ELECTRON TRANSPORT IN DISCHARGES WITH INTERNAL ION TRANSPORT BARRIERS IN DIII–D

presented by
C.M. Greenfield
for

B.W. Stallard[1], G.M. Staebler, C.L. Rettig[2], M.E. Austin[3], D.R. Baker, L.R. Baylor[4], K.H. Burrell, M.S. Chu, J.C. DeBoo, J.S. deGrassie, E.J. Doyle[2], P. Gohil, R.J. Groebner, J. Lohr, G.R. McKee[5], R.L. Miller, M. Murakami[4], W.A. Peebles[2], C.C. Petty, R.I. Pinsker, B.W. Rice[1], T.L. Rhodes[2], R.E. Waltz, L. Zeng[2] and the DIII–D Team
General Atomics, San Diego, CA

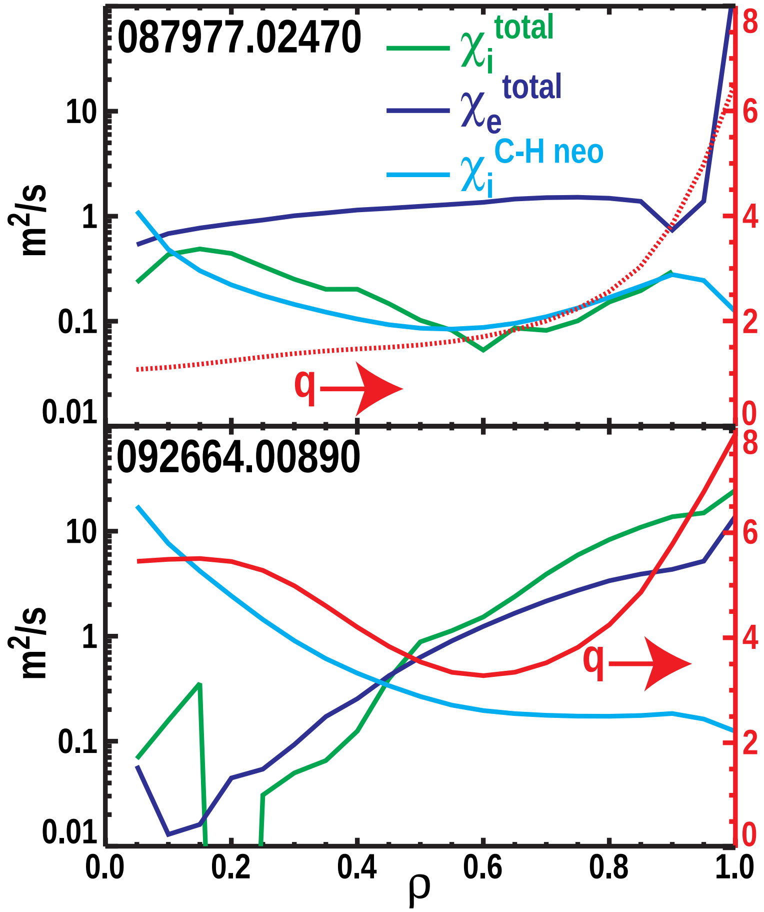
Workshop on Physics Requirements for Advanced Tokamaks
San Diego, California, USA
March 9-11, 1999

[1] Lawrence Livermore National Laboratory, Livermore, California
[2] University of California, Los Angeles, California
[3] University of Texas, Austin, Texas
[4] Oak Ridge National Laboratory, Oak Ridge, Tennessee
[5] University of Wisconsin, Madison, Wisconsin

DIII–D
NATIONAL FUSION FACILITY
SAN DIEGO

TRANSPORT IN THE ELECTRON CHANNEL IS NOT AS WELL UNDERSTOOD AS THAT IN THE ION CHANNEL

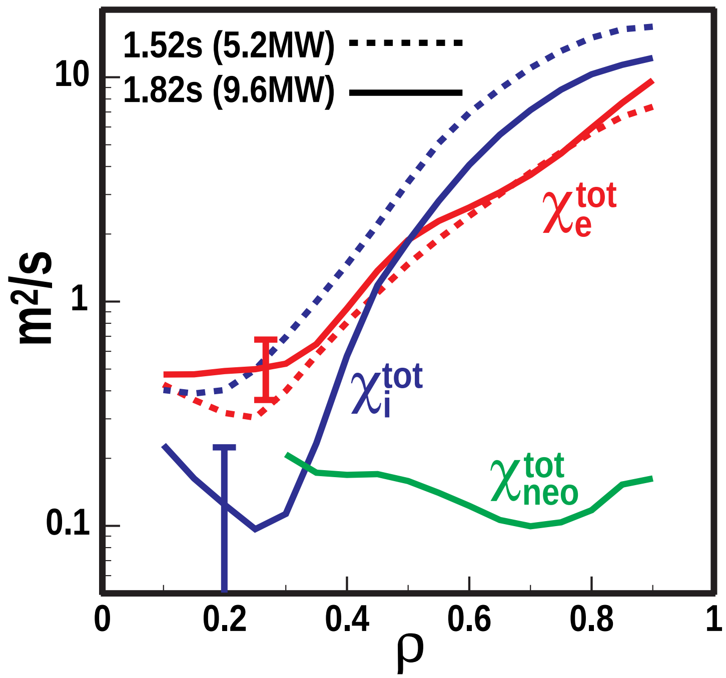
- Most discharges with internal transport barriers (ITB) exhibit reduced transport only in the ion channel.
  - Transport reduced to neoclassical levels throughout the plasma.
  - *E*×*B* shear suppression paradigm appears to work (Rettig, previous talk).
- Some discharges also exhibit improved transport in the electron channel.
  - This appears to be connected to more negative shear in the q profile.
  - Even when reduced, electron transport is still anomalous.
- Electron transport can be *increased* using additional electron heating.
- Experiments have been done using rf to probe transport in the electron channel.

