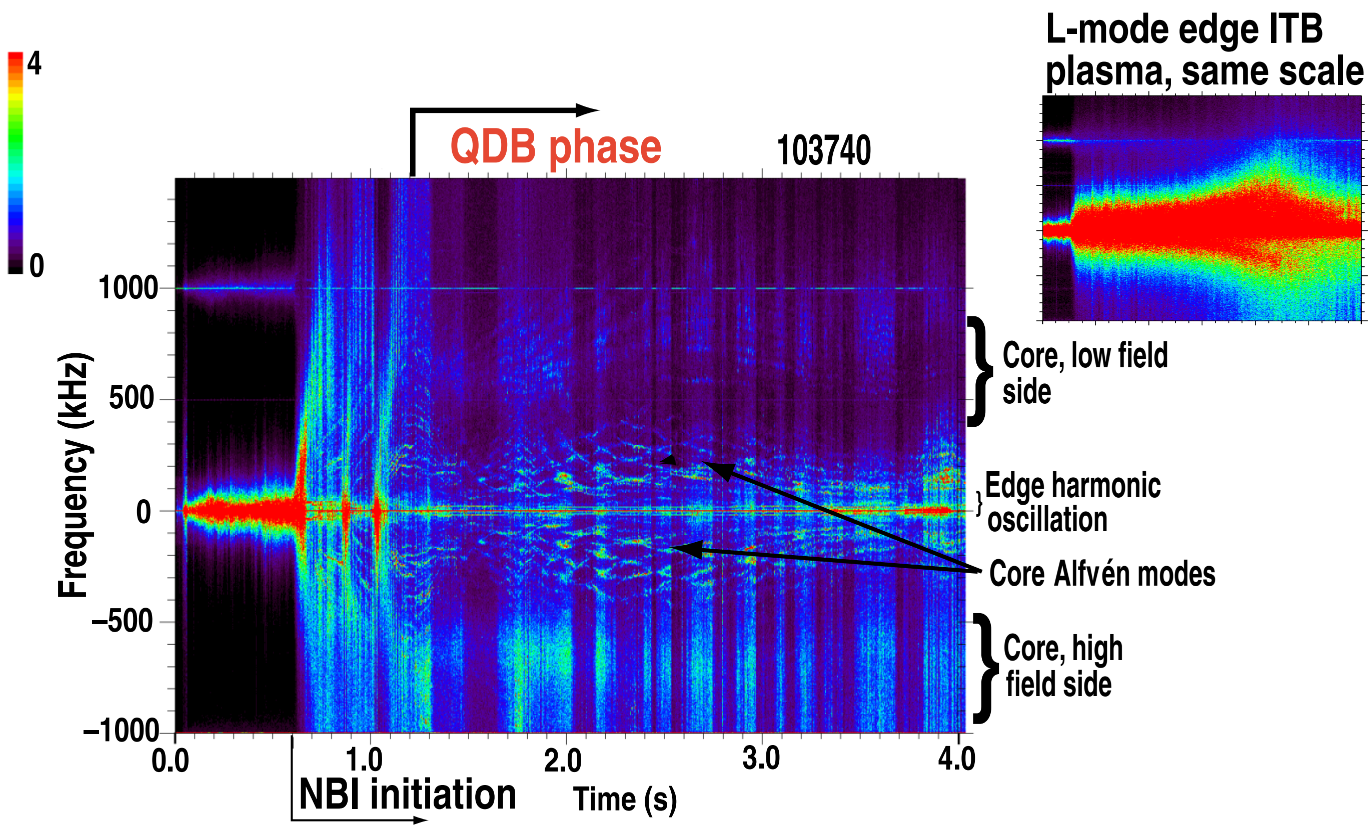
TURBULENCE IS REDUCED THROUGHOUT MOST OF THE QDB PLASMA

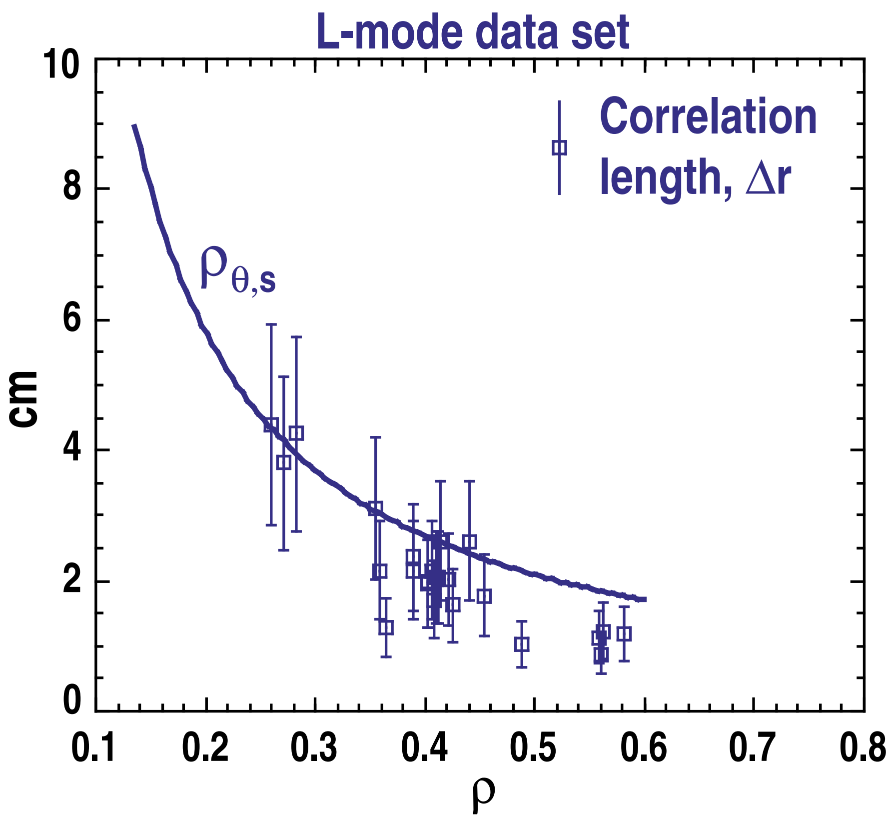
- With reduced broadband turbulence, core Alfvén modes are clearly visible in FIR scattering data, as are the low frequency edge harmonic oscillations associated with QH-mode operation.

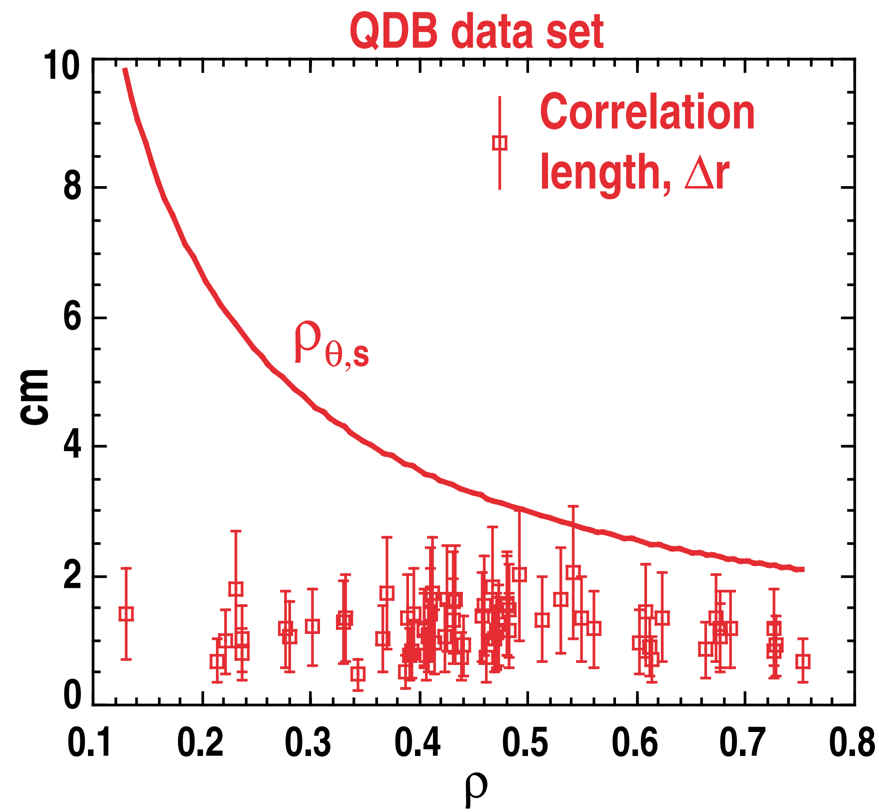


DECREASED CORE TURBULENCE CORRELATION LENGTHS IN QDB REGIME INDICATE REDUCED TURBULENCE TRANSPORT STEP SIZE

- In L-mode, correlation lengths are observed to scale approximately with the poloidal ion gyroradius $\rho_{\theta,s}$ (or 5-8 ρ_s)

- In QDB discharges, core correlation lengths are significantly different: factor of 2-8 smaller than L-mode.





