Edge Localized Mode Control in DIII-D using Magnetic Perturbation-Induced Pedestal Transport Changes

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for

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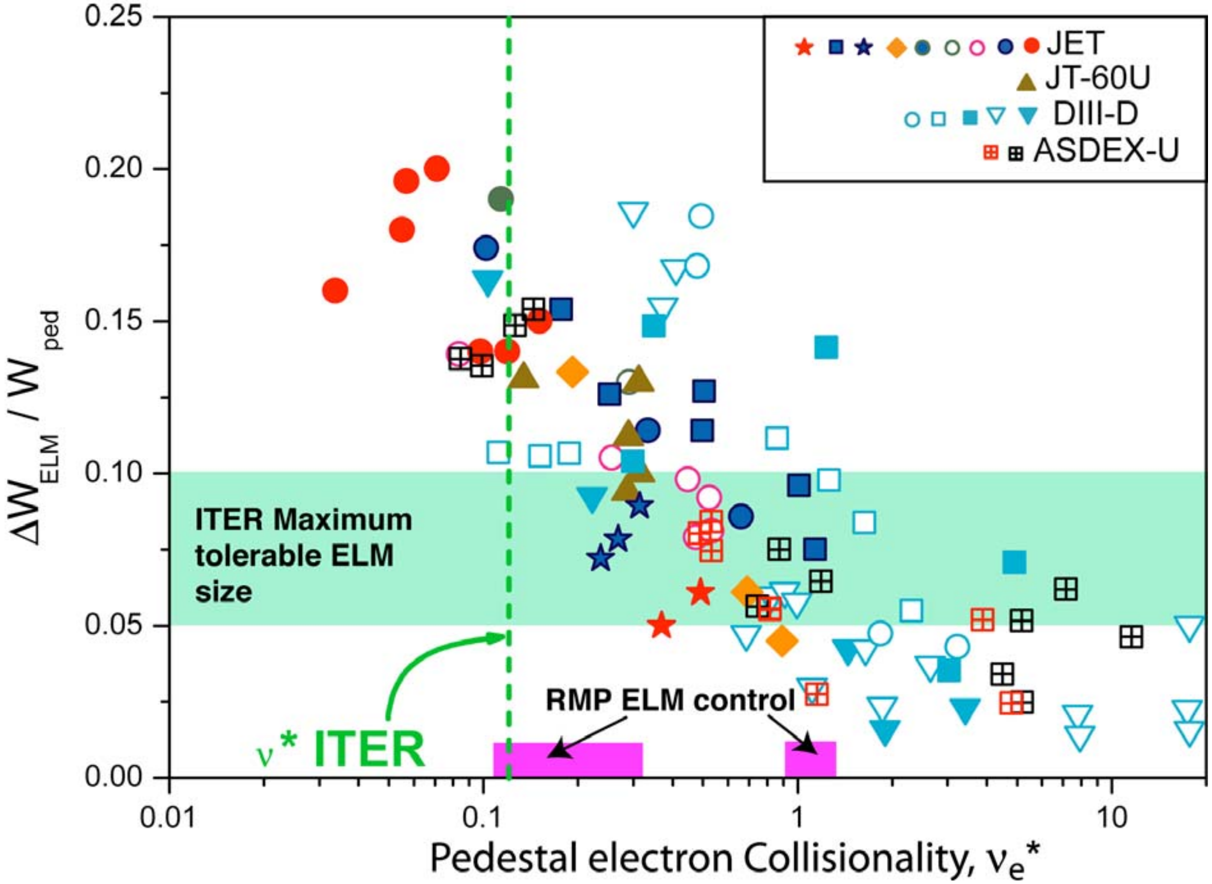
UCSD

ELM control is a critical issue for burning plasmas.

- $\Delta W_{ELM}/W_{PED}$ increases as pedestal collisionality ν_e^* drops



Loarte PPCF 45 1549

- Pedestal collisionality also affects RMP ELM control
  - RMP penetration decreases at lower ν_e^*
  - Parallel transport increases at lower ν_e^*

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Summary and Results

- ELMs have been completely suppressed using an edge-resonant magnetic perturbation (RMP) in ELMy H-modes with ITER-relevant pedestal electron collisionality ν_e^* and ITER-similar shape (ISS).
- ELMs are suppressed by lowering the pedestal pressure gradient below the Peeling-Ballooning stability limit for Type I ELMs.
- Pedestal pressure gradient reduction is controlled with RMP strength $\delta b_r^{m,n}/B_T$.
- Pedestal pressure gradient is reduced primarily by increased particle transport
- Density fluctuations increase 1.5-2x during RMP, consistent with increased convective particle transport.

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Edge Resonant Magnetic Perturbations (RMPs) suppress ELMs at ITER-relevant collisionalities in DIII-D

- Minimum perturbation $\delta b_r^{m,n}/B_T$ for ELM suppression varies with shape:

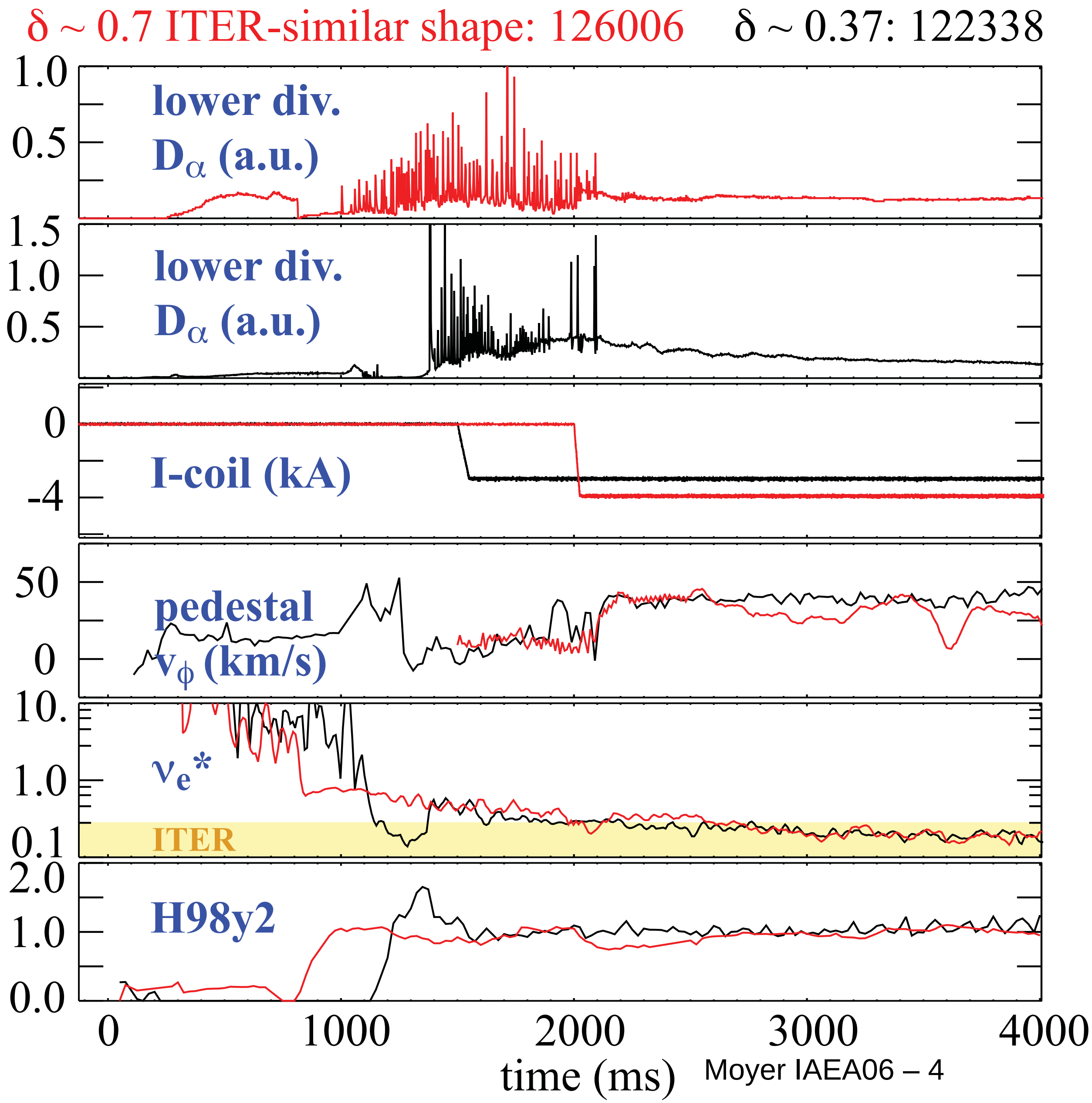
$\delta b_r^{m,n}/B_T \sim 3.2\times10^{-4}$

at $\delta \sim 0.7$

$\delta b_r^{m,n}/B_T \sim 2.8\times10^{-4}$

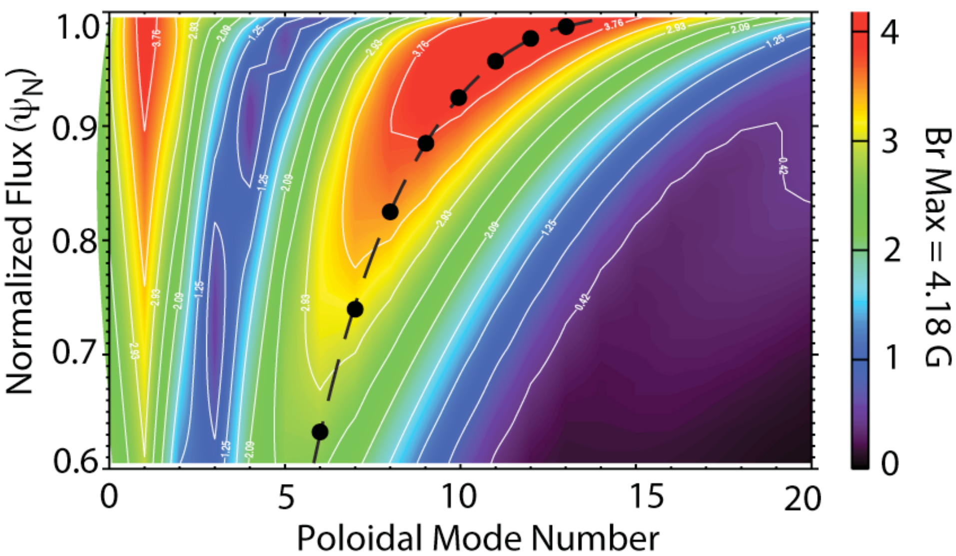
at $\delta \sim 0.37$

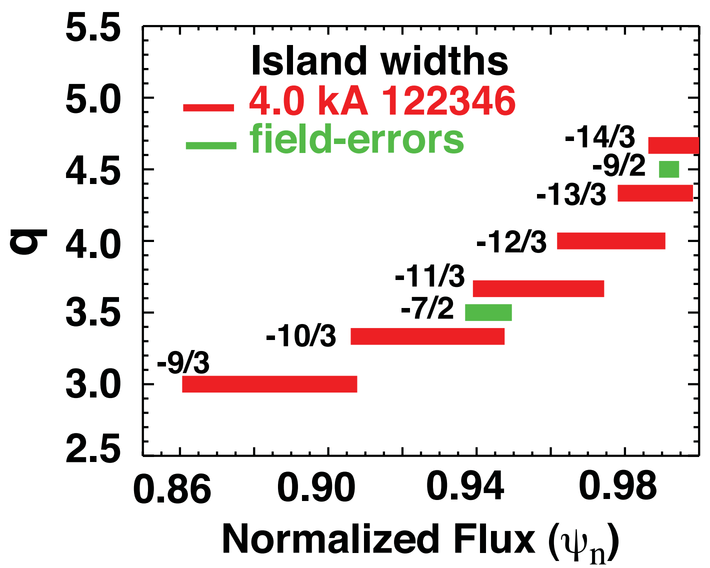
Burrell PPCF 47 B37 (05)
Evans Phys. Plasmas 13 (06)
Evans Nature Physics 2 419 (06)



Need to localize perturbation to pedestal to avoid degrading performance or triggering NTMs

- Elongation → slow pitch angle change with radius on LFS → low m's not well localized by magnetic shear
- Magnetic shear → rational surfaces close together near separatrix → small RMP gives island overlap





- Magnetic field penetration model - see V. Parail; M. Becoulet, this mtg.
  - penetration high where collisionality is high and toroidal rotation is low → edge localized

$$B^{r,pl}_{m,n} = \frac{B^{r,vac}_{m,n}}{\sqrt{1+(\Omega\tau_L/2m)^2}} \quad \text{where} \quad \begin{aligned}\Omega &= 2\pi nf \\ \tau_L &= 2\left(\sqrt{1+2q^2}\tau_A\right)^{2/3}\tau_\eta^{2/3}\tau_\nu^{-1/3}\end{aligned}$$

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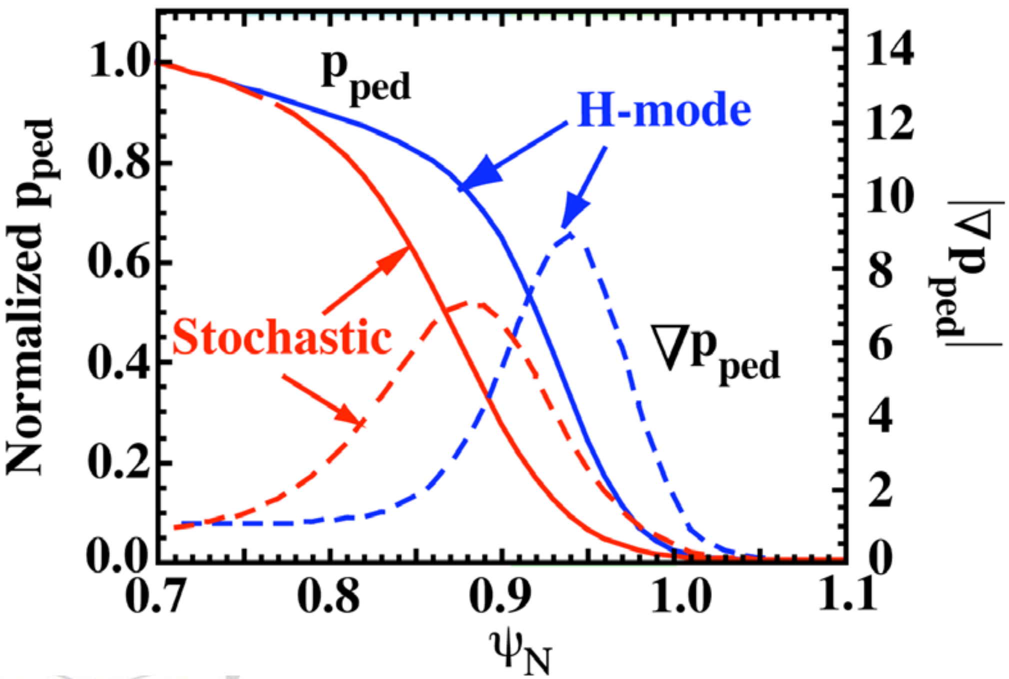
Use RMP to increase steady-state transport through pedestal to lower ∇p below ELM stability limit.

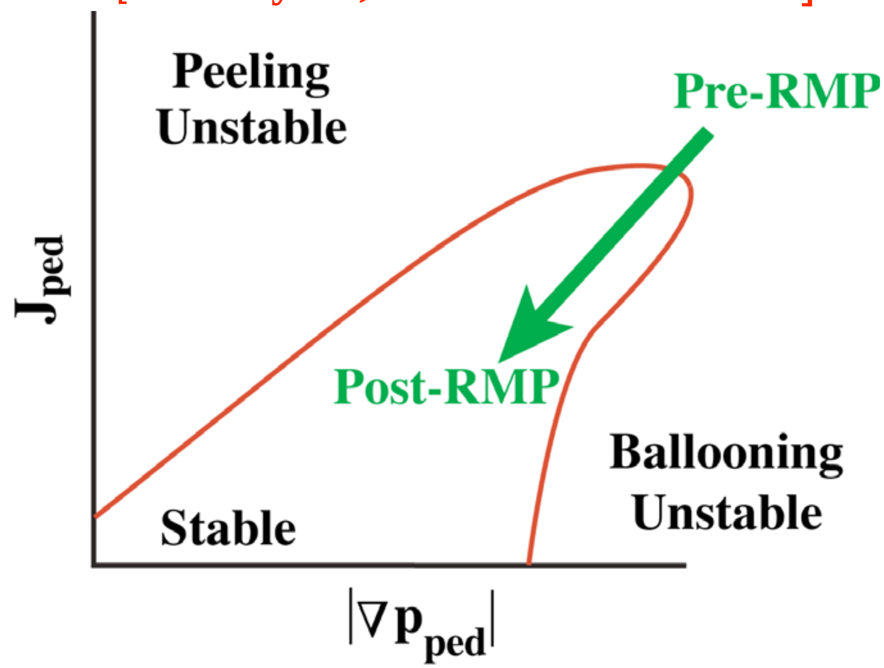
- Edge RMP → stochastic field in pedestal → increased steady-state transport
- Reduced ∇p_{ped} → stable P-B operating point controlled by RMP amplitude
- Must maintain pedestal height (stiff core transport coupled to pedestal height.

Schematic Pedestal Profiles



Schematic P-B Stability Diagram

[P.B. Snyder, H.R. Wilson PoP2002]



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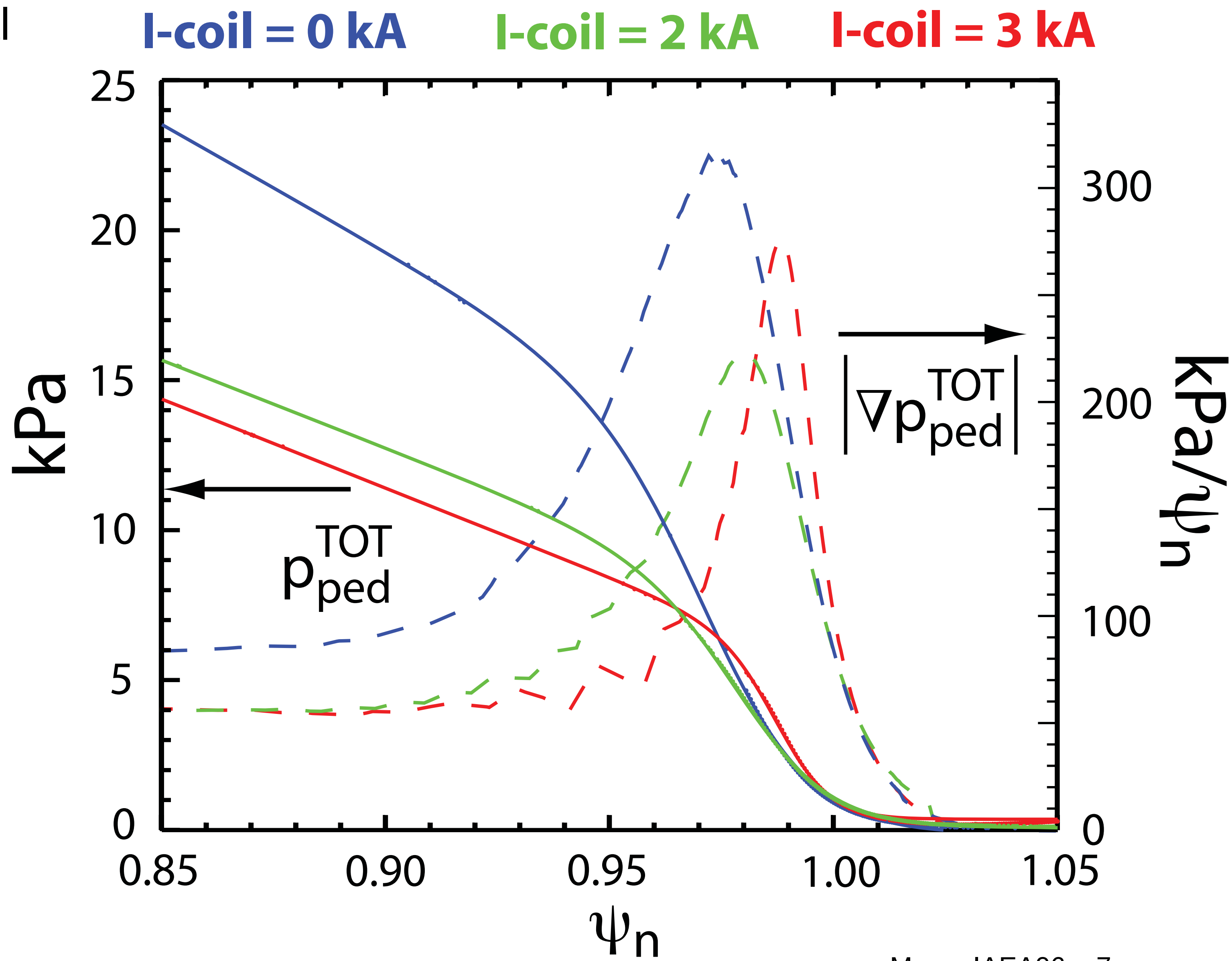
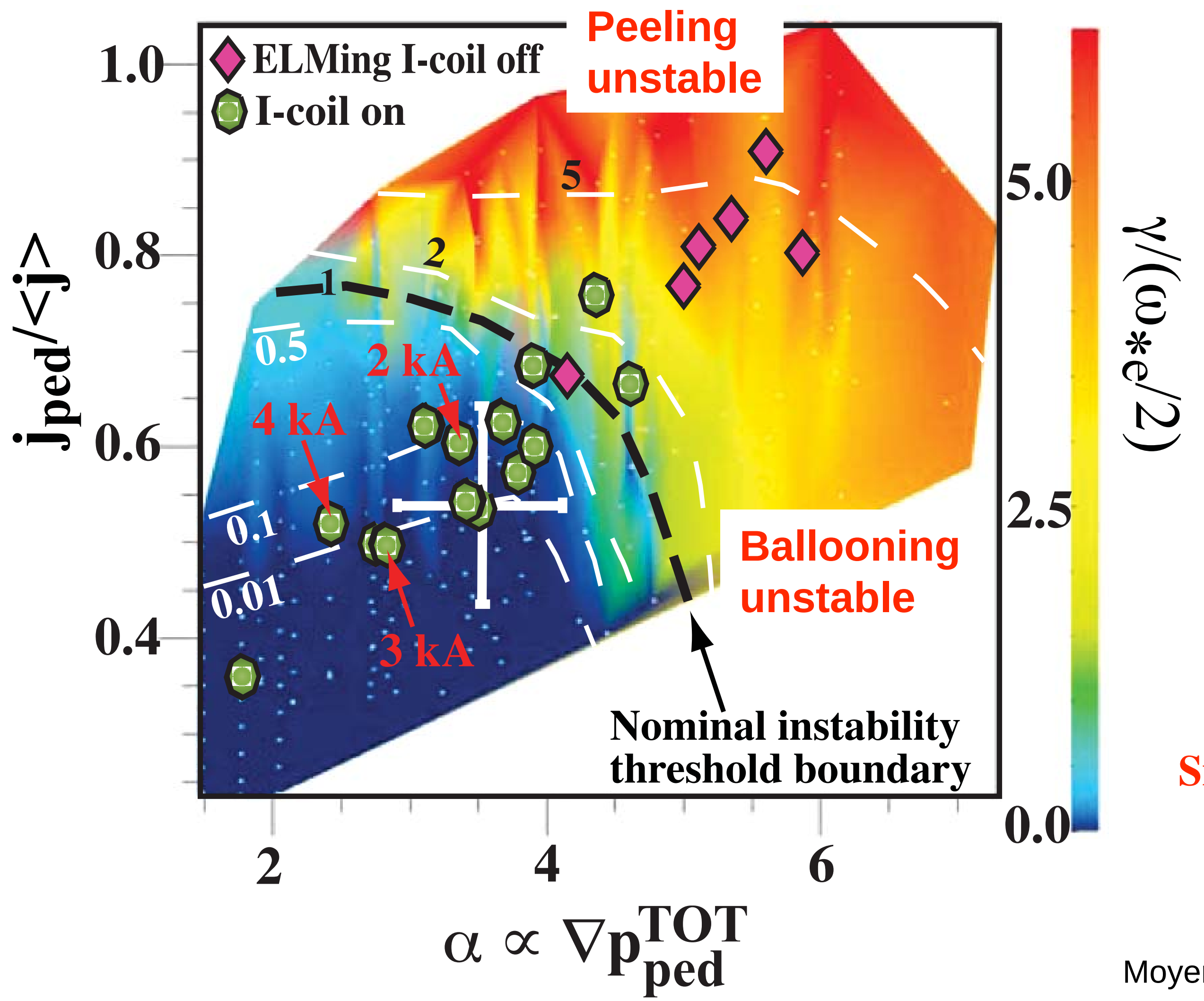
Edge RMP suppresses large ELMs by significantly lowering the pedestal pressure gradient.

- Total pedestal pressure is reduced during RMP pulse below P-B stability boundary
- I-coil current controls ∇p_{ped}
- ∇p_{ped} is reduced, narrowed, and shifted out in radius



RMP-assisted ELM-free H-modes are linearly stable to Peeling-Ballooning modes.

