Edge Similarity Experiments on DIII-D and C-Mod

presented by

Rick Moyer

Center for Energy Research
University of California, San Diego

in collaboration with

D. Mossessian, R.J. Groebner, T. Osborne, N. Brooks, D. Colchin, M. Greenwald, A. Hubbard, L. Lao, C. Rost, D. Rudakov, P. Snider, G. Wang, J.G. Watkins, P. West, S. Wolfe, X.Q. Xu, and L. Zeng

MIT PSFC Q T Y U I O P UC San Diego

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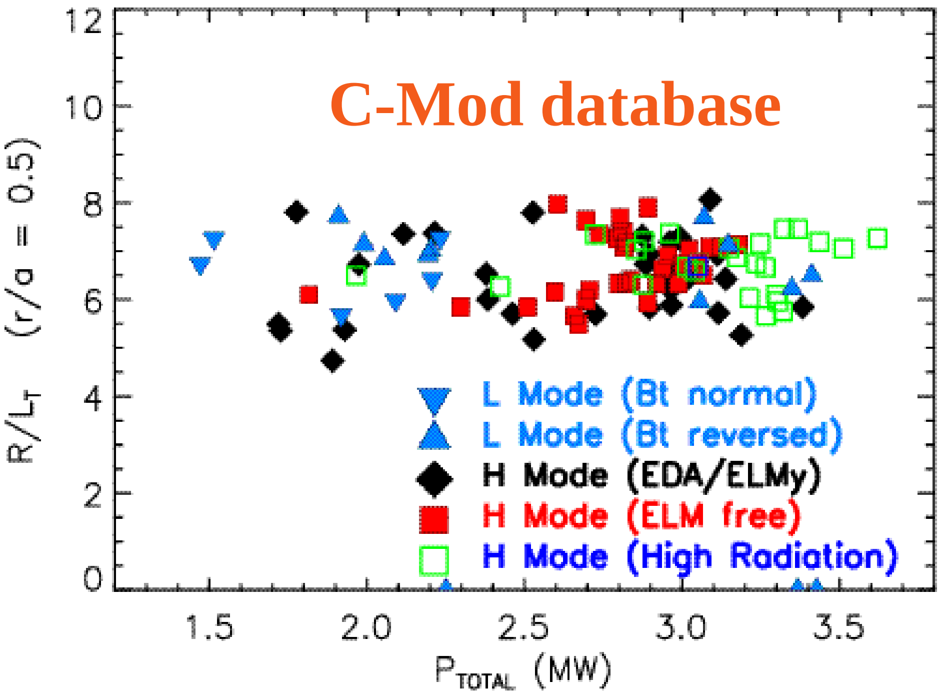
Motivation for experiments on similarity of H-mode pedestals in DIII-D and C-Mod

- **Goal: study the similarity of the H-mode pedestal and its effect on H-mode physics and global plasma confinement in two different tokamaks in plasmas with matched local edge dimensionless parameters.**
  - **Investigate the relative importance of "plasma physics" versus "atomic physics" in controlling the pedestal stability, height, and width**
  - **Investigate the scaling of pedestal parameters with dimensionless parameters and machine size**
  - **Correlate H-mode behavior (ELM-free, ELMy, EDA…) with shape and pedestal plasma parameters**

The pedestal temperature plays an important role in setting core plasma performance.

- In critical gradient models, the pedestal temperature is an additive offset to the core temperature
- In critical gradient length models, the core temperature is a multiplicative factor times the pedestal temperature (what is predicted by ITG/ETG theories.
- C-Mod database shows that the temperature gradient scale length L_T at ρ=0.5 is independent of input power and confinement mode!



Courtesy M. Greenwald

- Need predictive capability to scale to next generation devices

Experimental approach: obtain H-mode pedestals with matched dimensionless parameters

- **Study similarity of H-mode pedestal on 2 tokamaks in plasmas with:**
  - **dimensionless parameters (β,ρ*, ν*, q_{95}) matched at the top of the pedestal**
  - **matched shape (κ,δ, and ε) → stability**

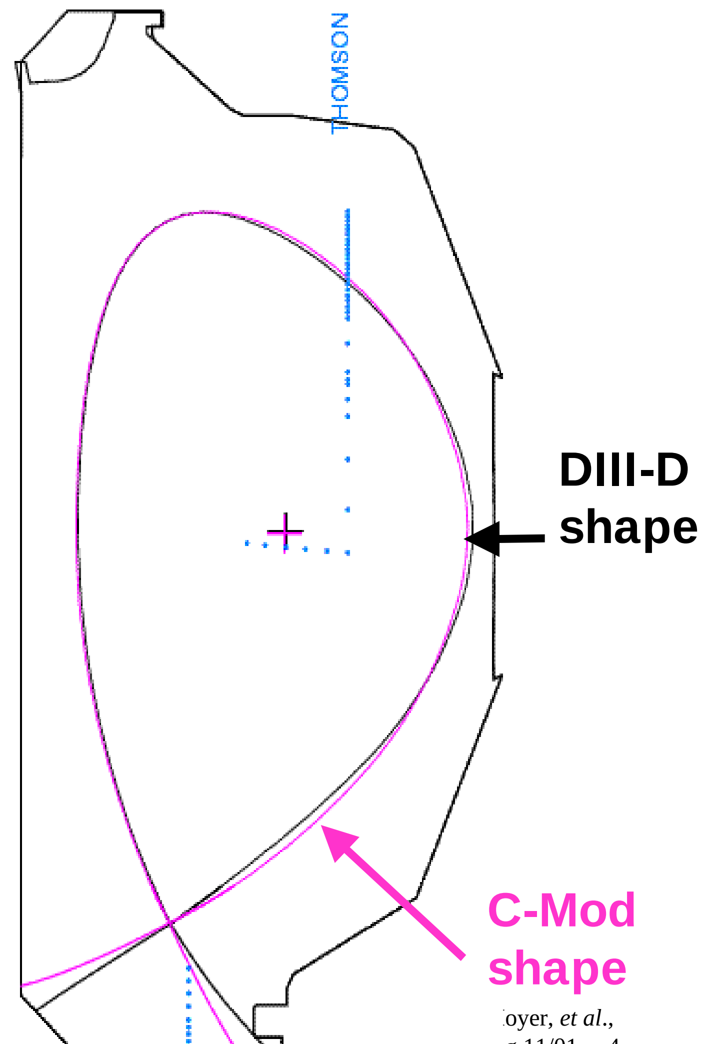
- **Target dimensionless parameters:**

$$\nu \sim \frac{a n_e}{T_e^2} \approx 2 \qquad \rho \sim \frac{T_e^{1/2}}{B_T a} \approx 5\times 10^{-3}$$

$$q \sim \frac{a B_T}{I_p} \approx 4.5 \qquad \beta \sim \frac{T_e n_e}{B_T^2} \approx 5\times 10^{-3}$$

$$\varepsilon = \frac{a}{R} \approx 0.3$$

D. Mossessian **Oral CO1.006**
Monday afternoon



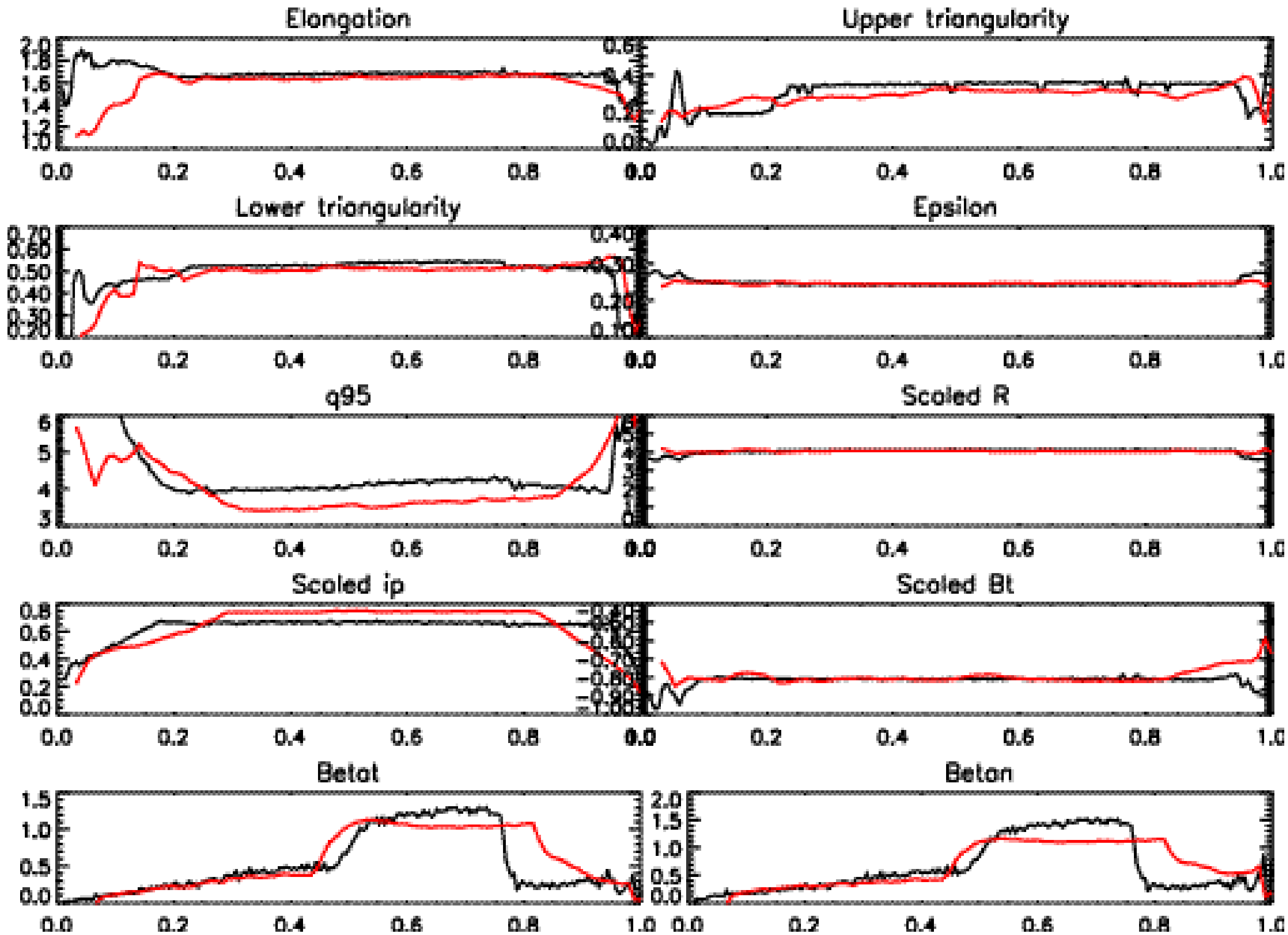
Match local edge dimensionless parameters at top of pedestal in H-mode.

- **Run DIII-D plasma to match typical C-Mod EDA and ELMy H-modes.**

Parameter	C-Mod	DIII-D	Scaling
R	0.7 m	1.7 m	~a
a	0.2 m	0.48 m	~a
ε	0.28	0.28	
B_T	5.4 T	1.8 T	$\sim a^{-5/4}$
I_p	1 MA	0.73 MA	$\sim a^{-1/4}$
n_e	3e20 m^{-3}	5e19 m^{-3}	$\sim a^{-2}$
T_e	600 eV	390 eV	$\sim a^{-1/2}$

Comparison of shape and global plasma parameters for DIII-D (black) and C-Mod (red).

