Wide q_{95} Windows for Edge-Localized-Mode Suppression by Resonant Magnetic Perturbations in the DIII-D Tokamak

by

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With

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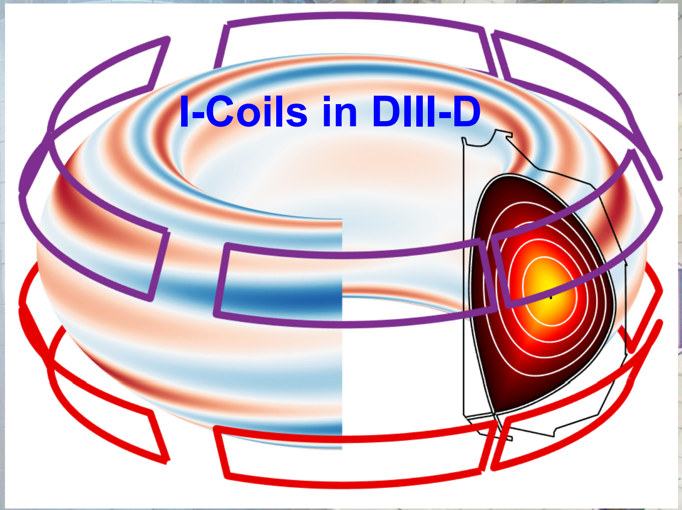
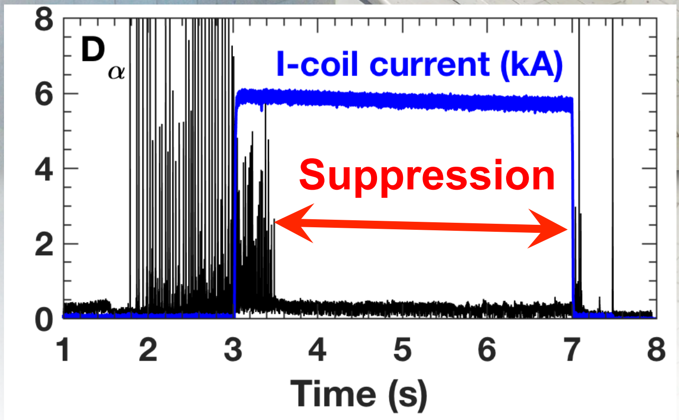




Presented at the

PPPL theory seminar

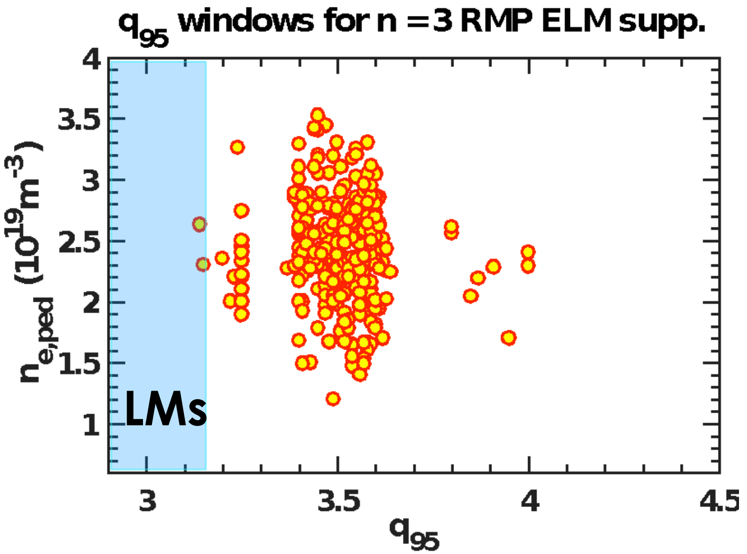
December 12, 2019

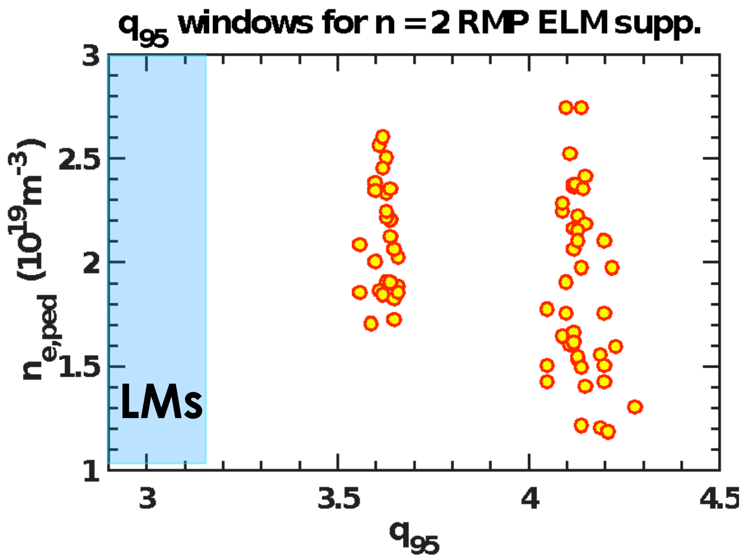
RMPs suppress ELMs in separate q_{95} windows

- **q_{95} windows for ELM suppression are well studied in DIII-D ISS plasmas**
  - $1.5<\beta_N<2.5$, 4Nm<T<8.5Nm
  - Three q_{95} windows for n=3 RMP
  - Two q_{95} windows for n=2 RMP
  - Core locked modes (LMs) for q_{95} < 3.2

- **Sensitivity within the magic windows costs a lot of experimental time on existing machines**
  - Cannot be guessed in future machines like ITER

- **Goal: Use our understanding of ELM suppression to predict q_{95} windows**





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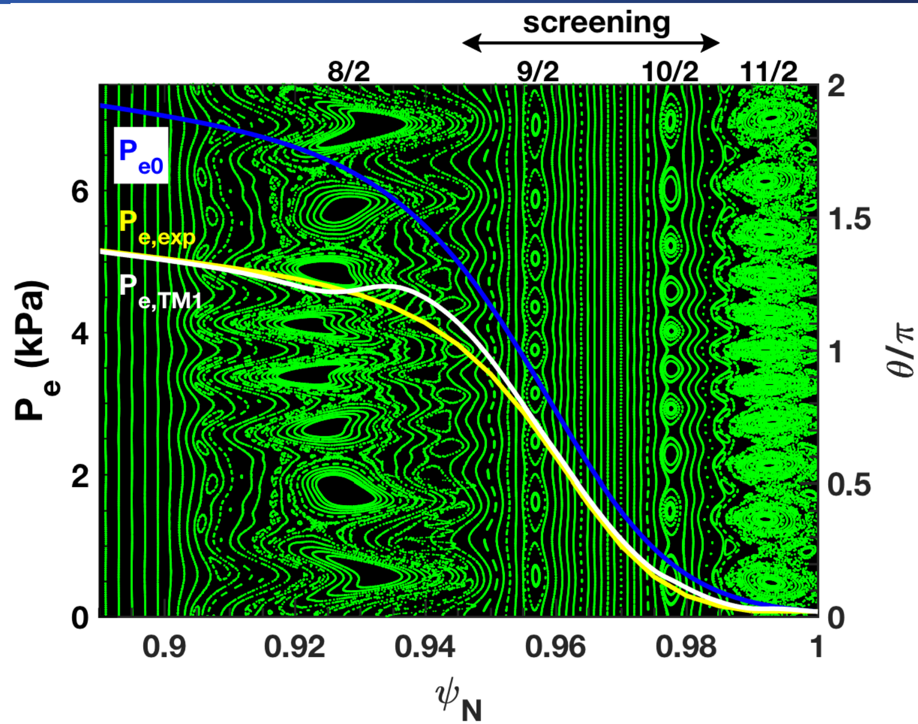
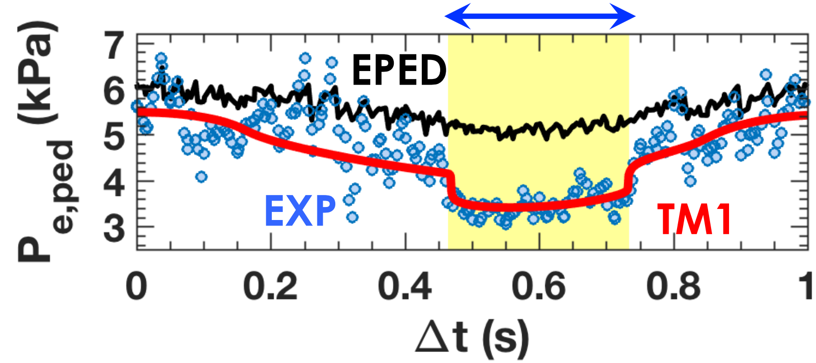
Previously, TM1 simulated the plasma response to explain the pump-out and ELM suppression by n=2 RMPs in DIII-D

