QUIESCENT DOUBLE BARRIER H–MODE PLASMAS IN THE DIII–D TOKAMAK

by

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INTRODUCTION

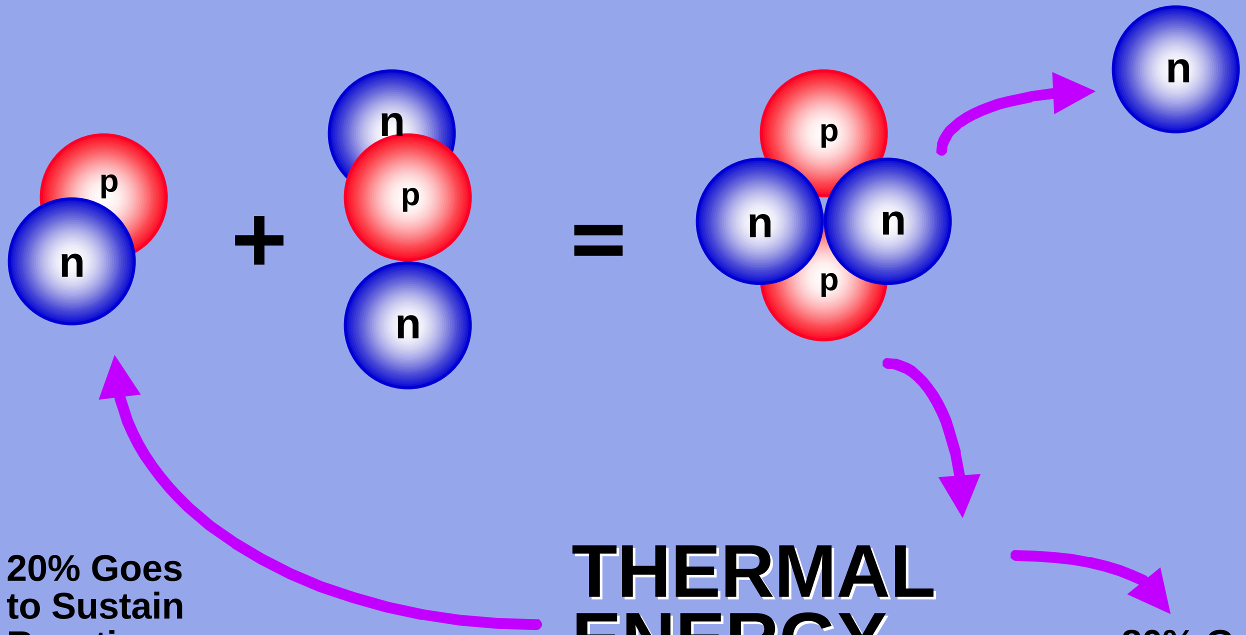
- History of magnetic confinement fusion can be thought of as the continuing development of ever more stable plasma configurations
- The early years included theoretical and experimental work that led to magnetic configurations that were grossly MHD stable
- Energy loss, however, has long been known to be significantly larger than predicted by theory based on collisional transport. This is though to be due to the effects of small scale (micro) turbulence (scale length ~ ion gyroradius)
- Recently, techniques for controlling and suppressing microturbulence using sheared E×B flows have been developed
  - First seen in plasma edge (H–mode)
  - Developed about a decade later in plasma core (internal barriers)
- Quiescent H–mode and quiescent double barrier (QDB) plasmas represent a significant advance in reduced transport plasmas
  - Bursting edge MHD instability (edge localized mode) is absent in quiescent H–mode
  - Lack of edge localized modes allows core and edge barrier to co-exist and to persist for long periods of time (to date, 3.5 s or 25 τ_E)
  - QDB operation is compatible with engineering requirements for a fusion reactor

ORGANIZATION OF TALK

- Introduction to toroidal magnetic fusion plasmas
- Short summary of advanced tokamak basics
- Quiescent H–mode edge plasmas
- Quiescent double barrier plasmas
- Conclusions

Fusion Process

Deuterium + Tritium = Energy + n

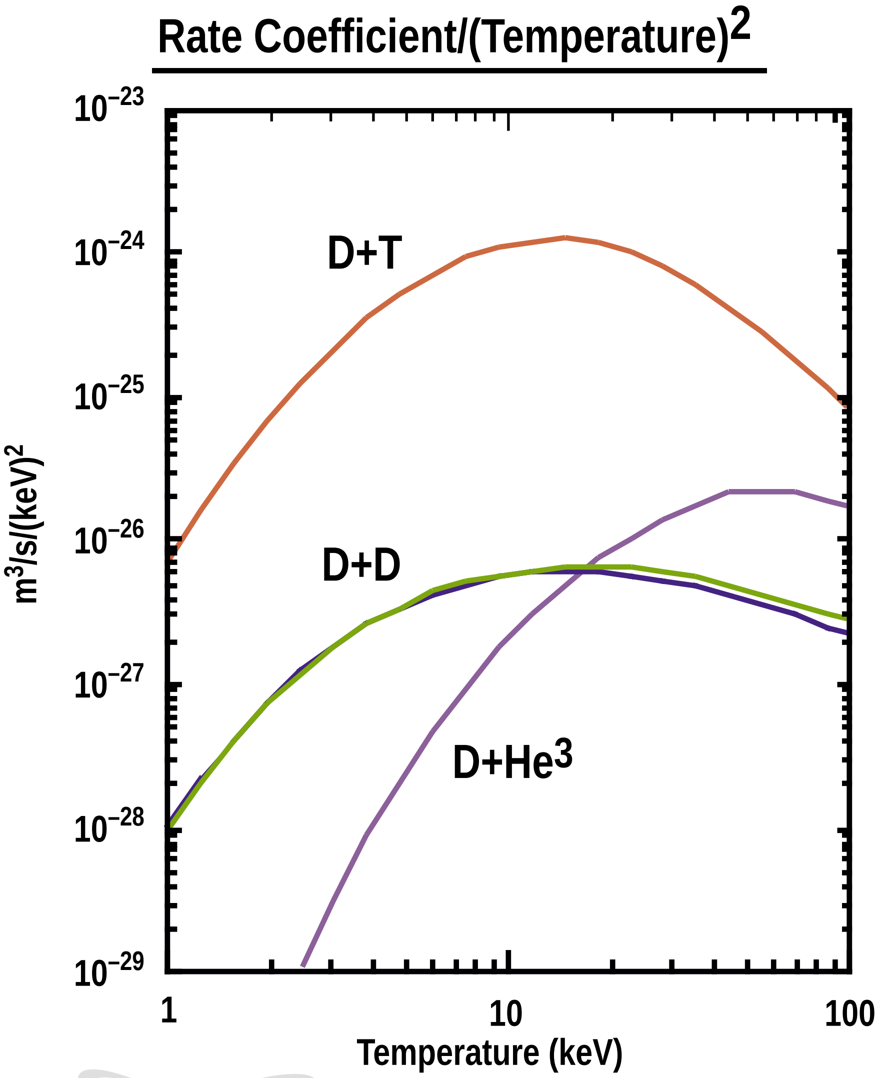


20% Goes to Sustain Reaction

THERMAL ENERGY

80% Goes to Generate Electricity

FOR FIXED PRESSURE, D+T and D+D THERMONUCLEAR FUSION RATE ARE OPTIMUM AT TEMPERATURES OF 10–20 keV



- **Fusion power density**

$$P_f/V = n_x\, n_y \langle \sigma_{xy} v \rangle E_{xy} \;\; \mathrm{W/m^3}$$

$$\propto (\text{pressure})^2 \, \frac{\langle \sigma v \rangle}{T^2}$$

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FUNDAMENTALS OF TOROIDAL MAGNETIC FUSION PLASMAS

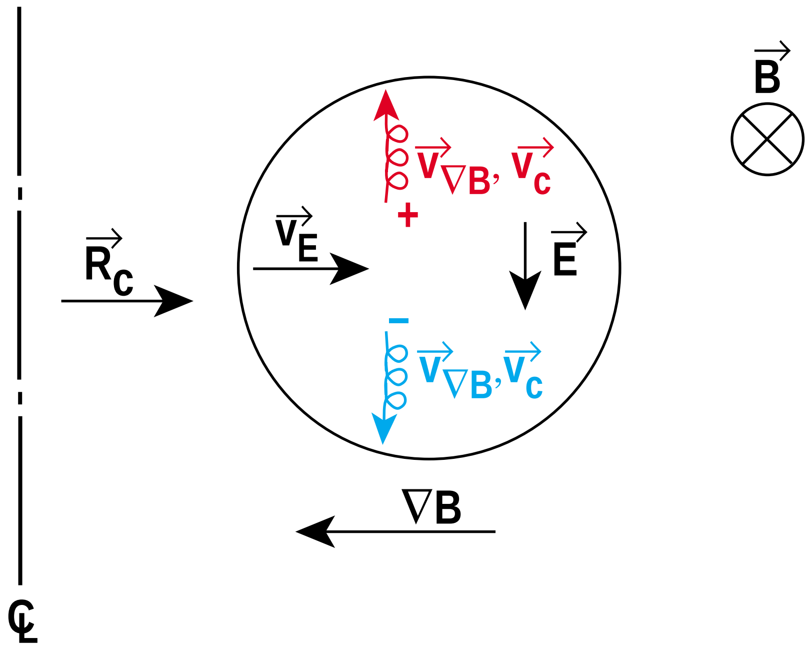
- Since nuclear binding energies enormously exceed atomic binding energies, any collection of particles where thermonuclear fusion happens will be a plasma
  - To overcome Coulomb repulsion between nuclei, energies of 10s to 100s of keV are required
  - In thermonuclear fusion, these energies correspond to the temperature of the constituents

- Some means of keeping the heat from leaking out of the plasma is needed in order to produce a self-sustaining fusion reaction
  - Using magnetic fields provides one way to do this which is potentially steady state

- A toroidal magnetic field topology is advantageous, since closed field line configurations can be created where the field lines don't intersect material surfaces

CONFINEMENT NOT POSSIBLE WITH A PURELY TOROIDAL FIELD

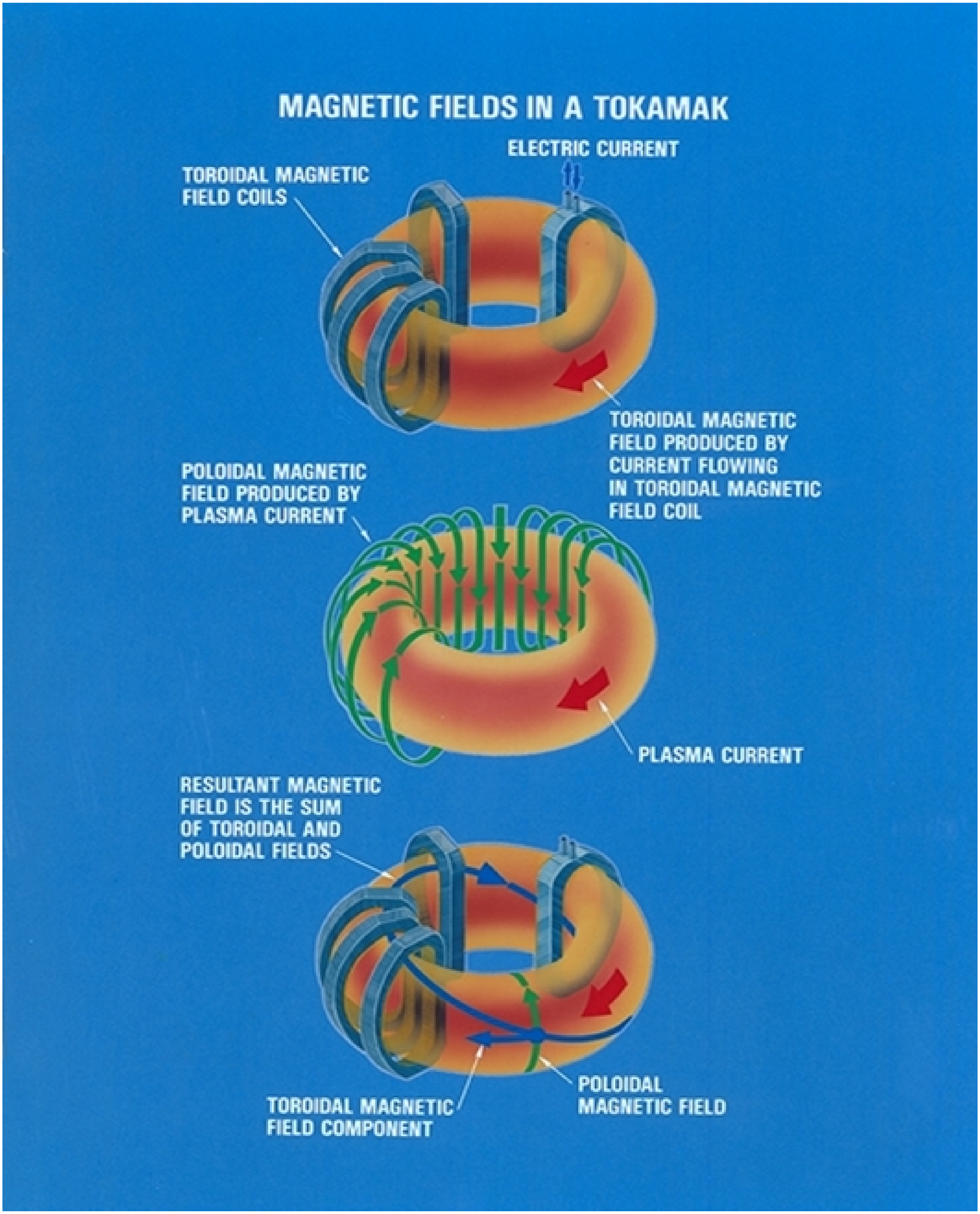
- Charge separation leads to outward $\vec{E} \times \vec{B}$ drift



$$\vec{v}_{\nabla B} = \frac{\frac{1}{2} m v_\perp^2}{eB^3} \vec{B} \times \nabla B$$

