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

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In collaboration with:

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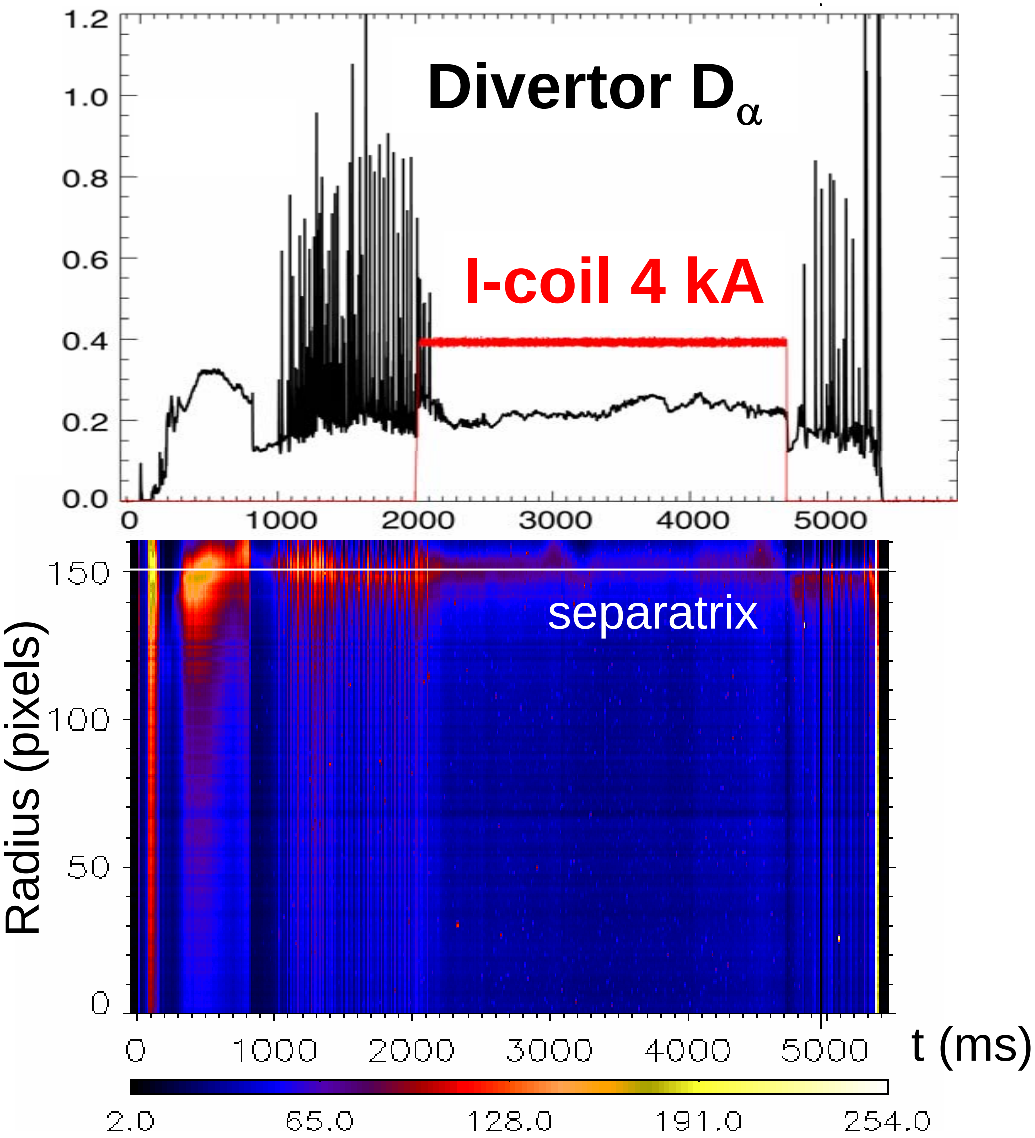
UCSD

Edge resonant RMPs suppress Type I ELMs in DIII-D

- **Pedestal becomes very quiet as imaged in CIII light (J. Yu, this mtg.).**

QuickTime™ and a
decompressor
are needed to see this picture.

