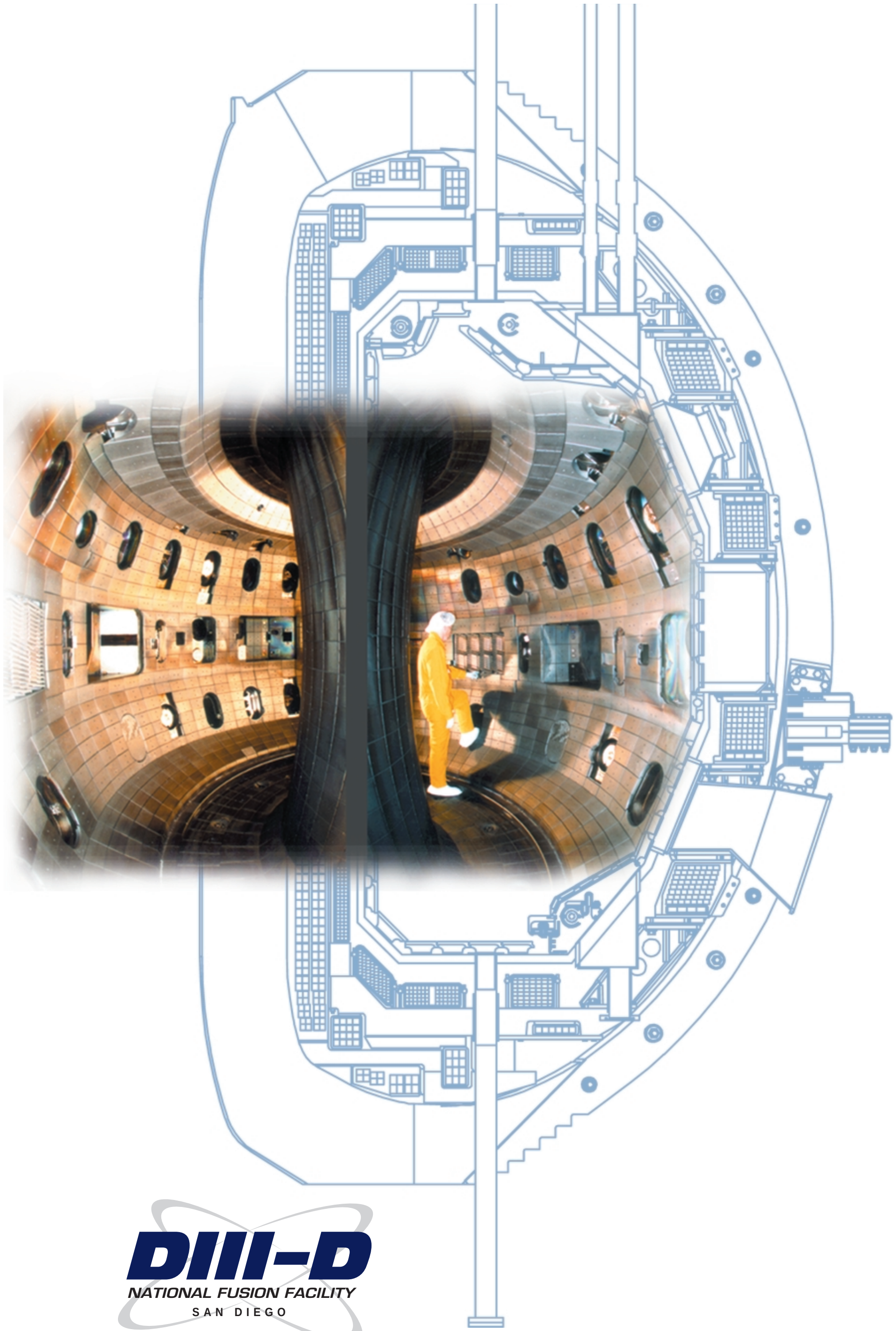

The Quiescent Double Barrier Regime in the DIII-D Tokamak

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OVERVIEW

- Introduction
  - What is the Quiescent Double Barrier (QDB) regime?
- The Quiescent H-mode (QH-mode) edge
  - Detailed characteristics and conditions required for QH-mode operation
    - ★ To date, only obtained with counter-NBI and divertor pumping
- Quiescent Double Barrier (QDB) operation
  - Core transport and fluctuations
  - Impurity issues
- Summary

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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
- EHO: Edge Harmonic Oscillation
  - —A continuous MHD mode usually associated with QH-mode operation

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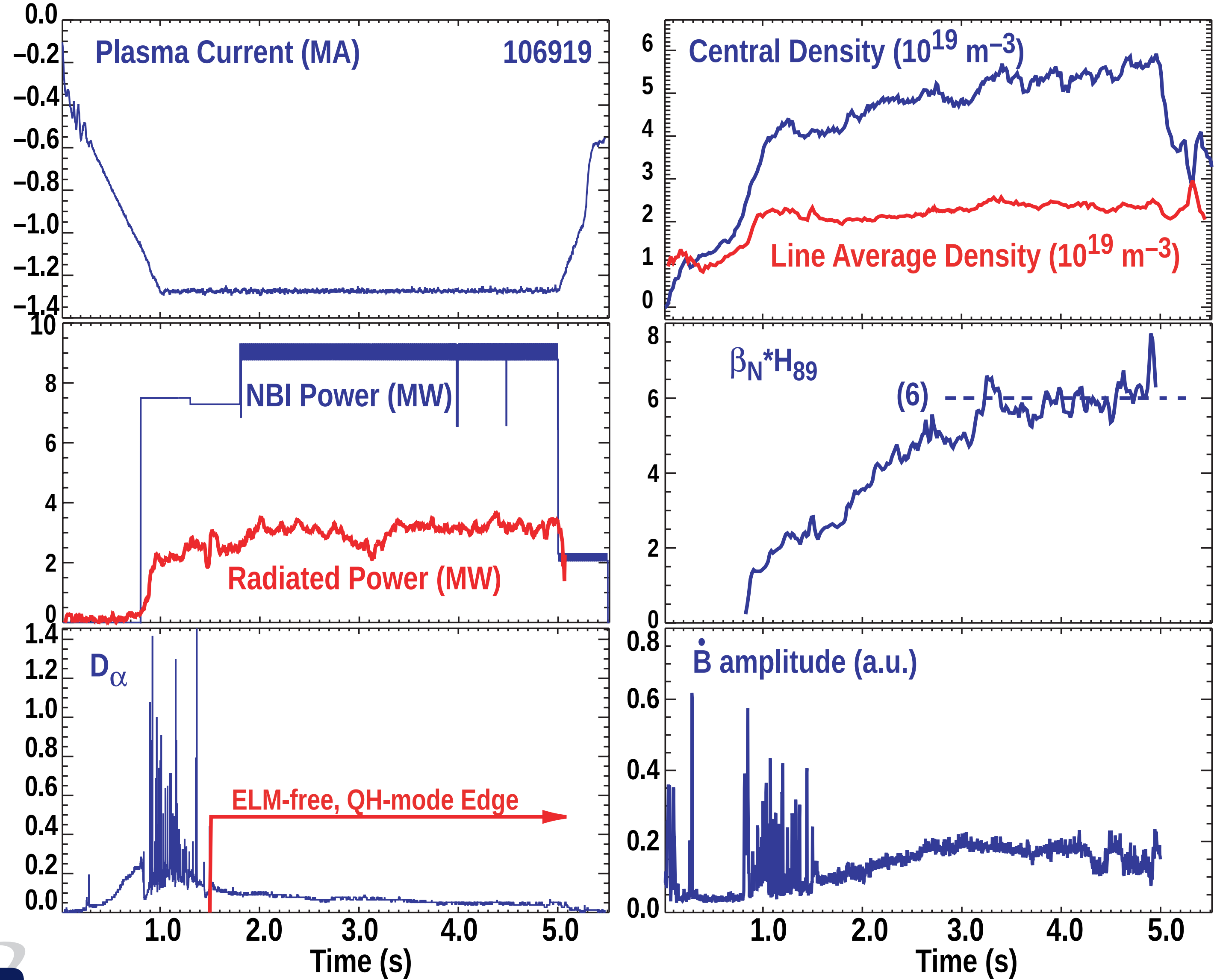
SUSTAINED ELM-FREE H-MODE OPERATING REGIME OBTAINED WITH DENSITY AND RADIATED POWER CONTROL



