

STUDIES OF EDA H-MODE IN ALCATOR C-MOD

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ABSTRACT

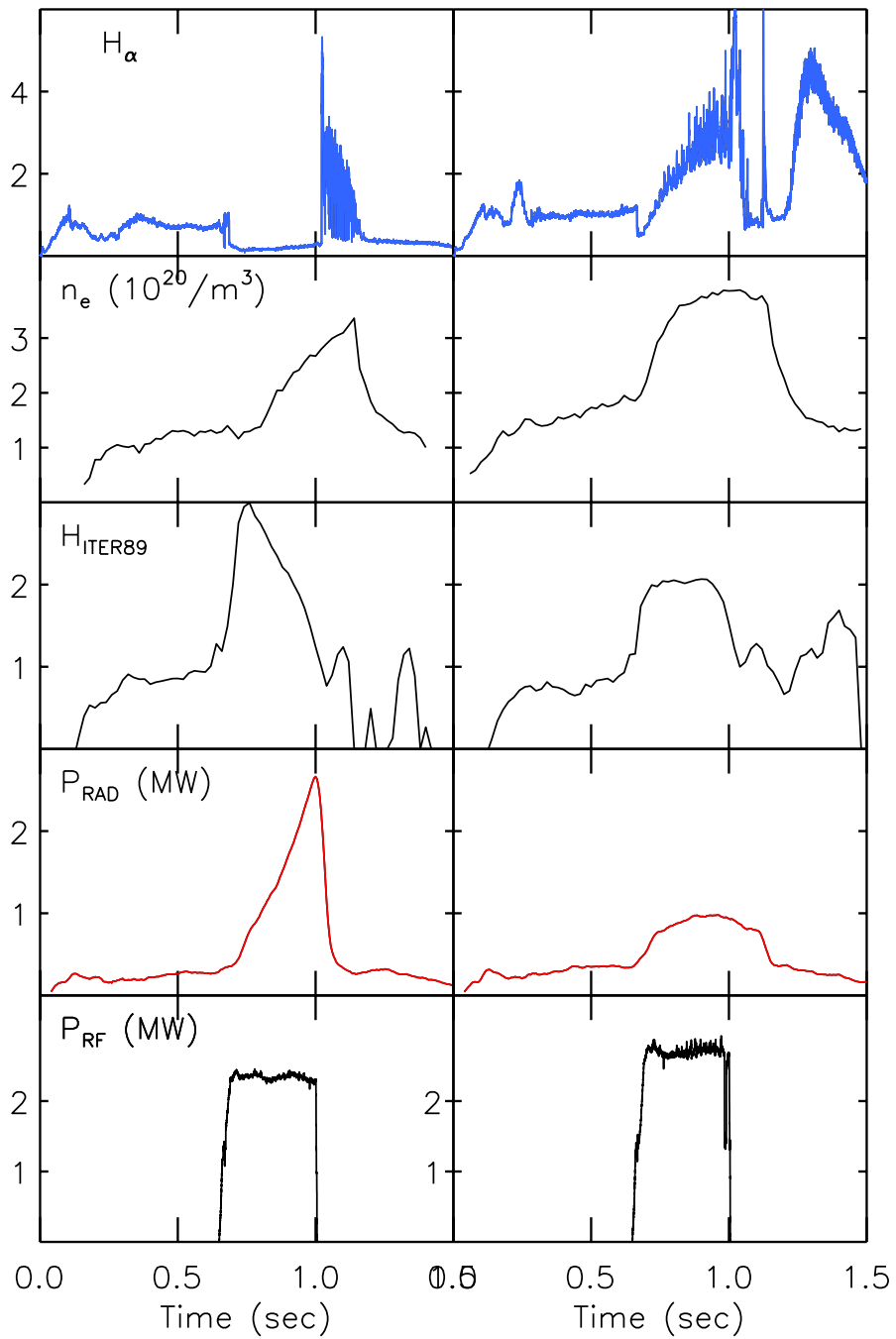
The advantages of EDA H-modes include good energy confinement and no impurity accumulation or large ELMs. In EDA, the edge pressure gradients are at or above the ideal ballooning limit but are not relaxed by type I ELMs; instead a continuous process would seem to be at work. This process is probably related to broadband and quasi-coherent fluctuations which are seen with reflectometry, probes, PCI and magnetic pick-up loops. The coherent component has a frequency on the order of 100 kHz in steady state but shifts to much higher frequencies as the plasma transitions to or from ELMfree. We note that the Doppler shift in the shear layer may make an important contribution to the lab frame frequency. The coherent feature is dominant in the PCI and probe measurements, which show a well defined spatial structure with $k_{\theta} \approx 5\text{cm}^{-1}$. Recent simulations of drift Alfvén turbulence show a coherent surface mode arise as the pedestal pressure gradient approaches an MHD stability limit.

**TYPE I ELM_y DISCHARGES ARE NOT SEEN IN C-MOD
INSTEAD, A REGIME THAT WE HAVE CALLED EDA
(ENHANCED D α) IS OBSERVED**

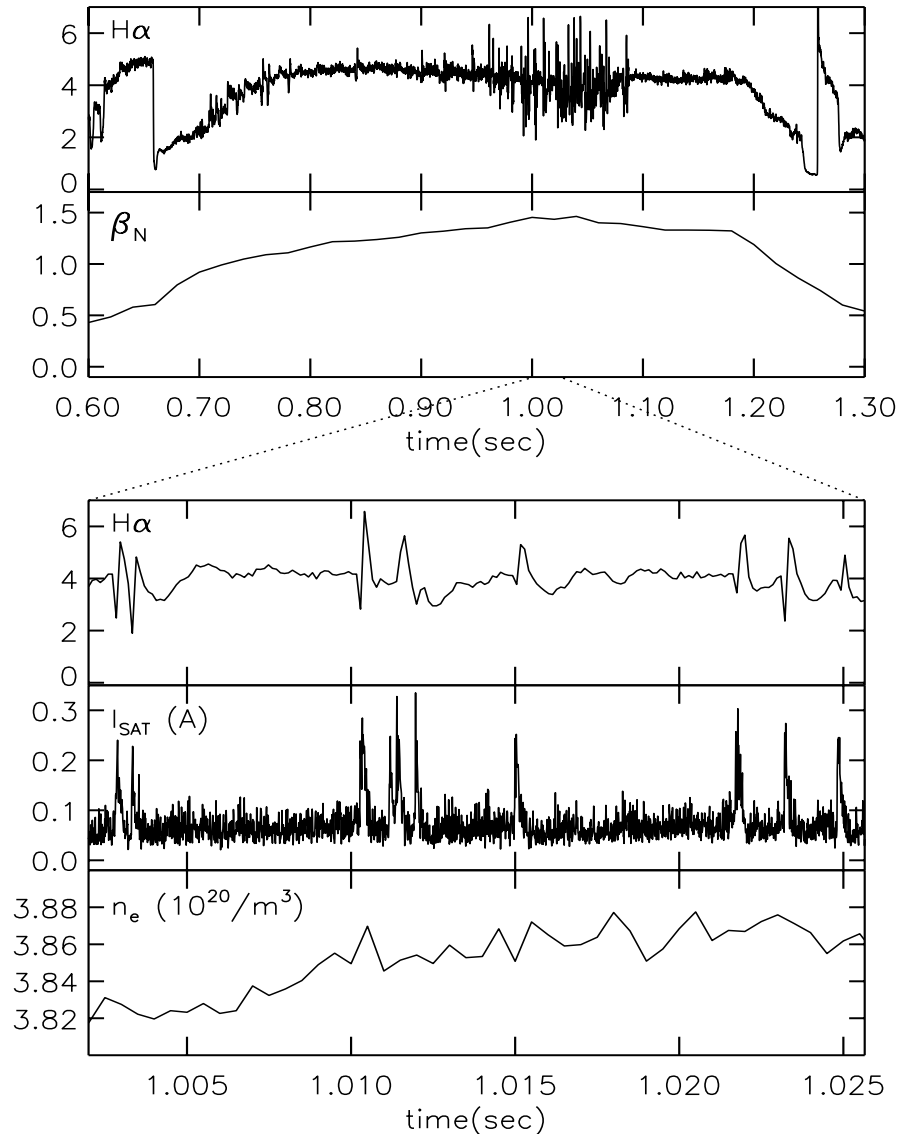
- First signature - enhanced level of light from neutral deuterium
- Particle confinement much lower than ELM-free
- **No strong accumulation of impurities**
- Energy confinement slightly lower than ELM-free (10-20%)
- **No large discrete ELMs**
- So far, we don't see type I ELMs, though pressure gradient challenges MHD ballooning stability limit
- T_e well above type III boundary
- EDA regime shows **continuous** degradation of pedestal rather than relaxation oscillation

EDA may be closely related to JET LPC H-mode
Shares many characteristics with type II or other “small”
ELM regimes (DIII-D, JT60-U, JFT-2M).

EDA H-MODES DO NOT SHOW IMPURITY ACCUMULATION



SMALL ELMs ARE OFTEN SEEN ON TOP OF EDA

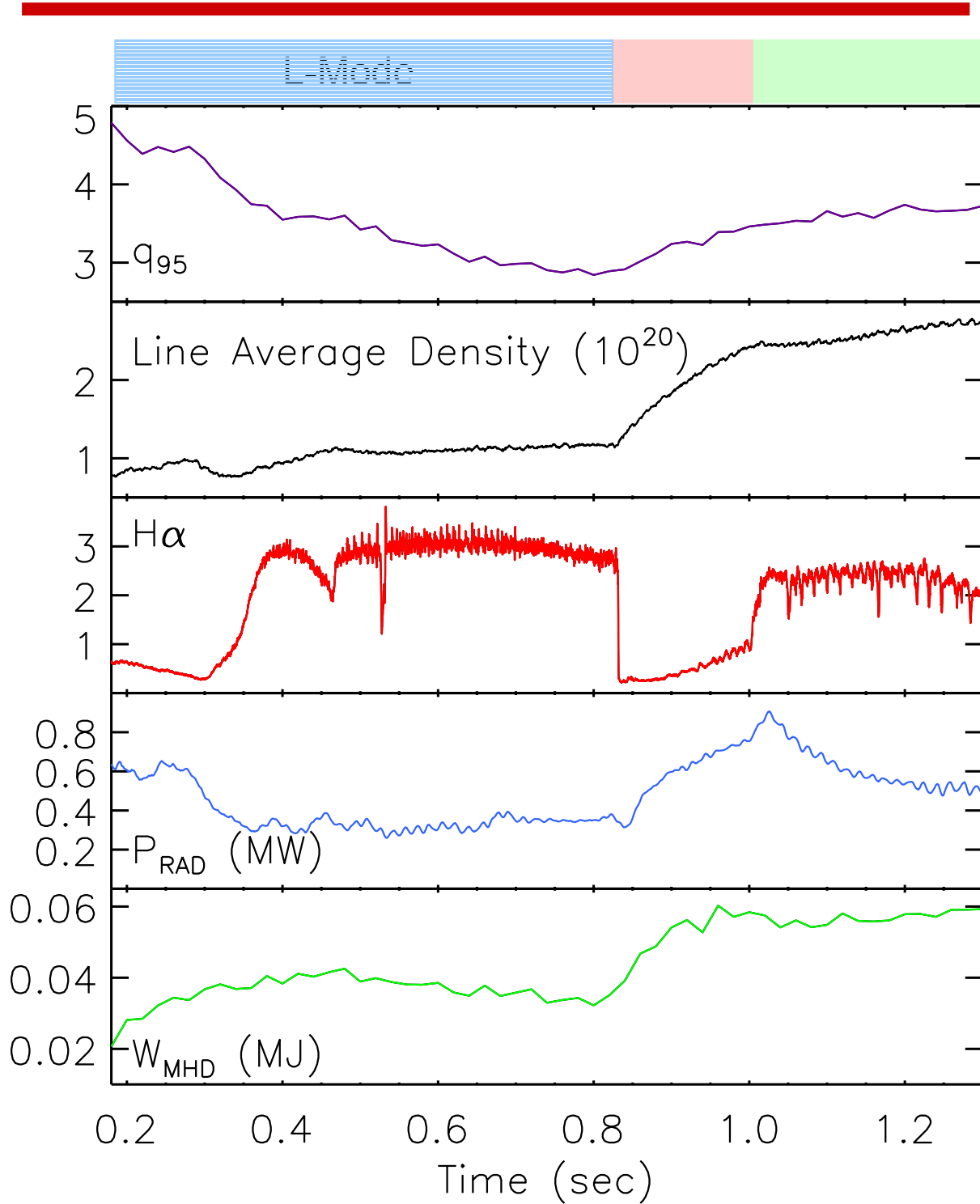


- Seen when $\beta_N > 1.2 - 1.3$
- Negligible net loss of energy or particles detected by core diagnostics

