LOCAL ANALYSIS OF CONFINEMENT AND TRANSPORT IN NEUTRAL BEAM HEATED DIII–D DISCHARGES WITH NEGATIVE MAGNETIC SHEAR

Presented by

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*for the DIII–D Team**

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GENERAL ATOMICS

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IN COLLABORATION WITH

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KEY POINTS

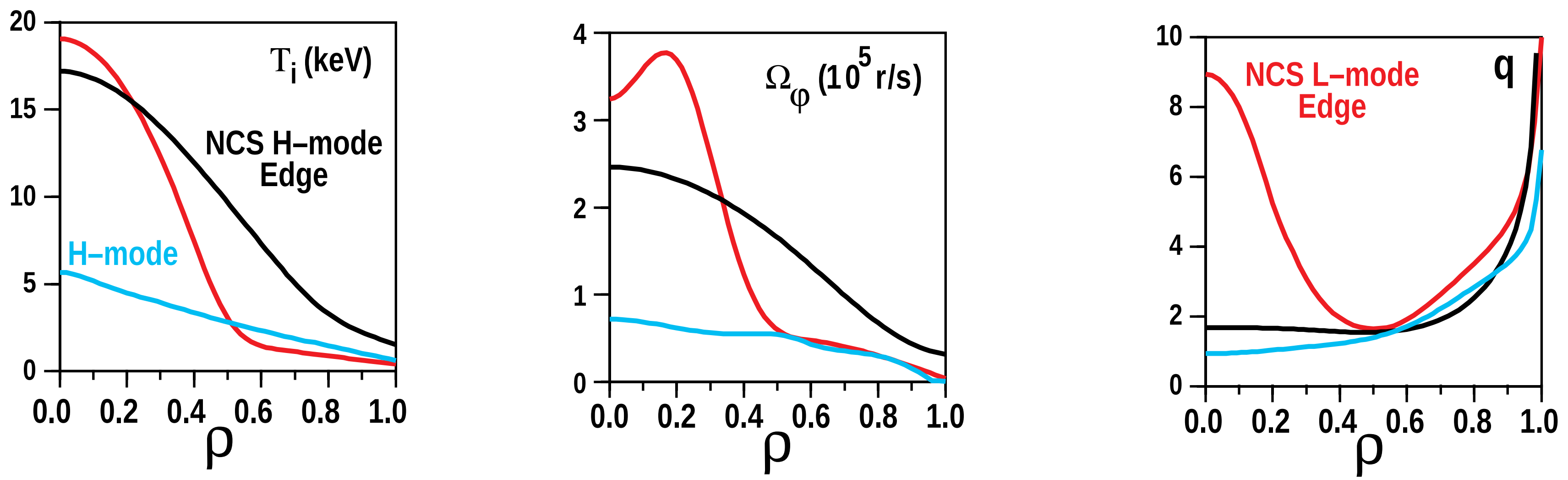
- **Plasmas with weak or negative central magnetic shear have exhibited reduced particle, heat, and momentum transport**

- **Local suppression of plasma turbulence has been correlated with transport reduction**

- **E×B shear decorrelation of turbulence is the leading candidate for explaining the reduced transport**

NEGATIVE CENTRAL SHEAR PLASMAS SHOW A DRAMATIC IMPROVEMENT OVER DISCHARGES WITH A MONOTONIC q PROFILE

- Negative Central Shear (NCS) meaning a plasma with either weak or negative shear
- NCS with an L–Mode edge
  - NCS combined with L–mode edge conditions
  - Strong T_i and Ω_ϕ peaking inside NCS region
- NCS with an H–Mode edge
  - NCS combined with ELM–free H–mode edge conditions
  - Broader profiles



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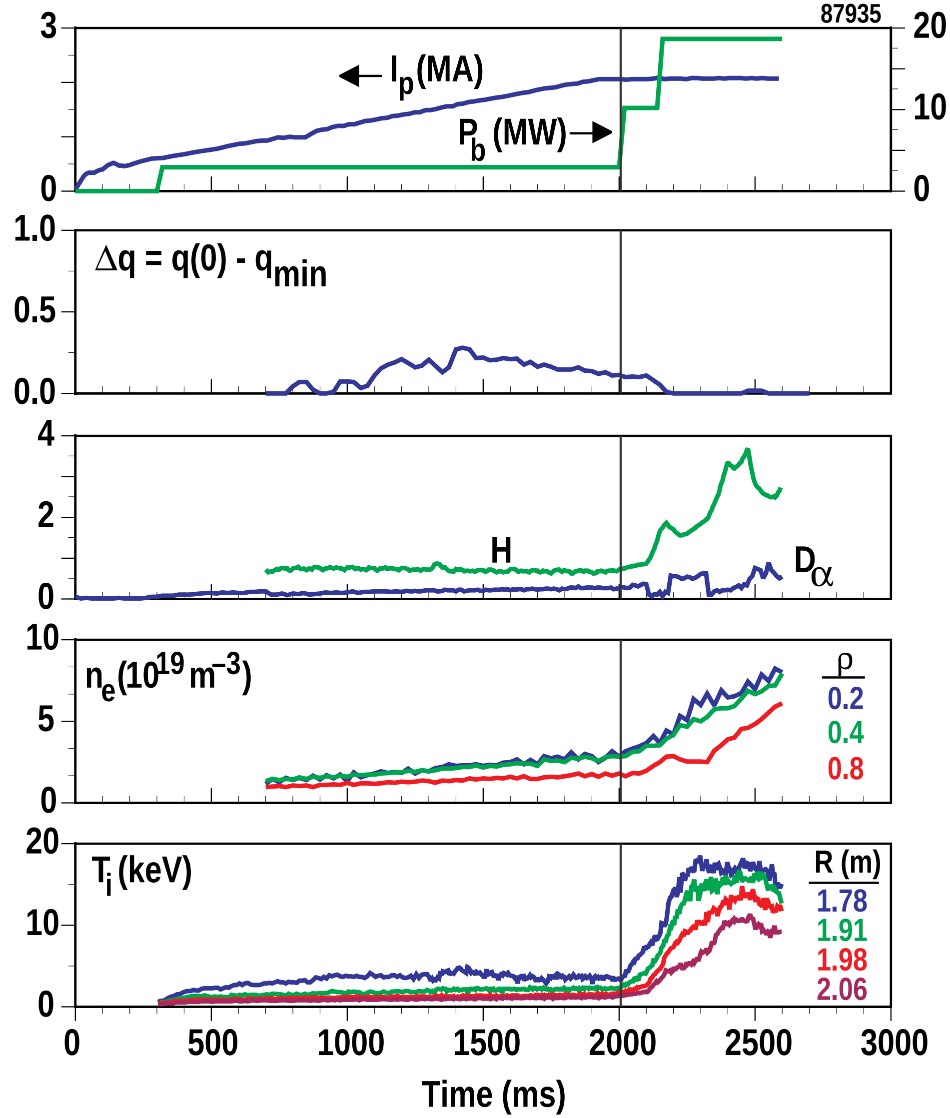
PLASMA POSITION ALLOWS NCS L– AND H–MODE EDGE CONTROL