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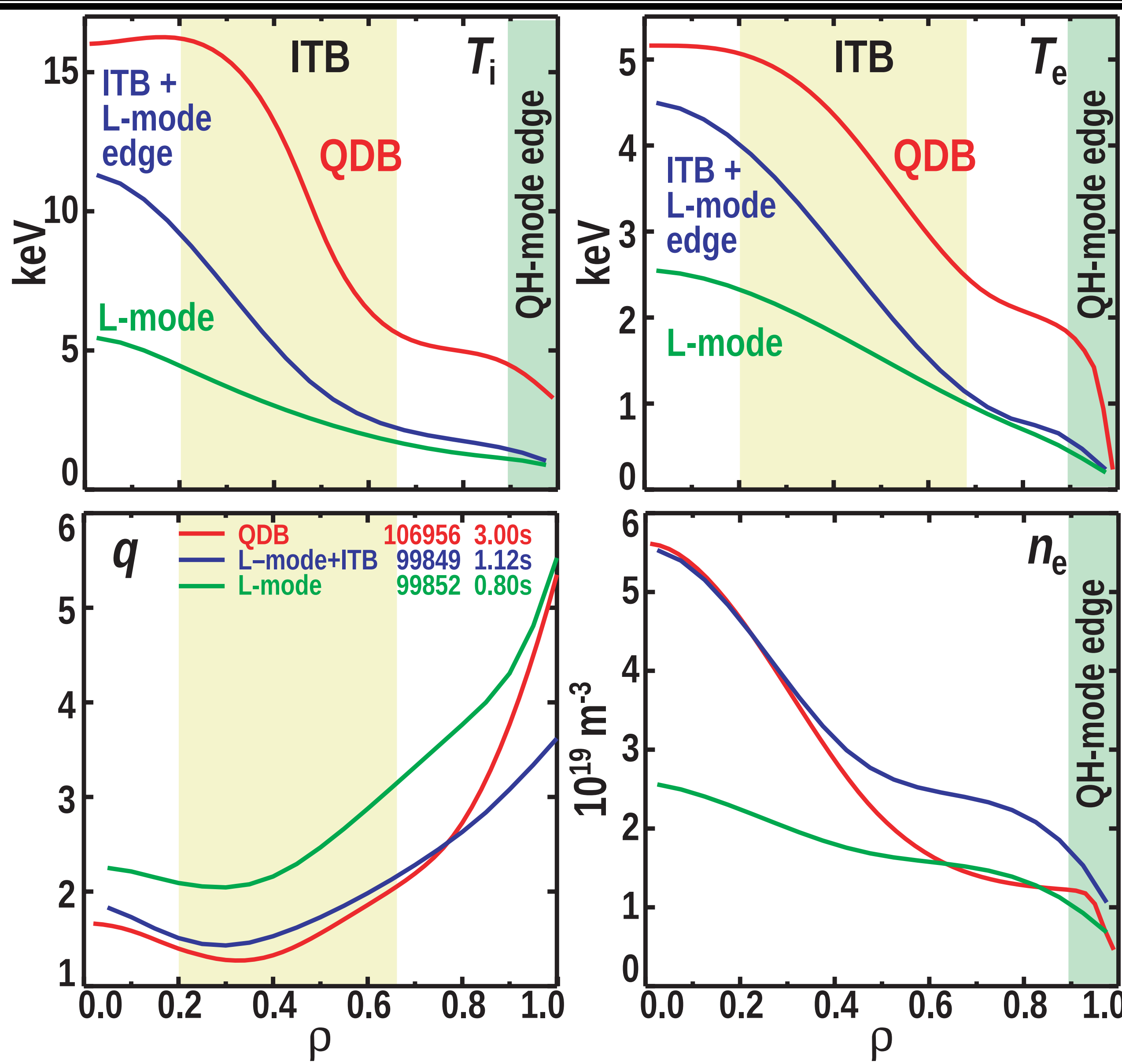
- Maintains quiescent ELM-free edge for >3.5 s, ~25τ_E

QDB REGIME COMBINES CORE TRANSPORT BARRIER WITH QUIESCENT EDGE BARRIER — "QUIESCENT DOUBLE BARRIER"

- Edge pedestal elevates central temperatures, improving fusion performance



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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, JET and ASDEX-U
  - ELMs can couple to core MHD modes, limiting beta and performance
- **QDB plasmas address these issues:**
  - Provides high quality ELM-free H-mode with density and radiated power control
  - The QH-mode edge is compatible with ITBs
  - Demonstrated 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

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QUIESCENT H-MODE (QH-MODE) EDGE

- Issues addressed in this section include:
  - Operational conditions required to obtain QH-mode
  - Edge and divertor conditions
  - Density and radiated power control is provided by an edge harmonic oscillation (EHO), which generates particle transport
  - Characteristics of the EHO
    - ★ Is the EHO really an edge mode?

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CONDITIONS REQUIRED FOR QH-MODE/QDB OPERATION

- **Key operational conditions to obtain the QH-mode edge are:**
  - Neutral beam injection counter to the plasma current (counter-NBI), at power levels ≥2.5 MW (higher power at higher current)
  - Divertor pumping to reduce the edge density and neutral pressure
  - A gap between the plasma edge and the outer wall (low toroidal field side) of ~10 cm

- **QH-mode has been obtained with**
  - Both lower and upper single-null discharges
  - $0.67 \leq I_p$ (MA) ≤ 1.6 and $0.95 \leq B_T$ (T) ≤ 2.1
    - ★ Most work done at $1.2 \leq I_p$ (MA) ≤ 1.6 and $1.8 \leq B_T$ (T) ≤ 2.1
  - With triangularity δ of 0.16 - 0.7 and q of 3.7 - 4.6

- **Obtaining an ITB inside the QH-mode edge to form a QDB plasma is straightforward using conventional ITB formation techniques**

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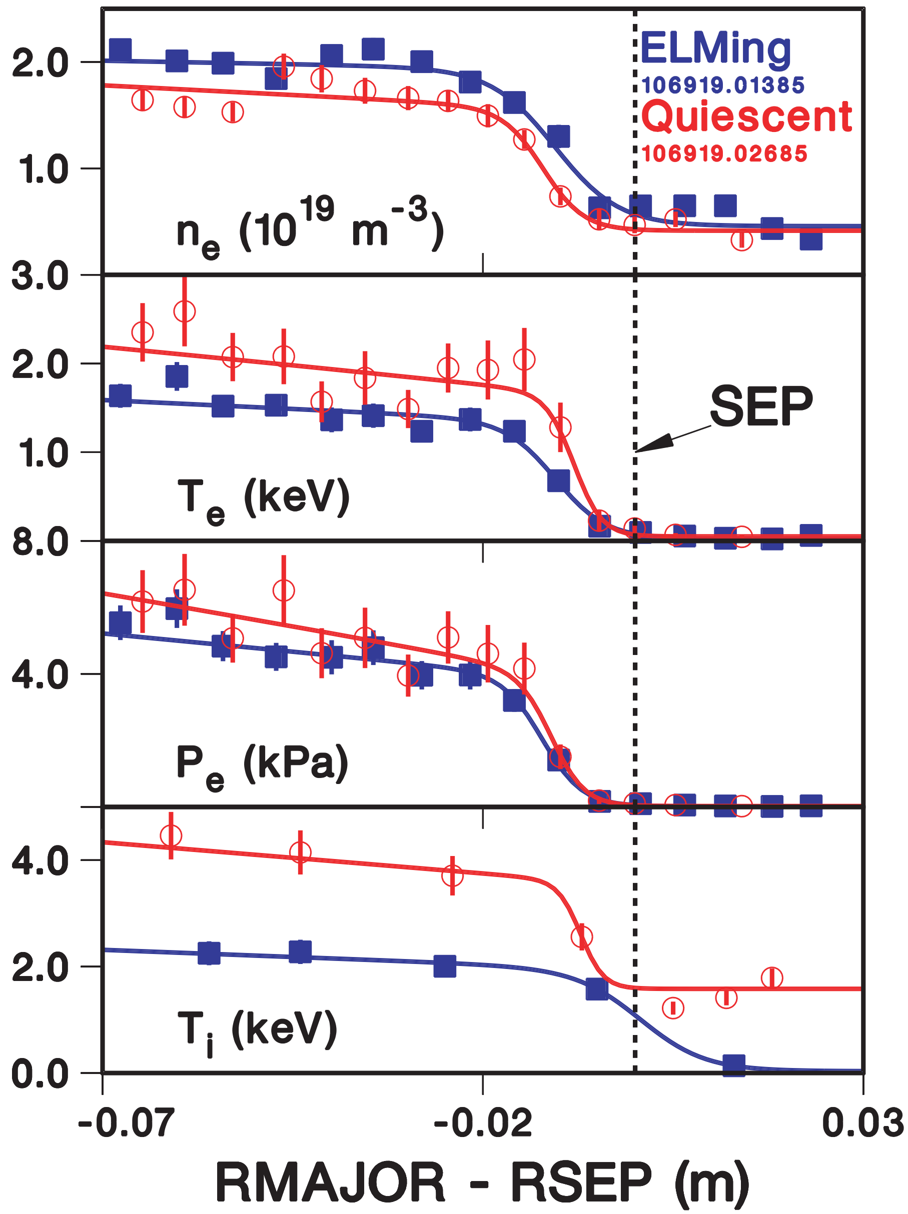
THE PLASMA EDGE DURING THE QUIESCENT PHASE IS AN H-MODE EDGE

- Edge gradients in quiescent phase are comparable to those in ELMing phase
  - Note high T_i pedestal
- QH-mode edge also has other standard H-mode signatures
  - Edge E_r well
  - Reduced turbulence



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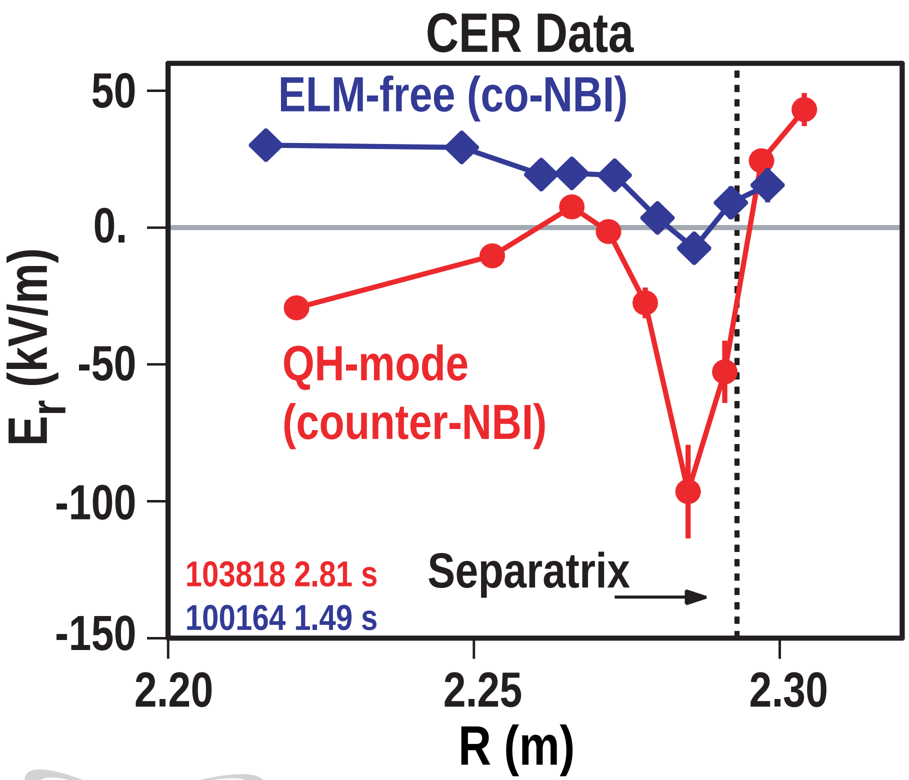
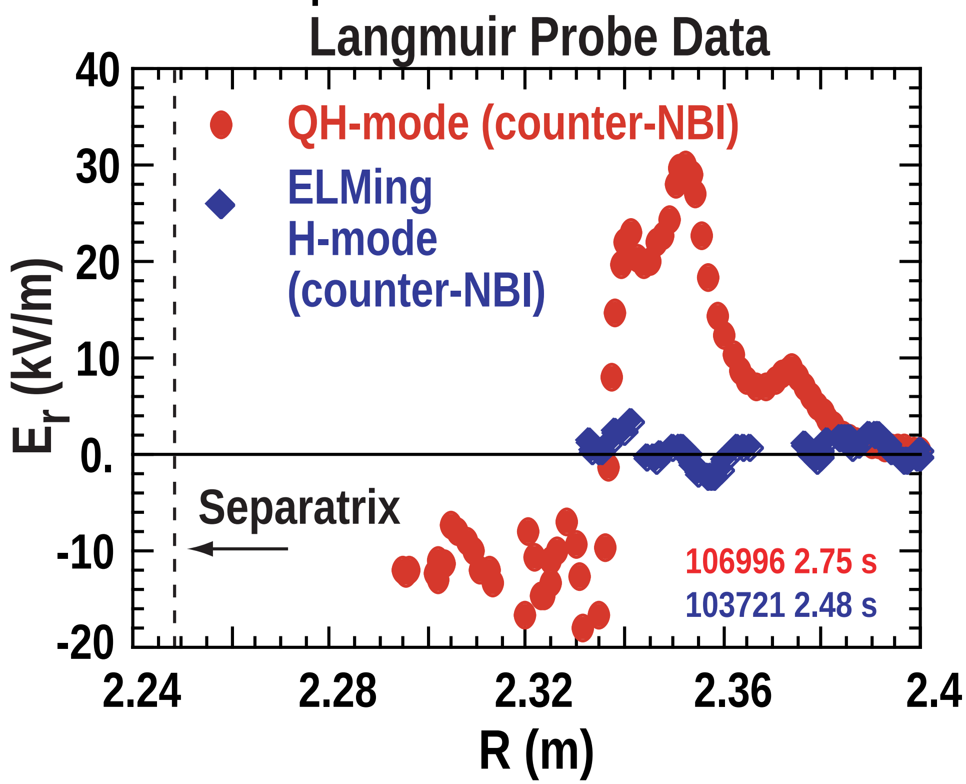
QH-MODE PLASMAS HAVE LARGE EDGE RADIAL ELECTRIC FIELD, E_r