- **DIII-D I_p, $B_{T,}$ and timebase scaled with machine size. β_t (Betat) and β_n (Betan) are volume averaged values**



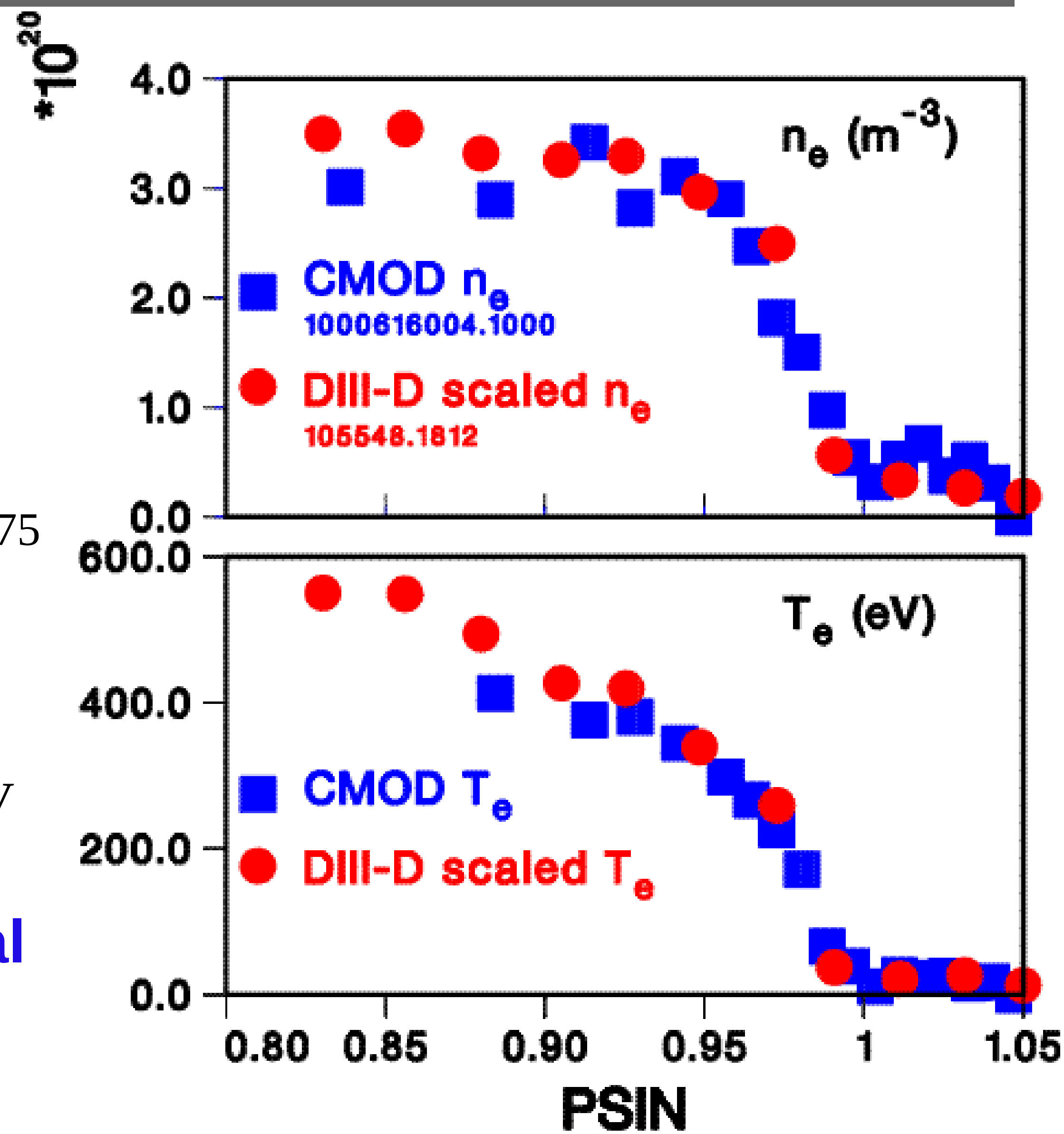
A good match in pedestal profiles was obtained at a power close to the expected scaling

- **Edge profiles at 1812 ms (DIII-D) 1 s (C-Mod EDA)**
- **Power through pedestal should scale as:**

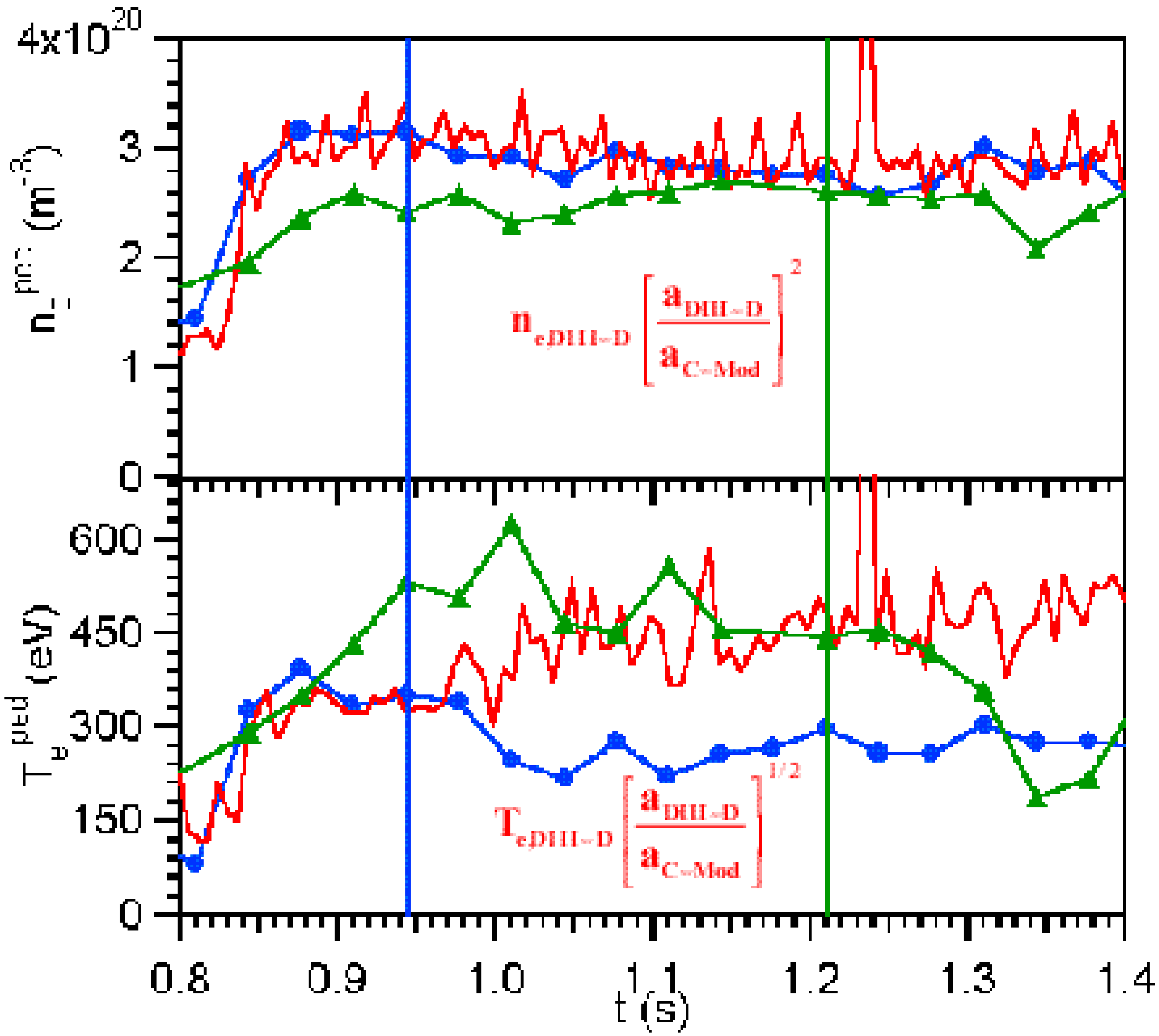
$$P_{sep}^{D3D} \sim P_{sep}^{CMod} \left(\frac{a^{CMod}}{a^{D3D}} \right)^{0.75}$$

$$\approx 1.15e6 \left(\frac{.22}{.56} \right)^{0.75} \approx 570\,kW$$

Compared to actual 490 kW



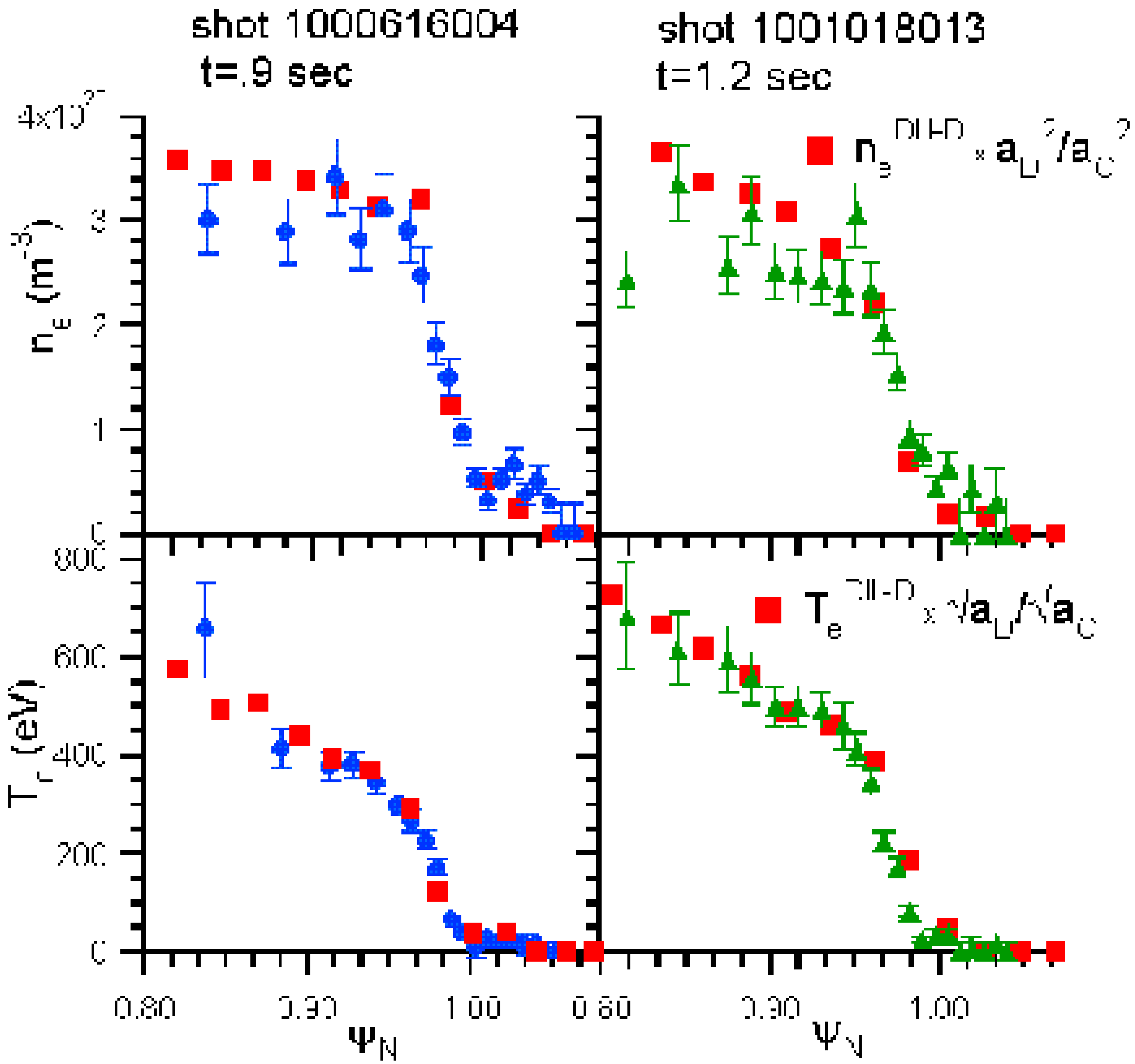
Dimensionlessly similar pedestals were obtained for EDA and ELMy C-Mod discharges.



- **DIII-D 105548 (red)**
- **C-Mod EDA 1000616004 (blue)**
- **C-Mod ELMy 1001018013 (green)**

Figure from:
D. Mossessian
Oral CO1.006
Monday afternoon

Dimensionless plasma parameters match across the entire transport barrier region.