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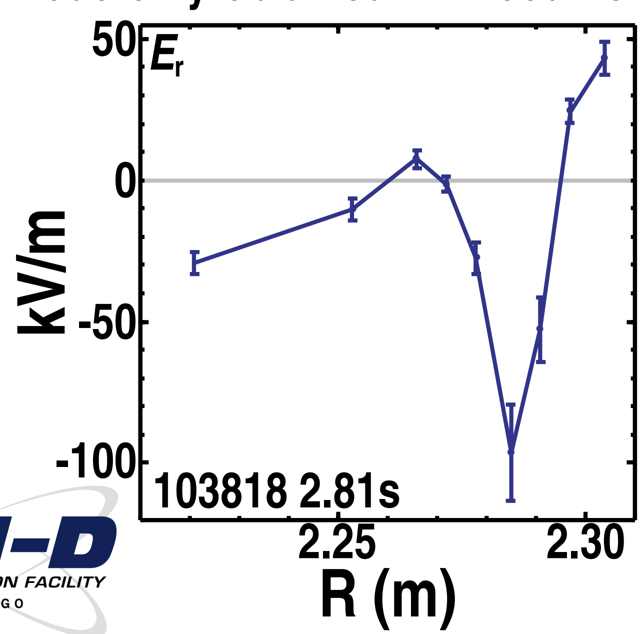
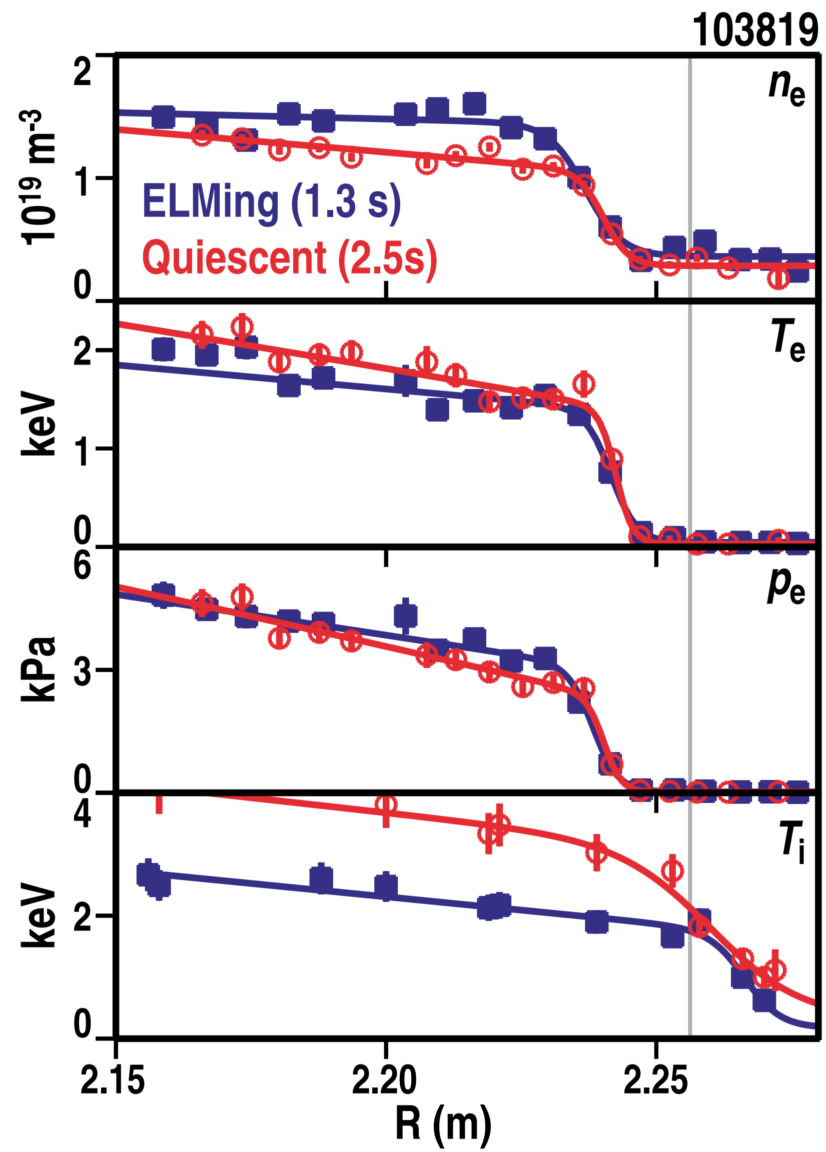
THE ELMLESS "QUIESCENT H-MODE" EDGE IS A KEY FEATURE OF THE QDB REGIME

- ELM-free regime... but particle transport near boundary is sufficient to allow density control via cryopumping.
- Edge gradients similar to ELMing phase.
  - Extremely deep E_r well.
- Elimination of ELMs' periodic divertor heat pulses a desirable feature for reactor class devices.
- QH-mode only obtained with counter-NBI.





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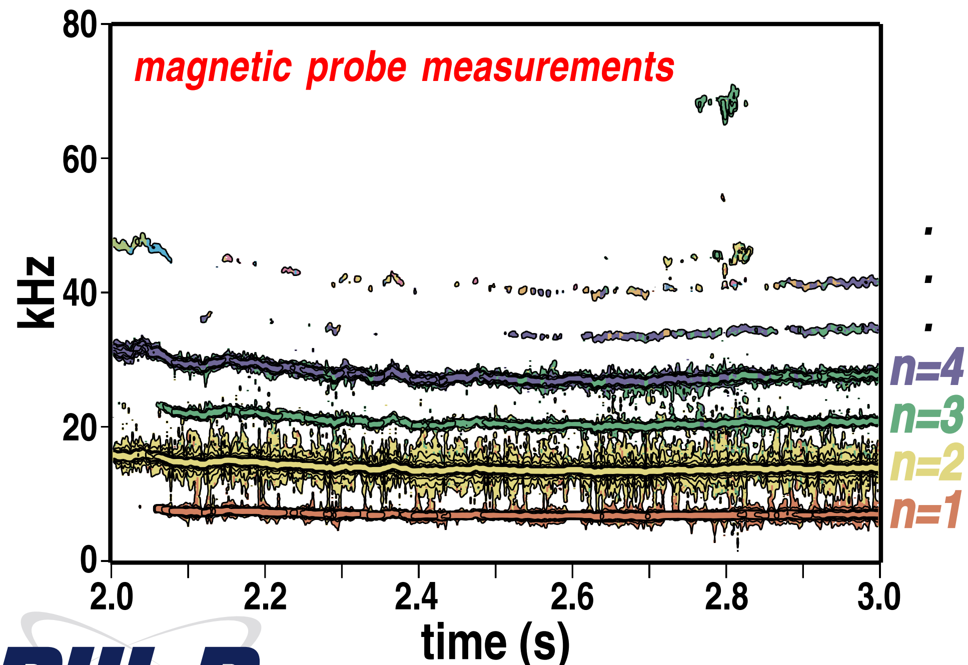
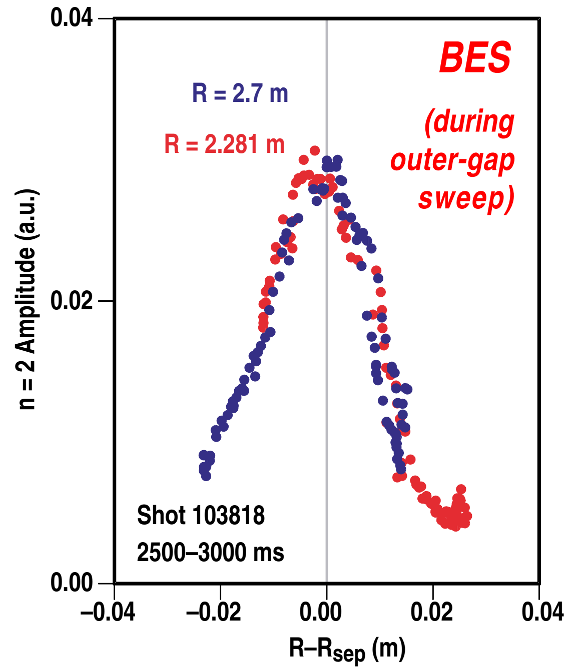
EDGE HARMONIC OSCILLATION BELIEVED RESPONSIBLE FOR DESIRABLE FEATURES OF THE QH-MODE EDGE

- Localized near edge of plasma.
- Can appear at one or more toroidal mode numbers: *n*=1-10 has been seen.
  - Sometimes shifts mode number during QH-mode with no apparent change to profiles.
- Visible in density, temperature and magnetic fluctuations.
- Drives enhanced particle transport.
  - Allows particle control.