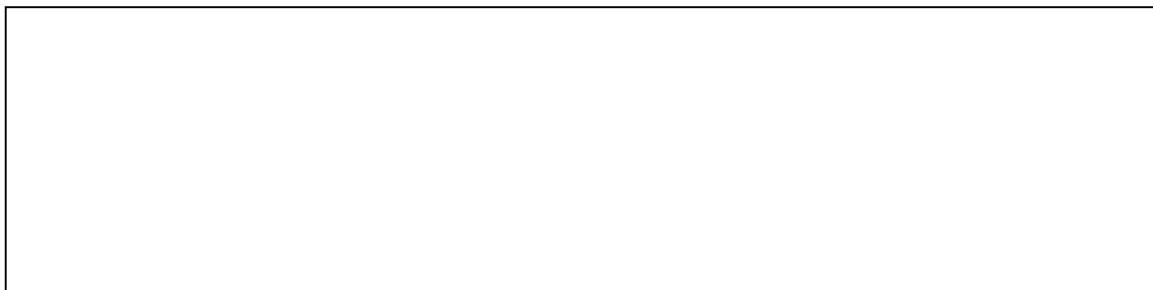
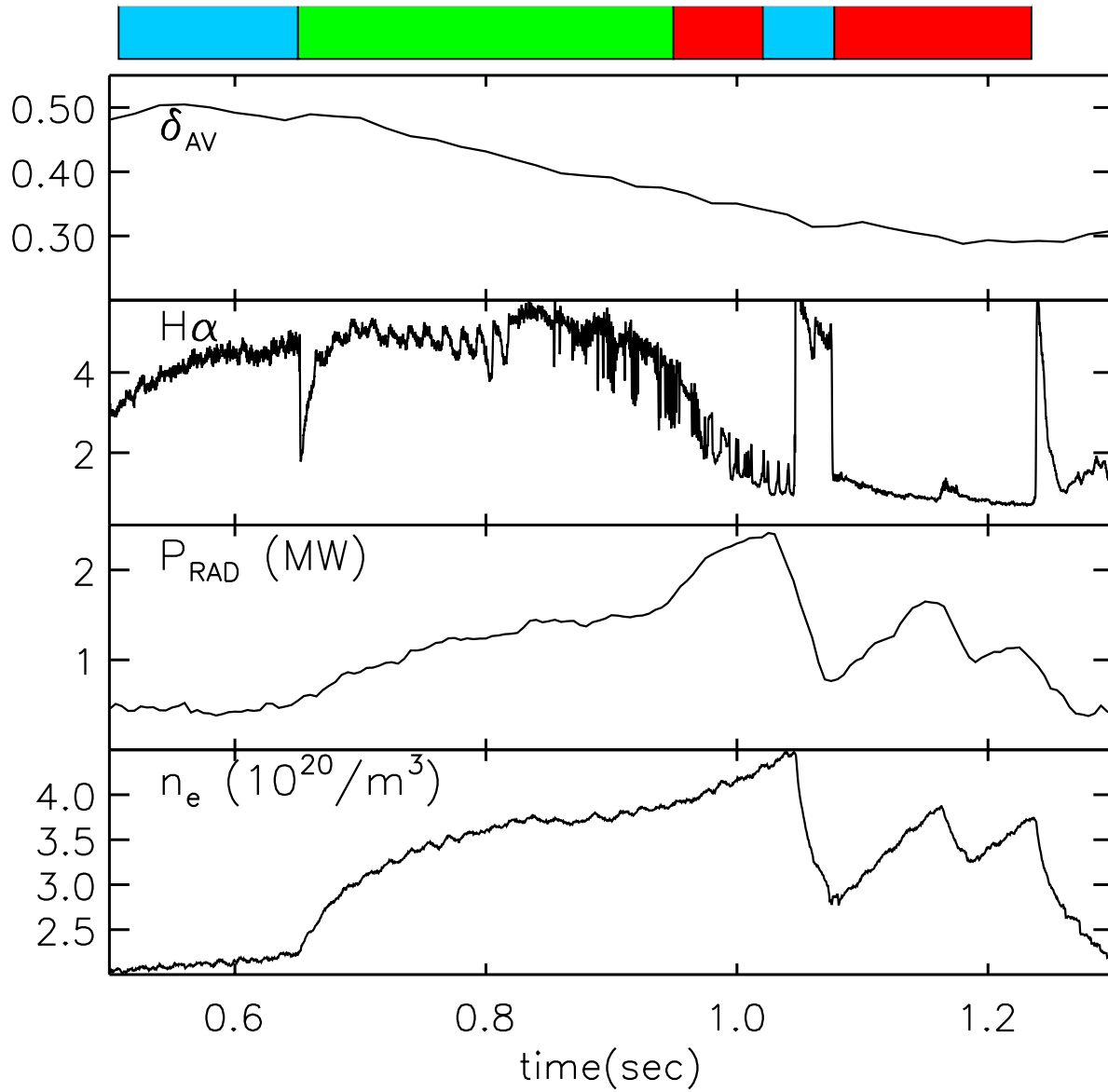
THE EDA REGIME IS SEEN IN OHMIC AS WELL AS RF HEATED DISCHARGES

- The boundary between EDA and ELMfree H-modes was studied and found to depend most strongly on safety factor (q) and shape (d).
- Low q (< 3.5) and low d (< 0.3) favor ELMfree.
- High q (> 4.0) and higher d (> 0.35) favor EDA.
- The same boundary is seen for RF and ohmic heating.
- EDA phenomenology is essentially the same in OH and RF plasmas.
- **This observation would seem to rule out mechanisms based on direct RF interaction or through the influence of fast particles.**

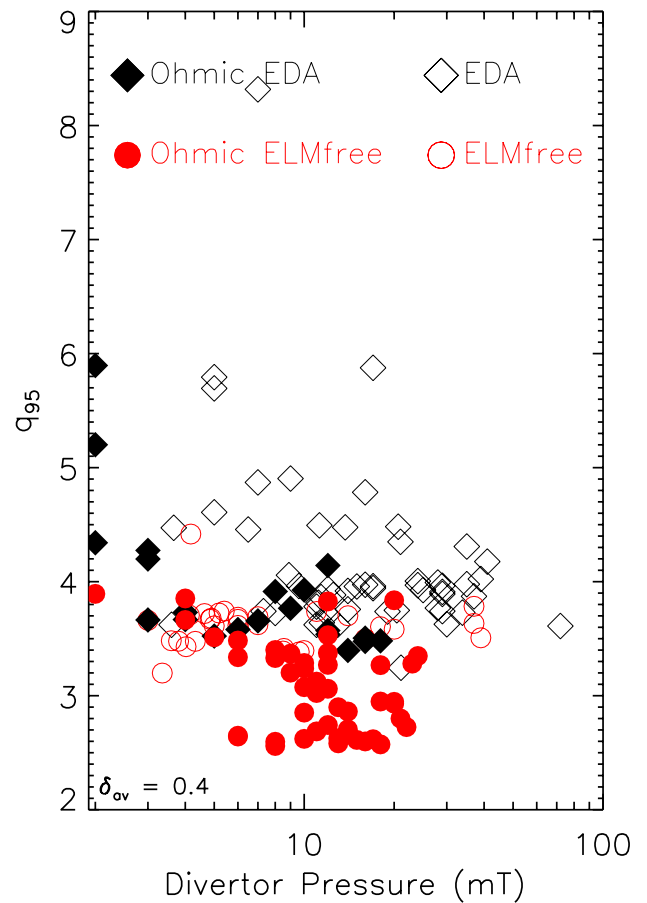
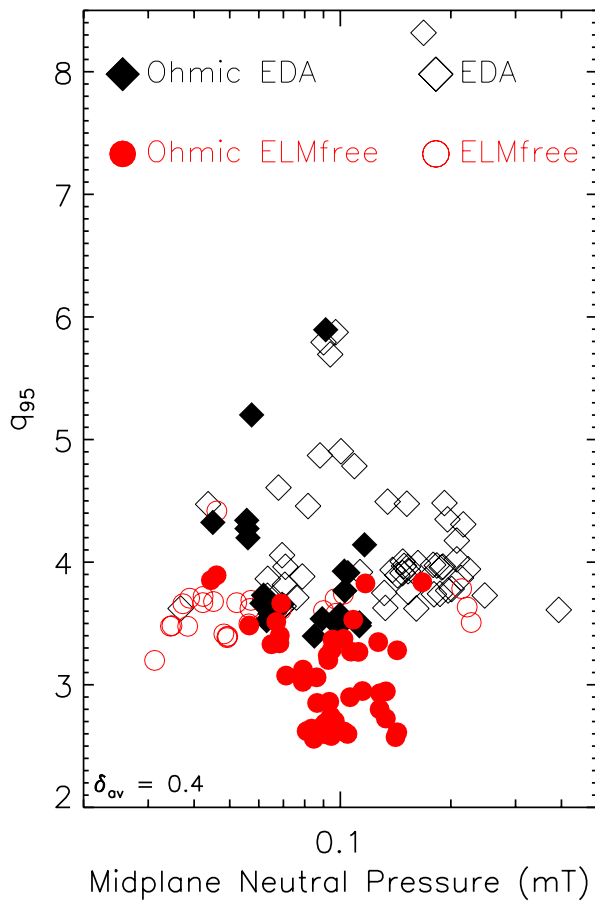
EDA H-MODES ARE READILY OBTAINED WITH OHMIC HEATING ALONE