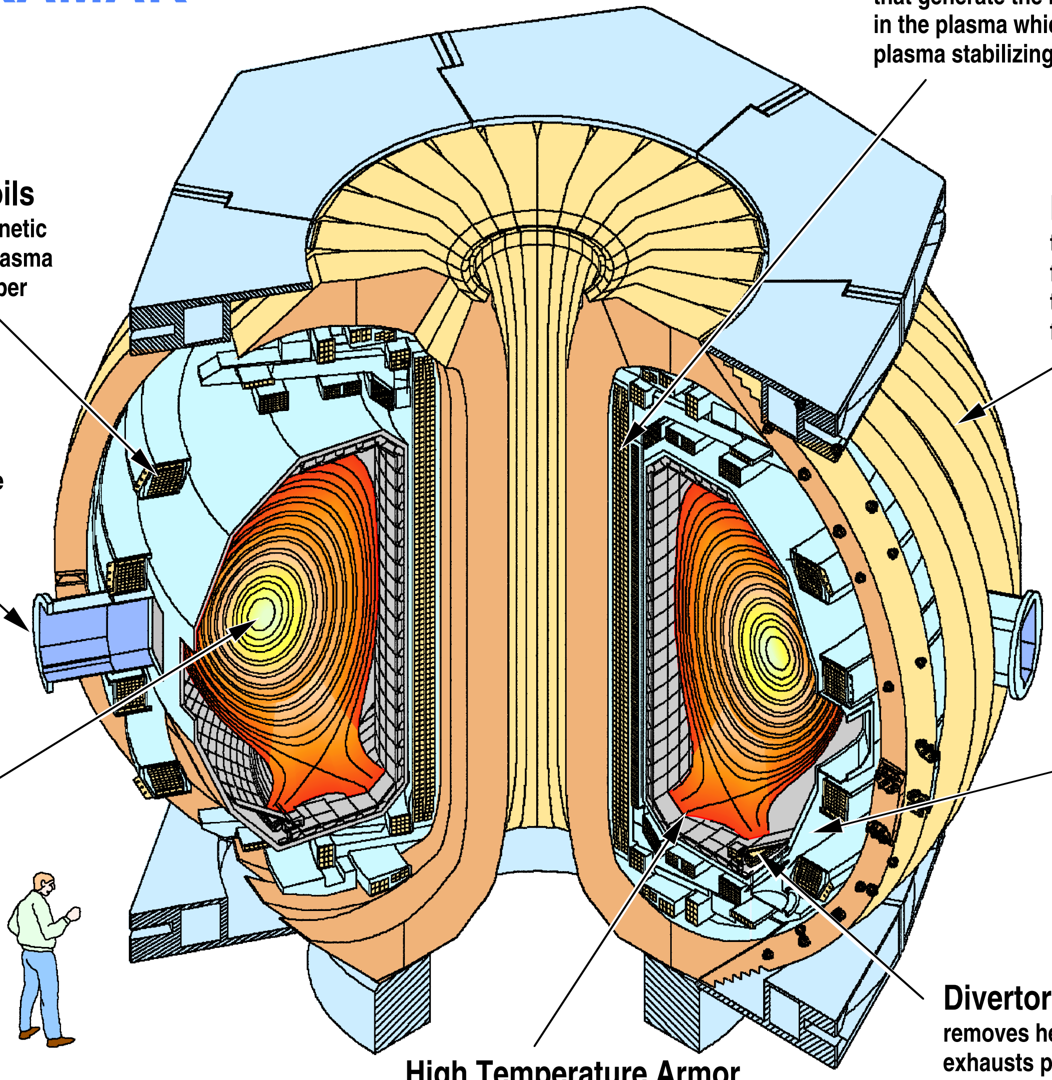
$$\vec{v}_C = -\frac{m v_\parallel^2}{eB^2} \frac{\vec{B} \times \vec{R}_c}{R_c^2}$$

$$\vec{v}_{\vec{E} \times \vec{B}} = \frac{\vec{E} \times \vec{B}}{B^2}$$



$$q = \frac{\#\ \text{Toroidal Circuits}}{\#\ \text{Poloidal Circuits}}$$

DIII–D TOKAMAK



High Current Coils
that generate the high currents
in the plasma which produce a
plasma stabilizing magnetic field

High Current Coils
that produce the magnetic
fields that keep the plasma
centered in the chamber

High Current Coils
that produce the main magnetic
field (toroidal field) that suspends
the high temperature plasma away
from the vacuum vessel

Ports
where diagnostics are
mounted to measure
plasma properties

Vacuum Vessel
to prevent air from
contaminating the
fusion fuel (plasma)

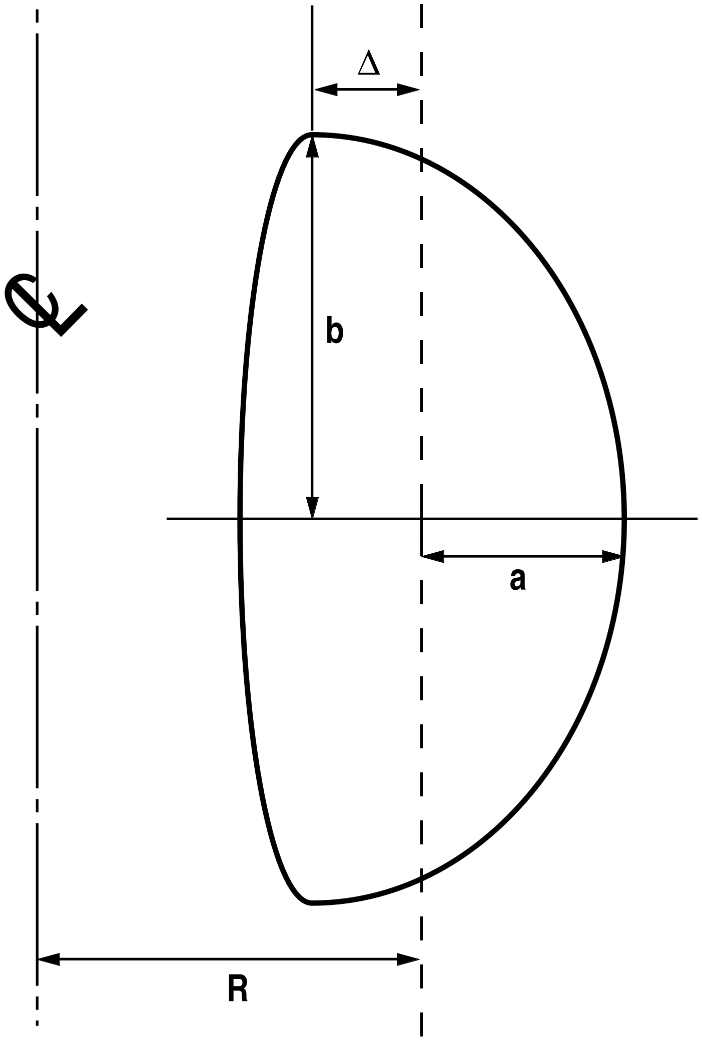
Plasma
high temperature ions
which fuse releasing
energy

Divertor
removes heat and
exhausts particles from
plasma

High Temperature Armor
to protect the vacuum vessel
from the hot plasma

GENERAL ATOMICS

FUNDAMENTAL DEFINITIONS OF PLASMA SHAPE



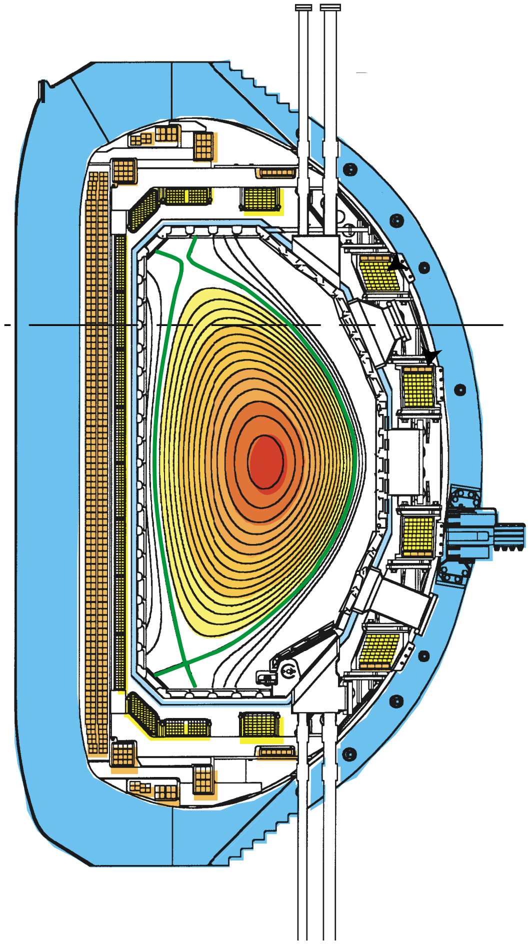
Aspect Ratio
$A = R / a$

Elongation
$\kappa = b / a$

Triangularity
$\delta = \Delta / a$

DIII–D PARAMETERS

	Max	Usual Operation
Magnetic field (T)	2.2	1.5–2.2
Current (MA)	3	0.5–2
Major radius (m)	1.7	1.7
Minor radius (m)	0.7	0.5–0.7
Elongation	2.2	1.5–1.8
Pulse length (s)	10	2–5
Neutral beam energy (kV)	90	50–80
Beam power (8 beams) (MW)	20	1–12
110 GHz rf power (MW)	4.5	0.5–2



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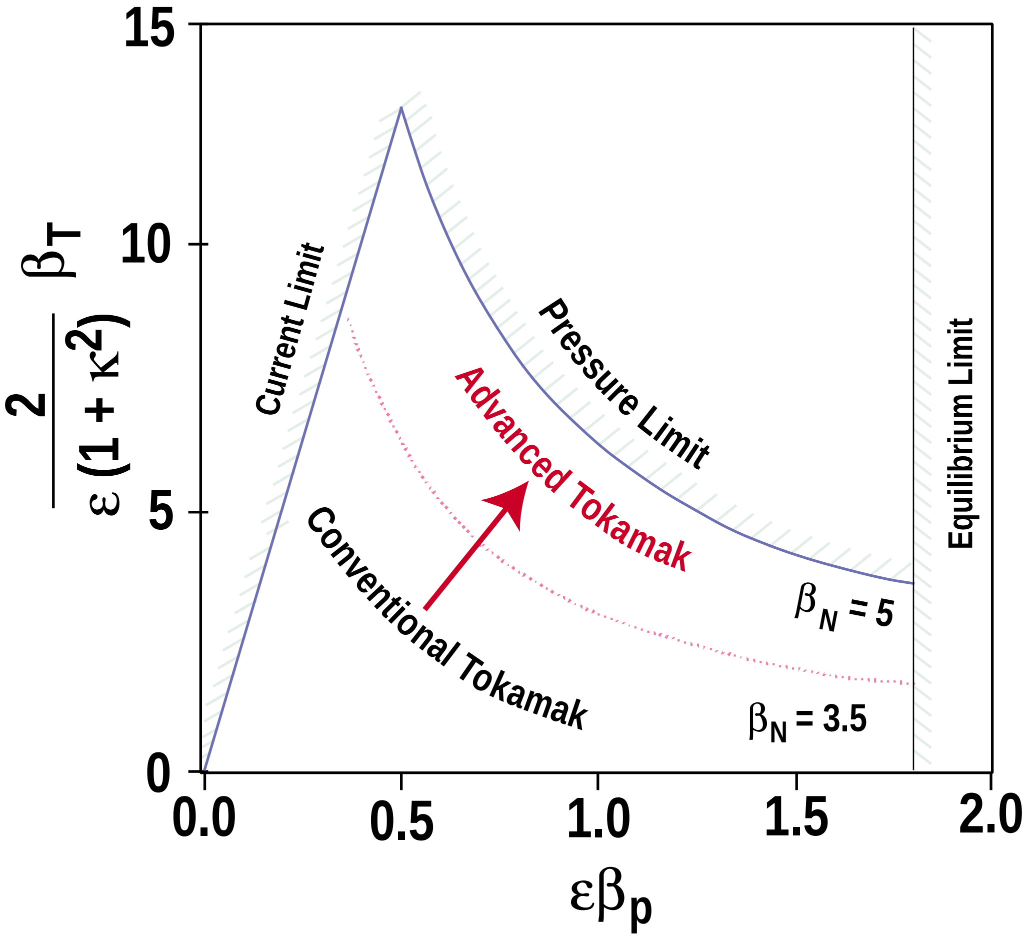
ADVANCED TOKAMAK BASICS

- In the range of densities and temperatures for planned magnetic fusion devices, increasing fusion power density requires increasing plasma pressure
  - Power density $\propto \langle p^2 \rangle \propto \beta_T^2 \; B_T^4$
  - $\beta_T = \langle p \rangle / (B_T^2 / 2 \mu_0)$
- To achieve the plasma pressure needed for fusion, energy confinement time τ_E must be big enough that the total power P_T (fusion plus auxiliary) flowing through the plasma can produce that pressure
  - $\langle p \rangle = (2/3) \, \tau_E \, P_T$
  - τ_E depends on many plasma parameters; generally increases with size
  - Convenient normalized measure of energy confinement is $H_{89} = \tau_E / \tau_{ITER89P}$
- Tokamak plasmas require a toroidal current I to maintain the configuration; a portion of this is self-generated (bootstrap) provided by the plasma itself. Since current drive costs power, we want to maximize bootstrap current for steady-state operation
  - $f_{BS} = C_{BS} \, \varepsilon^{1/2} \, \beta_p$
  - $\beta_p = \langle p \rangle / (\mu_0 \, I^2 / 2 \, \Gamma^2)$
  - Γ is plasma poloidal circumference, $\varepsilon = a/R$ is inverse aspect ratio