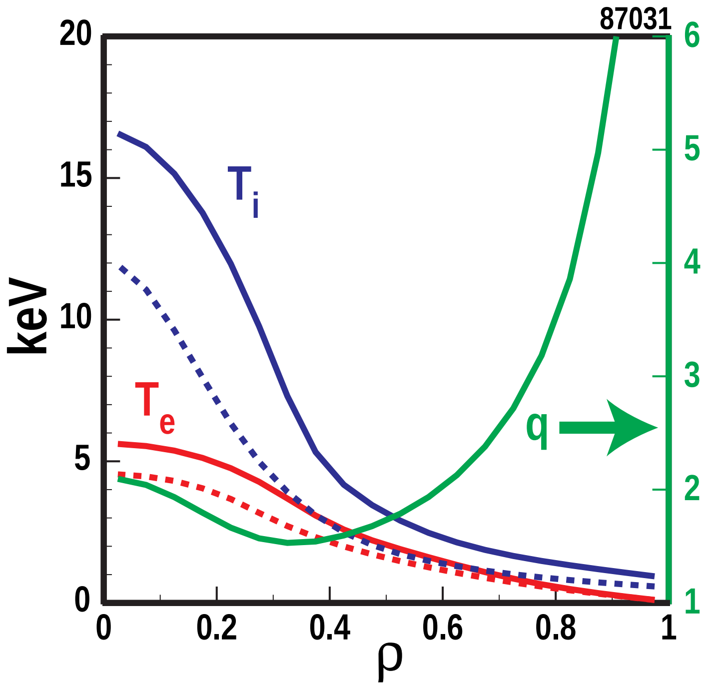


OUTLINE

- Reduction in ion thermal transport after formation of ITB is not accompanied by reductions in the electron channel in case with low magnetic shear.
- Reductions in electron transport are observed with stronger negative magnetic shear.
- Application of direct electron heating to a discharge with an ITB can increase transport in the ion, electron and momentum channels.
  - Impact on electrons does not propagate inward from heating location.
- Accepted theory does not explain all of the observed phenomenology.
  - *Improvements are needed before accurate theory-based modeling can be used to predict behavior.*

ELECTRON DIFFUSIVITY UNAFFECTED BY ITB FORMATION WITH LOW MAGNETIC SHEAR



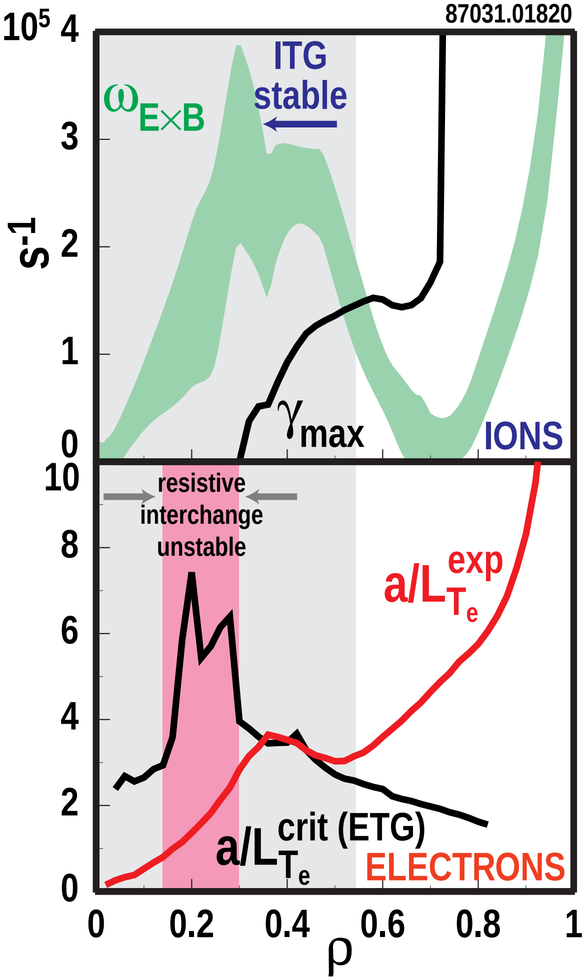


- Ion transport barrier expands and χ_I drops with increased heating power.
- Only a small change is observed in the electron diffusivity.

(χ^{tot} defined from total power flux)