For discharges with similar parameters at top of the pedestal

DIII-D & C-Mod have the same pedestal width in flux coordinates

➜pedestal width scales with machine size

Figure from:
D. Mossessian
Oral CO1.006
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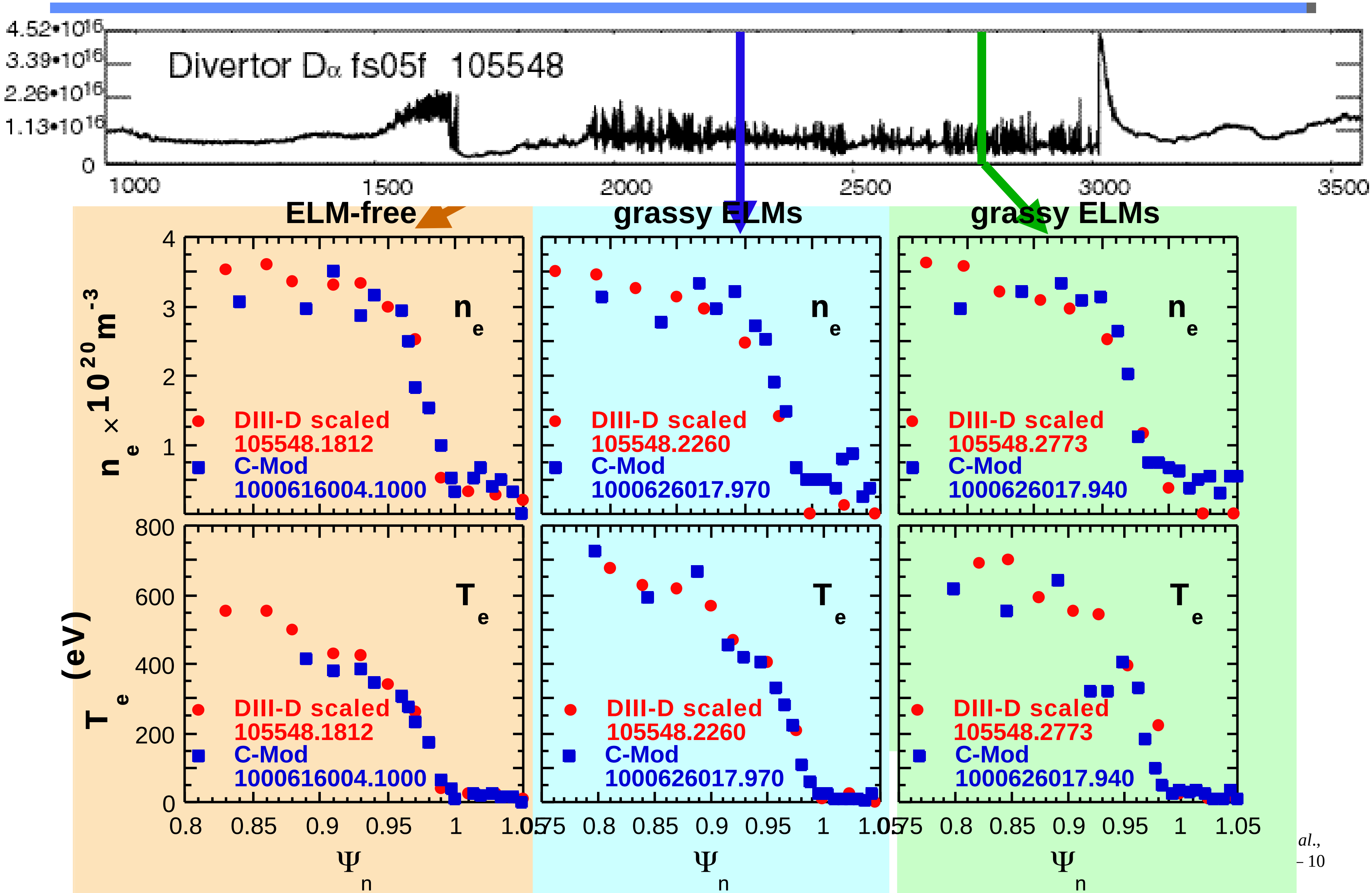
DIII-D discharges evolved into dimensionally similar to C-Mod high β_p ELMy H-modes.



al.,
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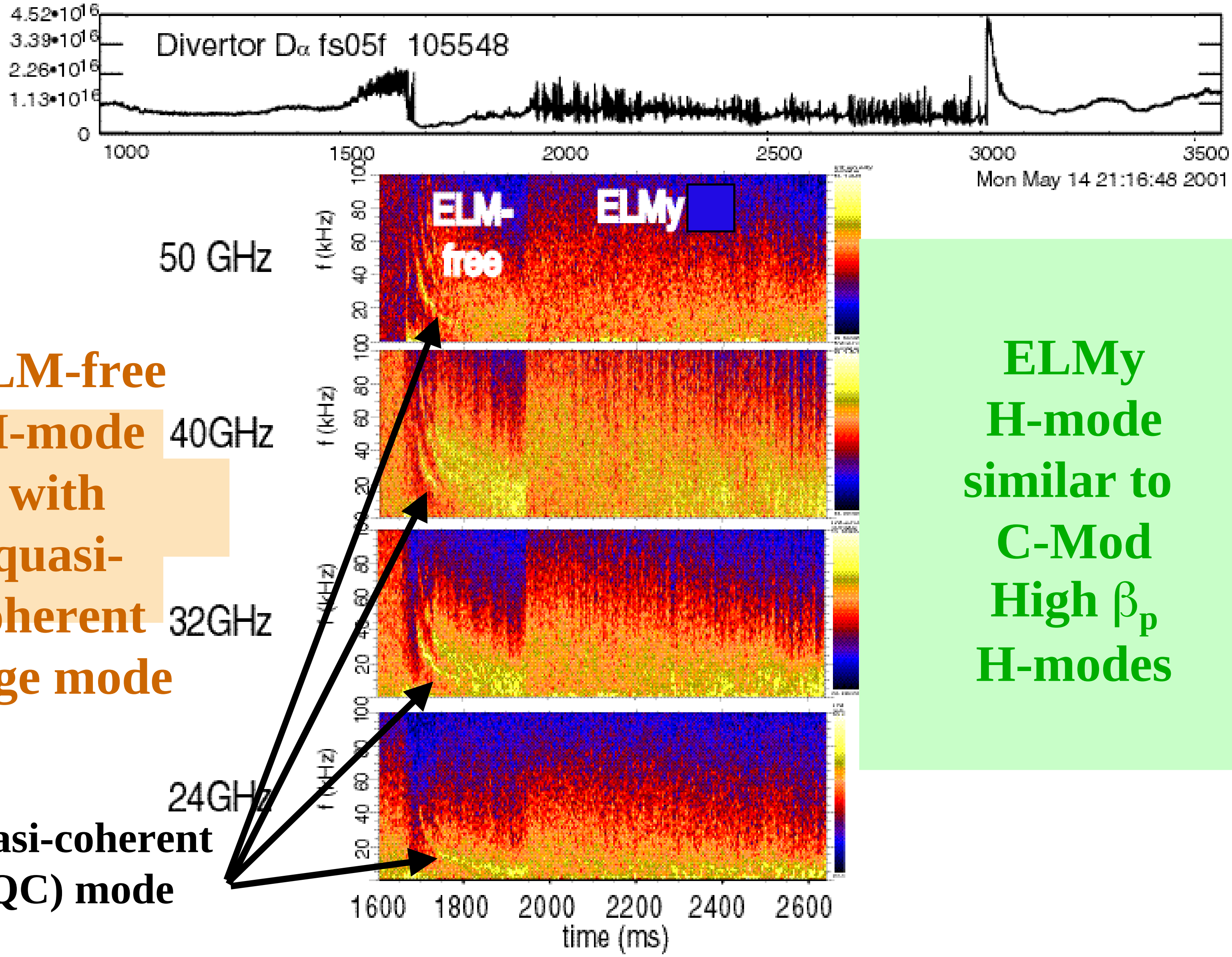
Discharges with matched dimensionless pedestals have similar ELM behavior



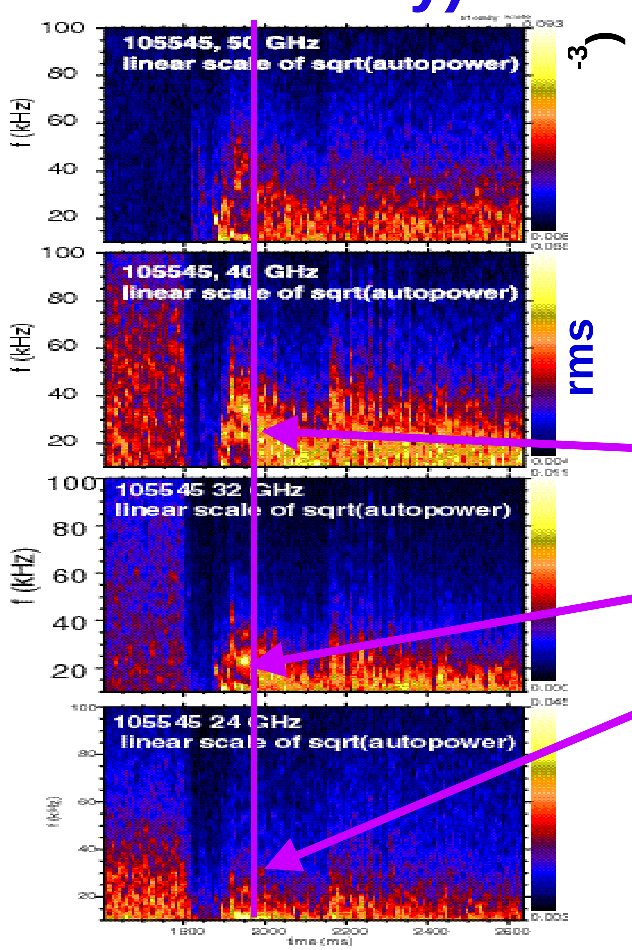
ELM-free H-mode with quasi-coherent edge mode

