QUIESCENT H–MODE PLASMAS IN THE DIII–D TOKAMAK

by

K.H. BURRELL

In Collaboration with:

M.E. Austin,[†] D.P. Brennan,[‡] J.C. DeBoo, E.J. Doyle,[◊] P. Gohil, C.M. Greenfield, R.J. Groebner, L.L. Lao, T.C. Luce, M.A. Makowski,[£] G.R. McKee,[△] R.A. Moyer,[#] M. Porkolab,[§] T.L. Rhodes,[◊] J.C. Rost,[§] M.J. Schaffer, B.W. Stallard,[£] E.J. Strait, M.R. Wade,[¶] G. Wang,[◊] J.G. Watkins,[¢] W.P. West, and L. Zeng

[†]University of Texas
[‡]Oak Ridge Institute for Science Education
[◊]University of California, Los Angeles
[£]Lawrence Livermore National Laboratory
[△]University of Wisconsin, Madison
[#]University of California, San Diego
[§]Massachusetts Institute of Technology
[¶]Oak Ridge National Laboratory
[¢]Sandia National Laboratories, Albuquerque

Presented at
The 43rd Annual Meeting of the Division of Plasma Physics
Long Beach, California

October 29 through November 2, 2001

DIII–D NATIONAL FUSION FACILITY SAN DIEGO

GENERAL ATOMICS

267–01/KHB/wj

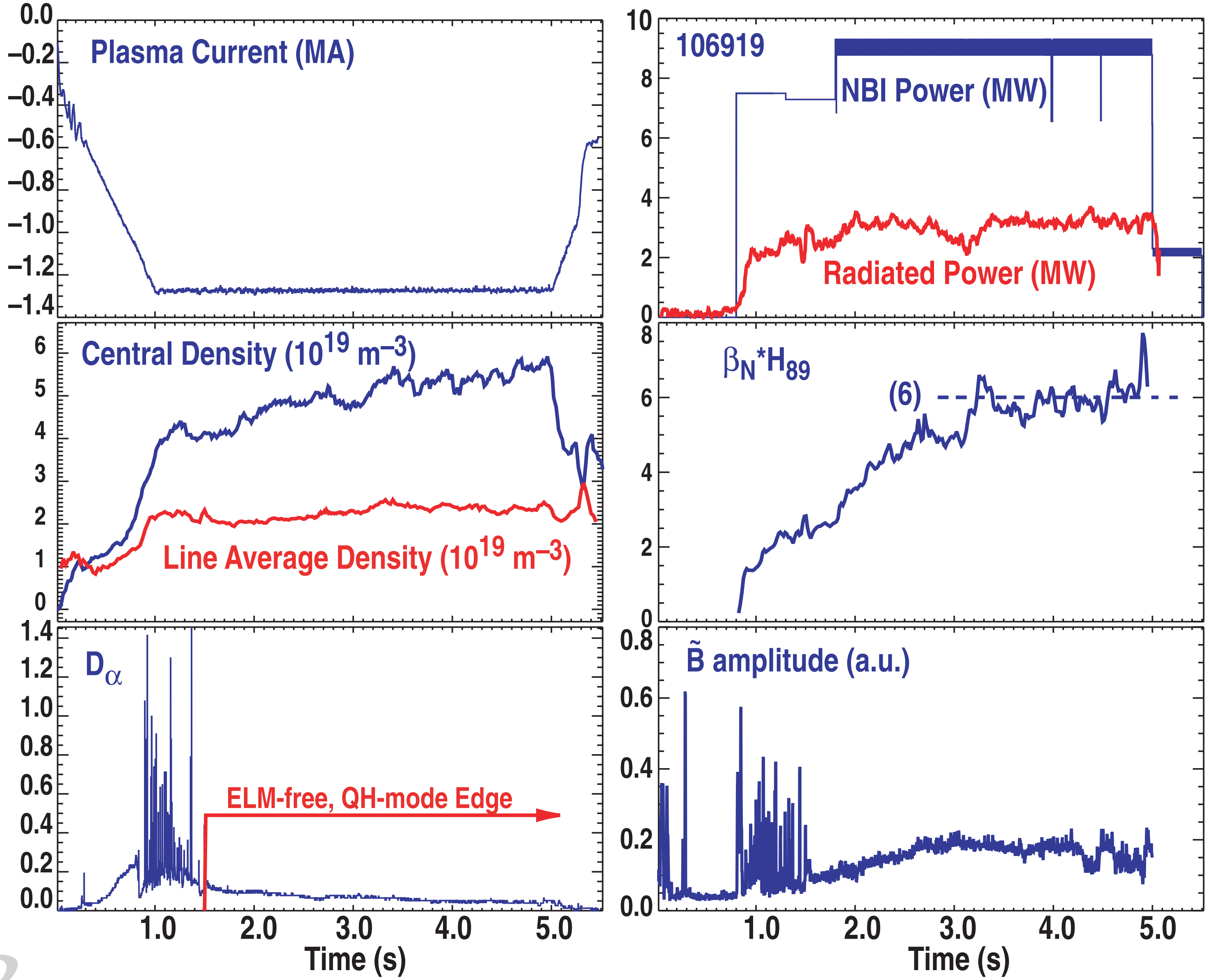
INTRODUCTION

- 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 a possible solution to these problems by combining
  - 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 radiated power levels
  - Potential for steady-state operation
    - ★ 3.5 s or 25 τ_E achieved to date
    - ★ Duration limited only by machine hardware constraints

INTRODUCTION (Continued)

- Combined edge and core transport reduction yields high performance
  - $H_{89} \leq 2.4$, $\beta_N \leq 2.9$, $\beta_T \leq 3.9\%$
  - $\beta_N H_{89} = 7$ for 10 τ_E
- This poster discusses the quiescent H–mode edge plasma
  - Companion poster by E.J. Doyle focusses on the additional core barrier physics

