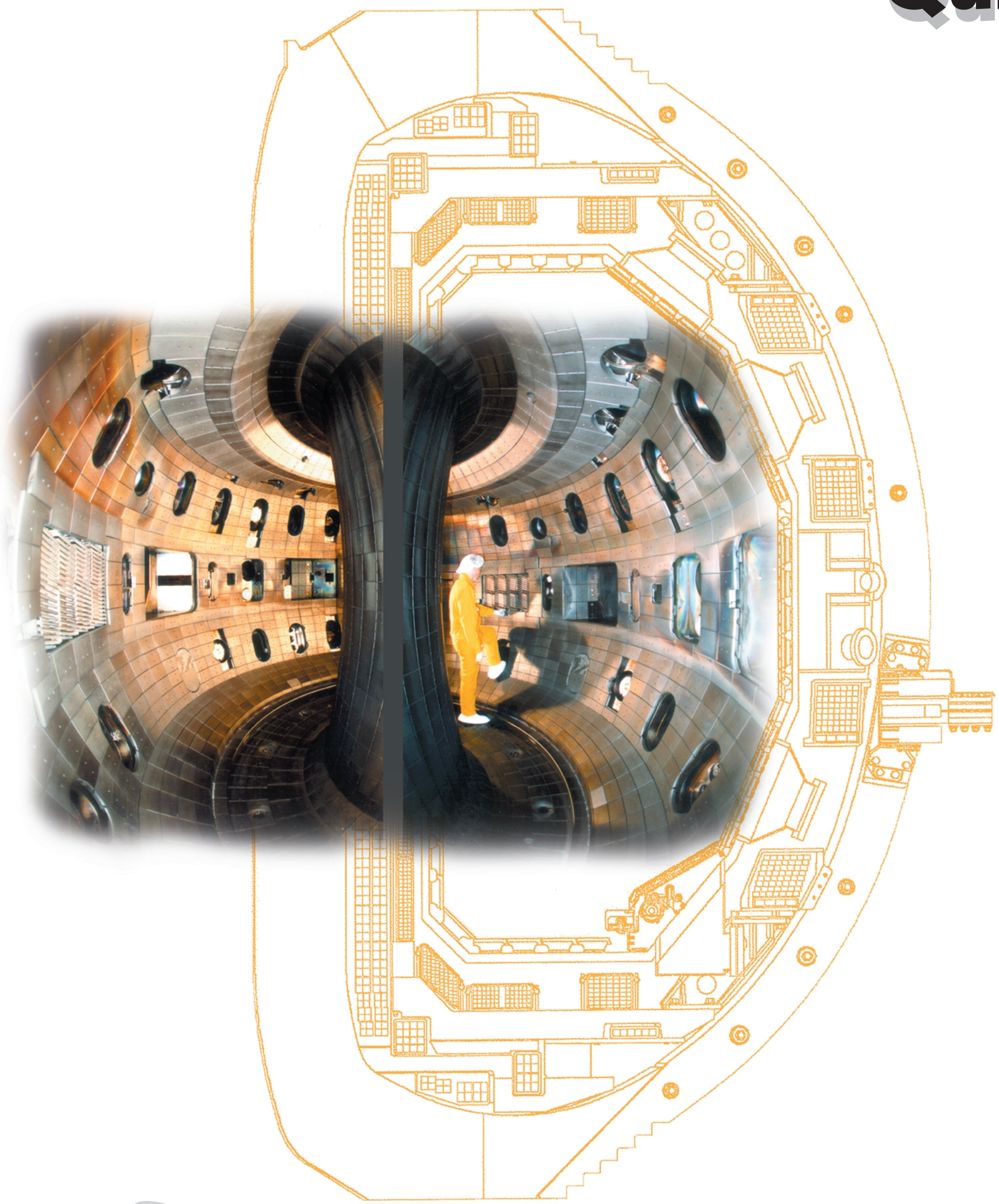
Quiescent Double Barrier H–mode Plasmas in the DIII–D Tokamak



by
K.H. Burrell
for the DIII–D Research Team

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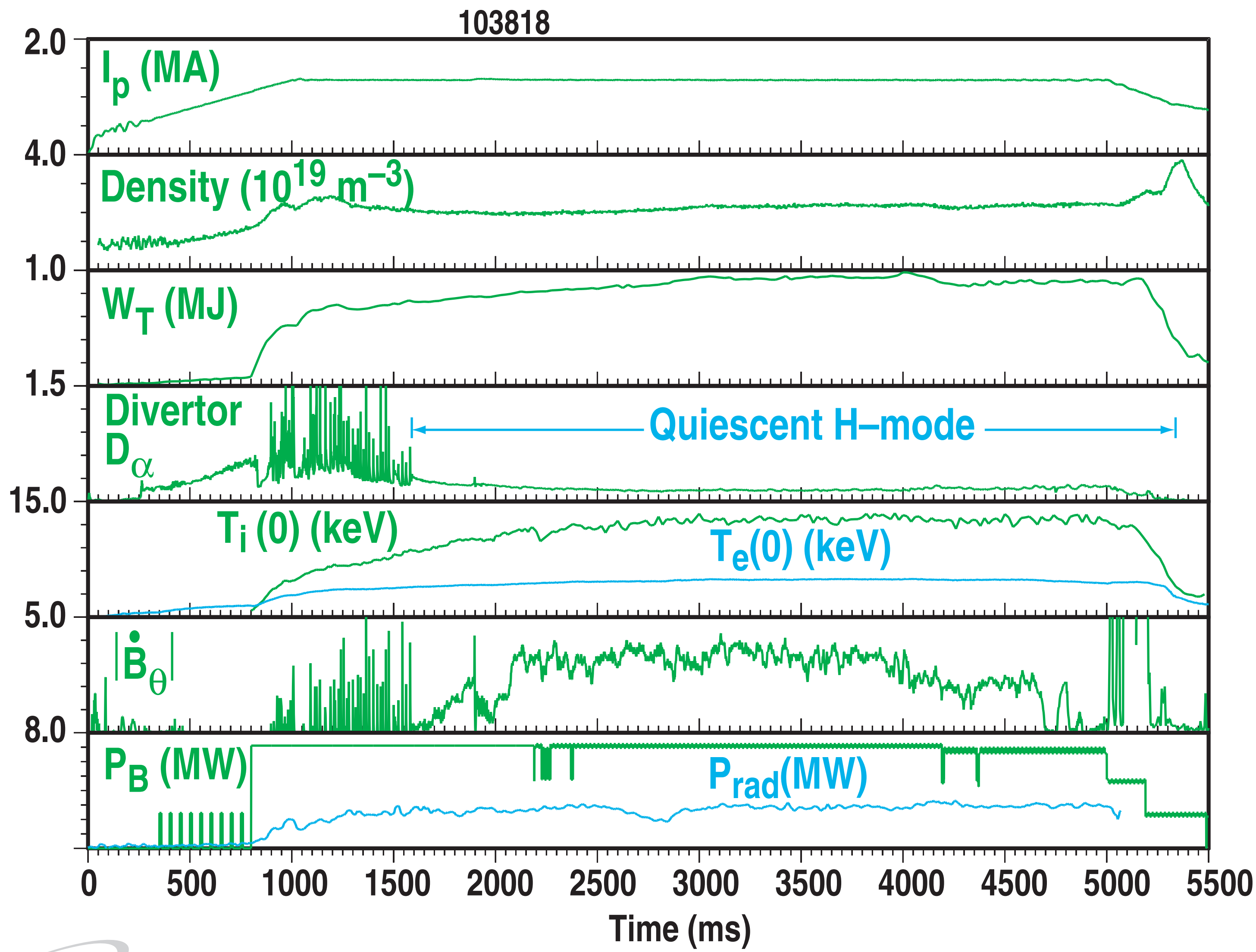
INTRODUCTION

- **Owing to superior energy confinement, H–mode operation is the choice for next-step tokamak devices based either on conventional or advanced tokamak physics**
- **This choice has a significant cost because of effects of ELMs**
  - Pulsed heat load to divertor plates can lead to rapid erosion
  - Giant ELMs can couple to core MHD modes and limit beta
  - Giant ELMs can also destroy core transport barriers required to create optimized AT plasmas
- **Recently created, quiescent double barrier H–mode plasmas demonstrate how to avoid this cost**
  - ELM-free, controlled density H–mode edge
  - Reduced core transport region (internal transport barrier)
- **Quiescent H–mode edge has H–mode edge transport barrier plus**
  - No bursting edge behavior associated with ELMs
  - Controlled density and impurity levels
  - Potential for steady-state operation
    - ★ 3.5 seconds or 25 τ_E achieved to date
    - ★ Duration limited only by beam pulse duration
- **Combined edge and core transport reduction yields sustained high performance**
  - $H_{89} \lesssim 2.4$, $\beta_N \lesssim 2.9$
  - $\beta_N H_{89} = 7$ for $>5\ \tau_E$

