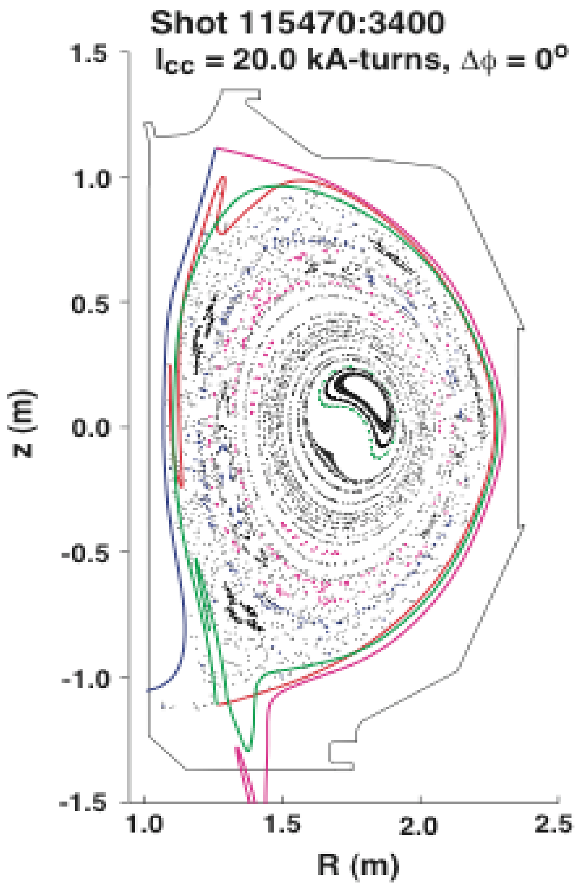
ELM suppression with a stochastic boundary in DIII-D



T. E. Evans, R. J. Groebner, R. J. La Haye, T. H. Osborne, M. J. Schaffer - *General Atomics, San Diego, CA, USA*

R. A. Moyer - *UCSD, La Jolla, CA, USA*

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K. H. Finken - *FZ-Jülich, Germany*

N. Ohyabu, S. Masuzaki - *NIFS, Japan*

J. Harris, D. Pretty - *Australian National University, Australia*

H. Reimerdes - *Colombia University, NY, USA*

MHD Workshop, 3-5 November 2003,
Austin, Texas

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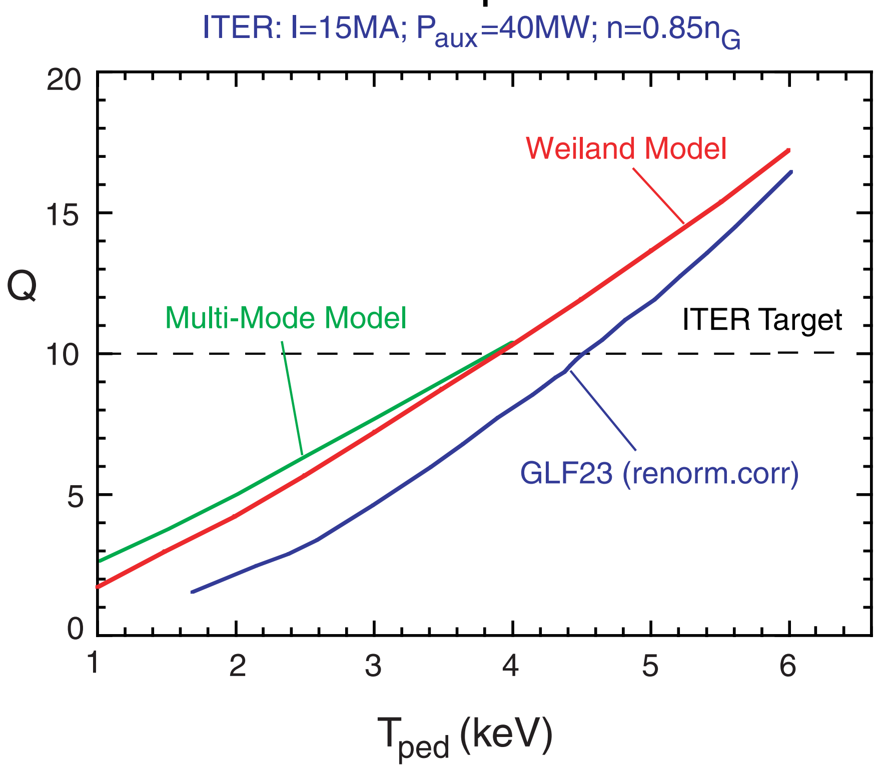
Pedestal control is a critical issue for next-step fusion devices

- Core performance is tightly coupled to pedestal height by stiff radial transport



> Pedestal T_e uncertainty affects ITER Q_{fus} more than transport model

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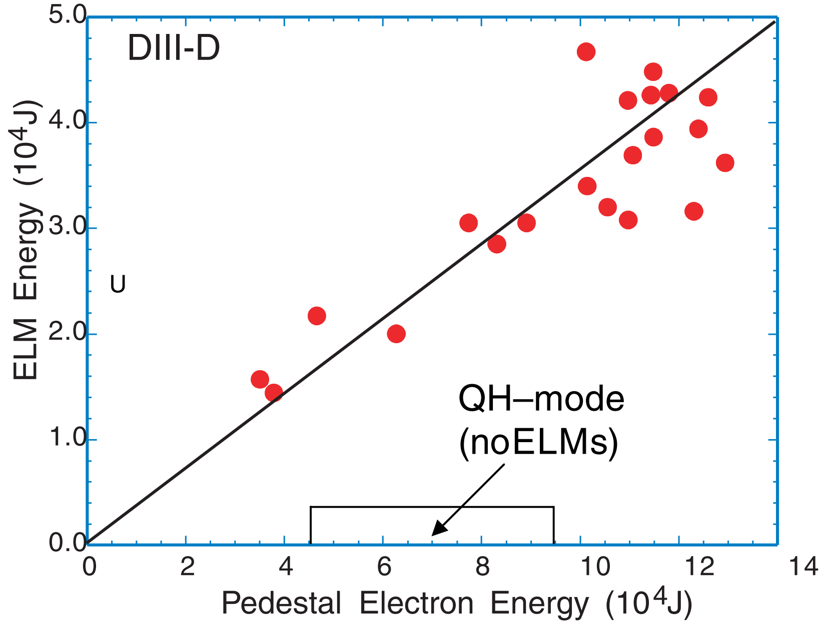
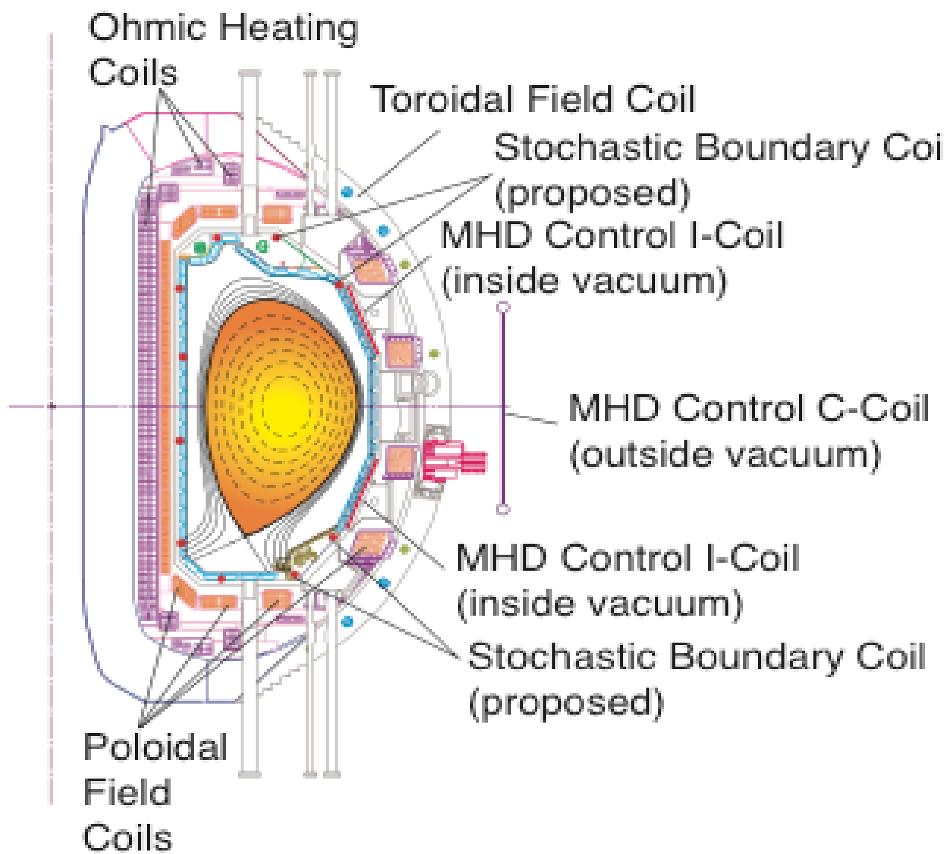
- ELMs affect core plasma performance...
  > Directly by reducing pedestal height
  > Indirectly by affecting pedestal stability



- ELMs limit divertor plate lifetime
  > Impulsive heat flux erodes material

An edge stochastic layer may be a good solution for pedestal control

- Dedicated pedestal control experiments, using the error field correction coil (C-coil) and internal MHD control coil (I-coil) were initiated in 2003 on DIII-D
- First results from these experiments look very promising
- Additional experiments are planned for 2004
- If these experiments with the existing coils continue to look favorable a new set of coils will be installed in DIII-D that are specifically designed to optimize the edge stochastic layer



