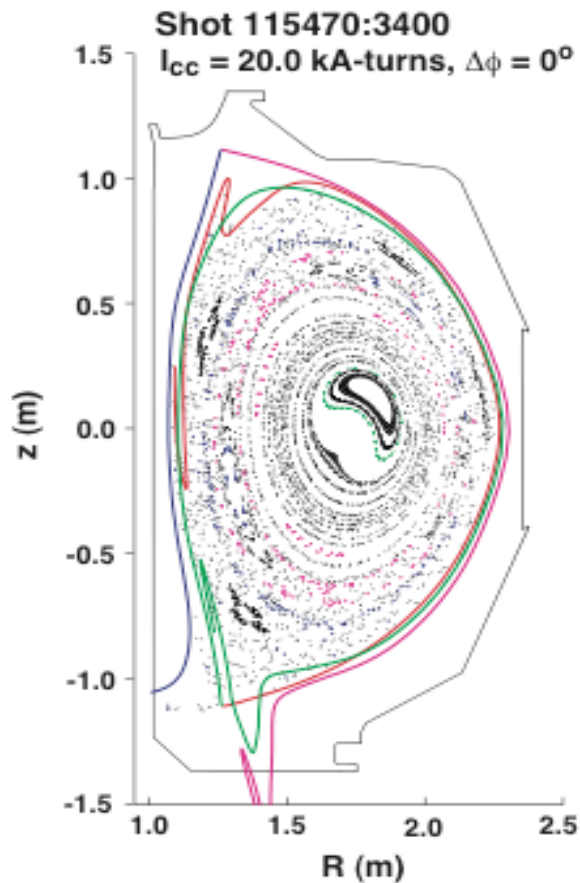


ELM suppression with a stochastic boundary in DIII-D



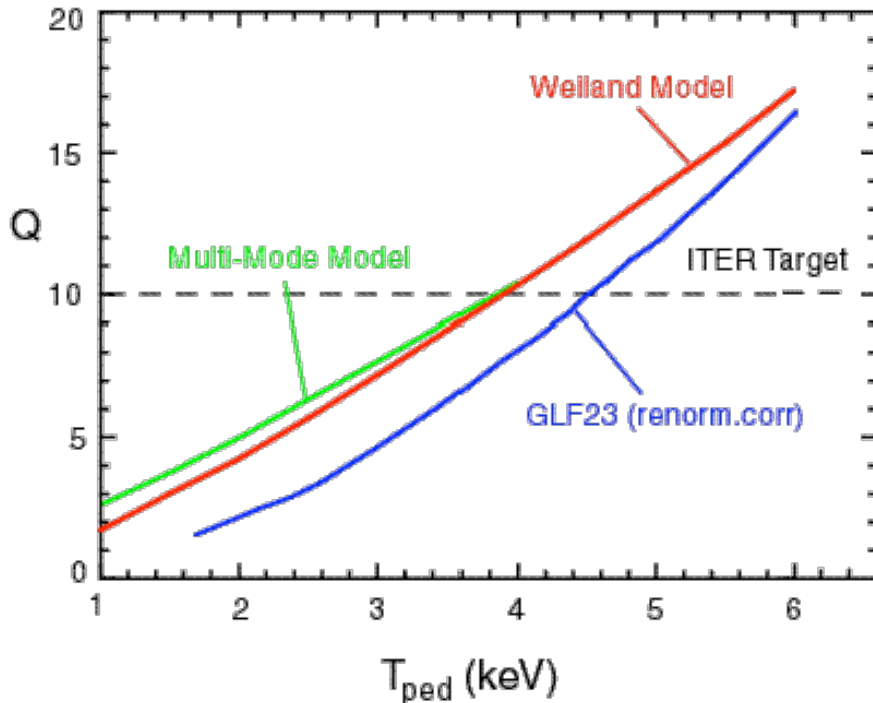
T. E. Evans, R. J. Groebner, R. J. La Haye, T. H. Osborne,
M. J. Schaffer - *General Atomics, San Diego, CA, USA*
R. A. Moyer - *UCSD, La Jolla, CA, USA*
J. G. Watkins - *Sandia National Laboratory, USA*
T. L. Rhodes, G. Wang, L. Zeng - *UCLA, Los Angeles, CA, USA*
P. R. Thomas - *CEA Caderache, France*
M. E. Fenstermacher, M. Groth, C. J. Lasnier - *LLNL, CA, USA*
K. H. Finken - *FZ-Jülich, Germany*
N. Ohya, S. Masuzaki - *NIFS, Japan*
J. Harris, D. Pretty - *Australian National University, Australia*
H. Reimerdes - *Columbia University, NY, USA*

Error Field Workshop, 1 November 2003,
Albuquerque, NM

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

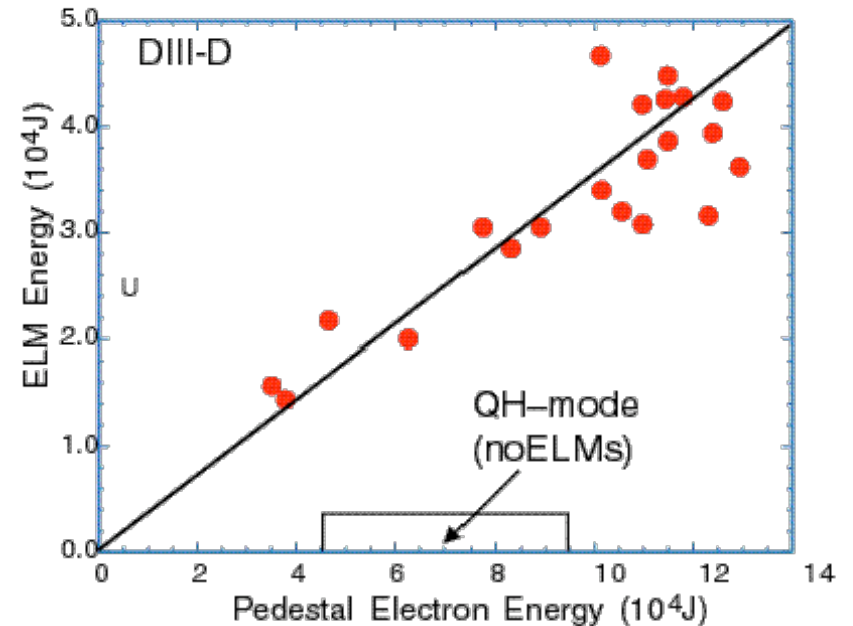
- Core performance is tightly coupled to pedestal height by stiff radial transport

ITER: $I=15\text{MA}$; $P_{\text{aux}}=40\text{MW}$; $n=0.85n_G$



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

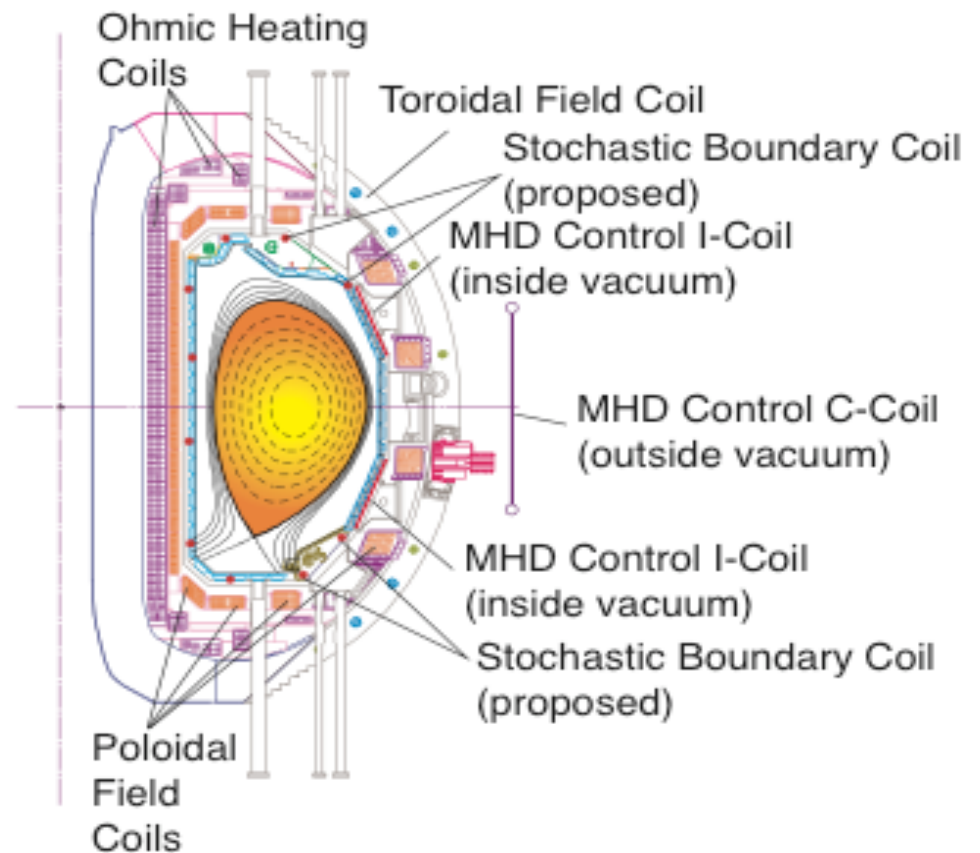
- ELMs affect core plasma performance...
 - Directly by reducing pedestal height
 - Indirectly by affecting pedestal stability



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

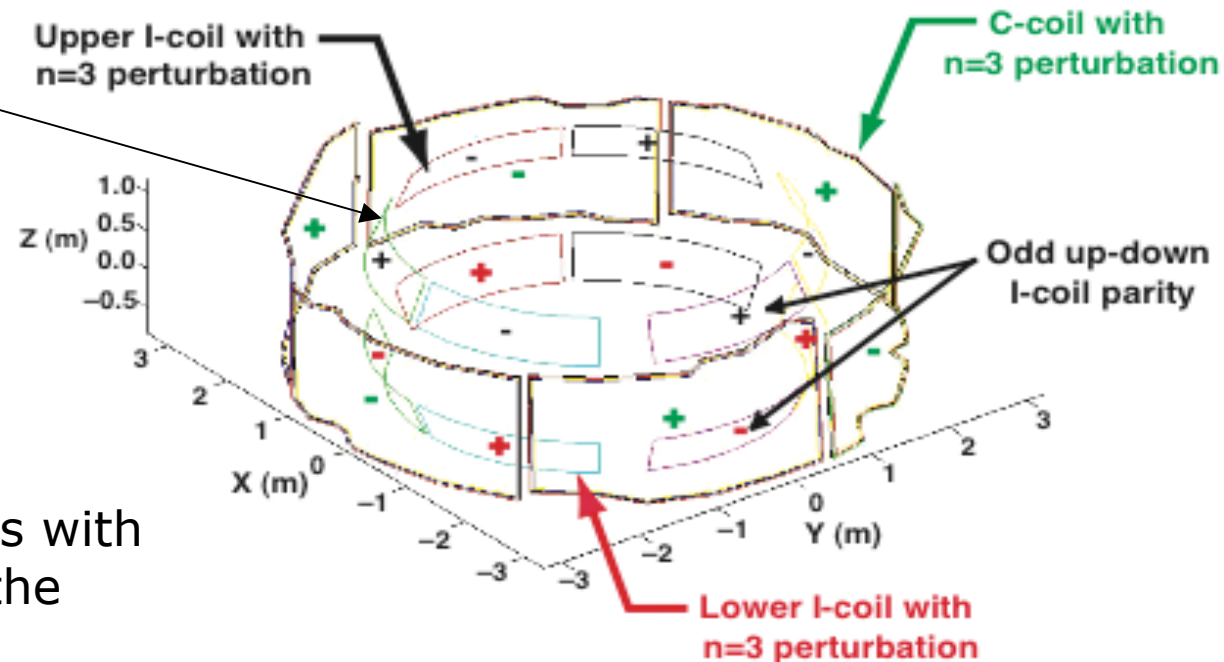
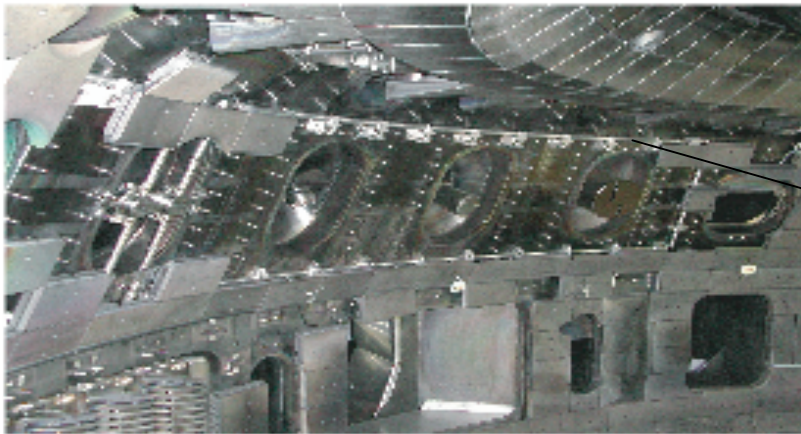
An edge stochastic layer may be a good solution for pedestal control