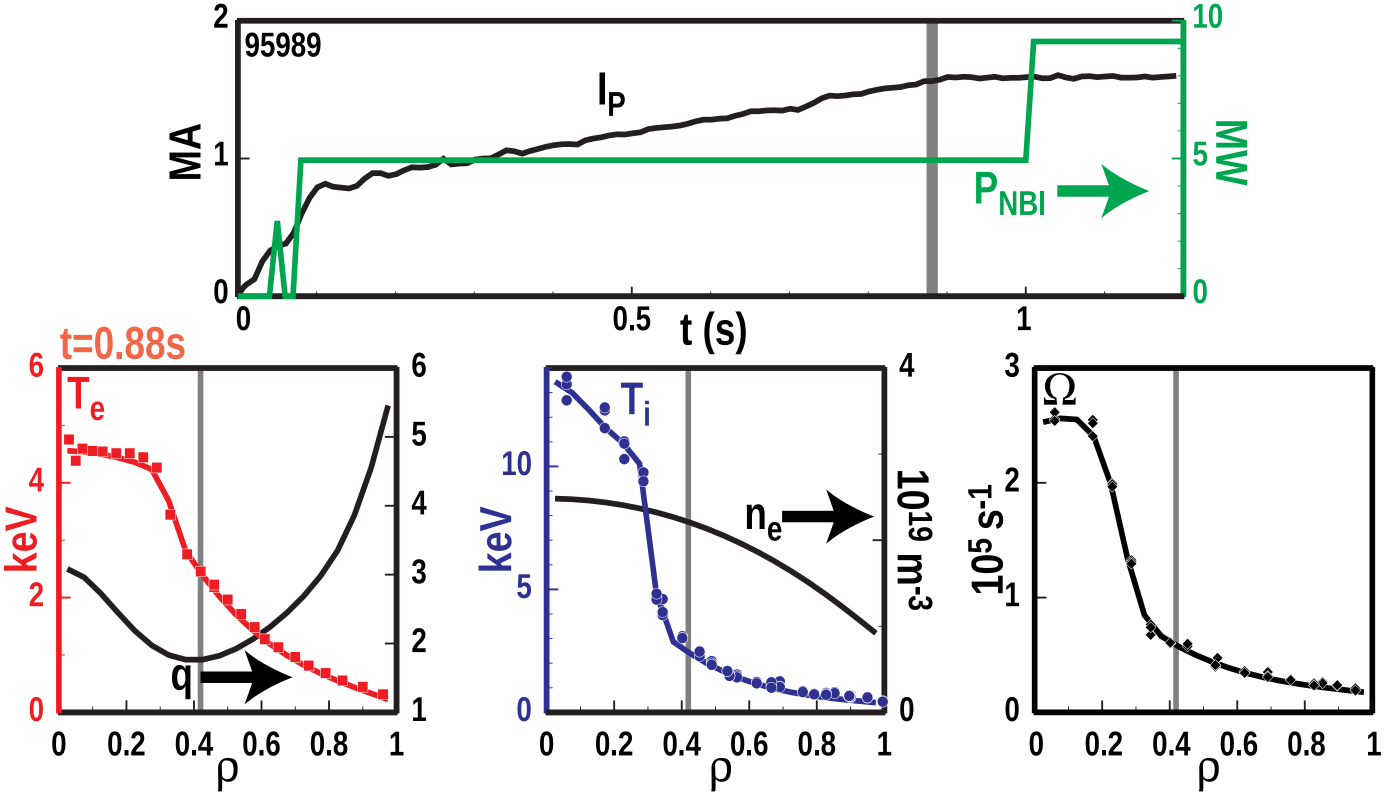
ELECTRON TEMPERATURE GRADIENT (ETG) MODES MAY CONTROL ELECTRON DIFFUSIVITY JUST INSIDE THE ITB

- Drift wave modes calculated with linear gyrokinetic stability (GKS) code.
  - Non circular, finite aspect ratio equilibria, fully electromagnetic dynamics.
- E×B shearing rate determined by CER.
- ITG/ETG modes unstable outside ITB.
  - ETG unstable where normalized electron temperature gradient a/Lt_e exceeds calculated critical value.
- ETG marginally stable just inside ITB ($0.35 \leq \rho \leq 0.5$)... does ETG control χ_e?
- Resistive interchange modes predicted unstable near axis where ETG stable.
  - Might increase transport.
  - At low power, both resistive interchange and ETG stable... something else controls transport near the axis.



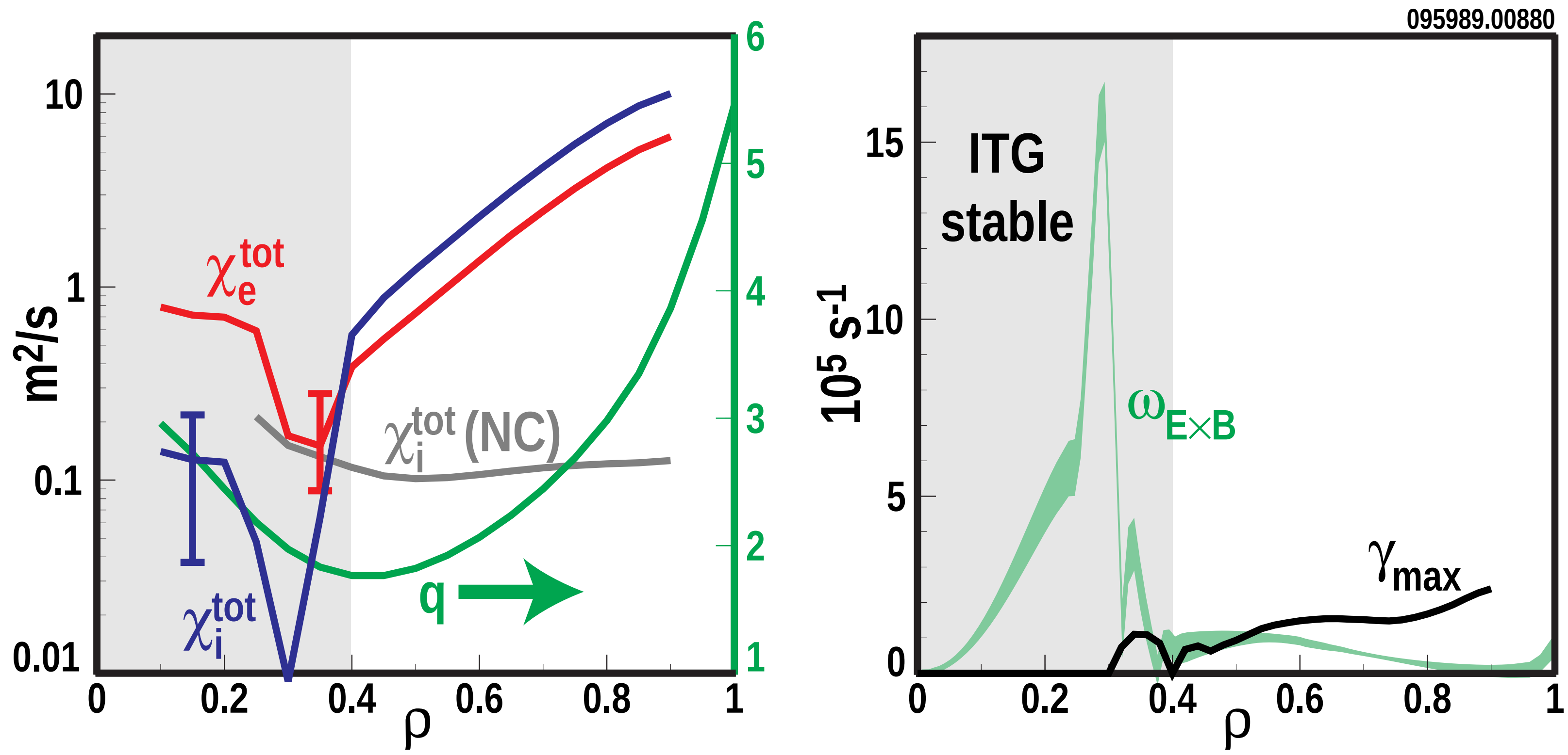
DIII–D NATIONAL FUSION FACILITY SAN DIEGO