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



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

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

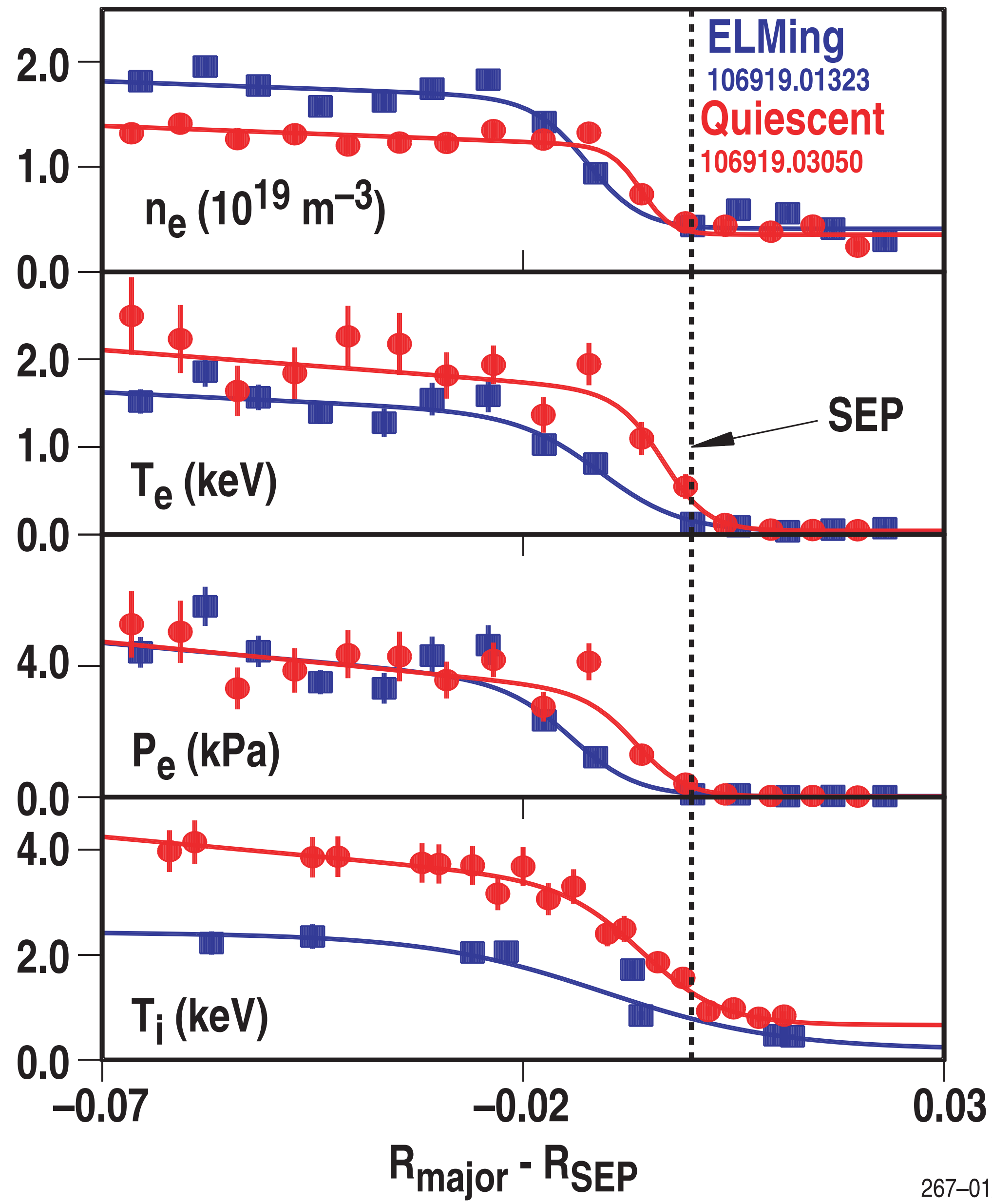
183-01/rs

KEY QUESTIONS FOR QUIESCENT H–MODE

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

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

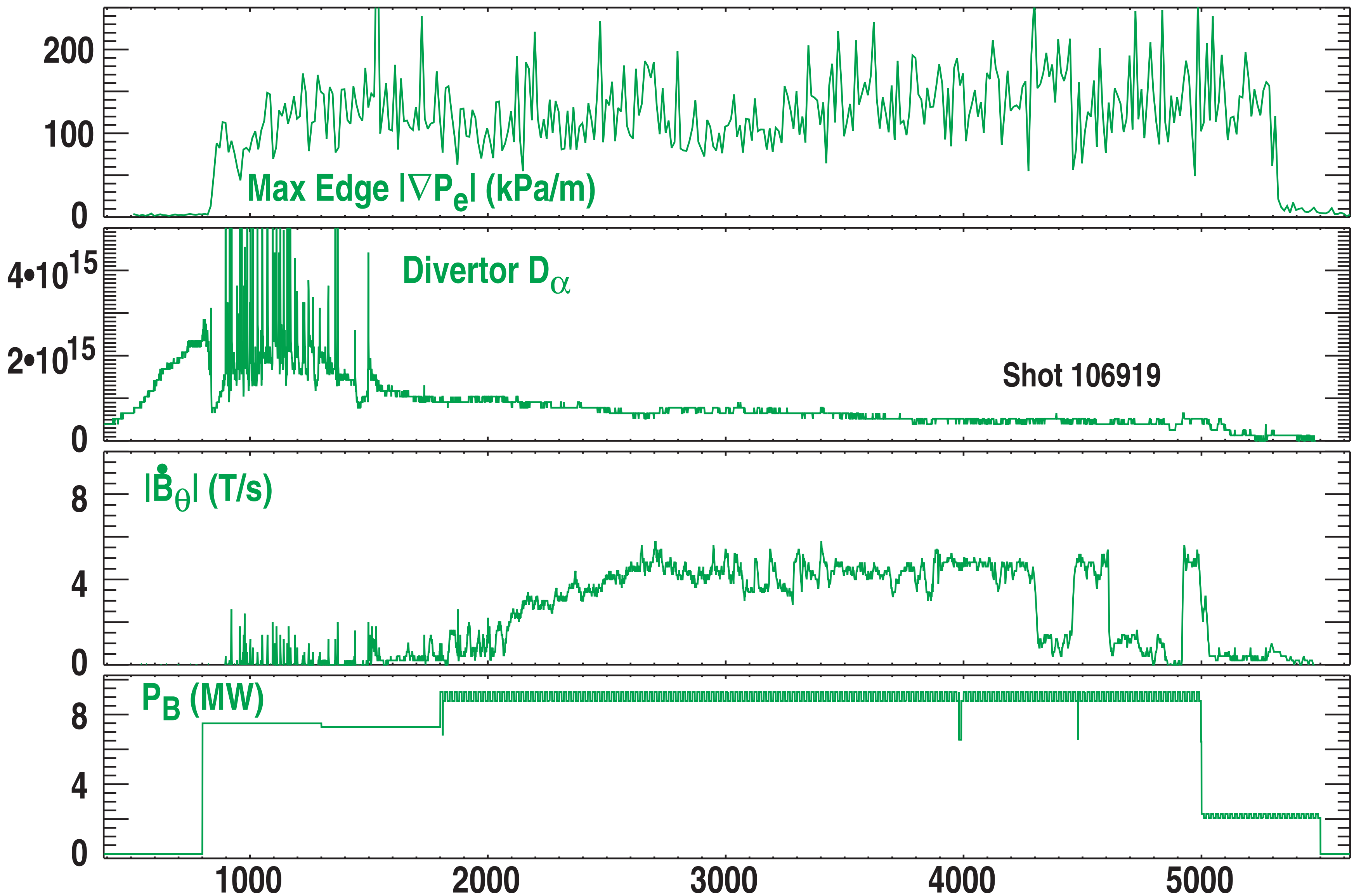
- Edge gradients in quiescent phase are comparable to those in ELMing phase
  - Note high T_i pedestal
- QH–mode edge also has other standard H–mode signatures
  - Edge E_r well
  - Reduced turbulence



DIII–D NATIONAL FUSION FACILITY SAN DIEGO

267–01/KHB/wj

EDGE ∇P_e DOES NOT CHANGE WHEN ELMs DISAPPEAR



DIII–D NATIONAL FUSION FACILITY SAN DIEGO

183–01/KHB/ci

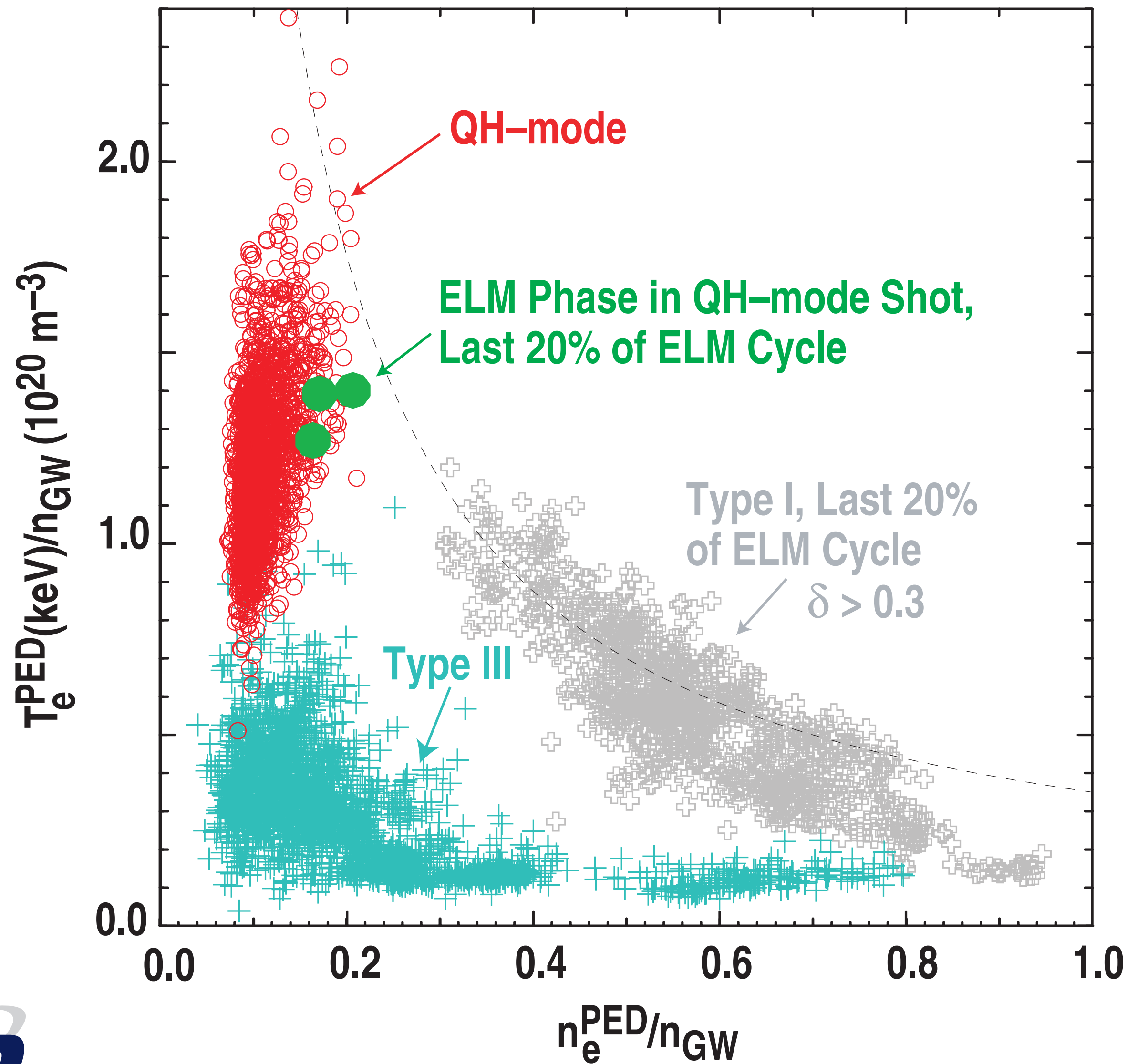
QUIESCENT H–MODE OPERATION SEEN OVER BROAD RANGE OF PLASMA CONDITIONS

- **Key conditions are**
  - Neutral beam injection counter to plasma current at power levels above 3.0 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 ($3.7 \leqq q \leqq 5.8$) explored to date

- **Most work done with $1.0 \leqq I_p$ (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