QUIESCENT H–MODE HAS CONSTANT DENSITY AND IMPURITY LEVELS FOR LONG PULSES



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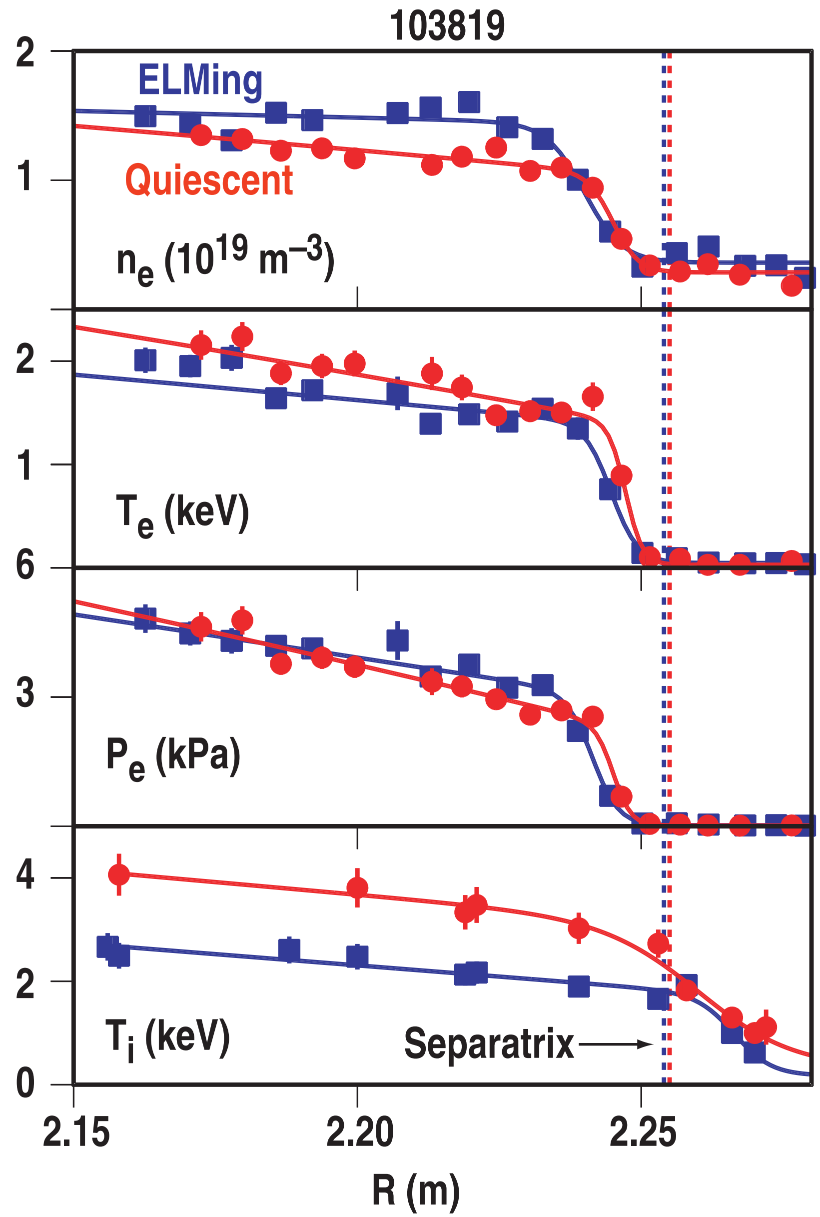
KEY QUESTIONS FOR QUIESCENT H–MODE

- Is this really H–mode?
- Do the edge gradients change when the ELMs go away?
- What are the plasma conditions required for quiescent H–mode operation?
- How are density and impurity levels controlled?
- What is the nature of the edge harmonic oscillation?
- How does this compare to enhanced D_α (EDA) operation in C–Mod?

STEEP EDGE GRADIENTS SHOW QUIESCENT PHASE IS H–MODE

- Edge gradients in quiescent phase are as steep as those in ELMing H–mode



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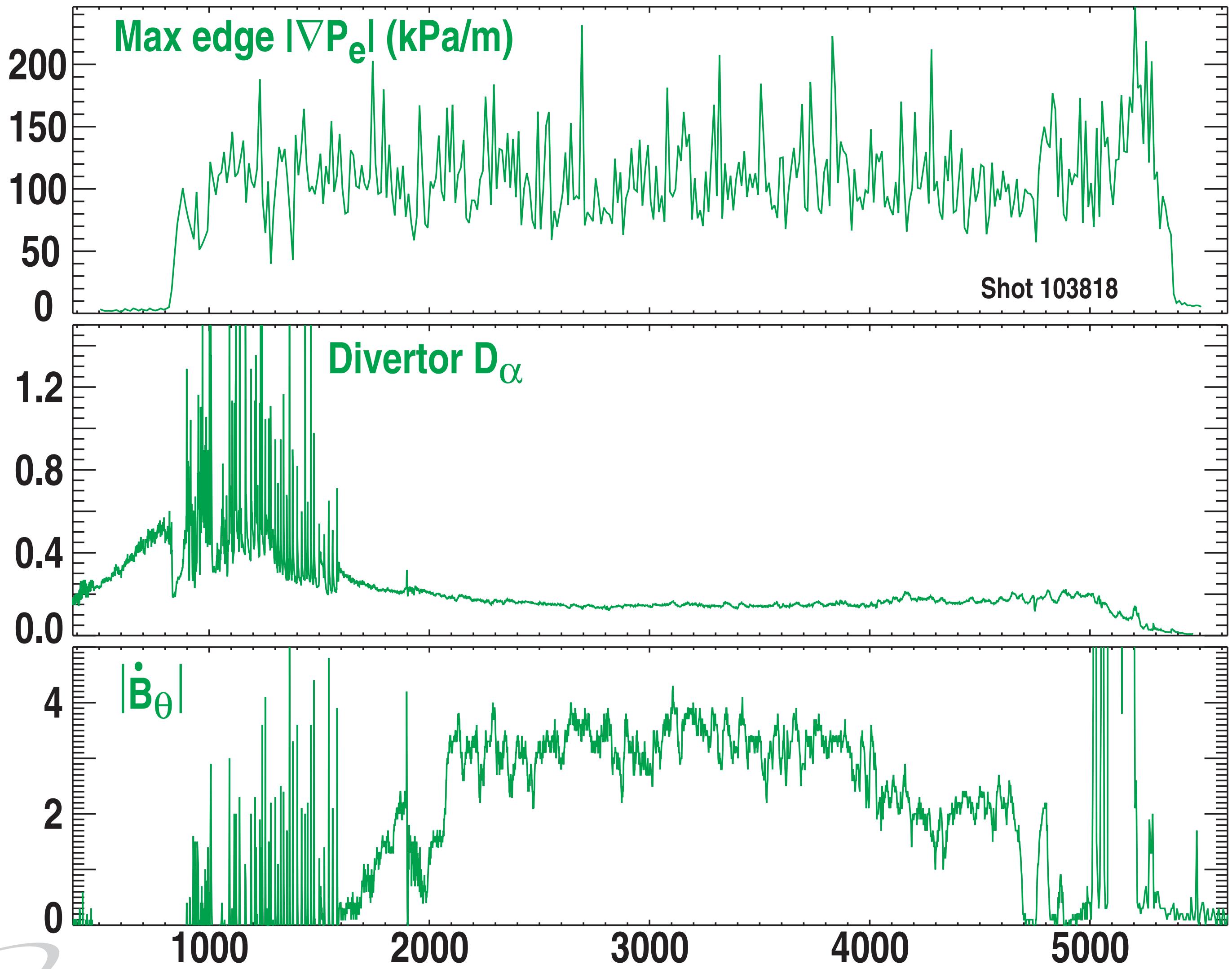
EDGE ∇P_e DOES NOT CHANGE WHEN ELMS DISAPPEAR



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QUIESCENT H–MODE OPERATION SEEN OVER BROAD RANGE OF PLASMA CONDITIONS

- **Key conditions are**
  - Neutral beam injection counter to plasma current at power levels above 3.7 MW
  - Cryopumping to reduce the neutral pressure and edge density (pedestal density typically 1.2×10^{19} m^{-3})
  - Sufficient distance between plasma edge and wall on low toroidal field side (~10 cm)

- **Quiescent operation seen**
  - In single-null plasma with ion ∇B drift both towards and away from X–point (double-null not yet attempted)
  - Over entire range of triangularity ($0.16 \leqq \delta \leqq 0.75$) and q ($3.7 \leqq q \leqq 4.6$) explored to date

- **Most work done with $1.2 \leqq I_p$ (MA) $\leqq 1.6$ and $1.8 \leqq B_T$ (T) $\leqq 2.1$**
  - Also have quiescent H–mode examples at 0.67 MA and 0.95 T

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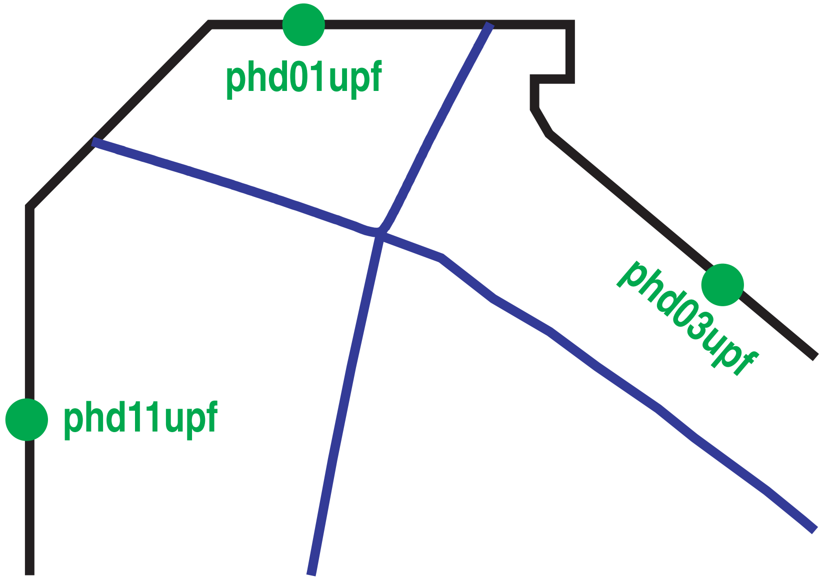
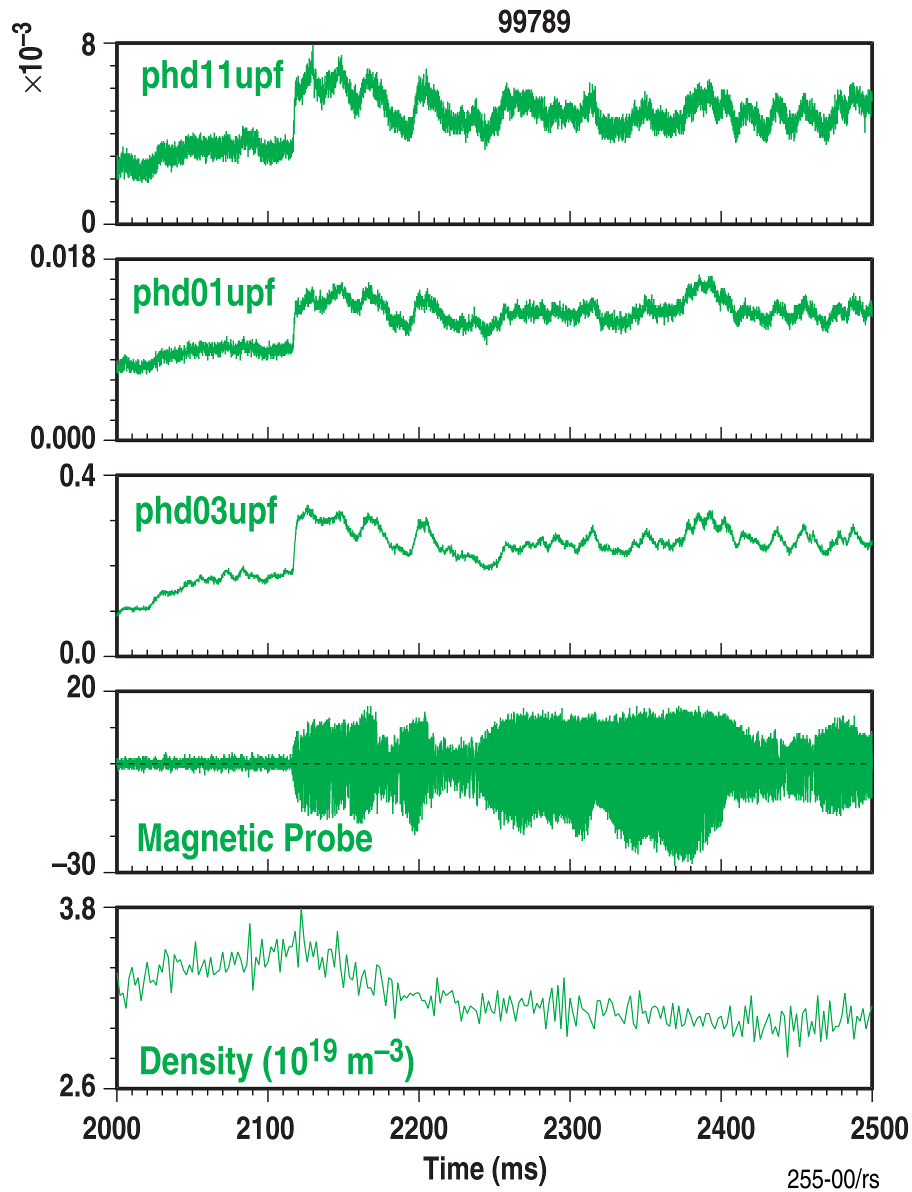
D_α RADIATION RISES THROUGHOUT DIVERTOR AND $\bar{n}_e$ DROPS WHEN EDGE HARMONIC OSCILLATION STARTS





