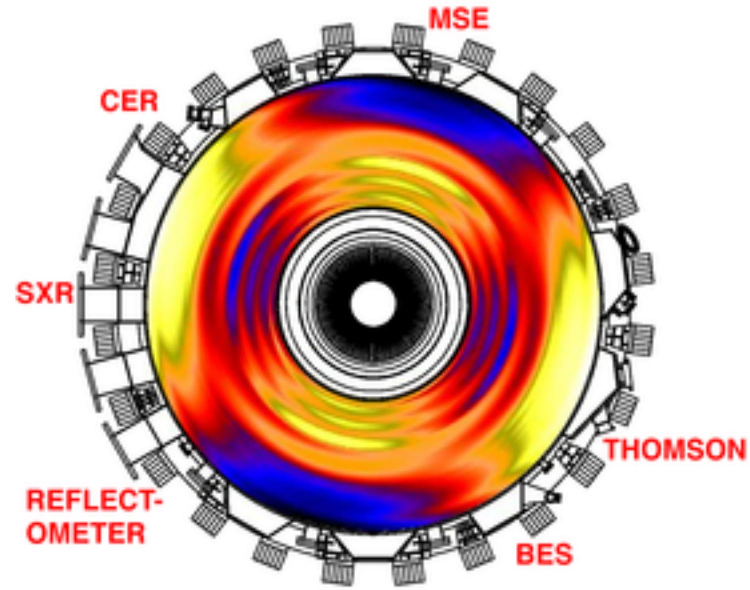
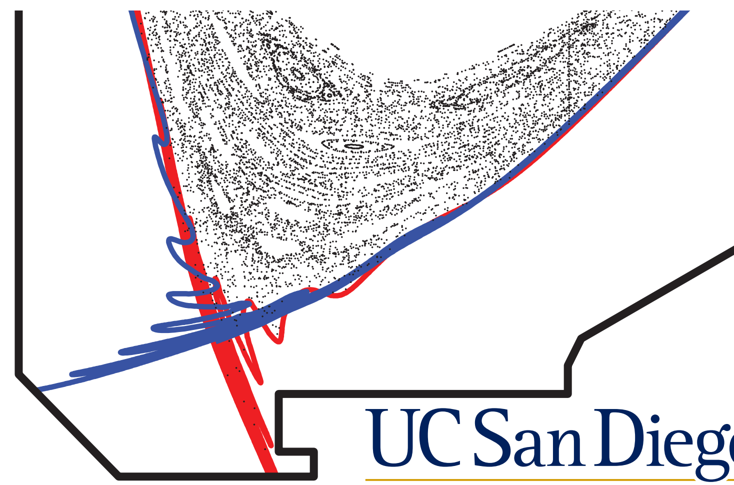
Plasma Rotation and Radial Electric Field Response to Resonant Magnetic Perturbations in DIII-D



by
R.A. Moyer

Presented at the
54th Annual APS Meeting
Division of Plasma Physics
Providence, Rhode Island

October 29 — November 2, 2012



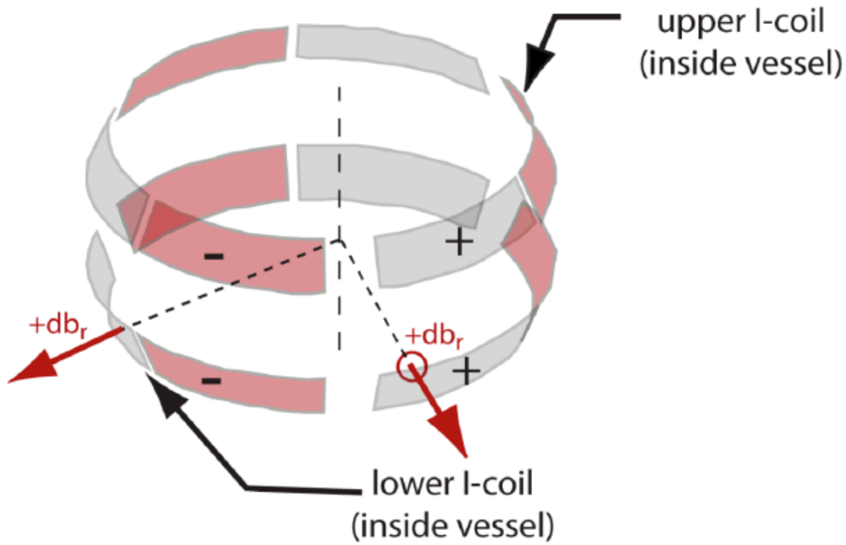
DIII-D NATIONAL FUSION FACILITY SAN DIEGO

UC San Diego

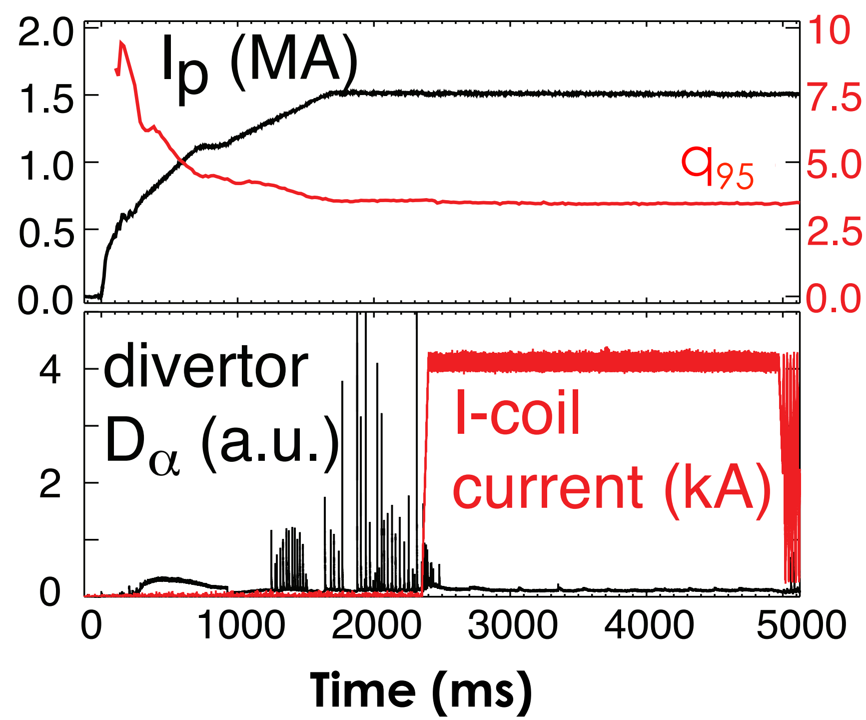
Resonant Magnetic Perturbations Have been Used to Mitigate or Suppress ELMs in Many Tokamaks

- **The impulsive power loading to the divertor from cyclic Edge Localized Modes (ELMs) will greatly reduce the ITER divertor lifetime**
- **Magnetic perturbations that are field line pitch aligned (resonant) in the edge are produced with internal coils in DIII-D ("I-coils")**

DIII-D I-coil consistent of 2 rows of 6 segments

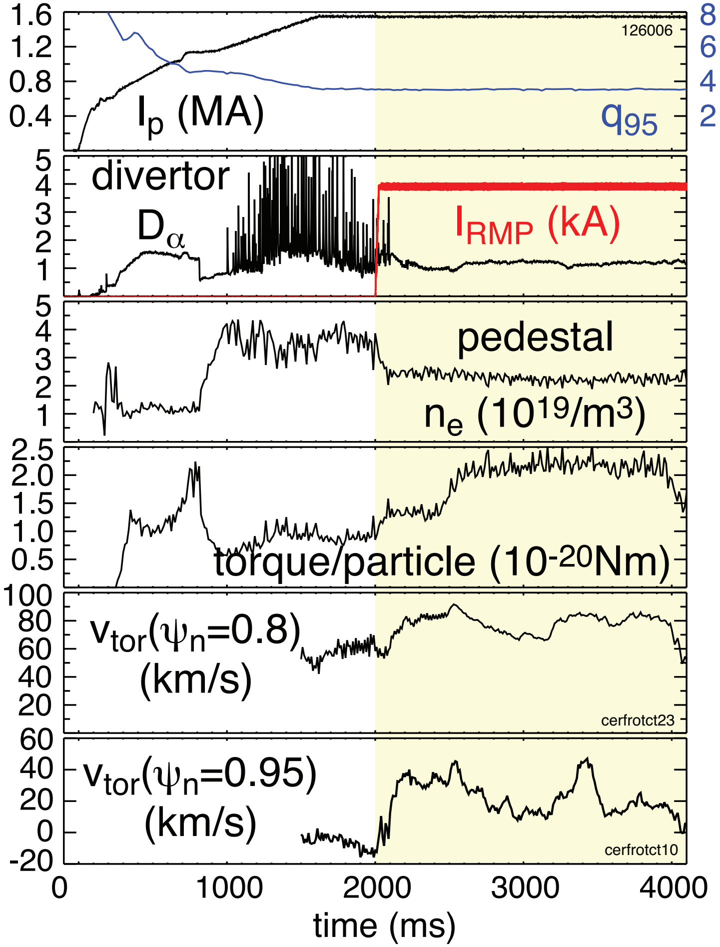


ELM suppression in DIII-D



Dynamic Response of E_r Provides Insight into the Plasma Response to RMPs and the Physics of ELM Suppression

n = 3 RMP in ELMing H-mode produces ELM suppression



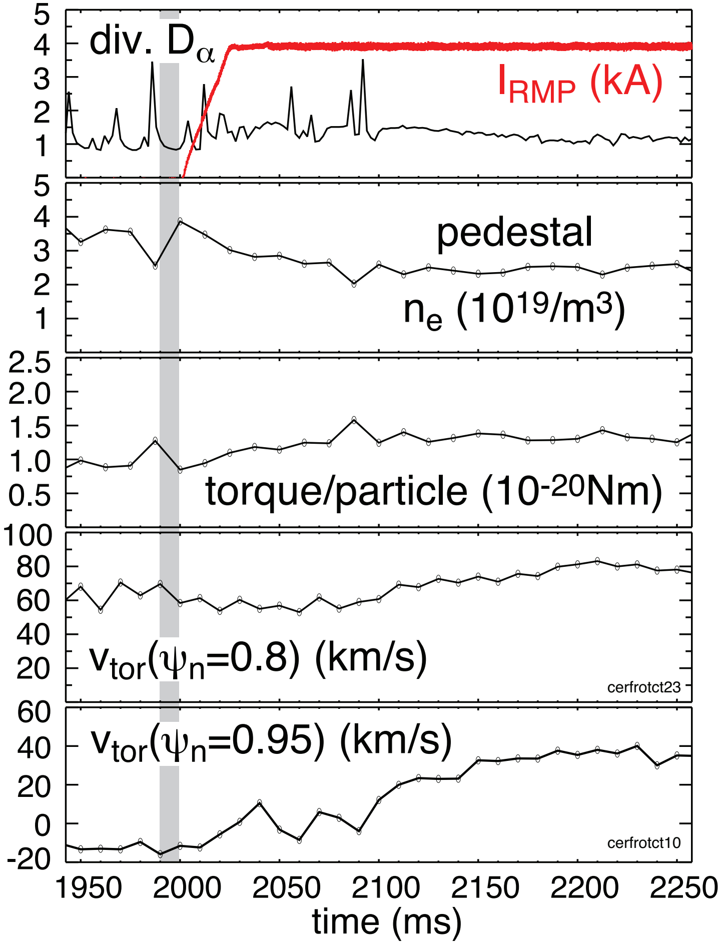
E_r from CER spectroscopy of carbon VI ions using single ion radial force balance

$$E_r = \frac{1}{n_i Z_i e}\nabla P_i - v_{\theta i} B_\phi + v_{\phi i} B_\theta$$

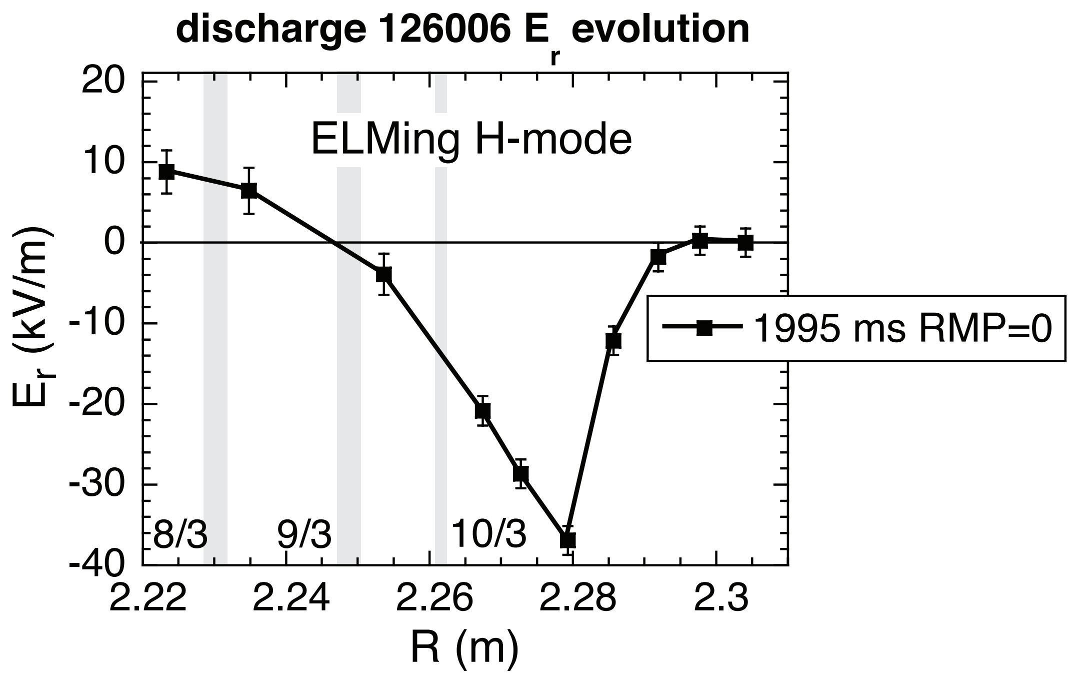
NATIONAL FUSION FACILITY SAN DIEGO

Adding the RMP to ELMing H-mode Causes an Evolution from ELMing to Mitigated ELMs to ELM Suppression

Density drops and edge toroidal rotation v_{tor} increases

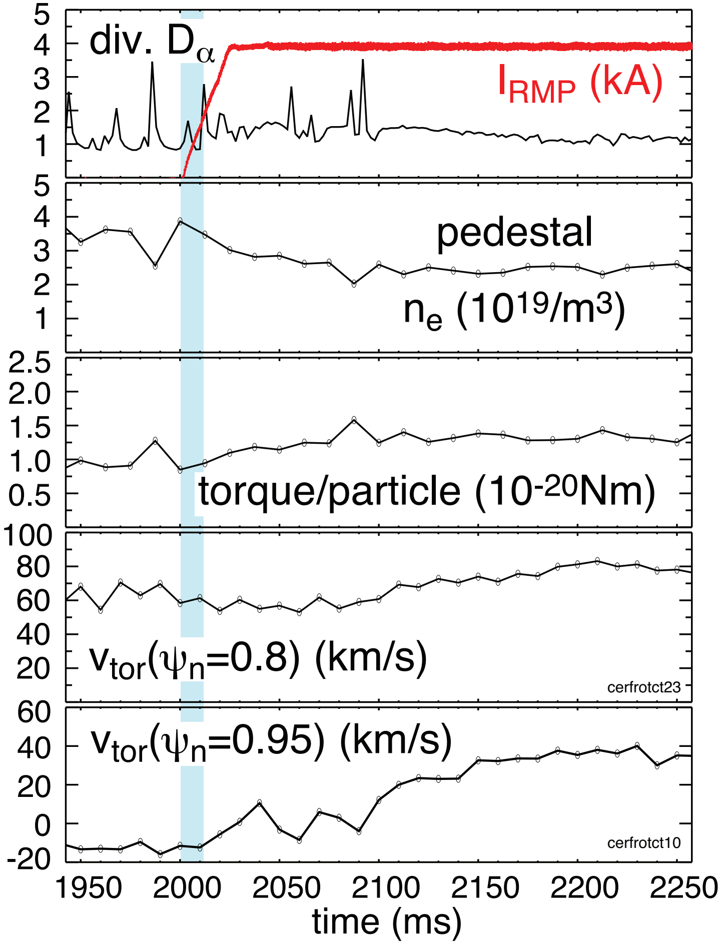


ELMing H-mode before RMP

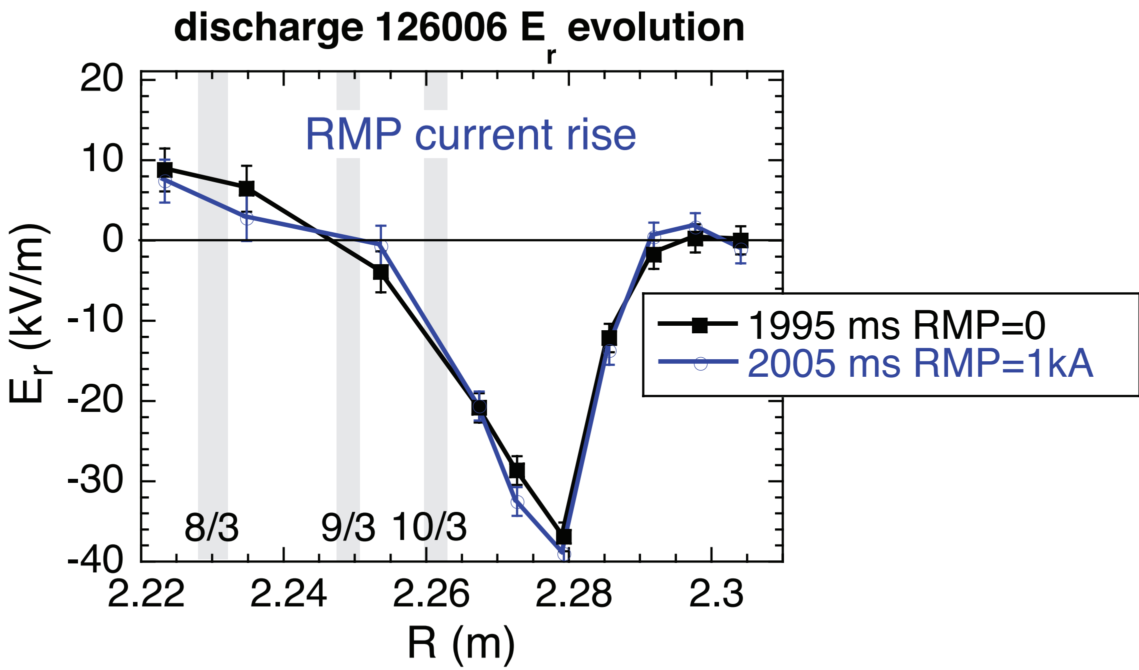


Adding the RMP to ELMing H-mode Causes an Evolution from ELMing to Mitigated ELMs to ELM Suppression

