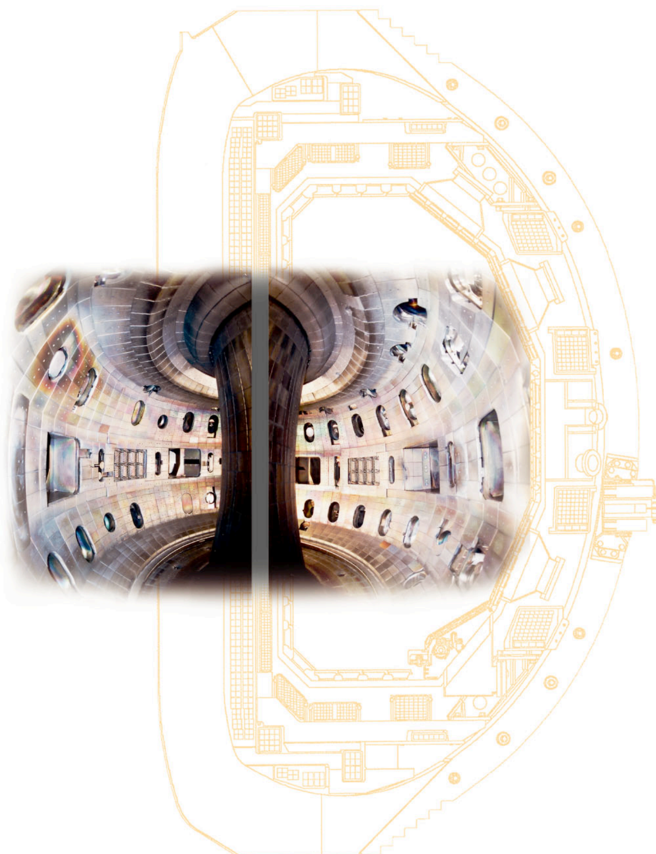
Suppression of large edge localized modes with a stochastic magnetic boundary in high confinement DIII-D plasmas



Presented by

T. E. Evans

General Atomics, San Diego, CA, USA

With contributions from:

R. J. Groebner, G. L. Jackson, R. J. La Haye, A. W. Leonard, T. H. Osborne, M. J. Schaffer, W. P. West - *General Atomics, San Diego, CA, USA*

R. A. Moyer, J. A. Boedo, D. L. Rudakov - *UCSD, La Jolla, CA, USA*

J. G. Watkins - *Sandia National Laboratories, USA*

M. Becoulet, P. R. Thomas- *CEA Cadarache, France*

M. E. Fenstermacher, M. Groth, C. J. Lasnier - *LLNL, CA, USA*

K. H. Finken - *FZ-Jülich, Germany*

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

E. J. Doyle, T. L. Rhodes, G. Wang, L. Zeng - *UCLA, Los Angeles, CA, USA*

S. Masuzaki, N. Ohyabu - *National Institute for Fusion Science, Gifu-ken, Japan*

H. Reimerdes - *Columbia University, New York, NY, USA*

M. R. Wade - *ORNL, Oak Ridge, TN, USA*

EX/2-5Ra

20th IAEA Fusion Energy Conference

1-6 November 2004, Vilamoura, Portugal

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

GENERAL ATOMICS

DIII-D has made substantial progress toward developing an ELM control solution for ITER

Evans EX2-5Ra

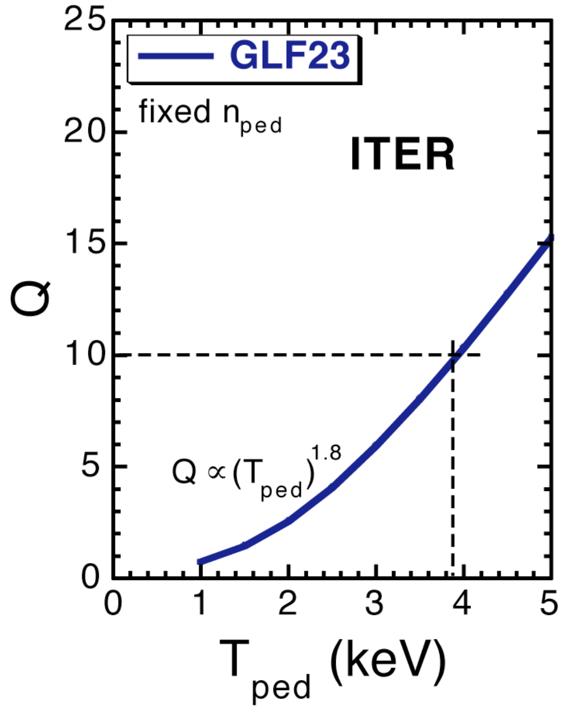
- Type-I ELMs are suppressed with resonant magnetic perturbations
  - no confinement degradation
  - good suppression for $\Delta t \sim 9\tau_E$ (some isolated ELMs remain)
- A new type of dynamical state replaces Type-I ELMs
  - transport dominated by small, high frequency fluctuations
    - » Magnetic fluctuations increase at higher frequencies and shift to higher toroidal mode numbers (n = 1– 3 core modes shift to n = -2 to -5 edge modes)
  - divertor surface temperature spikes reduced by at least a factor of 5
  - divertor particle flux impulses reduced by at least a factor of 8
  - stored energy impulses from the pedestal reduced by a factor of 3
- Suppression is resonant in: q95, shape, I-coil configuration, etc.
  - field errors have a significant impact on ELM character
- Good suppression is obtained in high triangularity (δ=0.76), ITER scenario 2 (δ=0.60) and lower single null (δ=0.37) shapes
- Looks promising for ITER ELM control

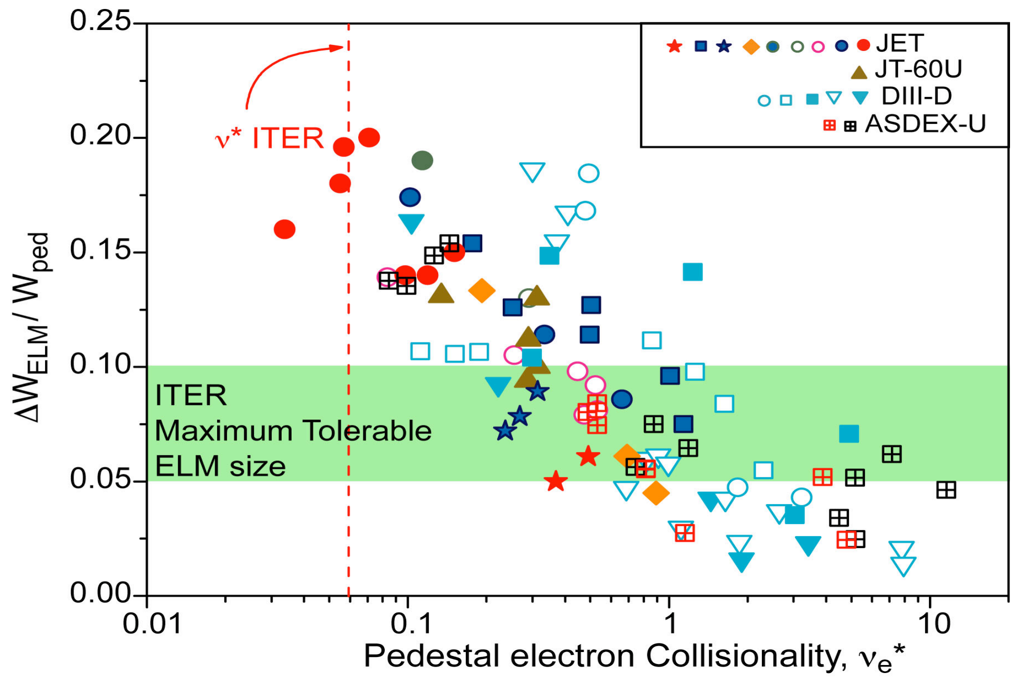
MOTIVATION AND APPROACH

ELM control is a high priority ITER issue

Evans EX2-5Ra

- $T_e^{ped} \geq \sim 4$ keV for $Q \geq 10$ in ITER





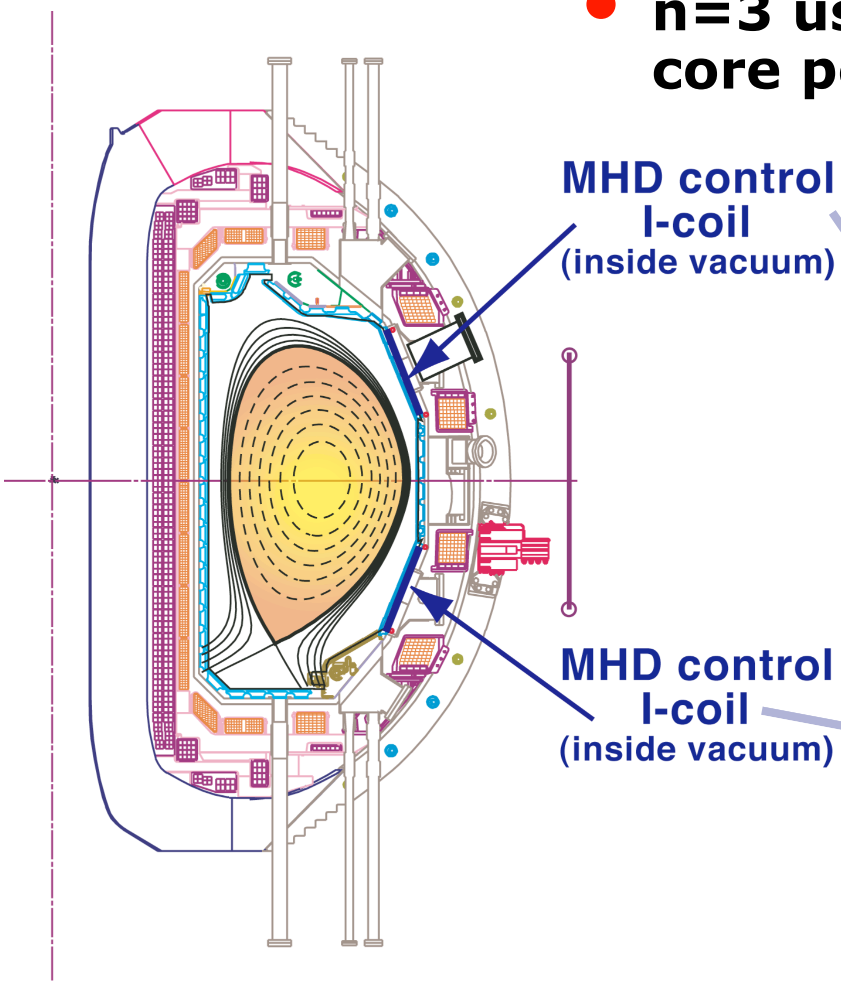
- Normalized ELM energy ($\Delta W_{ELM}/W_{ped}$) increases with T_e^{ped}
- In ITER $\Delta W_{ELM}/ W_{ped}$ > 20%
  - exceeds carbon ablation limit by a factor of 2-4

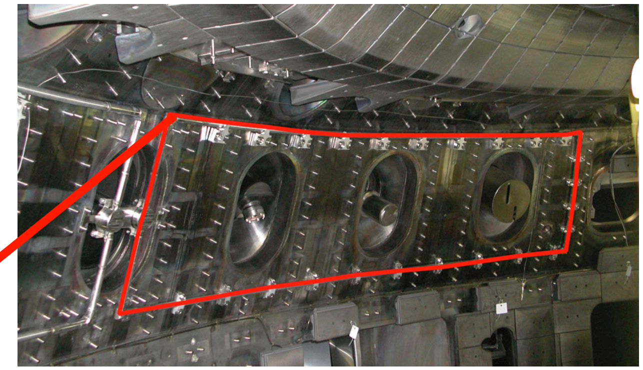
DIII-D NATIONAL FUSION FACILITY SAN DIEGO

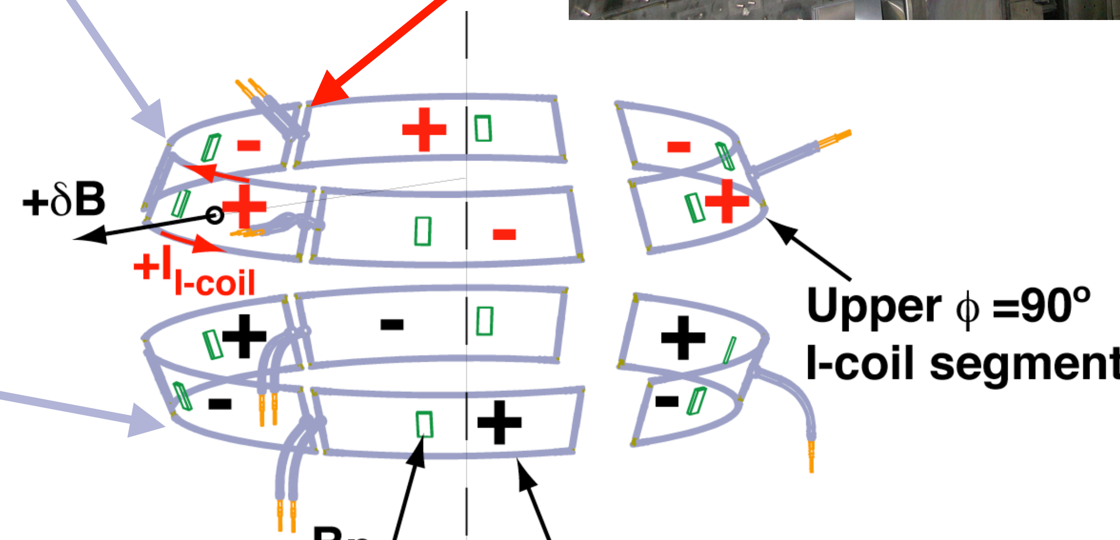
The DIII-D I-coil provides a flexible system for n=3 ELM control experiments