- CER data show large E_r in SOL and very deep E_r well inside separatrix
- Langmuir probe data also show large E_r in SOL
  - SOL E_r is at normal levels in ELMing counter-NBI discharge
  - Change is associated with QH-mode, not counter-NBI per se





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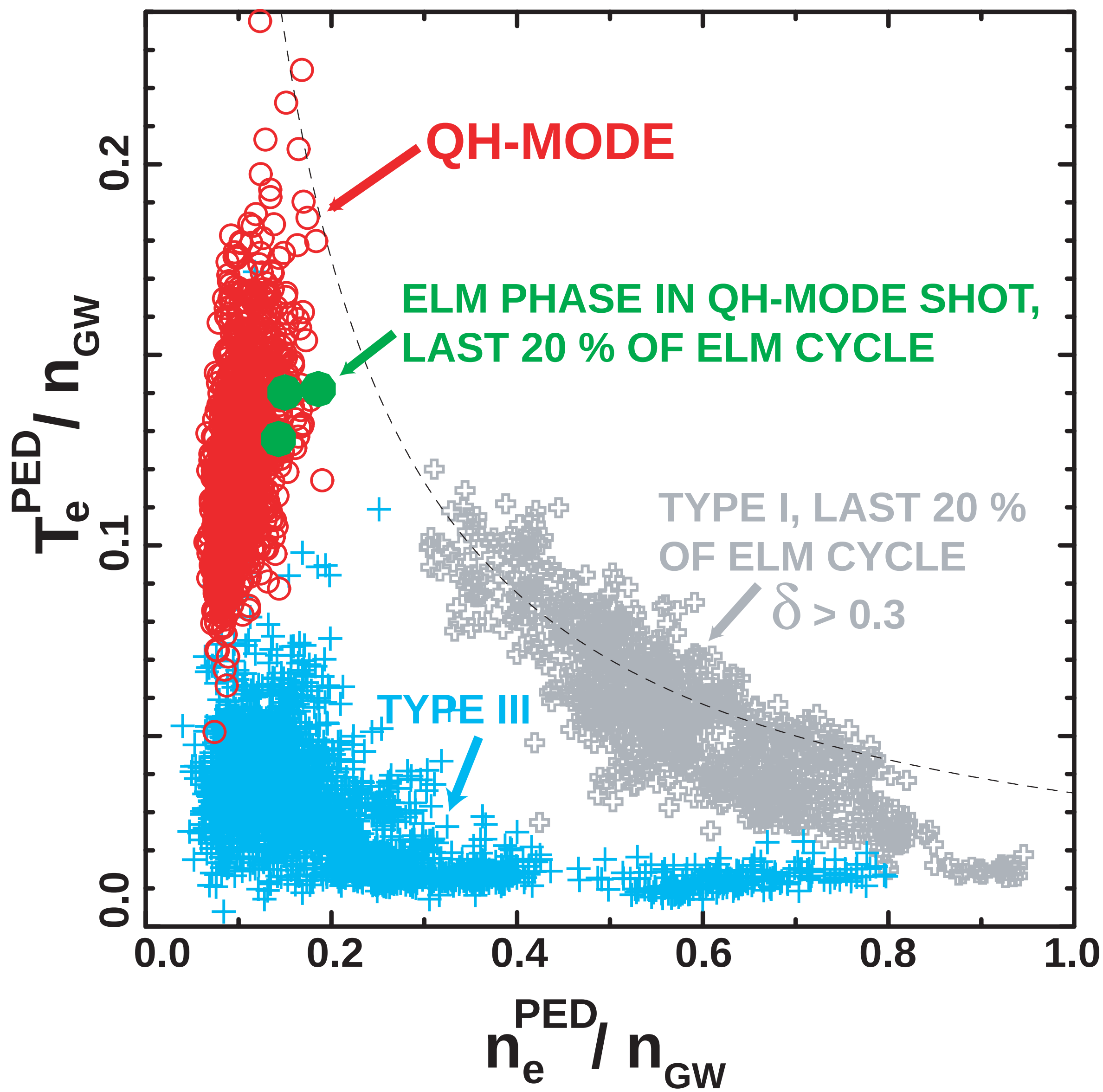
QH-MODE EDGE HAS LOWER DENSITY AND HIGHER TEMPERATURE THAN CONVENTIONAL ELMING H-MODE



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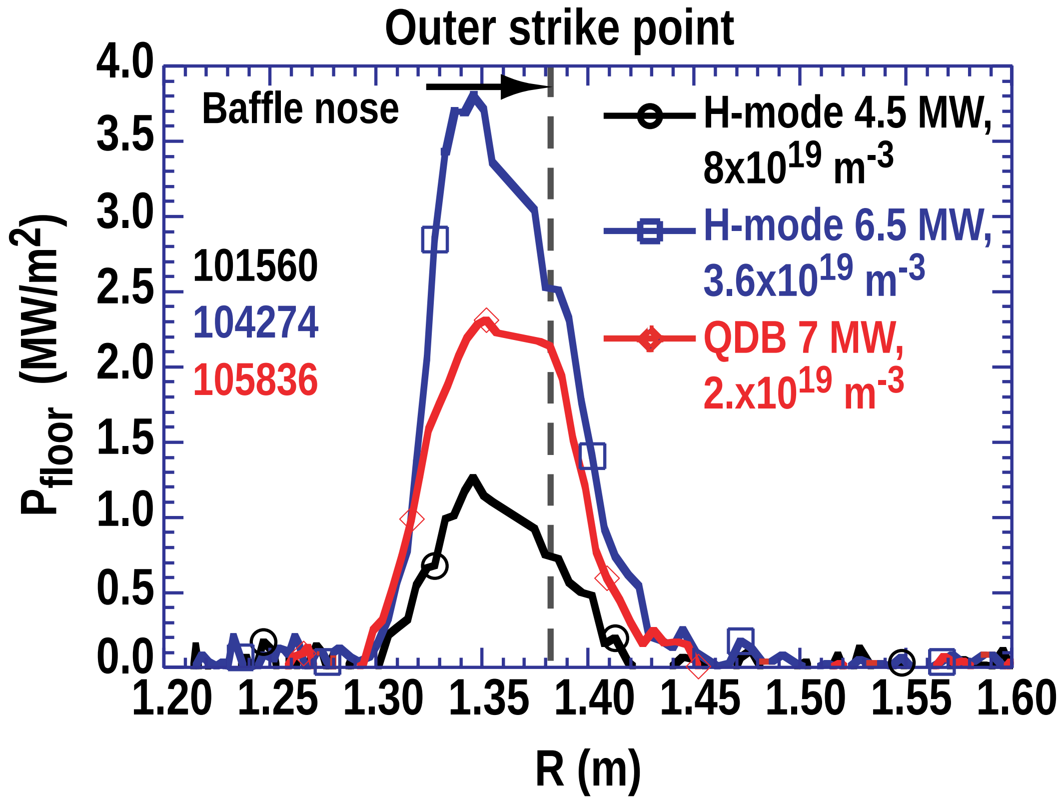
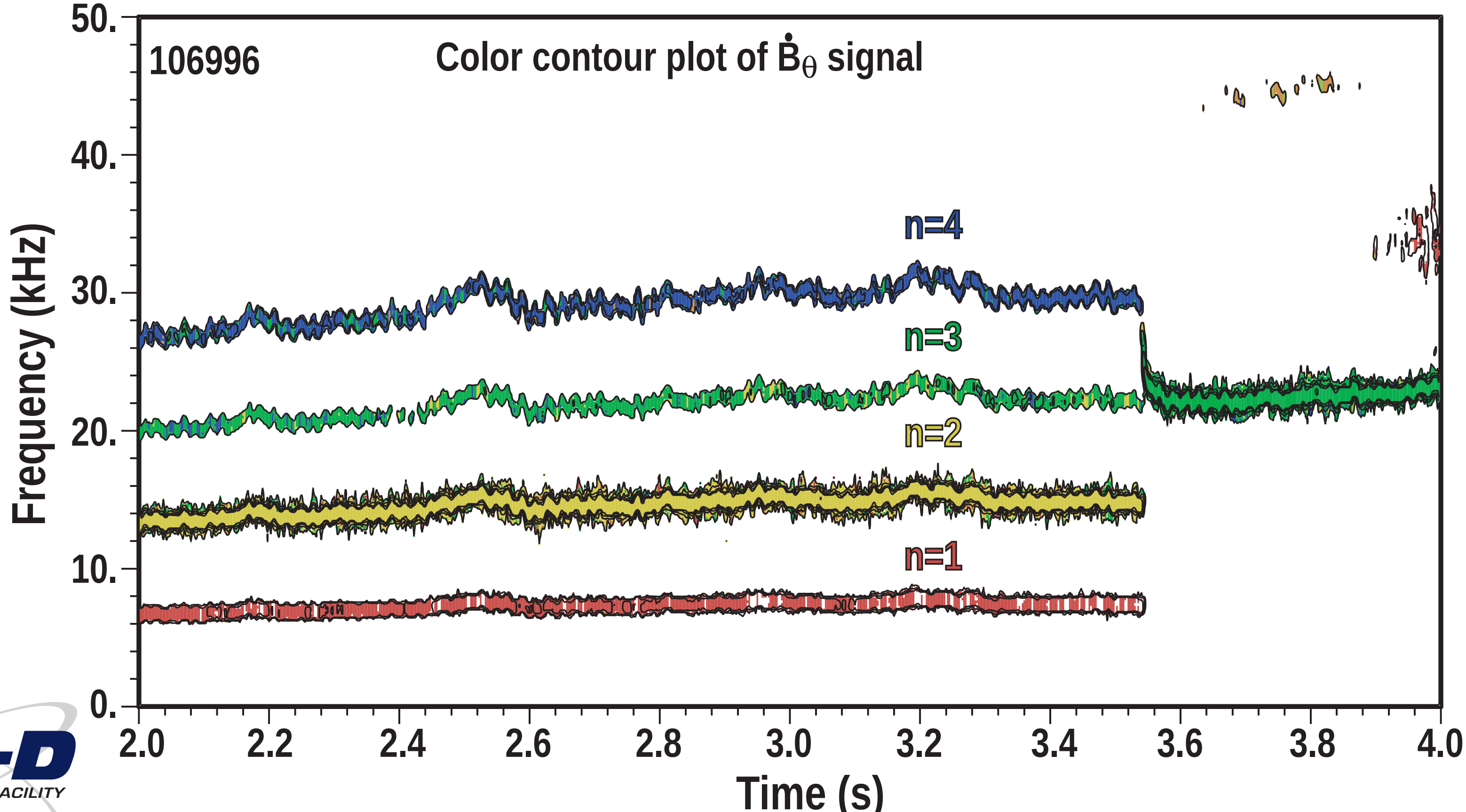
QDB OPERATION HAS MODERATE HEAT FLUX TO THE DIVERTOR TARGET PLATES