- 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



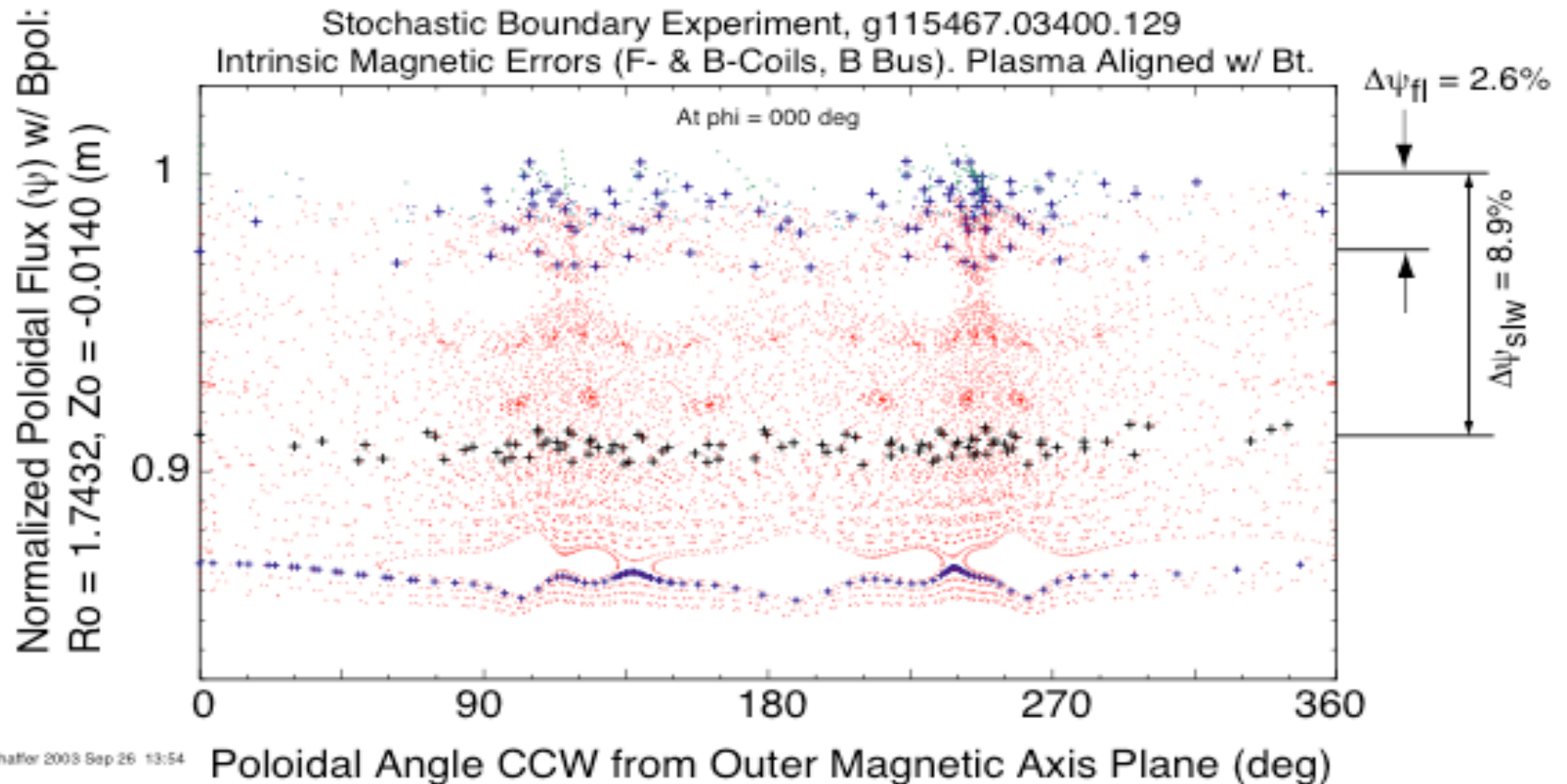
The I-coil operated alone or in combination with the C-coil gives good control flexibility

- 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.

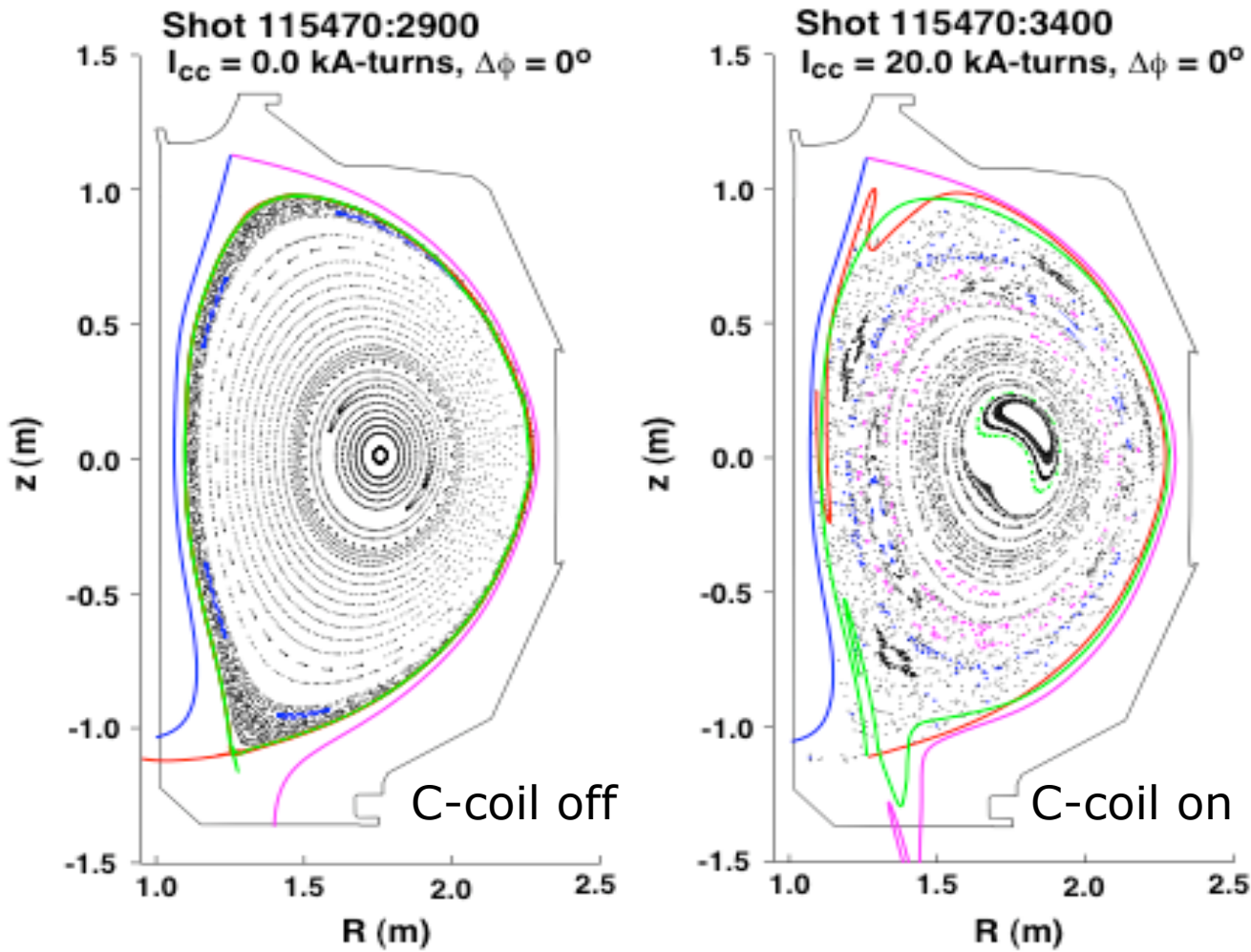
The stochastic layer structure is characterized by its width $\Delta\psi_{slw}$ and poloidal magnetic flux loss $\Delta\psi_{fl}$



- 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)**.

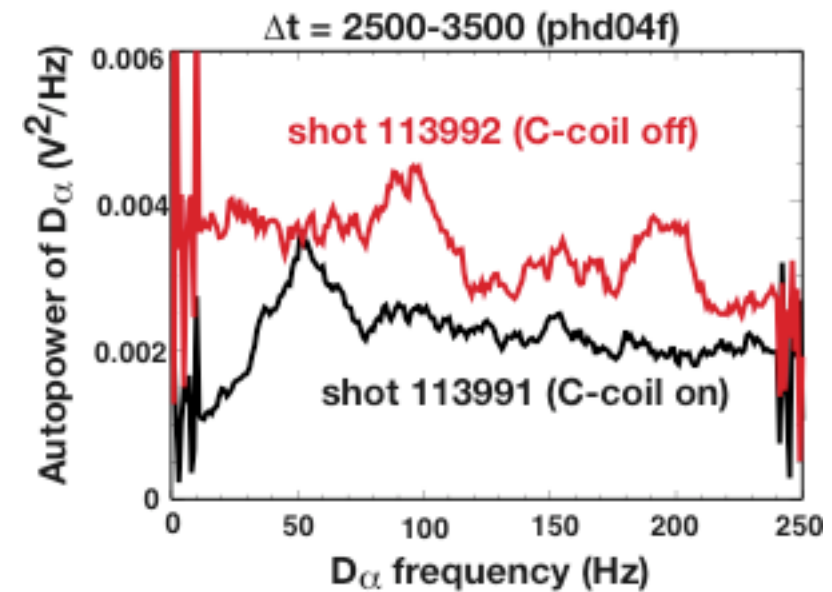
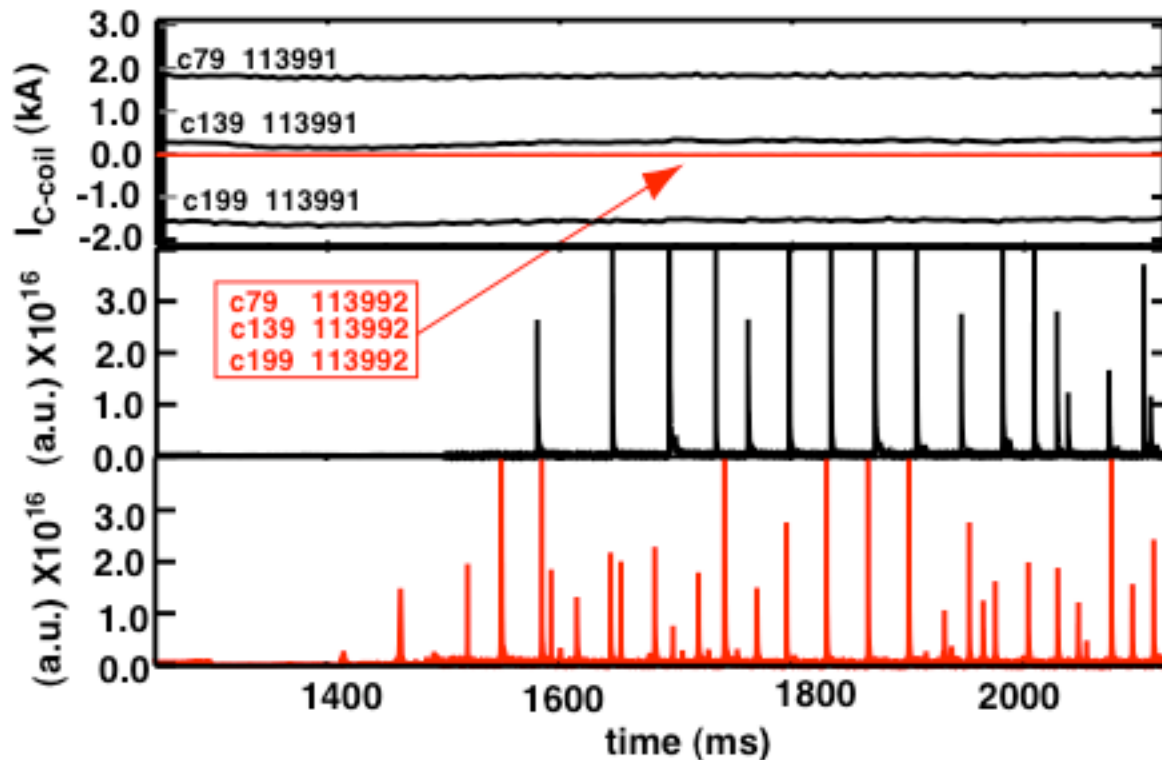
TRIP3D modeling (no plasma response included)