- **Pedestal-foot island causes density pump-out**
- **Pedestal-top island lowers pedestal pressure and stabilizes PBMs (ELITE & EPED) → suppress ELM**
- **Separation of island chains preserve the ETB during ELM suppression**



8/2 penetration vs. ELM supp



Q. Hu, *et al.*, POP **26**, 120702 (2019)

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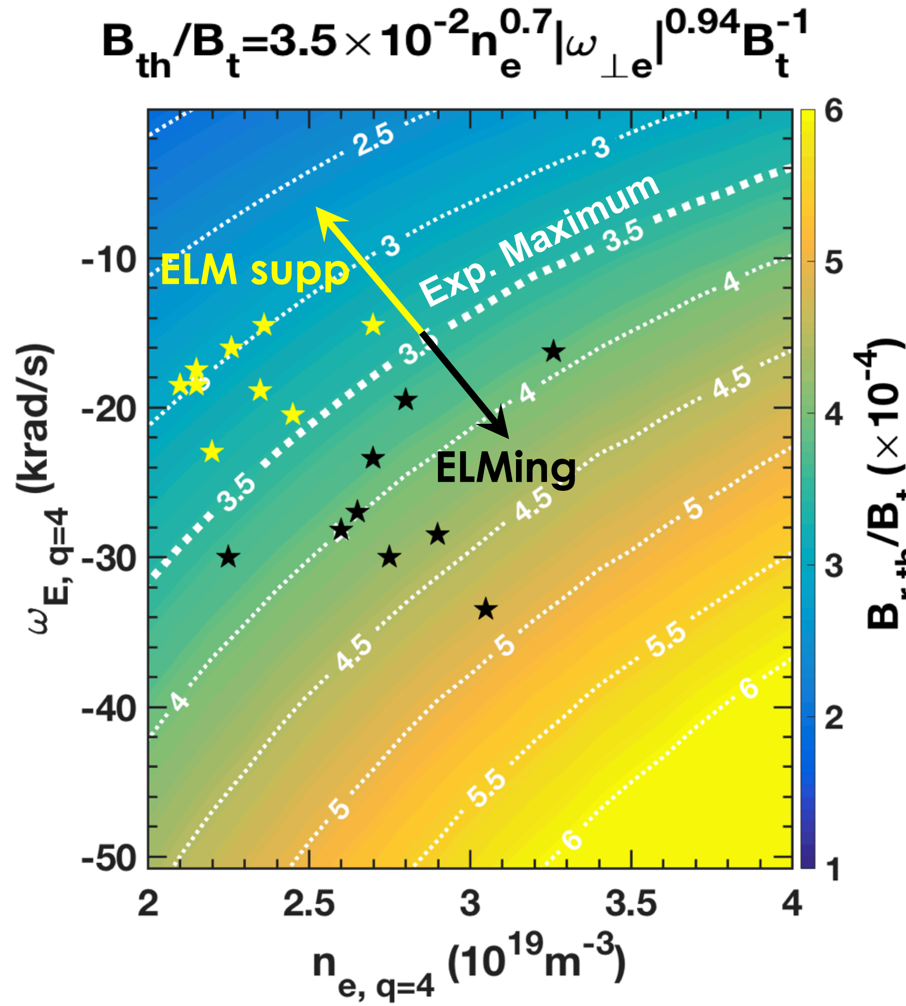
- **Pedestal-top penetration determines the access conditions of low density and high rotation [1]**



[1] C. Paz-Soldan, et al., NF **59**, 056012 (2019)

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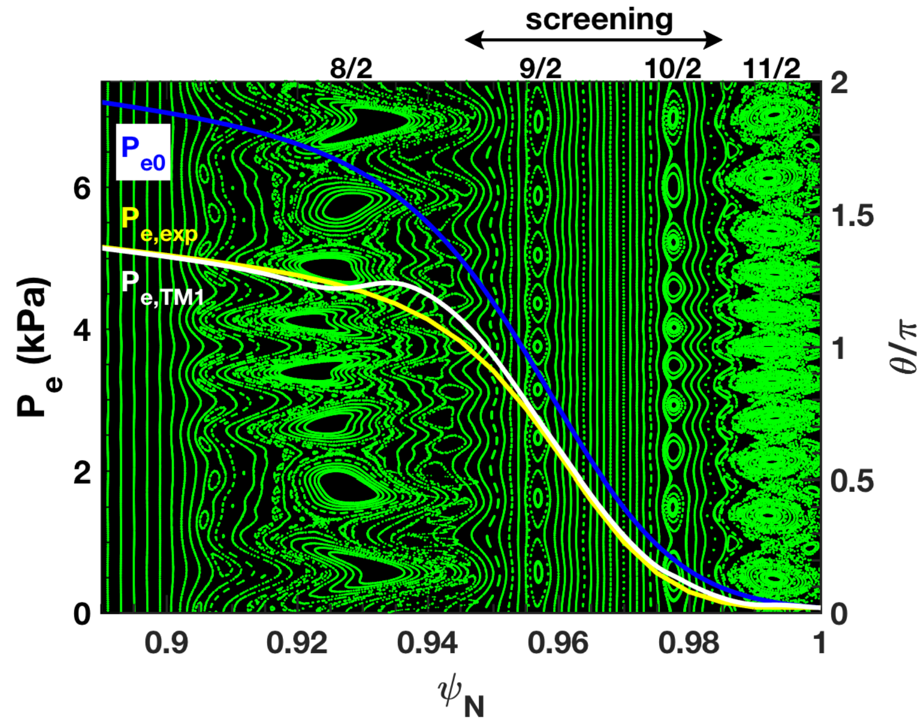
- Separation of island chains preserve the ETB during ELM suppression
- Pedestal-top penetration determines the access conditions of low density and high rotation
- **This understanding and the TM1 model can possibly explain and predict the q_{95} windows by the reduction in pedestal pressure – this talk**



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Outline

- Introduction of nonlinear MHD code TM1
- Simulation of q_{95} windows for n=3 and n=2
- Demonstration of wide q_{95} windows of ELM suppression for n=3
- Summary

Nonlinear two-fluid model TM1 is used to simulate edge plasma response to RMP

- **Cylindrical, circular cross-section geometry**
- **Nonlinear, resistive, two-fluid model [1]:**
- **Long time-dependent modeling** with > 1 s evolution

$$\frac{d\psi}{dt} = E - \eta j + \boxed{\Omega(\nabla_\parallel n_e + \nabla_\parallel T_e)} \longleftarrow \text{diamagnetic drift}$$

$$\frac{du}{dt} = -C_s^2 \nabla_\parallel P / n_e + \mu_\perp \nabla_\perp^2 u$$

$$\rho \frac{d}{dt} \nabla^2 \phi = \vec{e}_\varphi \cdot (\nabla \psi \times \nabla j) + \rho \mu \nabla^4 \phi + S_m$$

$$\frac{dn_e}{dt} = \boxed{\frac{\omega_{ce}}{\nu_e} \nabla_\parallel j} - \nabla_\parallel (n_e u) + \nabla \cdot (D_\perp \nabla n_e) + S_n$$

$$\frac{3}{2} n_e \frac{dT_e}{dt} = \boxed{\frac{\omega_{ce}}{\nu_e} T_e \nabla_\parallel j} - T_e n_e \nabla_\parallel u + n_e \nabla \cdot (\chi_\parallel \nabla_\parallel T_e) + n_e \nabla \cdot (\chi_\perp \nabla_\perp T_e) + S_e$$

Ion polarization current

- **Experimental parameters used in simulations**
  - Transport coefficients derived from measured profiles (~1m^2/s at pedestal top)
  - Neoclassical resistivity (10^{-7} Ωm at pedestal top, 10^{-6} Ωm at pedestal foot)

[1] Q. Yu, et al., POP **10**, 797 (2004); NF **51**, 073030 (2011);
S. Gunter, et al., JCP **209**, 354 (2005)

Cylindrical model is relevant for RMP effect on edge plasma in DIII-D low-collisionality plasmas

- 3D field effect on ballooning stability is negligible in low-collisionality ITER similar shape (ISS) plasmas [1]
- Neoclassical transport shows minimal increase with plasma kink response [2]
- This leaves resonant response, suitable for TM1 analysis using helical boundary condition from full toroidal code GPEC [3] by including geometry effect