Evans EX2-5Ra

- n=3 used to minimize core perturbations







n=3 (odd up-down parity)

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

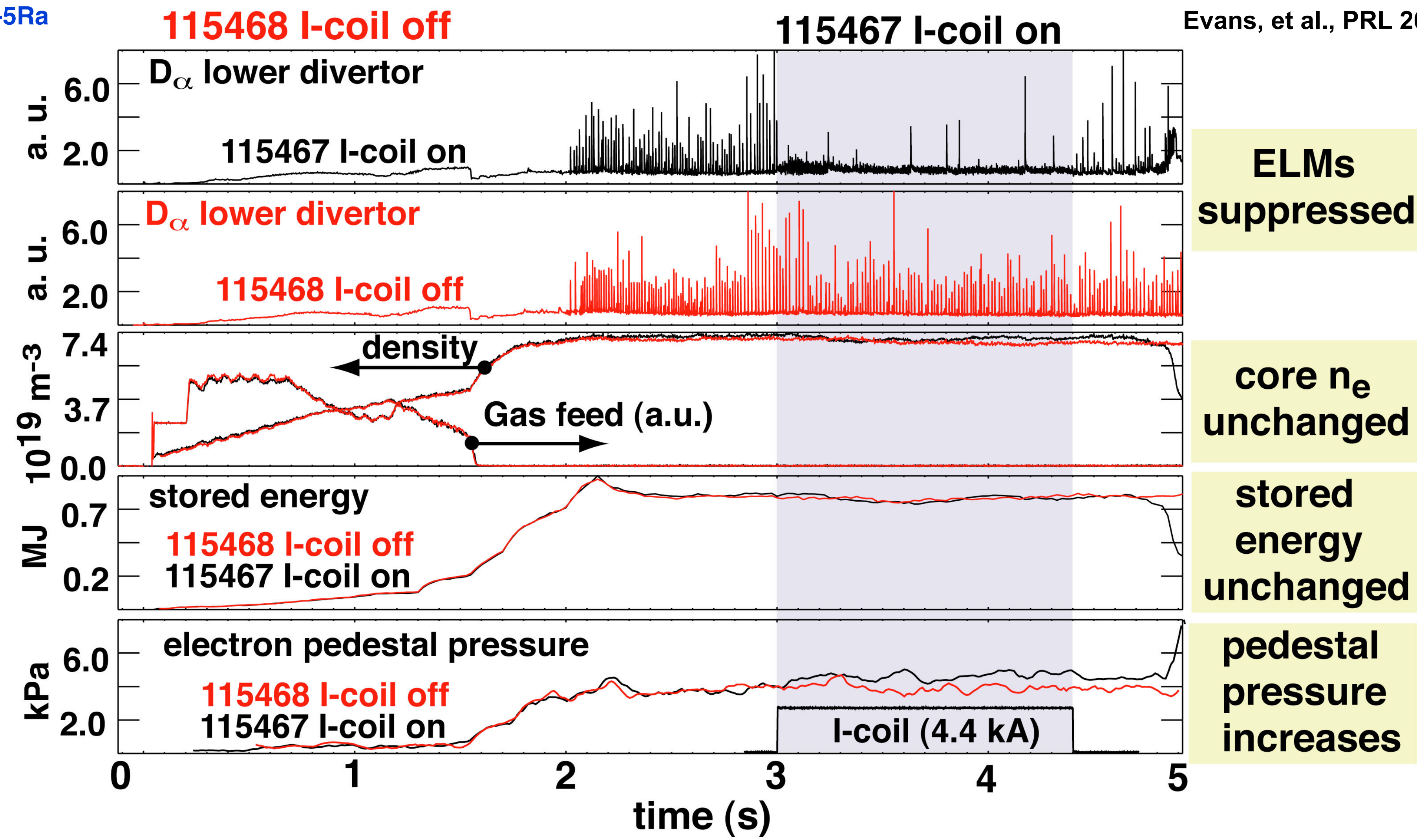
DIVERTOR IMPULSES ARE SIGNIFICANTLY REDUCED DURING I-COIL ELM SUPPRESSION

Evans EX2-5Ra

ELMs are suppressed without degrading confinement

Evans EX2-5Ra

Evans, et al., PRL 2004



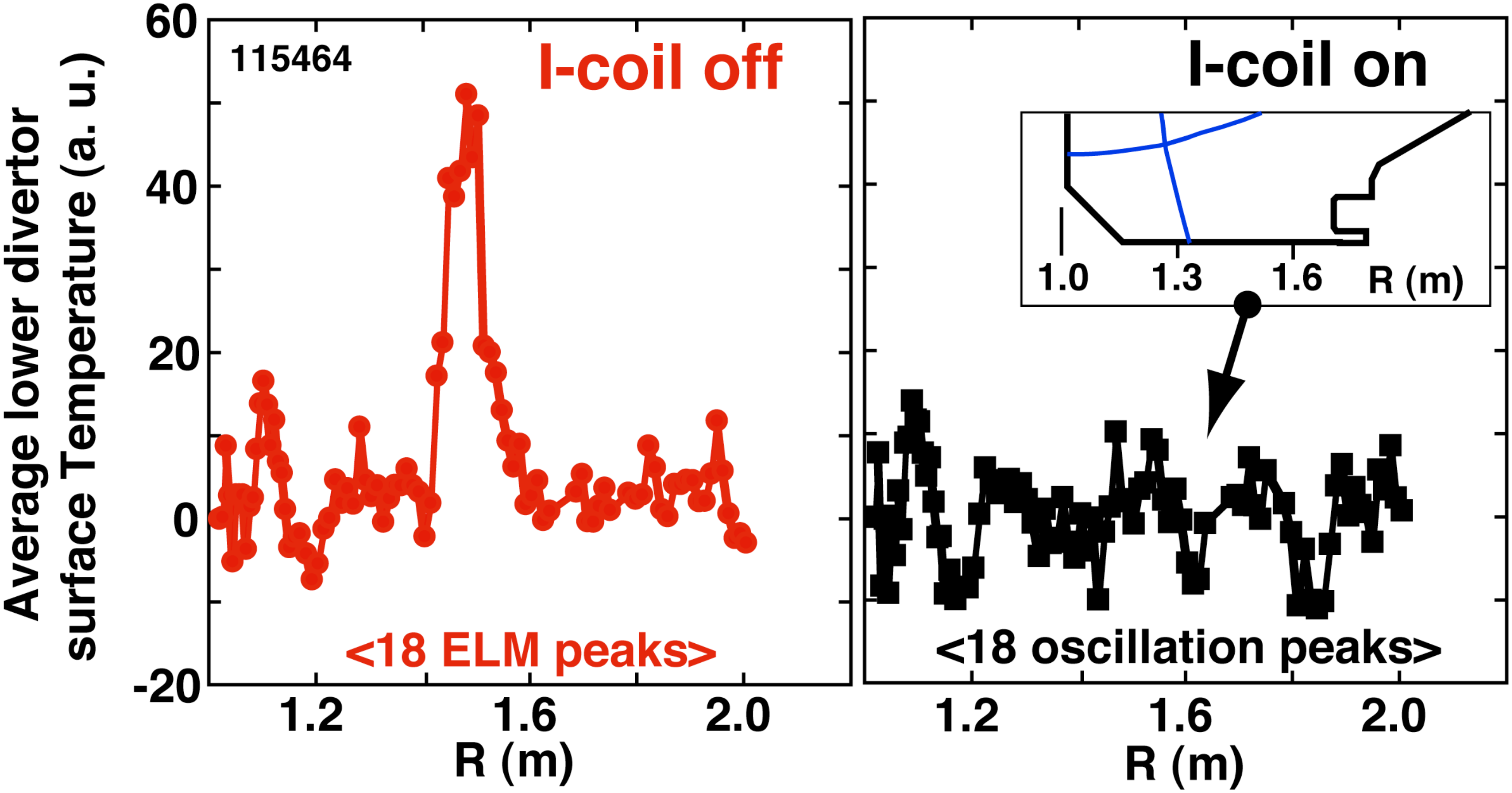
- Several isolated ELM-like events remain
- ELMs return after I-coil pulse turns off

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Peaks in the divertor surface temperature due to ELMs are reduced by at least a factor of 5 with the I-coil

Evans EX2-5Ra

C. Lasnier LLNL

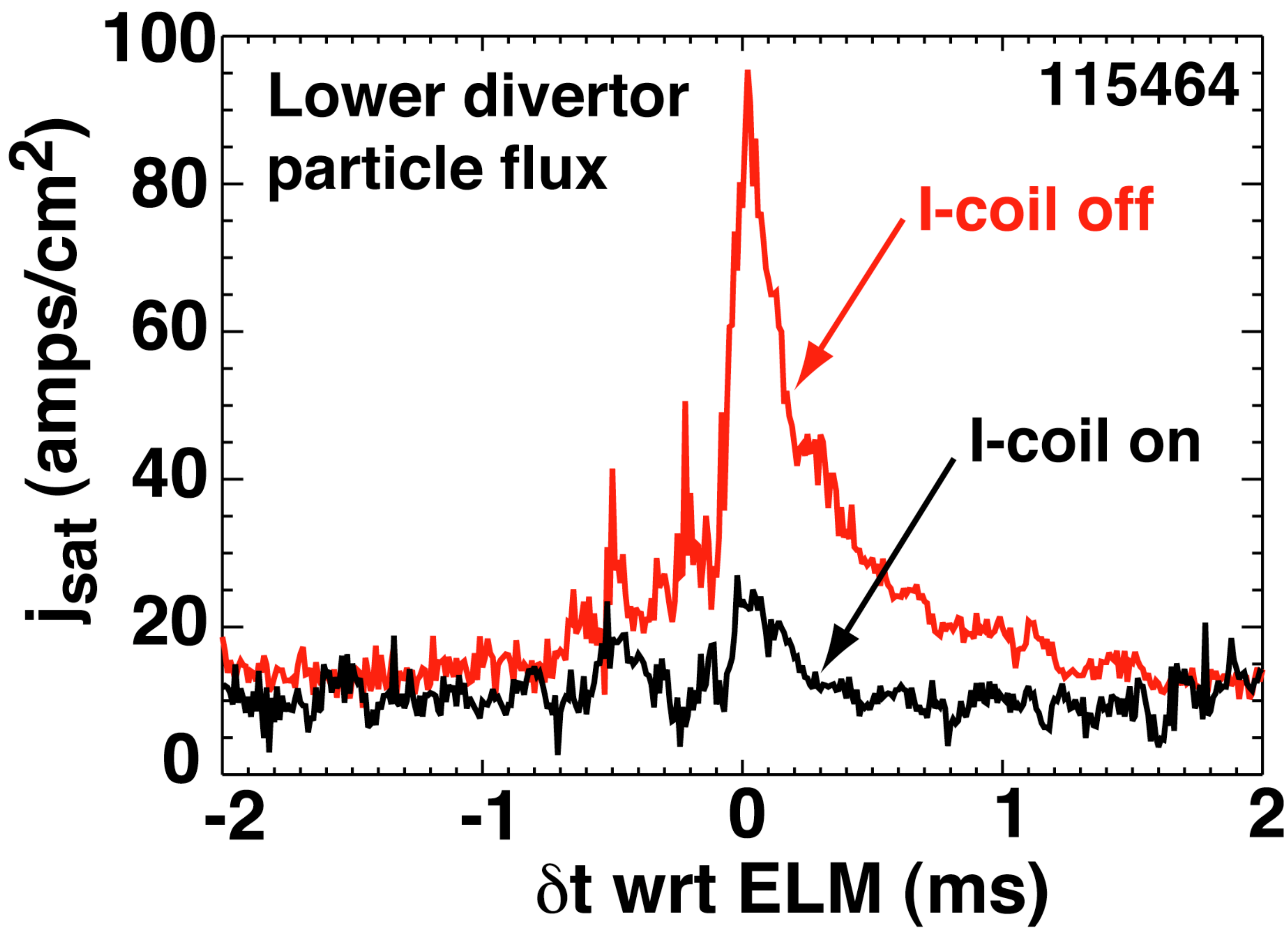


DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Langmuir probes show a factor of 8 reduction in the impulsive particle flux to the divertor

Evans EX2-5Ra

J. Watkins SNL



- Reduction in particle flux impulses due primarily to amplitude reduction not δt

