ABSTRACT, POSTER LP1 12
THURSDAY 11/7/2001, APS DPP CONFERENCE, LONG BEACH

Recent Results from the Quiescent Double Barrier Regime on DIII-D

E.J. Doyle, K.H. Burrell, T. Casper, J.C. DeBoo, A. Garofalo, P. Gohil, C.M. Greenfield, R.J. Groebner, J. Kinsey, L.L. Lao, C.J. Lasnier, M. Makowski, G.L. McKee, R.A. Moyer, G. Porter, T.L. Rhodes, G.M. Staebler, B.W. Stallard, G. Wang, W.P. West, L. Zeng and the DIII-D Team, DIII-D National Fusion Facility, San Diego, California—

The Quiescent Double Barrier (QDB) regime combines internal transport barriers with a quiescent, ELM-free H-mode edge (QH-mode), yielding sustained, high performance plasmas. In the QH-mode edge, benign MHD activity, usually in the form of an Edge Harmonic Oscillation (EHO), provides density and radiated power control In recent experiments, physics understanding of the mechanisms leading to the formation of the QDB plasmas has been improved, and both absolute ($\beta \le 3.8\%$, $S_n \le 5.5 \times 10^{15}$ s^{-1}) and relative ($\beta_N H_{89}=7$ for $10\tau_E$) performance increased A signature of operation with a QH–mode edge appears to be very large radial electric fields in the edge and SOL. In the plasma core, simulations and modeling replicate many of the features of the observed transport and fluctuation behavior, including the ion temperature profile and turbulence correlation lengths. Slow high-Z impurity accumulation ($\tau \ge 500$ ms) is observed in the center of many QDB plasmas, and is the subject of ongoing analysis.

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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
  - Edge Harmonic Oscillation (EHO)
  - Divertor and SOL conditions
- Quiescent Double Barrier (QDB) operation
  - Core transport and fluctuations
  - Impurity issues
  - Density peaking
- 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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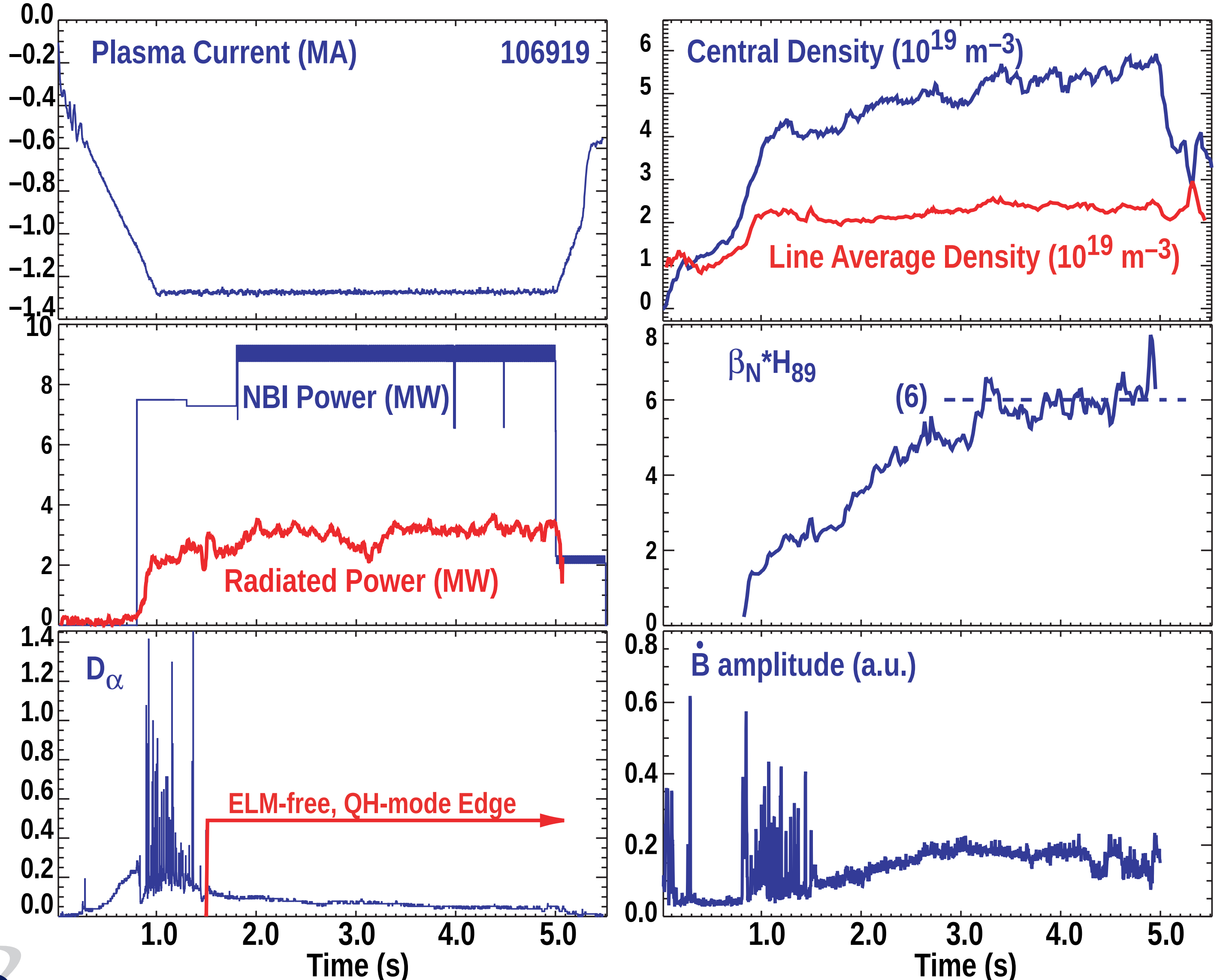
SUSTAINED ELM-FREE H-MODE OPERATING REGIME OBTAINED WITH DENSITY AND RADIATED POWER CONTROL



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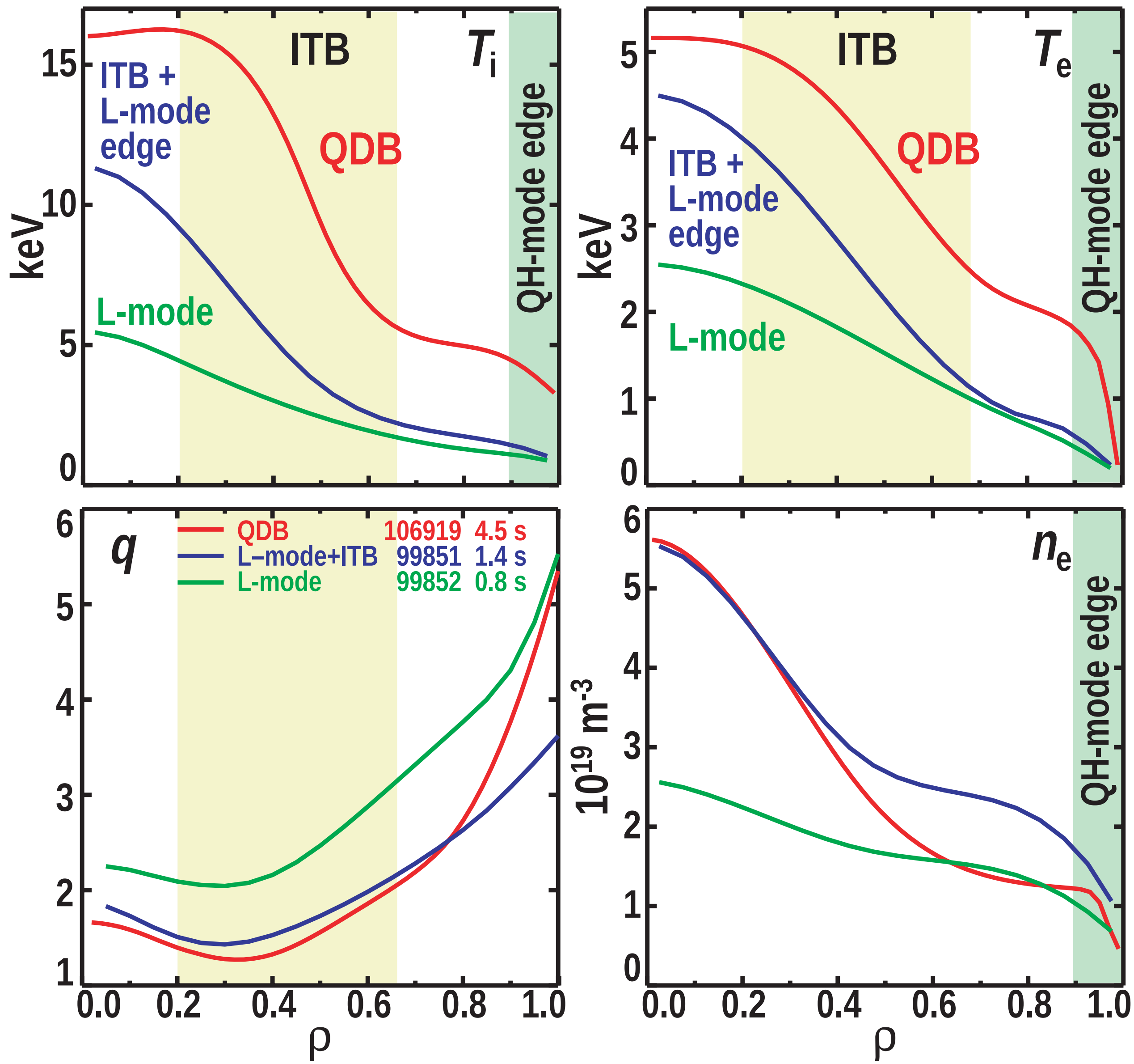
- Maintains quiescent ELM-free edge for >3.5 s, ~25τ_E

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 and JET
  - — 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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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