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

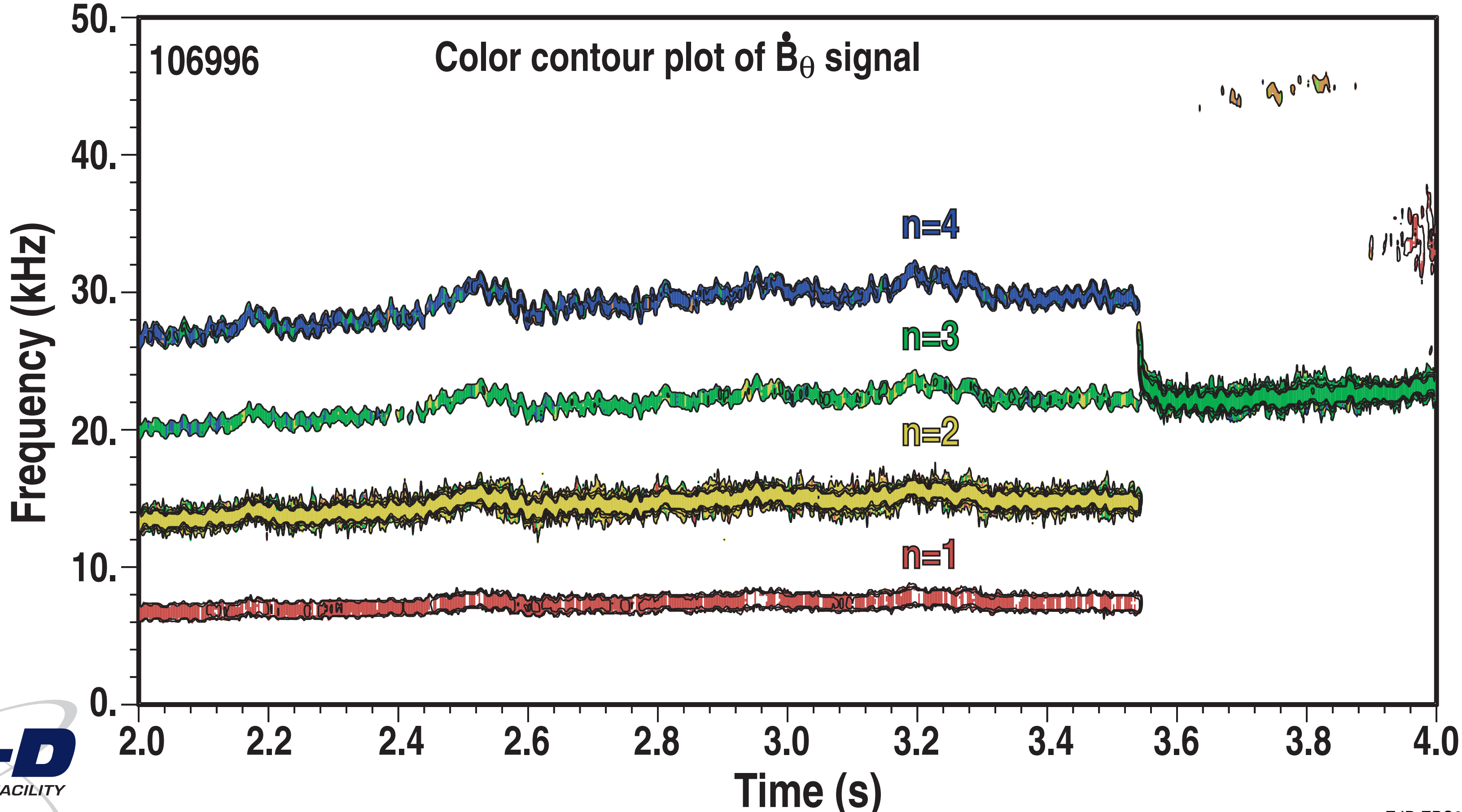


DIII–D NATIONAL FUSION FACILITY SAN DIEGO

267-01/KHB/wj

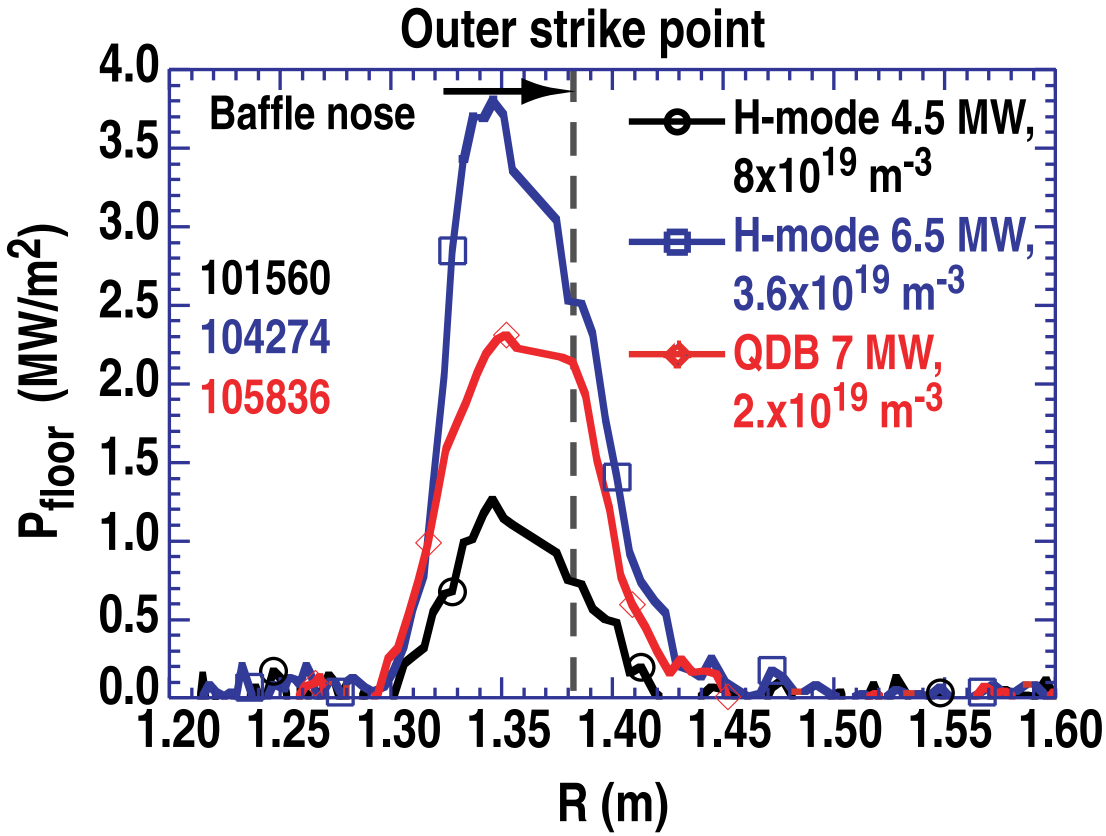
QUIESCENT OPERATION IS USUALLY ASSOCIATED WITH THE PRESENCE OF AN EDGE HARMONIC OSCILLATION (EHO)

- 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



DIII-D NATIONAL FUSION FACILITY SAN DIEGO

QUIESCENT H–MODE OPERATION HAS MODERATE HEAT FLUX TO THE DIVERTOR TARGET PLATES

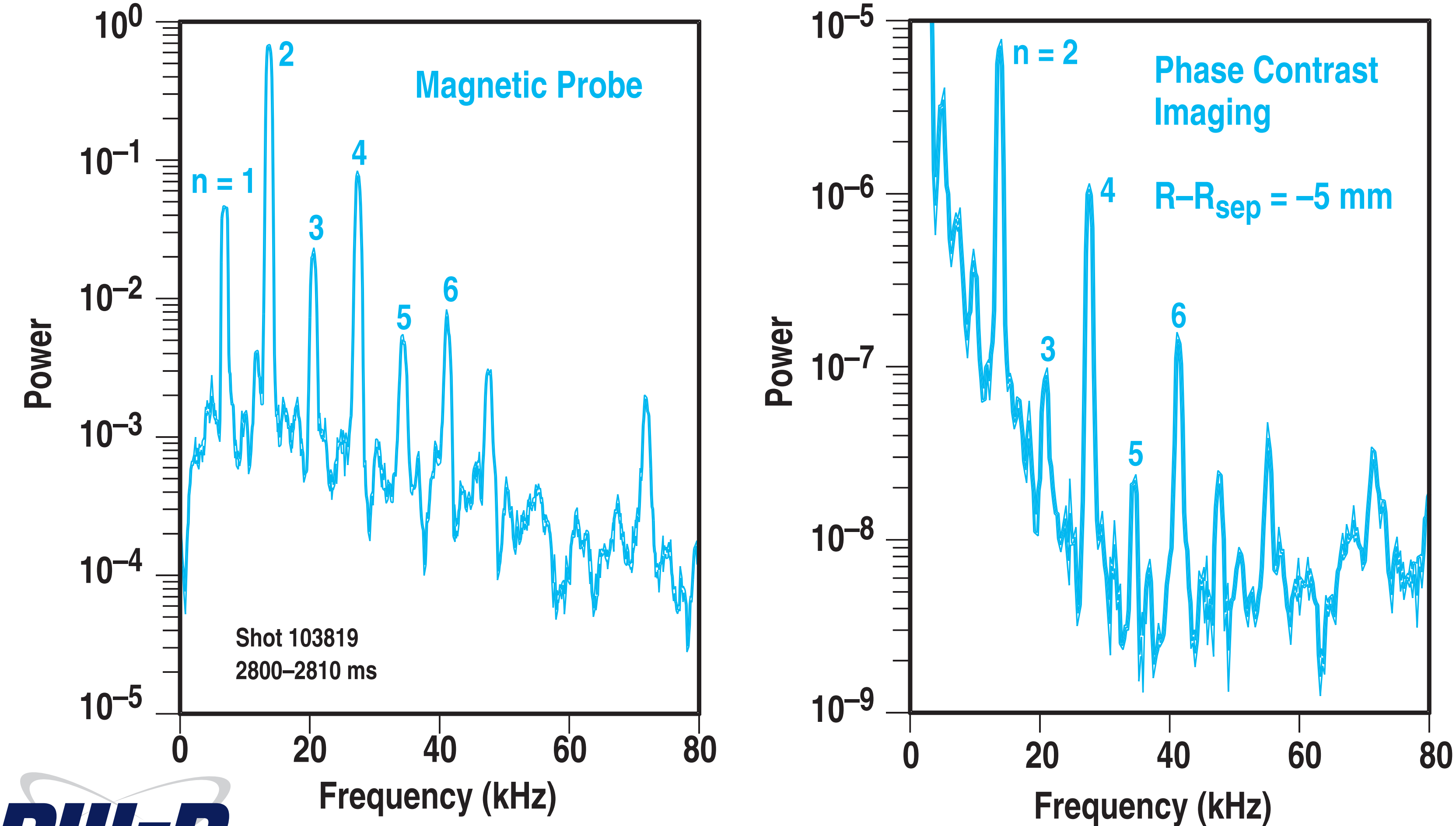


- Edge harmonic oscillation spreads heat flux?
- Note that present-day devices can match anticipated core or edge reactor conditions, but not both
  - Reactor relevant core plasmas in present-day devices may have non-optimal divertor conditions