126003, CIII



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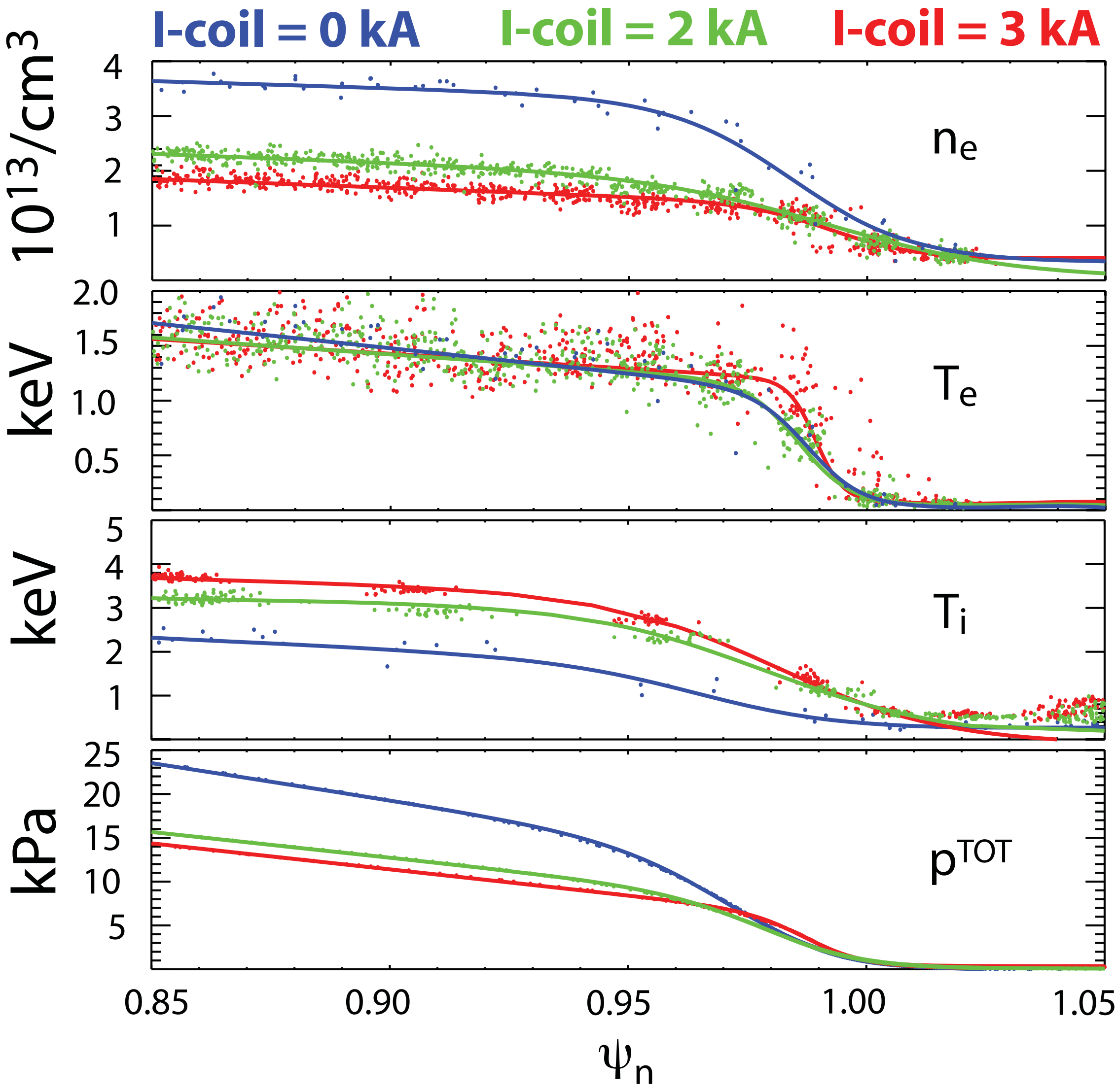
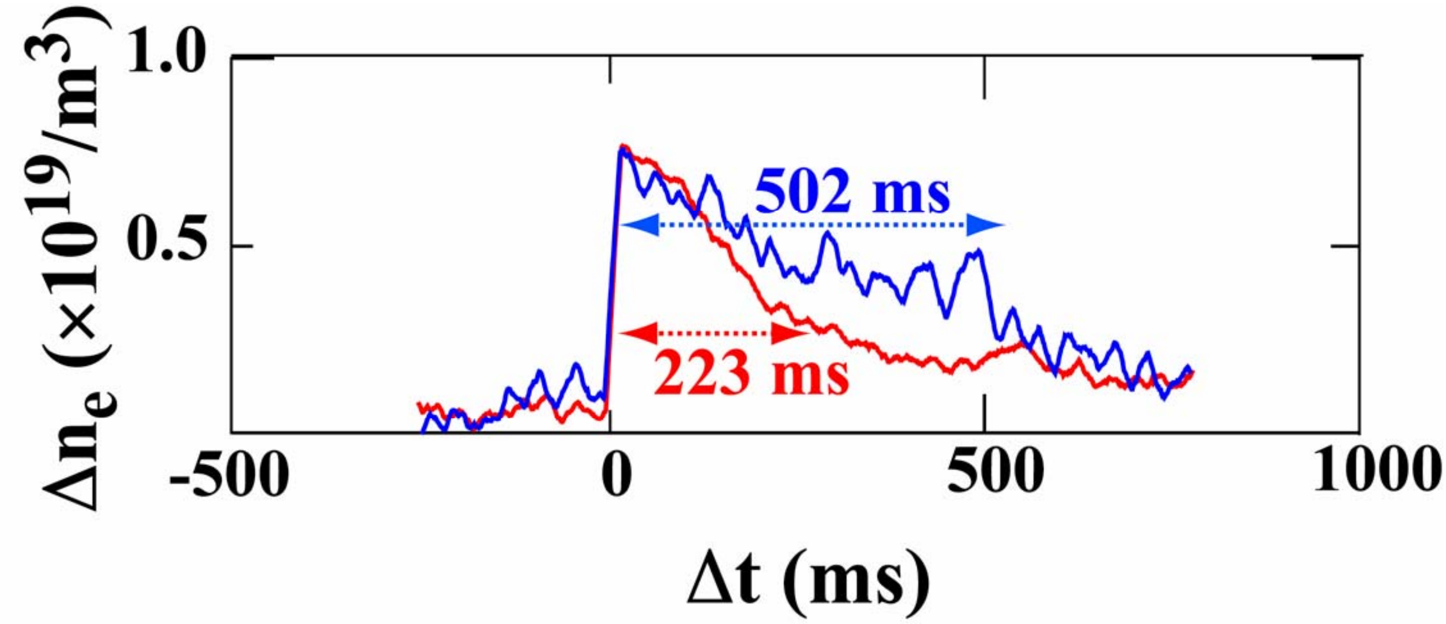
Paradox: why does RMP have large effect on pedestal density but little on pedestal T_e?

- **global particle balance change**
  - QL estimate →3-4x increase in D_{eff}
- **T_e profile flattens at top of pedestal**
  - qualitatively consistent with QL estimate
  - quantitatively consistent for $0.85 < \psi_n < 0.94$ with transport analysis by Stacey and Evans
- **T_e increases for $0.98<\psi_n< 1$**



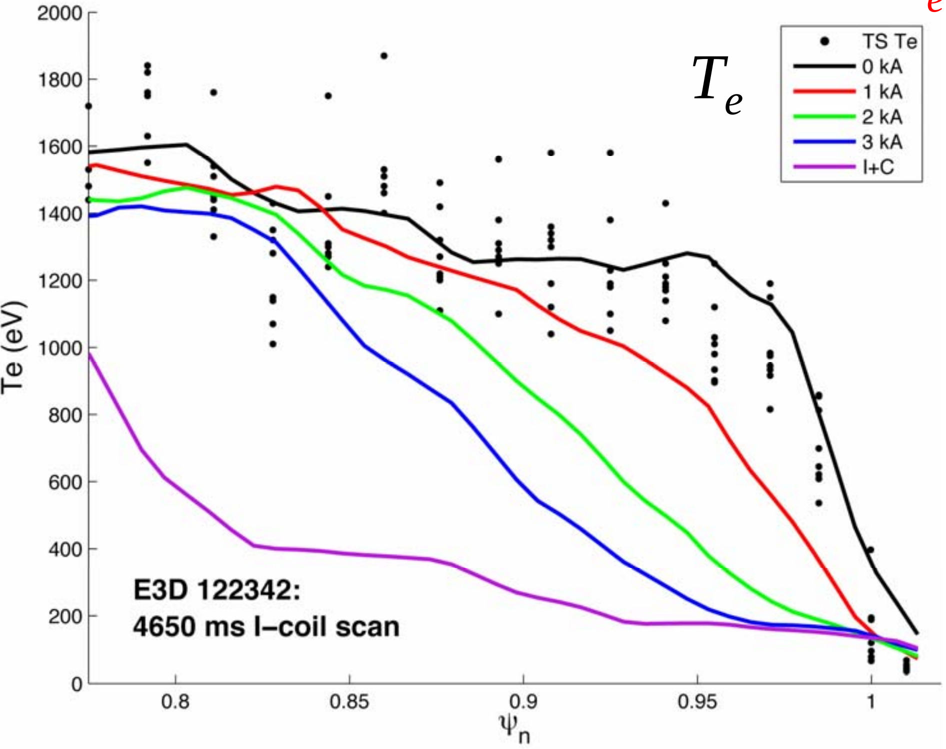
Pellet perturbation experiments confirm that τ_p^* is reduced a factor of 2.