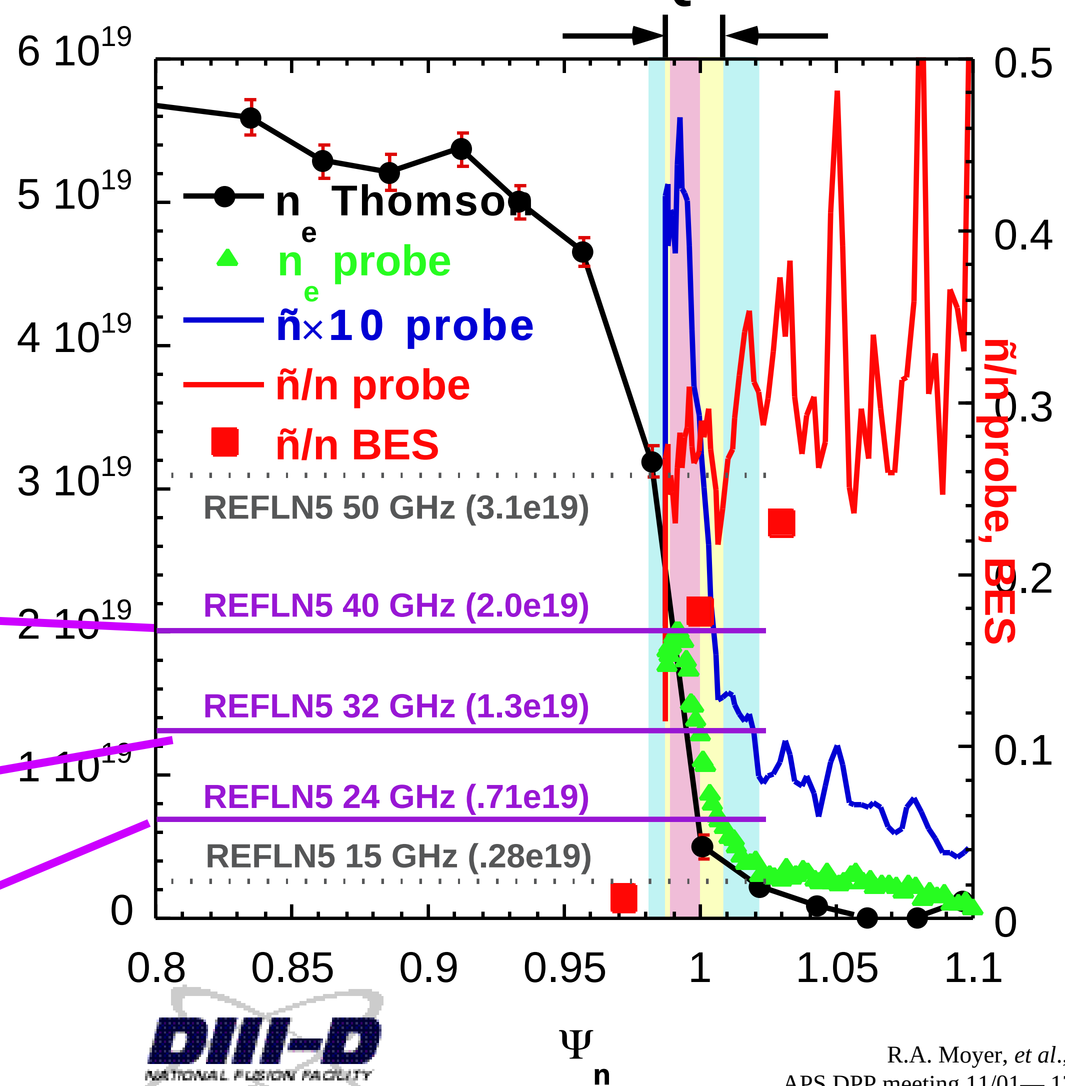
Quasi-coherent (QC) mode

ELMy H-mode similar to C-Mod High β_p H-modes

Quasi-Coherent mode is located in the lower half of the density pedestal.

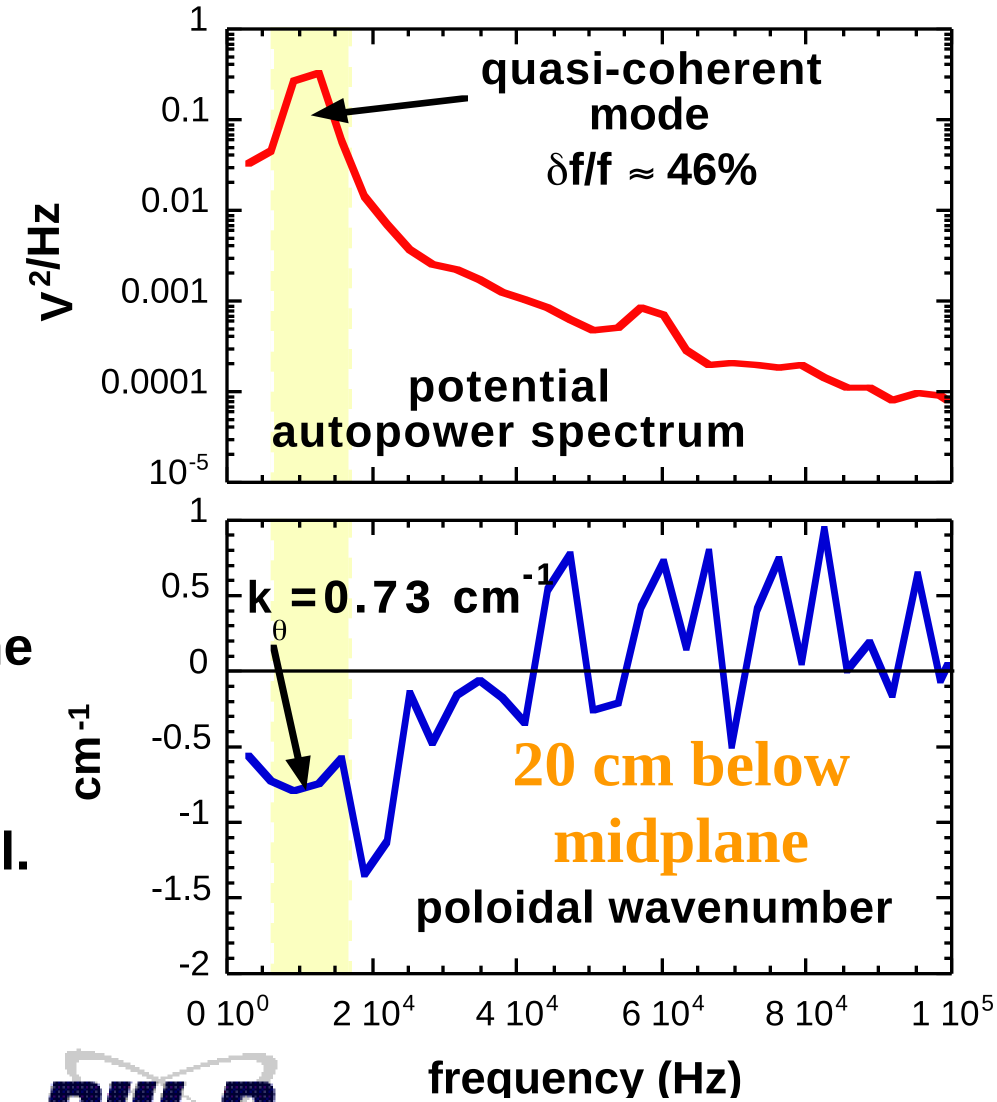
- **Location verified by probe, BES, reflectometry)**





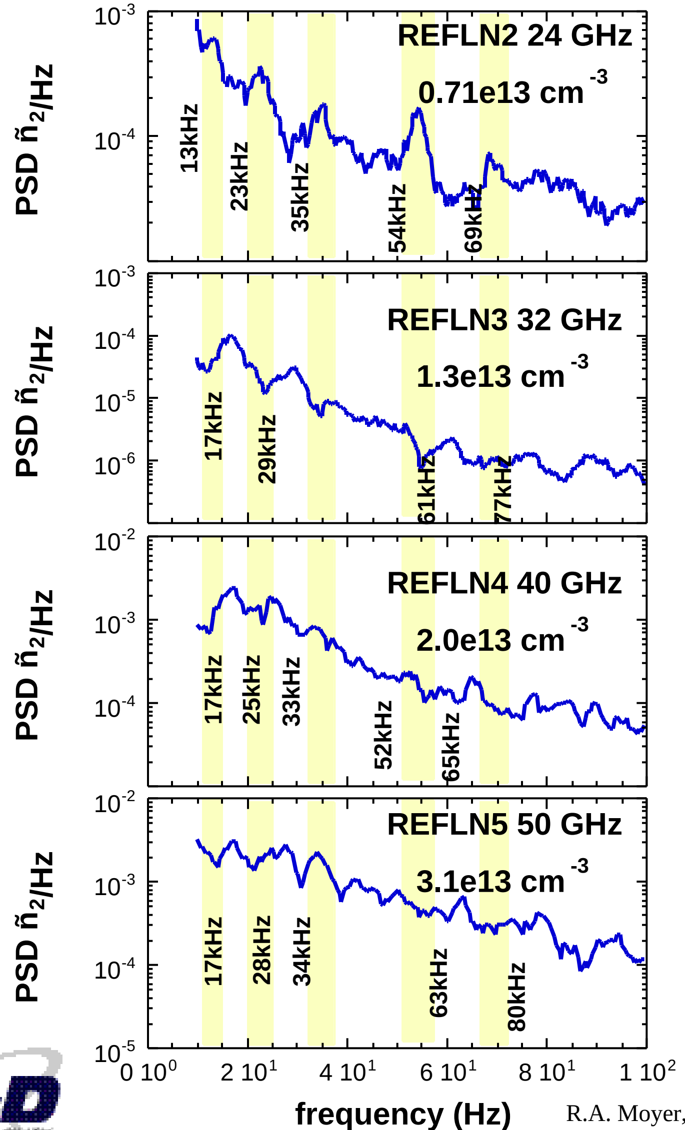
QC mode poloidal wavenumber scales with device size.

- **k_θ varies with poloidal angle in C-Mod:**
  - **C-Mod outboard midplane**
    k_θ = 1.2–1.5 cm^{-1}
  - **DIII-D outboard midplane**
    k_θ = 0.52–0.63 cm^{-1} (BES) × (.56/.22) = 1.3–1.6 cm^{-1} in C-Mod
  - **DIII-D 20 cm below midplane**
    k_θ = 0.73 cm^{-1} (probe) ➔ k_θ increases toward X-point like C-Mod and BOUT simul.
  - **Effective poloidal mode number m = 40-50**
  - **Edge q = 4 ➔ n = 10-12 consistent with C-Mod**



QC-mode consists of several quasi-coherent frequencies that vary with radius.

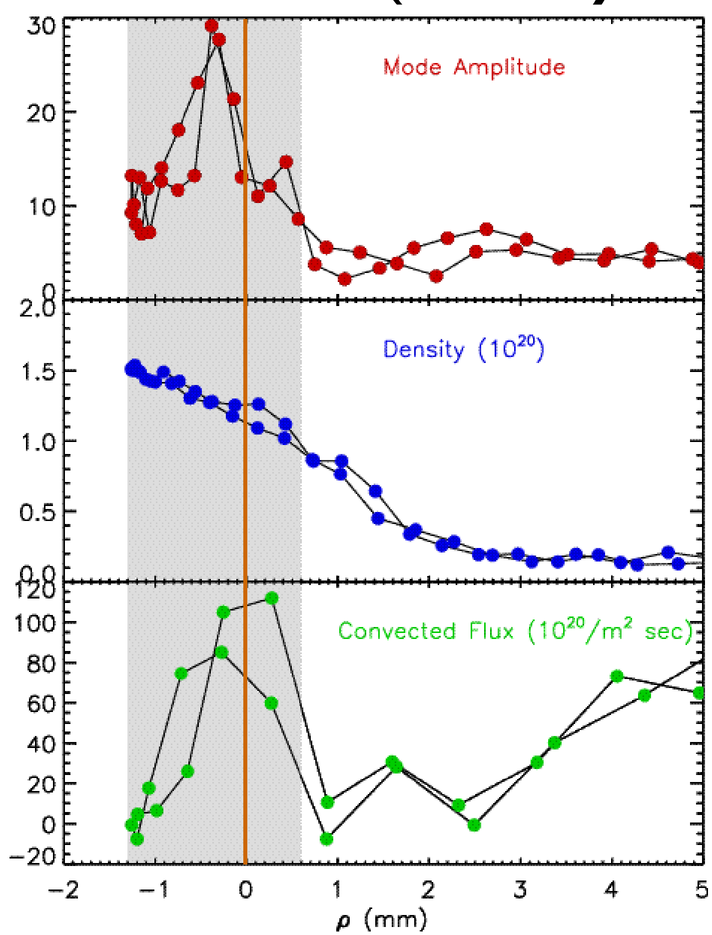
- **Base frequency is 12–13 kHz**
- **Structure is NOT harmonic!**
- **BES sees double peaks at 11and 14 kHz but nothing at higher frequencies**
- **Probe sees a single peak at 13 kHz, and a second peak at 58 kHz**