EDA-ELM-free BOUNDARY IS A FUNCTION OF δ



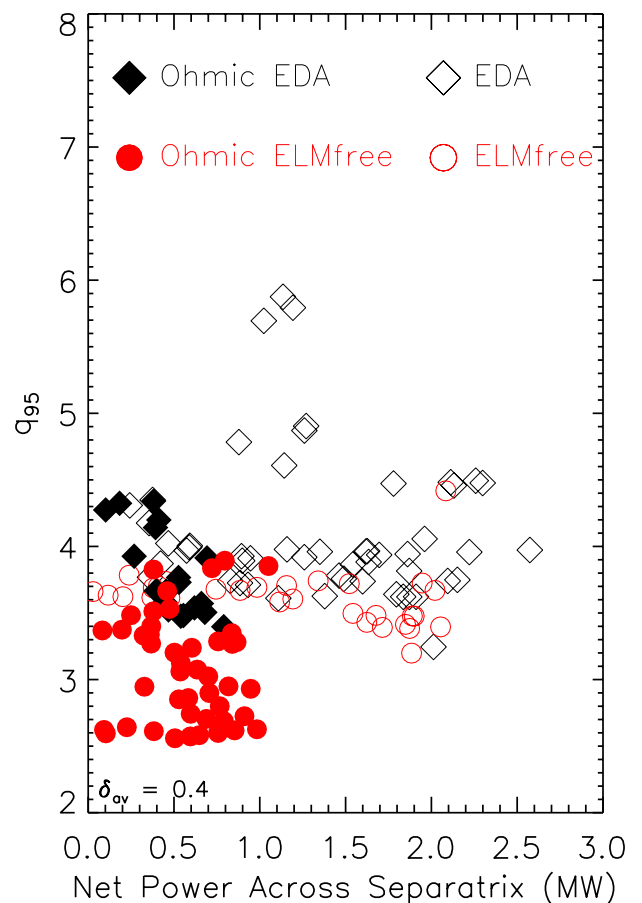
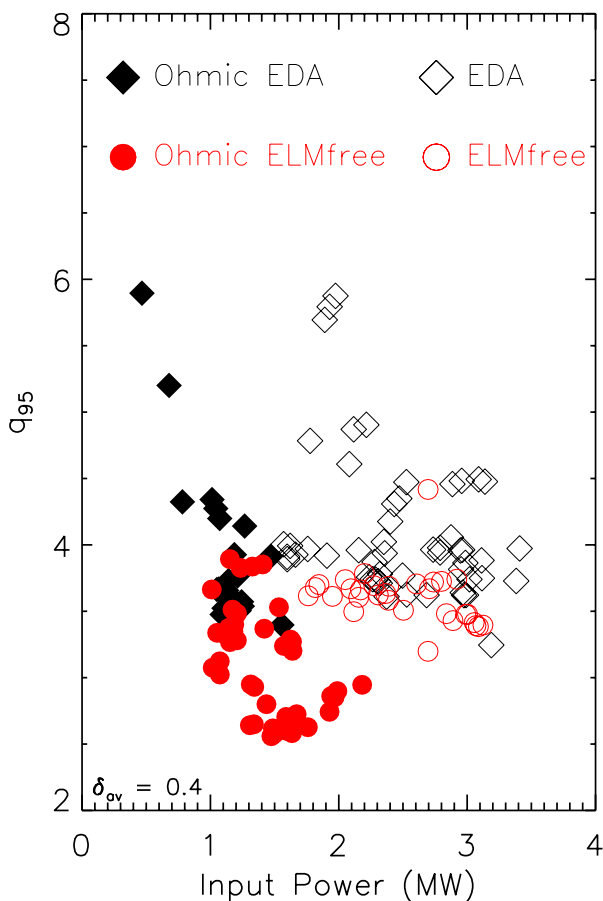
EDA SEEN AT $Q > 3.5$ WITH SIMILAR BOUNDARY FOR OHMIC AND ICRF PLASMAS



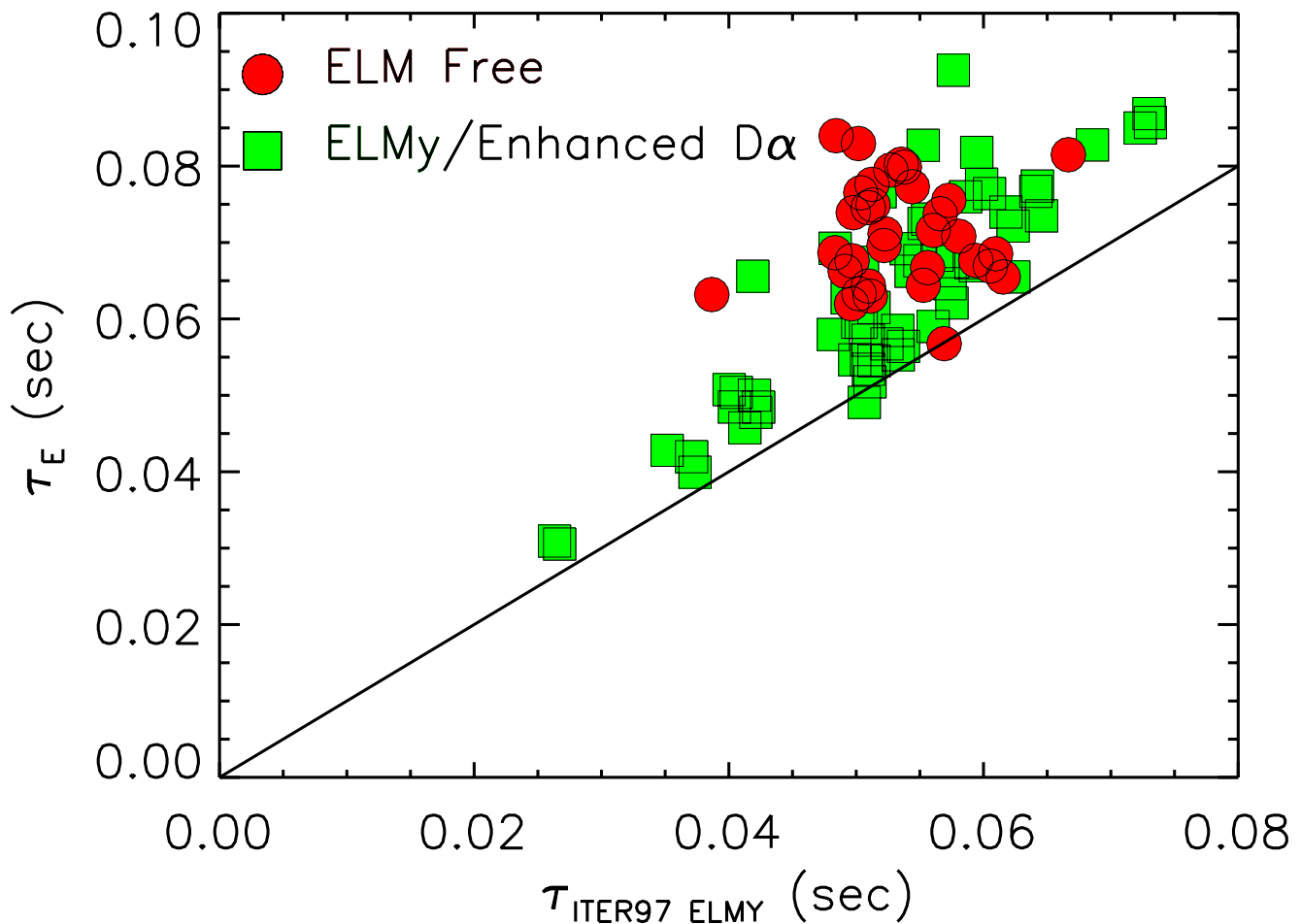
- Dependence on neutral density is apparently weak at best.
- If anything, the EDA has a wider operating range in Ohmic plasmas

NO STRONG DEPENDENCE IS SEEN ON TOTAL OR NET POWER

- While there is anecdotal evidence for power dependence of the EDA/ELMfree boundary, statistical studies do not bear this out.
- Both EDA \Rightarrow ELMfree and ELMfree \Rightarrow EDA transitions have been observed following impurity injection.

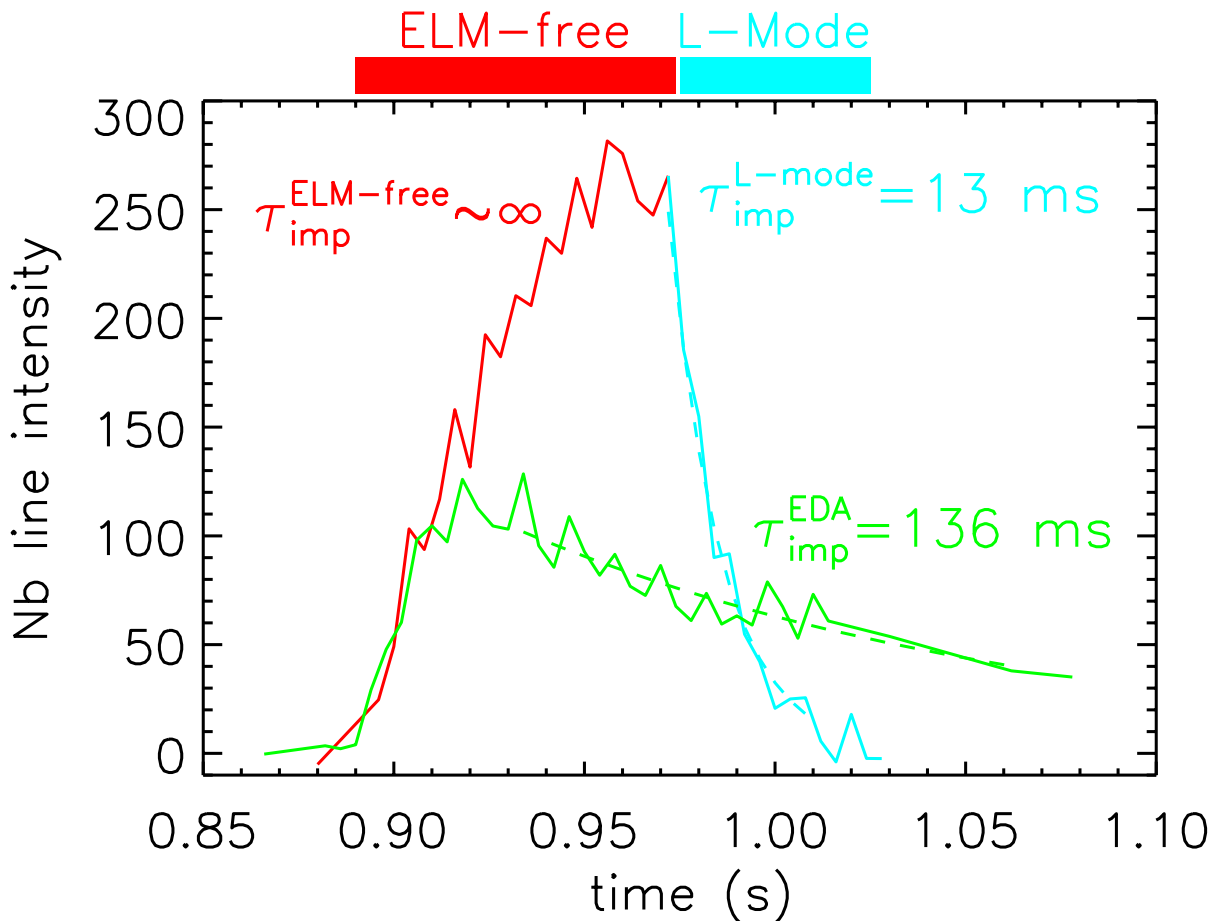


THE BEHAVIOR OF THE BEHAVIOR OF EDA DISCHARGES HAVE ENERGY CONFINEMENT ONLY SLIGHTLY LESS THAN ELM-FREE



- C-Mod data are in rough agreement with latest ITER H-mode scaling laws (though about 15% higher)
- for ELM-free: $H_{ITER89} = 2.1$
- for EDA: $H_{ITER89} = 1.9$