A COMPACT STEADY-STATE TOKAMAK REQUIRES OPERATION AT HIGH β_N



$$\beta_T \, \beta_p = 25 \left(\frac{1+\kappa^2}{2}\right)\left(\frac{\beta_N}{100}\right)^2$$

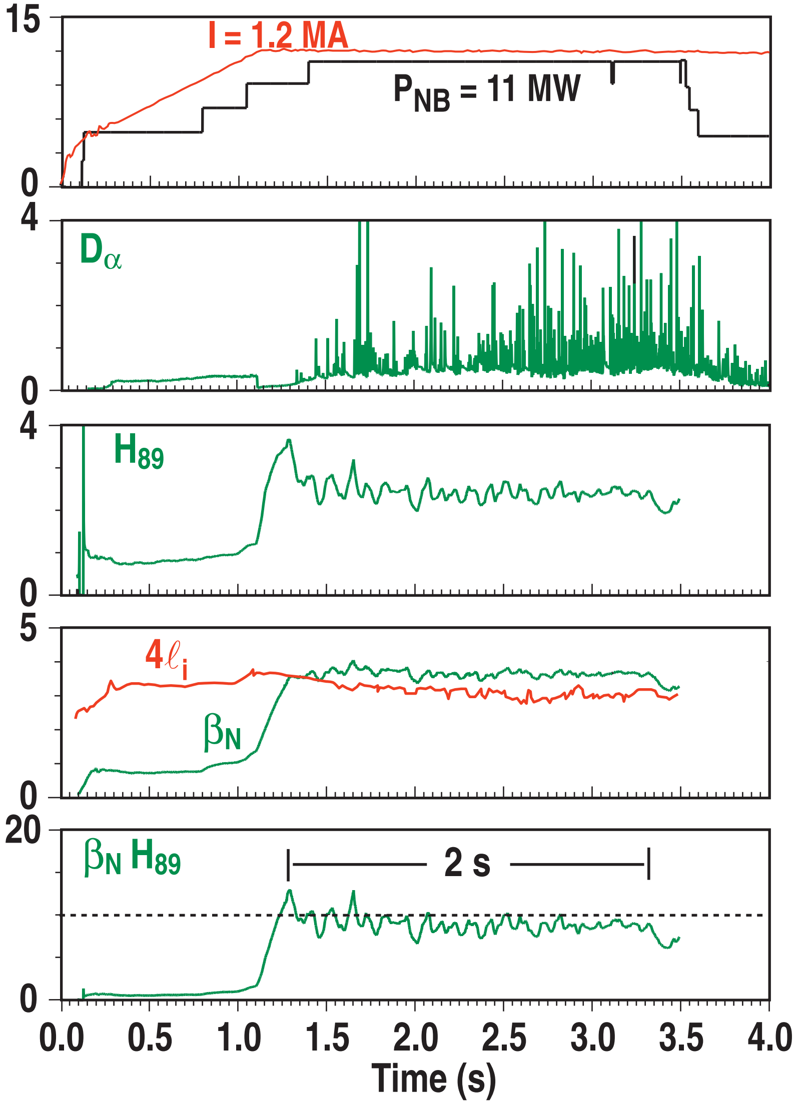
$$\beta_N \equiv \beta_T / (\mathrm{I}/aB_T)$$

κ = vertical plasma elongation

a = plasma half-width

ε = inverse aspect ratio

$\beta_N H_{89} \geq 9$ SUSTAINED FOR 2 s IN ELMing H–MODE PLASMA IN DIII–D WITH $f_{bs} \approx 0.5$ (NON-INDUCTIVE CURRENT FRACTION ≈ 0.75)



- Neutral beam heating during current ramp used to shape radial profile of plasma current
- β_T = 4.6%
- Duration is ~16 τ_E
  - Comparable to current relaxation time

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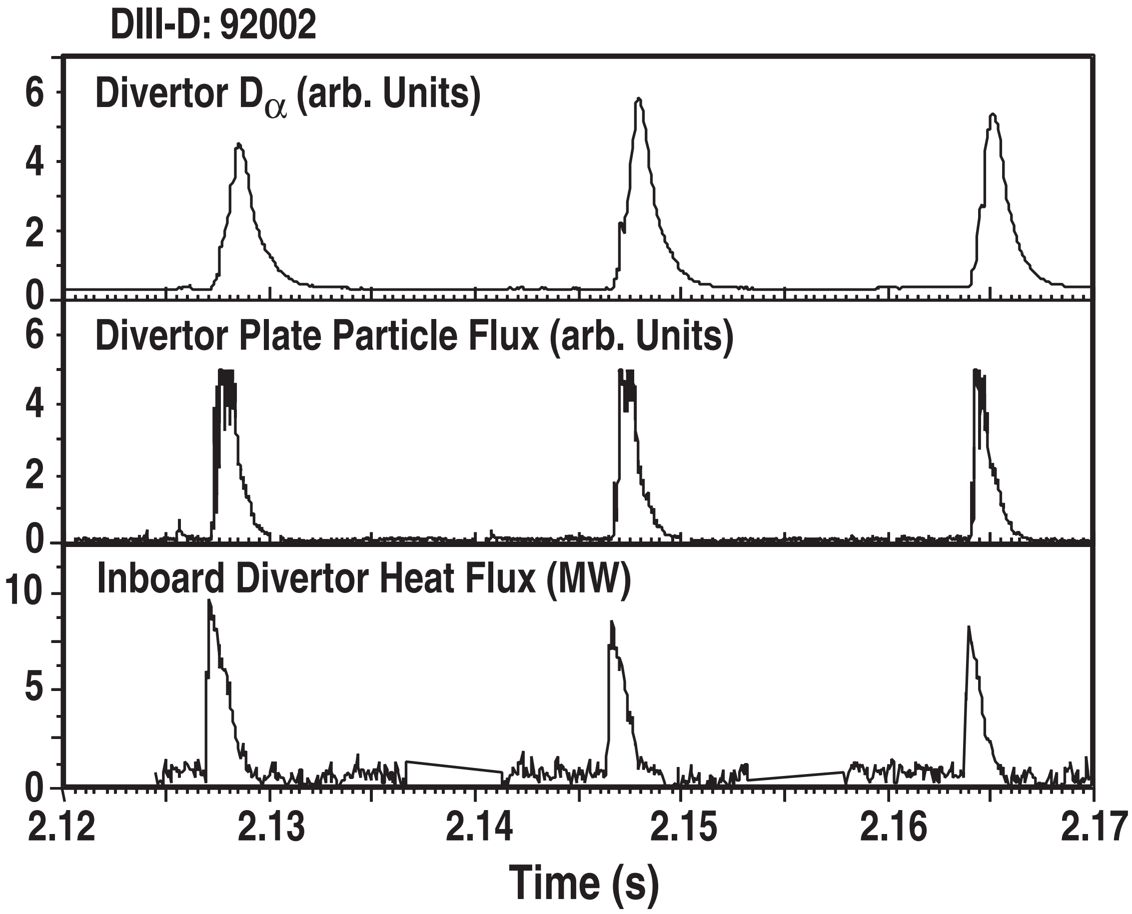
ELMs RELEASE PARTICLES AND ENERGY INTO THE SOL



- ELMs are a common feature of H–mode
- ELM instability results from steep gradients just inside separatrix
- Fast parallel transport produces large perturbation to divertor plasma

INTRODUCTION TO QUIESCENT H–MODE AND QUIESCENT DOUBLE BARRIER PLASMAS

- 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
  - $H_{89} \leqq 2.4$, $\beta_N \leqq 2.9$
  - $\beta_N H_{89} = 7$ for $>5\ \tau_E$

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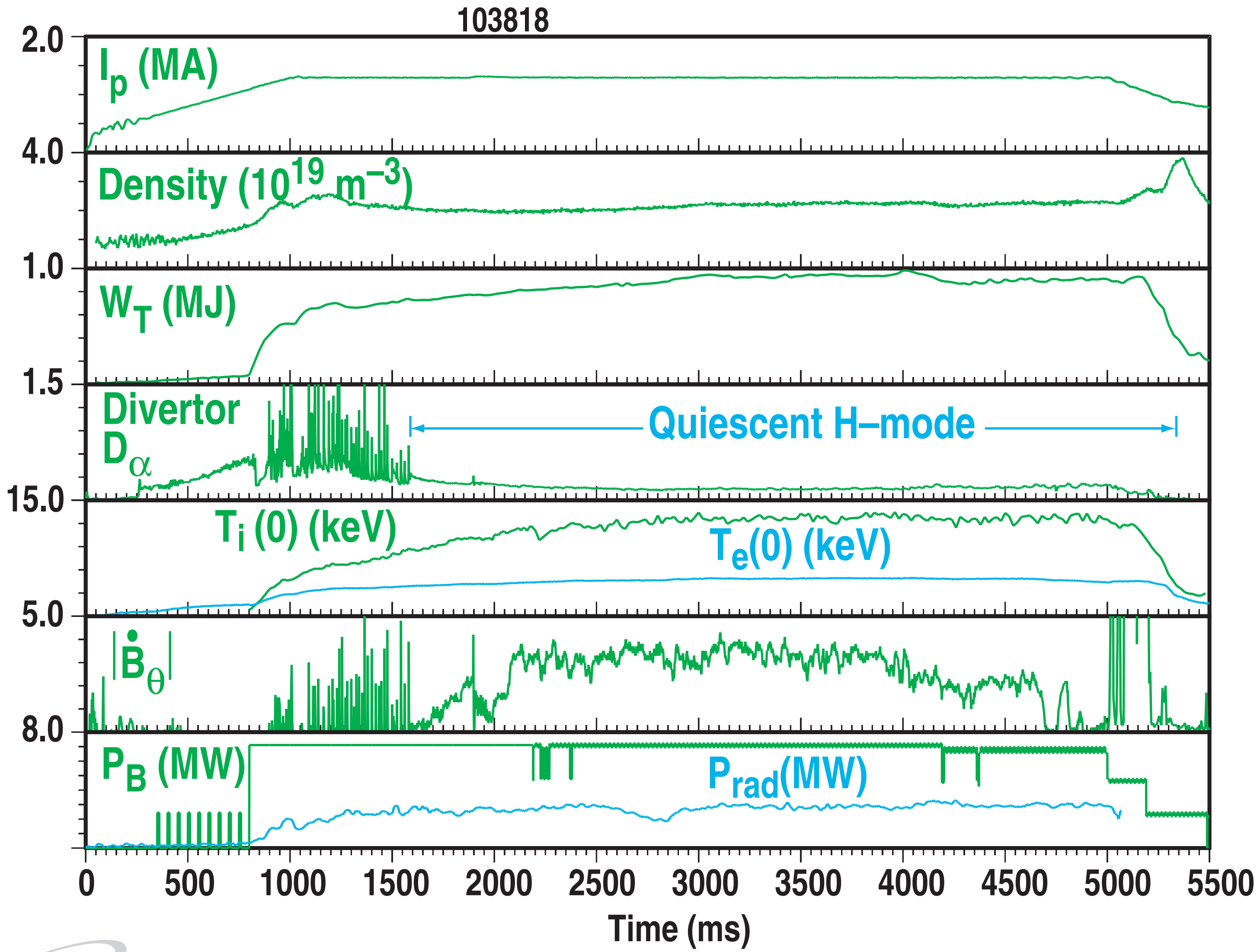
QUIESCENT H–MODE HAS CONSTANT DENSITY AND RADIATED POWER LEVELS FOR LONG PULSES



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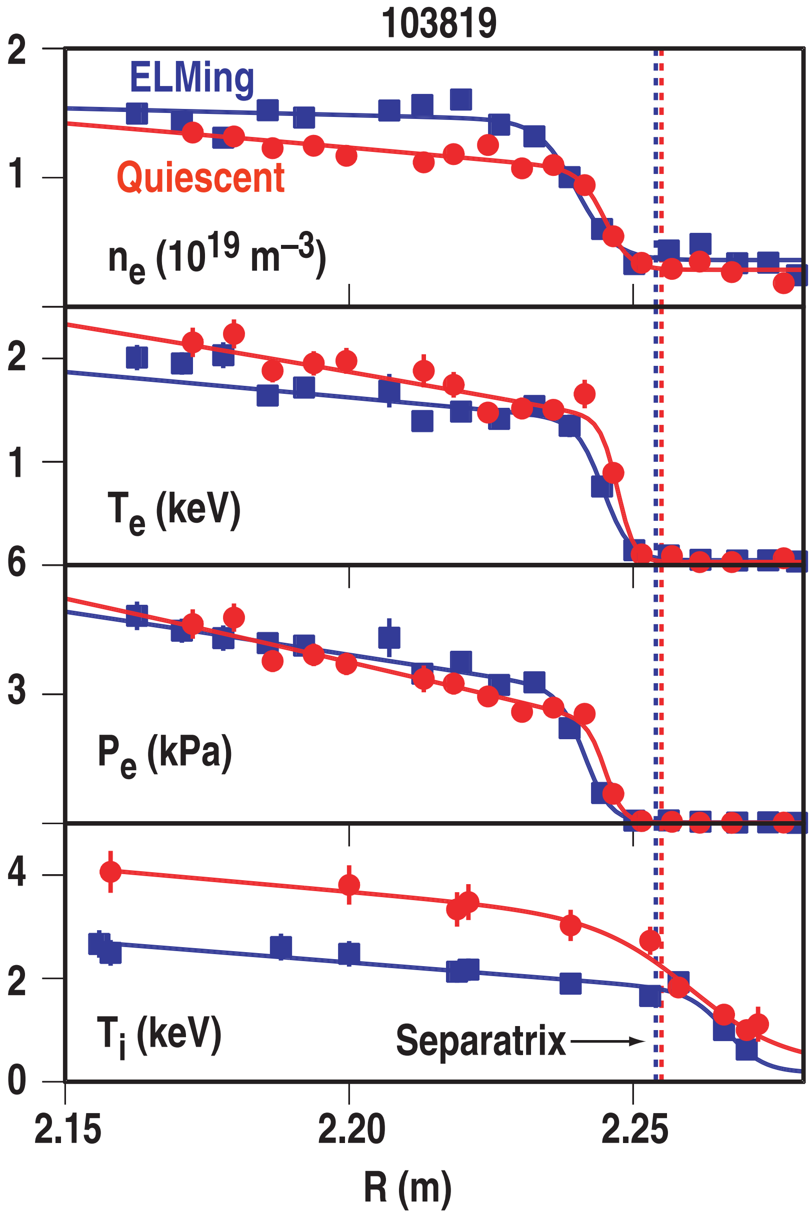
KEY QUESTIONS FOR QUIESCENT H–MODE