- Increasing RMP can push pedestal deep into linearly stable regime; see P.B. Snyder, this meeting



Snyder, Osborne

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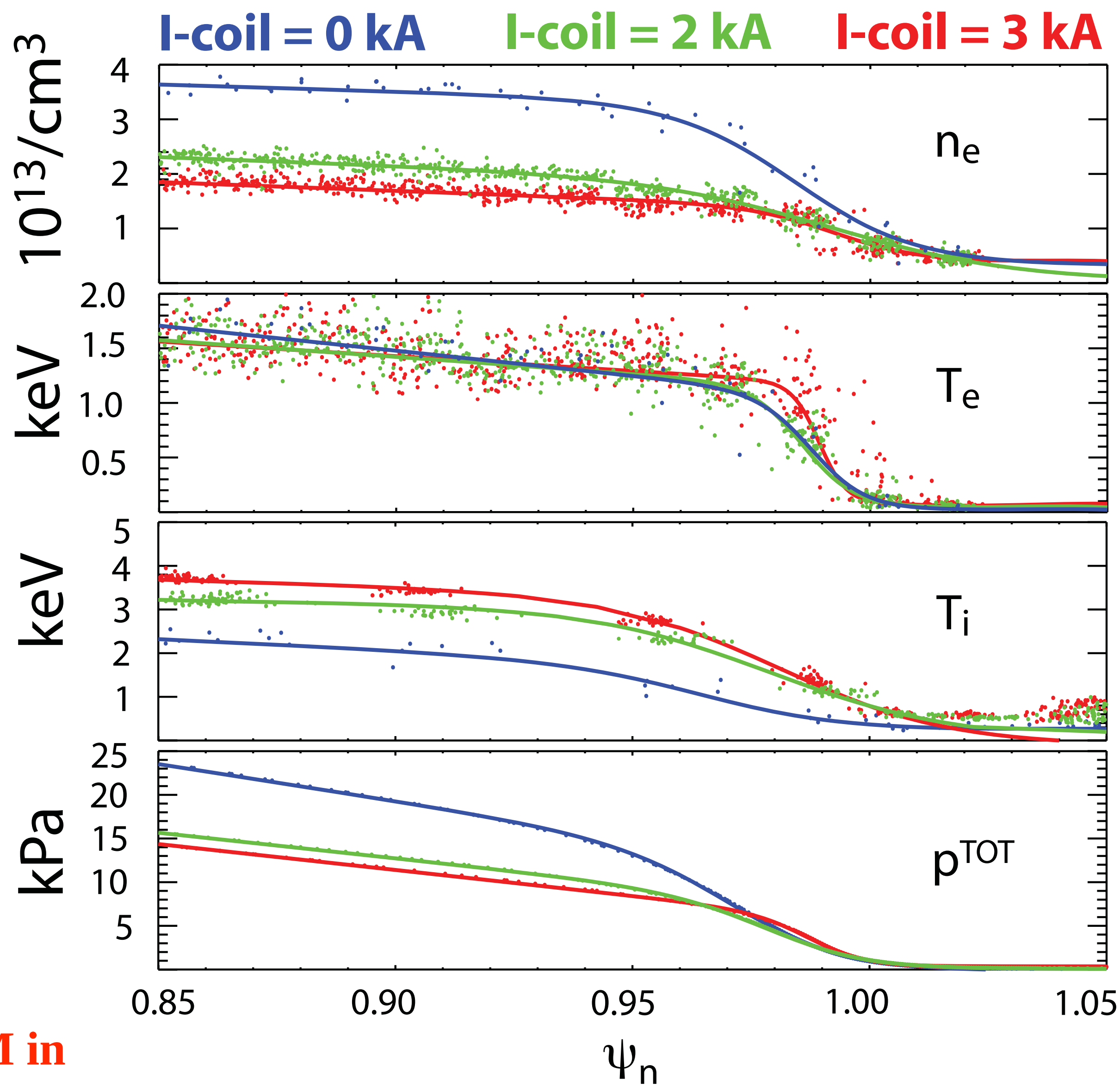
I-coil RMP has largest effect on density profile, not T_e profile at low collisionalty.

- global particle balance change
  - P-B modes stabilized by density pumpout similar to QH mode [see P.B. Snyder this meeting]
  - QL estimate →3-4x increase in D_{eff}
- T_e profile flattens at top of pedestal
  - qualitatively consistent with quasi-linear estimate
  - quantitatively consistent for $0.85 < \psi_n < 0.94$ with transport analysis by Stacey and Evans
- T_e steepens for $0.98 < \psi_n < 1$
- Heat transport modeling with 3D fluid code E3D→vac. field destroys H-mode pedestal



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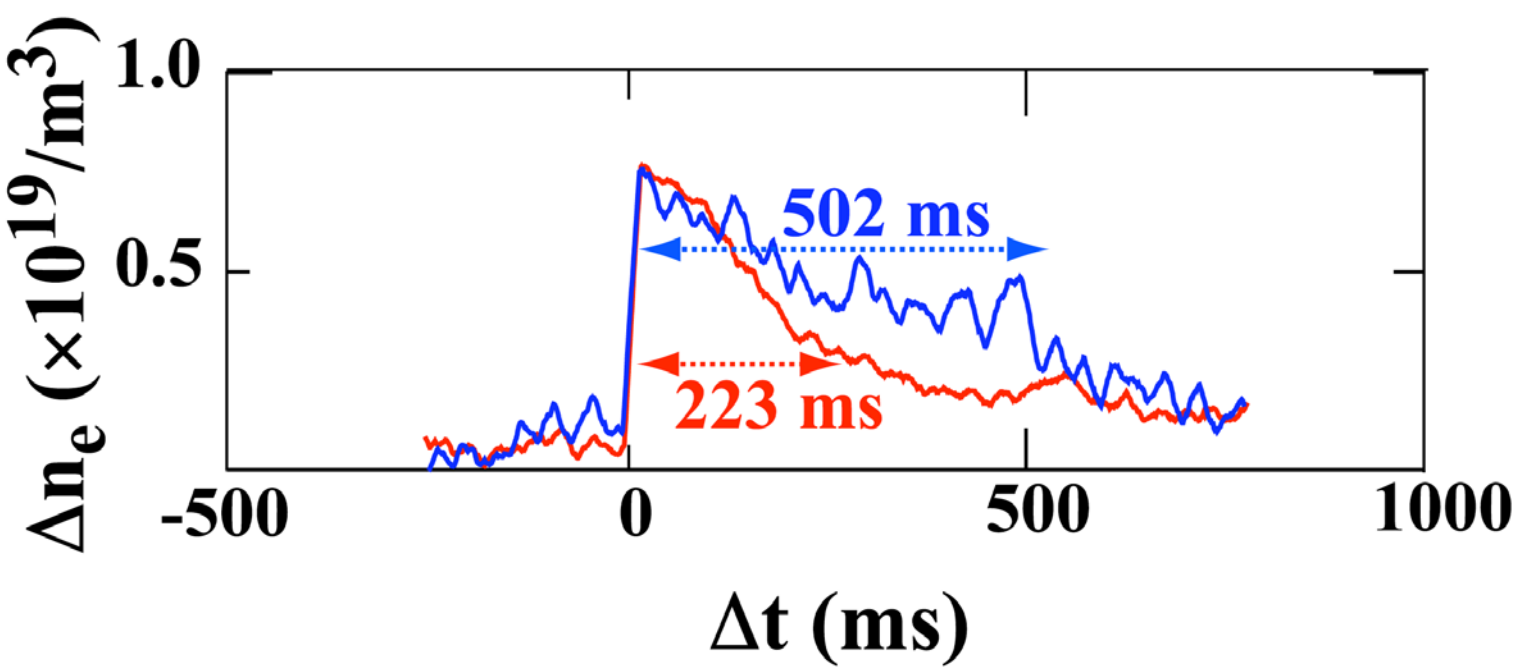
Joseph JNM in press (2007)

τ_p^* reduced a factor of 2 in pellet perturbation experiments with similar recycling ($\rightarrow \tau_p$ change)

- Identical pellets injected into discharges with $\nu_e^* \sim 0.2$, $\delta \sim 0.7$, and similar recycling conditions:
  - I-coil = 0 kA, ELMing H-mode
  - I-coil = 4 kA, RMP-assisted ELM-free H-mode



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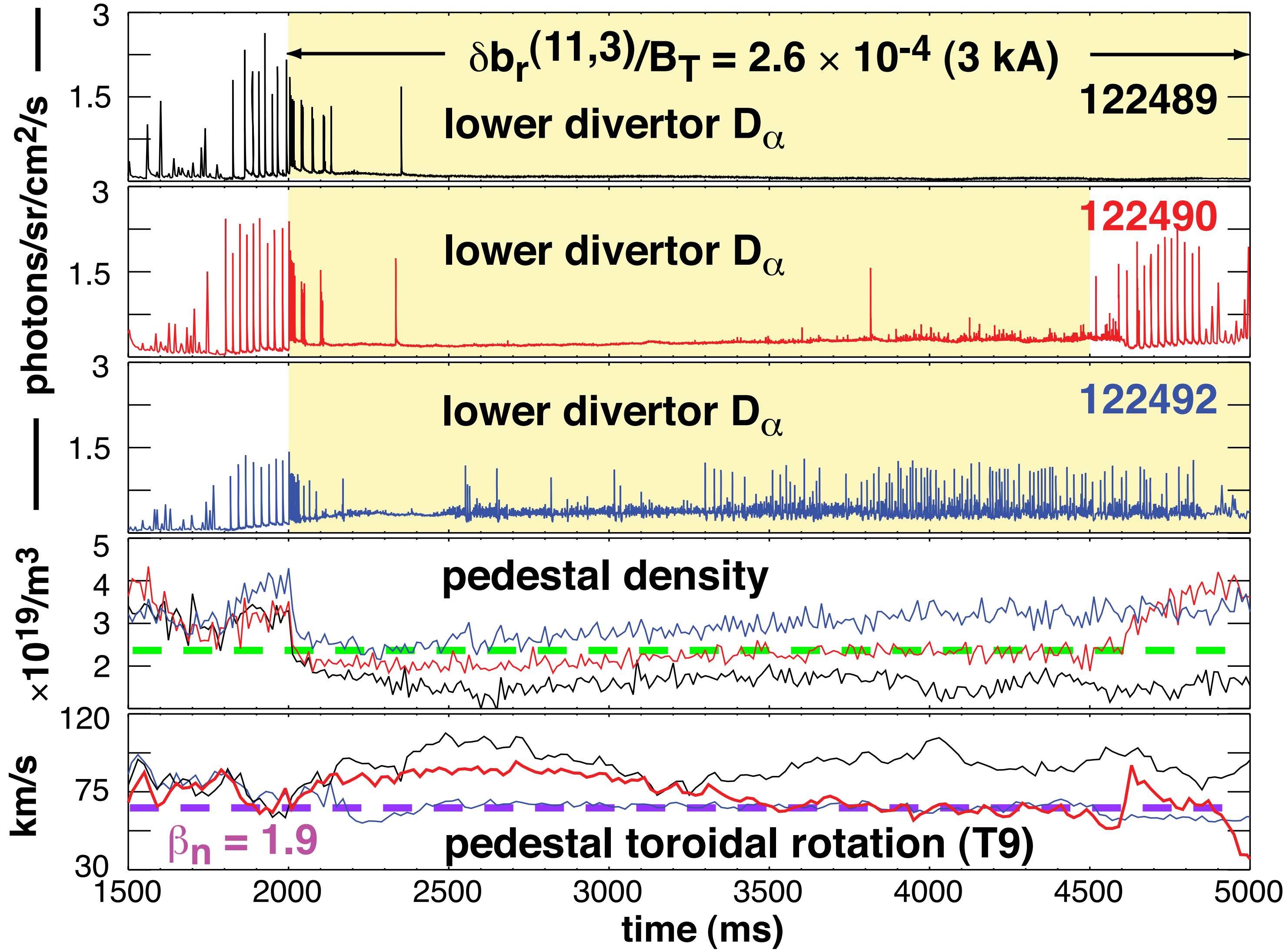
D2 puffing raises pedestal density in ELM-suppressed phase until a limit where small ELMs onset.

- Onset of small ELMs is correlated with density upper limit and pedestal v_ϕ lower llimit.
- Density limit increases with RMP strength and neutral beam power
- Similar to weak RMP results at $\nu_e^* \sim 1$ but at $\nu_e^* \sim 0.15$



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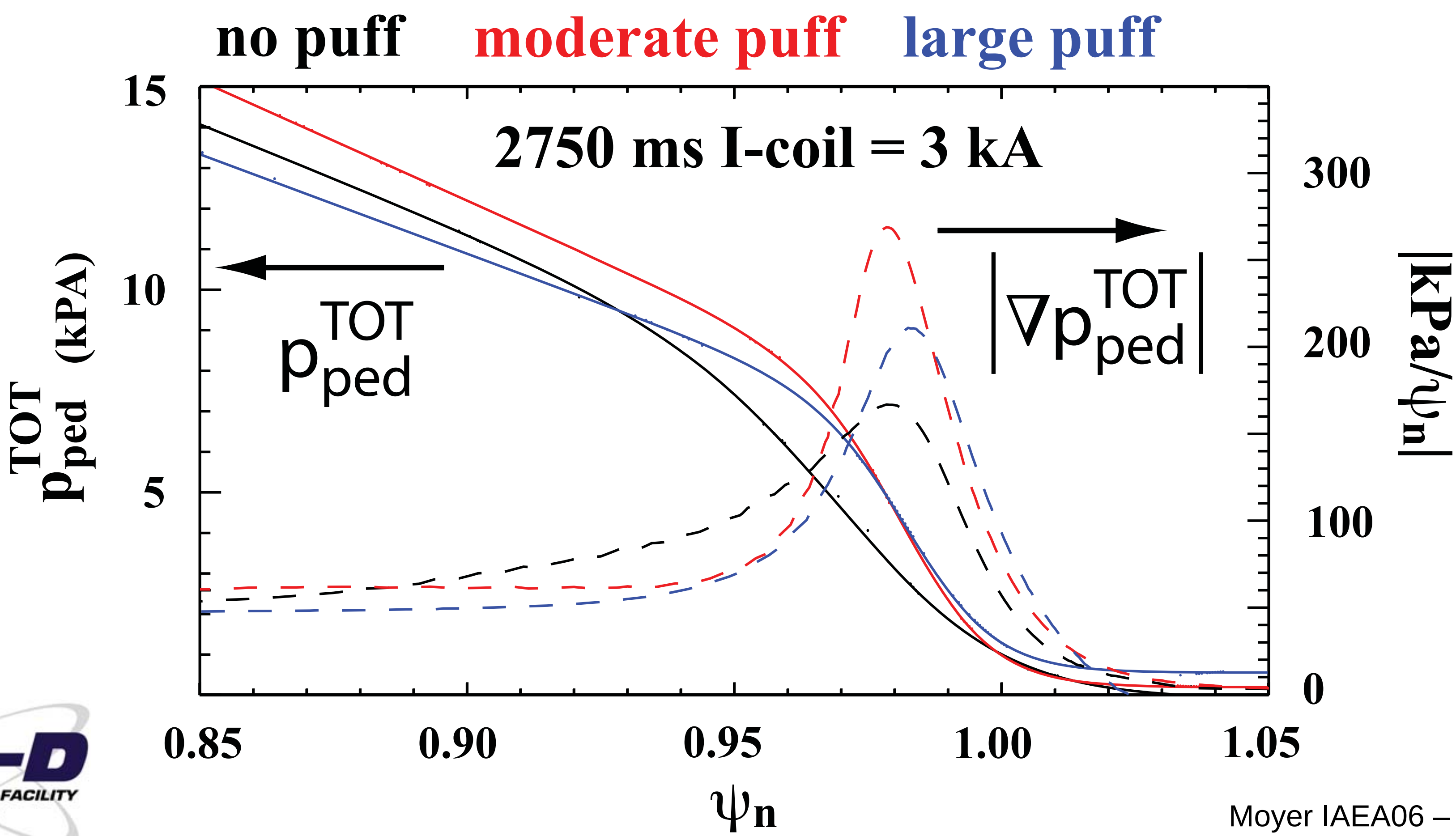
D2 puffing into RMP-assisted ELM-free H-mode raises ∇p_{ped}^{TOT} until n=30 P-B modes are destabilized.

- D2 puffing into RMP-assisted ELM-free H-mode gradually raises pedestal pressure and pressure gradient.
- Discharge becomes unstable to high n =30 P-B modes about the time that small ELMs/events onset during I-coil phase
- Small ELMs/events may be acceptable ITER operating regime.



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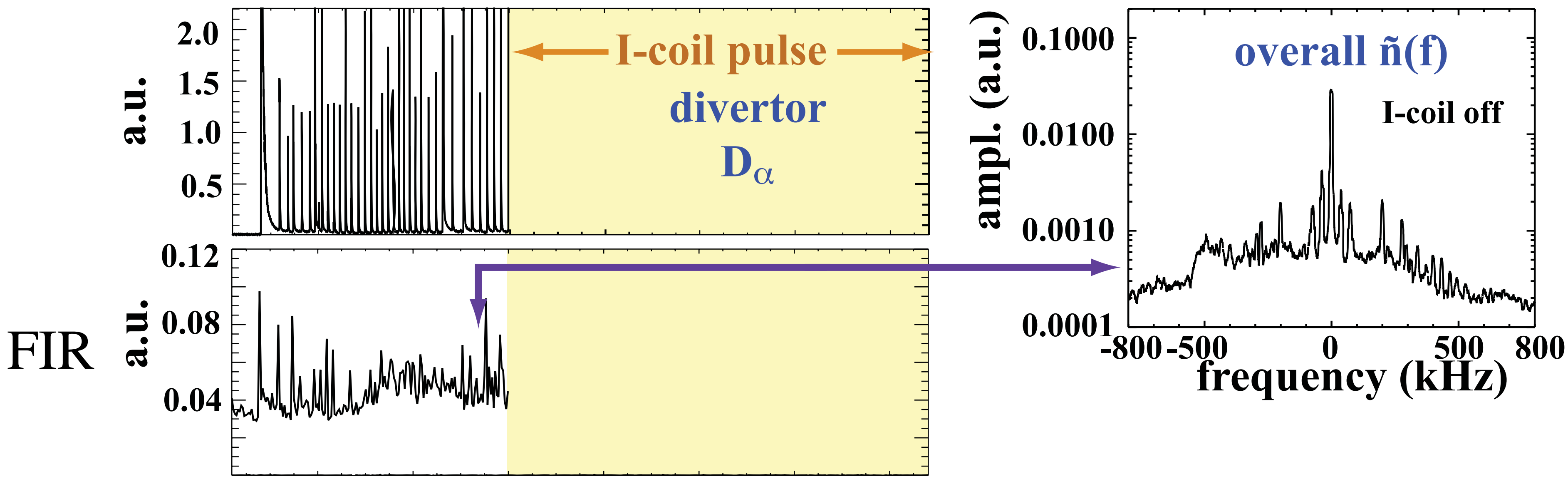
Increased particle transport during RMP may be due to increased fluctuation-driven transport.

- FIR scattering: k_θ = 1 cm^{-1} not spatially localized



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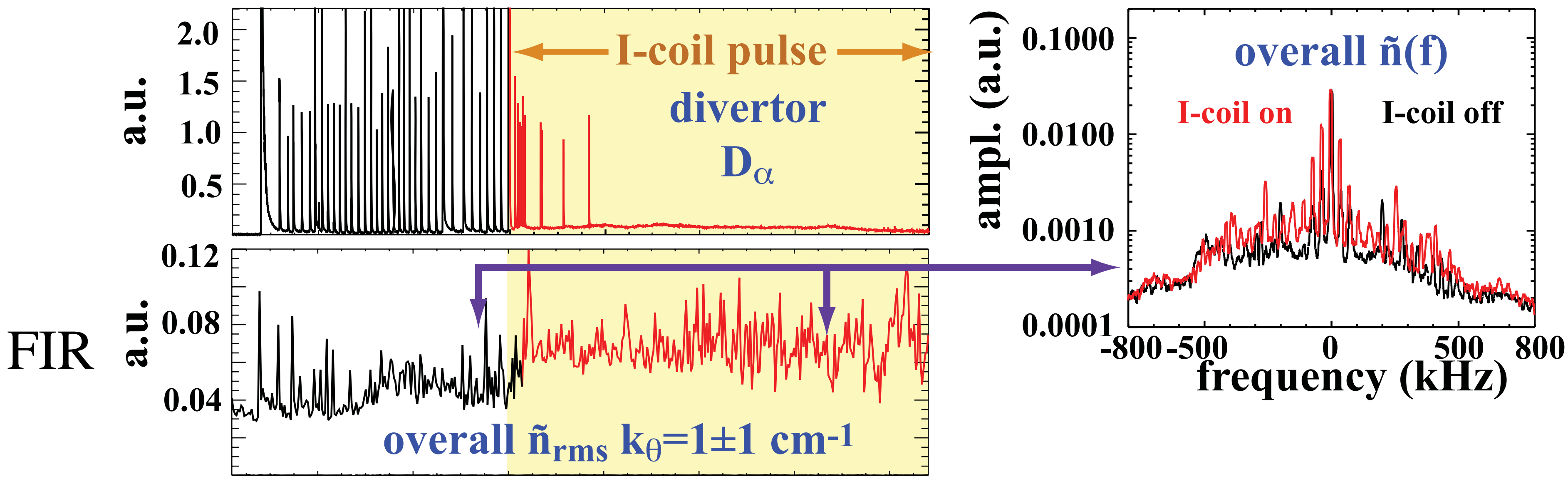
- FIR scattering: k_θ = 1 cm^{-1} not spatially localized → increased coherent modes and broadband turbulence → 1.5x increase in $\tilde{n}_{rms}$



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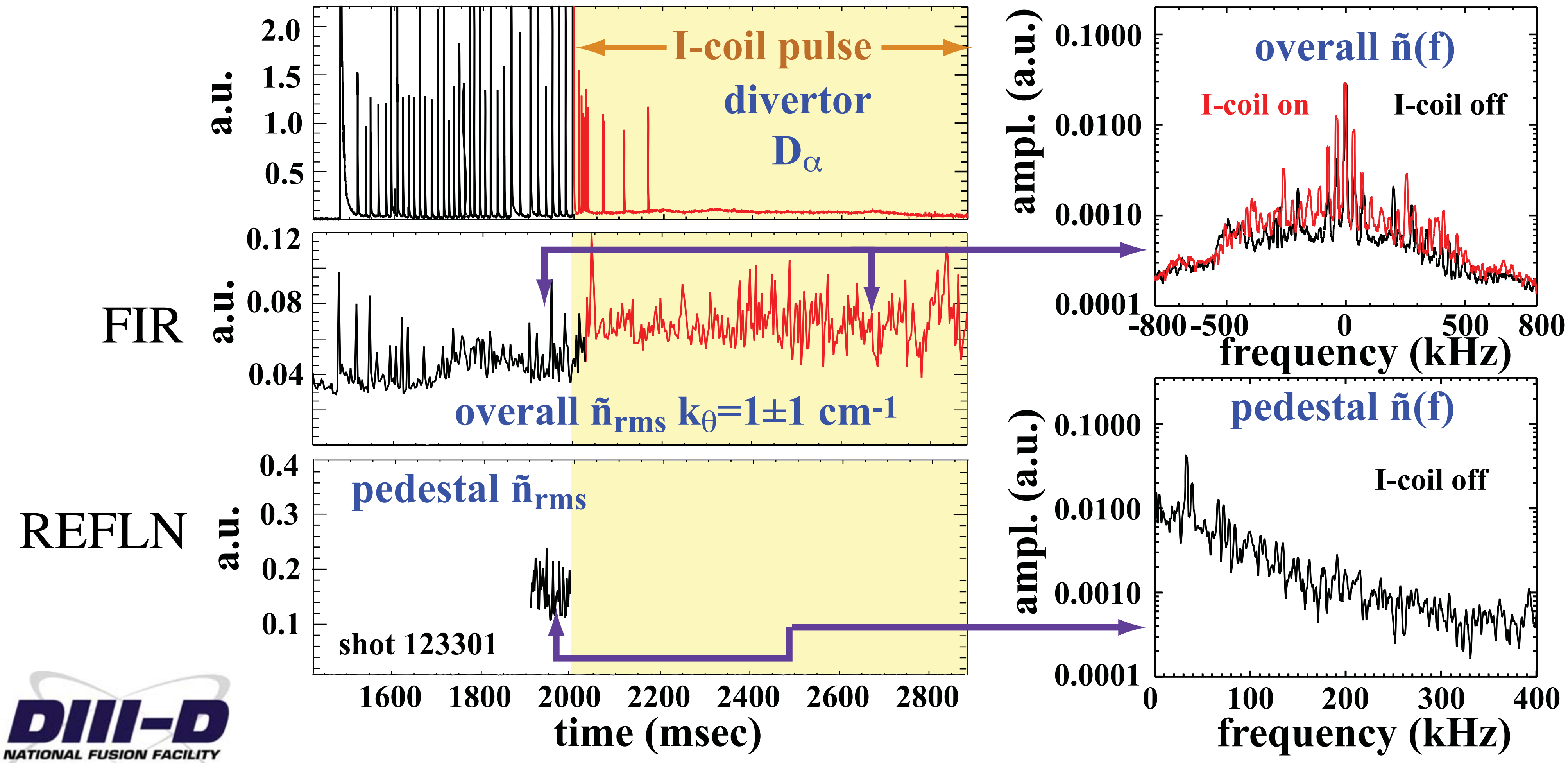
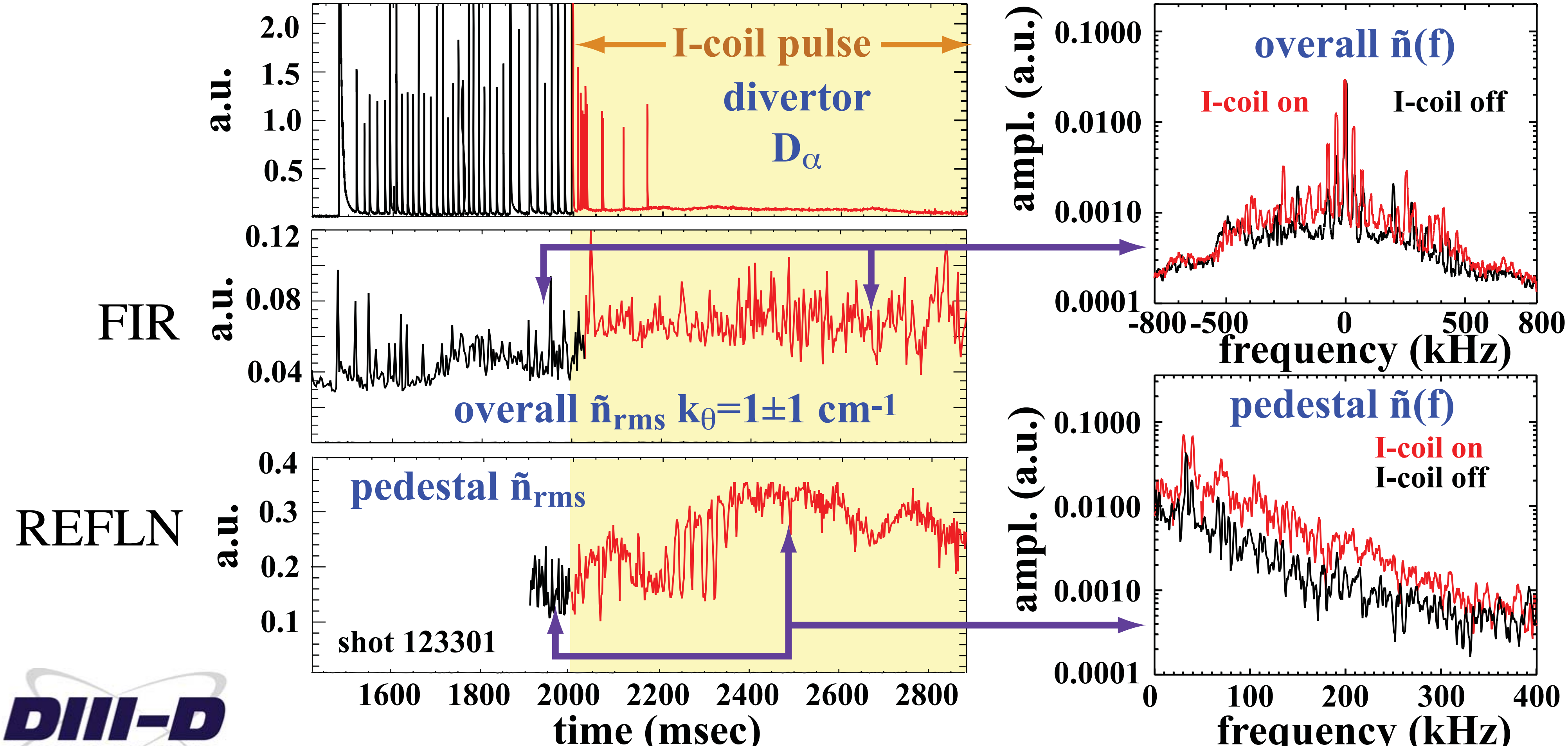


Increased particle transport during RMP may be due to increased fluctuation-driven transport.

