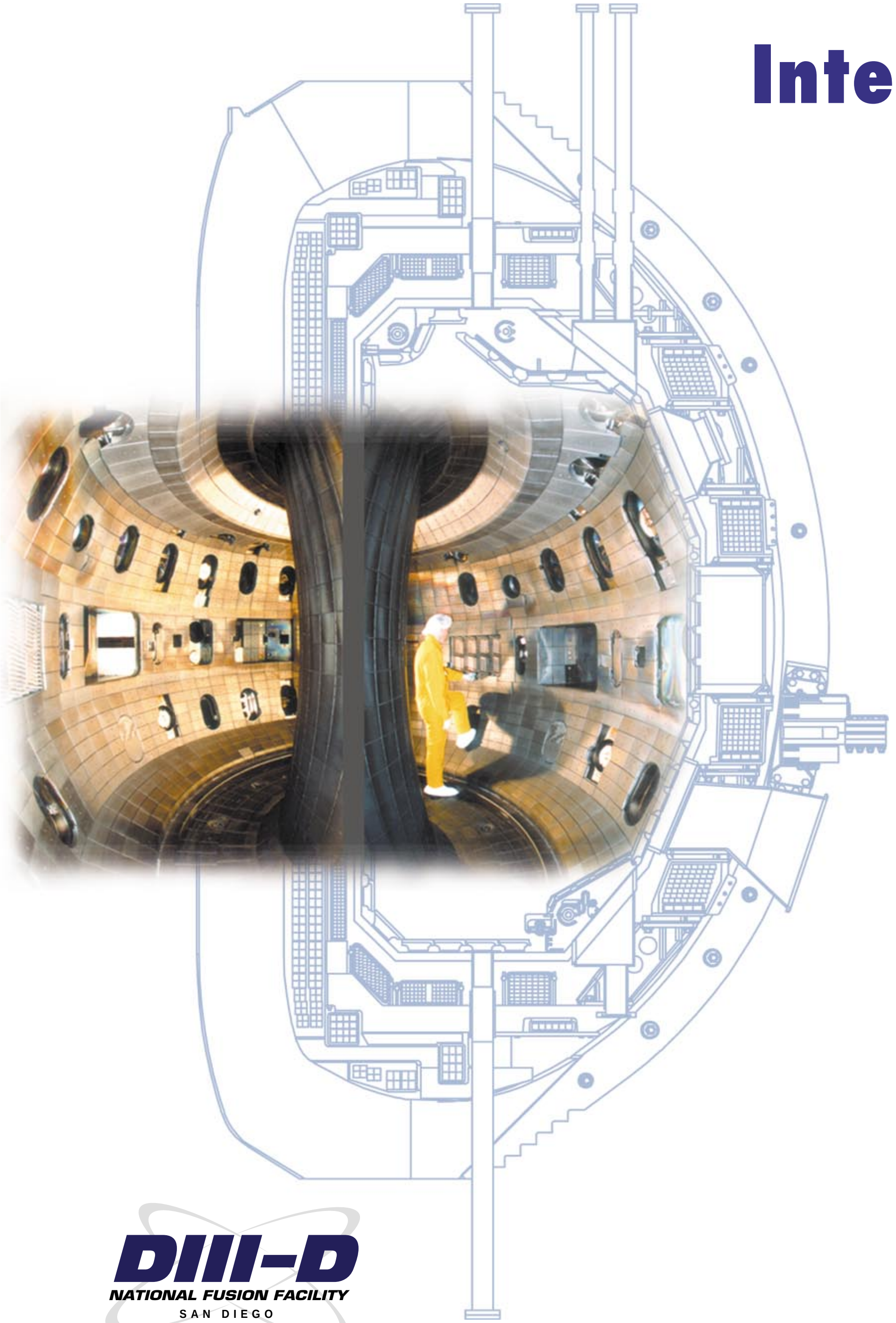

Internal Transport Barriers in the DIII-D Tokamak

by
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For the DIII-D Research Team

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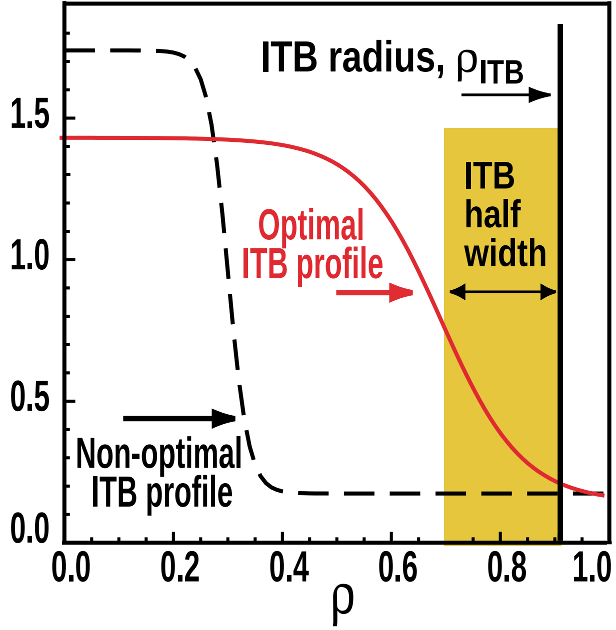
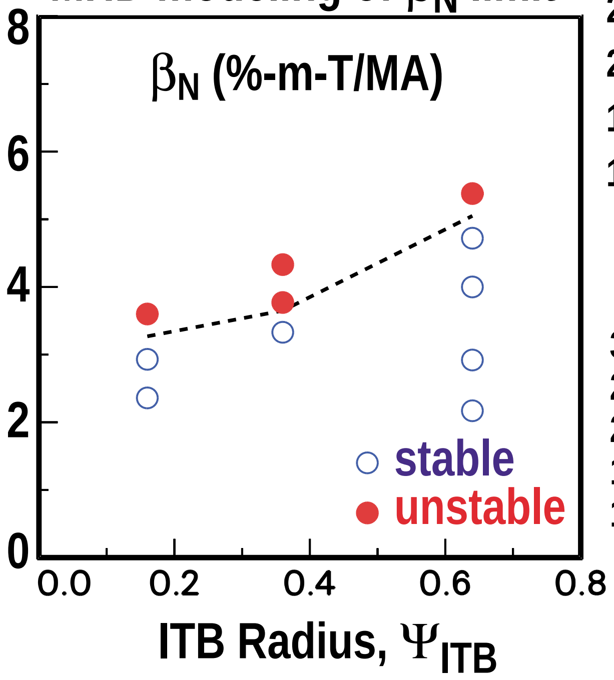
MOTIVATION —
IMPORTANCE OF ITB RESEARCH

- Obtaining ITBs with large radius and barrier width leads to:
  - Higher fusion performance
    - ★ Assist in obtaining significant fusion gain (Q~10) in Next Step burning plasmas
  - Improved MHD stability limits
    - ★ More compact and/or economic powerplants
  - Improved bootstrap current alignment
    - ★ Assist in achieving steady-state tokamak operation