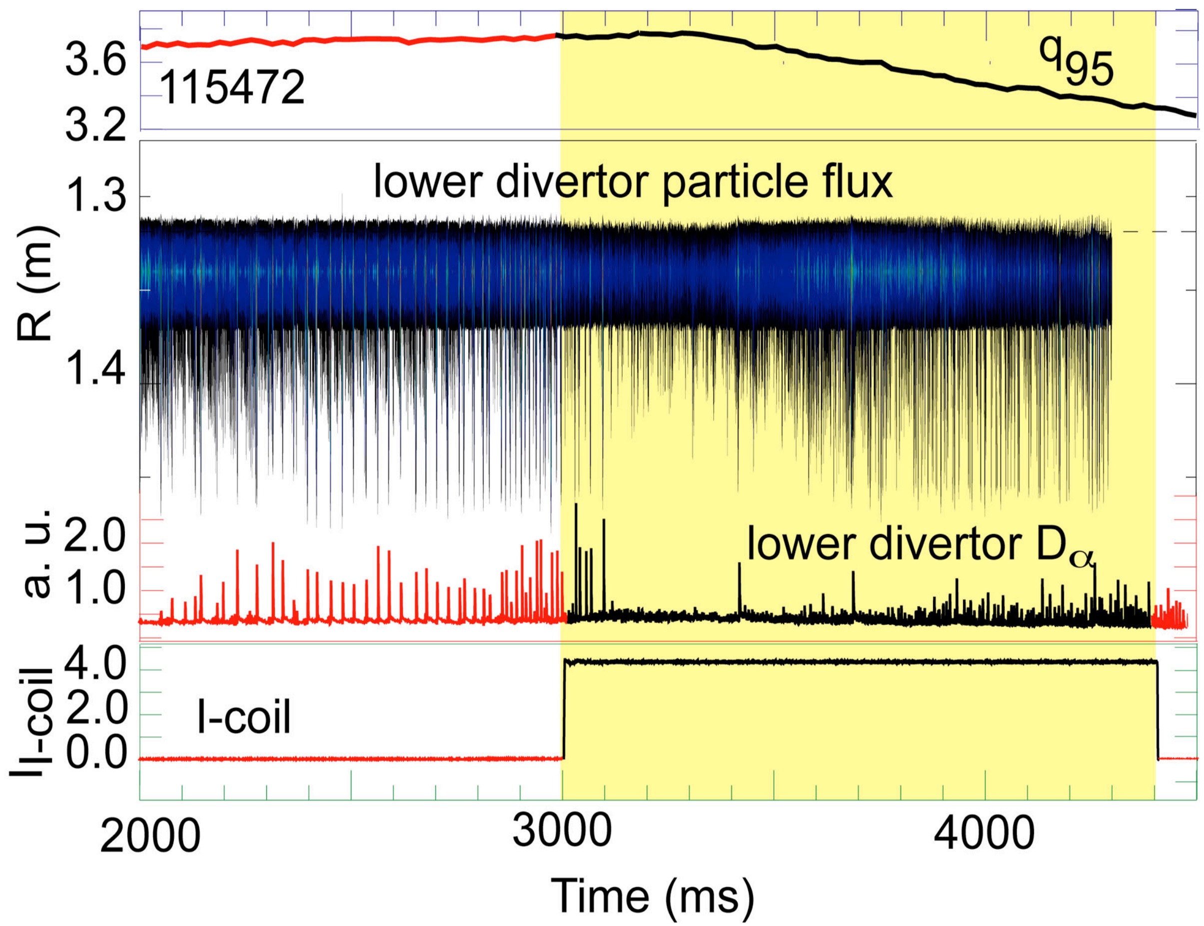
DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Radial extent of ELM driven lower divertor particle flux is significantly reduced inside resonant q_{95} window

Evans EX2-5Ra

J. Watkins SNL

- **Inside the I-coil resonance window $3.7 \leq q_{95} \leq 3.5$:**
  - **the amplitude of large particle flux impulses are reduced**
  - **the spatial extent of large particle flux impulses are reduced**
- **Large particle flux impulses return (amplitude and spatial extent) below the resonant window $q_{95} < 3.5$**
- **Particle flux and D_α recycling impulses are reduced by a factor of 3-6 during the I-coil pulse**



DIII-D NATIONAL FUSION FACILITY SAN DIEGO

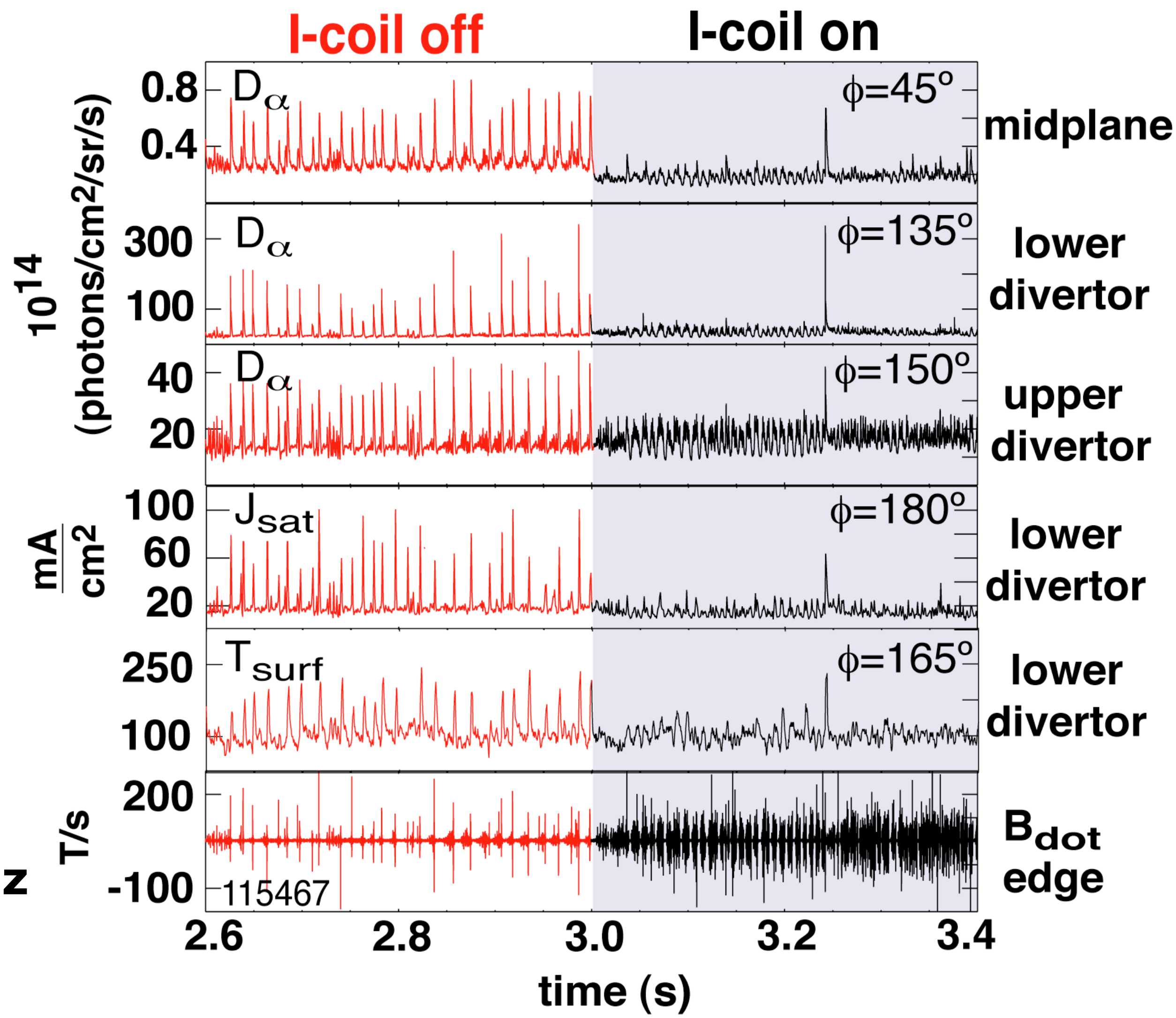
SUBSTANTIAL CHANGES IN PEDESTAL DYNAMICS SEEN DURING ELM SUPPRESSION

Evans EX2-5Ra

Dynamical state of pedestal changes globally

Evans EX2-5Ra

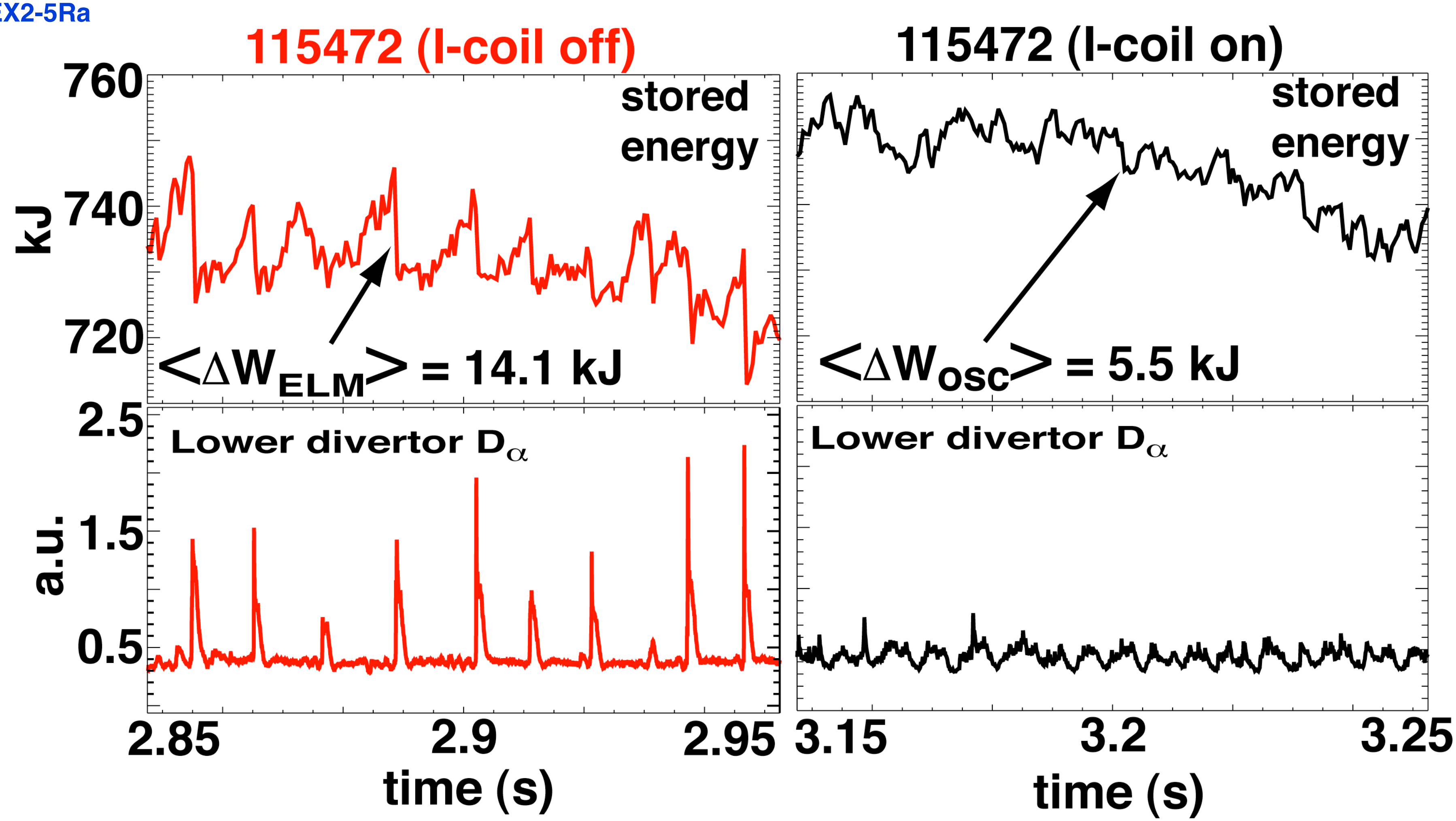
- **Suppression seen on:**
  - all D_α arrays (outer midplane, upper and lower divertor, inner wall)
  - particle flux and heat flux to the primary (lower) divertor
- **ELM transport is replaced by an increase in edge magnetic field and density fluctuations**
  - modulated by a 130 Hz coherent oscillation



DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Stored energy drops are smaller and slower with the I-coil reducing the impulses by > 3X