- Edge harmonic oscillation spreads heat flux?
- Note that present-day devices can match anticipated core or edge reactor conditions, but not both
  - Reactor relevant core plasmas in present-day devices may have non-optimal divertor conditions

QUIESCENT OPERATION IS USUALLY ASSOCIATED WITH THE PRESENCE OF AN EDGE HARMONIC OSCILLATION (EHO)

- EHO is seen on magnetic, density and electron temperature fluctuation diagnostics during QH-mode operation
  - Quiescent operation also obtained with a global 1/1 mode (single example)
- Toroidal mode mixture (amplitude and harmonic content) can change spontaneously
  - Edge profiles, density and impurity control not sensitive to mode mixture



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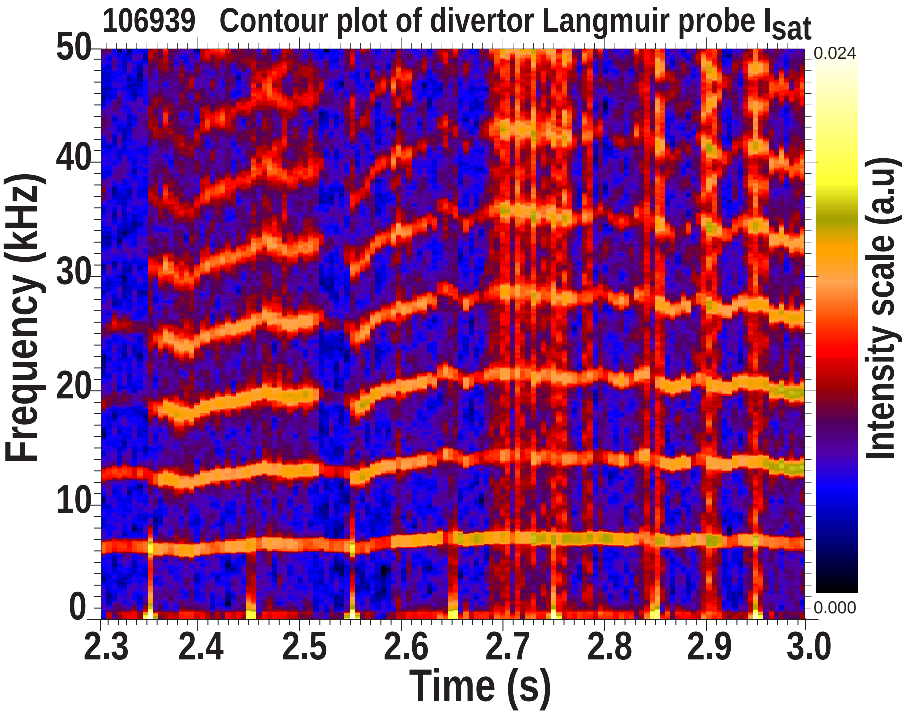
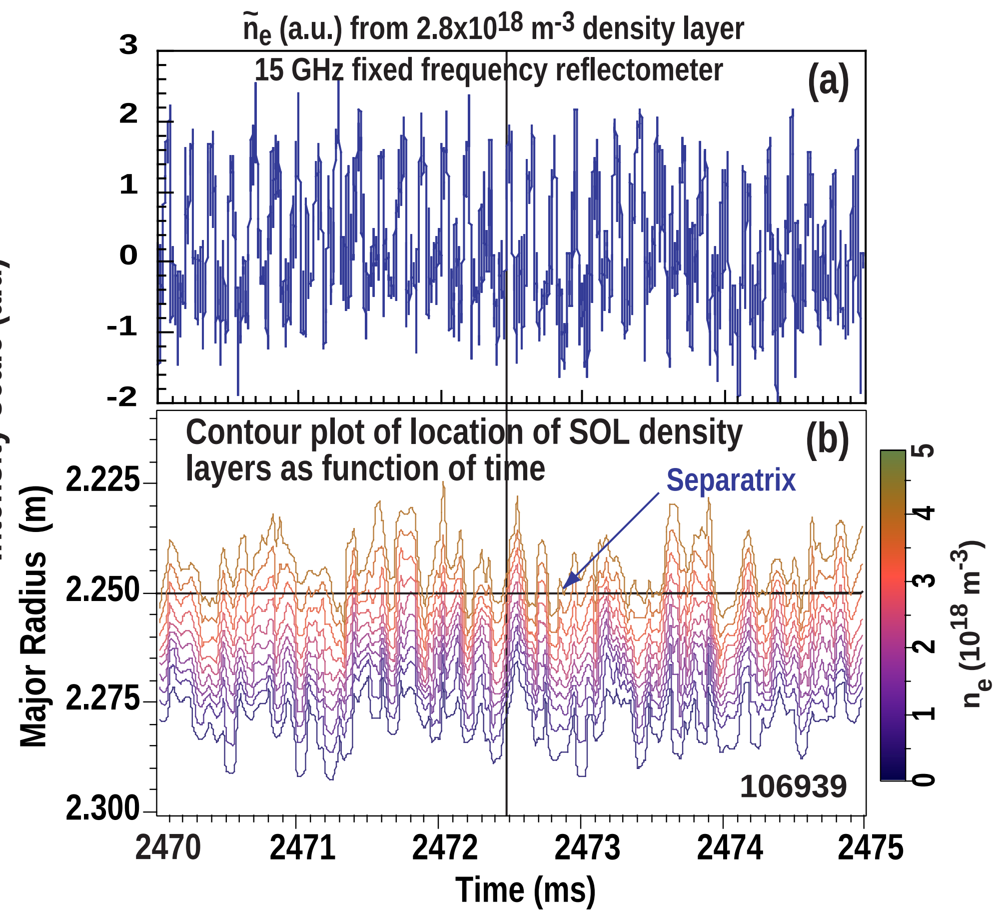
THE EHO CAUSES PARTICLE TRANSPORT — EHO MODULATES BOTH PARTICLE FLUX TO DIVERTOR AND SOL DENSITY PROFILE

- Divertor Langmuir probe I_{sat} signal shows particle flux is modulated at EHO frequencies
  - EHO harmonics account for ~100% of the total flux to the probe



- High resolution profile reflectometer system shows scrape-off layer (SOL) density profile is modulated at EHO frequency