- The EHO has been observed between ELMs in ELMy discharges with both co- and counter-NBI.
- *ELMs eliminated only with counter-NBI.*

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Burrell, BI1.002

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 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.**

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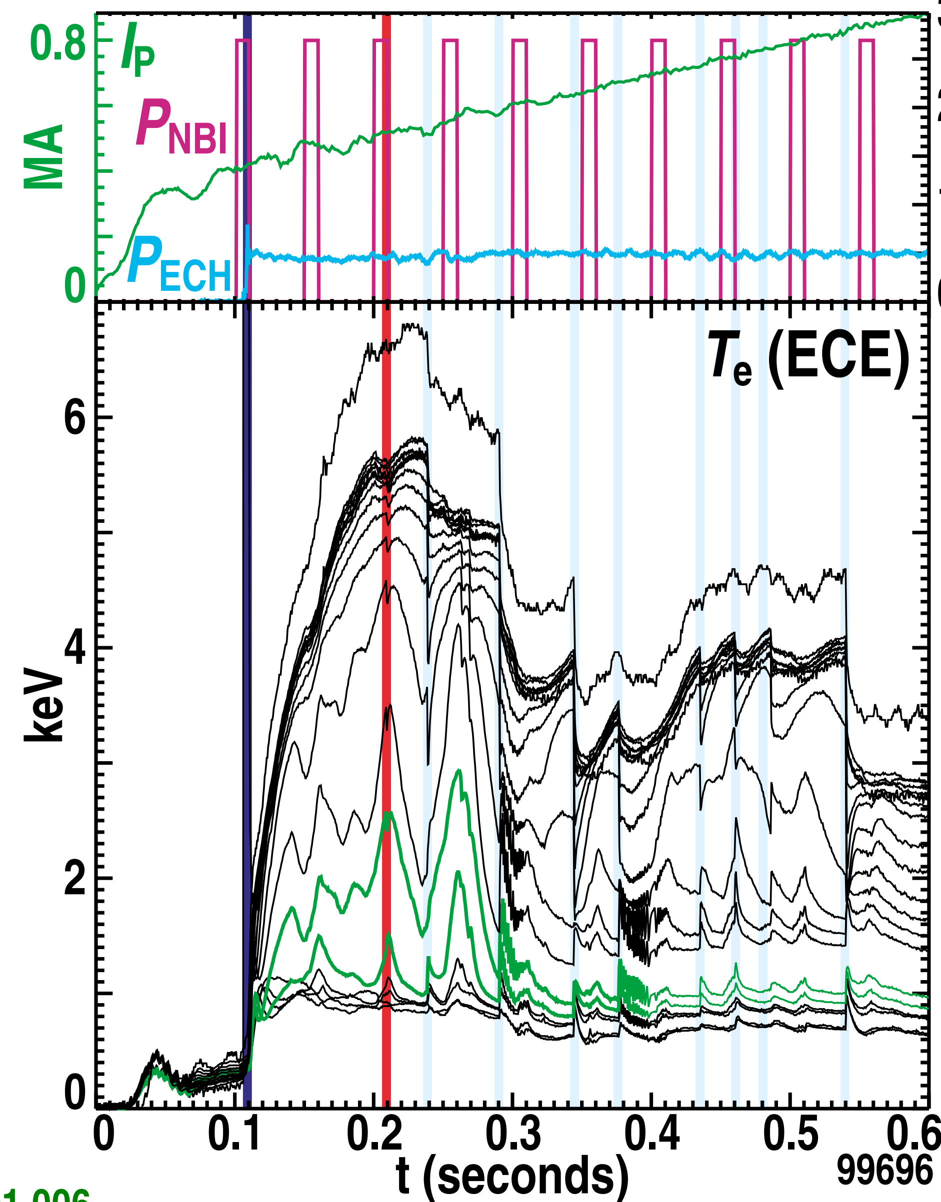
DIRECT ELECTRON HEATING GENERATES AN ELECTRON INTERNAL TRANSPORT BARRIER

- Beam blips for MSE and CER, time averaged P_{NBI}≈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 increases 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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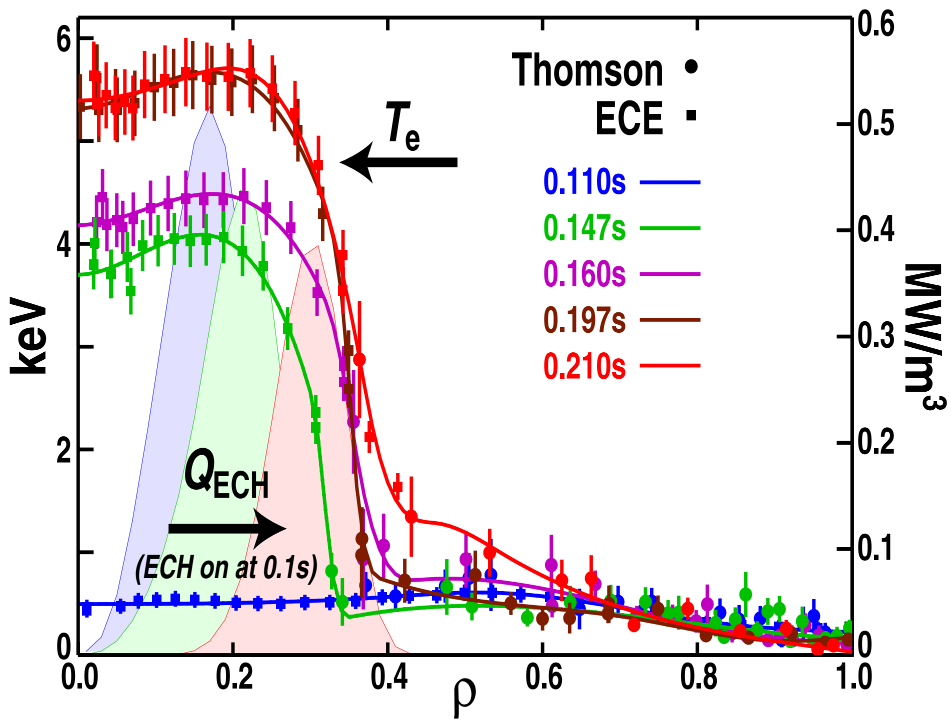
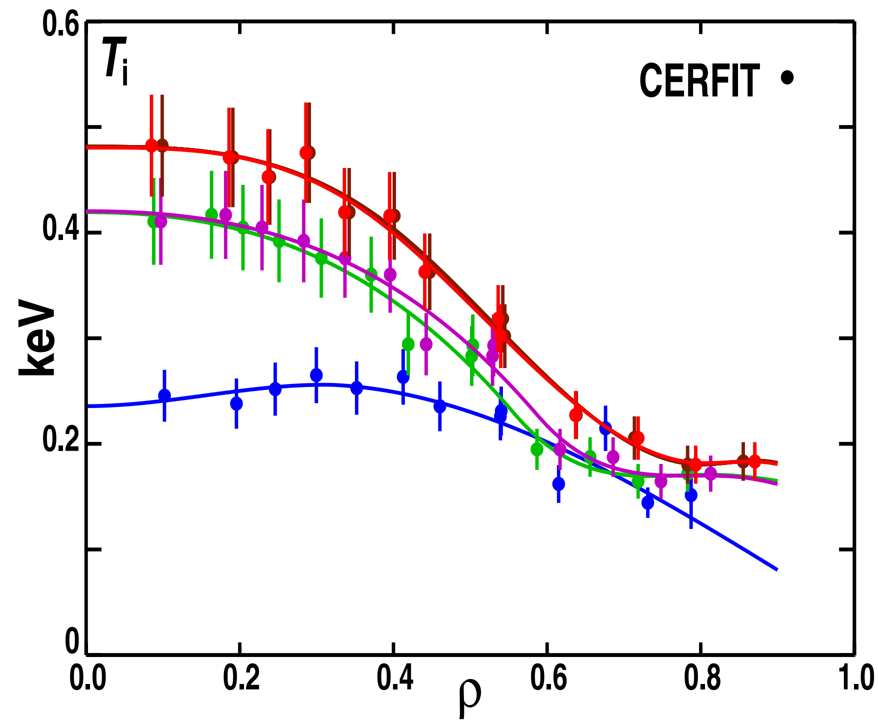
Prater, M01.006