[1] I. Holod, *et al*., Nucl. Fusion **57**, 016005 (2017)

[2] R. Hager et al Nucl. Fusion **59** 126009 (2019)

[3] J-K. Park and N.C. Logan, POP **24**, 032505 (2017)

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- Introduction of nonlinear MHD code TM1
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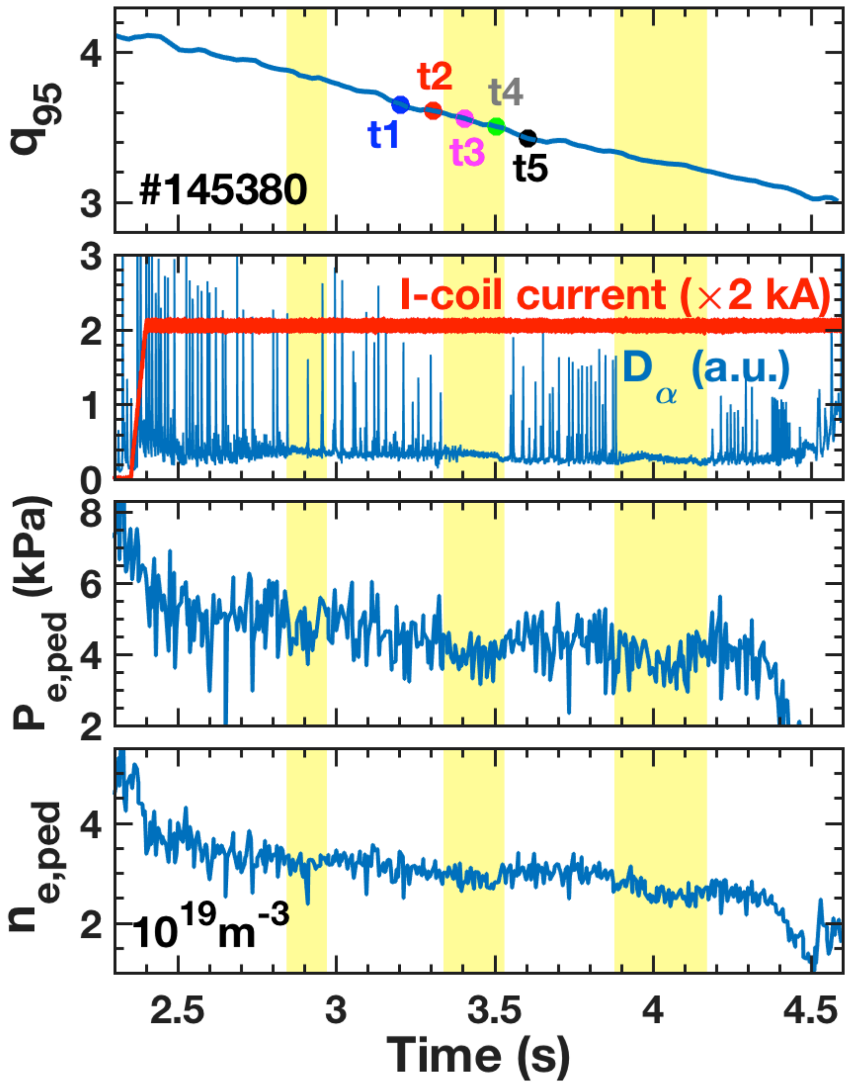
Narrow q_{95} Windows of ELM Suppression Seen in DIII-D

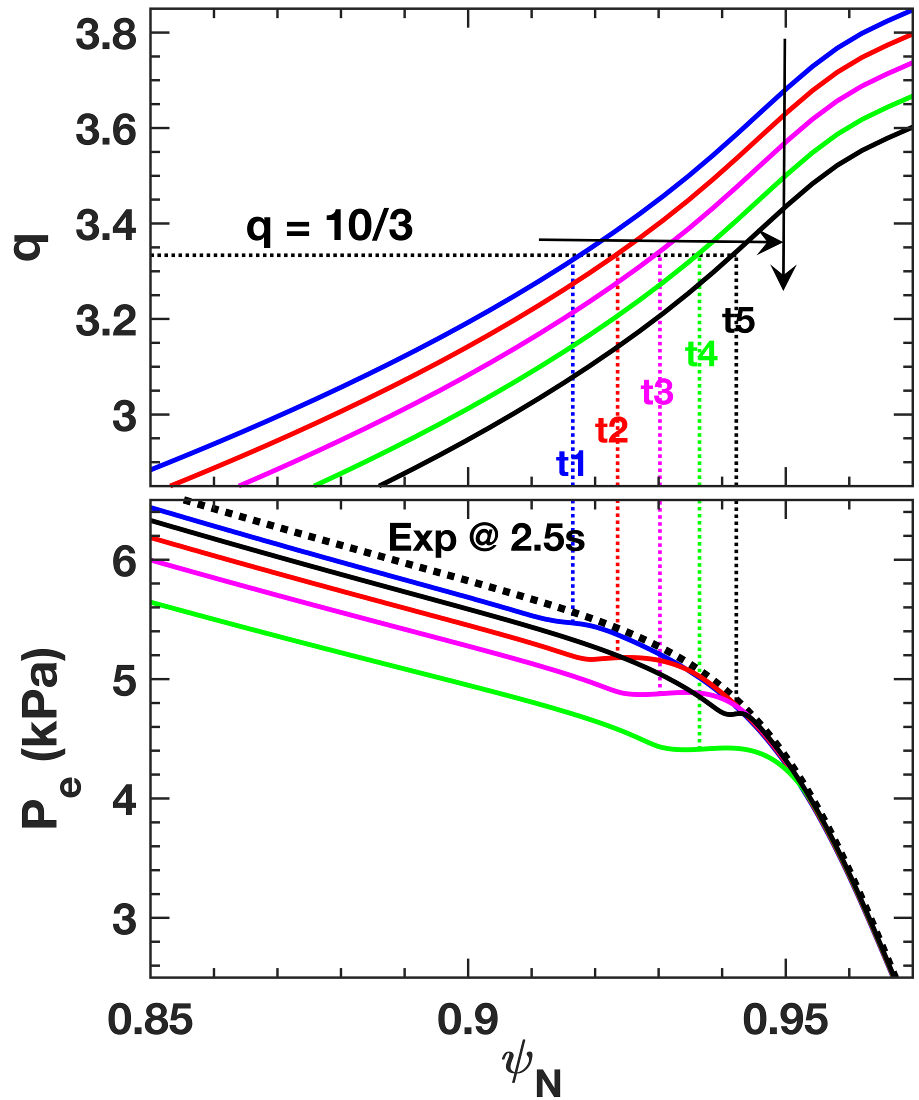
- **n=3 RMP ELM suppression with q_{95} ramping downward**

  #145380:
  $n_{e,ped}$=3.5x10^{19}m^{-3}



TM1 modeling shows reduction in pedestal pressure by RMP is sensitive to q_{95}

- **RMP affects pedestal pressure**
  - 10/3 RMP penetrates at pedestal-top from t1 to t4, shielded at t5
  - Stronger reduction in pedestal pressure for t3 and t4