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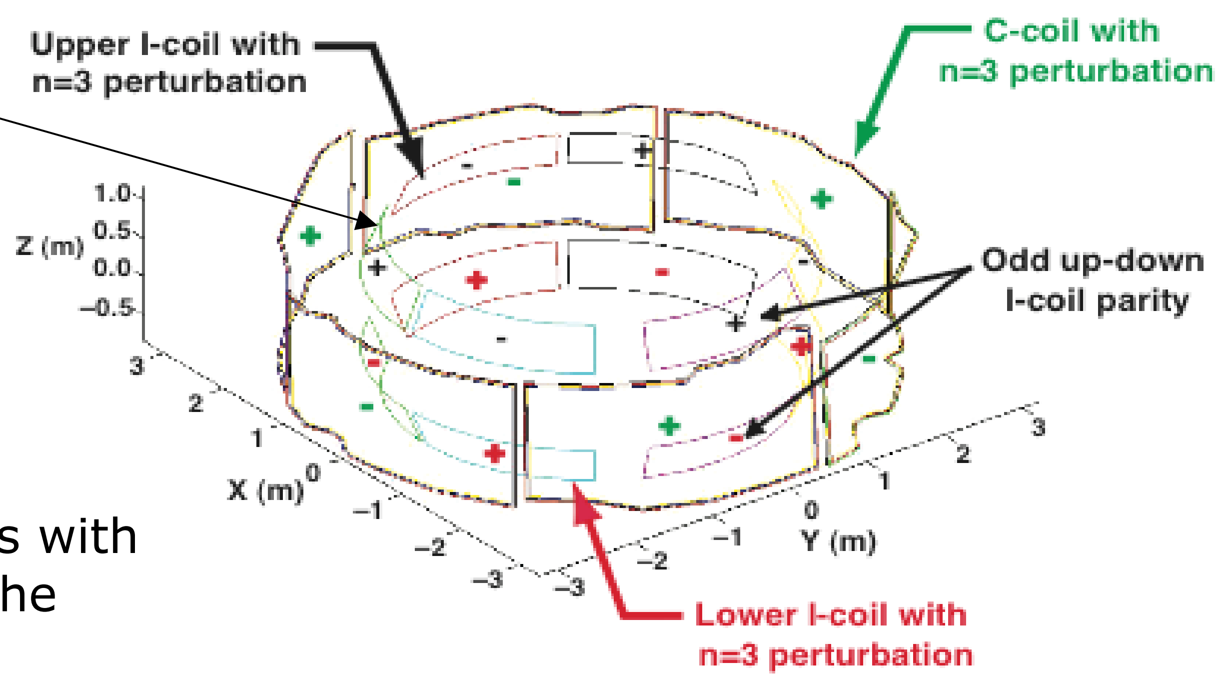
The I-coil operated alone or in combination with the C-coil provides additional flexibility

- The C-coil and I-coil are typically operated in an n=1 configuration for core MHD control but can also be operated in a variety of configuration for edge 3-D control studies.



- They can be combined and configured for n=3 operations with a relatively small impact on the core plasma.

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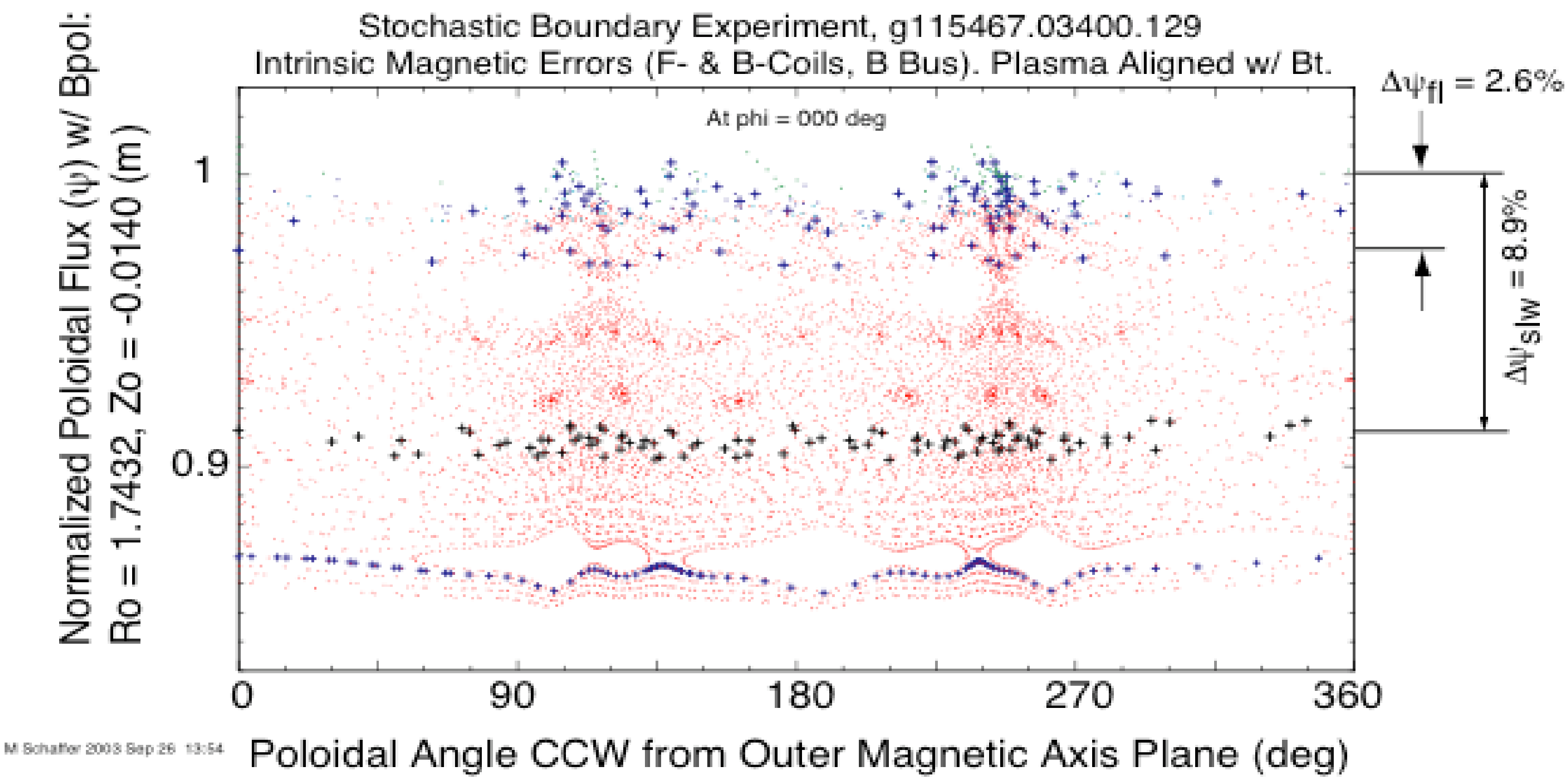
The stochastic layer structure is characterized by its width $\Delta\psi_{slw}$ and poloidal magnetic flux loss $\Delta\psi_{fl}$



- Rectangular Poincaré plot showing a TRIP3D calculation of the magnetic structure in DIII-D pedestal with **measured error fields only (no C- or I-coil)**.

No plasma response included

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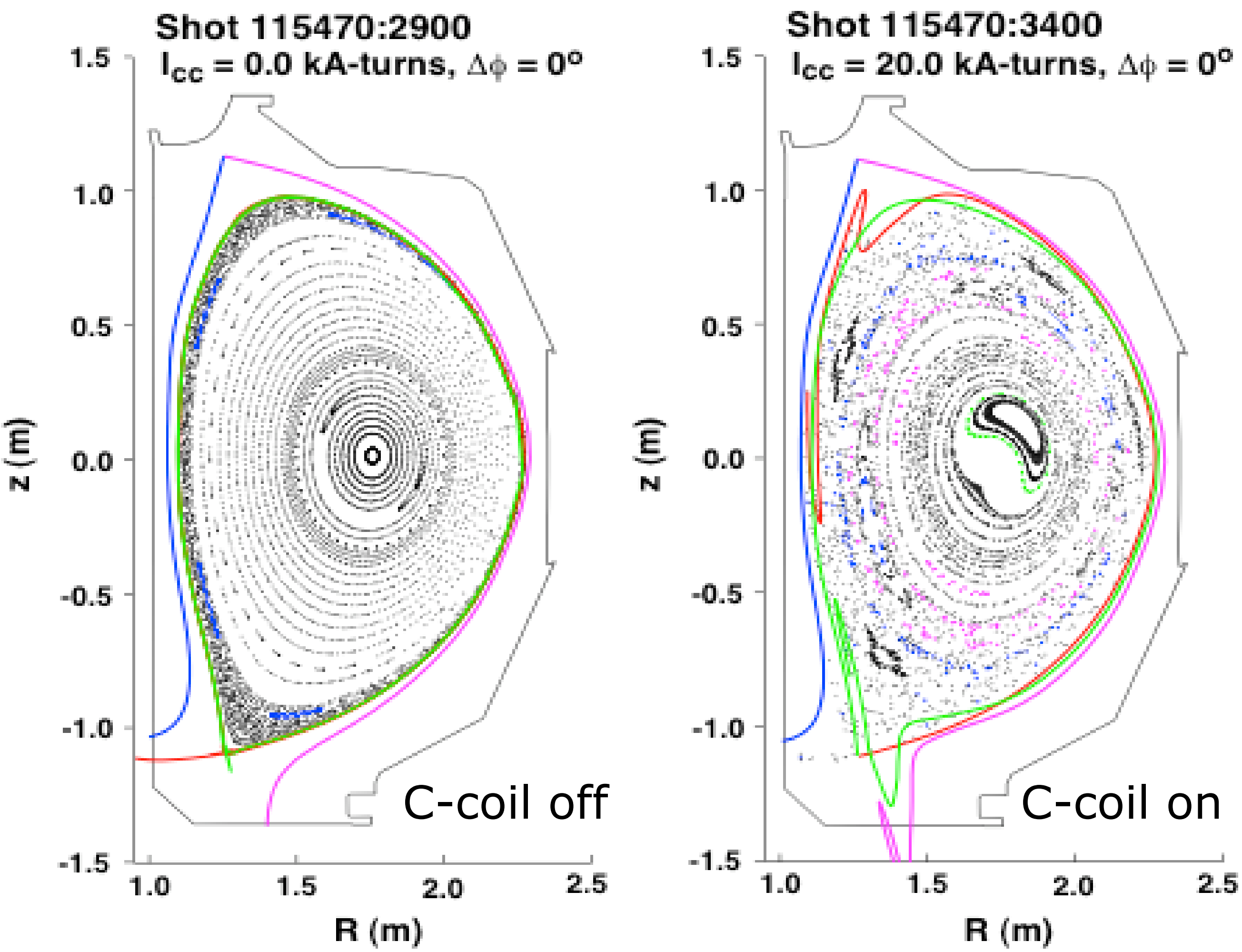
Standard n=1 error field correction with the C-coil creates large core perturbations with a relatively wide stochastic layer



No plasma response included

- With 20 kA-turns in the C-coil $\Delta\psi_{slw}$ increases from 6.2% due the f-coil error fields to 45.4% while $\Delta\psi_{fl}$ increases from 0.2% to 23.3%.
- Although the C-coil is typically operated well below 20 kA-turns for standard error correction it produces a significant edge stochastic layer in most cases.