- 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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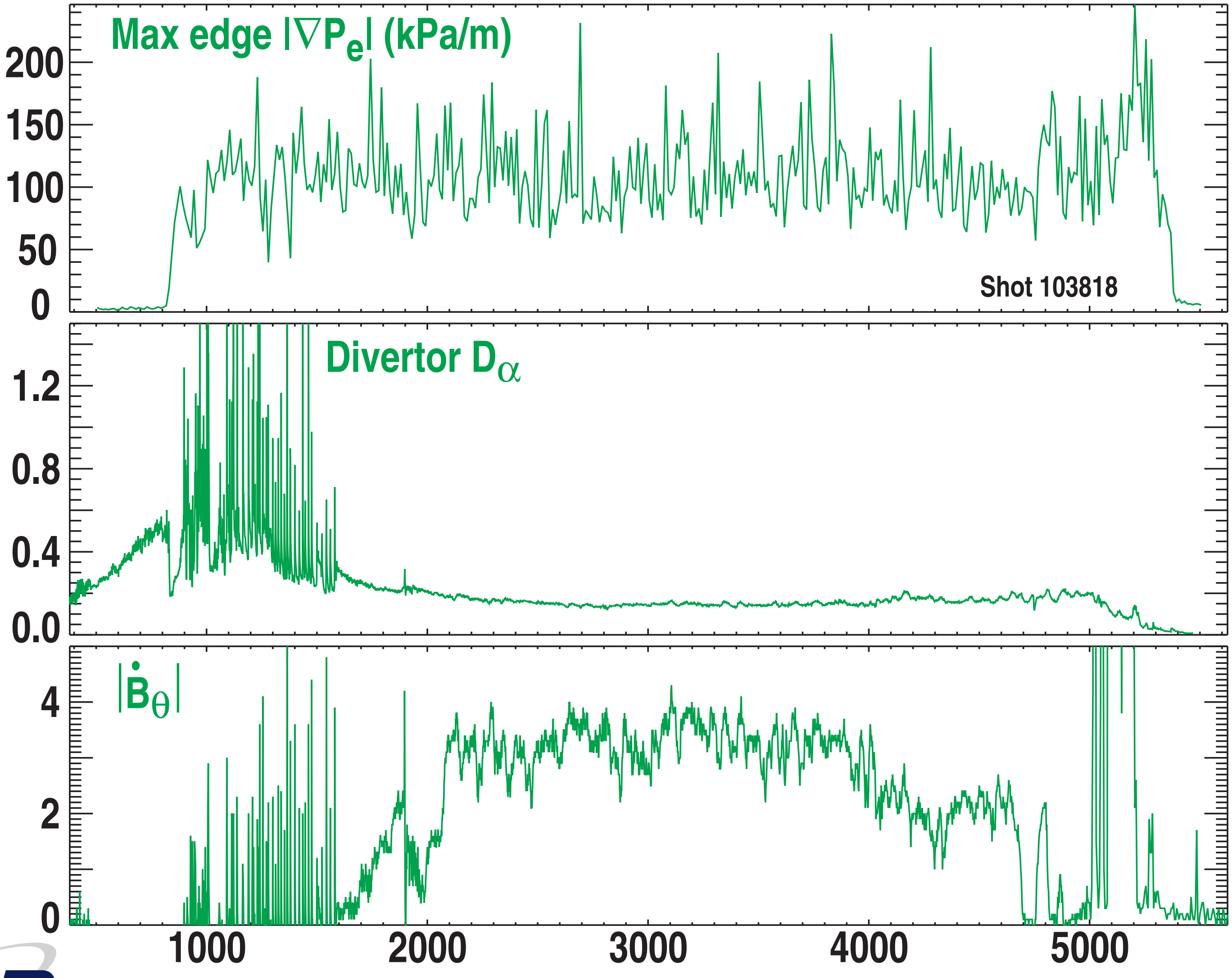
EDGE ∇P_e DOES NOT CHANGE WHEN ELMS DISAPPEAR



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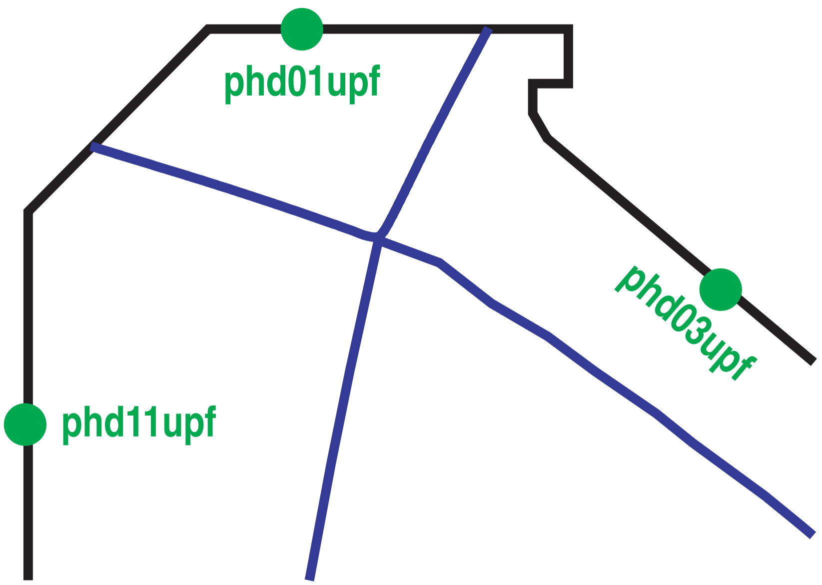
QUIESCENT H–MODE OPERATION SEEN OVER BROAD RANGE OF PLASMA CONDITIONS

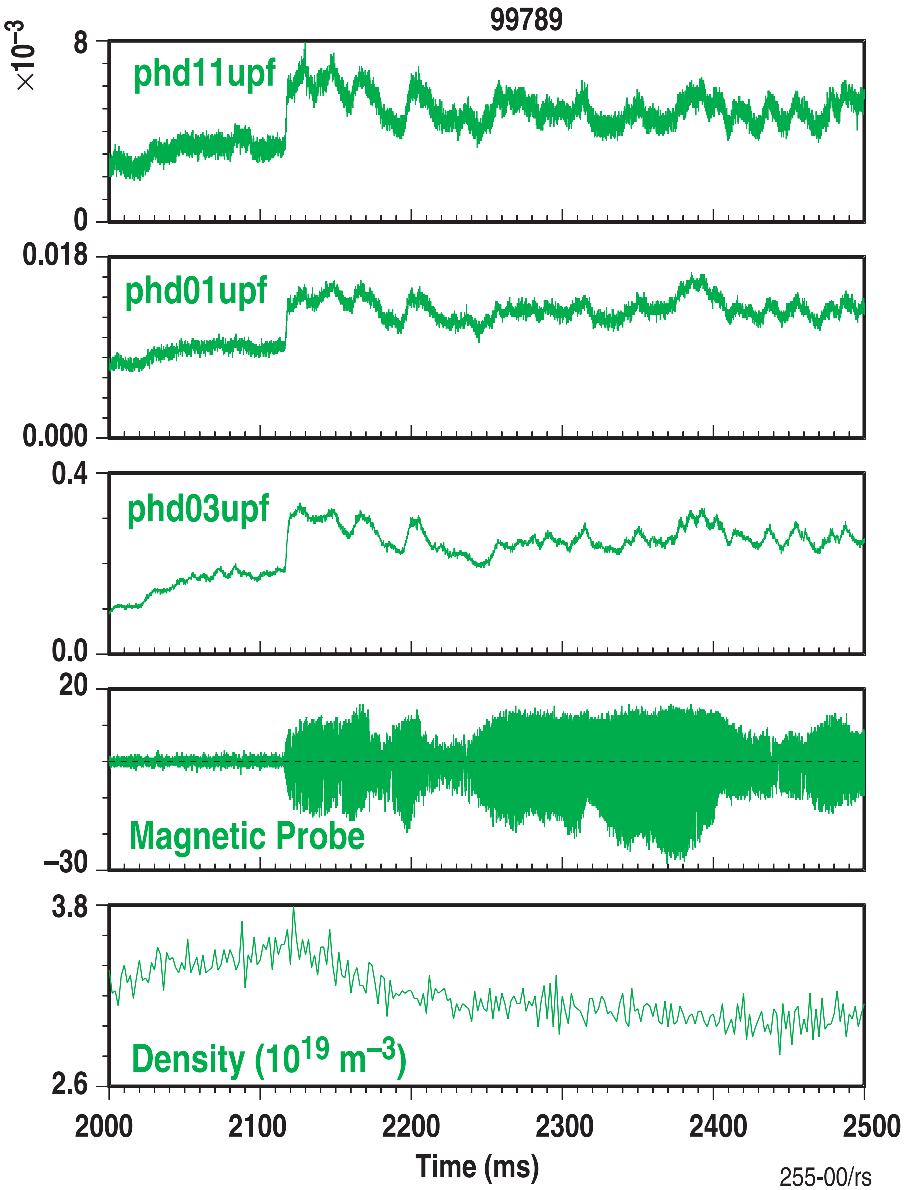
- Key conditions are
  - Neutral beam injection counter to plasma current at power levels above 3.7 MW
  - Cryopumping to reduce the neutral pressure and edge density (pedestal density typically 1.2×10^{19} m^{-3})
  - Sufficient distance between plasma edge and wall on low toroidal field side (~10 cm)

- 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

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





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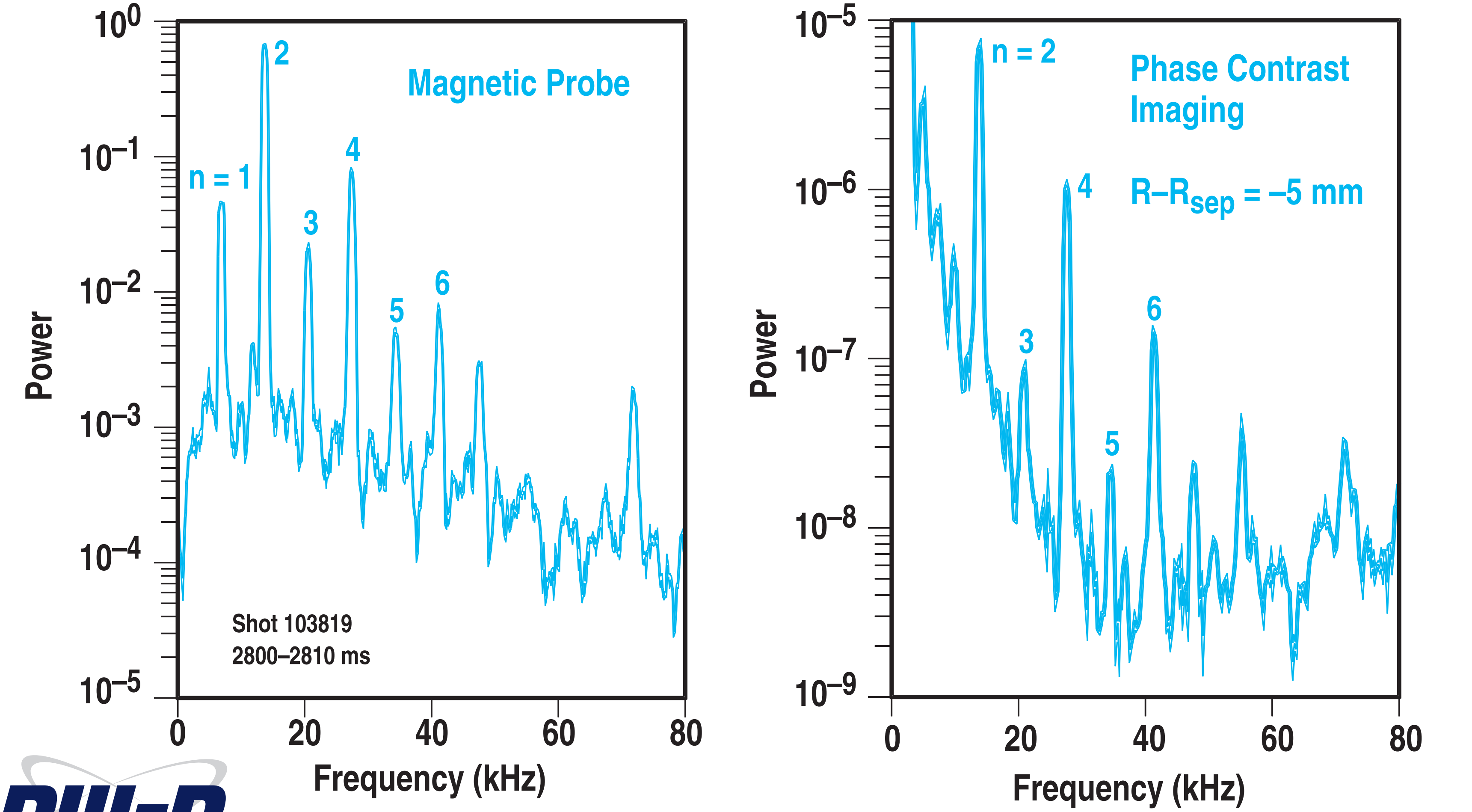
EDGE HARMONIC OSCILLATION SEEN ON $\dot{B}_\theta$ AND DENSITY DIAGNOSTICS