ELECTRON TEMPERATURE GRADIENT BECOMES LARGER WITH INCREASINGLY NEGATIVE MAGNETIC SHEAR



- Electron temperature profile becomes flat near magnetic axis.
- Steepest T_e gradient occurs just inside ρ_{qmin}.

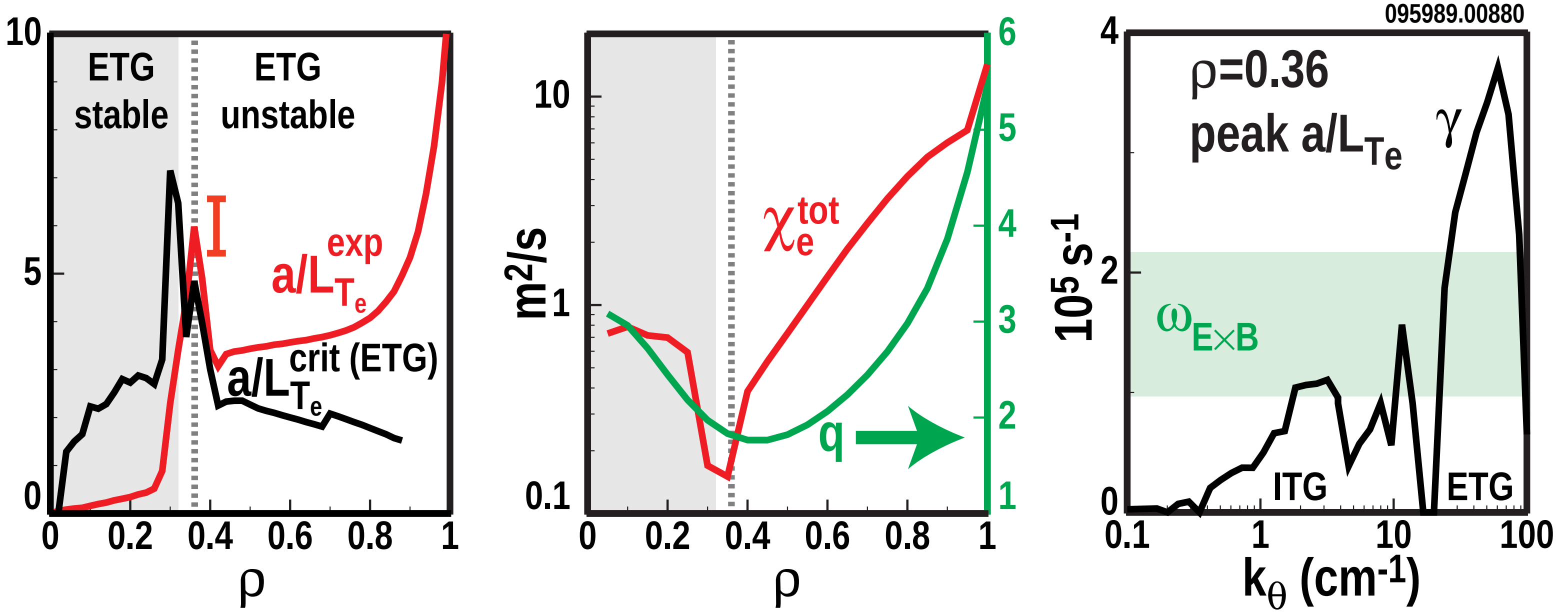
ITG MODES ARE STABLE WITHIN THE ITB



- An ion transport barrier forms where $\omega_{E\times B} > \gamma_{max}$, in the same region as the χ_e reduction.