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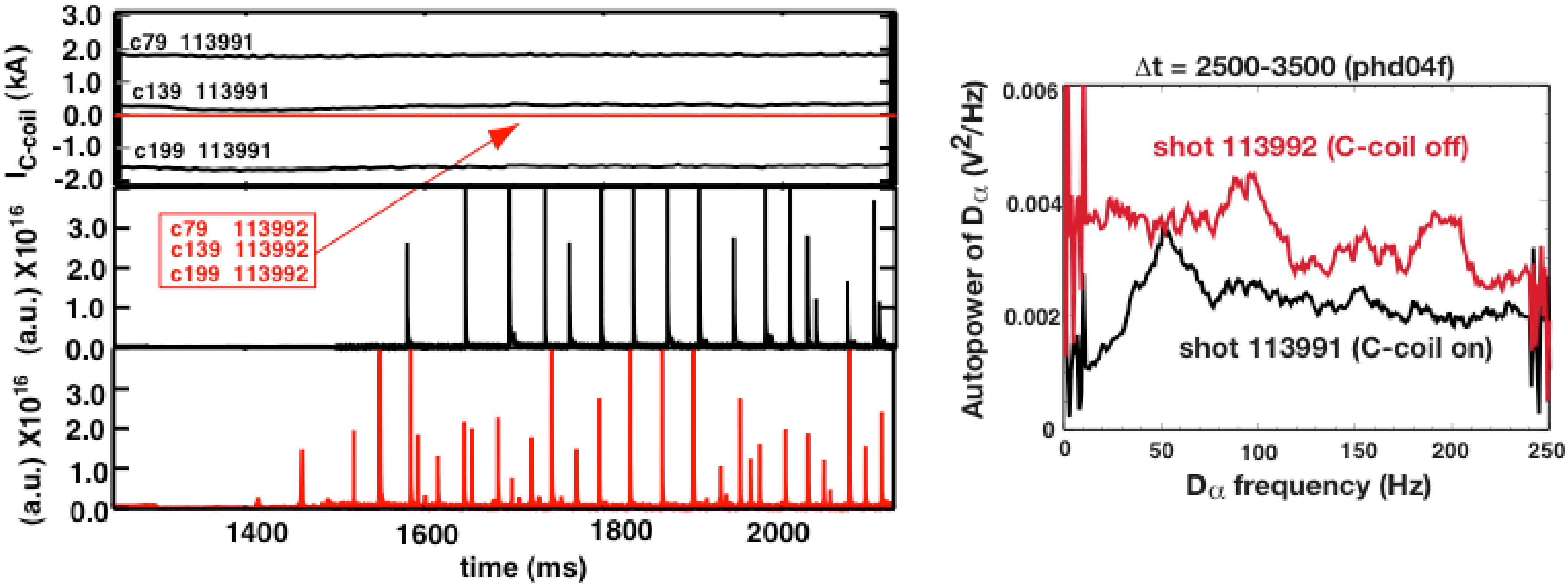
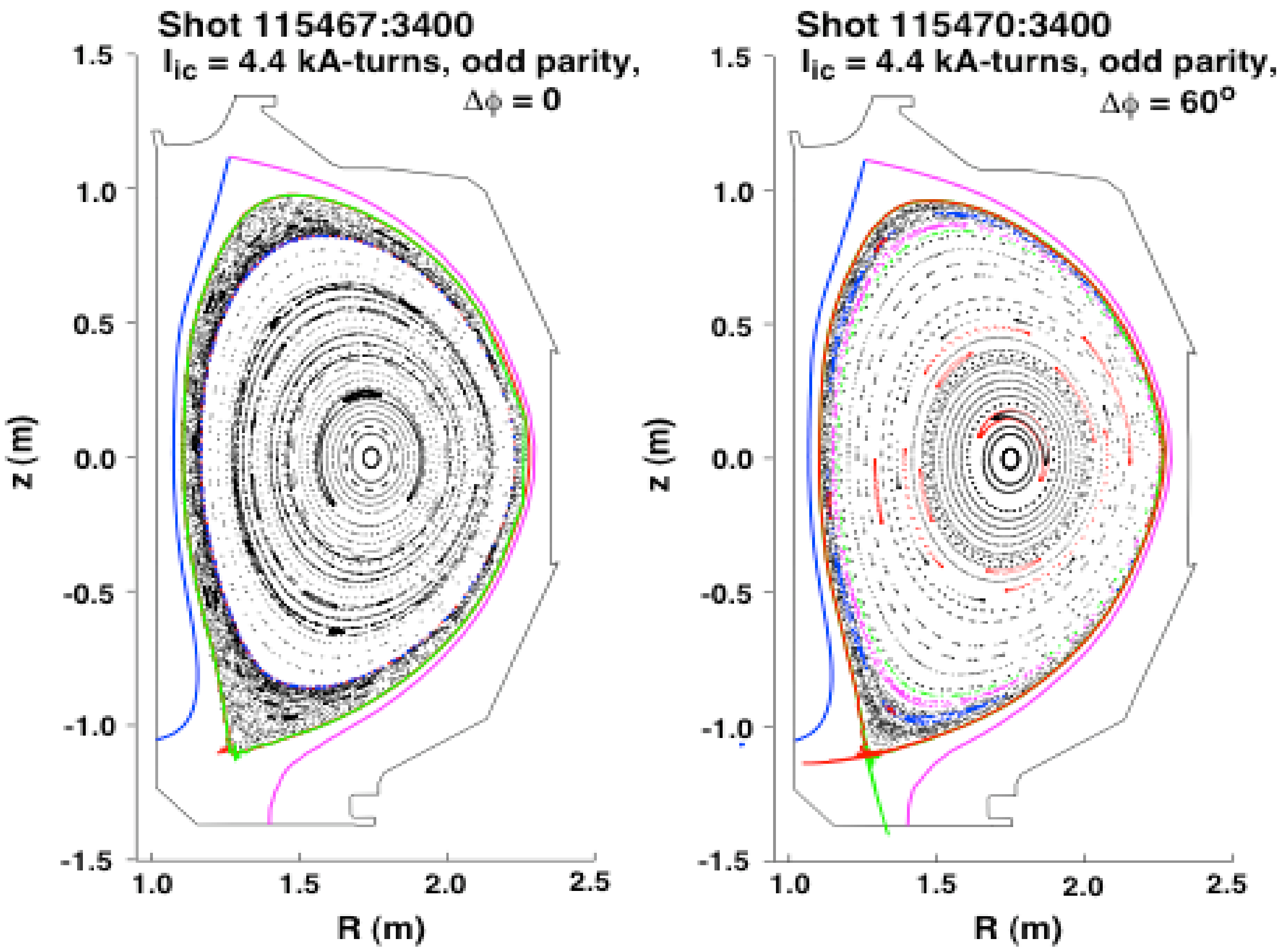
Identical discharges with and without the C-coil have significantly different ELM characteristics



- The ELM free period is longer and the ELM frequency is lower with the C-coil operating in the standard error field correction mode.
- The ELMs are more irregular without the C-coil and have a broader power spectrum.

In the n=3 configuration, with full I-coil current, the edge stochastic layer is significantly smaller than with the C-coil and the core islands are smaller



No plasma response included

- The toroidal phase of the I-coil perturbation has a small effect on the stochastic layer due to a difference in the mixing with intrinsic error fields, with $\Delta\phi$=0, $\Delta\psi_{slw}$=12.6% and $\Delta\psi_{fl}$=1.7% while with $\Delta\phi$=60^o, $\Delta\psi_{slw}$=10.2% and $\Delta\psi_{fl}$=0.7%.
- Although the stochastic layer is smaller with the I-coil the effect on ELMs is larger.

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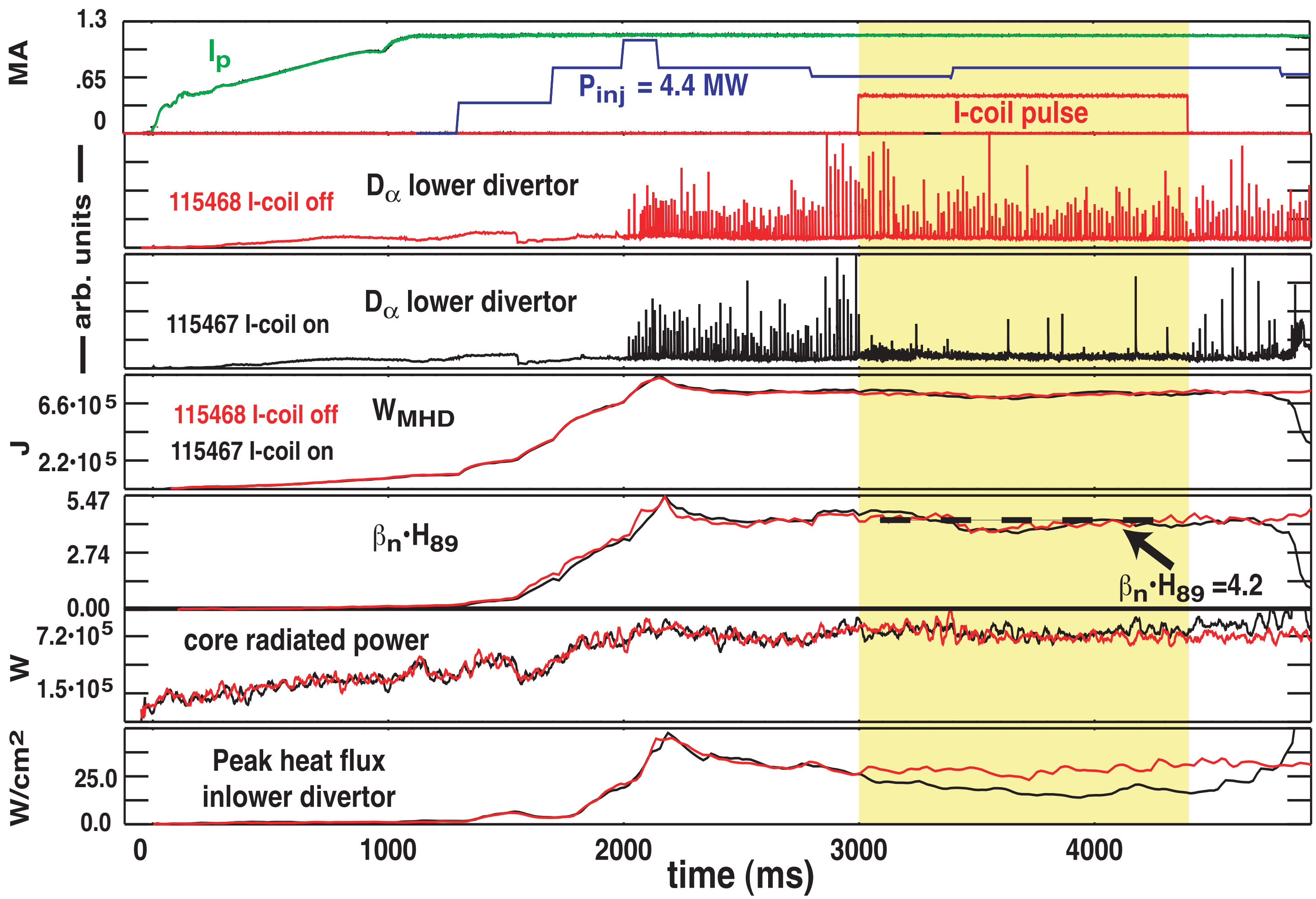
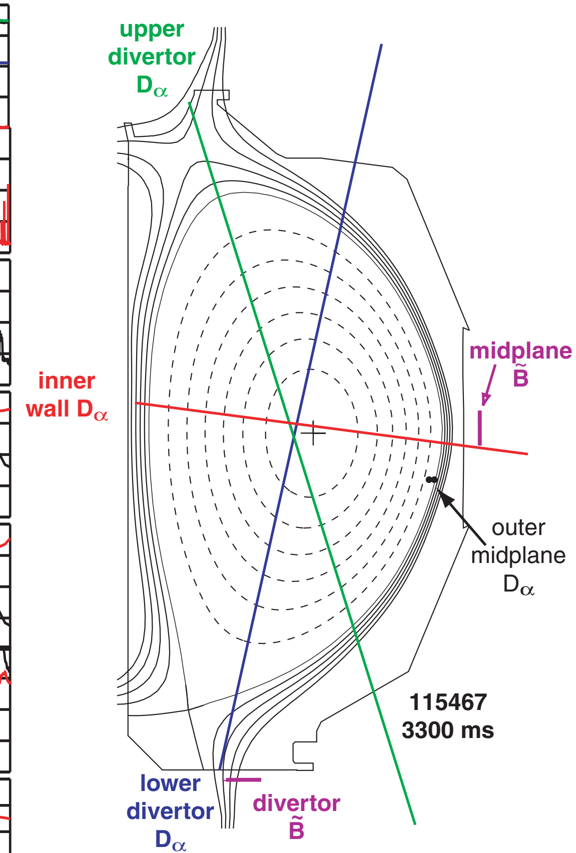
Large ELMs are suppressed without degrading the core confinement during the n=3 I-coil pulse