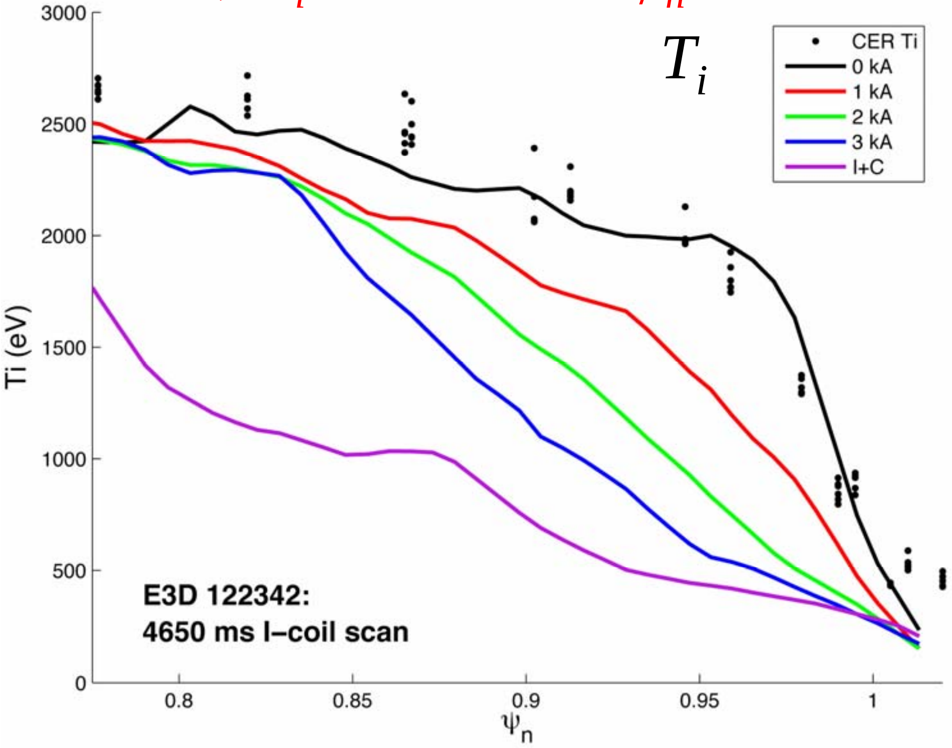
- **Identical pellets injected into discharges with $\nu_e^* \sim 0.2$, $\delta \sim 0.7$, and similar recycling conditions → τ_p changes**
  - I-coil = 0 kA, ELMing H-mode
  - I-coil = 4 kA, RMP-assisted ELM-free H-mode



Heat transport modeling of stochastic layer with E3D fluid Monte Carlo code predicts T_e pedestal collapse

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





- **Constant temperature BC's (more power into edge as I-coil current increases to maintain inner boundary T_e)**
- **Result is consistent with conventional expectations for electron thermal transport in a stochastic layer**

Joseph JNM in press (2007)

Possible resolutions to the paradox of particle pumpout without increased electron thermal transport

- **Rotational screening of the RMP:**
  - Seen in MHD simulations with JORIK code (E. Nardon et al.)and preliminary NIMROD extended MHD code runs (V. Izzo and I. Joseph, Sherwood Theory mtg.)
  - If δb_r doesn't penetrate, then what changes the global particle balance?
- **Tokar model: combined impact of:**
  - particle flows along perturbed **B**
  - reduction of neoclassical perpendicular transport with decreasing density
  - nonlocality of parallel electron heat transport at low collisionality
- **Increased E x B convection across separatrix:**
  - Convection cells in MHD modeling (Nardon; Izzo) with enhanced resistivity, but weaken if resistivity is closer to experimental values
  - Leads to increased particle and electron thermal transport in fluid transport models without the heat flux limits

Tokar model [PRL 98 095001 (2007)] reproduces qualitative behavior of pedestal profiles:

- **combined impact of**
  - ll particle transport in stochastic field
  - neoclassical ⊥ transport $\kappa_\perp \sim n^2$
  - reduction of ll heat flux below free-streaming limit

$$\kappa_{\|} = \kappa_{\|}^{SH} \Big/ \left(1 + \frac{\xi_{SH}}{\xi_{FS}} \frac{\lambda}{L_T}\right)$$

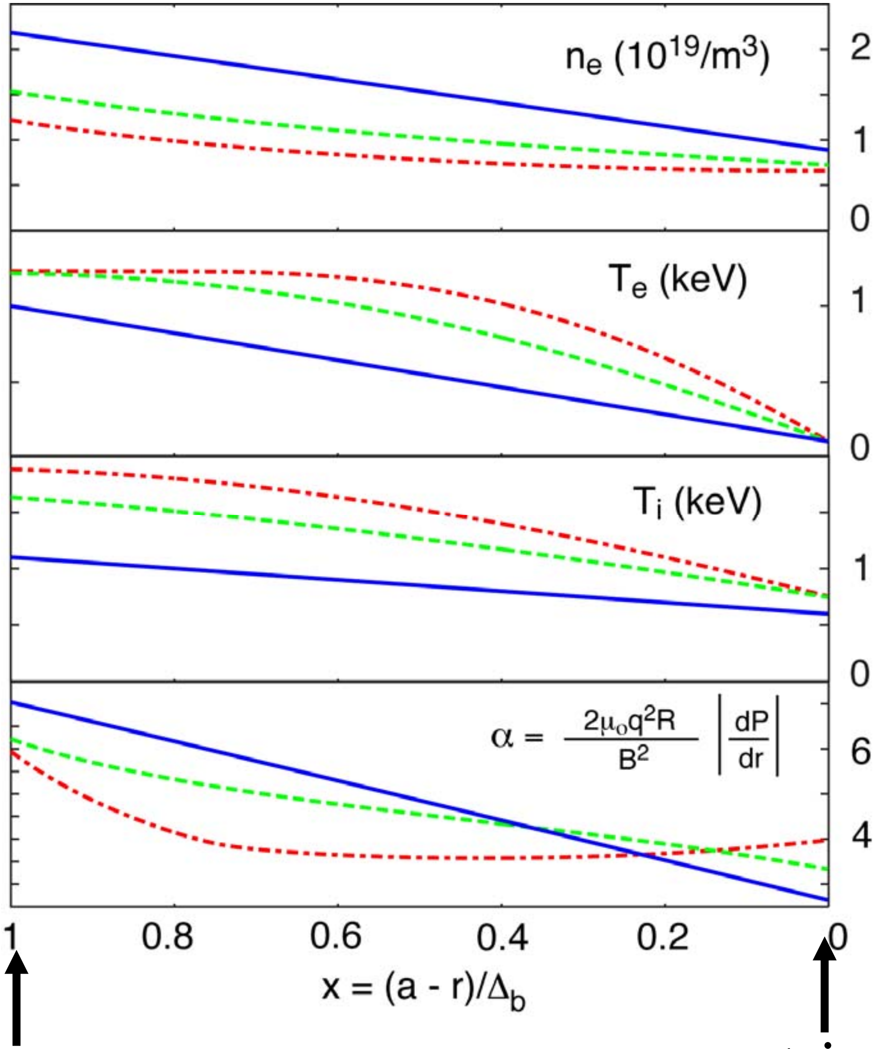
where $\xi_{SH} \approx 3$ and $\xi_{FS} \leq 0.1$

$$q_r \approx -\left(\kappa_\perp + \frac{\kappa_{\|}^{SH} \alpha_r^2}{1 + \alpha_r \dfrac{\xi_{SH}}{\xi_{FS}} \dfrac{\lambda}{T} \left|\dfrac{\partial T}{\partial r}\right|}\right) \frac{\partial T}{\partial r}$$