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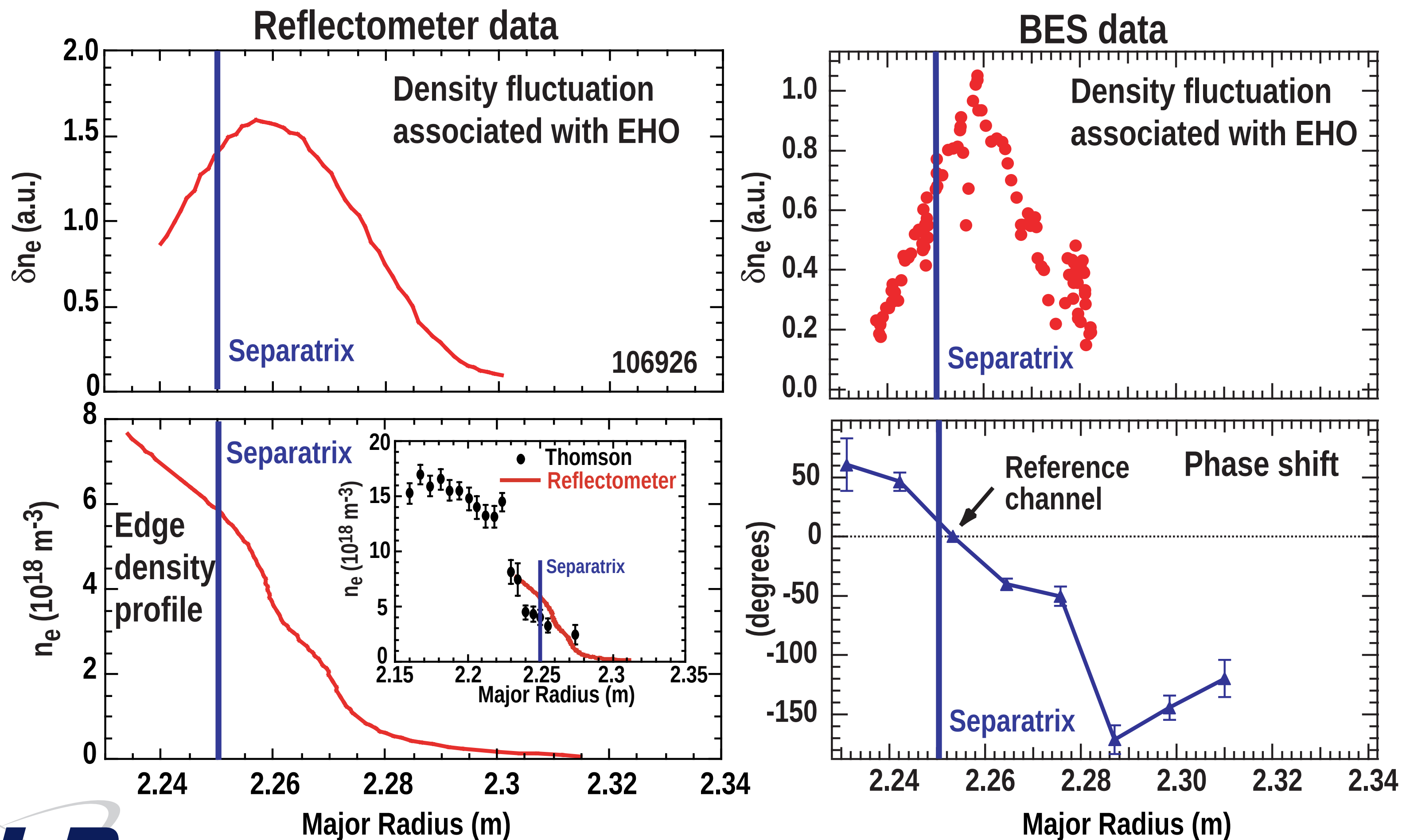
THE EDGE HARMONIC OSCILLATION (EHO) IS LOCATED AT THE BASE OF THE EDGE PEDESTALS

- High resolution measurements with Beam Emission Spectroscopy (BES) and profile reflectometer systems indicate that the EHO is located at the base of the edge profile pedestals, at or slightly outside the separatrix



CHARACTERISTICS OF THE EHO ON DIII-D AND COMPARISON TO THE ELM-FREE EDA H–MODE ON C-MOD

	Edge Harmonic Oscillation (DIII–D)	Quasi-Coherent Mode (C–MOD)
Increase D_α level in divertor	Yes	Yes
Increase particle transport across separatrix	Yes	Yes
Location	Foot of edge barrier	Edge density barrier
Frequency	6–10 kHz (n=1)	60–200 kHz
Frequency spread Δf (FWHM)/f	0.02	0.05–0.2
Toroidal mode number	Multiple, variable mix n=1–10	Unknown
Poloidal wavelength	~100 cm (m~5)	~1 cm
Edge colisionality	Collisionless	Collisional

- Different edge modes on two different machines both generate ELM-free H-mode operation

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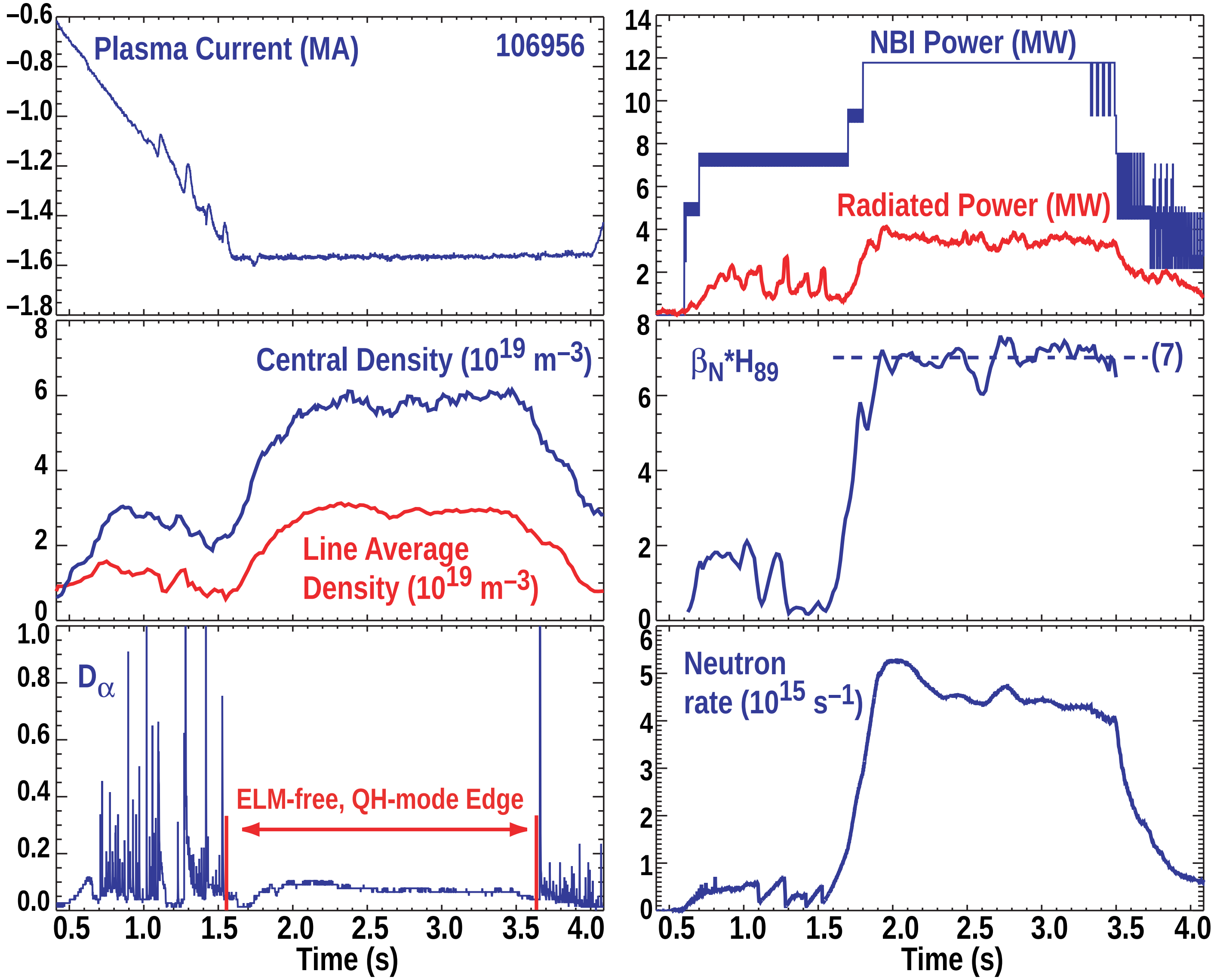
QUIESCENT DOUBLE-BARRIER (QDB) OPERATION

- Issues addressed in this section include:
  - Performance obtained in QDB regime
  - Transport and fluctuation analysis and modeling
  - Impurity issues
    - ★ High-Z impurities accumulate
  - Ways to address density peaking

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

- $\beta_N H_{89}$=7 for 10 τ_E (1.6 s)
- Example of quiescent operation without EHO, but with global 1/1 mode
- Same performance obtained in discharges with EHO



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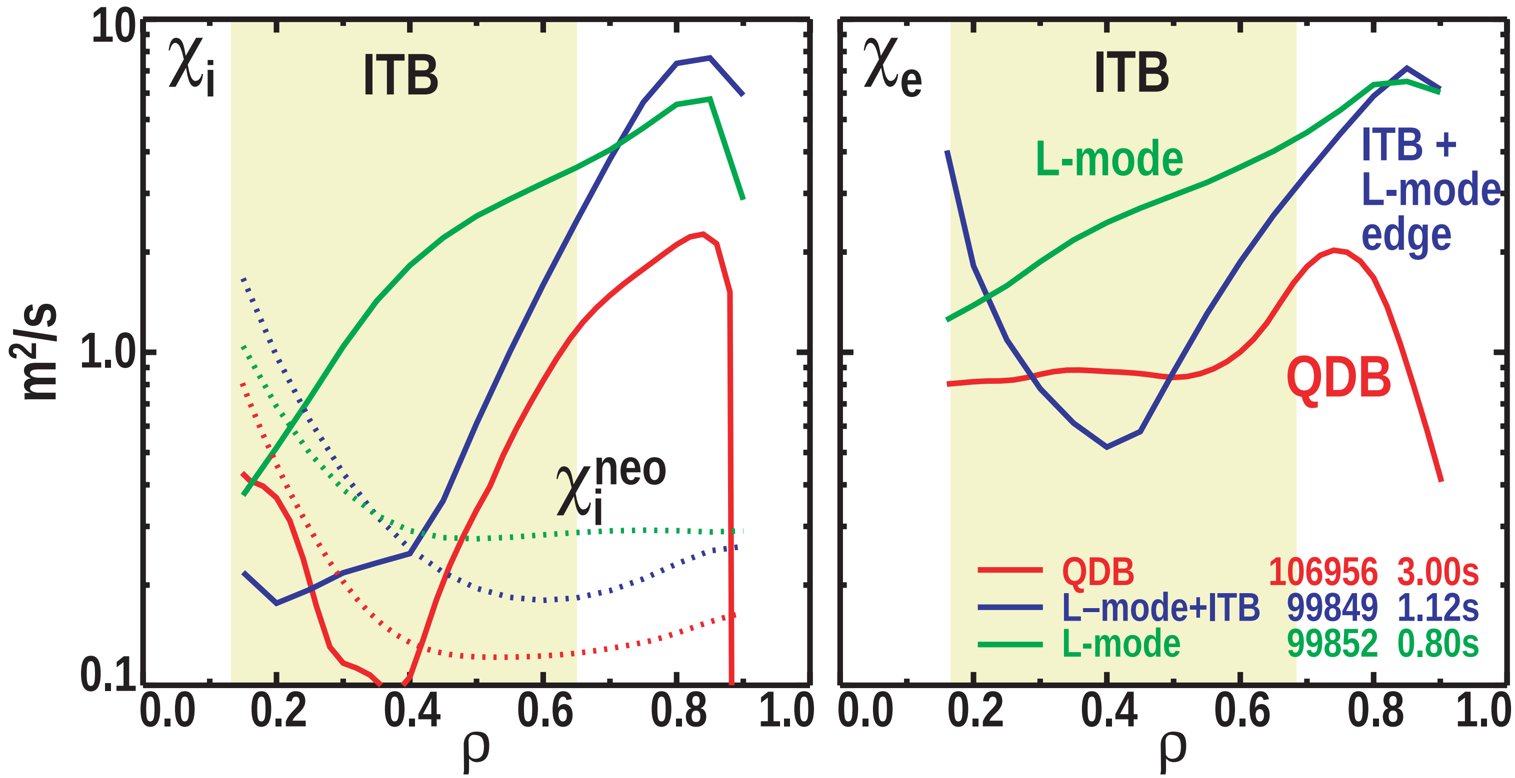
TRANSPORT ANALYSIS CONFIRMS PRESENCE OF DOUBLE (CORE AND EDGE) TRANSPORT BARRIERS