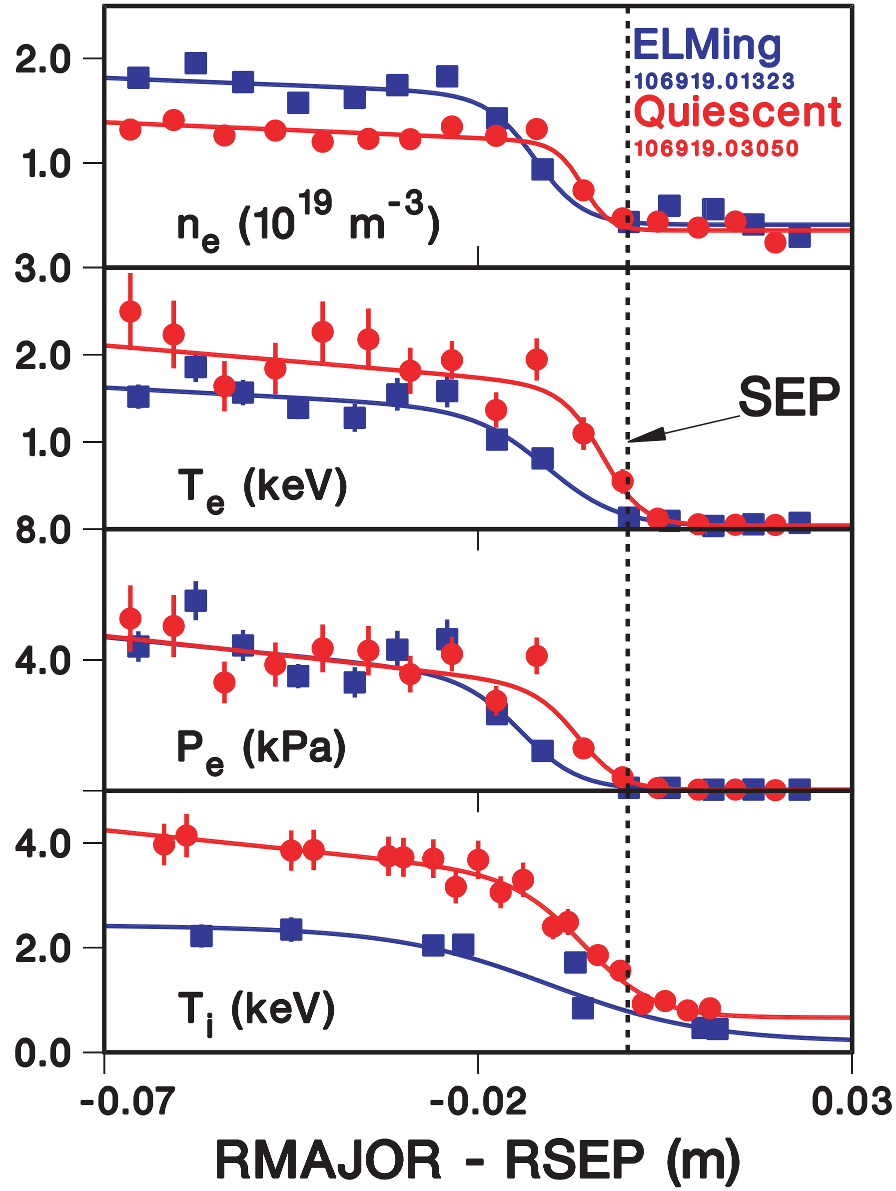
QUIESCENT H-MODE (QH-MODE) EDGE

- 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?

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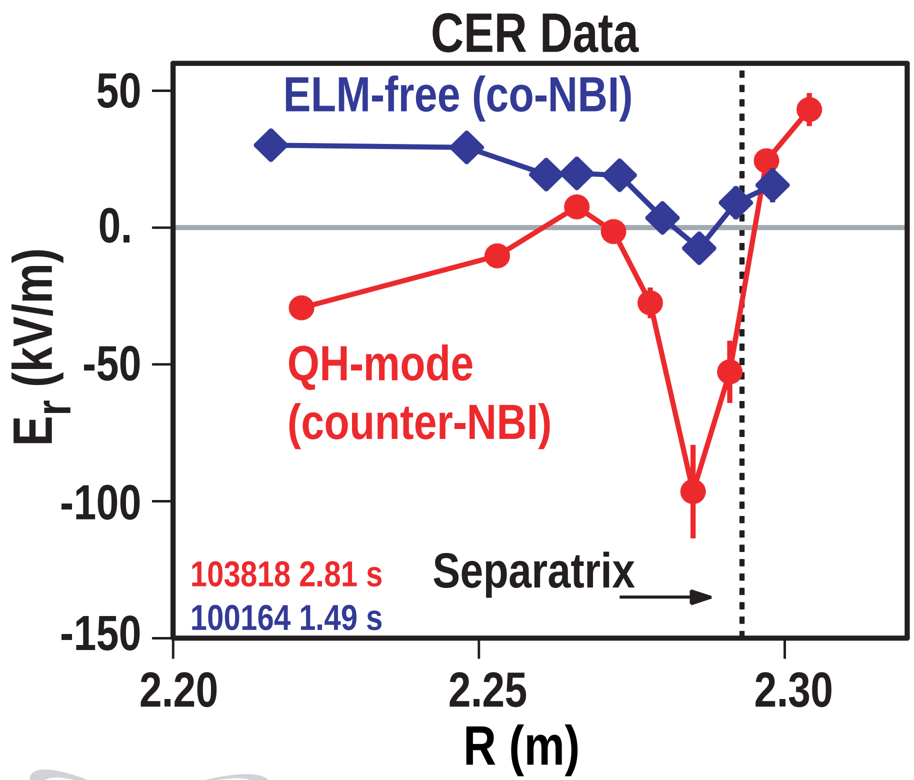
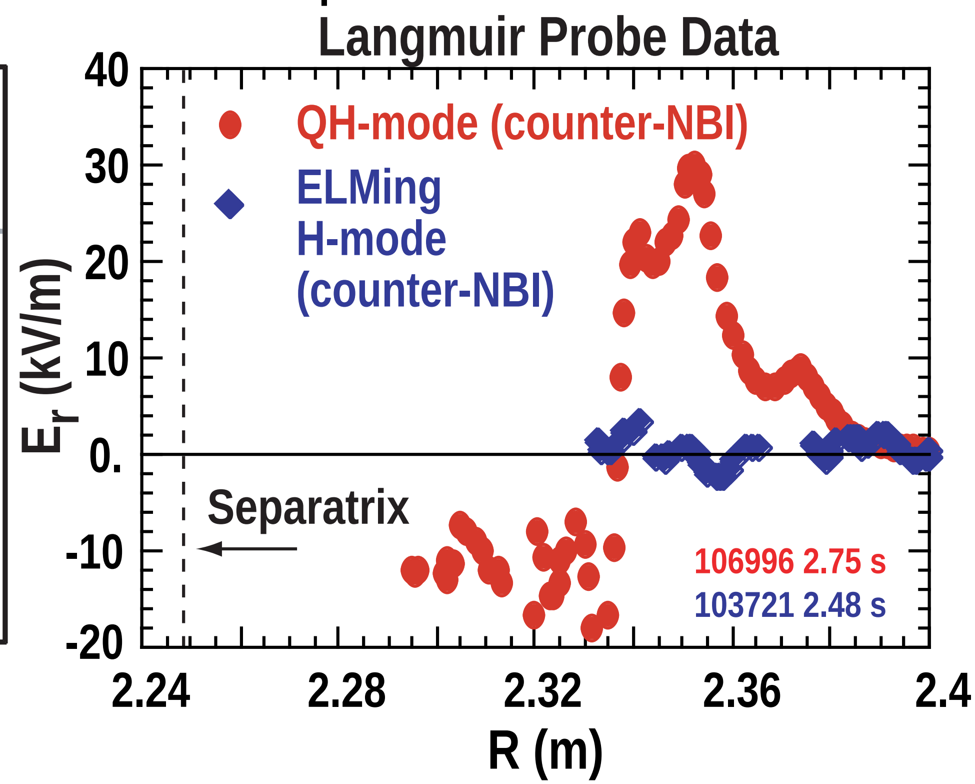
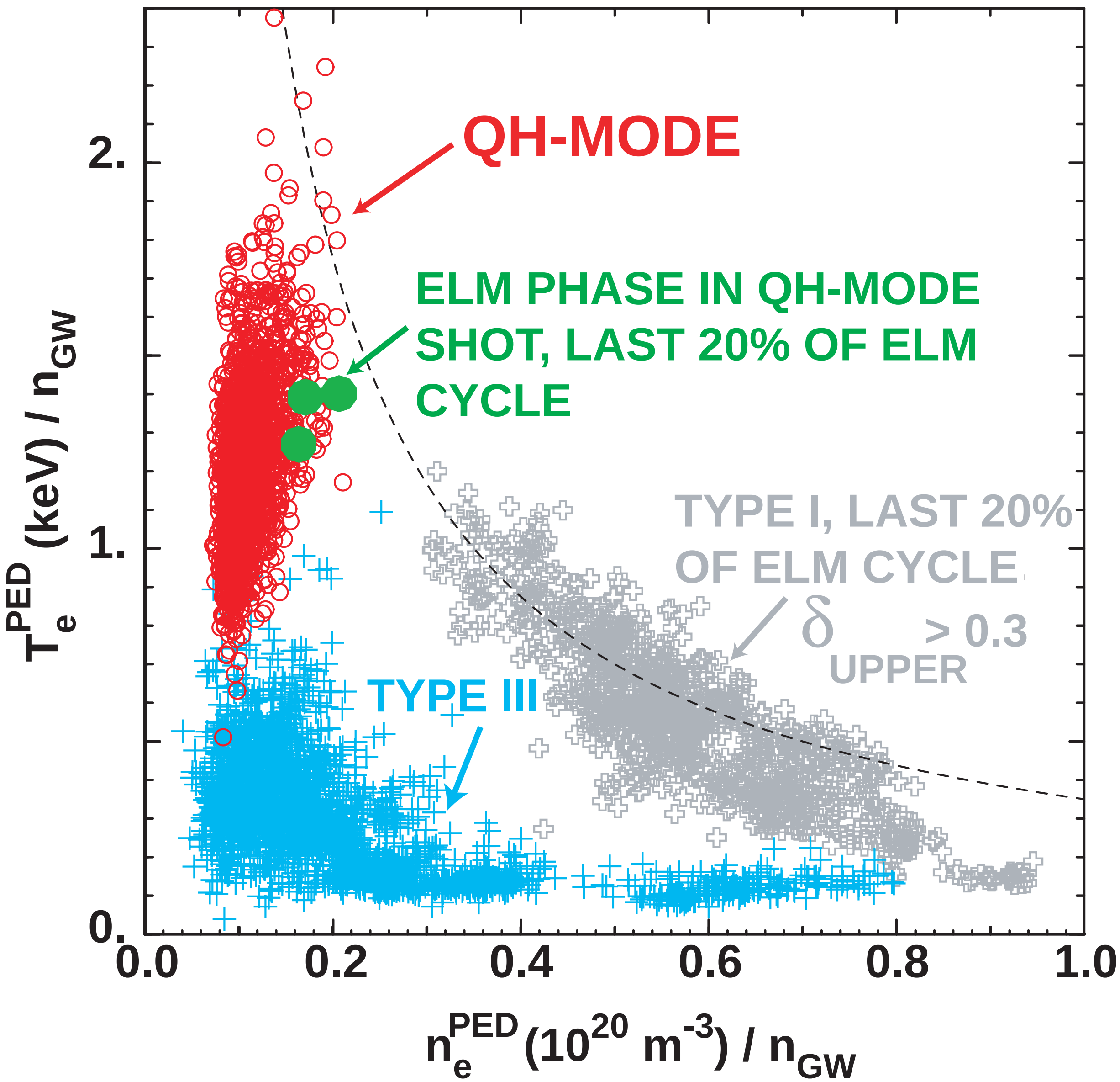
QH-MODE PLASMAS HAVE LARGE EDGE RADIAL ELECTRIC FIELD, E_r