- Double -null divertor with δ~0.8
- Early NBI during I_p ramp
  - Low target n_e, high T_e
  - Freeze J(r) in core resulting in reversed or flat q profile
- L–mode and H–mode edge control accomplished by null bias
- Internal barrier forms with higher power NBI
  - H factors (τ relative to ITER89–P) of up to 4 have been achieved
  - Rapid increase in T_i and Ω_ϕ
  - Modest increase in T_e and n_e resulting in larger T_i / T_e



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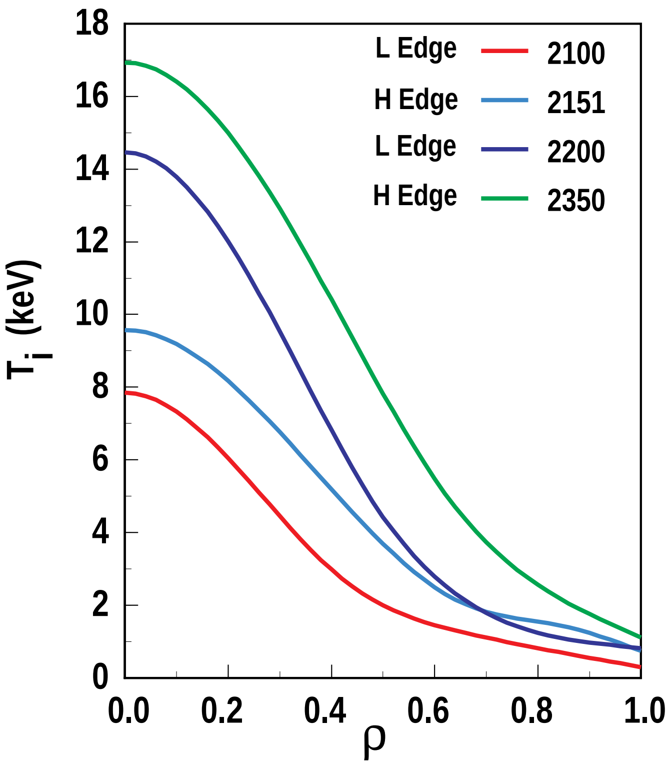
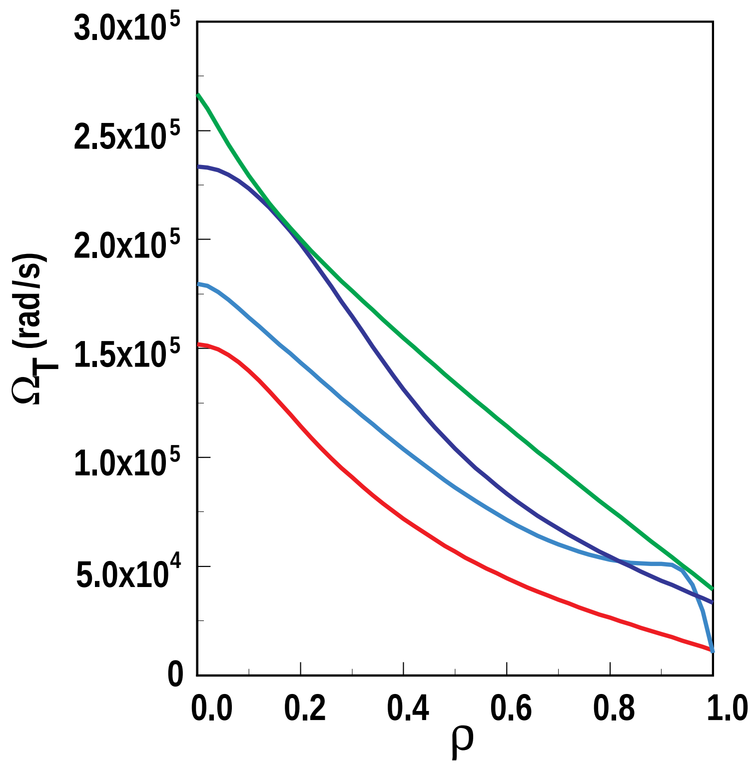
L–MODE EDGE NCS PROFILES ARE MORE PEAKED THAN IN H–MODE EDGE DISCHARGES