Evans EX2-5Ra

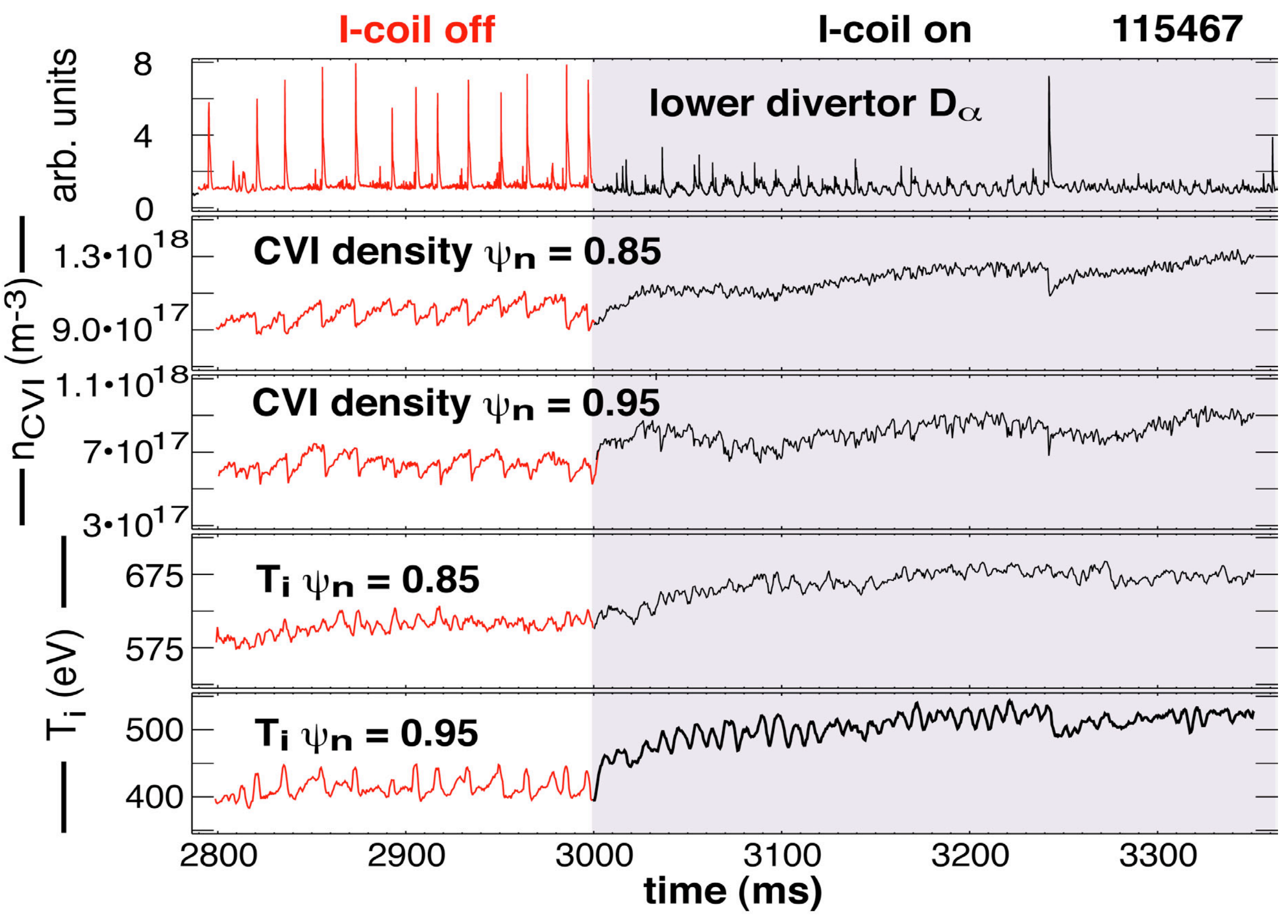


DIII-D NATIONAL FUSION FACILITY SAN DIEGO

I-coil pulse suppresses the convective loss channel along B field

Evans EX2-5Ra

- ELM **suppression** obtained at high density with small ΔT_e and little conductive energy loss
- I-coil pulse **modifies** ELMs at lower density with a more significant conductive loss
  - limited run time allotted in 2004 for low n_e ELM suppression work
  - I-coil current limit (4.4 kA) expected to increase to 7 kA in 2005

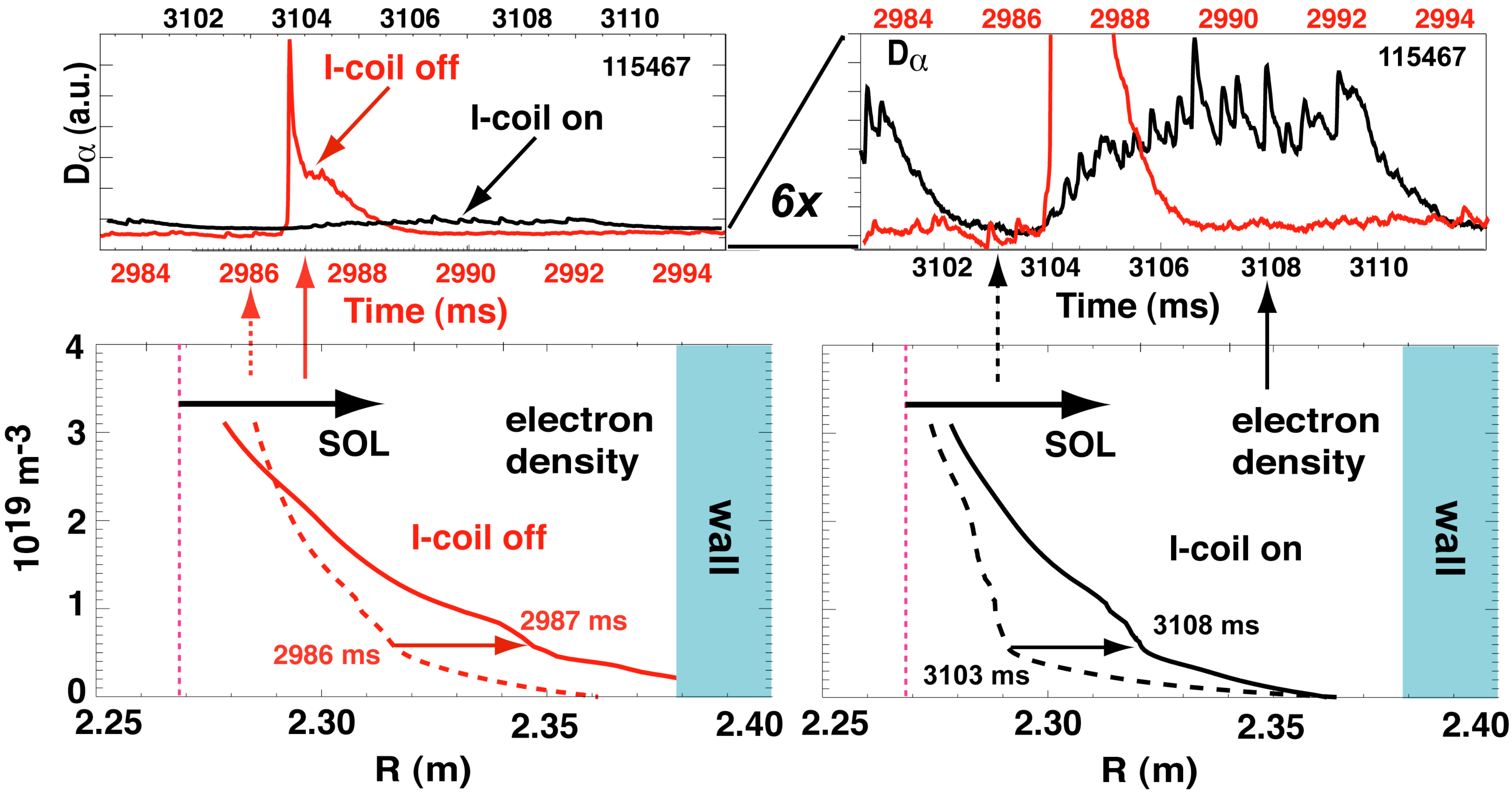


DIII-D NATIONAL FUSION FACILITY SAN DIEGO

I-coil reduces ELM density impulses to the wall

Evans EX2-5Ra

L. Zeng UCLA



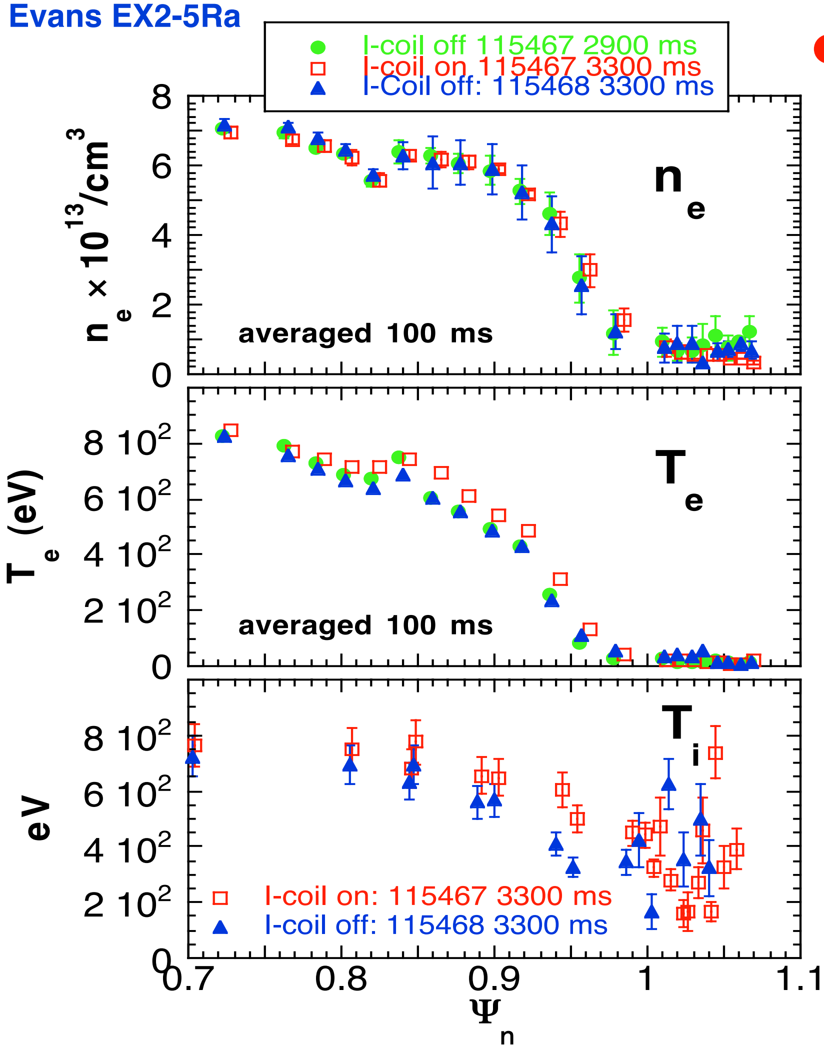
- **High frequency fluctuations replace ELM transport**
  - **bursty, intermittent and less impulsive**

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

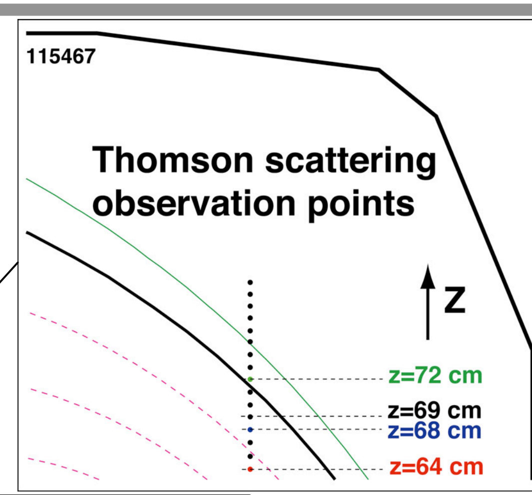
MODEST PEDESTAL PROFILE CHANGES ARE CONSISTENT WITH UNALTERED CONFINEMENT

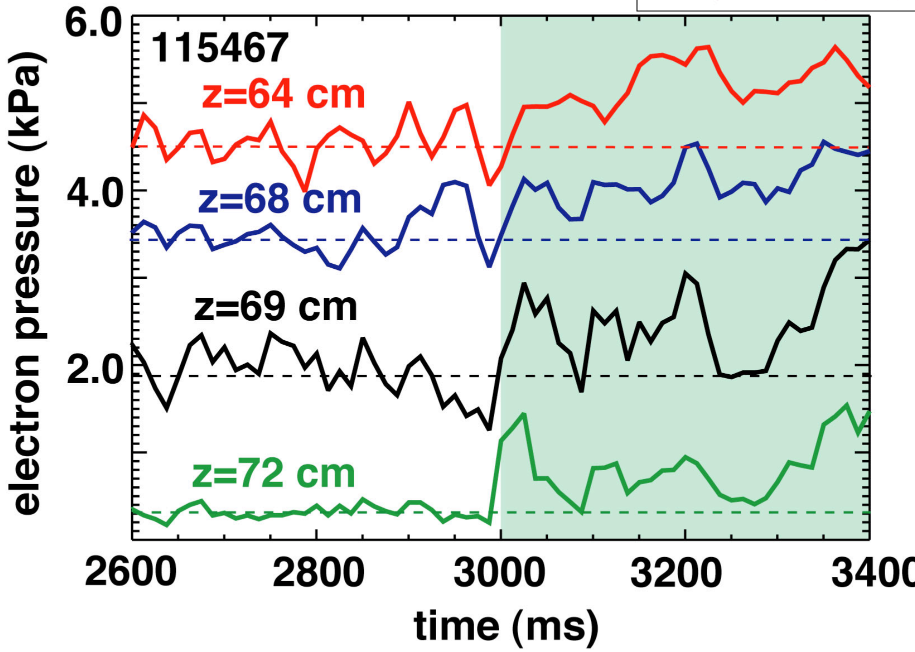
Time averaged pedestal profiles do not show edge flattening due to strong stochaticity