- 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





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



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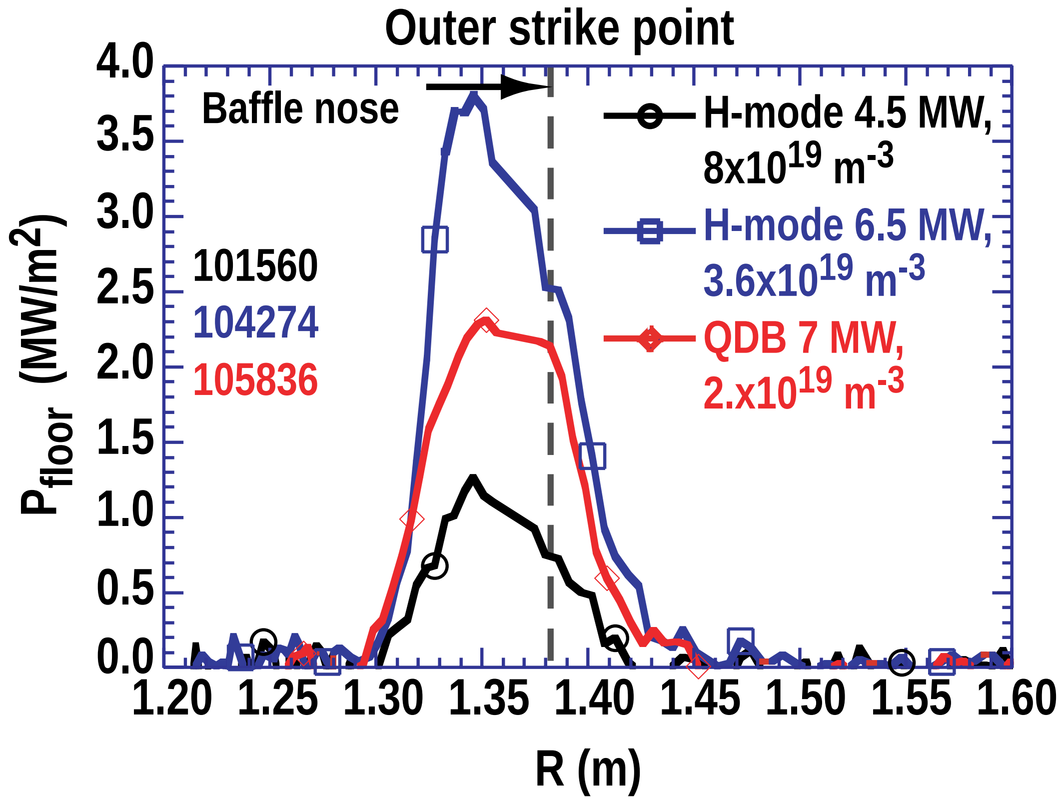
QDB OPERATION HAS MODERATE HEAT FLUX TO THE DIVERTOR TARGET PLATES



- 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

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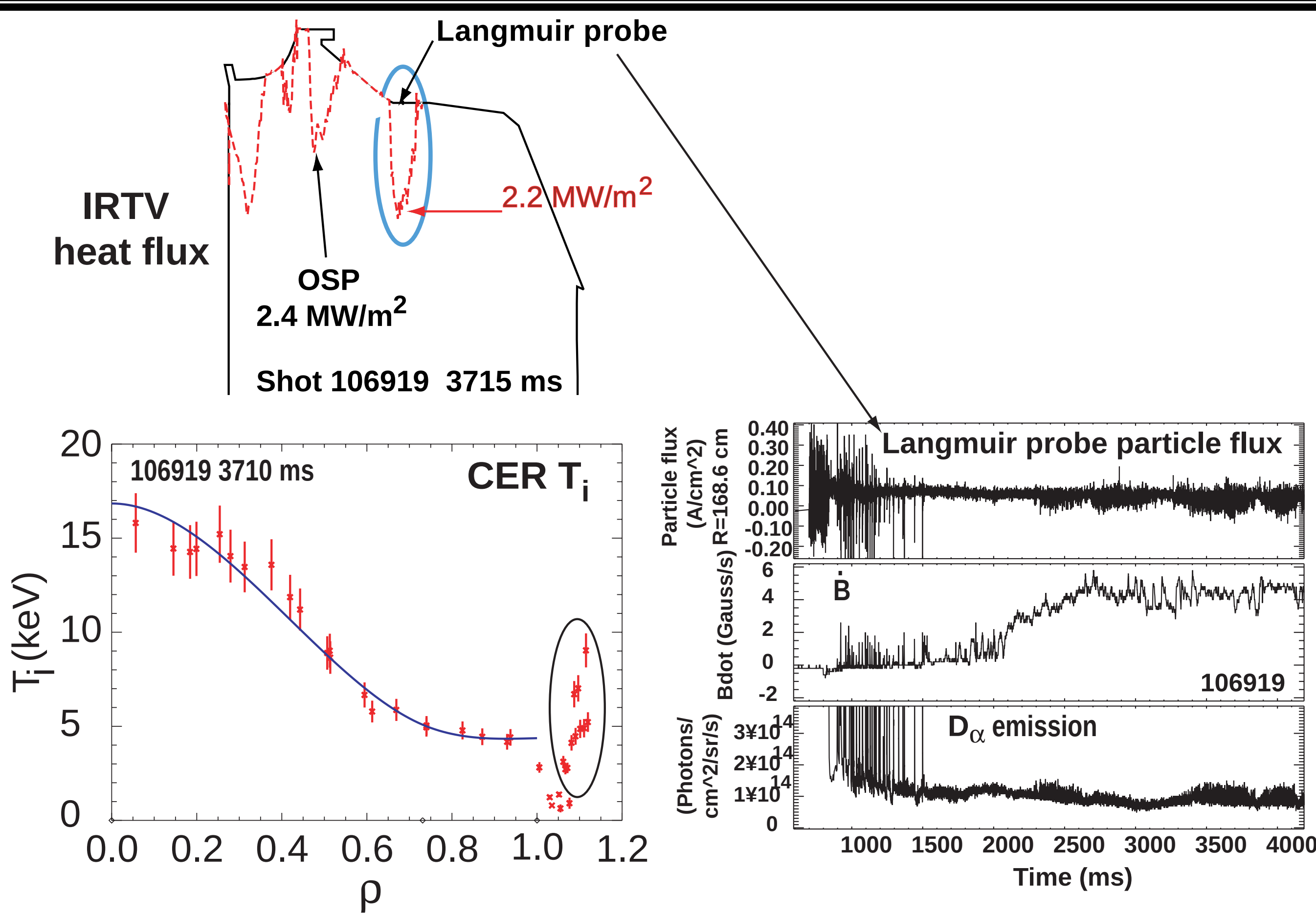
QDB OPERATION HAS SIGNIFICANT HEAT FLUX TO THE BAFFLE PLATE, 3-4 MIDPLANE CM OUTSIDE SEPARATRIX



- Heat flux, hot ions and particle flux all observed 3-4 midplane cm outside sepratrix during EHO (see Lasnier, LP1 36, this session)
  - Heat flux to baffle plate is consistent with midplane SOL T_i measurements