DIII–D NATIONAL FUSION FACILITY SAN DIEGO

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

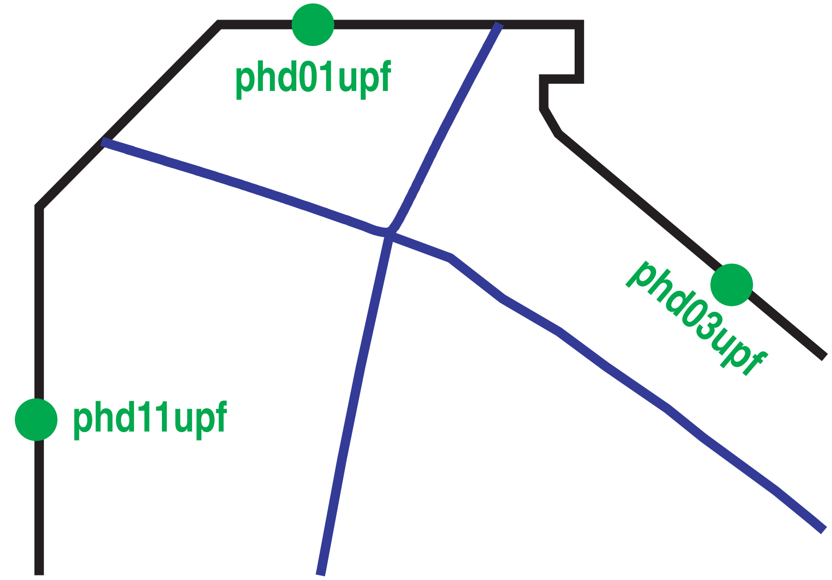
- Presence of $\dot{B}_\theta$ signal demonstrates significant electromagnetic component to oscillation



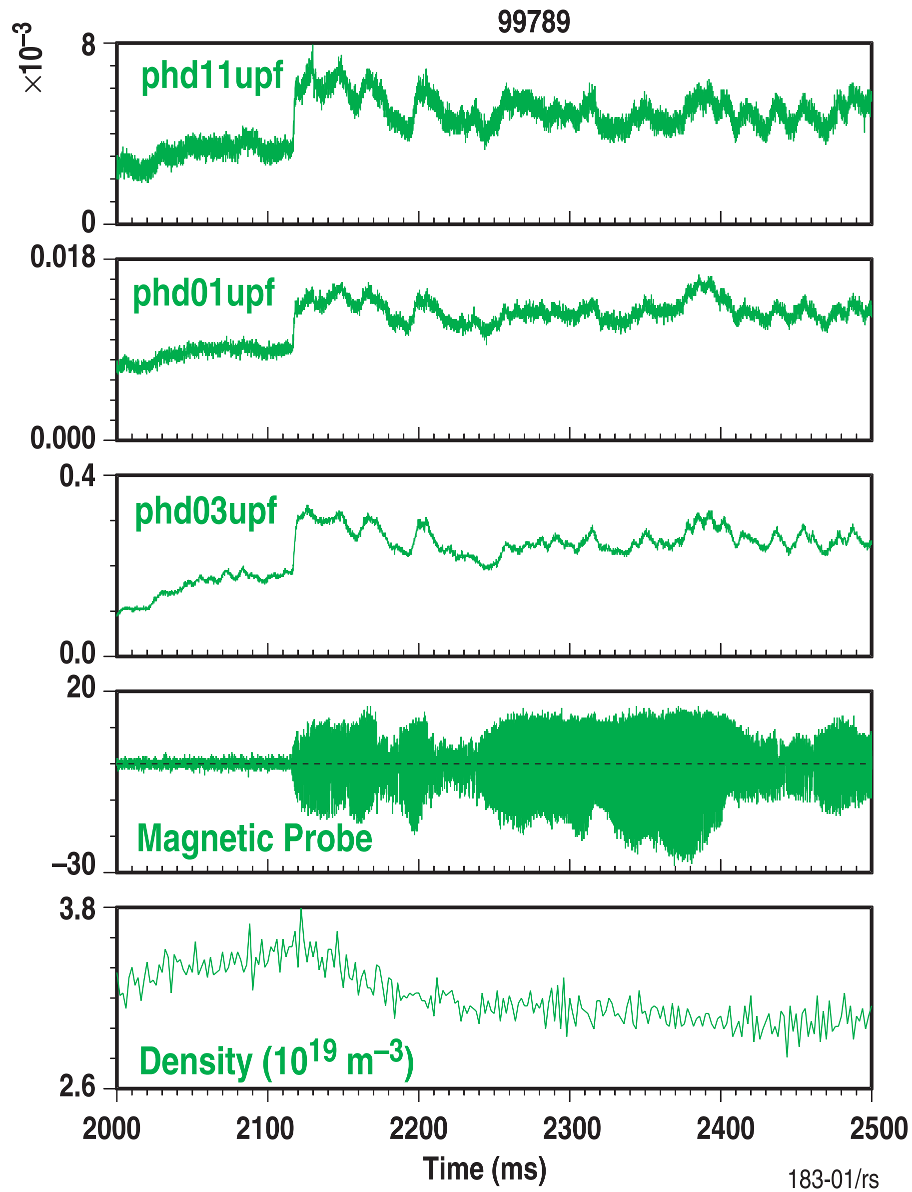
DIII–D
NATIONAL FUSION FACILITY
SAN DIEGO