Evans EX2-5Ra



- Thomson pedestal data show modest increase an in electron pressure with I-coil

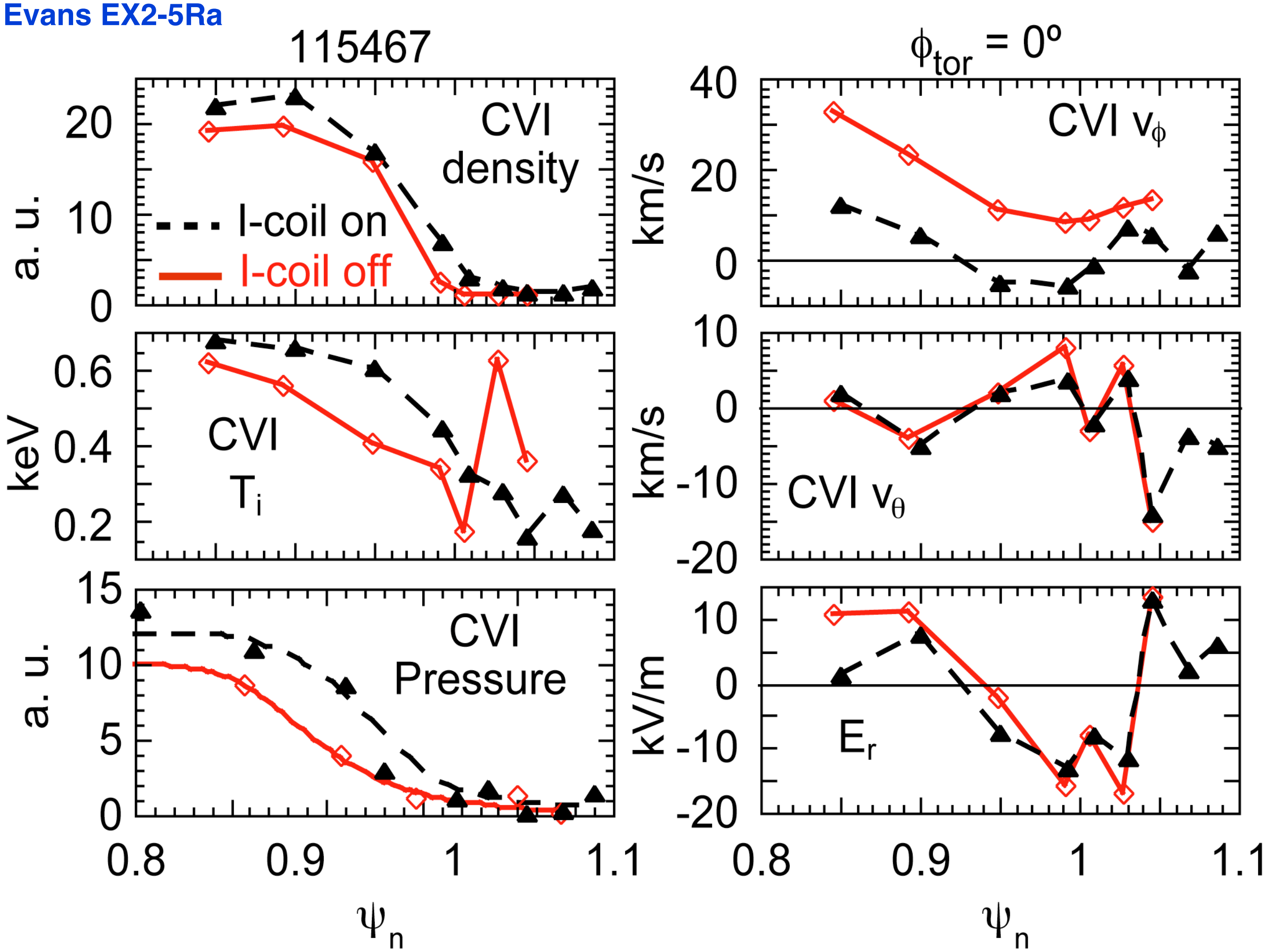




DIII-D NATIONAL FUSION FACILITY SAN DIEGO

CVI ion measurements show a broadening of T_i and P_{CVI} across the pedestal but E_r and v_θ are preserved

Evans EX2-5Ra



- Toroidal rotation drops through 0 and reverses in edge!
- H-mode transport barrier is preserved
  - v_θ & E_r well don't change
  - Increased ∇P_i offsets change in V_ϕ in single ion force balance
- T_i and ∇P_i^{CVI} changes may be important for j_{BS} and stability

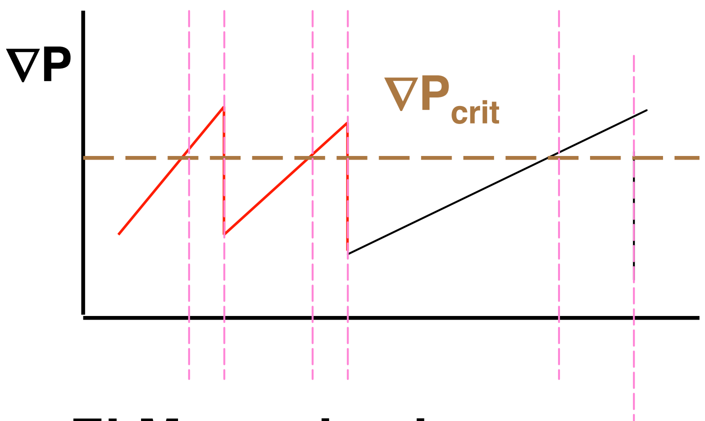
DIII-D NATIONAL FUSION FACILITY SAN DIEGO

I-coil pulse delays variation of total pedestal pressure relative to ELM cycles without I-coil

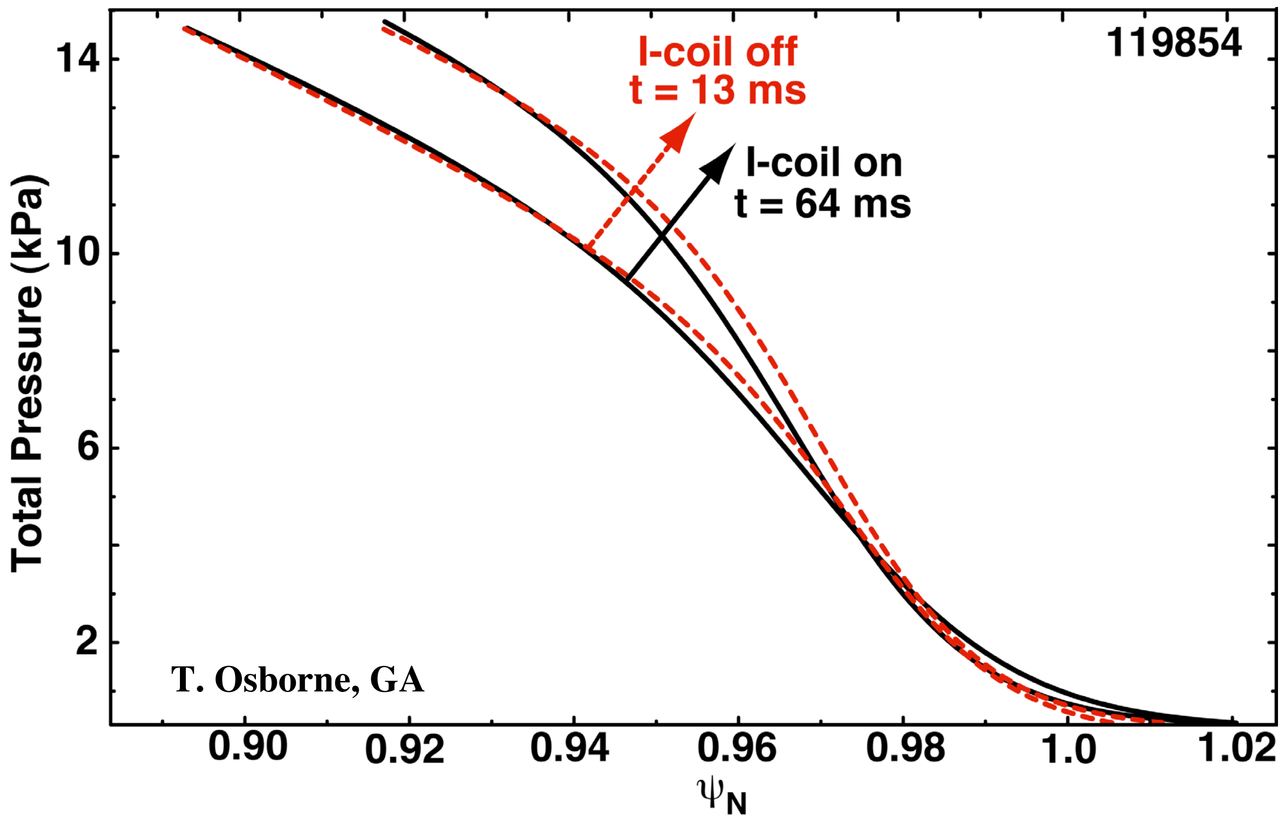
Evans EX2-5Ra

- Time between ELMs = 13 ms on average without the I-coil
- Time between isolated events/ELMs = 64 ms with I-coil.

Unstable phases



ELM spacing increases:
13 ms -> 64 ms
ELITE linearly unstable
time increases:
5 ms -> 28 ms



DIII-D NATIONAL FUSION FACILITY SAN DIEGO

ROTATION DROPS AND MAGNETICS SHOW POWER REDISTRIBUTION FROM LARGE ELMS TO SMALL SCALE, HIGH FREQUENCY FLUCTUATIONS

Evans EX2-5Ra

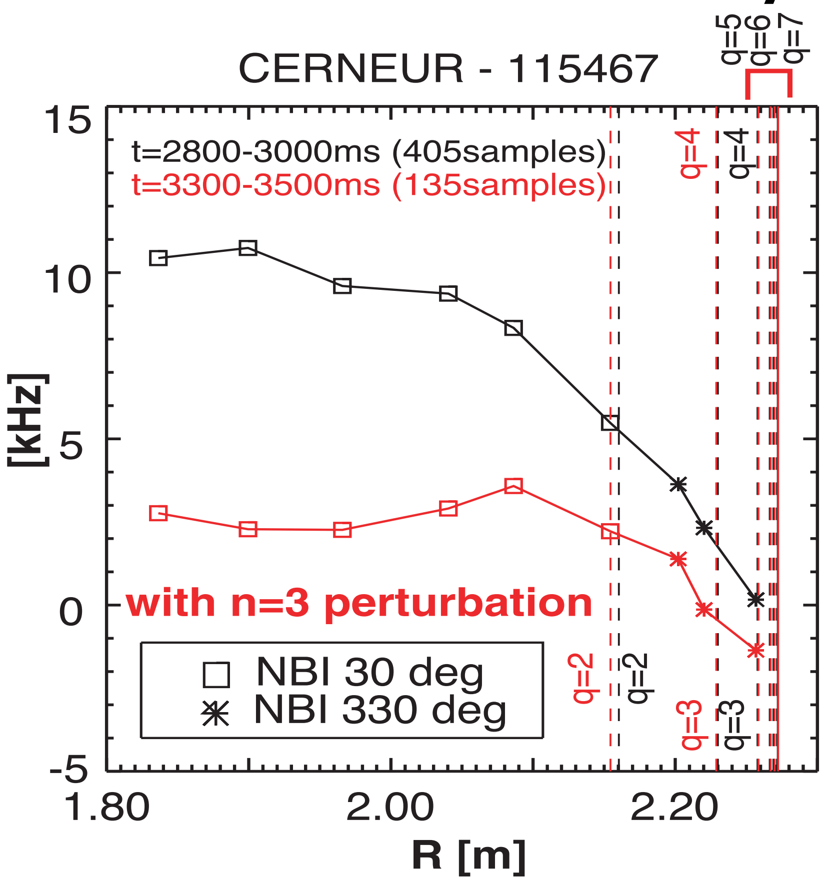
DIII-D NATIONAL FUSION FACILITY SAN DIEGO

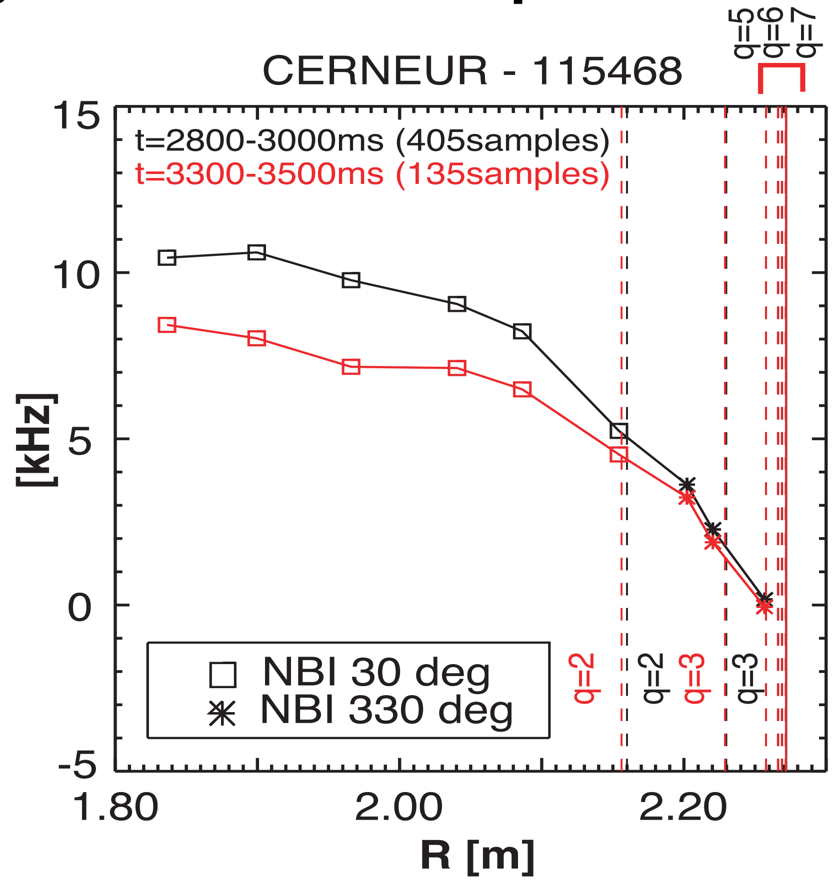
Strong toroidal rotation damping seen during ELM suppression