ELECTRON TRANSPORT BARRIER DEVELOPS RAPIDLY FOLLOWING ECH ONSET





- Profiles flat or slightly hollow inside barrier.
- Barrier location expands ahead of ECH heating location.
- Barriers with nearly identical profiles have been observed with co- and counter-ECCD and pure heating (radial launch).
- Smaller response in T_i profile appears even without ECH.

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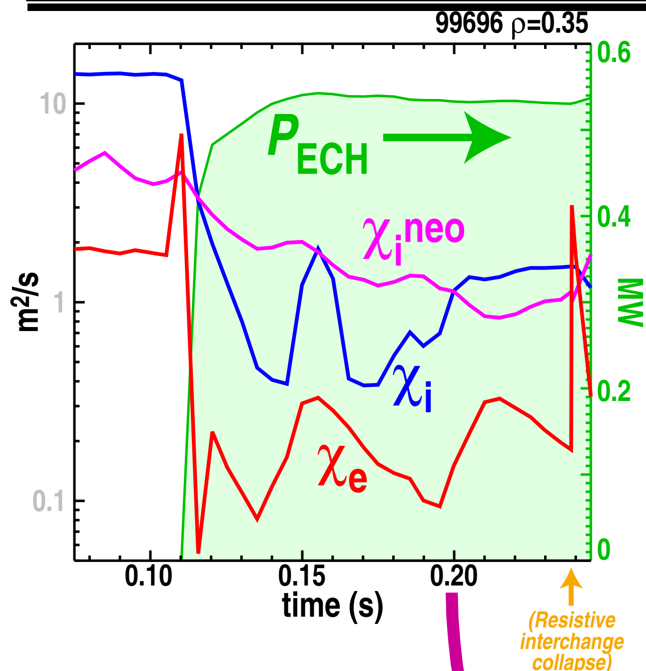
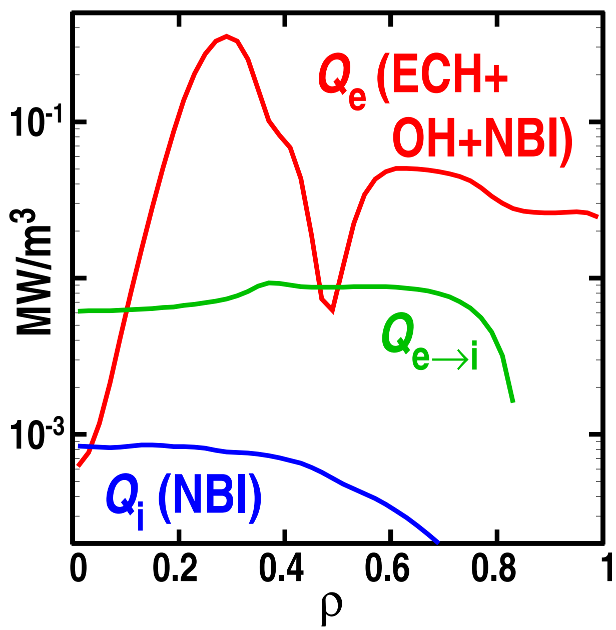
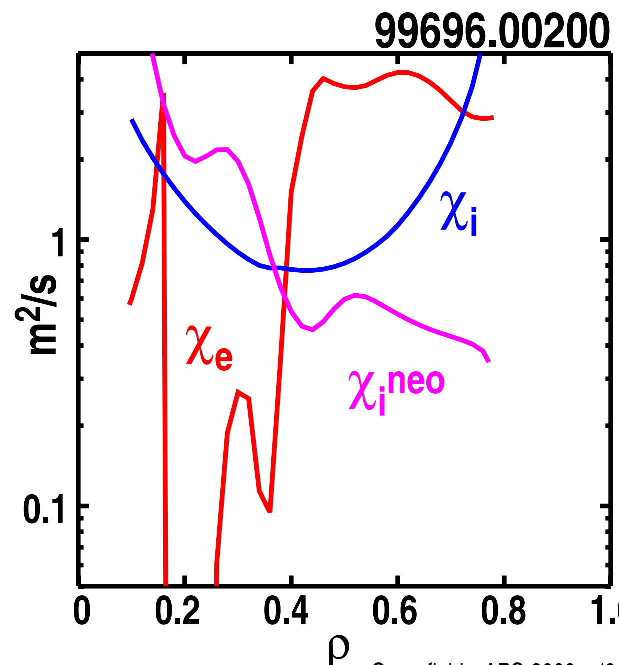
TRANSPORT DECREASES IN BOTH THE ION AND ELECTRON CHANNELS AT THE ECH TURNON



- Rapid decrease of both electron and ion diffusivities after ECH onset.
  - *Relative change in χ profiles are accurately determined* despite large uncertainties in *quantitative* transport values.
    - Uncertainty in *q* profiles ⇒ uncertainty in ohmic power near axis.
    - Large, localized source appears at e-ITB location due to ECH.
- Electron diffusivity becomes extremely small in barrier region.
- Change in ion temperature profile small due to small power to ion channel.





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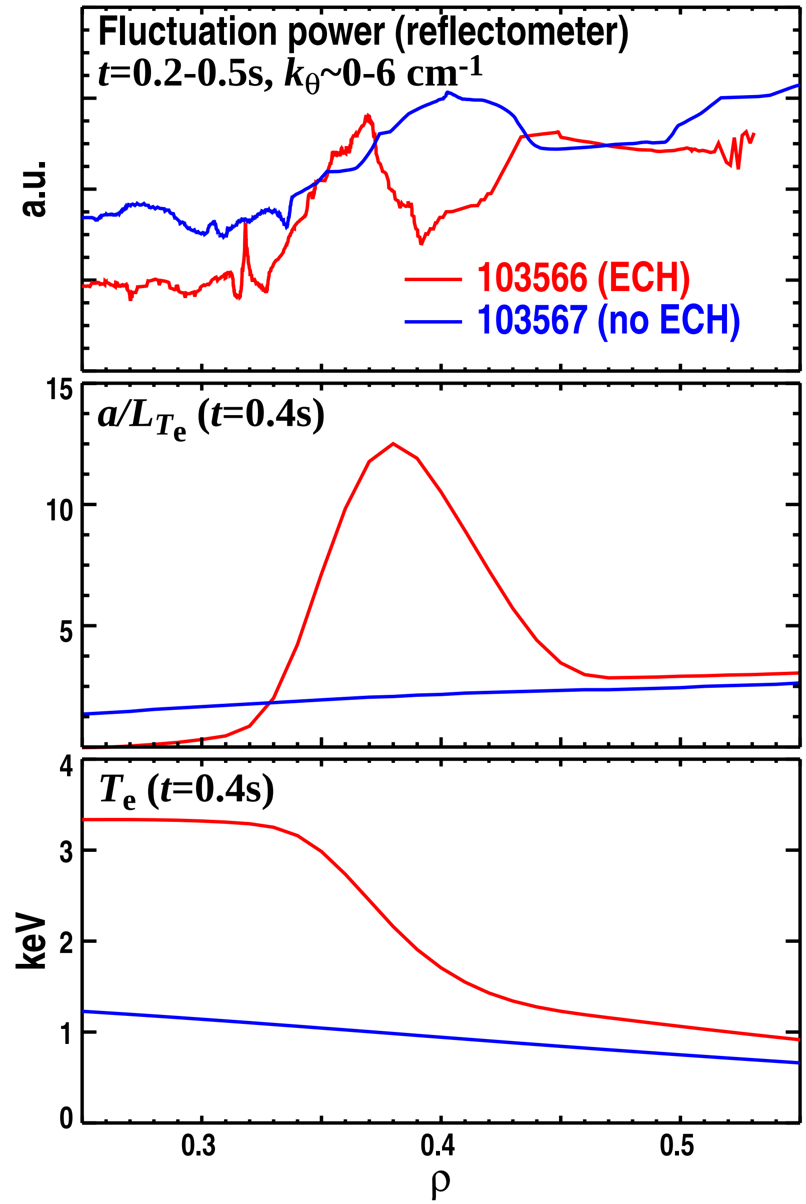
REFLECTOMETER INDICATES CORE FLUCTUATION INTENSITY REDUCED WITH ECH

- Low-*k* measurement indicative of ITG and/or TEM stability.
- Reduction appears consistent with hypothesis that both low- and high-*k* turbulence must be stabilized for formation of e-ITB.
  - Peak at $\rho \approx 0.37$ may correlate with feature in shearing rate profile; requires further analysis.