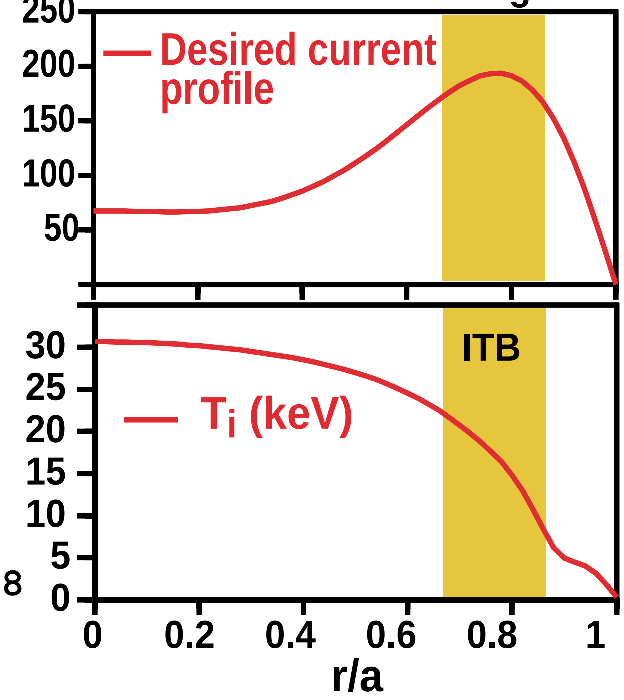
Schematic ITB T_i profiles



MHD modeling of β_N limit



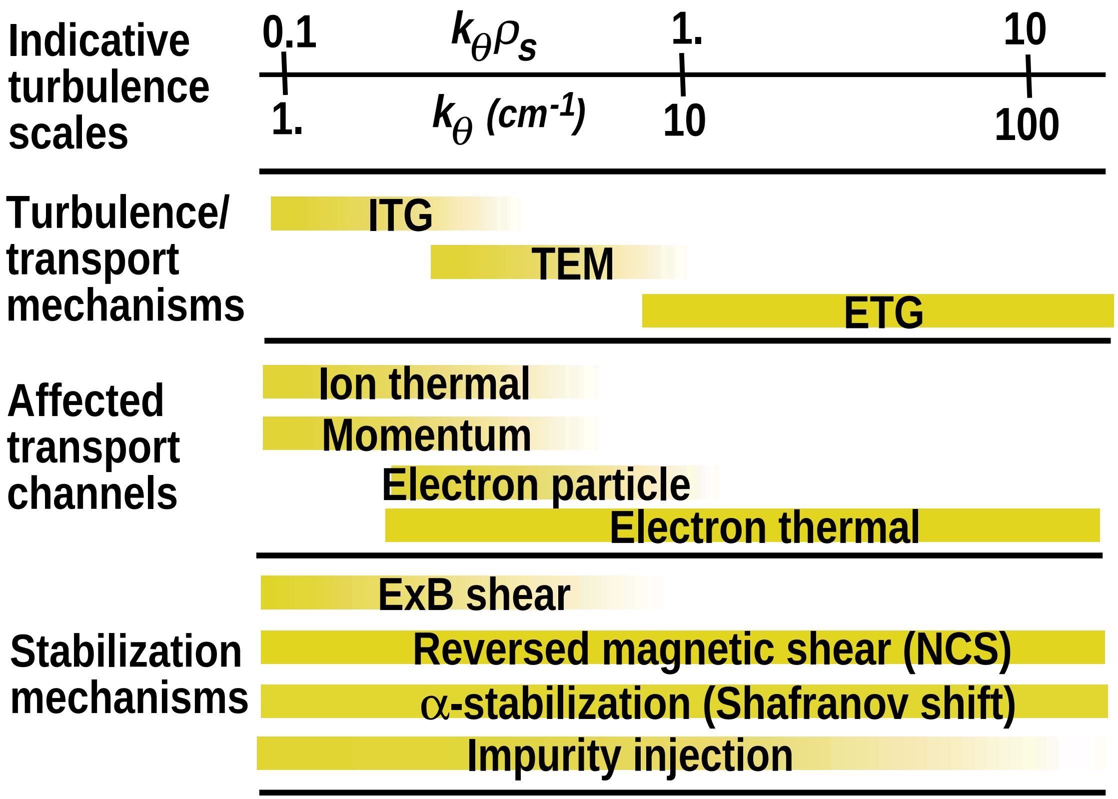
ARIES-AT Modeling



OVERVIEW

- Significant progress on DIII-D in addressing critical issues for ITB research:
  - Improved understanding of physical mechanisms responsible for ITB formation
    - ★ Evidence for a range of turbulence/transport reduction mechanisms
  - New Quiescent Double Barrier (QDB) regime provides sustained, high quality ITB operation with an ELM-free H-mode edge, allowing us to examine:
    - ★ Edge-core integration issues, e.g. effect of ELMs
    - ★ ITB sustainment
    - ★ Impurity accumulation
  - MHD stability will determine ultimate performance limit of ITB plasmas
    - ★ Stabilization of resistive wall modes (RWM) and neoclassical tearing modes (NTM) demonstrated on DIII-D. Invited talk by on RWM results by M. Okabayashi, Wednesday

UNDERSTANDING OF ITB FORMATION CONDITIONS FLOWS FROM UNDERSTANDING OF TRANSPORT DRIVE AND SUPPRESSION MECHANISMS



Indicative turbulence scales

$k_\theta \rho_s$: 0.1 — 1. — 10

k_θ (cm^{-1}): 1. — 10 — 100

Turbulence/ transport mechanisms

ITG

TEM

ETG

Affected transport channels

Ion thermal

Momentum

Electron particle

Electron thermal

Stabilization mechanisms

ExB shear

Reversed magnetic shear (NCS)

α-stabilization (Shafranov shift)

Impurity injection

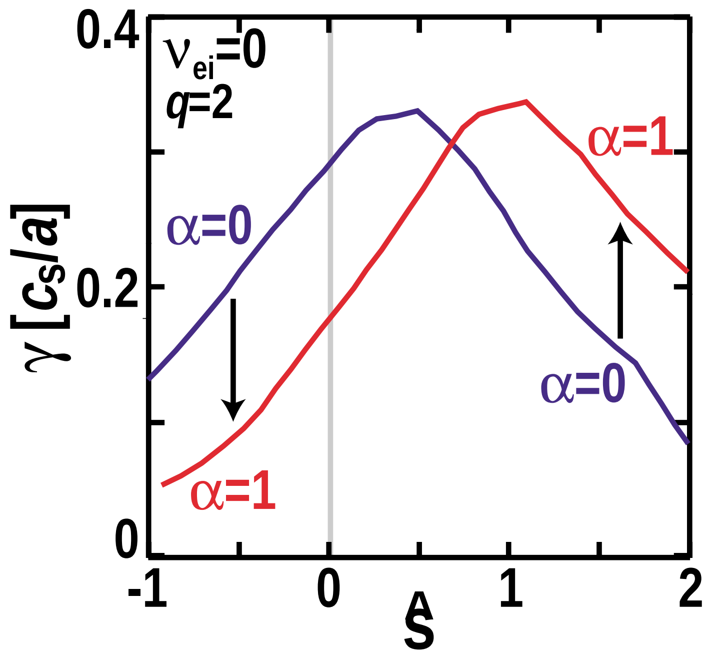
- Theory-based modeling predictions for turbulence and transport drive and control mechanisms are compared to experiment
- DIII-D results indicate following turbulence control mechanisms can be effective:
  - — α-stabilization/Shafranov shift
  - — *q* profile
  - — Growth rate reduction via impurity injection
  - — Sheared ExB flows (rotation)
- Direct evidence for ETG modes is lacking

α-STABILIZATION AND NEGATIVE MAGNETIC SHEAR ARE PREDICTED TO REDUCE TURBULENCE GROWTH RATES

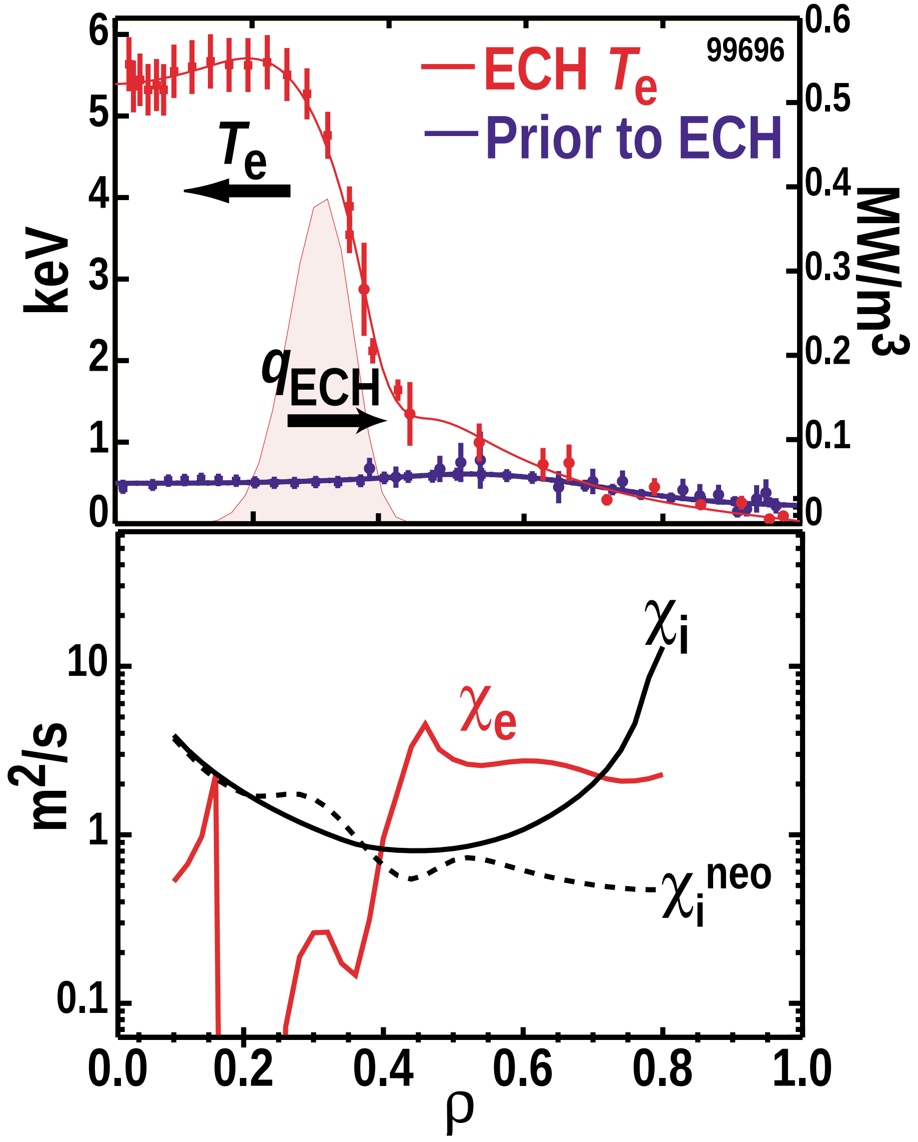
- Theory calculations, e.g. Waltz et al, Phys Plasmas 1997, indicate that turbulence growth rates can be reduced by negative magnetic shear and α-stabilization (Shafranov shift)
  - Where α is the normalized pressure gradient (ballooning parameter)

- In comparisons to theory, extensive use is made of the GLF23 transport model
  - Drift-wave based model (ITG, TEM, ETG), providing quasilinear estimates of transport
  - Includes ExB shear, α-stabilization, magnetic shear and dilution effects

- ExB shear predicted to suppress turbulence when the shearing rate ω_{ExB} exceeds the turbulence linear growth rate γ