- Type I ELMs suppressed in high performance ELMing H-modes (β_n•H = 4.2) with and edge resonant perturbation.





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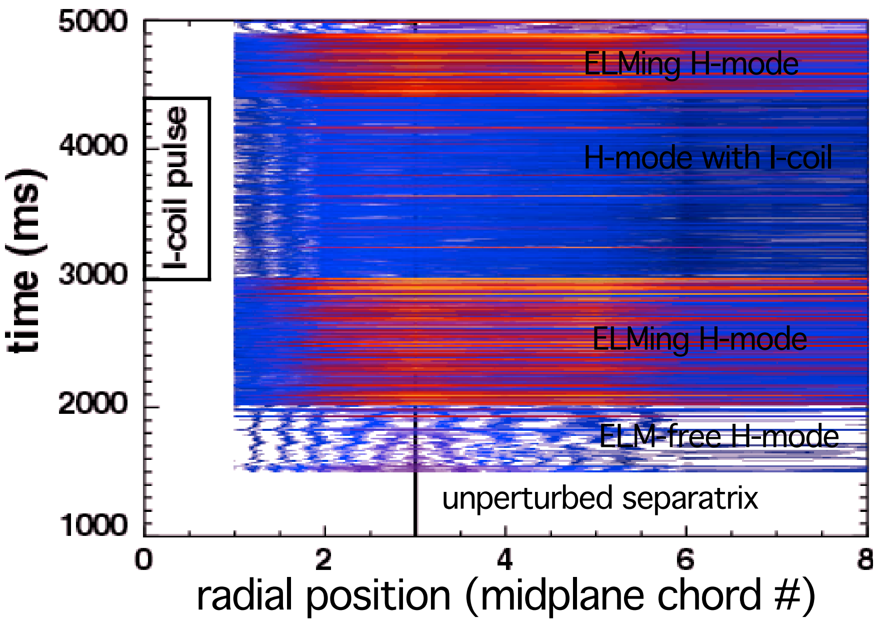
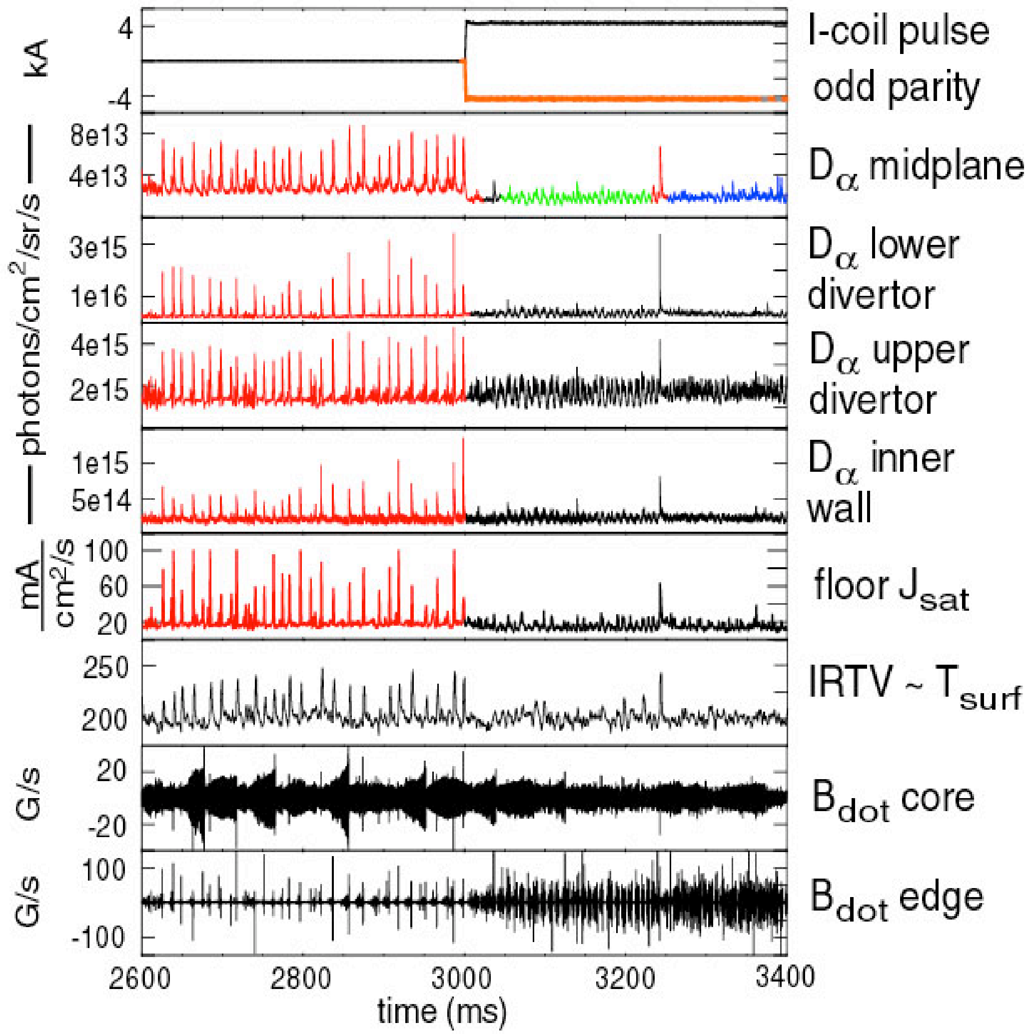
Large 70 Hz type-I ELMs are converted into small 150 Hz oscillations punctuated by isolated events

- Suppression is global and readily apparent on:
  - > All D_α arrays (outer midplane, upper and lower divertor, inner wall
  - > Particle flux and heat flux to the primary (lower) divertor