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



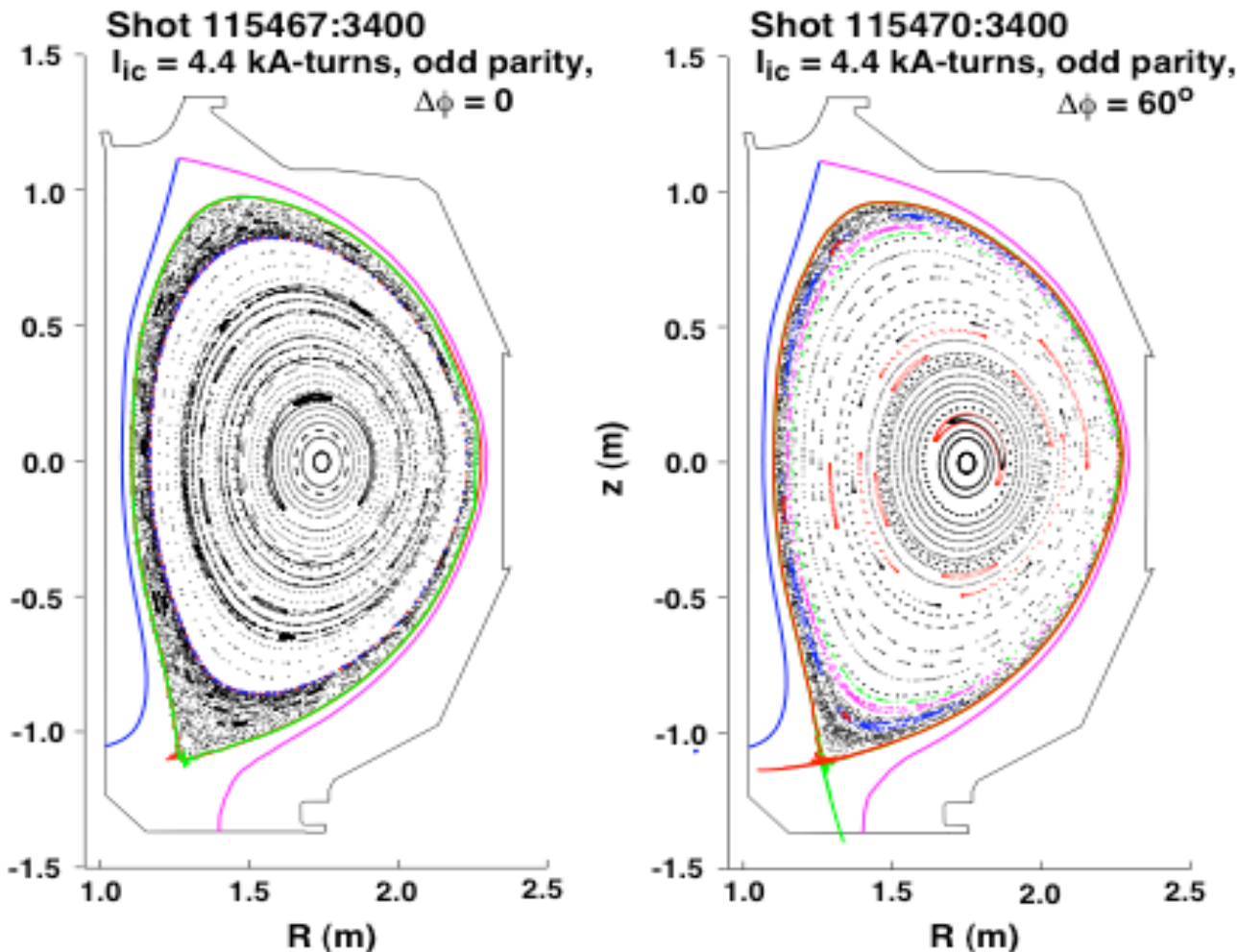
- With 20 kA-turns in the C-coil ϵ_{slw} increases from 6.2% due the f-coil error fields to 45.4% while ϵ_{fl} increases from 0.2% to 23.3%.
- Although the C-coil is typically operated well below 20 kA-turns for standard error correction it produces a significant edge stochastic layer in most cases.

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

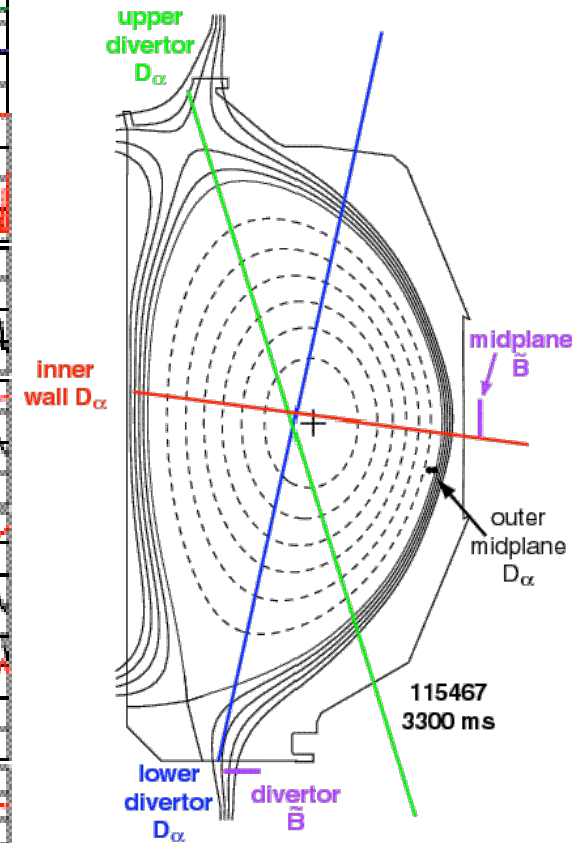
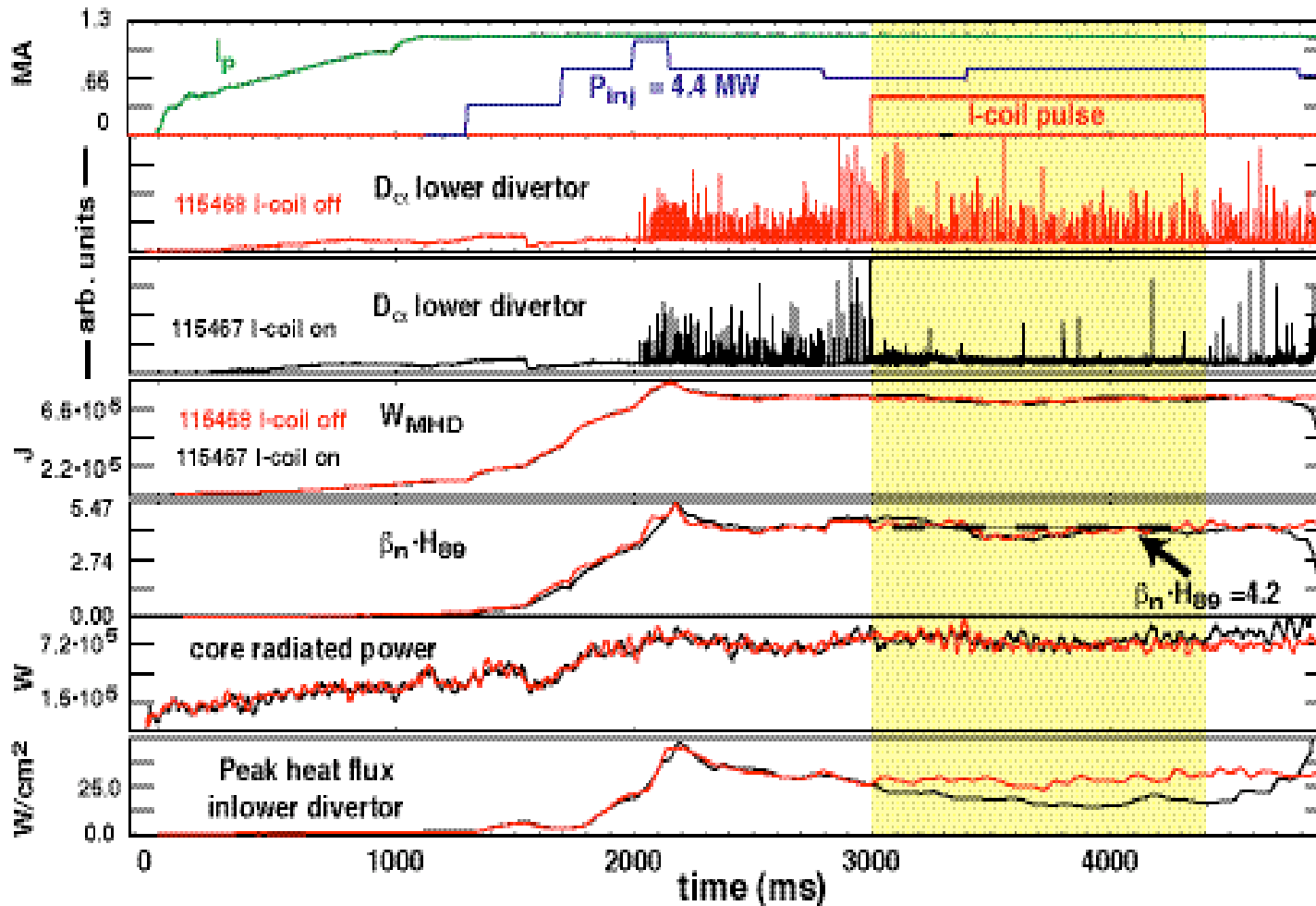


- The toroidal phase of the I-coil perturbation has a small effect on the stochastic layer due to a difference in the mixing with intrinsic error fields, with $\epsilon = 0$, $\epsilon_{slw} = 12.6\%$ and $\epsilon_{fl} = 1.7\%$ while with $\epsilon = 60^\circ$, $\epsilon_{slw} = 10.2\%$ and $\epsilon_{fl}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

TRIP3D modeling (no plasma response included)

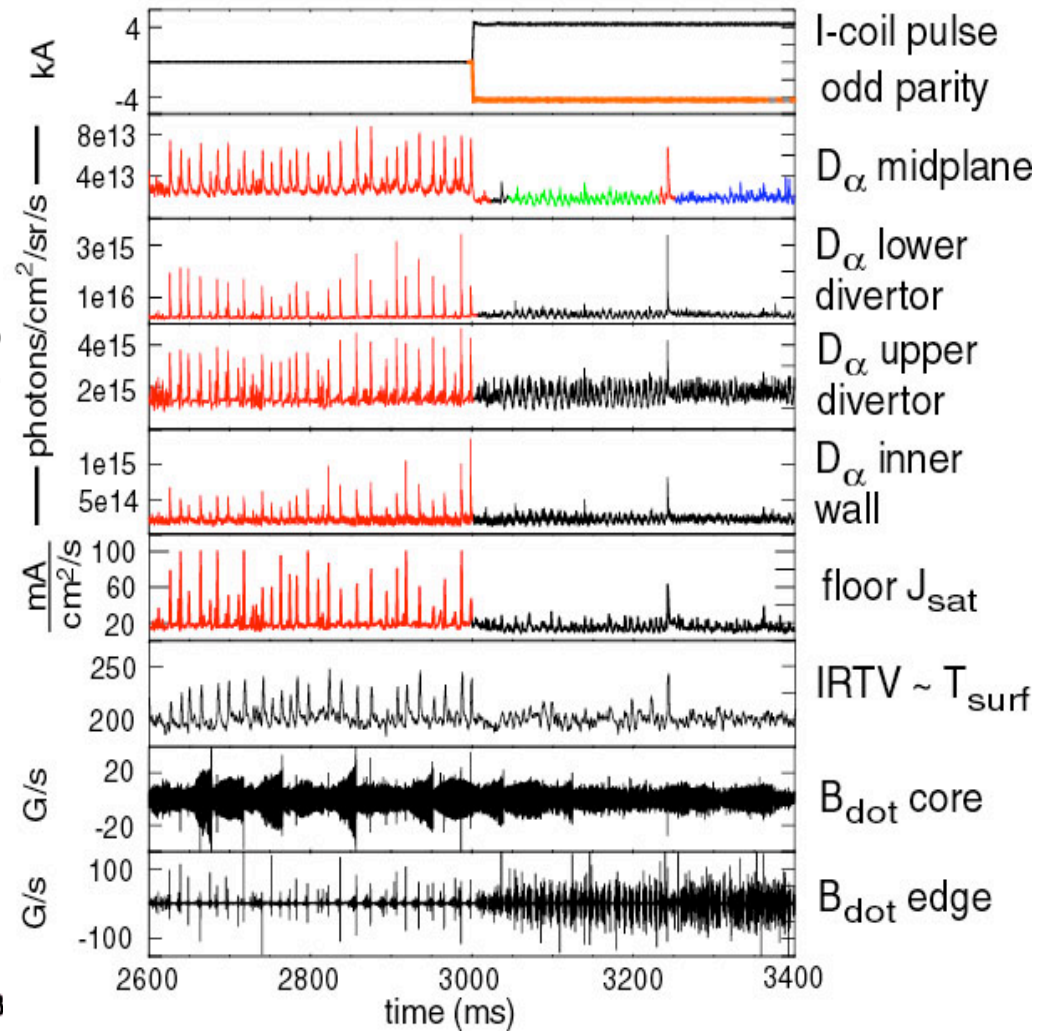
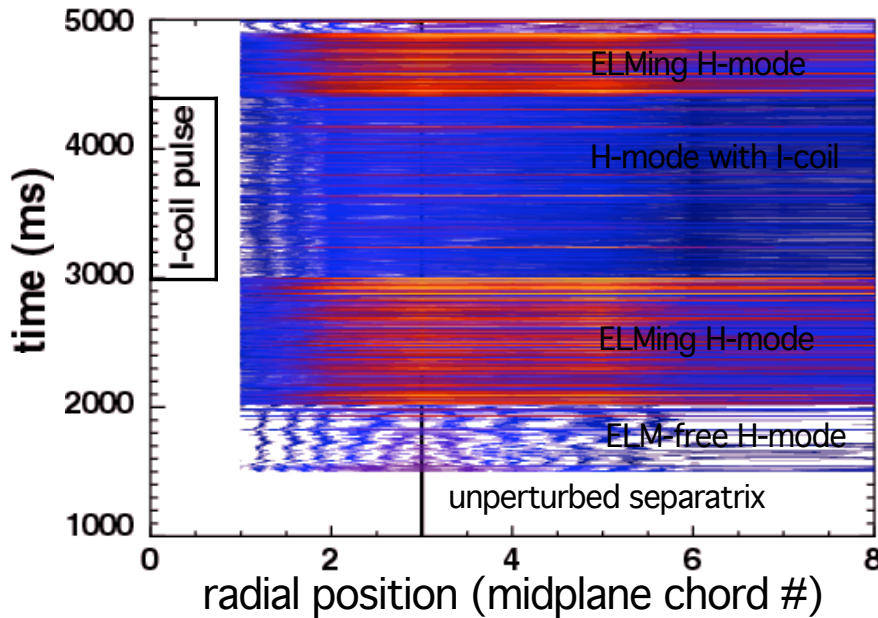
Large ELMs are suppressed without degrading the core confinement during the n=3 I-coil pulse

- Type I ELMs suppressed in high performance ELMing H-modes ($\beta_n \cdot H_{99} = 4.2$) with and edge resonant perturbation.