THE BEHAVIOR OF INJECTED IMPURITIES IS CONSISTENT WITH THAT OF INTRINSIC IMPURITIES



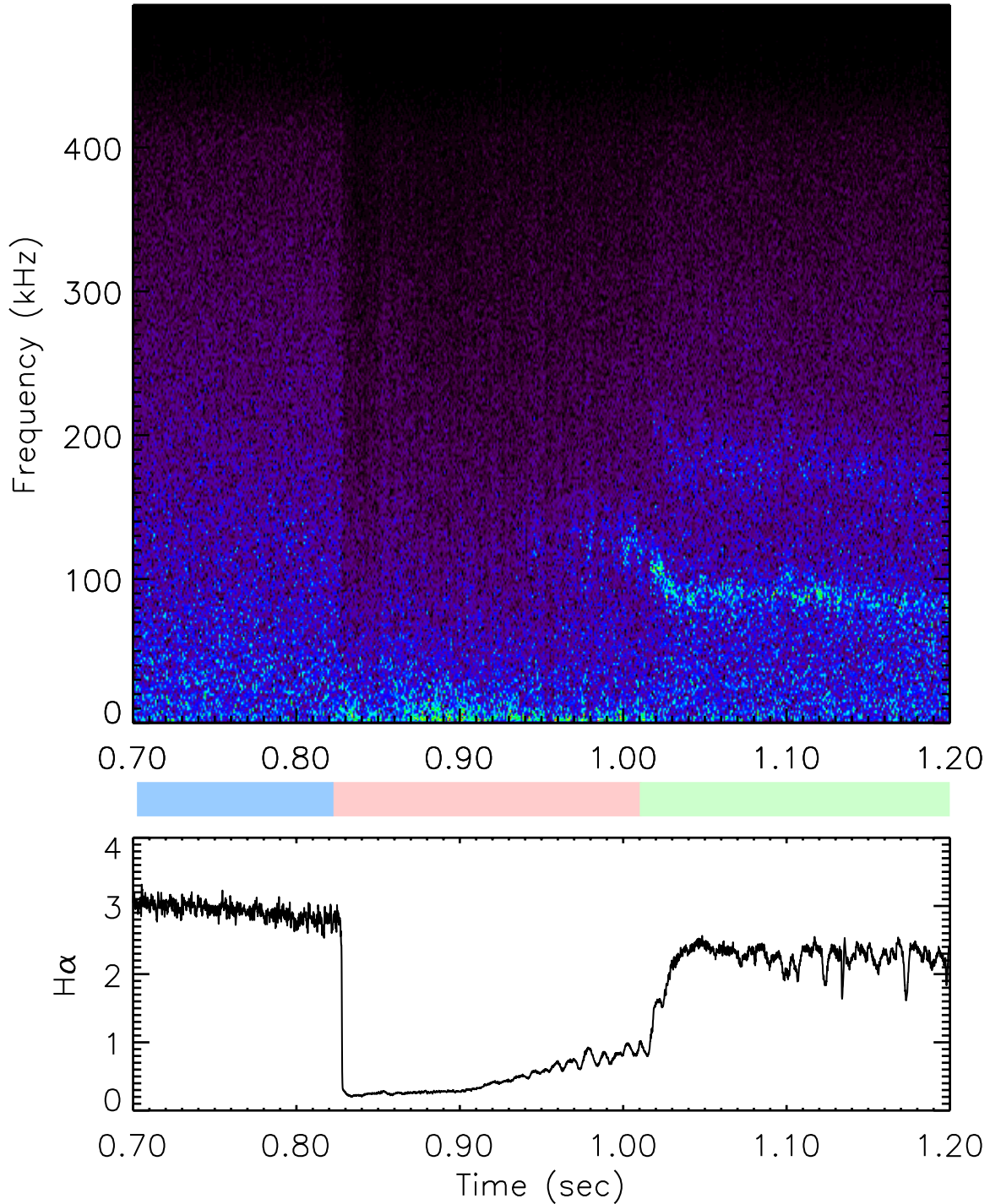
- In ELM-free H-modes, τ_I is too long to measure. $\tau_I \gg \tau_E$
- For EDA, $\tau_I \sim 2-3 \times \tau_E$
- For L-Mode, $\tau_I < \tau_E$

A **KEY SIGNATURE** OF EDA IS QUASI-COHERENT FLUCTUATIONS LOCATED IN PEDESTAL

- Observed with reflectometry, PCI, probes.
- Frequency on the order of 100 kHz
- $k_{\theta} \sim 5 \text{ cm}^{-1}$ ($m > 100$)
- Fluctuations propagate in the electron diamagnetic direction at roughly the electron diamagnetic velocity.
- Fluctuation frequency scales inversely with pedestal width.
- The fluctuations are localized in the edge barrier region.
- **Analysis of probe signals demonstrates that significant particle transport is caused by these modes.**
- An increase in background turbulence is seen with reflectometry and magnetics. (See Lin KP1.38)
- Magnetics diagnostics do not see the coherent feature - m probably too high.

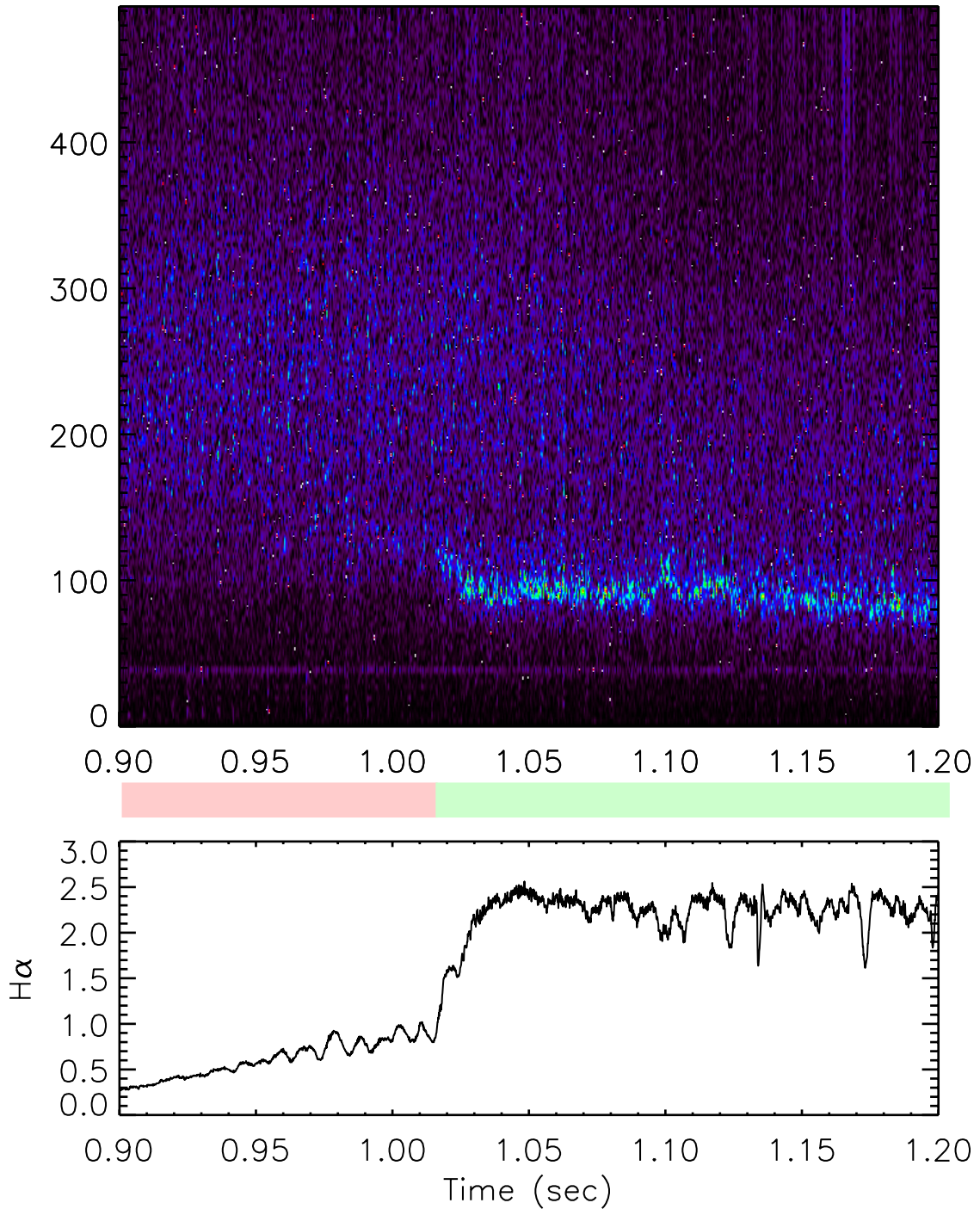
THE QUASI-COHERENT FLUCTUATIONS ARE SEEN WITH REFLECTOMETRY

Density Fluctuations 88GHz – Shot 990831014

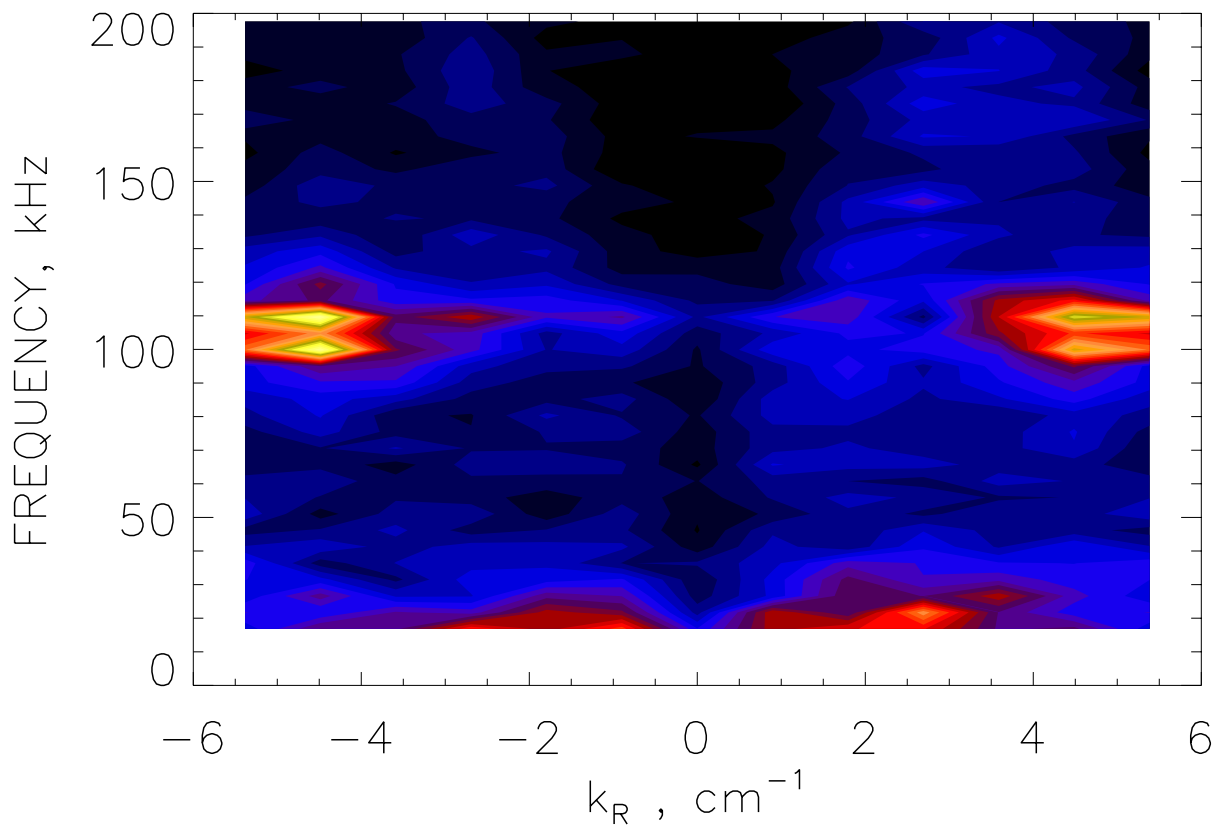


SIMILAR FLUCTUATIONS SEEN WITH PCI

PCI Fluctuations for Shot 990831014



PCI SHOWS A SIGNAL WITH A WELL DEFINED ω AND k STRUCTURE

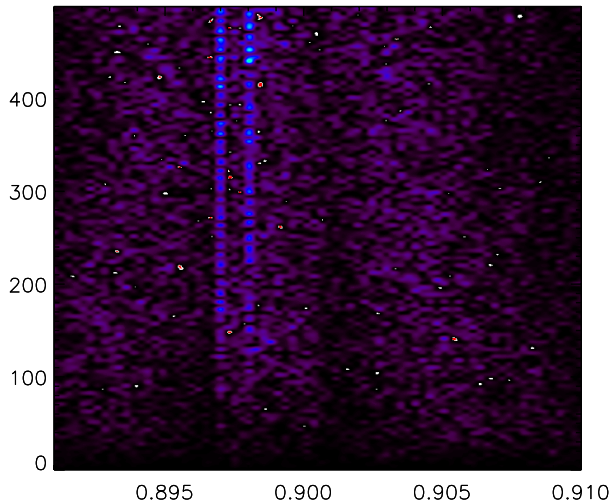


- Data taken from a short interval of time during EDA H-mode
- ω and k are modulated slightly by sawteeth