- L–Mode edge NCS plasma profiles peak inside NCS region (ρ<0.5)
  - Leads to pressure driven MHD instabilities (β_N~2.0–2.5)
- Broad H–Mode edge NCS plasma profiles result in enhanced performance
  - Combination of L–mode NCS core with H–mode edge





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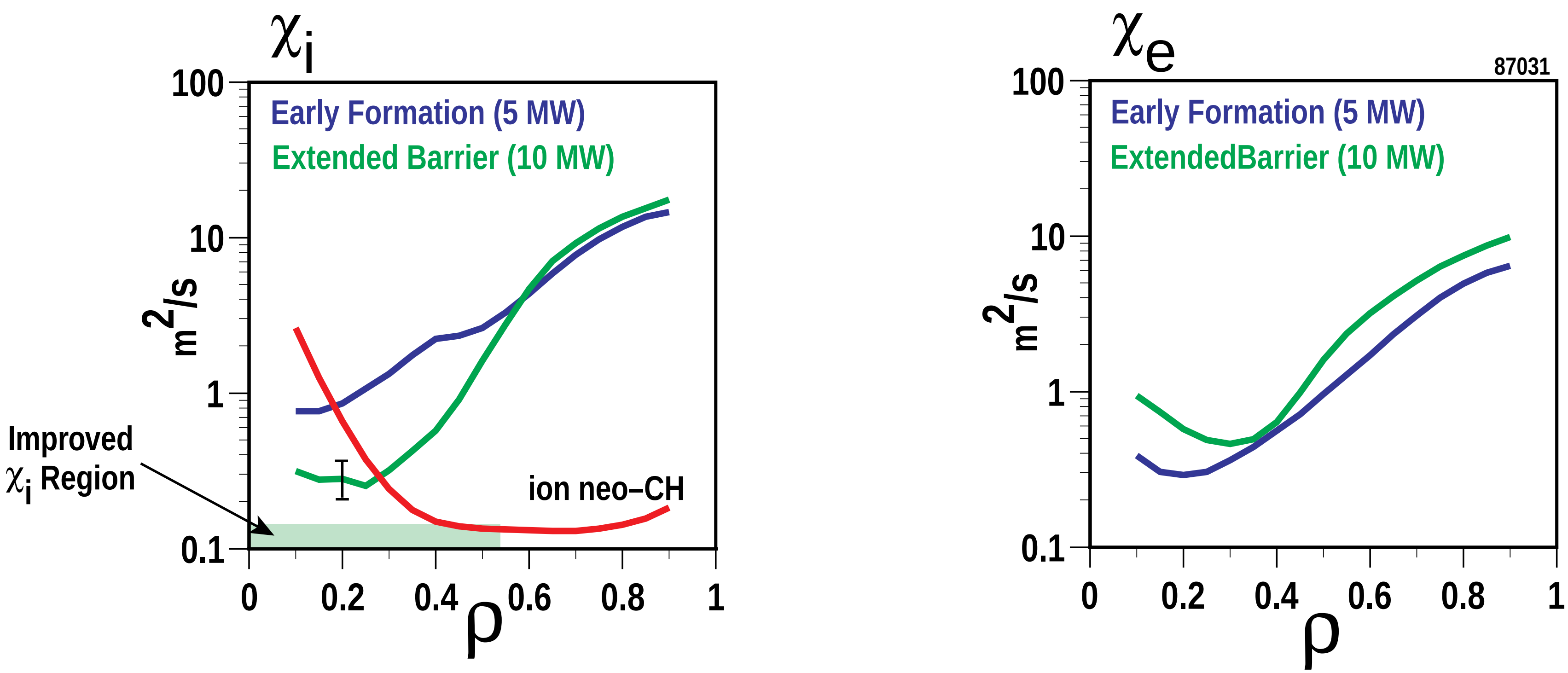
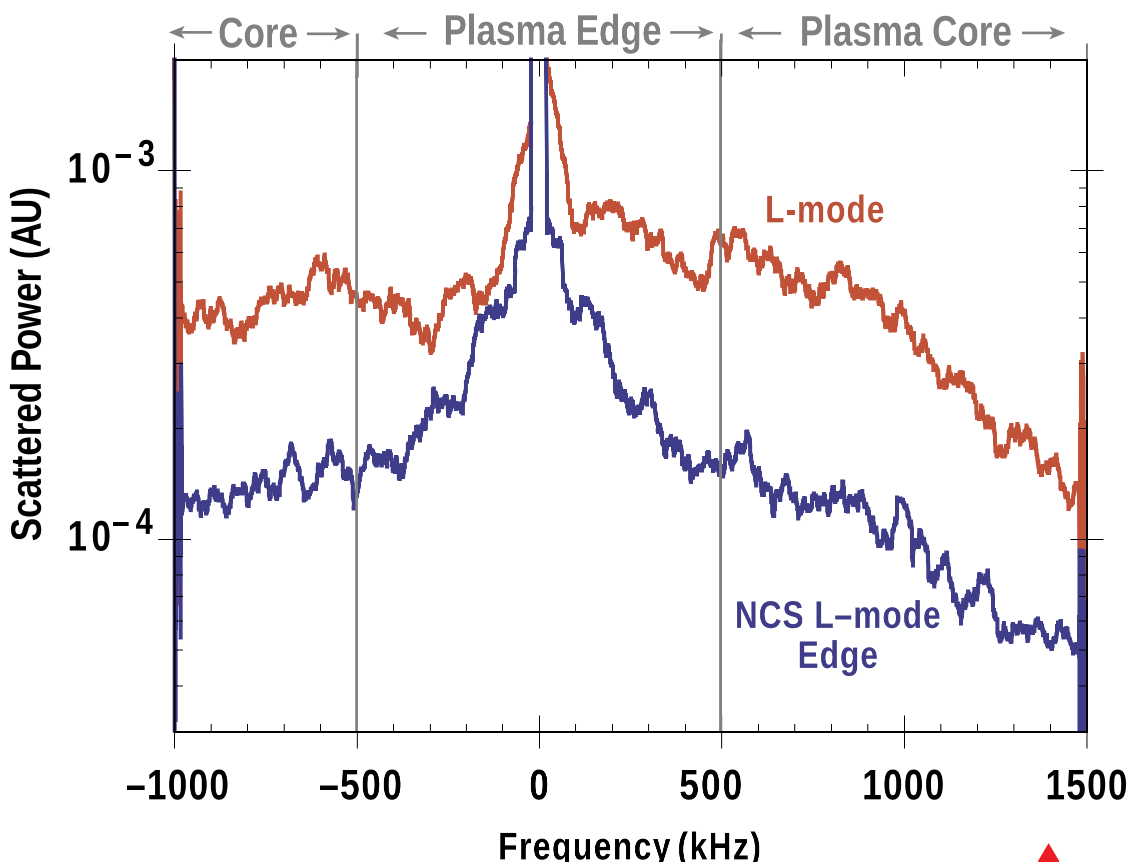
L–MODE EDGE PLASMA HAS REDUCED ION DIFFUSIVITY INSIDE NCS AREA AFTER FORMATION OF TRANSPORT BARRIER