Density drops and edge toroidal rotation v_{tor} increases



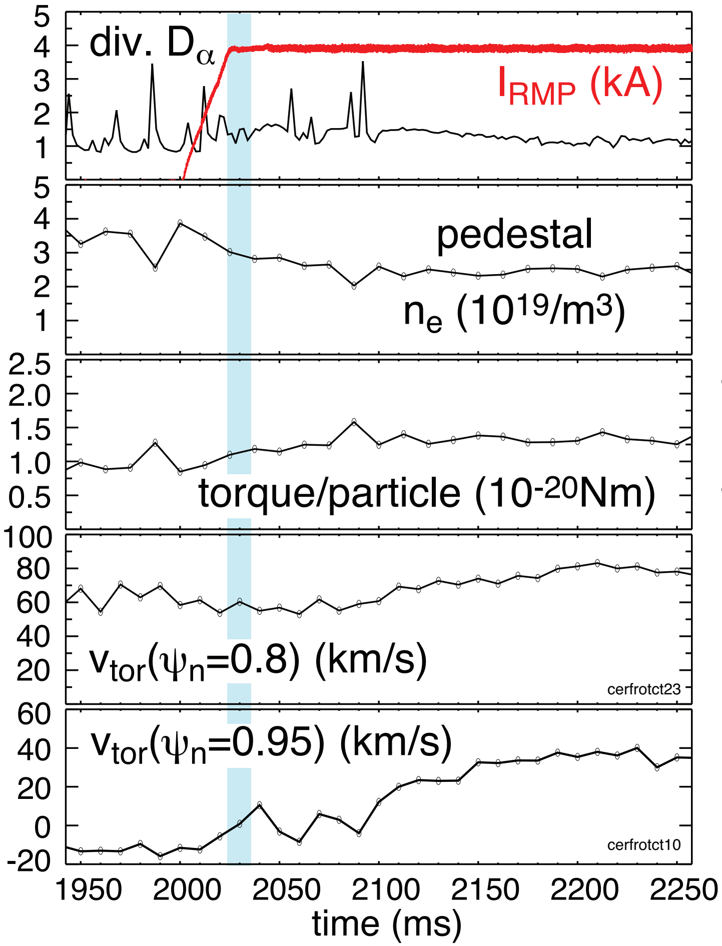
Mitigated ELMing phase as RMP current rises



DIII-D NATIONAL FUSION FACILITY SAN DIEGO

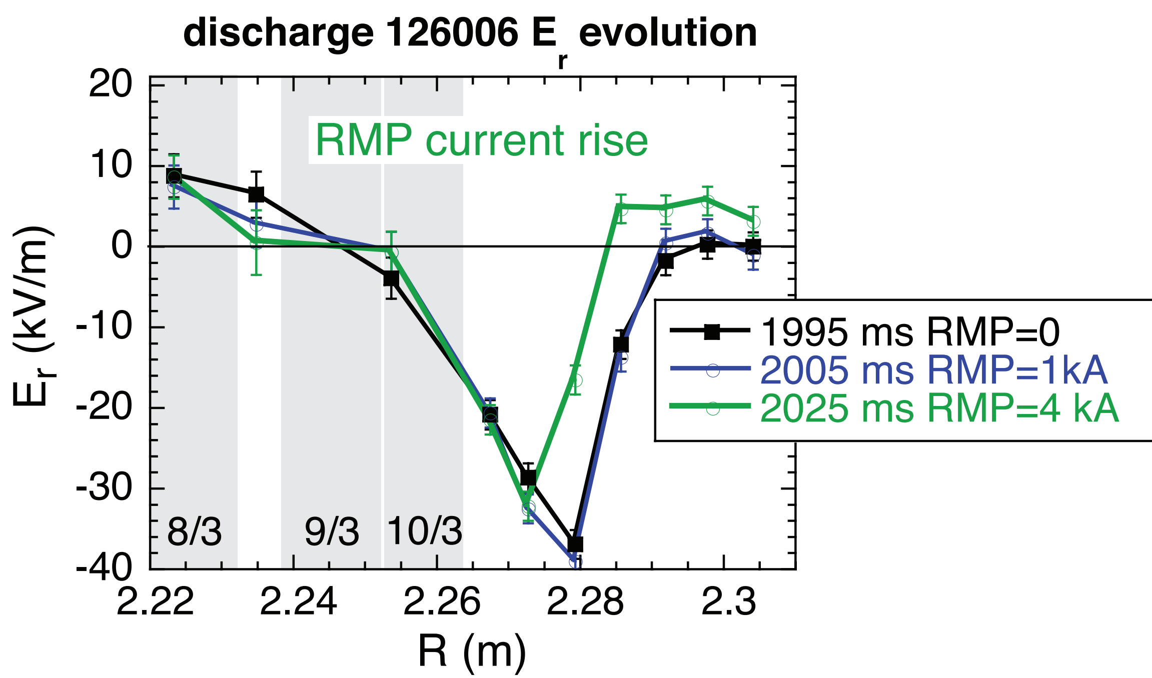
Adding the RMP to ELMing H-mode Causes an Evolution from ELMing to Mitigated ELMs to ELM Suppression

Density drops and edge toroidal rotation v_{tor} increases



Mitigated ELMing phase at full RMP

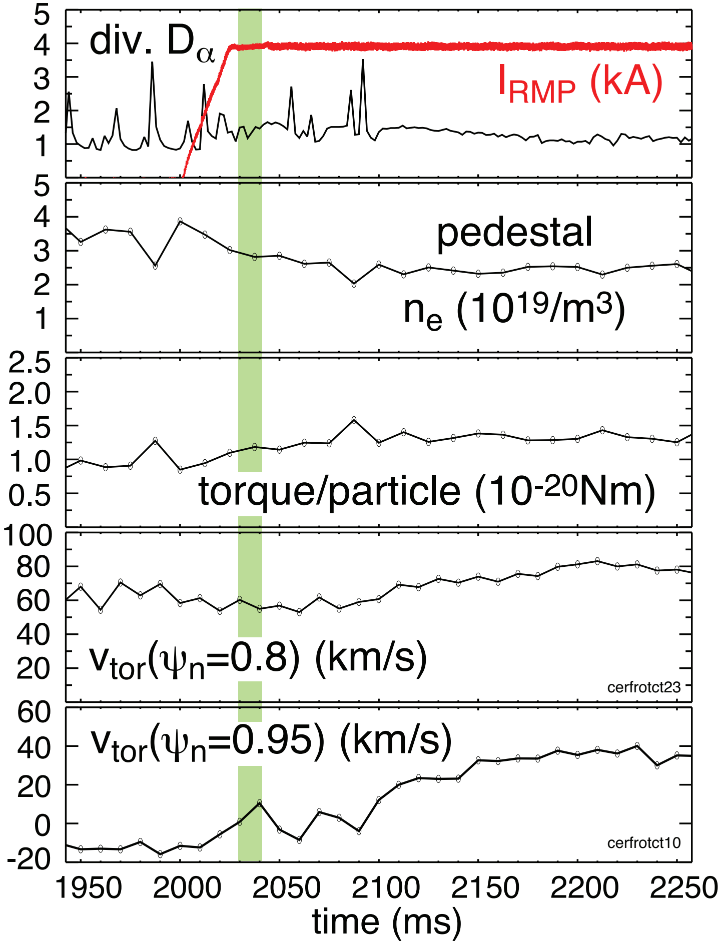
E_r well is displaced inward 5-6mm as fast as RMP rises



DIII-D NATIONAL FUSION FACILITY SAN DIEGO

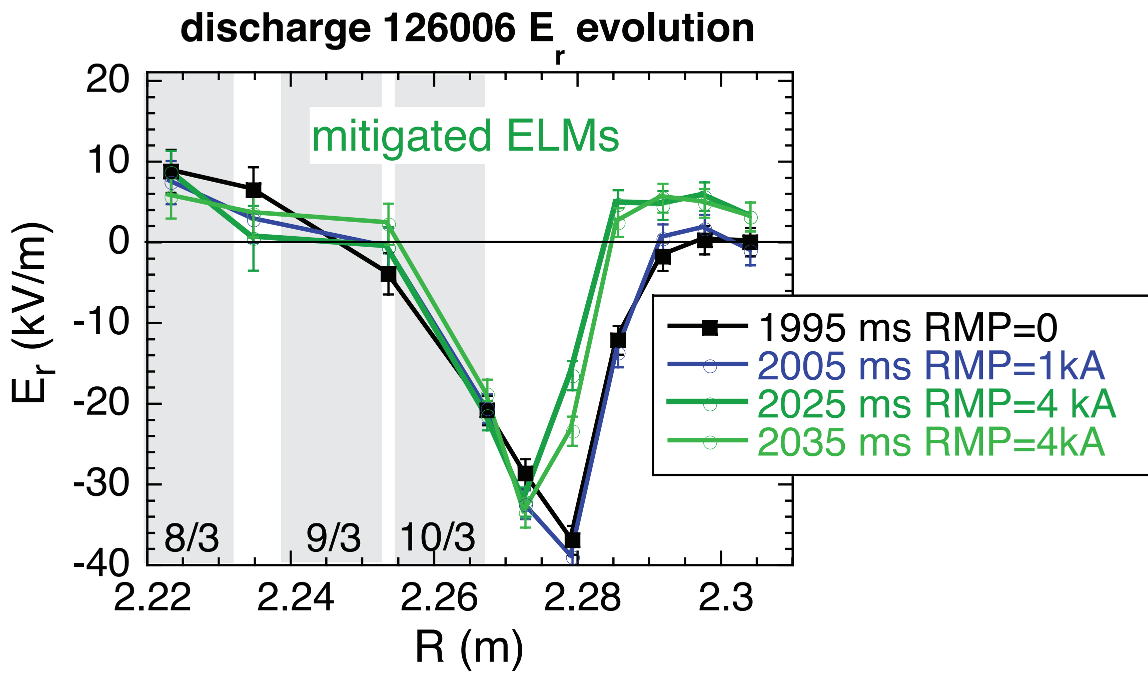
Adding the RMP to ELMing H-mode Causes an Evolution from ELMing to Mitigated ELMs to ELM Suppression

Density drops and edge toroidal rotation v_{tor} increases



Mitigated ELMing phase at full RMP

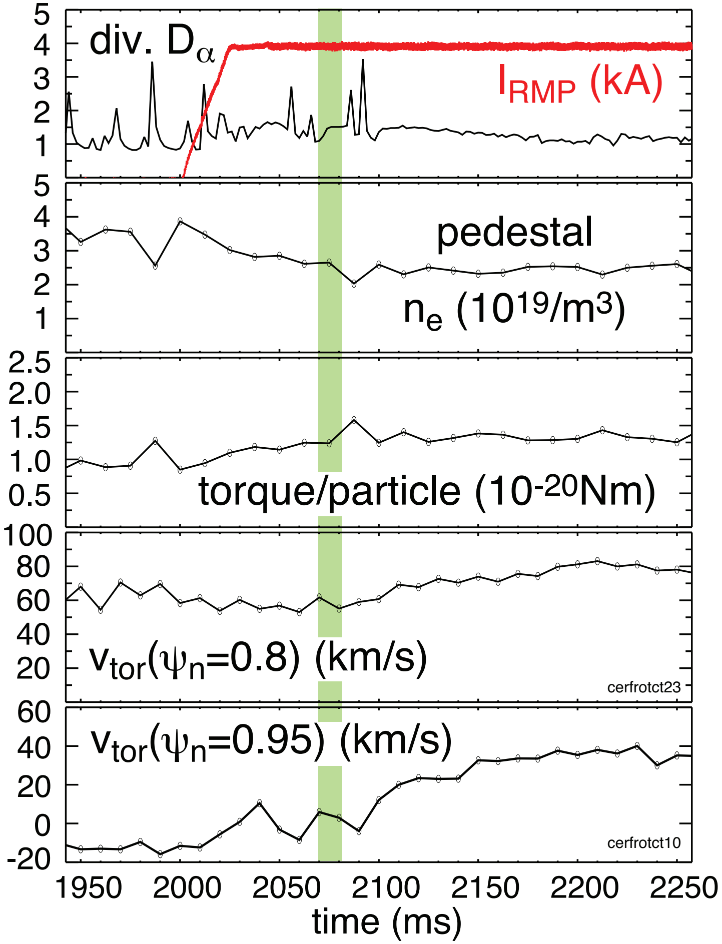
E_r profile flattens where 8/3 and 9/3 rational surfaces are



DIII-D NATIONAL FUSION FACILITY SAN DIEGO

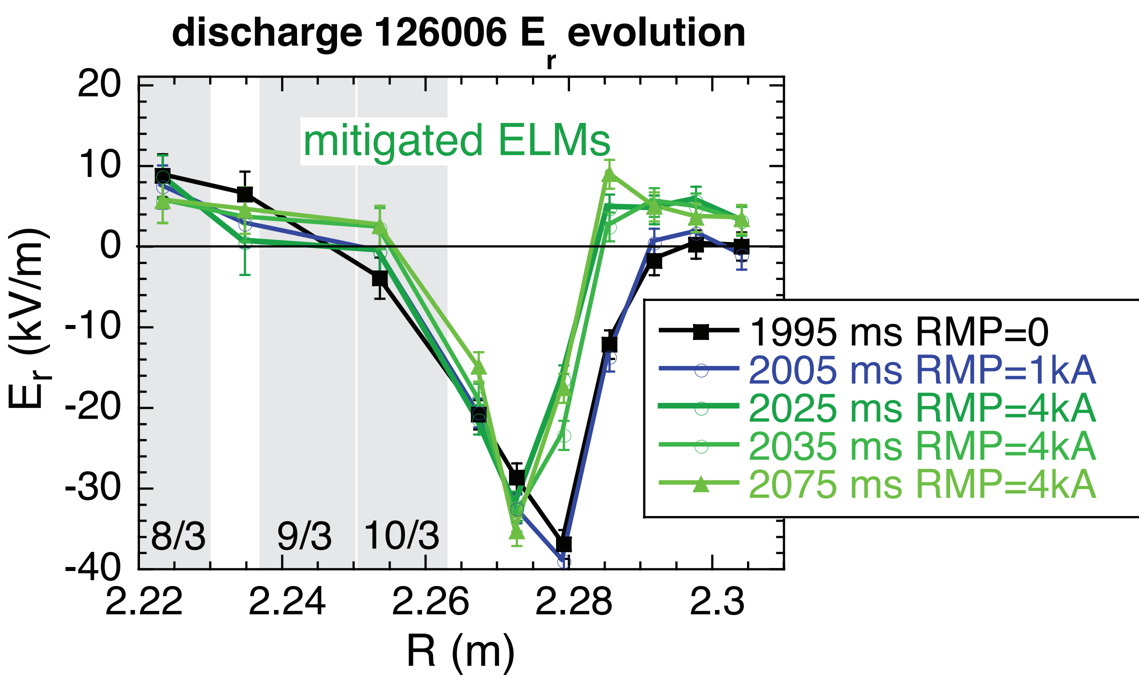
Adding the RMP to ELMing H-mode Causes an Evolution from ELMing to Mitigated ELMs to ELM Suppression