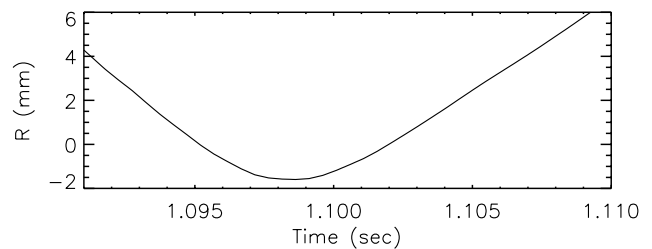
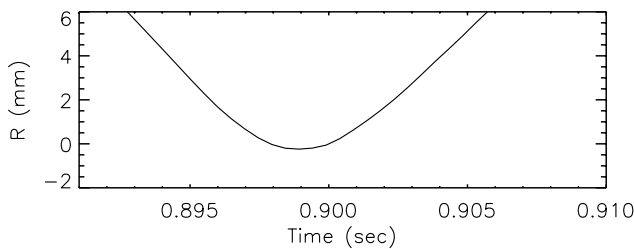
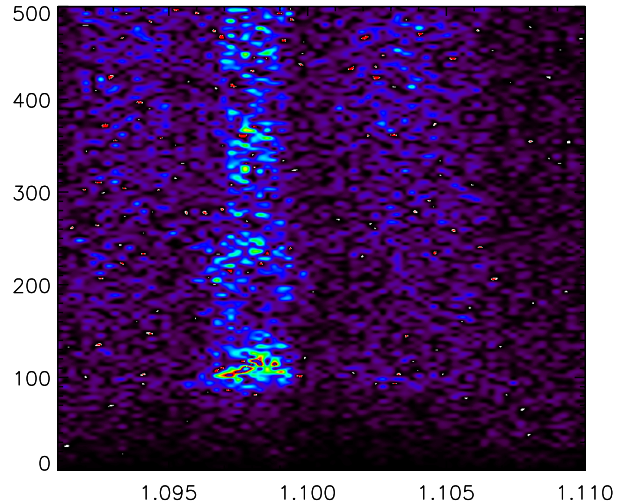
(See Mazurenko R02.08)

A SET OF SCANNING LANGMUIR PROBES HELPS LOCALIZE THE MODE

FSP_1–North Potential Fluctuations – 990831014



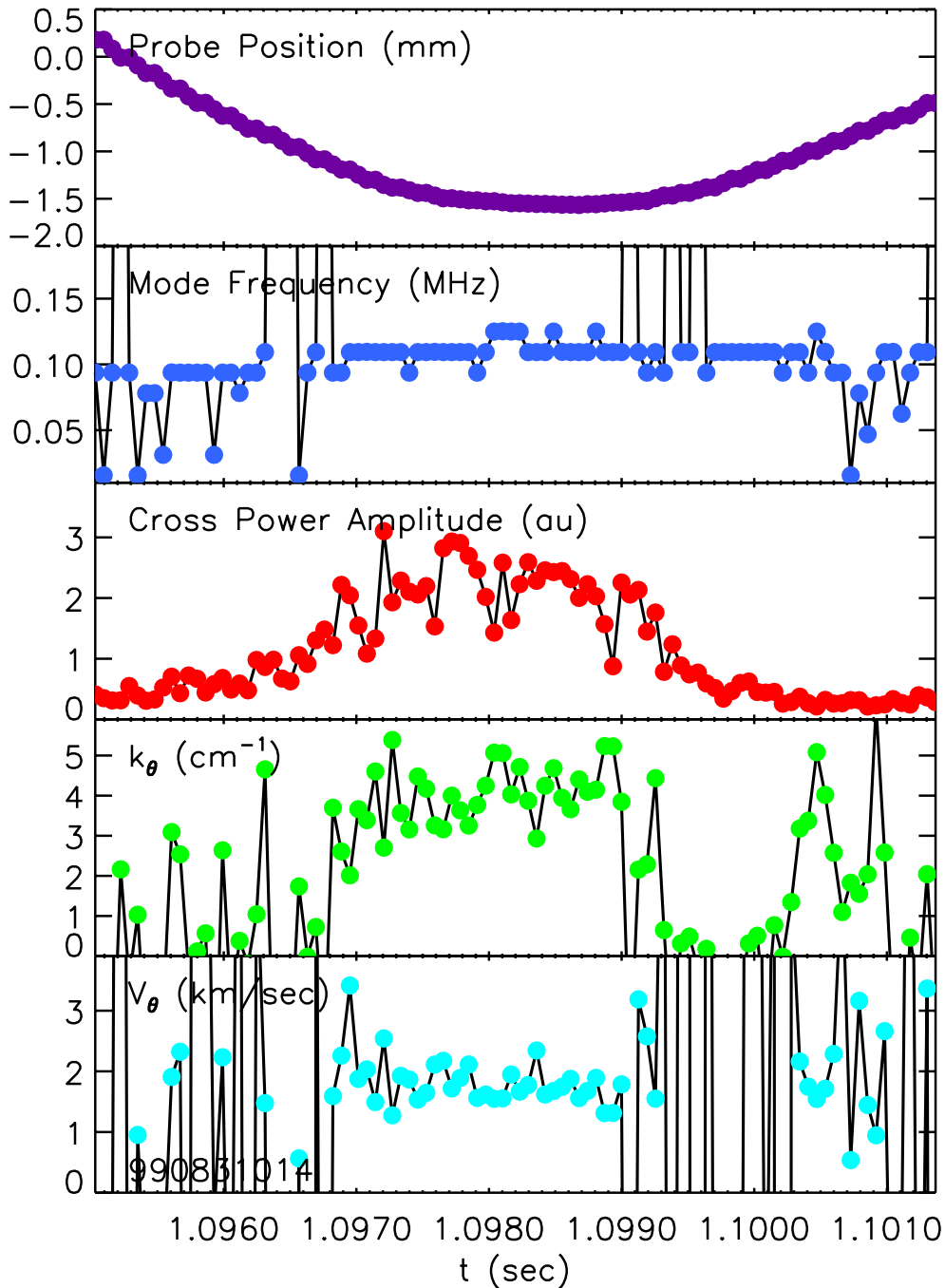
FSP_1–North Potential Fluctuations – 990831014



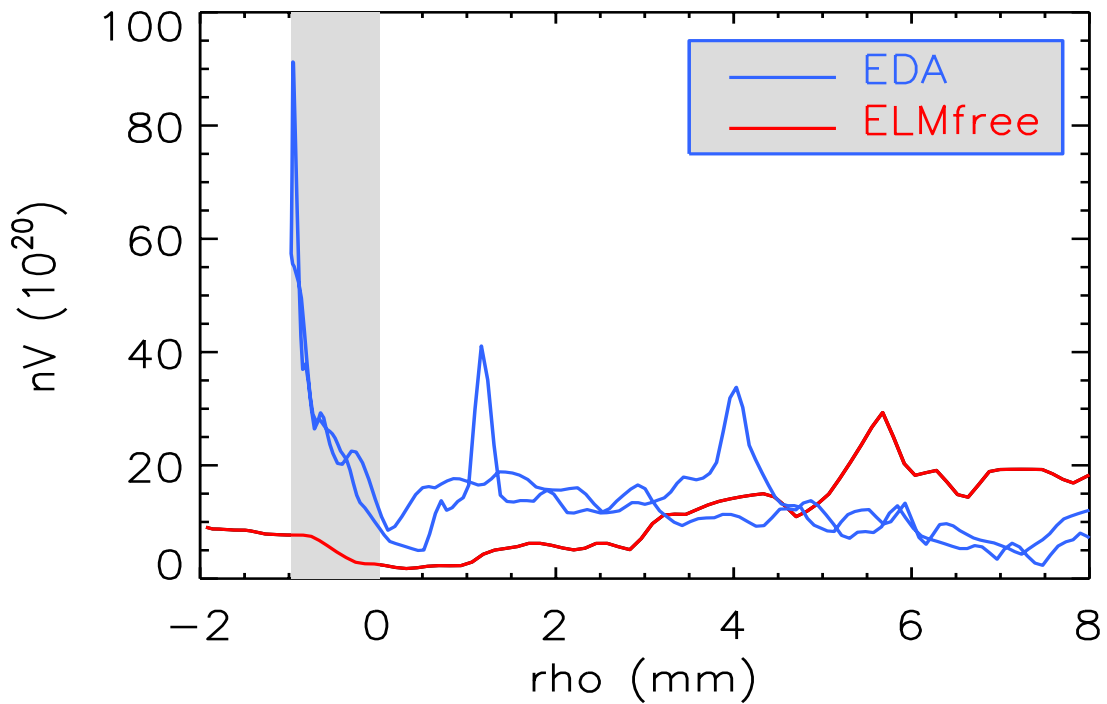
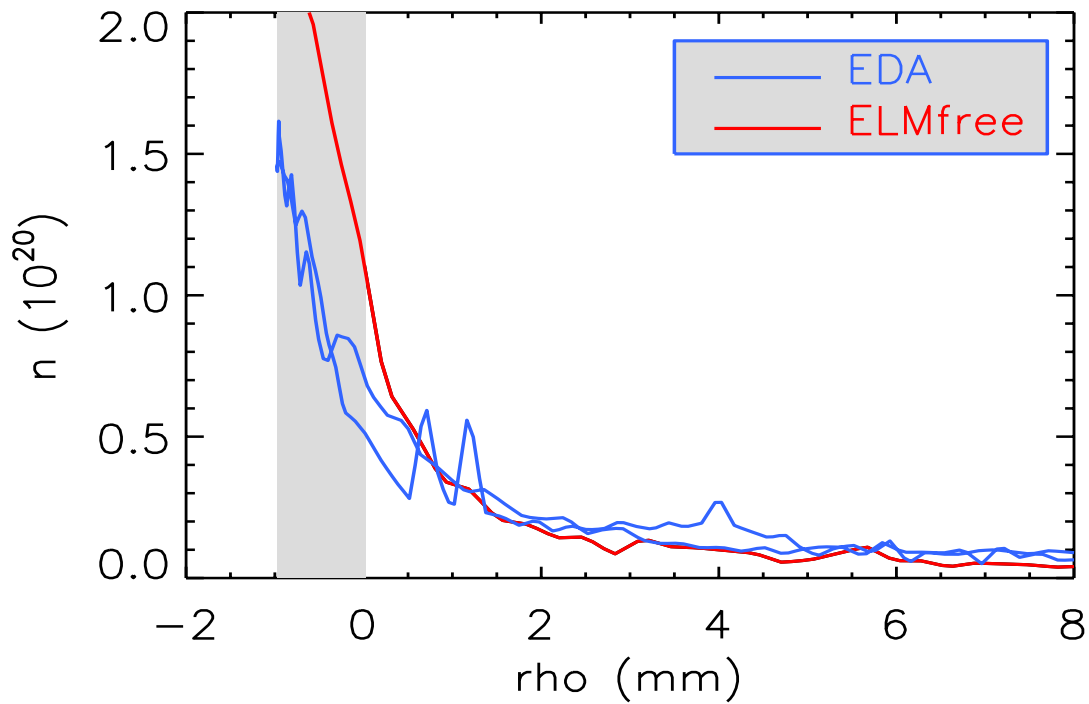
- Two arrays are available, each with multiple probes.
- These can be configured to local temperature and density or floating potential
- Fluctuations in ion saturation current and floating potential and their relative phase are measured
- Fluctuations are seen only in EDA and only when the probe crosses/approaches the separatrix.