DIII–D
NATIONAL FUSION FACILITY
SAN DIEGO

ELECTRON ITB FORMED WHEN ELECTRON TEMPERATURE GRADIENT INCREASES WITH ETG CRITICAL GRADIENT



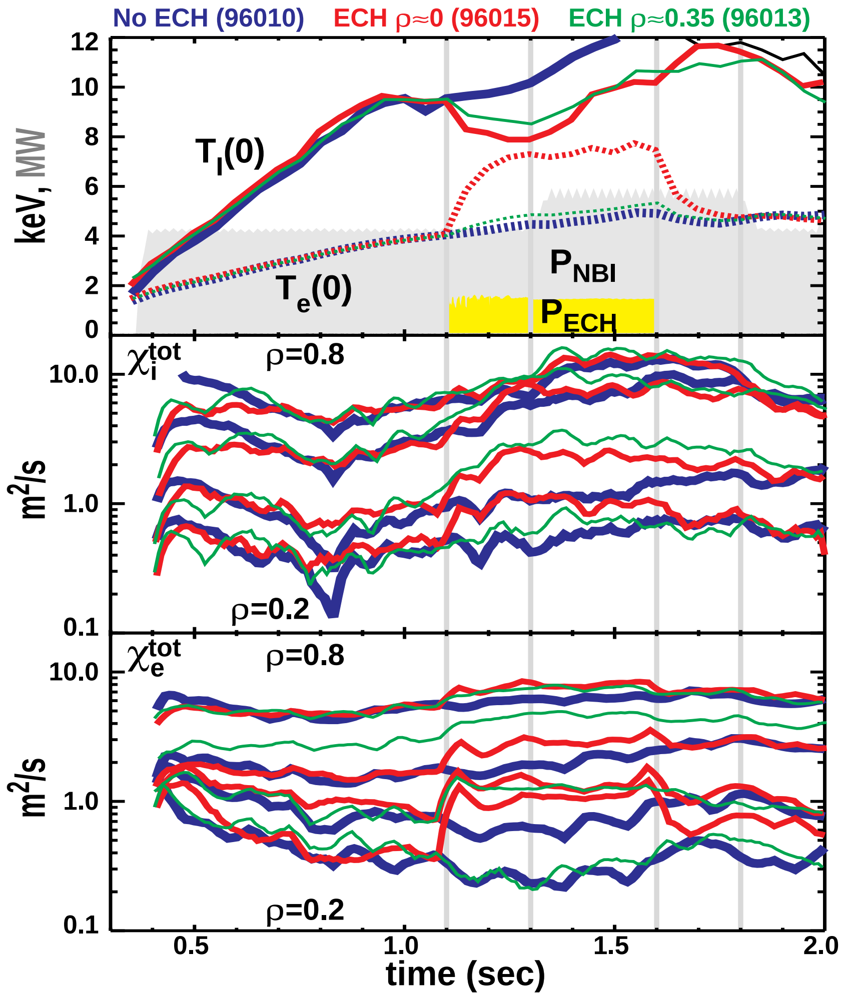
- Just inside ITB, a/L_{te} tracks rising critical gradient.
  - Supports hypothesis that ETG controls χ_e in this region.
- Unstable ETG may limit minimum of χ_e.
- Minimum value of χ_e similar to observations in JT-60U and JET.
- Something other than ETG controls transport near the axis.

IMPACT OF DIRECT ELECTRON HEATING ON TRANSPORT

- Direct electron heating (ECH or fast wave) impacts all transport channels.
  - Electron thermal
    - Increased diffusivity with electron heating larger than expected for simple "power degradation."
  - Ion thermal
    - Increase is more than would be expected for ITG model when $T_i/T_e \Rightarrow 1$.
    - Effect propagates inside heating radius.
  - Momentum
    - Effects are similar to ion channel.
- We are attempting to identify controlling transport mechanisms for these cases. Candidates include:
  - Microtearing.
  - Resistive interchange.

CENTRAL ELECTRON HEATING WITH ECH RAISES THE CENTRAL ELECTRON TEMPERATURE, BUT REDUCES THE CENTRAL ION TEMPERATURE AND ROTATION

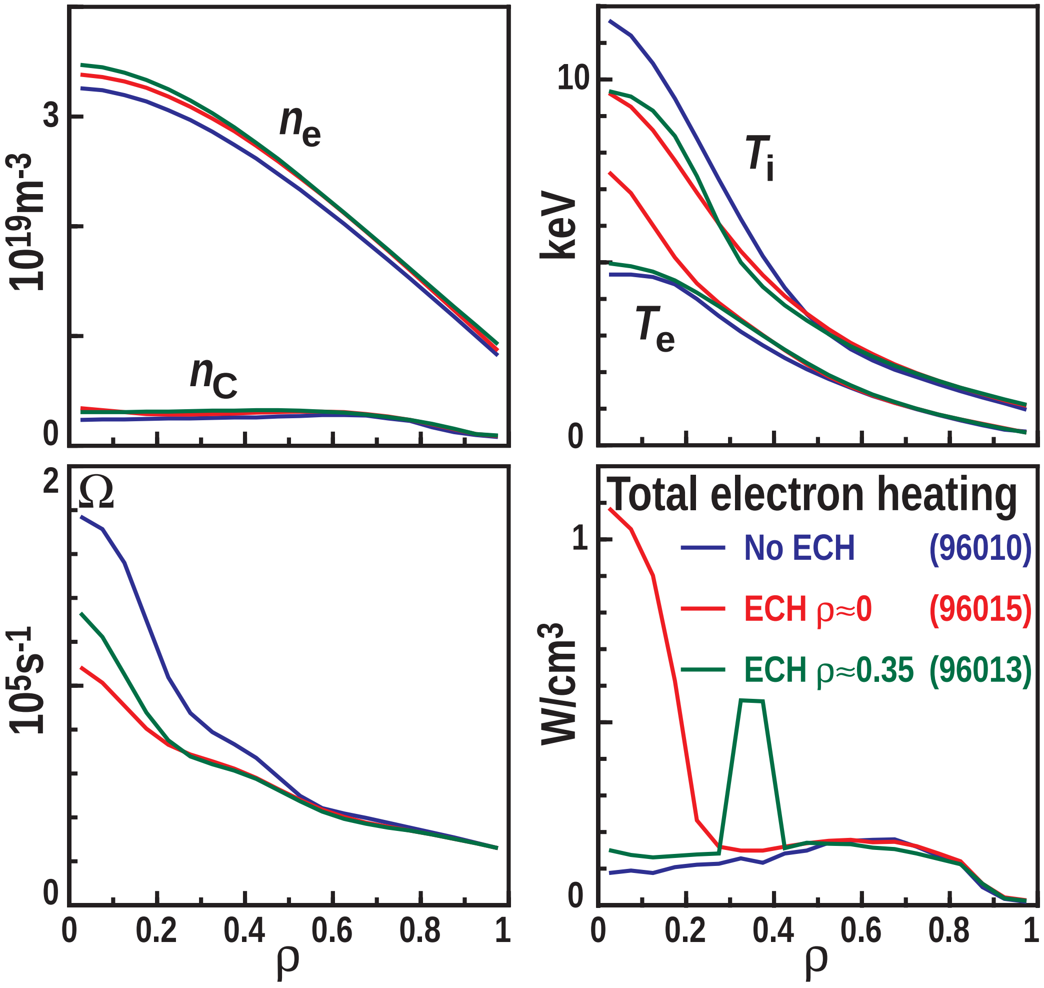
- Electron heating (EH) impedes or reduces development of the ITB.
  - Central electron heating:
    - Reduces central ion temperature.
    - Increases χ_e and χ_I everywhere.
  - Off-axis electron heating:
    - Reduces central ion temperature with little or no effect on central electron temperature
    - Increases χ_I everywhere and χ_e only outside the heating location.
- Not heating method dependent: fast wave (FW) electron heating and electron cyclotron heating (ECH) have same effect.