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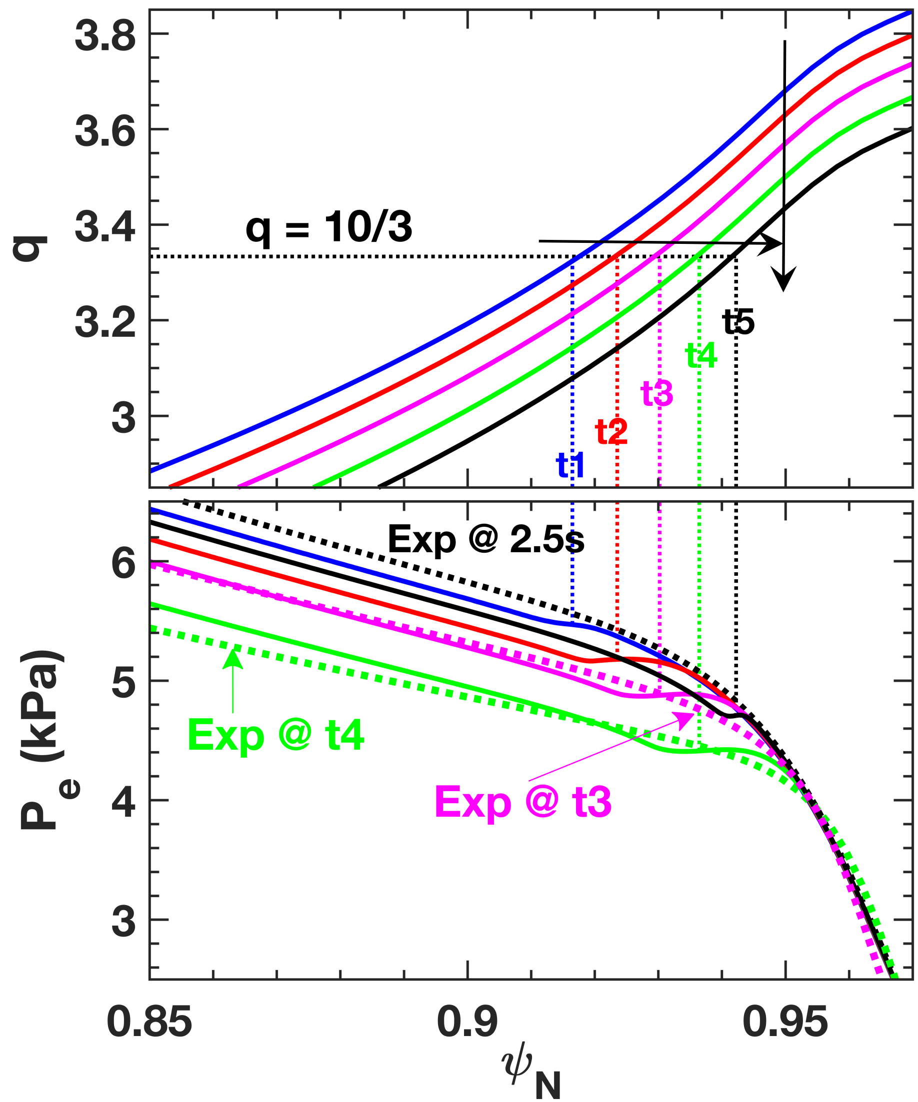
  - Stronger reduction in pedestal pressure for t3 and t4
  - TM1 modeled pressure profile consists with experiment (t3, t4)



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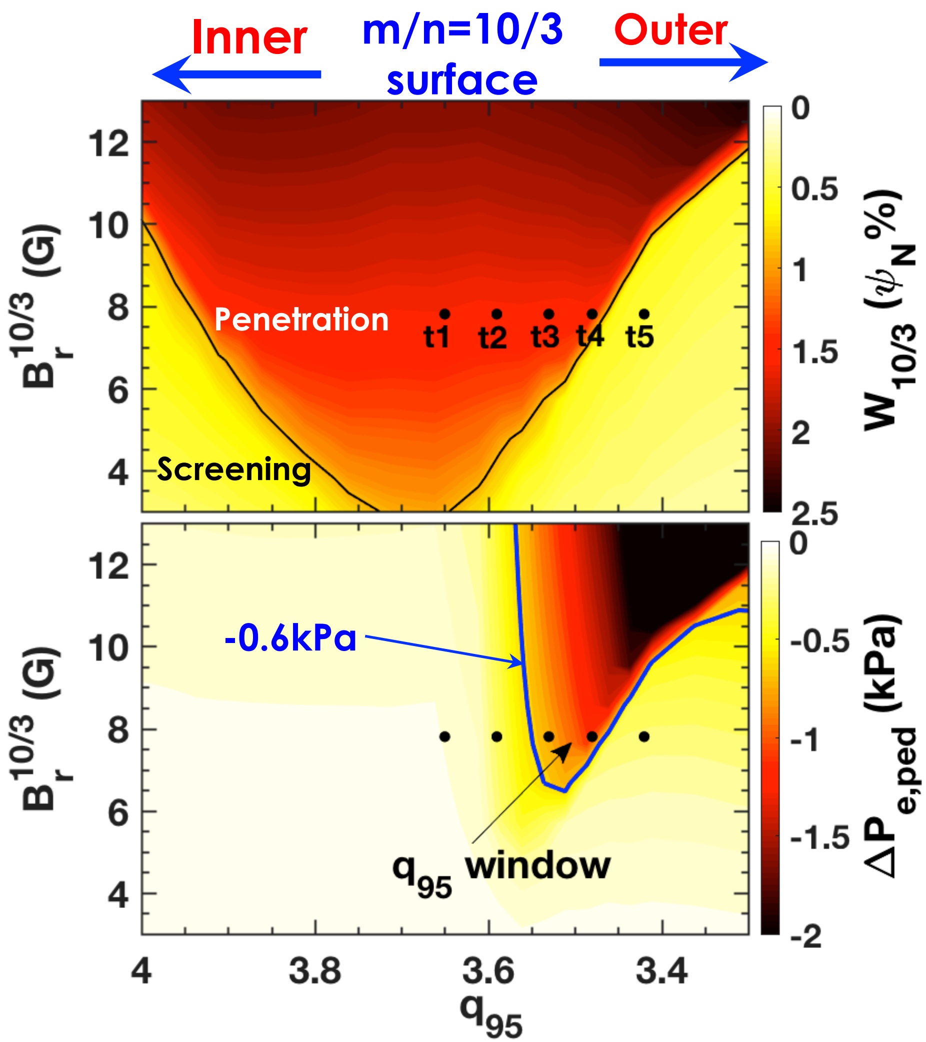
TM1 modeling shows m/n=10/3 RMP penetration determines the q_{95}=3.5 window

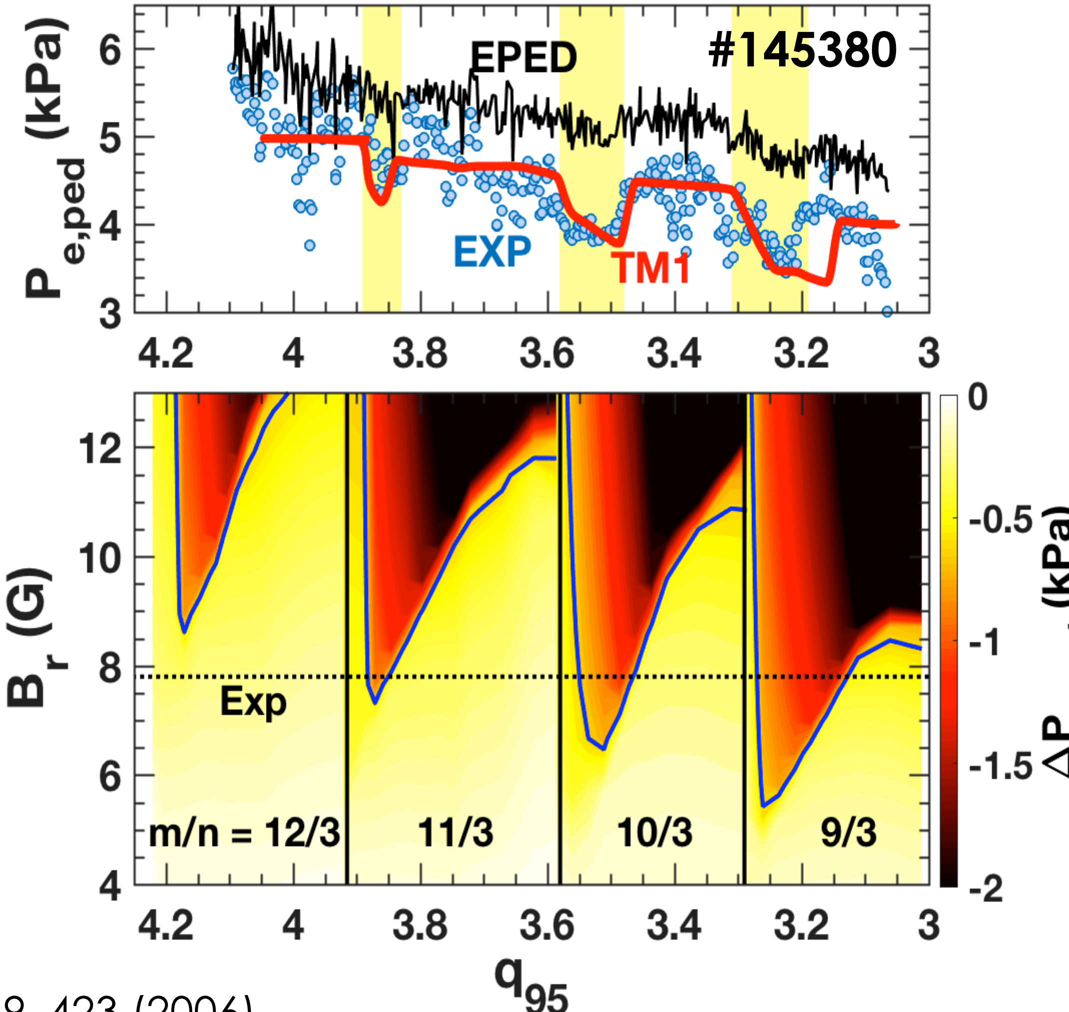
- **10/3 RMP affects pedestal pressure**
  - Island must be close to the top of pedestal to sufficiently reduce pedestal pressure and suppress ELM
  - → An island too far in can't reduce pedestal pressure
  - → Stronger RMP is required to trigger an island too far out