255-00/rs

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



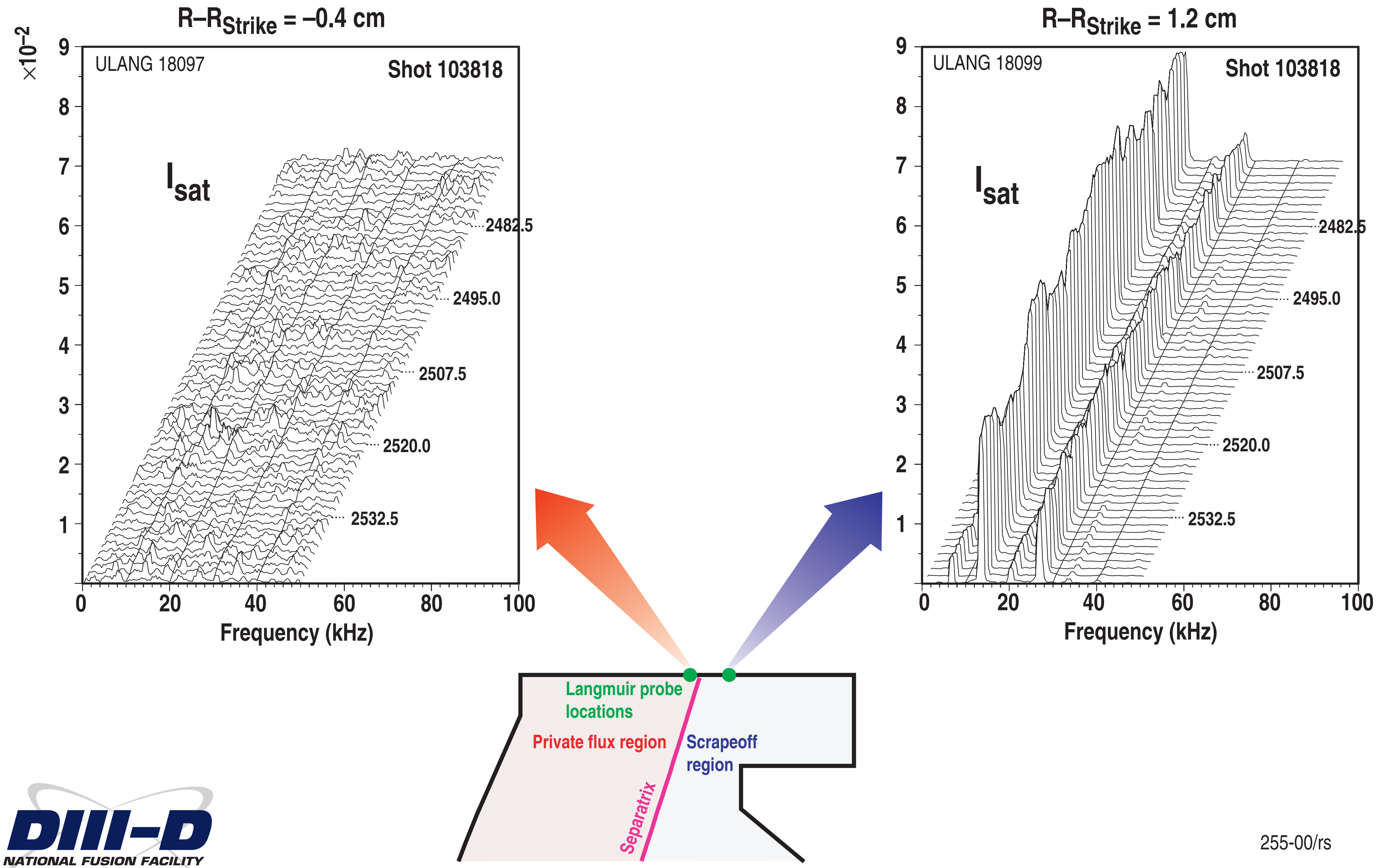
- Divertor shape for 1999 campaign



183-01/rs

DIII–D NATIONAL FUSION FACILITY SAN DIEGO

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

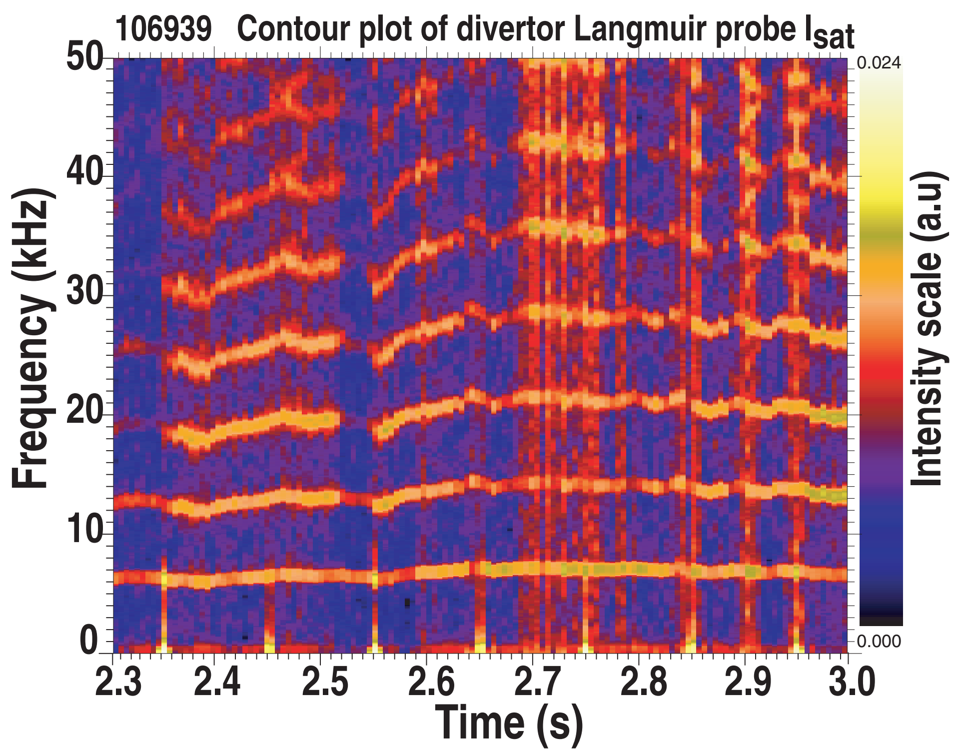


DIII–D
NATIONAL FUSION FACILITY
SAN DIEGO

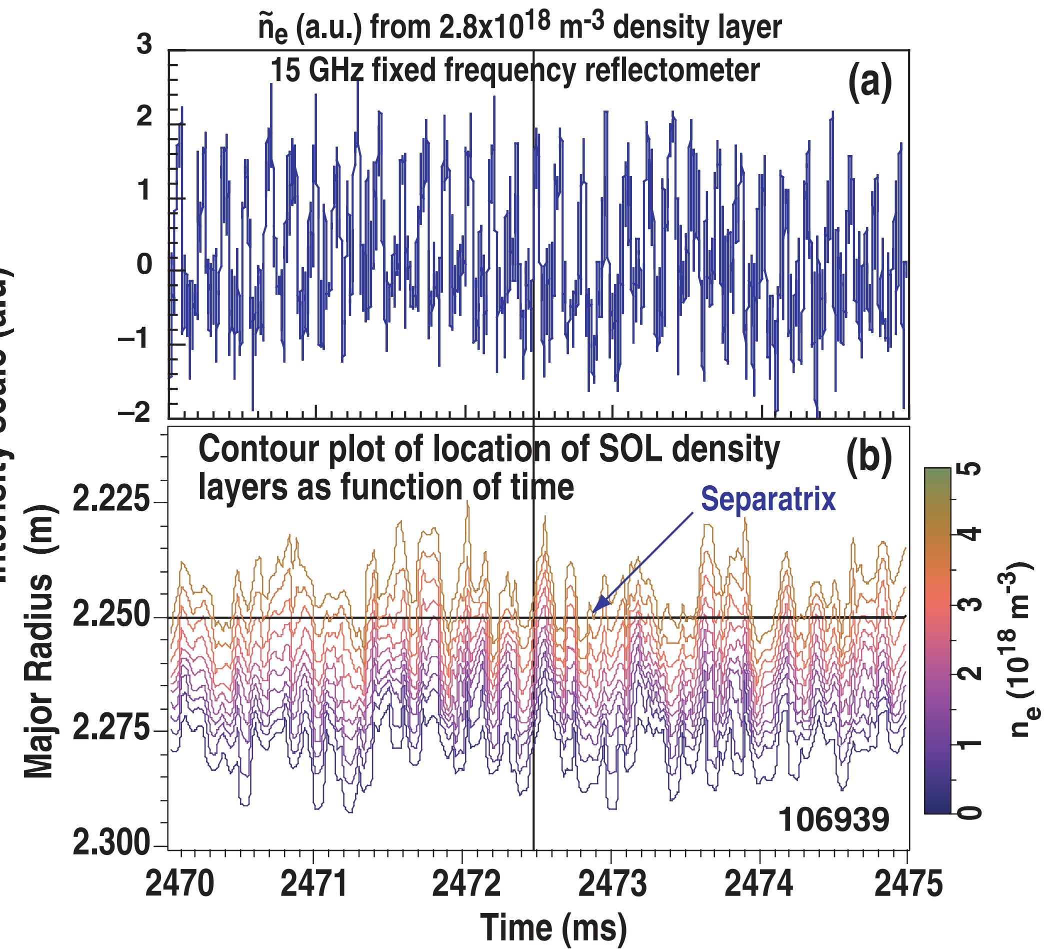
255-00/rs

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

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



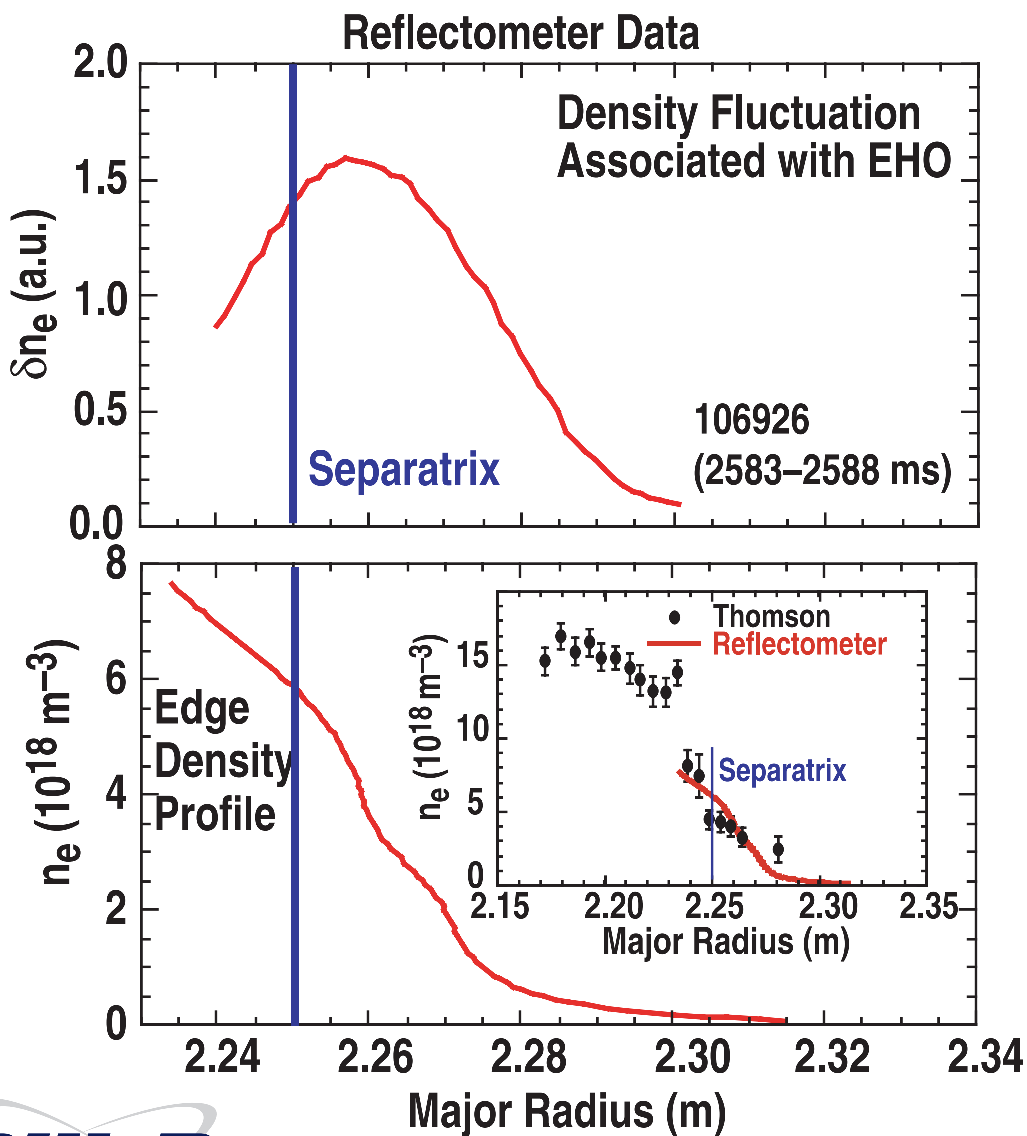
- High resolution profile reflectometer system shows scrape-off layer (SOL) density profile is modulated at EHO frequency