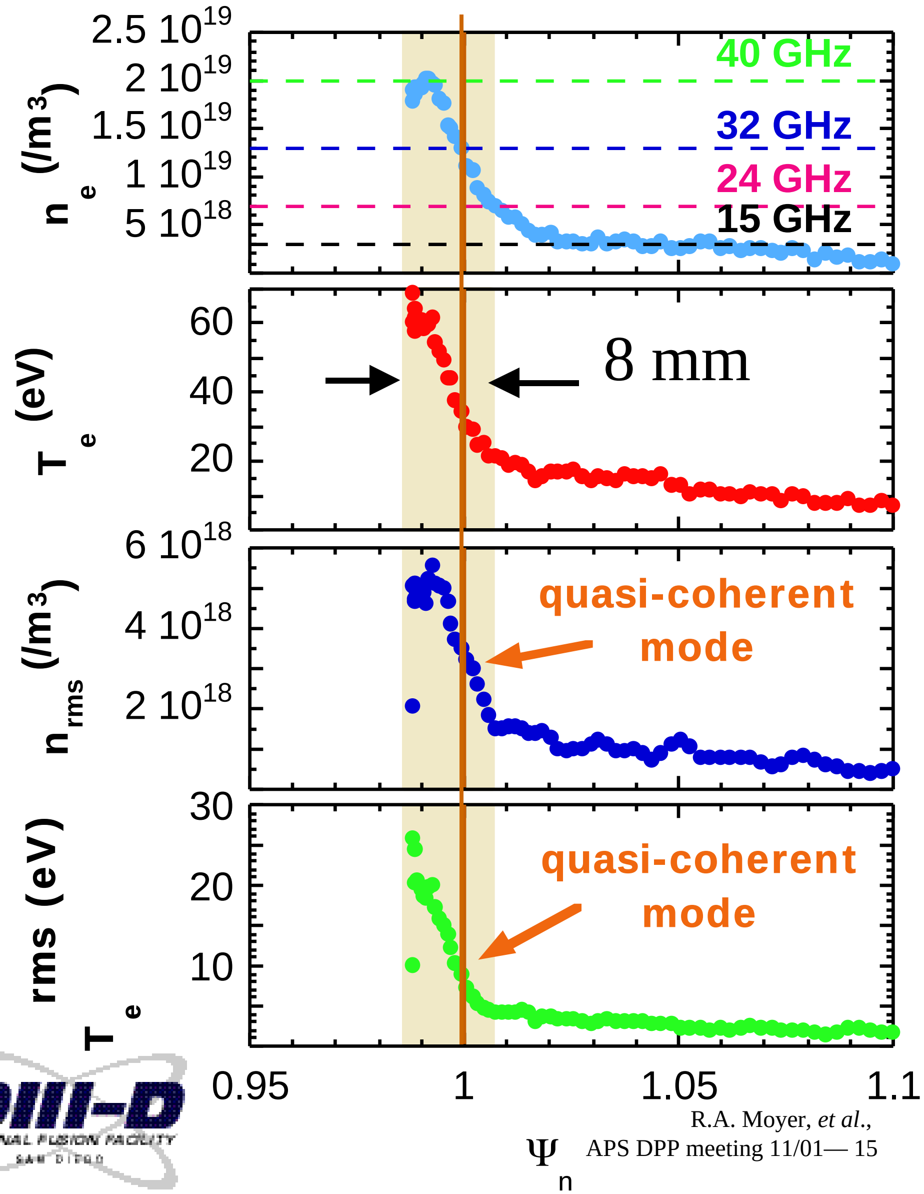
QC mode straddles separatrix (C-Mod & DIII-D) and radial width scales with device size

δr=2.2 mm (C-Mod); 8 mm (DIII-D)

$\delta r \approx \delta r^{\text{C-Mod}} \times (.56/.22) = 6$ mm



C-Mod data: B.LaBombard

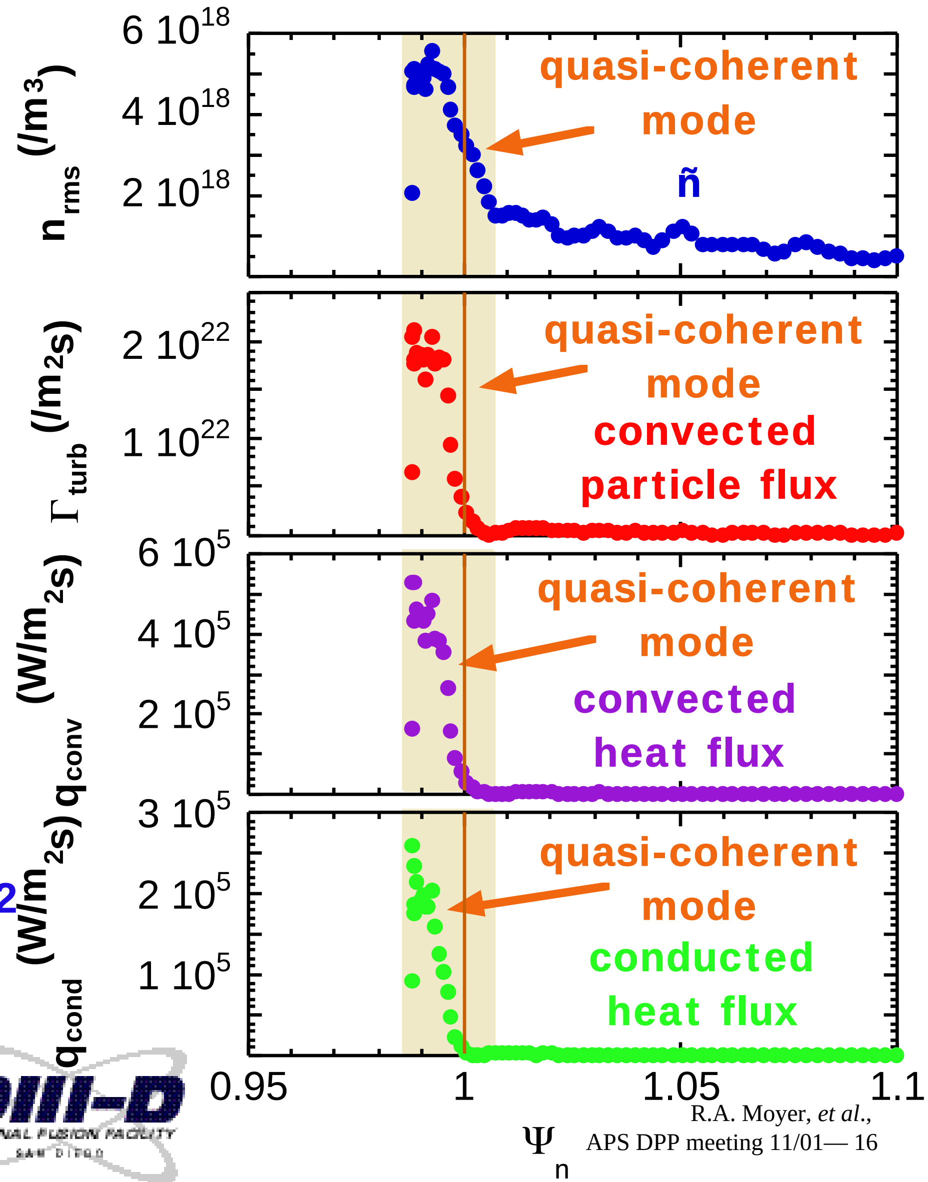


R.A. Moyer, *et al.*, APS DPP meeting 11/01— 15

Quasi-coherent mode in DIII-D drives substantial particle and heat flux, as in C-Mod.

- QC mode in DIII-D ELM-free phase drives substantial **local** particle and heat flux
- Fluxes peak at $\Psi_n = 0.99 \rightarrow$ error in EFIT separatrix location?
- Local total heat flux

$$q_{tot} = q_{conv} + q_{cond}$$
$$= 6.5e4 \text{ W/m2}$$
$$>> P_{sep} = .49 \text{ MW}/46 \text{ m}^2$$
$$= 1.1e4 \text{ W/m}^2$$



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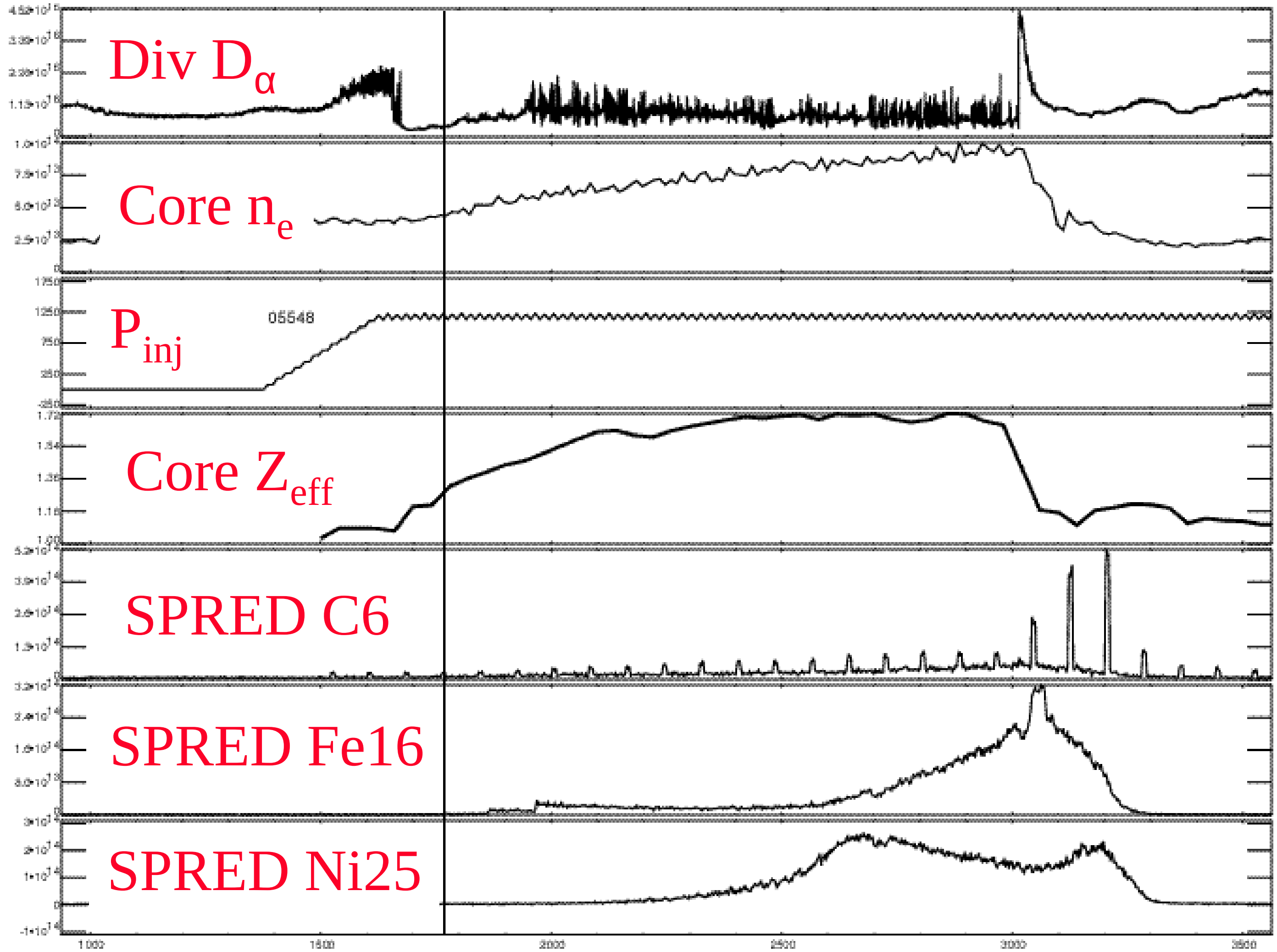
Despite large local transport from QC mode, DIII-D discharges are not stationary.