Evans EX2-5Ra

H. Reimerdes Columbia U

- Modeling indicates small islands on 4/3, 3/2, and 2/1 surfaces
- Sawteeth lost on soft X-ray signal as rotation drops



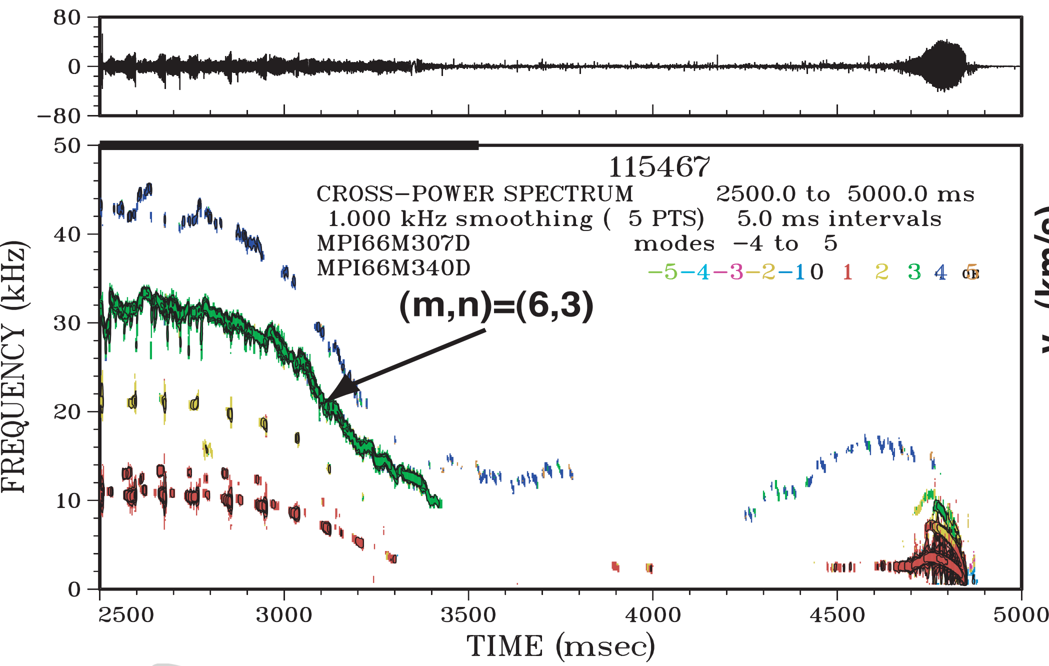


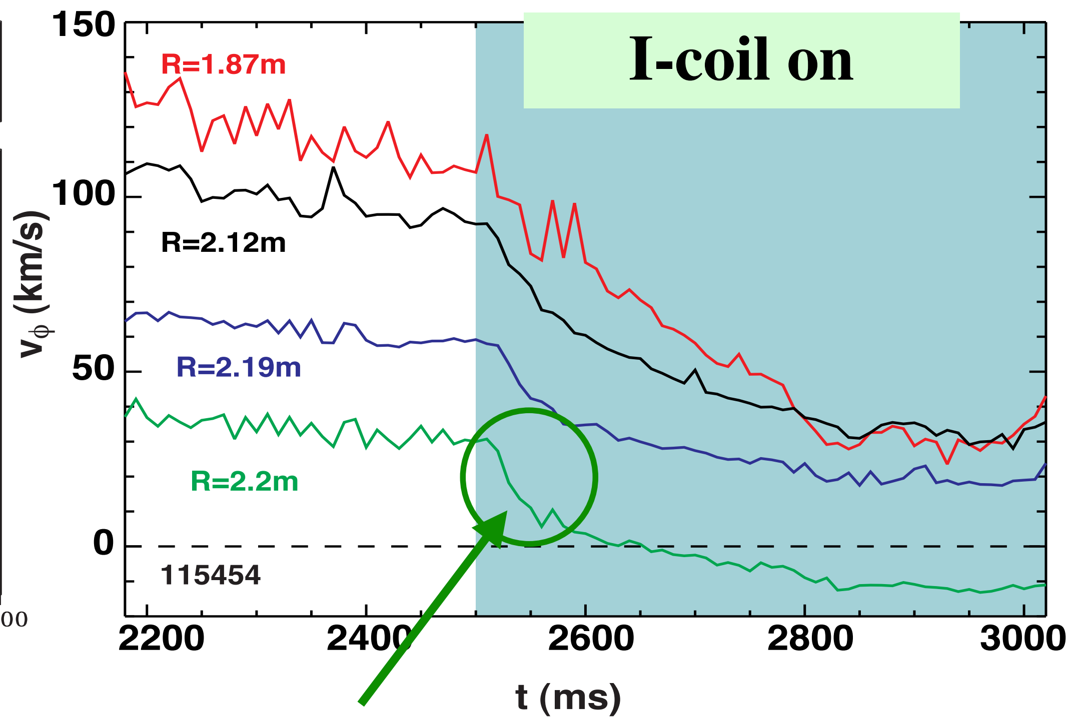
DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Loss of edge toroidal momentum takes about 50 ms and reverses direction after ~ 130 ms

Evans EX2-5Ra

- Core rotation decays in 300 ms; edge has a fast drop (~50 ms) followed by a slower decay
  - Mirnov coils see slowing down in the downshift of internal MHD modes (here, q=1 & 2)
- ELMs suppressed within 1 ELM cycle ≈ 15 ms

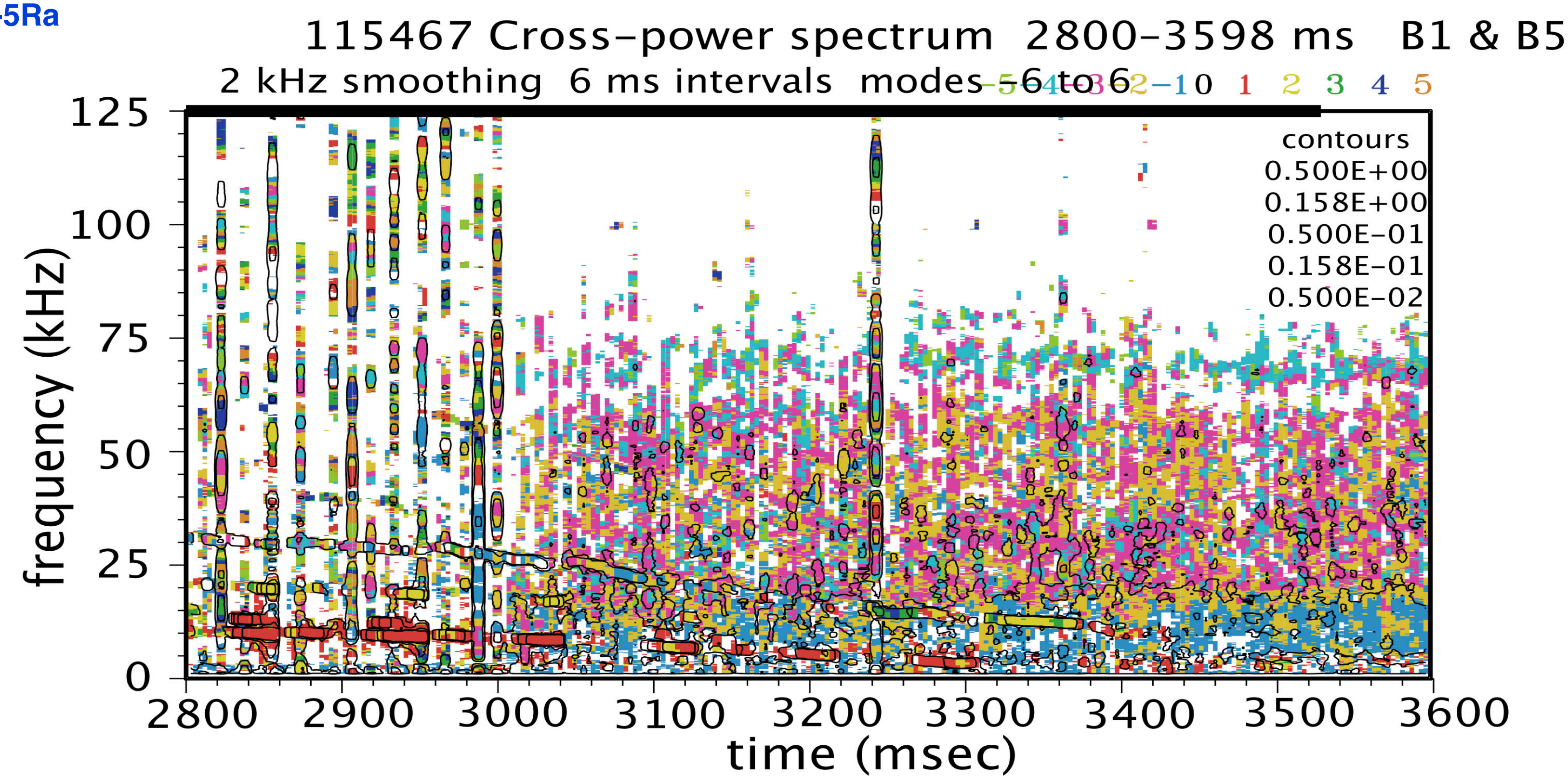




Initial fast drop in edge

Amplitude of magnetic fluctuations increase at higher frequencies and mode numbers

Evans EX2-5Ra



- **Power in edge B_θ fluctuations increases up to f_N = 50 kHz**
- **quiet intervals between ELMs fill in with higher n edge modes**
  - **n = 1– 3 core modes shift to n = -2 to -5 edge modes**

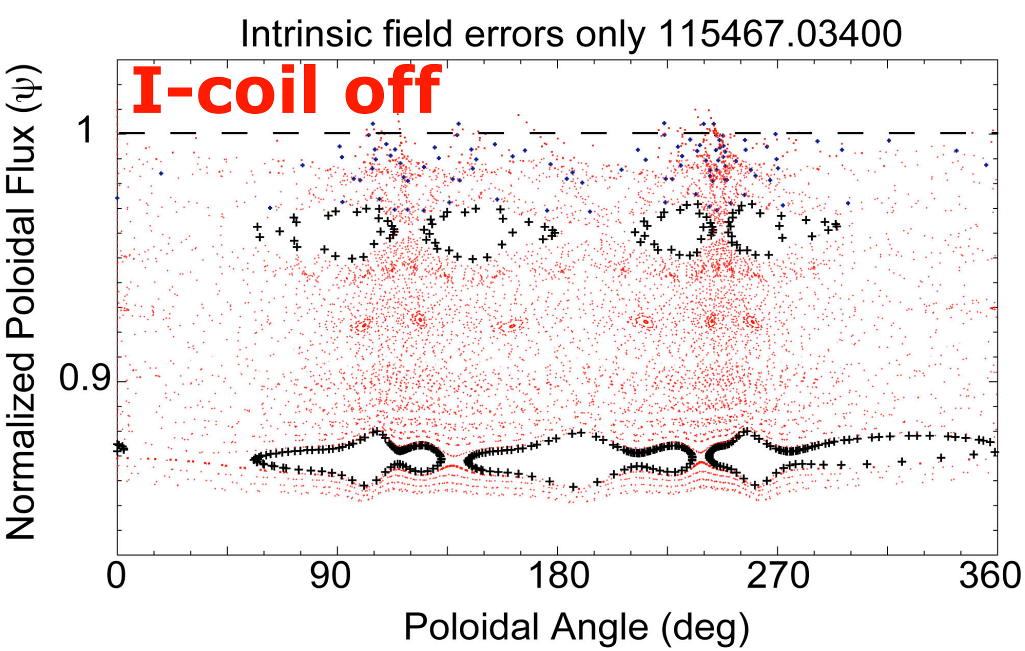
DIII-D NATIONAL FUSION FACILITY SAN DIEGO