Density drops and edge toroidal rotation v_{tor} increases



Mitigated ELMing phase at full RMP

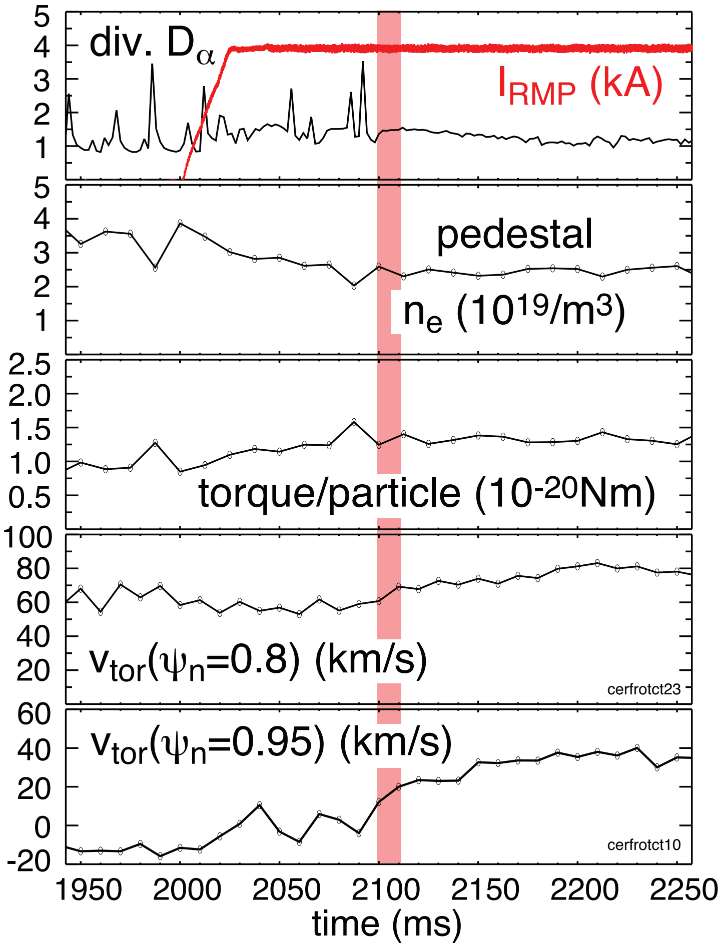
E_r profile flattens where 8/3 and 9/3 rational surfaces are



DIII-D NATIONAL FUSION FACILITY SAN DIEGO

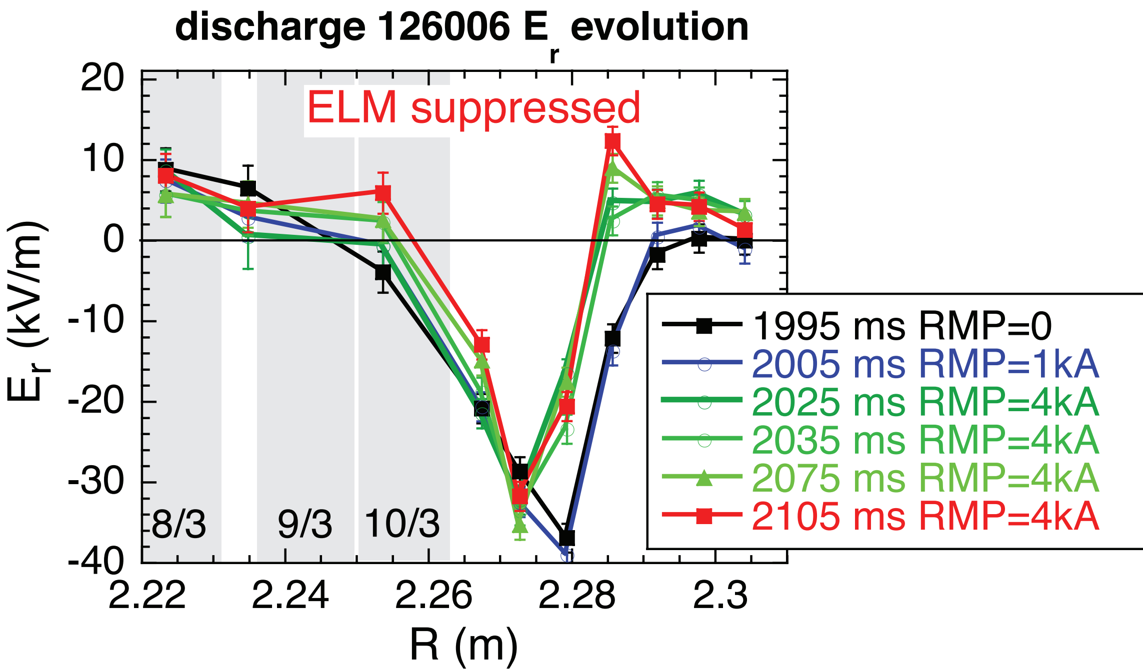
Adding the RMP to ELMing H-mode Causes an Evolution from ELMing to Mitigated ELMs to ELM Suppression

Density drops and edge toroidal rotation v_{tor} increases



ELM suppressed phase

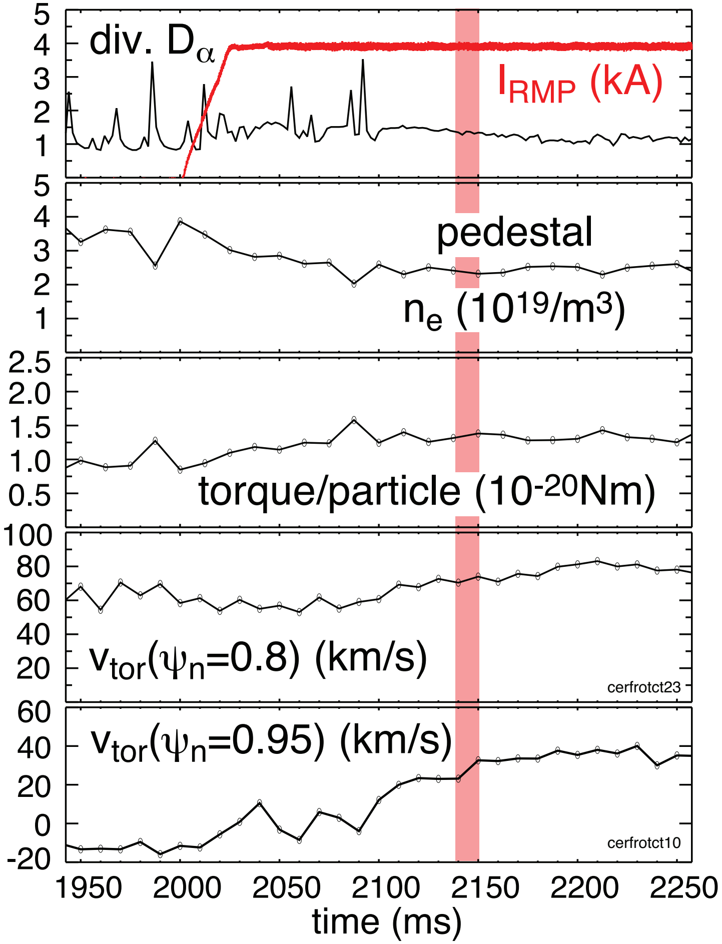
E_r profile flattens at 8/3 and 9/3 surfaces and narrows further



DIII-D NATIONAL FUSION FACILITY SAN DIEGO

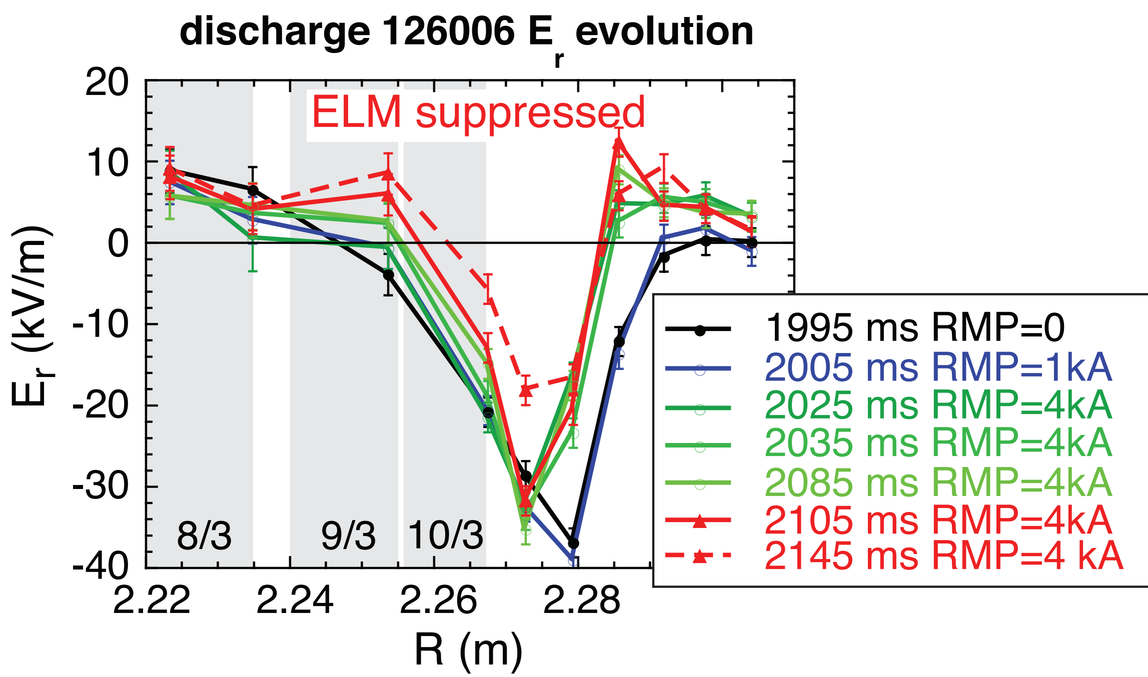
Adding the RMP to ELMing H-mode Causes an Evolution from ELMing to Mitigated ELMs to ELM Suppression

Density drops and edge toroidal rotation v_{tor} increases



ELM suppressed phase

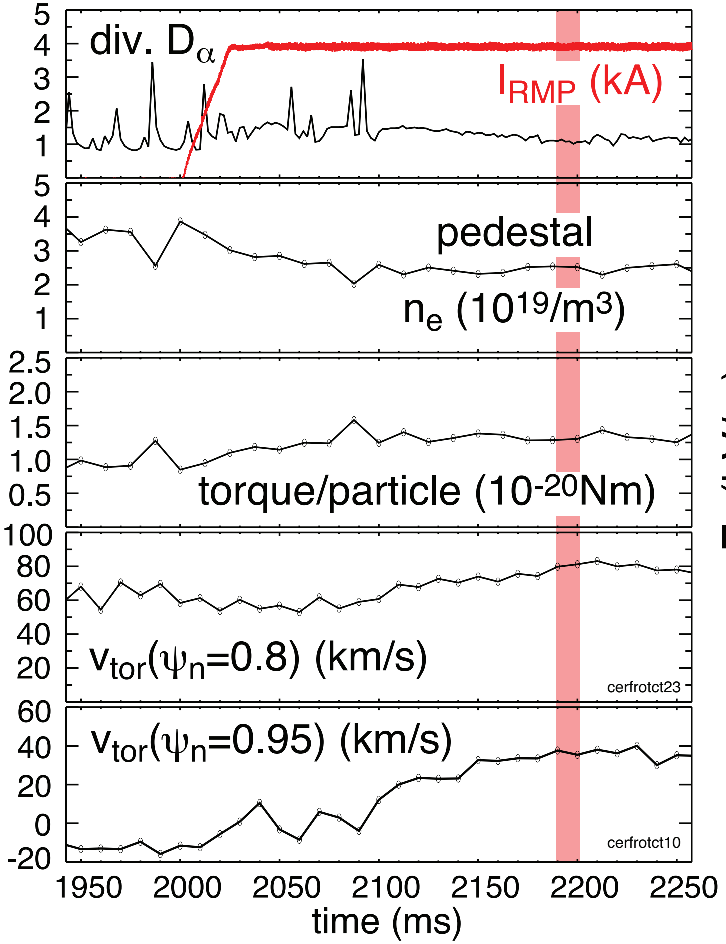
E_r profile flattens at 8/3, 9/3 surfaces, narrows further and becomes shallower



DIII-D NATIONAL FUSION FACILITY SAN DIEGO

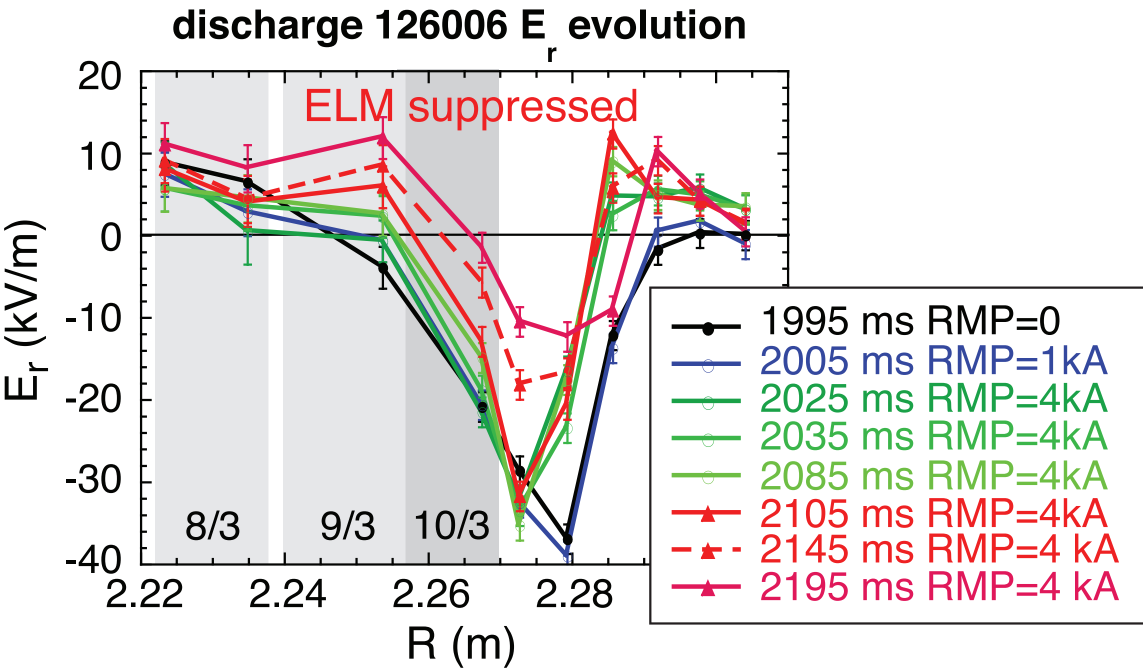
Adding the RMP to ELMing H-mode Causes an Evolution from ELMing to Mitigated ELMs to ELM Suppression

Density drops and edge toroidal rotation v_{tor} increases



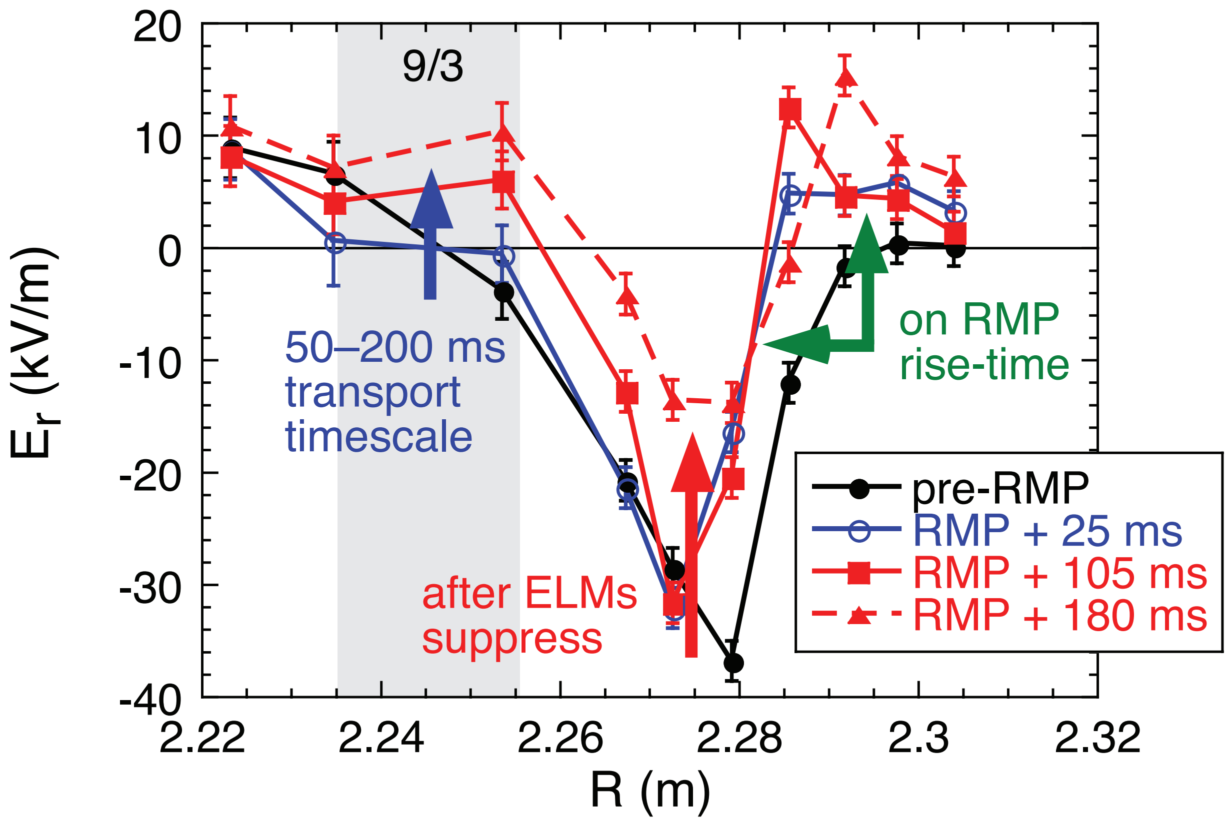
ELM suppressed phase

E_r profile shifts out to initial position



H-mode E_r Well Shifts, Narrows from Both Sides, and Becomes Shallower in Three Steps