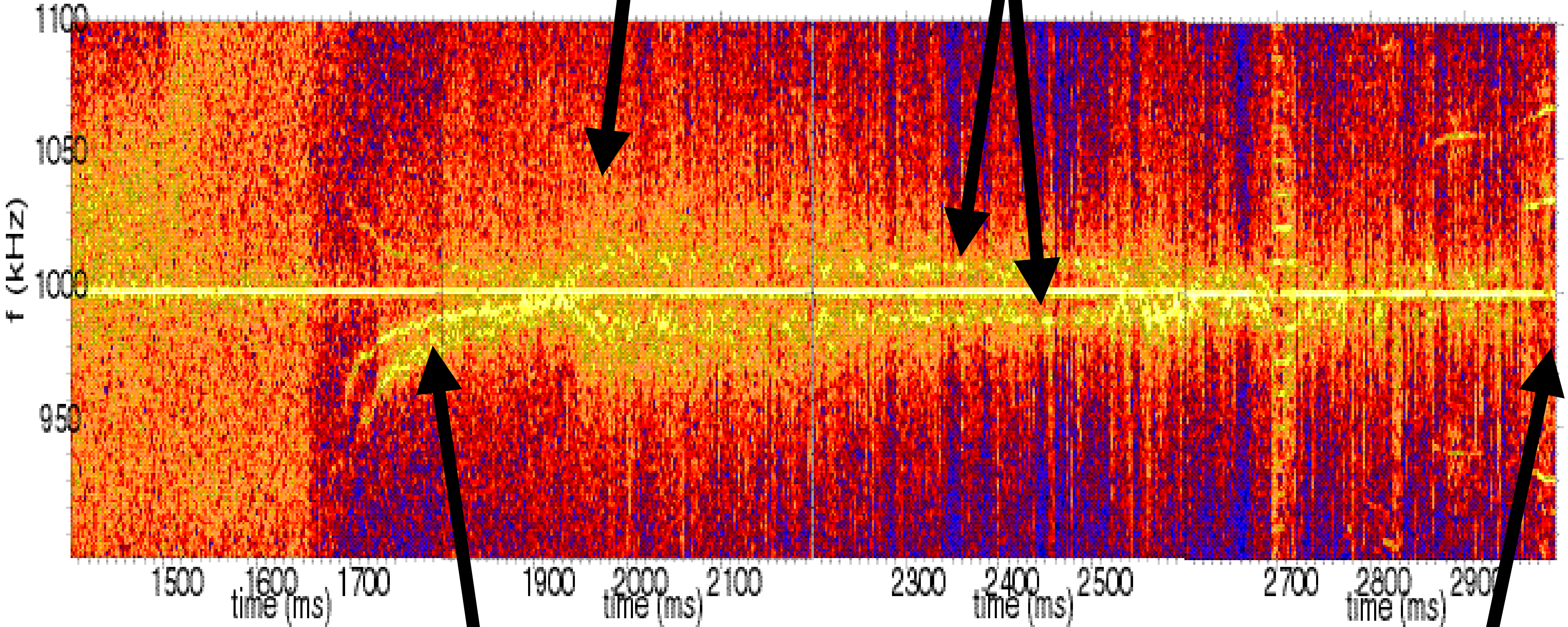
- **ELM-free H-mode like density peaking & impurity accumulation**



After the ELMs onset, the FIR scattering sees a core n=1 mode at low frequency

Small ELMs

Core mode (n=1)



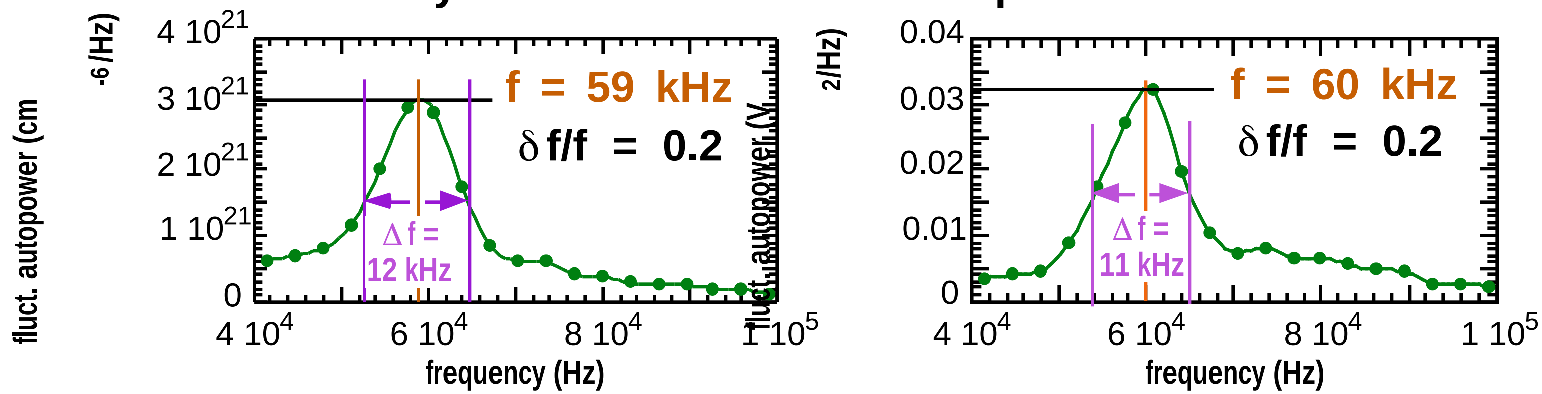
Edge quasi-coherent
Mode slows down

H-L back transition

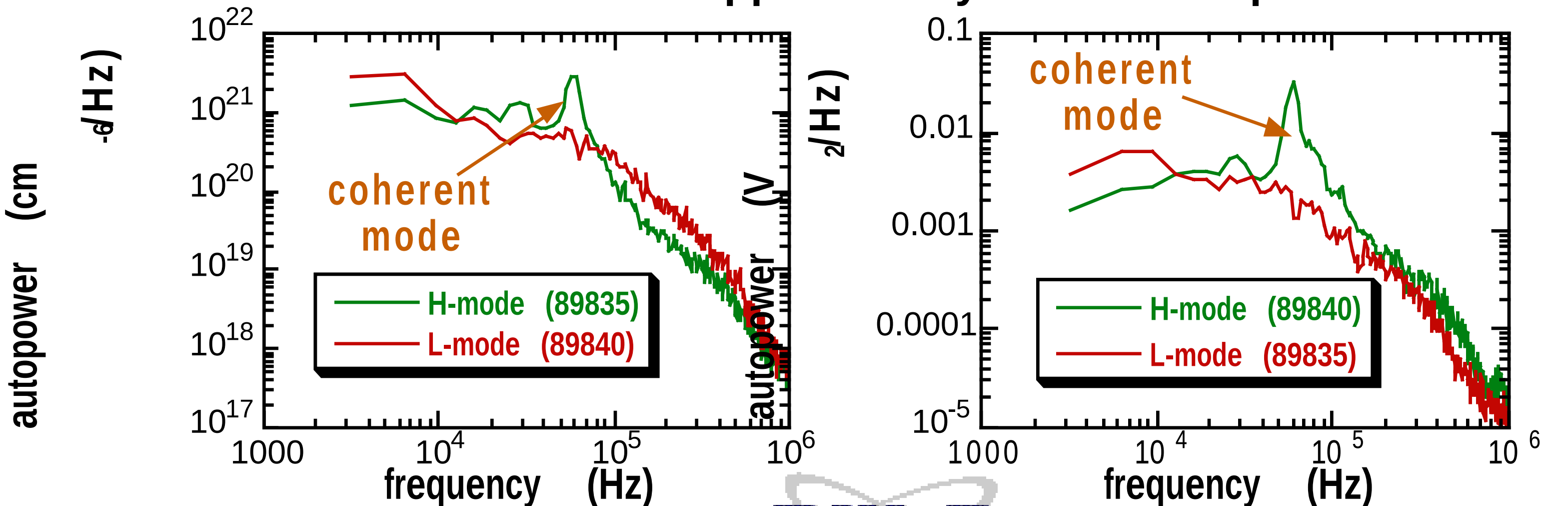
QC mode is similar to QC mode in ELM-free H-modes following very slow L-H transitions

- Moyer et al., Plasma Phys. Control. Fusion 41 243

density fluctuations   potential fluctuations

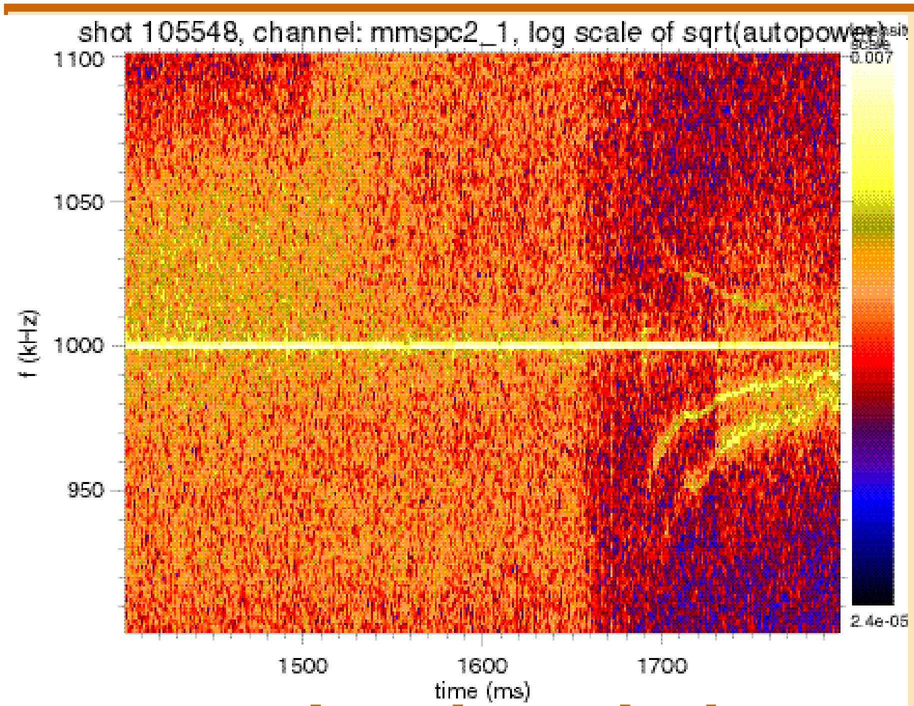


coherent mode appears only in H-mode phase:

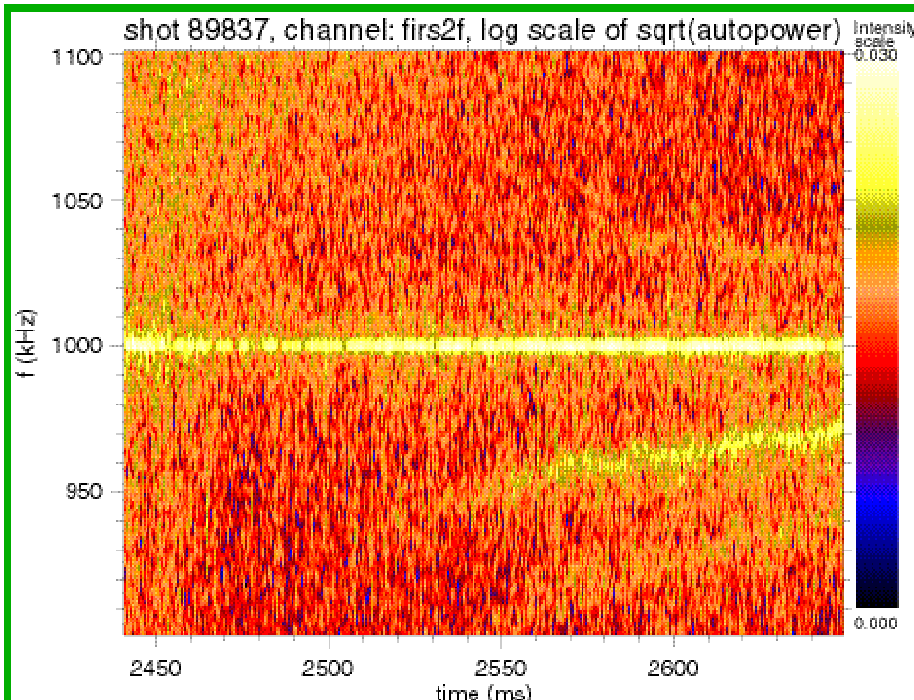


Coherent mode starts 10–50 ms into RLM-free H-mode in both cases.