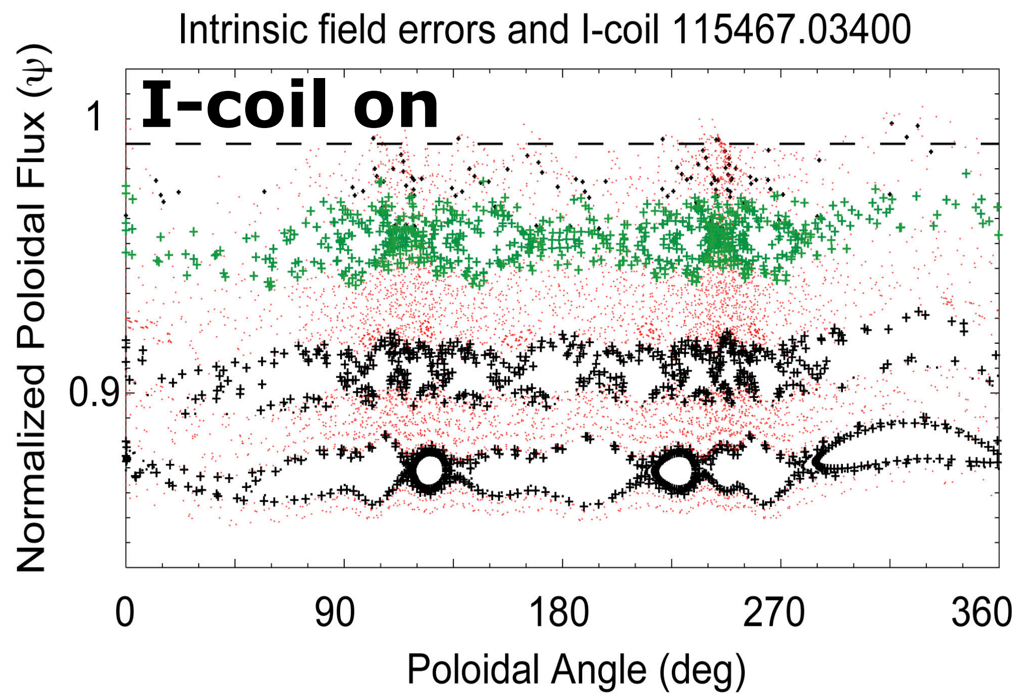
MODELING CONFIRMS IMPORTANCE OF SMALL SCALE MAGNETIC ISLANDS

Field line integration modeling indicates that small islands may be linked to ELM suppression mechanism

Evans EX2-5Ra

- **Small scale, high k_θ, remnant islands formed across the pedestal with $\phi_{tor}=0^o$**
  - **due to mixing of I-coil and field-error spectrum**



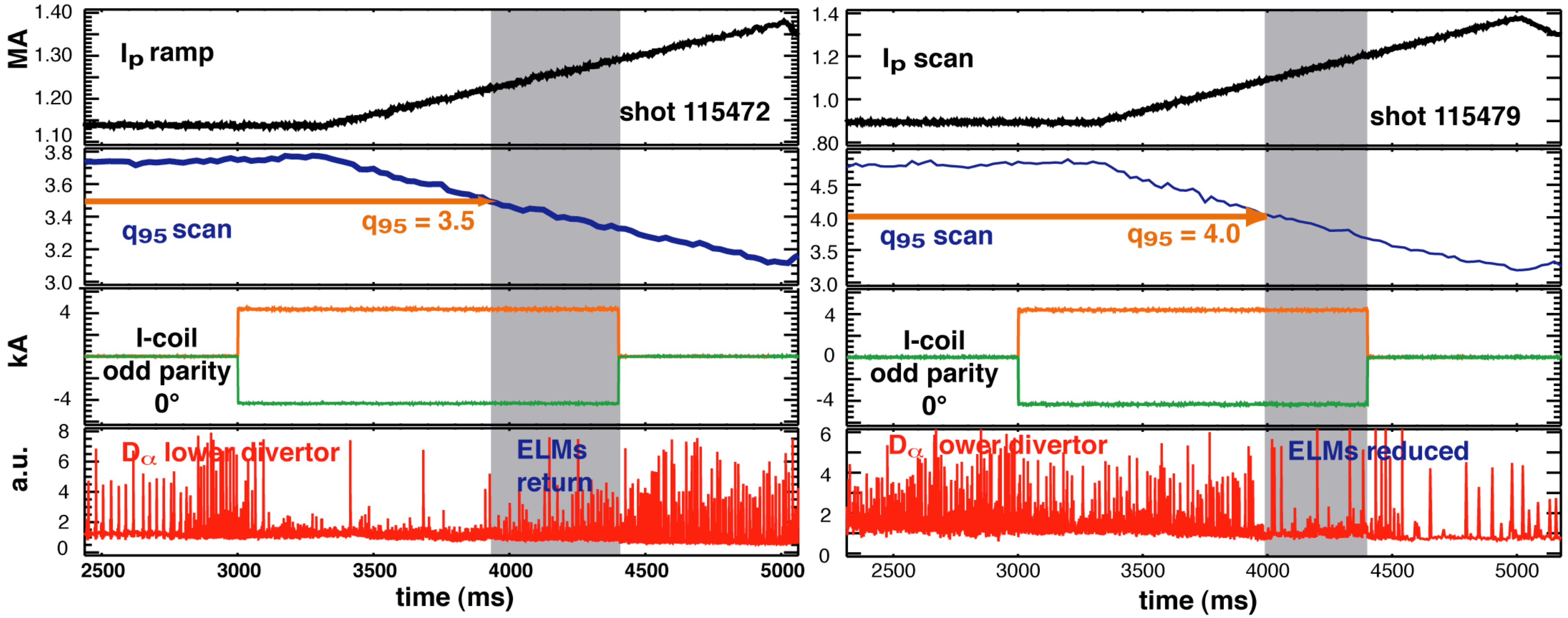


TRIP3D modeling (no plasma response included)

Resonant character of ELM suppression verified during q-scans

Evans EX2-5Ra

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

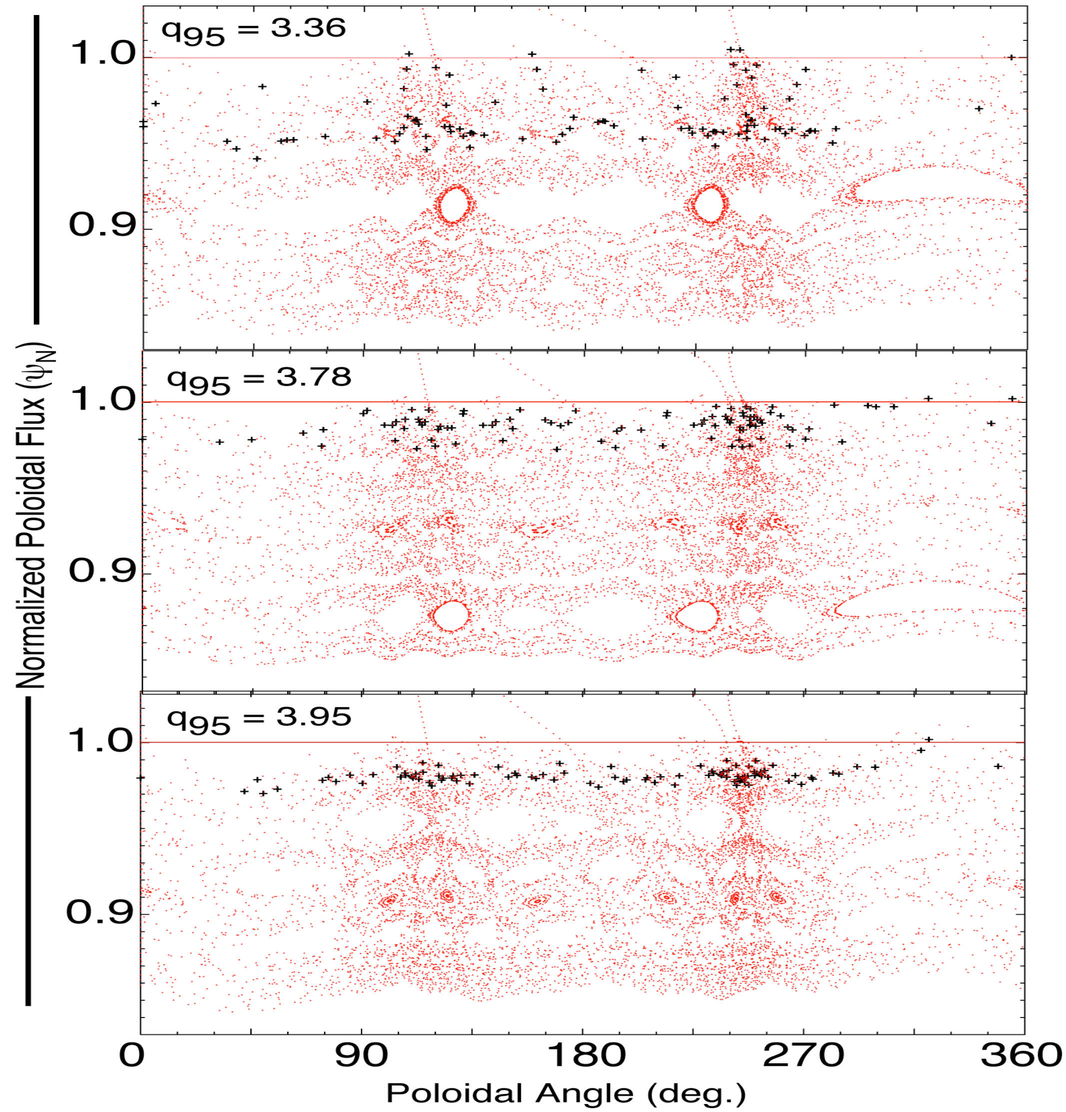


DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Islands change size and shape during q scan - local stochastic minimum at q_{95} = 3.7

Evans EX2-5Ra

- **Suppression when (9,3) island is at/near top of pedestal**
- **Density of small scale states due to I-coil and field-error mixing is a maximum at q95 = 3.7**
  - **But edge stochastic loss region is minimized**



tee-04IAEA-27/33

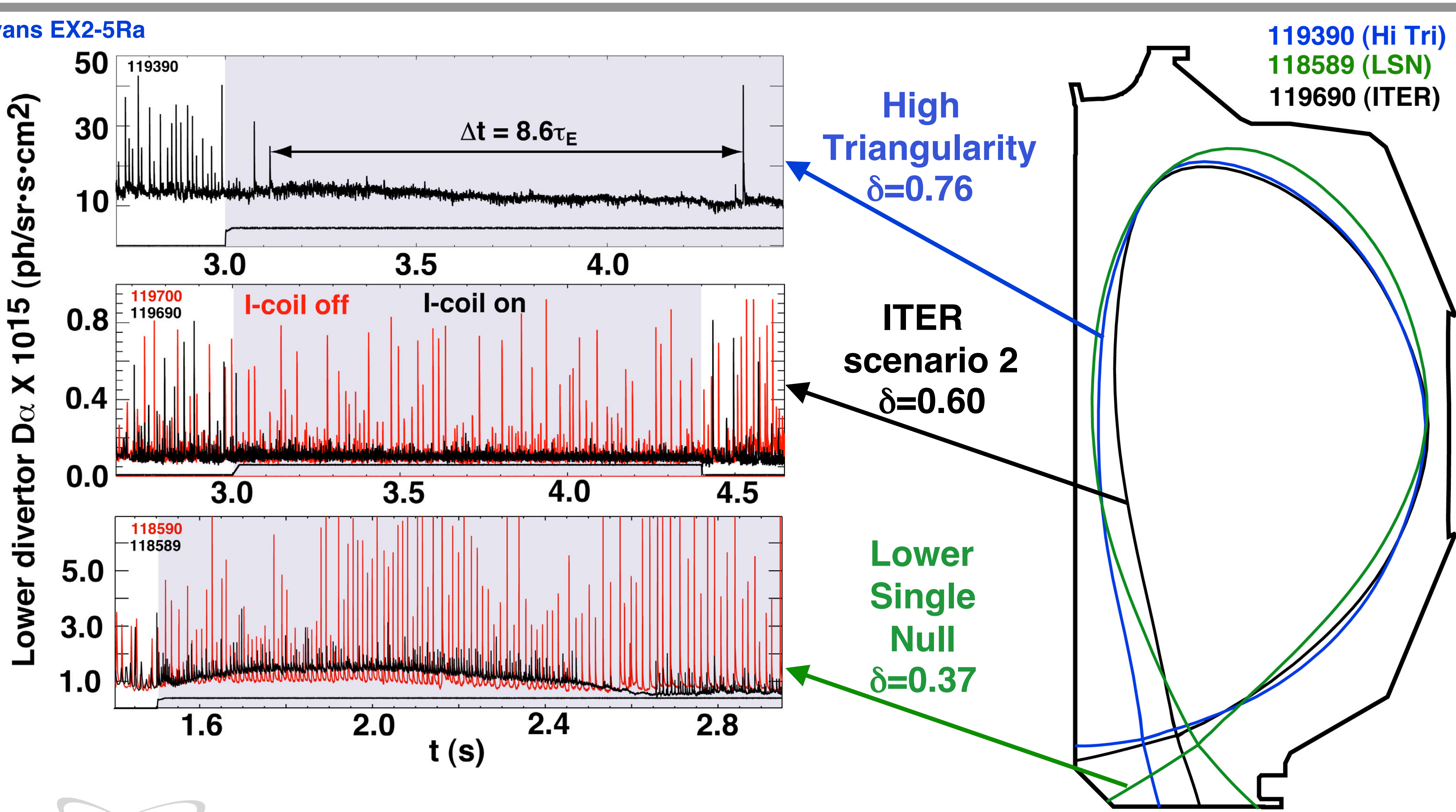
DIII-D NATIONAL FUSION FACILITY SAN DIEGO