where the stochastic field is described by

$$\alpha_r = \sqrt{D_{FL}/L_K}$$

with D_{FL} = field line diffusivity and L_K = Kolmogorov length

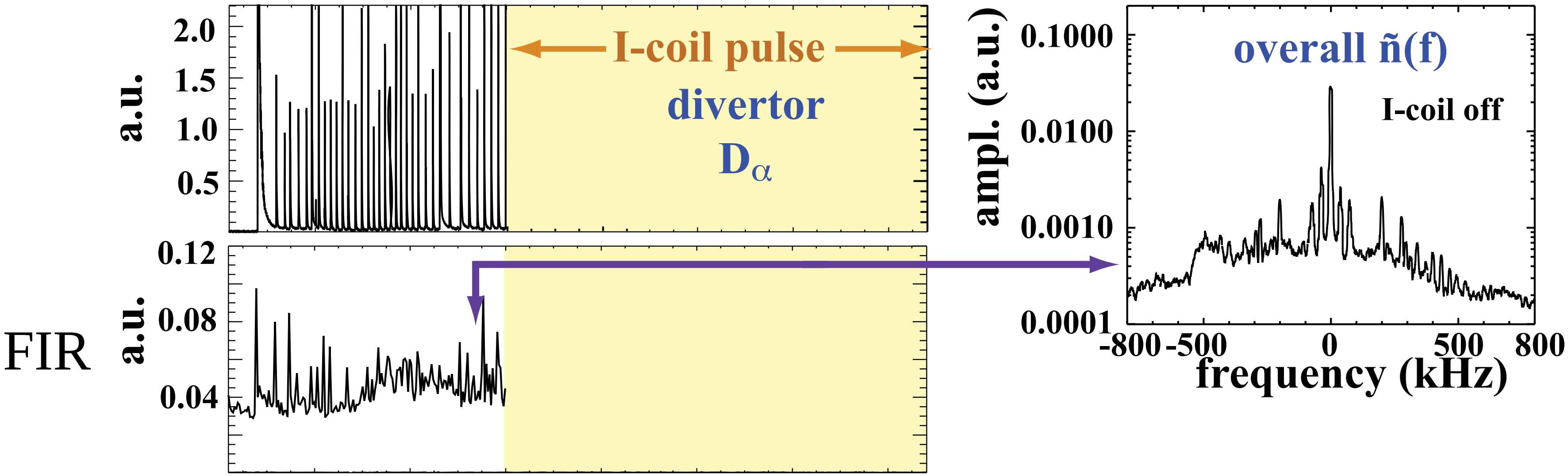


Top of electron barrier

separatrix

Increased particle transport may be due to increased fluctuation-driven E x B convective transport.

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



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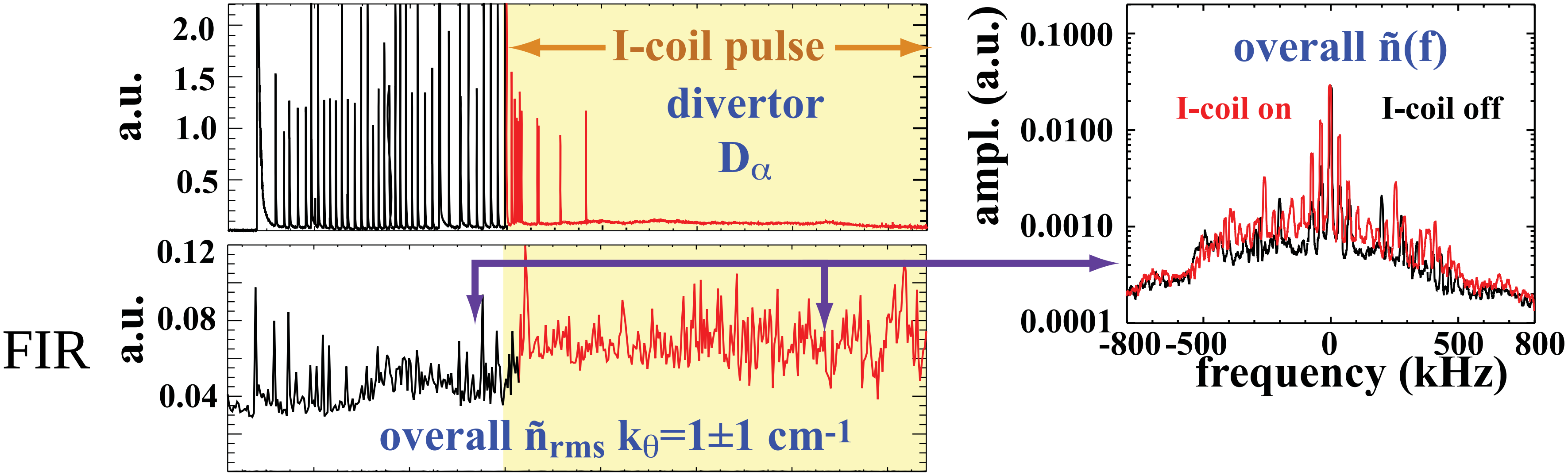
- **FIR scattering: $k_\theta = 1\ cm^{-1}$ not spatially localized → increased coherent modes and broadband turbulence → 1.5x increase in $\tilde{n}_{rms}$**



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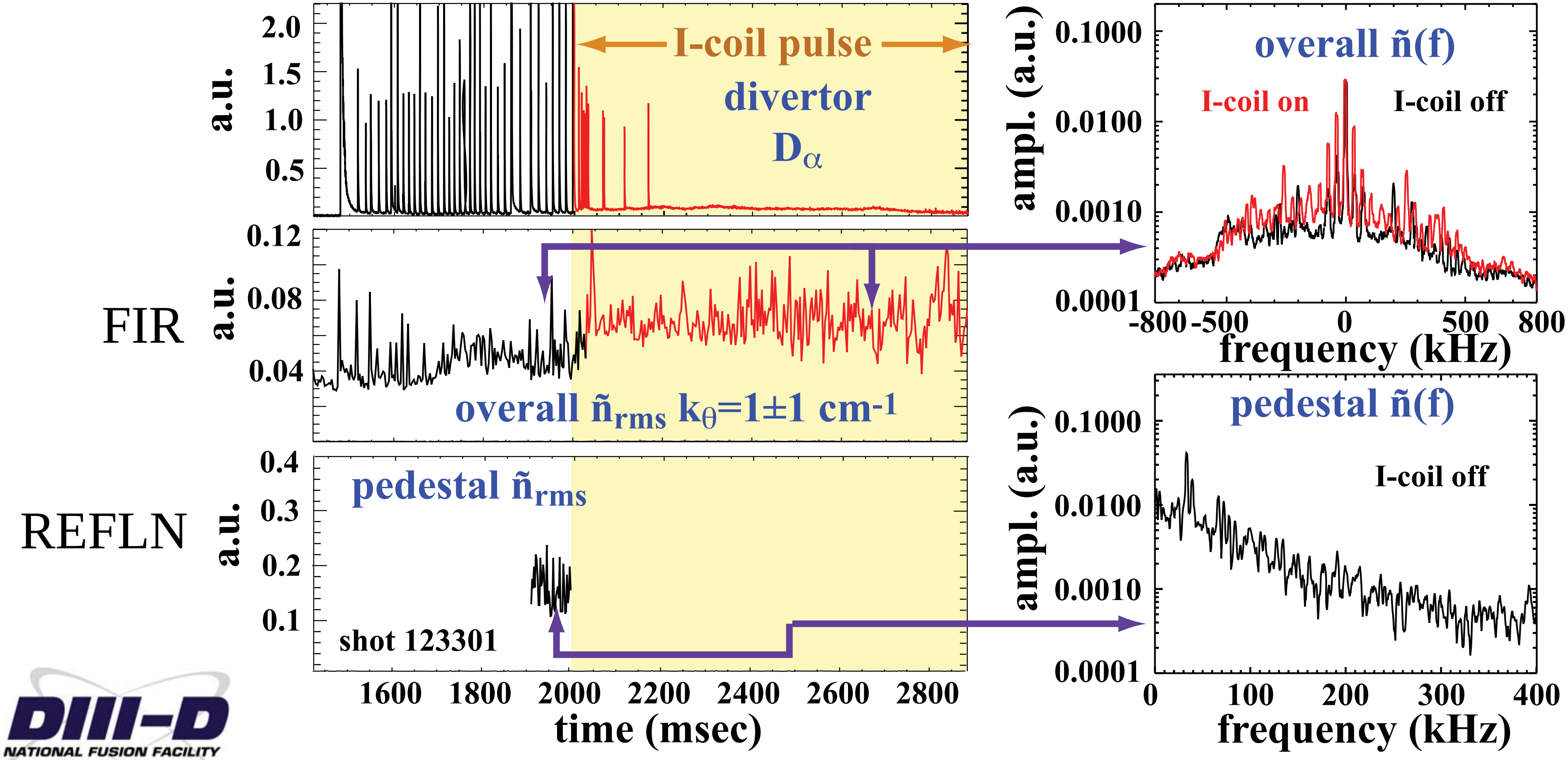