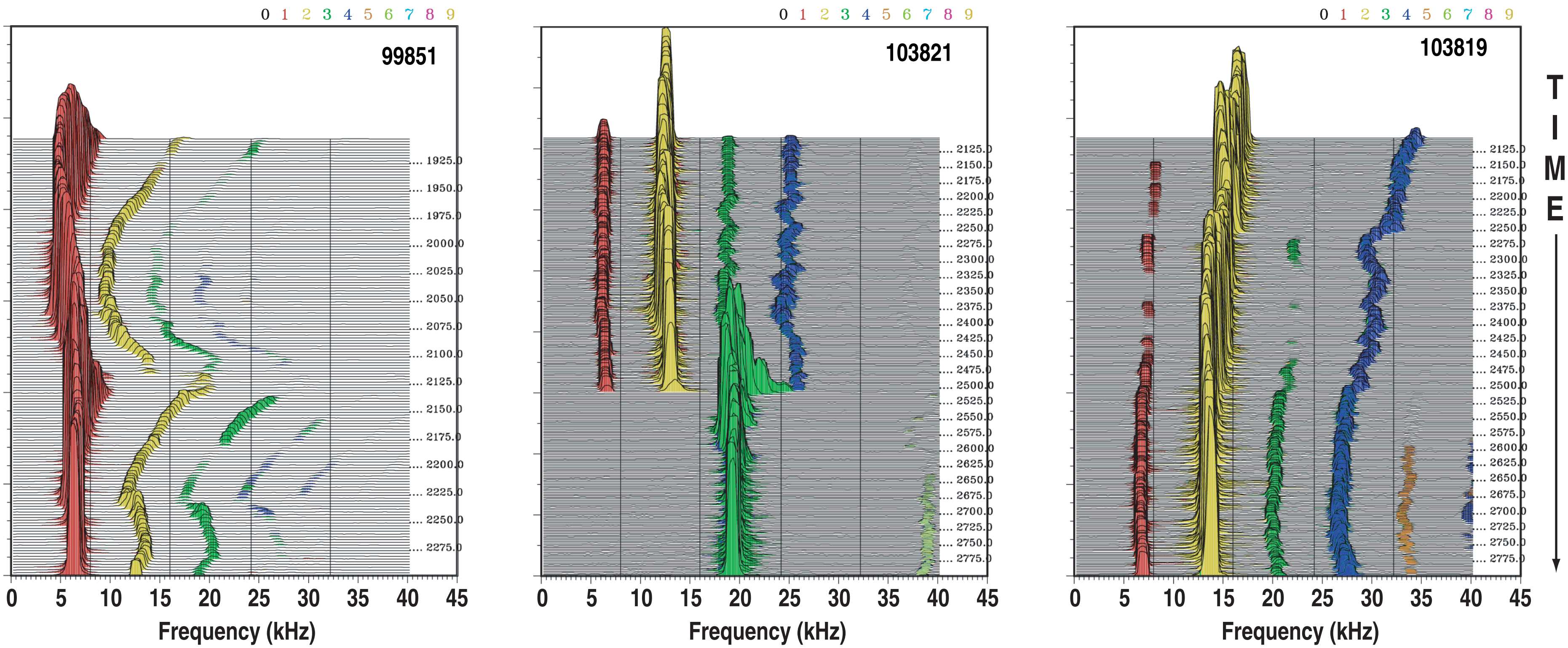
- Presence of $\dot{B}_\theta$ signal demonstrates significant electromagnetic component to oscillation



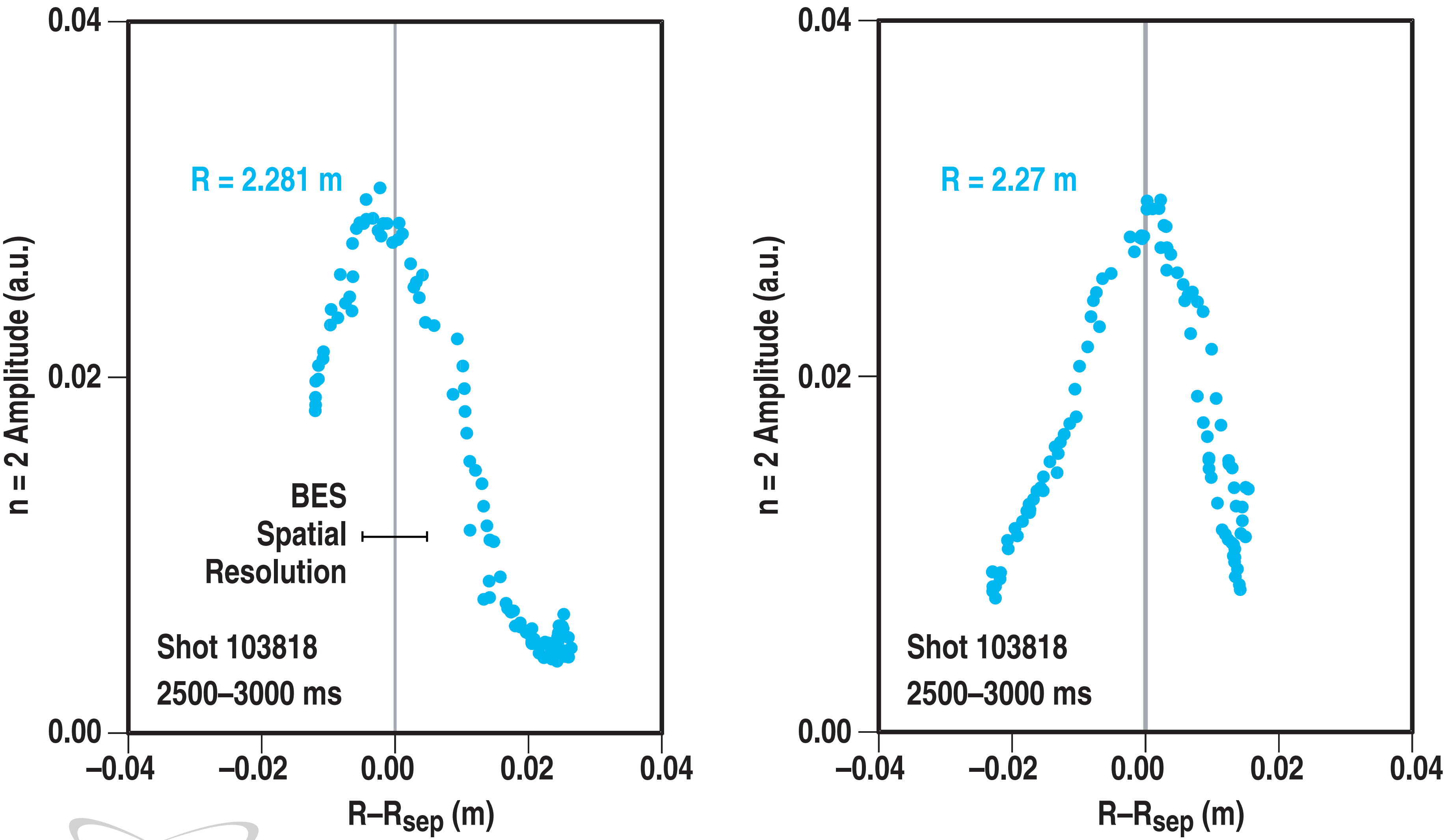
MIX OF TOROIDAL MODE NUMBERS VARIES IN EDGE HARMONIC OSCILLATION

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

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



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



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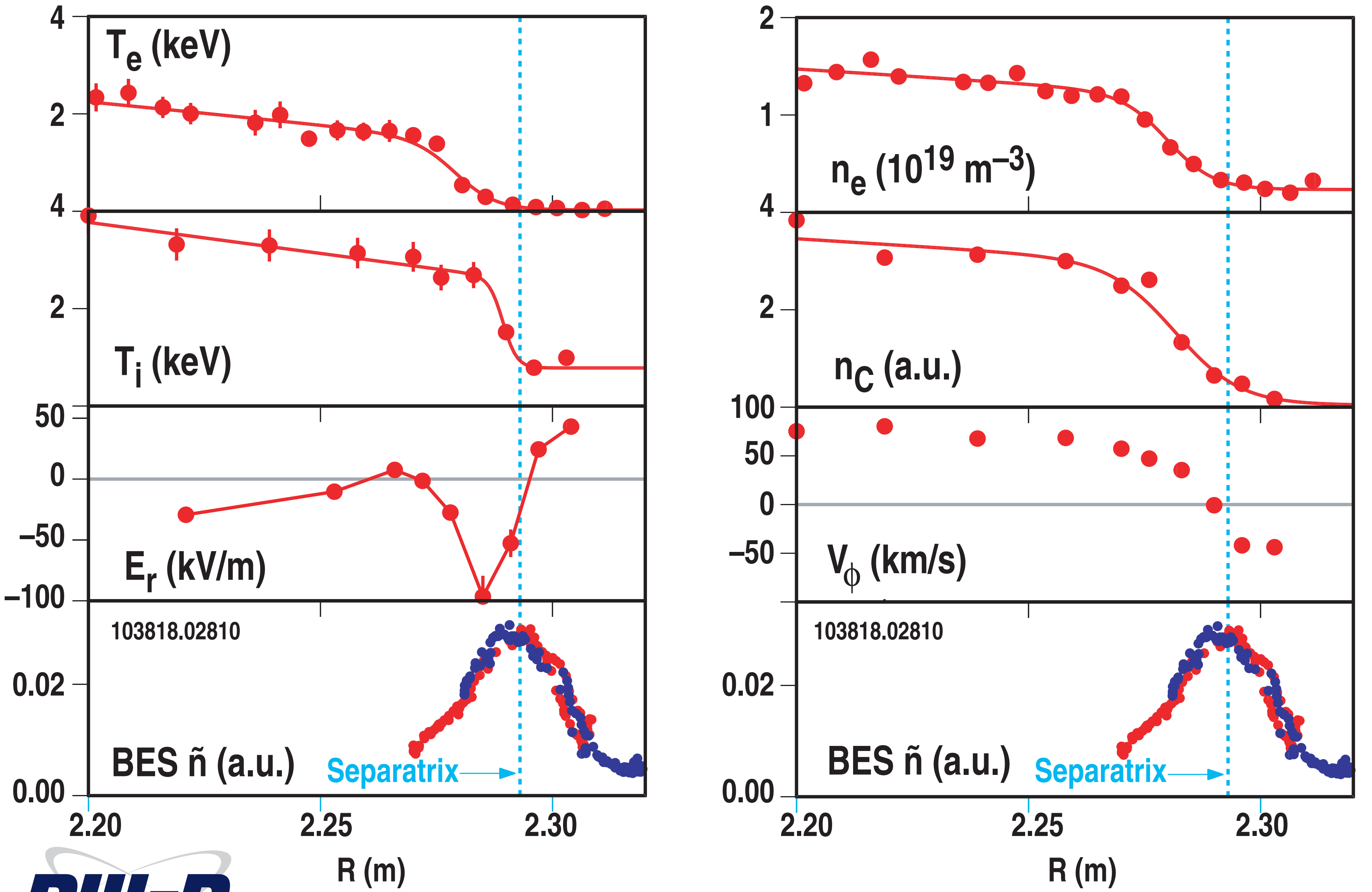
MAXIMUM IN ñ LOCATED CLOSEST TO MAXIMUM GRADIENTS IN E_r AND V_ϕ



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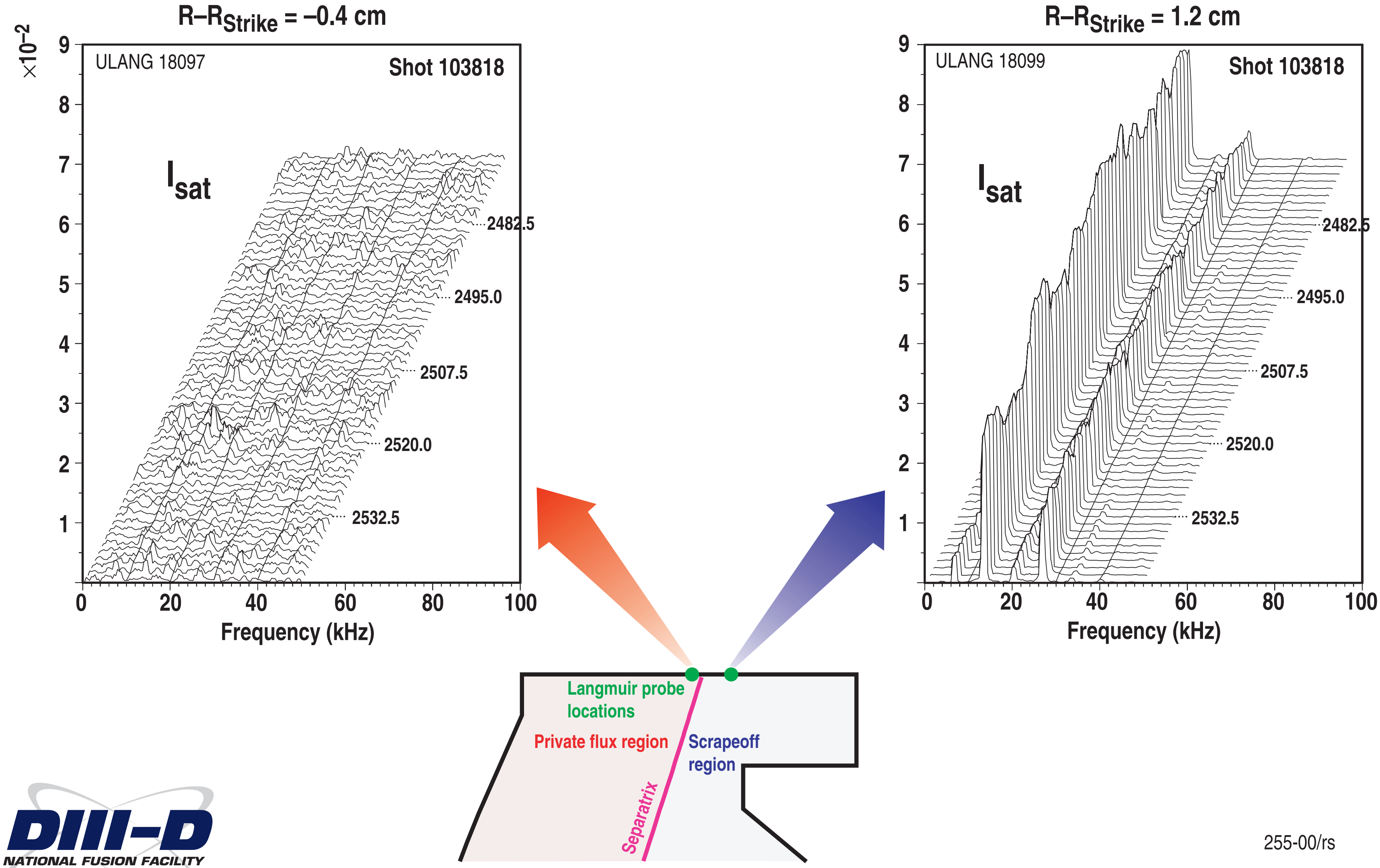
DIVERTOR LANGMUIR PROBES SHOW EDGE HARMONIC OSCILLATION MODULATES PARTICLE FLUX TO DIVERTOR PLATE FROM SCRAPE OFF LAYER