EVIDENCE FOR ROLE OF α-STABILIZATION PROVIDED BY ELECTRON THERMAL ITBs OBTAINED WITH LOCALIZED ECH



- E-ITB develops rapidly following ECH onset

- Electron transport reduced

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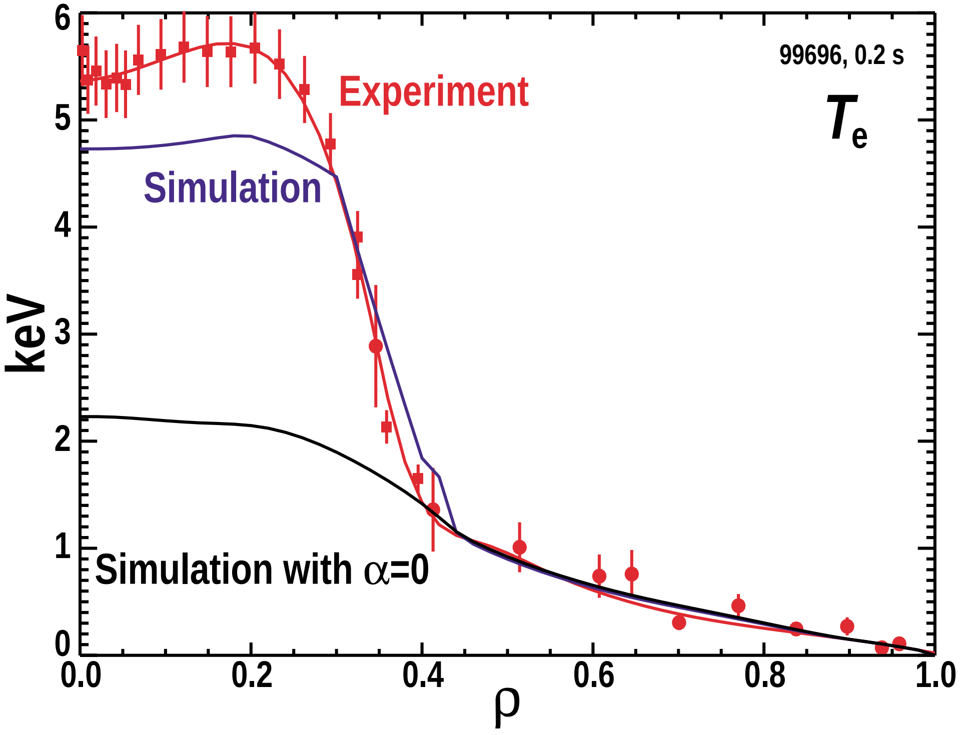
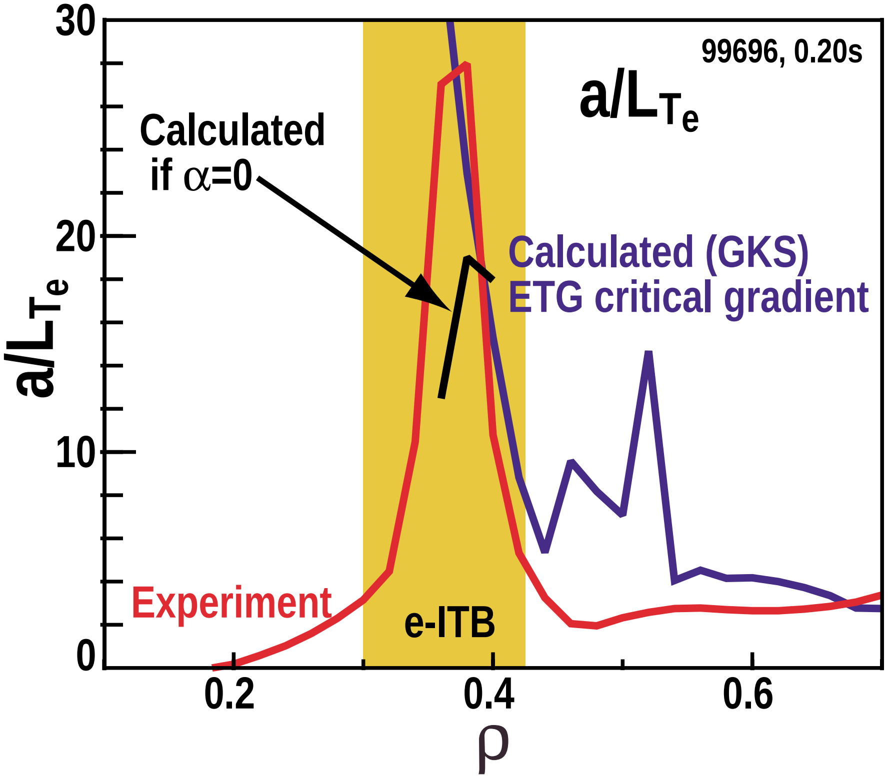
SIMULATIONS INDICATE α-STABILIZATION IS CRITICAL IN FORMATION OF ELECTRON ITB

- Dynamical simulations using GLF23 model maintain E-ITB only if α is sufficiently large
  - GLF23 also reproduces dynamics of barrier evolution

- Results also provide indirect evidence for ETG modes:
  - T_e gradient at location of E-ITBs consistently observed to be at marginal stability to ETG mode





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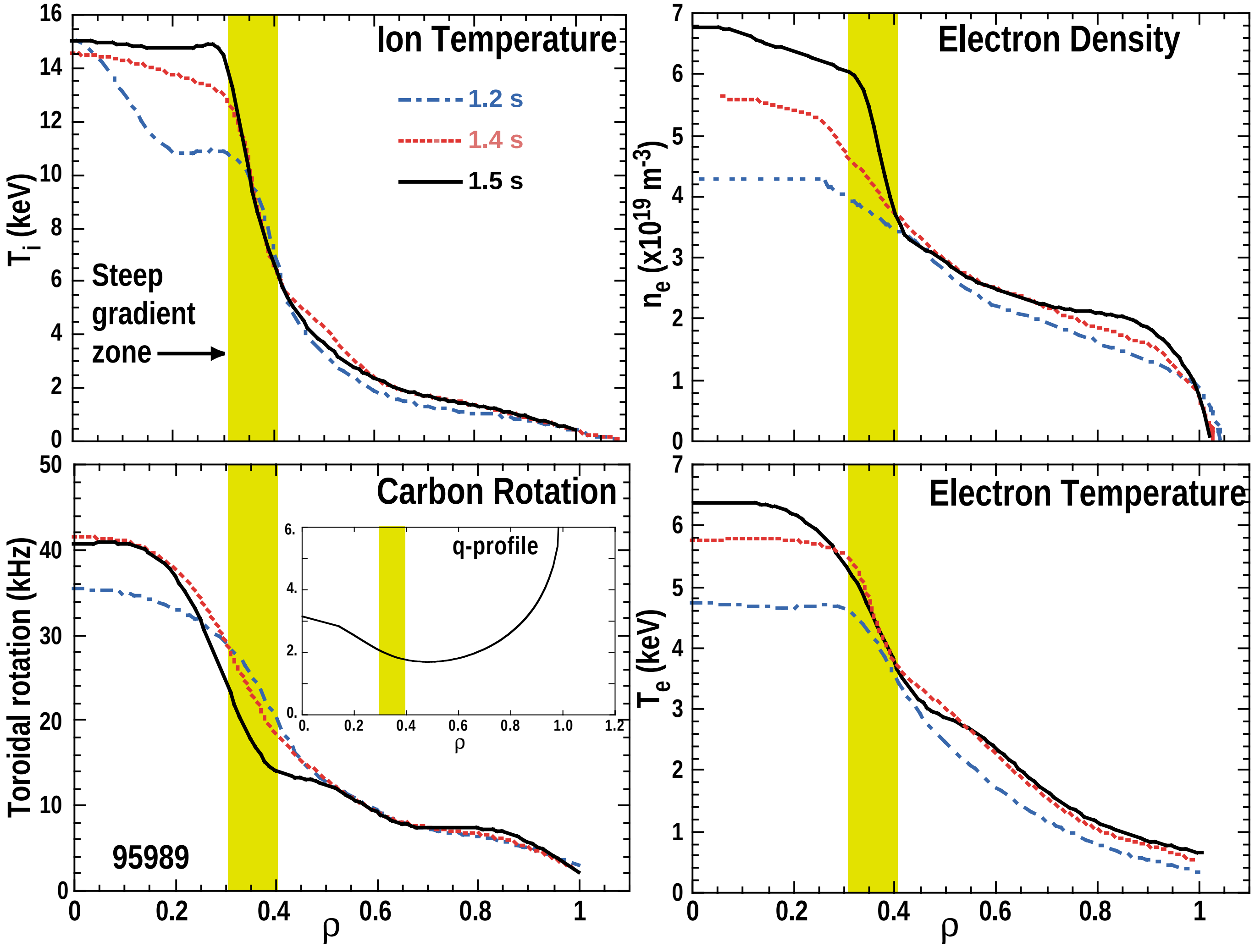
SUBSTANTIAL EVIDENCE FROM MANY EXPERIMENTS FOR ROLE OF *q*-PROFILE IN FACILITATING ITB FORMATION

- On DIII-D, use of strong negative shear, plus high heating power results in ITBs in all four transport channels

- Without strong negative shear, ITBs on DIII-D often limited to ion thermal and angular momentum channels



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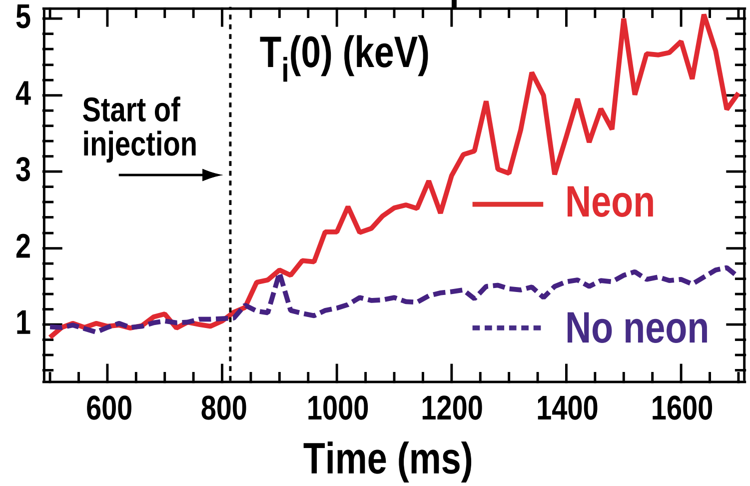
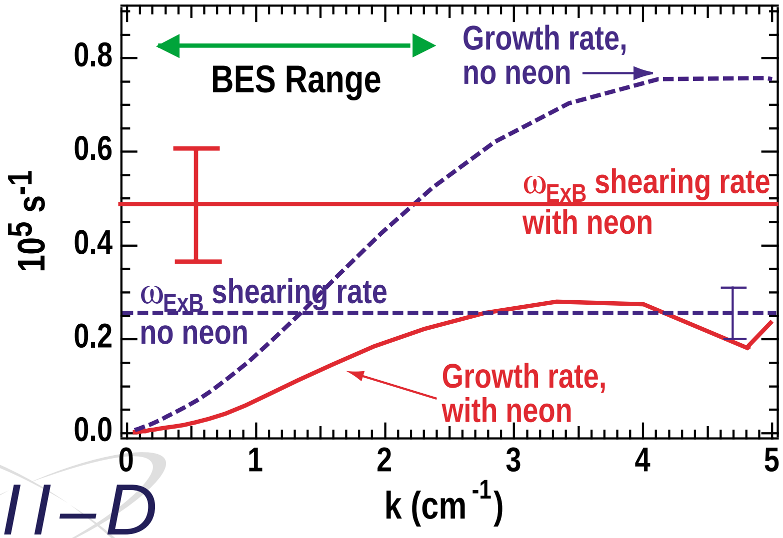
IMPURITY DILUTION CAN REDUCE TURBULENT TRANSPORT BY REDUCING GROWTH RATES AND INCREASING ExB SHEAR

