Recent Results from RMP ELM suppression experiments in DIII-D

R.A. Moyer, J.A. Boedo, V.A. Izzo, I. Joseph,
S. Mordijck, D.L. Rudakov, J.H. Yu, *UCSD*

T.E. Evans, N.H. Brooks, T.H. Osborne, P. Gohil,
J.S. deGrassie, A.W. Leonard, T.W. Petrie *GA*

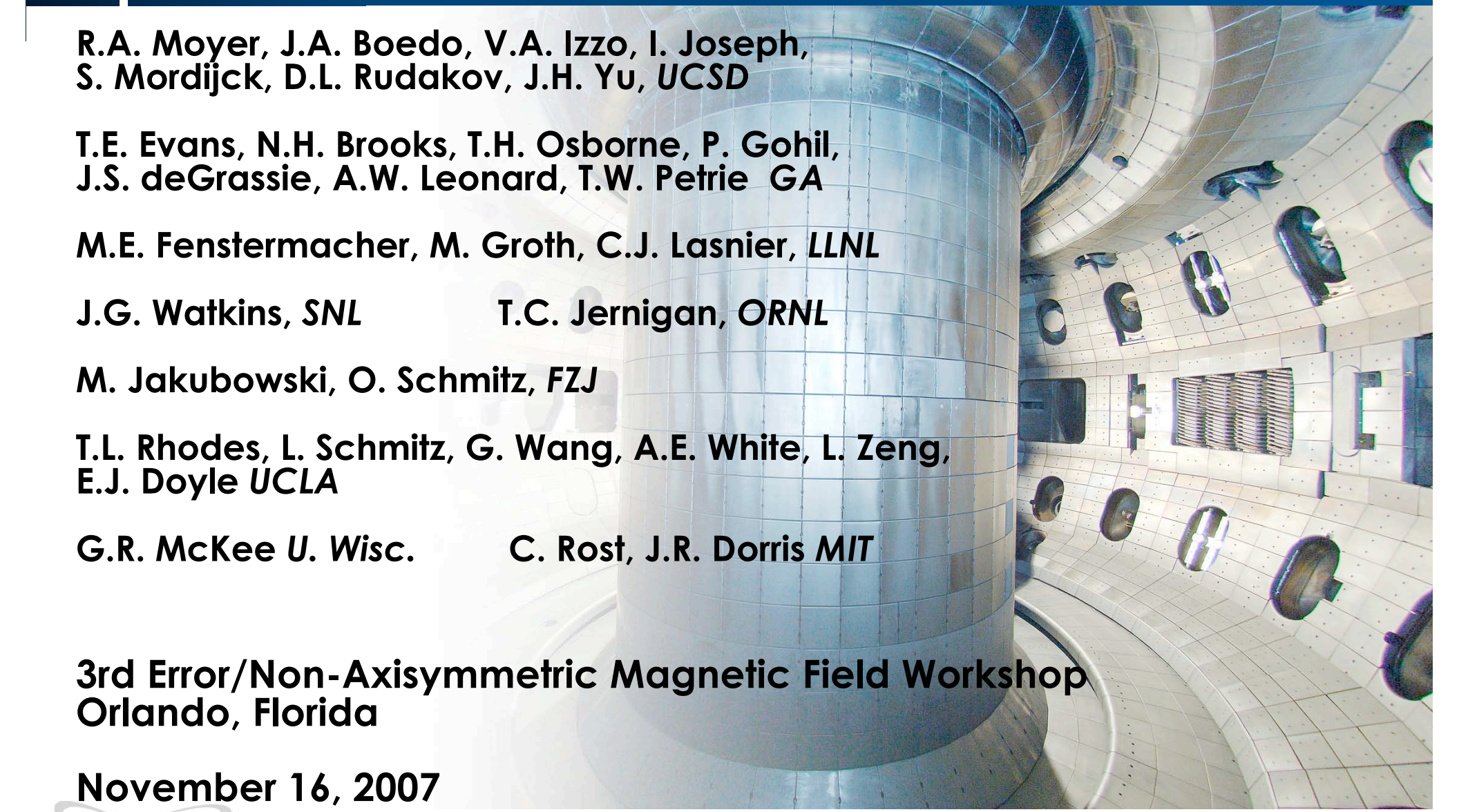
M.E. Fenstermacher, M. Groth, C.J. Lasnier, *LLNL*

J.G. Watkins, *SNL* T.C. Jernigan, *ORNL*

M. Jakubowski, O. Schmitz, *FZJ*

T.L. Rhodes, L. Schmitz, G. Wang, A.E. White, L. Zeng,
E.J. Doyle *UCLA*

G.R. McKee *U. Wisc.* C. Rost, J.R. Dorris *MIT*



3rd Error/Non-Axisymmetric Magnetic Field Workshop
Orlando, Florida

November 16, 2007

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UCSD

Recent results from RMP ELM suppression experiments highlight critical uncertainties

- **Plasma response to the RMP** is being investigated with 3 magnetic field models :
  - **TRIP3D vacuum field model** (no plasma response):
    - Predicts strike point footprints in the particle flux (but not heat flux) [O. Schmitz and M. Jakobowski, FZJ; Watkins, SNL; **Joseph, UCSD this workshop**]
    - Operationally predicts ELM suppression based on width of vacuum field magnetic island overlap region [Fenstermacher, et al.]
  - **IPEC Ideal Perturbed Equilibrium Code**: Park, Menard, and Boozer: **[Park, Boozer this workshop]**
    - Application to RMP ELM control cases beginning
    - 2-state magnetic field model:
      - outer % in Ψ_N with full vacuum field/stochastic → reproduce footprints
      - Ideal perturbed equilibrium inside of the stochastic region; where is the boundary between the perturbed equilibrium and the stochastic layer?
  - **Extended MHD:** JOREK [Nardon and Becoulet], NIMROD [Izzo, Kruger], M3D [Strauss]
    - Predict formation of E x B convection cells that enhance particle transport
    - Rotation leads to "screening" of the applied RMP, but not yet using rotation profile in experiments (counter-toroidal rotation just inside separatrix)
    - RMP rise time $\tau_{RMP} \rightarrow 0$ in toroidal simulations (Izzo); impact of finite $\tau_{RMP} \sim 20$ ms ~ τ_{rec} being investigated in reduced (slab) geometry [Kruger]

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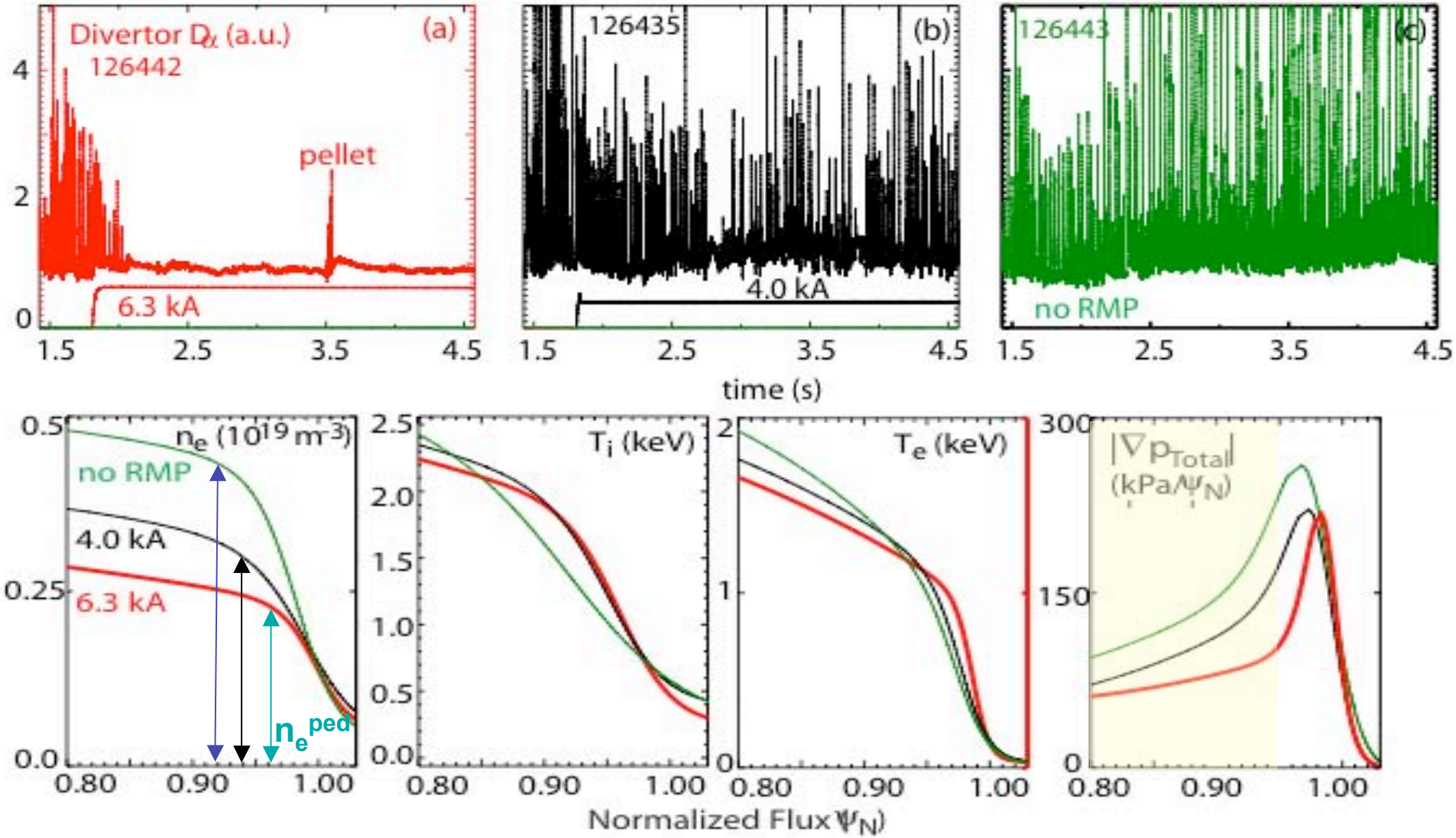
Plasma profile changes suggest that RMP effect in the region $0.8 < \Psi_N < 0.95$ might be important



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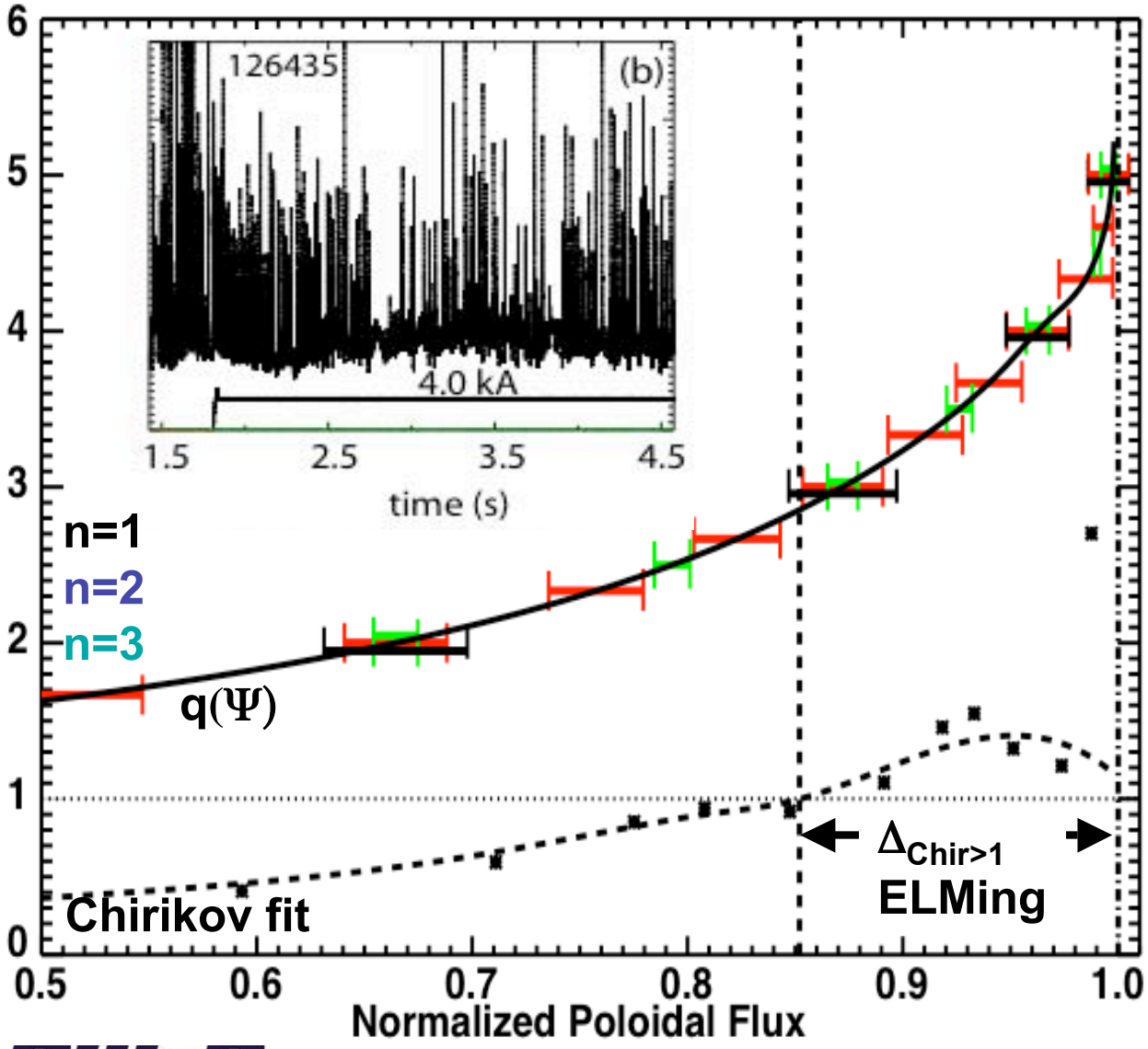
At Low I-coil Current Islands in Vacuum Field Model Overlap Beyond Pedestal But ELMs Remain



- Chirikov parameter σ_{CH} = (average island size) / (island separation)
- Strong stochasticity for $\sigma_{CH} > 1.0$
- Vacuum island overlap (SURFMN) satisfies Chirikov parameter > 1.0 from edge to $\Psi_N = 0.85$
  - $\Delta_{Chir>1} = 0.15$
- Note $\Delta_{Chir>1} / \Delta_{ped} \sim 2.8$

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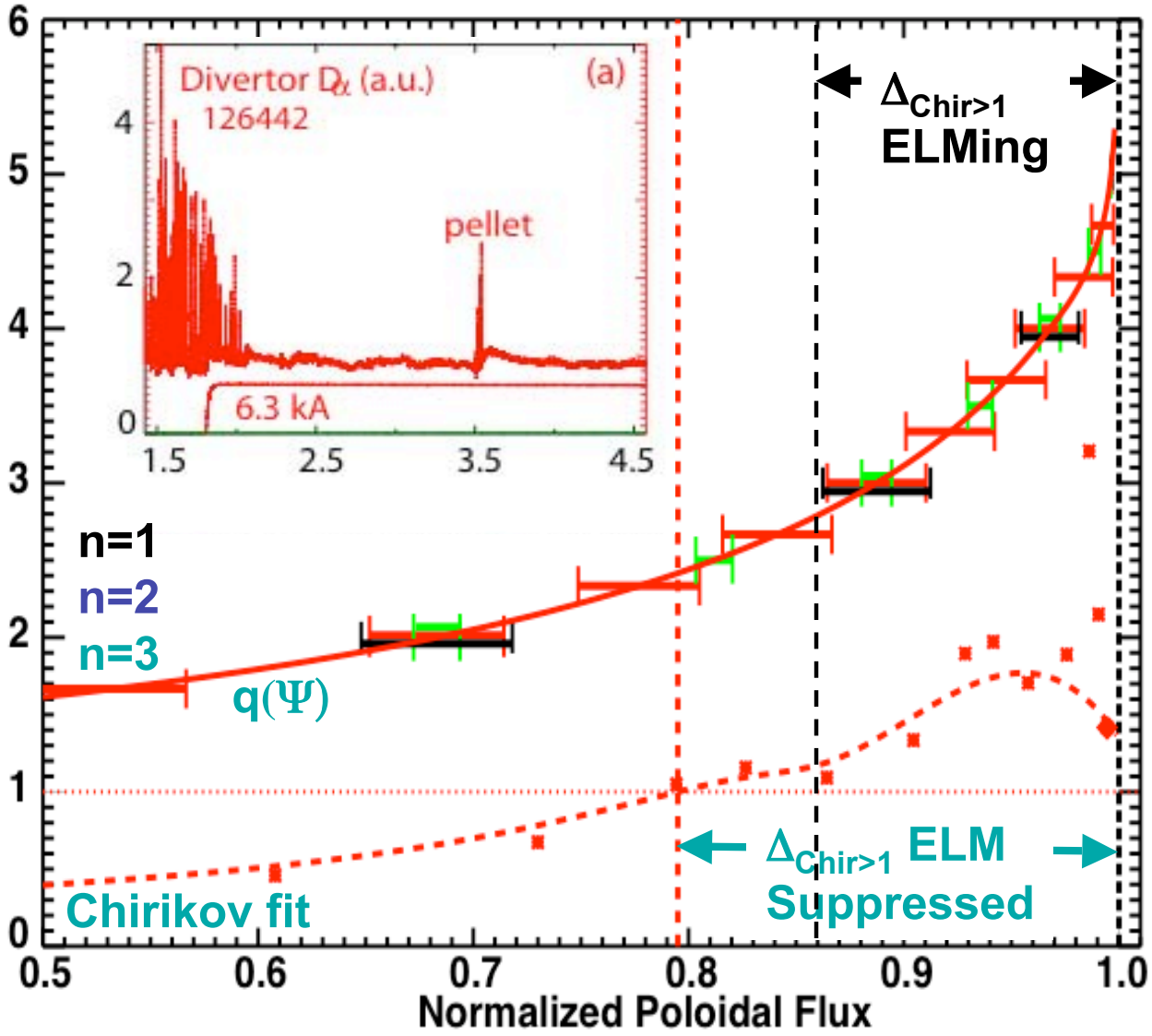
During ELM Suppression Magnetic Island Overlap Region in Vacuum Field Model Larger



- Vacuum island overlap satisfies $\sigma_{CH} > 1.0$ from edge to $\Psi_N = 0.8$
  - Island overlap width $\Delta_{Chir>1} = 0.20$
- Note $\Delta_{Chir>1} / \Delta_{ped} \sim 4.3$
- Suggests correlation of threshold $\Delta_{Chir>1}$ and ELM suppression
  - Possible range $0.15 < \Delta_{Chir>1} < 0.20$