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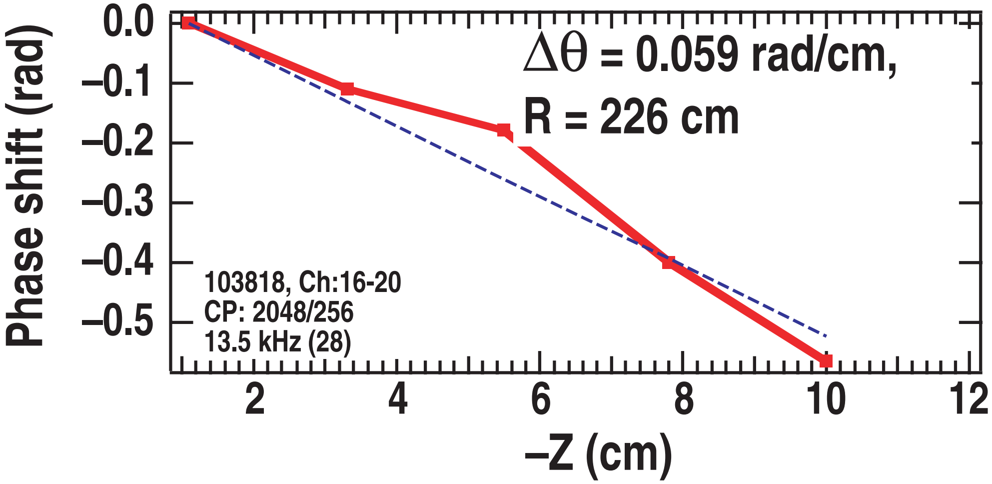
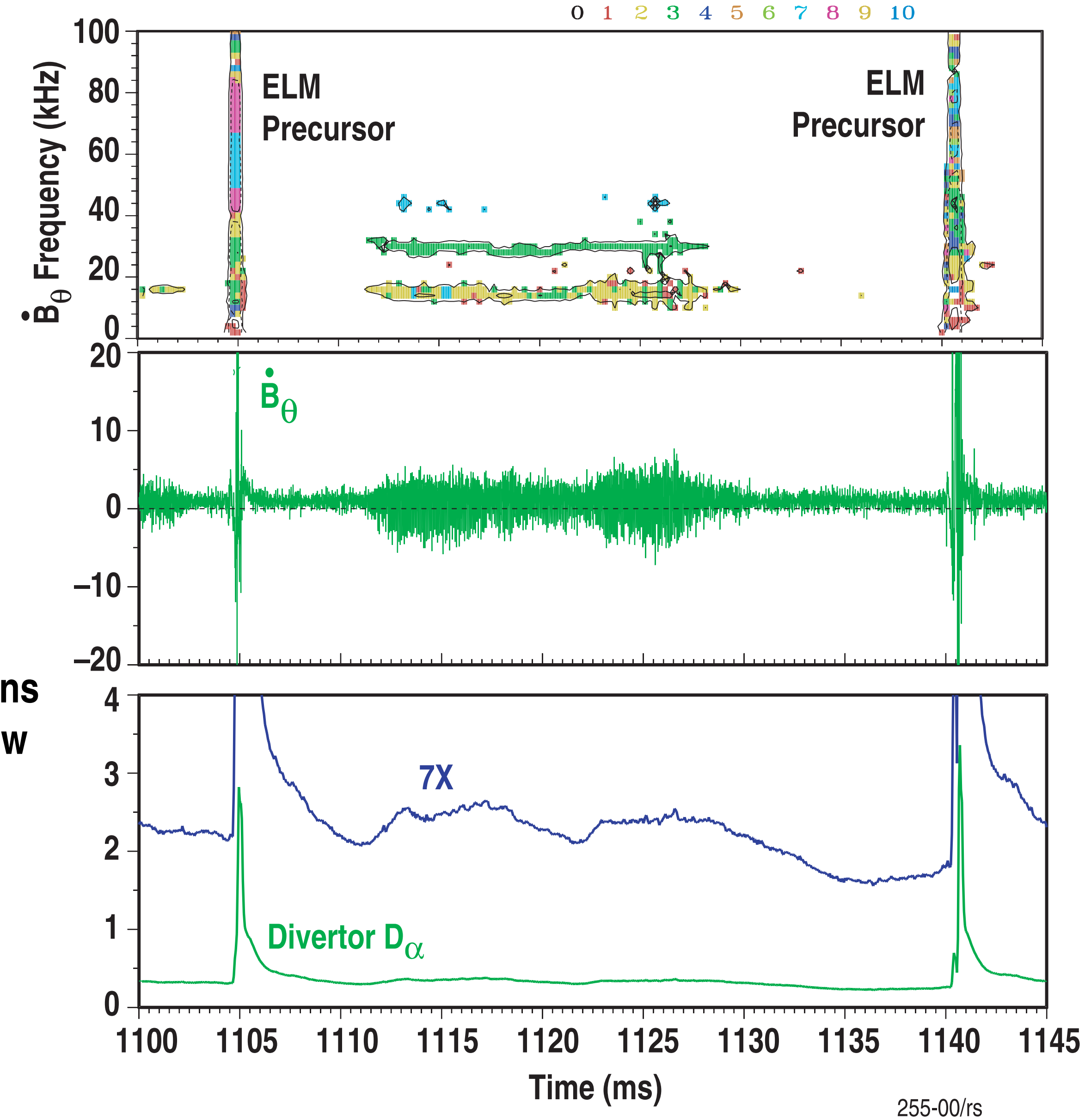
BES AND POLOIDAL MAGNETIC PROBE ARRAY GIVE POLOIDAL WAVELENGTH AROUND 1 m

- 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



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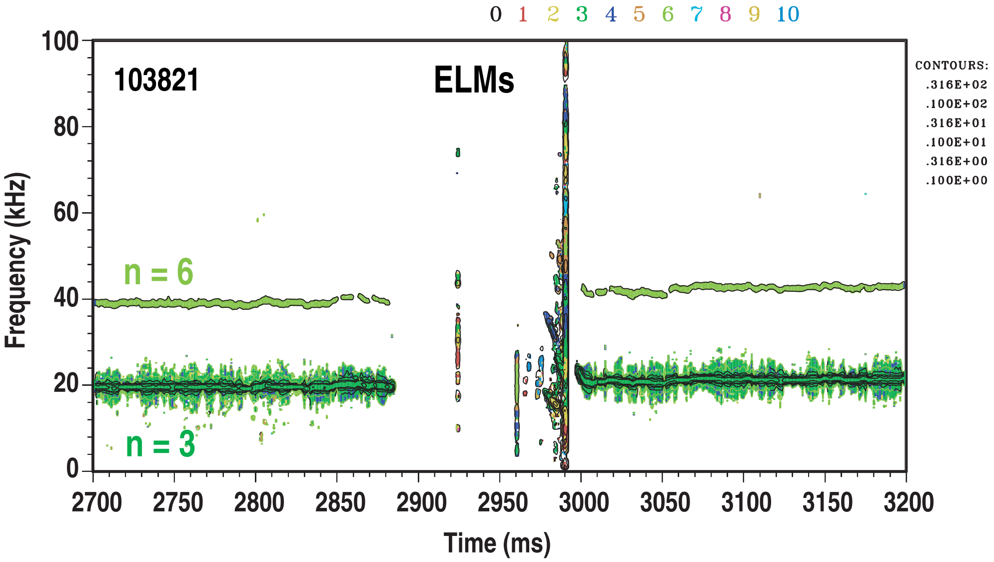
EDGE HARMONIC OSCILLATION DOES NOT APPEAR TO BE A SATURATED ELM PRECURSOR

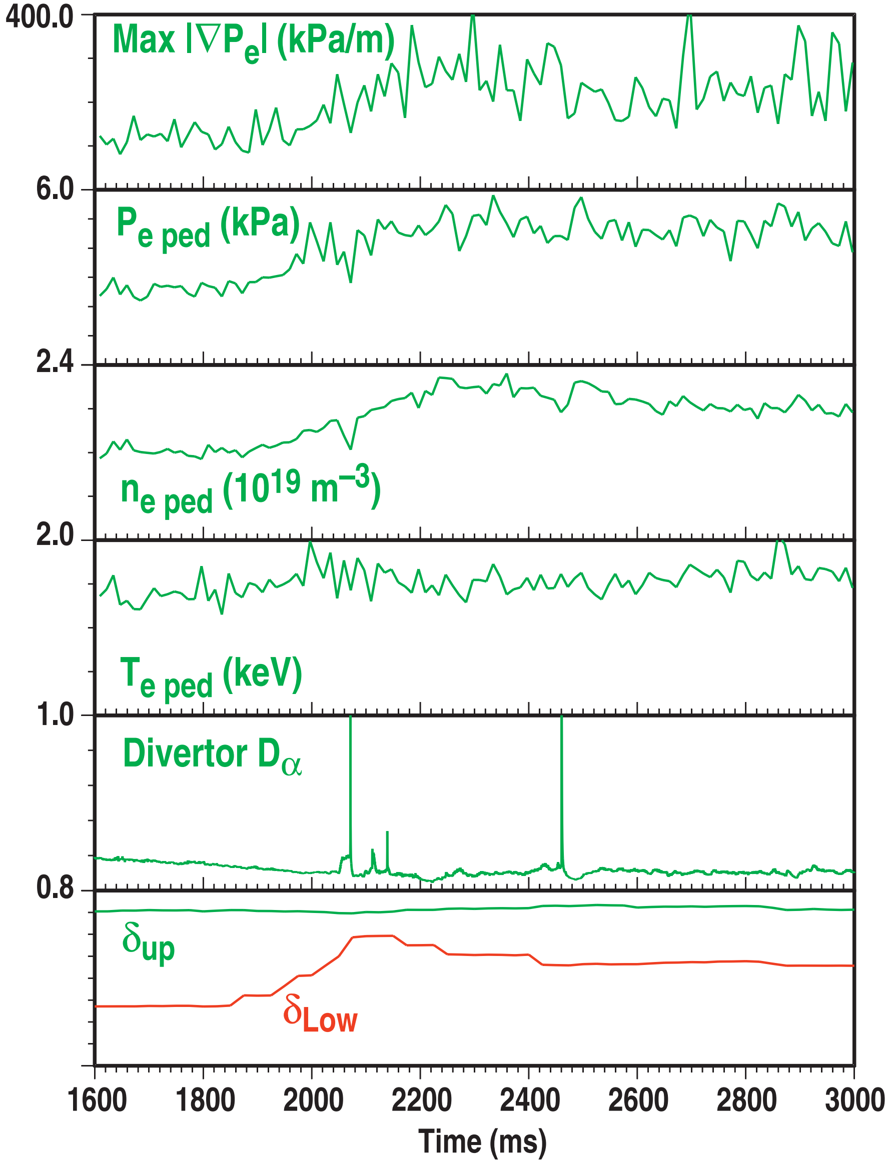
- When conditions are marginal for the edge harmonic oscillation, we have many cases where the oscillation disappears and yet ELMs do not appear for 10’s of milliseconds
  - This sequence is not what one expects for a precursor