DIII-D NATIONAL FUSION FACILITY SAN DIEGO

183-01/rs

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

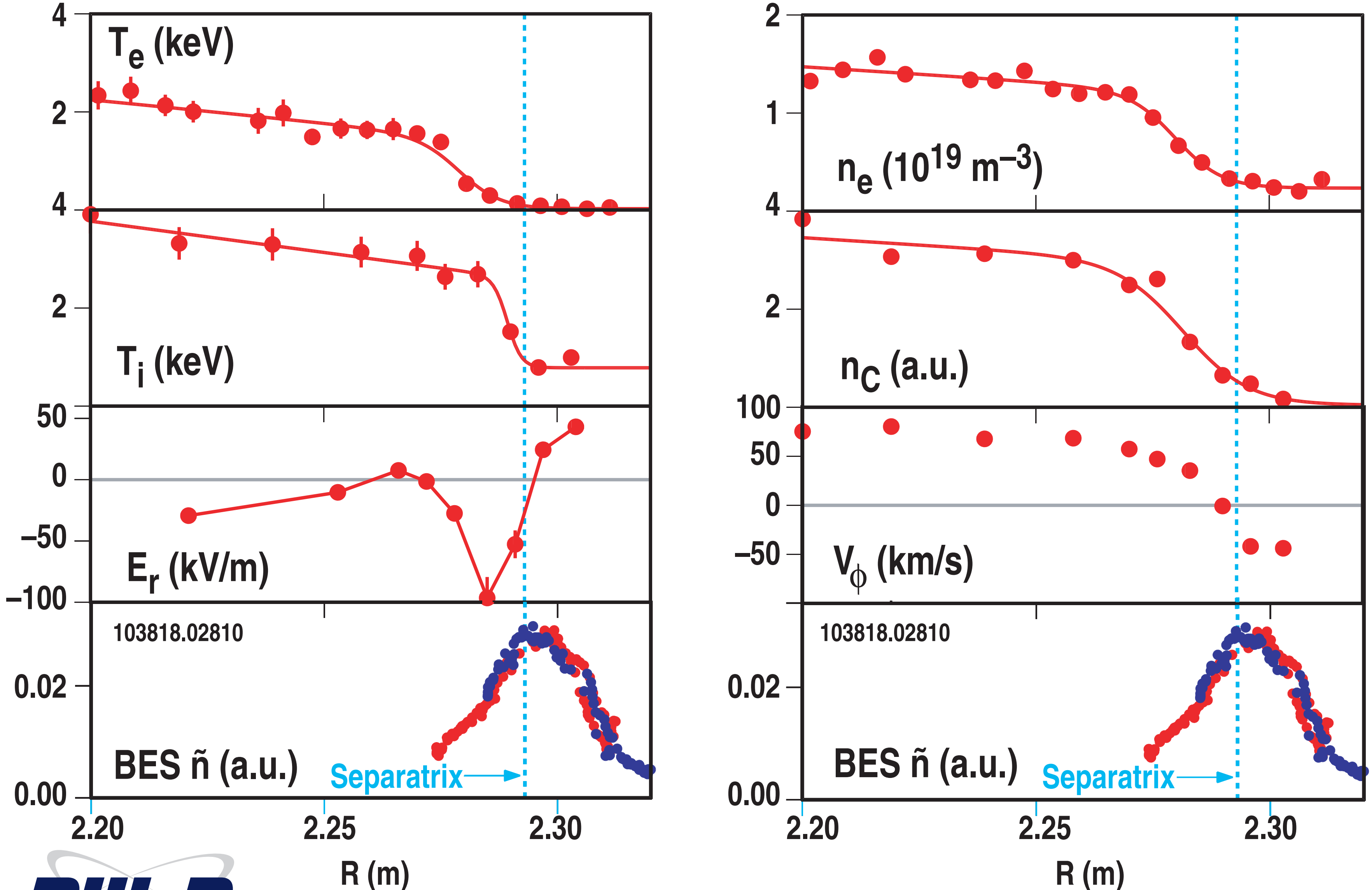


- High time resolution measurements with profile reflectometer system indicate that the EHO is located at the base of the edge profile pedestals, at or slightly outside the separatrix

DIII–D NATIONAL FUSION FACILITY SAN DIEGO

267–01/KHB/wj

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

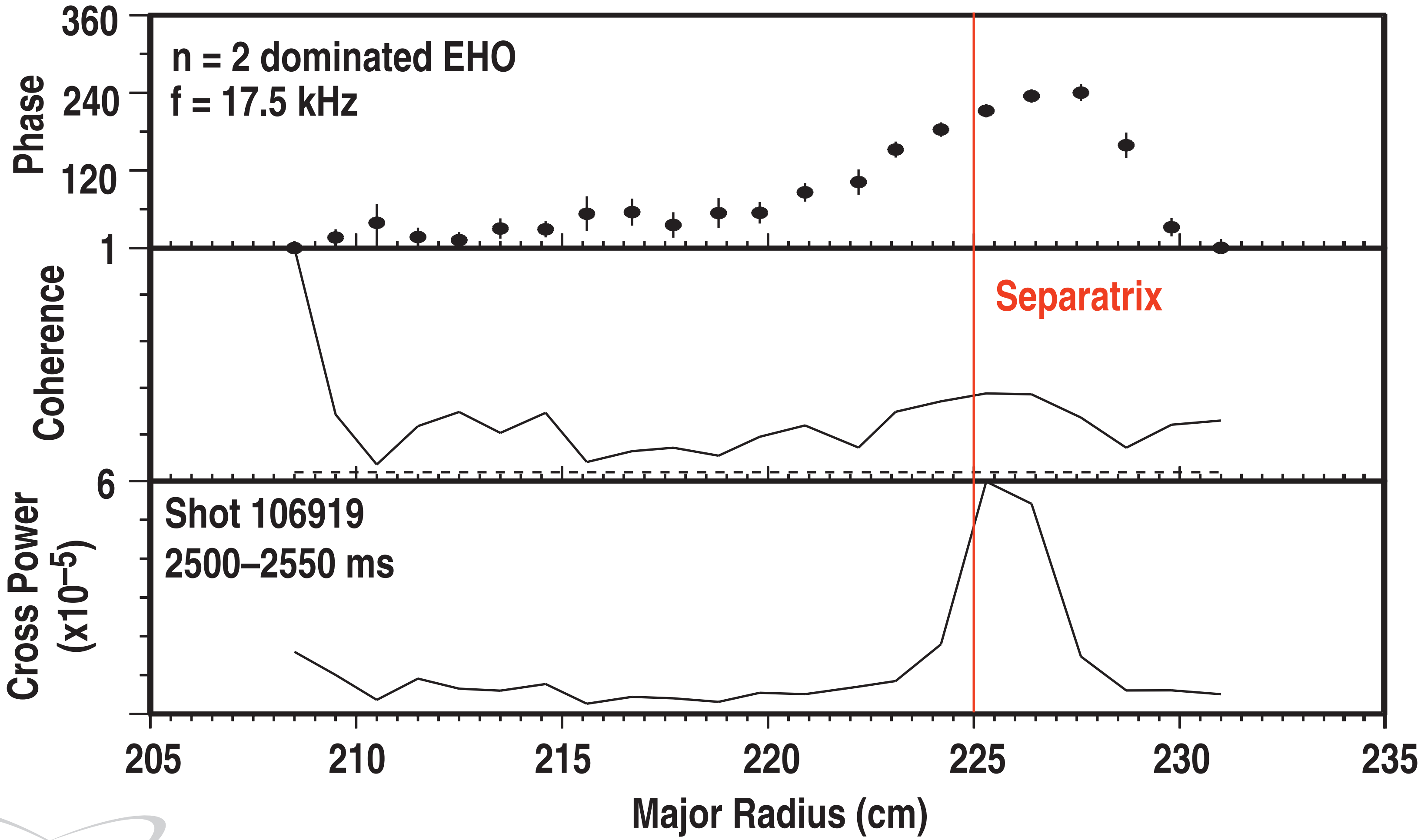


DIII–D
NATIONAL FUSION FACILITY
SAN DIEGO

183–01/KHB/ci

TYPICAL VARIATION OF EHO PHASE WITH RADIUS SHOWS NO SIGN OF TEARING LAYER INSIDE SEPARATRIX

- Phase varies continuously — no 180° reversal across a tearing layer
- ñ measurement from BES radial array