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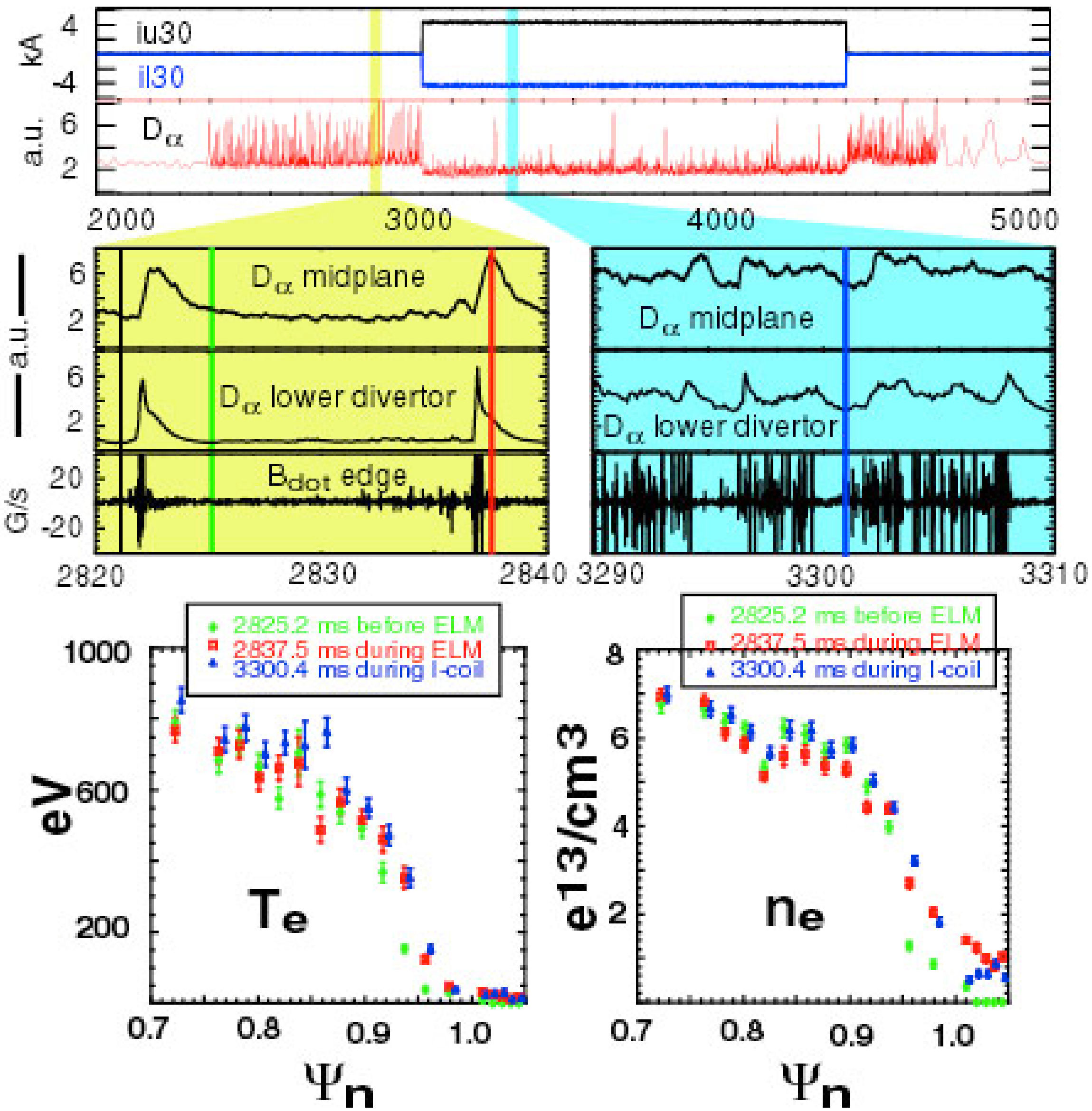
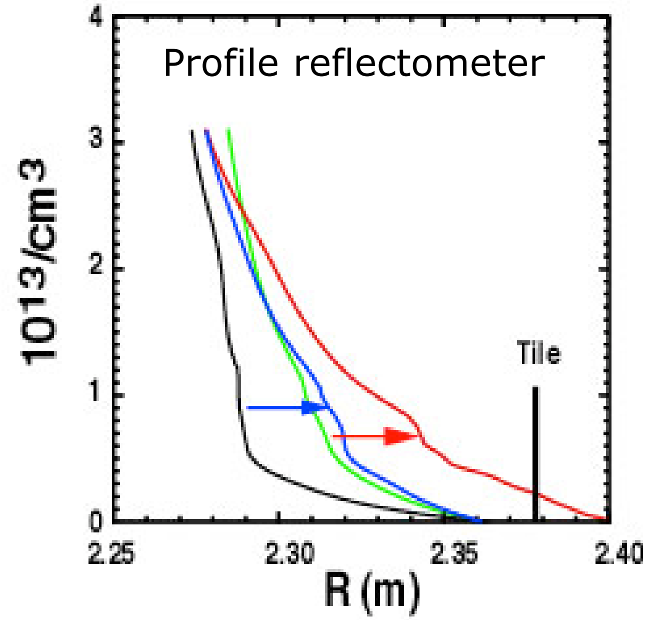
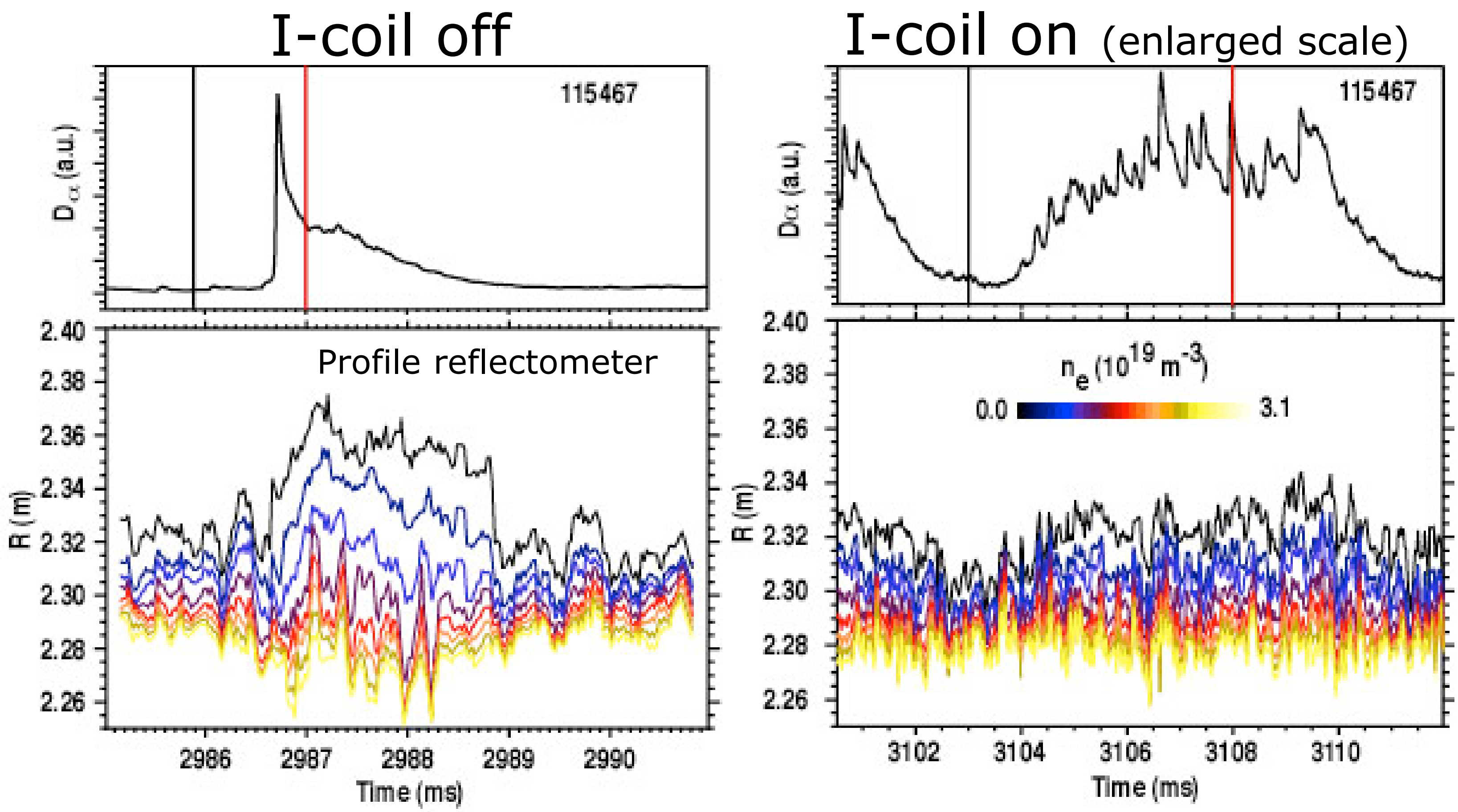
Large ELMs are replaced with irregular recycling





- "quiet time" pedestal density profile with I-coil on is steeper than the profile between ELMs with the I-coil off:
  - > But the rapid oscillations broaden profile

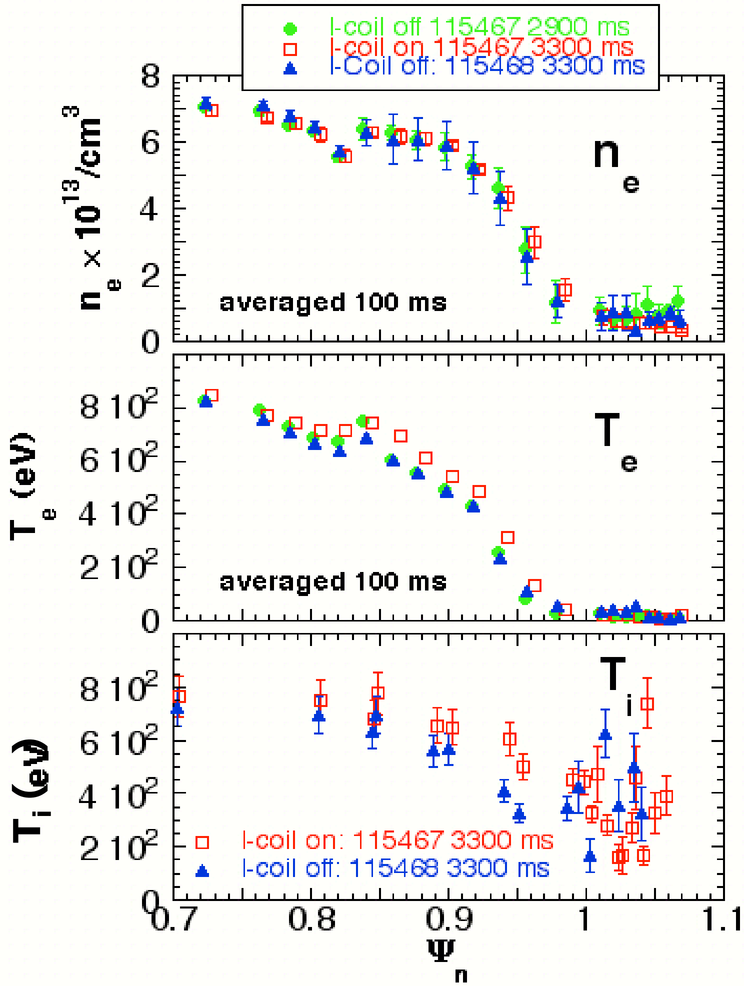
The n_e profile broadening is smaller during the irregular recycling than with the large ELMs



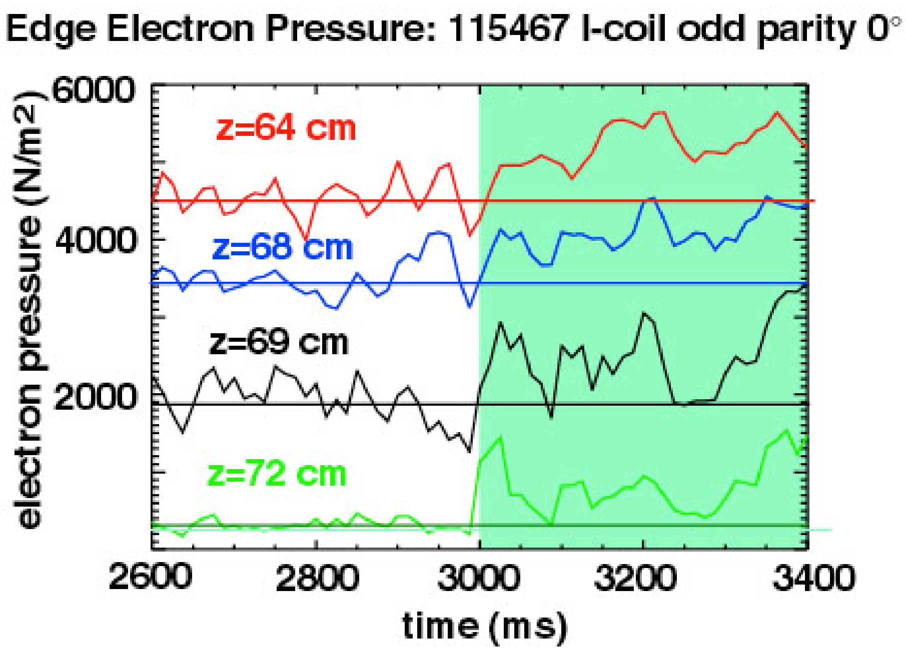
- “duty cycle” of Type I ELM is mostly “quiet” between ELMs (4.5 ms out of 6 ms cycle)
- “duty cycle” of oscillations is mostly “high” with only brief quiet intervals (6 of 7 ms)

Time averaged pedestal profiles have a steeper gradient region with a similar pedestal height

- Increase in edge density and T_e not what one would expect from a stochastic layer