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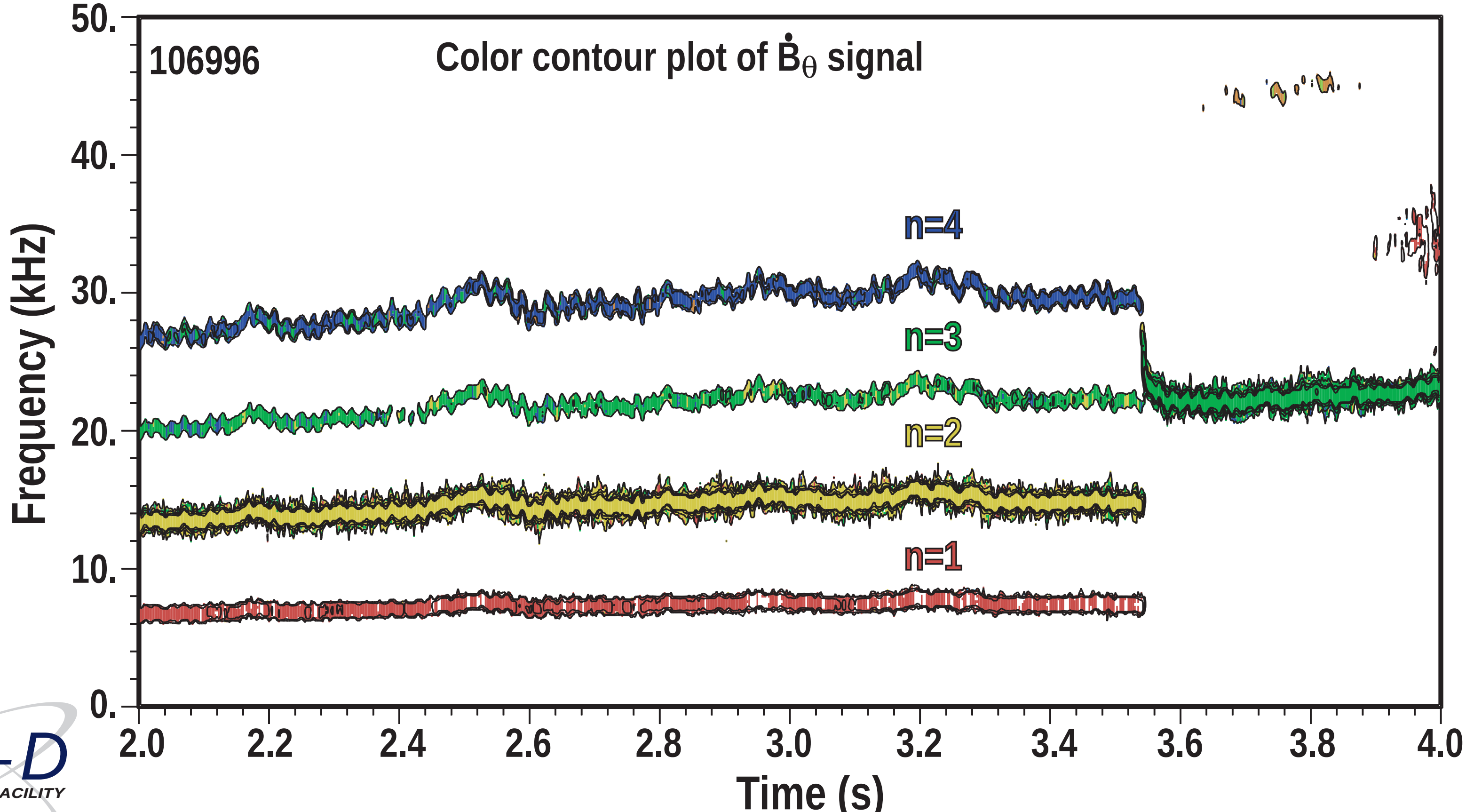
QUIESCENT OPERATION IS USUALLY ASSOCIATED WITH THE PRESENCE OF AN EDGE HARMONIC OSCILLATION (EHO)

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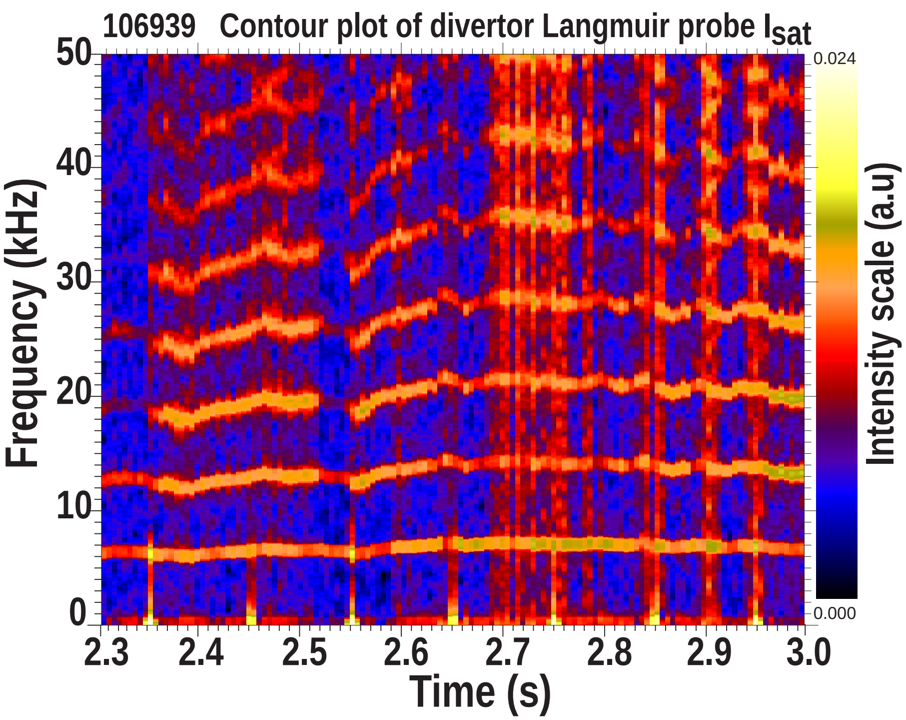
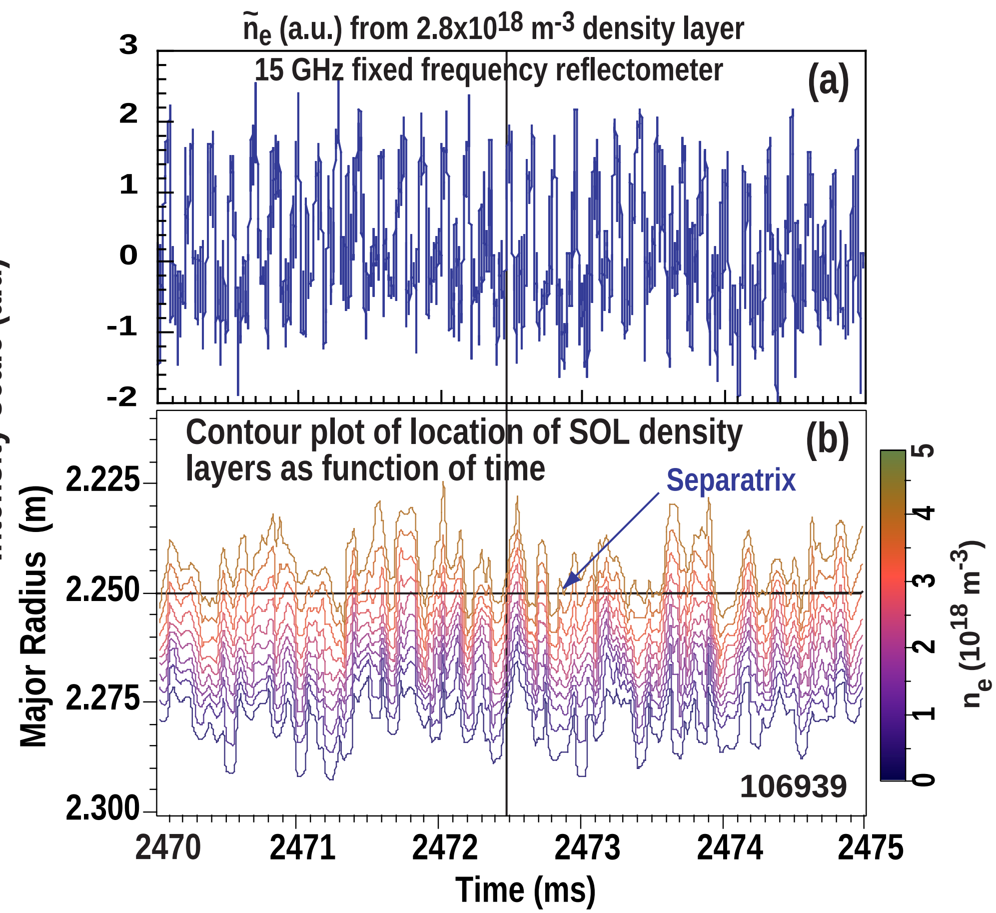
THE EHO CAUSES PARTICLE TRANSPORT — EHO MODULATES BOTH PARTICLE FLUX TO DIVERTOR AND SOL DENSITY PROFILE