- Ion transport about 4 times smaller inside NCS region (ρ<0.5) with more power
  - factor of 10 reduction has been observed at constant power
- Electron transport does not change within calculated uncertainties
  - 50% reduction has been observed in other discharges



NCS L–MODE EDGE DISCHARGE HAS LOWER CORE FLUCTUATIONS

- **Reduced core fluctuations (FIR) correlated with reduced ion transport**
  - Scattered Power proportional to $\tilde{n}_e^2$
- **Fluctuation reductions consistent with reduced turbulence**
  - e.g. Ion Temperature Gradient (ITG or η_i) modes



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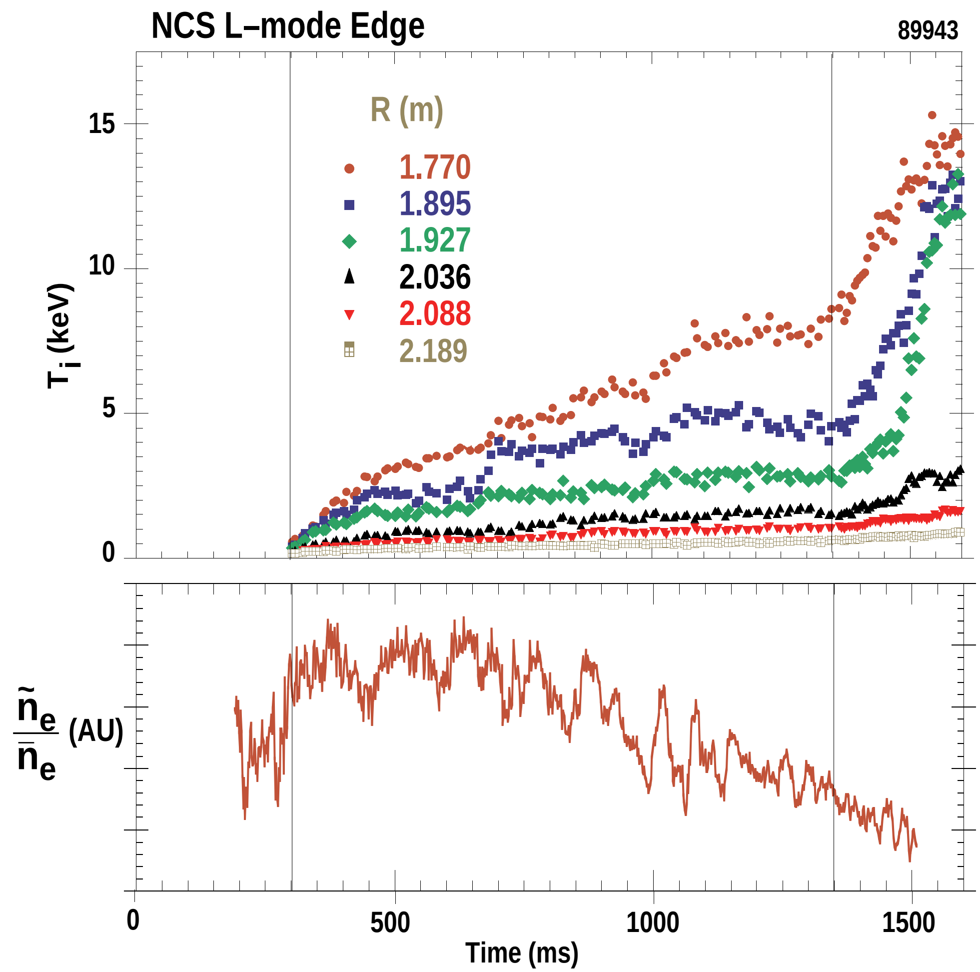
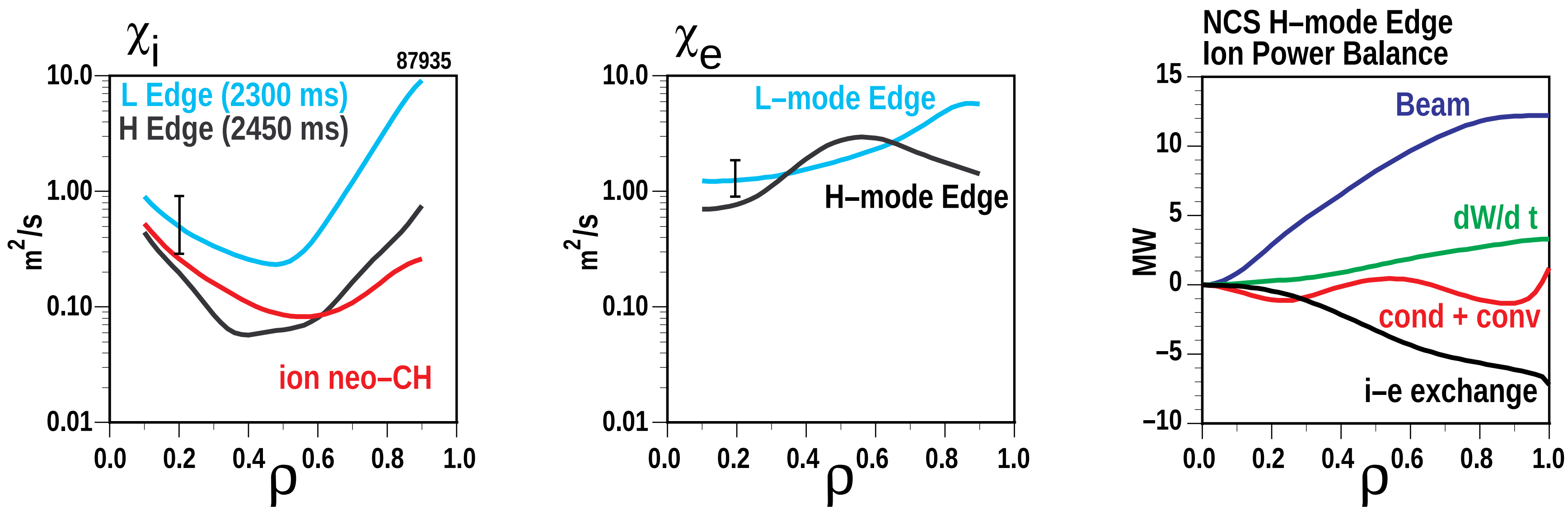
FLUCTUATIONS DECREASE IN TIME DURING NCS DISCHARGE