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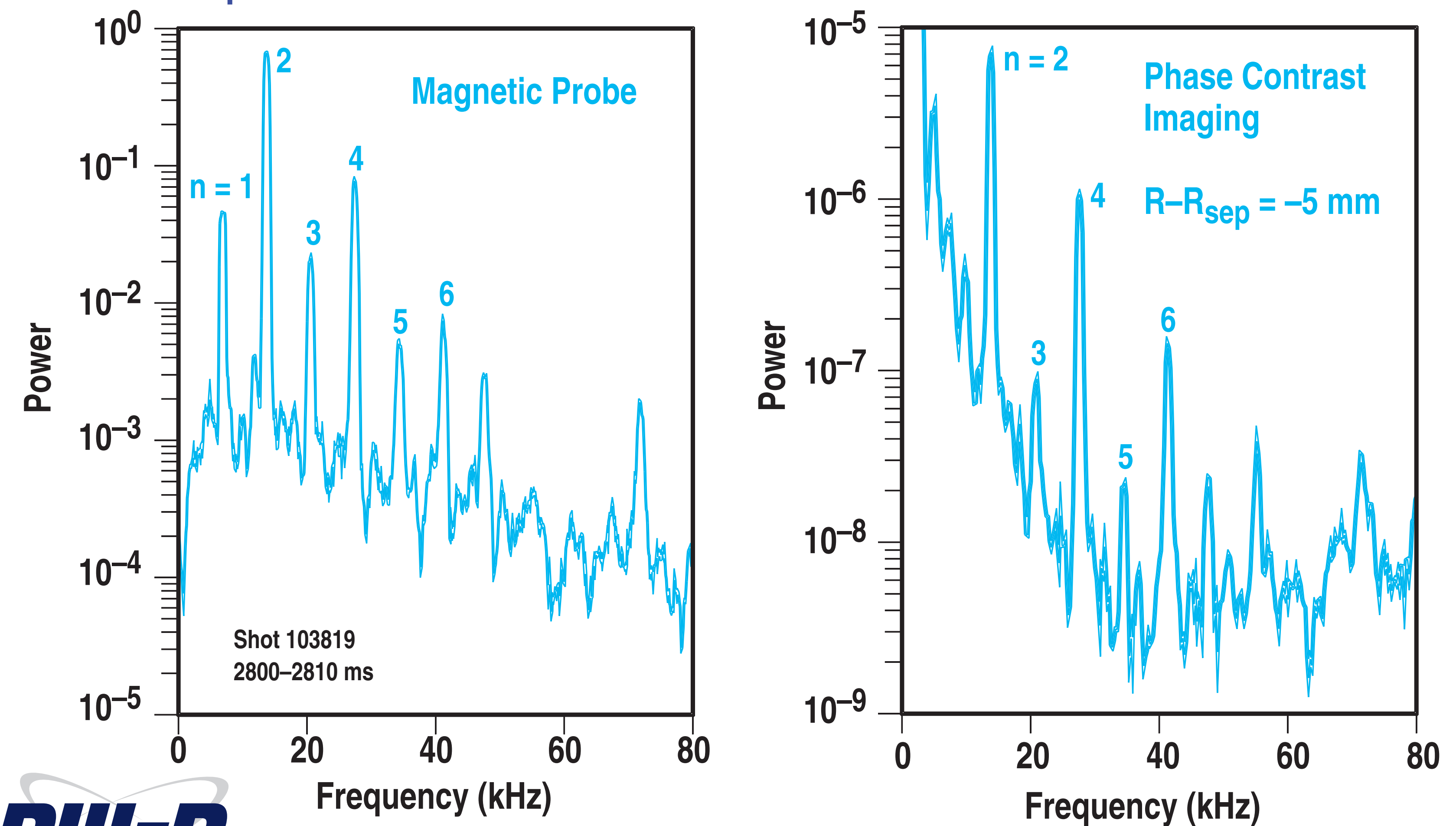
EDGE HARMONIC OSCILLATION SEEN ON $\dot{B}_\theta$ AND DENSITY DIAGNOSTICS

- Presence of $\dot{B}_\theta$ signal demonstrates significant electromagnetic component to oscillation



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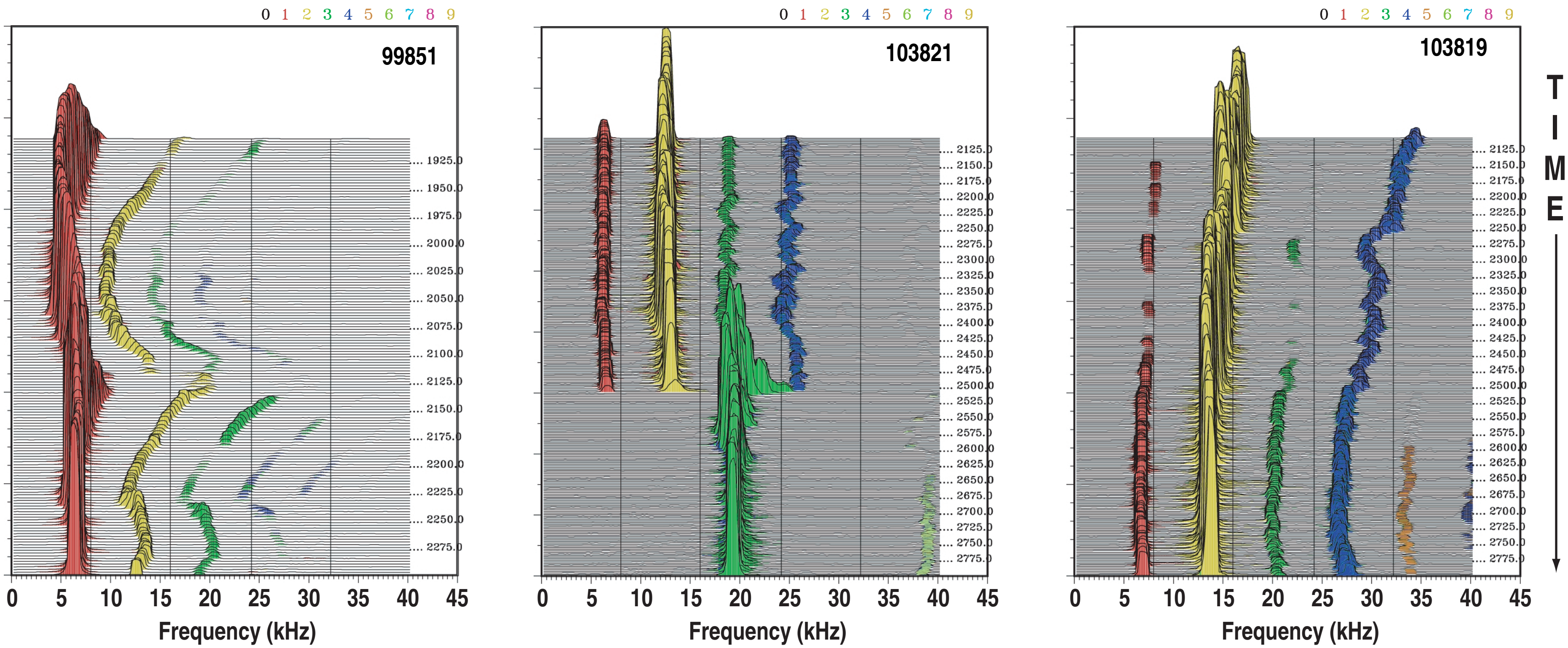
MIX OF TOROIDAL MODE NUMBERS VARIES IN EDGE HARMONIC OSCILLATION

- Edge profiles, density and impurity control not sensitive to mix of toroidal mode numbers