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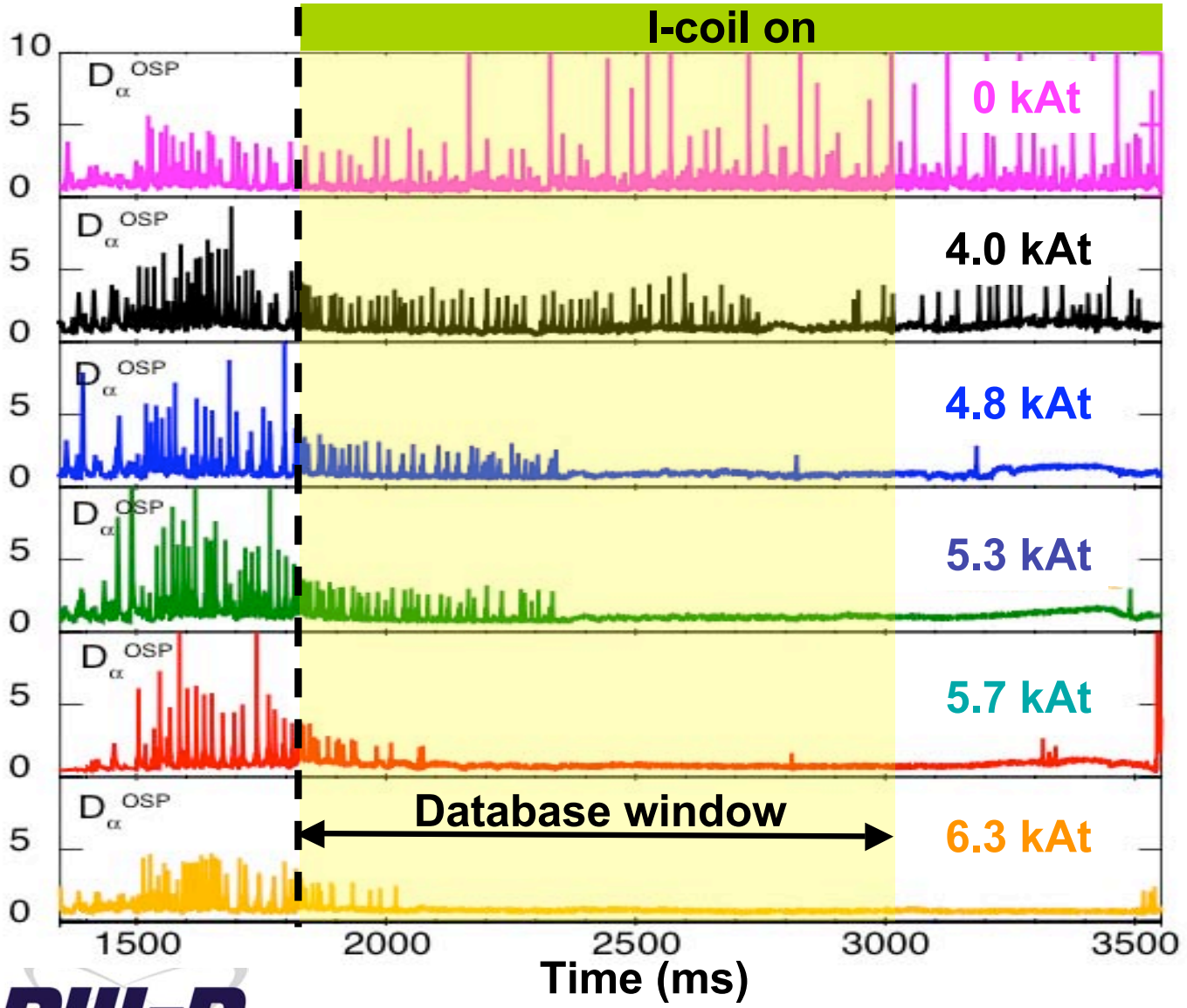
I-coil Current Scan at Fixed Shape and q_{95} Produces Systematic Change in ELM Behavior



- Provides multi-ELM sampling
  - 24 kinetic EFIT timeslice windows per shot
  - Multiple ELMs for many of the EFIT windows
- Similar sampling of other scans
- Complete suppression earlier at higher I-coil current

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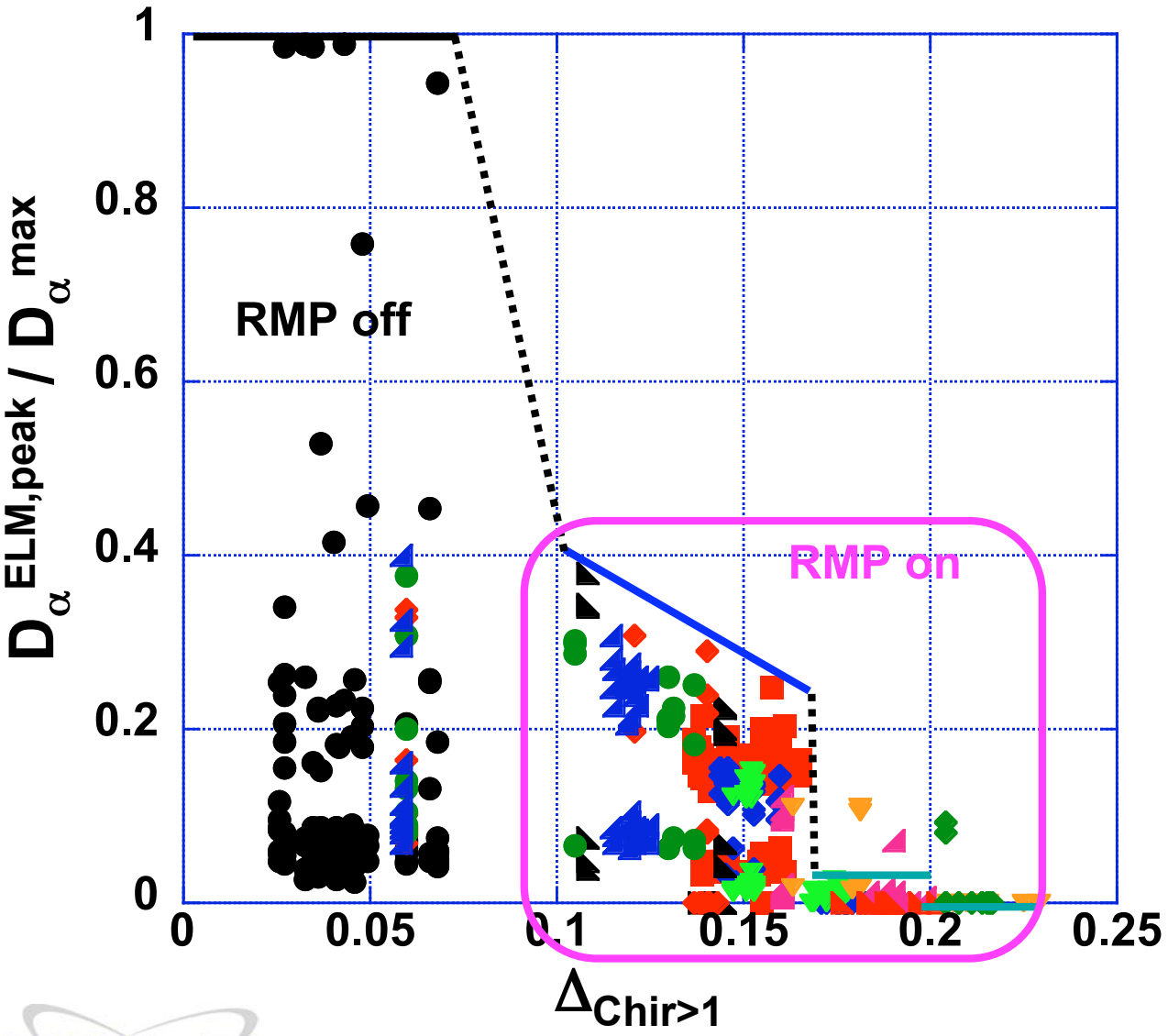
Maximum ELM Size Correlated with Width of Edge Region Satisfying $\sigma_{CH} > 1.0$



- ELM size from fast D_α at outer divertor strikepoint
  - Normalized to largest ELMs without RMP in database
- Full spectrum of ELM sizes both without and with RMP
  - Consistent with non-linearity of ELM instability

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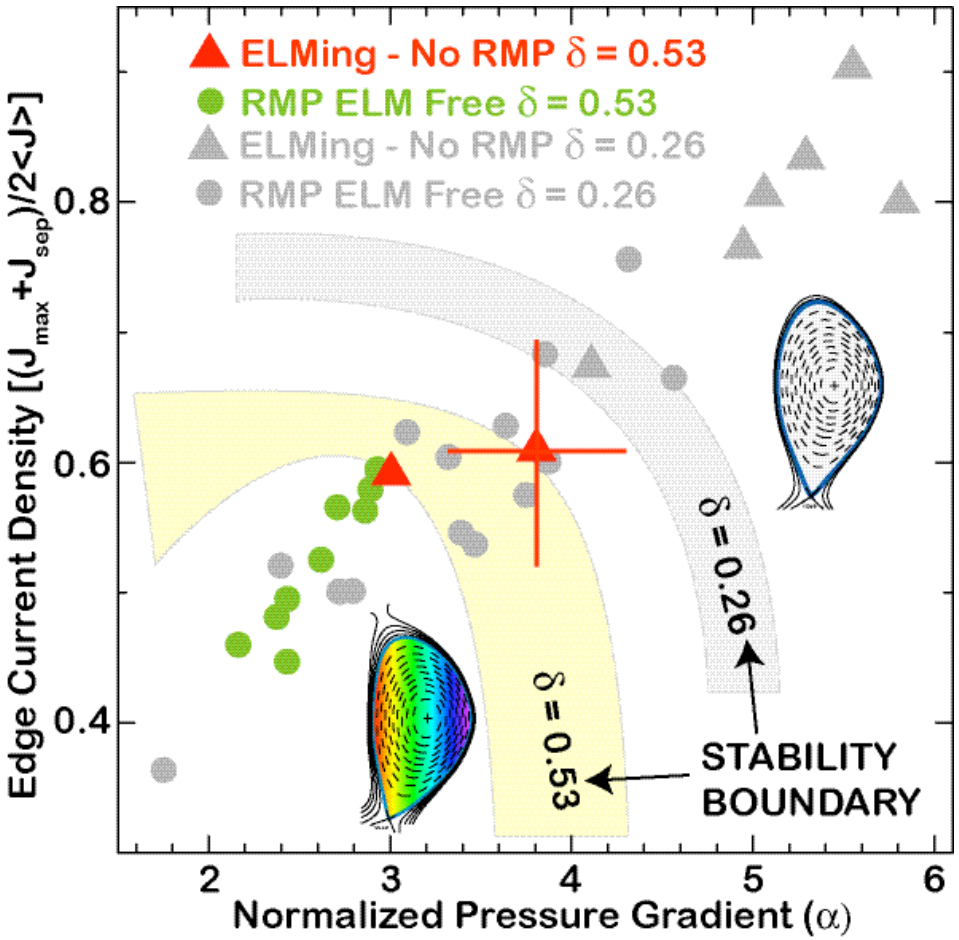
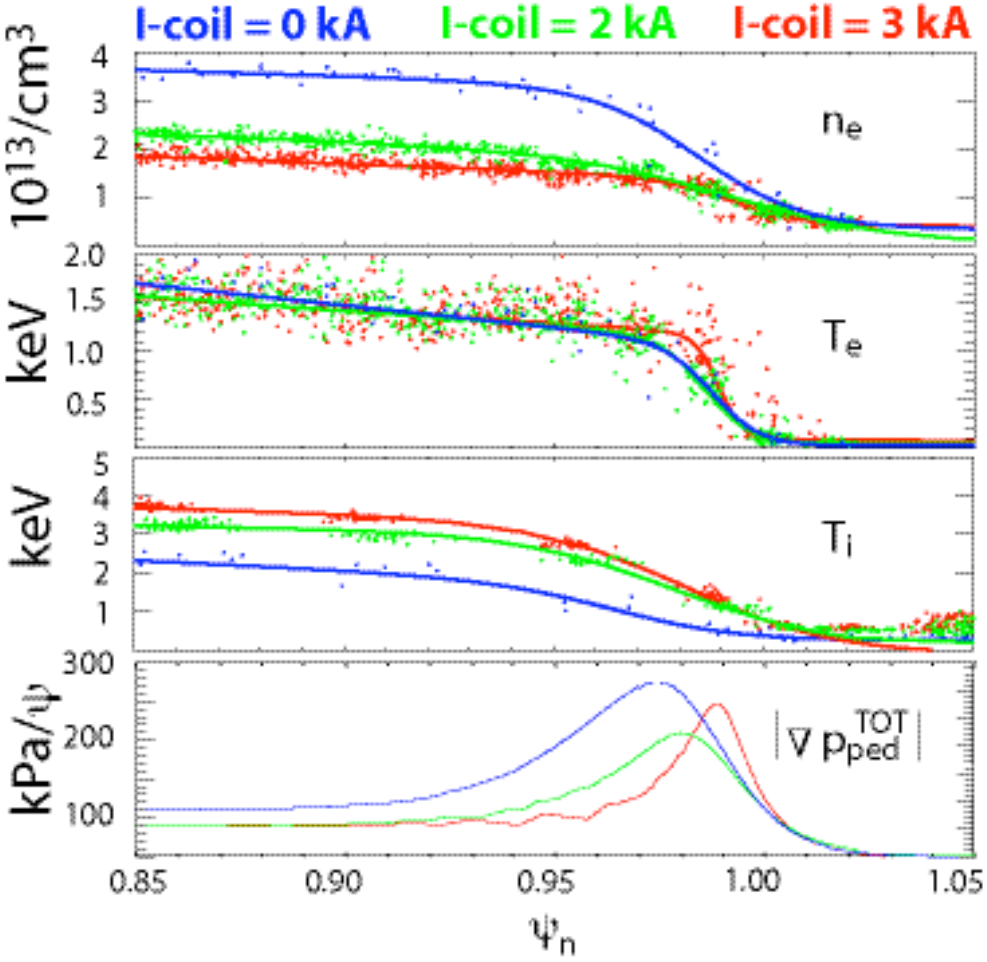
RMP ELM-suppressed H-modes are linearly stable to peeling-ballooning modes.

- Largest change in pedestal density profile->critical to understand global particle balance and particle transport.



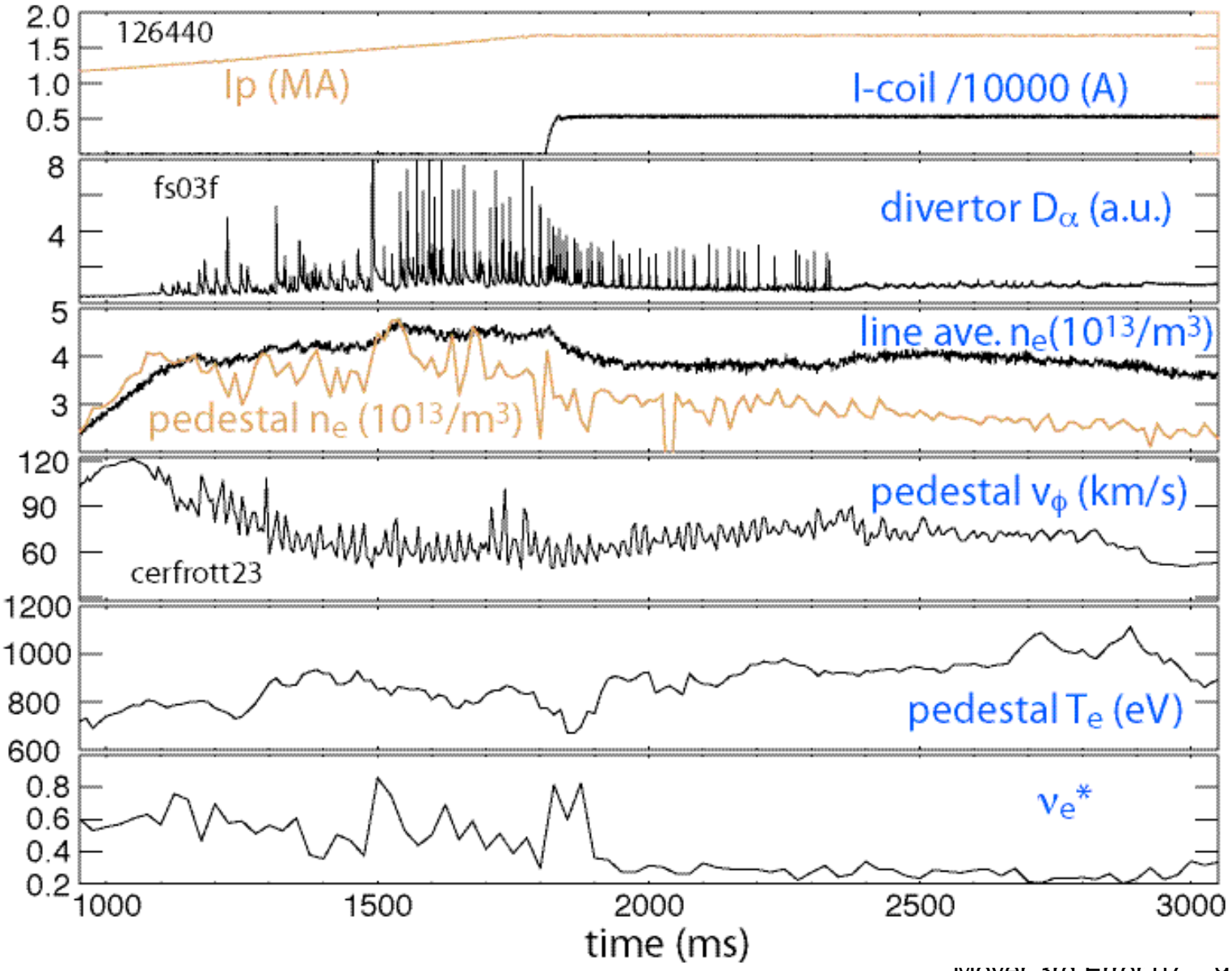


from Osborne APS06

Density pumpout is not sufficient to stabilize ELMs

- ELMs remain after pumpout is over until resonant window for suppression and vacuum island overlap
- Indicates a missing parameter controlling ELM suppression

Fenstermacher BI1.00002



Transport model should provide increased particle but only weak (~ 2x) increase in electron thermal transport

Stochastic layer transport:

- Electron thermal transport in vacuum field model destroys H-mode pedestal **[Joseph PSI 07; SFP 07 submitted to Nucl. Fusion 07]**
- Need to "shut off" parallel electron heat conduction…
  - Sheaths and Flux-limited transport at low colllisionality **[Tokar PRL 07]**
  - Electrostatic confinement of electrons in $\phi_{pl} \sim T_e$ potentials **[XGC: Park, Chang]**
  - ϕ at target plates → -100s of V with footprint structure in RMP ELM suppressed discharges **[Watkins, SNL]**; E_r in boundary integrates to ~ T_e at $\Psi_N = 0.99$ (500 eV)
- …while enhancing cross-field particle transport:
  - Increased SOL convective transport ("blobs") during RMP ELM suppresion **[Boedo EPS07, APS07]**
  - E x B convection cells in remnant island region
    - Potentials modified by islands and sheaths of lost field lines; measured in TEXT Ergodic Magnetic Limiter experiments **[Takamura PF (87), Evans EPS (87), Wooton JNM (90)]**
    - Predicted in extended MHD modeling **(JOREK: Nardon and Becoulet; NIMROD: Izzo]**
  - Increased drift wave turbulence due to E_r modifications **[Moyer IAEA06, APS07]**
    - E_r changes measured for $0.7 < \Psi_N < 1$ when RMP is applied (before ELM suppression)
    - increase in broadband $\tilde{n}_{rms}$ for $0.75 < \rho < 1$ at both ion ($k_\theta \sim 1$ inv. cm) and electron ($k_\theta \sim$ 4-5 inv. cm) scales
    - $\tilde{n}_{rms}$ increases 2x → Γ → $\tilde{n}_{rms}^2$ → 4x consistent with density change

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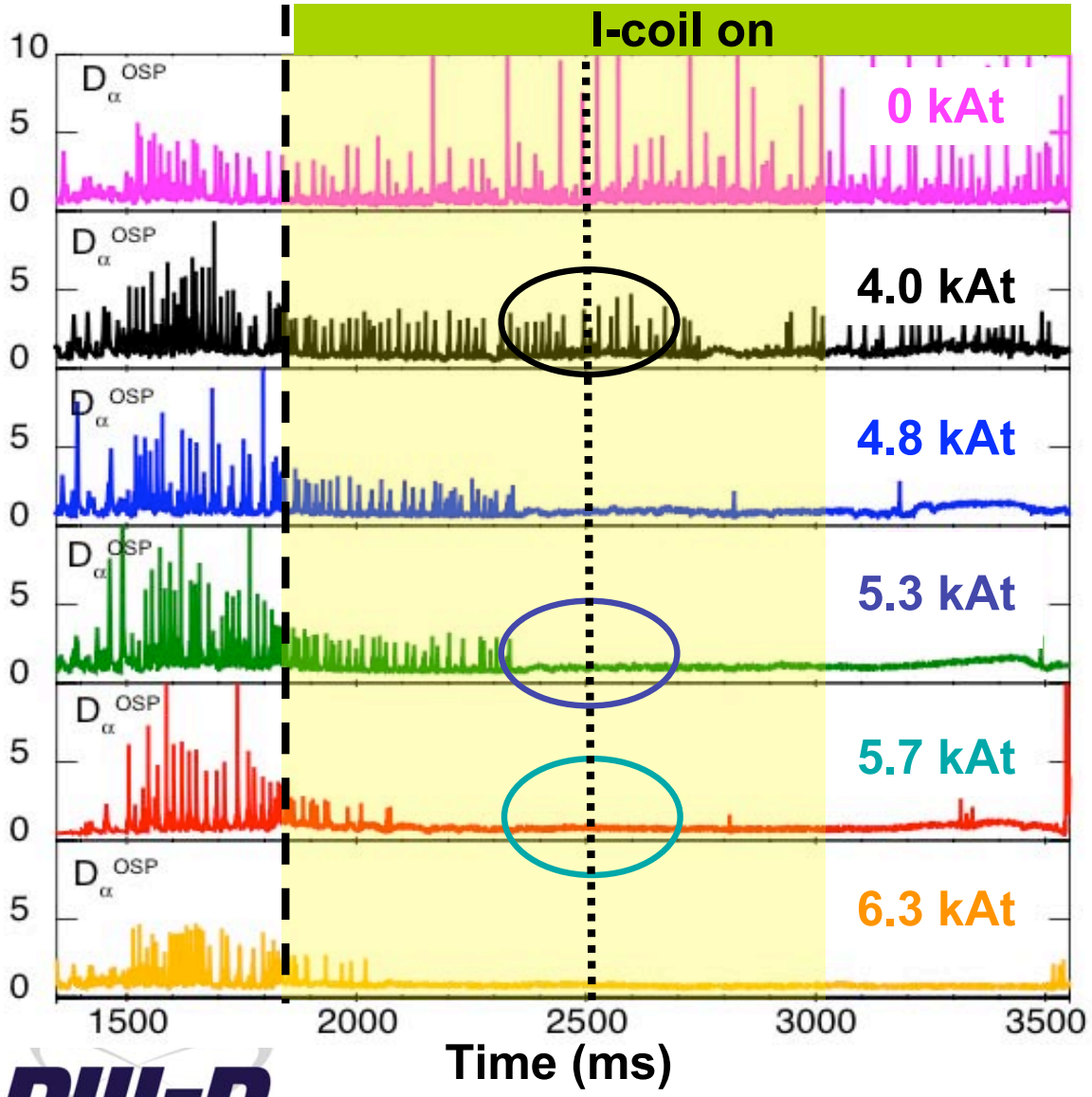
Is ELM Size Ordering by $\Delta_{Chir>1}$ Due to Field Line Loss from Remnant Island Region?



- Multiple suggestions [1-3] that ExB convective cells could play a role if threshold region contains:
  - Remnant islands
  - Field lines with short connection length to targets
- Field line tracing (TRIP3D) in kinetic EFIT + RMP vacuum fields
  - Compare ELMing vs ELM suppressed cases

1. Takamura PF (1987)
2. Evans EPS (1987)
3. Wooton JNM (1990)

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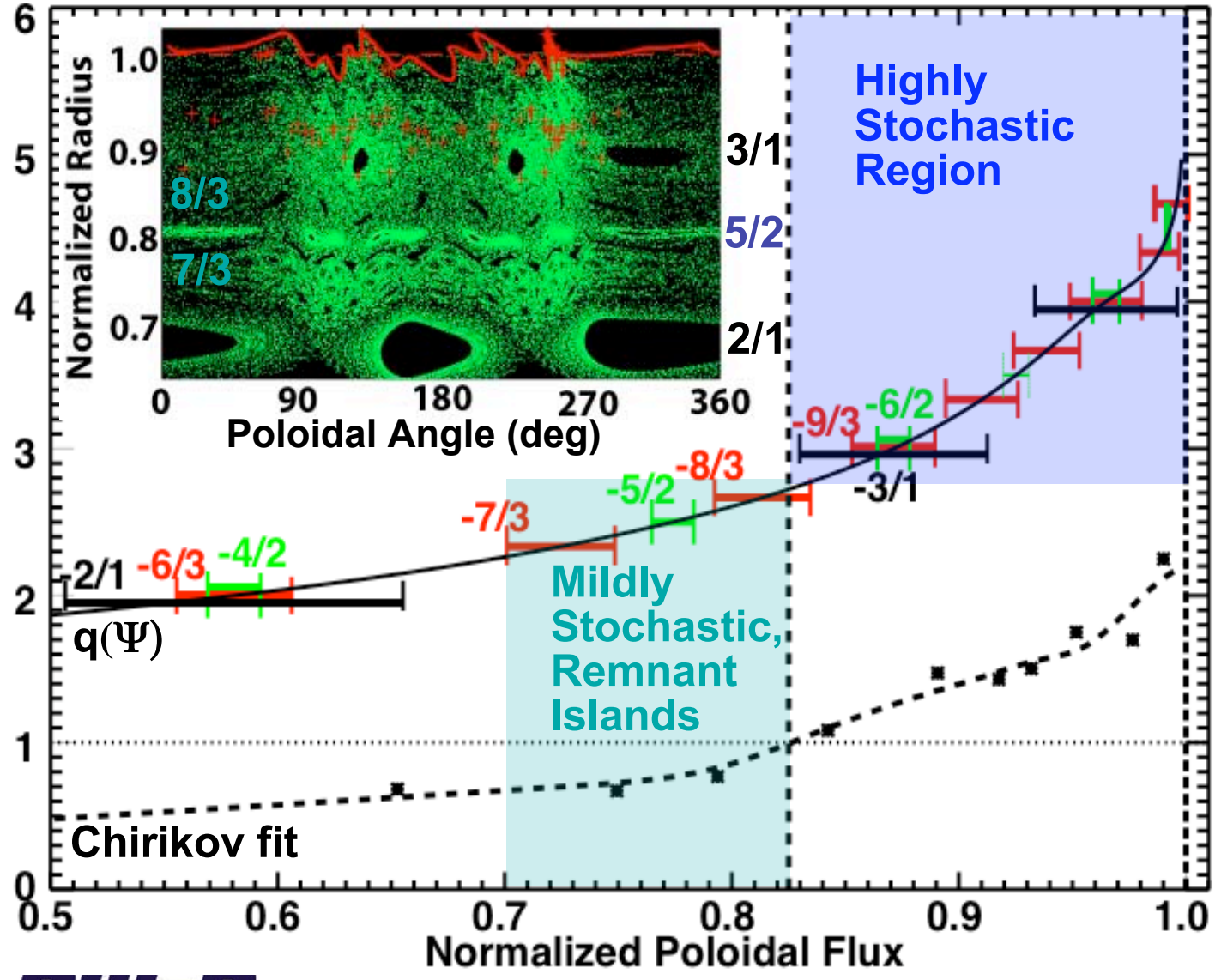
Vacuum Field Contains Remnant Islands Adjacent to Stochastic Region



- Stochastic region from q~3 surface outward
- Remnant islands at q=8/3, 5/2, 7/3 surfaces may be weakly coupled

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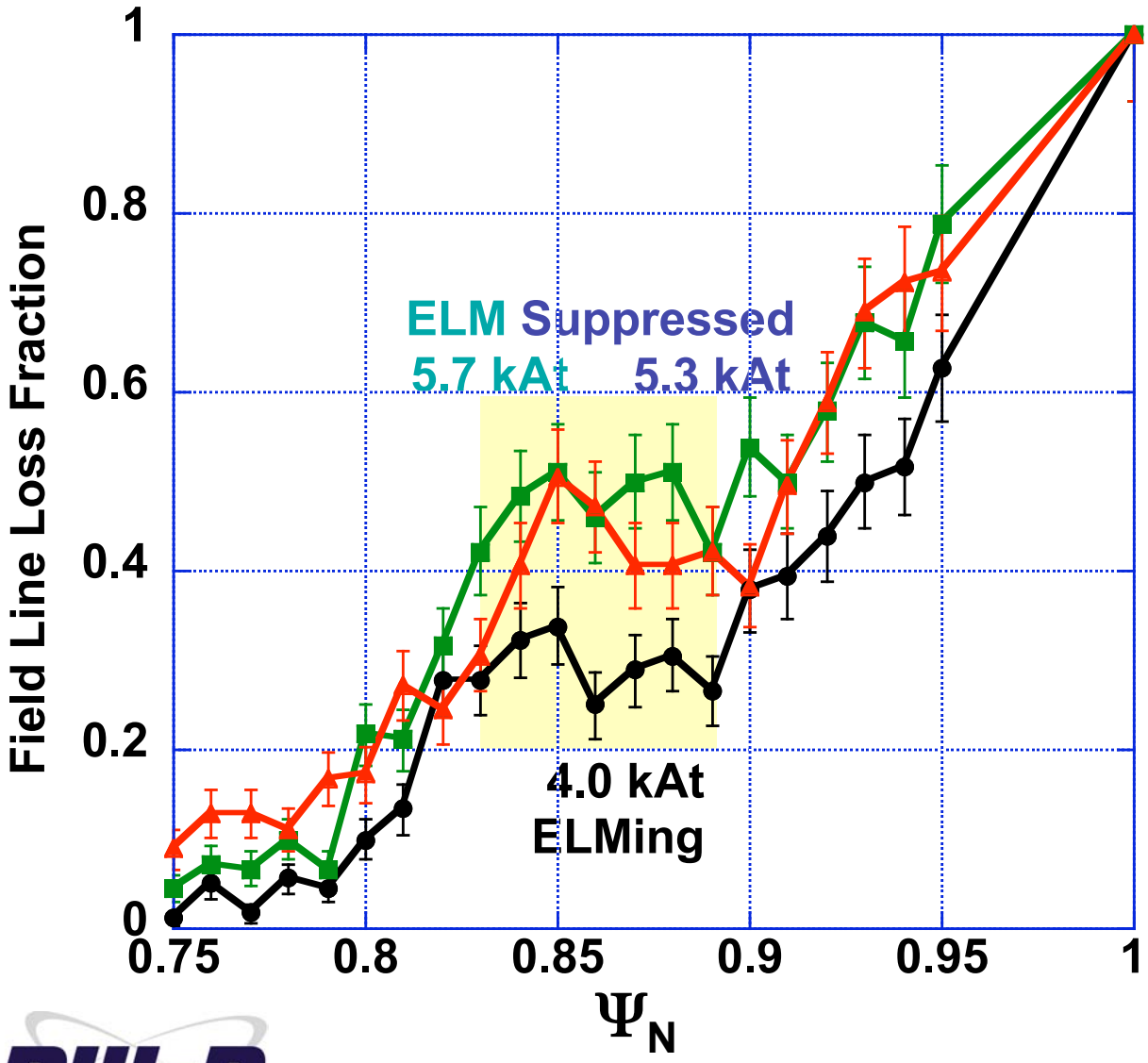
Field Line Loss Fraction From Remnant Island Region $0.83 < \Psi_N < 0.89$ Higher in ELM Suppressed Cases



- Traced field lines
  - Launched with uniform poloidal distribution on unperturbed flux surfaces
  - Forward traced until strike outer divertor or 200 toroidal transits
- Field line loss fraction up to 2x higher for $0.83 < \Psi_N < 0.89$

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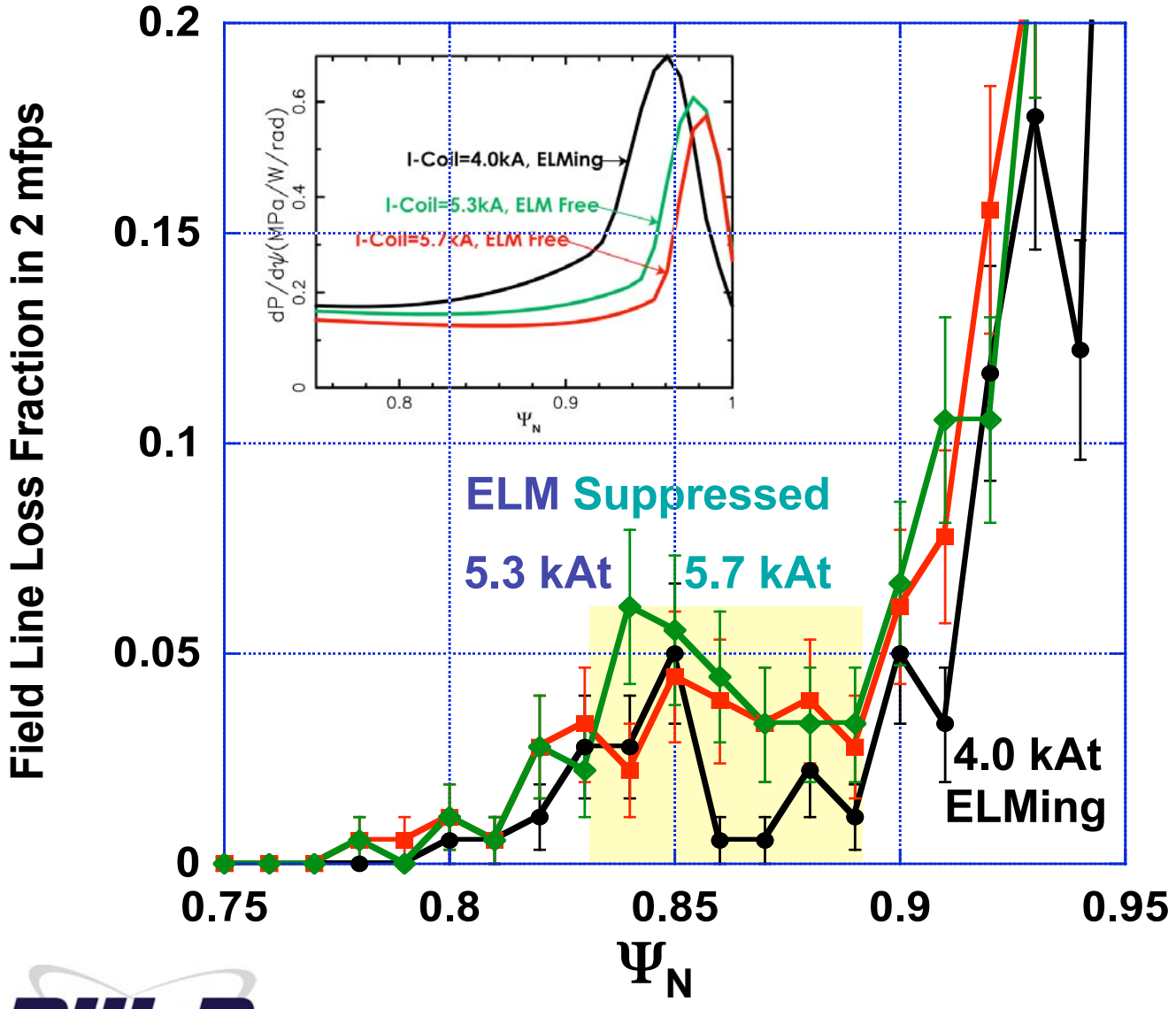
Field Line Loss Fraction with Short Connection Length Higher in ELM Suppressed Cases



- Criterion for "short" connection length: $L_c < 2 * \lambda_{ei}$ (electron-ion collisional mean free path in pedestal)
- Short connection length to divertor targets affects potential deep in edge plasma
  - ExB convection cells may play a role in changes to plasma profiles