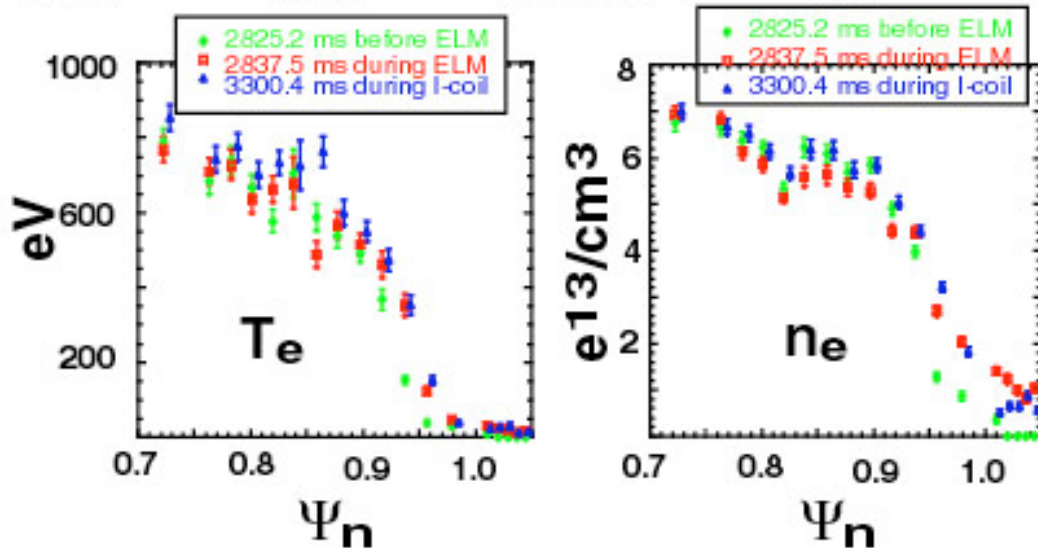
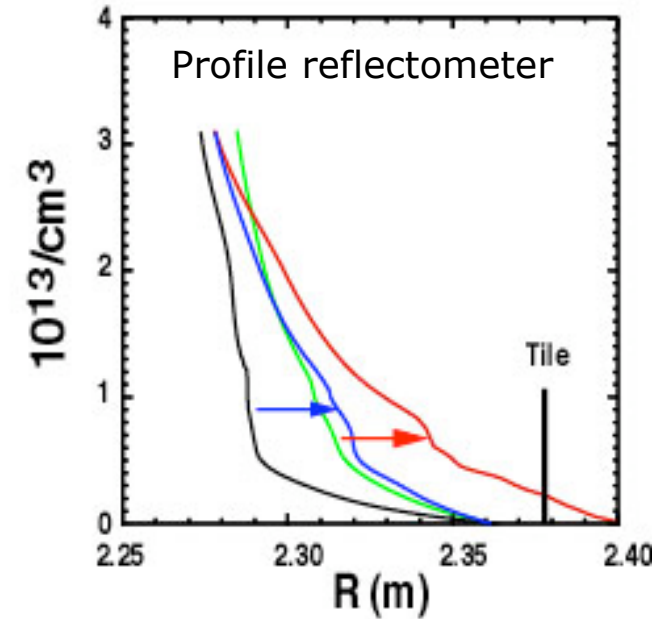
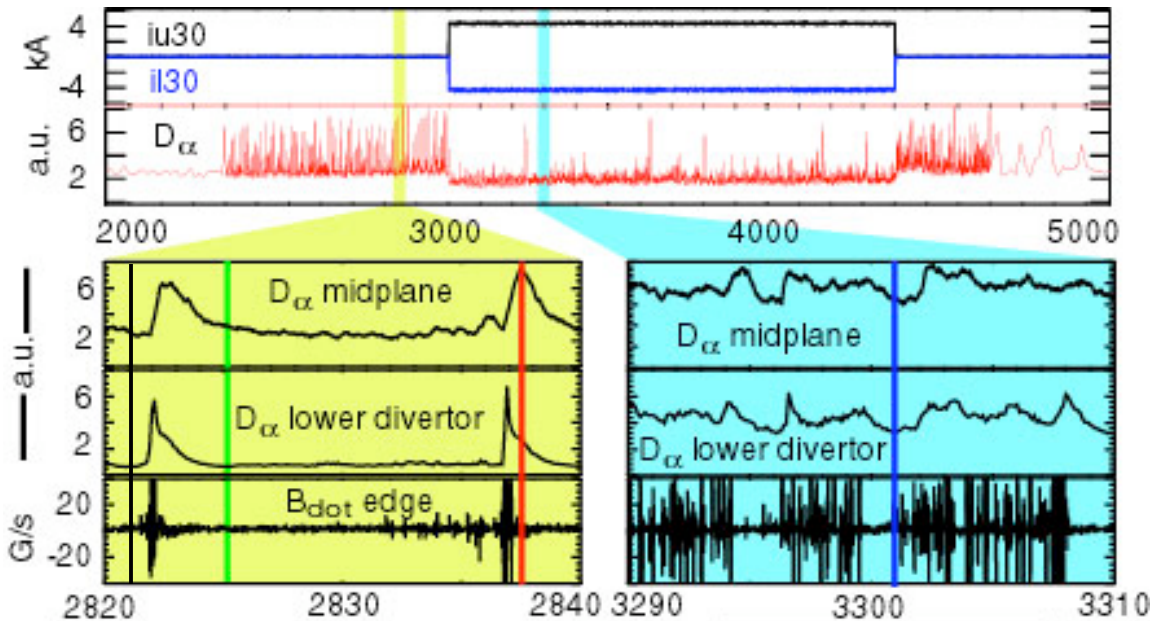


Large 70 Hz type-I ELMs are converted into small 130 Hz oscillations punctuated by isolated events

- 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

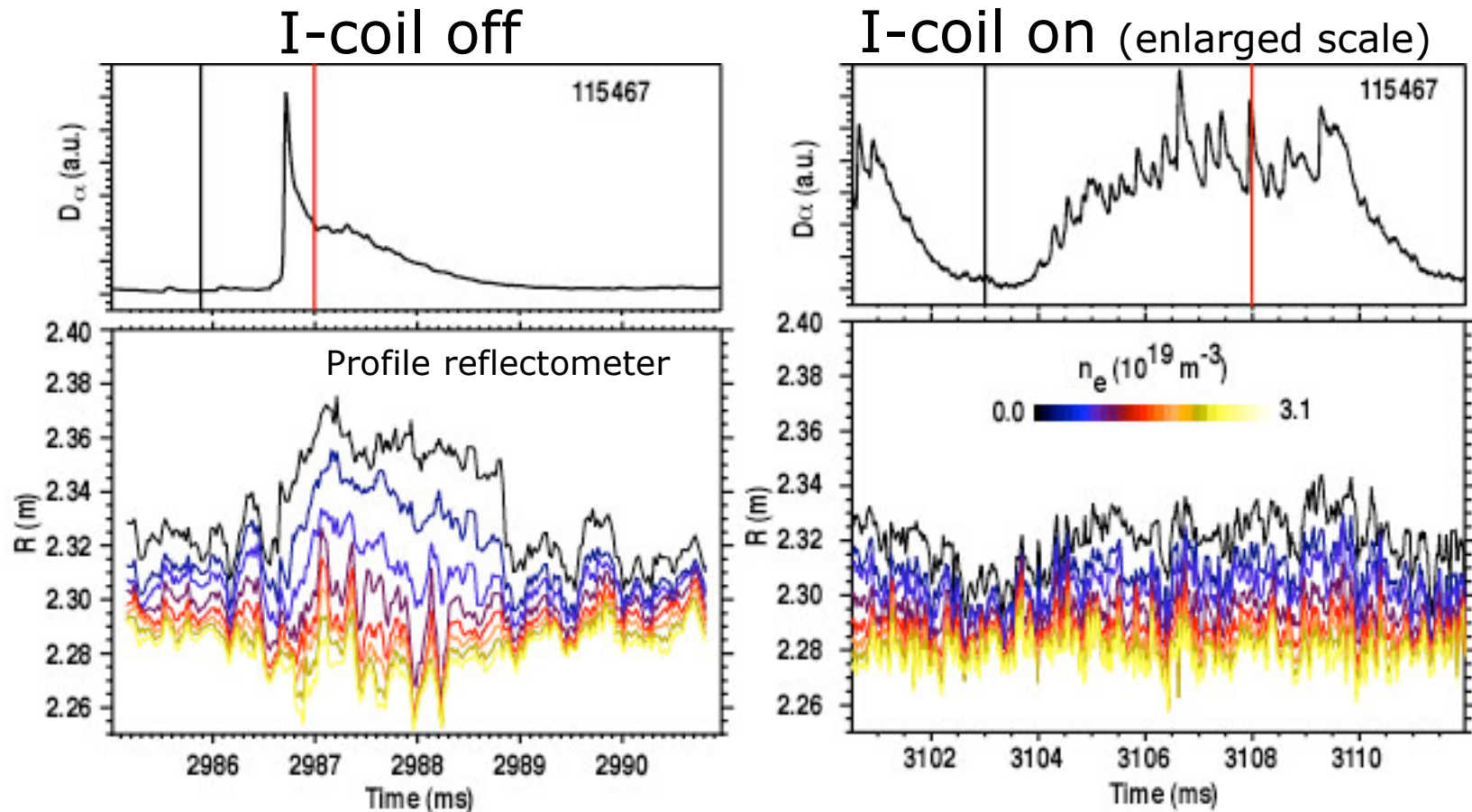


Large ELMs are replaced with irregular recycling



- “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

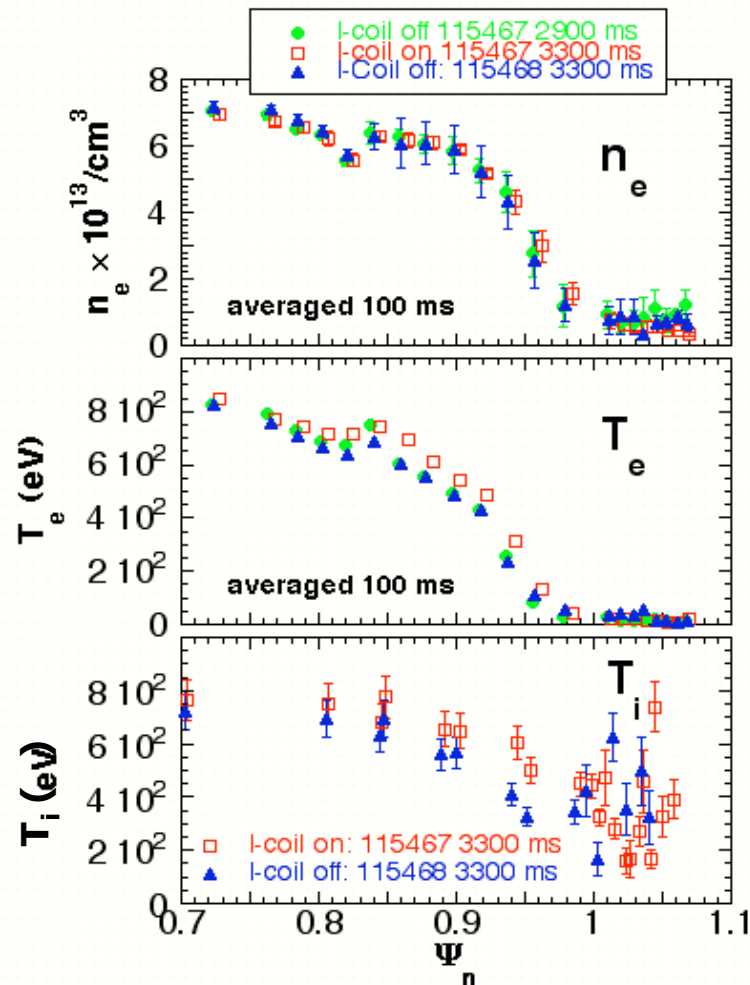


- “duty cycle” of Type I ELM is mostly “quiet” between ELMs (4.5 ms out of 6 ms cycle)
- “duty cycle” of oscillations is mostly “high” with only brief quiet intervals (6 of 7 ms)

L. Zeng, G. Wang, UCLA

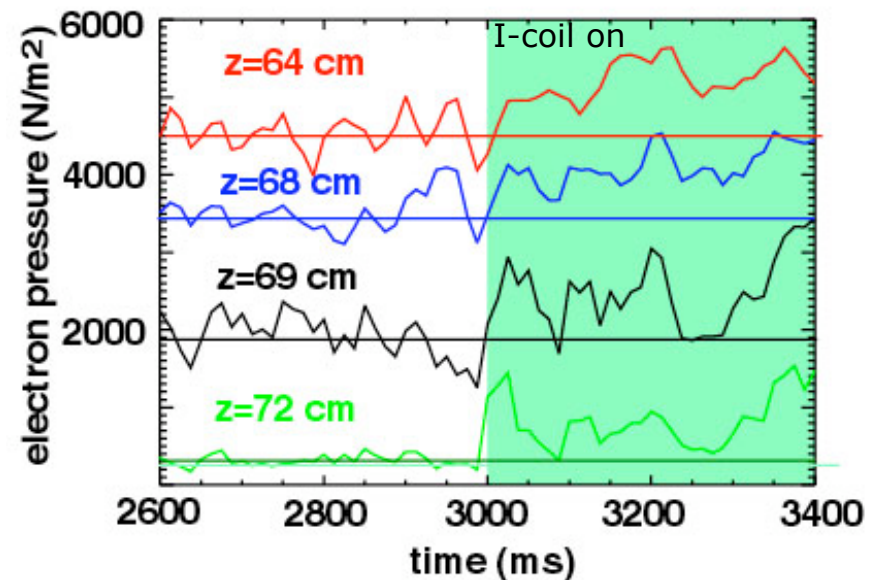
Time averaged pedestal profiles have a steeper gradient region with a similar pedestal height