- Core density fluctuations (FIR) reduce as T_i increases with NCS established



ADDITION OF H–MODE EDGE TO THE NCS L–MODE REDUCES ION DIFFUSIVITY OVER ENTIRE PLASMA

- L–Mode edge discharge has reduced χ_i inside weak central shear area
- H–Mode edge discharge has reduced χ_i over entire cross–section
  - Approaches Chang–Hinton neoclassical at all radii
  - Neutral beam power balanced by ion-electron exchange and dW_i/dt
- Electron diffusivity remains relatively unchanged



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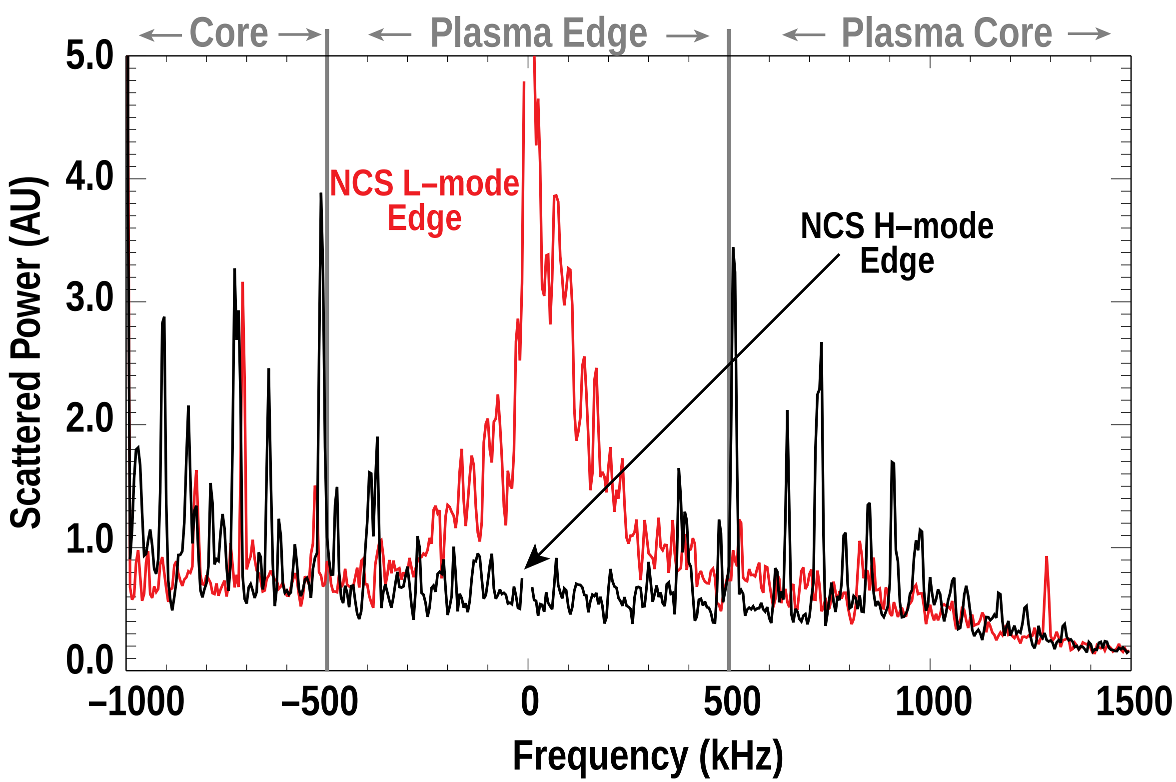
NCS H–MODE EDGE DISCHARGE HAS LOW CORE/EDGE FLUCTUATIONS