- 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

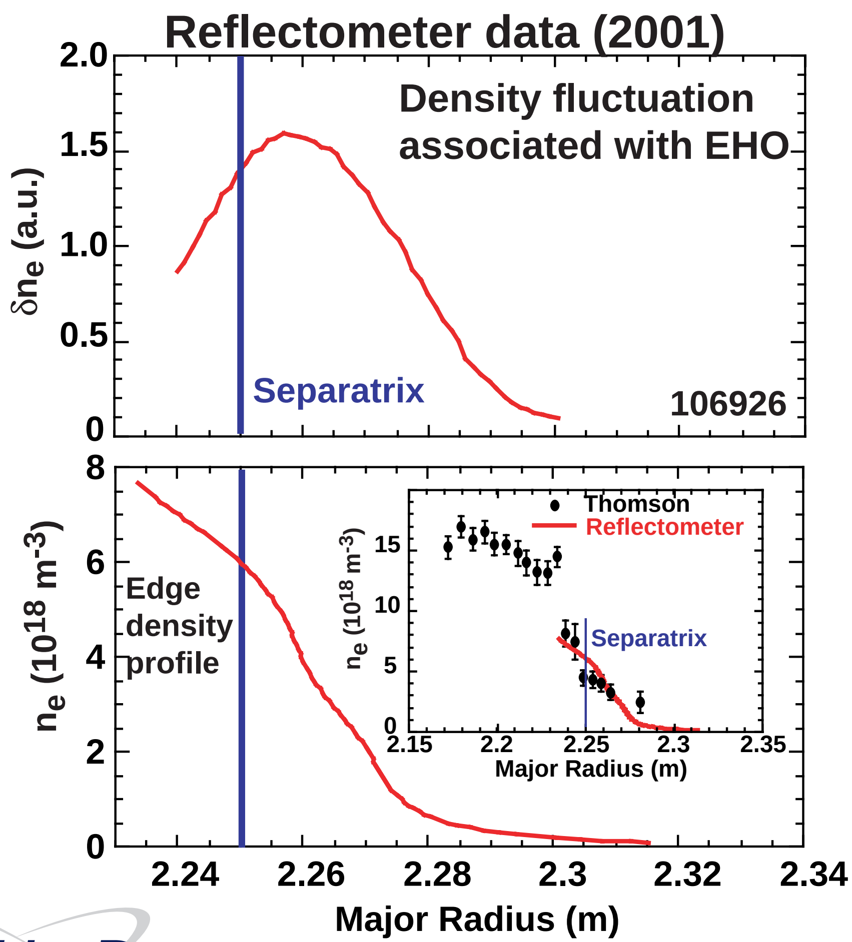


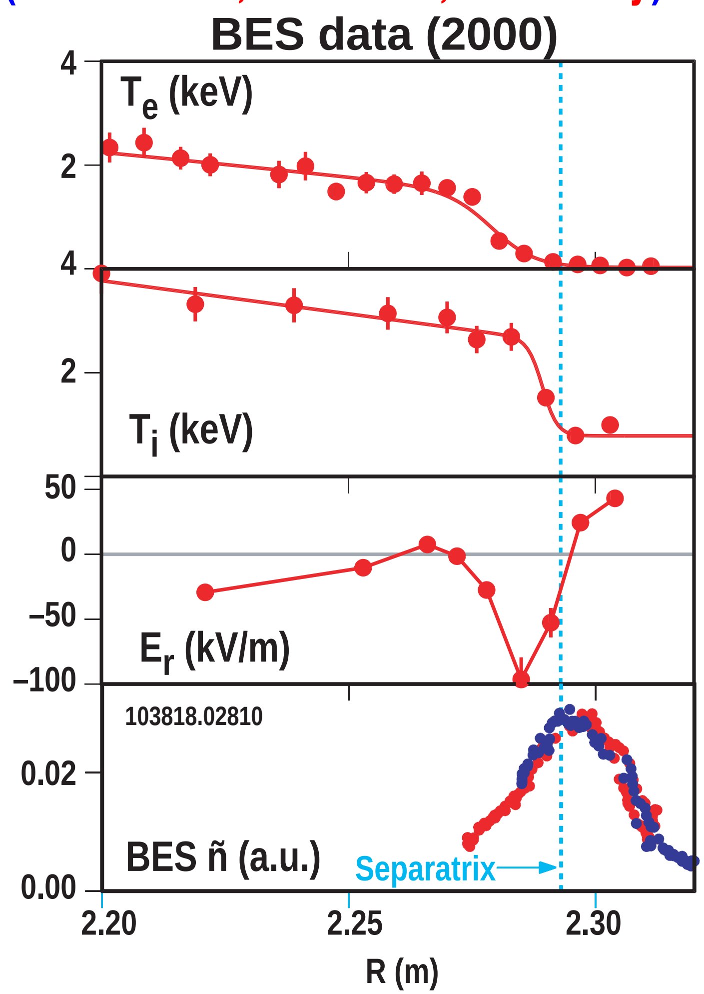
- High resolution profile reflectometer system shows scrape-off layer (SOL) density profile is modulated at EHO frequency



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 (see Burrell, ROP1 17, Thursday)





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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 ion collisionality	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

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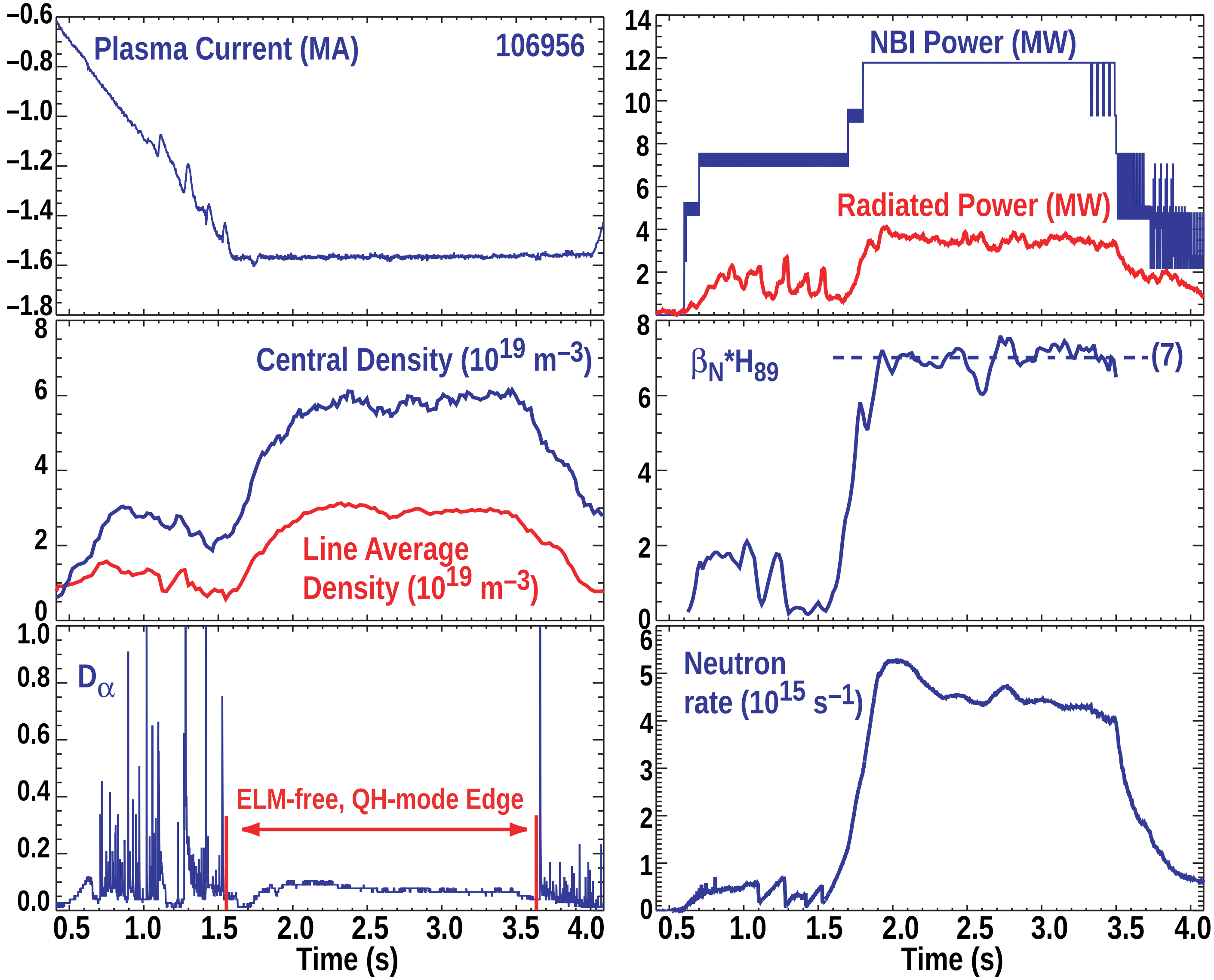
COMBINATION OF CORE ITB AND QH-MODE EDGE RESULTS IN SUSTAINED HIGH PERFORMANCE

- $\beta_N H_{89}$=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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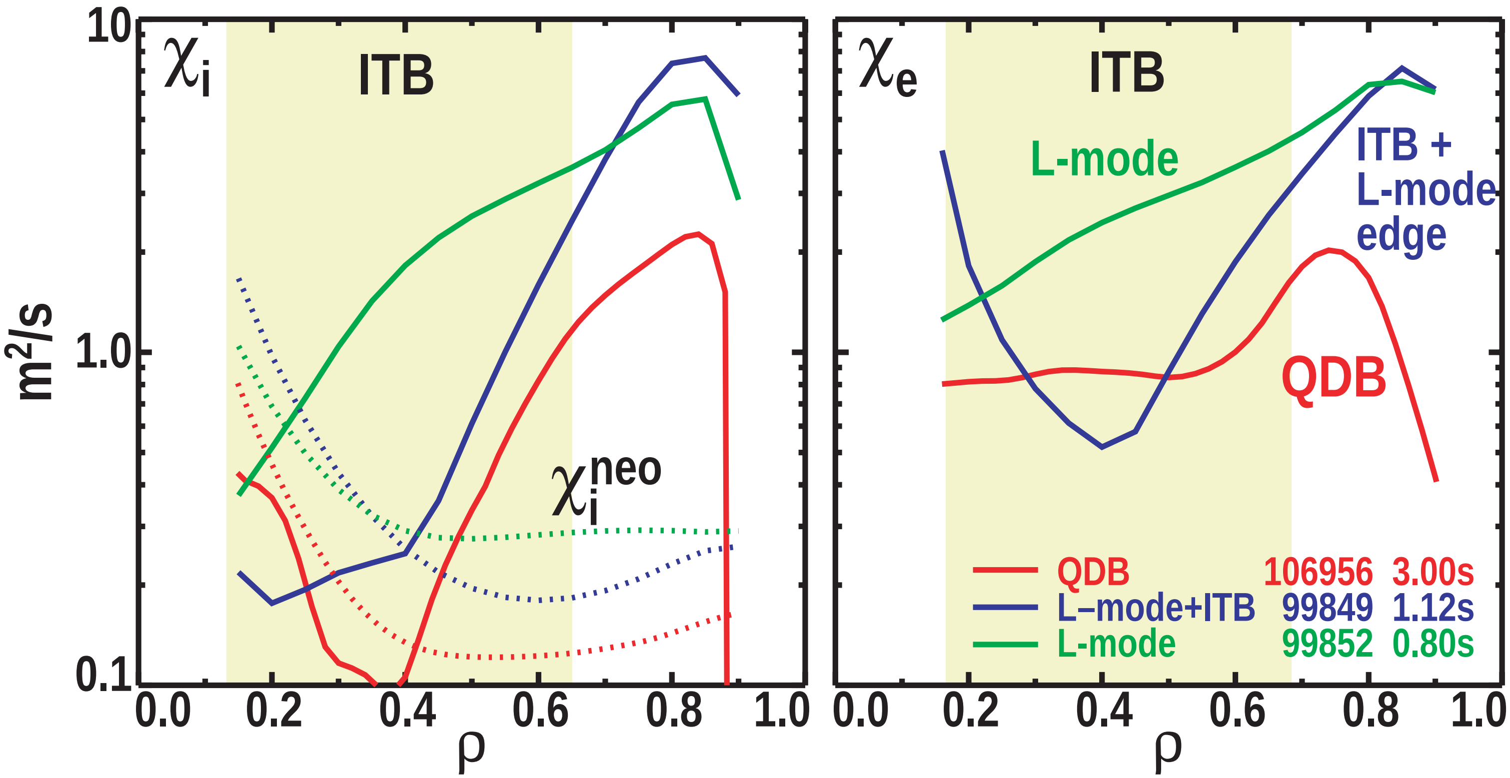
TRANSPORT ANALYSIS CONFIRMS PRESENCE OF DOUBLE (CORE AND EDGE) TRANSPORT BARRIERS