(See Labombard - R02.09)

PROBE SIGNALS CAN BE ANALYZED TO DETERMINE WAVELENGTH OF COHERENT MODE

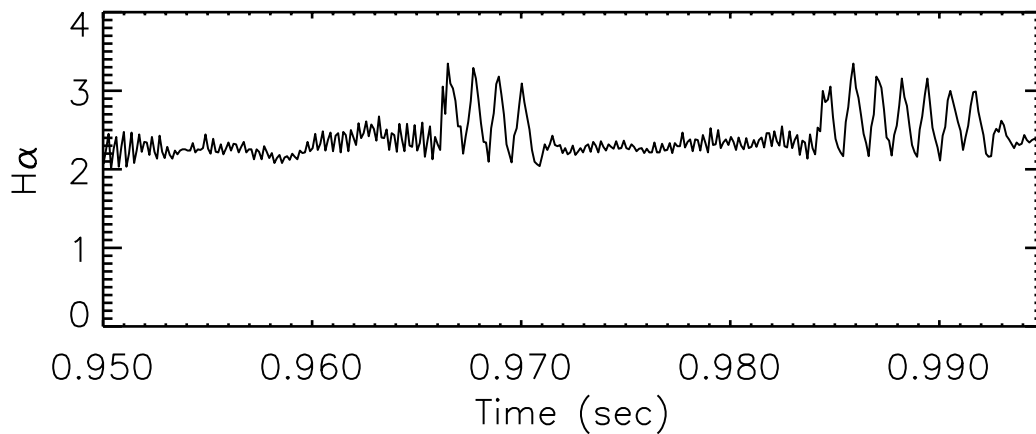
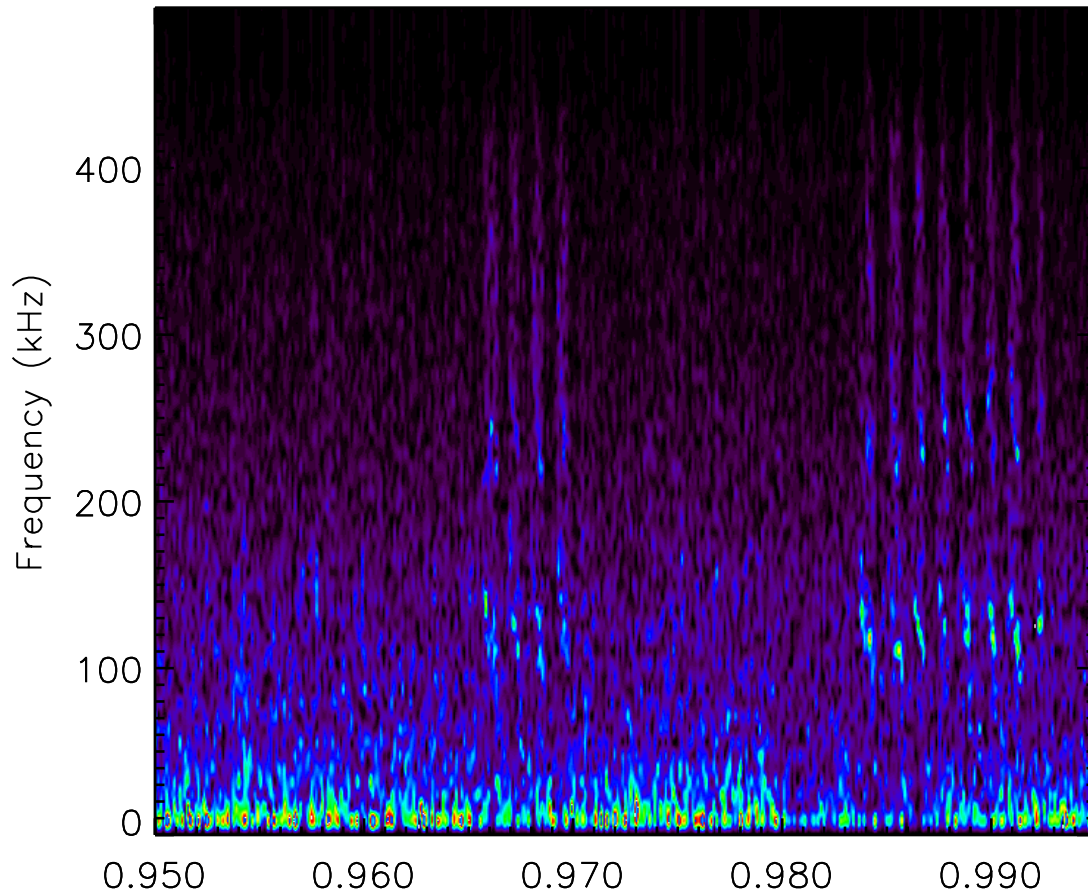


ANALYSIS OF $\langle \tilde{n}\tilde{E} \rangle$ SHOWS THAT THE OSCILLATIONS DRIVE SIGNIFICANT PARTICLE TRANSPORT



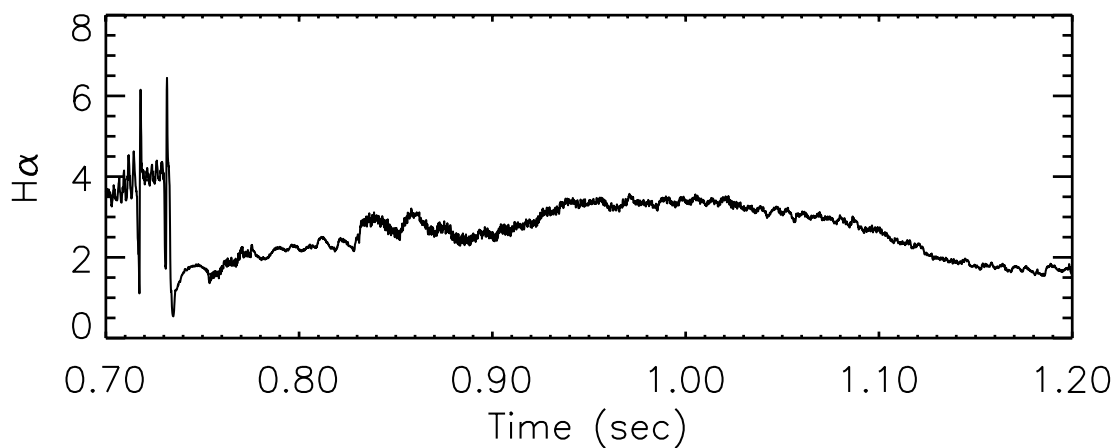
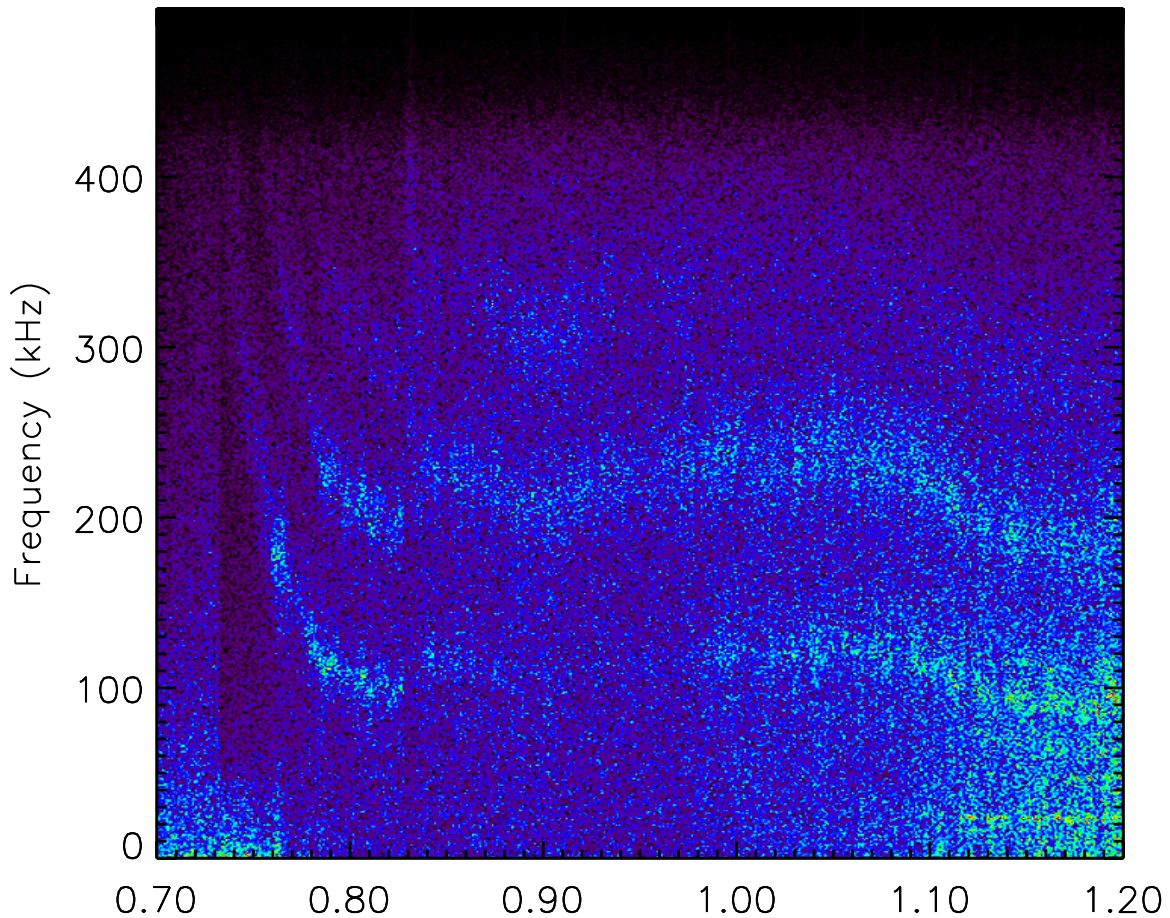
"DITHERS" BETWEEN EDA AND ELMFREE SUGGEST BIFURCATION BETWEEN THE REGIMES