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



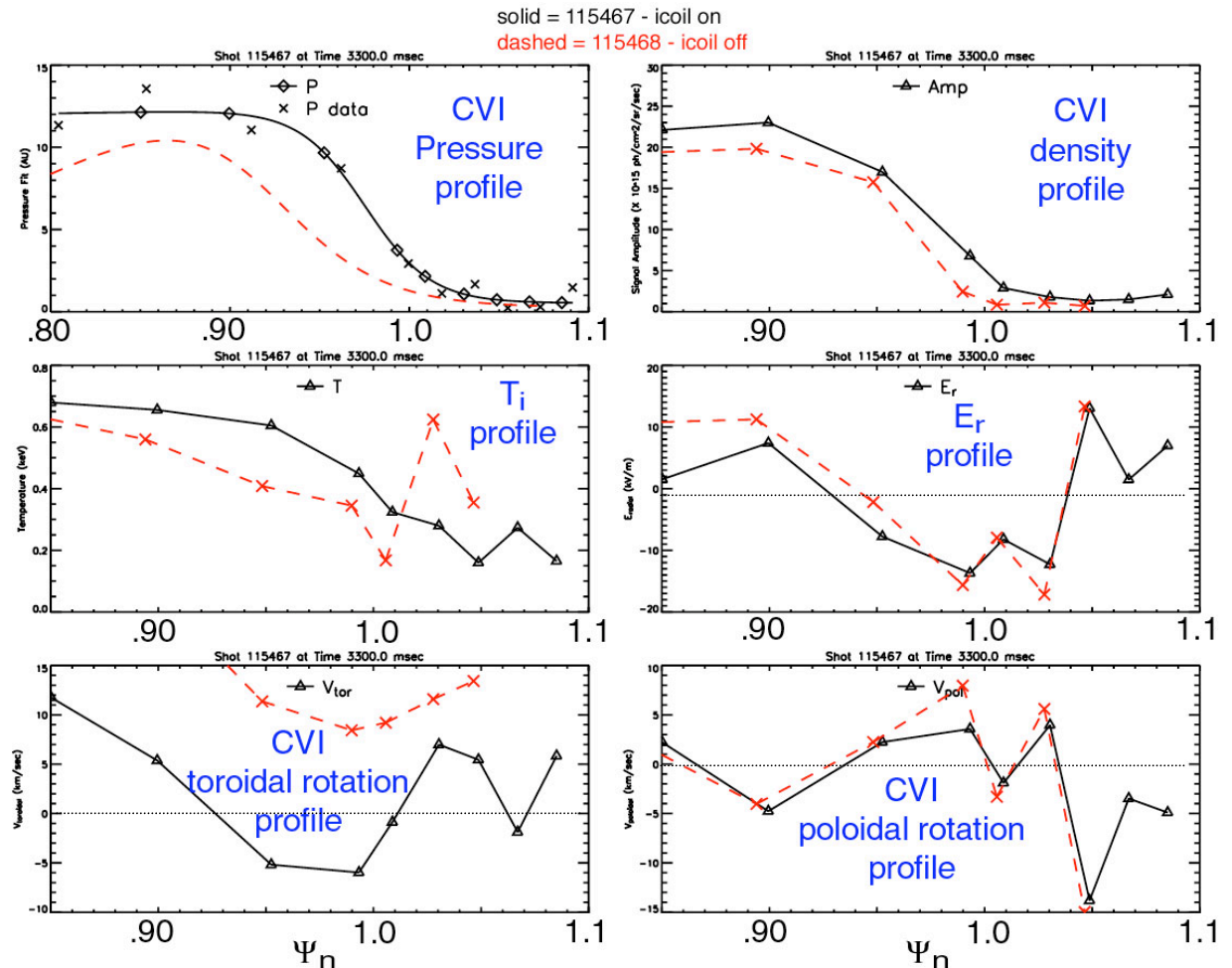
- Thomson chords in the pedestal clearly show increase in electron pressure

Edge Electron Pressure: 115467 I-coil odd parity 0°



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

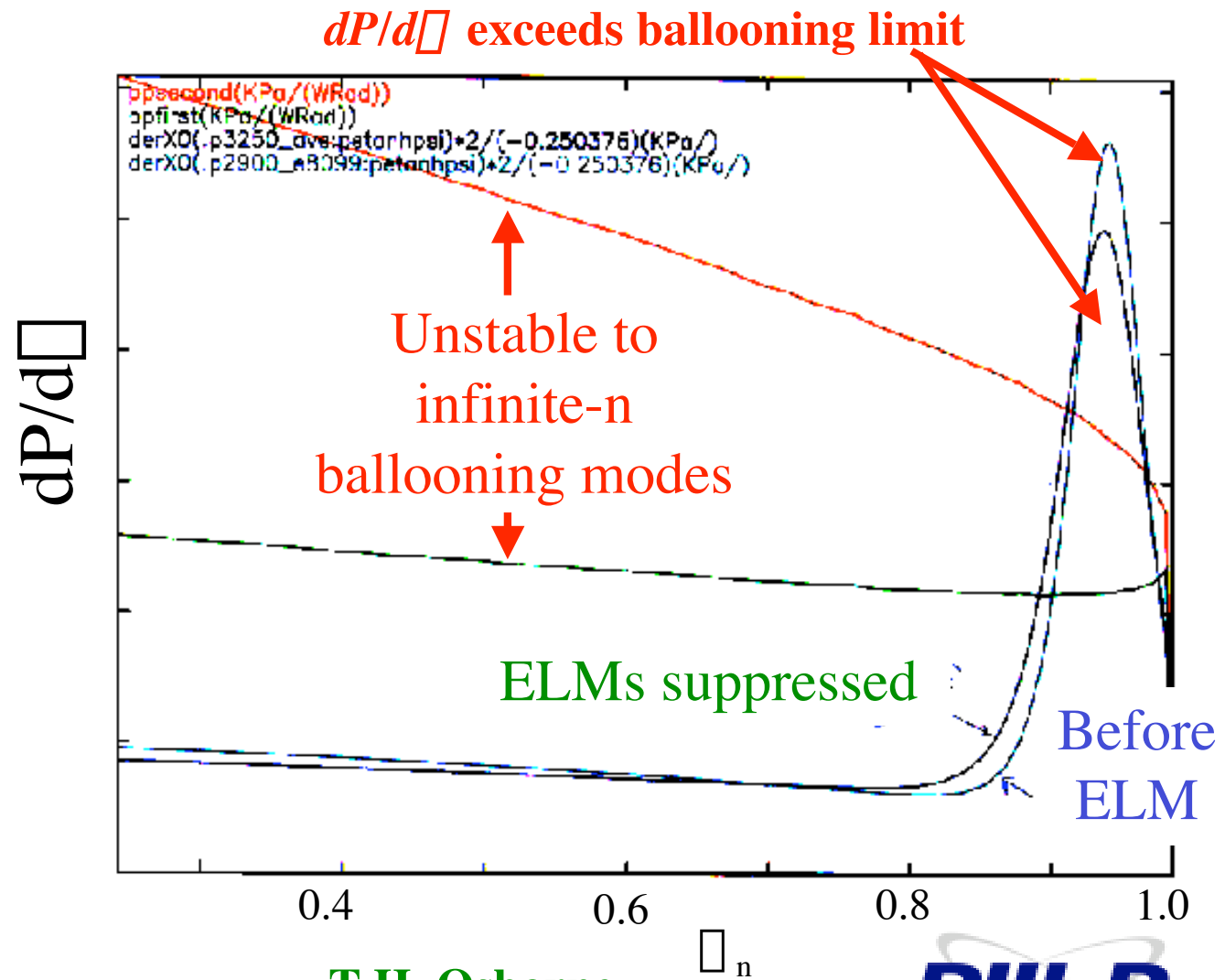
- Toroidal rotation drops through 0 and reverses in edge!
- But, H-mode transport barrier is preserved
 - > v_{\square} & E_r well don't change
 - > Increased $\text{grad}P_i$ offsets change in V_{\square} in single ion force balance



R.J. Groebner

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

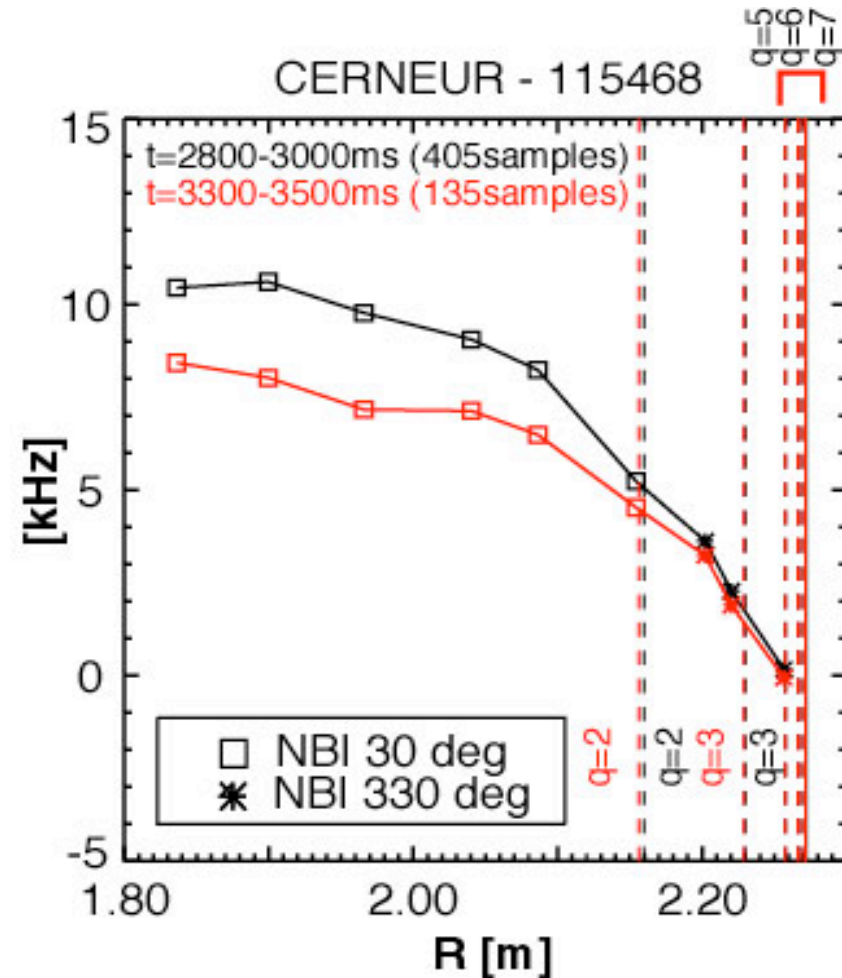
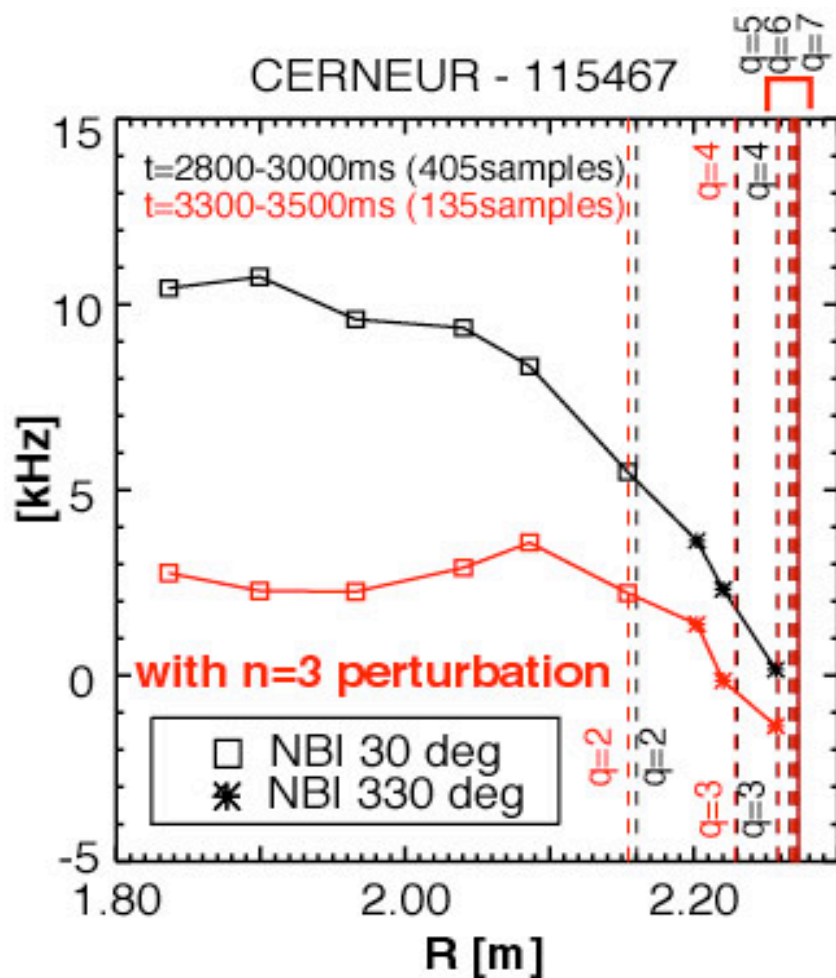
- BALOO calculations using $P = 2P_e$ suggest that the pedestal profiles aren't constrained by the infinite n ballooning limit
- Changes to ion pedestal profiles (T_i and P_i^{CVI}) may be important for j_{BS} and stability