- Results from neon injection into co-NBI plasma with L-mode edge, no prior ITB
- Results explain physics of RI-mode:
  - Linear growth rates reduced and ExB shearing rate increased
  - Density fluctuations dramatically reduced
  - Core temperatures rise, energy confinement and neutron rate double, profiles broaden

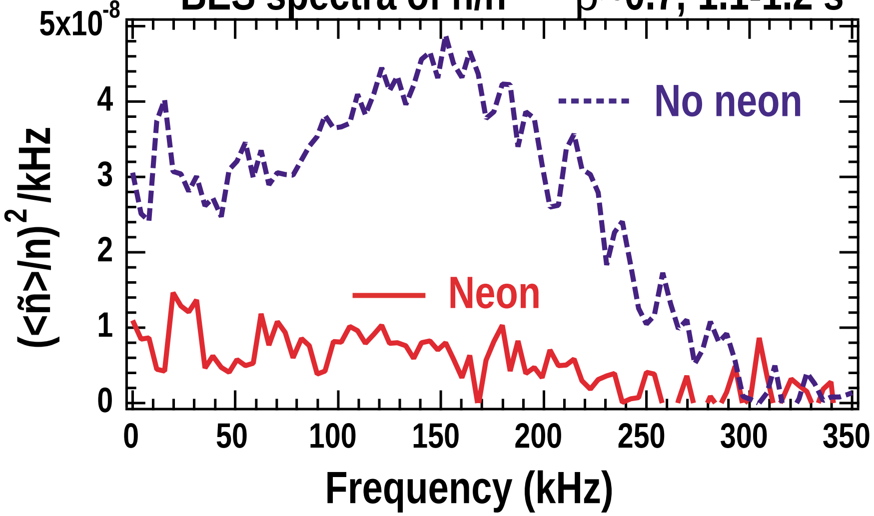
Central ion temperature



Turbulence growth and shearing rates



BES spectra of ñ/n ρ~0.7, 1.1-1.2 s



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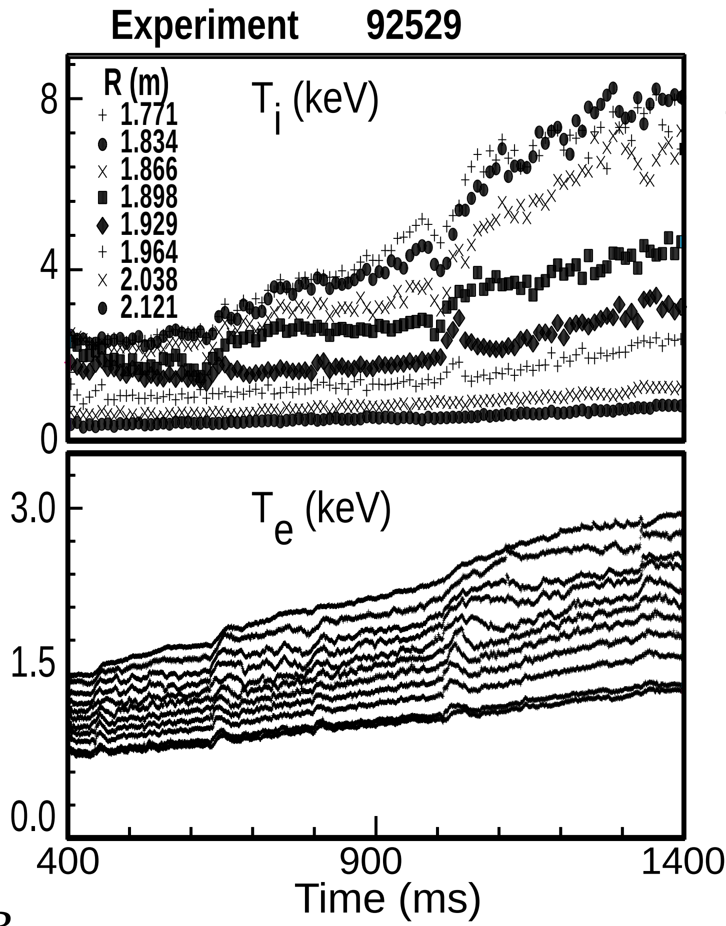
ExB SHEAR FLOW IS MOST STUDIED TRANSPORT BARRIER FORMATION MECHANISM (EDGE AND CORE)

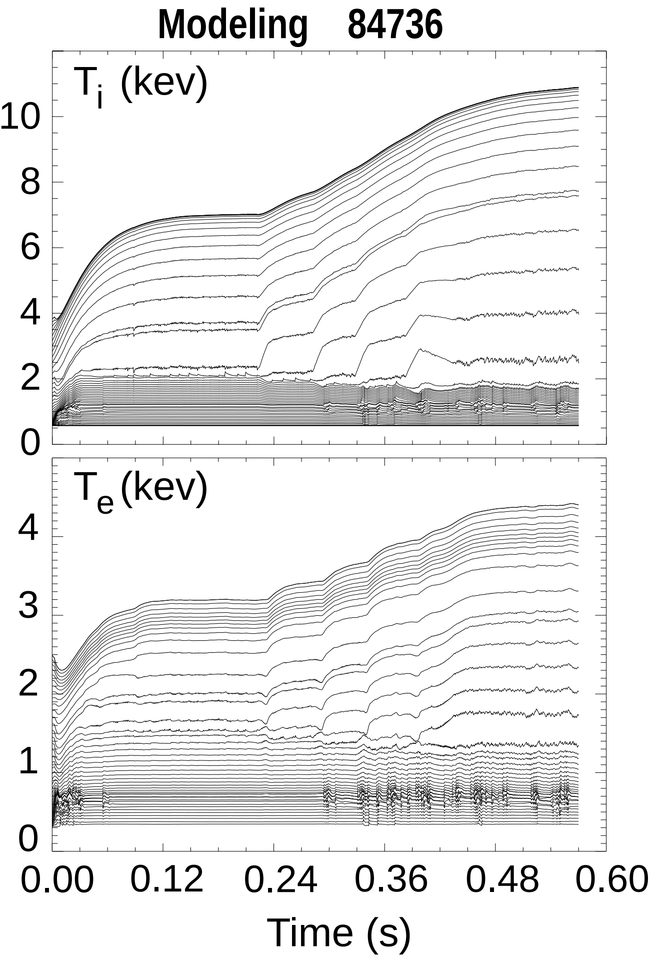
- **Self-consistent dynamical modeling using GLF23 can explain details of step-wise formation of ITBs on DIII-D**
  - **Steps are generated by a competition between the ∇P and $v_\phi B_\theta$ contributions to E_r and the ExB shearing rate in co-NBI discharges**

$$E_r = \frac{\nabla P_i}{e n_i Z_i} - v_\theta B_\varphi + v_\phi B_\theta$$

Experiment 92529



Modeling 84736



- **Occurrence of steps sometimes correlates with presence of rational q values**

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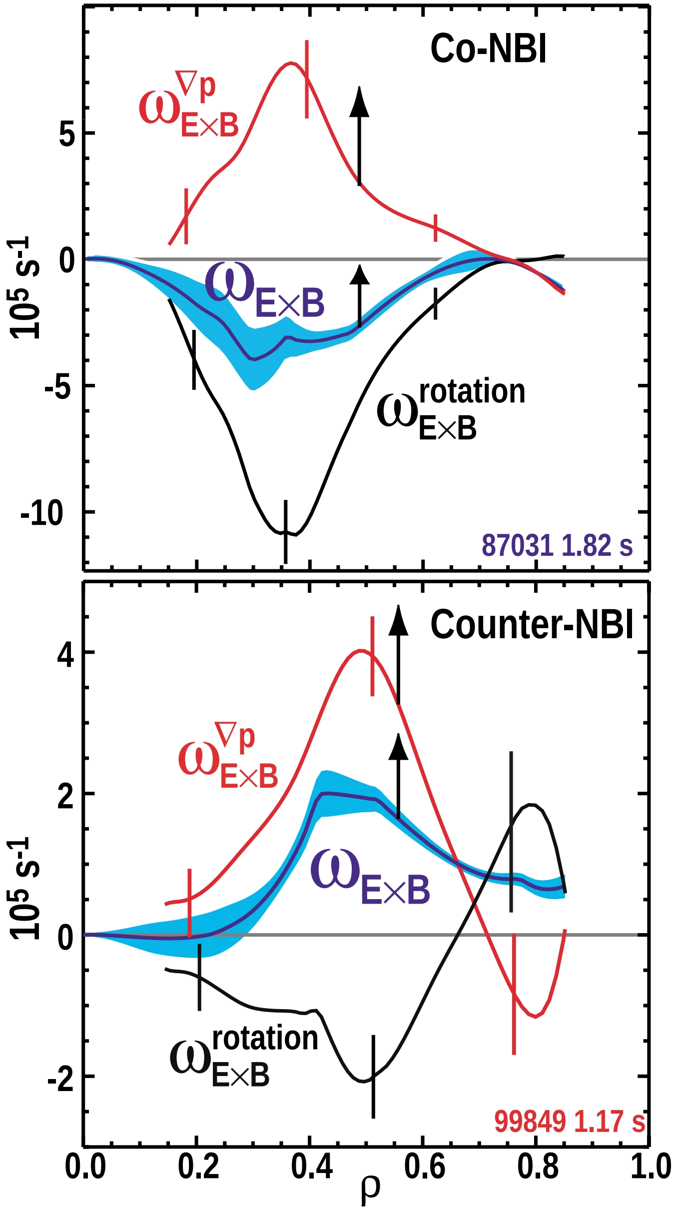
INTERPLAY OF TERMS IN ExB SHEARING RATE $\omega_{E\times B}$ IS DIFFERENT FOR CO- AND COUNTER-NBI