Density Fluctuations 88GHz – Shot 990521019

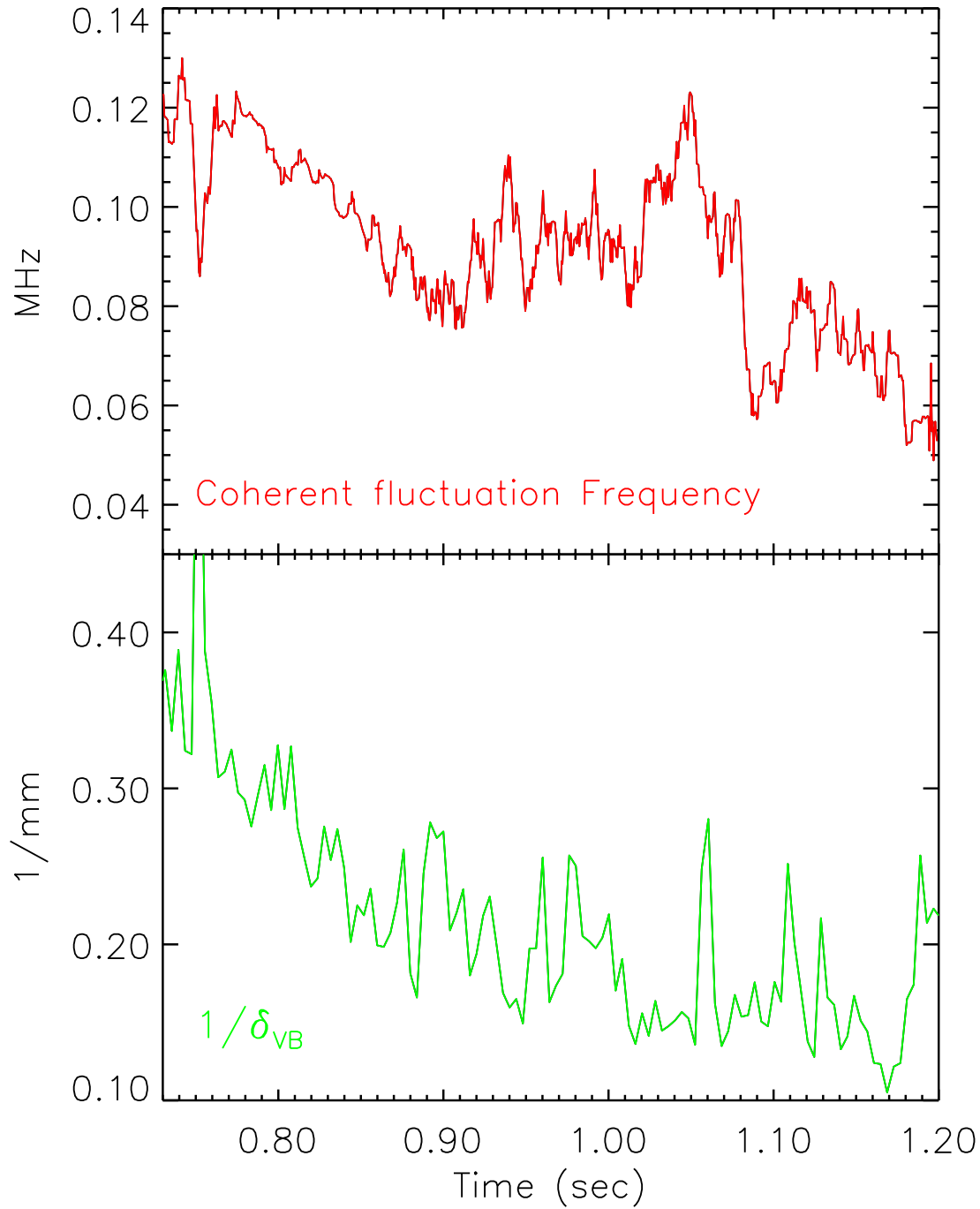


FLUCTUATION FREQUENCY IS HIGHER AS THE PLASMA TRANSITIONS IN AND OUT OF EDA

Density Fluctuations 88GHz – Shot 990304021



FLUCTUATION FREQUENCY VARIES INVERSELY WITH PEDESTAL WIDTH, SUGGESTING A DIAMAGNETIC ORIGIN FOR THE FREQUENCY

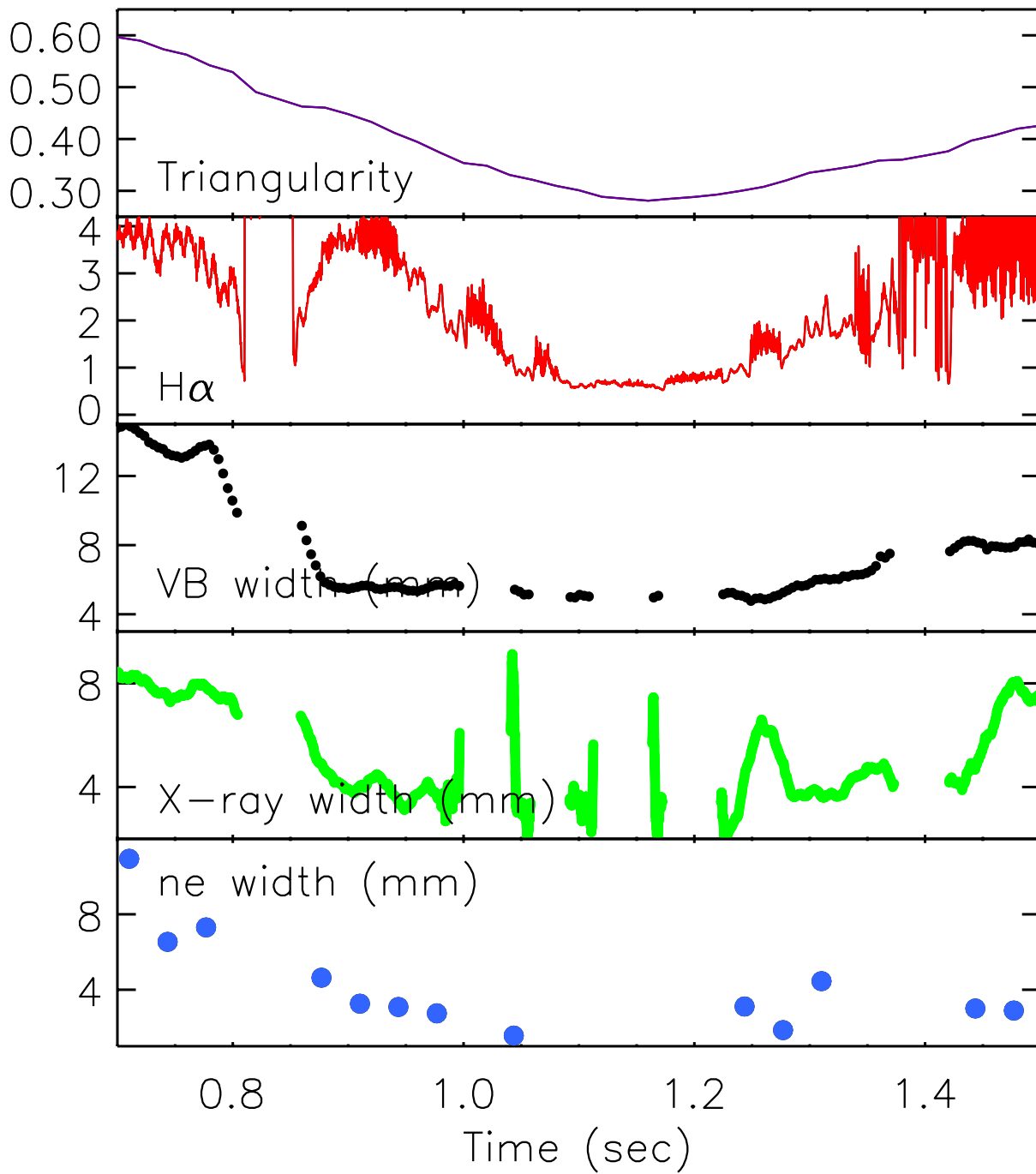


PEDESTAL PROFILES

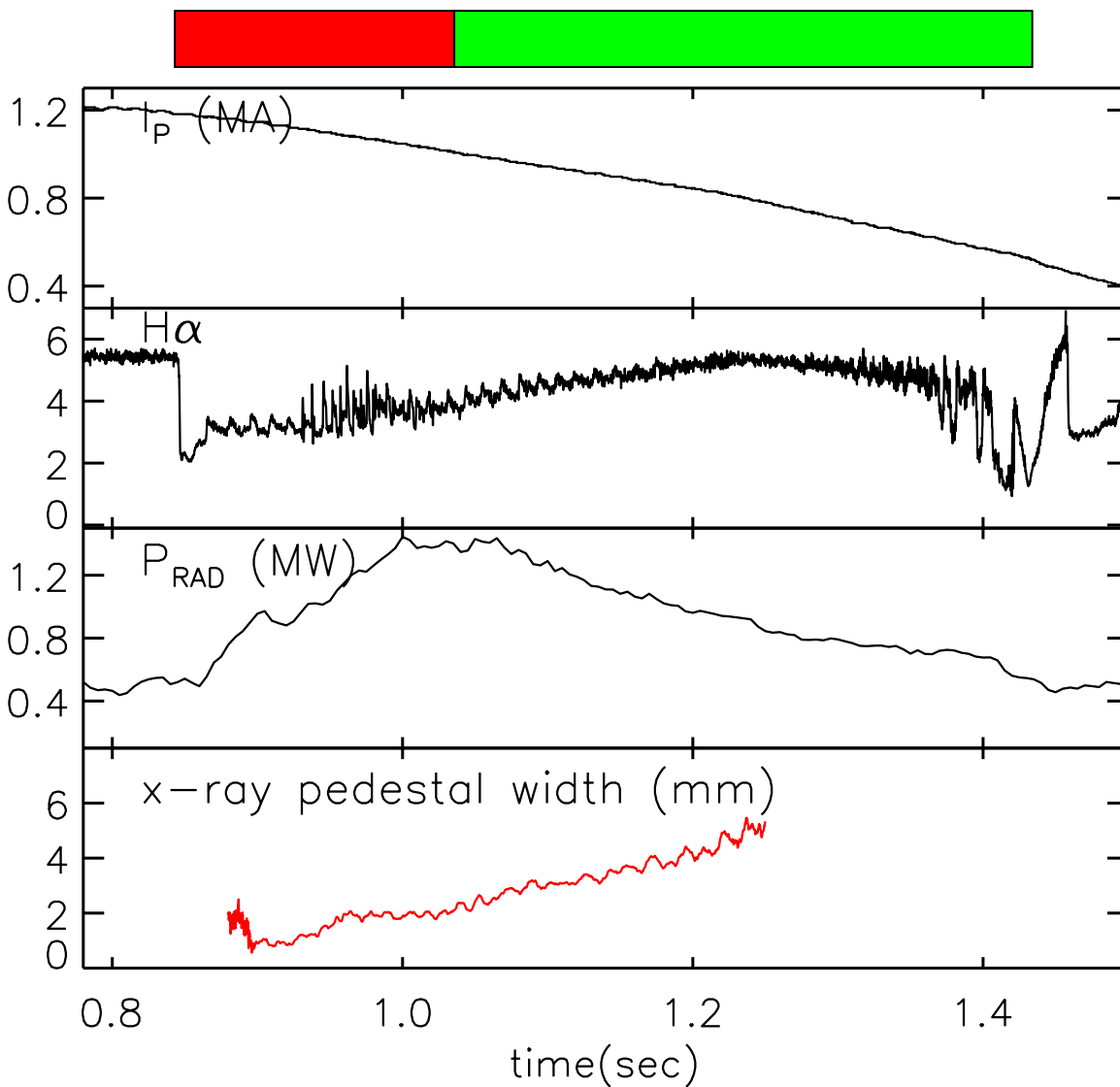
- Density pedestal profiles widths scale with q and δ (triangularity) - the same parameters that determine the EDA/ELMfree boundary.
- Lower q and lower δ result in narrower pedestals (and typically ELMfree plasmas)
- Widths vary from 2-10 mm for plasma and impurity density to 8-12 mm for temperature.
- Little variation in temperature profiles have been seen so far.
- This may be consistent with observed change in particle transport at ELMfree/EDA transition and the lack of change in energy transport.