$\dot{B}_\theta$ Power Spectra



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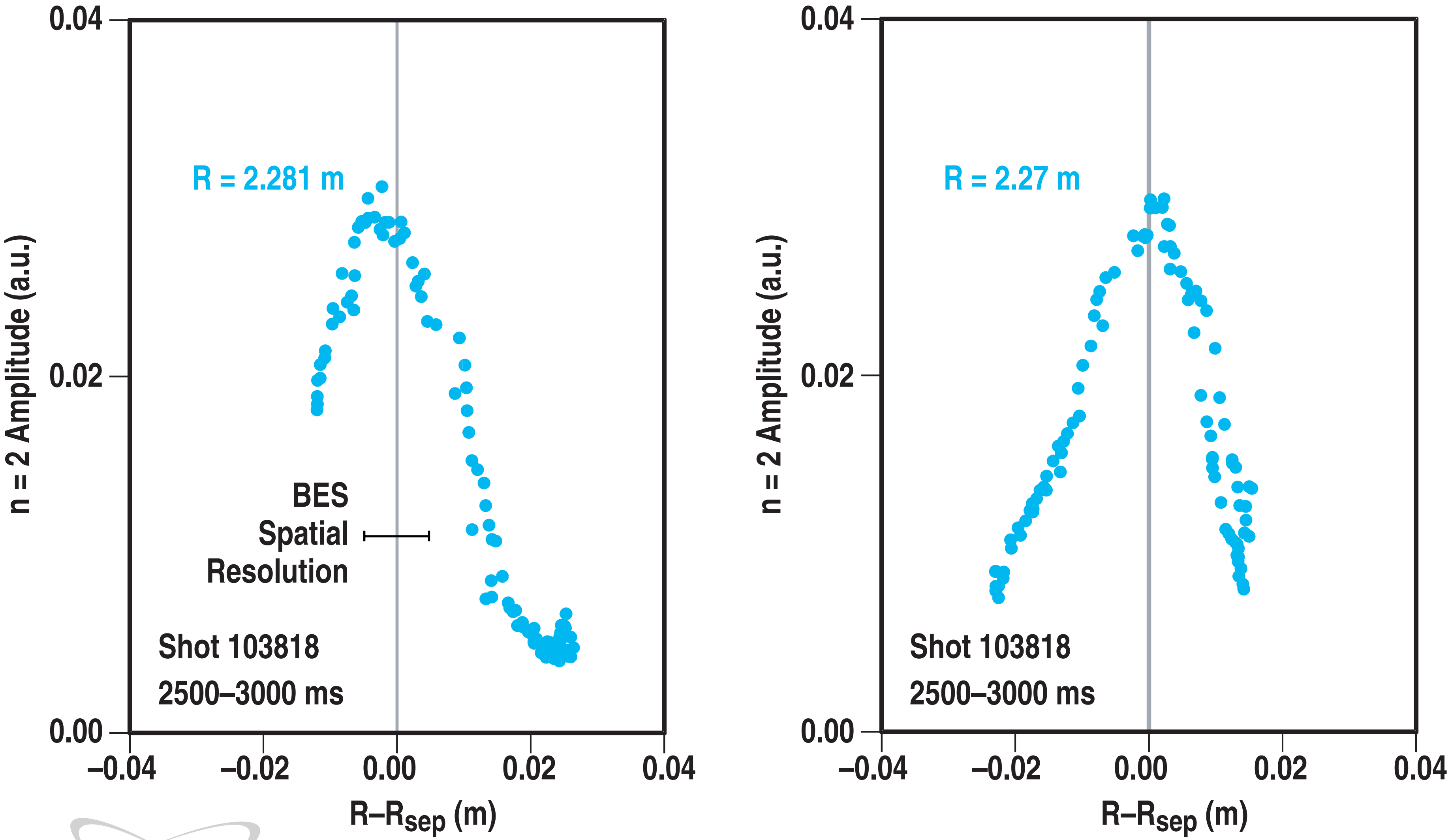
BES DENSITY FLUCTUATION AMPLITUDE DUE TO EDGE HARMONIC OSCILLATION PEAKS AT SEPARATRIX



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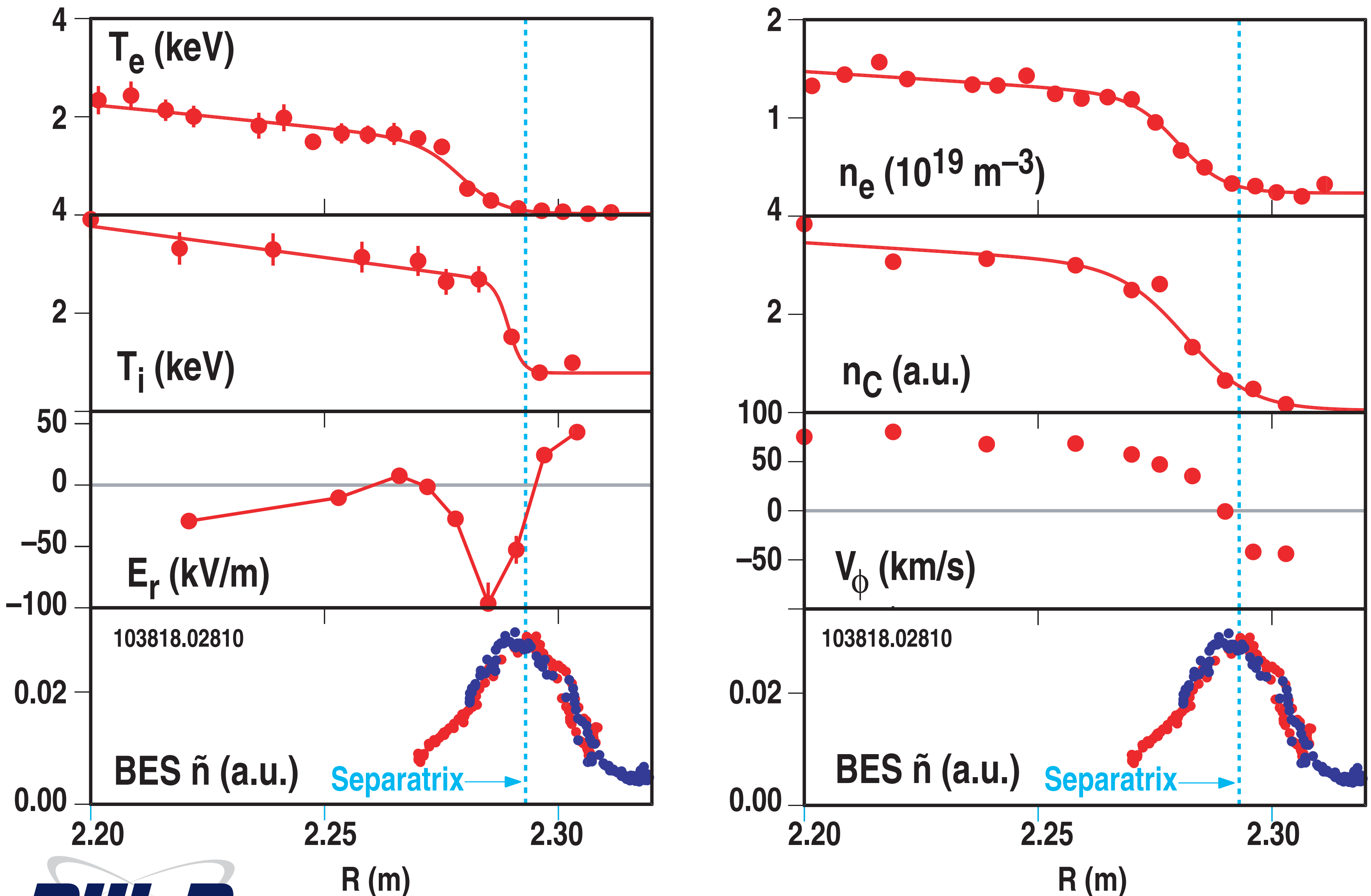
MAXIMUM IN ñ LOCATED CLOSEST TO MAXIMUM GRADIENTS IN E_r AND V_ϕ



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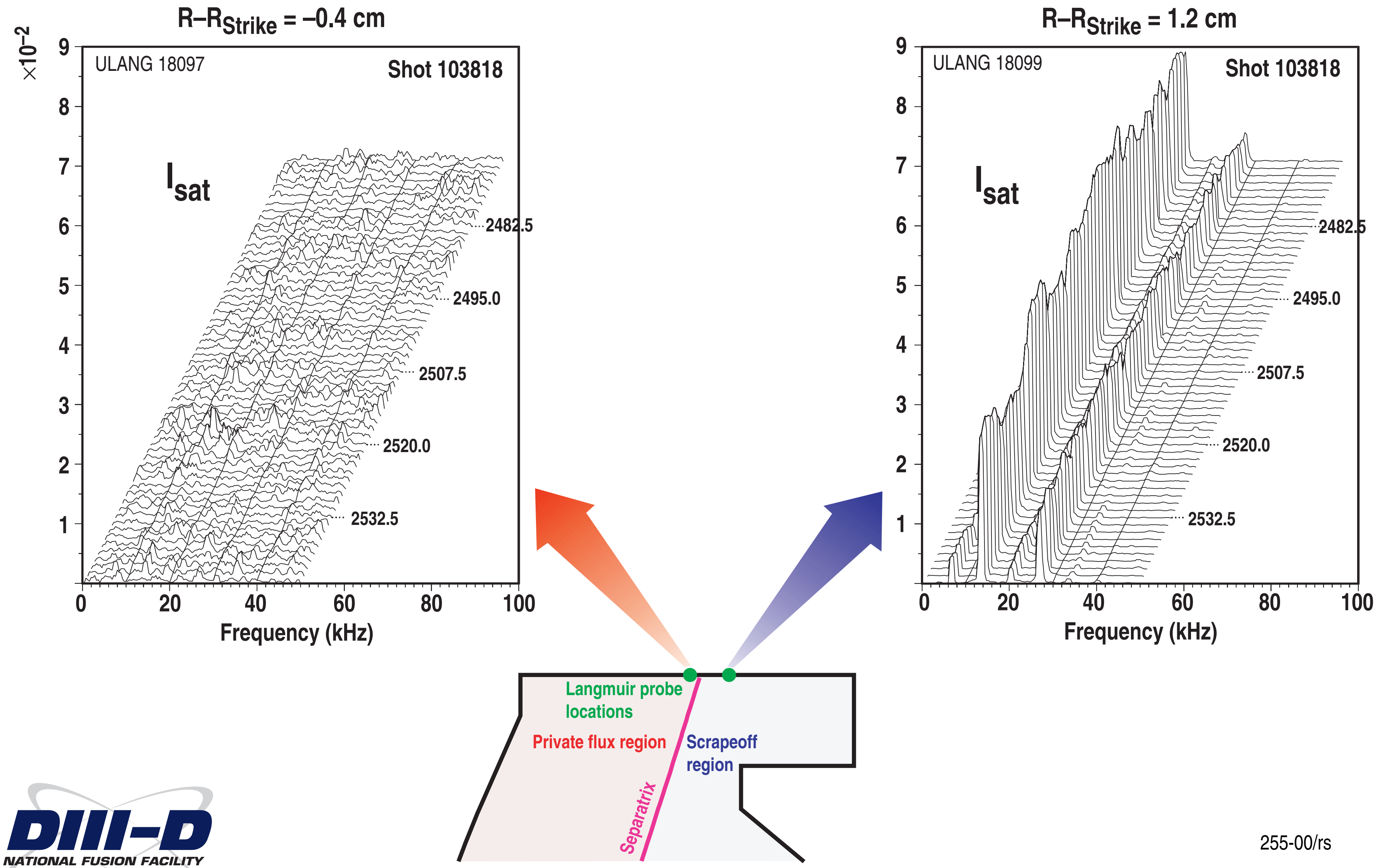
DIVERTOR LANGMUIR PROBES SHOW EDGE HARMONIC OSCILLATION MODULATES PARTICLE FLUX TO DIVERTOR PLATE FROM SCRAPE OFF LAYER