- 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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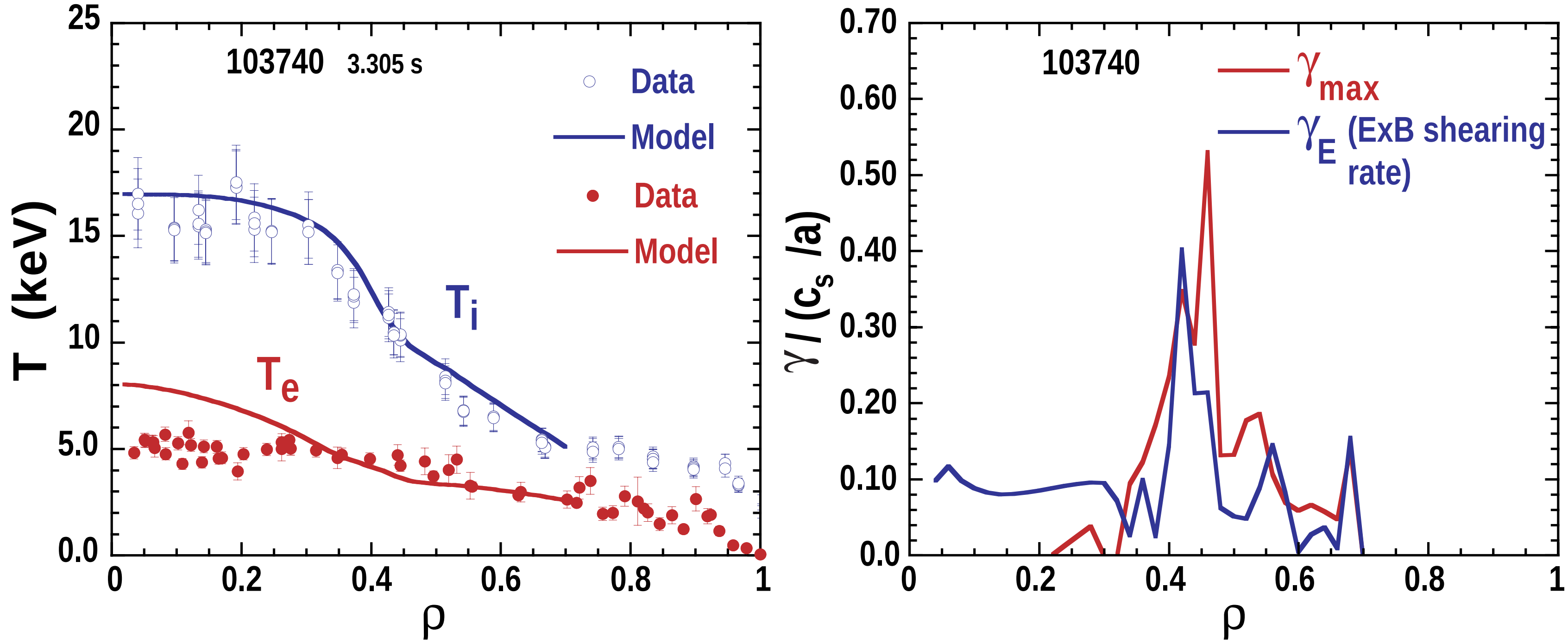
SIMULATIONS USING THE GLF23 MODEL REPRODUCE THE QDB CORE ION BARRIER



- **Steady-state simulation reproduces core ion temperature barrier**
  - Core T_e profile not accurately reproduced
- **Prediction is that core turbulence is not completely suppressed**
  - Turbulence growth rate and ExB shear in approximate balance
  - GKS code makes similar prediction

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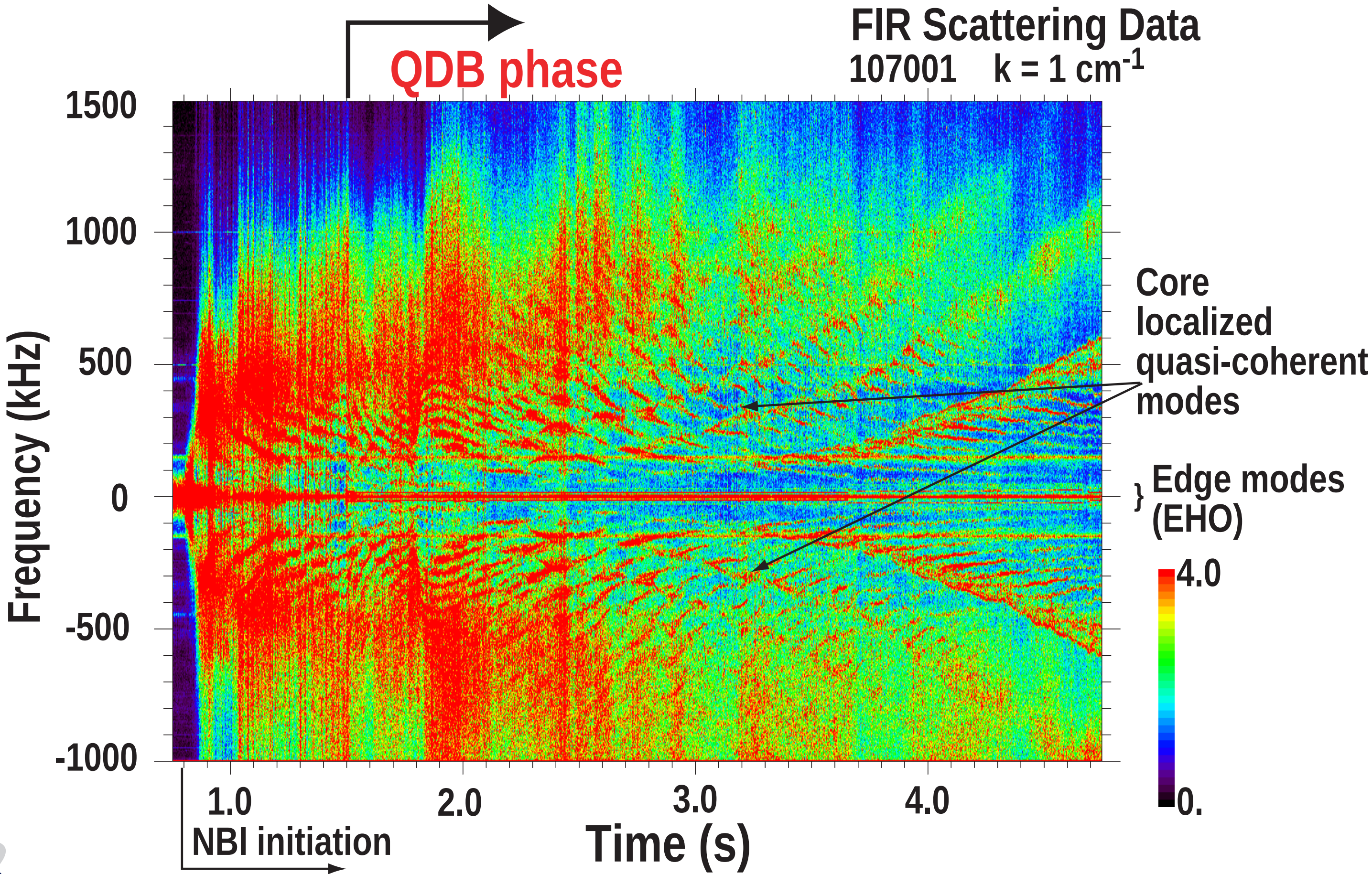
CORE TURBULENCE IS NOT ELIMINATED IN QDB PLASMAS, IN AGREEMENT WITH GLF23 AND GKS MODELING

- FIR scattering and reflectometer data show core turbulence is not eliminated
- High frequency quasi-coherent modes are often visible in scattering data
  - Reflectometer data indicate these modes are localized to $\rho \sim 0-0.4$