TM1 simulation shows pedestal pressure reduction in ELM suppression windows

- Simulated reduction in pedestal pressure agrees with experiment
- Pressure drops well below EPED prediction during ELM suppression
- PBM is stabilized from ELITE [1]
- Narrow q_{95} window is a consequence of narrow islands and no stochasticity

  → $\Delta q_{95} = 1/n$ (n=3)



[1] Evans T. E., *et al.*, Nat. Phys. **2**, 419–423 (2006)

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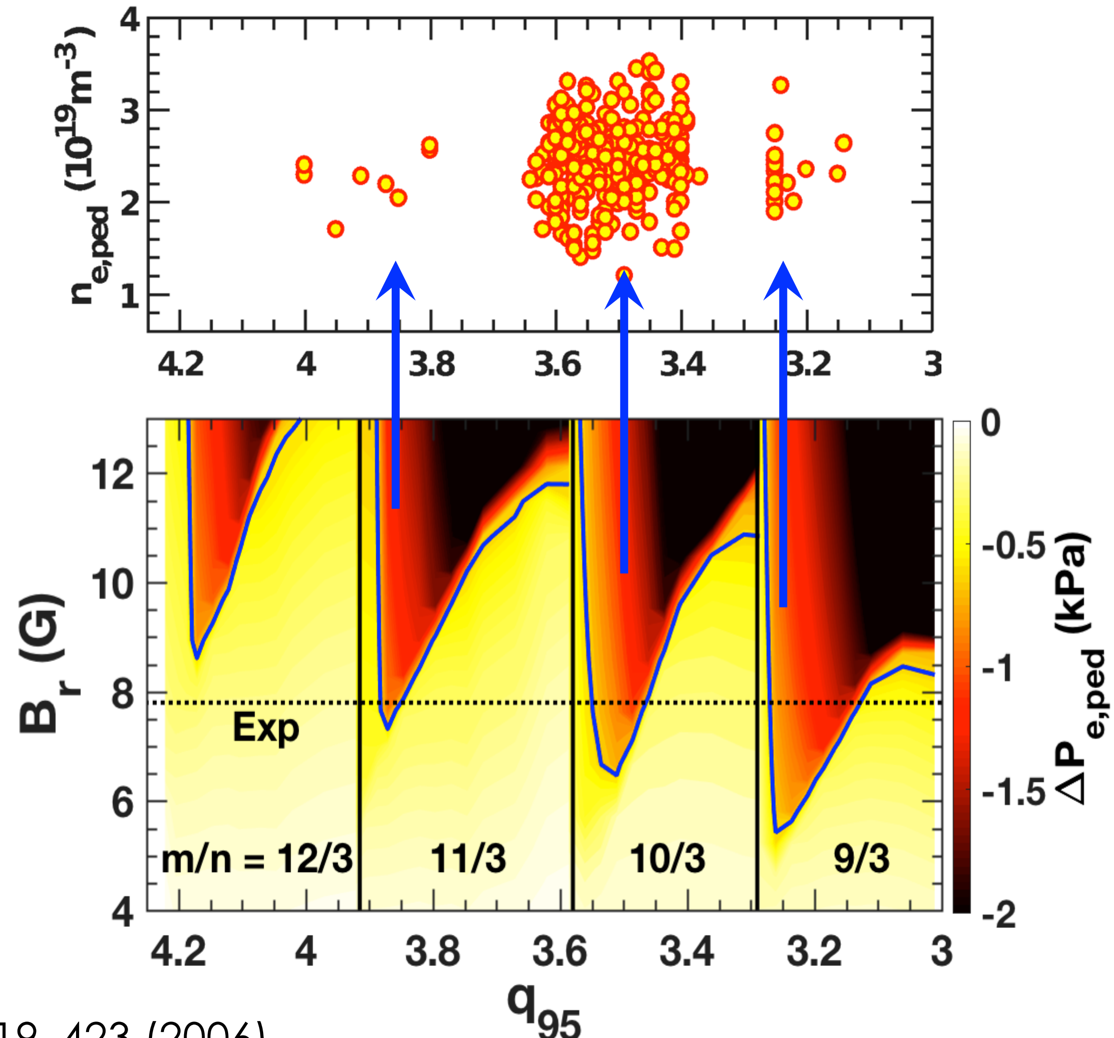
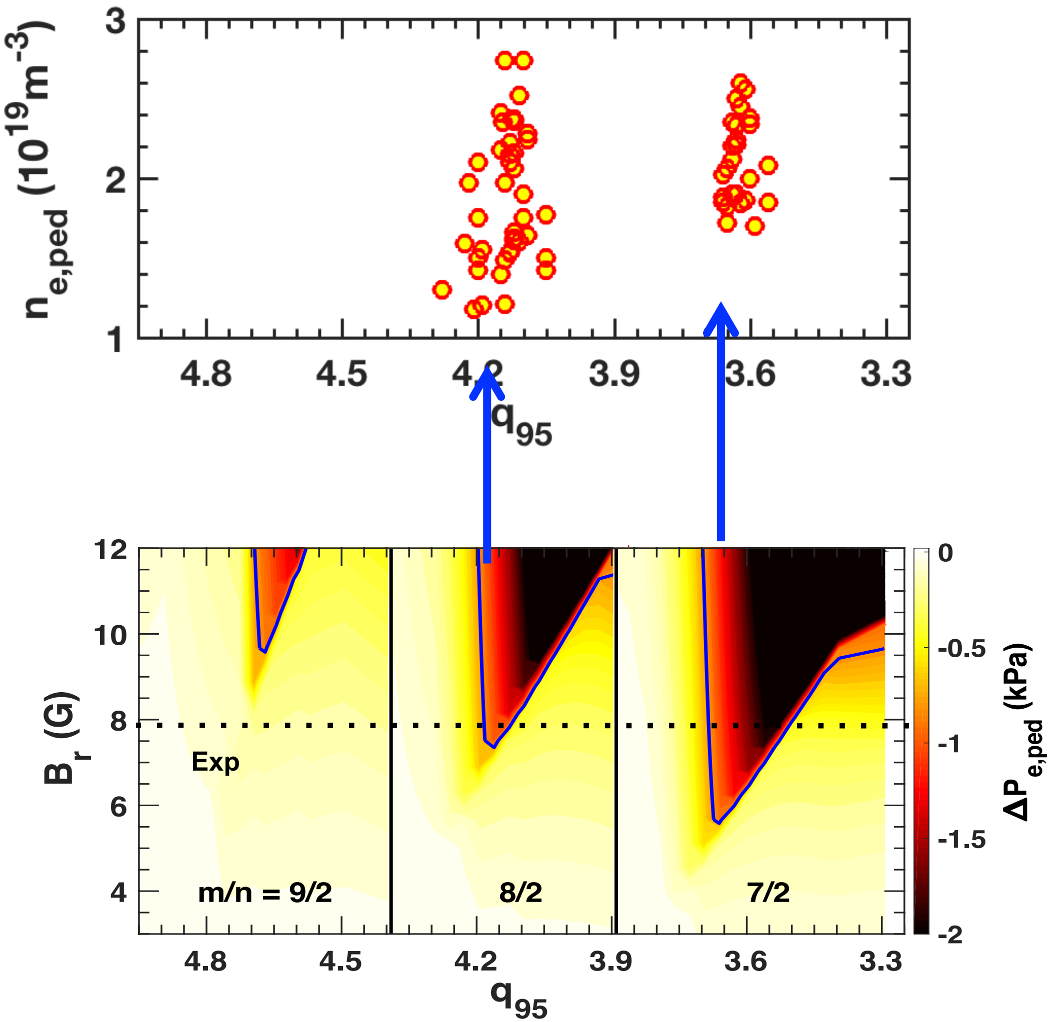