- **1[st] change**
  - Fast rise to $E_r > 0$ at separatrix (displacement and electron loss)
- **2[nd] change**
  - Rise of E_r near the 9/3 surface on the core side of E_r well during ELM mitigation
- **3[rd] change**
  - Shift of E_r to more positive values/ shallower E_r well



Prompt Change in E_r Well Radius is Caused by Non-Resonant Interaction of the RMP with the Separatrix

- **RMP lifts degeneracy of the stable and unstable manifolds, leading to displacement of the plasma boundary**
- **E_r well shifts inward 5-6 mm at 325° consistent with MAFOT manifold calculations of the inward shift of the stable manifold**

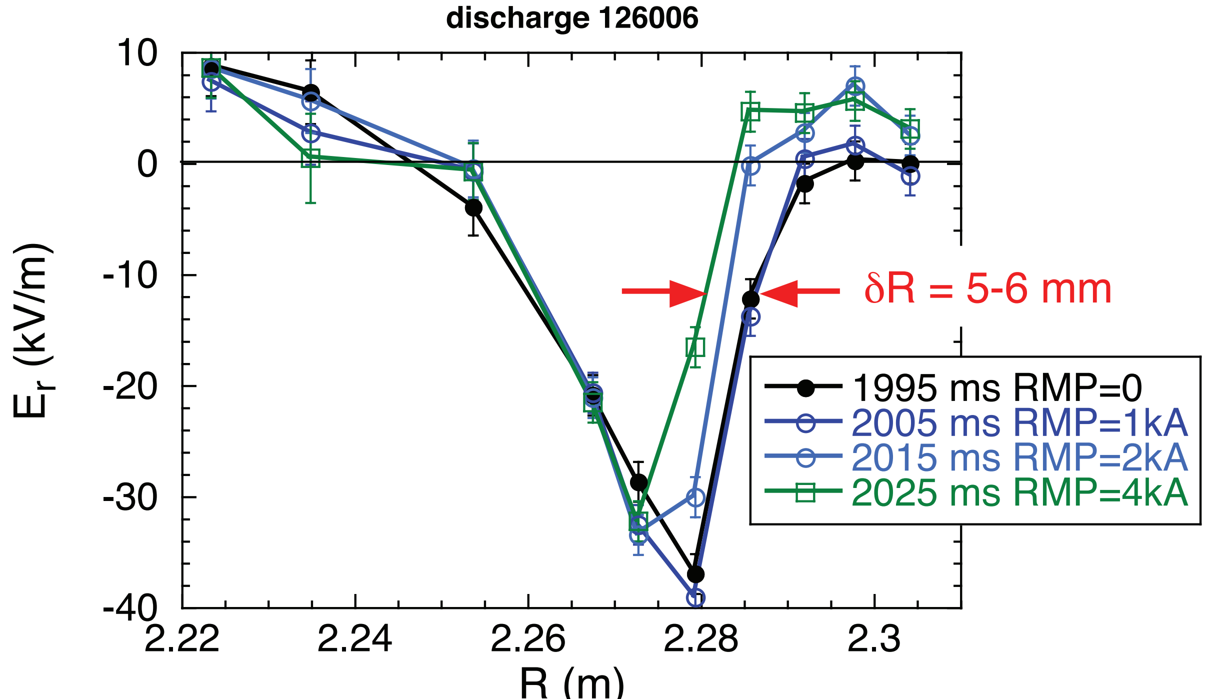
D.M. Orlov, *et al.*, GP8.077

T. E. Evans, *Chaos, Complexity and Transport: Theory and Applications, World Scientific Press (2008) 147-176*

M.W. Shafer, *et al.*, *Nucl. Fusion* (2012) in press

R.A. Moyer, *et al.*, *Nucl. Fusion* (2012) sub. to

A. Kirk, *et al.*, Phys. Rev. Lett. **108** (2012) 255003



DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Prompt Change in E_r Well Radius is Caused by Non-Resonant Interaction of the RMP with the Separatrix

- **CER E_r profiles suggests that the boundary is determined by the location of the manifold with the shortest connection length to either divertor**
  - Separatrix is split prior to the RMP by the error fields and the error field correction (C-coil) fields

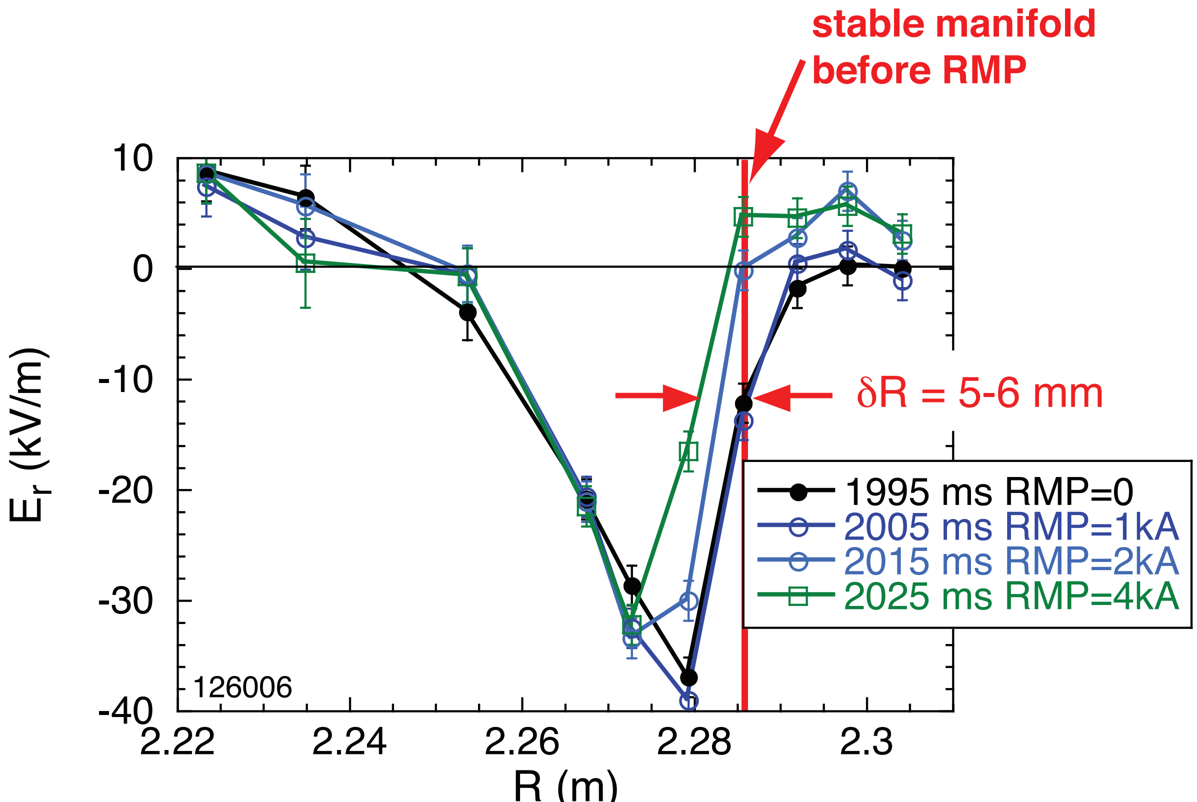
D.M. Orlov, *et al.*, GP8.077

T. E. Evans, *Chaos, Complexity and Transport: Theory and Applications, World Scientific Press (2008) 147-176*

M.W. Shafer, *et al.*, *Nucl. Fusion* (2012) in press

R.A. Moyer, *et al.*, *Nucl. Fusion* (2012) sub. to

A. Kirk, *et al.*, Phys. Rev. Lett. **108** (2012) 255003



Prompt Change in E_r Well Radius is Caused by Non-Resonant Interaction of the RMP with the Separatrix

- **CER E_r profiles suggests that the boundary is determined by the location of the manifold with the shortest connection length to either divertor**
  - Separatrix is split prior to the RMP by the error fields and the error field correction (C-coil) fields

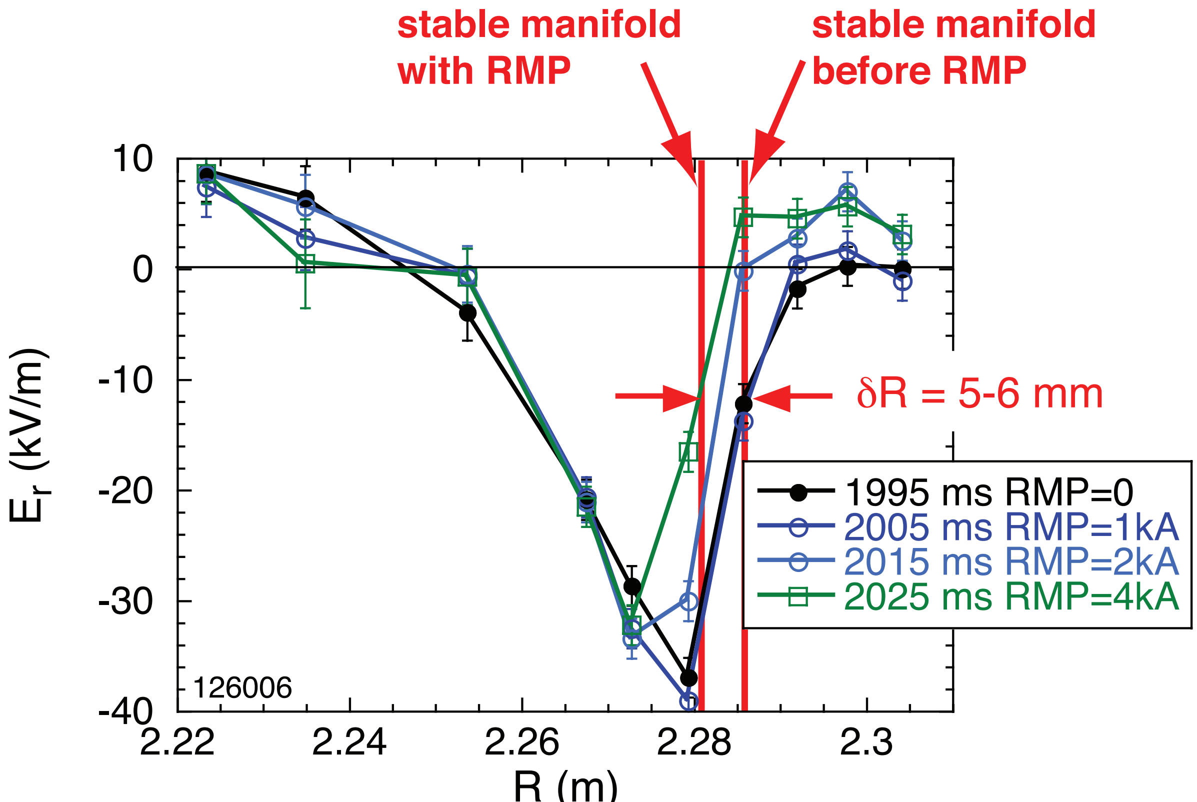
D.M. Orlov, *et al.*, GP8.077

T. E. Evans, *Chaos, Complexity and Transport: Theory and Applications, World Scientific Press (2008) 147-176*

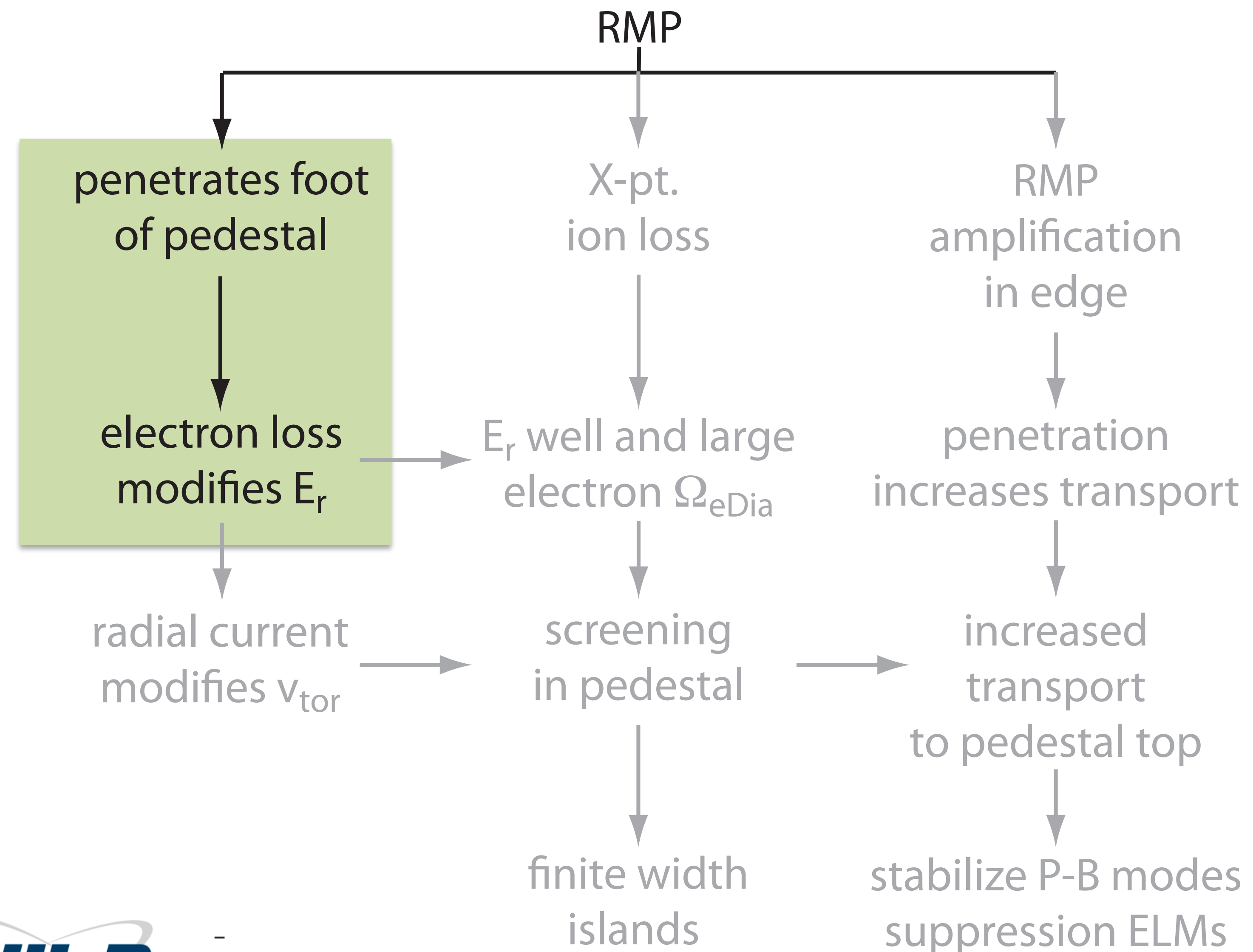
M.W. Shafer, *et al.*, *Nucl. Fusion* (2012) in press

R.A. Moyer, *et al.*, *Nucl. Fusion* (2012) sub. to

A. Kirk, *et al.*, Phys. Rev. Lett. **108** (2012) 255003



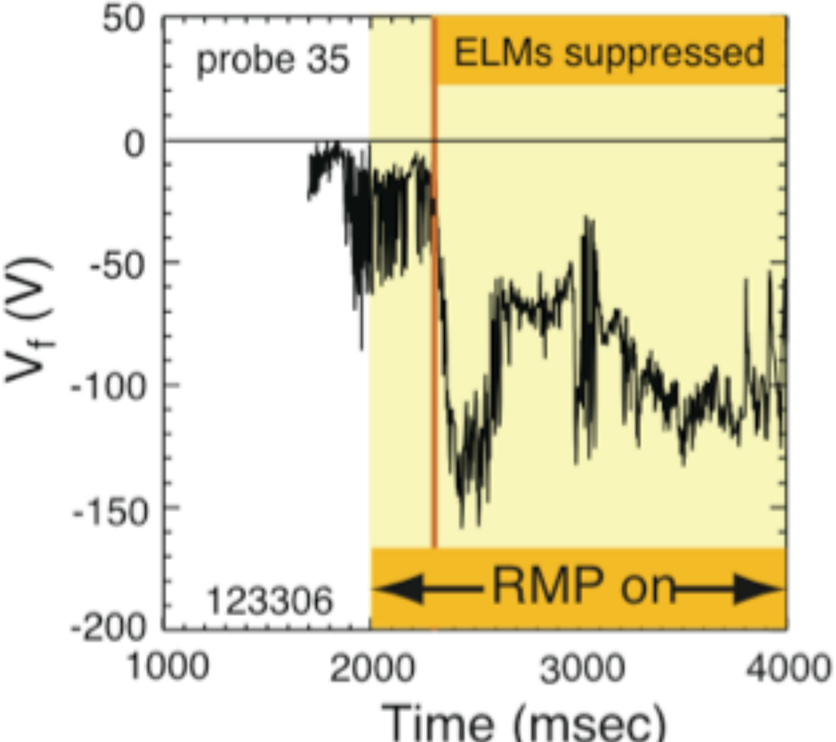
Radial Electric Field E_r Plays a Central Role in the Evolution from ELMing to ELM Suppressed H-mode