- mode frequencies < 0 in FIR coherent scattering spectrum → mode is inside the edge E_r well.
- Also seen weaker signature at f > 0 (positive E_r) suggests exists at zero-crossing in E_r well.



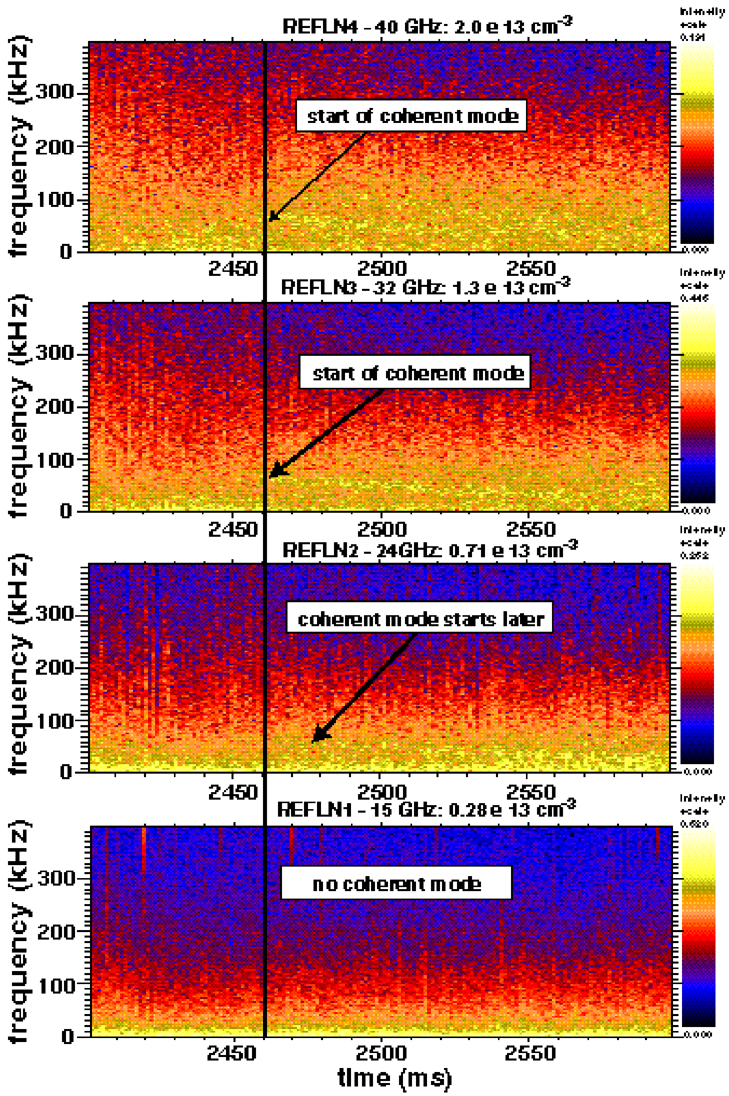
C-Mod similarity discharge

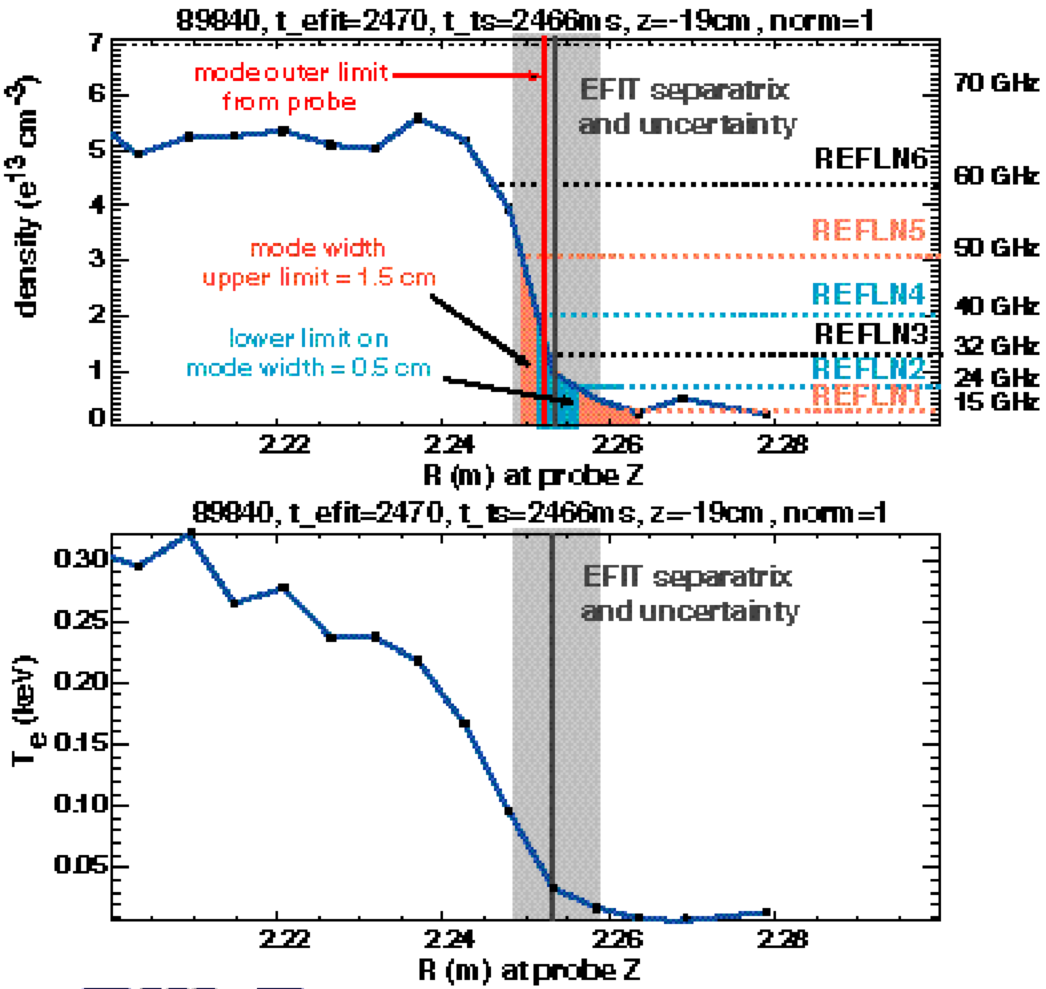


Very slow L-H transition

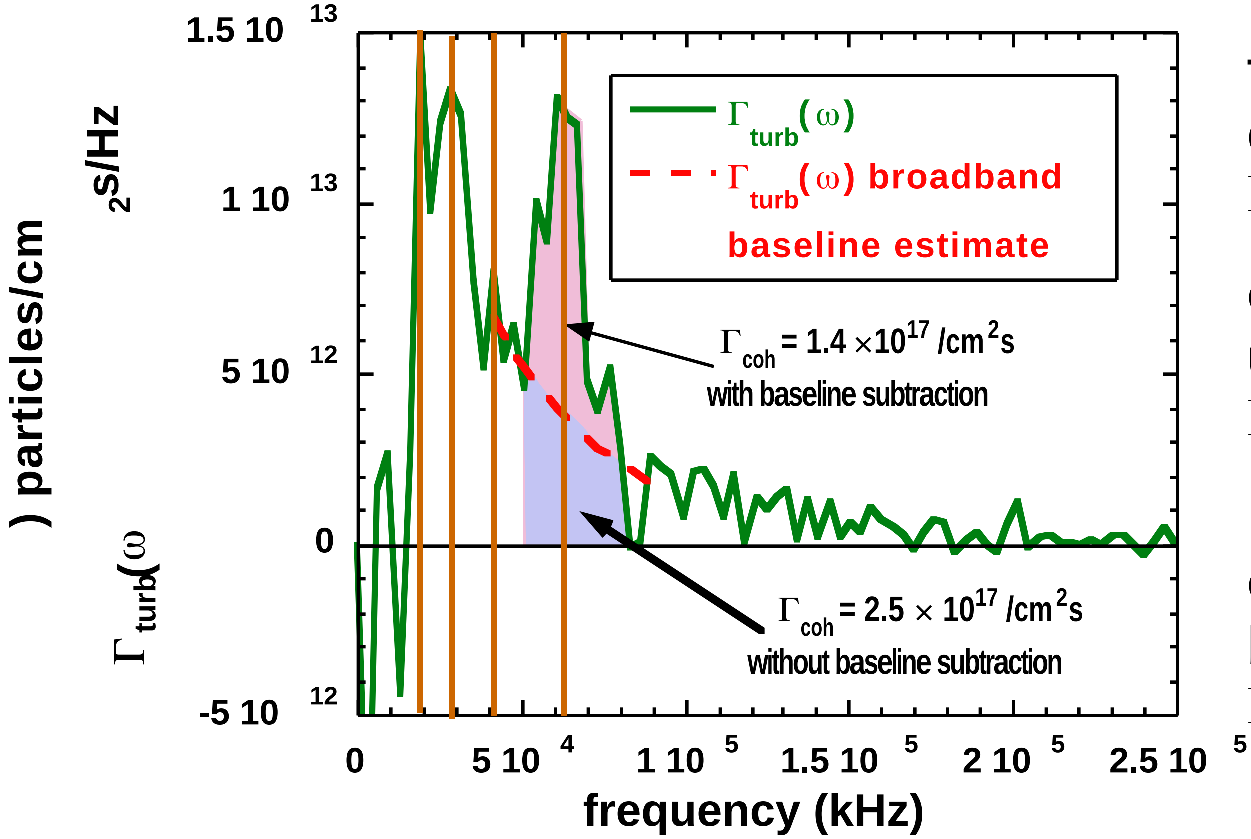
Previous QC mode also occupied the lower half of the H-mode pedestal (0.7–2e13 cm^{-3})

- δr ≈ 0.5–1.5 cm vs. 0.8 cm for C-Mod similarity shot





Previous quasi-coherent mode also caused substantial transport in ELM-free H-mode.



total fluctuation-driven flux:
Γ_{turb} = 6.1 ×10^{17}/cm^2s

coherent mode upper bound:
Γ_{coh} = 2.5 × 10^{17}/cm^2s
= 41%

coherent mode lower bound:
Γ_{coh} = 1.4 × 10^{17}/cm^2s
= 22%

- Some evidence for multiple peaks as seen in the C-Mod similarity discharges
  - Near 20, 30, 40, and 60 kHz