ELM SUPPRESSION IS SEEN WITH VARIOUS SHAPES AND I-COIL CONFIGURATIONS

Evans EX2-5Ra

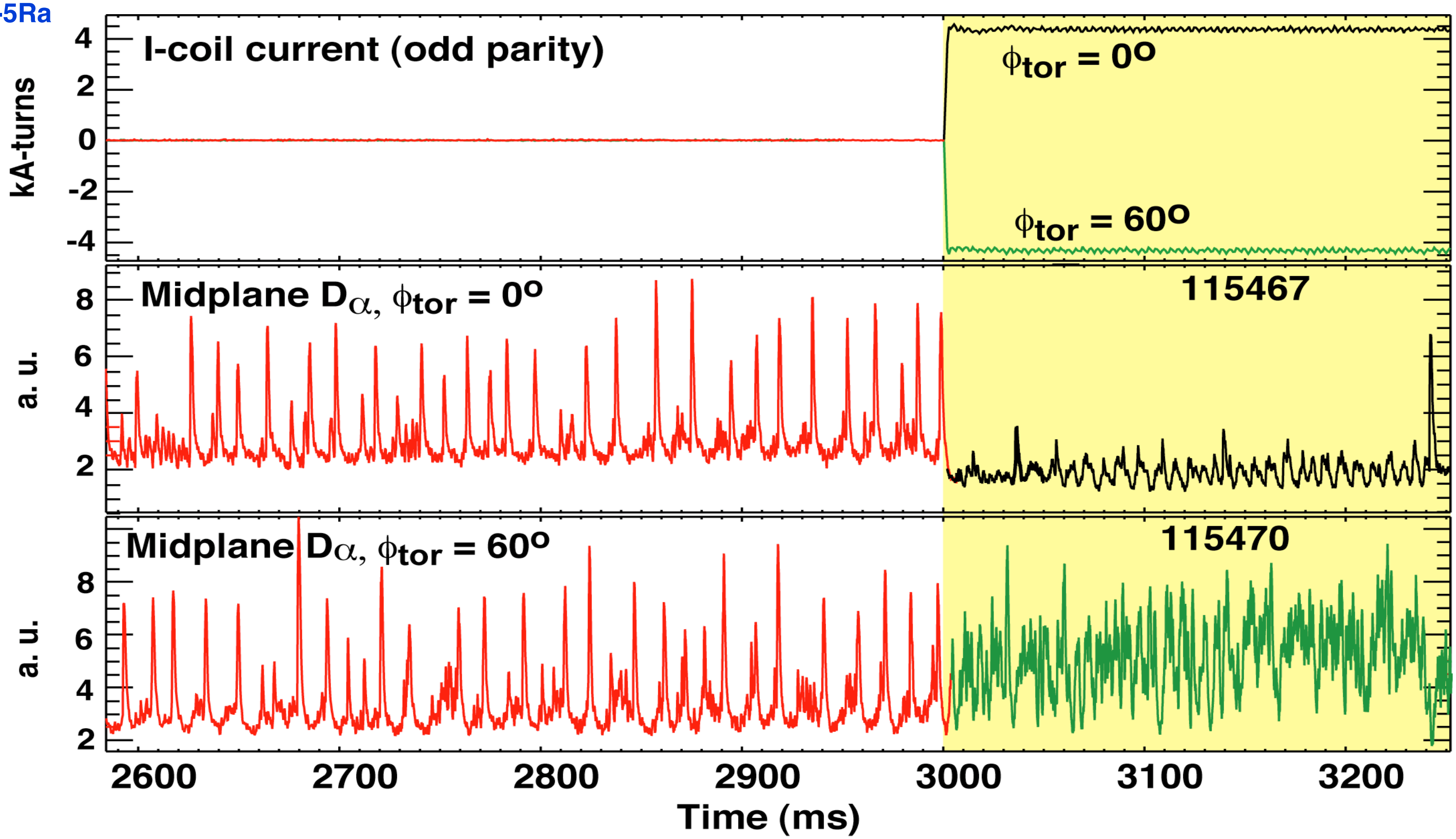
Good ELM suppression is obtained in LSN, high triangularity and ITER scenario 2 shapes

Evans EX2-5Ra



Changing the toroidal phase of the I-coil significantly increases the midplane D_α

Evans EX2-5Ra

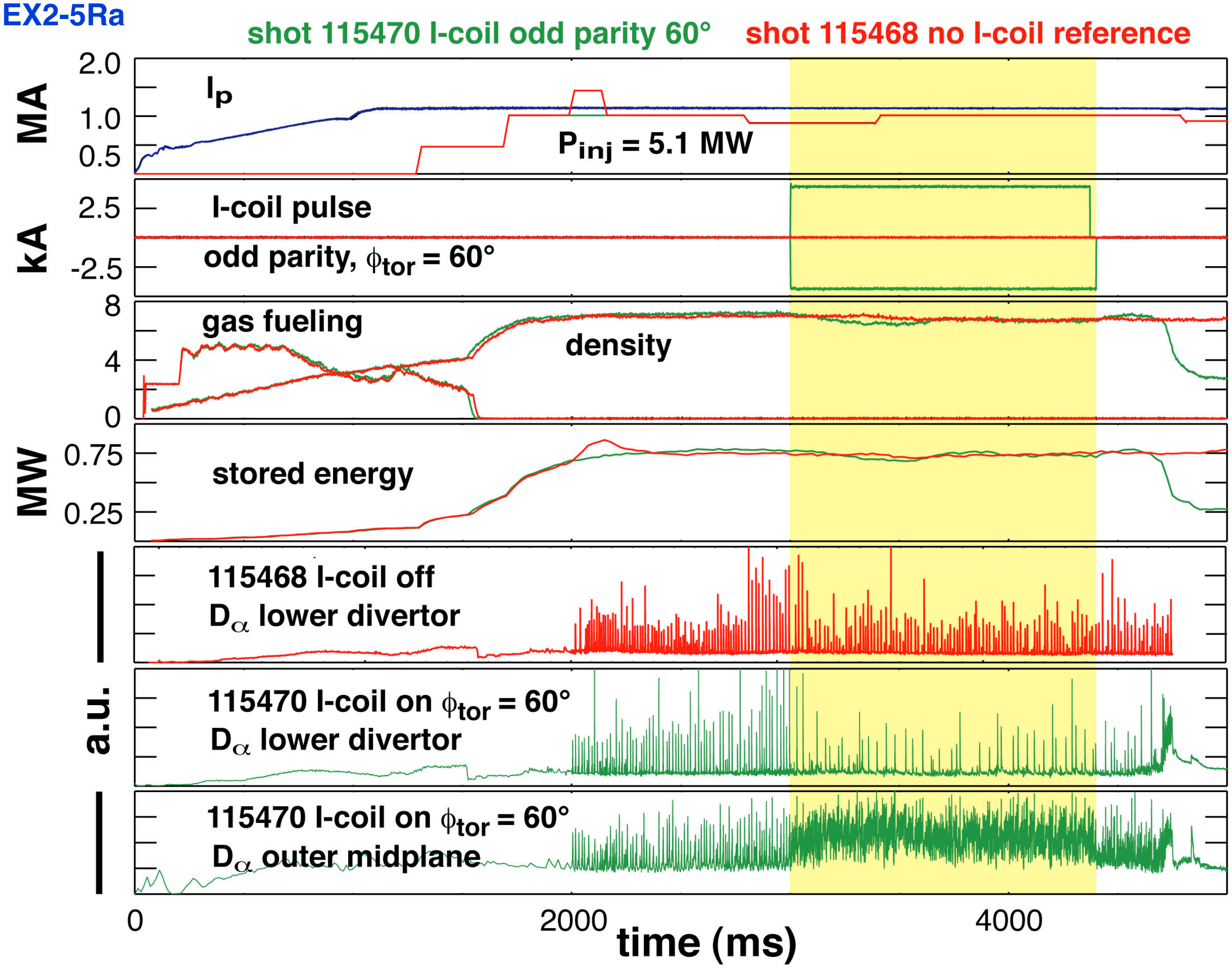


- More stochastic with ϕ_{tor} = 60° than with ϕ_{tor} = 0°

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

With ϕ_{tor} = 60° the ELM frequency and amplitude is reduced in the divertors - more I-coil current needed?

Evans EX2-5Ra

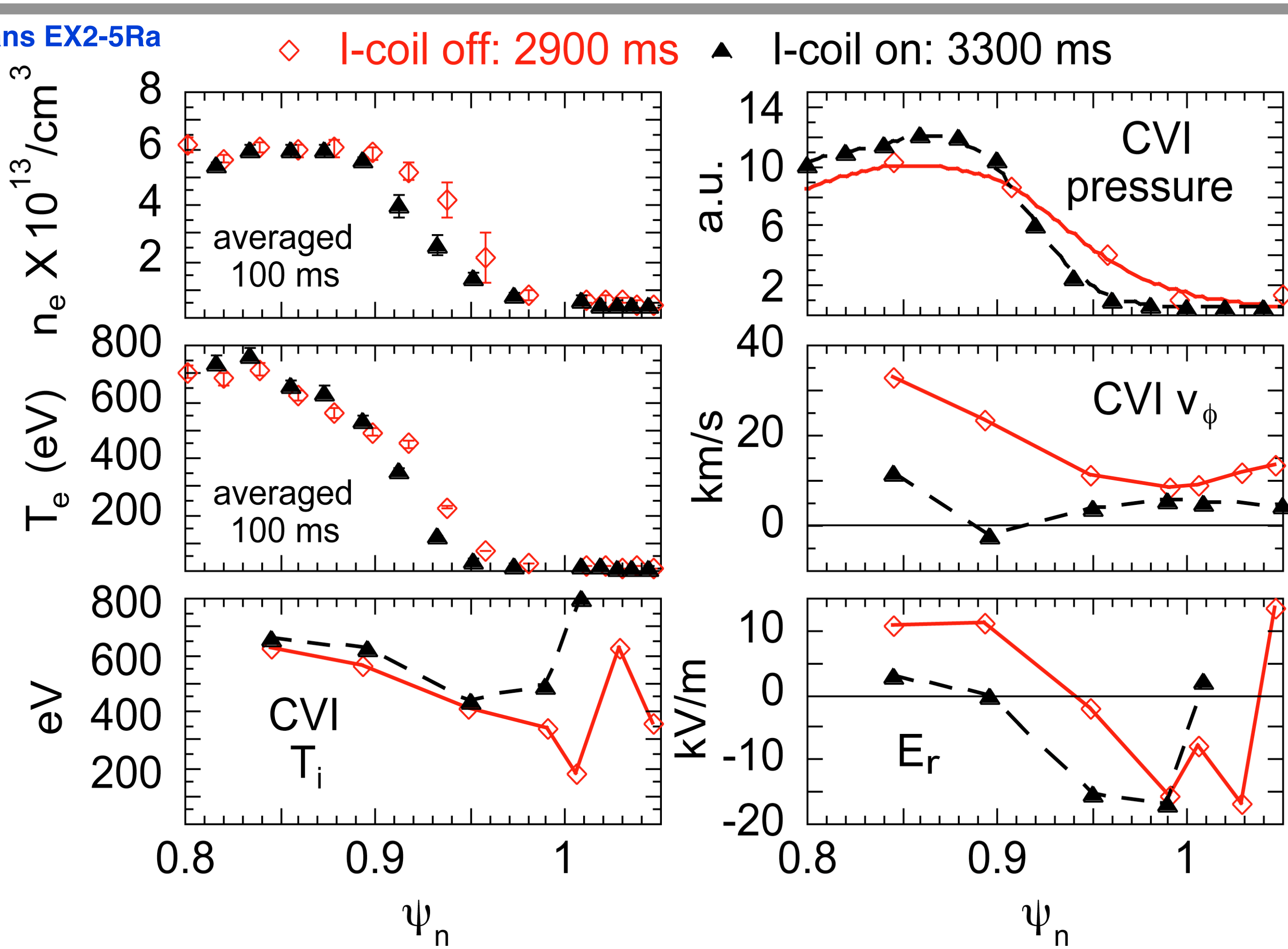


- Odd parity, ϕ_{tor} = 60° perturbations reduce ELMs in divertor
- Midplane D_α increases:
  - baseline covers remaining ELMs
  - Has classic stochastic character
  - Similar to EDA mode

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

The pedestal ion and electron channels have a more stochastic character with $\phi_{tor} = 60°$

Evans EX2-5Ra



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

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Summary and Conclusions

- Type-I ELMs are suppressed with resonant magnetic perturbations
  - no confinement degradation
  - good suppression for $\Delta t \sim 9\tau_E$ (some isolated ELMs remain)
- A new type of dynamical state replaces Type-I ELMs
  - transport dominated by small, high frequency fluctuations
    - Magnetic fluctuations increase at higher frequencies and shift to higher toroidal mode numbers (n = 1– 3 core modes shift to n = -2 to -5 edge modes)
  - divertor surface temperature spikes reduced by at least a factor of 5
  - divertor particle flux impulses reduced by at least a factor of 8
  - stored energy impulses from the pedestal reduced by a factor of 3
- Suppression is resonant in: q95, shape, I-coil configuration, etc.
  - field errors have a significant impact on ELM character
- Good suppression is obtained in high triangularity (δ=0.76), ITER scenario 2 (δ=0.60) and lower single null (δ=0.37) shapes
- Looks promising for ITER ELM control