- Reduced edge fluctuations (FIR) in NCS H–mode edge case correlated with reduced ion transport over entire plasma cross-section
  - Approximatately neo-classical ion transport in NCS H–mode edge



BASIC FEATURES OF SHEAR STABILIZATION MODEL

- Negative or weak magnetic shear allows stabilization of high n MHD modes (e.g., ideal ballooning modes)

- q > 1 everywhere stabilizes sawteeth

- Lack of these instabilities plus application of additional heating allows pressure and rotation gradients to build, thus increasing radial electric field

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

- Local transport bifurcation can occur based on sheared E×B flow decorrelation of turbulence [Hinton & Staebler, Phys. Fluids B5, 1281 (1993)]

E×B FLOW SHEAR AND TURBULENCE

- Effect of E×B flow shear can be quantified by comparing the change in flow shear to turbulence growth rates

- Change in E×B flow shear determined by Doppler shift shear rate [Hahm & Burrell, Phys. Plasmas 2, 1648 (1995)]

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

- In previous work turbulent transport is completely suppressed when $\omega_{E\times B} > \gamma_{max}$ based on 3-D non–linear ITG simulations [Waltz et al., Phys. Plasmas 1, 2229 (1994)]

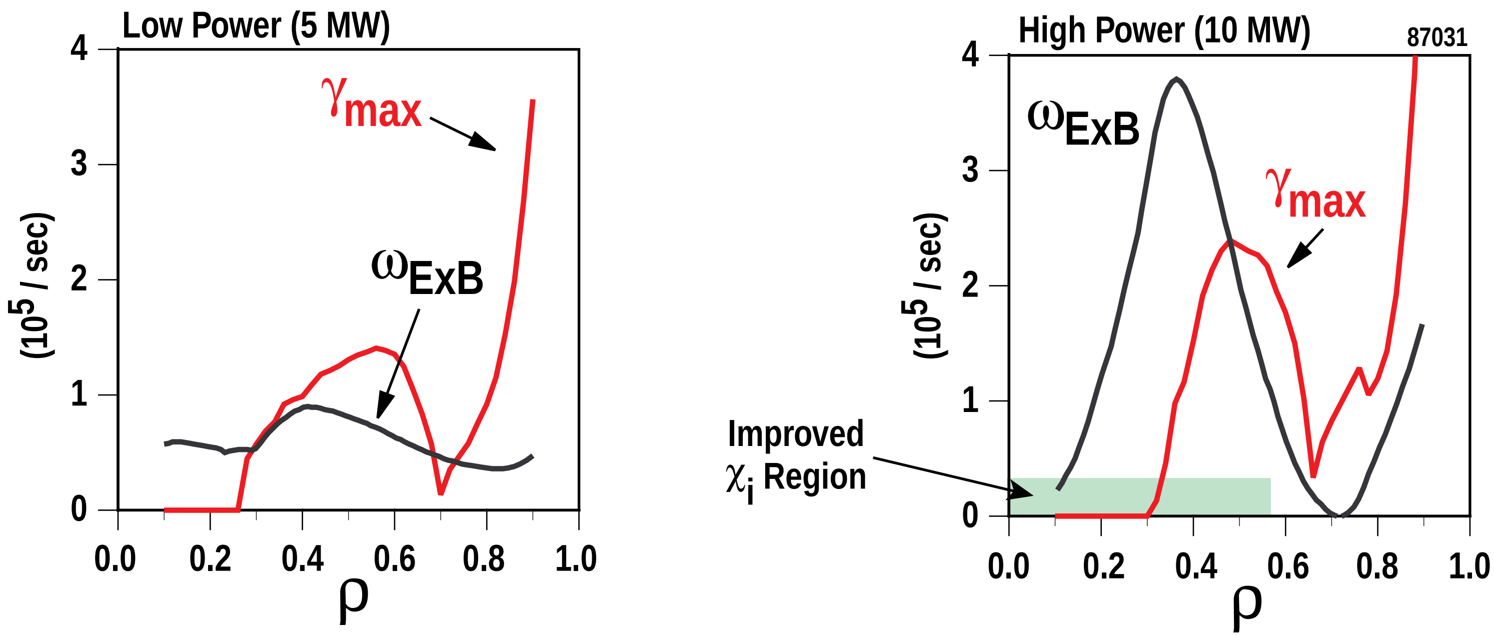
  – γ_{max} is the maximum growth rate without E×B shear

- In this paper maximum linear growth rate γ_{max} is calculated considering both the ITG and dissipative trapped electron modes

  – Calculated from 3-D ballooning mode gyrokinetic stability code in the electrostratic limit [Kotchenreuther et al., Bull. Am. Phys. Soc. 37, 1432 (1992)]