- Main ion shearing rate $\omega_{E\times B}$ can be separated into pressure and rotation terms

$$\omega_{E\times B} = \omega_{E\times B}^{\nabla p} + \omega_{E\times B}^{\text{rotation}}$$

- With counter-NBI, increasing the pressure gradient component increases $\omega_{E\times B}$, rather than reducing it, as with co-injection
  - Counter-NBI favorable for ITB expansion with L-mode edge
  - Counter-NBI experiments led to discovery of Quiescent Double Barrier (QDB) regime



QUIESCENT DOUBLE-BARRIER (QDB) OPERATION

- **Will examine:**
  - —Performance obtained in QDB regime
  - —Significance of QDB results
  - —Transport and fluctuation analysis and modeling
  - —Impurity issues
- **Some new acronyms:**
  - —QH-mode: Quiescent H-mode
    - ★ An ELM-free H-mode with density and radiated power control
  - —QDB: Quiescent Double Barrier
    - ★ Operation with an internal transport barrier (ITB) inside a QH-mode edge

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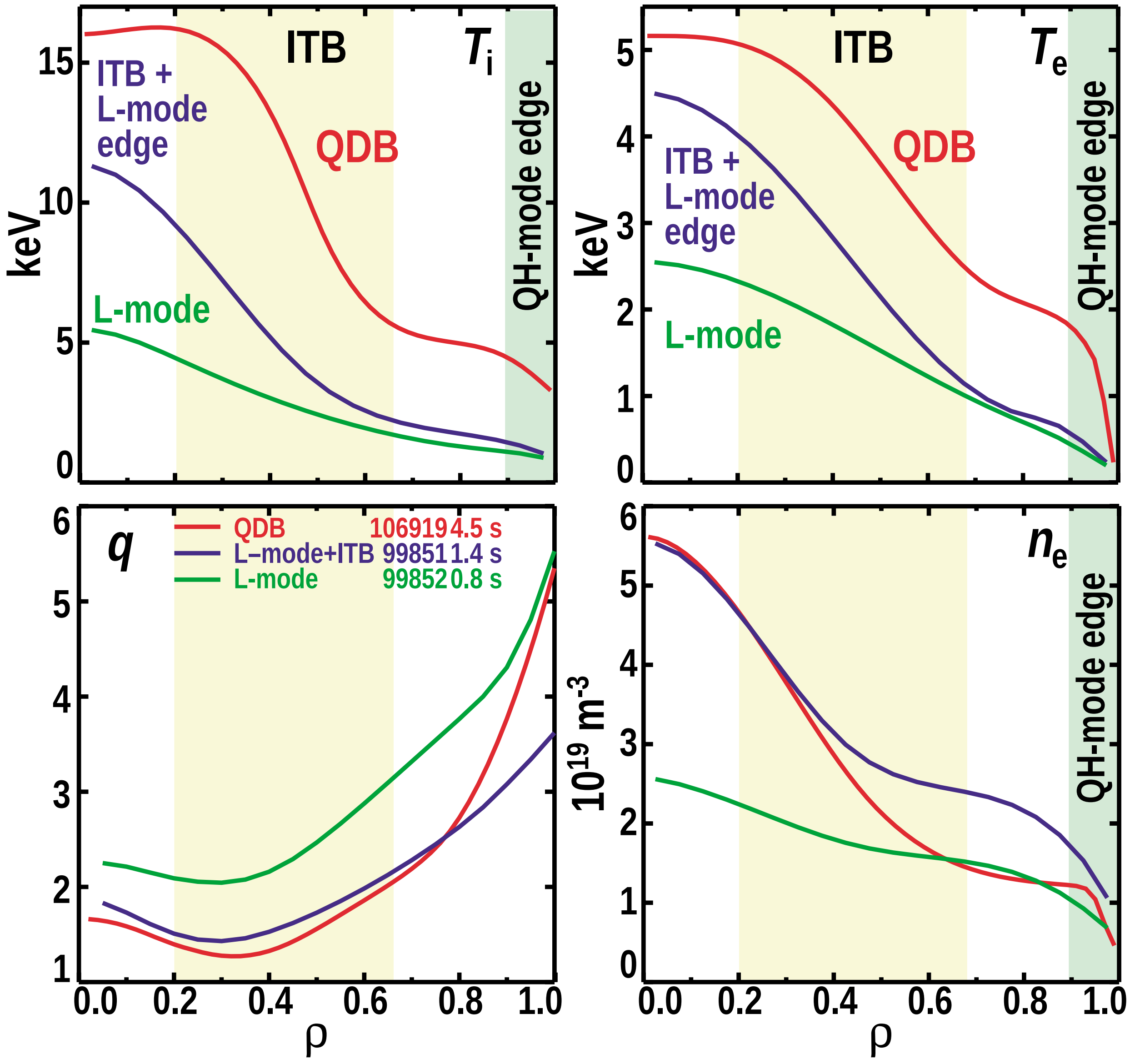
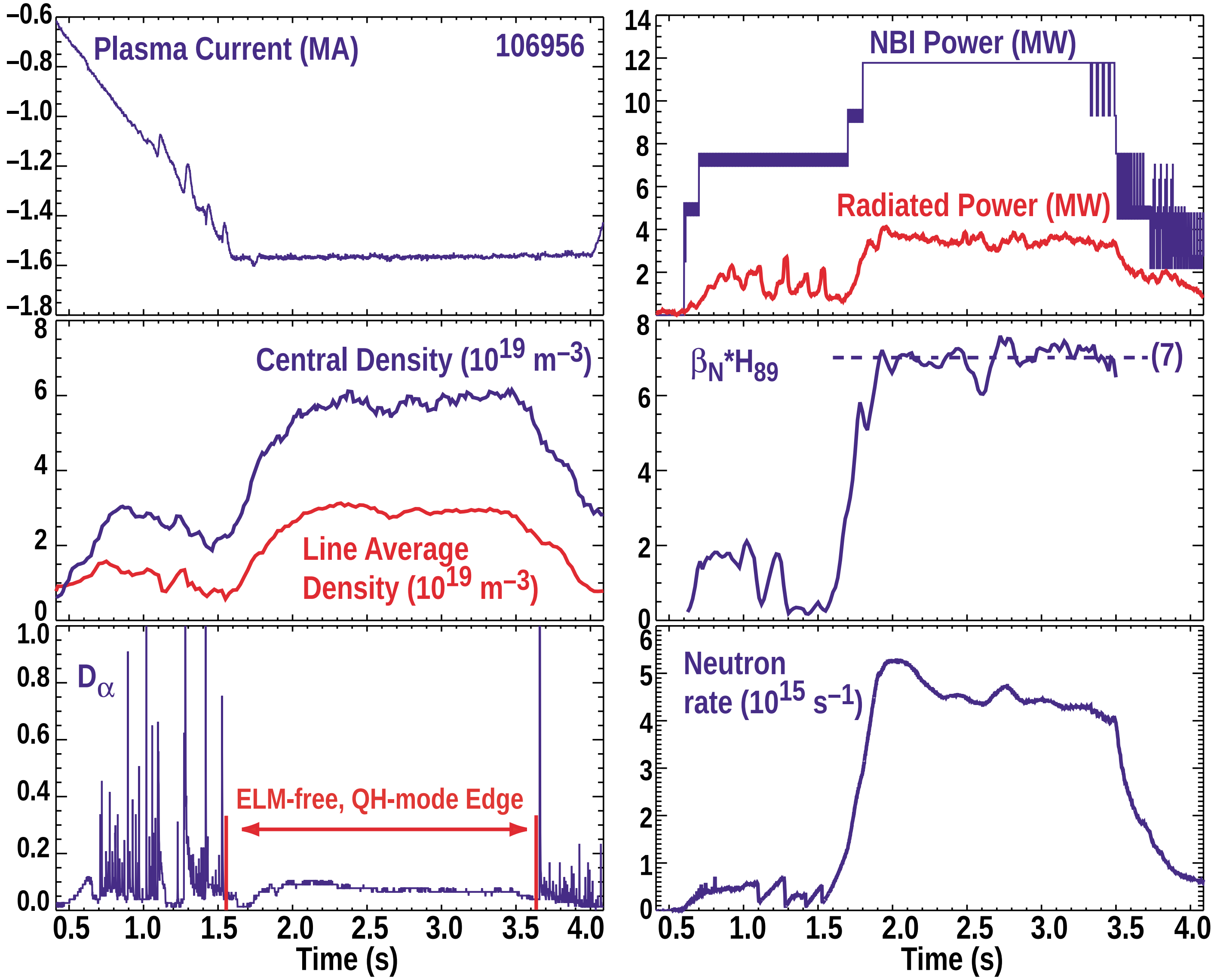
QDB REGIME OBTAINED USING COUNTER-NBI — COMBINES ITBs WITH ELM-FREE QUIESCENT H-MODE EDGE

- Edge pedestal elevates central temperatures, improving fusion performance



COMBINATION OF CORE ITB AND QH-MODE EDGE RESULTS IN SUSTAINED HIGH PERFORMANCE PLASMAS

- $\beta_N H_{89}$=7 for 10 τ_E (1.6 s)
- Duration limited by NBI sources
- Have maintained QH-mode for >3.5 s, ~25τ_E
- Feature of QH-mode is ELM-free operation with density and radiated power control
    - — Density controlled using divertor pumping



WHAT IS THE SIGNIFICANCE OF QDB OPERATION?