- Thomson chords in the pedestal clearly show increase in electron pressure



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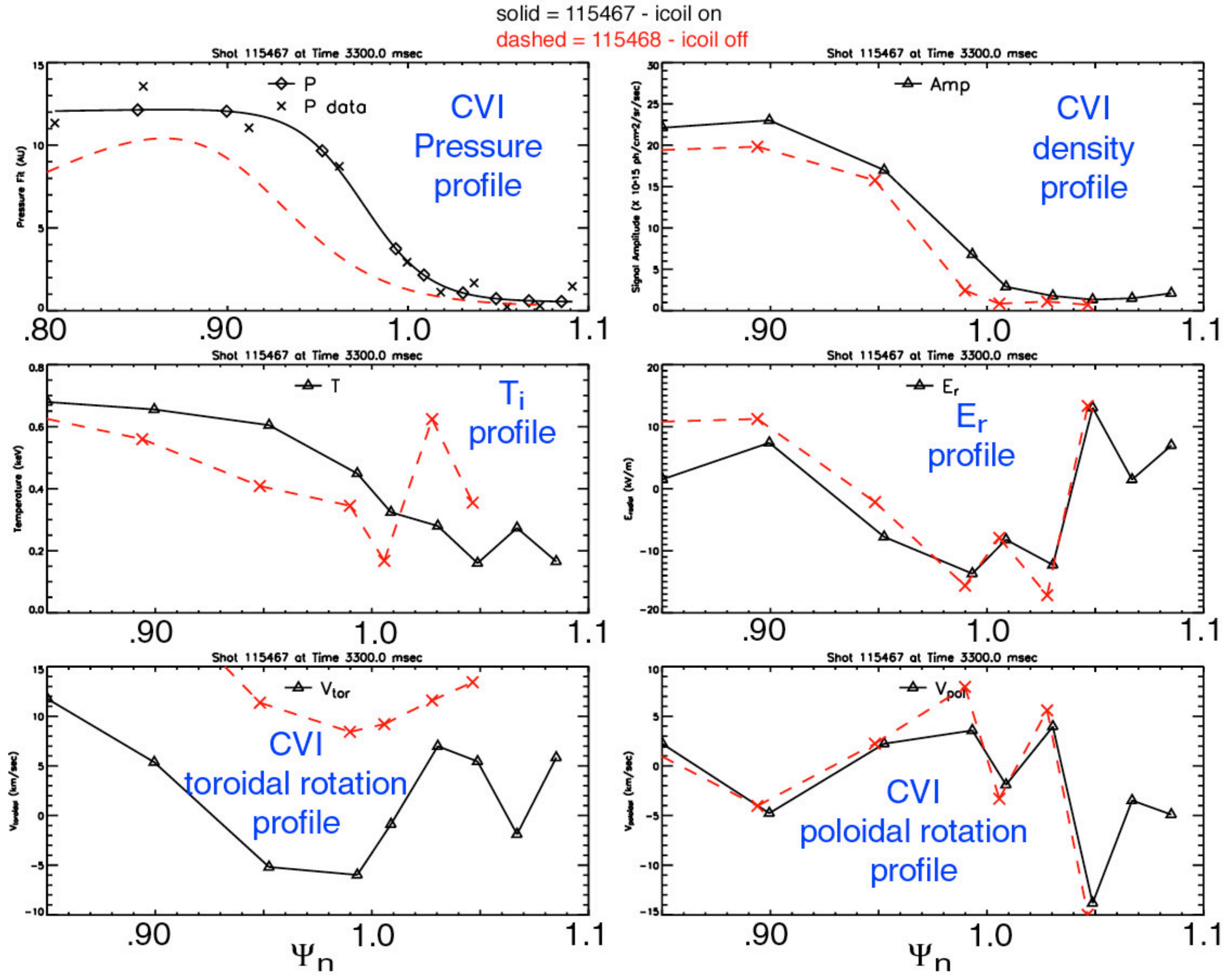
CVI ion measurements also show a broadening of the T_i and P_{CVI} across the pedestal

- Toroidal rotation drops through 0 and reverses in edge!
- But, H-mode transport barrier is preserved
  - > v_θ & E_r well don't change
  - > Increased gradP_i offsets change in $V_f \propto B_\theta$ in single ion force balance



R.J. Groebner

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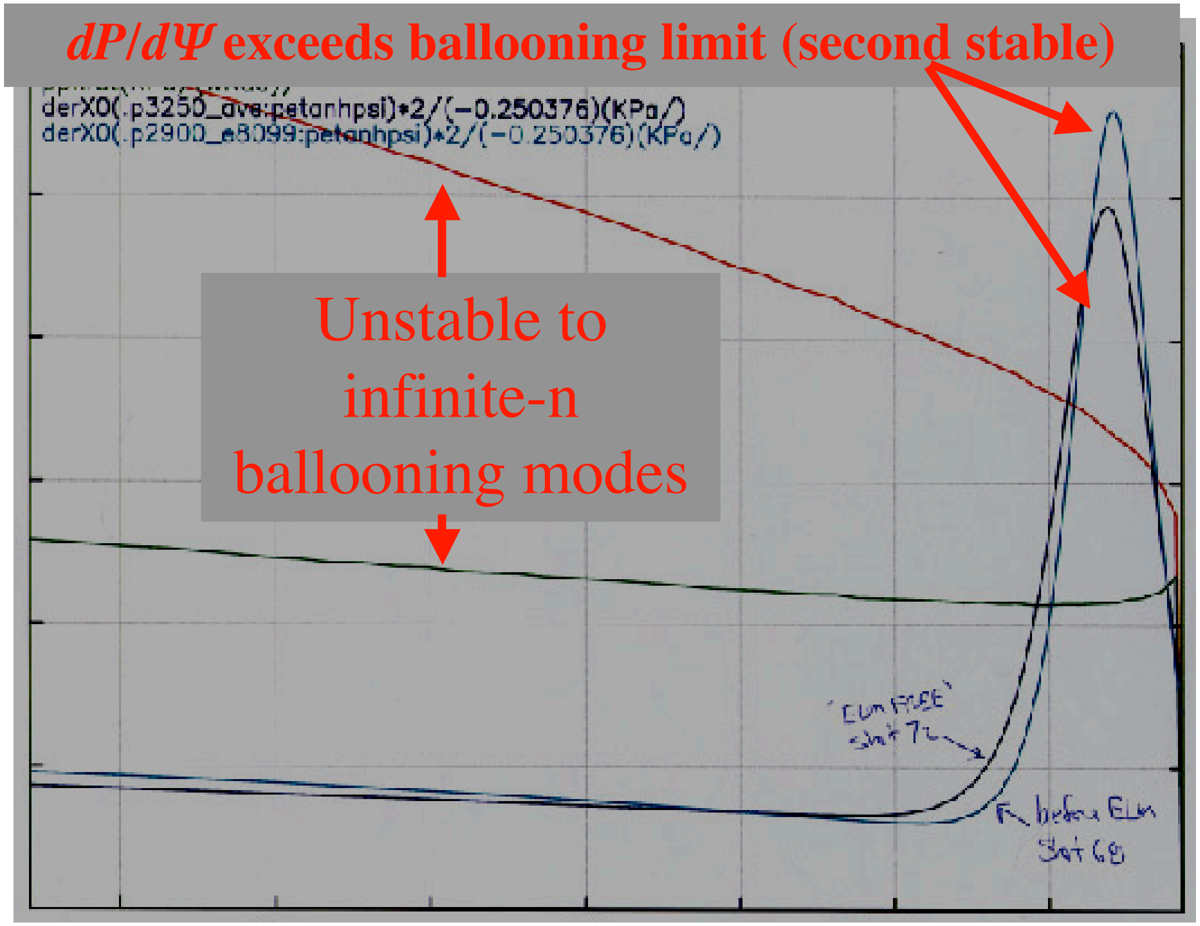
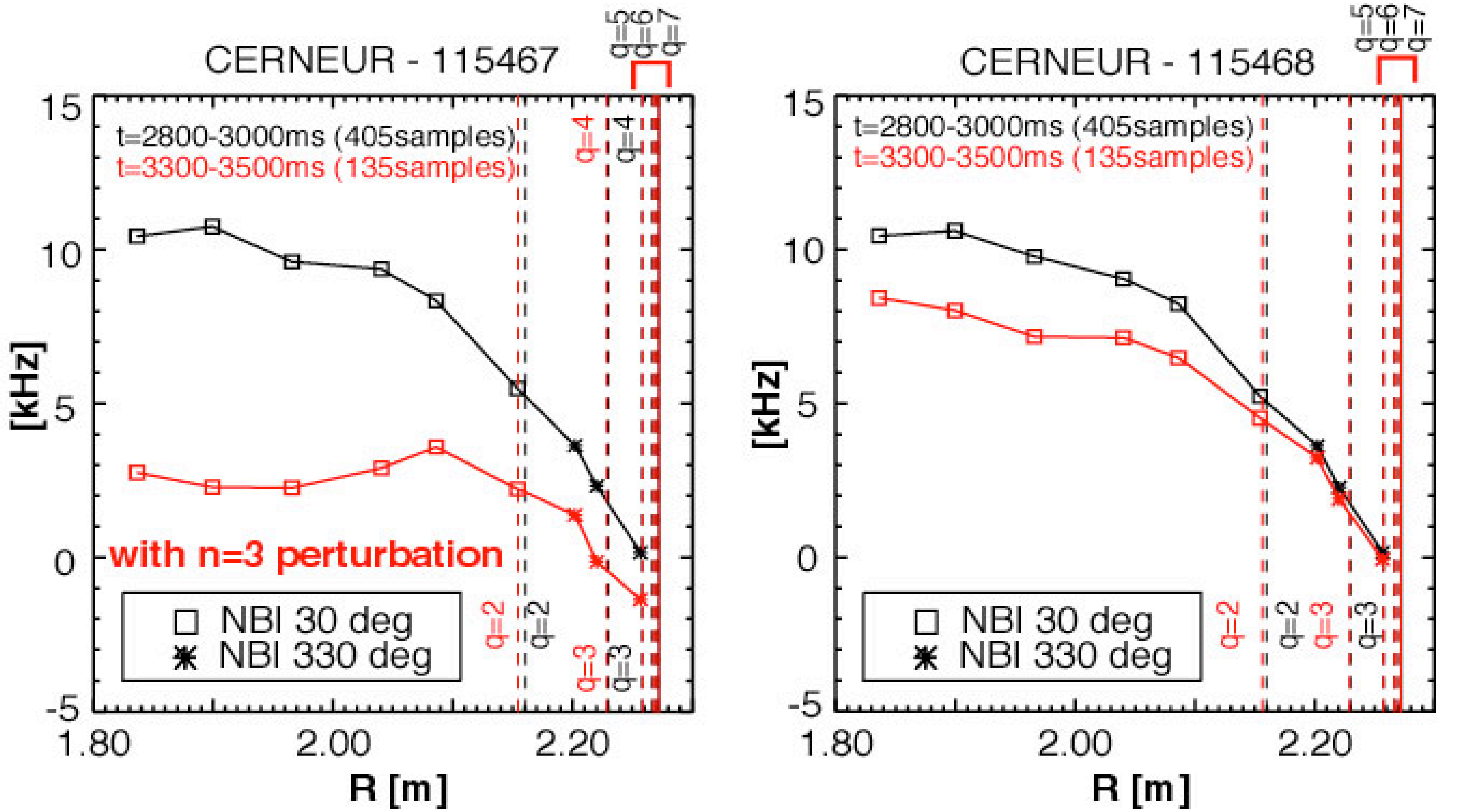
The relatively small changes in the pedestal profiles suggest the pedestal remains second stable