- 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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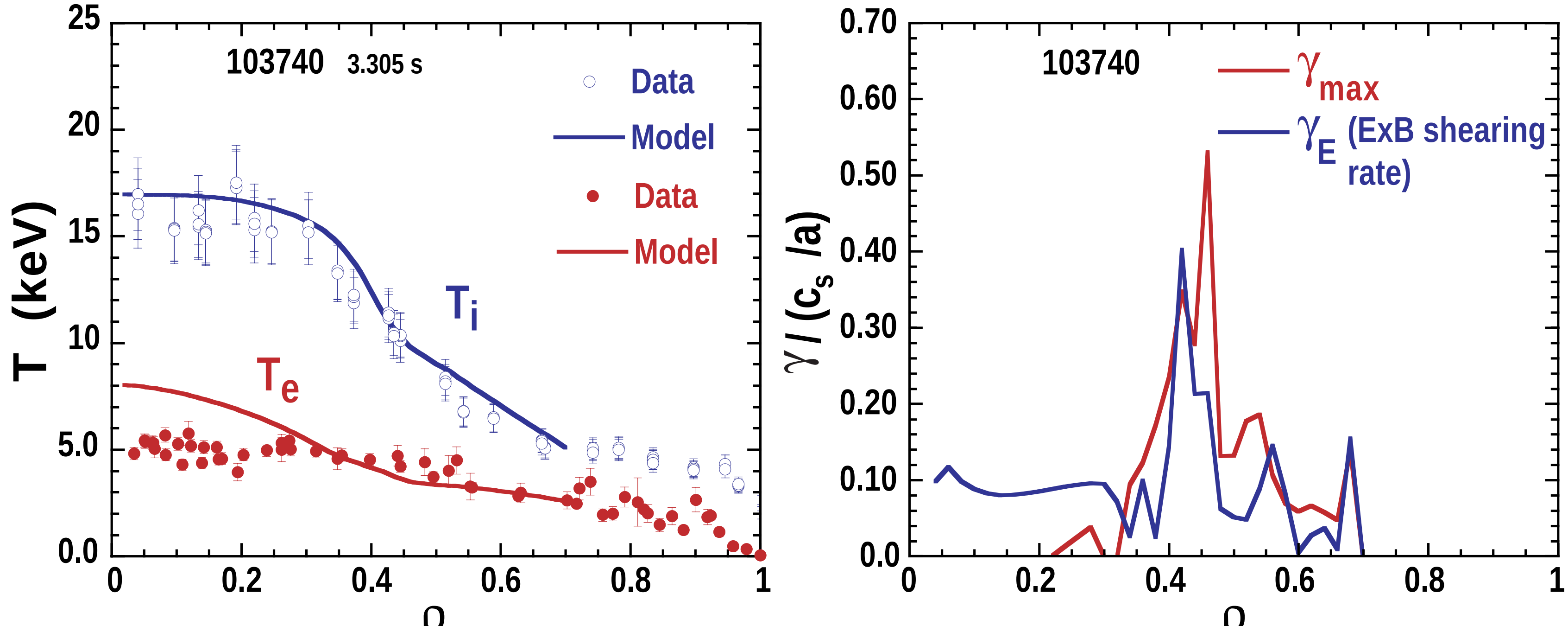
SIMULATIONS USING THE GLF23 MODEL REPRODUCE THE QDB CORE ION BARRIER (see Kinsey, QO1 12, Thursday)



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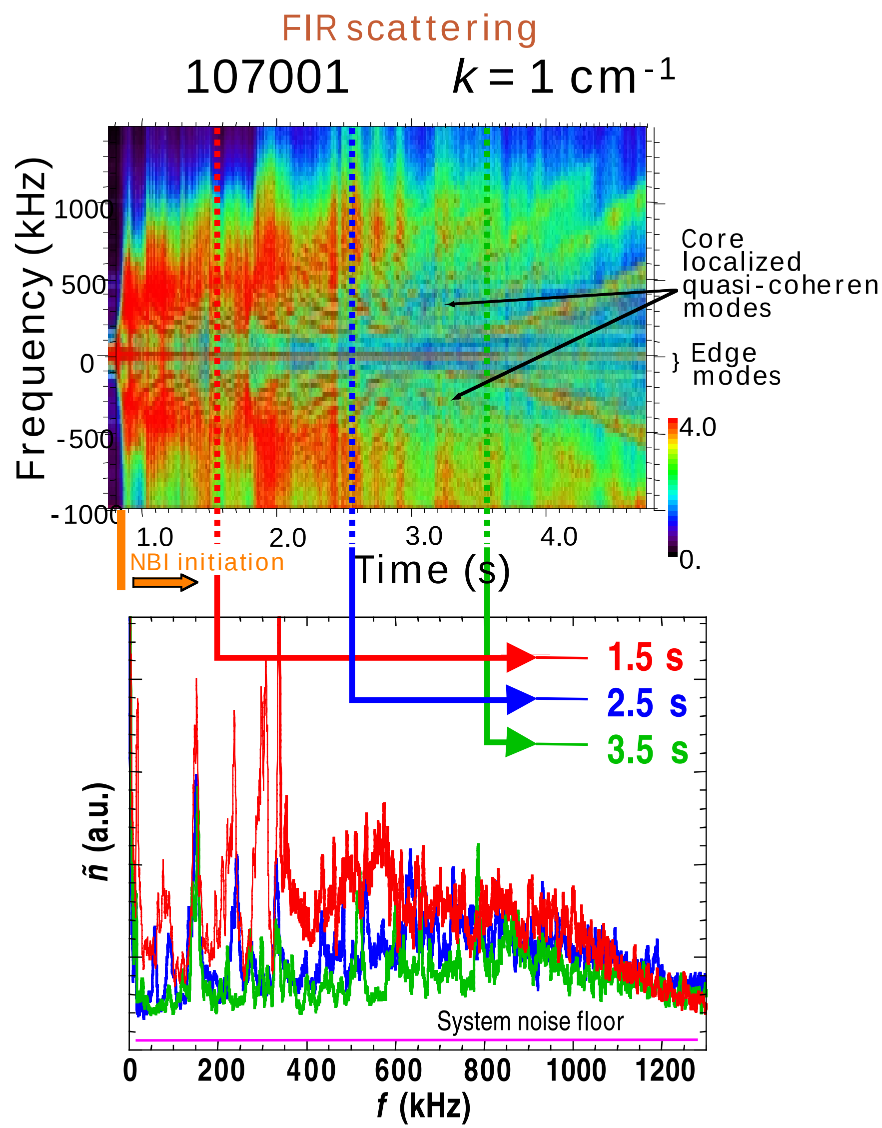
CORE BARRIER EXISTS WITHOUT COMPLETE TURBULENCE SUPPRESSION, IN AGREEMENT WITH GLF23 MODELING

- **Internal broadband turbulence is not completely suppressed as the QDB core barrier evolves (see Zeng, LP1 16, this session)**
  - **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.**



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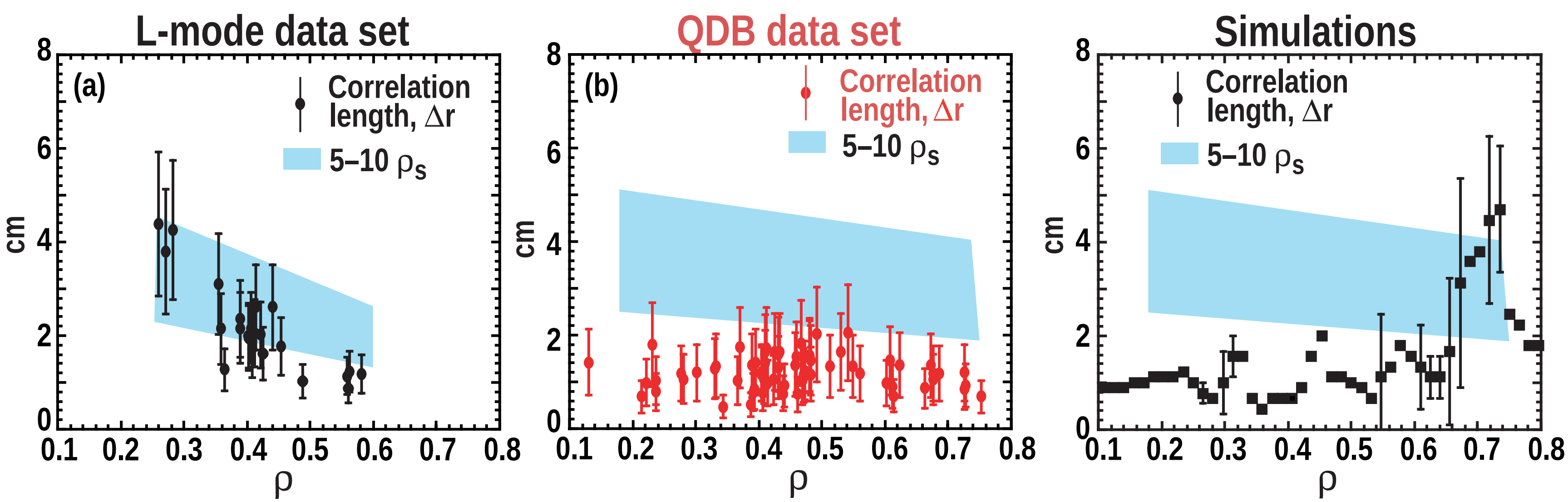
STEP SIZE FOR CORE TURBULENT TRANSPORT IS REDUCED IN QDB PLASMAS