- FIR scattering: k_θ = 1 cm^{-1} not spatially localized → increased coherent modes and broadband turbulence → 1.5x increase in $\tilde{n}_{rms}$
- reflectometry: localized to pedestal → increased turbulence → 2x increase in $\tilde{n}_{rms}$
- $D_{eff} \sim \tilde{n}_{rms}^2 \rightarrow D_{eff}$ increases 3-4x, consistent with change inferred from profiles.



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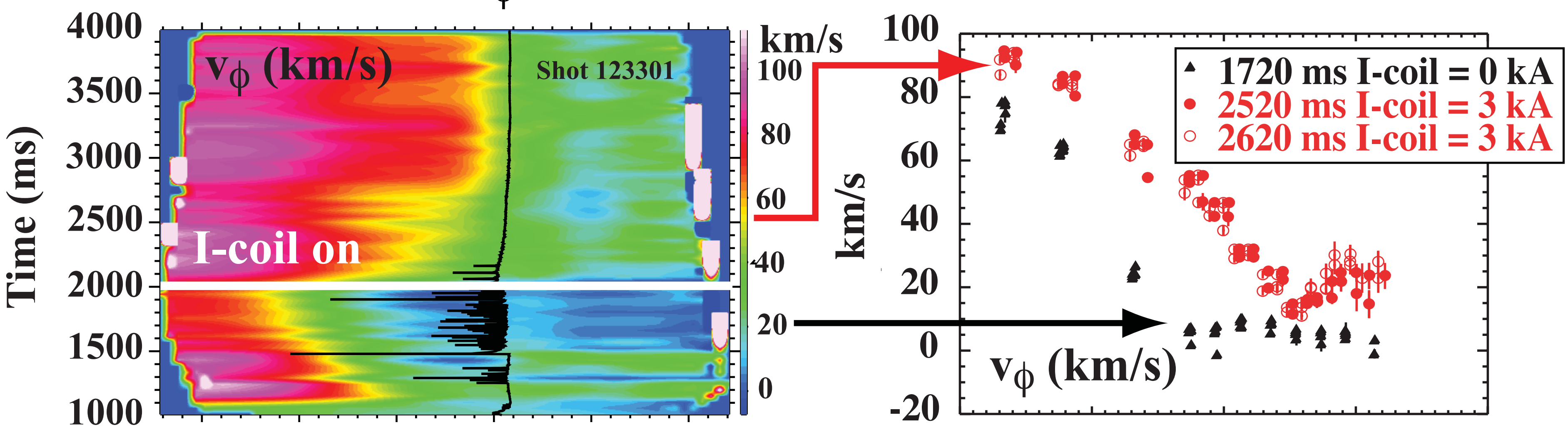
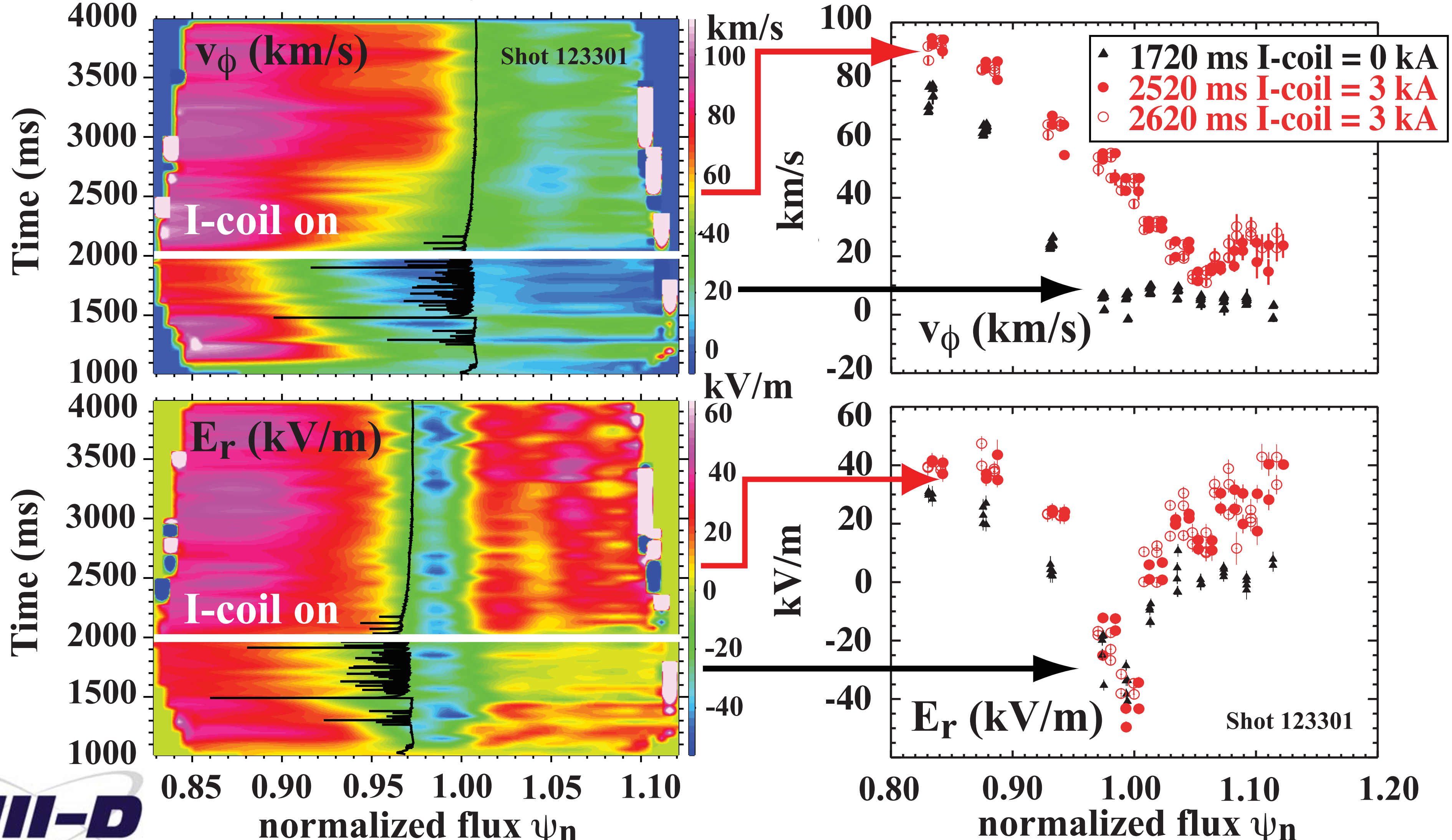
Pedestal toroidal rotation and E_r change promptly when RMP is applied and edge q resonant (3.4 < q95 < 3.7).

- H-mode pedestal v_ϕ spins up



Pedestal toroidal rotation and E_r change promptly when RMP is applied and edge q resonant (3.4 < q95 < 3.7).

- H-mode pedestal v_ϕ spins up and E_r well narrows.



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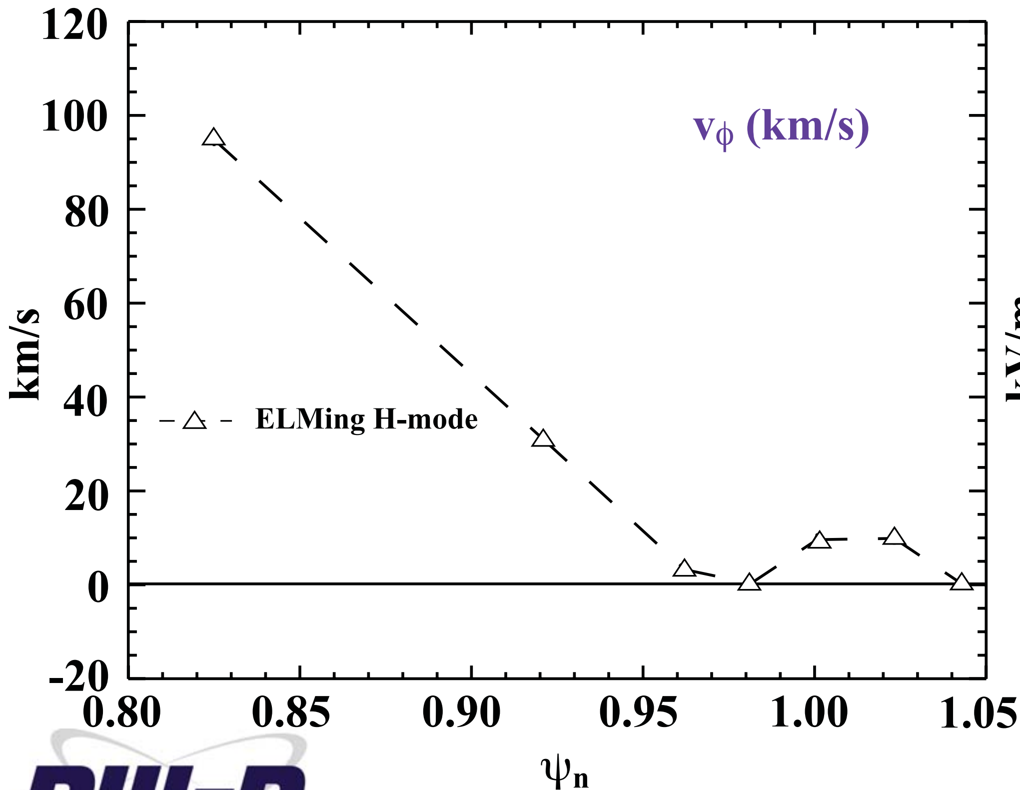
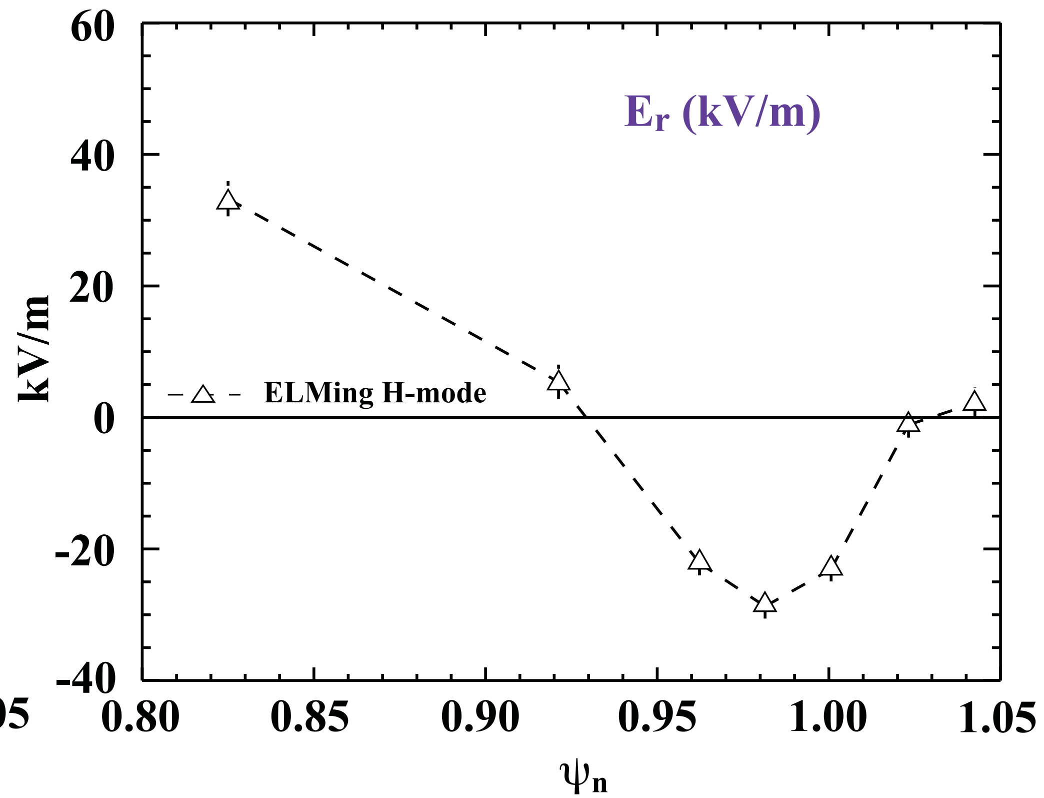
Onset of small ELMs as n_e^{ped} rises is correlated with decay of pedestal v_ϕ and degradation of E_r well.

- As n_e^{ped} rises, v_ϕ and E_r profiles become more like ELMing H-mode





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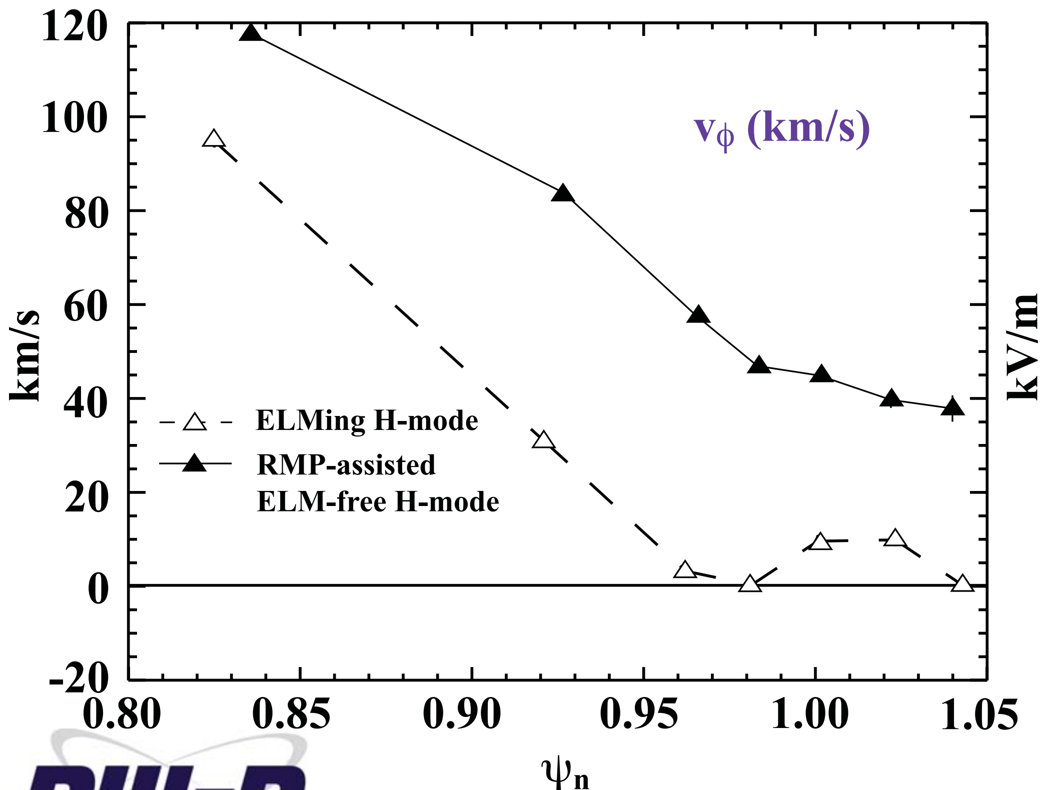

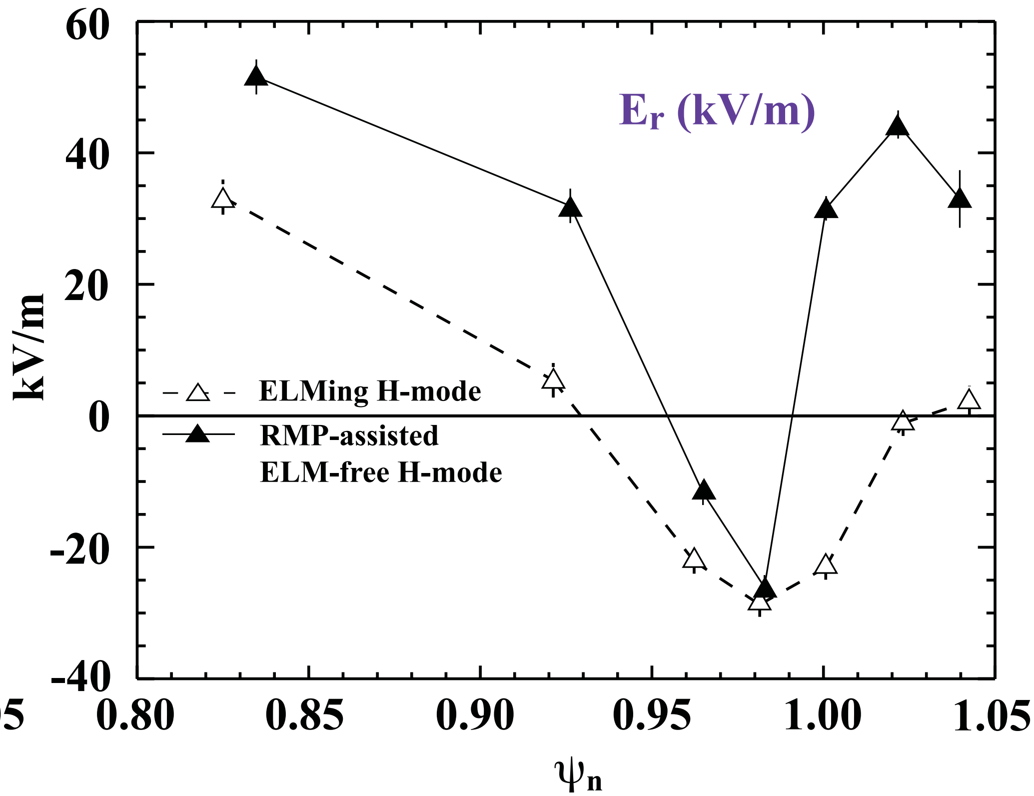

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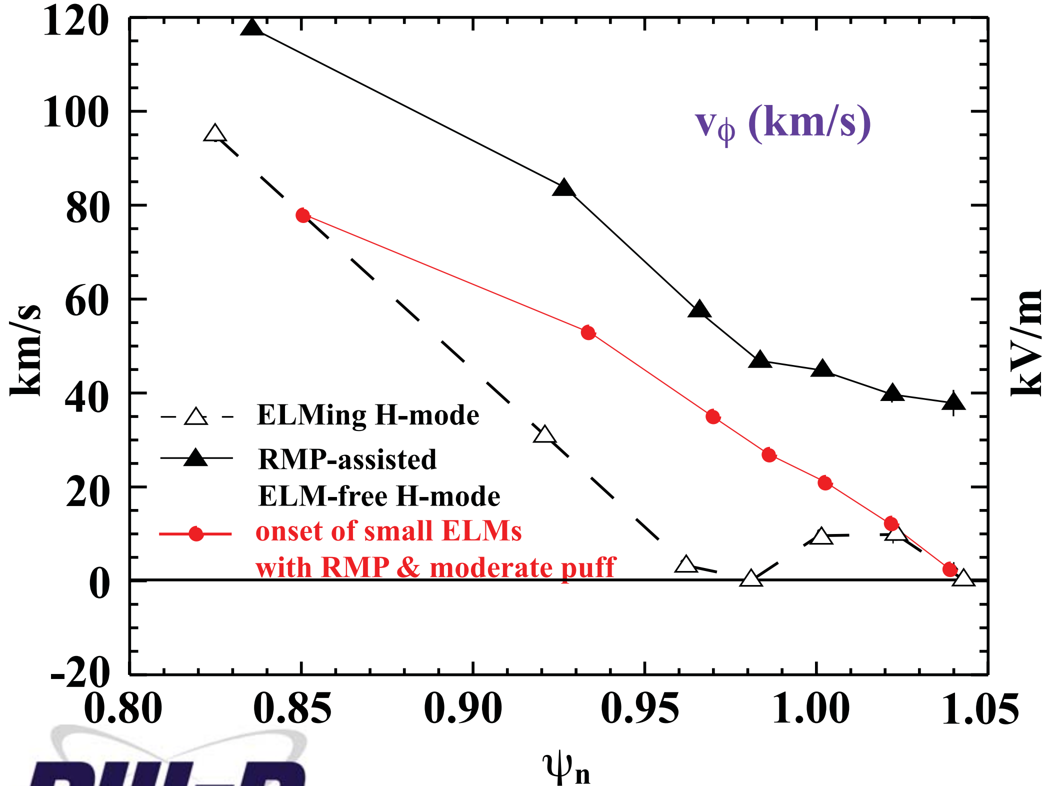
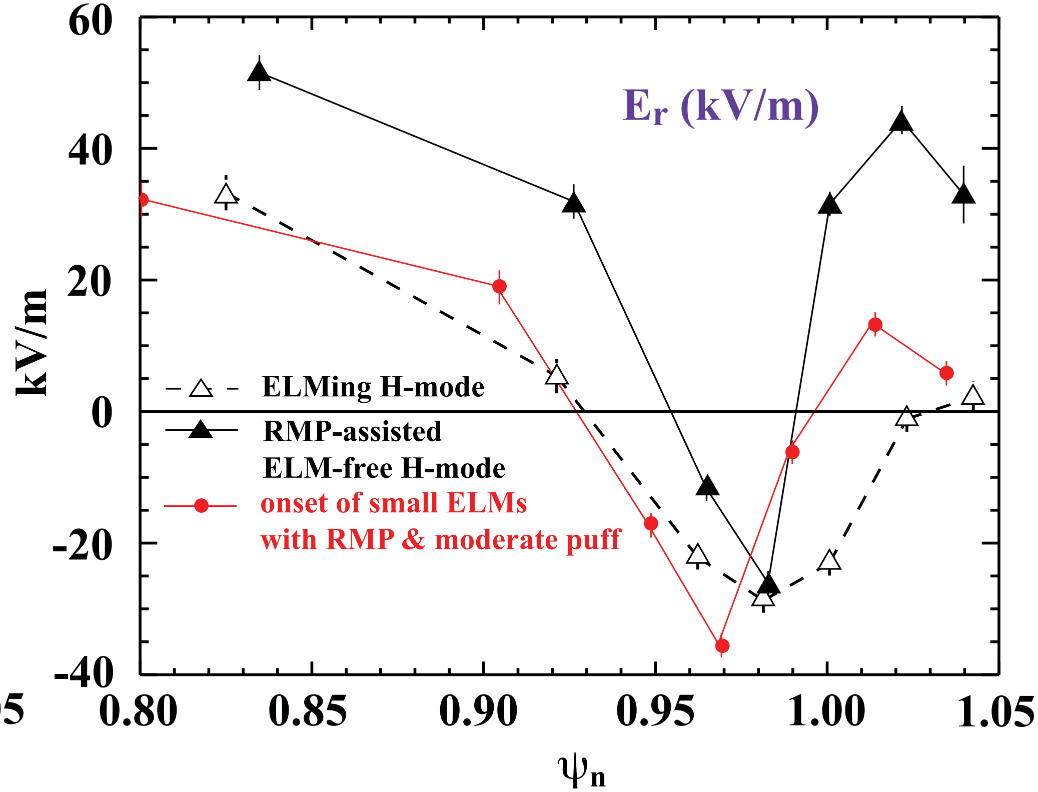
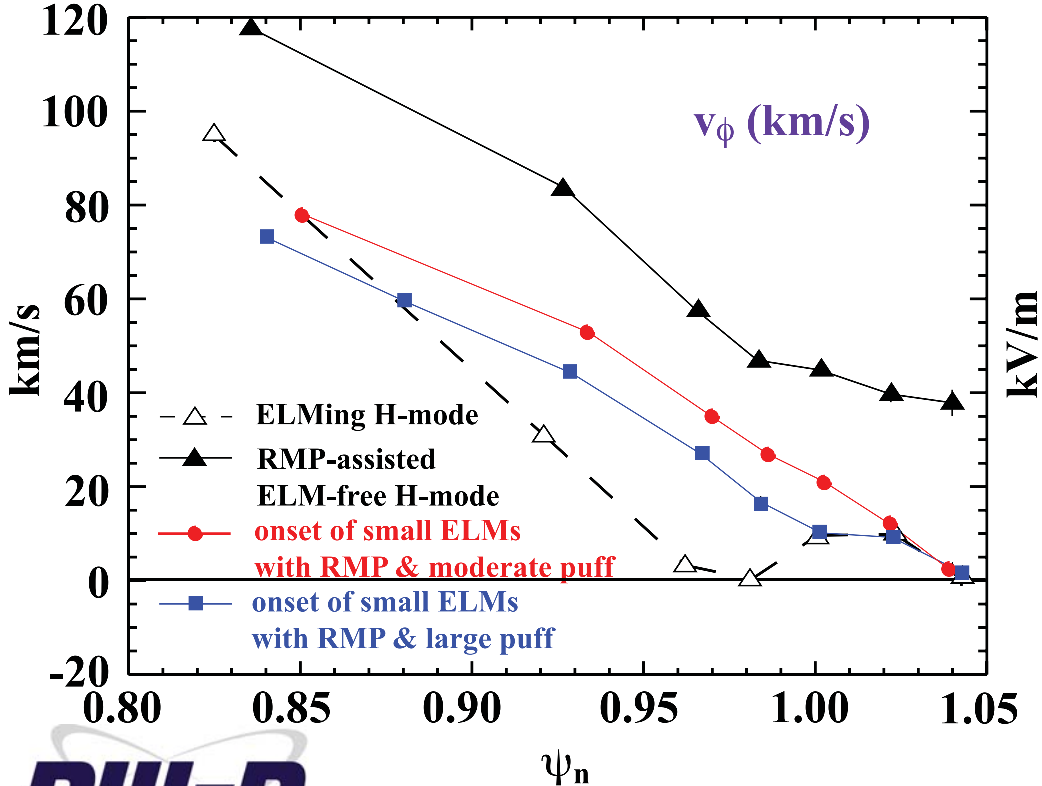
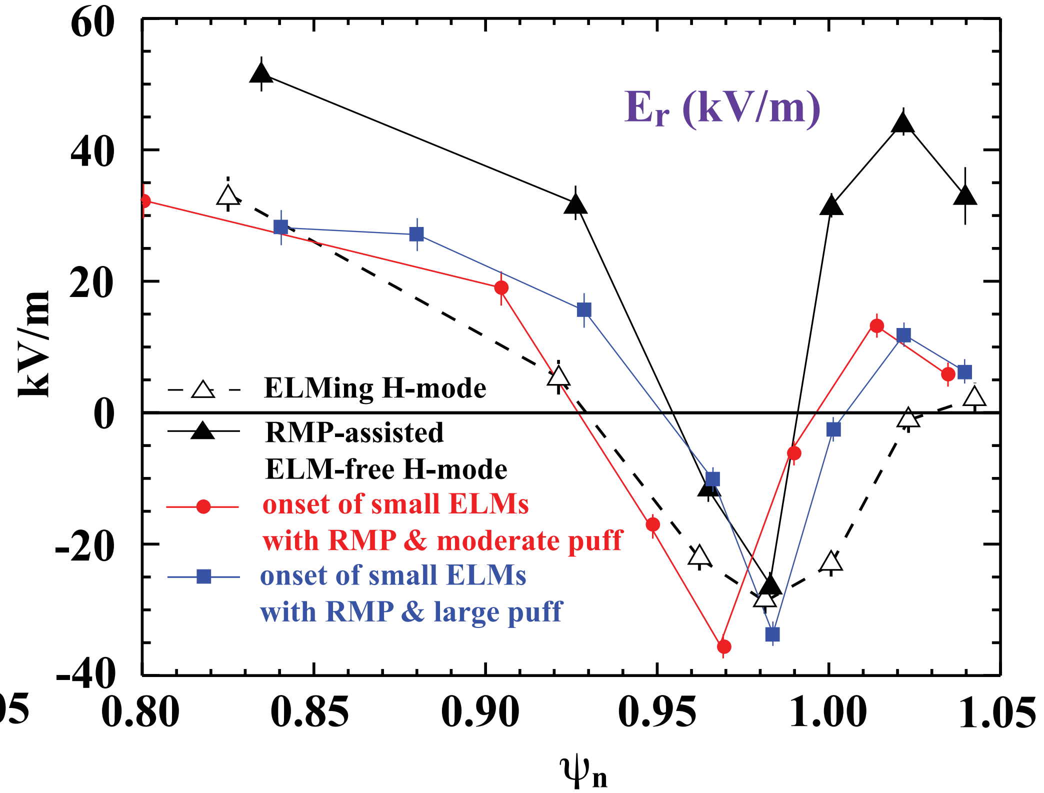