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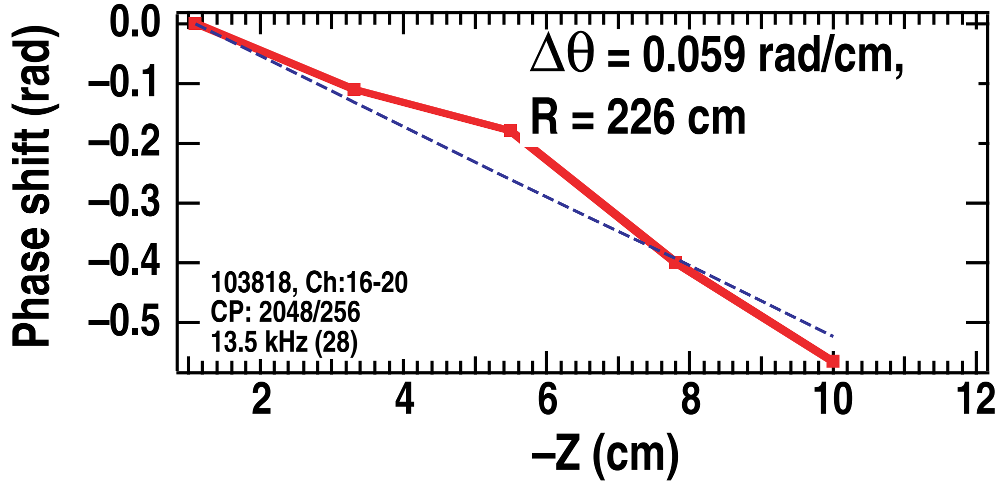
BES AND POLOIDAL MAGNETIC PROBE ARRAY GIVE POLOIDAL WAVELENGTH AROUND 1 m

- Phase shift from BES poloidal array gives λ ~ 1 m for n = 2 harmonic
  - Array only covers 10 cm
- Poloidal magnetic probe array has λ ≃ 1.3 m for n = 2 harmonic
  - Reasonable agreement with BES given uncertainty in measurements



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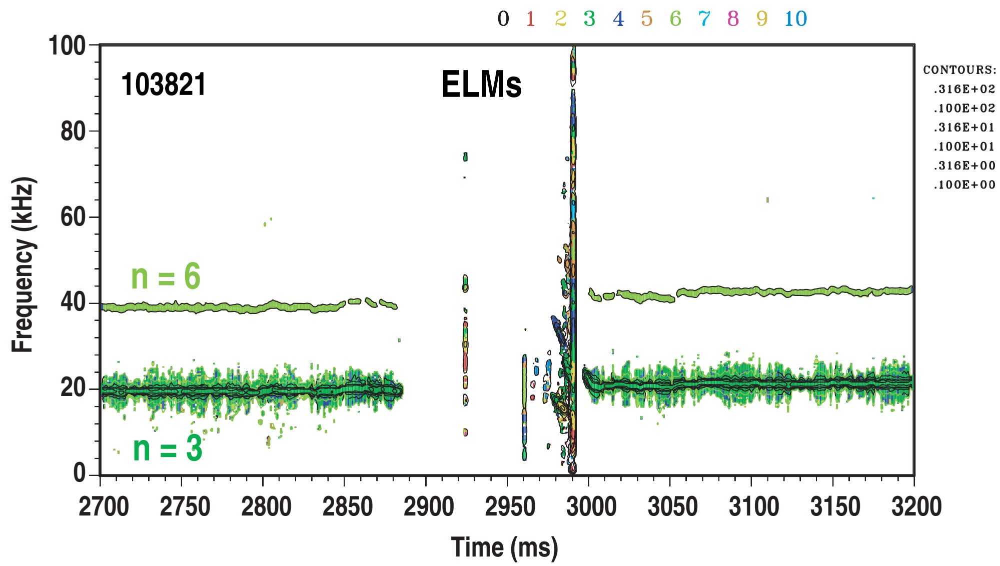
EDGE HARMONIC OSCILLATION DOES NOT APPEAR TO BE A SATURATED ELM PRECURSOR

- When conditions are marginal for the edge harmonic oscillation, we have many cases where the oscillation disappears and yet ELMs do not appear for 10’s of milliseconds
  - — This sequence is not what one expects for a precursor

$\dot{B}_\theta$ Power Spectrum



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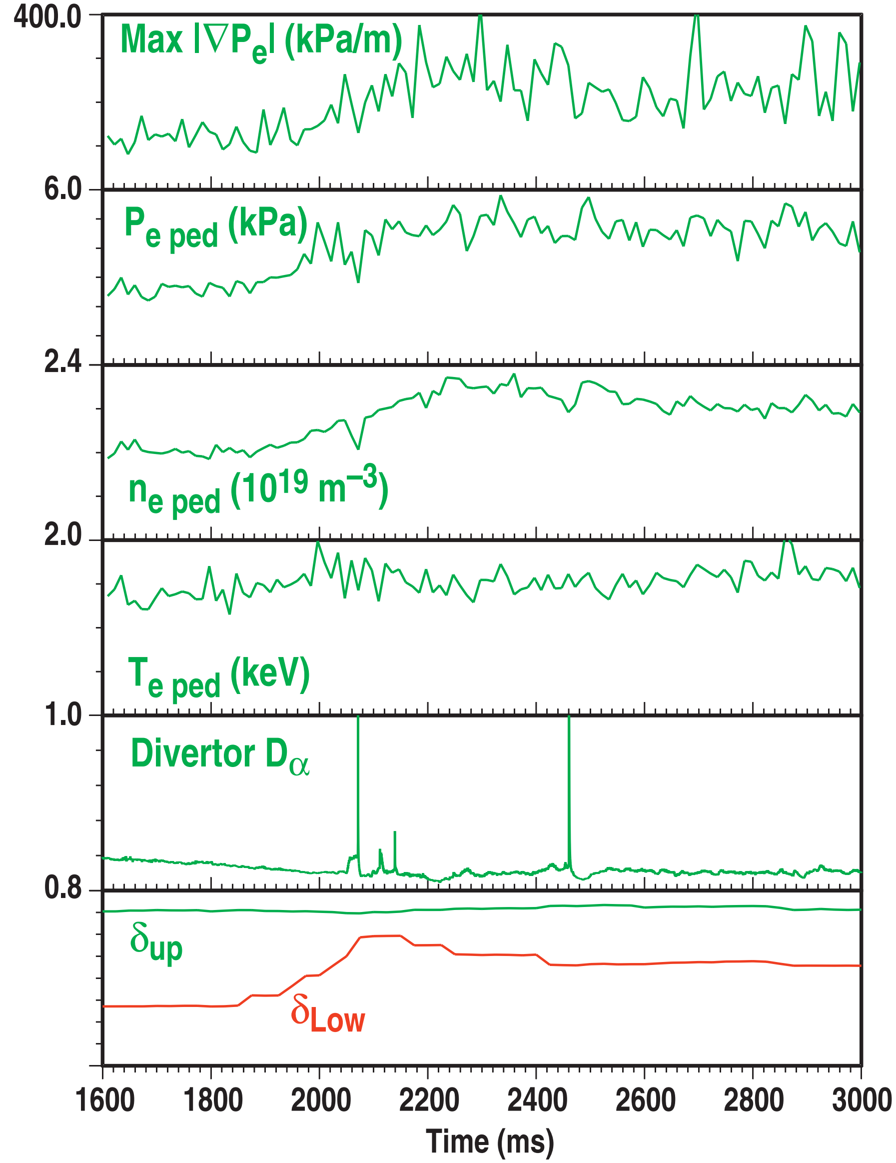
INCREASE OF EDGE GRADIENT AND PEDESTAL PARAMETERS WITH TRIANGULARITY SIMILAR TO THAT IN ELMING H–MODE

- Similarity suggests same basic stability mechanism governs edge gradient in ELMing and quiescent H–mode



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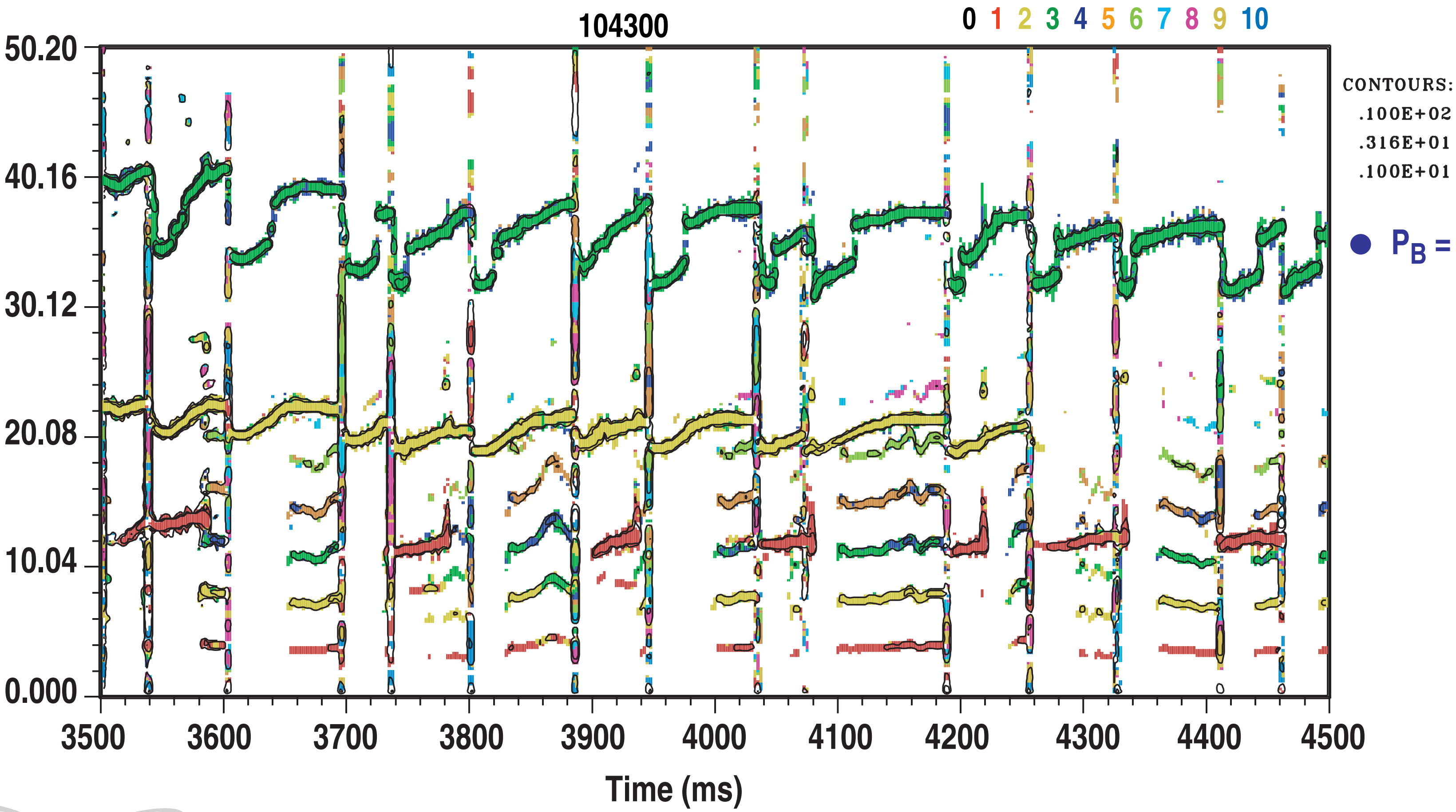
EDGE HARMONIC OSCILLATION HAS BEEN SEEN IN SOME LOW POWER, CO-INJECTED DISCHARGES