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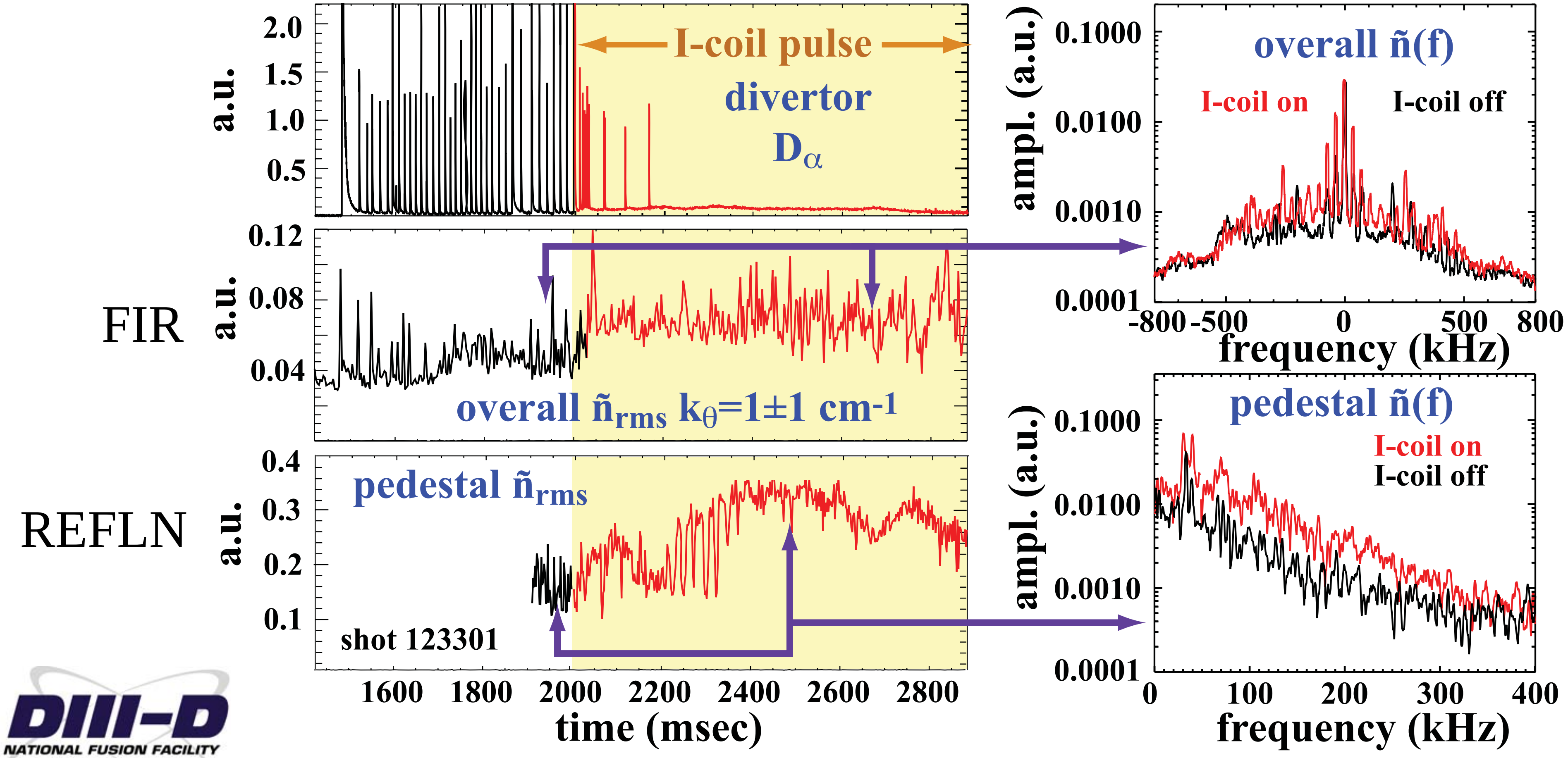
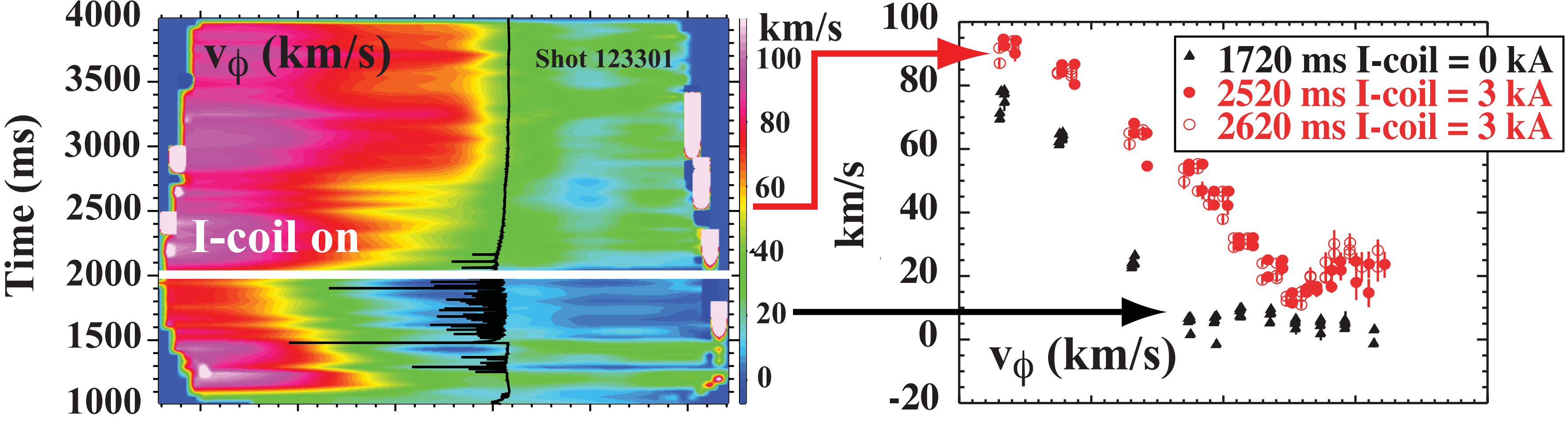
- FIR scattering: k_θ = 1 cm^{-1} not spatially localized → increased coherent modes and broadband turbulence → 1.5x increase in $\tilde{n}_{rms}$
- reflectometry: localized to pedestal → increased turbulence → 2x increase in $\tilde{n}_{rms}$
- $D_{eff} \sim \tilde{n}_{rms}^2$ → D_{eff} increases 3-4x,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