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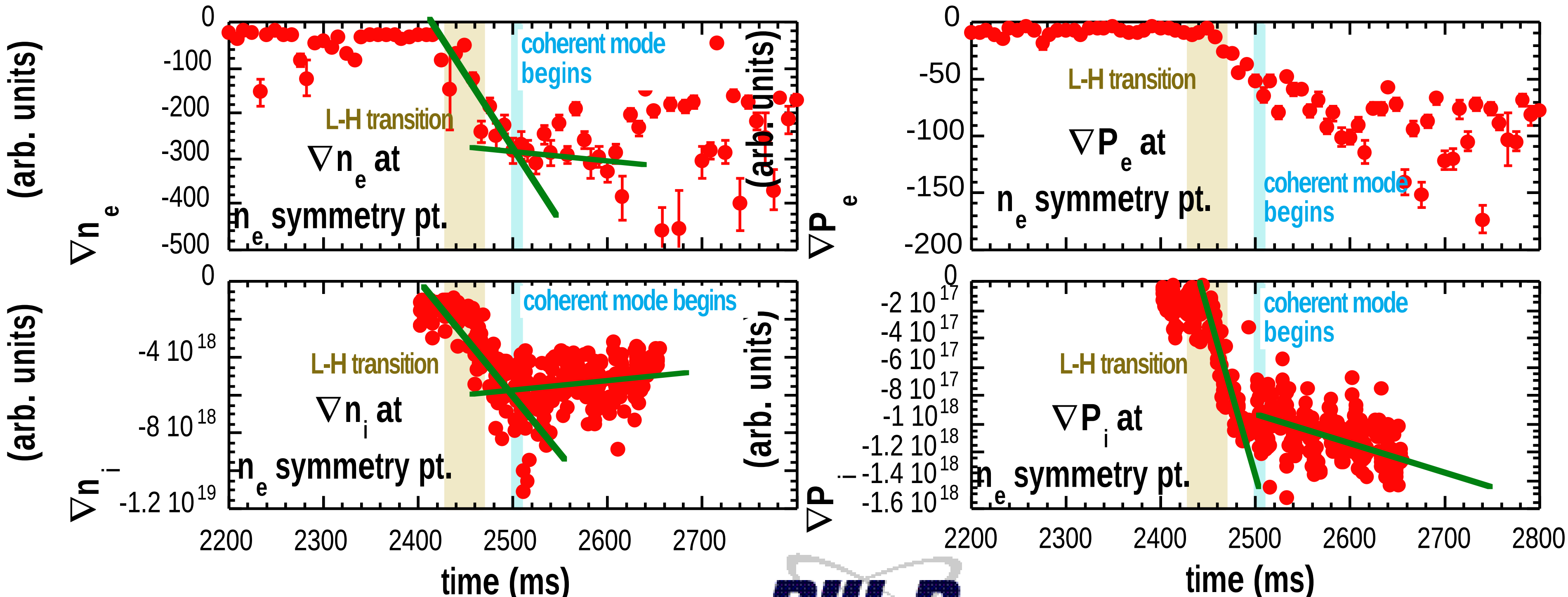
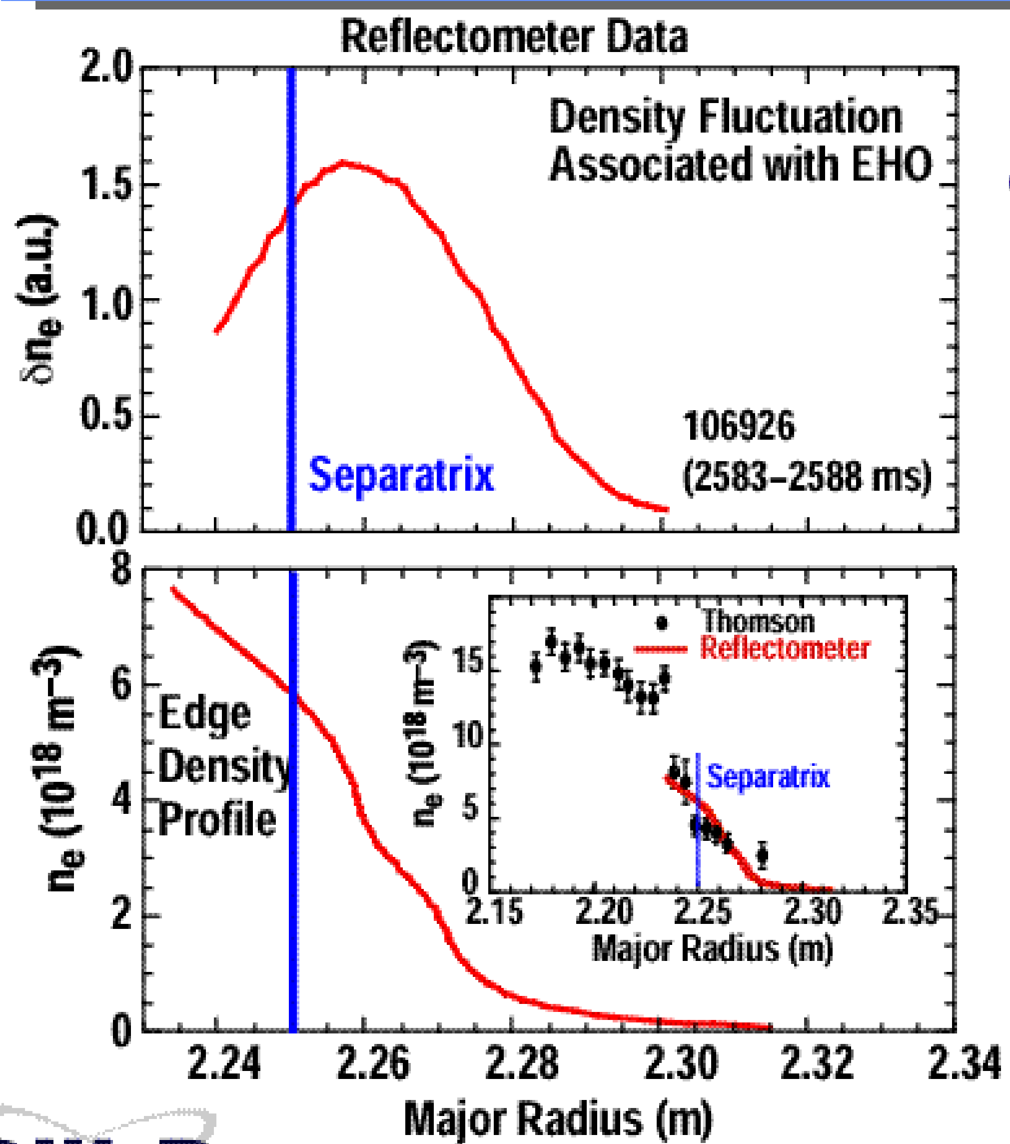
Previous QC mode onset near saturation of H-mode pedestal gradients.

- Strongest correlation is with edge density gradients (electron and ion).
- Together with large local particle flux suggests a causal link



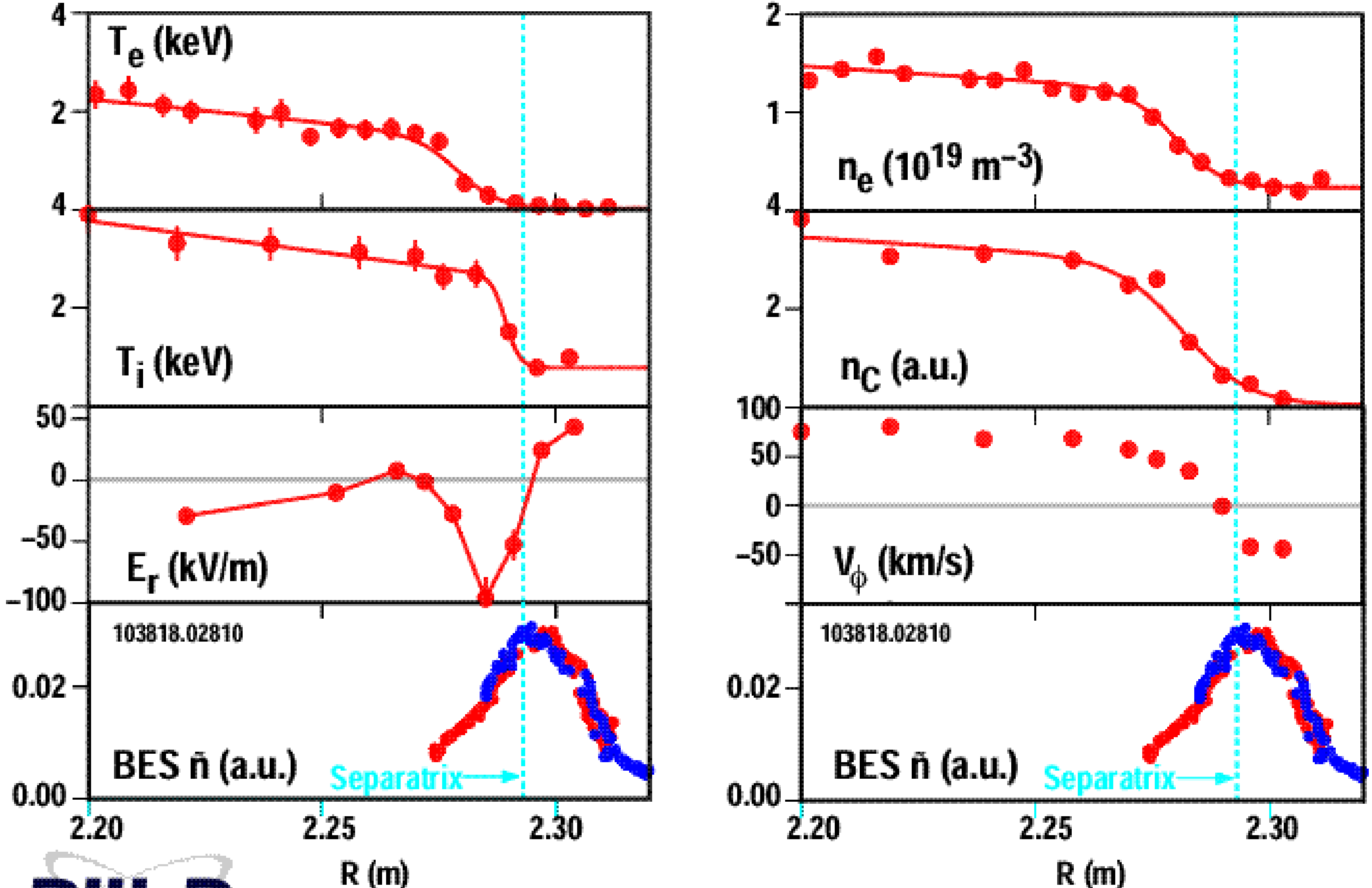
R.A. Moyer, *et al.*,

Comparison with Edge Harmonic Oscillation in DIII-D Quiescent H-modes



- 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

EHO also straddles the separatrix, with peak ñ where the E_r shear is greatest.



Characteristics of edge modes on DIII-D and C-Mod

- **EHO in DIII-D & QC mode in C-Mod generate ELM-free H-mode.**
- **QC mode in DIII-D only seen in ELM-free phase but doesn't generate stationary operation despite driving large local transport.**

	Edge Harmonic Oscillation (DIII–D)	Quasi-Coherent Mode Very Slow L-H (DIII-D)	Quasi-Coherent Mode C-Mod similarity discharges (DIII-D)	Quasi-Coherent Mode (C–Mod)
Increase Dα level in divertor	Yes	No	No	Yes
Increase particle transport across separatrix	Yes	Yes	Yes	Yes
Location	Foot of edge barrier	Lower half edge density barrier	Lower half edge density barrier	Lower half edge density barrier
Frequency	6–10 kHz (n=1)	50–60 kHz	11–15 kHz	60–200 kHz
Frequency spread Δf (FWHM)/f	0.02	0.20	0.46	0.05–0.2
Toroidal mode number	Multiple, variable mix n=1–10	Unknown	N ~ 10-12 if q=4	n~15-20 if q=4
Poloidal wavelength	~100 cm (m~5)	20–30 cm (m~20–30)	10–12 cm (m~40–50)	~1 cm (m~60–80)
Edge electron collisionality	Collisional	Collisional	Collisional	Collisional
Edge ion collisionality	Collisionless	Collisional	Collisional	Collisional

Summary

- **DIII-D discharges have been obtained which have dimensionlessly similar pedestals in H-mode to C-Mod at the appropriate dimensionlessly scaled power for both EDA and ELMy H-modes**
  - **Dimensionless parameters match across entire H-mode pedestal**
  - **For matched dimensionless pedestal parameters, ELM behavior matched**
  - **This regime in DIII-D was very sensitive to input power; 20% increase in P_{inj} (236 kW additional power) yielded Type I ELMs**
- **These dimensionally similar discharges have a 200 ms LM-free phase with a quasi-coherent mode similar to EDA H-modes in C-Mod, but no enhanced D_α level.**
  - **Mode characteristics are consistent with C-Mod QC mode**
  - **The quasi-coherent mode drives substantial local particle and heat transport as in C-Mod EDA H-modes.**
  - **Despite the QC mode transport, the ELM-free phase isn't stationary; after 200 ms, "grassy" ELMs begin**
- **Throughout the ELM-free and grassy ELMing phases, the core density and impurities accumulate in DIII-D, unlike the stationary core conditions in C-Mod**

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