DIII–D
NATIONAL FUSION FACILITY
SAN DIEGO

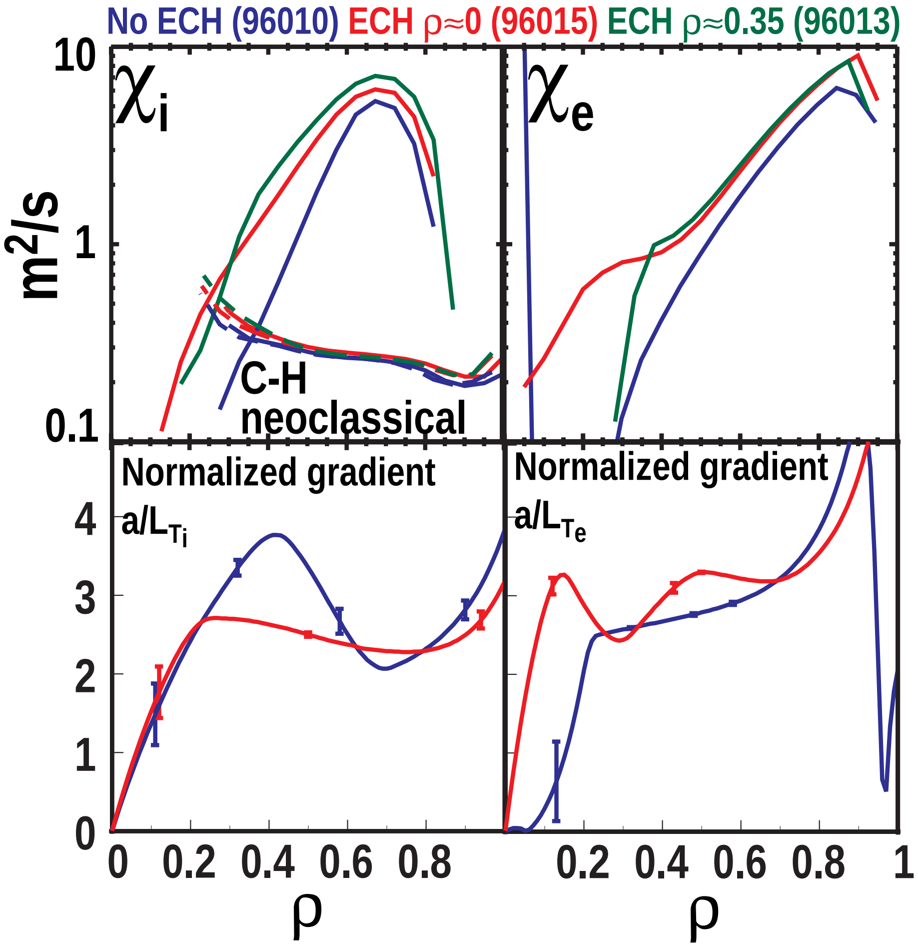
TEMPERATURE AND ROTATION PROFILES RESPOND TO ELECTRON HEATING IN DIFFERENT WAYS

- Electron and impurity densities similar in all three cases.
- Ion temperature and toroidal rotation both reduced in core with EH.
  - Little difference between on- and off-axis heating.
- Electron temperature elevated on axis only with central heating.
  - Slight elevation of $T_e(\rho\approx 0.35)$ in both on- and off-axis EH cases appears to be real.