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



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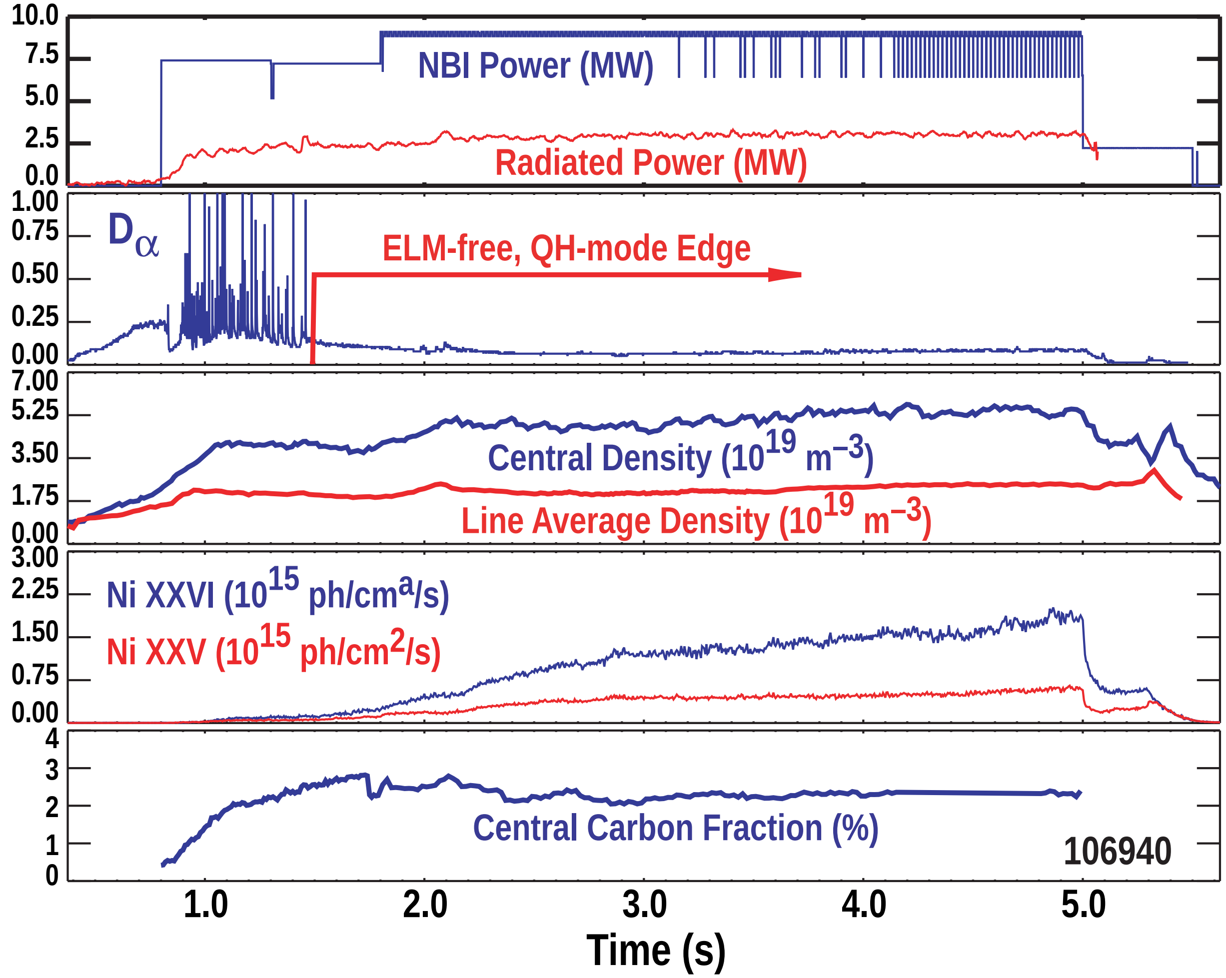
HIGH-Z IMPURITY ACCUMULATION IS AN ISSUE FOR LONG PULSE QDB DISCHARGES (West, invited talk KI1 04)



- 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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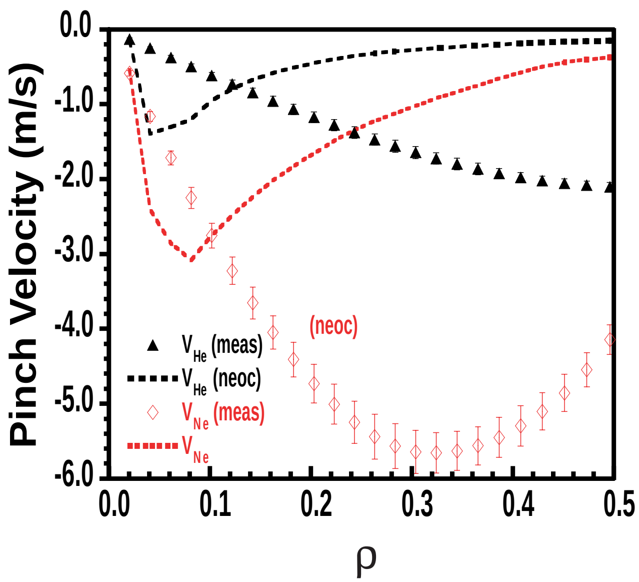
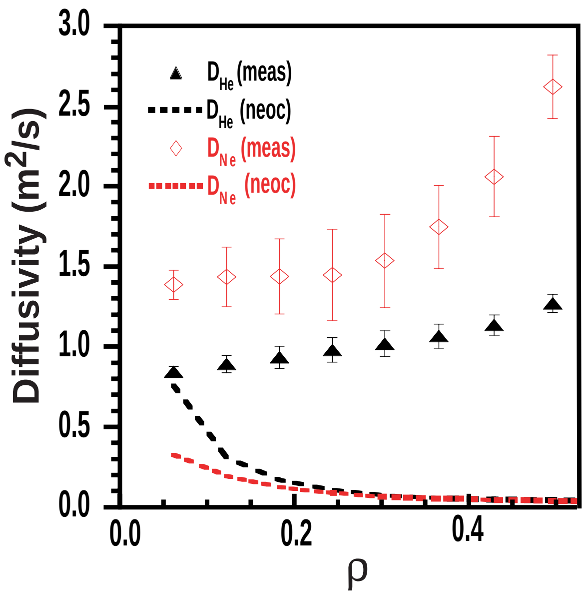
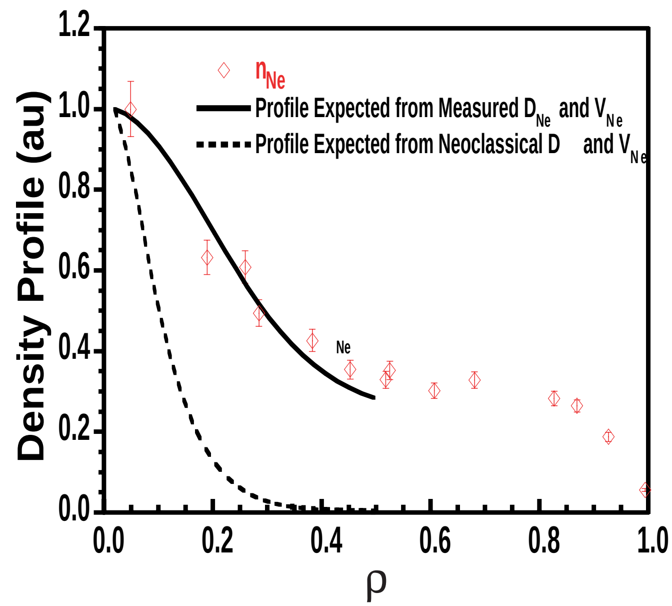
MEASURED IMPURITY TRANSPORT LARGER THAN NEOCLASSICAL FROM $0.1<\rho<0.5$

- Experimental D and v obtained from time dependence of measured impurity density profiles (from CER system)
- Neoclassical transport coefficients obtained from the NCLASS code
- Impurity transport is anomalous where measured χ_i is near neoclassical
- Measured neon profile is significantly less peaked than predicted by neoclassical transport rates







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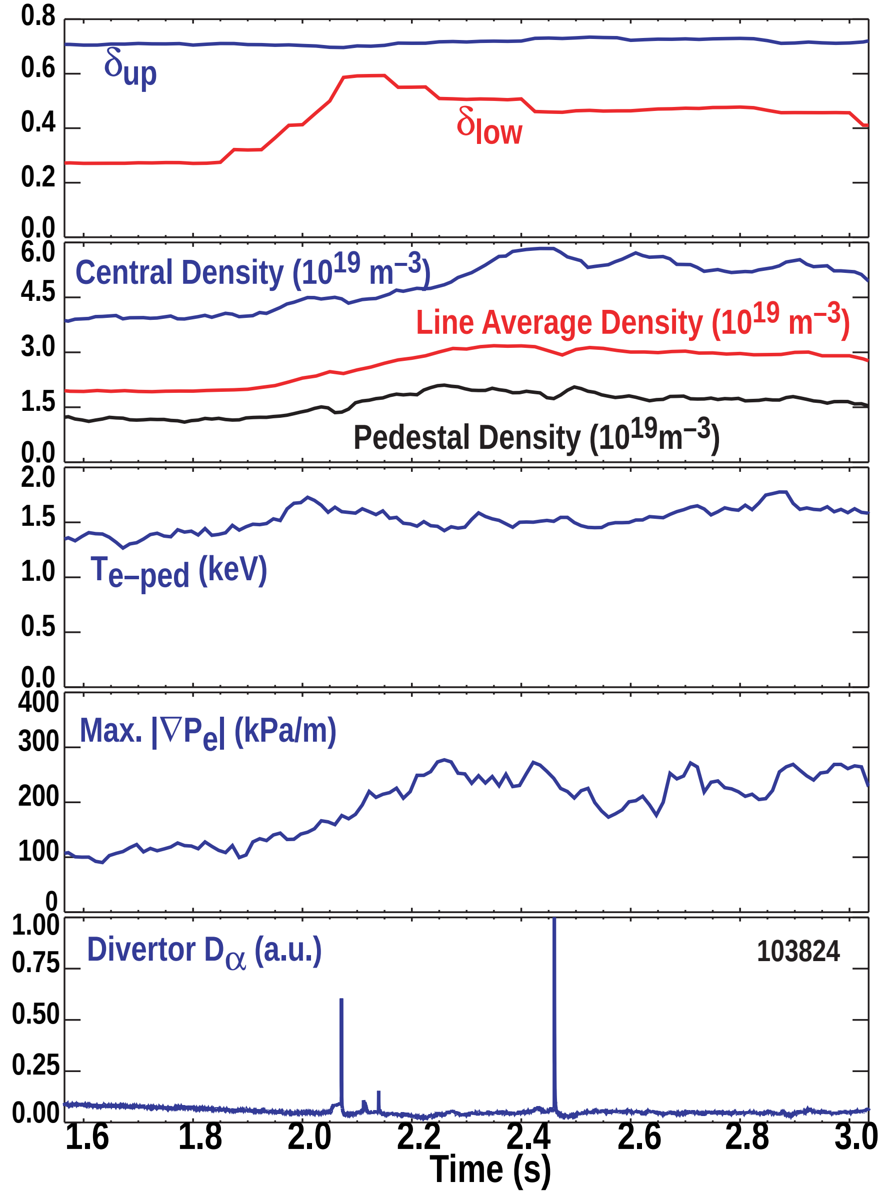
REDUCED DENSITY PEAKING IS REQUIRED FOR INCREASED PERFORMANCE - SEVERAL CONTROL TOOLS EXIST