- ELMs always present in co-injected shots with edge harmonic oscillation



- P_B = 2.6 MW

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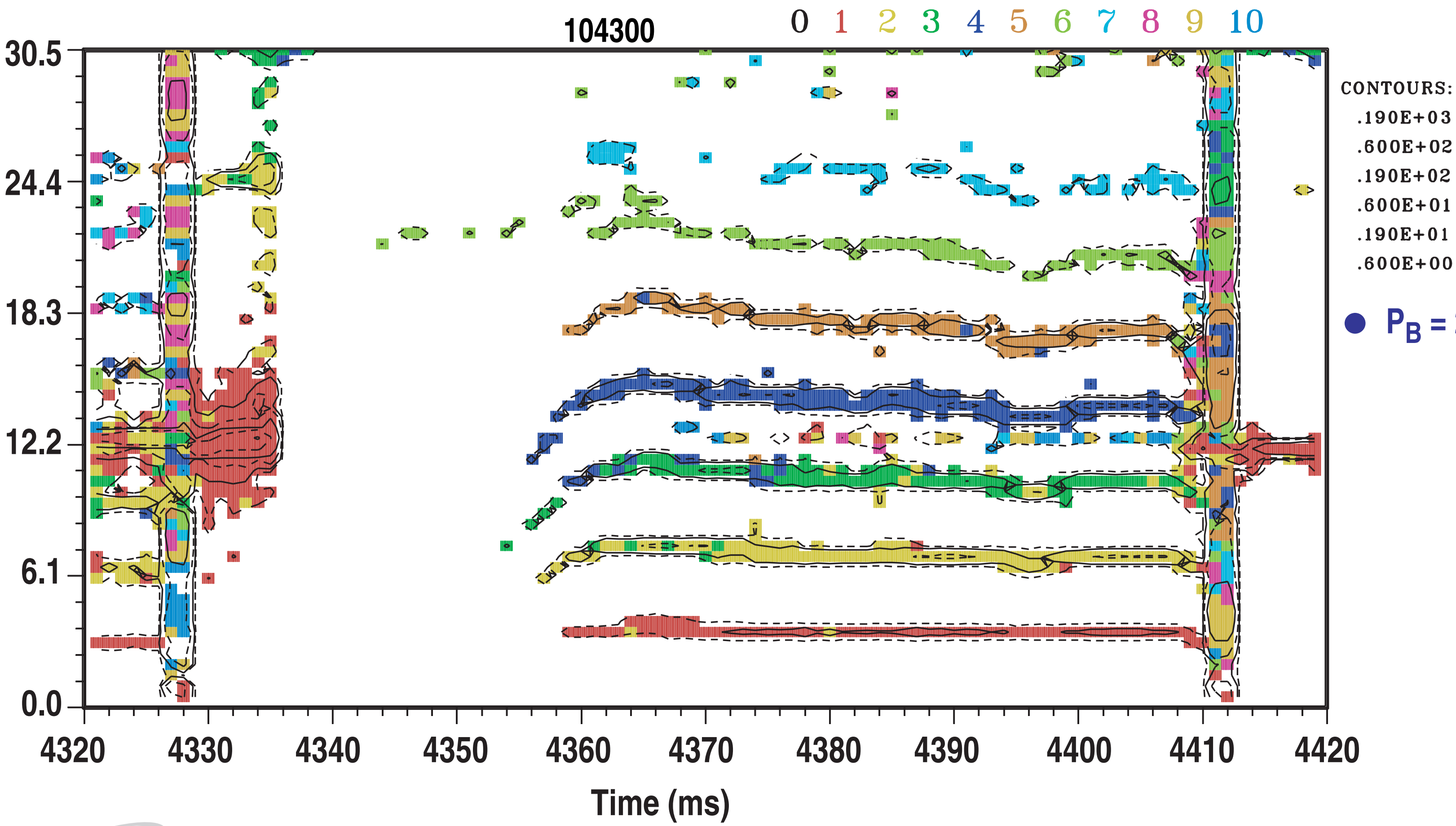

- P_B = 2.6 MW

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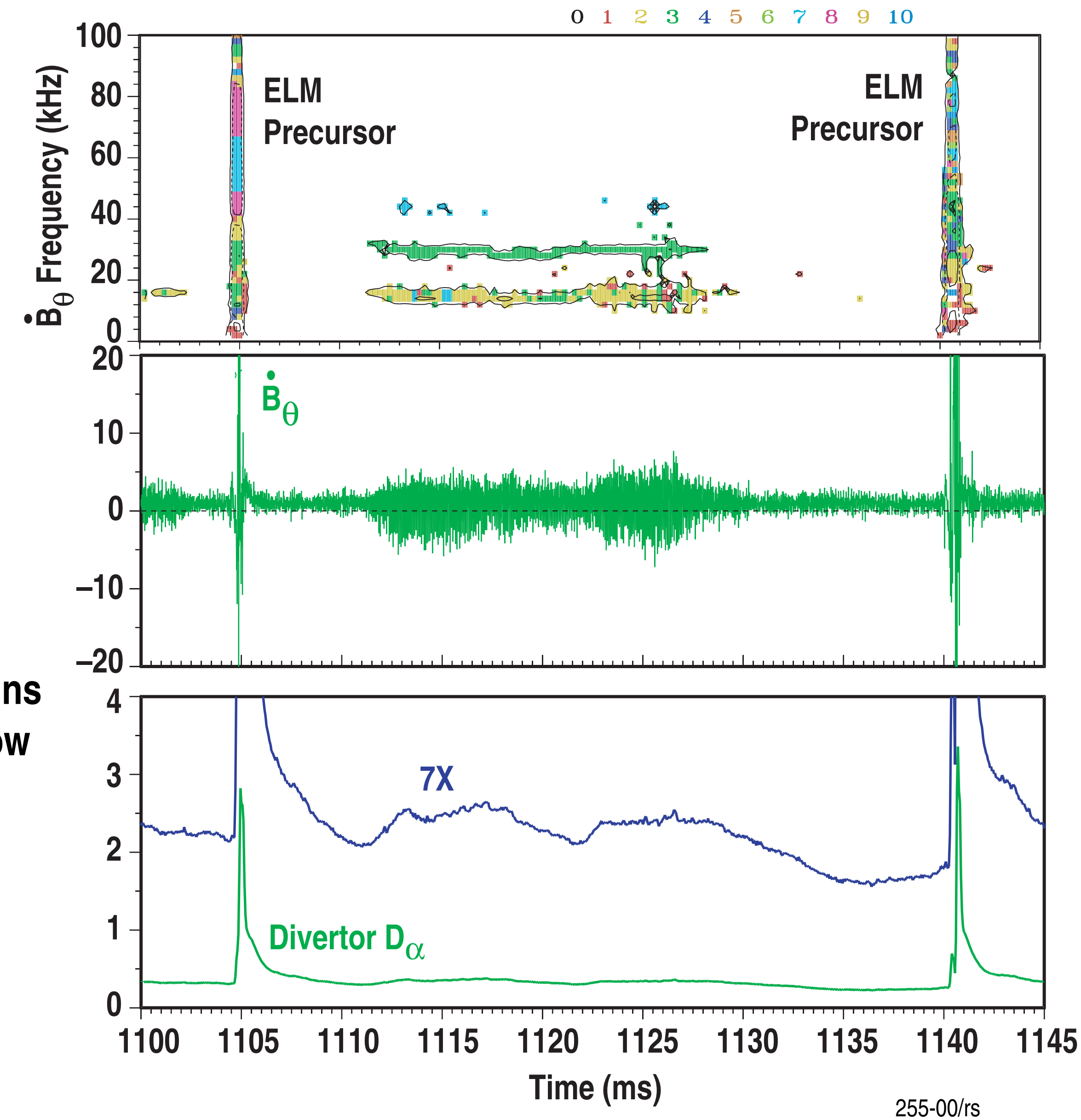
EDGE HARMONIC OSCILLATION IS NOT A SATURATED ELM PRECURSOR

- Early in shot before ELMs are completely gone, edge harmonic oscillation sometimes appears between ELMs
- Edge harmonic oscillation has different magnetic signature than ELM precursor
  - Edge harmonic oscillation can disappear before ELM happens
  - Frequency spectrum of ELM precursor is much broader, contains frequency components much below and much above those in edge harmonic oscillation
    - ★ Lowest frequency components are ones that appear first



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EDGE OSCILLATIONS ARE QUITE DIFFERENT IN DIII-D QUIESCENT H–MODE AND C–MOD EDA H–MODE

	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
Oscillations seen on	Magnetic probes at vessel wall	Magnetic probes in SOL
	BES, FIR, PCI, reflectometry, ECE, Langmuir probes in SOL and on divertor plate	PCI, reflectometry, Langmuir probes just inside the separatrix

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QUIESCENT DOUBLE BARRIER REGIME HAS REDUCED TRANSPORT CORE AND H–MODE EDGE BARRIER

- **Quiescent double barrier (QDB) operation combines core ITB with quiescent H–mode edge transport barrier**
  - Lack of giant ELMs means no degradation of reduced transport core
- **Counter injection allows operation for >5 seconds with q_{min} > 1.5**
  - No degradation of reduced transport core from sawteeth
- **β_N and H_{89} both increase with increasing input power**
  - H_{89} increase consistent with expectations based on E×B shear suppression of turbulence
  - To date β_N H_{89} = 7 achieved for >5 τ_E
- **Core and edge barriers do not merge**
  - E×B shear is small around ρ = 0.8 owing to negative core E_r from counter injection and negative H–mode edge E_r well