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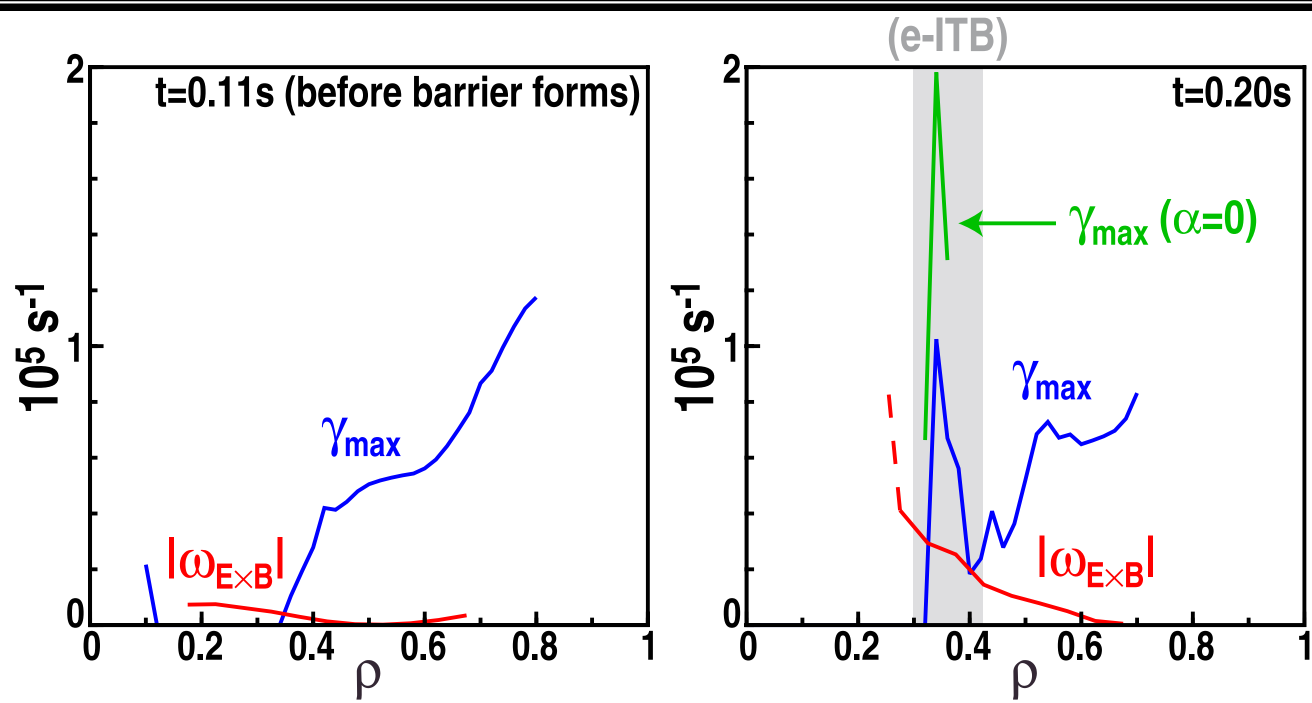
ESTIMATED E×B SHEAR IS NOT LARGE ENOUGH TO SUPPRESS LOW-*k* MODES



- 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 $\alpha \Rightarrow 0$ (β set to zero in calculation).

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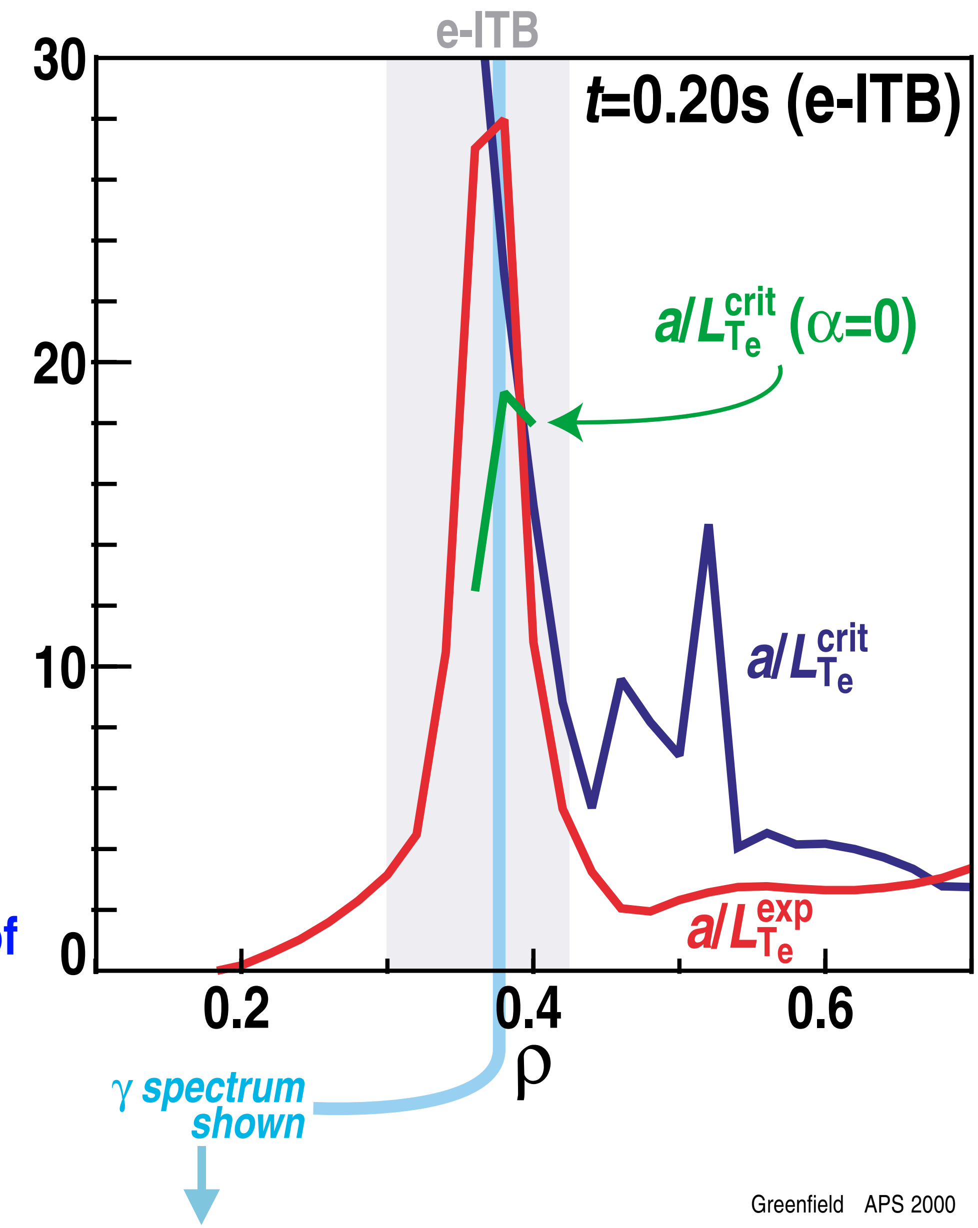
ELECTRON TEMPERATURE GRADIENT IS MARGINAL FOR STABILITY TO ETG MODES IN THE BARRIER