Boedo Oral GO3.02 Tu pm

Moyer, Watkins, Zeng Poster session UP8 Th pm

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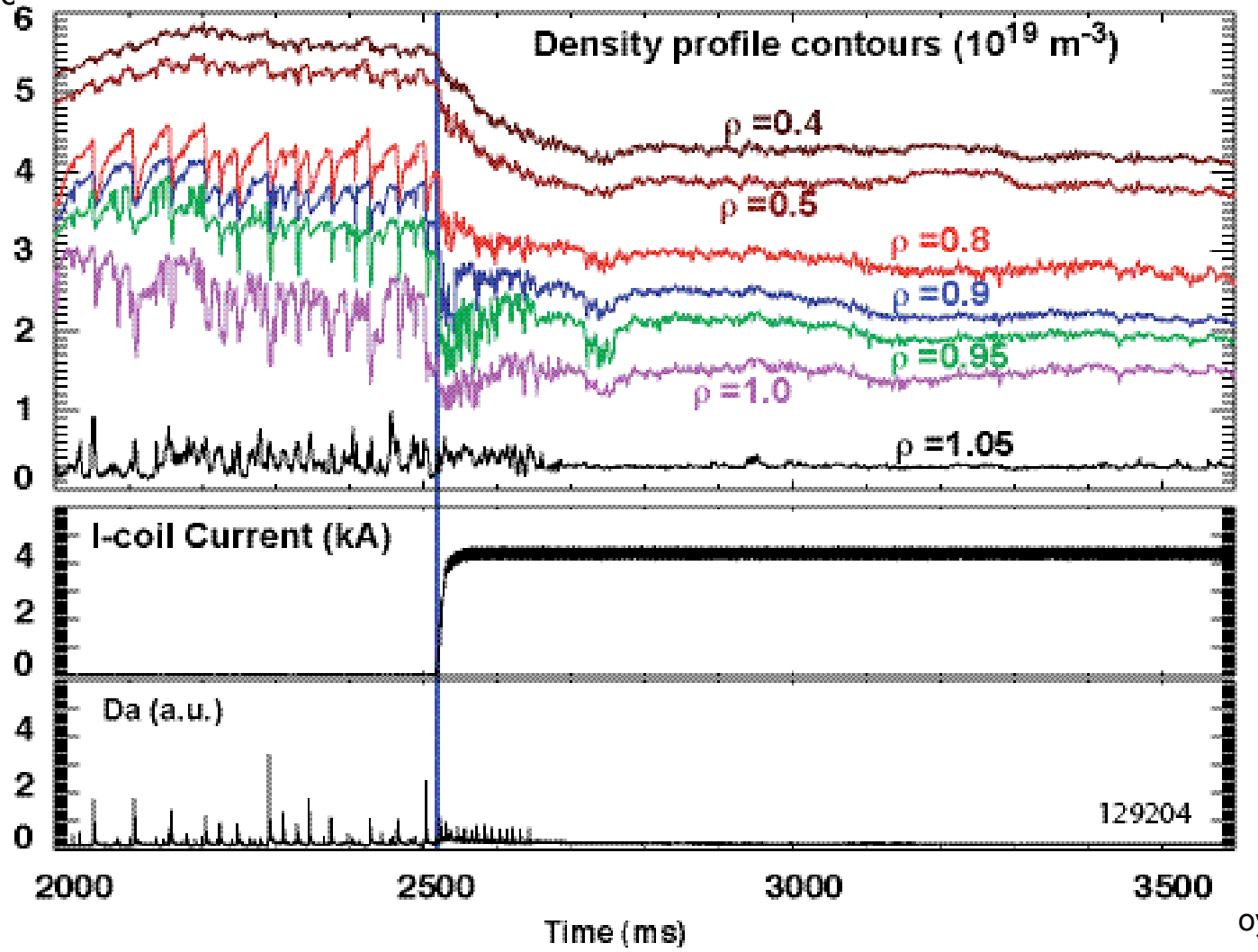
Density profile evolution has a 2-step character: fast pedestal change and longer core change

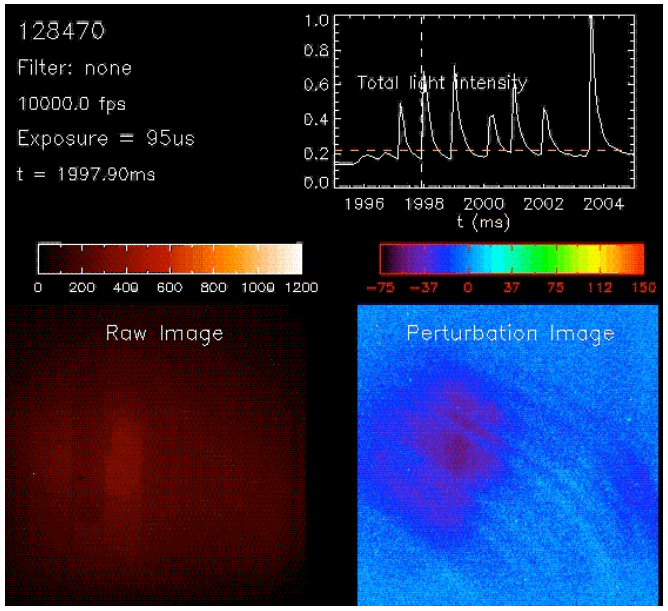
- Pedestal n_e drops with e-folding time of 77 ms [Zeng UP8.00026], followed by a broadening at the base [Boedo, G03.00002]
- Core n_e drops with e-folding time of 815 ms → adjustment to new b.c?



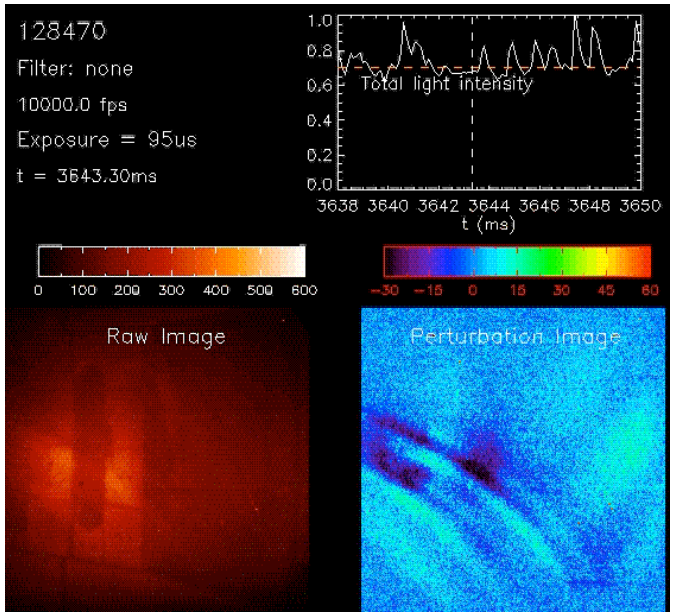
Filamentary structures in ELMing H-mode persist during RMP pulse (both ELMing and suppressed)

- visible emission from tangentially viewing UCSD fast framing camera **J. Yu UP8.00030**

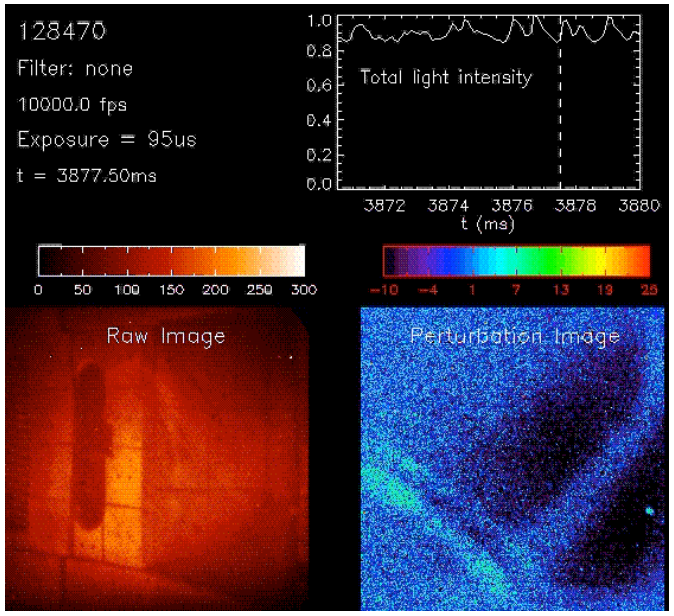
I-coil off inter-ELM



I-coil on inter-ELM



I-coil on ELM suppr



- Increased intermittent transport in boundary during RMP → large particle but little thermal transport **Boedo G03.00002**

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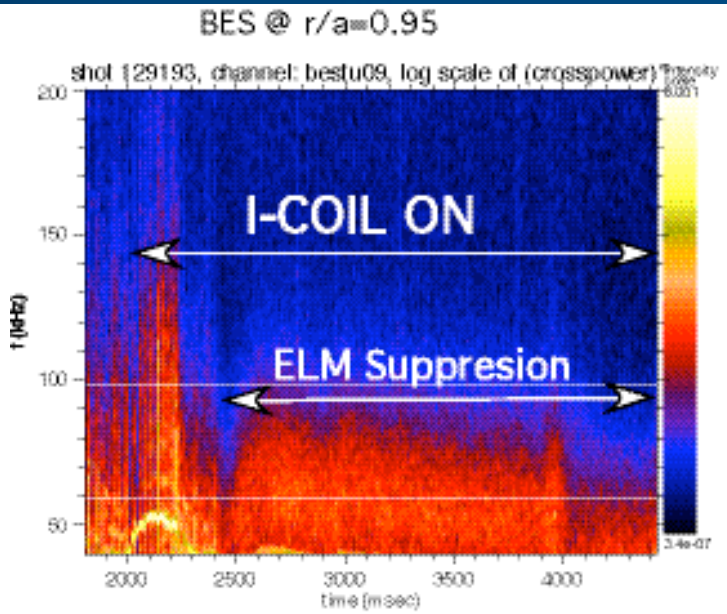
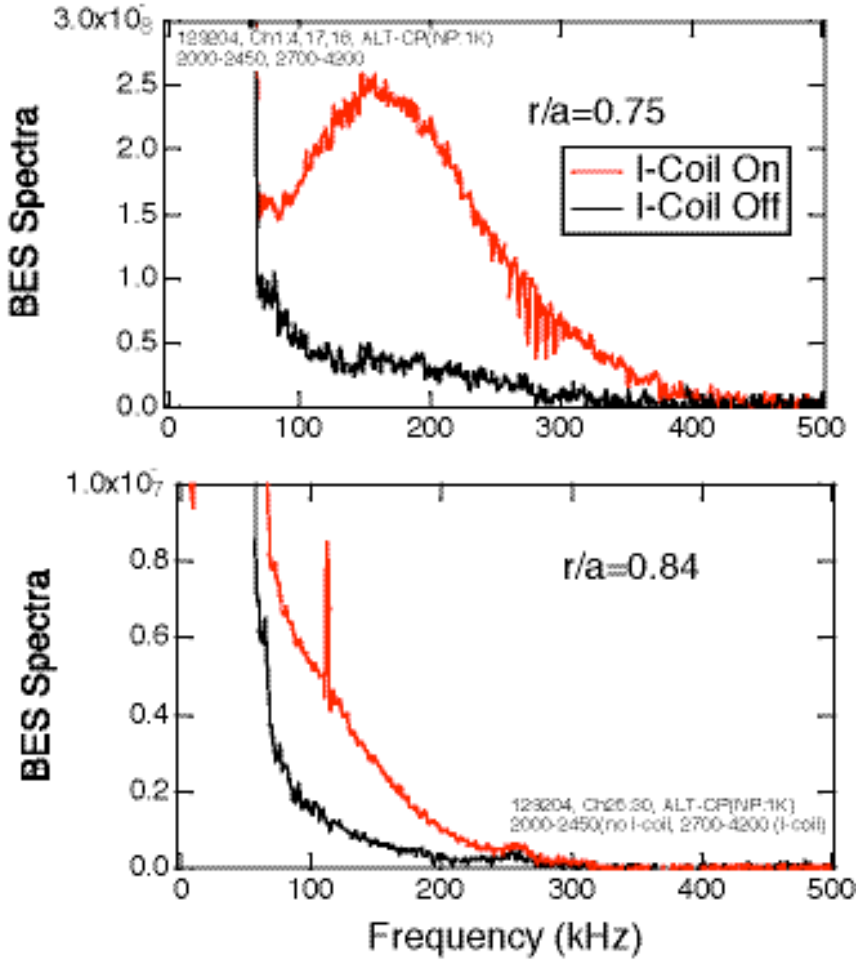
Ion scale fluctuations increase broadband across a wide radial extent 0.75 < ρ < 1 when ELMs suppress





BES analys
by G.R.
McKee, Un
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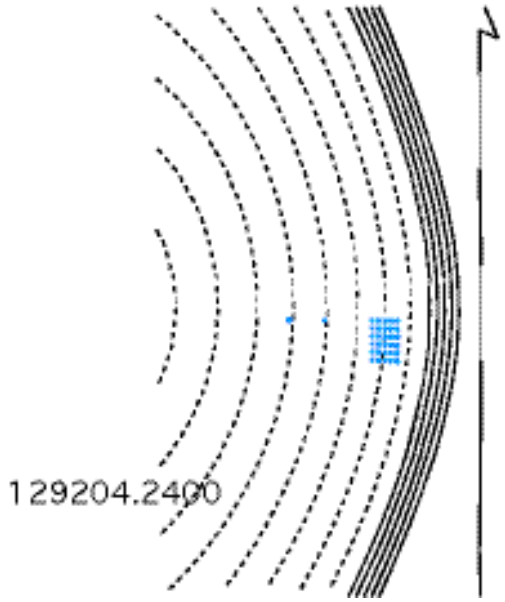

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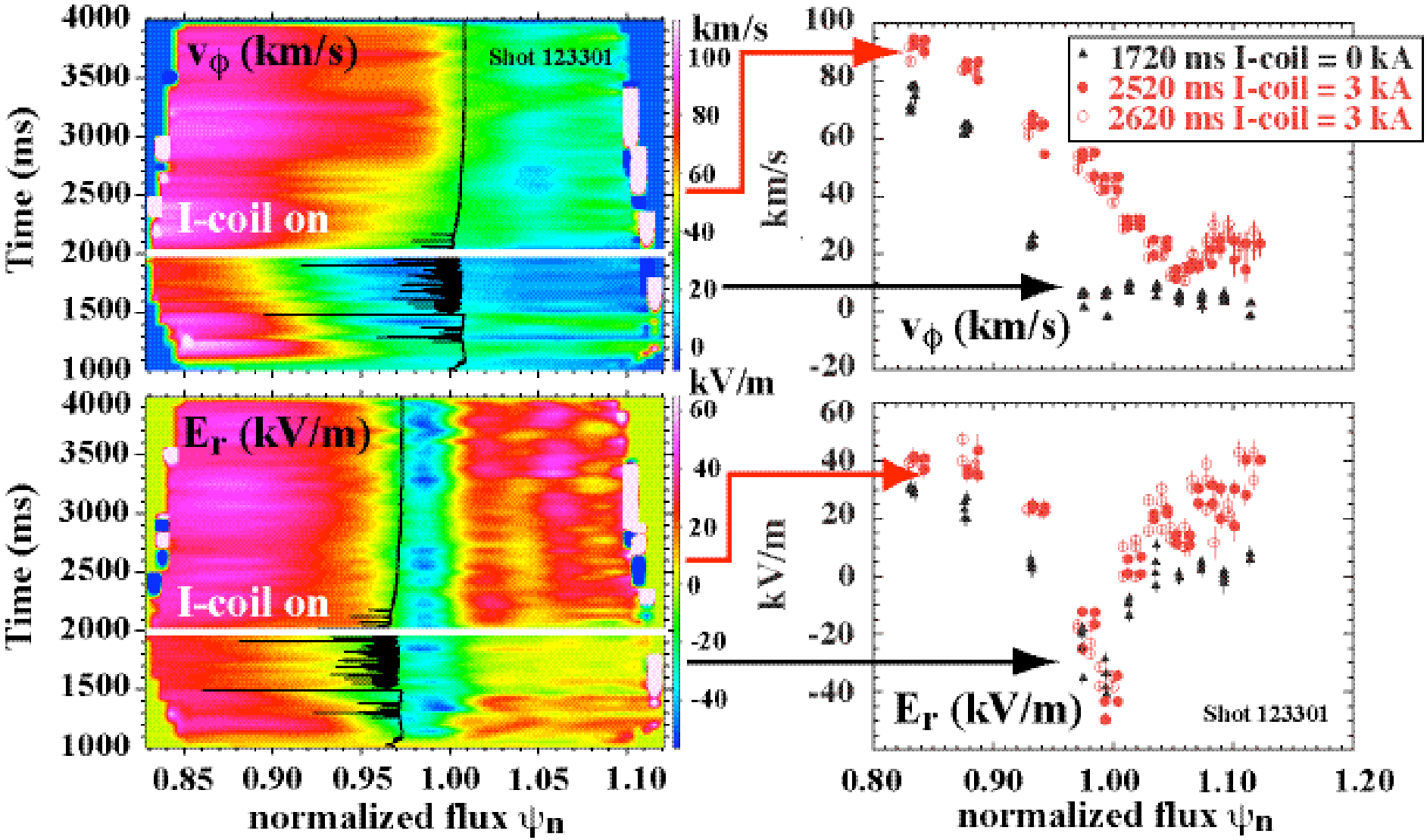
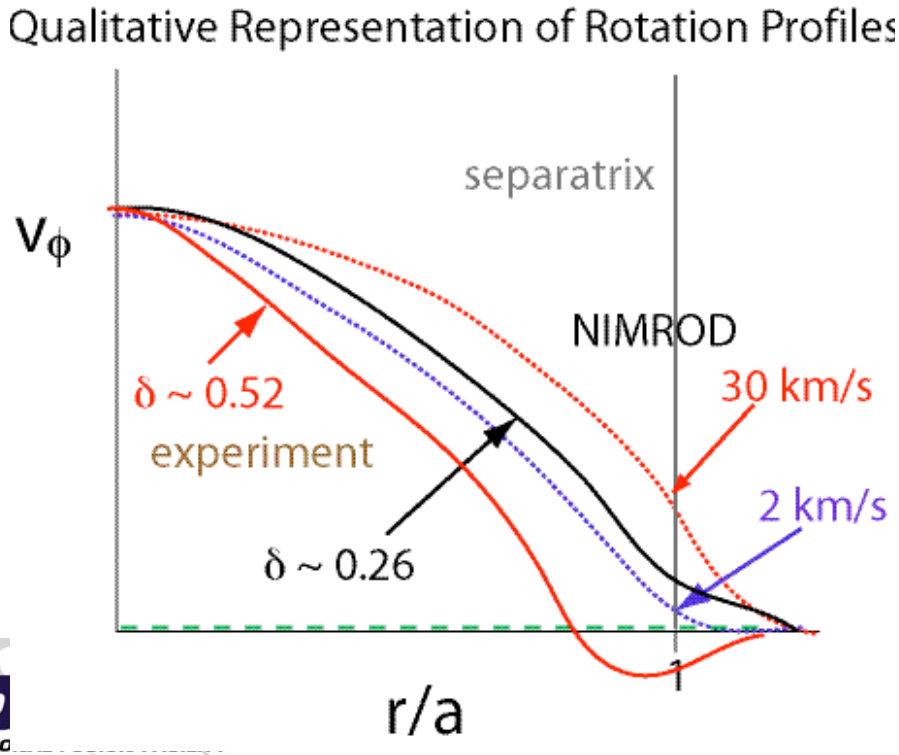
Pedestal toroidal rotation and E_r change promptly when RMP is applied and edge q resonant (3.4 < q95 < 3.7).