T.H. Osborne



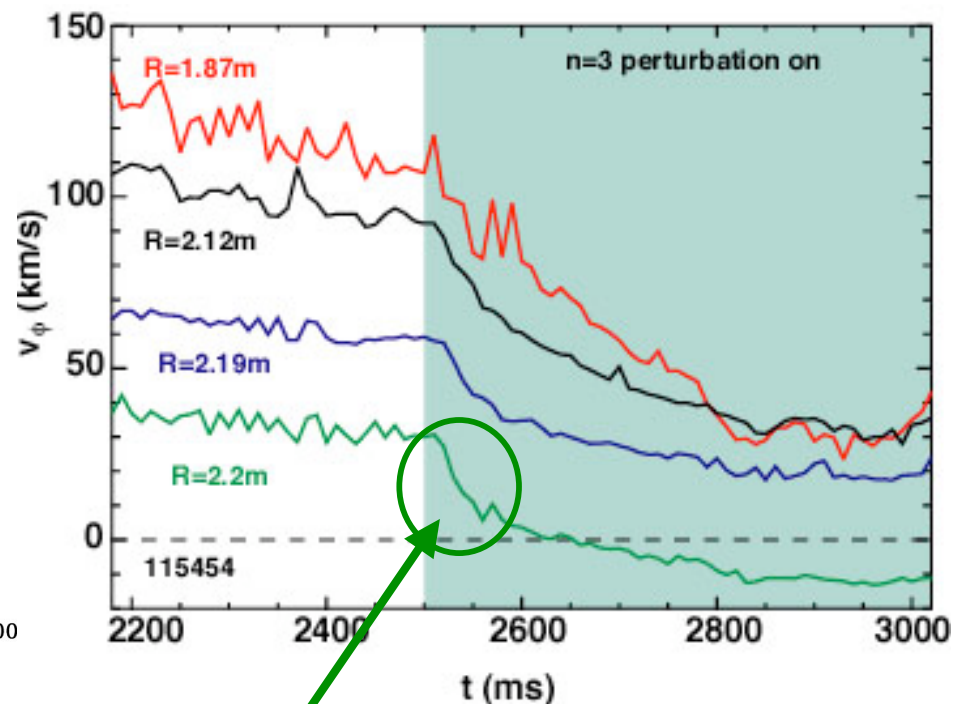
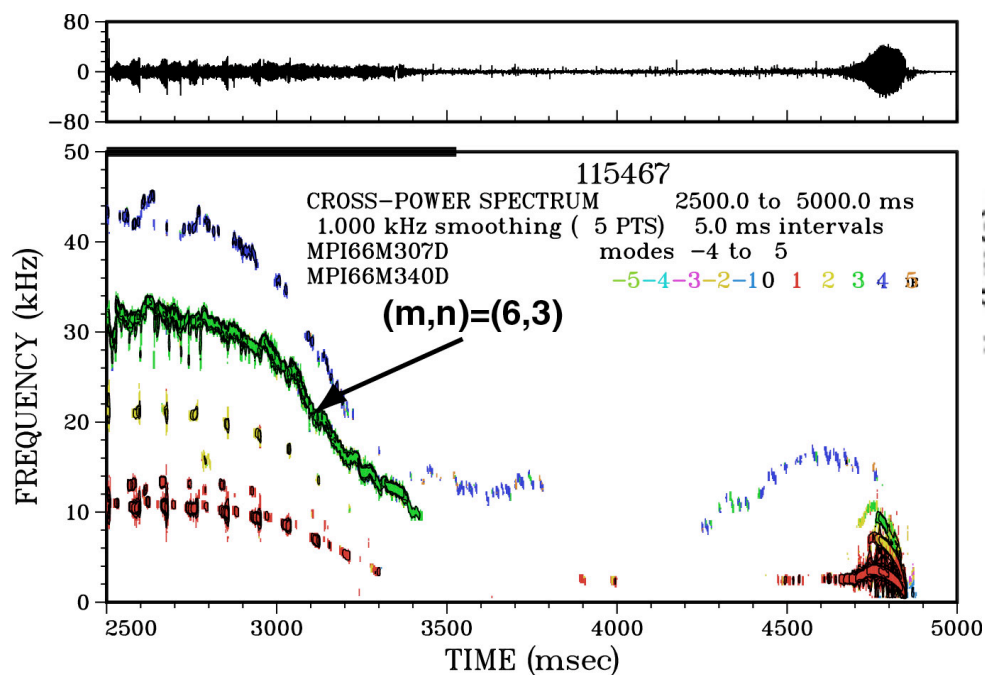
An unexpected result was the large loss of toroidal momentum in the core plasma



- TRIP3D modeling indicates small core perturbations - small islands ($\sim 1-2$ cm) are formed on 3/3 and 4/3 surfaces

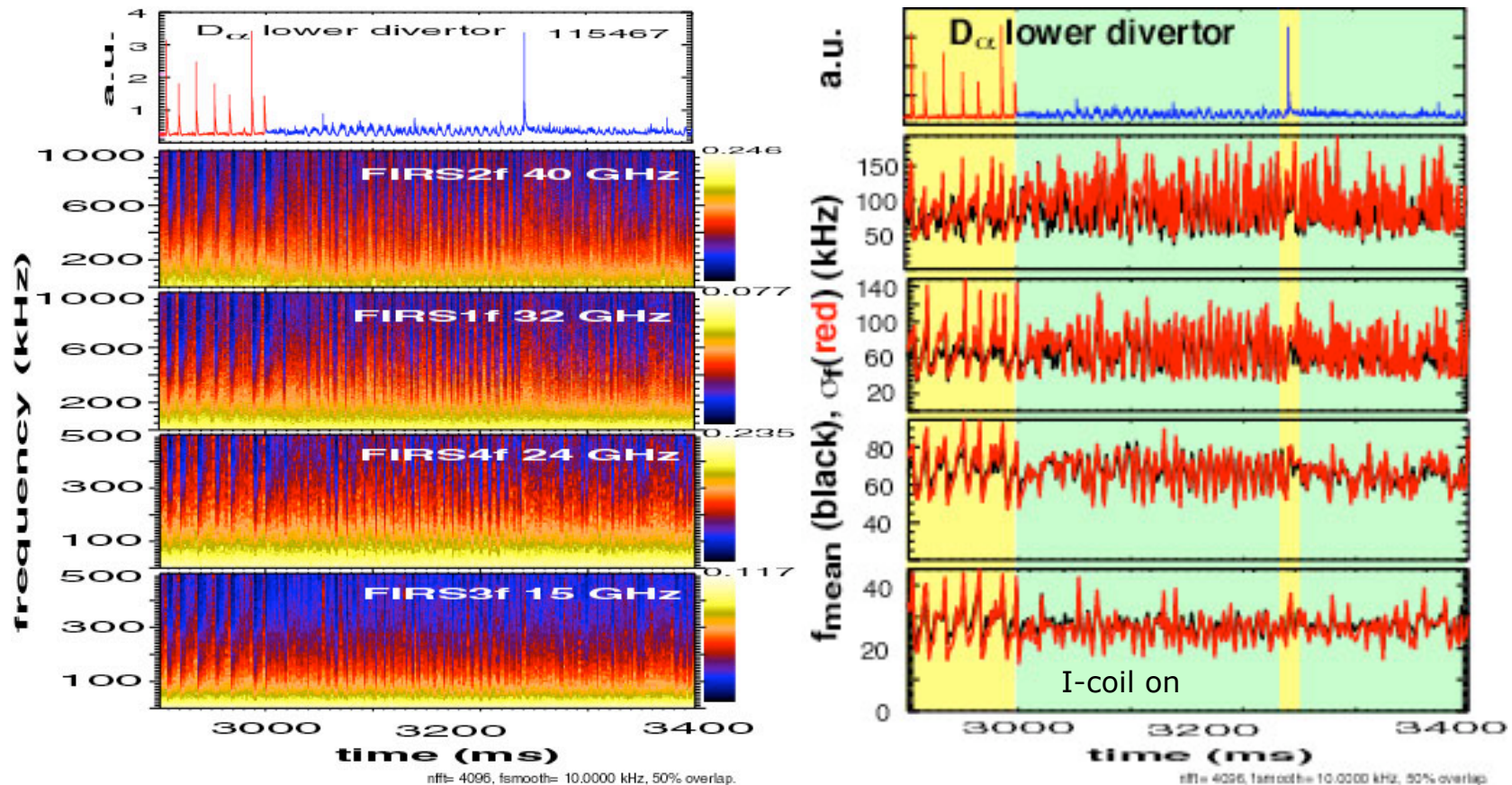
The loss of core toroidal momentum takes about 300 ms

- 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)



Initial fast drop in edge

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

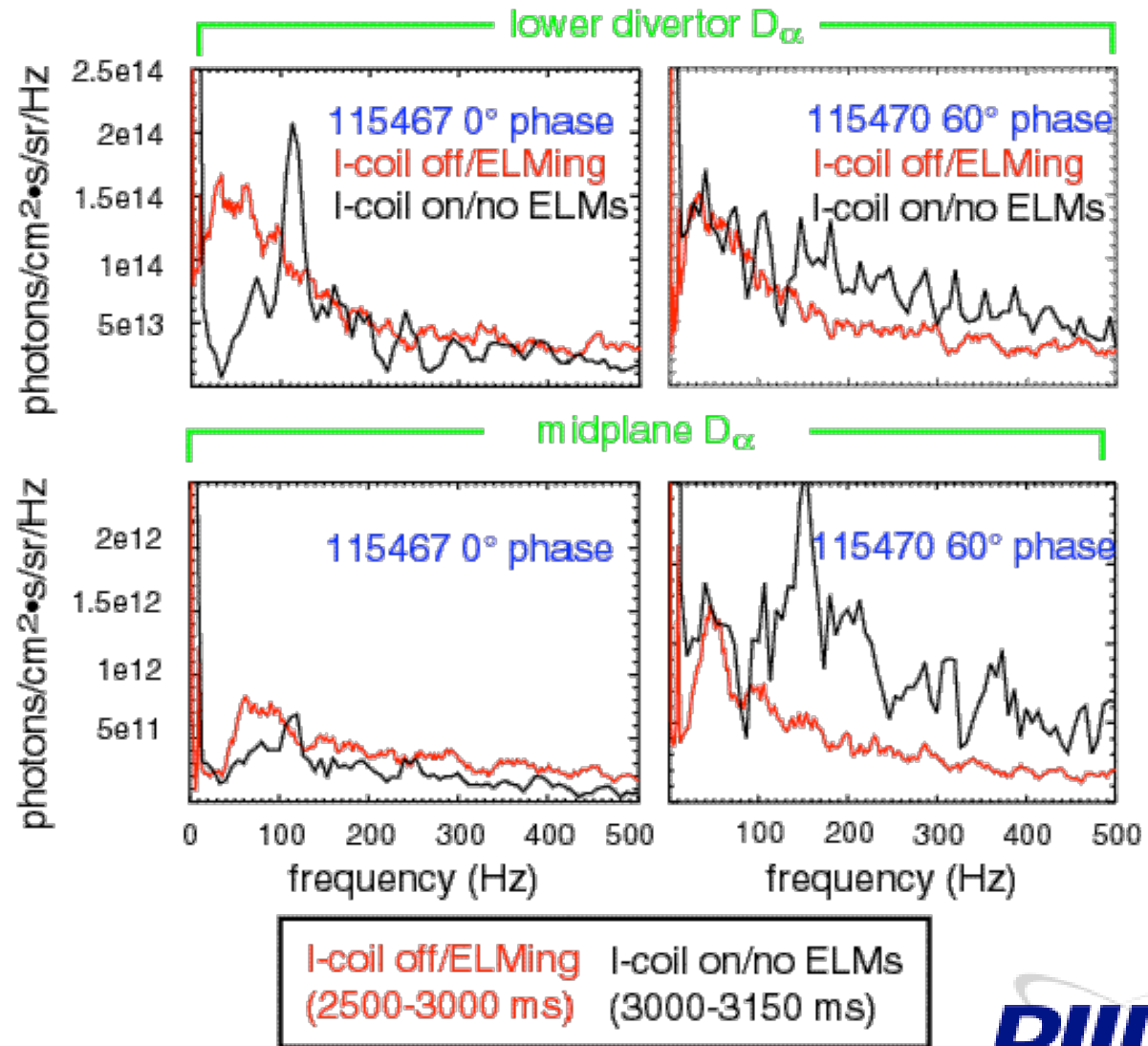


- Small, rapid oscillations appear in edge density and I_{sat} fluctuations as short bursts of fluctuations similar to those seen during the ELMing phase