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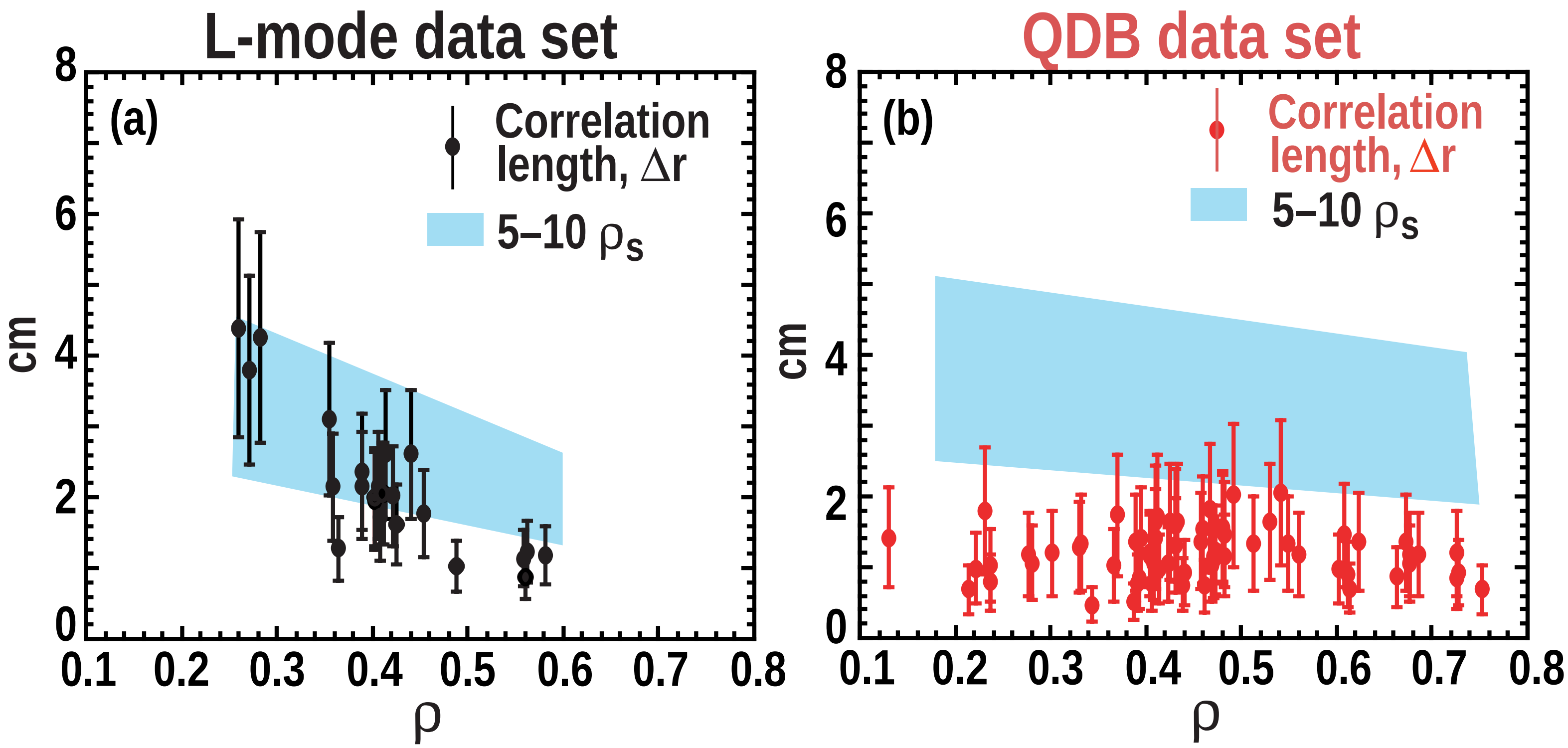
STEP SIZE FOR CORE TURBULENT TRANSPORT IS REDUCED IN QDB PLASMAS

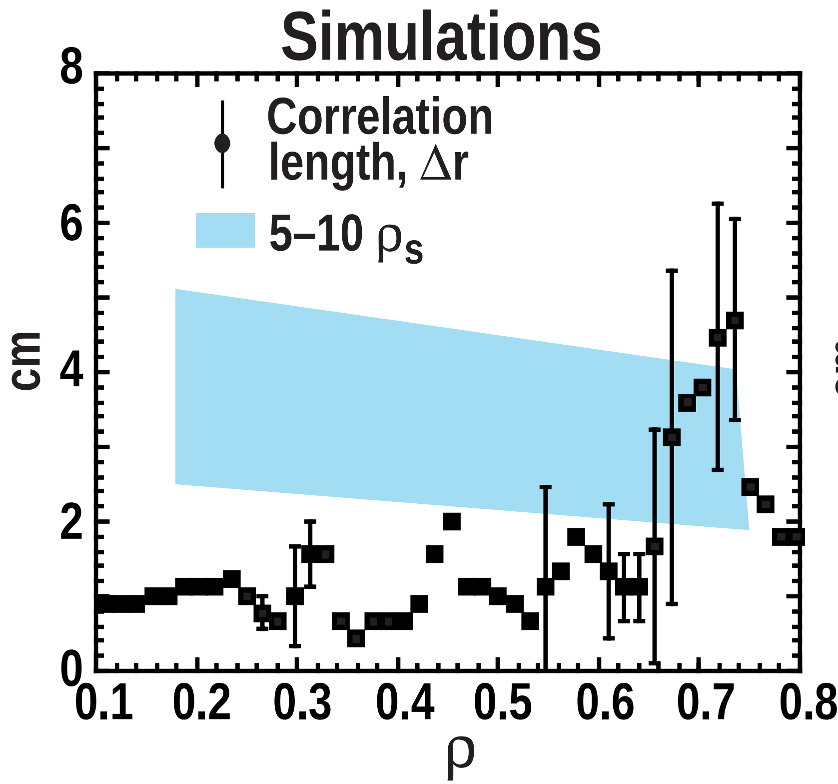
- In L-mode, correlation lengths are observed to scale approximately as 5-10ρ_s

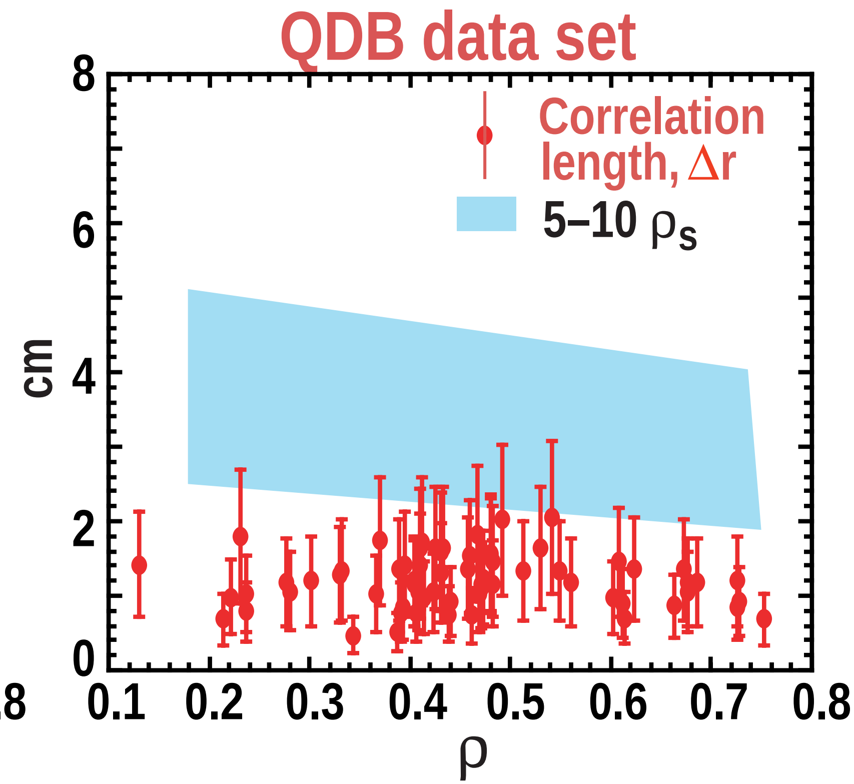
- In QDB plasmas, core correlation lengths are significantly lower than the scaling observed in L-mode



INITIAL THEORY-BASED MODELING REPLICATES OBSERVED CORE TURBULENT TRANSPORT STEP SIZE

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





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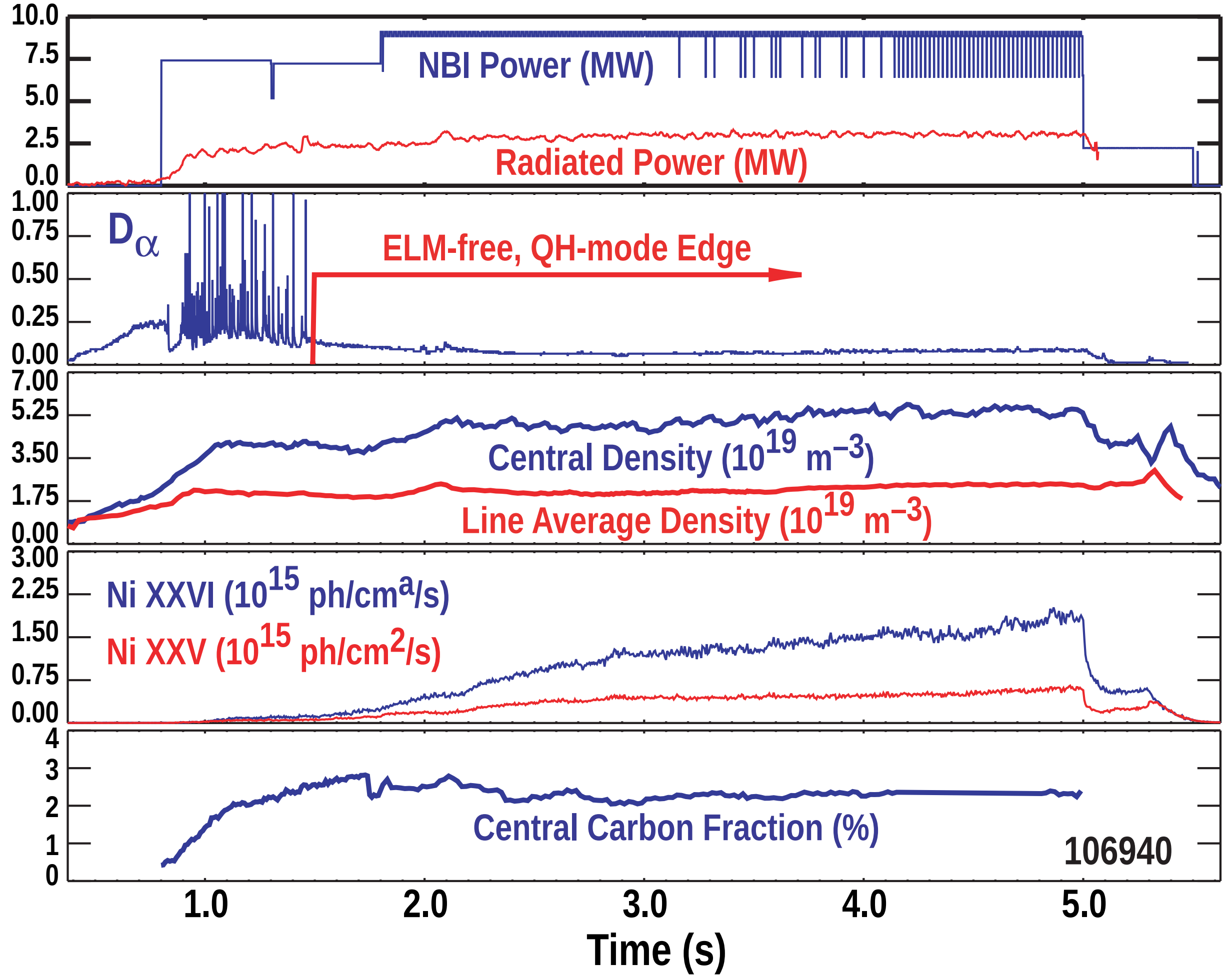
HIGH-Z IMPURITY ACCUMULATION IS AN ISSUE FOR LONG PULSE QDB DISCHARGES