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



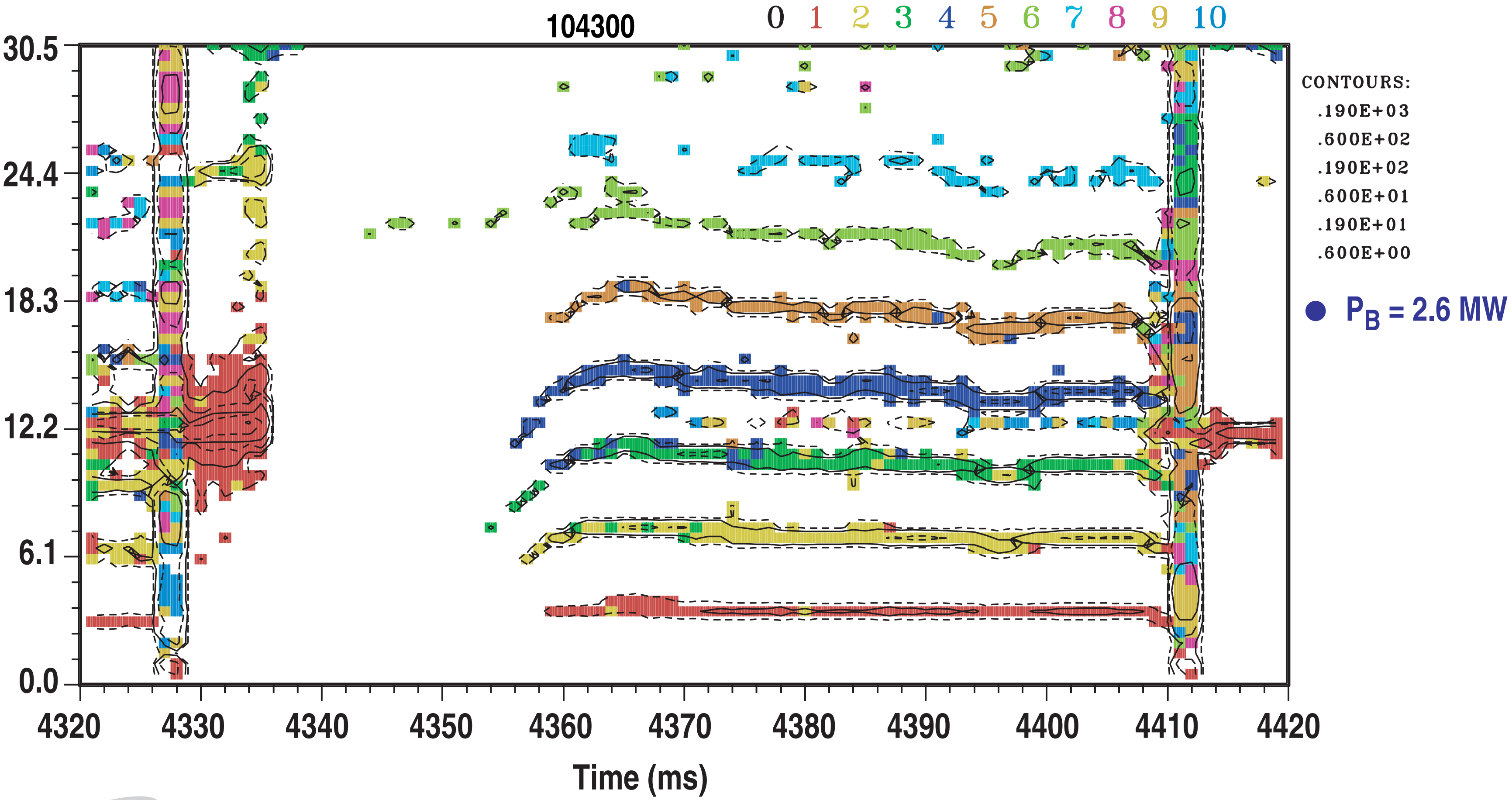
INCREASE OF EDGE GRADIENT AND PEDESTAL PARAMETERS WITH TRIANGULARITY SIMILAR TO THAT IN ELMING H–MODE

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



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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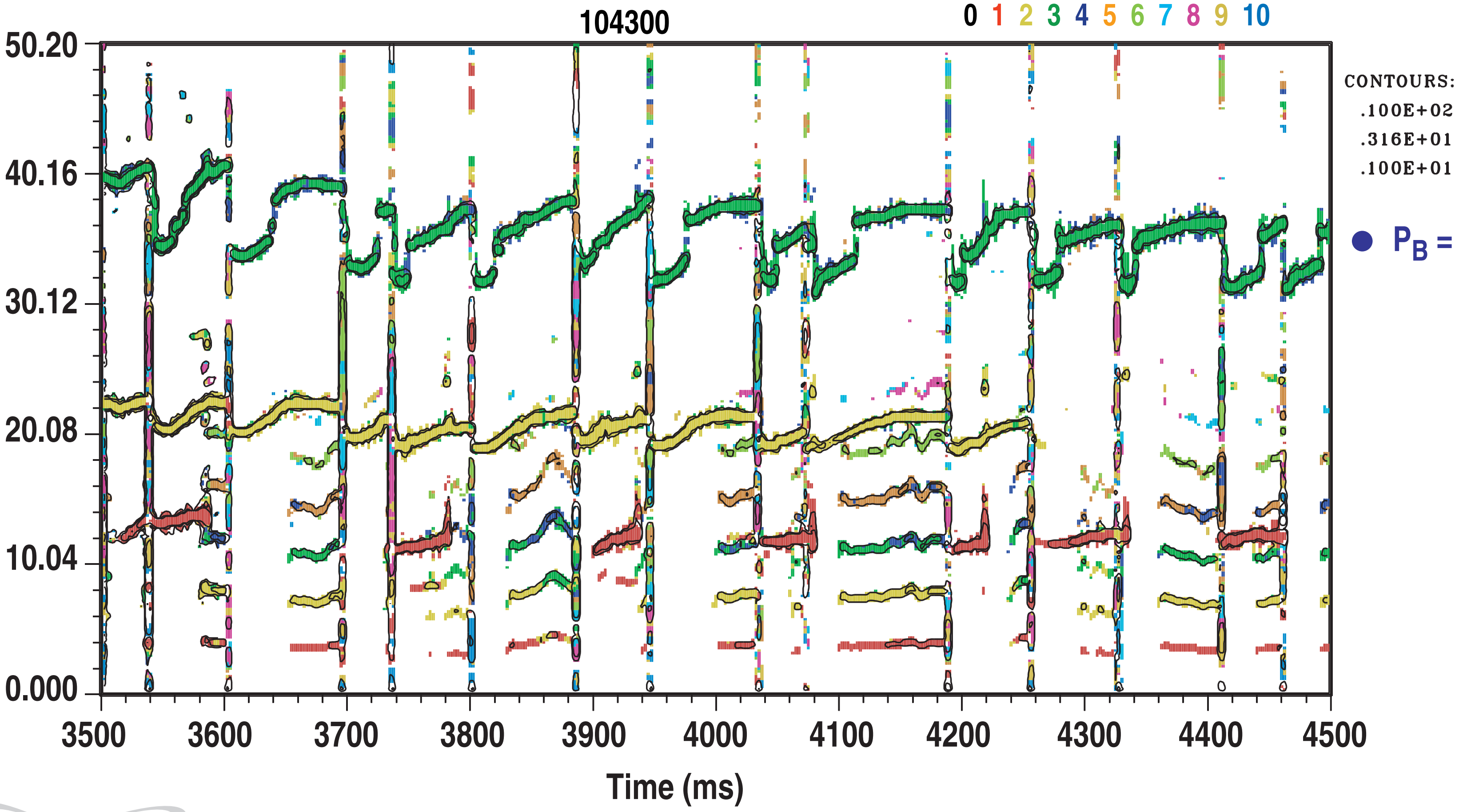

- $P_B = 2.6$ MW

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EDGE 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

FUNDAMENTAL QUESTION: WHY DO ELMs GO AWAY?

Two types of hypotheses explain this

- Edge harmonic oscillation lowers edge pressure gradient below MHD stability limit
  - Not consistent with measurements
  - Pressure gradient doesn't change as ELMs go away and amplitude of edge harmonic oscillation increases
- Stability boundary has moved
  - Finite Larmor radius stabilization by beam ions??
  - Change in edge current density??
  - E×B shear effects owing to very deep E_r well at plasma edge??

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 $\beta_N H_{89} = 7$ achieved for $>5\ \tau_E$
- Core and edge barriers do not merge
  - E×B shear is small around $\rho = 0.8$ owing to negative core E_r from counter injection and negative H–mode edge E_r well

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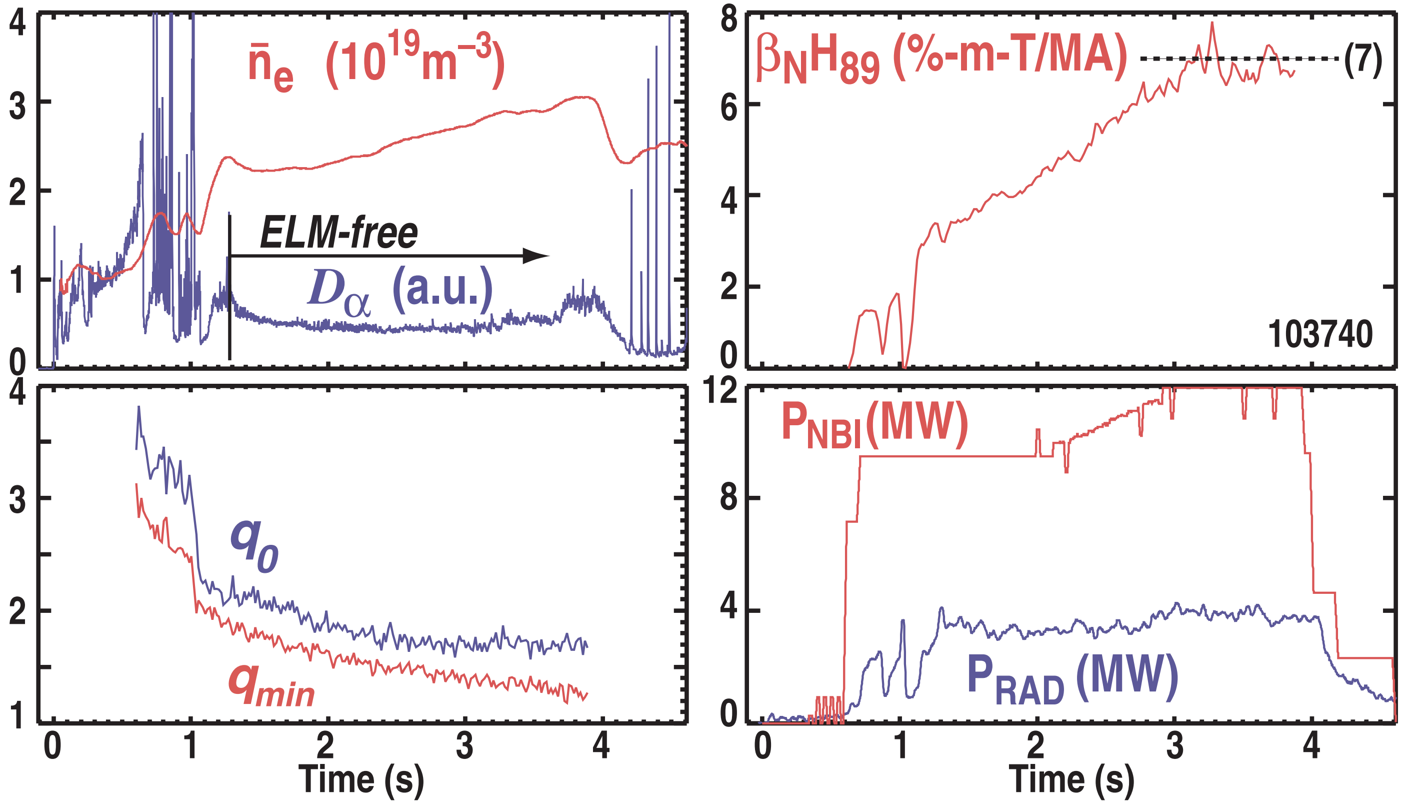
SUSTAINED HIGH PERFORMANCE HAS BEEN OBTAINED IN THE QUIESCENT DOUBLE BARRIER REGIME



- QDB regime is a long pulse, high performance candidate:
  - β_T = 3.3%, τ_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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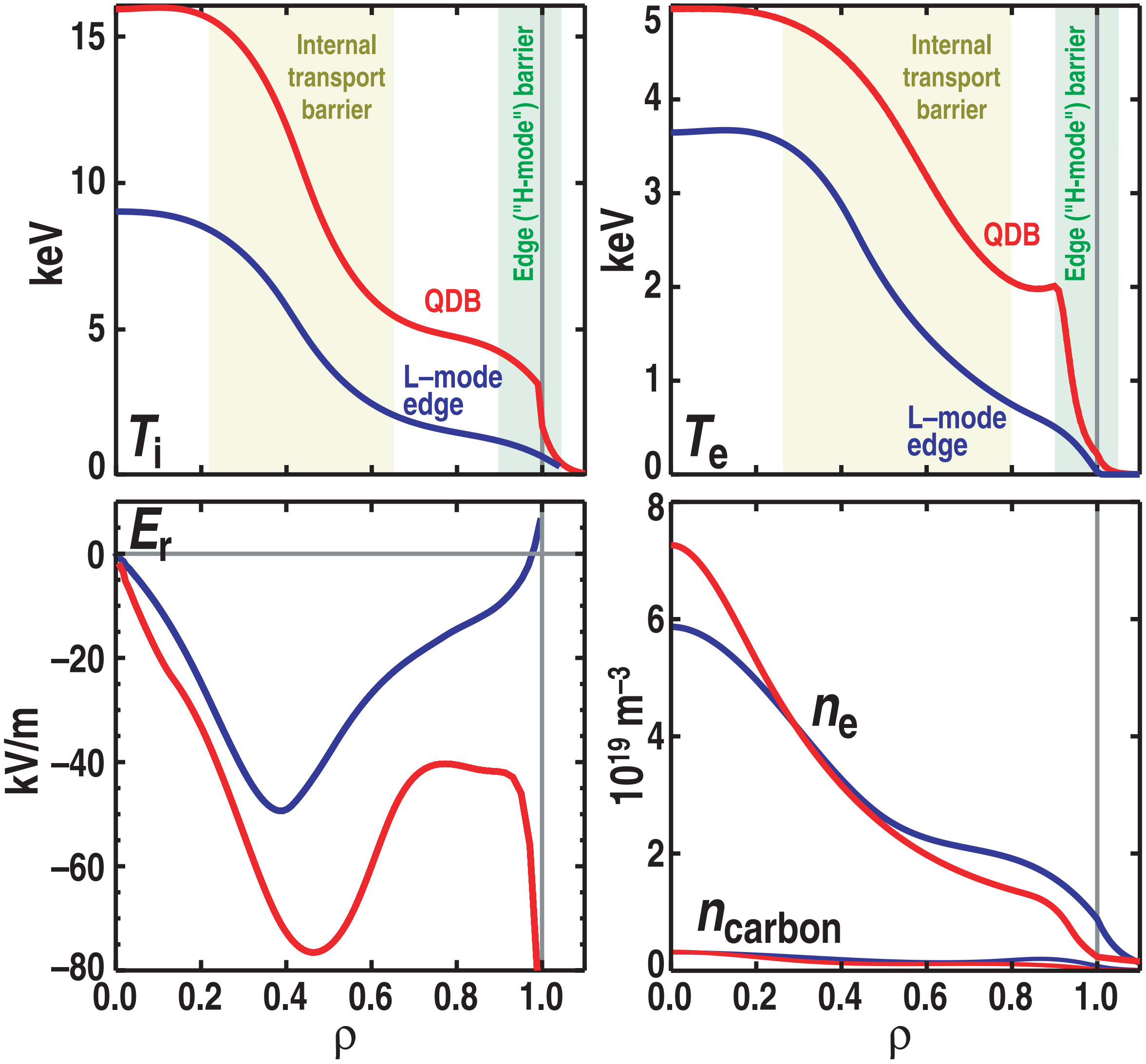
QUIESCENT H–MODE EDGE PEDESTAL ELEVATES CORE TEMPERATURE PROFILE WHILE MAINTAINING INTERNAL TRANSPORT BARRIER