[1] Evans T. E., *et al.*, Nat. Phys. **2**, 419–423 (2006)

TM1 simulated q_{95} windows for n=2 RMP ELM suppression

- **Modeled q_{95} windows agree with experiment**

- **TM1 modeled q_{95} windows**
  - **Δq_{95} =1/n (n=2)**



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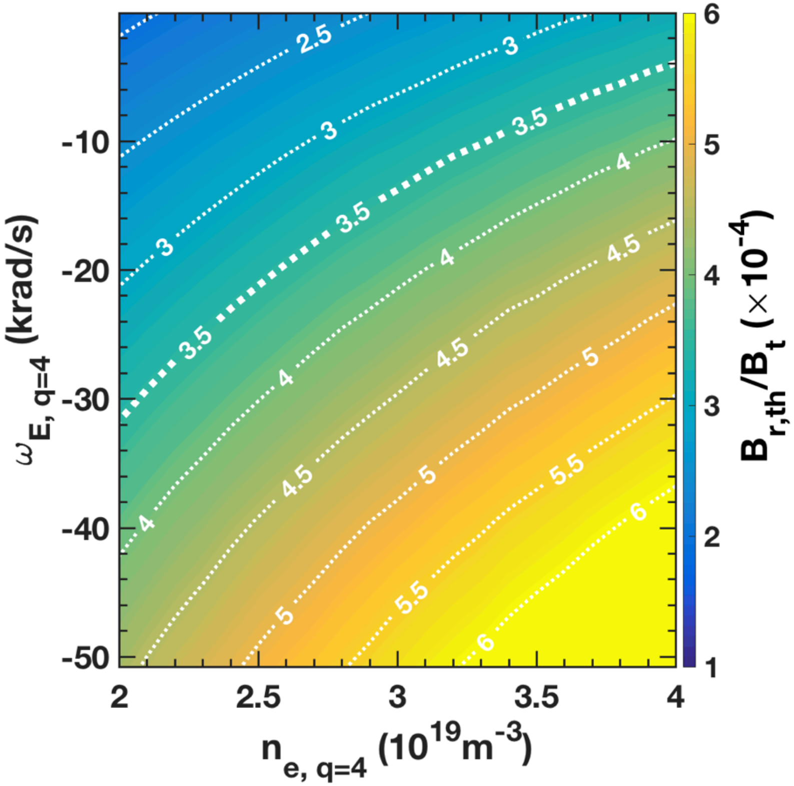
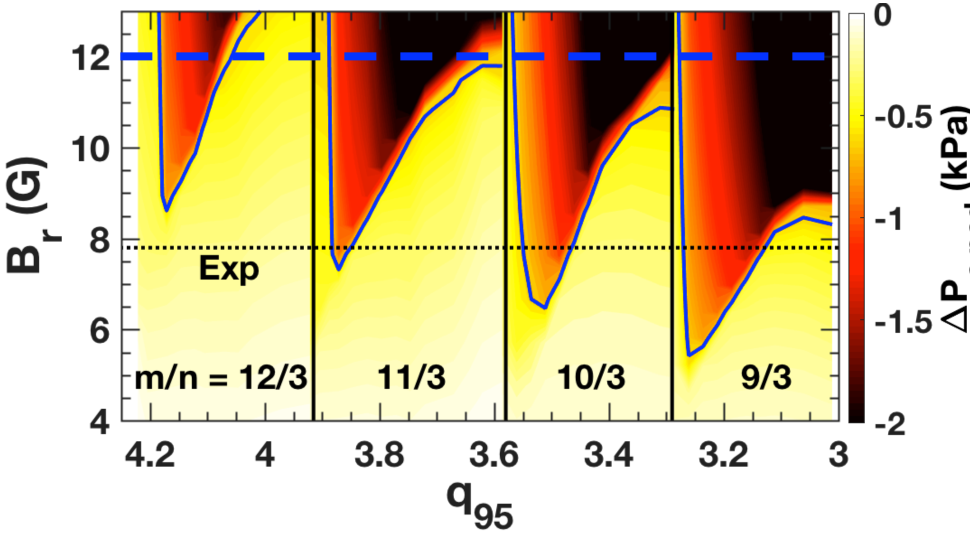
Expectation: As threshold decreases q_{95} windows expand and merge with each other

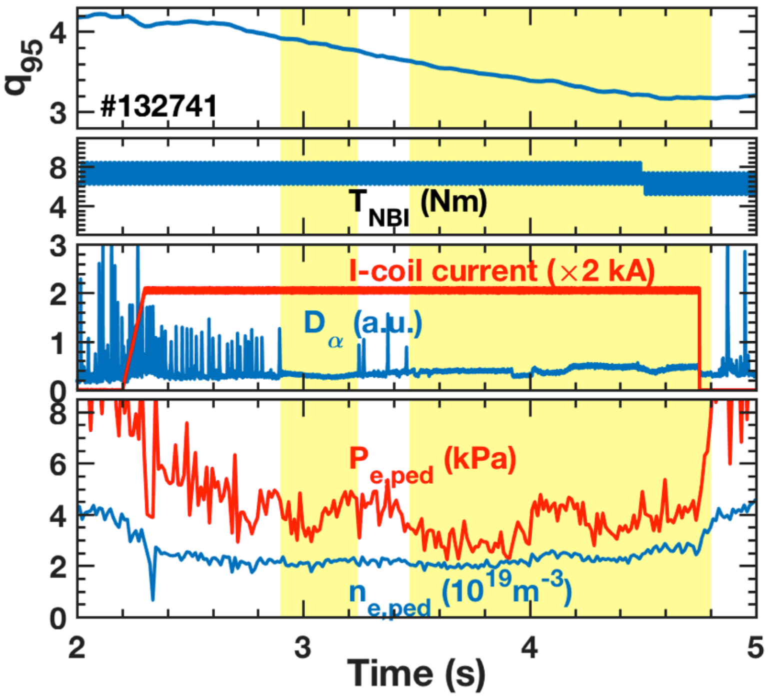
- **Threshold reduced at lower density or higher co-I_p rotation**





TM1 simulation shows expanding q_{95} windows for shot with lower density

#132741:
$n_{e,ped}$=2.5x10^{19}m^{-3}



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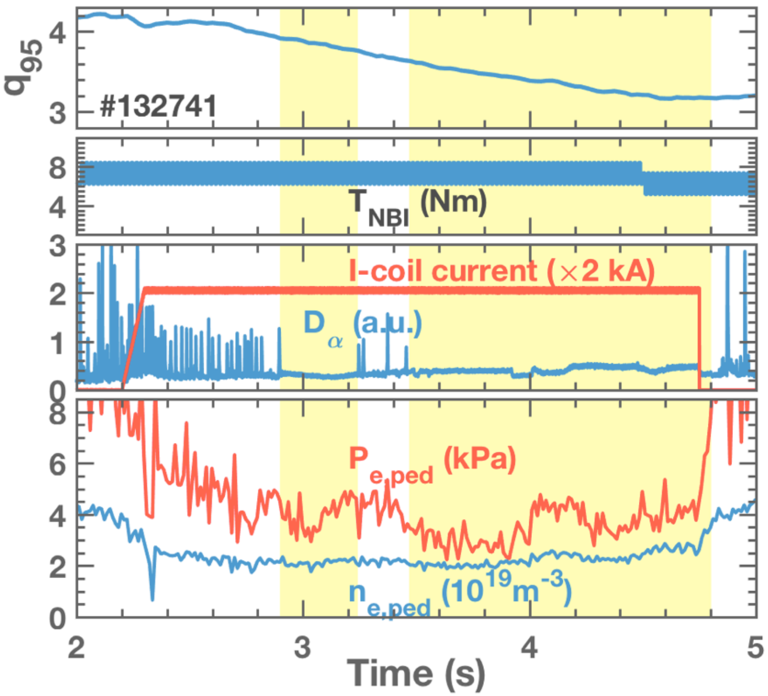