Onset of small ELMs as n_e^{ped} rises is correlated with decay of pedestal v_ϕ and degradation of E_r well.

- As n_e^{ped} rises, v_ϕ and E_r profiles become more like ELMing H-mode
- Changes in v_ϕ and E_r are similar to those seen in RMP-assisted ELM-free H-mode at $\nu_e^* \sim 1$ which also displays small, rapid ELMs/events
- suggests that E_r/velocity shear changes may regulate the transport response to the RMP, and therefore the ELM stability by altering ∇p





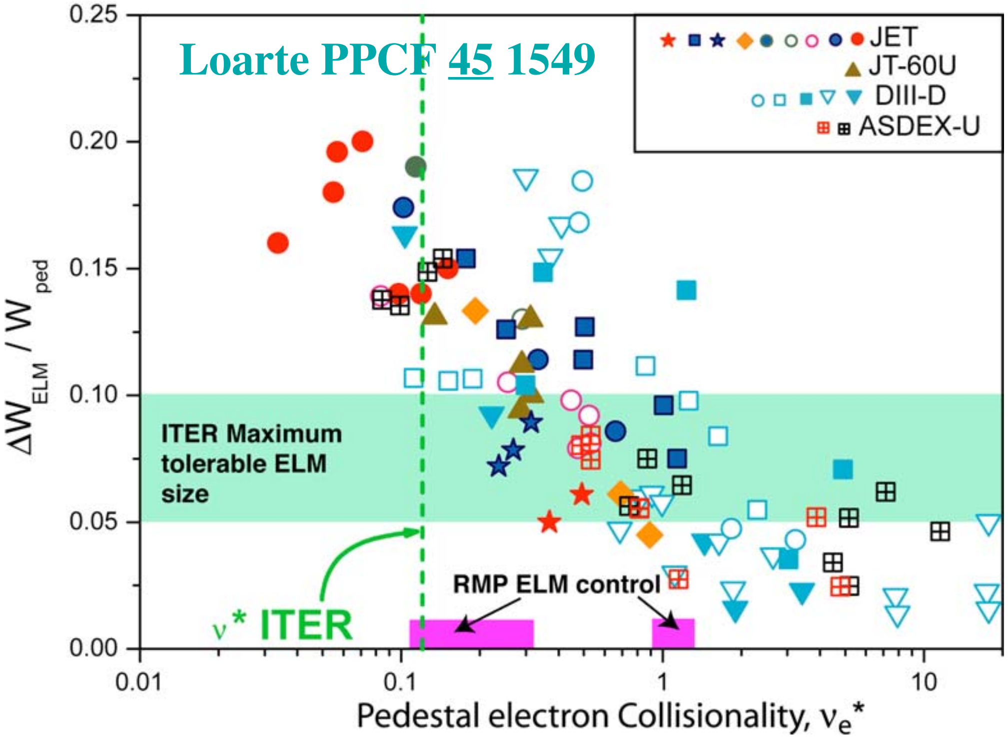
Summary and Conclusions

- Complete ELM suppression has been obtained in ELMy H-modes with ITER-relevent pedestal electron collisionality ν_e^* and ITER-similar shape (ISS) using an edge-resonant magnetic perturbation.
- ELMs are suppressed by lowering the pedestal pressure gradient below the Peeling-Ballooning stability limit for Type I ELMs.
- Pedestal pressure gradient reduction is controlled with RMP strength $\delta b_r^{m,n}/B_T$ above a shape-dependent minimum of 2.8×10^{-4} (δ~0.37) to 3.4×10^{-4} (δ~0.7).
- Pressure gradient is reduced primarily by RMP-induced particle transport.
- Density fluctuations increase 1.5-2x during RMP, consistent with increased convective particle transport.
  - Fluctuations may play similar role to Edge Harmonic Oscillation in QH-mode [see P.B. Snyder, this meeting]
  - $D_{eff} \sim n_{rms}^2$ increases 3-4x, consistent with density profile changes
  - Suggests that E_r/velocity shear changes due to RMP regulate transport, leading to reduced ∇p and stabilizing ELMs.

Backup Slides

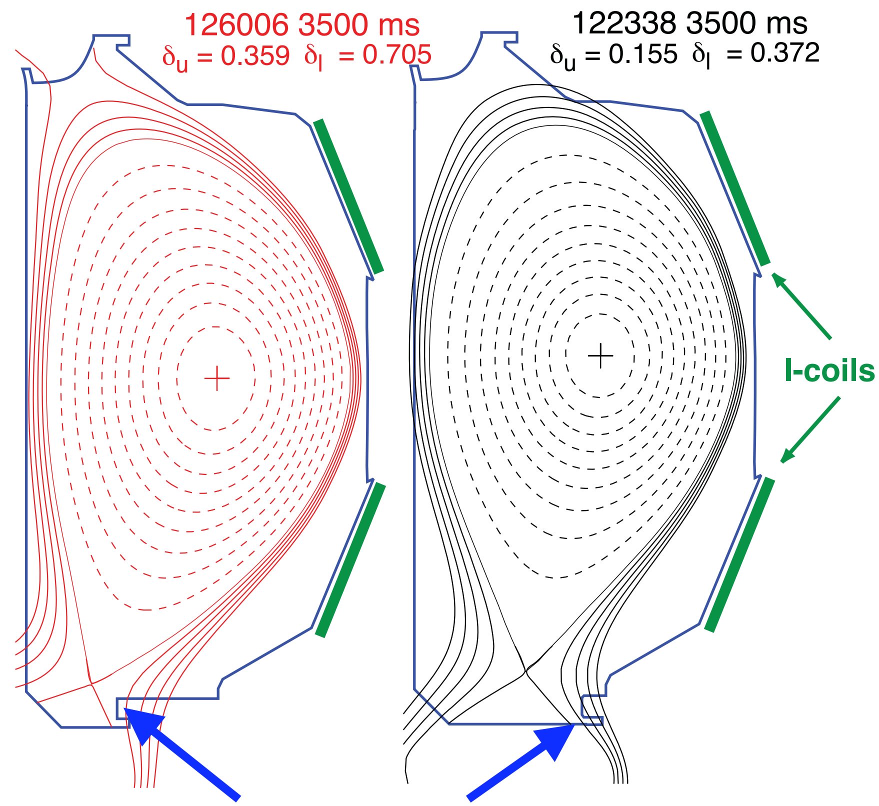
ELM control is a critical issue for burning plasmas.

- $\Delta W_{ELM}/W_{PED}$ increases as pedestal collisionality ν_e^* drops



  - RMP penetration decreases at lower ν_e^*
  - Parallel transport increases at lower ν_e^*

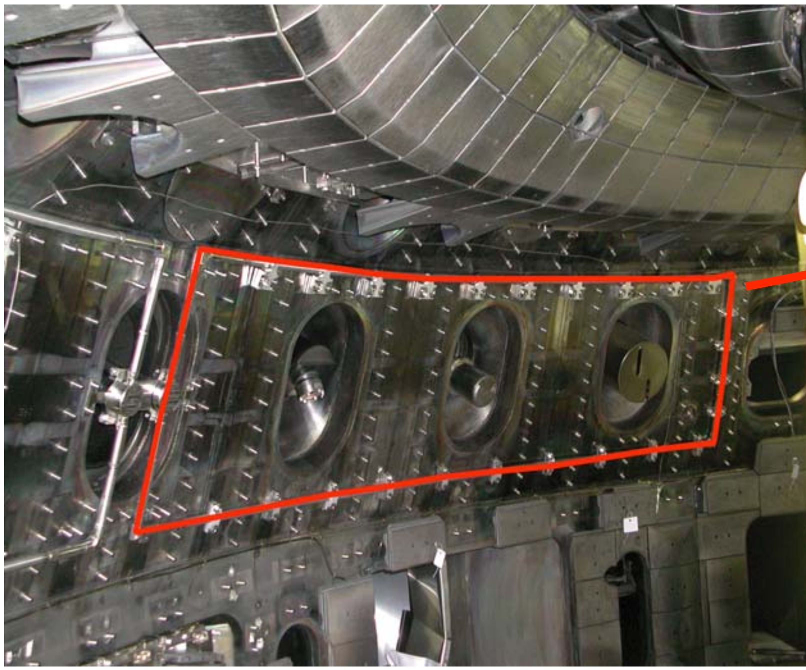
- ITER pedestal ν_e^* achieved in DIII-D by divertor pumping

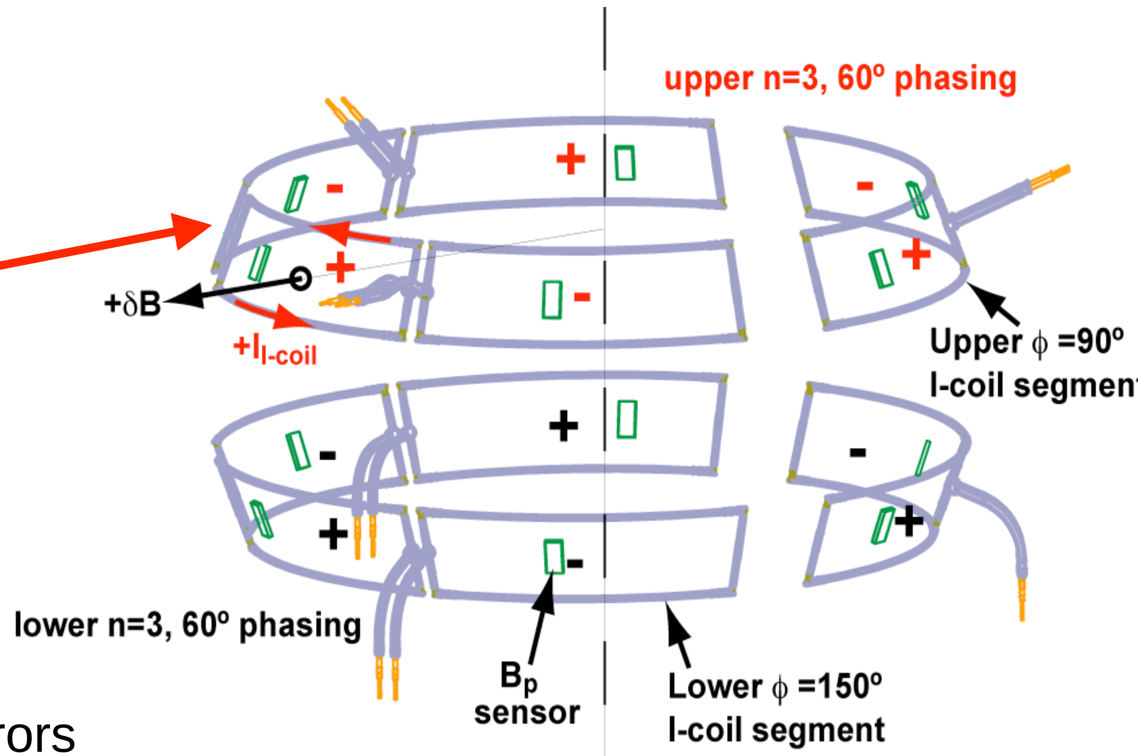


  - New lower divertor (2006) enables pumping high δ lower divertor to achieve ITER-relevent ν_e^*

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

- n = 3 used to minimize core perturbations.
- 9 < m < 15 Fourier harmonics form edge stochastic layer.





- Mixing with fixed intrinsic field errors
  - ϕ_{tor} = 0° or 60° gives different levels of stochasticity
  - δB_r for segment pairs in the same or opposite direction ("even" & "odd" parity)
  - Can use n=3 C-coil perturbation to boost n=3 $\delta b_r^{3,m}$

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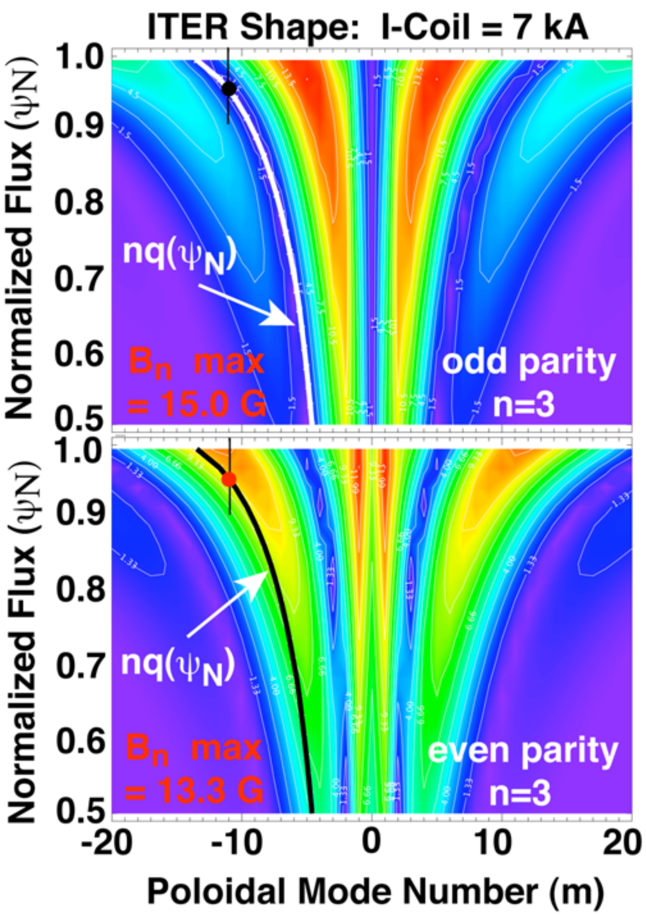
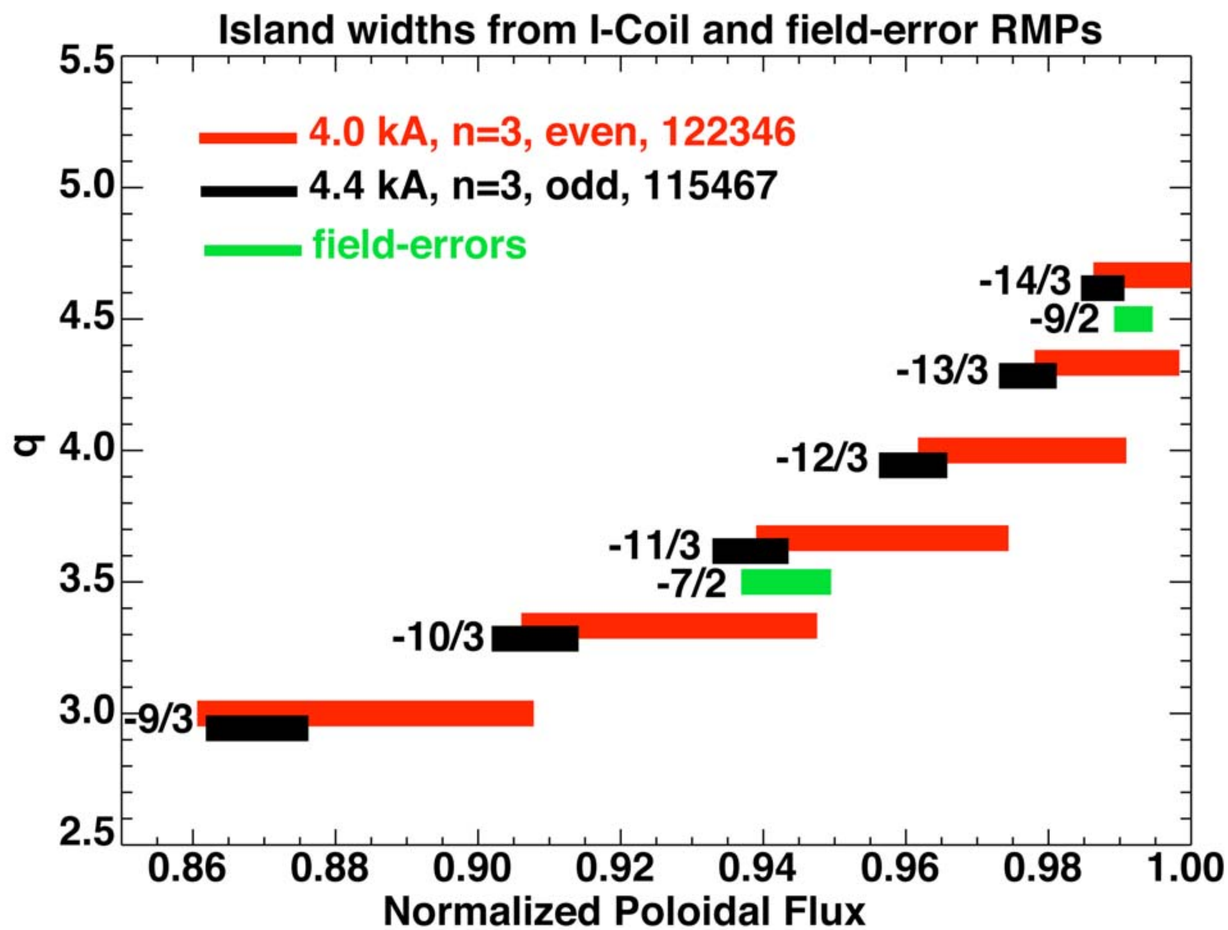
I-coil parity controls pedestal island overlap





- Both parities suppress ELMs
  - Odd (weak RMP) → small islands → little or no change in pedestal
  - Even (strong RMP) → stochastic → transport / pedestal control

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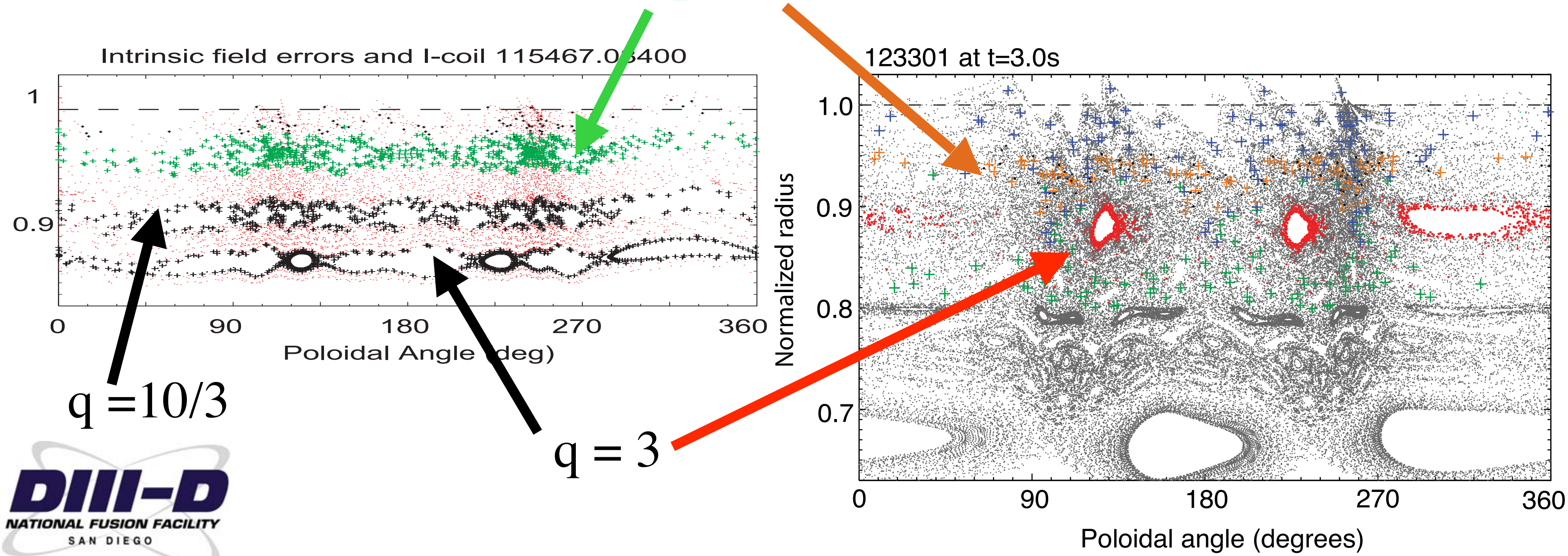
I-coil parity controls level of island overlap and stochasticity.

Moderate collisionality $\nu_e^* \geq 1$

- remnant islands mix with field error spectra
  - resonances at q=3, 10/3, & 4 with evidence for higher harmonics
- Edge toroidal rotation drops (braking from islands?)