L–mode edge
ITB (99849 1.12s)

QDB (103740 3.3s)



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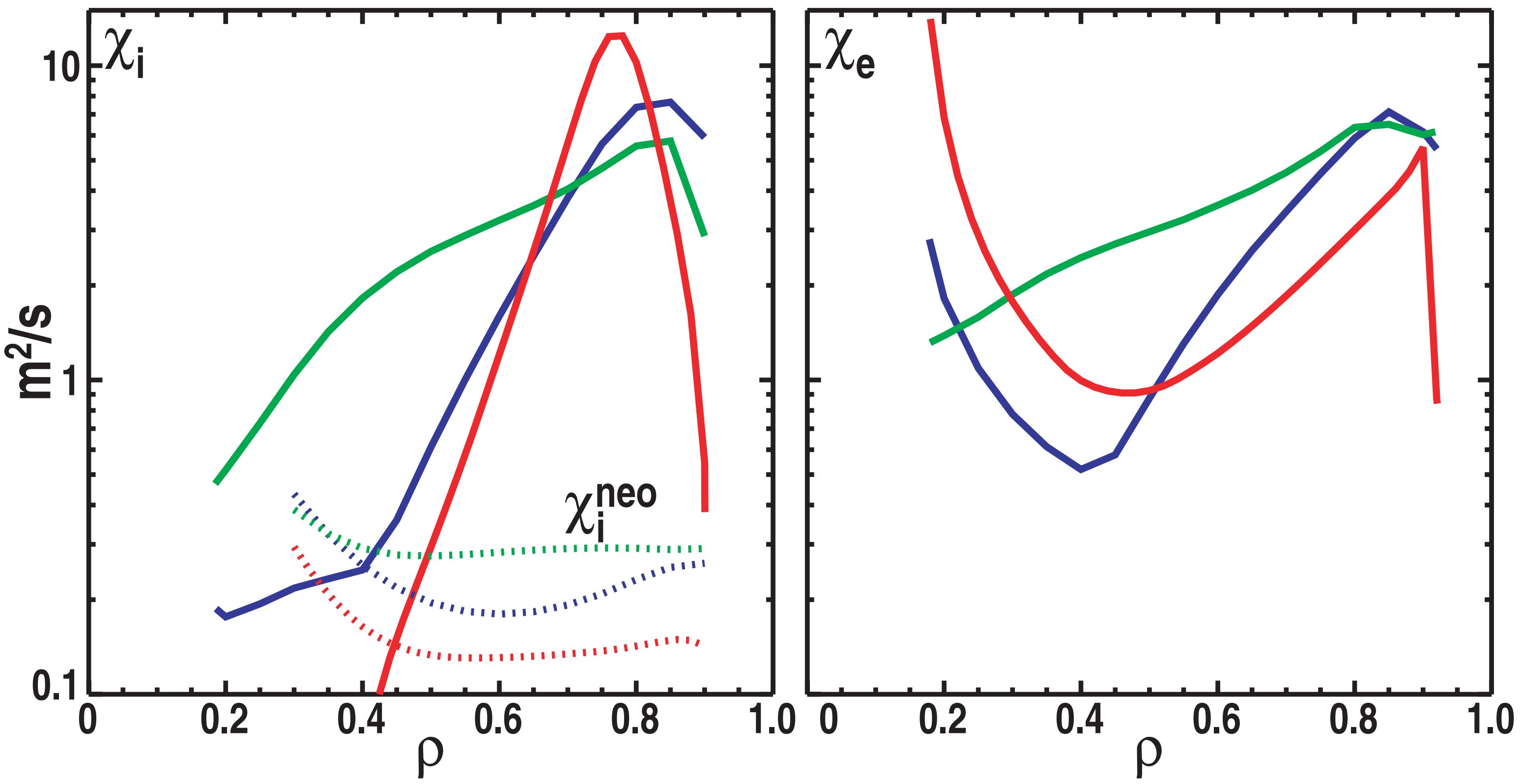
QDB ADDS EDGE TRANSPORT BARRIER TO REDUCED TRANSPORT CORE



L–mode edge ITB 99849 1.12 s

QDB 103740 3.3 s

L–mode 99852 0.80 s

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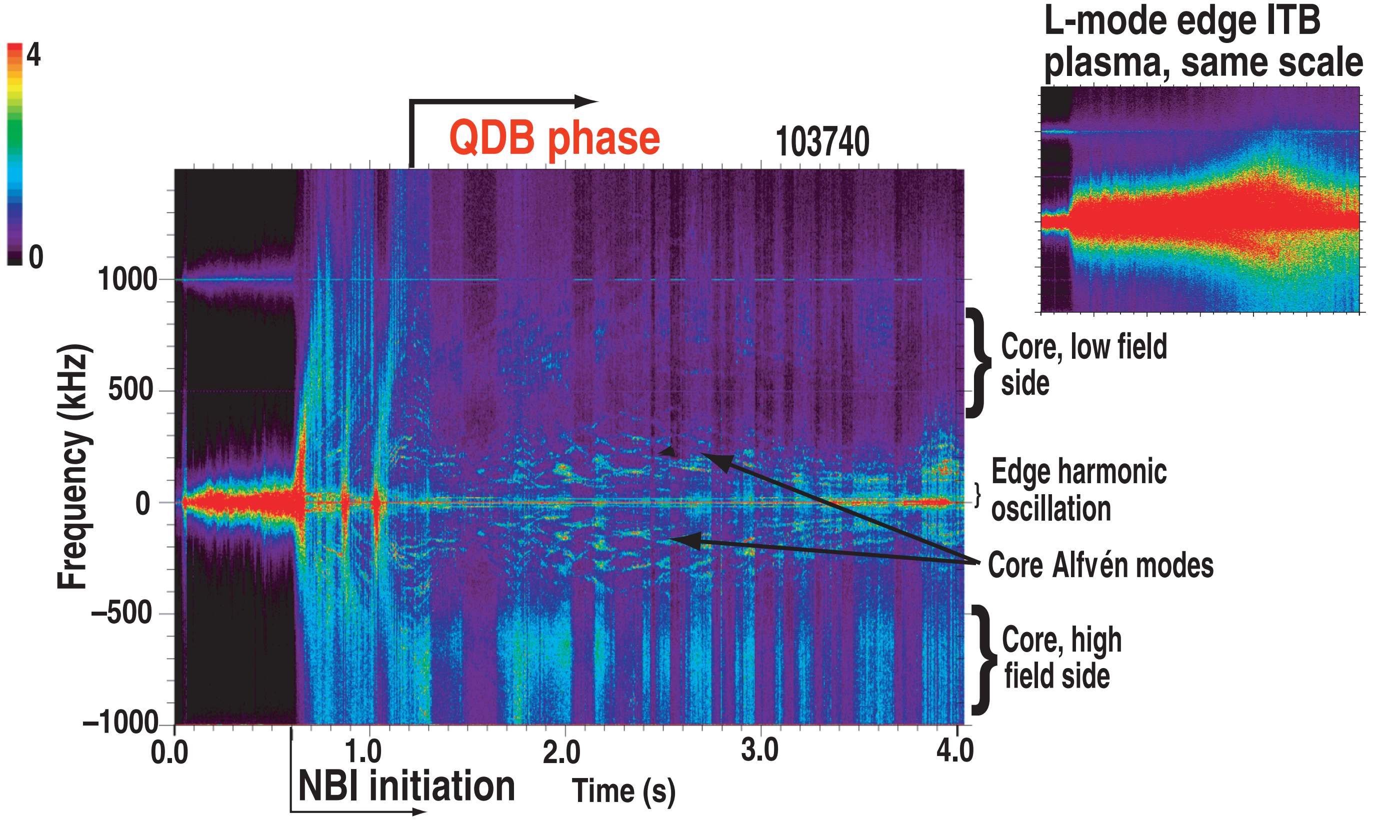
TURBULENCE IS REDUCED ACROSS MOST OF PLASMA DIAMETER IN QDB REGIME

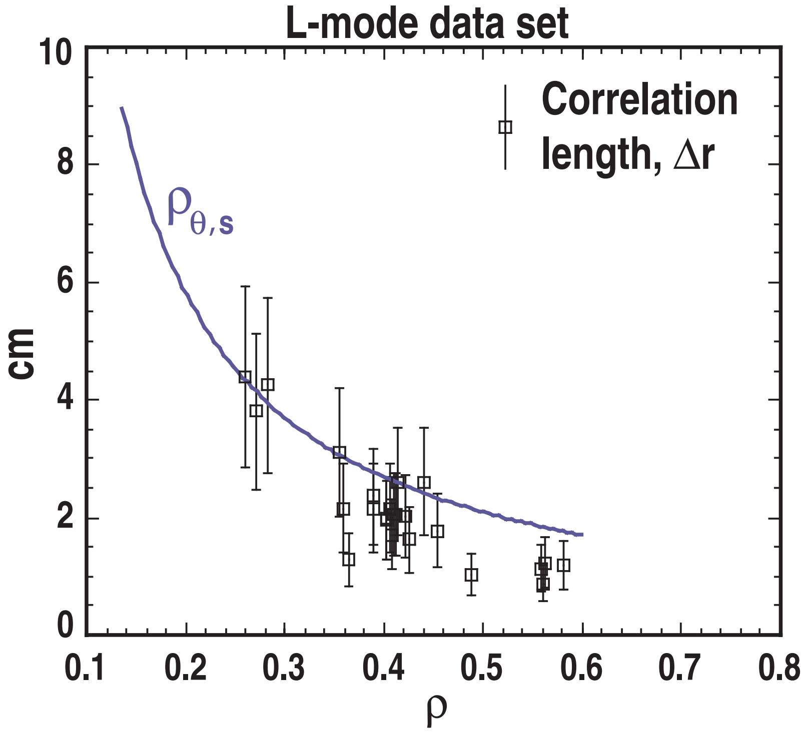
- With reduced broadband turbulence, core Alfvén modes are clearly visible in FIR scattering data, as is low frequency edge harmonic oscillation associated with QH-mode operation

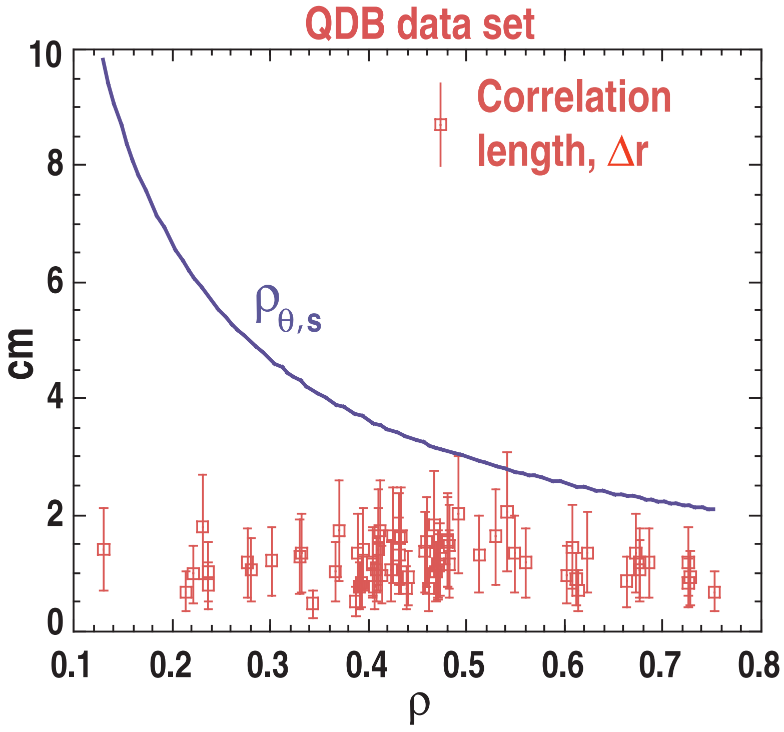


RADIAL STEP SIZE FOR TURBULENT TRANSPORT IS REDUCED IN QDB REGIME

- 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


L-mode data set


QDB data set

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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
  - $\beta_N H_{89} = 7$ for $>5\ \tau_E$
- 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

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