- Electron temperature gradient in barrier region at marginal stability level for ETG mode.
  - Consistent with previous observations with reduced core electron transport [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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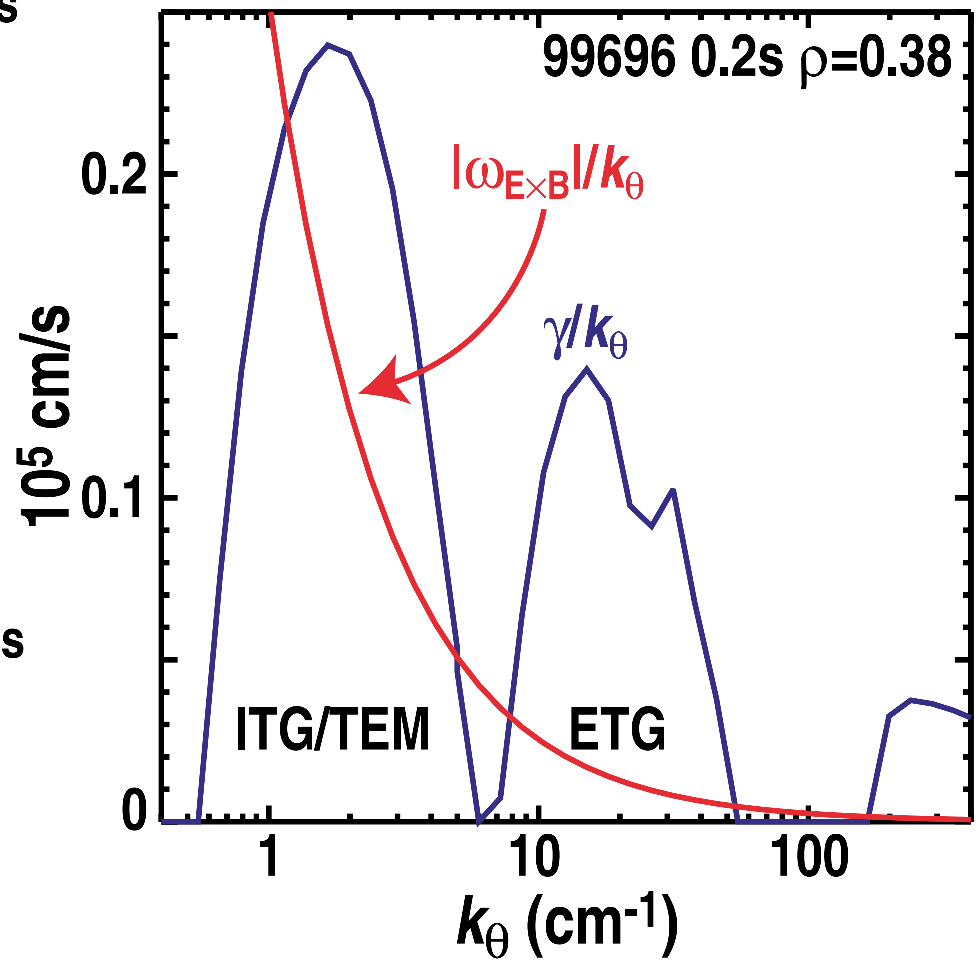
TRAPPED ELECTRON AND ELECTRON TEMPERATURE GRADIENT MODES BOTH HAVE SIGNIFICANT CALCULATED GROWTH RATES

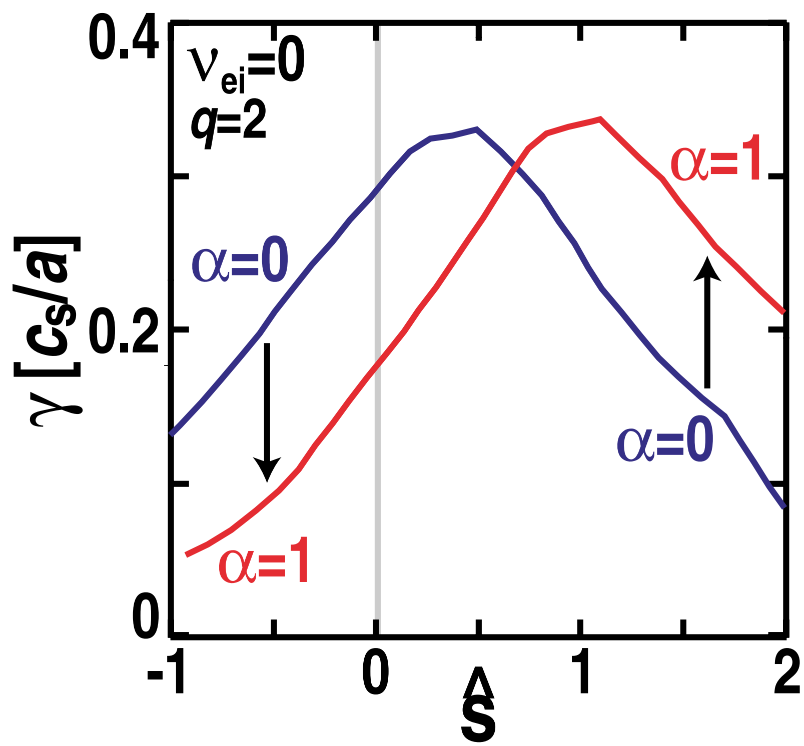
- Spectra shown at point with peak a/L_{Te}, where gradient slightly exceeds marginal level for ETG.
  - ETG feature vanishes at critical level.
  - Increases rapidly above critical level.
  - This condition can enforce marginality.

- 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.



NEGATIVE MAGNETIC SHEAR AND SHAFRANOV SHIFT CAN BE STRONGLY STABILIZING INFLUENCES

- In general, growth rate spectrum is reduced for negative magnetic shear in the collisionless limit [Waltz, *et al.*, Phys. Plasmas 4, 2482 (1997)].
  - Data shown for a typical case.
- Further reductions occur with increasing α.
  - Normalized pressure gradient $\alpha \equiv -\mu_0 P'(\Psi) V'(\Psi)(V/4\pi R_0)^{1/2}$
  - α can be *destabilizing* for strong positive shear.



Shafranov shift and α stabilization, both commonly used terms, are synonymous.

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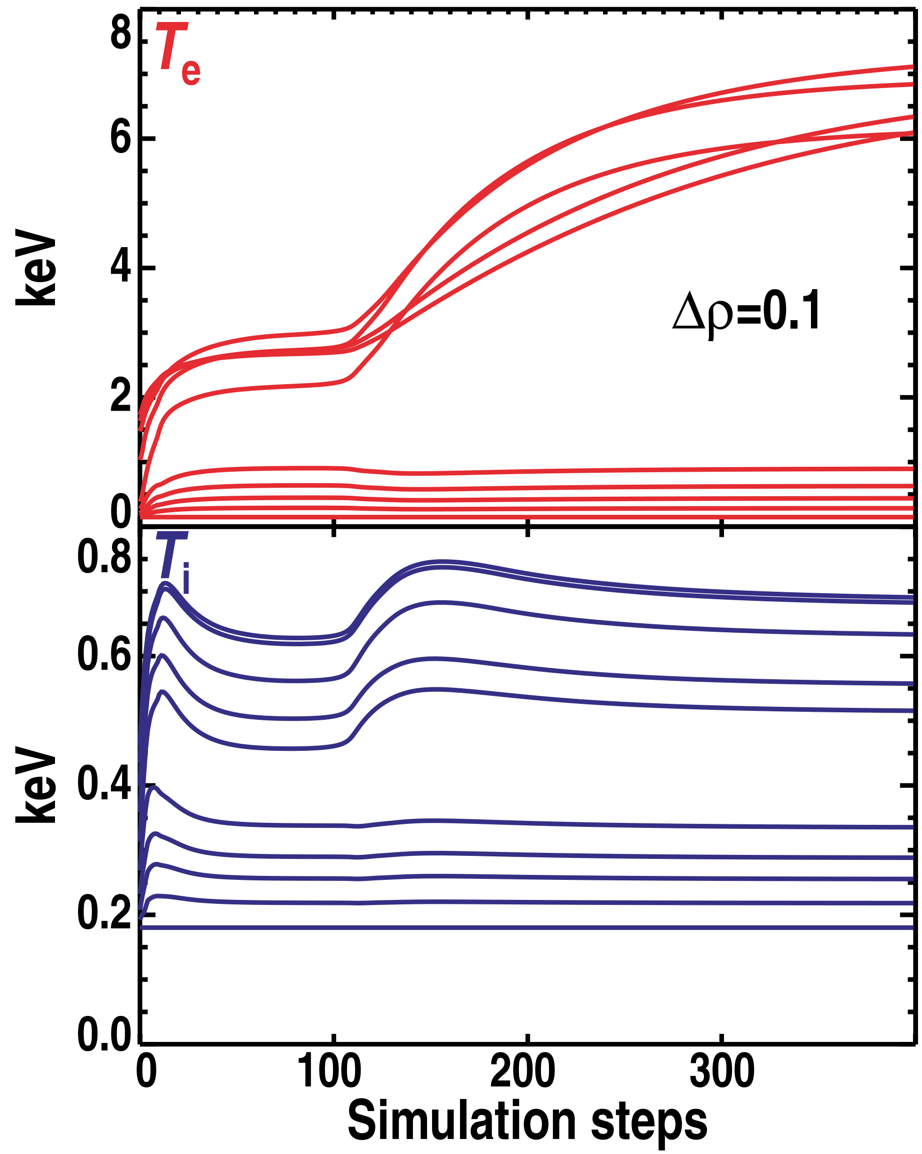
BIFURCATION IN ELECTRON TEMPERATURE PROFILE IS PREDICTED BY GLF23 MODEL