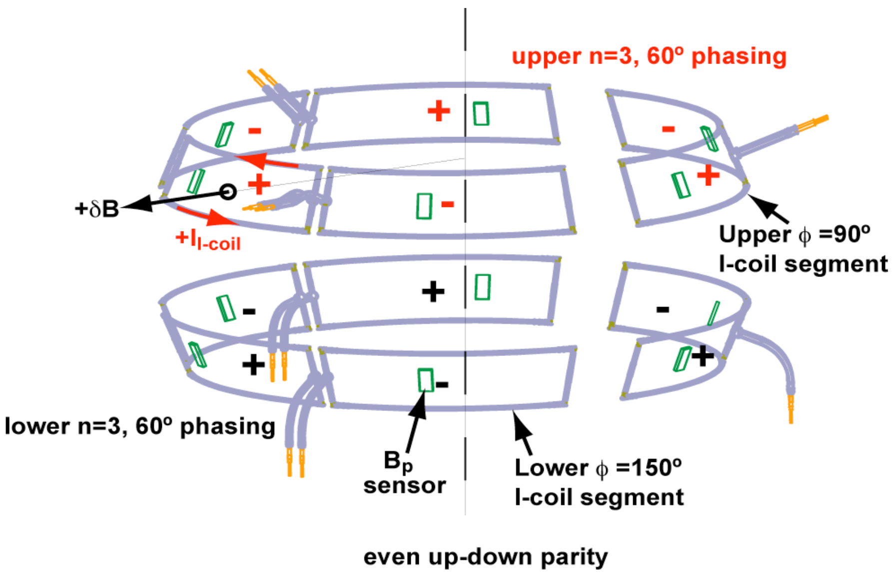
Low collisionality $\nu_e^* \sim 0.1$

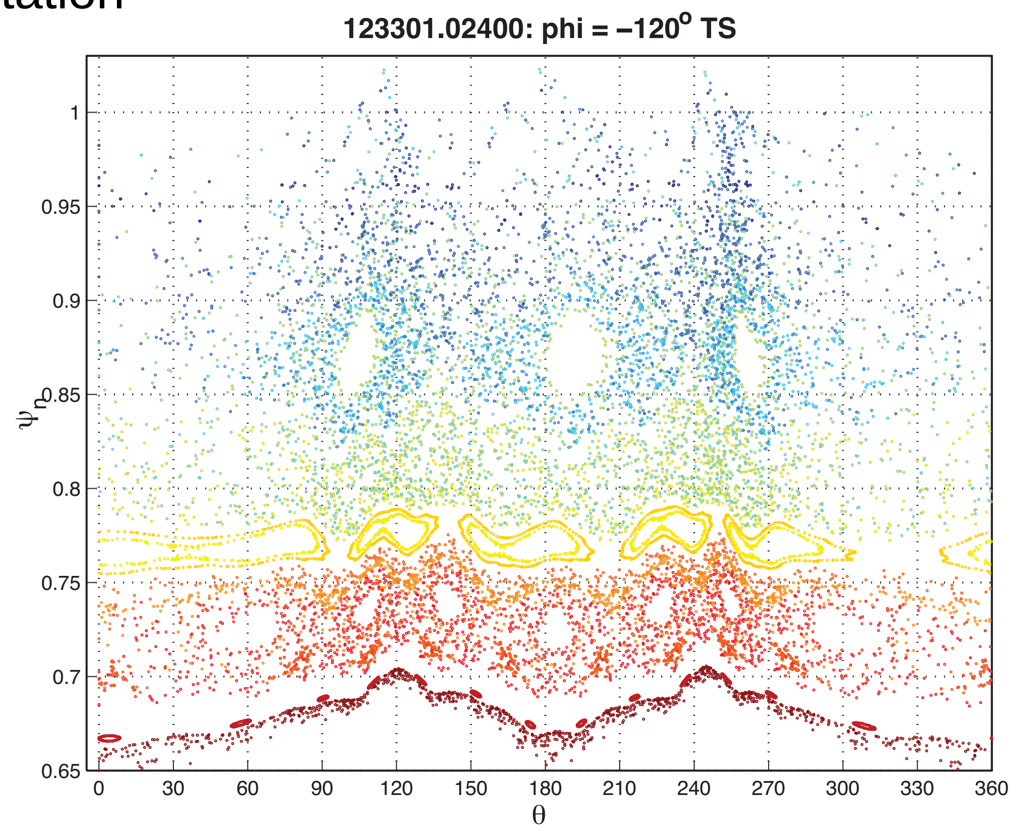
- Pedestal is substantially more stochastic
  - Remnant island at q=3 nearly destroyed
  - Remnant islands at q=10/3, 4 completely destroyed
- Less drag because of randomness of field line orientation?



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

- I-coil parity controls pedestal island overlap
  - Odd (weak RMP) → small islands → little or no change in pedestal
  - Even (strong RMP) → stochastic → transport / pedestal control
- We focus on n=3 even parity → strong edge resonant harmonics
  - Vacuum field island widths indicate overlap over plasma boundary in the absence of screening by beta or rotation





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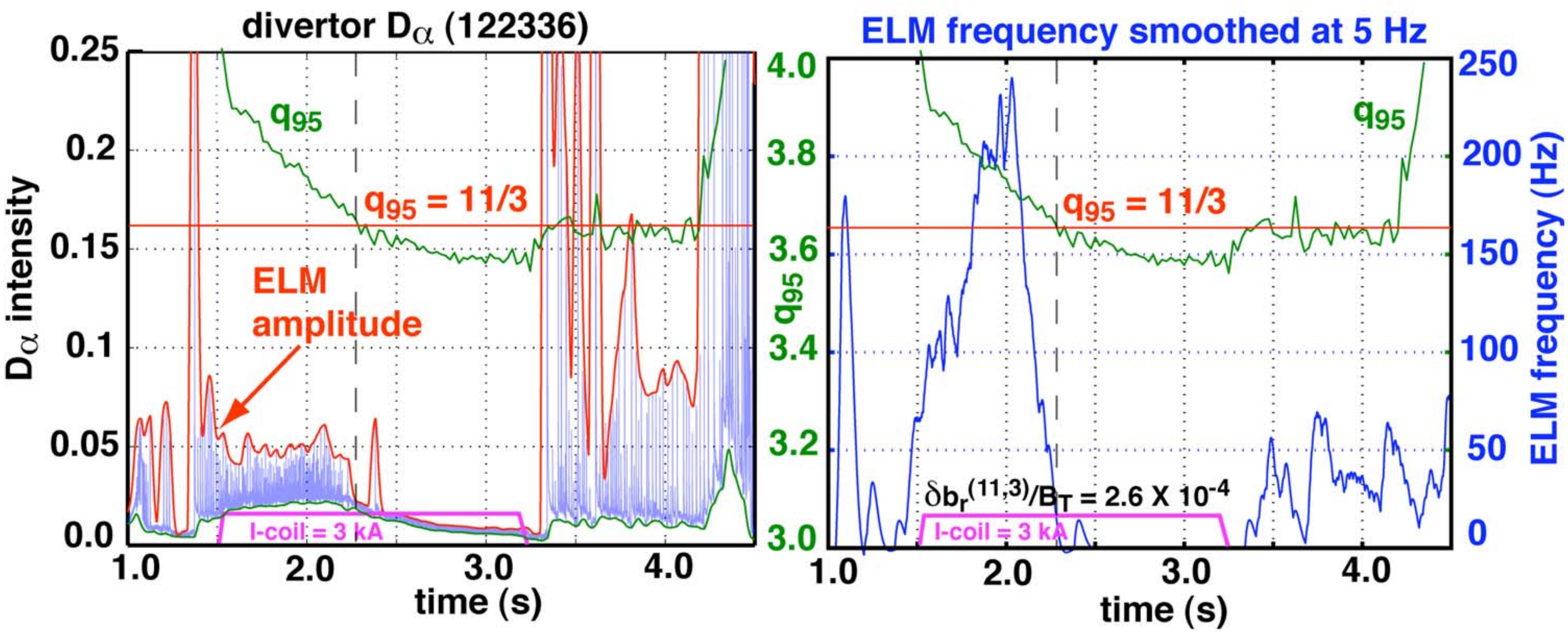
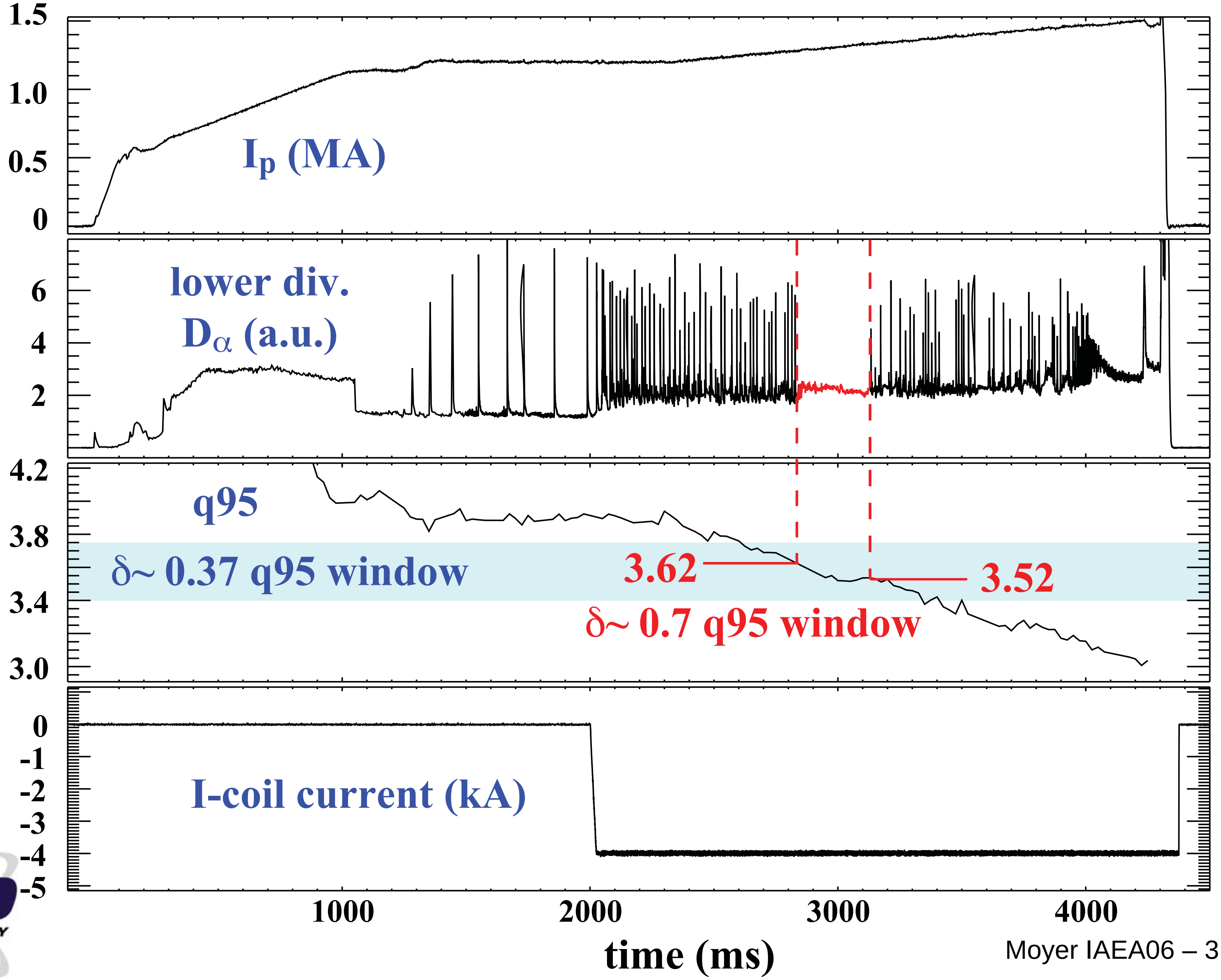
ELMs eliminated when resonant q_{95} condition satisfied with $\delta_{lower} = 0.36$ & $\nu_e^* \sim 0.1$



- $4.0 > q_{95} > 3.7 \rightarrow$ small, high frequency ELMs $\rightarrow$ no large impulses
- $3.7 > q_{95} > 3.4 \rightarrow$ no ELMs
- Following RMP pulse large ELMs return with ~250 ms delay

q_{95} resonant window in ITER Similar Shape (ISS) with δ_{lower} = 0.7 is narrower than for δ_{lower} = 0.37.



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Transport regimes regimes depend on ordering of λ_{mfp}, L_{corr}, L_{wall} (Rechester-Rosenbluth)

- Stochastic layer: collisionless transport
  - long field lines, stochasticity dominant

$$L_{corr} << \lambda_{mfp}, L_{wall} \qquad D_{RR} = D_{st} v_{th}$$

- Stochastic layer: collisional transport (fluid limit)
  - long field lines, both stochasticity & collisions active

$$\lambda_{mfp} << L_{corr} << L_{wall} \qquad \chi_{RR} = D_{st}\chi_{\parallel}/L_{corr}$$

- SOL: collisional transport (fluid limit)
  - short field lines, collisions dominant

$$\lambda_{mfp} << L_{wall} << L_{corr} \qquad \frac{L_{\perp}}{L_{wall}} = \sqrt{\frac{\chi_{\perp}}{\chi_{\parallel}}}$$

- SOL: collisionless parallel transport
  - very short field lines

$$L_{w} << \lambda_{mfp}, L_{c} \qquad \frac{L_{\perp}}{L_{wall}} = \sqrt{\frac{\chi_{\perp}}{L_{wall} v_{th}}} = \sqrt{\frac{\lambda_{mfp}\chi_{\perp}}{L_{wall}\chi_{\parallel}}}$$

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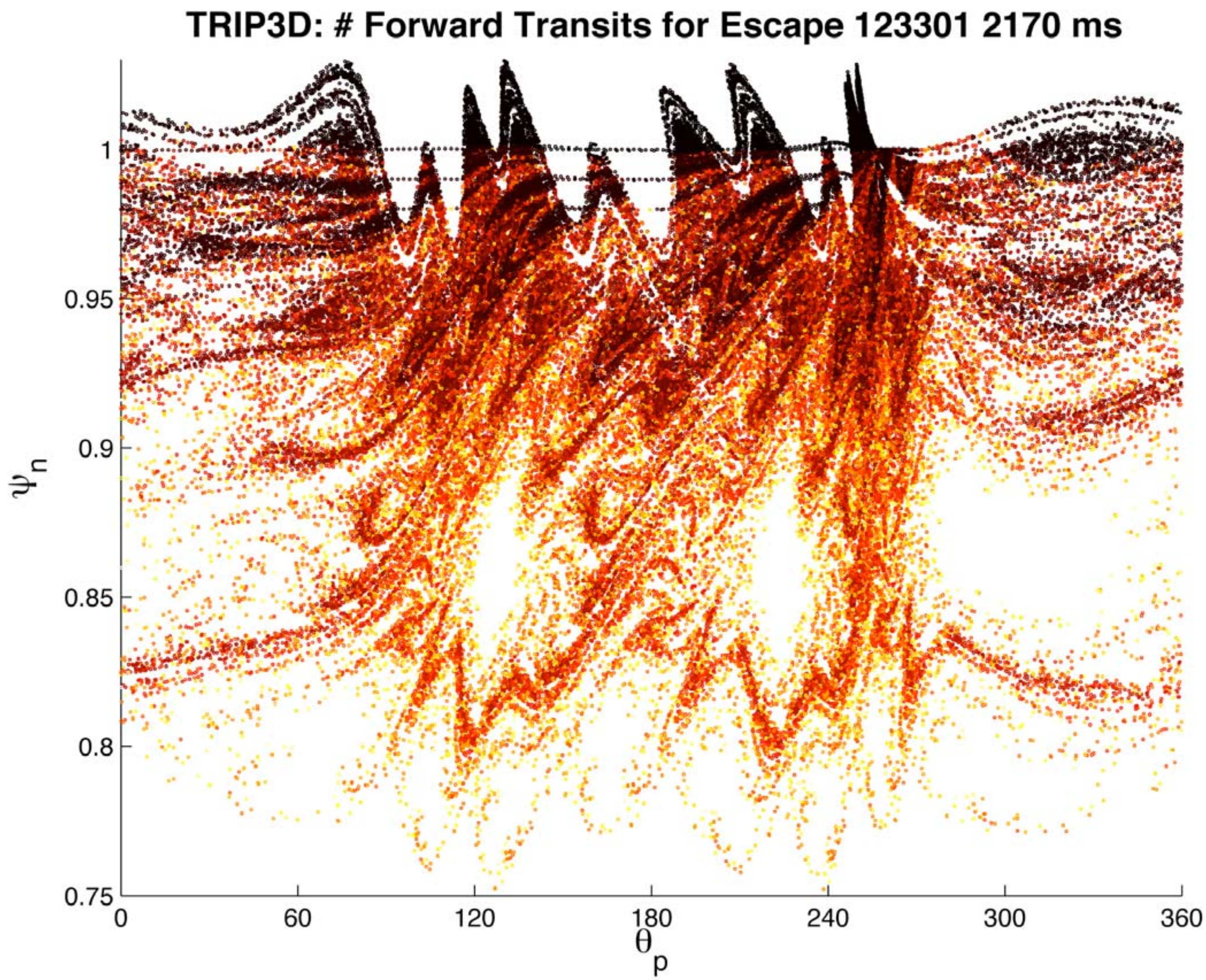
RMP induces magnetic diffusion and fractal structure in outer stochastic layer



- **Color = # toroidal transits for escape (red=201 max, black<10)**

E3D: 2 fluid transport code for ergodic 3D fields

see A.M. Runov P1-63 2006 PSI Mtg. (JNM in press 2007)

Solves Braginskii fluid equations in static background field

- Energy equation:

$$\tfrac{3}{2} n(\partial_t T + u_{||}\nabla_{||}T) = \nabla_{||}\kappa_{||}\nabla_{||}T + \nabla_{\perp}\kappa_{\mathrm{anom}}\nabla_{\perp}T - \Pi_{||}\nabla_{||}u_{||} + Q_{\alpha\beta}$$

- Parallel momentum: **(alpha testing)**

$$mn\left(\partial_t u_{||} + \nabla \frac{u_{||}^2}{2}\right) = qE_{||} - \nabla_{||}p + \Pi_{||} + \Pi_{\mathrm{anom}}$$

- Continuity: **(quasineutral)**

$$\partial_t n + \nabla_{||} n u_{||} = \nabla D_{\mathrm{anom}} \nabla n$$

- Sheath BC's: **(nonlinear, R. Chodura)**

$$\Gamma = nC_s \cos\theta_w \sim nT^{1/2} \qquad Q = \beta nTC_s \cos\theta_w \sim nT^{3/2}$$

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IPP Max-Planck-Institut für Plasmaphysik

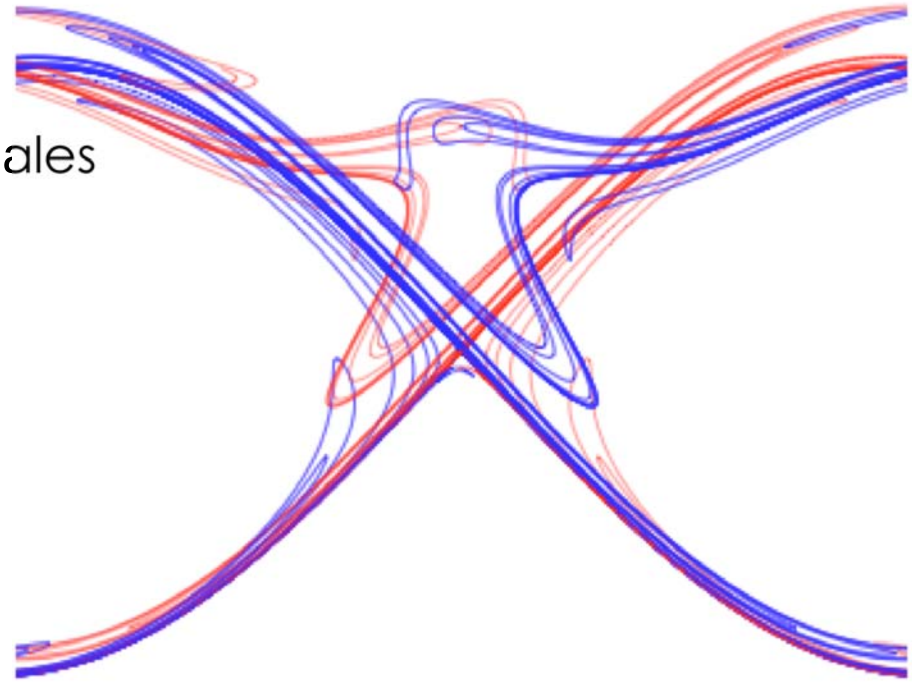
E3D: efficient *Monte-Carlo* 2 fluid code designed for TEXTOR DED, W7-X, etc.

- **Heat transport highly anisotropic**

$$\kappa_{\parallel}/\kappa_{\perp} = \chi_{\parallel}/\chi_{\perp} \sim 10^{8} - 10^{10}$$

  - Stochasticity can generate small scales

$$\ell_{\perp}/L_{c} \sim \sqrt{\chi_{\perp}/\chi_{\parallel}} \sim 10^{-4} - 10^{-5}$$



- **Simple finite elements cannot capture anistropy**
  - Requires high order/adaptive
  - May not capture 3D complexity
- **Solution: Monte-Carlo technique**
  - Let $T(x,t)$ = *probability distribution function* for heat packets
  - Use Brownian motion to describe evolution

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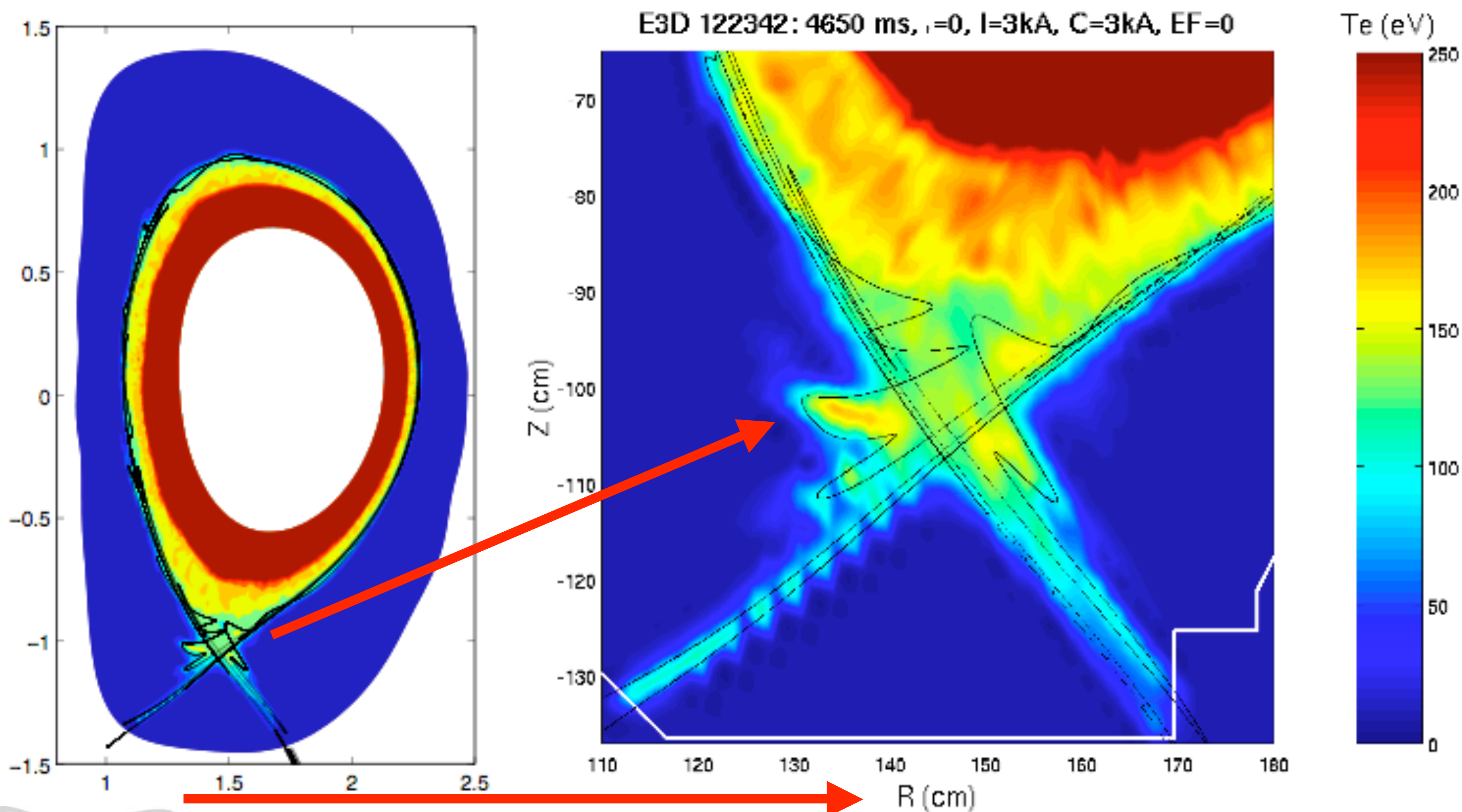
A.M. Runov P3-63, 2006 PSI, JNM 07 in press

IPP Max-Planck-Institut für Plasmaphysik

T_e profile follows homoclinic tangle
"Separatrix" = intersection of invariant manifolds



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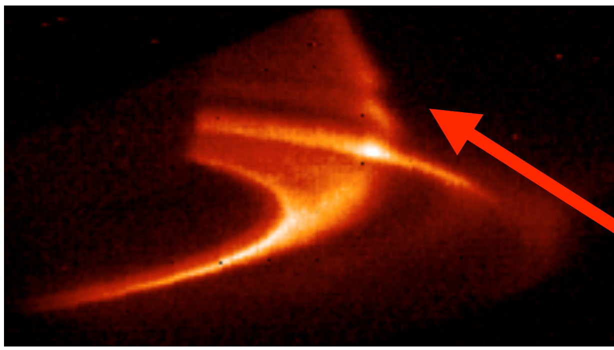
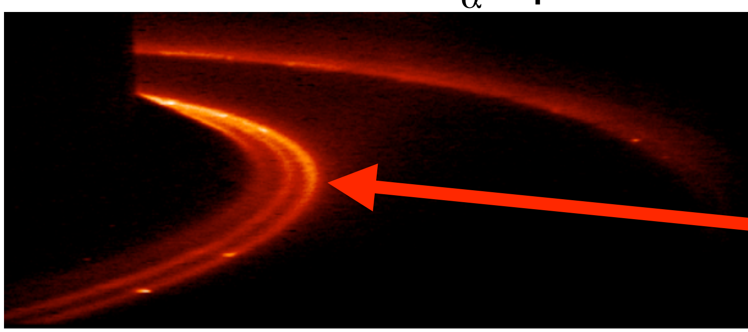
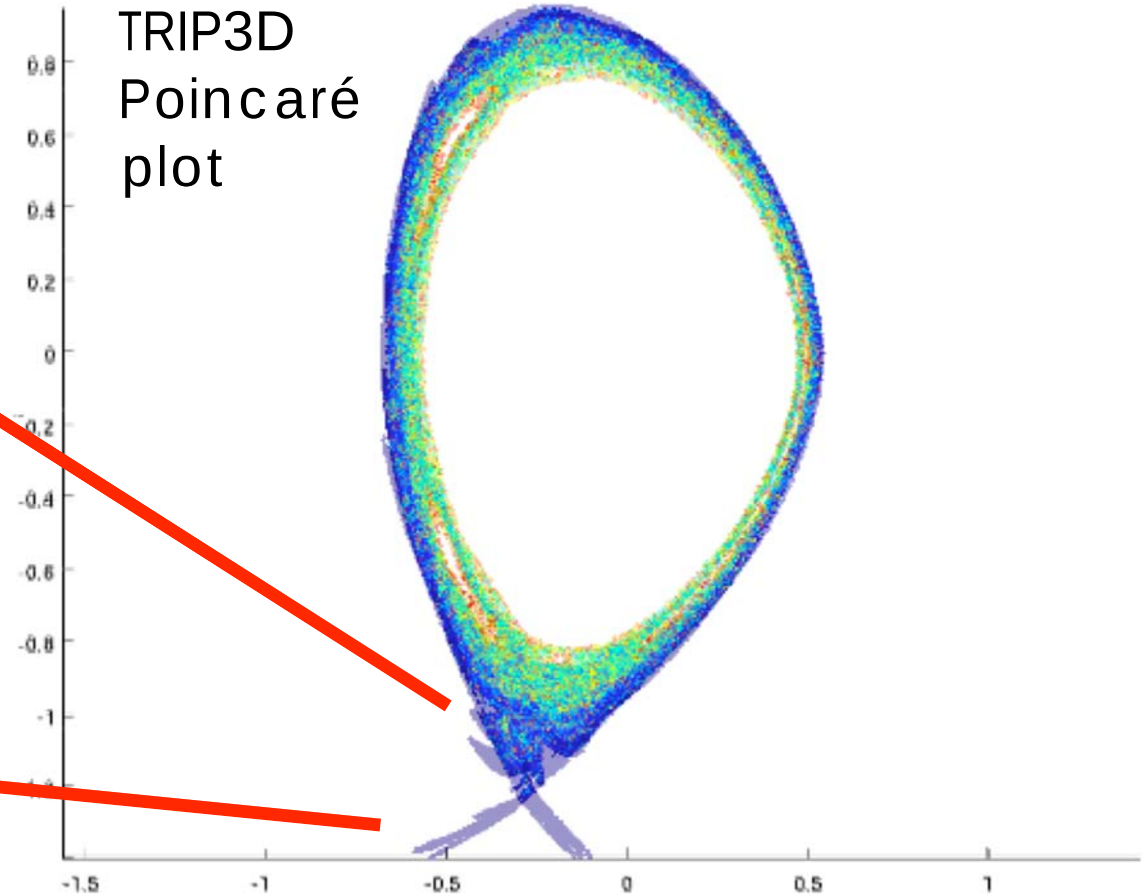
Xpt-TV experimental observations of “homoclinic tangle” confirm penetration of RMP at least into last few % in ψ_n.