- Nickel content increases with time, but contribution to radiated power is low, < 0.3 MW
- Low-Z impurities, e.g. carbon, stay approximately constant

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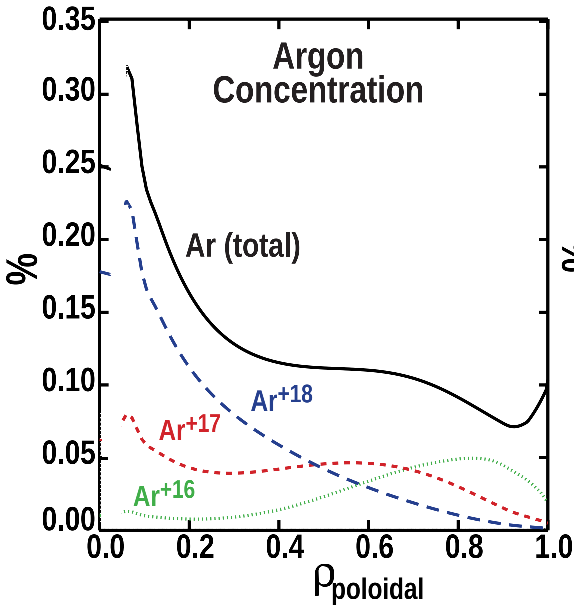
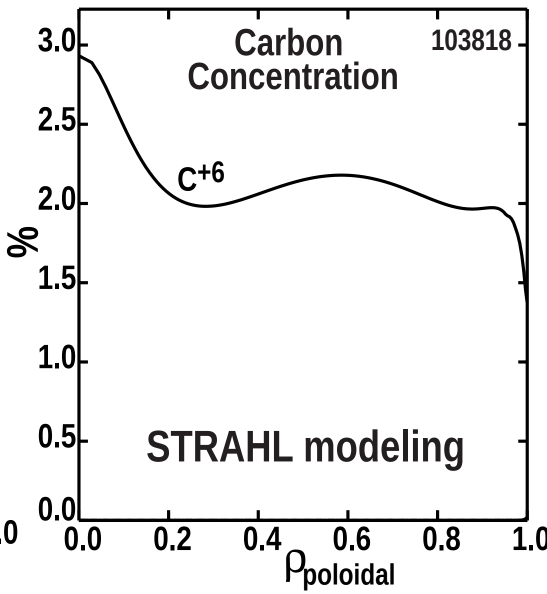
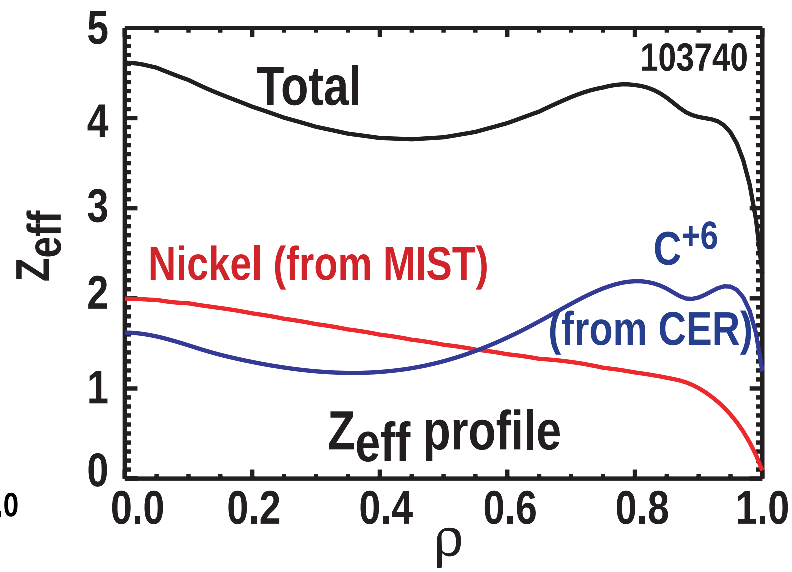
NEOCLASSICAL MODELING PREDICTS CENTRAL PEAKING OF HIGH-Z IMPURITIES, DUE TO PEAKED n_e PROFILE

- Neoclassical modeling predicts central peaking of high-Z impurities (such as Ar), due to peaking of density profile

- MIST modeling indicates Ni has substantial impact on Z_{eff}
  - Modeling is in good agreement with measured Bremsstrahlung







- Impurity transport experiment has been performed to determine if core high-Z accumulation is transport or source effect
  - Evidence exists for plasma-wall interactions, whch may provide an enhanced impurity source in these discharges

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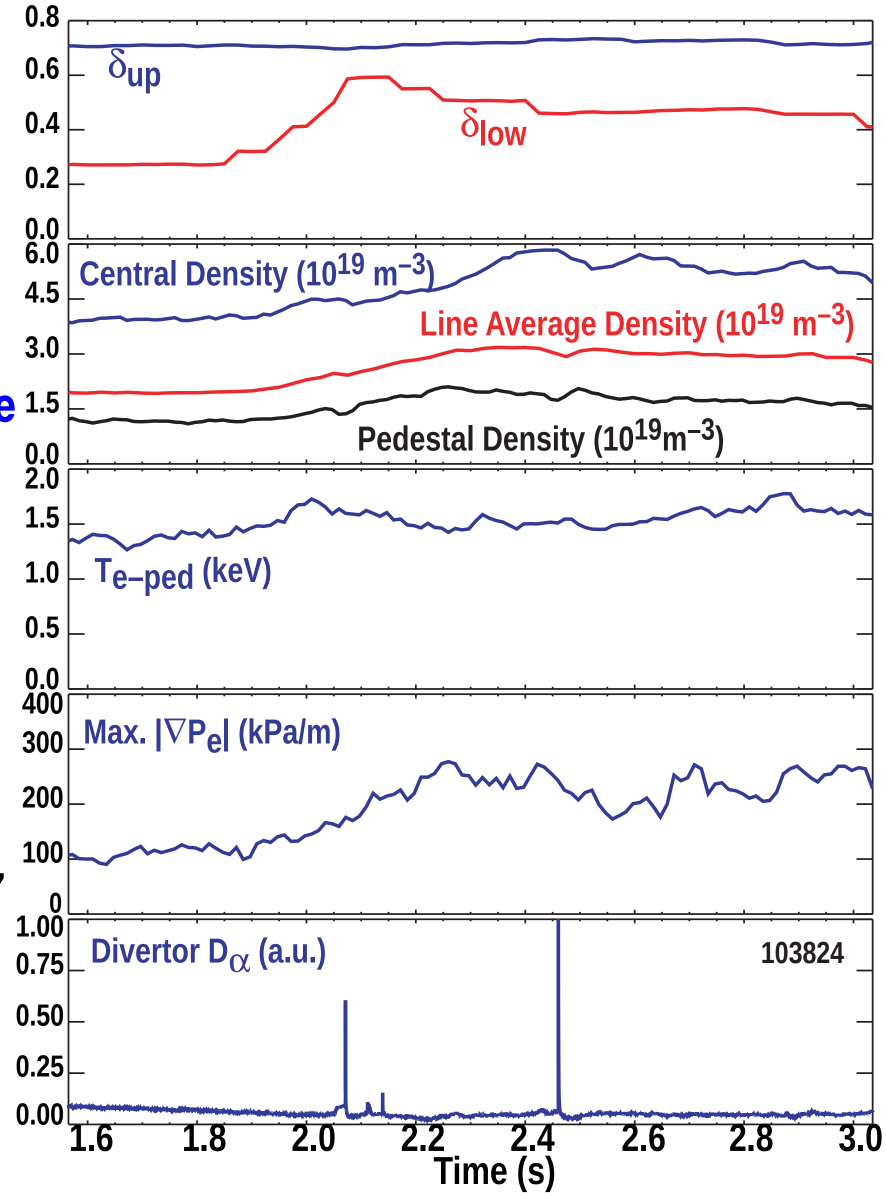
REDUCED DENSITY PEAKING IN QDB DISCHARGES WOULD YIELD MULTIPLE ADVANTAGES

- **Advantages include:**
  - Reduced central high-Z impurity accumulation
  - Improved bootstrap current alignment
- **Three approaches have shown promise in reducing the density peaking:**
  - Increased triangularity
  - Off-axis pellet injection
  - Impurity puffing
- **Example shown is of density change with increased lower triangularity δ_{LOW}**
  - $n_e(o)/n_{AVE}$ decreases from 2.0 to 1.7



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CONCLUSIONS

- QDB results demonstrate that it is possible to have sustained, high quality H-mode performance with an ELM-free edge, with density and radiated power control

- The QDB regime contains compatible core and edge transport barriers
  - QH-mode is normally associated with a continuous edge harmonic oscillation (EHO), which provides increased particle transport
  - Turbulence and transport behavior of QDB discharges is reproduced by initial simulations and modeling

- QDB regime has demonstrated 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

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