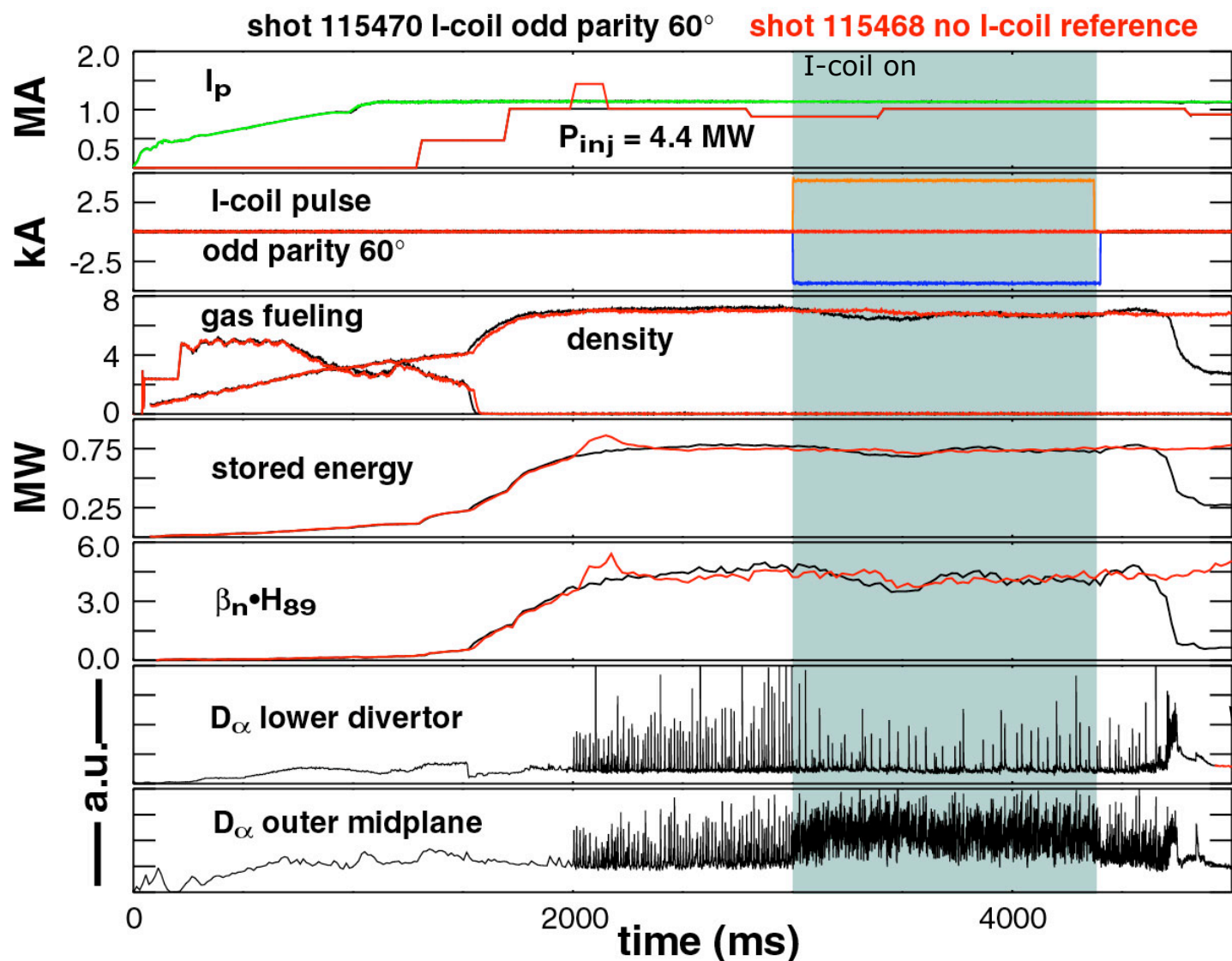
T.L. Rhodes

Changes in the toroidal phasing of the I-coil perturbation produce significantly different D_{α} characteristics

- For 0° phasing, Type I ELMs at 30-70 Hz are strongly suppressed and a 130 Hz oscillatory envelope appears
- For 60° phasing, the ELMs at 30-70 Hz aren't strongly affected, while higher frequencies increase strongly

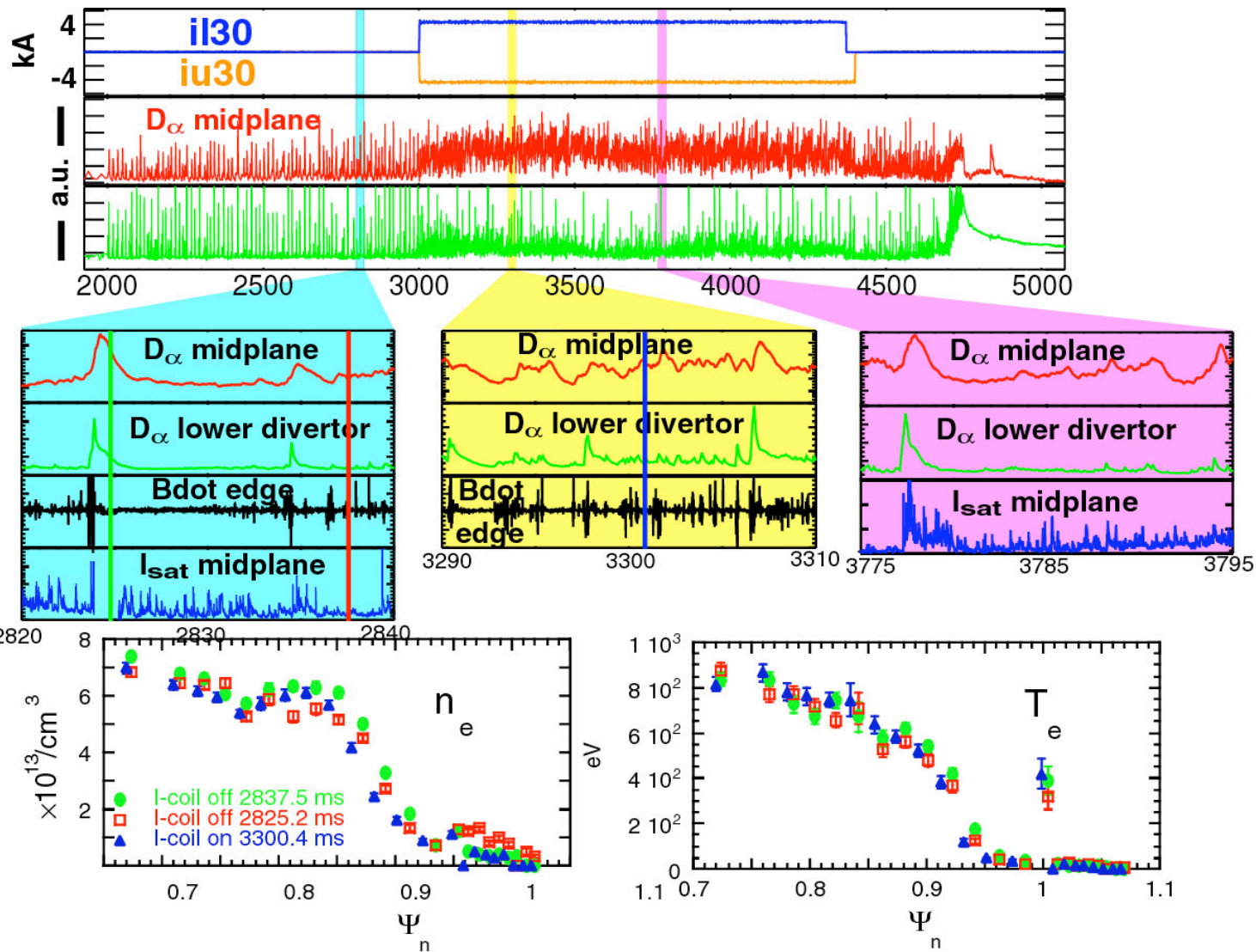


ELM suppression varies with the toroidal phase of the applied perturbation



- Perturbation with odd parity & 60° toroidal phase still reduces ELMs in the divertors
 - Midplane D_α has enhanced baseline level similar to EDA H-mode
- Baseline rises to "bury" ELMs

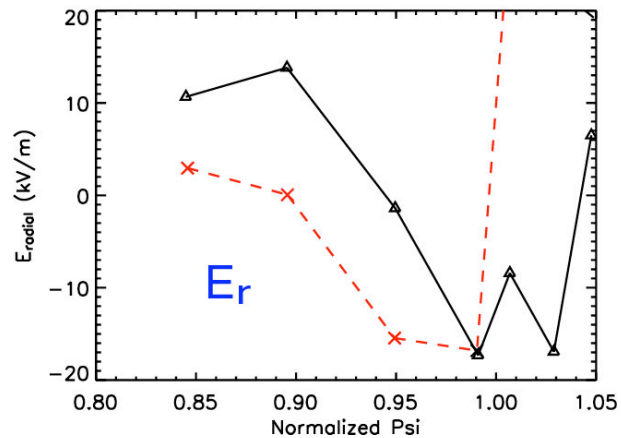
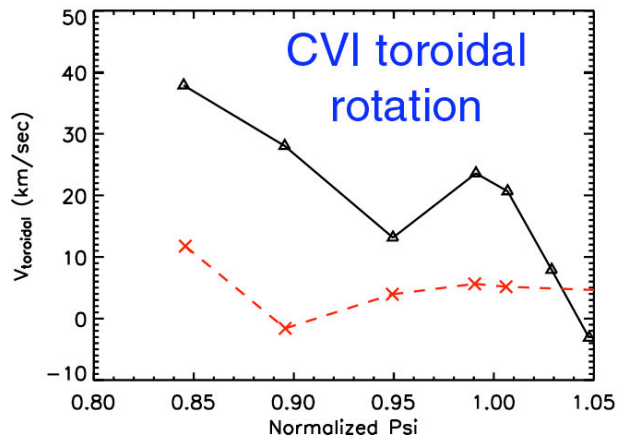
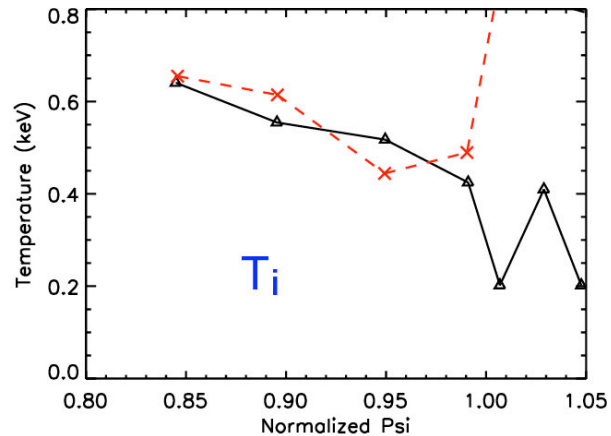
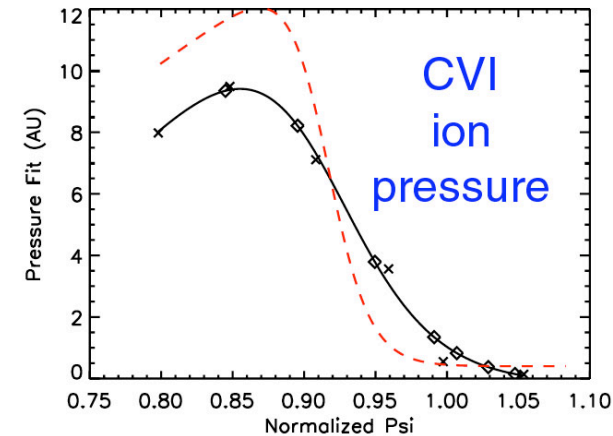
The 60° toroidal phase looks more stochastic than the 0° phase with the same I-coil current



- Increase in overall recycling level
- Profiles shrink inward
- “foot” of profiles moves in from unperturbed separatrix by 3-5%

The pedestal ion channel also looks more stochastic with the 60° toroidal phase

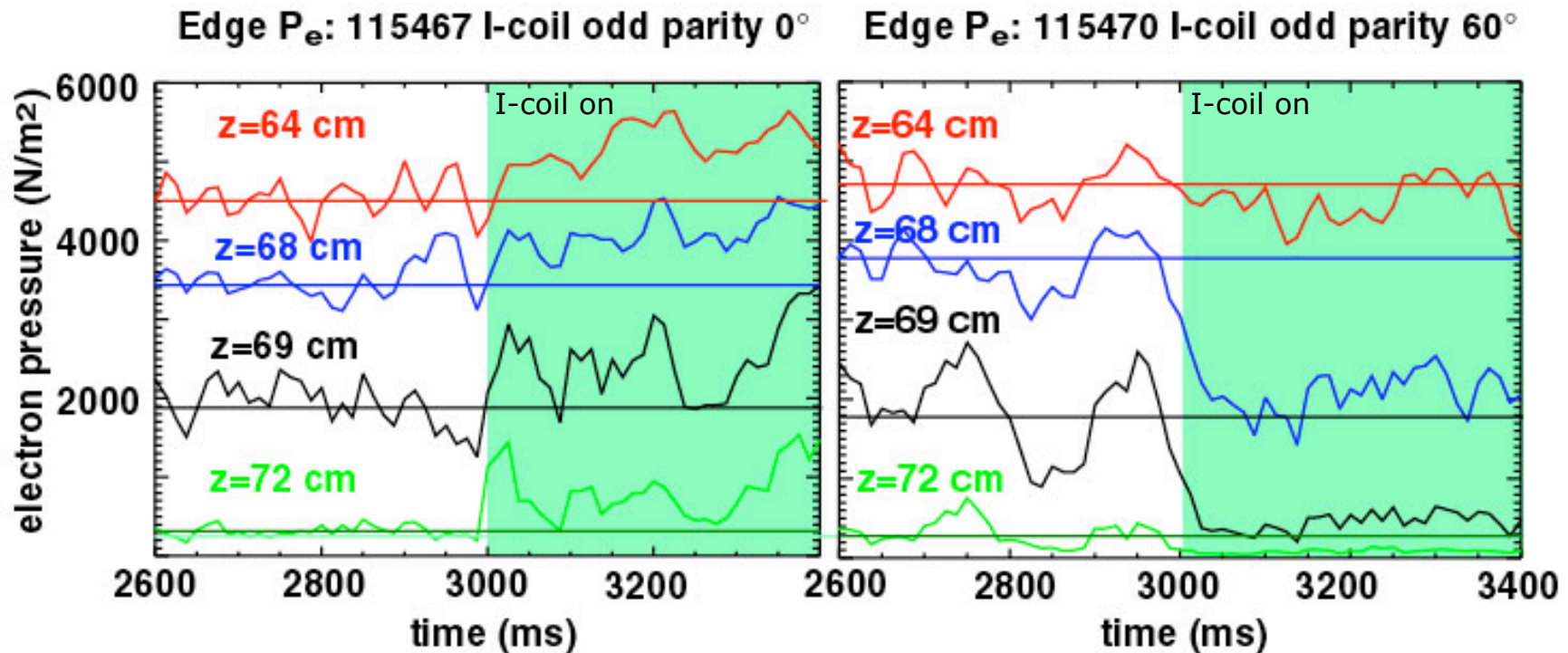
Shot 115470: solid line = 2909 ms
dashed line = 3300 ms