123300: filtered CIII Xpt-TV



123301: filtered D_α Xpt-TV





- T_e should reflect a superposition of both invariant manifolds
- Divertor plate striations often observed in experiment

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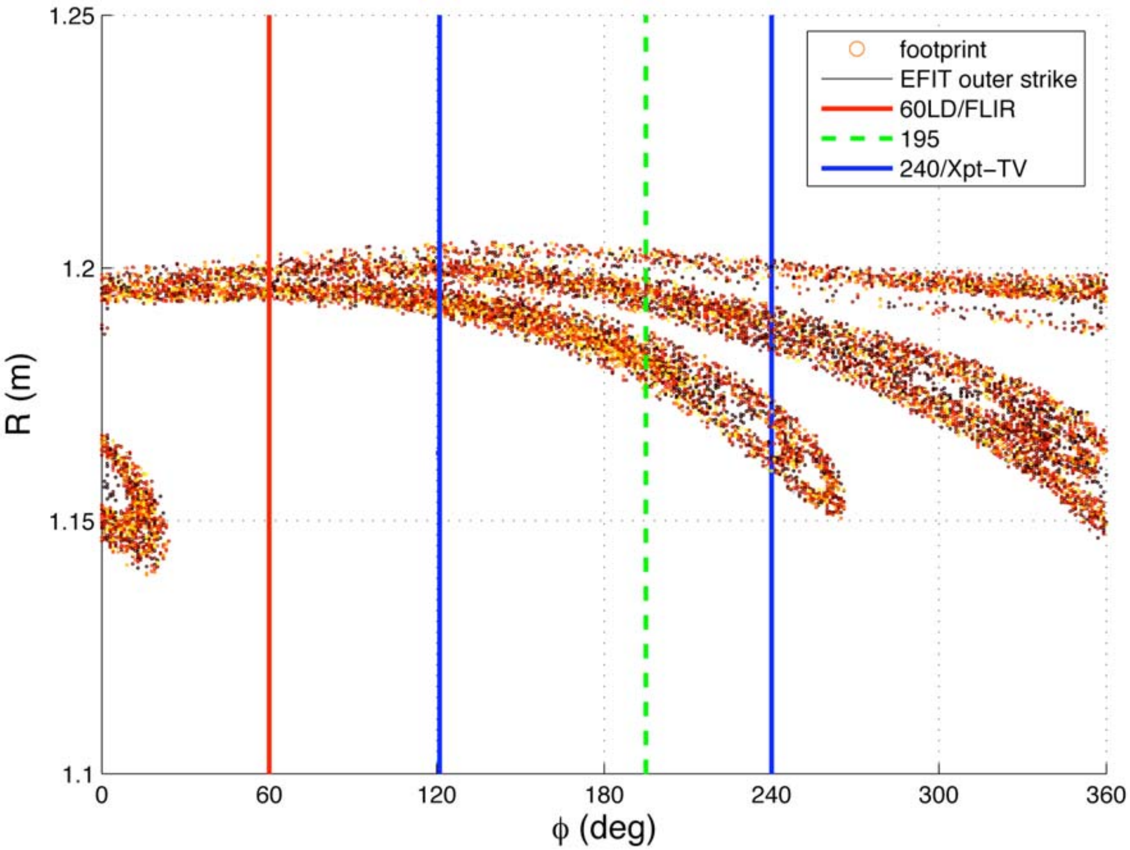
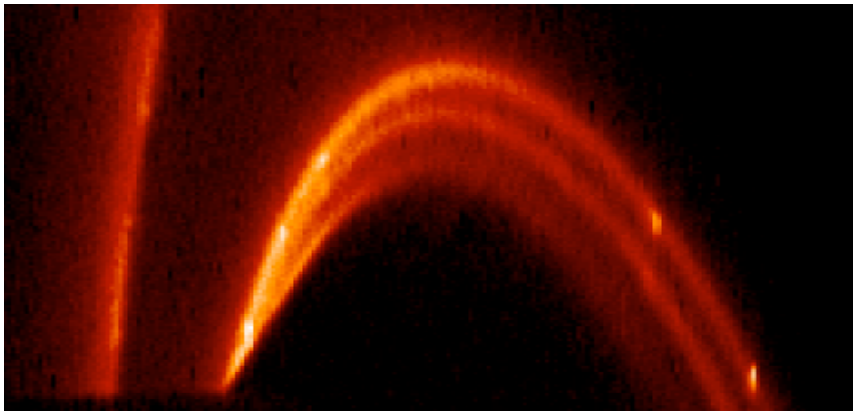
Magnetic footprint striations often observed during I-coil pulse

TRIP3D prediction:
123301 2170 ms inner strike point



filtered D_α Xpt-TV:

123301 2170 ms



- **Divertor strike pattern can be used to validate field model**

M. Fenstermacher I-8, M. Groth P1-12
2006 PSI Mtg. JNM in press (2007)

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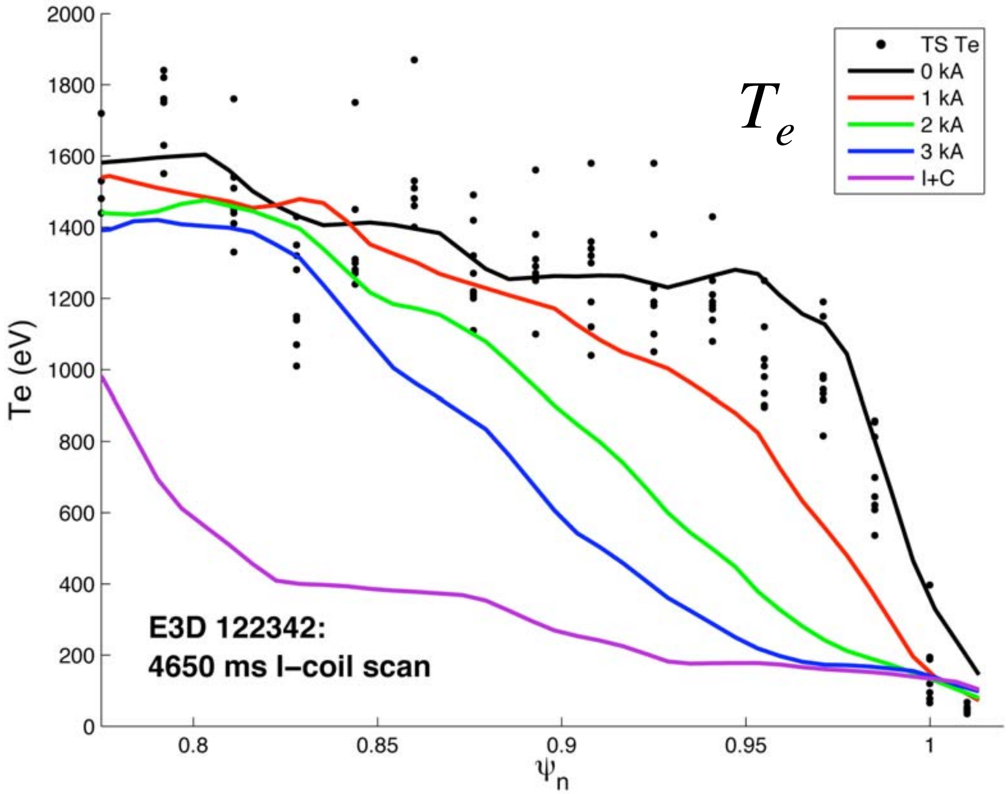
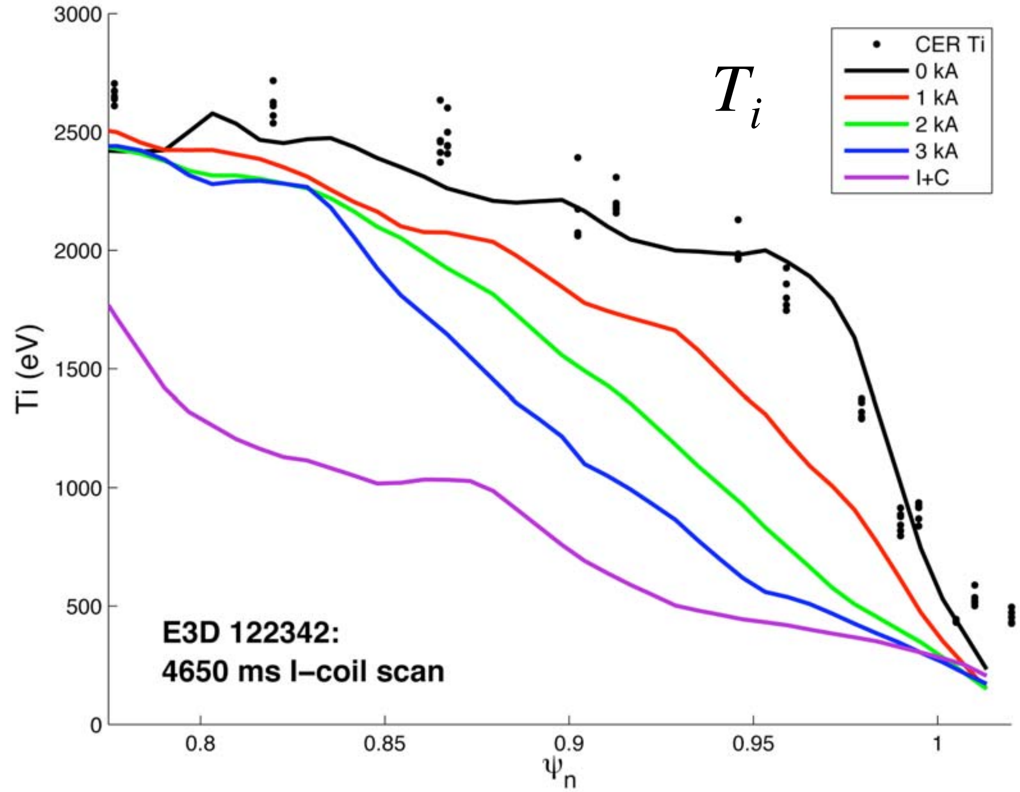
As I-coil ⇑: edge temperature cools ⇓

122342 at 4650 ms BC's: $T_e = 1.6\ keV$, $T_i = 2.6\ keV$ at $\psi_n = 77\%$



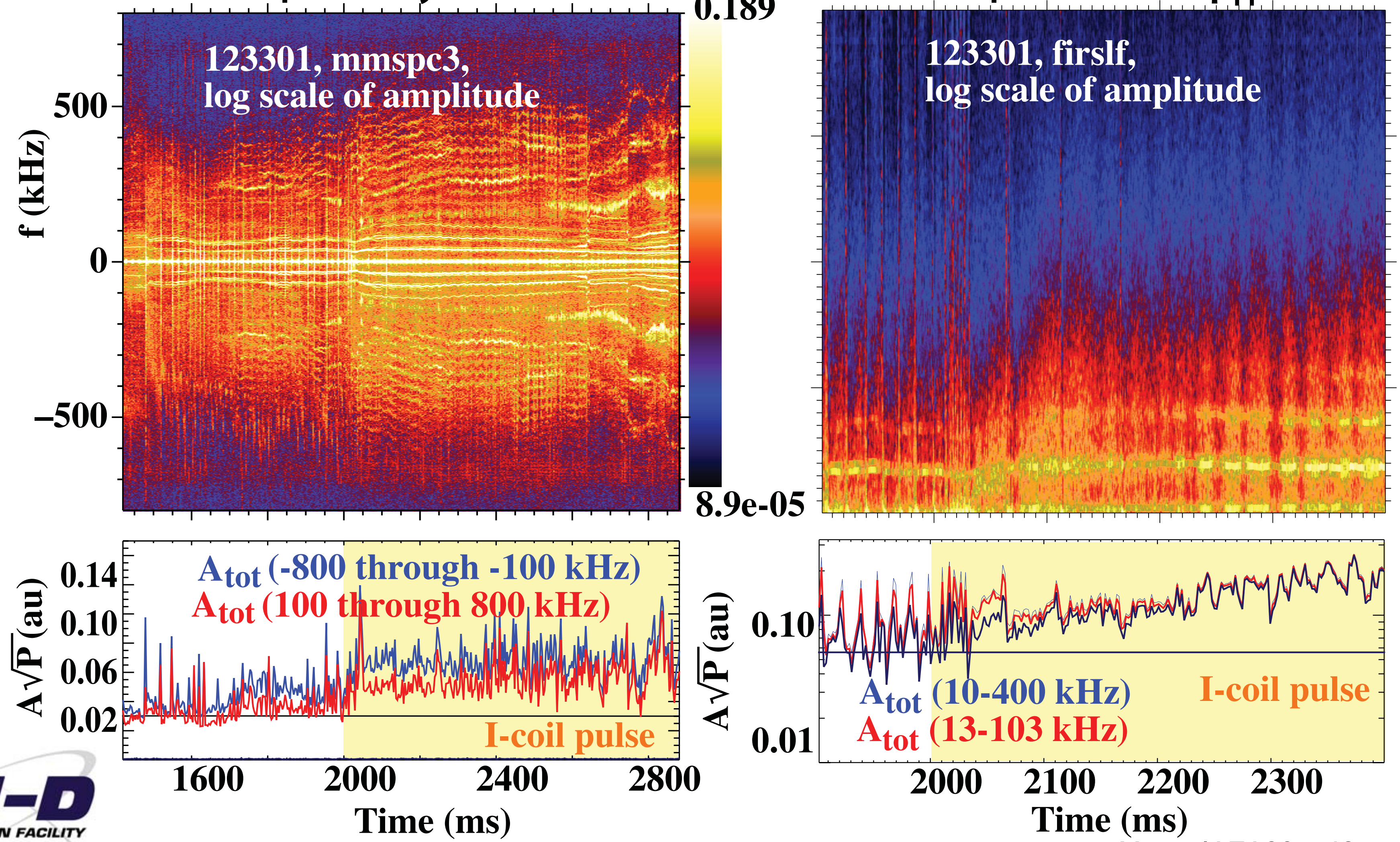


- **Constant temperature BC's**
- **Edge stochastic layer cools relative to pedestal**
  - remains hot compared to SOL

RMP application increases density fluctuations overall, including pedestal broadband turbulence

$k_\theta = 1 \pm 1\ cm^{-1}$ FIR scattering
not spatially localized

homodyne reflectometry
H-mode pedestal $\psi_n = 0.98$



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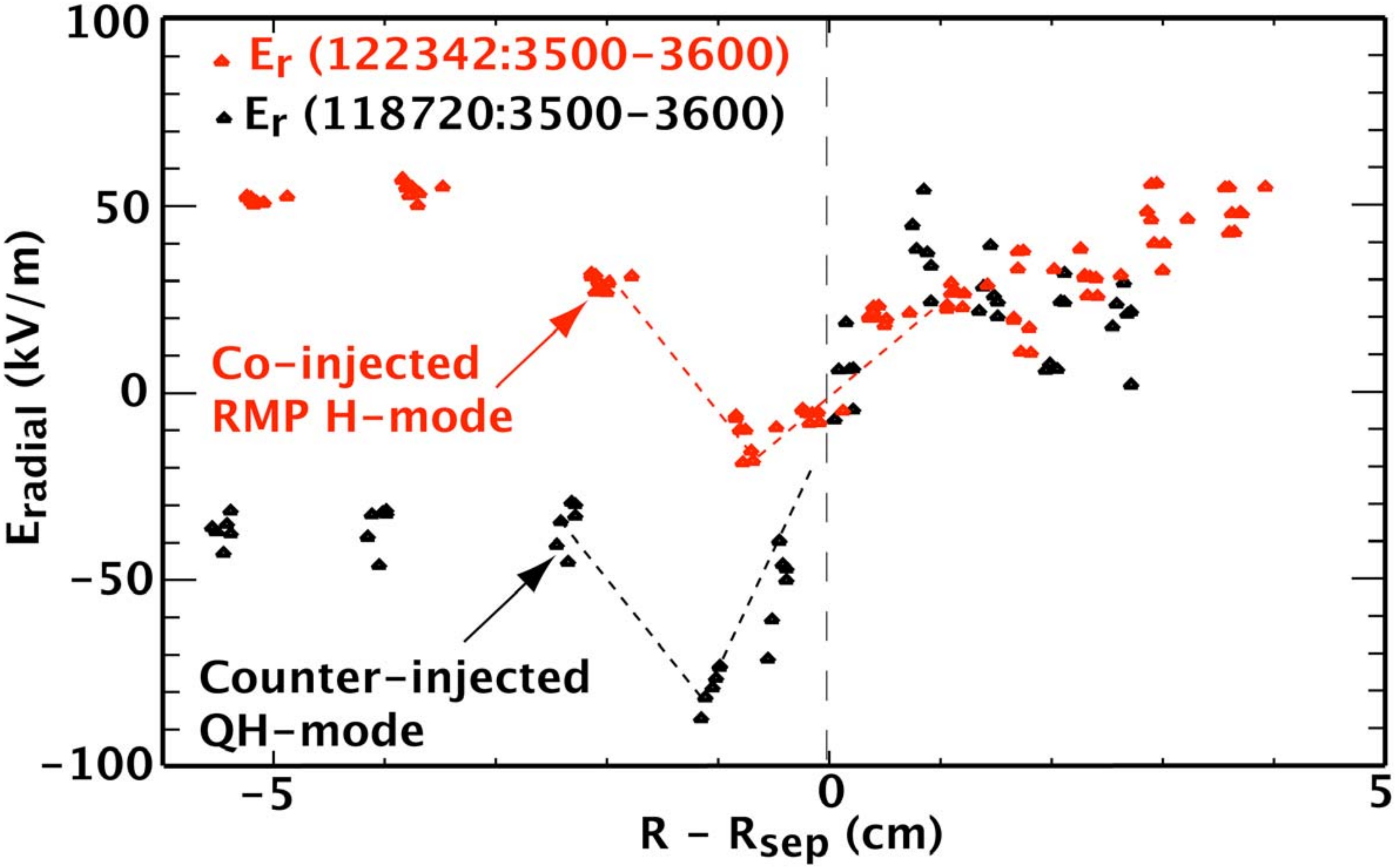
RMP-assisted ELM-free H-modes have shallower E_r wells than QH-modes



- E_r positive out to wall in both ELM-free plasmas; plasma potential → 1 kV at wall.
- E_r shear near separatrix higher in QH modes.

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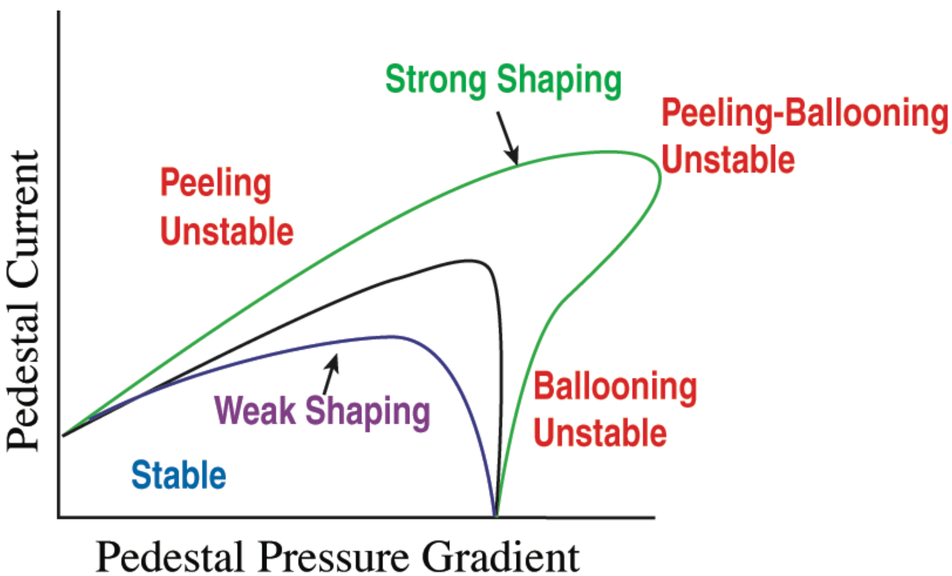
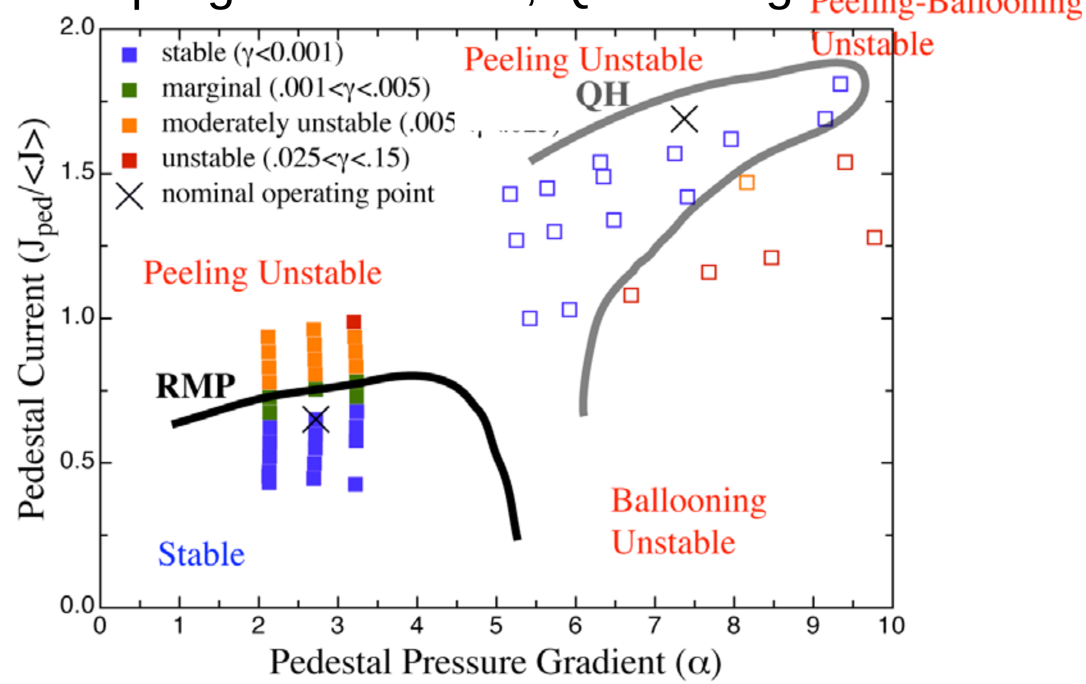
RMP ELM-free H-modes and QH modes both stable and near peeling boundary

Schematic P-B Stability Diagram
[P.B. Snyder, H.R. Wilson PoP2002]