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

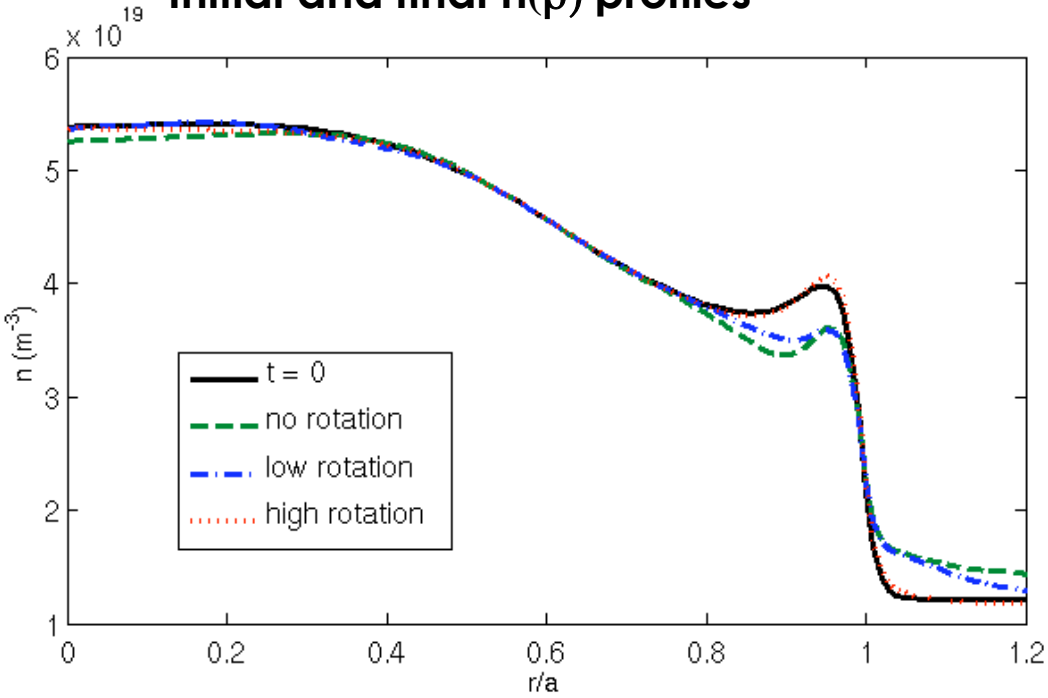


Extended MHD runs with JOREK and NIMROD predict formation of E x B convective cells

- JOREK simulations by E. Nardon & M. Becoulet
- Numerical experiments with NIMROD extended MHD code in full toroidal geometry **V. Izzo**
  - Uses ELM milestone equilibrium developed by D. Brennan and much higher resistivity
  - Experiments are near the no-wall limit $\beta_n \sim 2.4 l_i \rightarrow$ equilibrium unstable
  - instant rise time τ_{RMP}: experiment τ_{RMP} = 20 ms: $\tau_A << \tau_{rec} \sim \tau_{RMP} << \tau_R$
  - Effect of τ_{RMP} on plasma response & RMP penetration studied with NIMROD in reduced (slab) geometry: **Kruger Poster UP8.00025**



Initial and final n(ρ) profiles

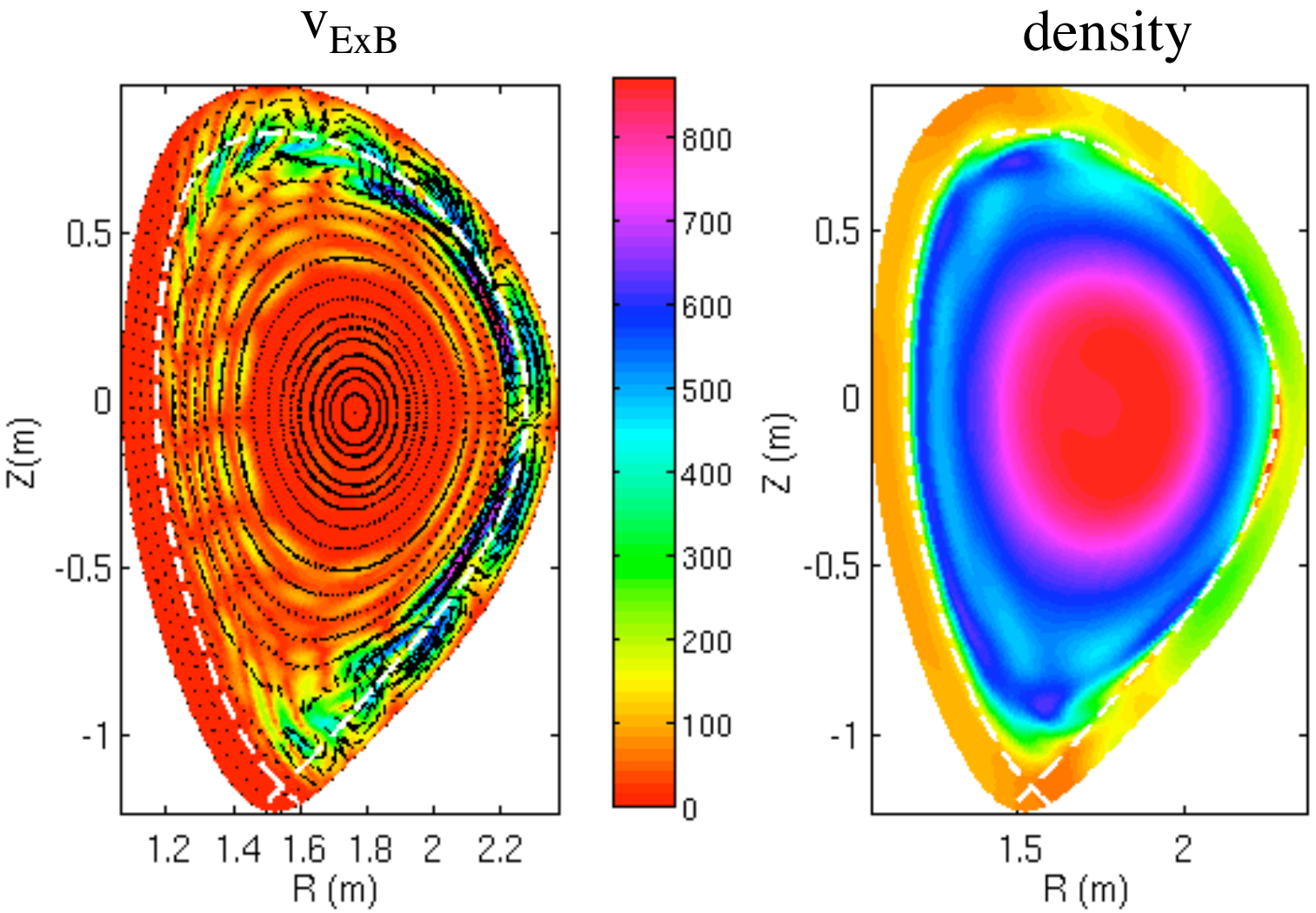


E x B convection cells form across separatrix for v_ϕ = 0 and increase radial particle transport into $\rho \sim 0.7$

- Contours of v_{ExB} (km/s) and density show particle transport modification in to $\rho \sim 0.7$ without toroidal rotation (vacuum field perturbation).

$V_\phi = 0$ case

NIMROD results provided by V. Izzo



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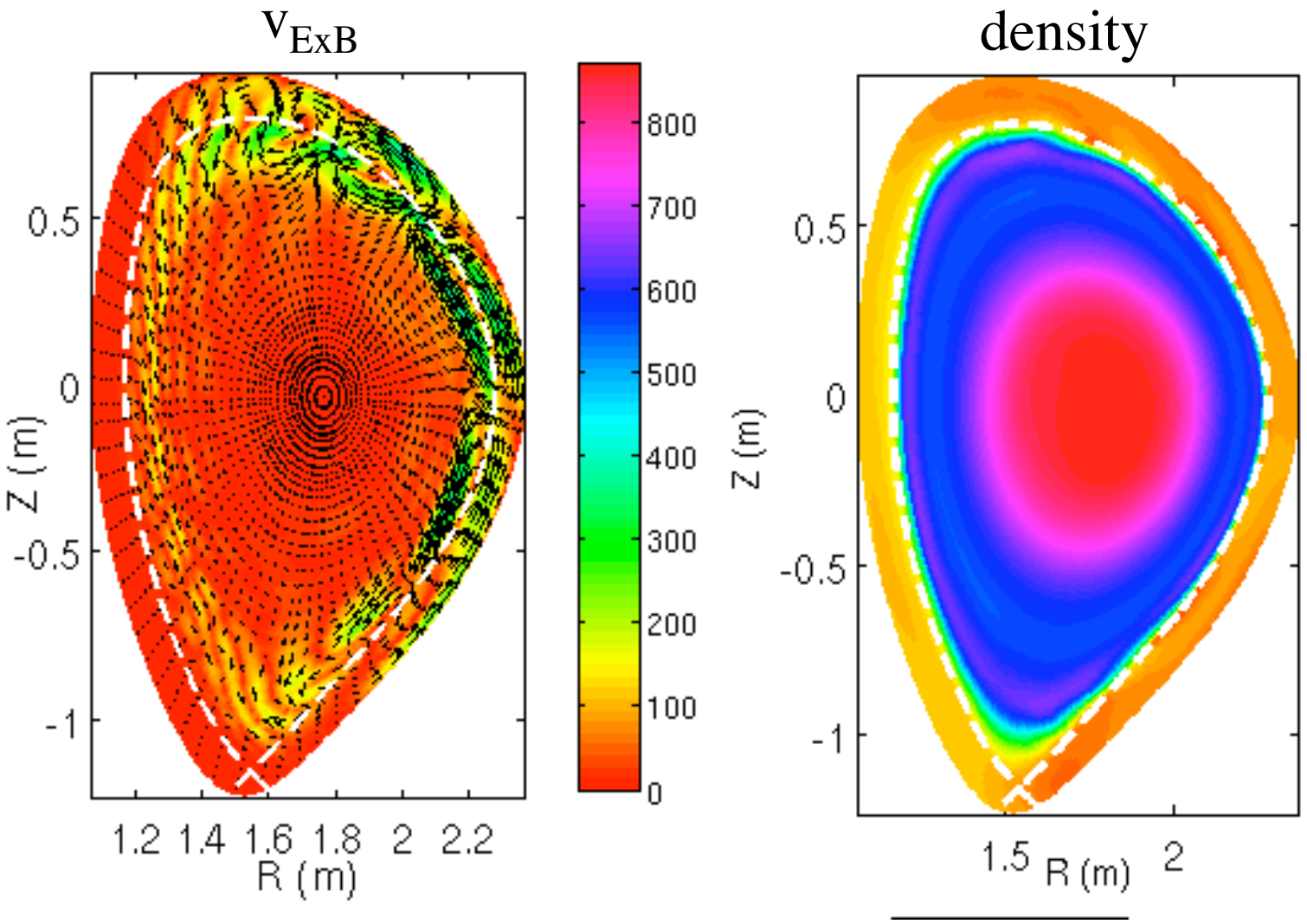
In high v_ϕ case, E x B convection cells exist, but at lower amplitude with little effect on density profile

- Contours of v_{ExB} (km/s) and density show transport modification localized to separatrix with high v_ϕ (significant screening of RMP).

High V_ϕ case



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Summary and Conclusions

- Fusion community appears polarized on the RMP ELM suppression results:
  - (largely tokamak) school of thought: parallel electron heat conduction is robust even with the limitations of Rechaster-Rosenbluth so the pedestal T_e has to drop (that is, χ_e must increase more than a factor 2) if the outer 15%+ of the plasma is stochastic (1/3 of the plasma volume!)
  - (other, including RFP & helical device)school of thought: the ratio of particle transport to thermal conduction in stochastic fields is "anomalous" **[I.e. Ding this morning]**;
- Physics missing from RR transport may "shut off" parallel electron heat conduction:
  - Flux limits to parallel heat conduction at low collisionality **[Tokar]**
  - Electrostatic confinement of electrons in the open flux tubes (yes, the boundary might look like a mirror!)
    - ✓ Appears consistent qualitatively with experimental results
    - ✓ seen in XGC numerical experiments using resonant field amplification of vacuum field **[Park this APS]**
    - ✓ GAMMA-10 uses ECH to spin the plasma after plugging, producing multi-keV electron and ion temperatures **[this APS]**
    - ✓ Maryland Mirror experiment applies the rotation with a center rod/electrode
  - Sheared rotation: The "ion root" in stellarators - breaking axisymmetry induces a radial current, **j** x **B** force, and sheared rotation
    - ✓ ambipolar potential has enough E_r shear to suppress transport

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Summary and Conclusions - II

- Whatever the result for parallel thermal conduction…
  - RMP is screened and no open field lines versus
  - some form of "plugging" of electron parallel losses on open field lines)
- …we need some form of enhanced particle transport (convection) to account for the density profile changes:
  - convective "blob" transport increases in experiment (is it enough?)
  - E x B convective cells measured in previous EML experiments
  - E x B convective cells seen in extended MHD models of plasma response in toroidal geometry
    - scaling with dissipation/viscosity, which is 100x the experiment
    - effect of RMP rise time on final state ("error field" or "forced reconnection"?)
  - **j** x **B** should efficiently damp the (axisymmetric) Zonal flow that regulates turbulence: consistent qualitatively with exp.
- Many groups are working on these issues (Thank you!) - but ITER needs answers urgently and we can always use more help!

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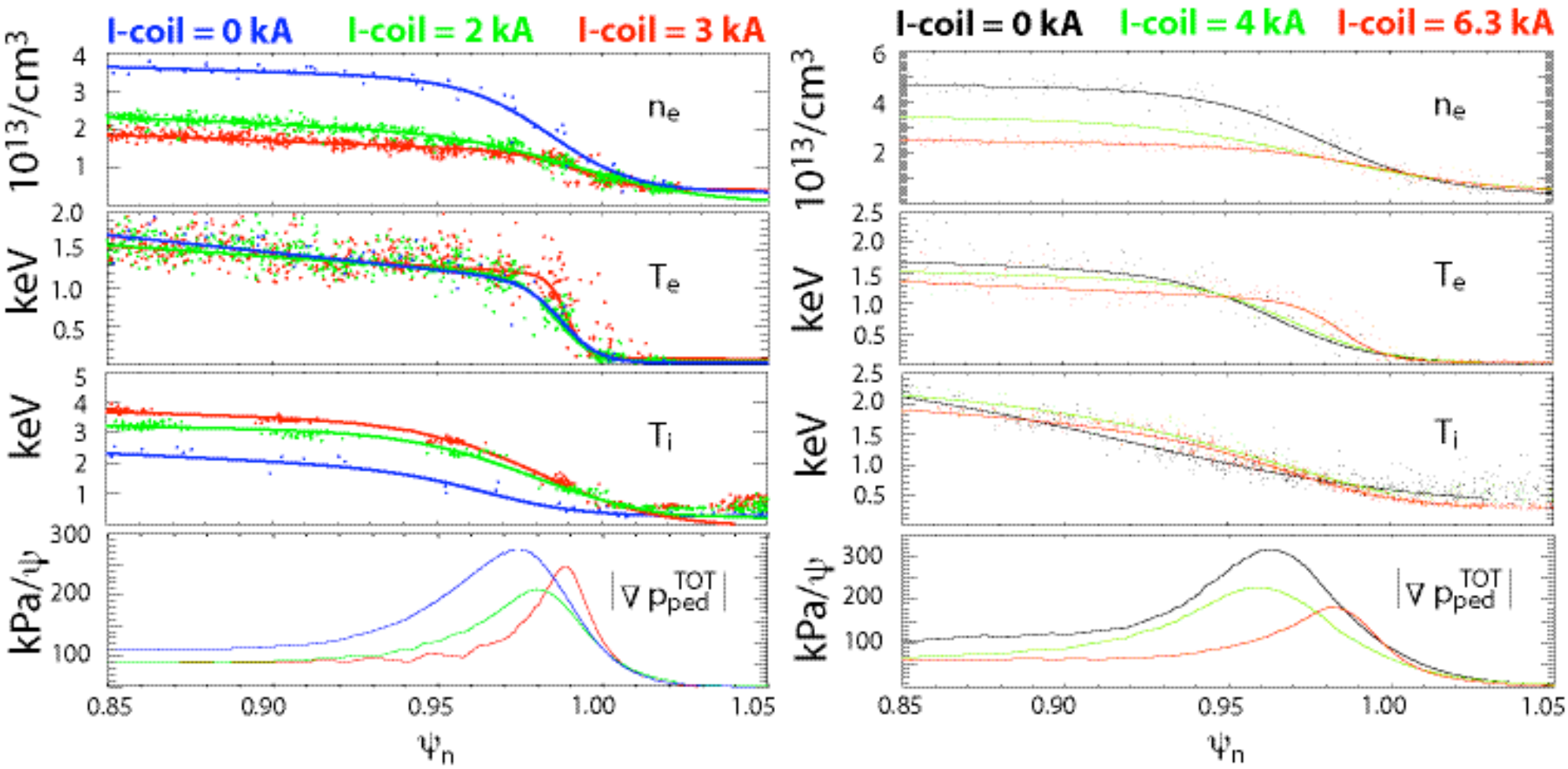
Backup slides

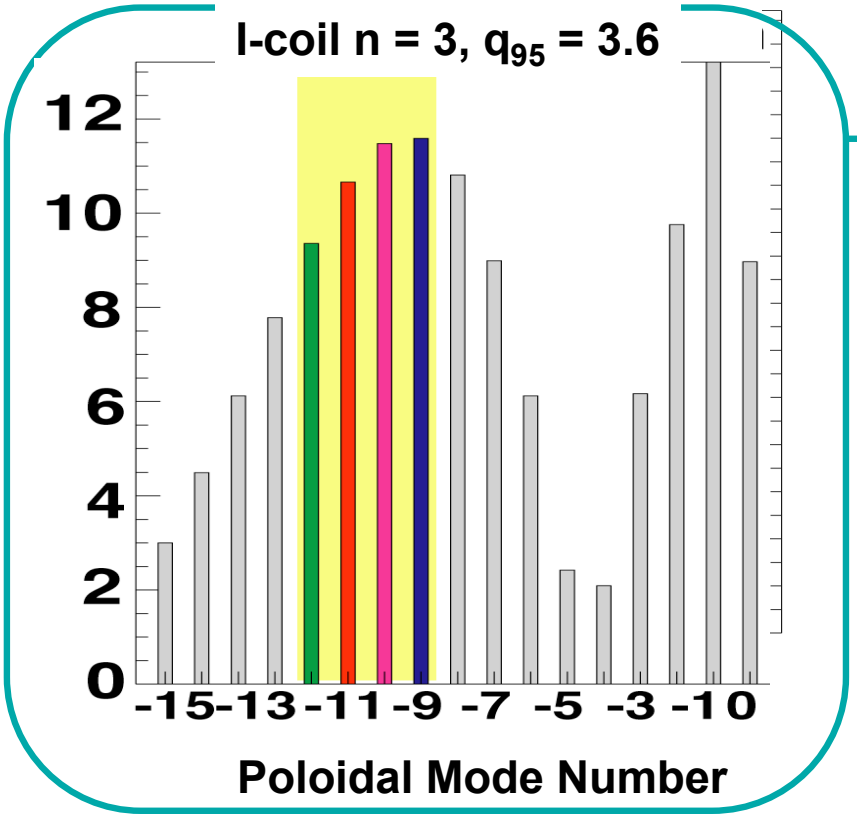
I-coil RMP has largest effect on density profile, not T_e profile at low collisionalty.