- Foot of CVI ion pressure moves inward
- E_r well shifts in by about 5% in poloidal flux

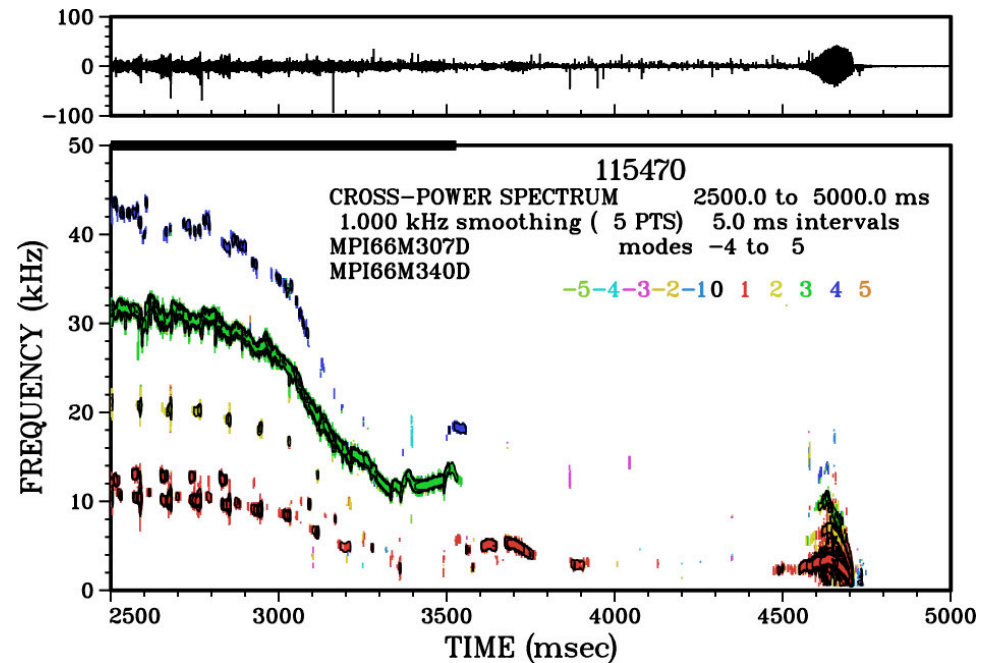
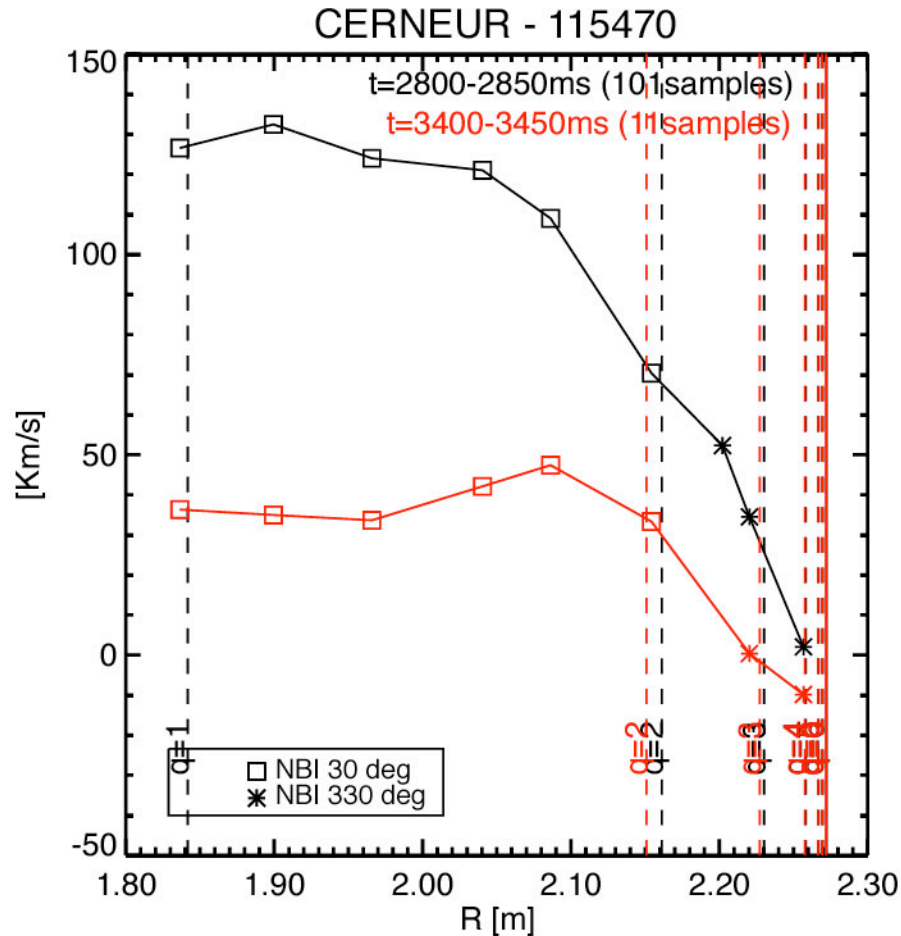
R.J. Groebner

The time dependent electron pressure response is significantly different with the two toroidal phases



- For 0° phasing, the pedestal profiles move outward; for 60° phasing, the pedestal profiles move inward
- The width of poloidal flux loss region predicted by TRIP3D is similar with both toroidal I-coil phases
 - > **Additional error field source can account for the difference**

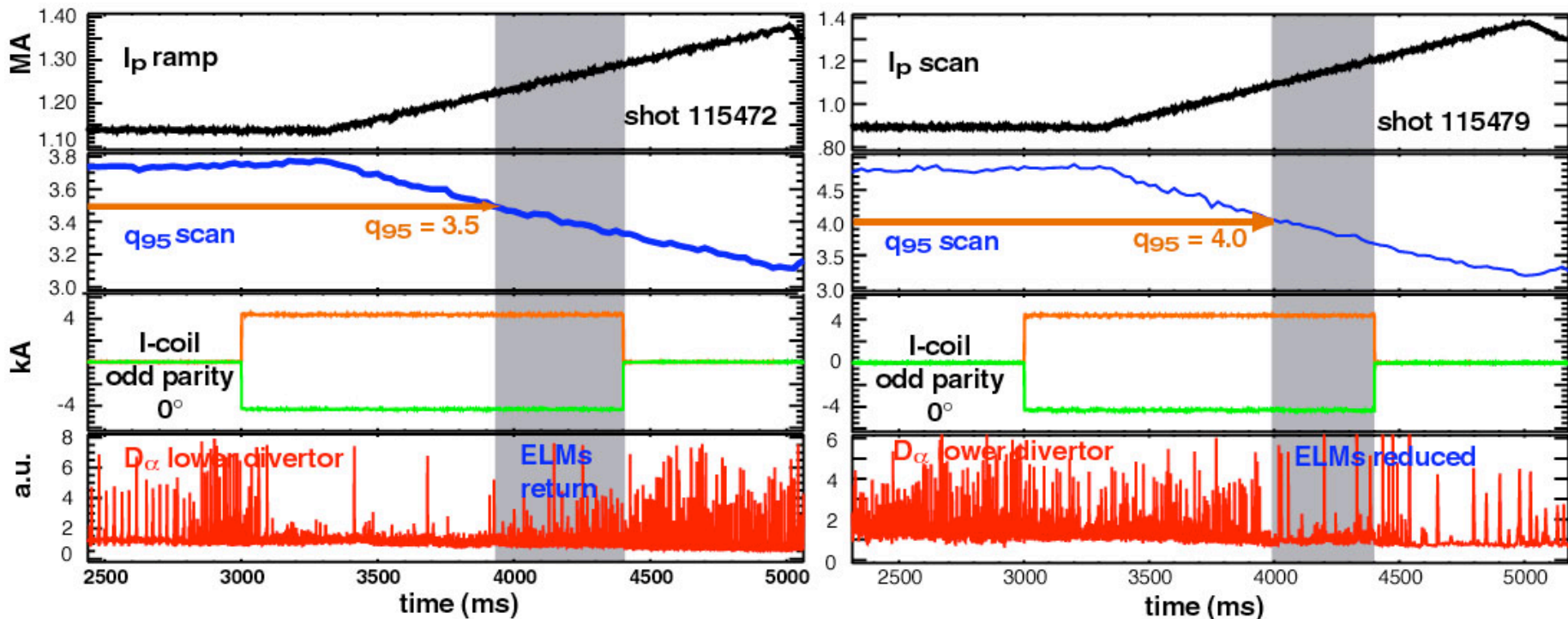
The decay of toroidal rotation in the edge and core is also seen with the 60° phase



- The I-coil, which was designed for feedback control of resistive wall modes, is not well adapted to stochastic boundary control!

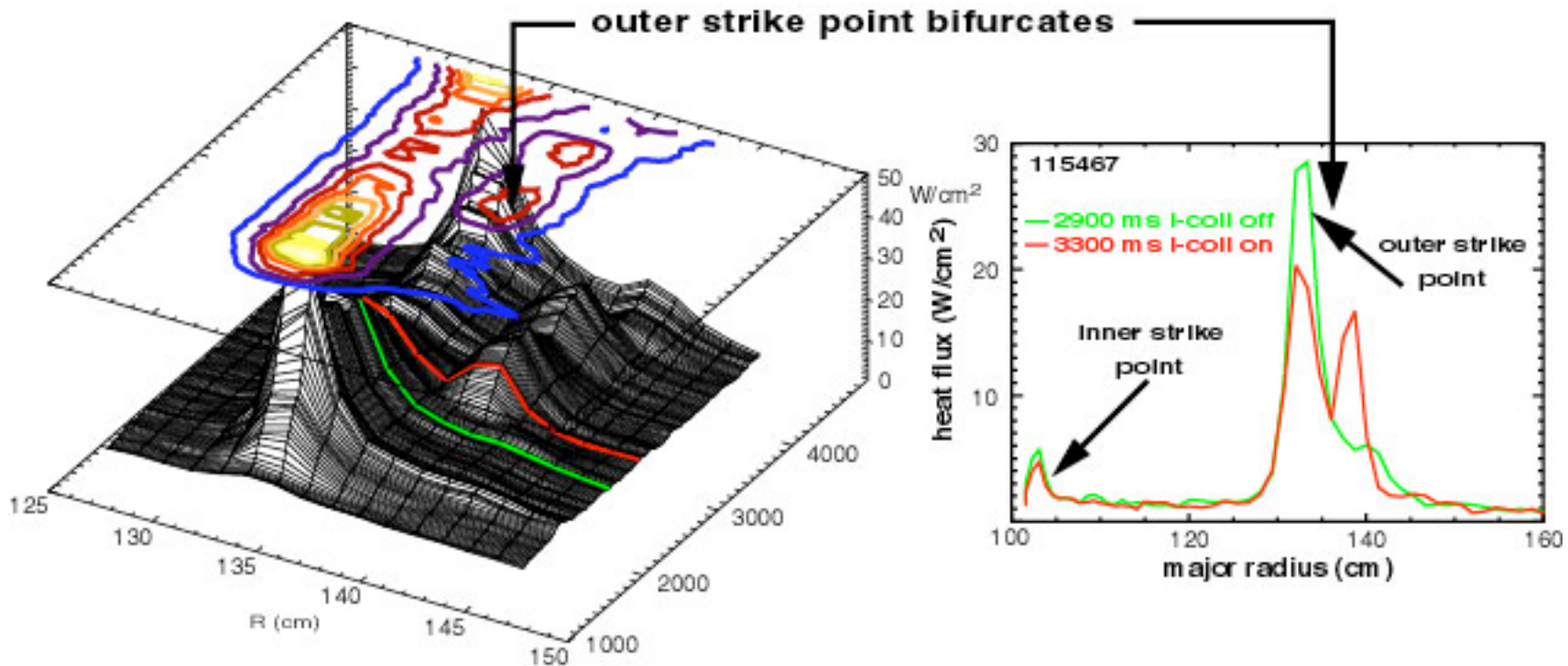
The resonant character of the ELM suppression is verified with q_{95} scans

- 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 $3.5 \leq q_{95} \leq 4.0$



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

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.**