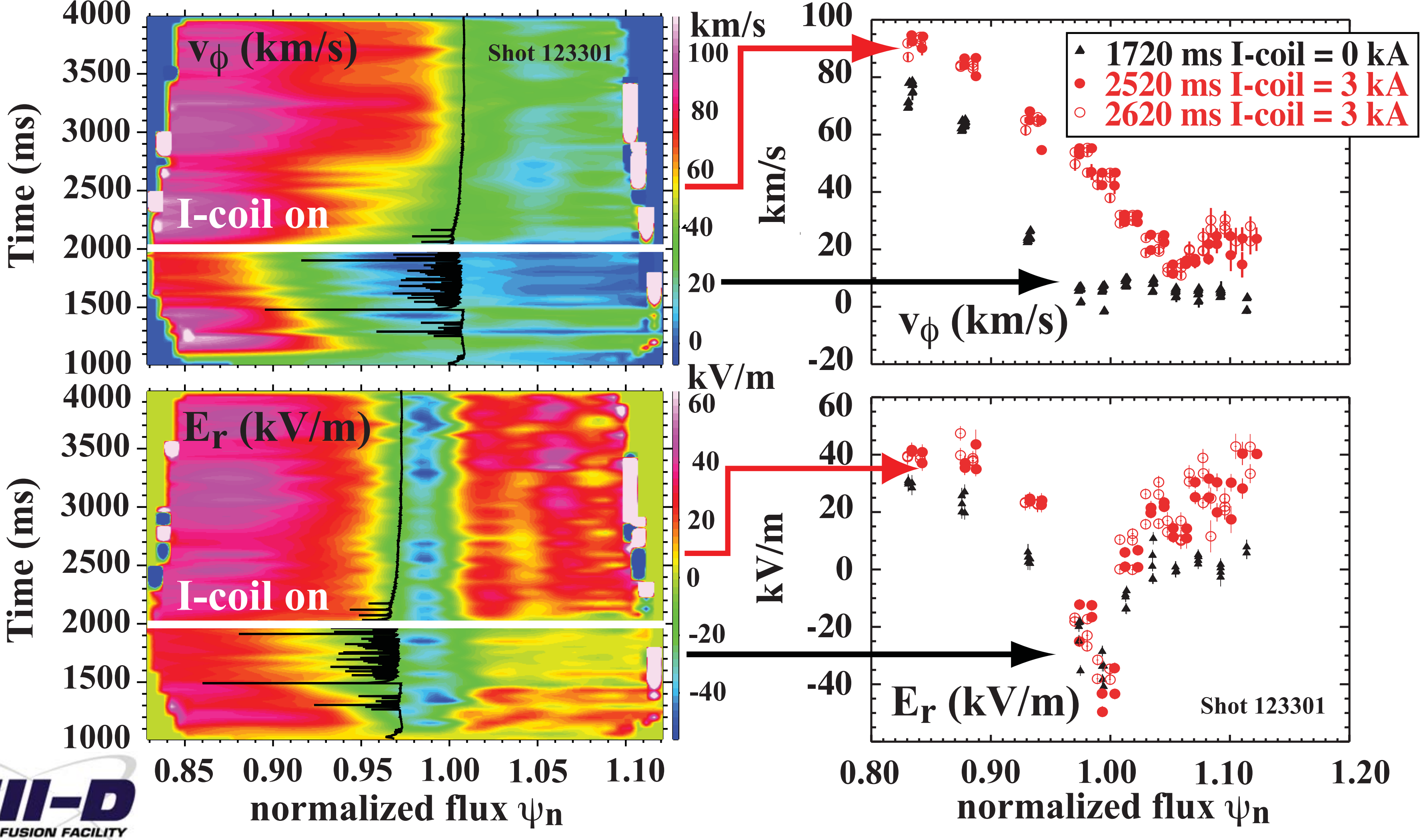
Pedestal toroidal rotation and E_r change promptly when RMP is applied and edge q resonant (3.4 < q95 < 3.7).

- **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).

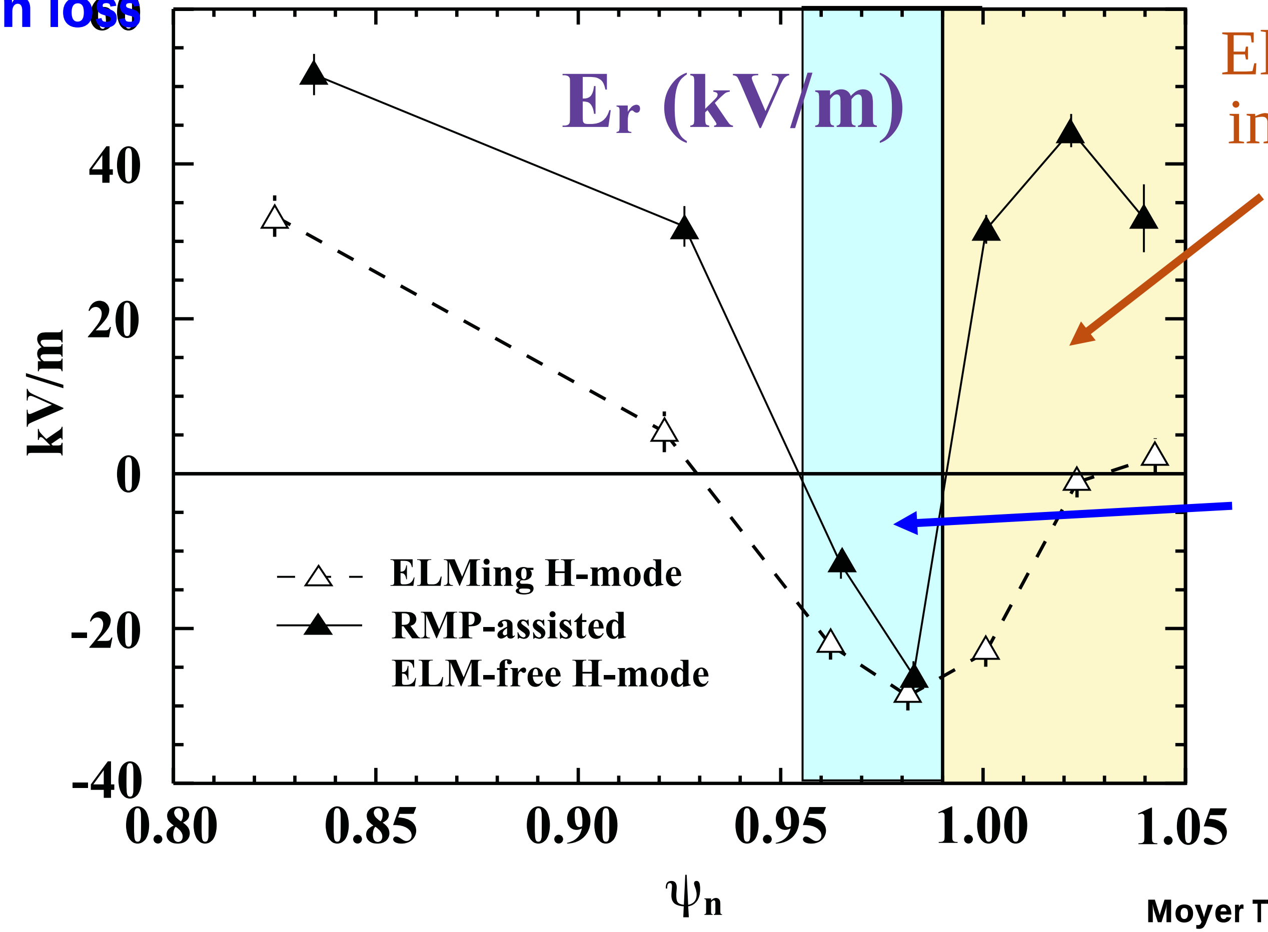
- **H-mode pedestal v_ϕ spins up and E_r well narrows.**