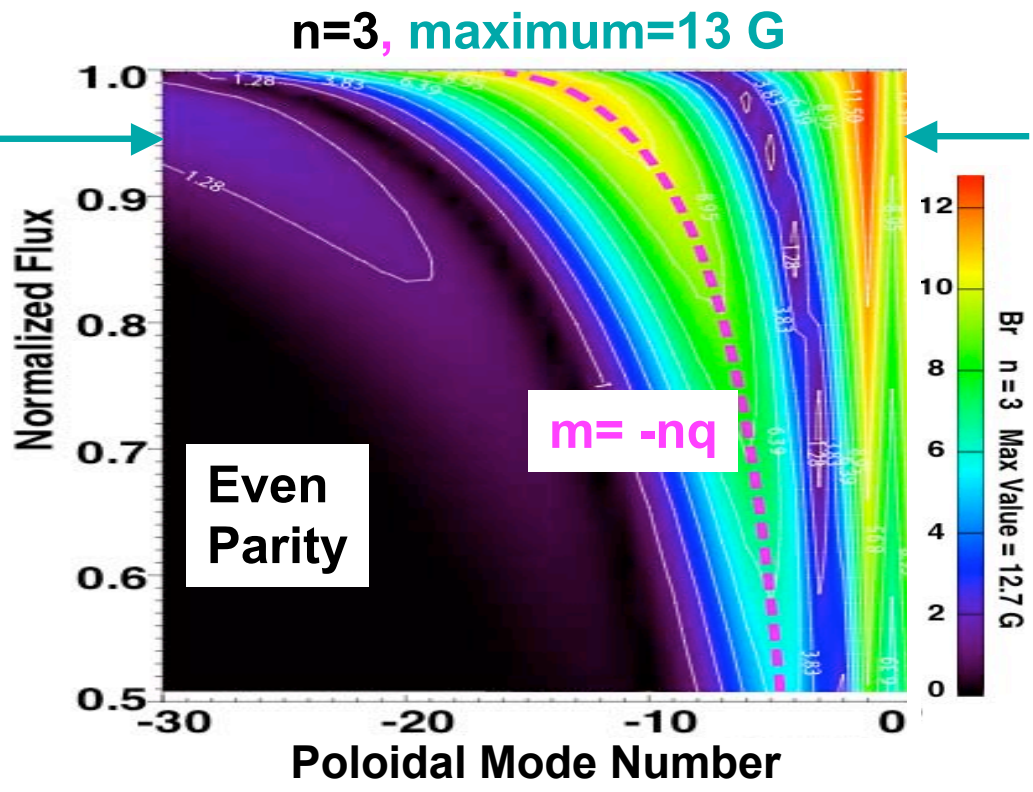
- Density profile change is largest contribution to pressure gradient reduction.

$\delta \sim 0.26$ $\delta \sim 0.53$



I-coil Even Parity n=3 Spectrum Optimum for Pitch Resonance at q_{95} ~ 3.6 in DIII-D





- Strength of I-coil n=3 RMP in pedestal depends on up/down parity of coil sets
  - Even parity (upper and lower loop δb_r same direction) gives maximum edge perturbation for $3 < q_{95} < 4$,
  - Edge perturbation $\delta b_r^{11/3}/B_T = 5 \times 10^{-4}$ at Ψ_N=0.95 for 6.3 kAt

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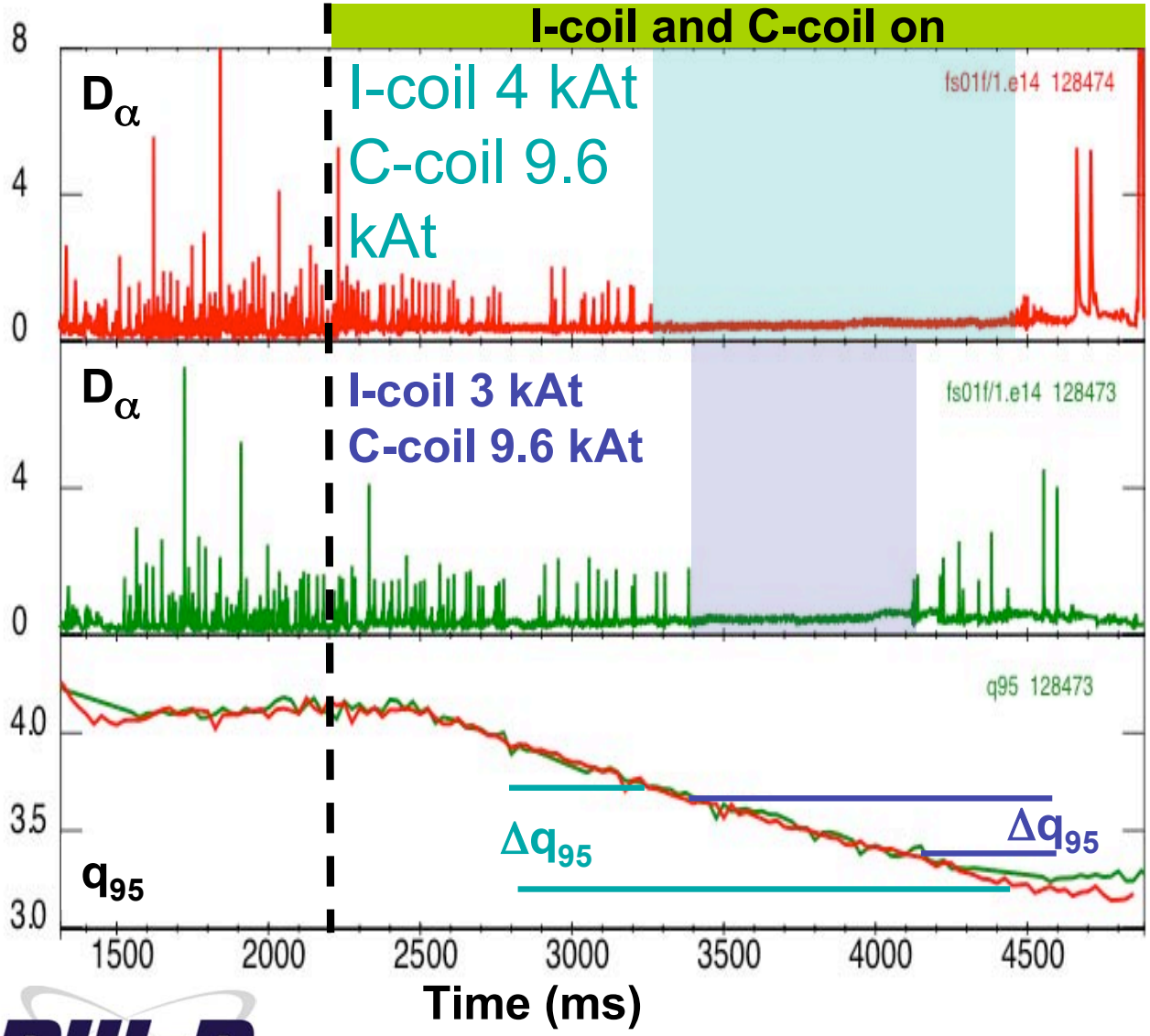
Safety Factor Resonance Window for ELM Suppression Expanded with n=3 RMP Strength



- I_p up ramps used to produce q_{95} down ramps
- Resonance window for suppression increased with I-coil current
  - At 3 kAt suppression for $\Delta q_{95} = 0.30$
  - At 4 kAt suppression for $\Delta q_{95} = 0.50$

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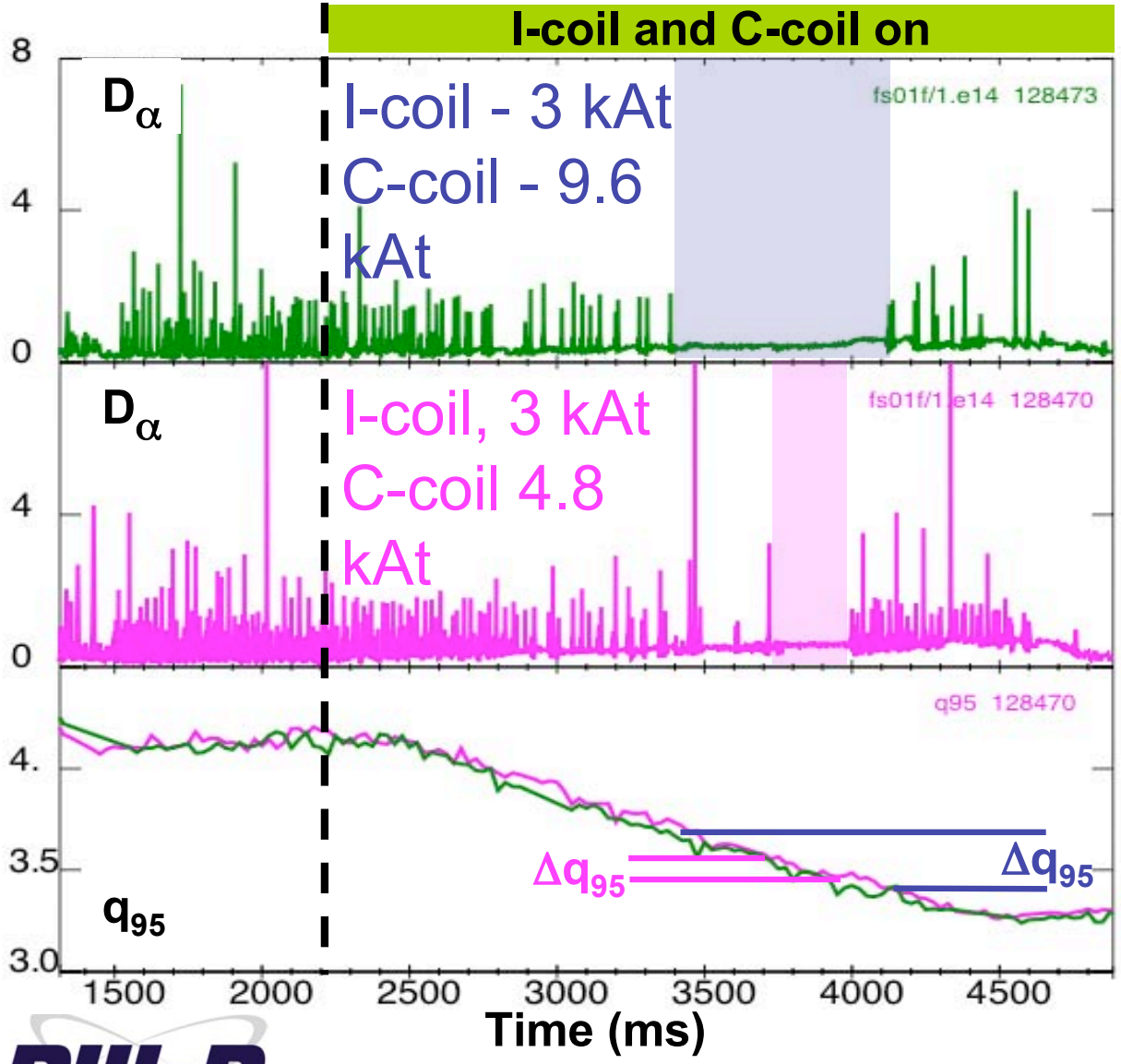
Resonance Window in q Expanded With Additional C-coil n=1 Field Combined With I-coil n=3 RMP in Edge



- Resonance window for suppression increased with C-coil current
  - At 4.8 kAt suppression for $\Delta q_{95} = 0.08$
  - At 9.6 kAt suppression for $\Delta q_{95} = 0.30$
- Changes seen in target particle flux splitting

Schmitz, Joseph, Watkins
Poster session UP8 Th pm

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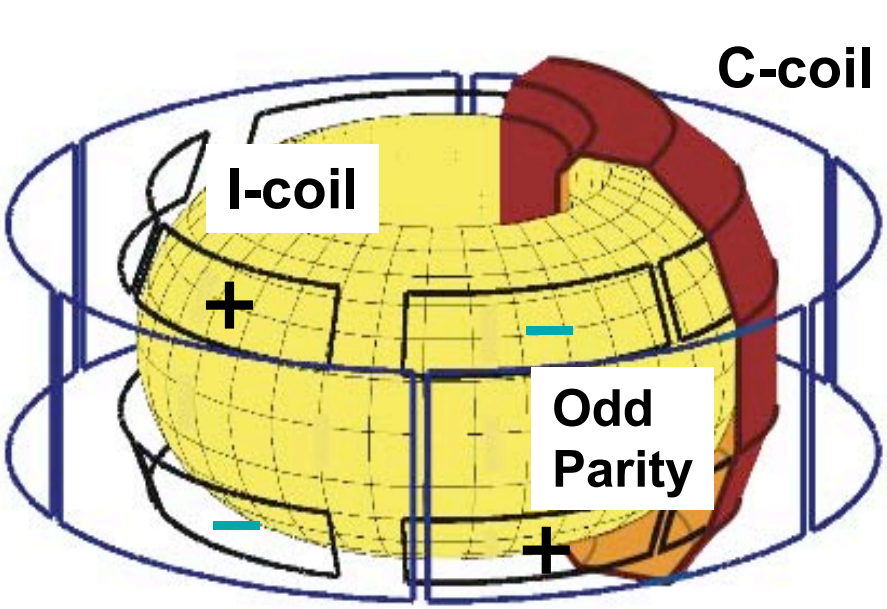
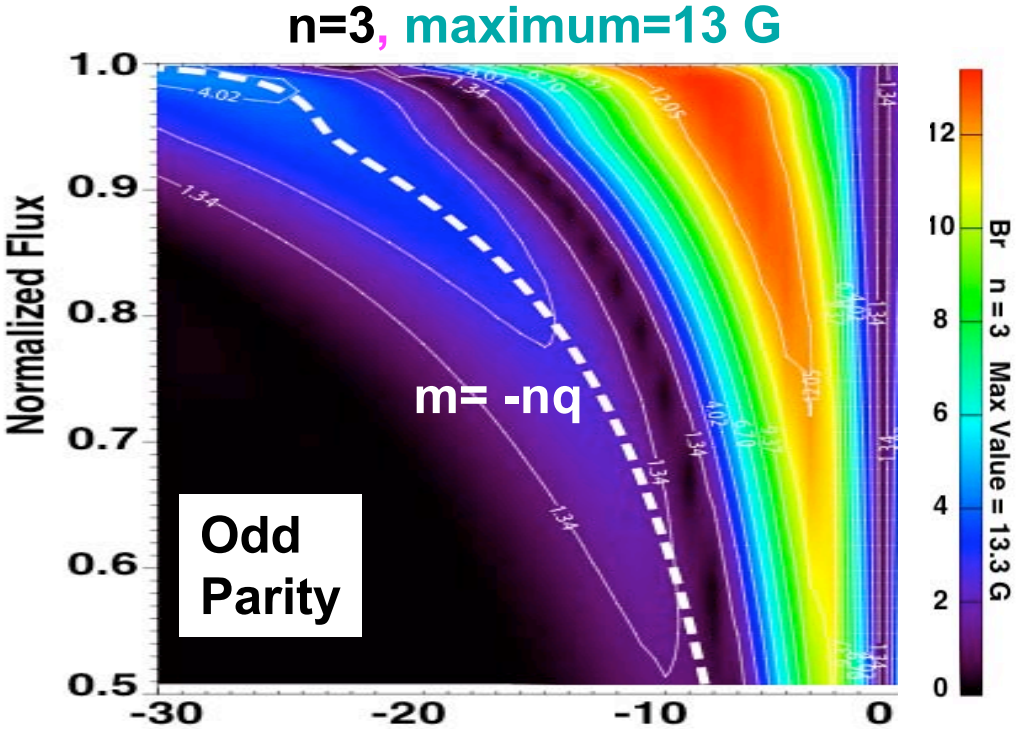
ELM Suppression Expected for Odd Parity n=3 I-coil RMP at Pitch Resonant q_{95}~7.5





- Edge pitch resonant lobe of spectrum aligns with q-profile for q_{95} ~ 7.5
- Odd parity n=3 produces weaker edge RMP than even parity
  - Edge perturbation $\delta b_r^{23/3}/B_T$ = 0.8 x 10^{-4} at Ψ_N=0.95 for 6.3 kAt