ExB FLOW SHEAR IS A LEADING CANDIDATE TO EXPLAIN STABILIZATION OF MICROTURBULENCE

- L–Mode edge NCS plasma
- In the early low power phase γ_{max} is greater than ω_{ExB} over most of the plasma
- In the high power phase $\omega_{ExB} > \gamma_{max}$ in the region of reduced transport



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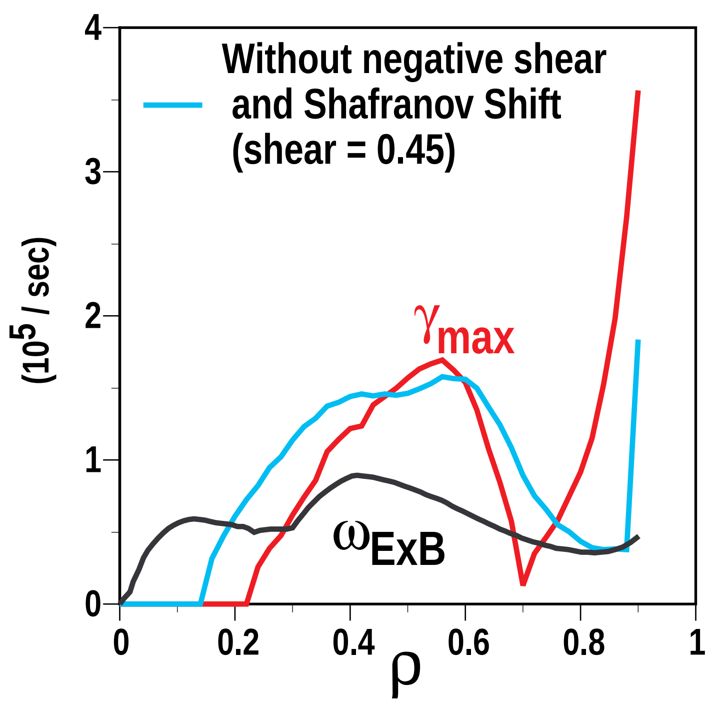
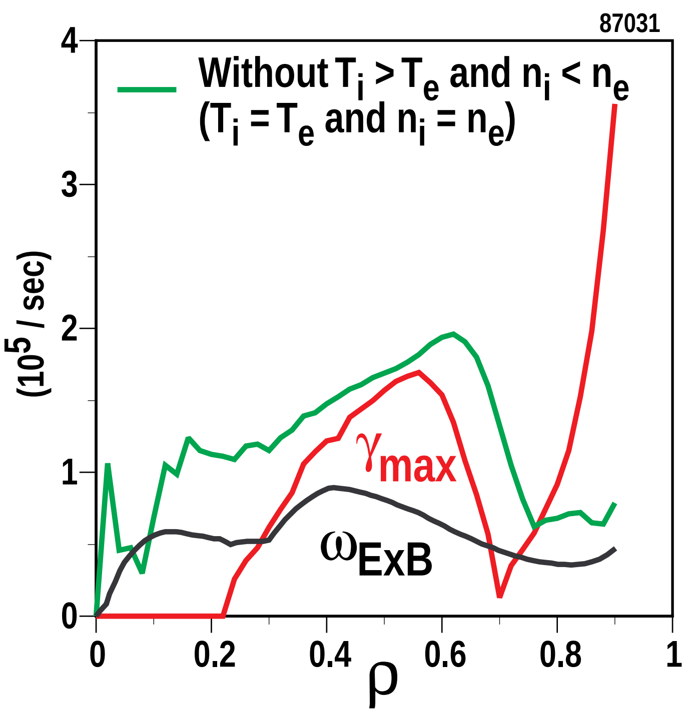
THE REGION OF STABILITY IN THE CORE RESULTS FROM SEVERAL FACTORS REDUCING THE GROWTH RATE

Negative Magnetic Shear and Shafranov Shift are Stabilizing



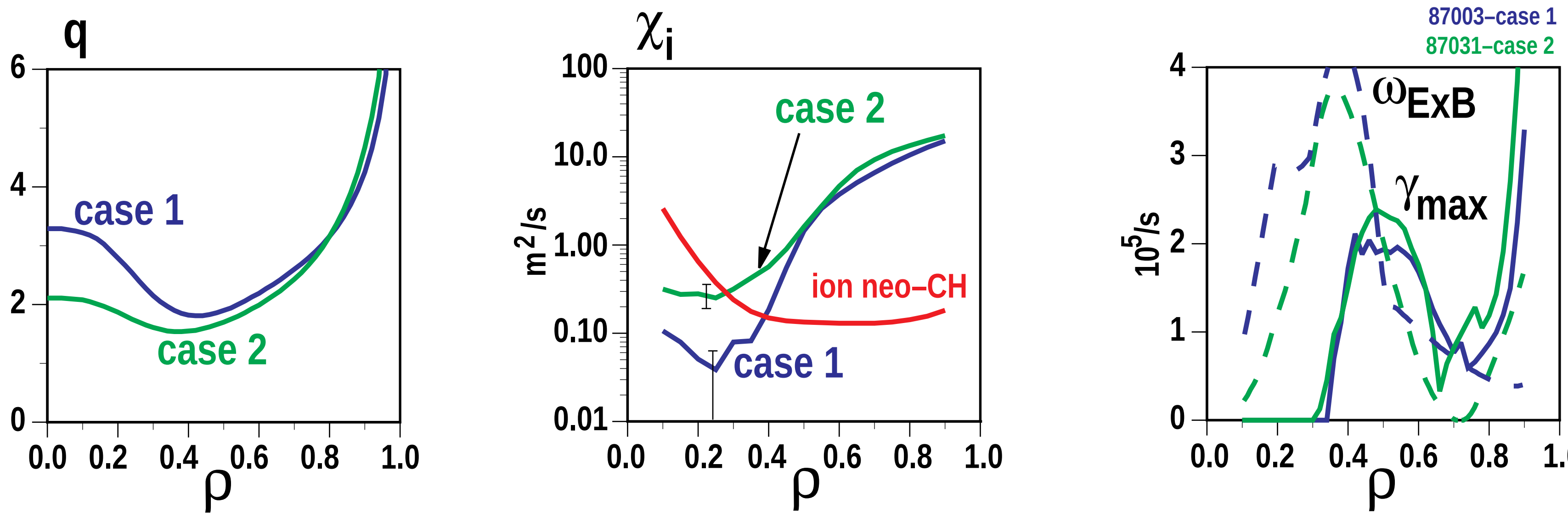
$T_i > T_e$ and Thermal Ion Dilution by Fast Ions are Stabilizing