- H-mode is the operating regime of choice for next-step devices, but has non-optimal features due to the impact of Edge Localized Modes (ELMs)
  - Pulsed heat loads to the divertor can cause rapid erosion
  - Type I (Giant) ELMs can inhibit or destroy the ITBs desired for advanced tokamak (AT) scenarios
    - ★ Double barriers have been achieved on JT-60U and JET
- QDB plasmas address critical next-step and ITB issues:
  - Provides high quality ELM-free H-mode, eliminating pulsed divertor heat loads
  - The QH-mode edge is compatible with ITBs
  - Sustained long pulse, high performance capability:
    - ★ >3.5 s or 25 τ_E achieved, limited only by beam pulse duration
    - ★ $\beta_N H_{89} = 7$ for 10 τ_E
  - Long pulse capability provides opportunity to study impurity accumulation issues in detail

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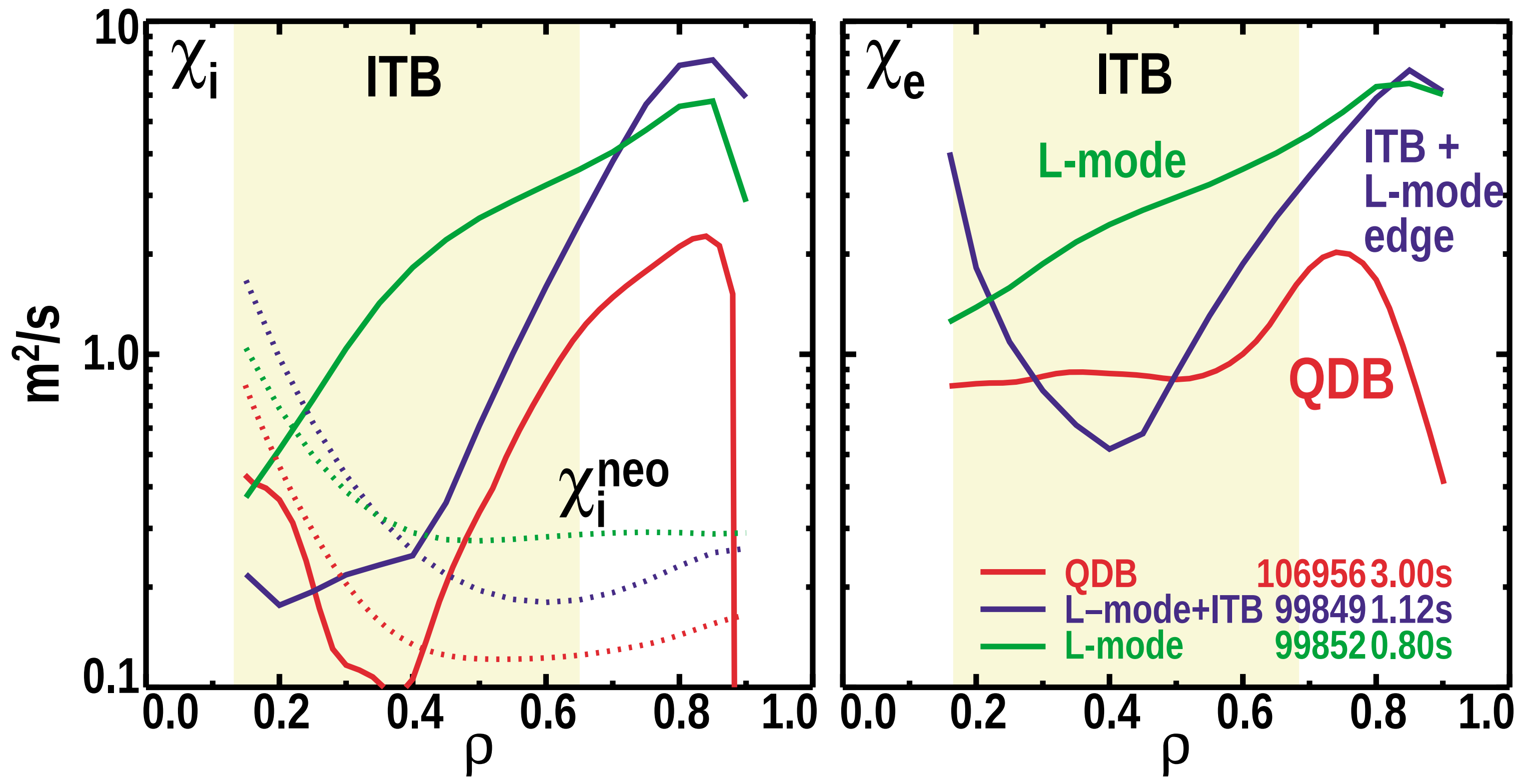
TRANSPORT ANALYSIS CONFIRMS PRESENCE OF DOUBLE (CORE AND EDGE) TRANSPORT BARRIERS



- Core transport is similar to that in ITB plasmas with an L-mode edge
  - —ITB refers to region of reduced transport relative to L-mode
- Edge transport is typical of H-mode
- Core and edge barriers are kept separate by region of low ExB shear

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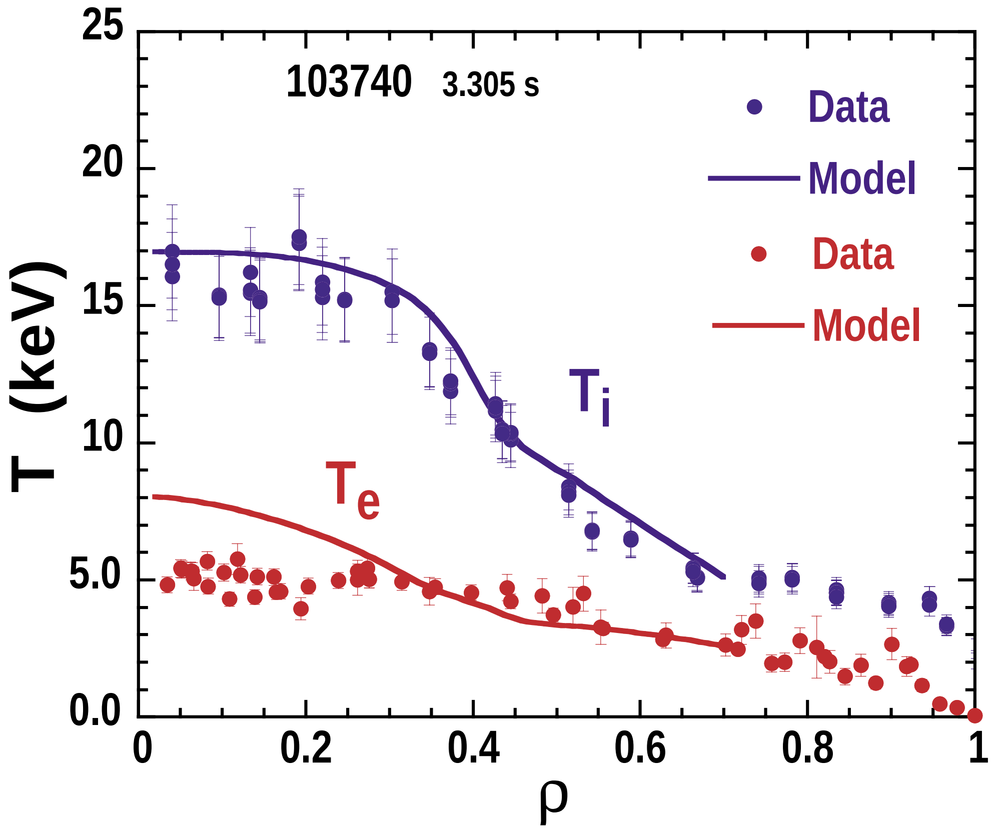
SIMULATIONS USING THE GLF23 MODEL REPRODUCE THE QDB CORE ION BARRIER



- Steady-state simulation reproduces core ion temperature barrier
  - Core T_e profile not accurately reproduced
- GLF23 also predicts core turbulence should not be completely suppressed, as ExB shearing rate and turbulence growth rate in approximate balance.