Positive E_r in Boundary → Space Potential Modified by Electron Loss Along Stochastic Field Lines

- **Strike point floating potential → strongly negative indicating loss of electrons from the pedestal**

  J.G. Watkins JNM 07, JNM 09

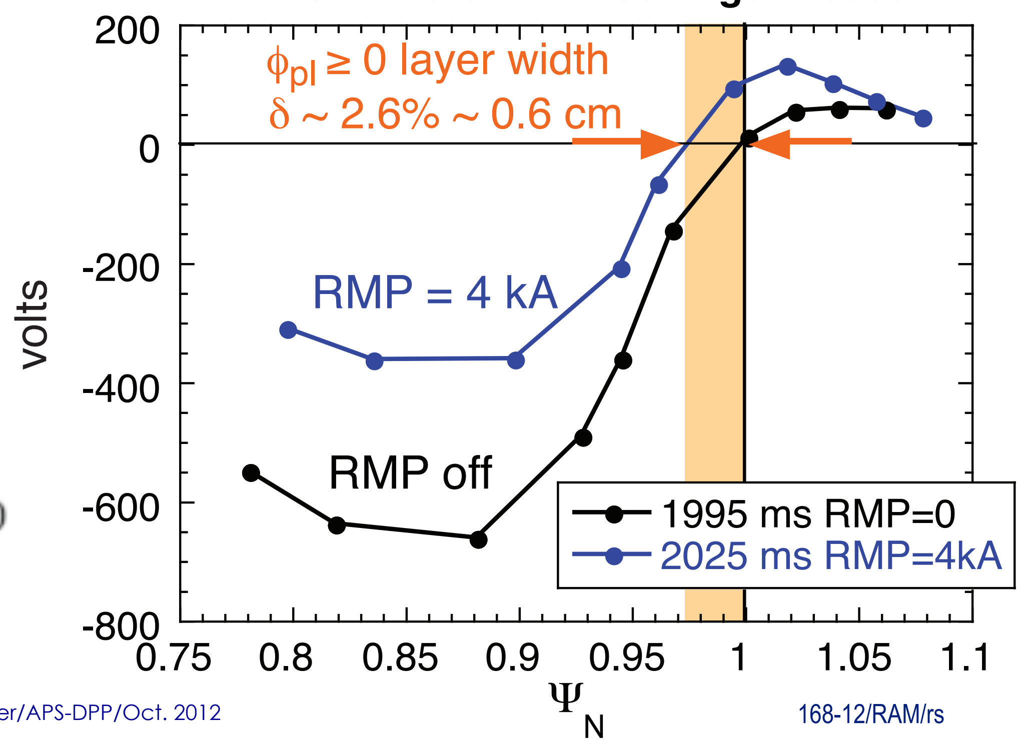


- **Plasma potential → positive as fast as RMP rises**

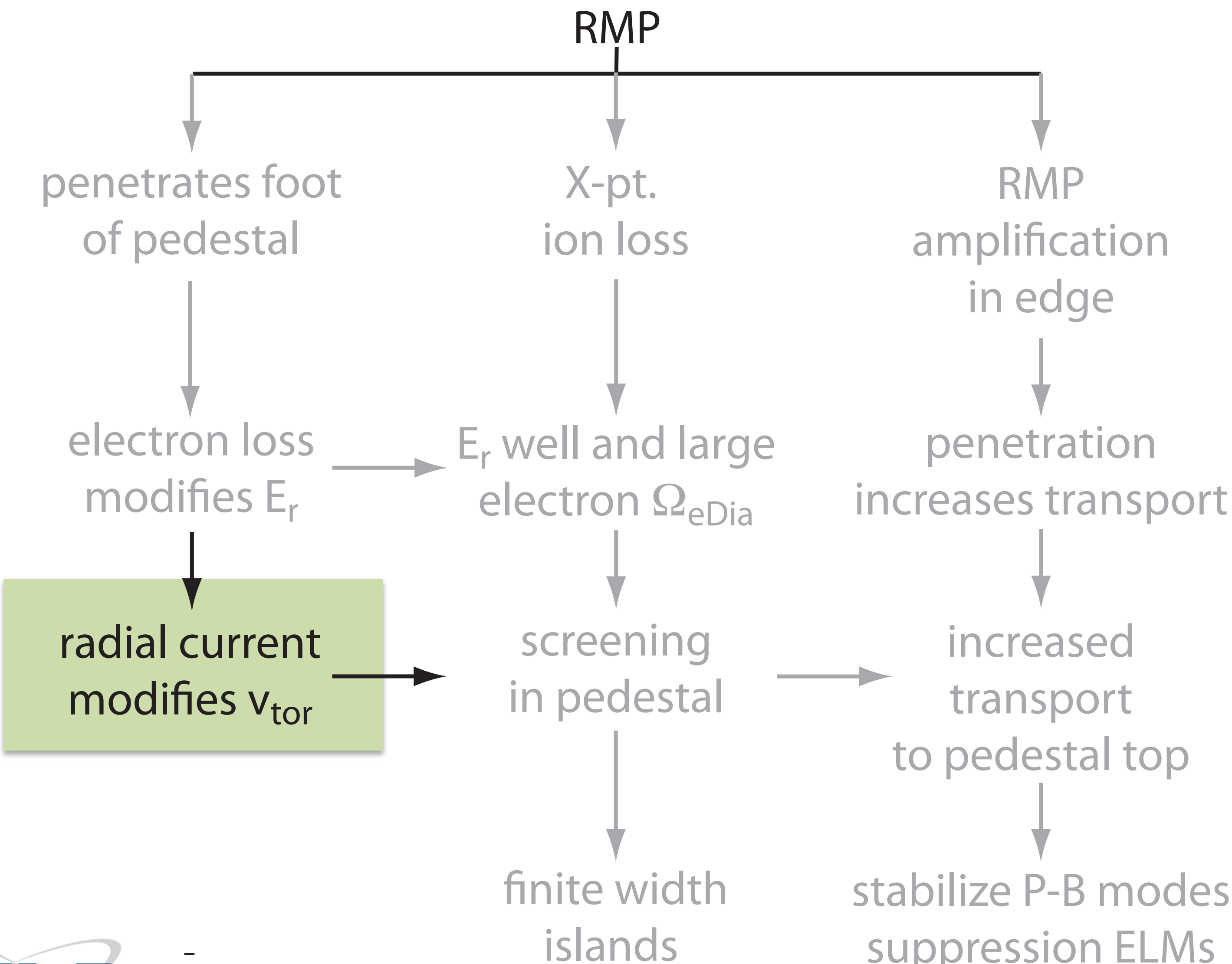
$$\phi_{pl} = \int E_r^{CER}(\psi_N)d\psi_N + \phi_{pl}^{probe}(\psi_N = 1.08)$$

- **Layer width where $\phi_{pl} \geq 0$ ~ 2.6% ~ 0.6 cm → open field line physics dominates (stochastic)**

Plasma Potential Discharge 126006



Radial Electric Field E_r Plays a Central Role in the Evolution from ELMing to ELM Suppressed H-mode

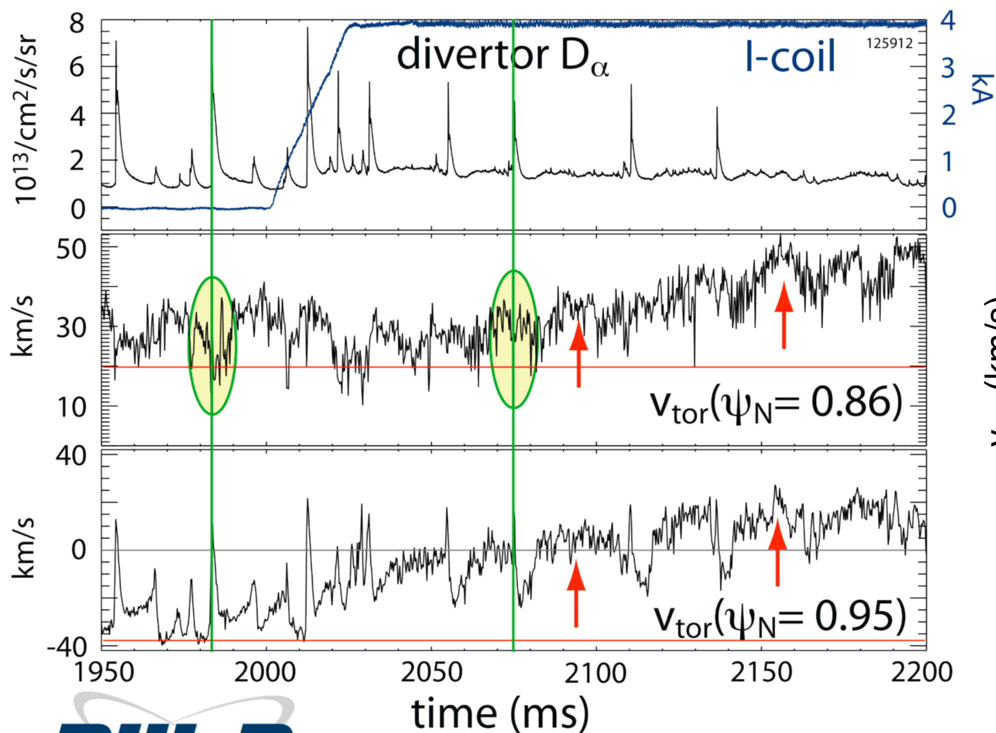


-

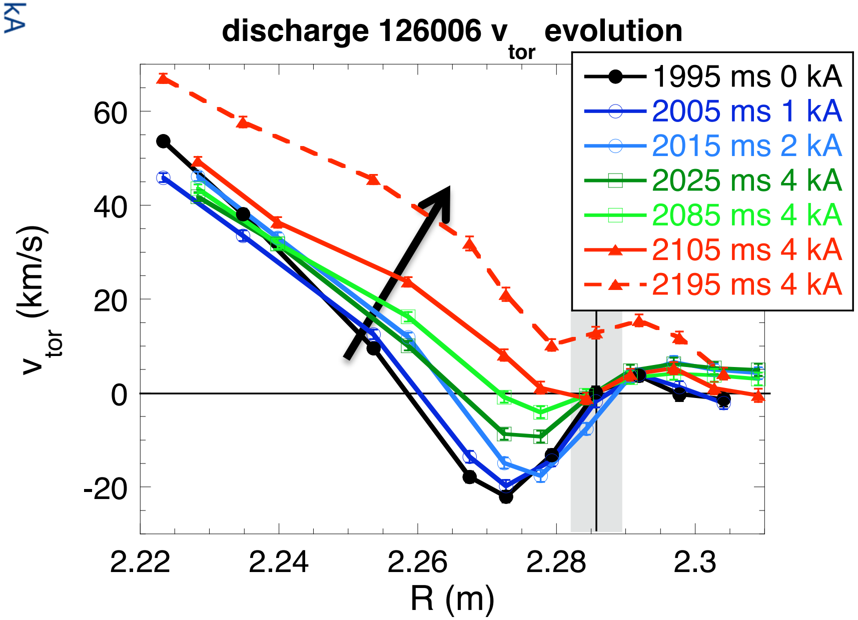
Narrowing of E_r Well is a Consequence of Increasing Toroidal Rotation at the Boundary Due to jxB Torque

- **As RMP rises, edge v_{tor} drops due to rapid, mitigated ELMs**
- **On transport timescale, v_{tor} increases at the boundary consistent with a jxB torque and propagates in due to viscosity**

ELMs lock v_{tor} at top of pedestal but fast CER shows ELMs "along for ride"



Edge spin-up fills in counter-I_p rotation at top of pedestal.

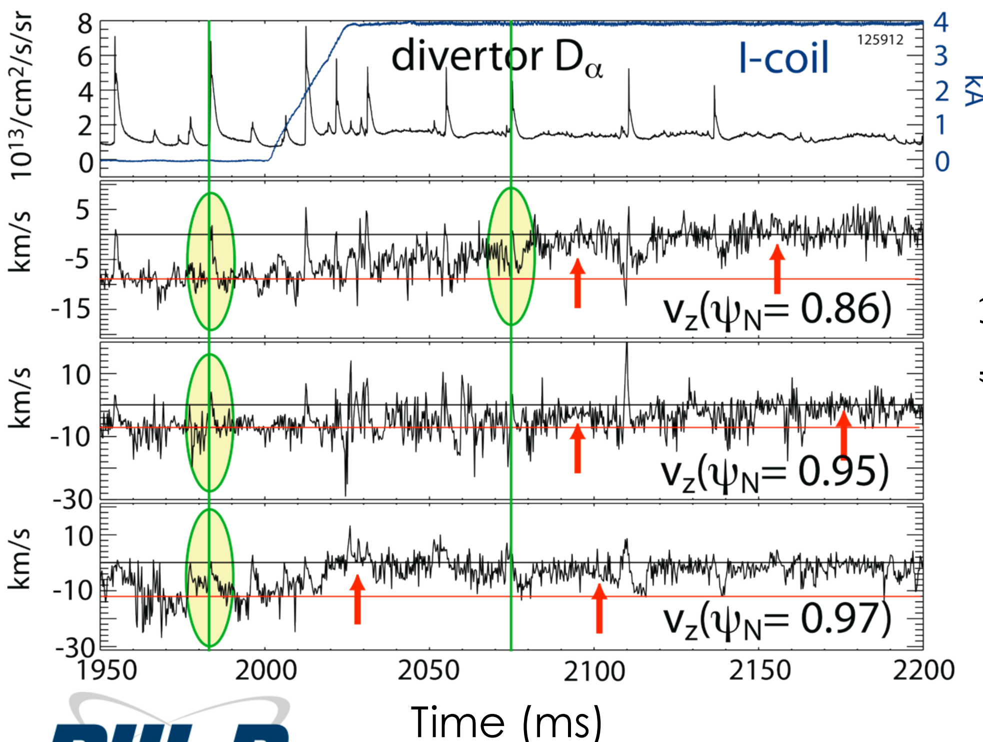


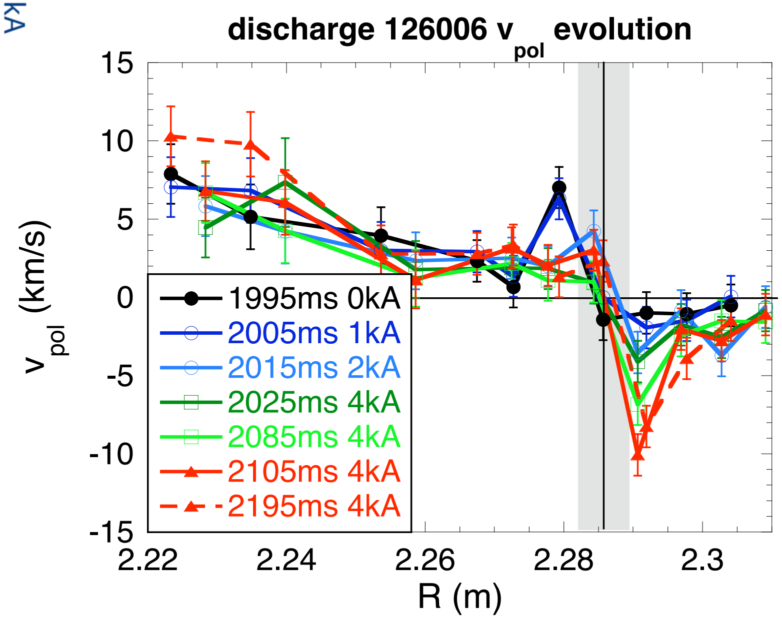
DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Change in Edge Poloidal Rotation is Small Except Near the Separatrix Where it Contributes to E_r Well

- **Change in v_{pol} at separatrix increases ExB shearing rate ω_{ExB} across boundary**