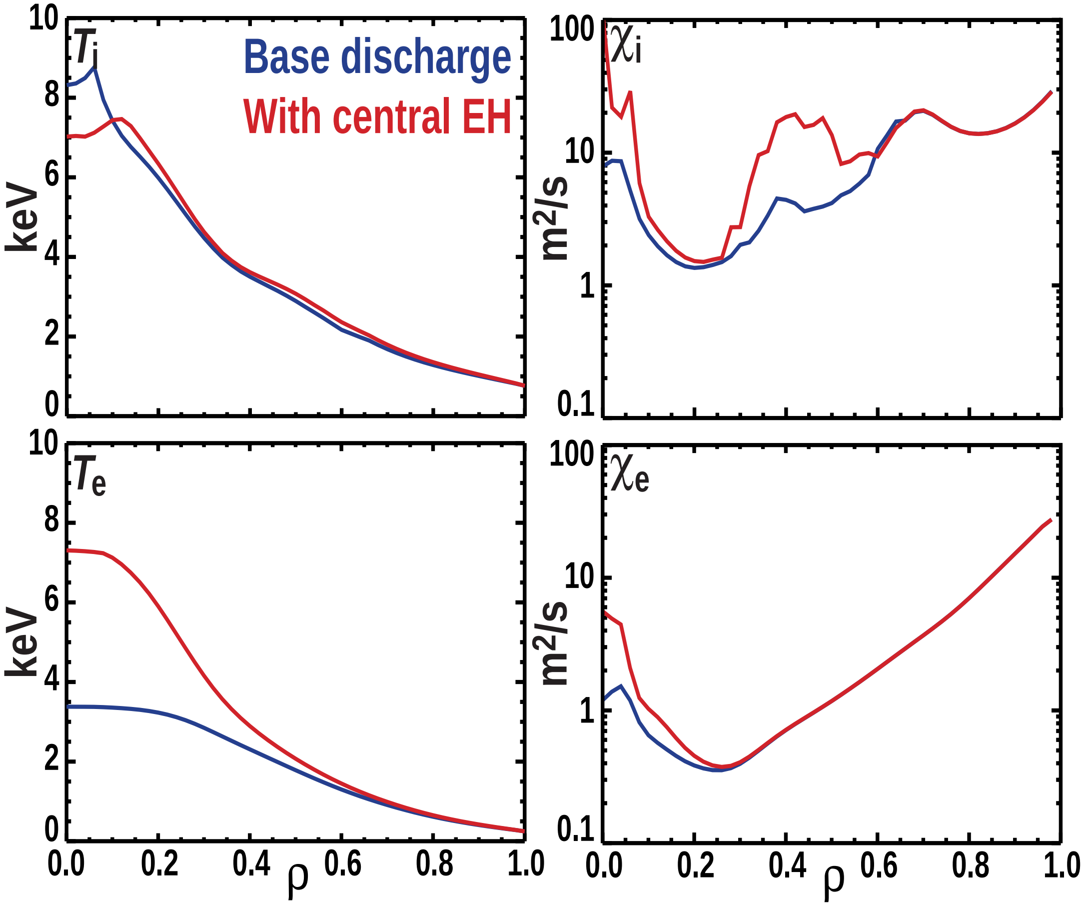
ELECTRON HEATING INCREASES TRANSPORT IN BOTH THE ELECTRON AND ION CHANNELS

- ITB is evident in all discharges.
  - Both in ions and electrons (*q* profiles are reversed in core).
- Both ion and electron ITBs occupy smaller spatial extent with EH.
  - Impact on electron channel does not propagate inside heating radius.
- Discharges with and without EH exhibit flattening of profiles near axis.



TRANSPORT MODELING DOES NOT FULLY REPRODUCE PLASMA RESPONSE TO CENTRAL ELECTRON HEATING

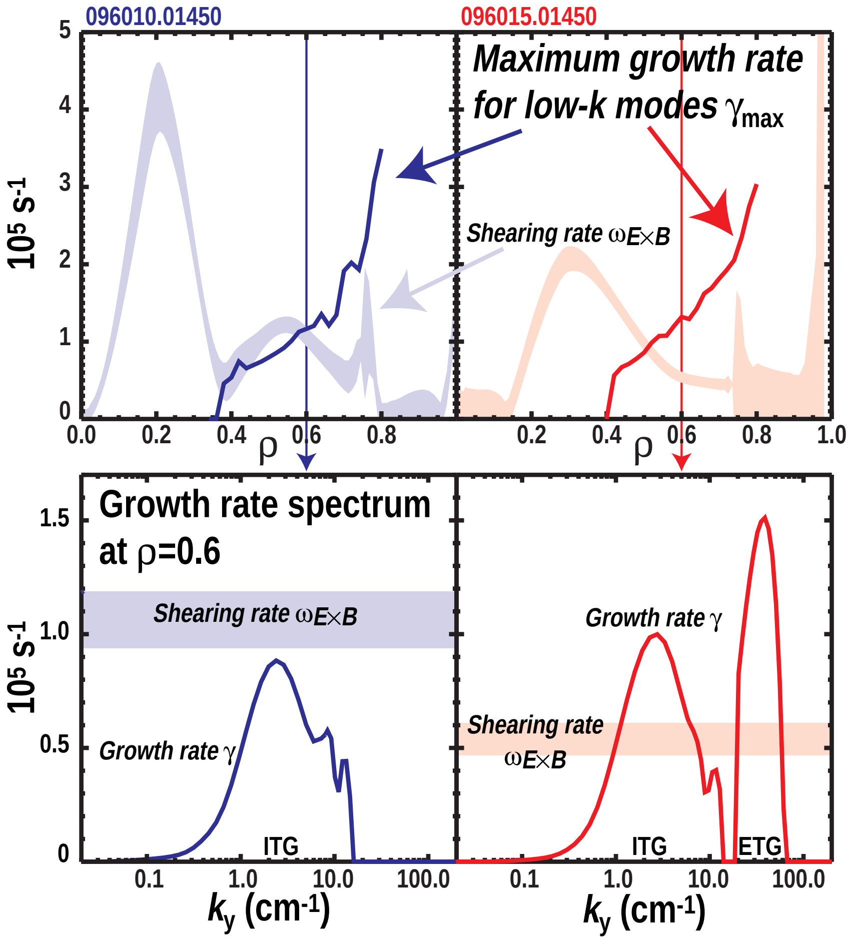
- Modeling based on shot 96015 (1MW central ECH)
  - ONETWO code used for analysis and simulation.
  - n_e and Z_{eff} profiles as measured.
  - χ_e based on analysis.
  - χ_i from IFS-PPPL model with empirical E×B shear suppression model.
- Electron temperature response qualitatively similar to experiment.
- Ion response small and more localized than experiment.