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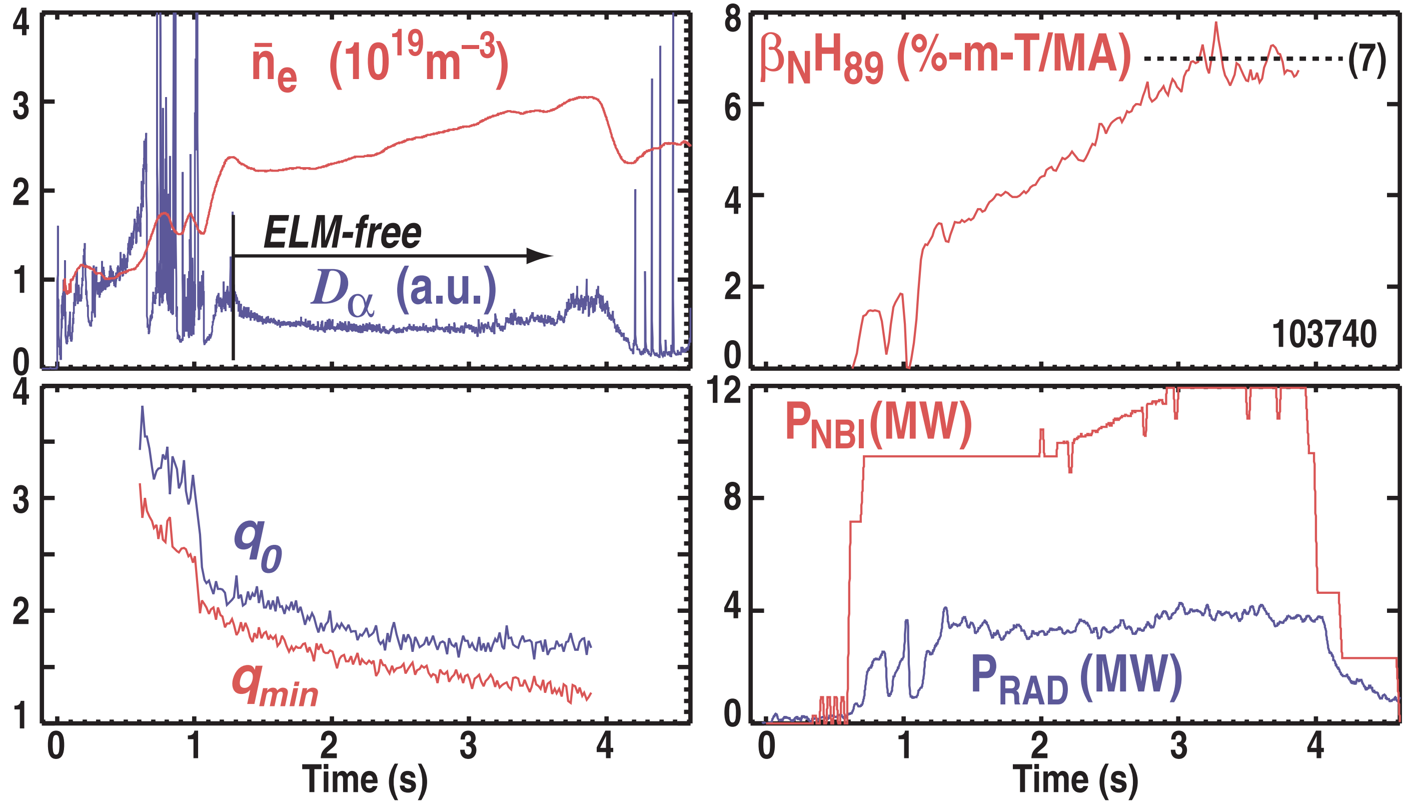
SUSTAINED HIGH PERFORMANCE HAS BEEN OBTAINED IN THE QUIESCENT DOUBLE BARRIER REGIME



- QDB regime is a long pulse, high performance candidate:
  - $\beta_T = 3.3\%$, $\tau_E = 150$ ms, $f_{BS} = 0.45$
  - Duration of high performance phase (>5 τ_E) limited by duration of NBI injection
  - Not yet optimized, potential for higher performance

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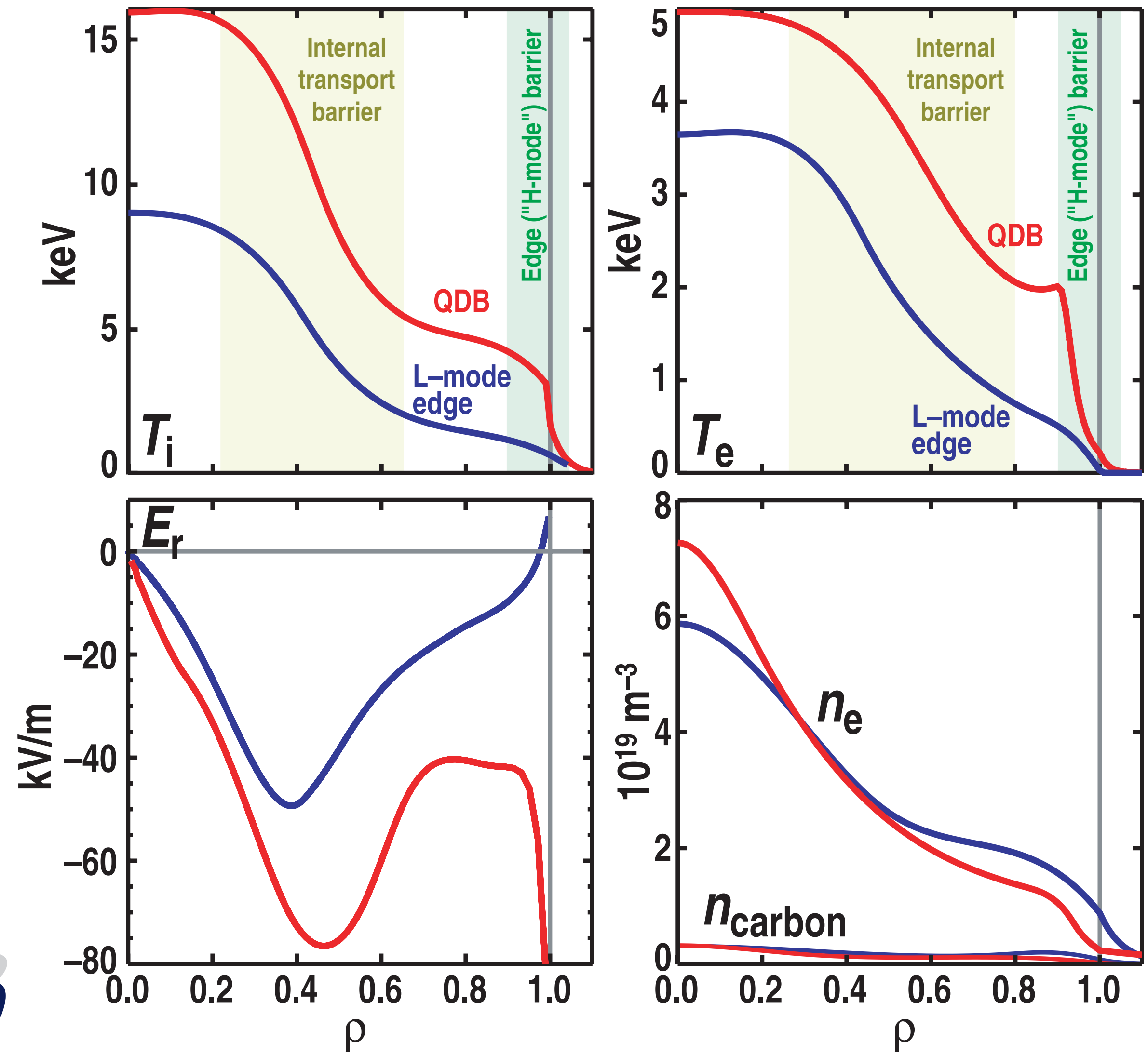
QUIESCENT H–MODE EDGE PEDESTAL ELEVATES CORE TEMPERATURE PROFILE WHILE MAINTAINING INTERNAL TRANSPORT BARRIER

L–mode edge
ITB (99849 1.12s)

QDB (103740 3.3s)



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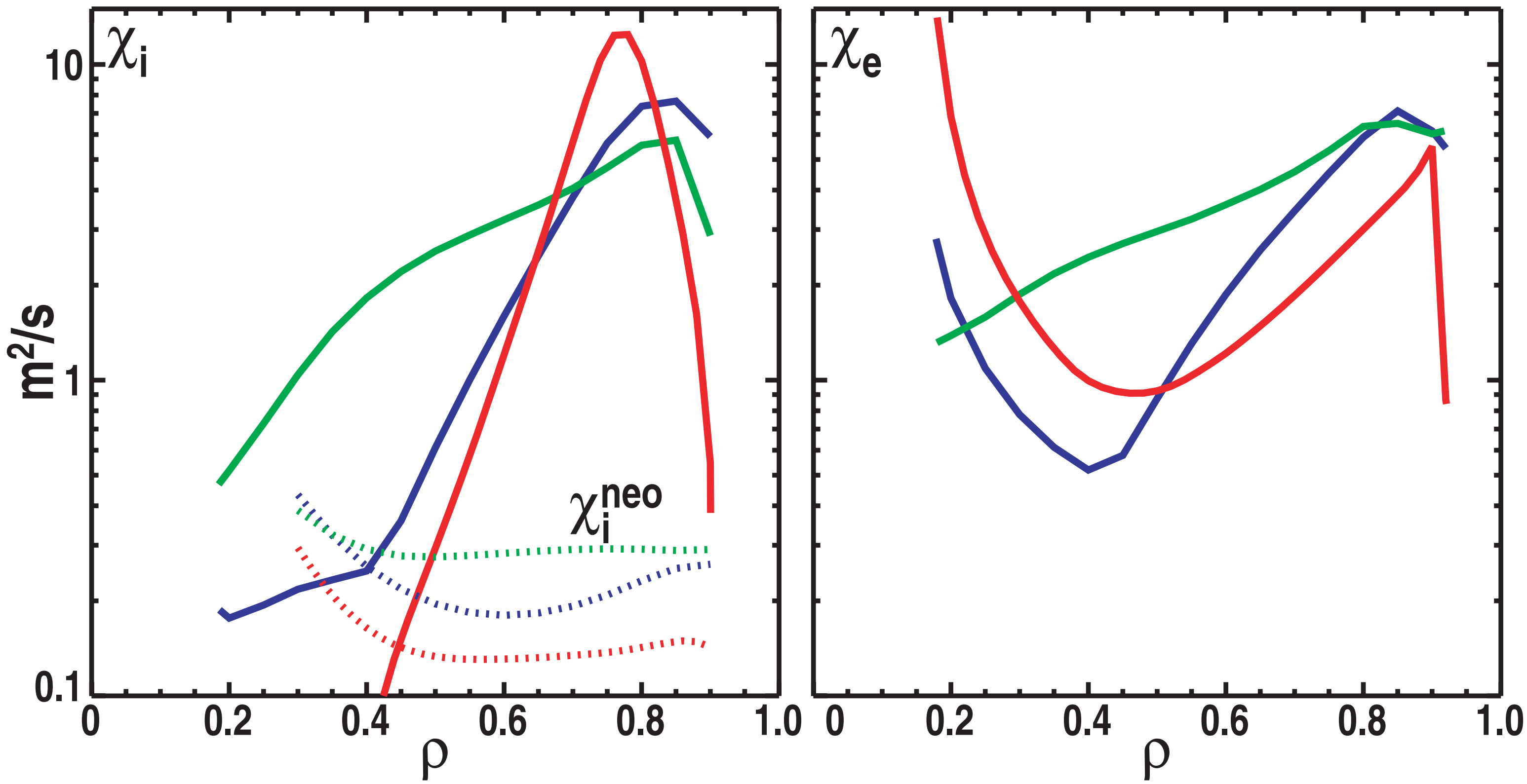
QDB ADDS EDGE TRANSPORT BARRIER TO REDUCED TRANSPORT CORE