- BALLOO infinite-n ballooning mode stability calculations demonstrate that the edge pedestal profiles are not constrained by the ballooning limit
  - kinetic EFITs and ELITE finite-n stability runs underway



T.H. Osborne

An unexpected result was the large loss of toroidal momentum in the core plasma

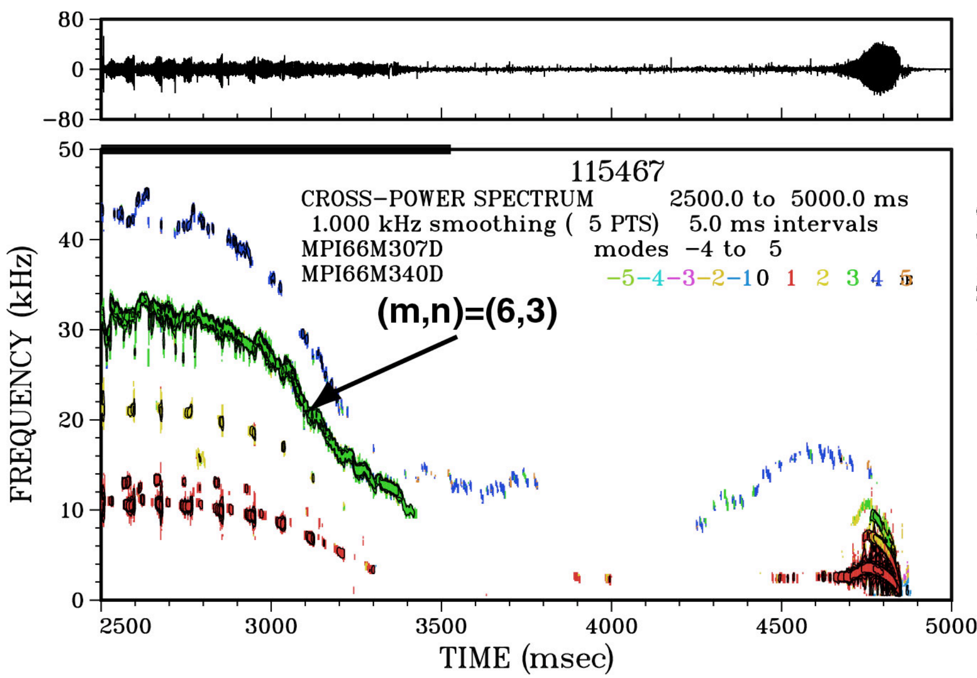


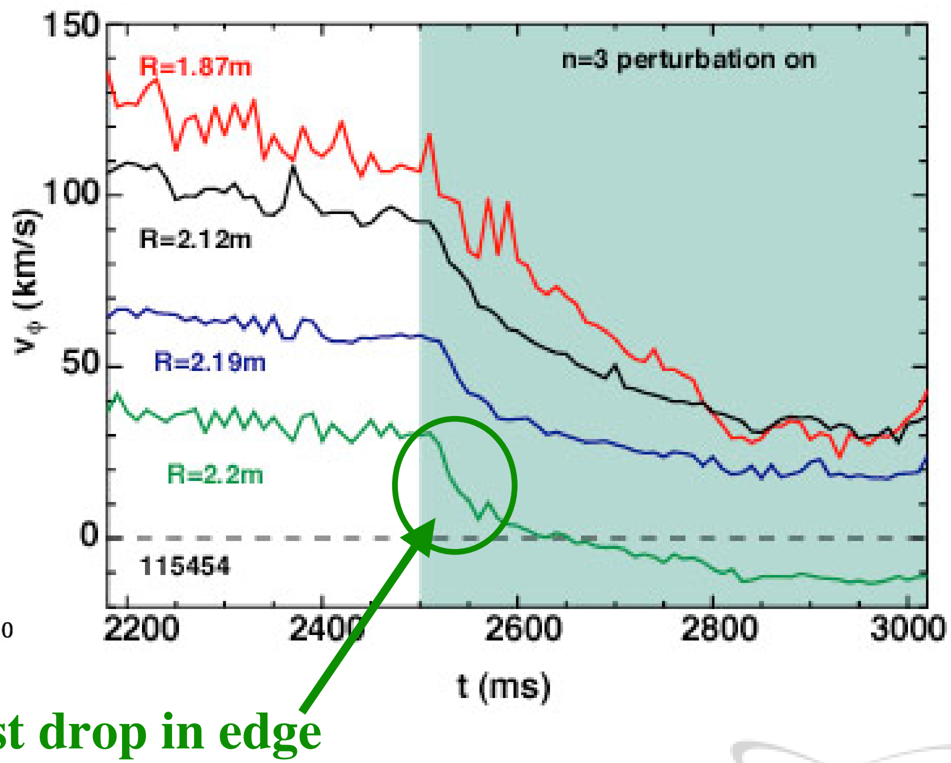
- TRIP3D modeling indicates not a “clean” edge perturbation - small islands are formed on 4/3, 3/2, and 2/1 surfaces

H. Reimerdes

The loss of core toroidal momentum takes about 300 ms

- Core rotation decays in 300 ms; edge has a fast drop (~50 ms) followed by a slower decay
- Main chamber Mirnov coils see the slowing down in the downshift of internal MHD modes (here, q=1 & 2)





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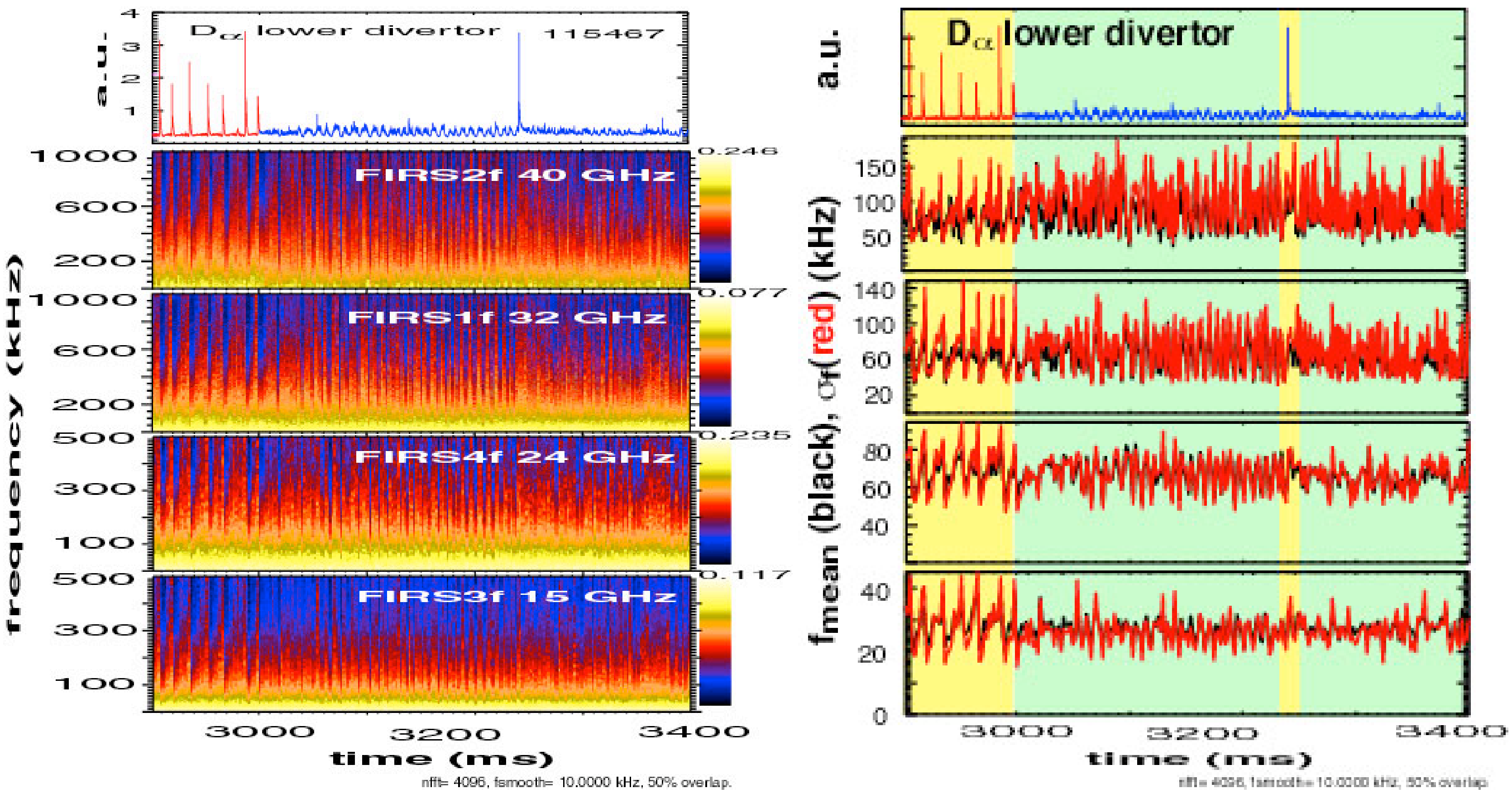
Fast edge diagnostics see signatures of small, rapid ELMs during the I-coil pulse



- Small, rapid oscillations appear in edge density and I_{sat} fluctuations as short bursts of fluctuations similar to those seen during the ELMing phase