E_r well formed by balance between X-pt ion orbit loss and rapid electron loss in stochastic field?

- **Outside of E_r well minimum, E_r becomes strongly positive all the way to the main chamber wall**
- **Persistence of E_r well: X-point structure is stable during RMP [Joseph] → continued ion orbit loss [Park, Chang] on top of rapid electron loss**

Some qualitative similarities to XGC simulations (Park et al., TTF 07)

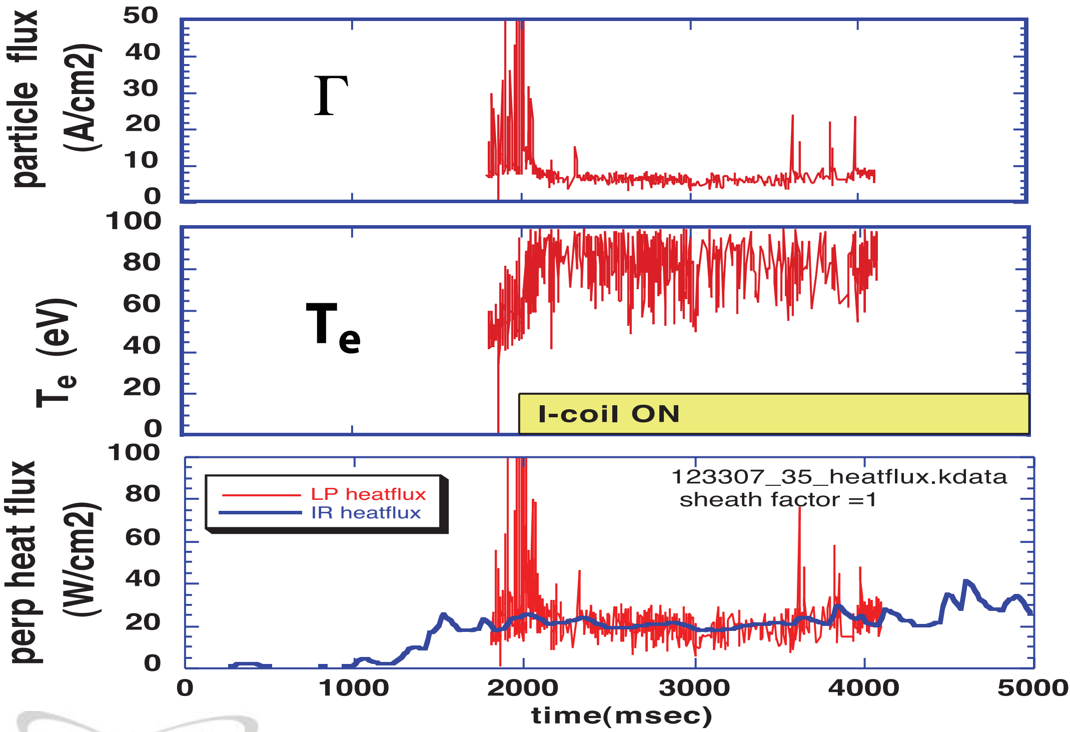


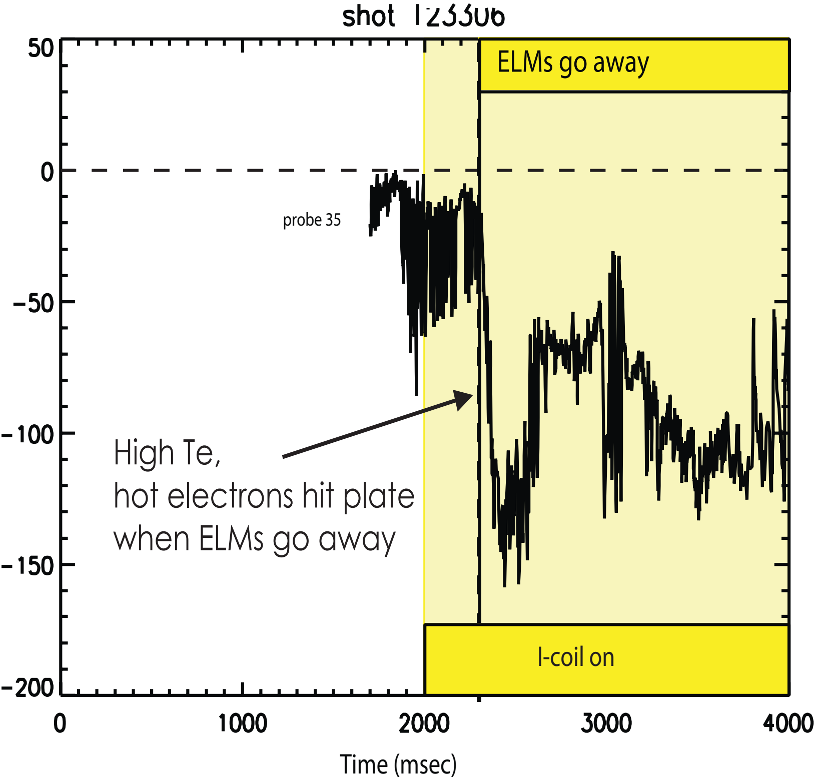
Electron loss in stochastic field

X-pt ion orbit loss

T_e rise near strike point and $V_{float} < 0$ during RMP are consistent with RMP penetration.