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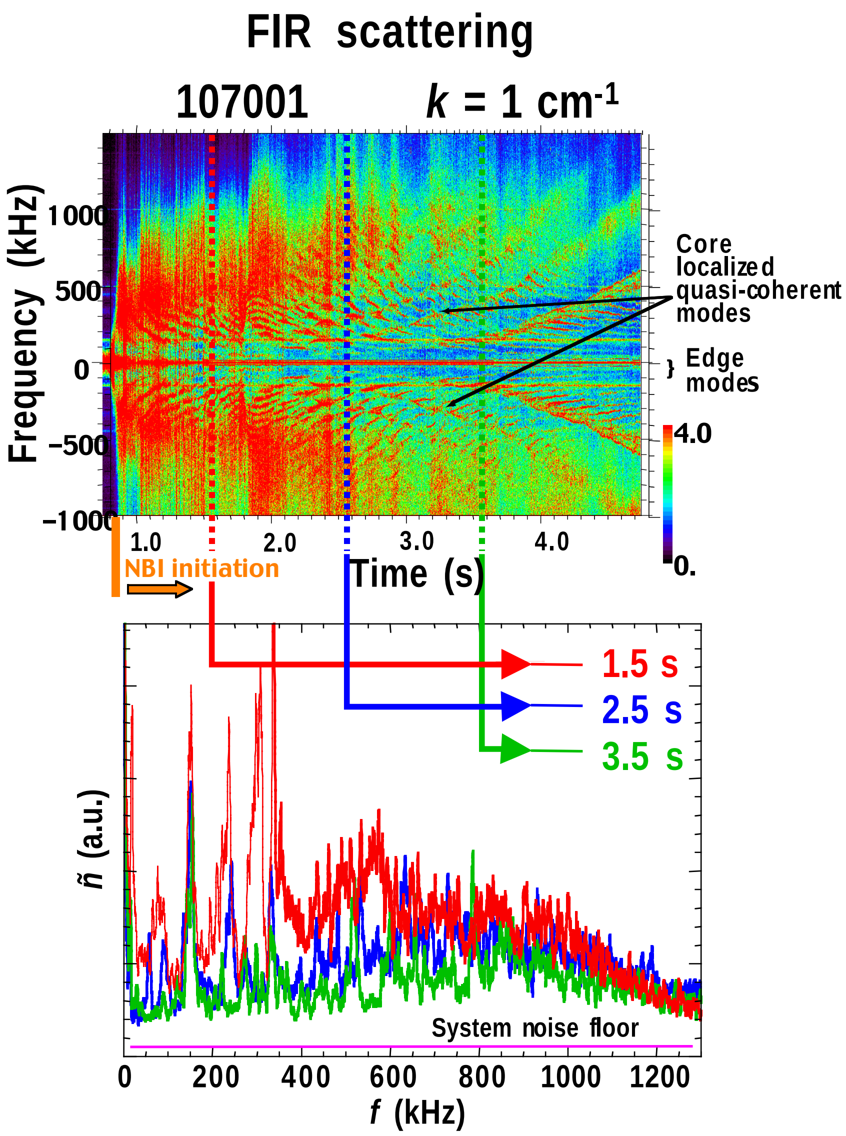
CORE BARRIER EXISTS WITHOUT COMPLETE TURBULENCE SUPPRESSION, IN AGREEMENT WITH GLF23 MODELING

- Internal broadband turbulence is not completely suppressed as the QDB core barrier evolves
  - Residual turbulence still significantly above the FIR scattering system detection limit
  - Contrasts with typical ITB in DIII–D, where core turbulence is suppressed to the noise floor

- High frequency coherent core modes are often detected.
  - Reflectometer data indicate these modes are localized to ρ~0-0.4.


FIR scattering

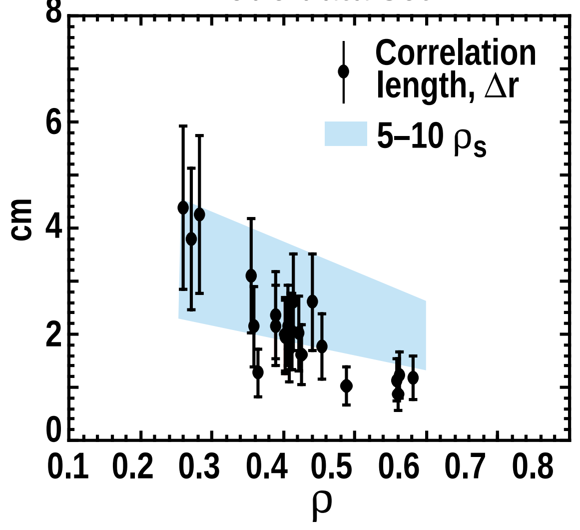
STEP SIZE FOR CORE TURBULENT TRANSPORT IS REDUCED IN QDB PLASMAS

- In L–mode, correlation lengths are observed to scale approximately as 5–10 ρ_s
  - Where ρ_s is the ion gyroradius evaluated using T_e

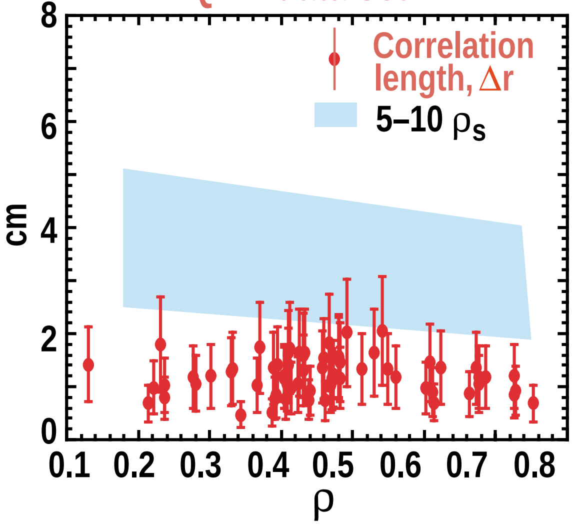
- In QDB plasmas, core correlation lengths are significantly lower than the scaling observed in L–mode

- Initial modeling using the UCAN global gyrokinetic code tracks core experimental trends and magnitude
  - ITG turbulence in circular geometry