Shaping: RMP weak, QH strong



- **Strong shaping allows access to higher ∇P such as in QH-modes**
- **P-B stability boundaries are a strong function of plasma shape**
  - At present RMP ELM-free discharges can not access low ν_{e*} in strongly shaped plasmas (because of pump location)
- **In 2006, low ν_{e*} RMP ELM-free operations in strongly shaped plasmas will be investigated**

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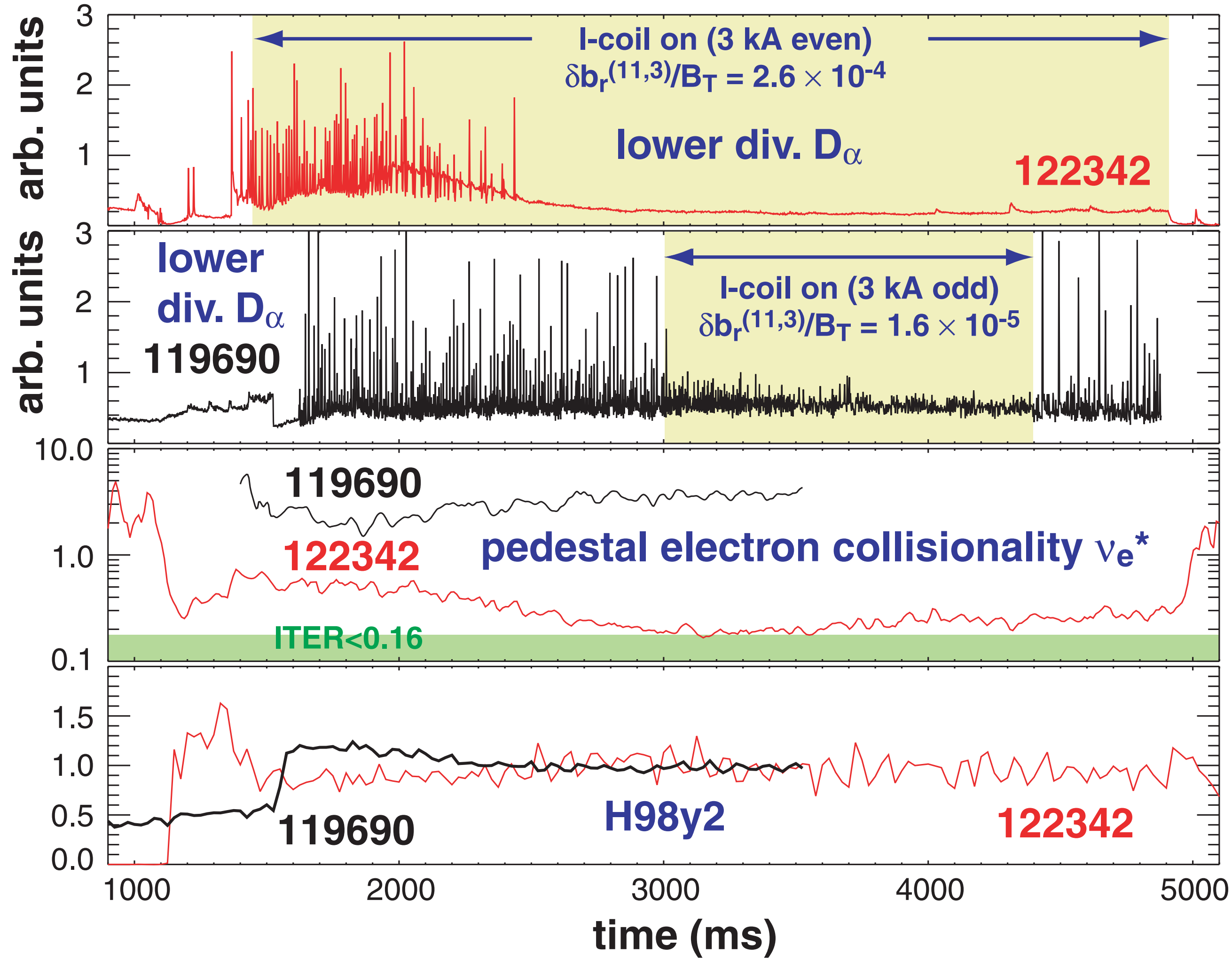
Edge Resonant Magnetic Perturbations (RMPs) have been used to eliminate large ELMs in in DIII-D

- Large ELMs can be eliminated by reducing ∇P below the peeling-ballooning limit

  P.B. Snyder, ***next*** contrib. oral BO3.00009

- Large ELMs can also be suppressed in discharges where ∇P is essentially unchanged
  - Large ELMs are replaced by smaller, more continuous events (Type II ELMs?)



T.H. Osborne, H-mode Workshop '05; Poster CP1.00004
M.E. Fenstermacher, Poster CP1.00003

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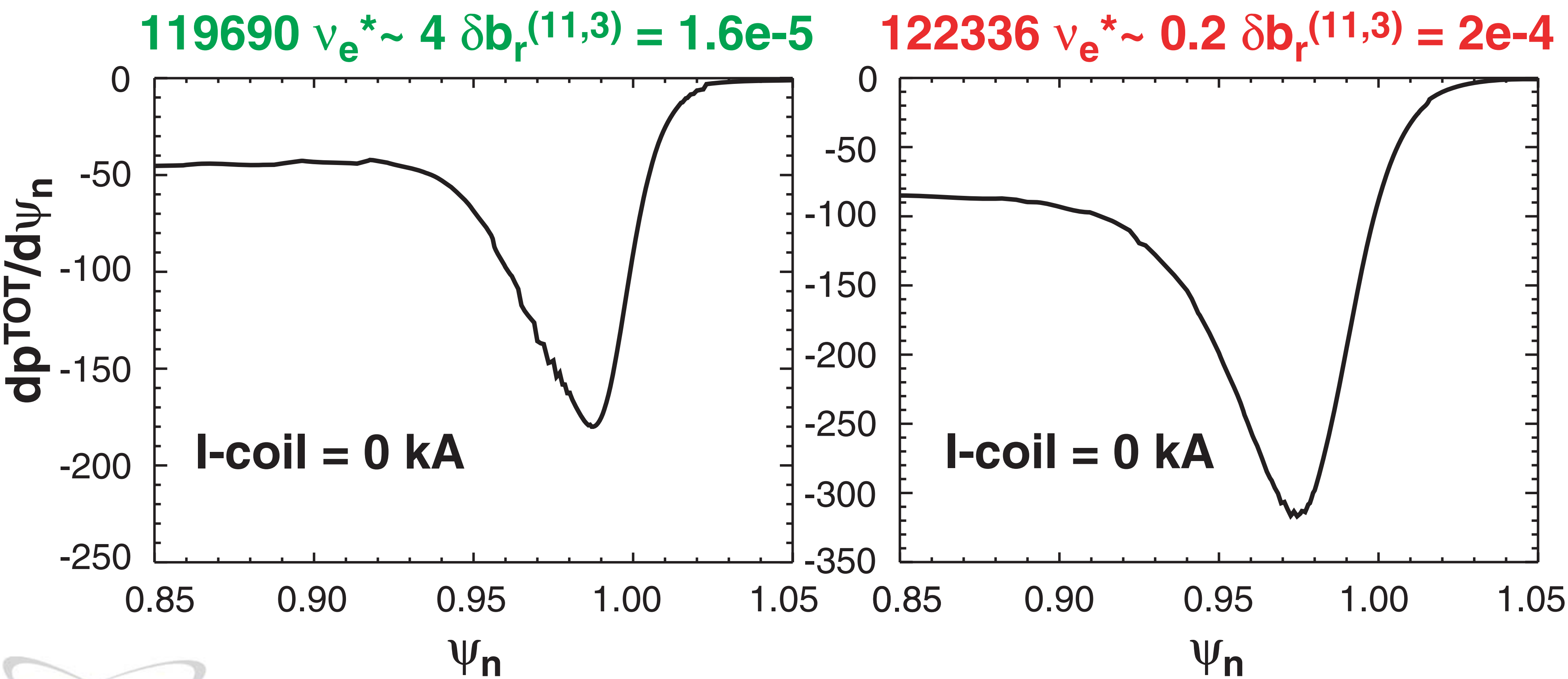
Edge RMP suppresses large ELMs without always significantly lowering ∇p^{TOT}.



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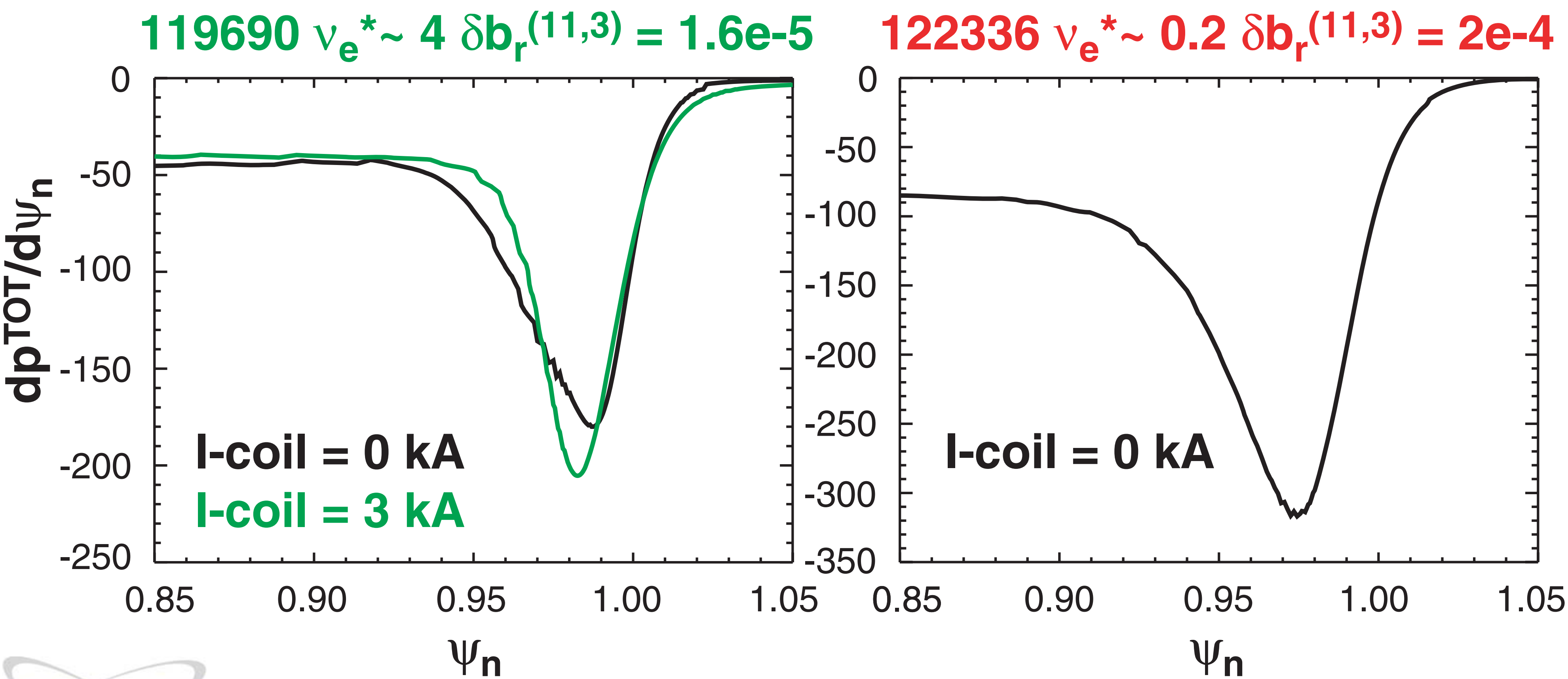
P.B. Snyder, ***next*** contrib. oral BO3.00009

Edge RMP suppresses large ELMs without always significantly lowering ∇p^{TOT}.

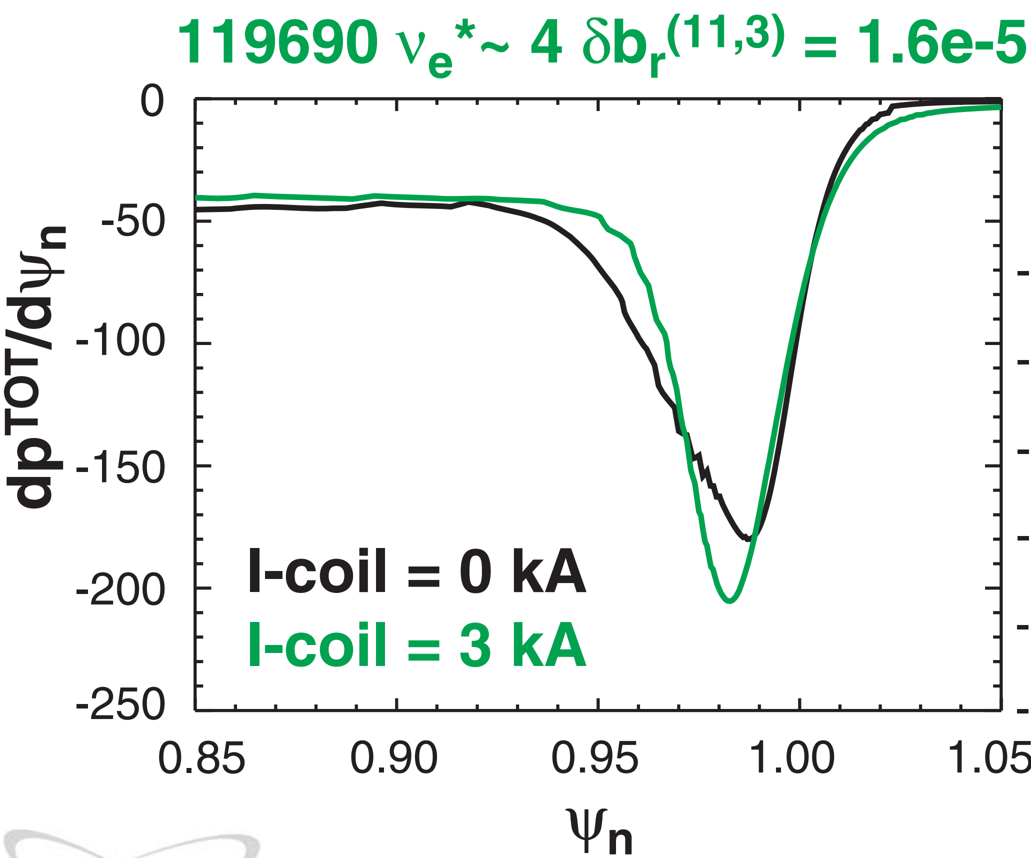
- Small changes to ∇p^{TOT} → always within error bar of peeling-ballooning bndry.

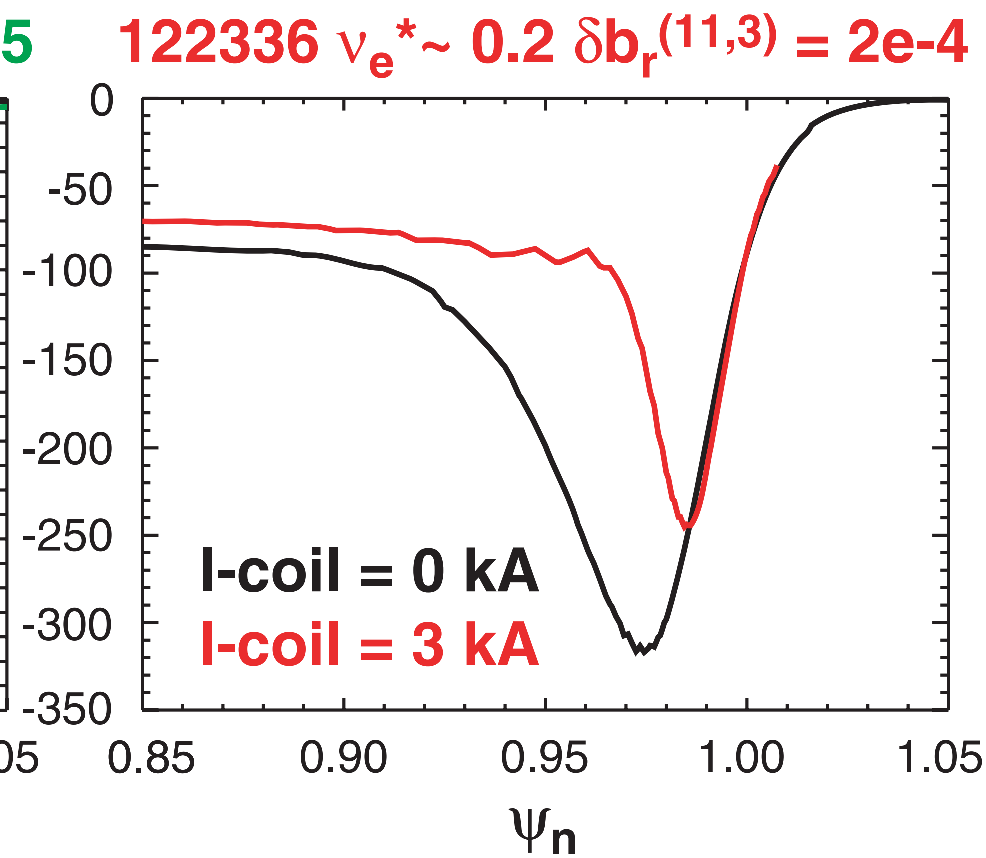


P.B. Snyder, ***next*** contrib. oral BO3.00009

Edge RMP suppresses large ELMs without always significantly lowering ∇p^{TOT}.

- Small changes to ∇p^{TOT} → always within error bar of peeling-ballooning bndry.
- I-coil changes ∇p^{TOT} peak, width, & location → alters stability as planned.

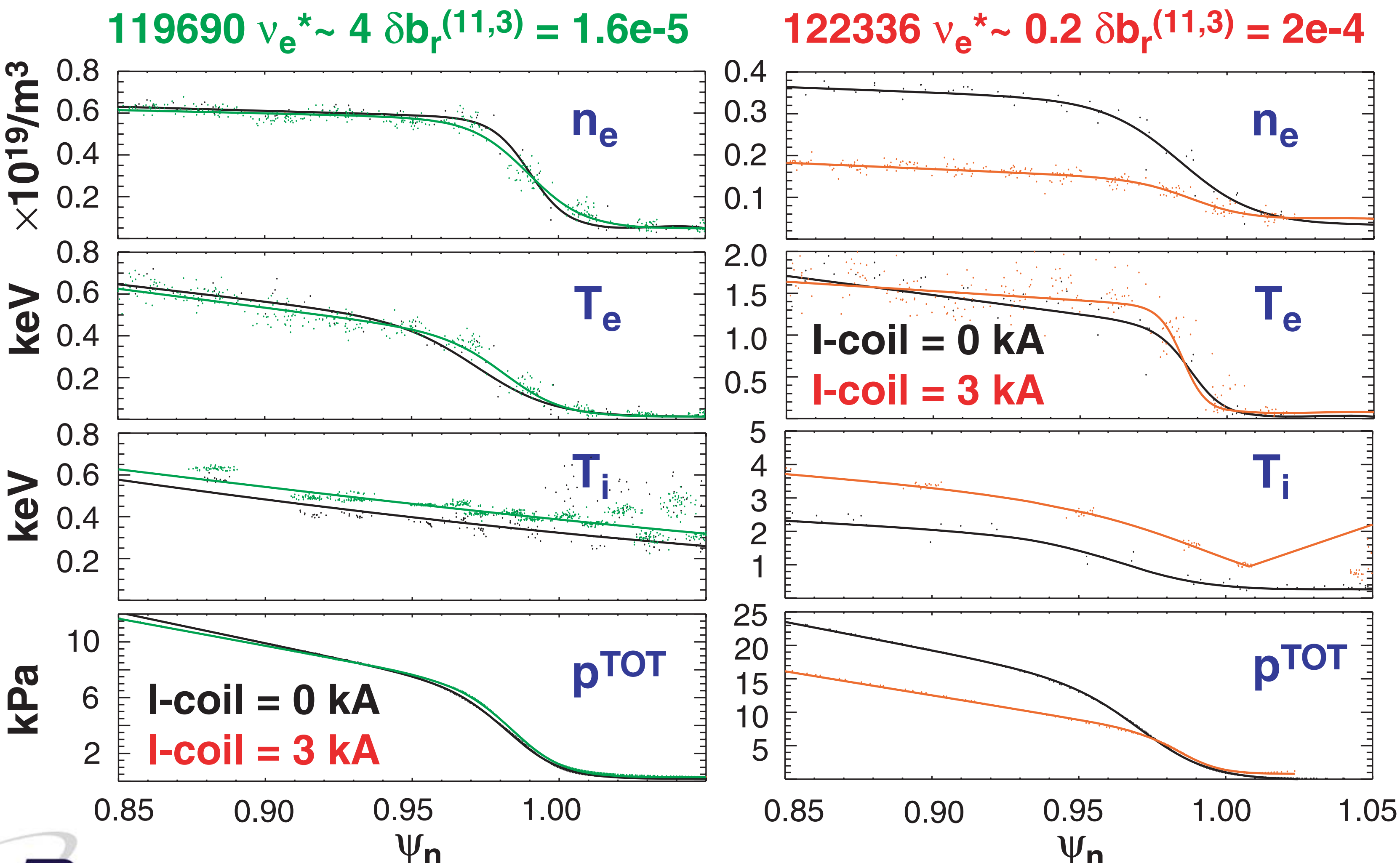




P.B. Snyder, ***next*** contrib. oral BO3.00009

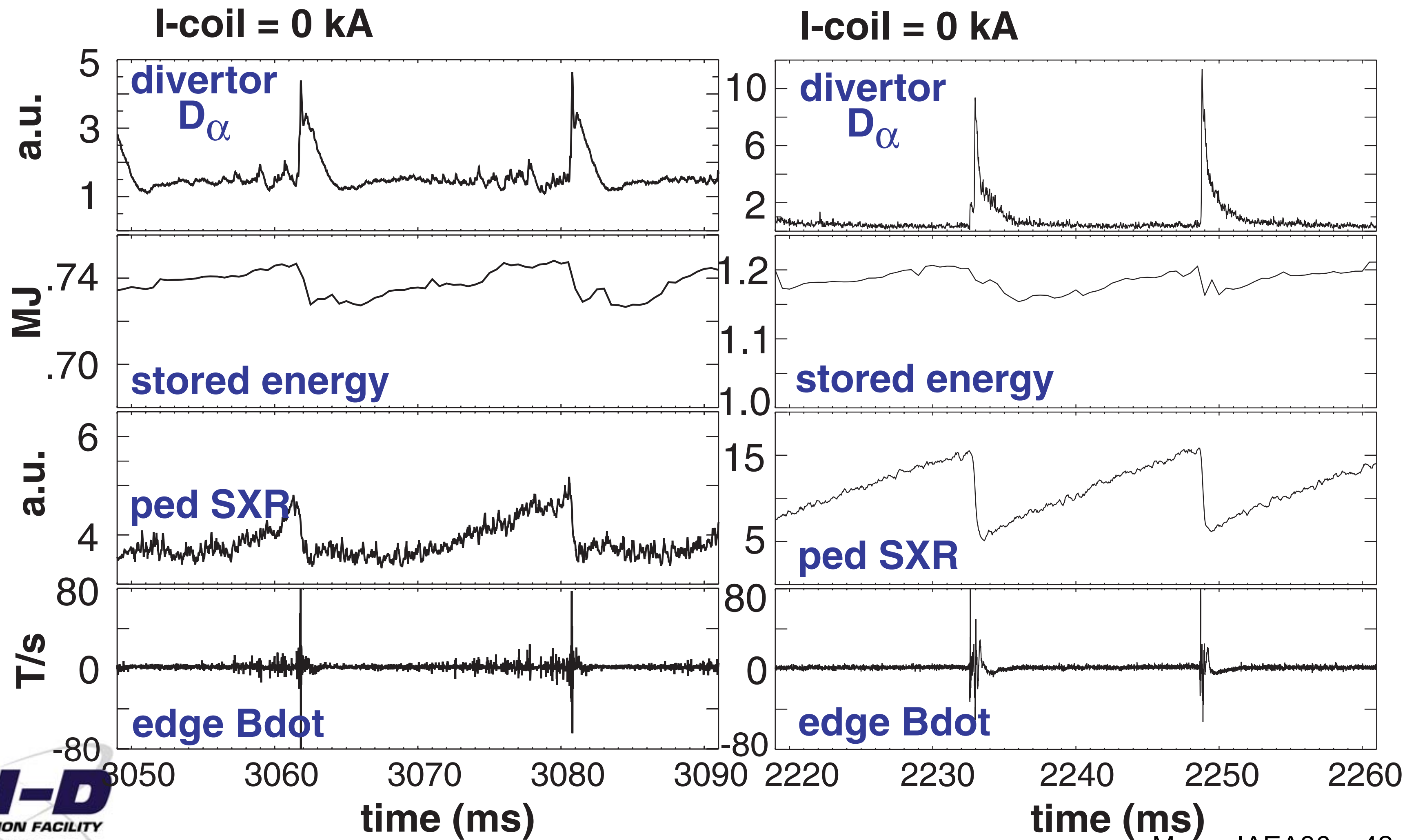
I-coil RMP has largest effect on density profile, not T_e profile.

- Not consistent with stochastic layer transport models .



- Pedestal pressure decreases with increasing I-coil current

Pedestal thermal energy loss is correlated with bursts of magnetic fluctuations.