- ω_{ExB} and γ_{max} calculated from experimental profiles during low power phase

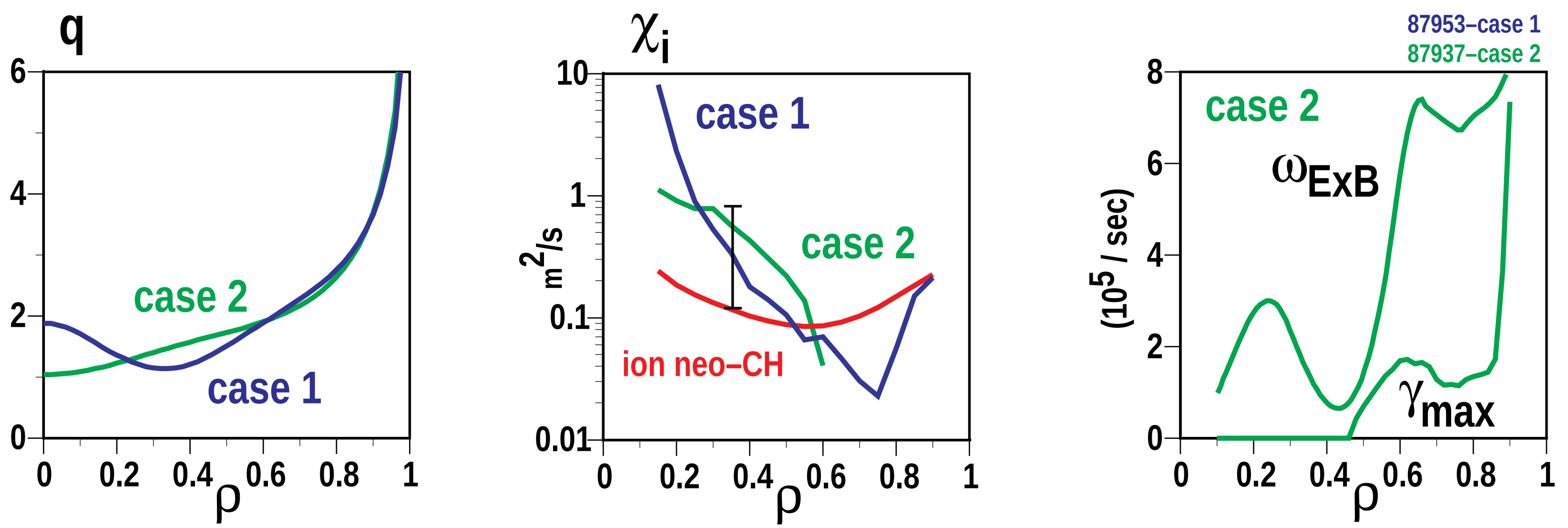
GREATER NEGATIVE SHEAR IN L–MODE EDGE REDUCES TRANSPORT

- χ_i reduced with larger Δq; within uncertainty χ_e remains the same
- γ_{max} and ω_{ExB} comparison does not explain the reduced ion transport
- No calculated instability ($0.01 < k_\theta \rho_s < 100$) at $\rho = 0.2$
  - Yet electron transport not observed to be electron neoclassical



GREATER NEGATIVE SHEAR DOES NOT CHANGE TRANSPORT IN NCS H–MODE EDGE PLASMA

- χ_i and χ_e do not change with larger Δq
- γ_{max} smaller than ω_{ExB} at all radii
  - consistent with neoclassical ion transport over entire plasma cross–section
  - combining NCS L–mode core transport with H–mode edge transport



SUMMARY

- NCS plasmas provide a robust and reliable enhanced confinement regime with both an L–mode and H–mode edge
  - τ_E up to 4 times ITER89–P
- NCS with L–mode edge
  - Peaked toroidal rotation, ion temperature and plasma density profiles consistent with an internal transport barrier
  - χ_i reduced to ion-neoclassical inside the transport barrier
  - Larger negative shear lowers ion transport
- NCS with H–mode edge
  - Broad plasma profiles consistent with improved transport over the entire plasma cross-section
  - χ_i reduced to ion-neoclassical over the entire plasma
  - Larger negative shear does not alter transport
- Lower transport is accompanied by reduced plasma fluctuations
- Primary candidate for microturbulence stabilization is sheared $E \times B$ flow
- NCS is necessary but not sufficient for enhanced confinement
  - Necessary for ballooning 2^{nd} stability
  - Sheared $E \times B$ flow must be large enough to overcome turbulence growth rates