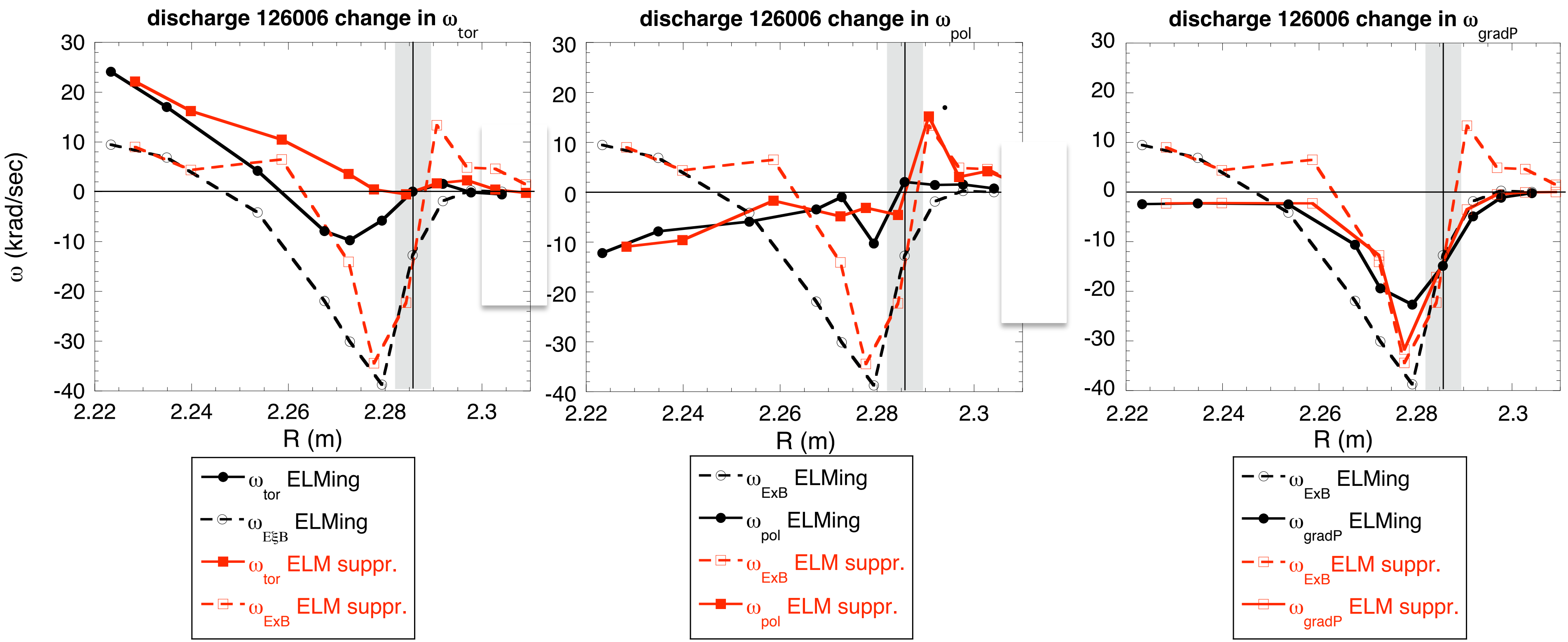
ELMs lock v_{pol} in edge but fast CER shows ELMs "along for ride"





Largest Contribution to Change in ω_{ExB} is from the Increase in Edge v_{tor}

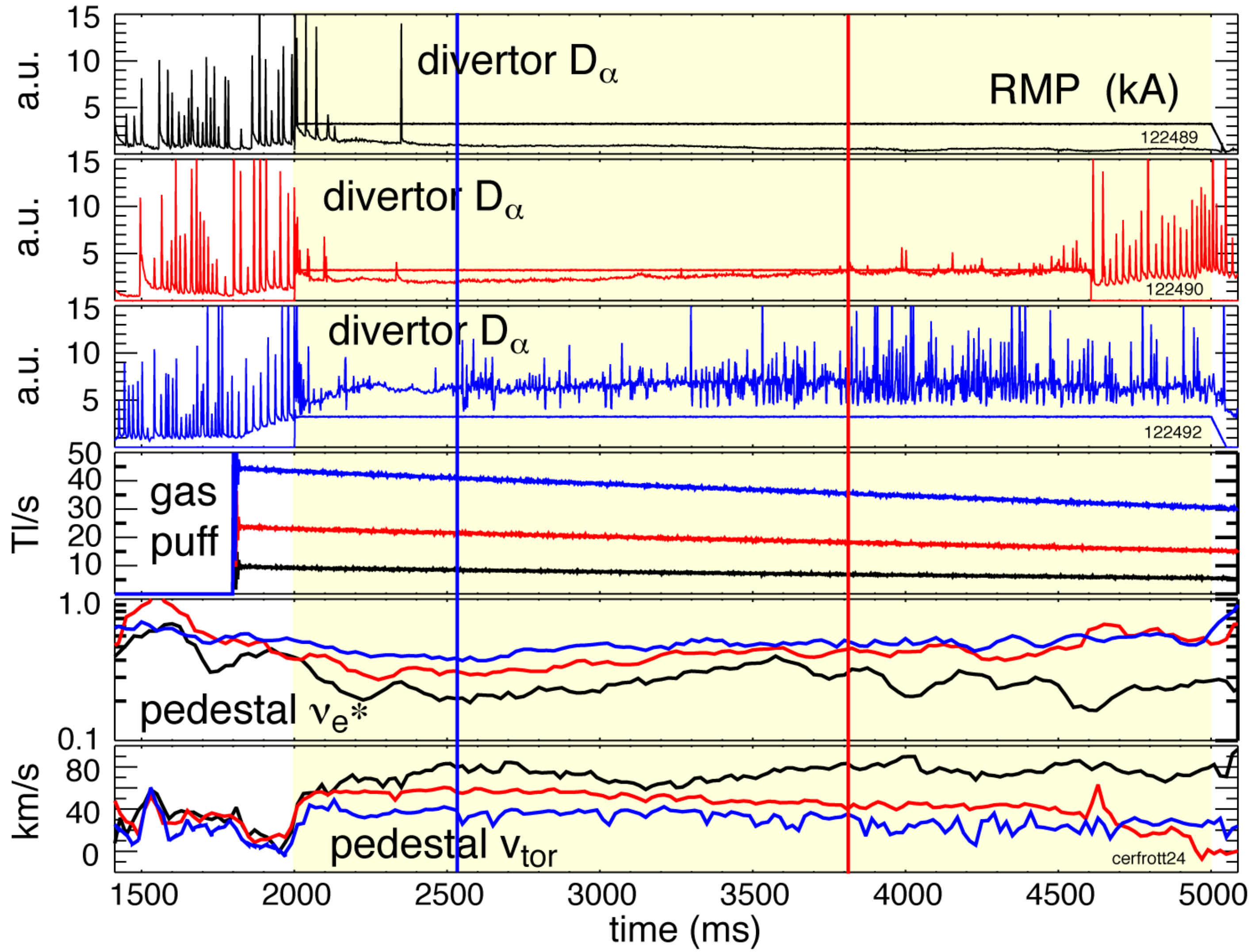
- **Spin-up of edge v_{tor} increases ω_{ExB} by 10–15 krad/s**
- **Rise in v_{pol} in SOL increases SOL ω_{ExB} by 10-12 krad/s**



Importance of v_{tor} and E_r Response has been Demonstrated in Collisionality/Density Scan with D_2 Puffing

- **Return of Type I ELMs is correlated with collisionality/ density upper limit (Ref.)**

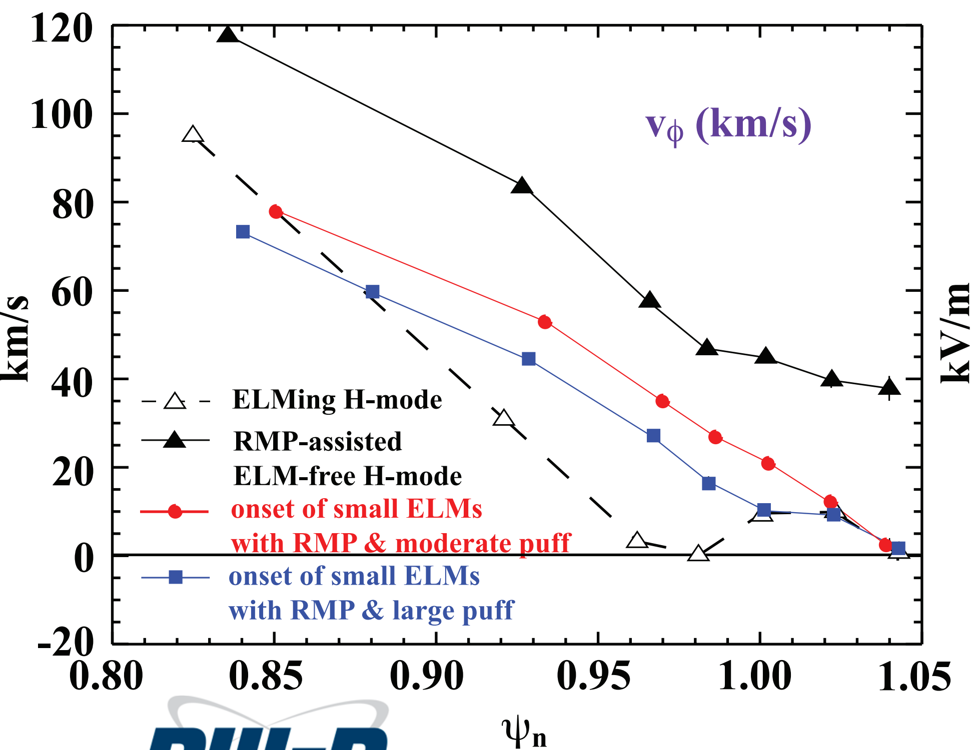
- **Return of Type I ELMs is also correlated with a drop in pedestal v_{tor} below about 40 km/s**

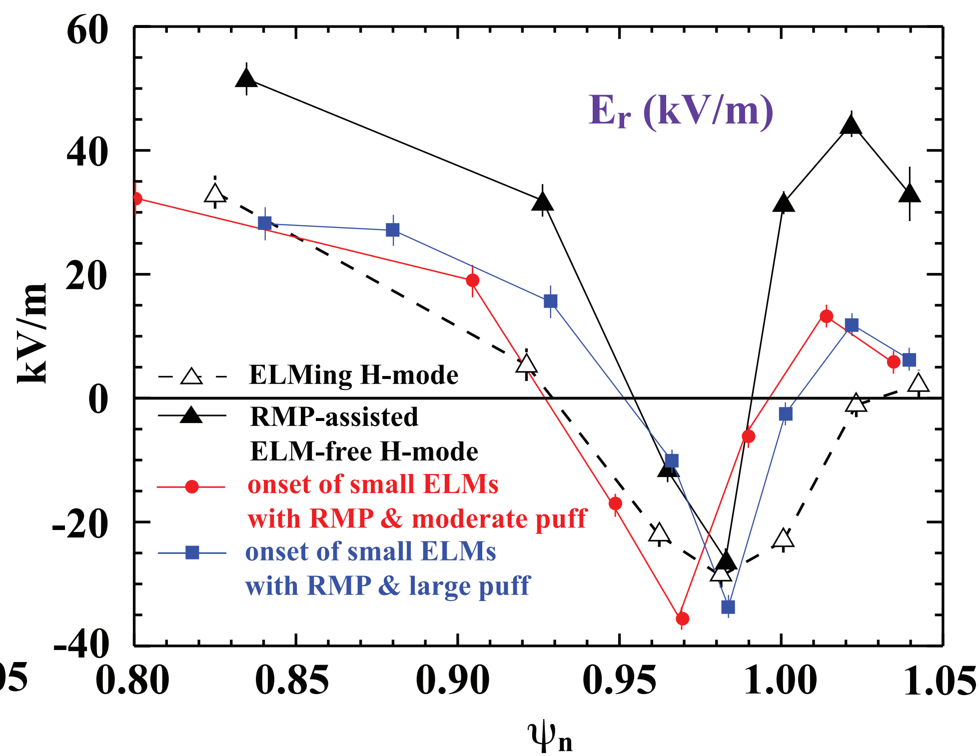


DIII-D NATIONAL FUSION FACILITY SAN DIEGO

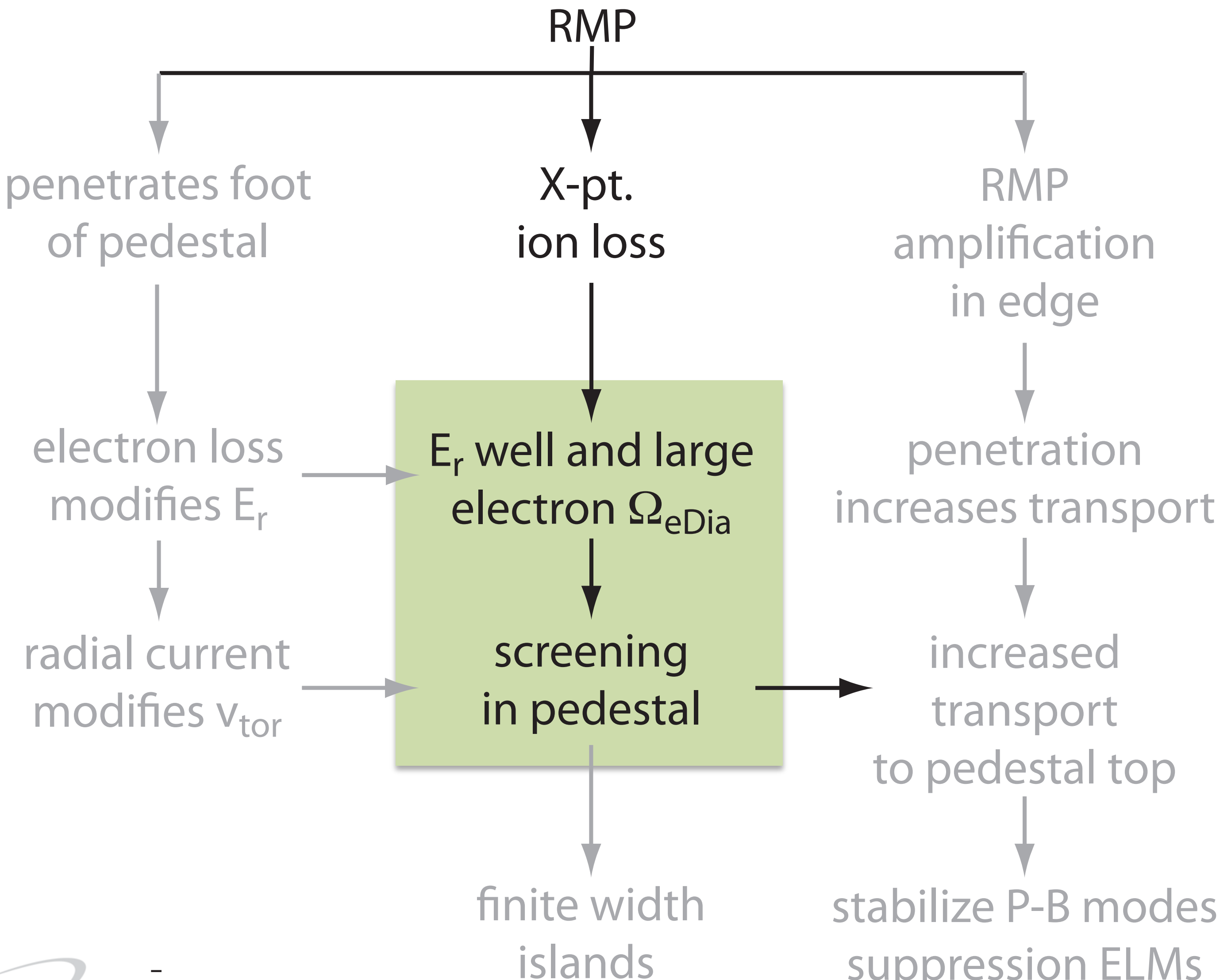
Type I ELMs with n ~30 Return as Pedestal ν_e^* and n_e Rise and Pedestal v_{tor} Drops, Broadening the E_r Well

- Increasing D_2 puff raises ν_e^* and n_e^{ped} , returning v_{tor} and E_r profiles toward ELMing H-mode





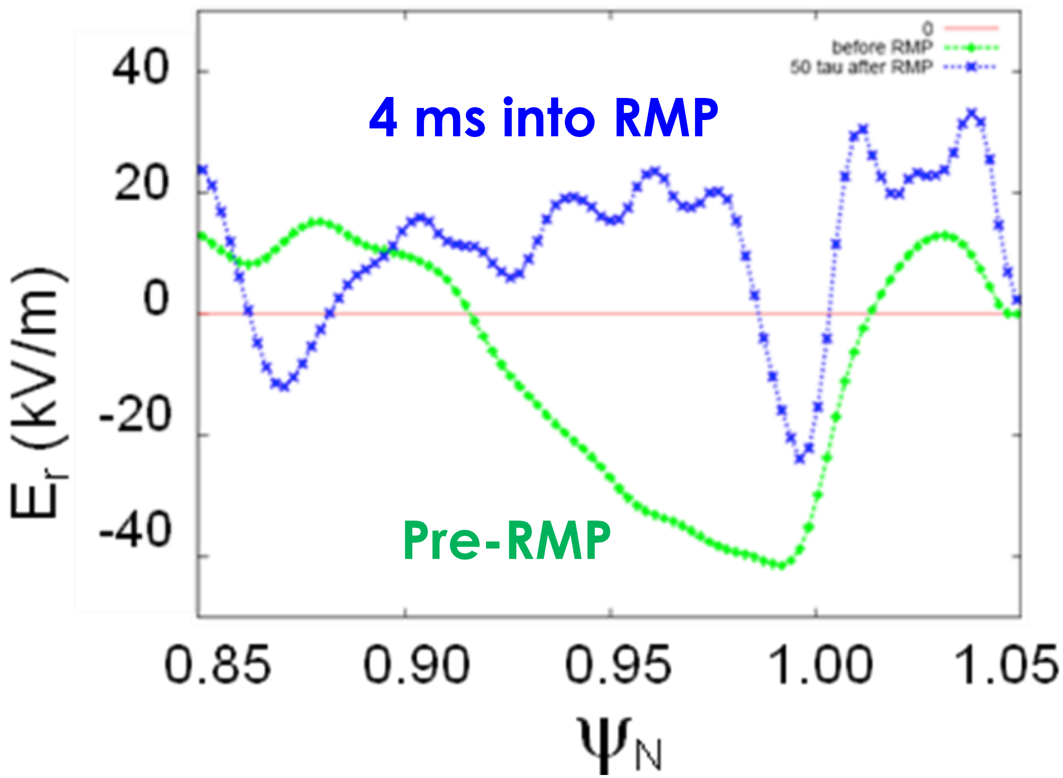
Radial Electric Field E_r Plays A Central Role in the Evolution from ELMing to ELM Suppressed H-mode