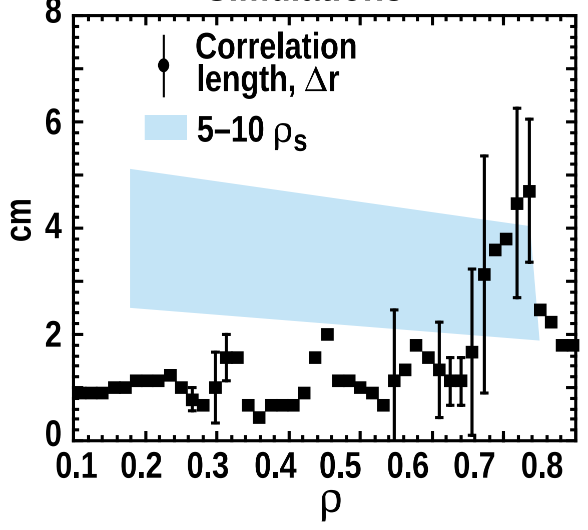
L–mode data set



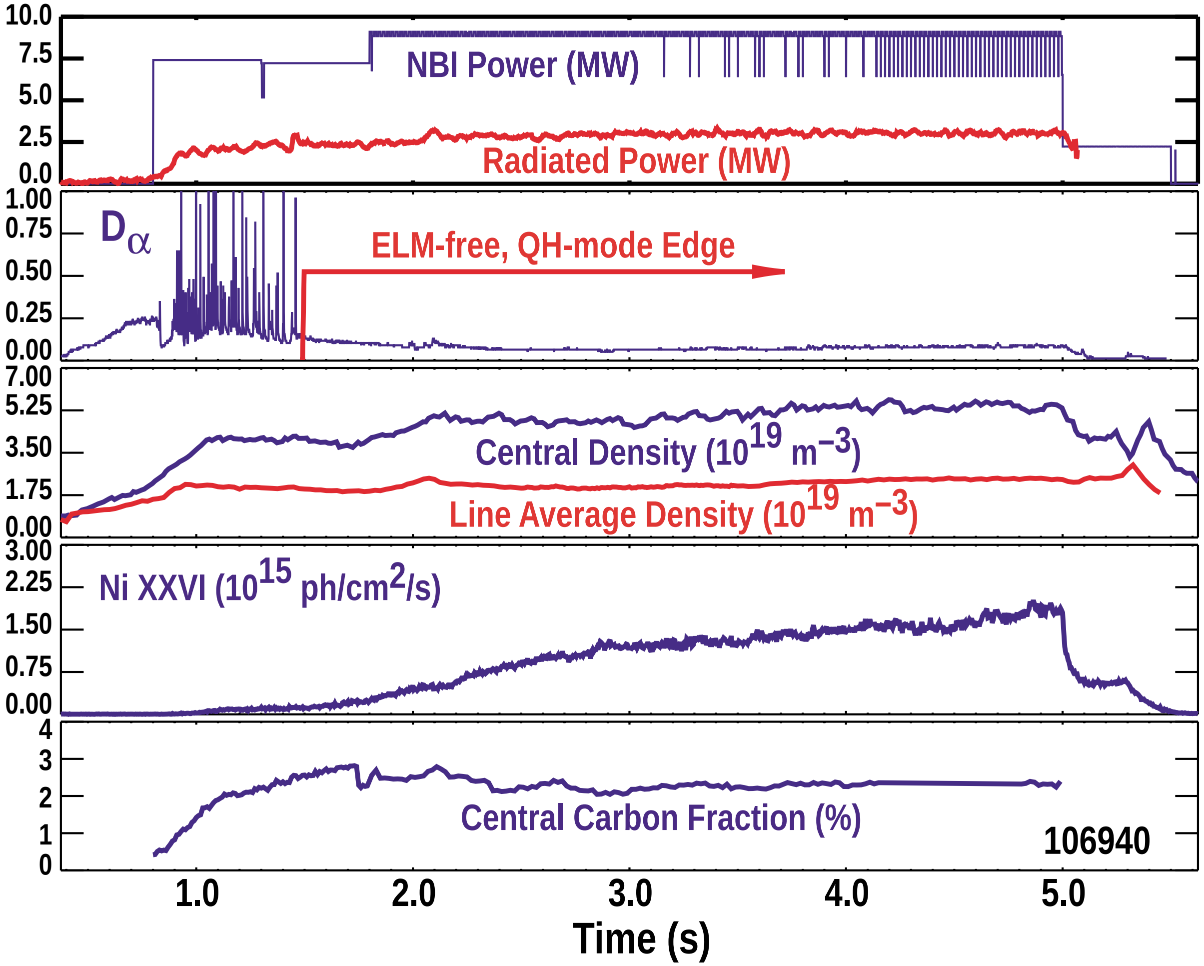
QDB data set



Simulations



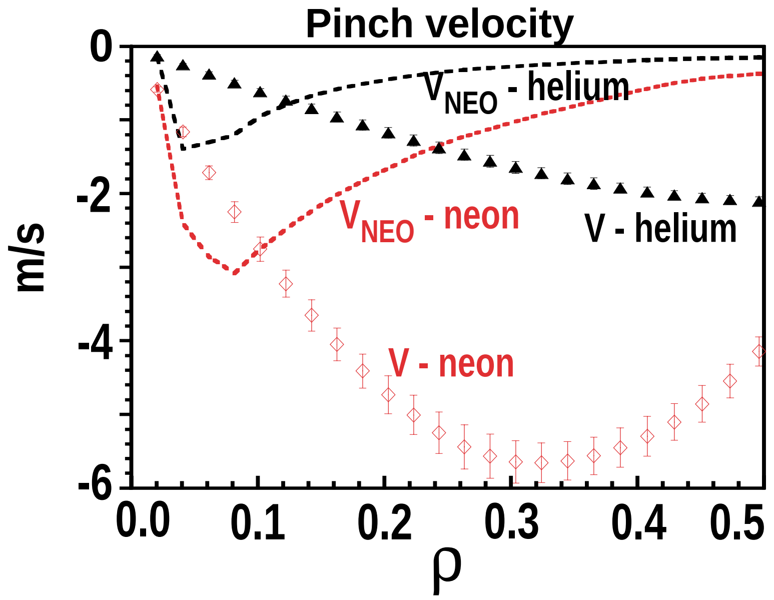
QDB DISCHARGES ALLOW US TO STUDY IMPURITY ACCUMULATION IN DIII-D ITB PLASMAS

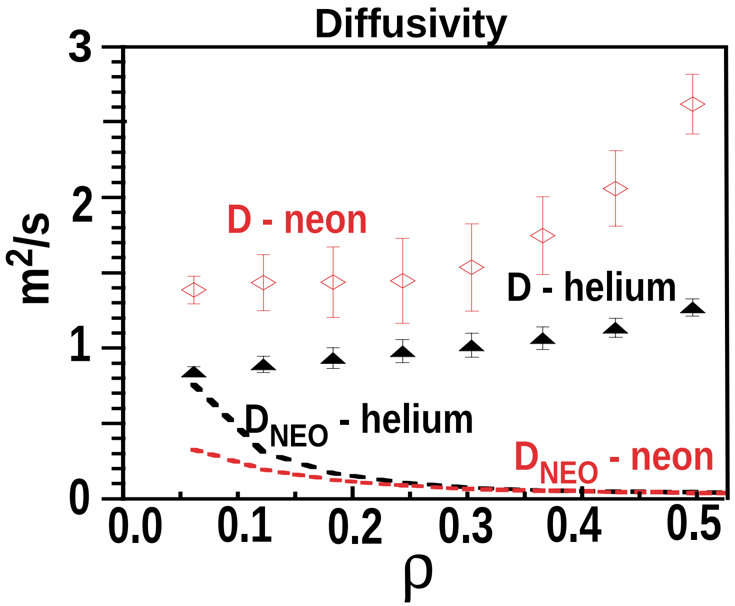


- Nickel content increases with time, but contribution to radiated power is low, < 0.3 MW. Large impact on Z_{eff}
- Low-Z impurities, e.g. carbon, stay approximately constant

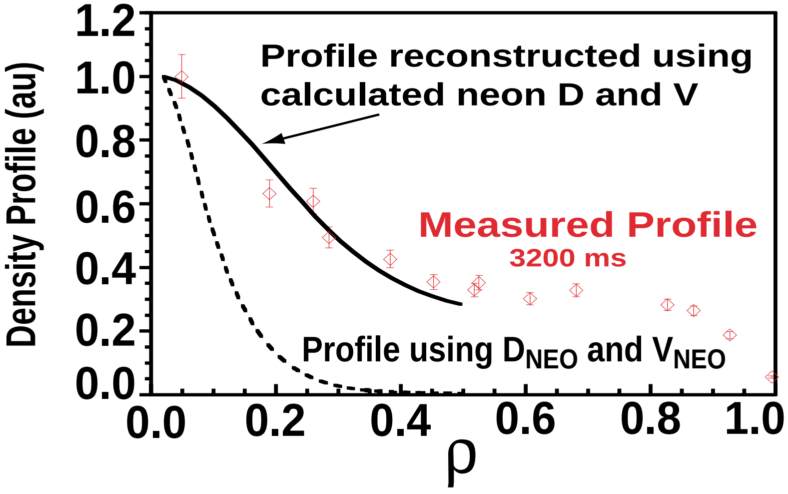
NEOCLASSICAL MODELING PREDICTS CENTRAL PEAKING OF HIGH-Z IMPURITIES, DUE TO PEAKED n_e PROFILE

- Measured impurity convection and diffusivity is larger than neoclassical from $0.1 < \rho < 0.5$





- Measured neon profile is less peaked than profile calculated using neoclassical transport



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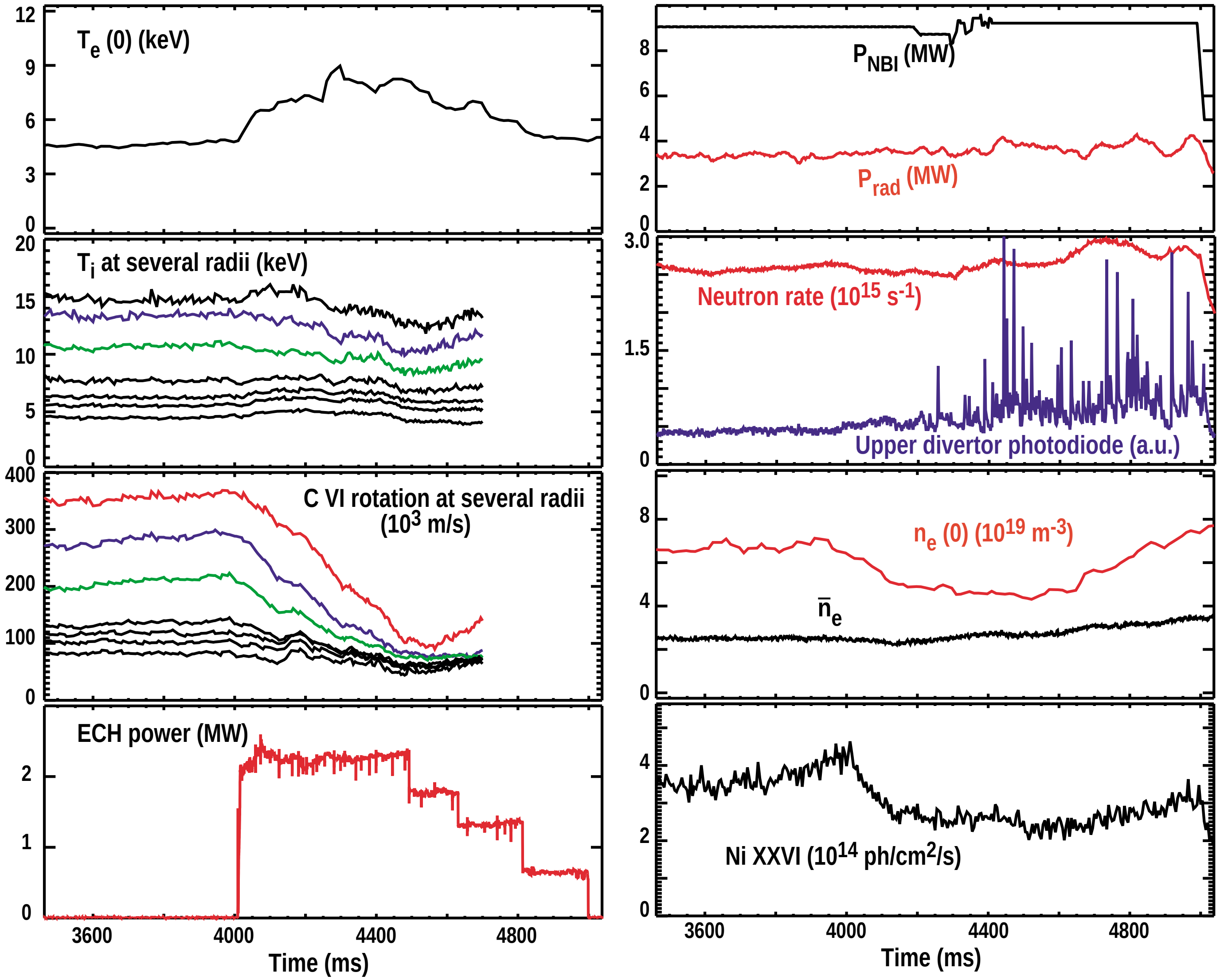
CONTROL TOOLS EXIST TO MODIFY DENSITY PROFILE AND REDUCE DENSITY PEAKING

- Example of use of central ECH to modify density profile
- $n_e(o)/n_{AVE}$ decreases from 2.6 to 1.7
- MIST modeling indicates Ni concentration is reduced
- Reduced density peaking would also improve bootstrap current alignment



CONCLUSIONS

- DIII-D results have improved our understanding of ITB formation conditions
  - Evidence for the effect of α-stabilization/Shafranov shift, magnetic shear, impurity injection, and sheared ExB flows

- QDB results demonstrate that it is possible to have long pulse, high performance ITB operation with an ELM-free H-mode edge, with density and radiated power control
  - >3.5 s or 25 τ_E achieved, limited only by beam pulse duration
  - $\beta_N H_{89} = 7$ for 10 τ_E
  - Pulsed divertor heat loads eliminated
  - Core and edge transport barriers are compatible
  - Turbulence and transport behavior of QDB discharges is reproduced by initial simulations and modeling
  - Issues are increasing the operating density, impurity accumulation and obtaining QDB with balanced or co-NBI (JT-60U has unique capability!)