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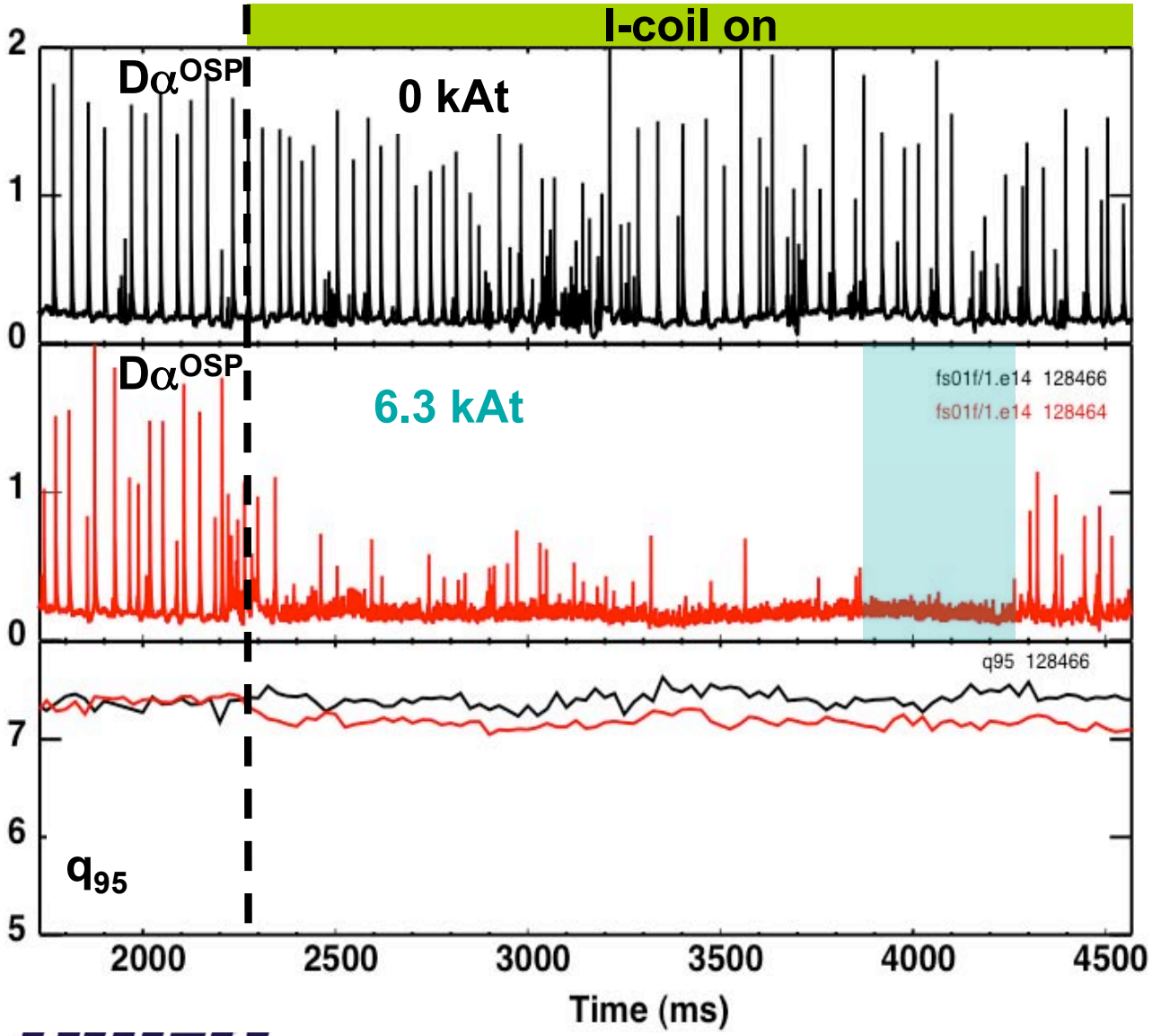
Strong ELM Mitigation Seen for Pitch Resonant Odd Parity I-coil at High q_{95} ~ 7.5



- Further confirmation that suppression is a resonant effect
- Remaining ELMs (Type-I) reduced factor of 20 (D_α) from no RMP case

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Particle balance indicates that walls must be doing most of the pumping in ELM-suppressed phase

- cryopumps exhaust particles transiently for 100–300 ms at start of I-coil pulse before ELMs are suppressed
- Increased transport & broader SOL = higher exhaust

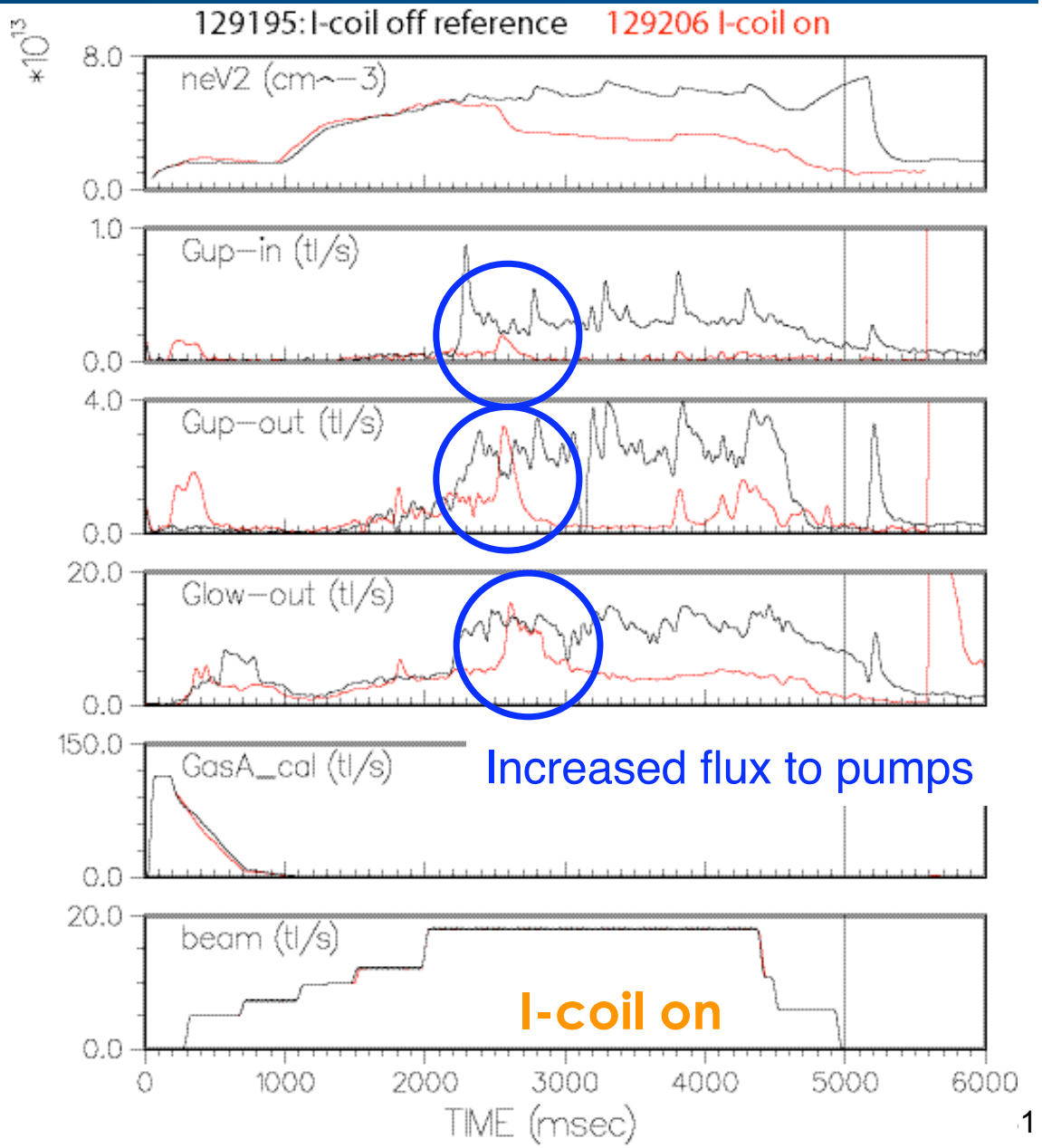
  L. Zeng UP8.00026
- Particle transport from higher frequency, smaller amplitude, more convective ELMs

  ΔW_{ELM} = 5–20 kJ before RMP

  ΔW_{ELM} = 2–5 kJ during RMP

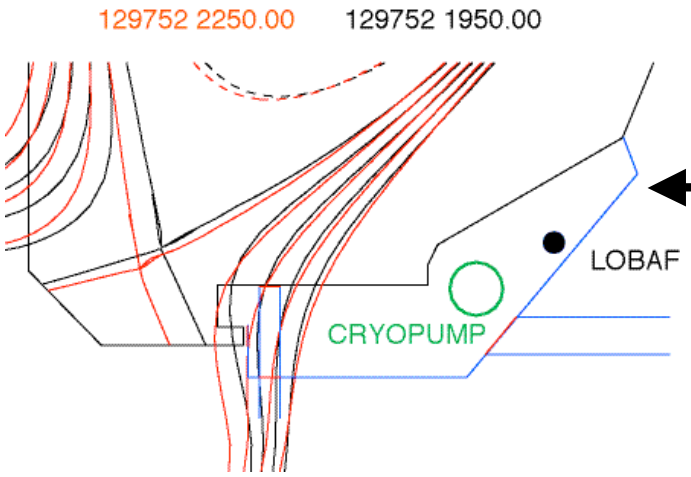
  O. Schmitz UP8.00034
- Wall pumping (main chamber?) plays significant role once ELMs suppress

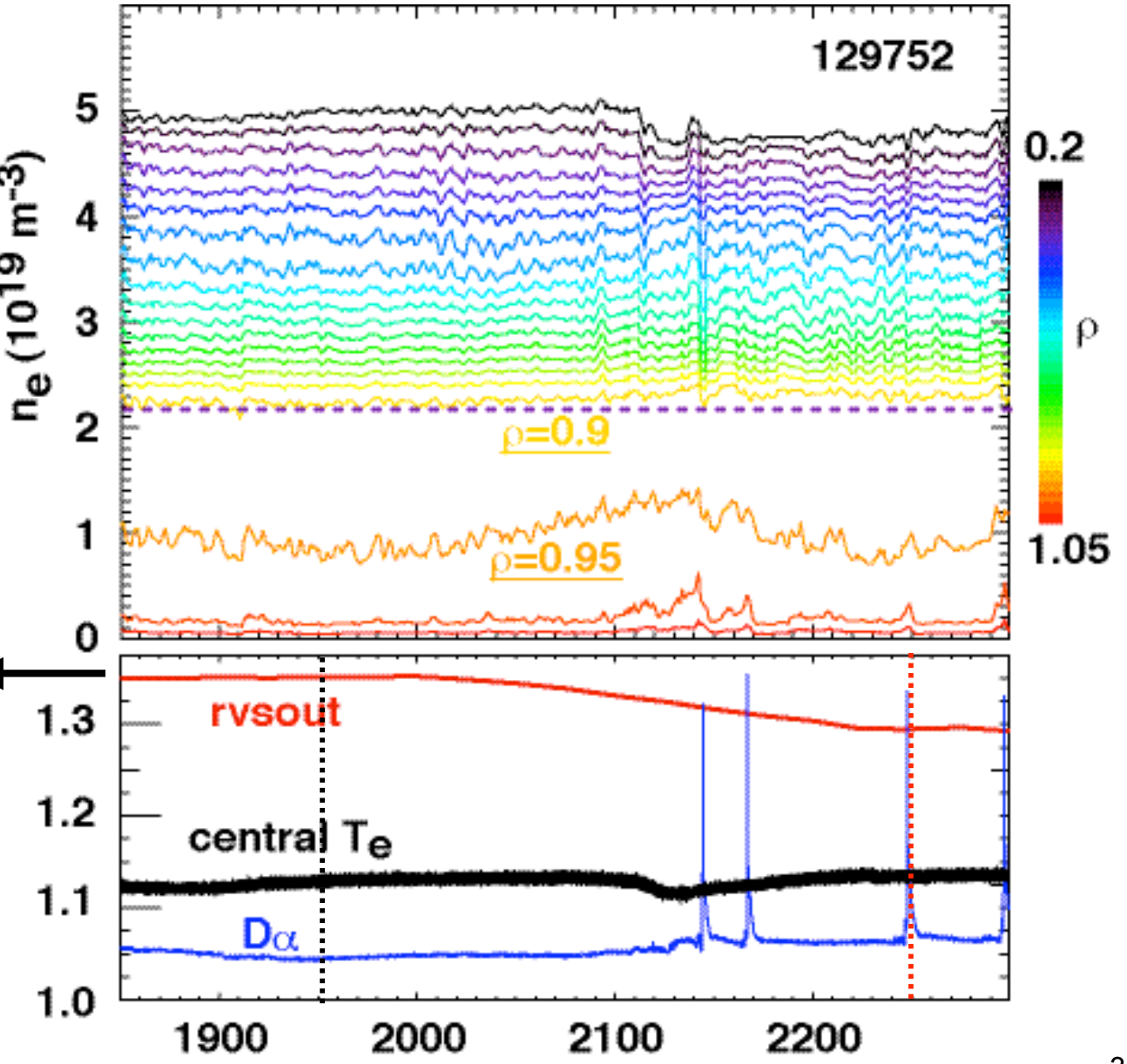
  Analysis by T.W. Petrie



Outer strike point scan causes prompt rise in pedestal n_e and a return to ELMing H-mode

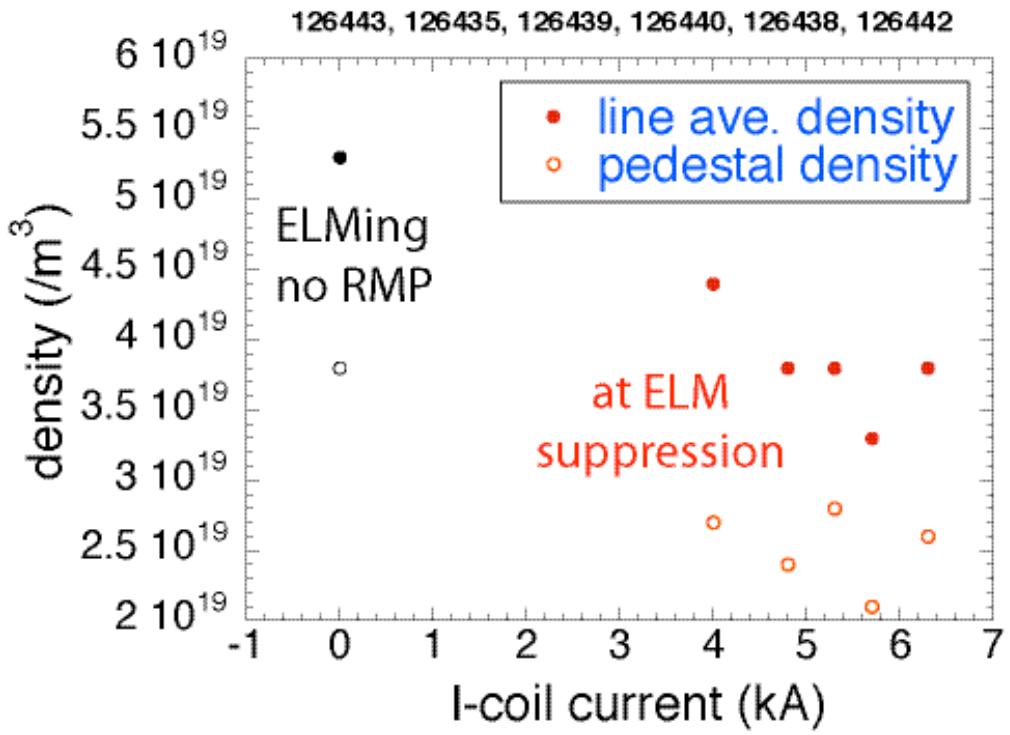
- n_e at ρ=0.95 ramps linearly as strike point moved away from pump

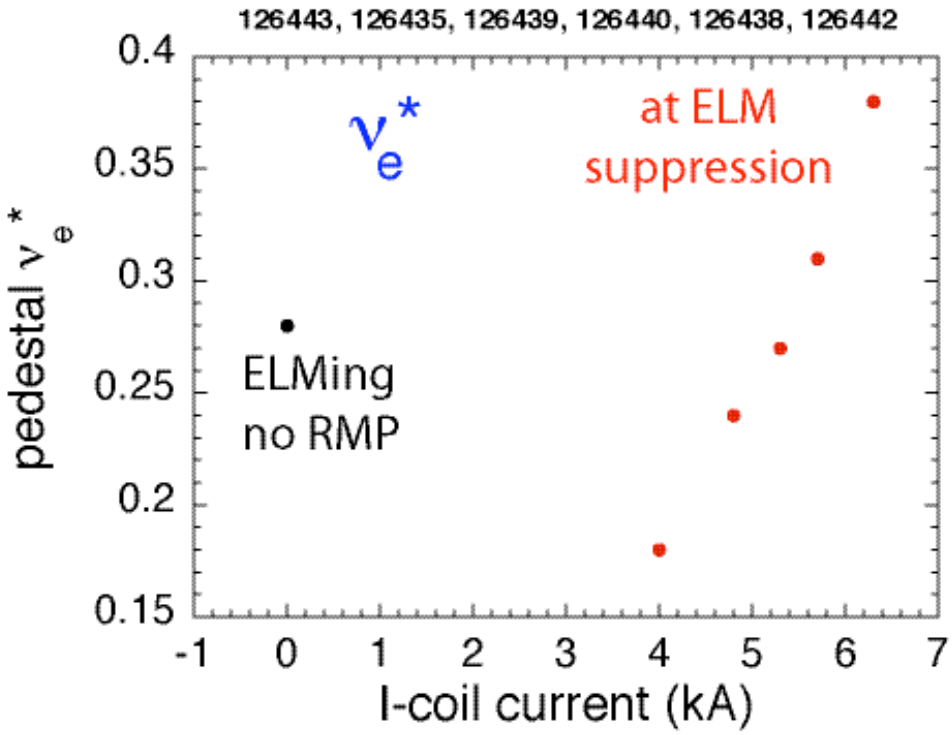




Line average density, pedestal density, and pedestal ν_e^* at ELM suppression don't order the data well.