The Radial Electric Field is Qualitatively Similar to the Self-Consistent Plasma Response Model XGC0

- **Shows qualitatively the three steps**
  - Rise in SOL E_r due to change in ambipolar potential
  - Narrowing of E_r well due to rise in core E_r
  - Shallower E_r well
- **Topological stability of X-point → robustness of X-pt ion orbit loss and H-mode E_r well**
- **XGC0 simulations demonstrate the importance of neoclassical effects**

XGC0 simulation with self-consistent plasma response

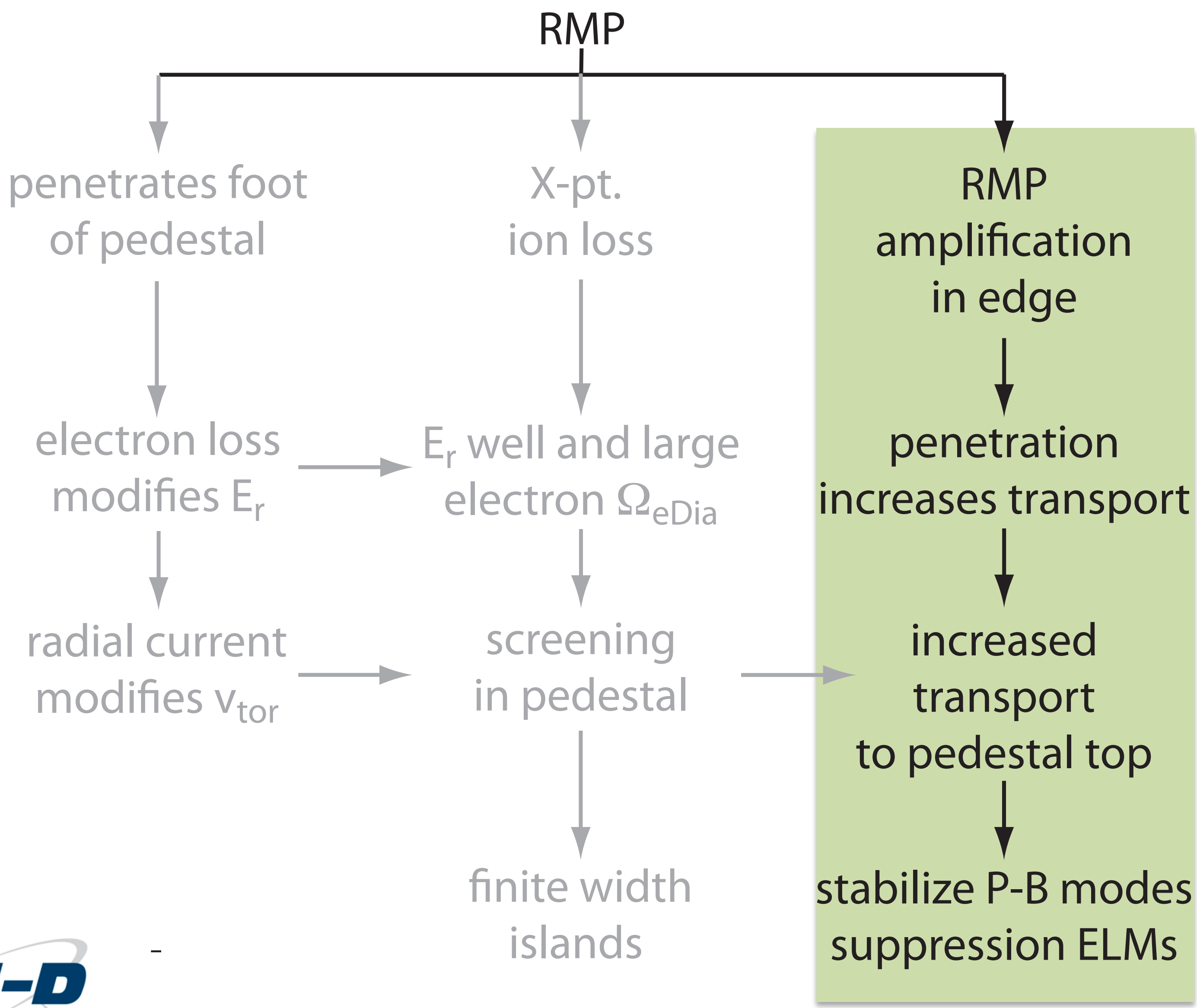


G.-Y. Park, C.S. Chang et al., Invited talk, APS DPP 2011

Magnetic Flutter Model Using M3D-C1 Plasma Response Qualitatively Captures these Changes in E_r

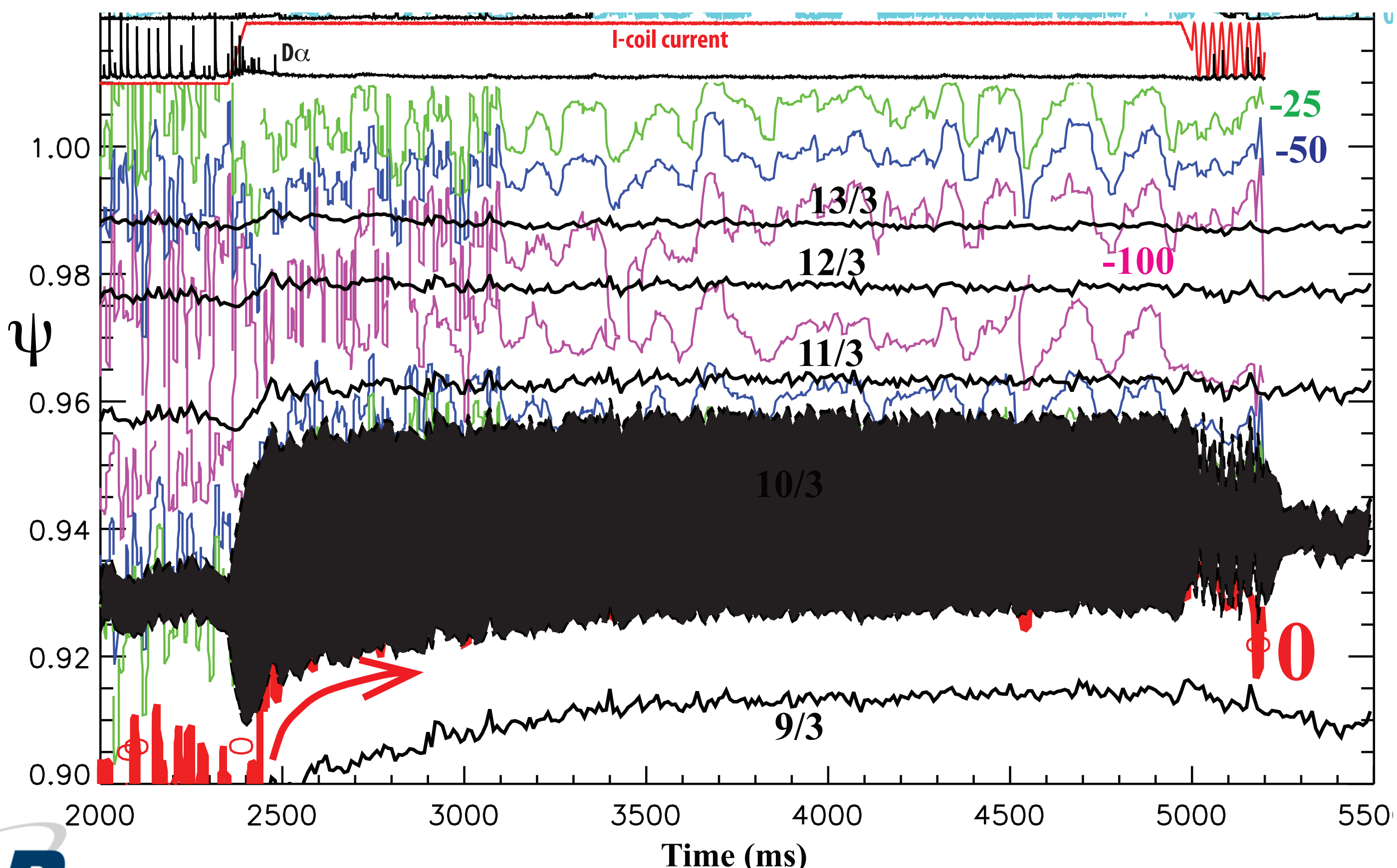
- **Predicts radius where E_r changes sign in the edge**
- **Predicts change in E_r well depth as a transition from ion to electron root (role of neoclassical ambipolar transport)**
  - This evolution occurs mostly after the ELMs are suppressed, and might not be necessary for ELM suppression

Radial Electric Field E_r Plays A Central Role in the Evolution from ELMing to ELM Suppressed H-mode



When the RMP is Applied, the Radius where the Electron v_{perp} ~ 0 Moves out Toward Top of the Pedestal

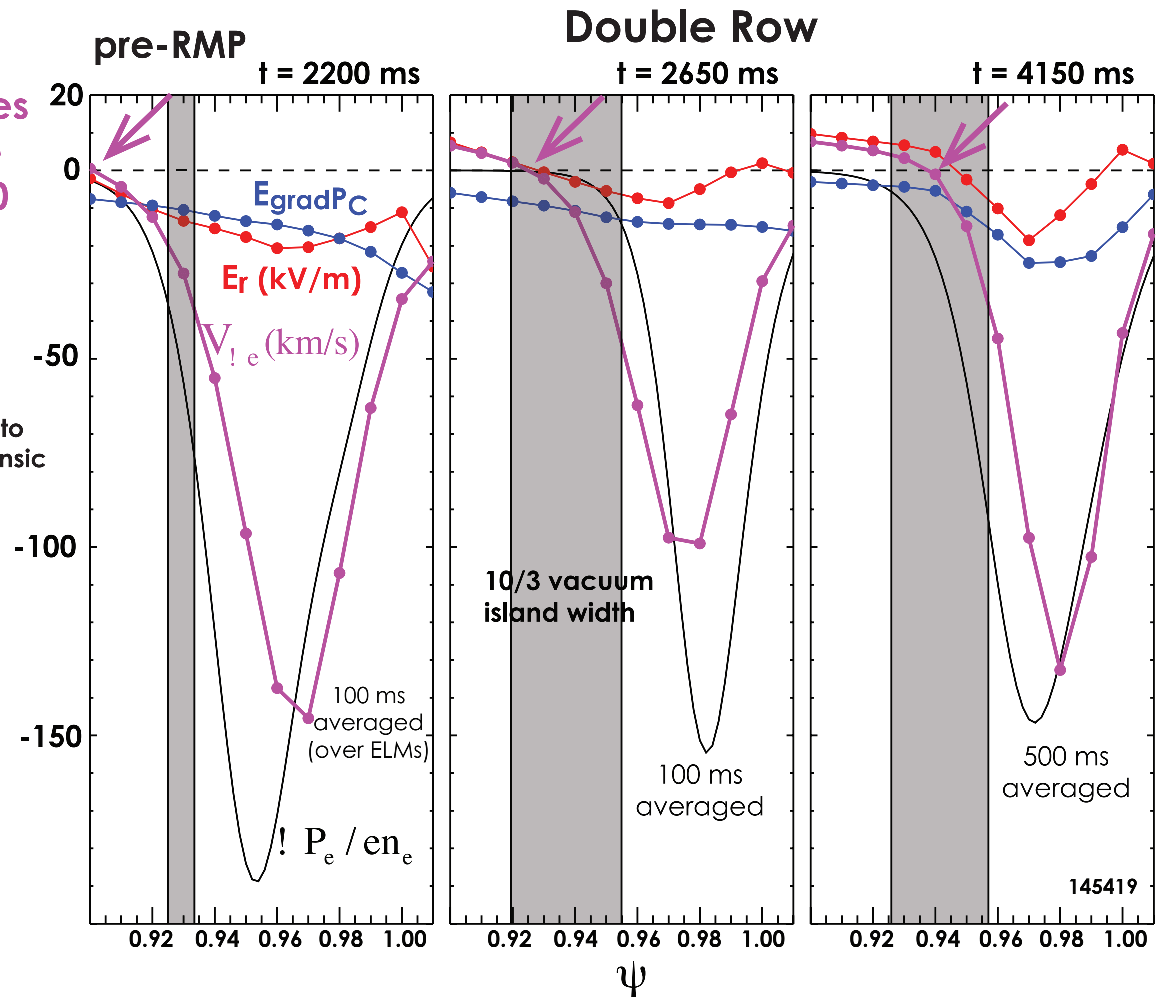
- **Color contours are contours of electron perpendicular velocity; $v_{perp,e} < 0$ is in the electron diamagnetic direction.**



$v_{perp,e}$ ~ 0 Point Moves Out Due to Shift in Radius of Electron Diamagnetic Rotation Profile and Increase in ExB Velocity Due to Toroidal Spin-up

indicates where $V_{\perp e} = 0$

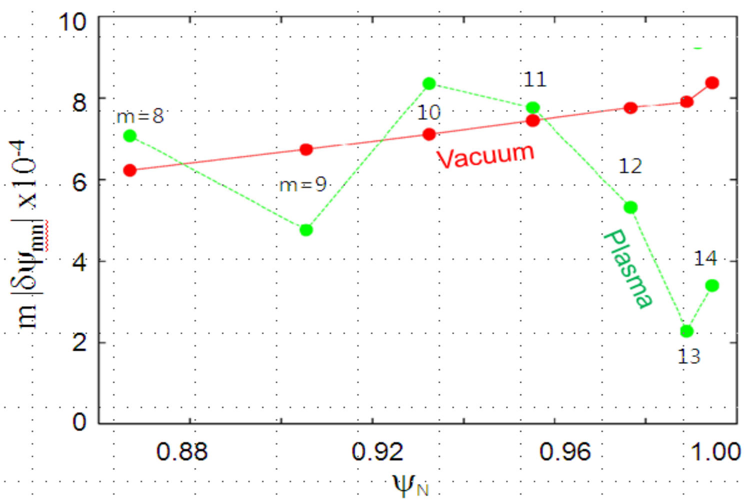
non-zero island pre-RMP is due to inclusion of intrinsic error field.