(See Mossessian R02.02, Marmar KP1.34, and Hughes KP1.33)

WIDTH OF EDGE PROFILES SCALES WITH δ

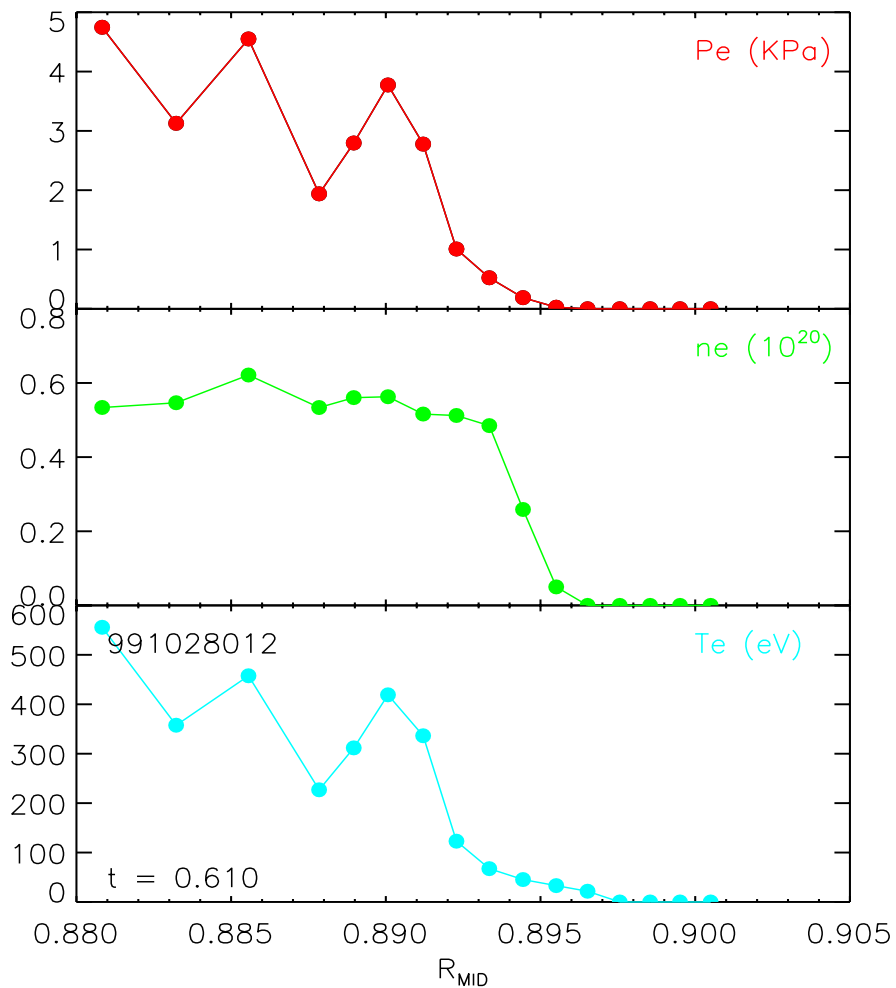


PEDESTAL WIDTH SCALES WITH I_p IN THE SAME MANNER AS THE EDA/ELM-FREE BOUNDARY



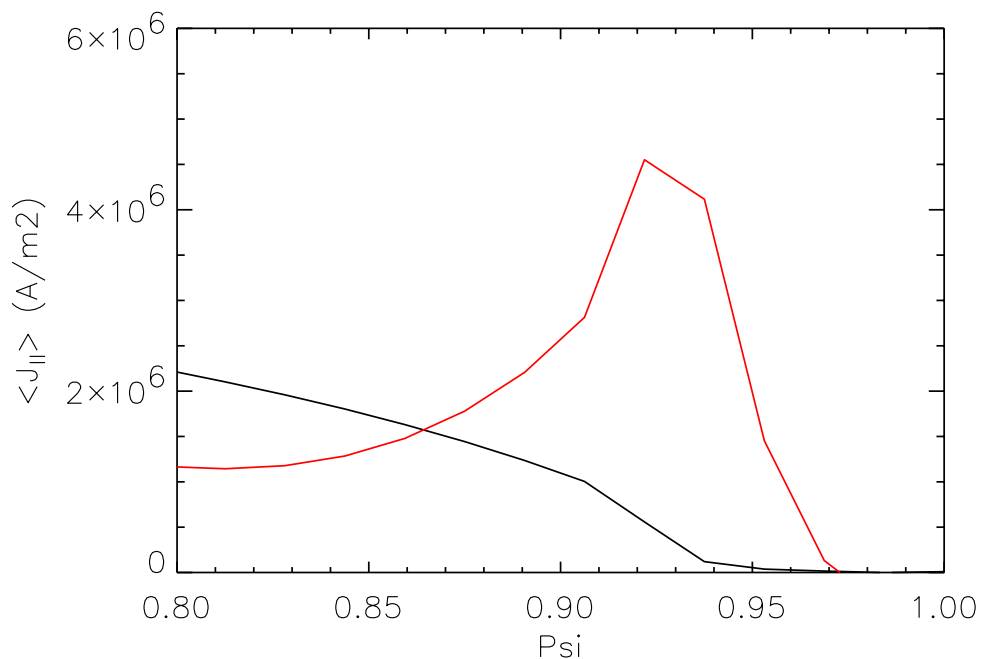
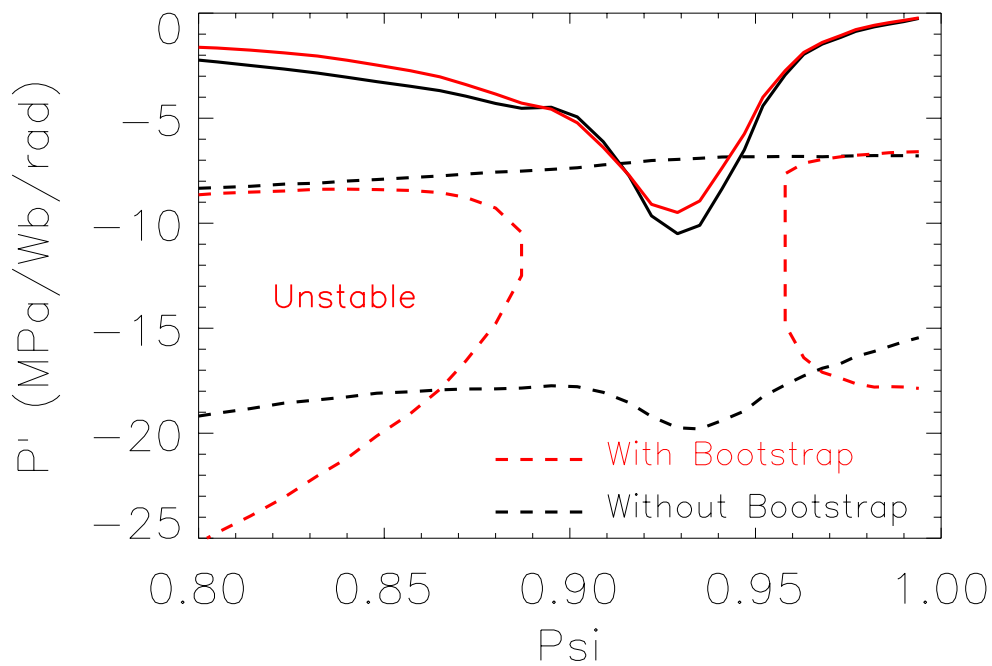
(see Pedersen R02.03 and Granetz R02.02)

PRELIMINARY MEASUREMENTS WITH IMPROVED THOMSON SCATTERING SYSTEM SHOWS DENSITY PEDESTAL OFFSET AND OUTSIDE OF TEMPERATURE PEDESTAL



Speculation: Since observed fluctuation exists in region of high density gradient, it would be no surprise that particle transport is effected rather than energy - there is no significant temperature gradient in this region.

THE PEDESTAL IS FOUND TO BE MHD STABLE ONLY WITH THE INCLUSION OF EDGE CURRENT

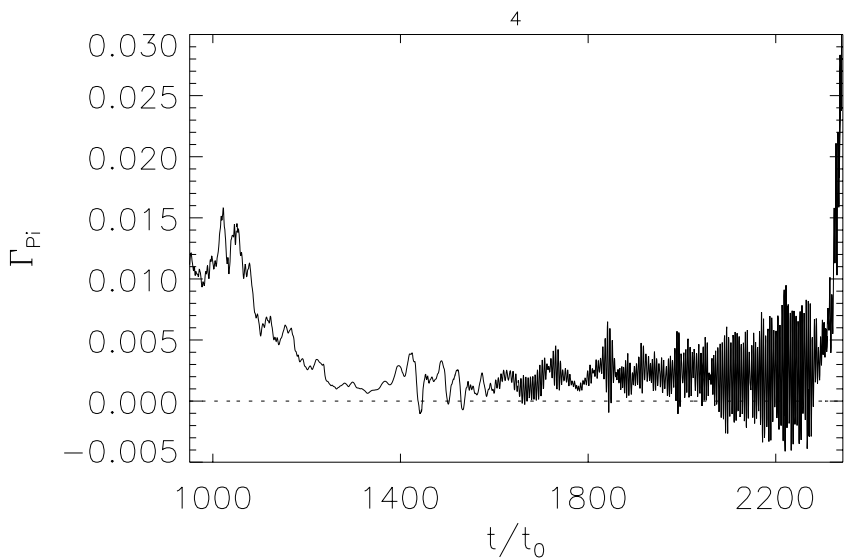
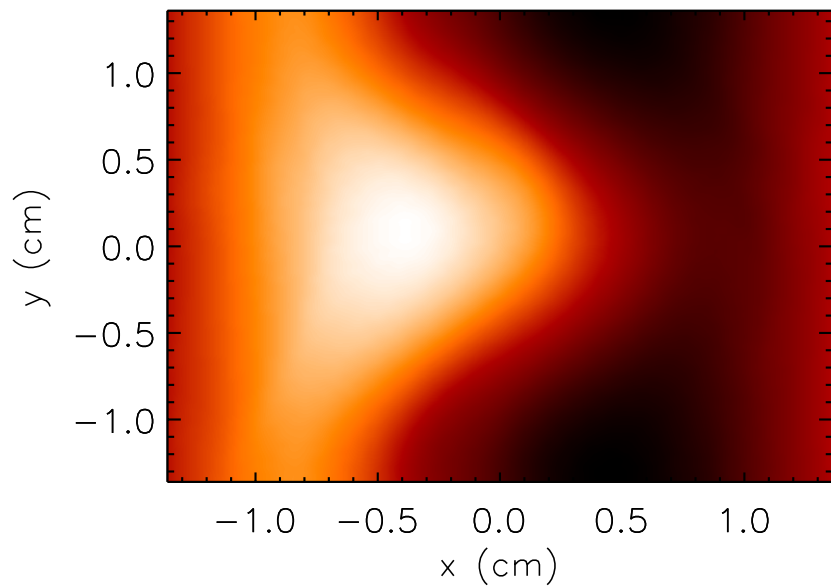


STABILITY OF THE H-MODE EDGE

- The dependence of the EDA/ELM-free boundary on δ and q are reminiscent of the MHD stability calculations done by Miller et al. (Bootstrap current and access to 2nd stability).
- However, due to its high density, the edge plasma in C-Mod is quite collisional ($\nu^* \sim 1-5$), so bootstrap current will be reduced.
- ¹Rogers and Drake (Phys. Plasmas **6**, 2797 (1999)) have proposed another mechanism - diamagnetic stabilization of MHD modes.
- They also point out that collisionless ballooning is destabilized at high q . (If this theory helps explain EDA, then we would expect EDA to be easier to obtain in hydrogen plasmas as well - an experiment to be done.)

SIMULATIONS OF DRIFT-ALFVEN TURBULENCE SHOW AN MHD-LIKE MODE ARISE AT HIGH EDGE PRESSURE GRADIENTS

The calculated k ($3-6 \text{ cm}^{-1}$) and frequency (50-200 kHz) of this mode¹ are in rough agreement with our measurements



SUMMARY

- The EDA H-mode regime combines good energy confinement, moderate particle confinement and no energy impulses to the first wall.
- EDA is easily obtained with ohmic heating alone - rules out fast particles or RF/Edge interactions as cause.
- EDA is most easily accessed at $q_{95} > 3.5$, $\delta > 0.35$
- The pedestal gradient is limited by a continuous rather than intermittent process, probably related to density and magnetic fluctuations which are observed. ($f \sim 100$ kHz, $k \sim 5$ cm⁻¹)
- The observed fluctuations drive significant particle flux.
- Dithering between EDA and ELMfree H-modes suggest a bifurcation between the regimes.
- Density pedestal widths scale in the same manner as EDA/ELM-free boundary.