- **Hot electrons and negative floating potential are consistent with connection of field lines from inside the pedestal with the divertor target plates**
  - formation of a flux loss layer over at least the last few % inside the separatrix.

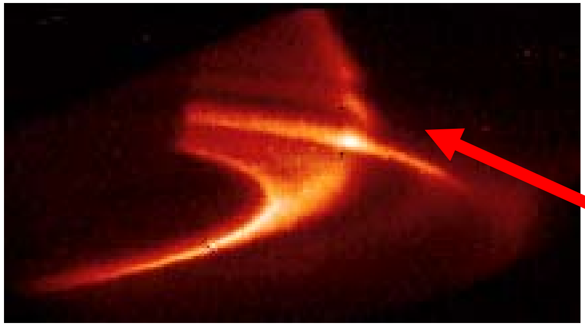




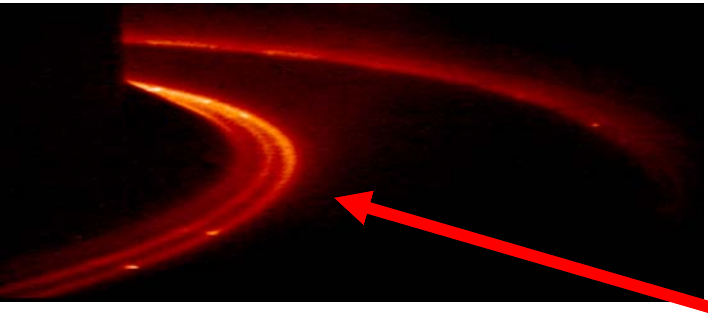
High Te, hot electrons hit plate when ELMs go away

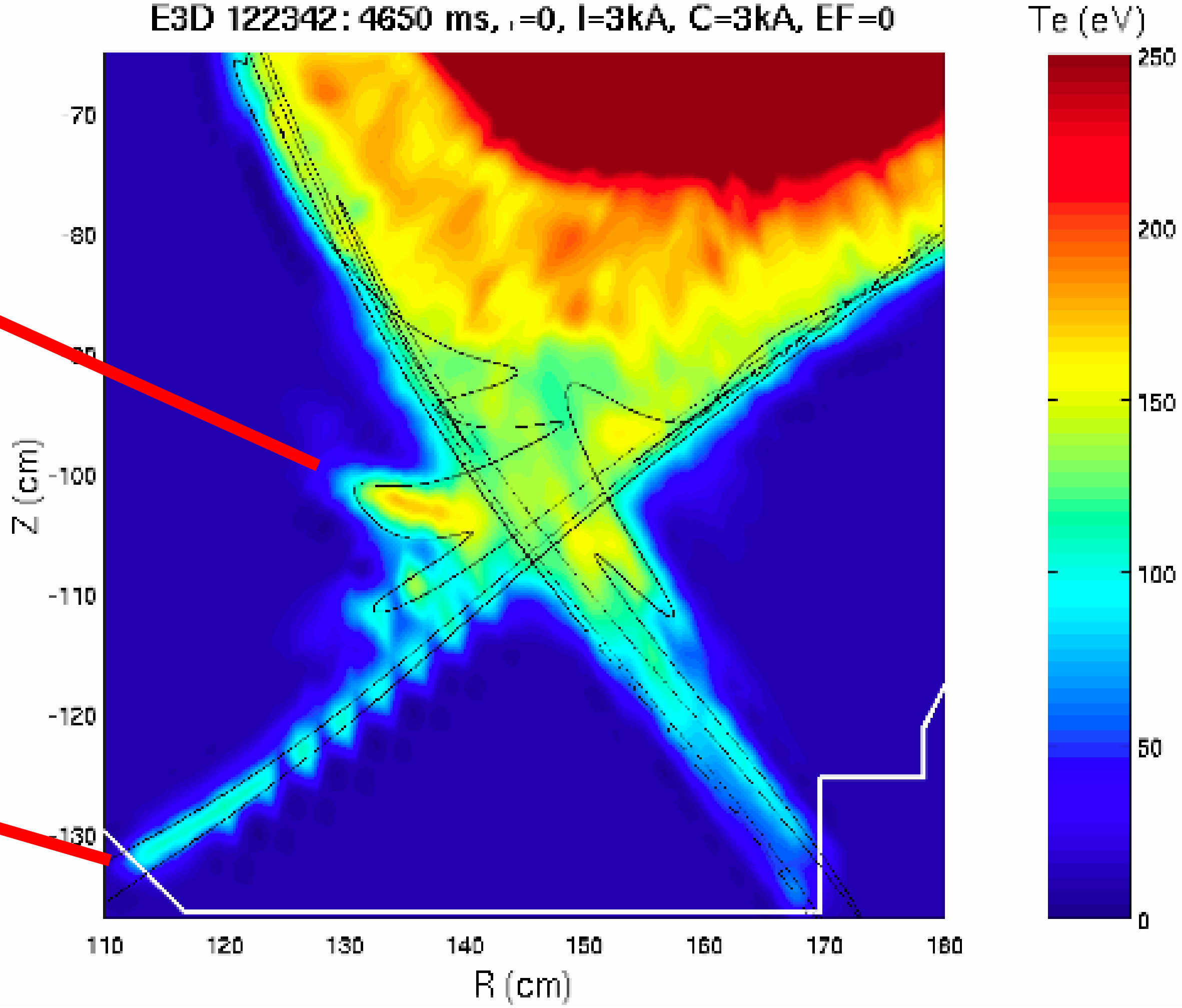
Xpt-TV experimental observations of “homoclinic tangle” confirm penetration of RMP at least into last few % in ψ_n.

123300: filtered CIII Xpt-TV



123301: filtered D_α Xpt-TV





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- **Demonstrates stability of X-point in presense of RMP**
- **Intersecting manifolds allow field lines to “tunnel” out of pedestal without island overlap ($\sigma_{CH} < 1$)**

Summary and Conclusions

- **RMP ELM control experiments pose a paradox for pedestal transport: how is the pedestal density reduced without any reduction in T_e?**
- **Does toroidal rotation screen the RMP?**
  - evidence for penetration at least to $\psi_n \sim 0.98$; NIMROD modeling underway to investigate δb_r(plasma)
  - If RMP is screened, what changes the particle balance?
- **Does RMP create $\underline{E} \times \underline{B}$ convection cells that enhance radial particle transport?**
  - Seen in high resistivity MHD simulations (JORIK & NIMROD) but the cells increase electron thermal transport as well (Izzo, NIMROD),
  - Cells become weaker at lower resistivity (Nardon, JORIK)
- **Do limits to the free-streaming parallel electron heat flux explain the low electron thermal transport?**
  - First suggested by S. Krasheninnikov; Tokar model is qualitatively consistent with experiment
- **RMP promptly alters—but doesn't destroy—H-mode E_r well**
  - similar to initial XGC results: balance between electron loss in stochastic field ($\phi \rightarrow$ positive) and X-point ion orbit loss ($\phi \rightarrow$ more negative)
  - ñ increases 2X &quasi-linear D_{eff} increases 4x, consistent with measured pedestal density profile change
- **We need a transport model that self-consistently treats both the H-mode edge transport barrier and the stochastic layer transport.**