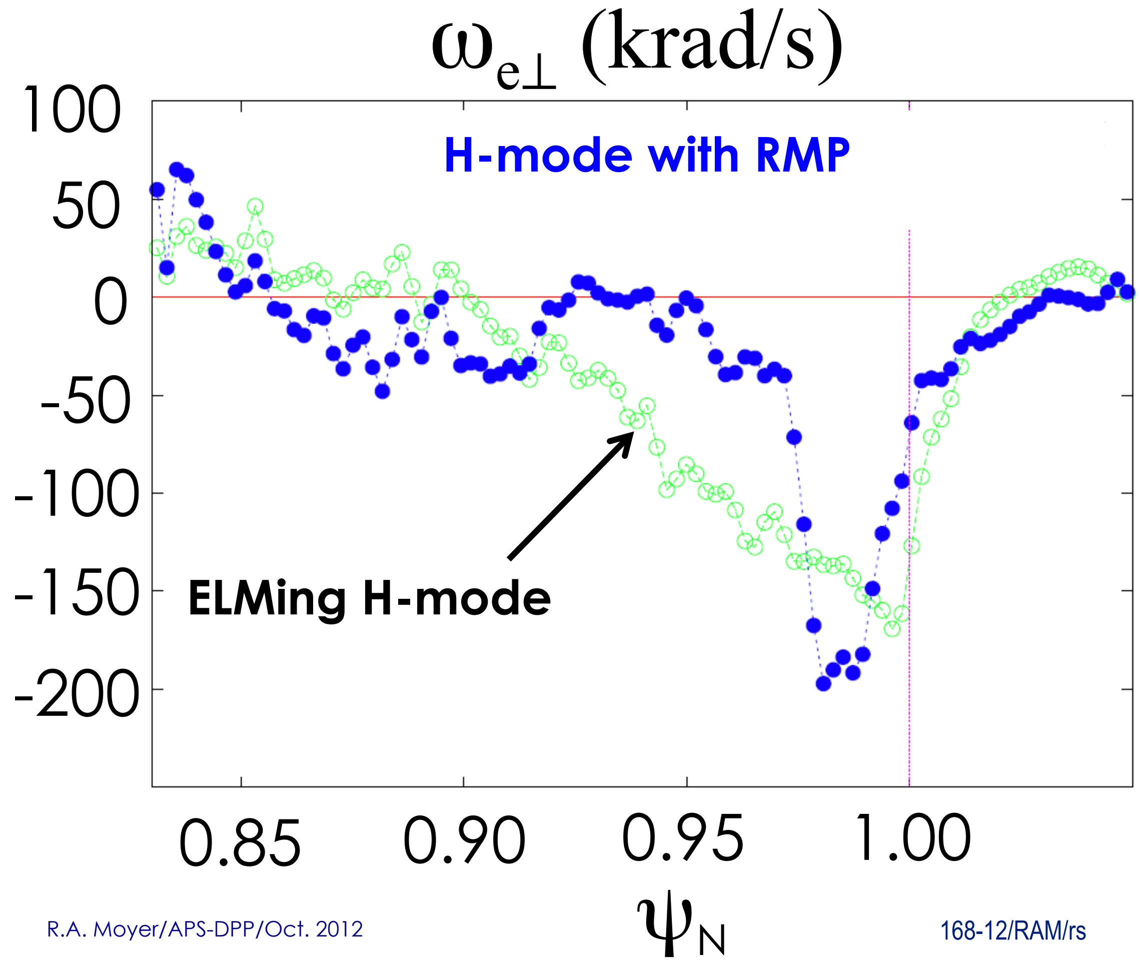


2-fluid M3D-C1 and Kinetic XGC0 Plasma Response Models Predict Dynamics Similar to the Experiment

- **RMP penetration and amplification at 10/3 & 11/3 resonant surfaces**
- **In XGC0 simulations, stochasticity depends sensitively on exact value of q_{95}**

XGC0 results



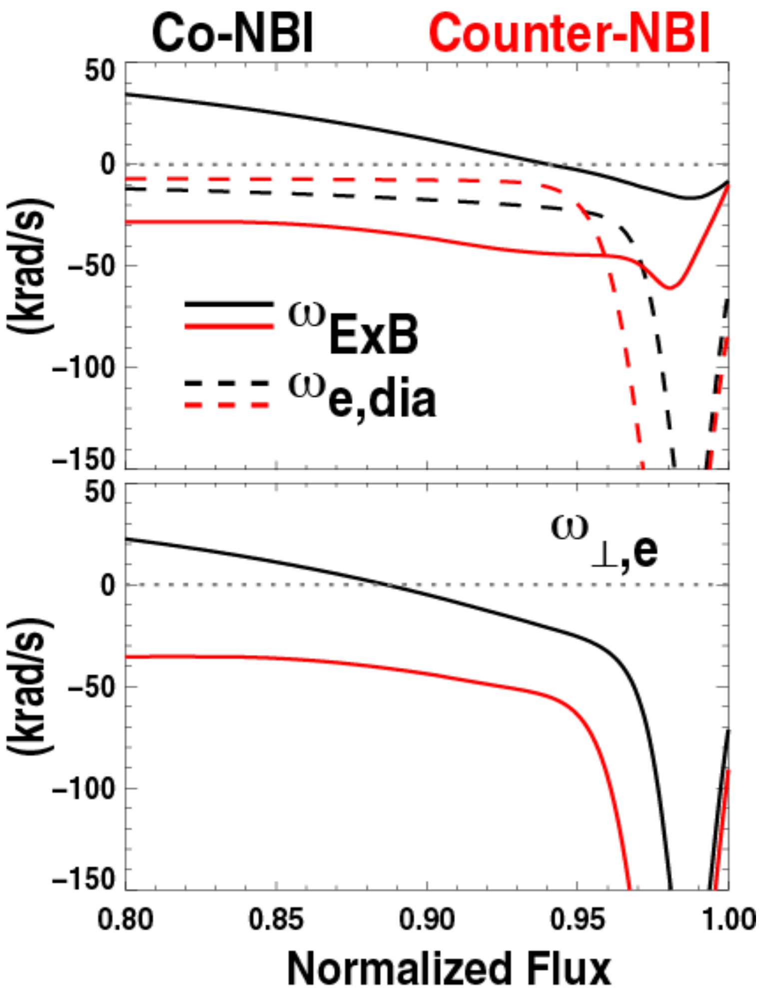


Importance of v_{tor} and $\omega_{perp,e}$ ~0 at top of Pedestal Can be Tested with Counter-NBI

- By switching sign of toroidal rotation, $\omega_{\perp,e}$ = 0 crossing at top of pedestal is eliminated

$$\omega_{\perp,e} = \omega_{ExB} + \omega_{e,dia}$$

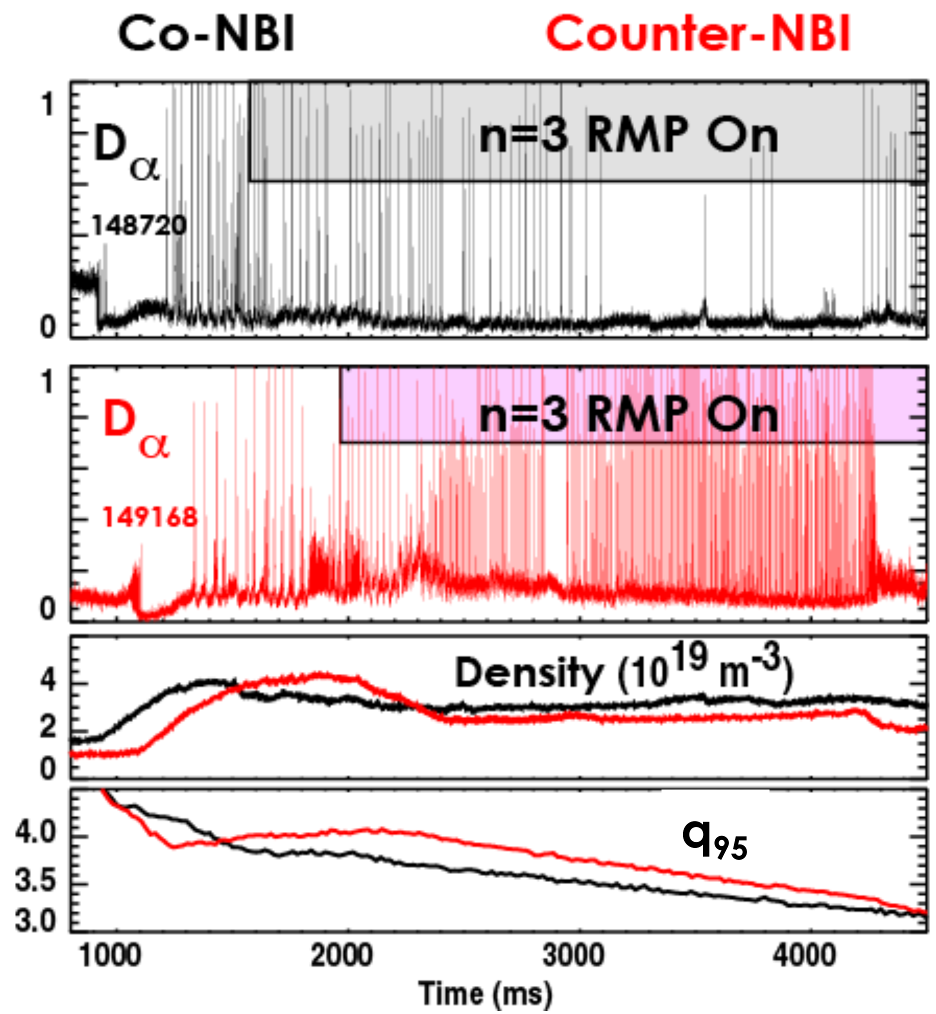
- If MHD response is strongly dependent on $|\omega_{\perp,e},e| \approx 0$, should be difficult to obtain ELM suppression with counter NBI



DIII-D NATIONAL FUSION FACILITY SAN DIEGO

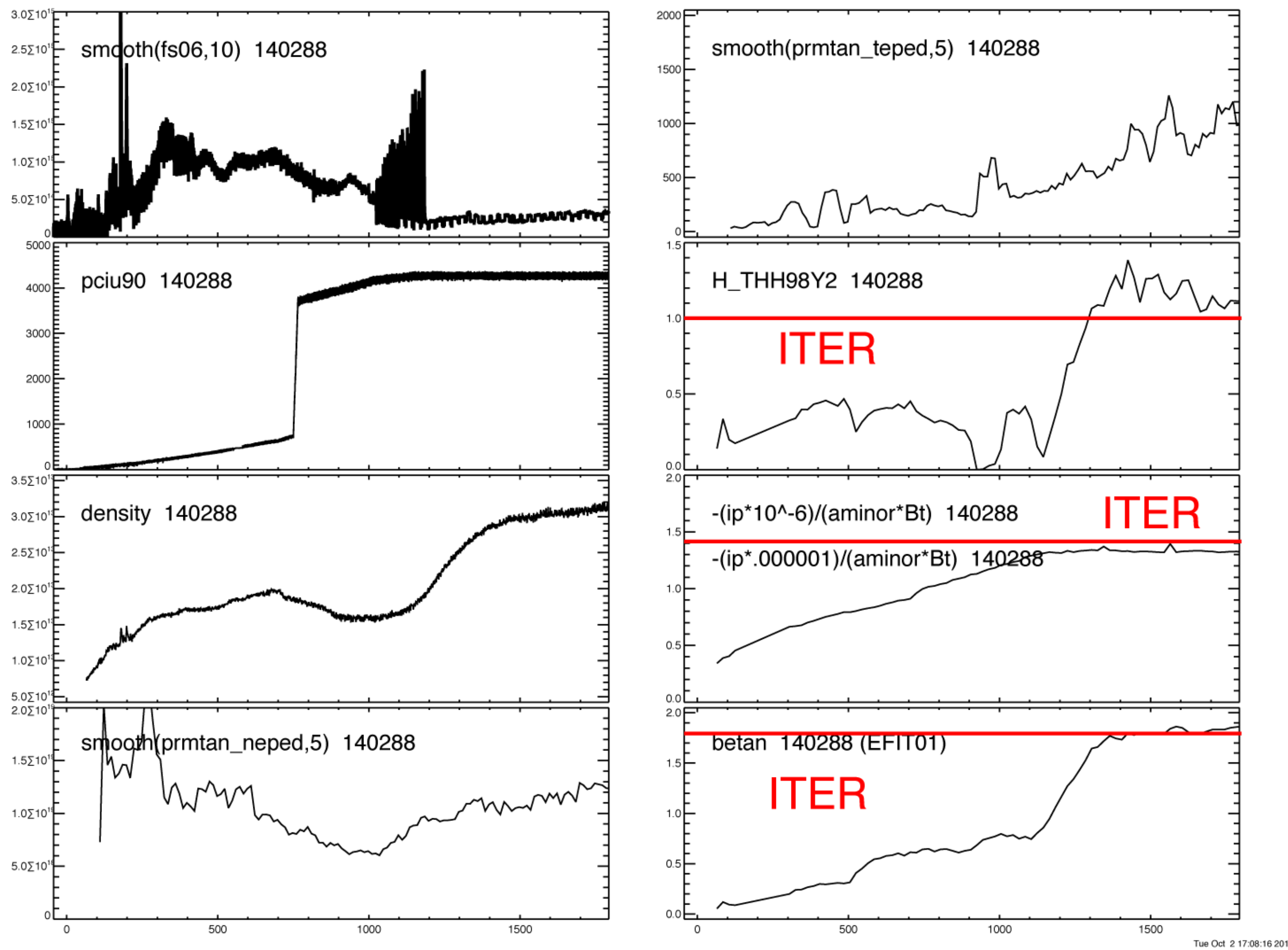
Lack of RMP ELM Suppression with Counter-NBI Verifies the Importance of $|\omega_{\perp,e}|$ at Top of Pedestal

- **ELMs remain in counter-NBI q_{95} ELM suppression window typically seen with co-NBI**
  - Even at comparable density
- **Small window of ELM suppression observed at $q_{95} \sim 4.0$**
  - EHO signature also observed → QH-mode?



ELM Suppression Has Been Achieved Without ELMs by Applying RMP in L-mode

- **Confirms that ELMs are not critical to the suppression physics**
- **Indicates that RMP-induced transport can stabilize Peeling-Ballooning modes without first modifying the pedestal to align the RMP**



DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Analysis of Dynamic Response of E_r and Rotation Support 2-fluid Plasma Response Physics

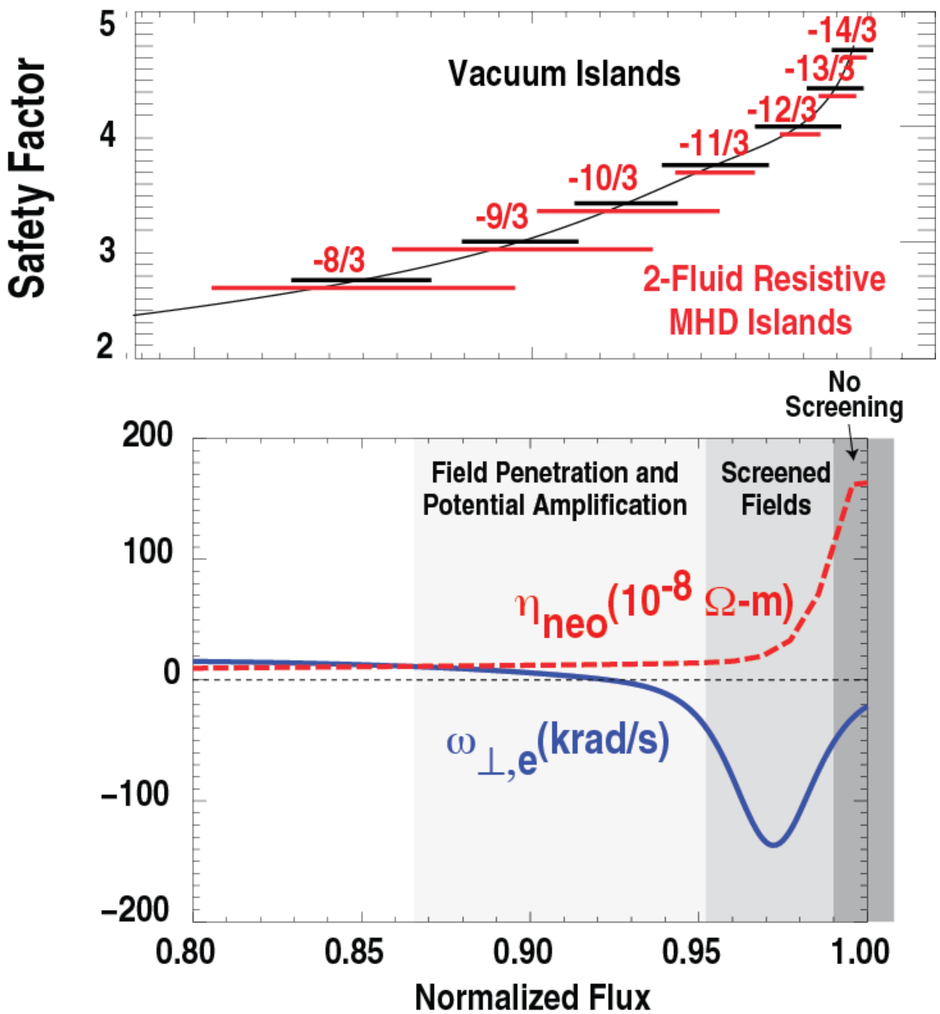
- **RMP displaces boundary and opens a 2-3% stochastic layer at foot of pedestal where resistivity is high and rotation low**
  - Hot electrons seen on divertor Langmuir probes
  - Plasma potential in edge becomes more positive
- **Stochasticity → radial current which spins up the pedestal plasma**
  - Fast v_{tor} rise spreads into edge on transport timescale due to viscosity
- **Change in E_r is consistent with**
  - Displacement of boundary, leading to electron loss along open field lines to the divertor, followed by modification of ambipolar potential
  - Changes are qualitatively consistent XGC0 and magnetic flutter models with plasma response included
- **Edge v_{tor} spin-up moves $\omega_{perp,e}$ ~ 0 point out toward top of pedestal, where plasma response models predict RMP amplification**
- **ELMs aren't needed to access ELM suppressed state**
- **RMP ELM suppression at ITER-like conditions has been achieved by applying RMP in L-mode before L-H transition**

Two-Fluid Models Predict Shielding Currents on Rational Surfaces Modify Plasma Response Significantly

- **In vacuum model, large islands generated in edge region**
- **Applied field shielded by image currents on rational surface if:**
  - Resistivity is small (true everywhere but edge)
  - Sufficient plasma rotation
- **Fields can "penetrate" at low perpendicular electron frequency**

$$\omega_{\perp,e} = \omega_{ExB} + \omega_{e,dia}$$

- **But penetration not a "hard" bifurcation as for isolated resonance:**
  → island size reduced in pedestal
  → island size amplified at top of pedestal



Wade IAEA 2012