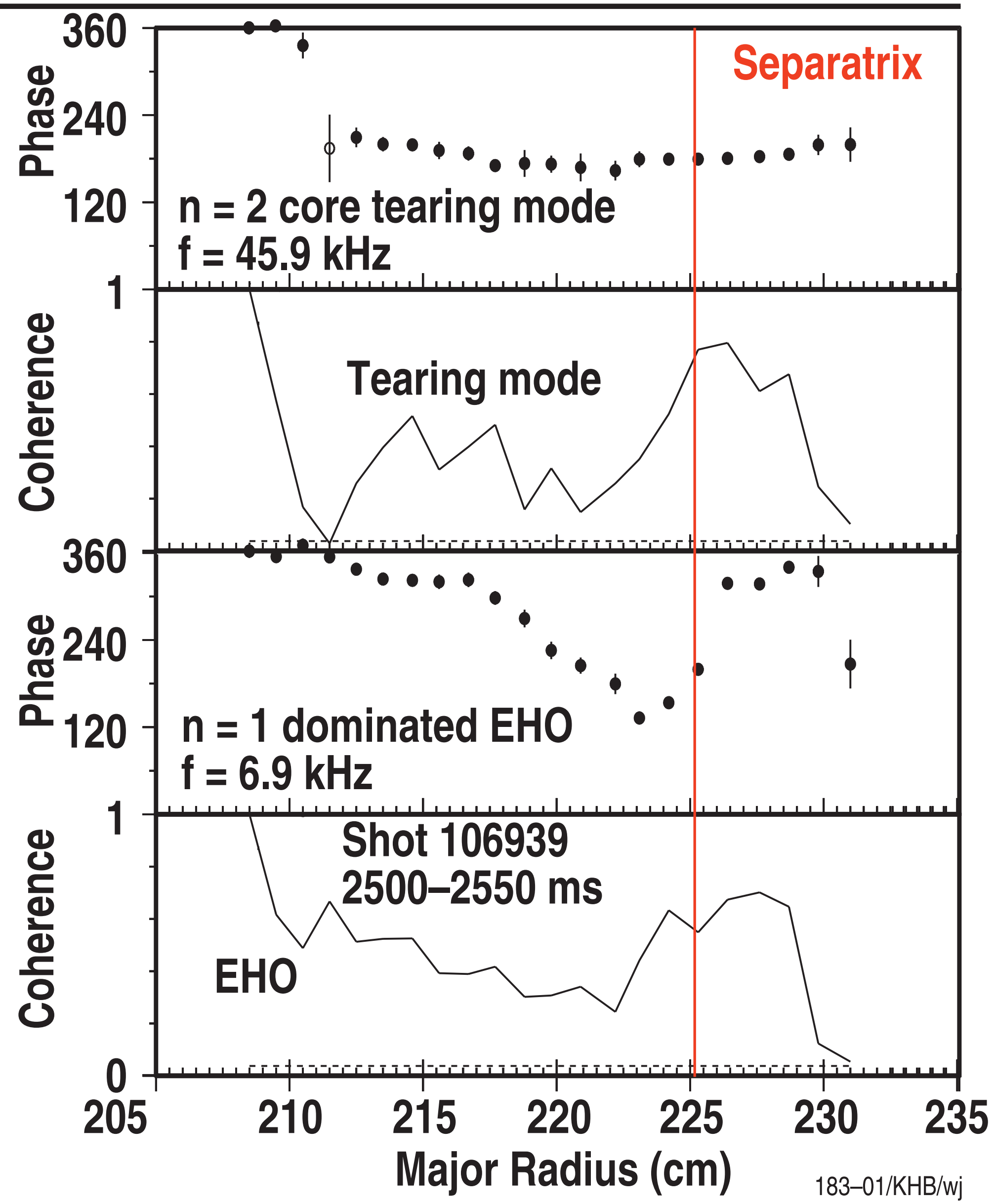


DIII–D
NATIONAL FUSION FACILITY
SAN DIEGO

183–01/KHB/wj

RADICALLY DIFFERENT RADIAL PHASE STRUCTURE DEMONSTRATES THAT EHO IS NOT A TEARING MODE LOCATED AT RATIONAL q SURFACE INSIDE PLASMA

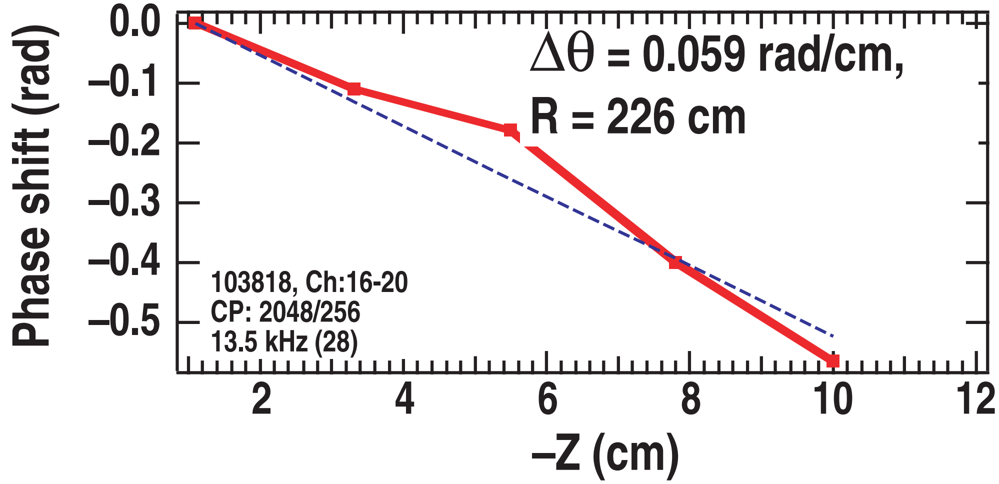
- ñ measurement from BES radial array
- EHO phase at small minor radius is dominated by common mode on beam caused by effect of edge ñ
  - Phase variation with radius shows little local ñ inside 222 cm