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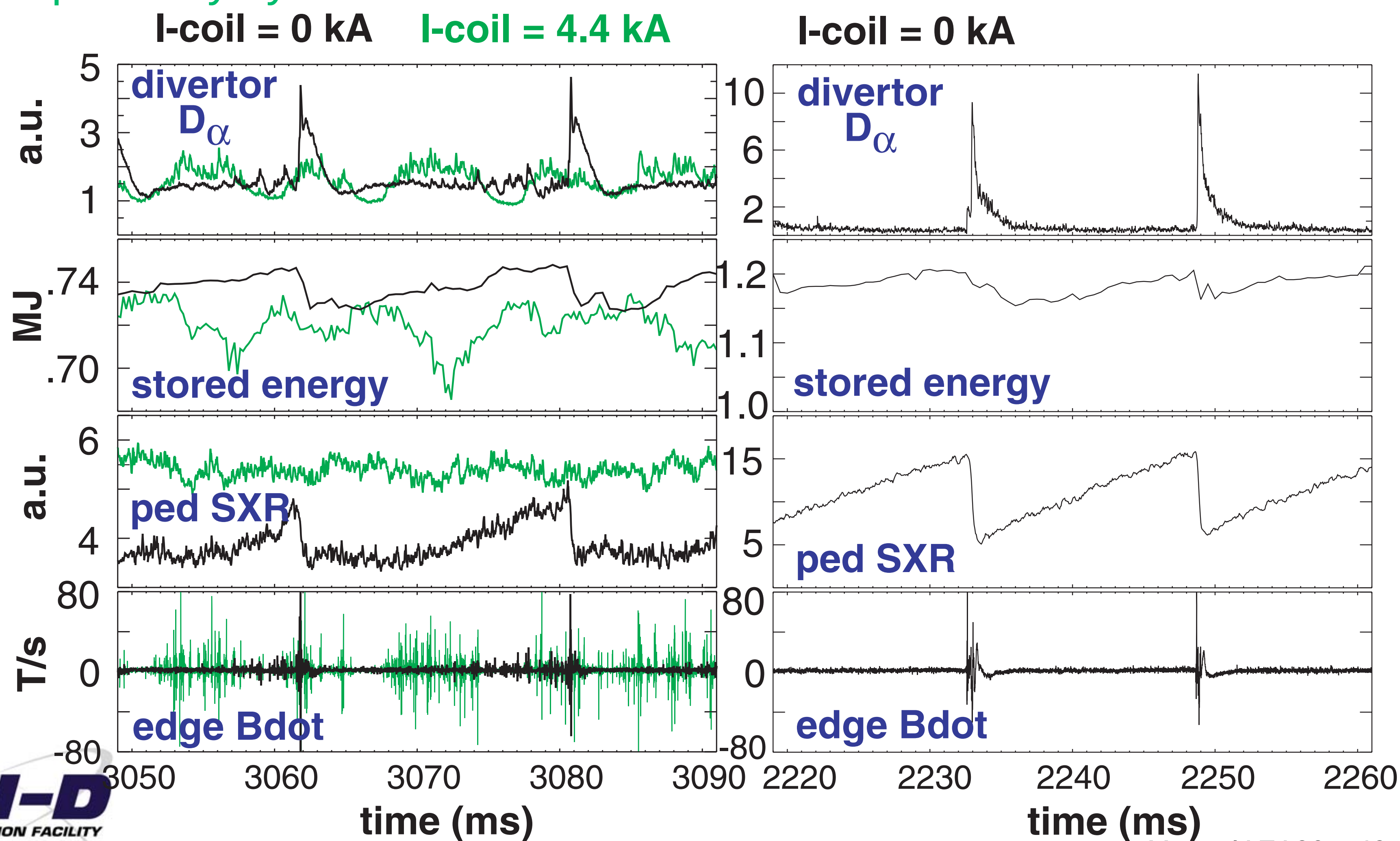
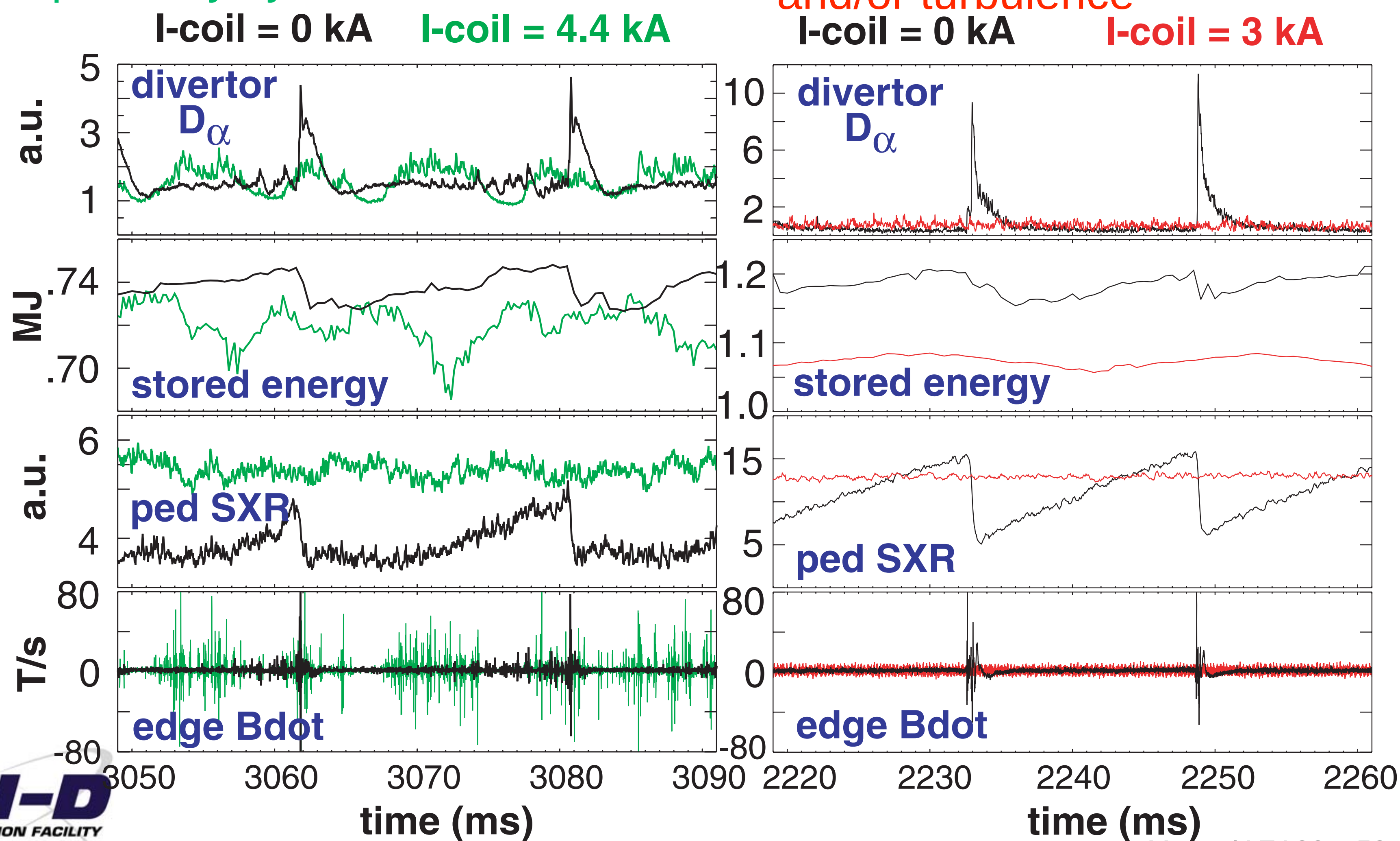
Pedestal thermal energy loss is correlated with bursts of magnetic fluctuations.

- At $\nu_e^* \sim 4$, enhanced small events → MHD mode → transport duty cycle increases



Pedestal thermal energy loss is correlated with bursts of magnetic fluctuations.

- At $\nu_e^* \sim 4$, enhanced small events → MHD mode → transport duty cycle increases
- At $\nu_e^* \sim 0.2$, no small events ∅ quiescent → stochastic transport and/or turbulence



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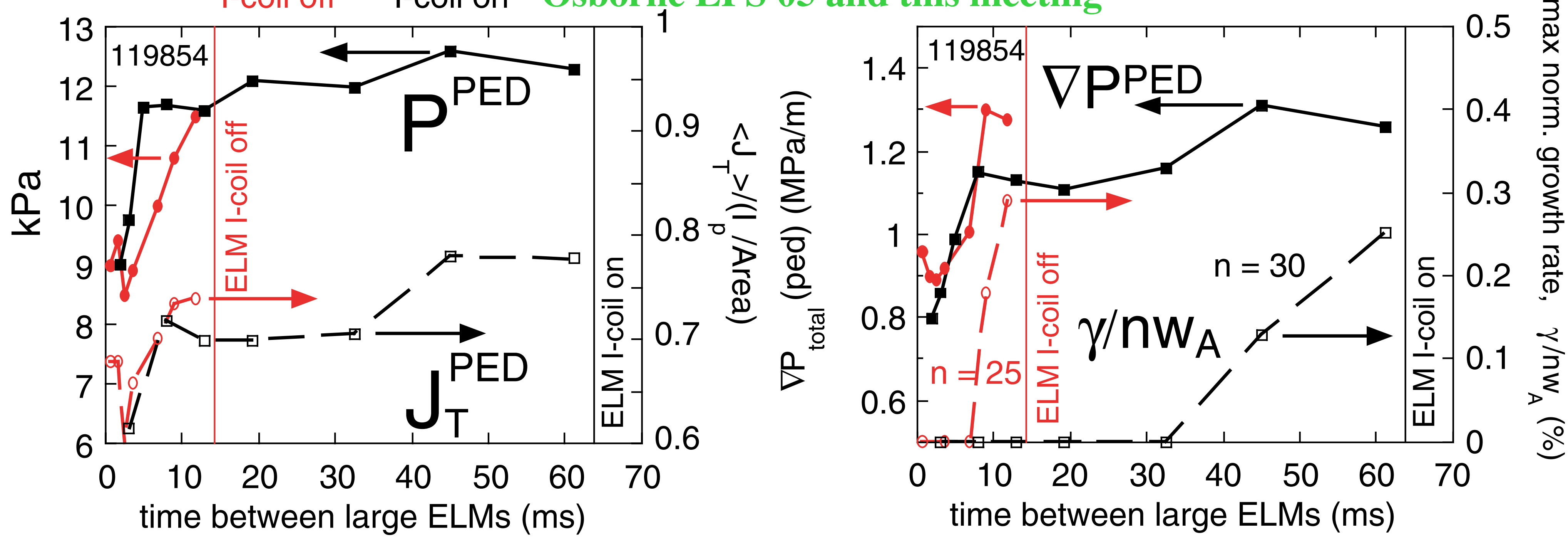
Recovery of pedestal ∇P to marginal stability slowed by small events during I-coil perturbation.

- Pedestal pressure P^{PED} & current J_T^{PED} similar after Type I ELM
- P^{PED} & J_T^{PED} **>** before Type I ELM with I-coil.
- Pedestal width > with I-coil

- Pedestal pressure gradient ∇P^{PED} recovers to marginally stable level more slowly

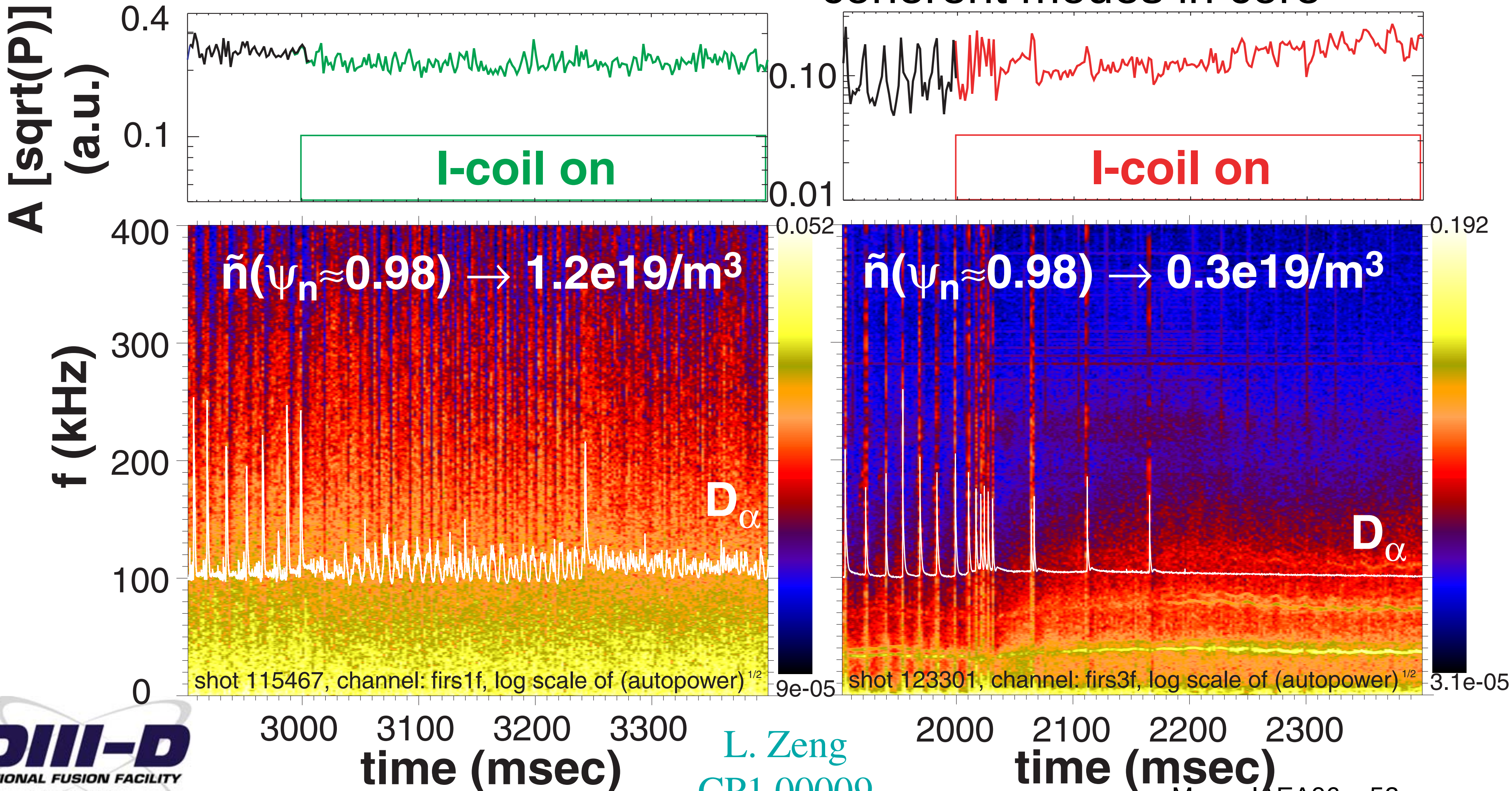
  14 ms (I-coil off) → 64 ms (I-coil on)

Osborne EPS 05 and this meeting



Density fluctuations in the pedestal change.

- At $\nu_e^* \approx 4$, $\tilde{n}_{rms}$ ~ constant, but more intermittency due to small ELM-like events
- At $\nu_e^* \approx 0.2$, $\tilde{n}_{rms}$ increases as ELMs stop
- coherent modes in core



L. Zeng
CP1.00009

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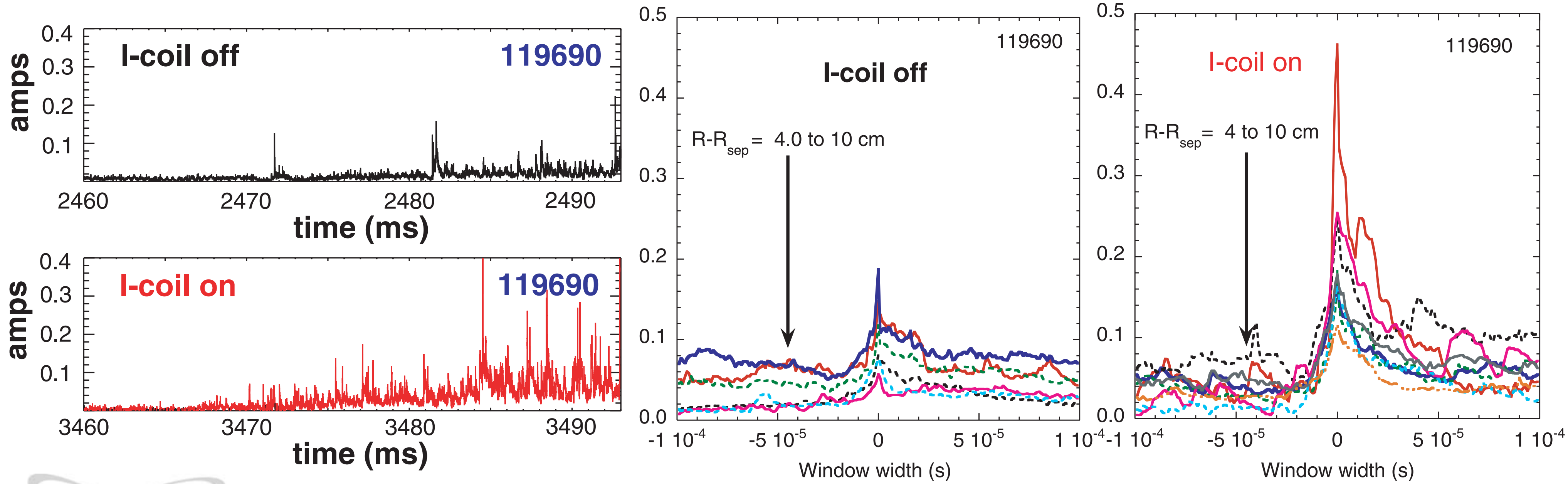
Intermittent transport during I-coil broadens the SOL and increases particle flux to wall

- Intermittent SOL transport increases during I-coil pulse.
- For $\nu_e^* \geq 1$, burst freq. increases 2×, amplitude increases 2–3×
- radial particle flux increases 2–3×
- Increased power and particle flux to main chamber wall instead of divertor.

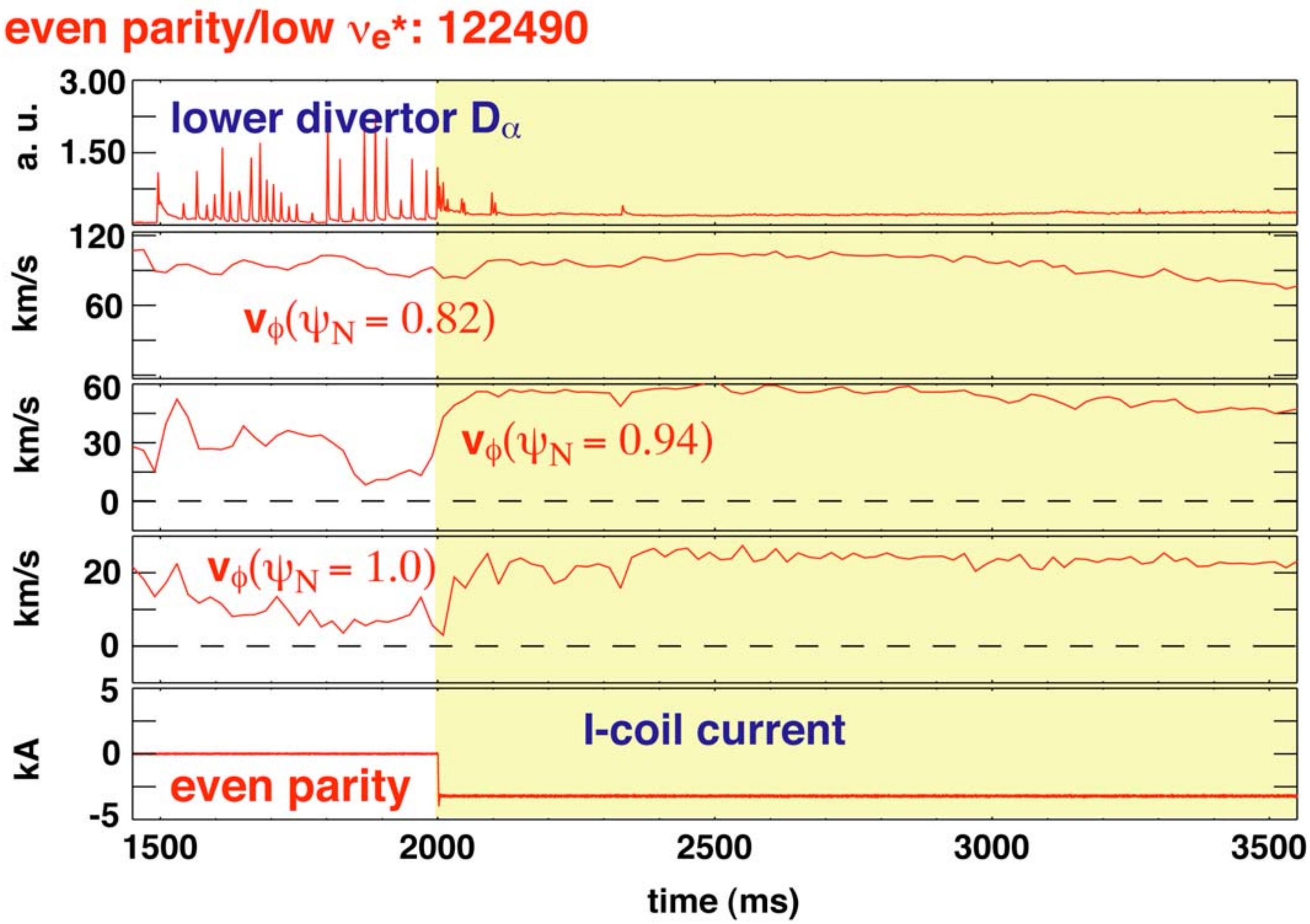
Reciprocating probe I_{sat} near outer midplane



J.A. Boedo et al. this meeting

Even parity I-coil: ELM-free H-modes at ITER-relevant ν_{e*}

T. E. Evans, K. H. Burrell, M. E. Fenstermacher, *et al.*, Phys. Plasmas, in press.



- **Low density**
  ν_{e*} ~ 0.1
- **Type-I ELMs vanish within** resonant **q_{95}-window**
- **Edge rotation** increases **after ELMs dissapear**

- **Plasma maintains equilibrium for long times (unlike usual ELM-free)**
- **Steady-state transport must replace ELM transport**

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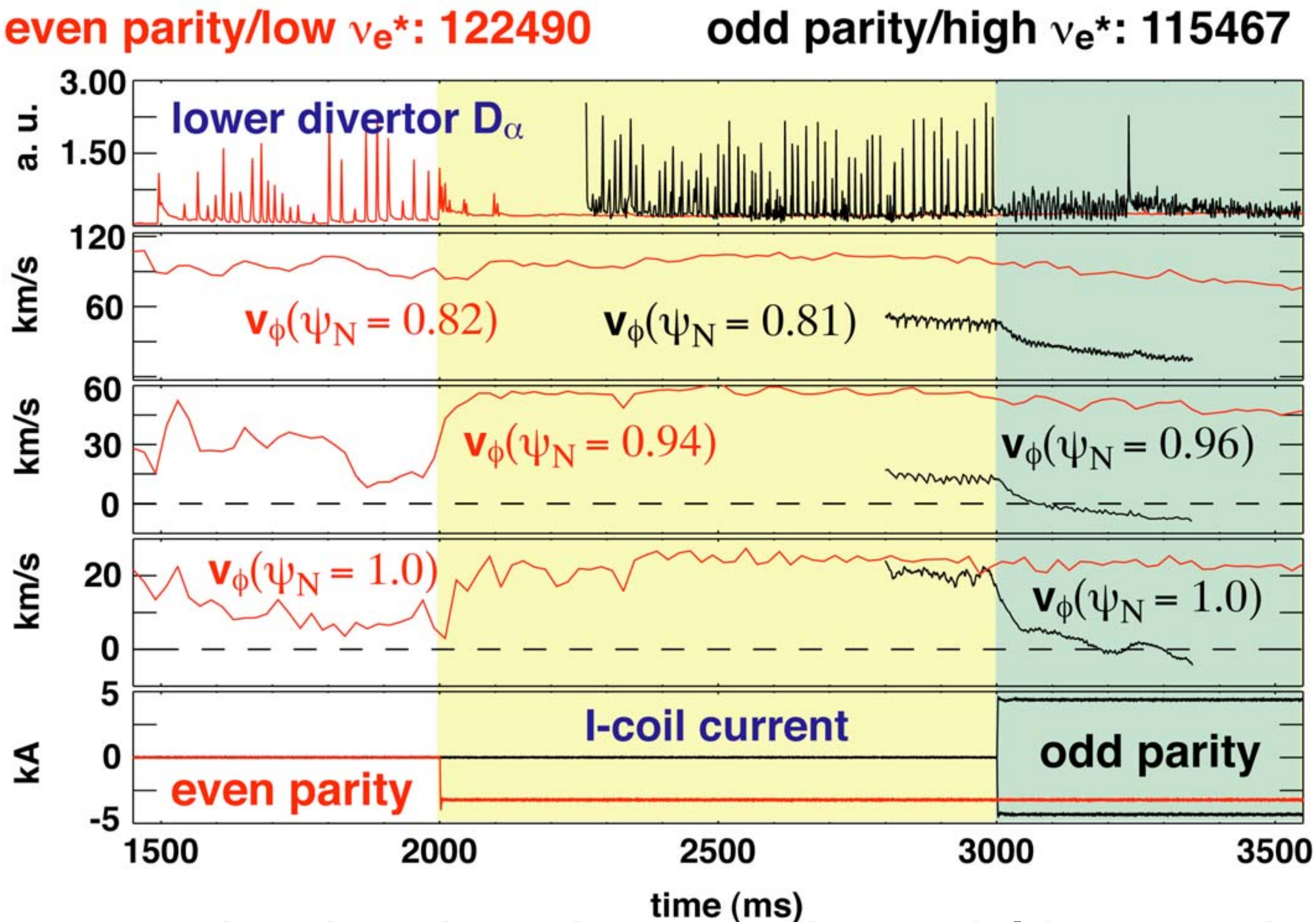
Odd parity I-coil: Type-I ELM-suppression

R. A. Moyer, T. E. Evans, T. H. Osborne, *et al.*, Phys. Plasmas 12 (2005) 056119.



- **Rotation damping taken as a sign of field penetration**

- **High density**
  ν_{e*} ~ 1

- **Type-I ELMs replaced with small Type-II grassy ELMS?**

- **Edge rotation** decreases **immediately after I-coil is energized**