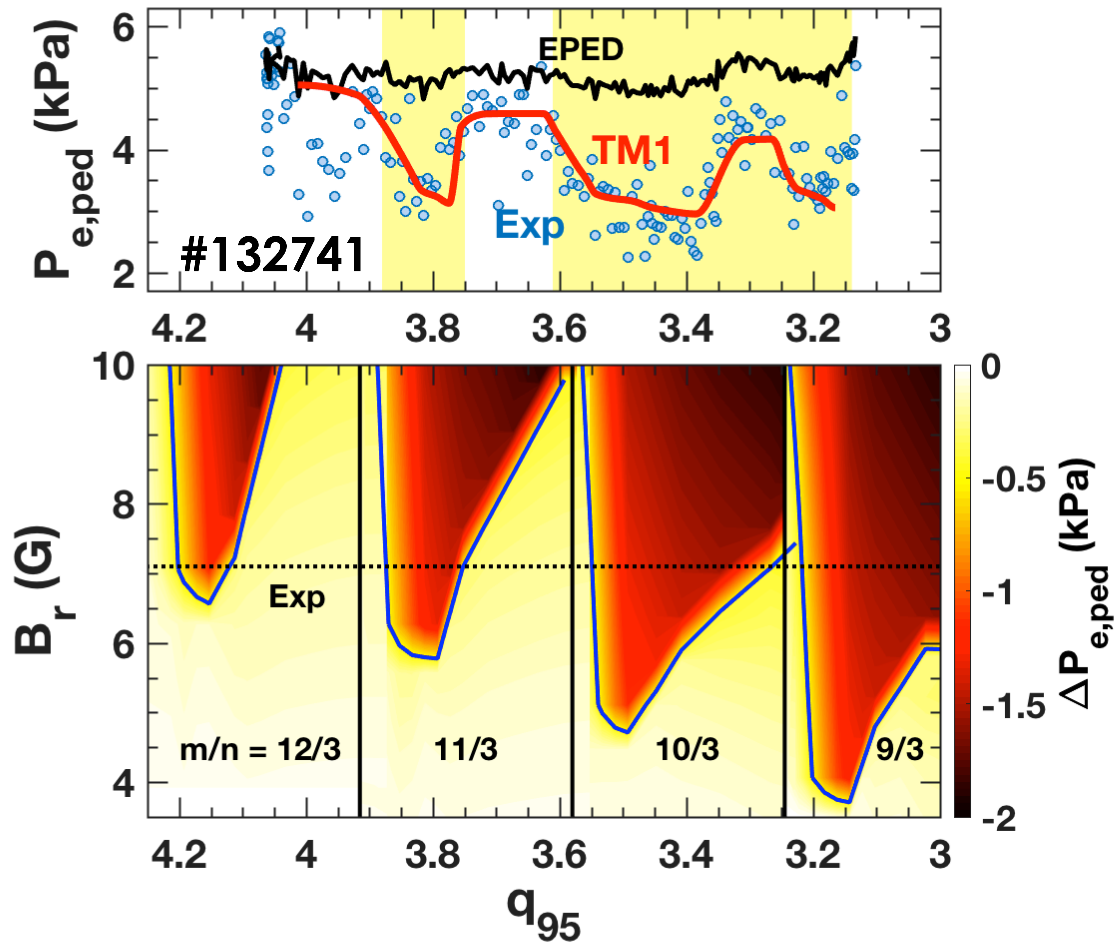

- **Strong variation in $P_{e,ped}$ correlates with q_{95} windows**

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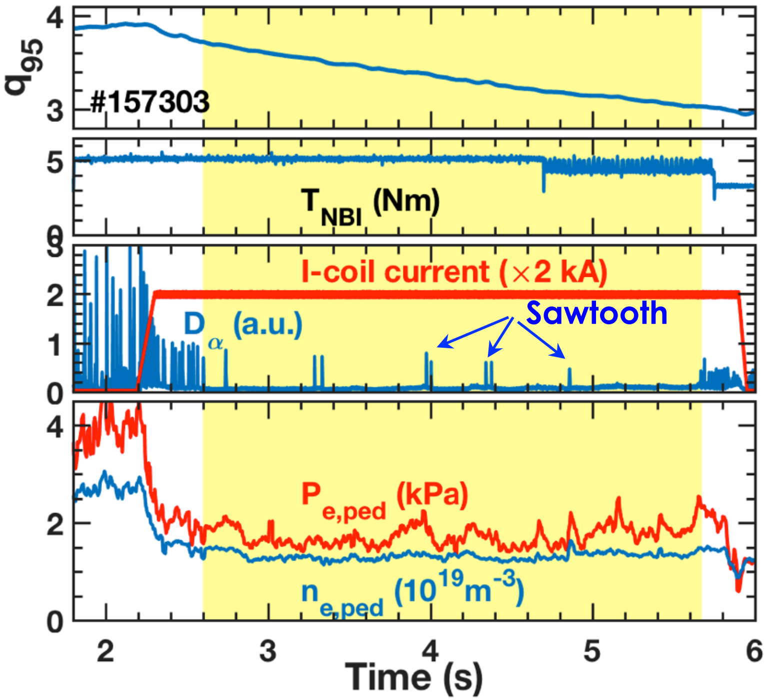
TM1 simulation shows full merging of q_{95} windows for shot 157303 with even lower density