- The GLF23 model, including both heat flux and momentum bifurcation mechanisms, dynamically follows bifurcations leading to formation of ITBs.
  - Includes ITG (ion temperature gradient mode), TEM (trapped electron mode), ETG (electron temperature gradient mode).
- *n*, *q*, sources, sinks, and equilibrium from analysis.
- T and v_φ profiles initialized at pre-barrier levels and are evolved including the effects of E×B shear stabilization calculated from predicted profiles.
  - Uses generalized E×B shearing rate [R.E. Waltz, R.L. Miller, Phys. Plasmas 6, 4265 (1999)].
- Boundary conditions enforced at ρ=0.9 using experimental data.
- Simulated evolution predicts barrier formation in T_e profile.



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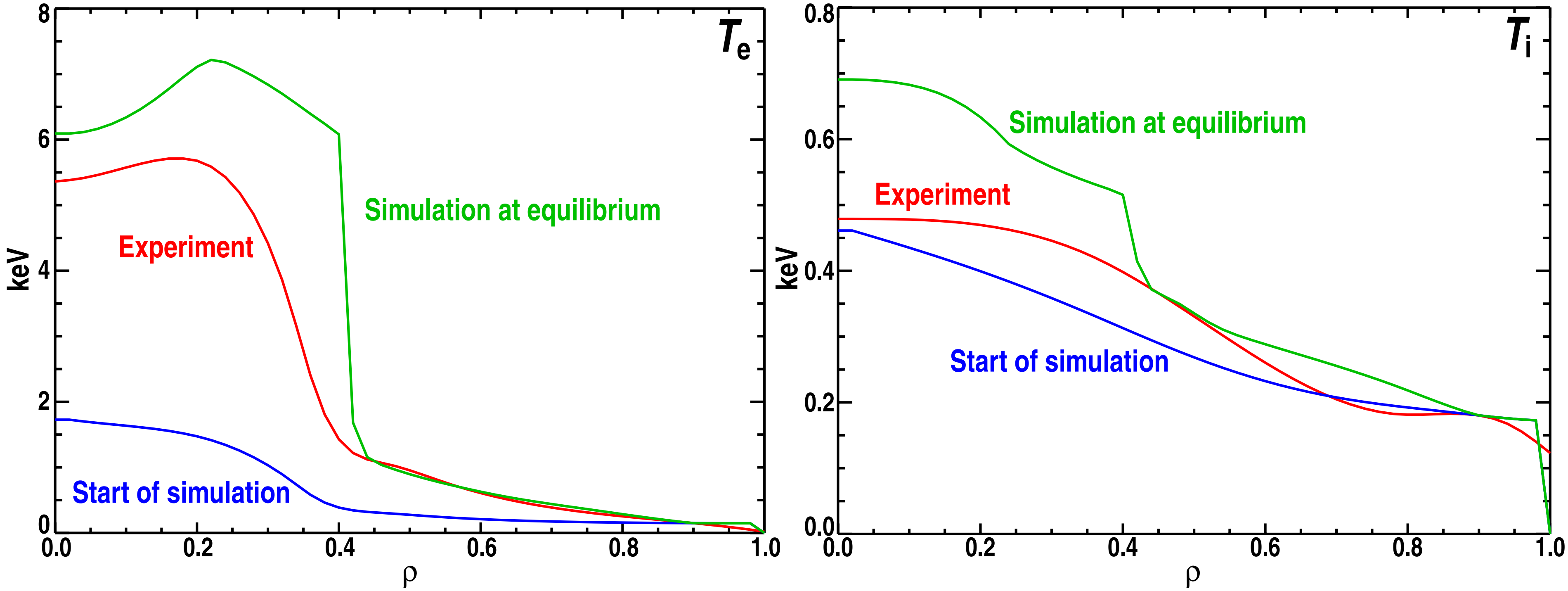
TIME DEPENDENT SIMULATION REPRODUCES ELECTRON THERMAL TRANSPORT BARRIER



- Dynamic simulation begins with experimental profiles prior to barrier formation.
- Electron ITB forms in simulation with sufficiently large α.
  - $\alpha = c_\alpha \alpha^{calc}$, 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×B shear, $c_\alpha \geq 1.7$ required for barrier formation.
  - *35% is well within experimental or numerical uncertainty.*