DIII–D
NATIONAL FUSION FACILITY
SAN DIEGO

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

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

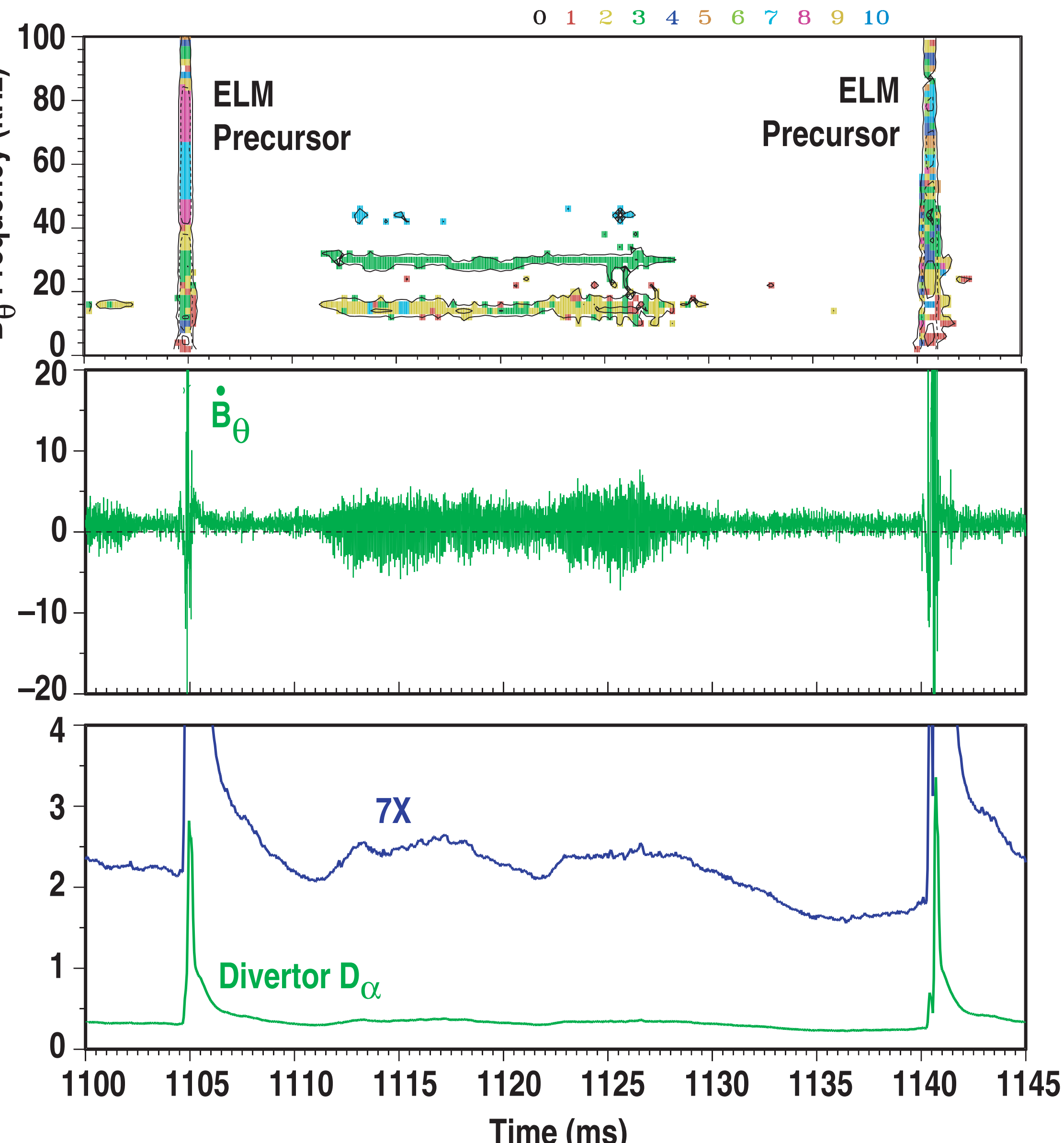


DIII–D
NATIONAL FUSION FACILITY
SAN DIEGO

255-00/rs

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

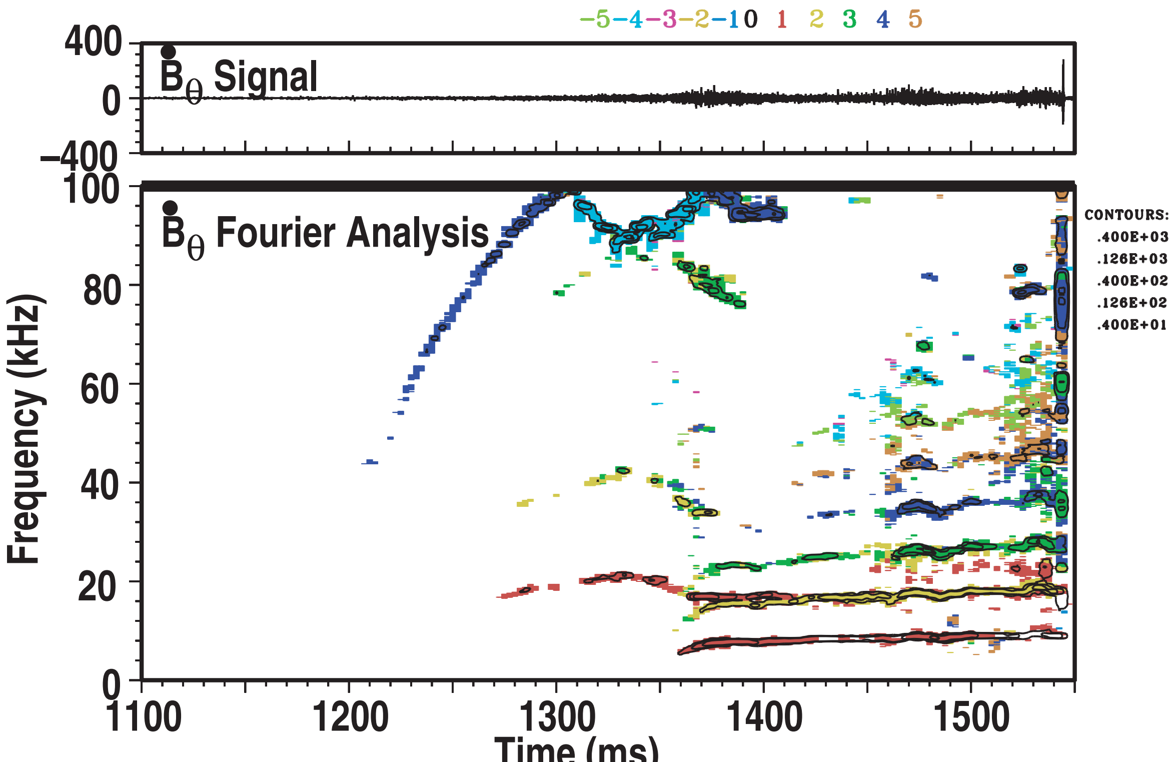


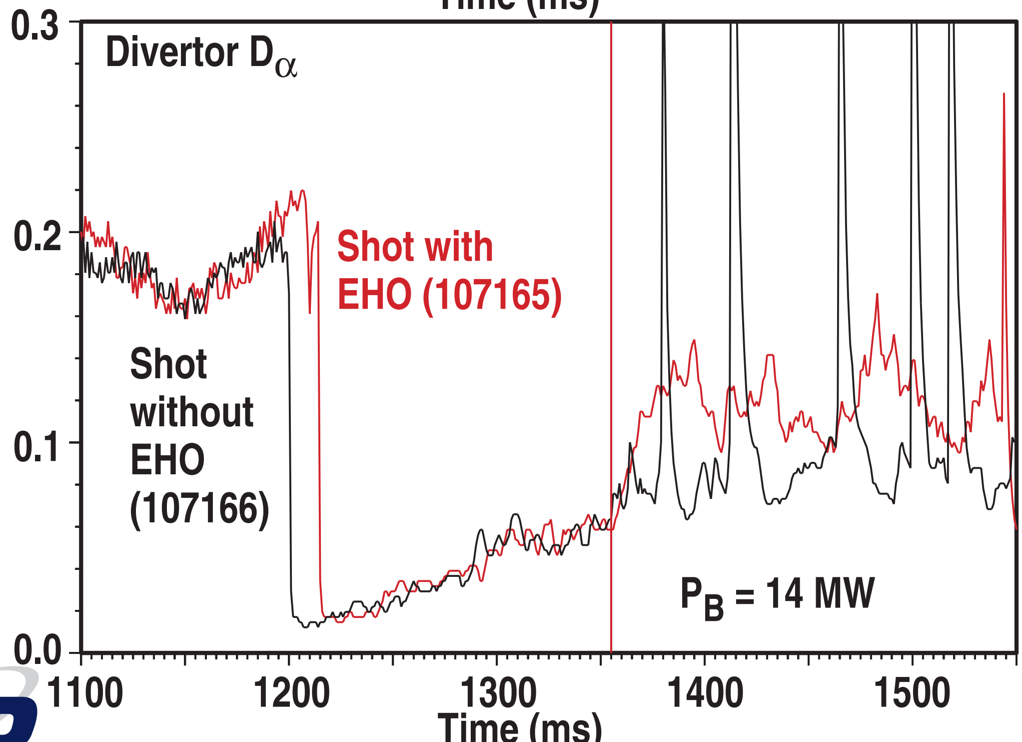
255-00/rs

DIII–D NATIONAL FUSION FACILITY SAN DIEGO

EHO SEEN IN SOME CO-INJECTED DISCHARGES WITH CRYOPUMPING TO LOWER DENSITY

- D_α baseline rises after EHO onset in both co- and counter-injection cases
- Quiescent H–mode NOT seen with co-injection





DIII–D NATIONAL FUSION FACILITY SAN DIEGO

183–01/KHB/wj

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

DIII–D NATIONAL FUSION FACILITY SAN DIEGO

MIT PSFC

183–01/KHB/ci

FUNDAMENTAL QUESTION: WHY DO ELMs GO AWAY?

Two types of hypotheses explain this

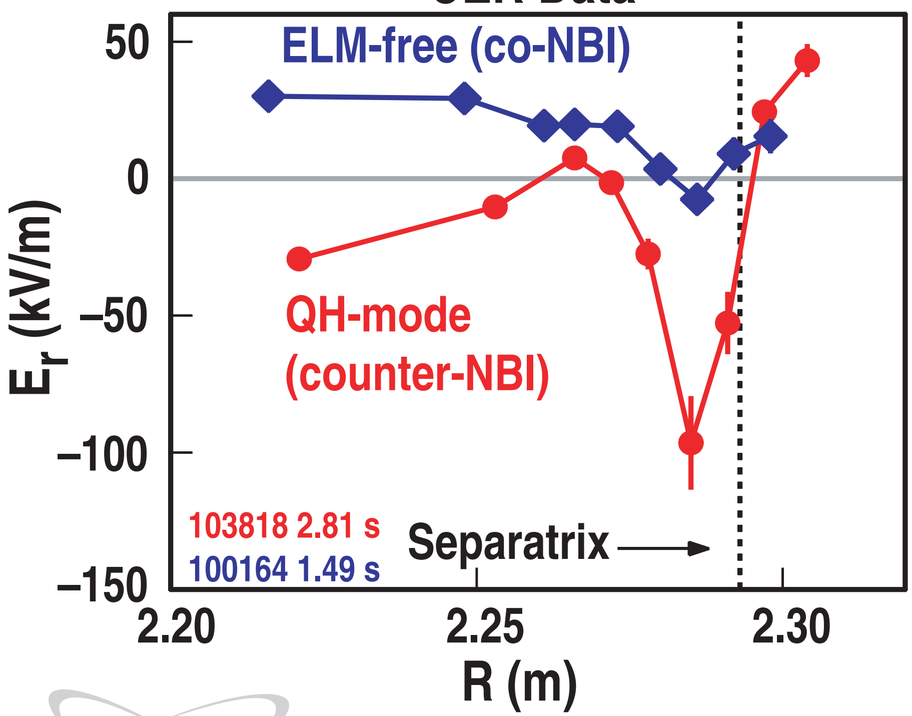
- Edge harmonic oscillation lowers edge pressure gradient below MHD stability limit
  - Not consistent with measurements
  - Pressure gradient doesn't change as ELMs go away and amplitude of edge harmonic oscillation increases
- Stability boundary has moved
  - Finite Larmor radius stabilization by beam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

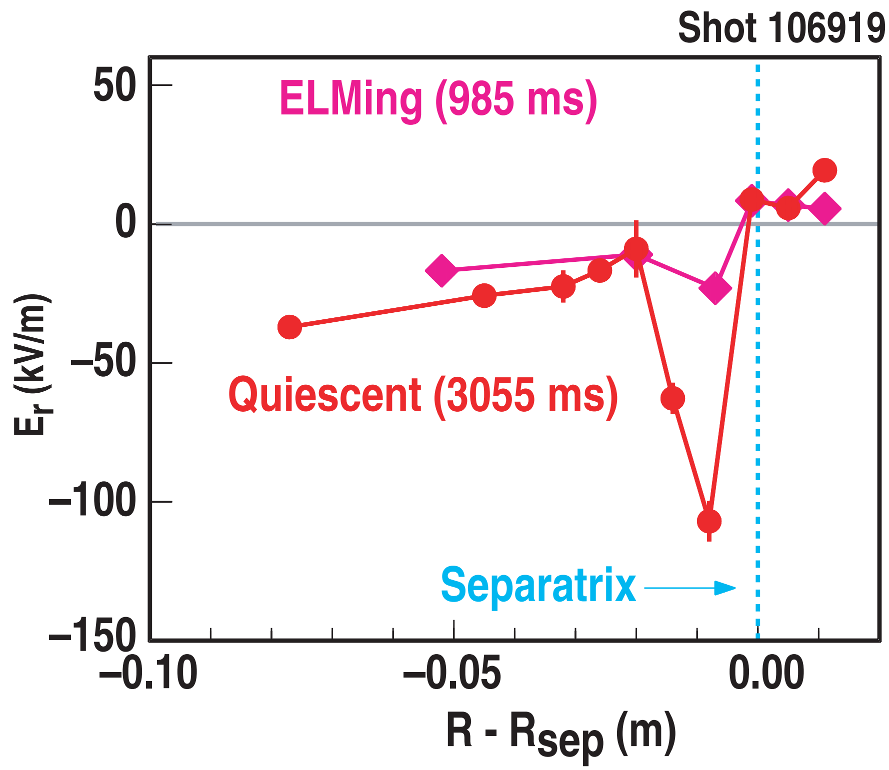
EDGE RADIAL ELECTRIC FIELD WELL IS DEEPER IN QUIESCENT PHASE

- CER data show much deeper E_r well in counter-injected quiescent H–mode than in co-injected ELM-free shot

- CER data show much deeper E_r well in quiescent phase than in ELMing phase of same discharge

CER Data





DIII–D
NATIONAL FUSION FACILITY
SAN DIEGO

267–01/KHB/wj

CONCLUSIONS

- Quiescent H–mode has the steep edge gradients characteristic of H–mode
- Quiescent H–mode operation requires counter-neutral beam injection plus cryopumping to lower the edge density
- Quiescent H–mode has constant density and radiated power levels without ELMs
  - Edge harmonic oscillation or, in one case, a core tearing mode provide the additional particle transport which allows constant density ELM-free operation
- The EHO is a non-sinusoidal electromagnetic oscillation which is localized just outside the separatrix
  - Radial structure is distinct from that expected due to a tearing mode on the q=3 or q=4 surface
  - EHO is not a saturated ELM precursor
- Quiescent H–mode is quite different from enhanced D_α (EDA) operation in Alcator C-Mod
- Why the ELMs go away is a major open issue for future work
  - Strong E_r gradients near plasma edge suggests a role for E_r shear in ELM stabilization
  - Including this effect in MHD stability theory is difficult but extremely important