T.L. Rhodes

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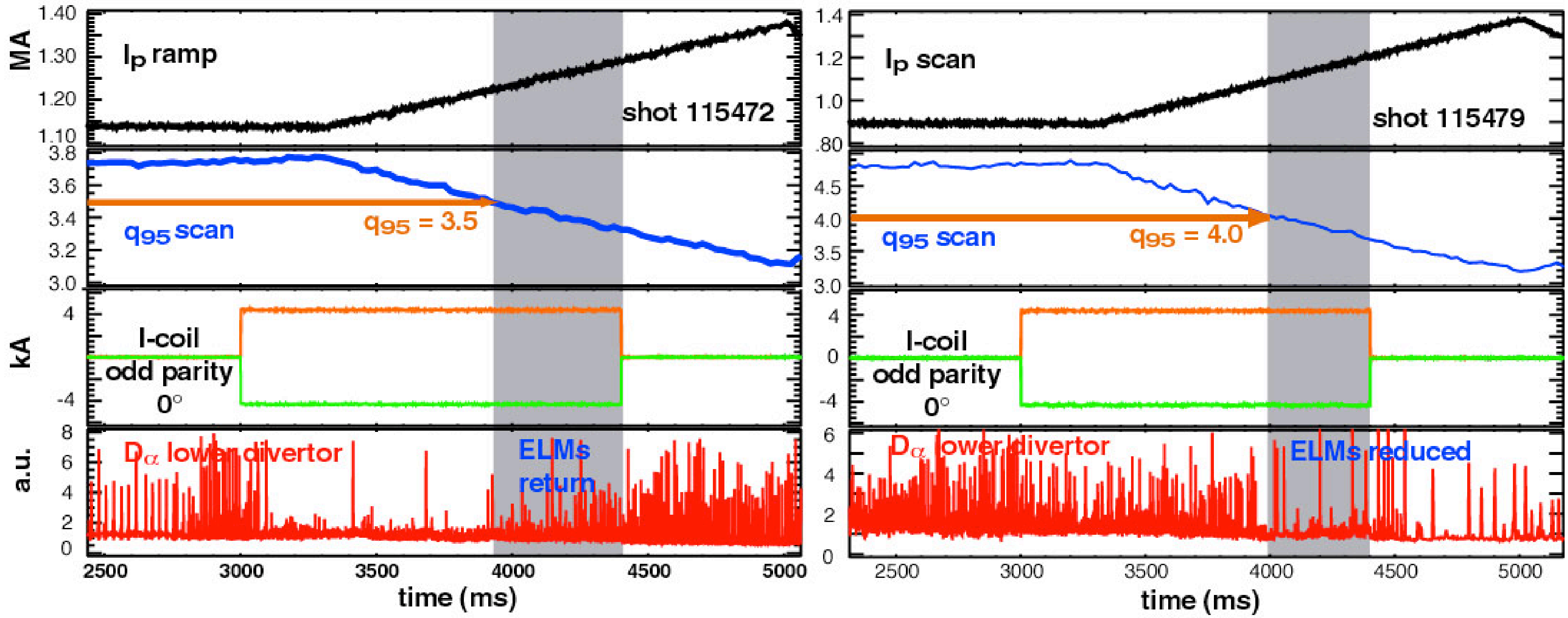
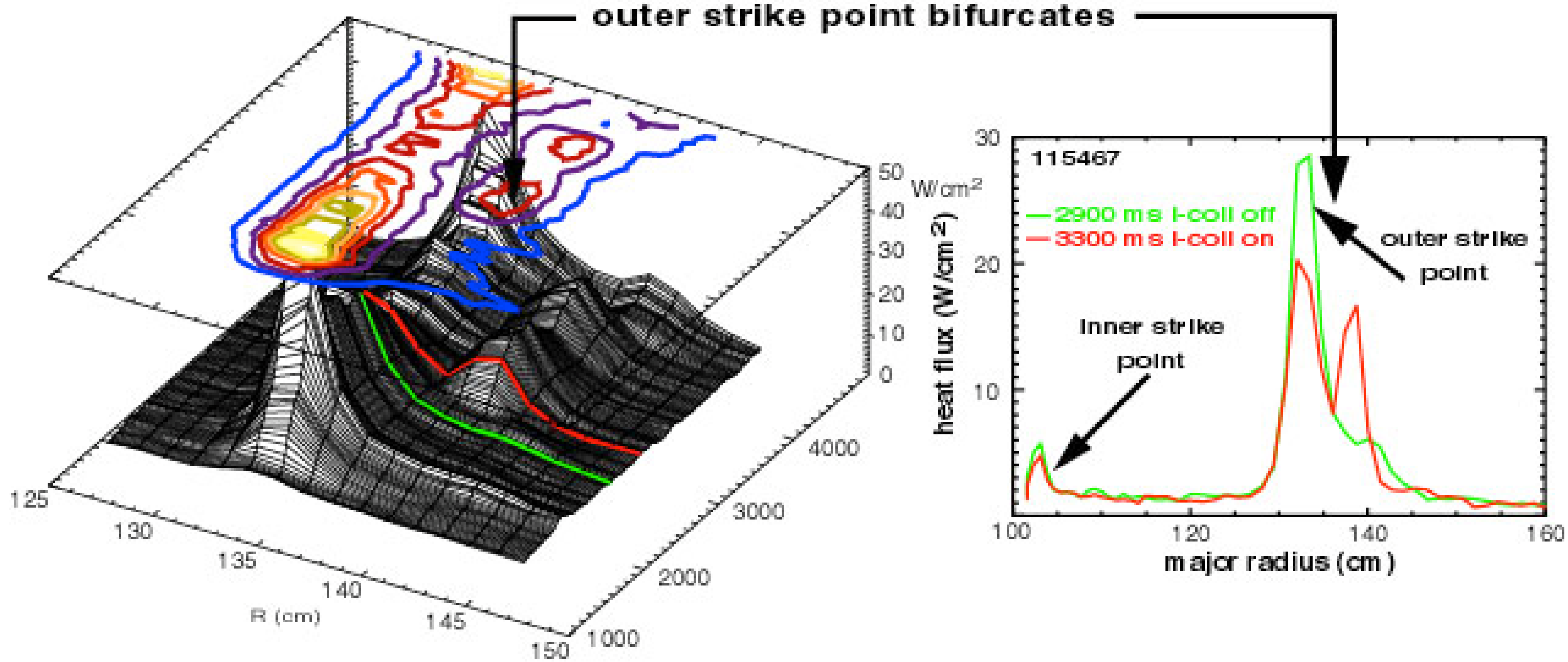
The resonant character of the ELM suppression is verified with q_{95} scans

- Plasma current was ramped during the I-coil pulse in a series of discharges to determine the optimum range of q_{95} for the ELM suppression
- Strong suppression of Type I ELMs for $3.5 \le q_{95} \le 4.0$



A splitting of the heat flux peak in the lower divertor during the I-coil pulse is indicative of a toroidal asymmetry

- Characteristic signature of an "error field"



C.J. Lasnier

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Summary and Conclusions I

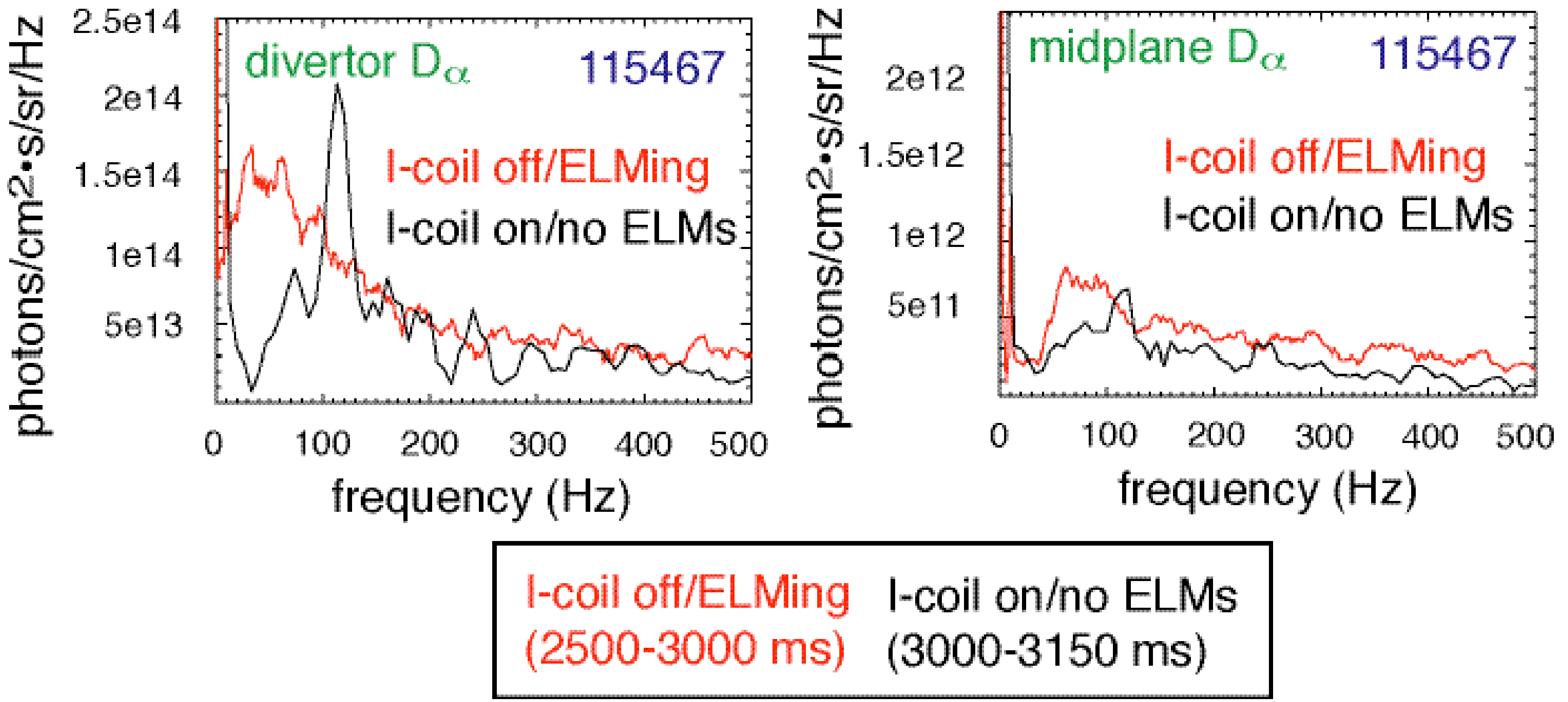
- **An edge resonant magnetic perturbation from the I-coils has been used to suppress Type I ELMs in high confinement DIII-D H-modes**
  - > Suppression is not (yet?) complete - Type I ELM rate drops from 70 Hz to about 7 Hz, assuming that the surviving large events are Type I ELMs
  - > Scaling to next-step devices is unknown! (we don’t have an ITER solution yet, just a promising start!); An obvious next step is to use an ITER shape (e.g. low triangularity single null divertor)
  - > The nature of the surviving irregular oscillations not yet determined (e.g. are they Type II ELMs?)
  - > Edge pedestal remains second stable (doesn’t fit Type II ELM model)
  - > Pedestal height is not reduced
  - > **Core confinement remains high despite a large loss of toroidal rotation**.

Summary and Conclusions II

- Optimal suppression was obtained with an odd parity, 0° toroidal phase perturbation to a plasma with $3.5 \leq q_{95} \leq 4.0$
  - > Suppression effect is resonant
- We have demonstrated directly that stochastic boundaries are compatible with high confinement H-mode edge radial transport barriers
- Because tokamaks have many sources of “intrinsic error fields”, divertor tokamaks likely have a weakly stochastic boundary all the time
- **3-D effects are important, even in nominally axisymmetric tokamaks**

  and
- **3-D effects may be useful for active control of the crucial H-mode pedestal region and ELM behavior**.

The ELM suppression is most pronounced for the large spikes between 30 and 100 Hz



- Type I ELMs at 30-100 Hz are strongly suppressed & the 130 HZ oscillatory envelope appears

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