NATIONAL FUSION FACILITY SAN DIEGO

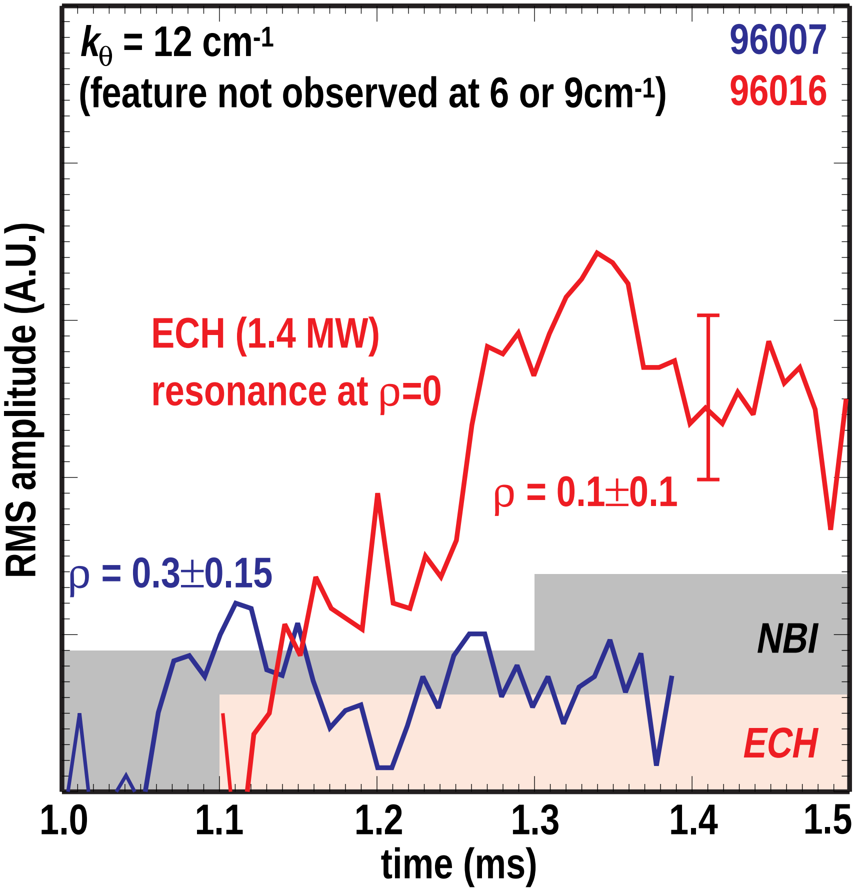
GYROKINETIC STABILITY CALCULATIONS INDICATE LONG AND SHORT WAVELENGTH DESTABILIZATION IN ELECTRON HEATED DISCHARGE

- Stability to drift ballooning modes calculated using a linear gyrokinetic stability (GKS) code.
  - Non-circular, finite aspect ratio equilibria with fully electromagnetic dynamics.
- E×B shearing rate calculated from CER.
- Growth rates are zero at $\rho \leq 0.3$ in both discharges.
- In non-EH discharge:
  - $\omega_{E\times B}$ has double-peak corresponding to feature in rotation profile.
  - Low-*k* modes stabilized by E×B shear.
  - Marginally stable near $\rho = 0.4$.
  - Unstable to ITG at $\rho > 0.6$.
- In EH discharge:
  - Second peak vanishes from $\omega_{E\times B}$.
  - Unstable to both ITG and ETG at $\rho > 0.5$.



DRIFT WAVE TURBULENCE DOES NOT PROVIDE A COMPLETE EXPLANATION OF TRANSPORT IN THESE DISCHARGES

- High *k* feature observed in FIR scattering data near axis in EH discharge.
  - Rotates in electron direction.
- GKS code predicts no unstable drift ballooning modes in this region at any *k*.
- Profile flattening near axis also unexplained.
- We are exploring some possibilities:
  - BALLOO code predicts resistive interchange unstable region near $\rho \approx 0.2$ in EH discharge.
  - Not responsible for profile flattening, which appears in both discharges.
- Microtearing stability is being assessed.



POSSIBLE PARTIAL EXPLANATIONS

- Much of electron and ion transport effects consistent with accepted theory:
  - Ion ITB appears when ITG calculated stable.
  - Electron ITB appears when ETG stable (or marginally stable).
    - Marginally stable condition may explain why even reduced electron transport is usually still anomalously high.
- Electron heating was applied during period when ITB was not fully formed.
  - E×B shearing rate was reduced, prevented barrier formation.
  - What would the result have been if electron heating were applied with a more fully developed barrier?
    - Electron heating may be useful as a pressure profile control tool.
- ITG and ETG destabilization near “foot” of barrier reduces gradients locally, so lower temperatures should be expected nearer to the axis.

UNANSWERED QUESTIONS

- What is the role of more negative shear in determining electron transport behavior?
- ITG and ETG destabilization cannot explain full impact of electron heating on parameters near axis.
- Short wavelength fluctuations measured in region where ITG and ETG both calculated stable.
  - Do these have any effect on transport?
- Role of resistive interchange and microtearing.
- Localized flattening of profiles near axis in all discharges.

CHALLENGES STILL REMAIN BEFORE WE CAN SUCCESSFULLY PREDICT TRANSPORT BEHAVIOR IN ADVANCED MODES

- Much (*but not all*) of the behavior of transport in the ion channel can be predicted, but effects from perturbations to other channels (ie. electrons) still not understood.
  - Understanding the underlying neoclassical transport has become important.
- We don't yet understand:
  - The electron channel.
  - Momentum transport.
  - Particle transport.

The transport community has been working to improve the situation through experiment/theory comparisons, and has made much progress. More progress is needed before we can claim a true predictive capability.