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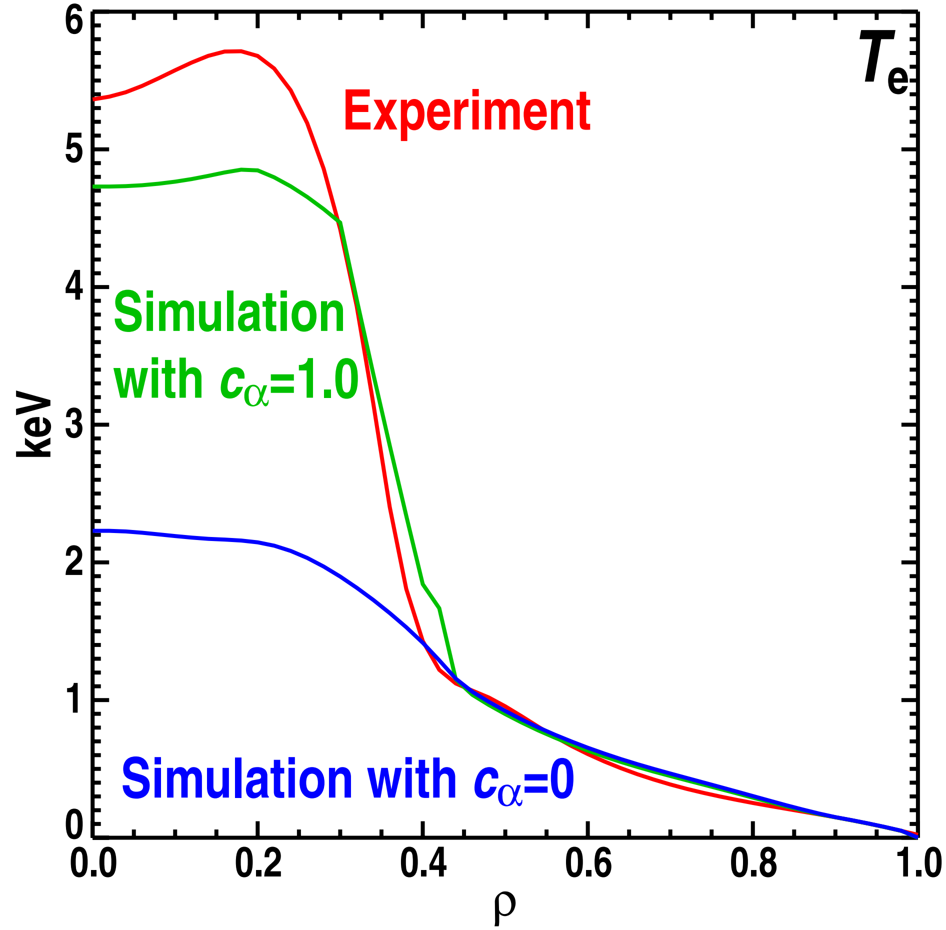
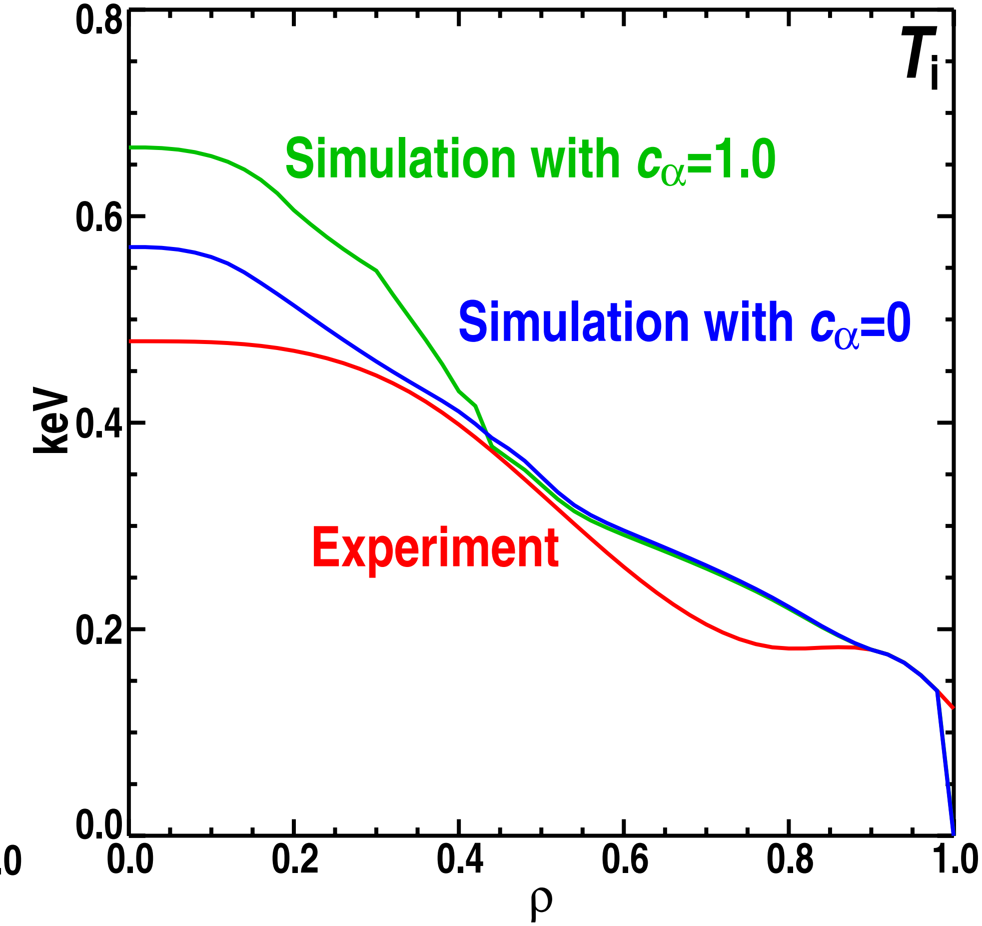
SIMULATED BARRIER ONLY MAINTAINED WHEN EFFECTS OF α-STABILIZATION ARE INCLUDED





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

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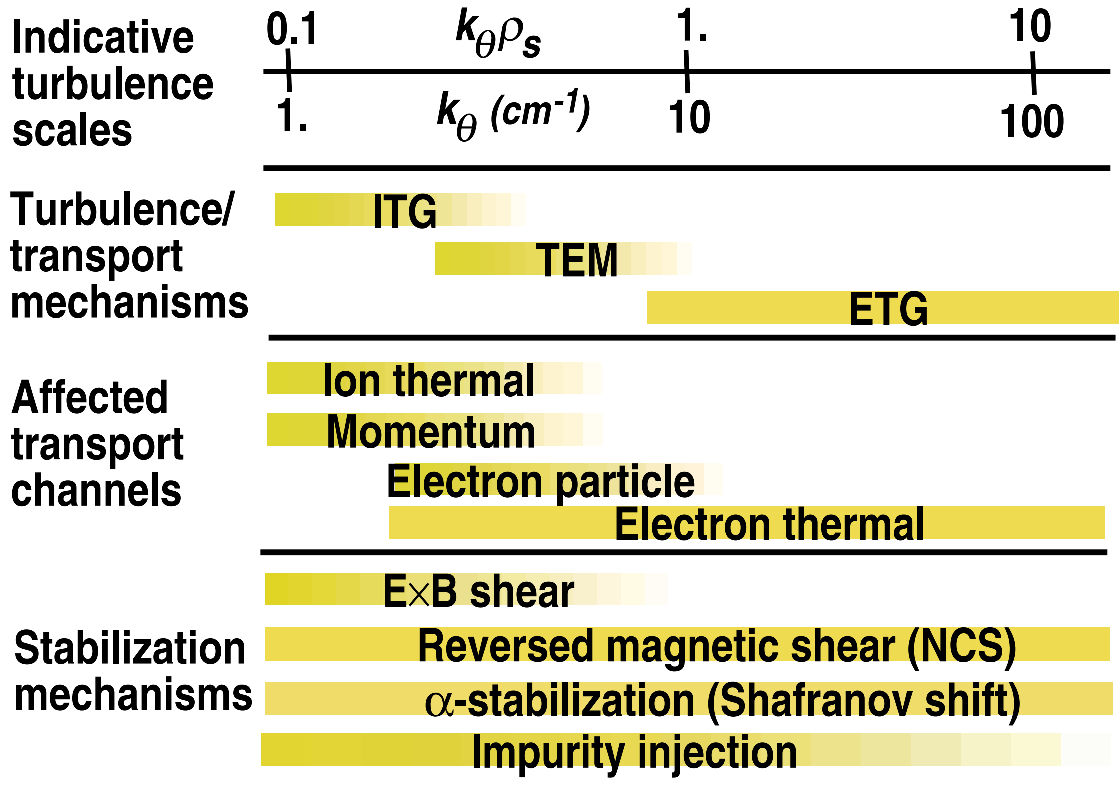
A WORKING MODEL FOR TRANSPORT AND ITS CONTROL

- Ion ITB can occur from stabilization of low-*k* modes alone.
  - Either E×B shear or α-stabilization can be effective by themselves.

- Electron ITB requires stabilization of turbulence at both low- and high-*k*.
  - E×B shear alone insufficient.
  - α-stabilization appears able to explain electron ITBs in DIII–D.
  - ETG streamer formation may complicate the picture, but streamers not expected with negative shear [F. Jenko, *et al.*, Phys. Plasmas 7, 1904 (2000)].

- Since the requirements for electron ITB formation are a superset of those for ion ITB formation, additional power to the ion channel in an electron ITB may trigger simultaneous electron and ion barriers.



SUMMARY

- Addition of a Quiescent H-mode edge to a counter-injected ITB plasma results in the sustainable high performance **Quiescent Double-Barrier regime**.
  - ELMs replaced by the more benign Harmonic Edge Oscillation.
    - Little or no impact on core barrier.
    - Allows particle control.
    - Eliminates pulsed divertor heat load characteristic of ELMs.
  - Separation between core and edge barriers provided by null in E∞B shearing rate.
  - Parameters obtained to date (all with I_P=1.3MA, B_T=1.8-2.1T): $\beta_N \leq 2.9$, $H^{89} \leq 2.5$, $\beta_N H^{89} \leq 7$, $S_N \leq 4 \times 10^{15}$ neutrons/s.
- Direct, localized electron heating (ECH) can trigger formation of a strong electron ITB.
  - Formation of e-ITB reproduced by theory-based simulations.
    - Requires α-stabilization; E×B shear not effective stabilizer of short scale modes.
  - Current understanding suggests simultaneous ion and electron barriers can be obtained by heating ions in the e-ITB target plasma.
- These results taken together support a working model for transport in which E×B shear and α-stabilization both stabilize turbulence at different scales, resulting in the frequent observation of ion ITBs and less frequent observation of electron ITBs.