L–mode edge ITB 99849 1.12 s
QDB 103740 3.3 s
L–mode 99852 0.80 s

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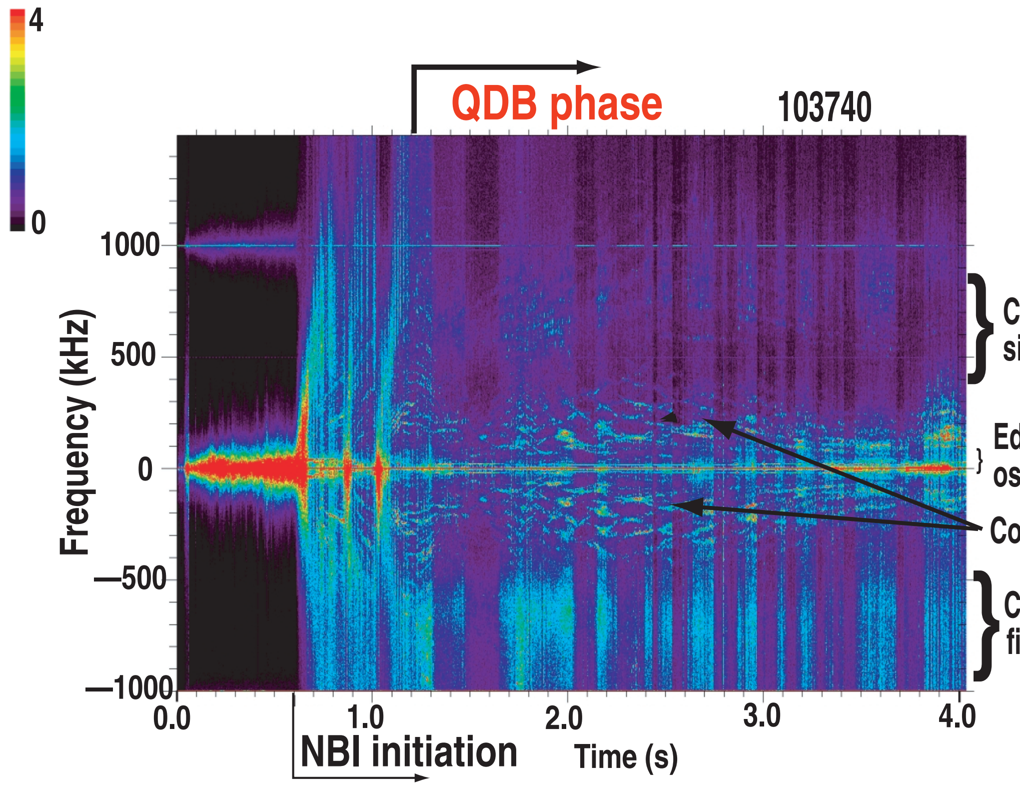
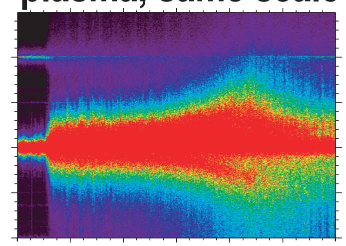
TURBULENCE IS REDUCED ACROSS MOST OF PLASMA DIAMETER IN QDB REGIME

- With reduced broadband turbulence, core Alfvén modes are clearly visible in FIR scattering data, as is low frequency edge harmonic oscillation associated with QH-mode operation





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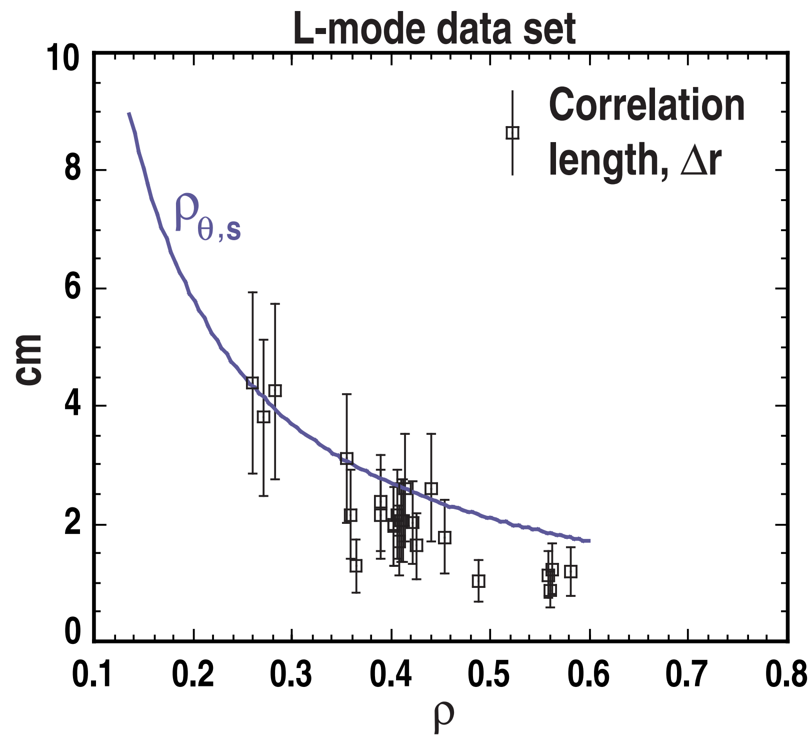
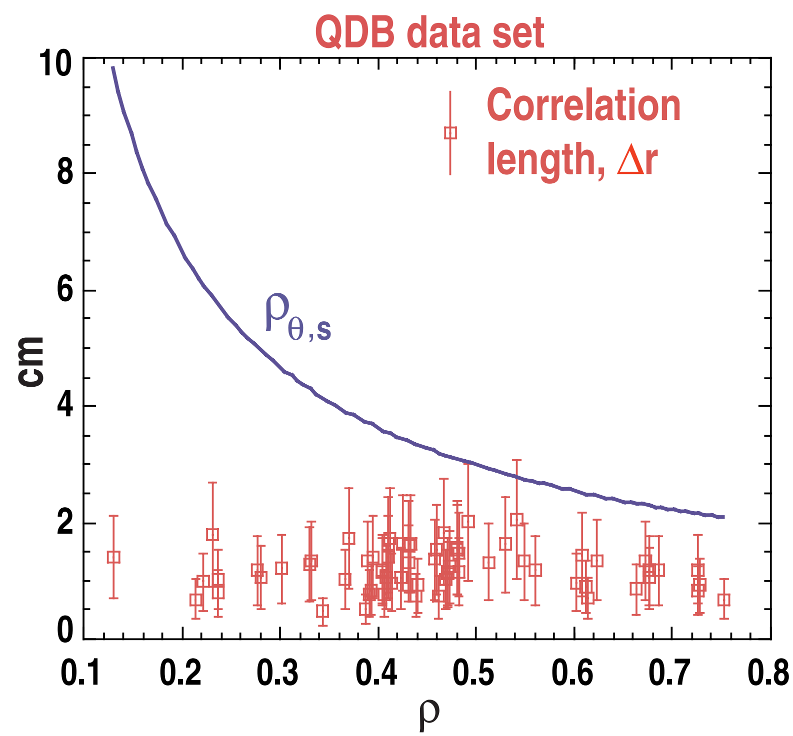
RADIAL STEP SIZE FOR TURBULENT TRANSPORT IS REDUCED IN QDB REGIME

- In L–mode, radial correlation lengths are observed to scale approximately with the poloidal ion gyroradius $\rho_{\theta,s}$ (or 5-8 ρ_s)

- In QDB plasmas, radial correlation lengths are factor 2–8 smaller than the L–mode scaling





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SUMMARY

- **Quiescent double barrier H–mode plasmas combine**
  - ELM-free, controlled density H–mode edge
  - Reduced core transport region (internal transport barrier)
- **Quiescent H–mode edge has H–mode edge transport barrier plus**
  - No bursting edge behavior associated with ELMs
  - Controlled density and impurity levels owing to edge harmonic oscillation
  - Potential for steady-state operation
    - ★ 3.5 seconds or 25 τ_E achieved to date
    - ★ Duration limited only by machine hardware constraints
- **Combined edge and core transport reduction yields sustained high performance**
  - β_N H_{89} = 7 for >5 τ_E
- **If we can find out how to produce these shots under reactor-relevant conditions, they would be a fusion reactor designer's dream**
  - High performance owing to double barrier
  - No pulsed divertor heat load from giant ELMs

MORE INFORMATION ON QUIESCENT DOUBLE BARRIER PLASMAS

- E.J. Doyle, et al., "Progress Towards Control of Internal Transport Barriers in DIII–D" — MO1.007 Wednesday morning

- C.M. Greenfield, et al., "Control of Internal Transport Barriers in DIII–D" — GP1.112 Tuesday morning

- W.P. West, et al., "Impurity Behavior in Steady-State, ELM-Free H–Mode Discharges on DIII–D" — GP1.121 Tuesday morning