- Advantages of reduced density peaking include:
  - Reduced central high-Z impurity accumulation
  - Improved bootstrap current alignment
- Control tools have (transiently) demonstrated ability to reduce density peaking (Gohil, LP1 4, this session):
  - Near on-axis ECH
  - 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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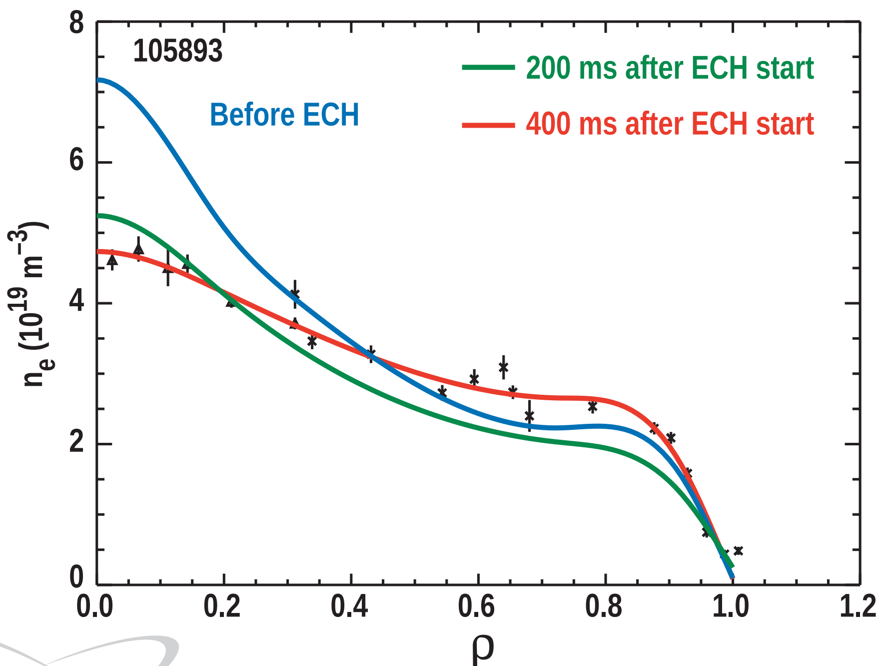
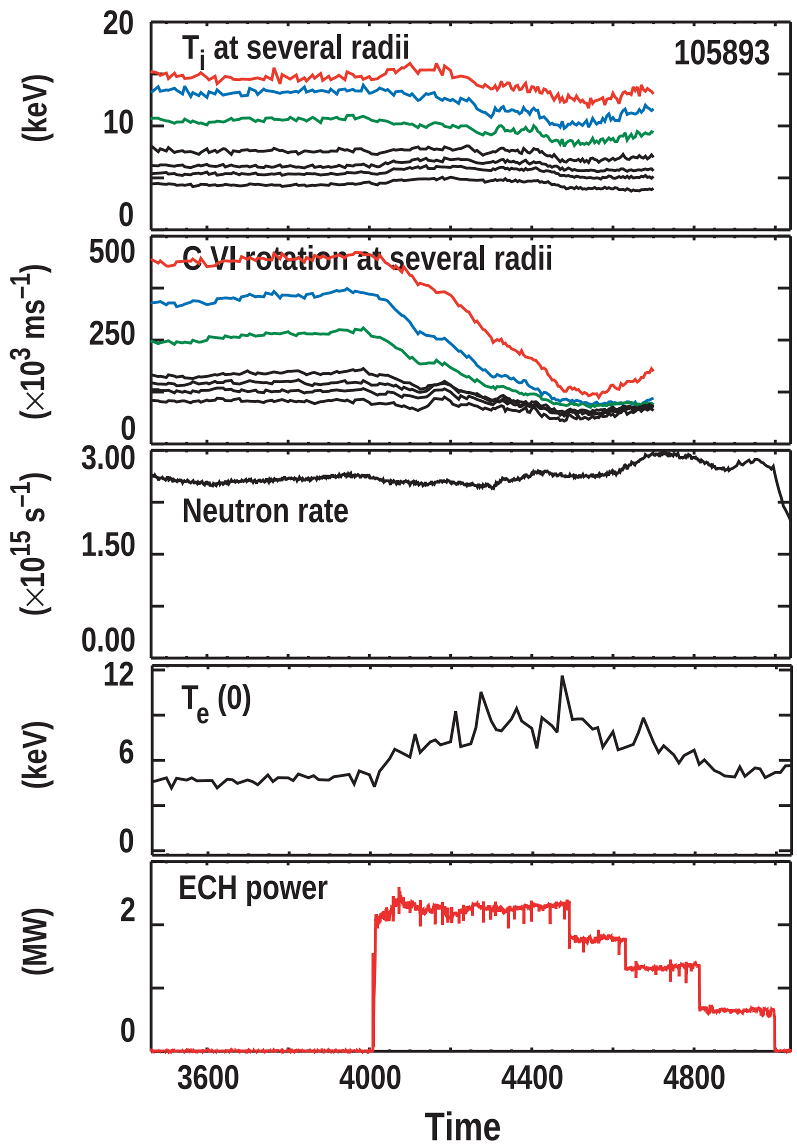
ON-AXIS ECH REDUCES THE CENTRAL DENSITY AND DENSITY PEAKING, WITH LITTLE EFFECT ON PERFORMANCE

- Electron density profile becomes broader and central density is reduced
  - Nickel XXVI emission is reduced, analysis required to determine if this is decrease in impurity content
- P_{ECH} ~ 2 MW, ρ_{ECH} ~ 0.12
- $n_e(o)/n_{AVE}$ decreases from 2.6 to 1.7





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ADVANCED TOKAMAK ISSUES FOR THE QDB REGIME

- Advanced Tokamak (AT) research seeks to produce a steady-state high performance regime
  - QDB appears to be an excellent target for sustainment using ECCD [Casper, *et al*., poster FP1.048, Tue. AM]
- Barriers to AT applications of the QDB regime:
  - Counter-NBI
    - ★ Balanced NBI (no momentum input) should be similar to counter for formation of separate barriers (both have pressure dominated E_r)
    - ★ Role of counter-NBI still unknown for EHO dominated edge
    - ★ Counter-NBCD is small but significant; needs to be overcome by current drive
  - Peaked density profile:
    - ★ Associated peaked pressure profile limits attainable plasma β.
    - ★ Narrow bootstrap current profile not optimal for steady-state sustainment.
    - ★ Neoclassical impurity transport leads to retention of high-*Z* impurities.
    - ★ Near-term studies of the QDB will focus on methods of broadening the density profile.

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
  - Addresses major issue in Fusion research, ELM induced pulsed divertor heat loads
- 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
  - Impurity accumulation is an issue. Control tools are available (shaping, ECH, pellets) to reduce density peaking and core impurity accumulation

FOR MORE INFORMATION RELATED TO THE QUIESCENT DOUBLE BARRIER REGIME...

- Invited talks, Wednesday and Friday
  - KI1.004: W.P. West, "*Energy, Impurity and Particle Transport in Quiescent Double Barrier Discharges in DIII–D.*" Poster this afternoon.
  - UI1.005: T.L. Rhodes, "*Comparison of Turbulence Measurements From DIII-D L-mode and High Performance Plasmas to Turbulence Simulations and Models.*"
- Poster, Tuesday morning
  - FP1.048: T.A. Casper, "*Predictive Modeling of Tokamak Configurations.*"
- Contributed oral, Tuesday morning
  - FO1.012: C.M. Greenfield, *et al.*, "*The Quiescent Double Barrier Regime in DIII-D.*"
- Posters, Wednesday afternoon
  - LP1.004: P. Gohil, *et al.*, "*Development of Methods to Control Internal Transport Barriers in DIII-D Plasmas.*"
  - LP1.016: L. Zeng, *et al.*, "*Fluctuation Characteristics of the QDB Regime in DIII-D.*"
  - LP1.036: C.J. Lasnier, *et al.*, "*Scrape-off Layer Characteristics of QH and QDB Plasma Compared with ELMing H-mode and Advanced Tokamak Plasma.*"
- Contributed oral, Thursday morning
  - QO1.012: J.E. Kinsey, *et al.*, "*Progress in Modeling Internal Transport Barrier Formation Using the GLF23 Transport Model.*"
- Poster, Thursday afternoon
  - RP1.017: K.H. Burrell, *et al.*, "*Physics of the Edge Harmonic Oscillation in Quiescent H-Mode Discharges in DIII-D.*"