- I-coil current scan on a single day with fixed shape and power
  - line average density, pedestal density, and pedestal collisionality taken at onset of ELM suppression





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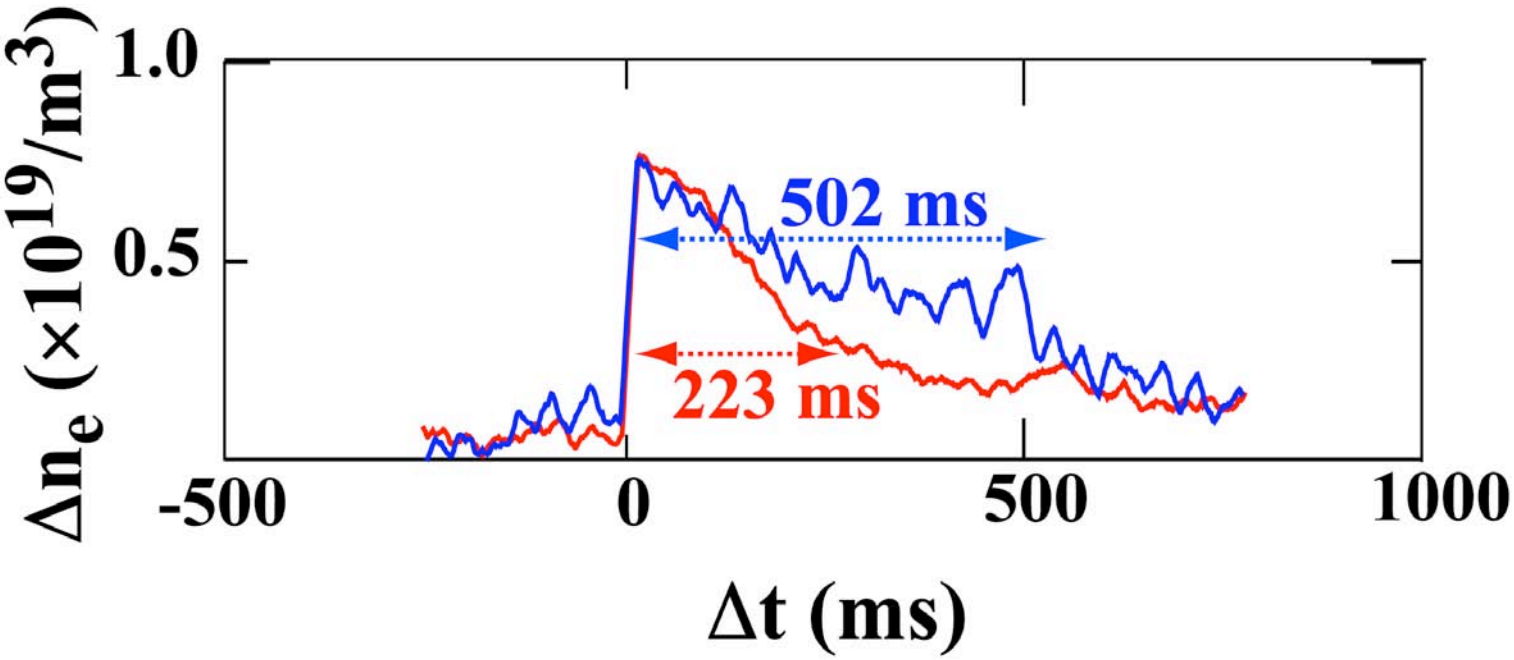
τ_p* reduced a factor of 2 in pellet perturbation experiments with similar recycling ($\rightarrow \tau_p$ change)

- Identical pellets injected into discharges with ν_e* ~ 0.2, δ ~ 0.52, and similar recycling conditions:
  - I-coil = 0 kA, ELMing H-mode
  - I-coil = 4 kA, RMP-assisted ELM-free H-mode



L. Baylor UP8.00031

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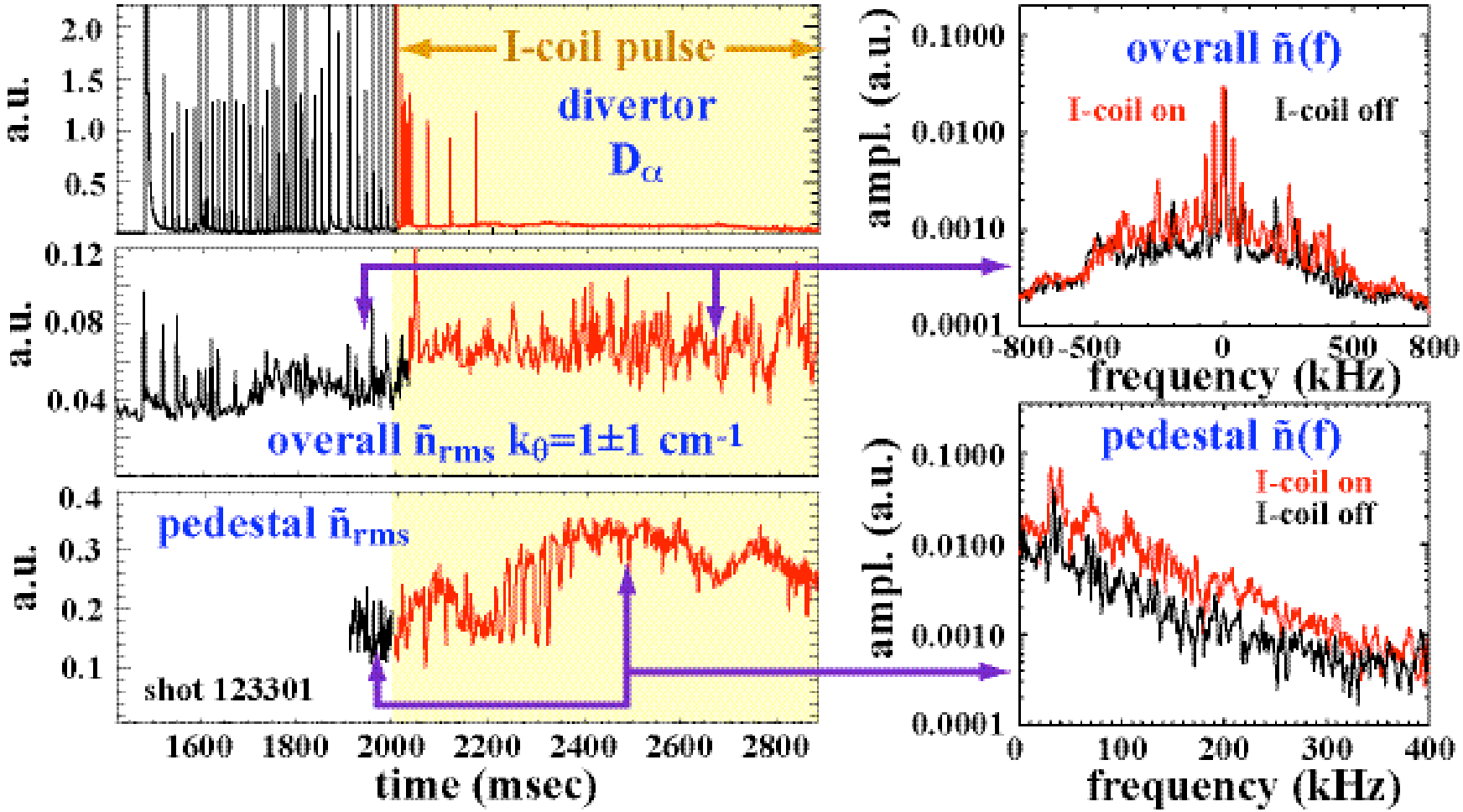
Increased particle transport during RMP may be due to increased fluctuation-driven transport.

- 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 $\tilde{n}_{rms}$
- $D_{eff} \sim \tilde{n}_{rms}^2$ → D_{eff} increases 3-4x, consistent with change inferred from profiles.



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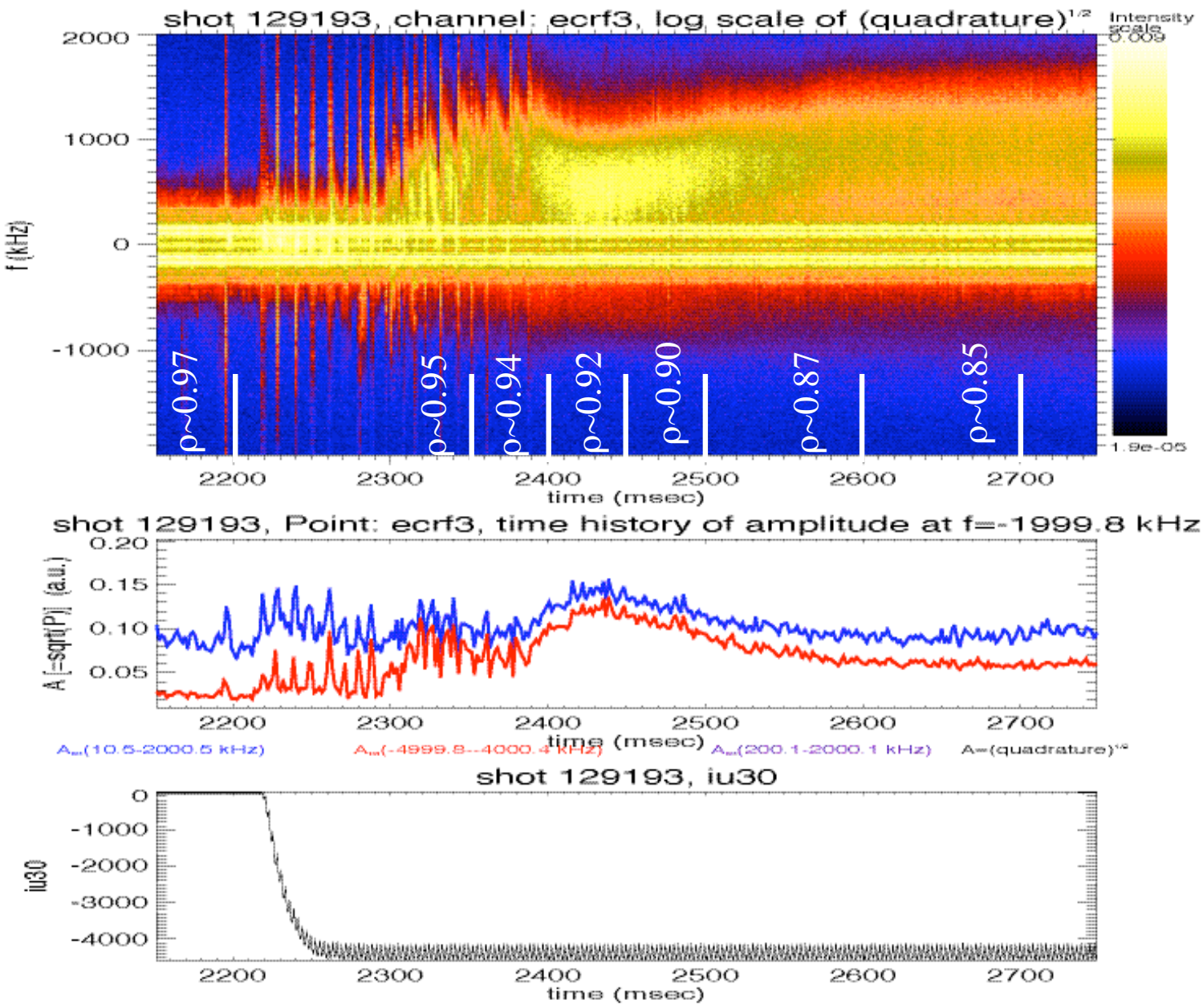
Intermediate k_θ ~ 4 to 5 inv. cm also increase broadband in the pedestal at ELM suppression

- Pedestal E_r changes at 2300 ms (ρ ~ 0.97)
- Fluctuations increase broadband when the ELMs suppress at 2500 ms (ρ ~ 0.90–0.94)

UCLA Doppler reflectometry by L Schmitz



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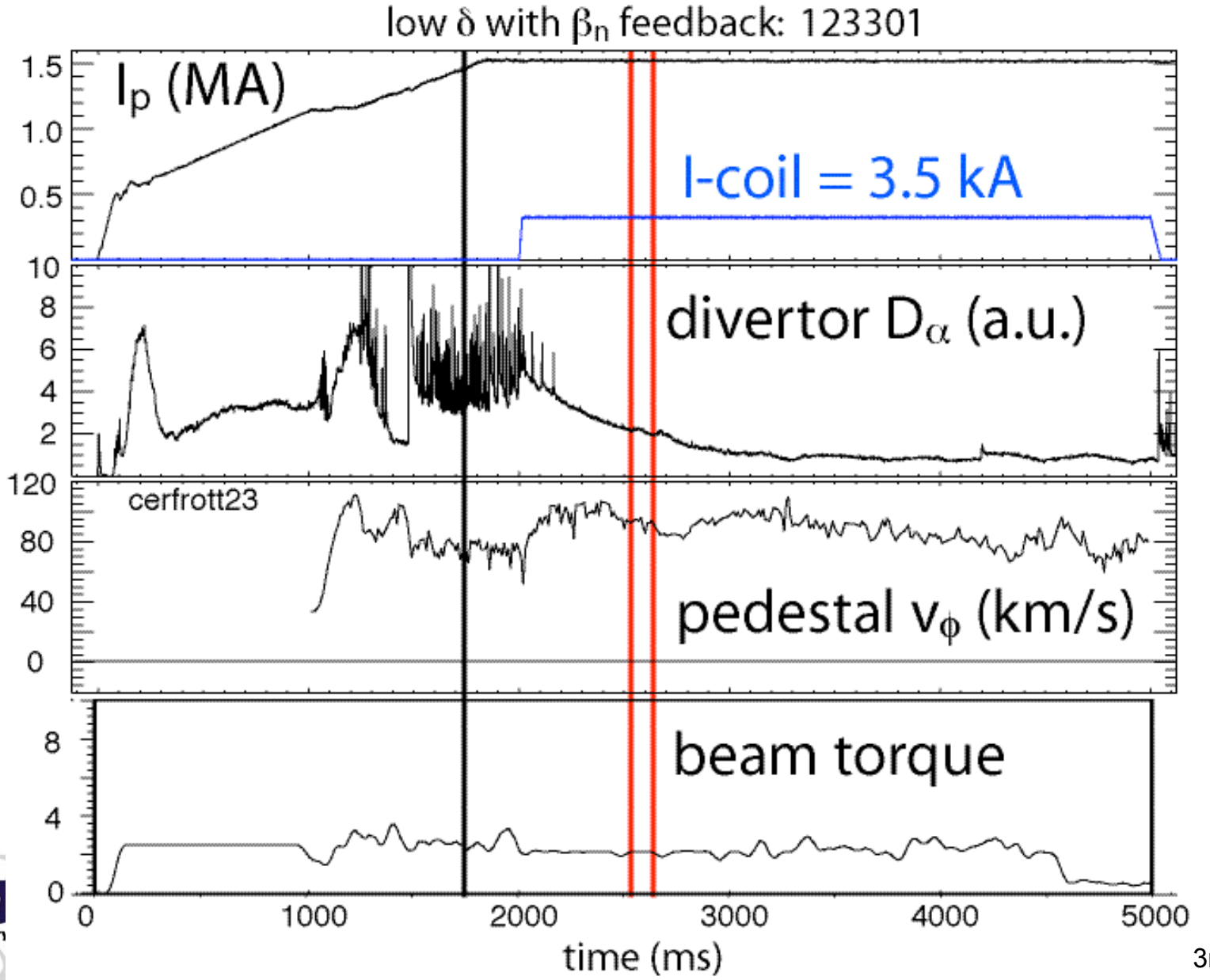
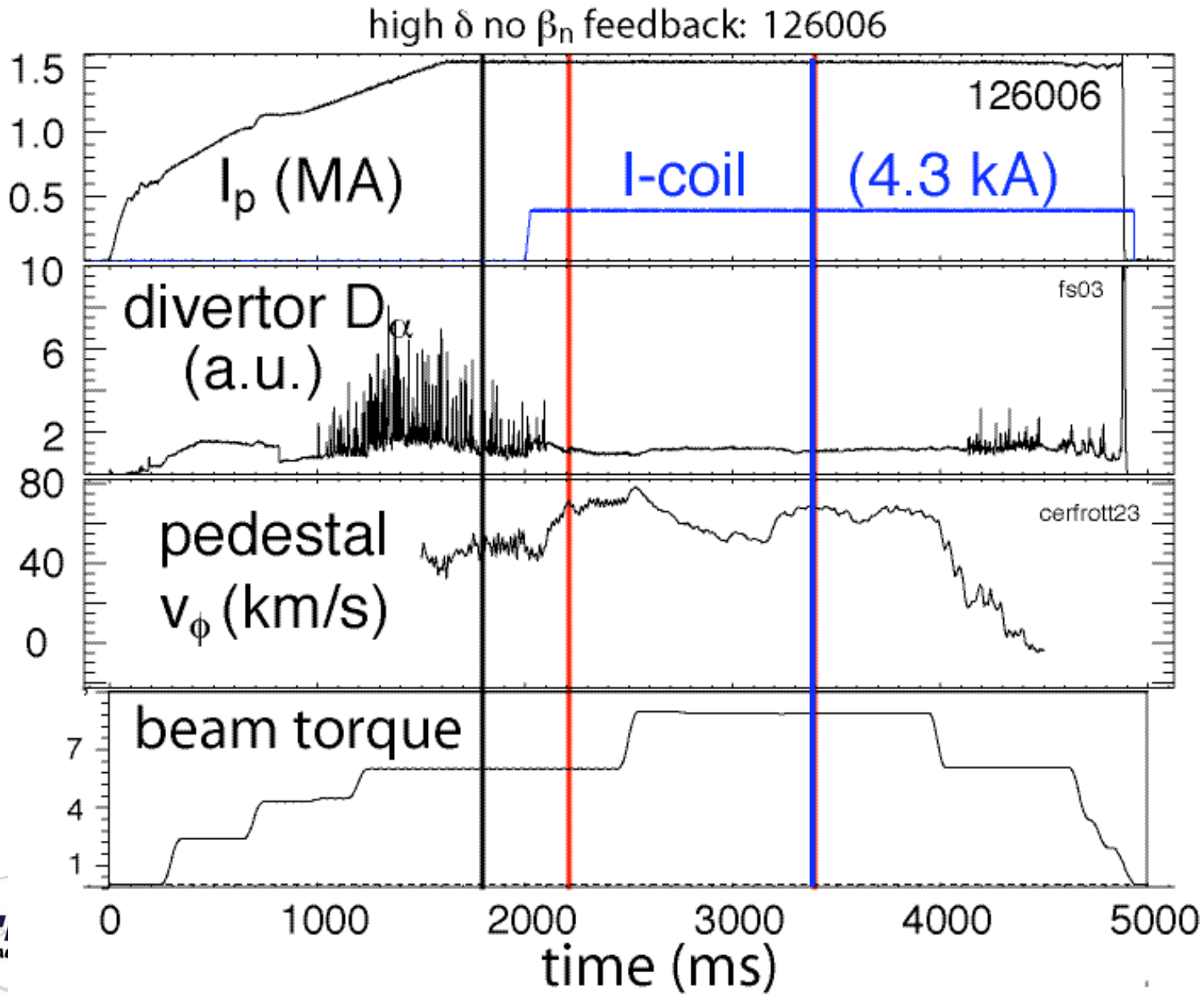
Pedestal toroidal rotation & E_r change promptly when RMP is applied and q_{95} resonant (RMP penetrates?)



Pedestal toroidal rotation & E_r change promptly when RMP is applied and q_{95} resonant (RMP penetrates?)



Similar prompt changes in v_ϕ and E_r in high $\delta \sim 0.52$ discharges at resonant q_{95}

- E_r well shift similar to deformations in preliminary IPEC modeling.