#157303:
$n_{e,ped}$=1.5x10^{19}m^{-3}



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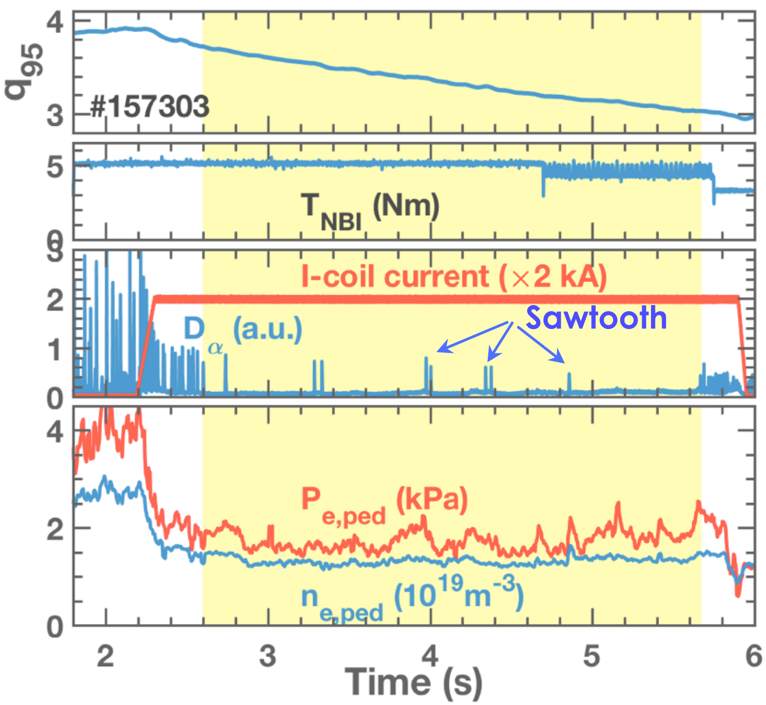
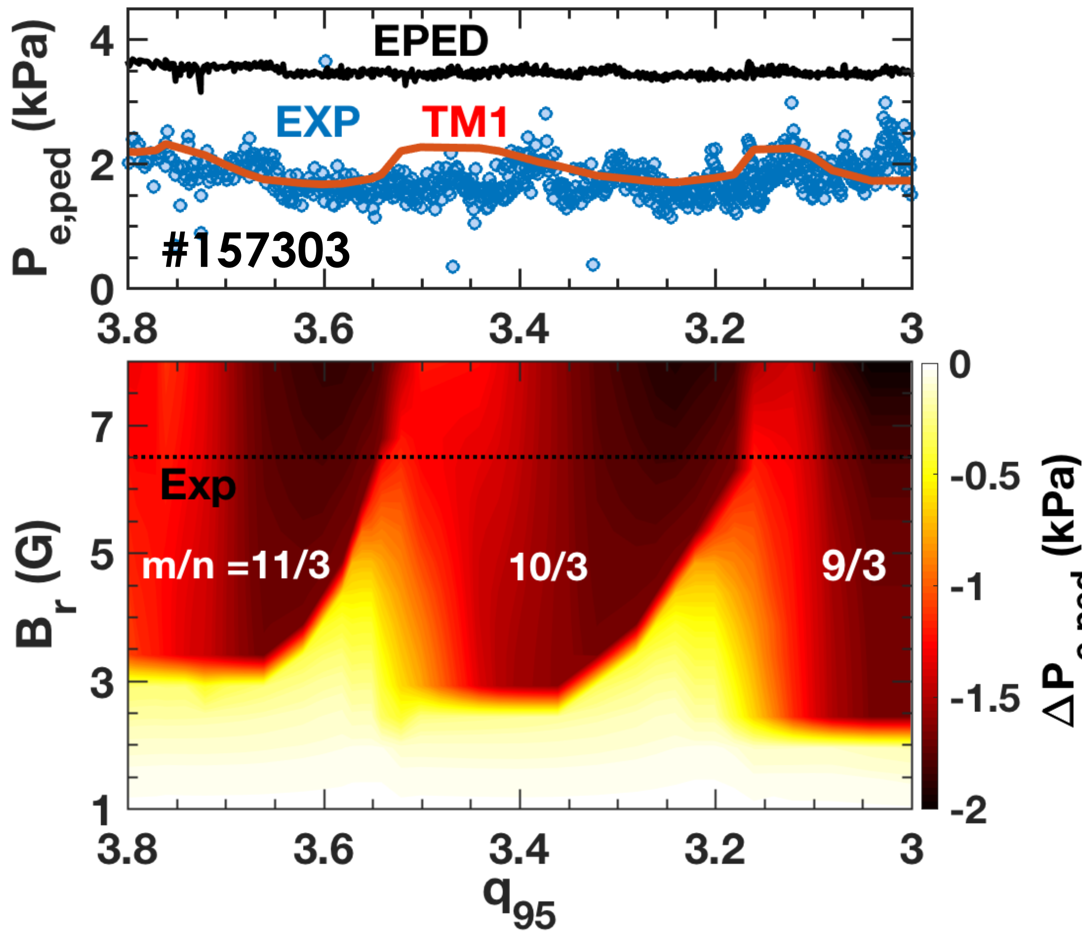
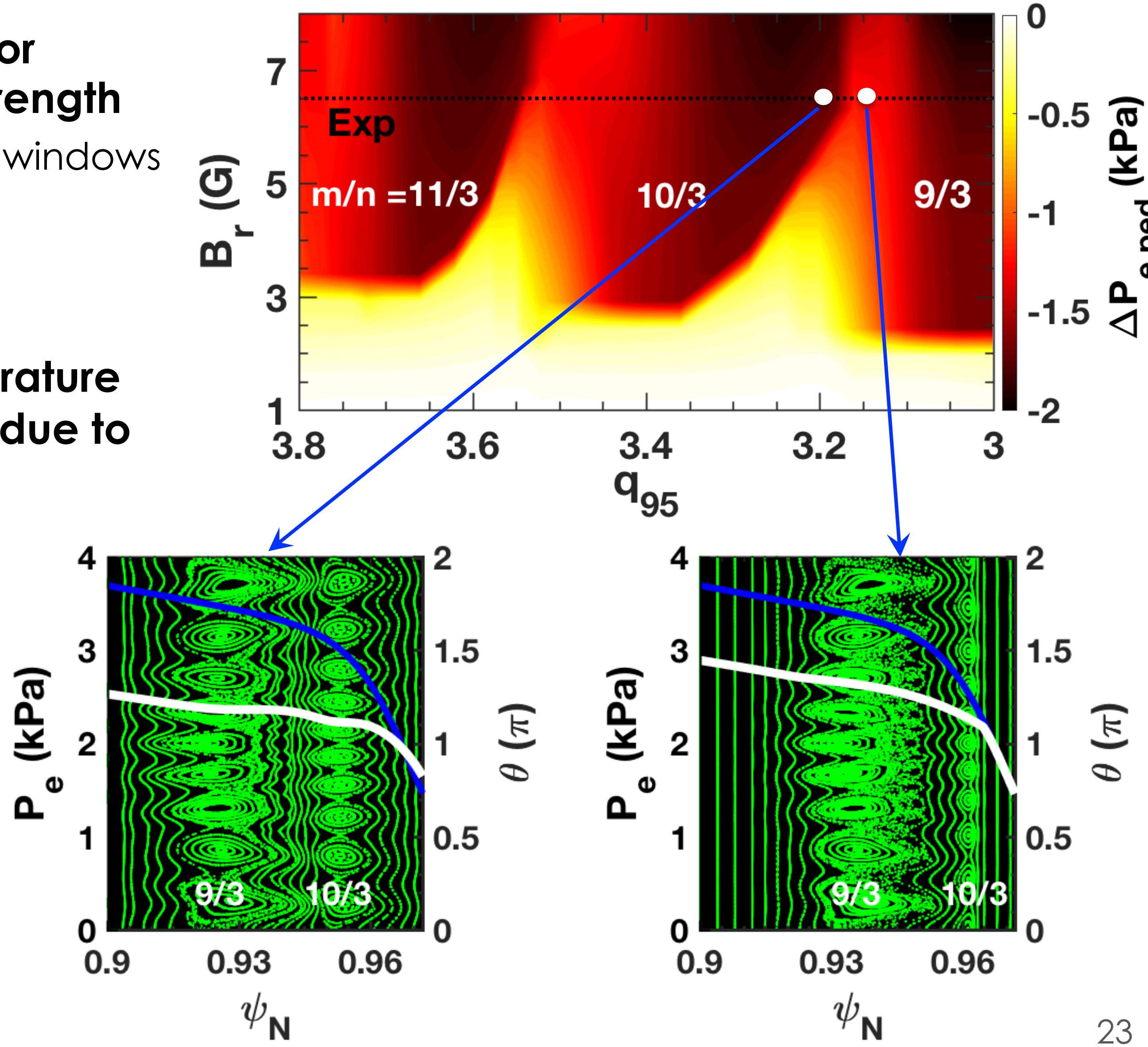




- **But merging of windows comes at a cost of suppressed pedestal pressure**

At merging, still no stochasticity, just well separate small islands

- q_{95} windows merge for experimental RMP strength
  - 11/3, 10/3 and 9/3 windows merge
- No change in temperature gradient in pedestal due to strong screening



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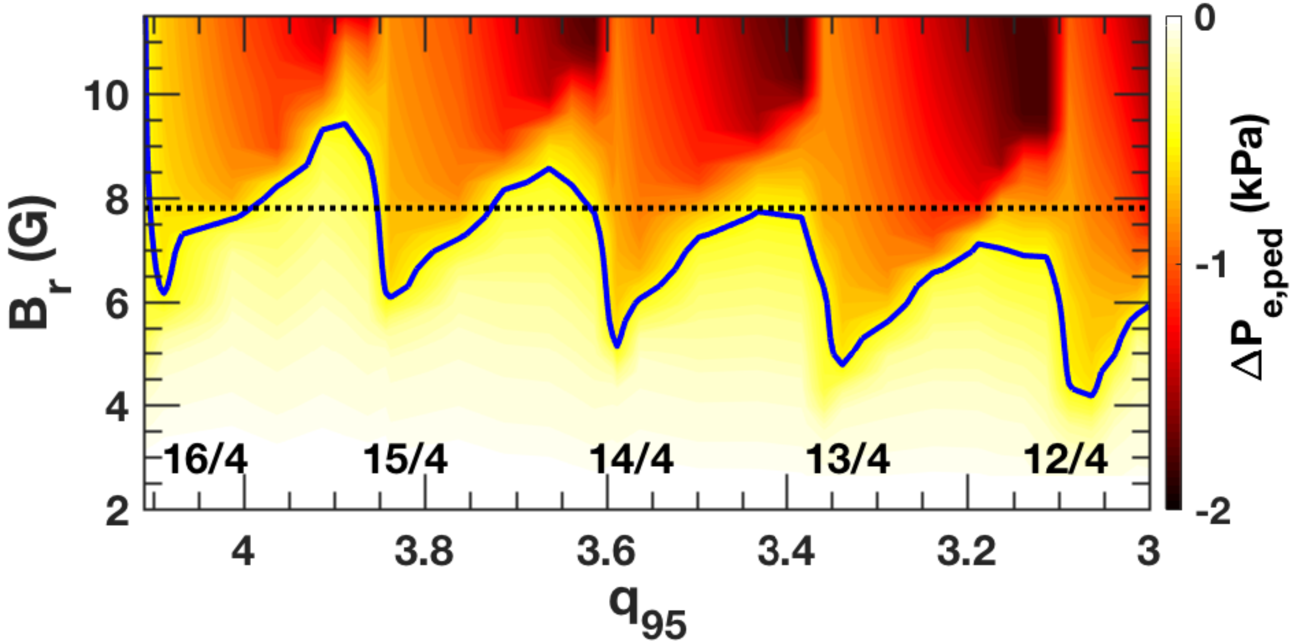
High-n RMP is preferable to suppress ELM with wide q_{95} and minimize pedestal pressure reduction



- **TM1 modeled q_{95} windows for n=4**
  - **Δq_{95} =1/n (n=4)**
  - **Denser resonant surface at the top of pedestal**

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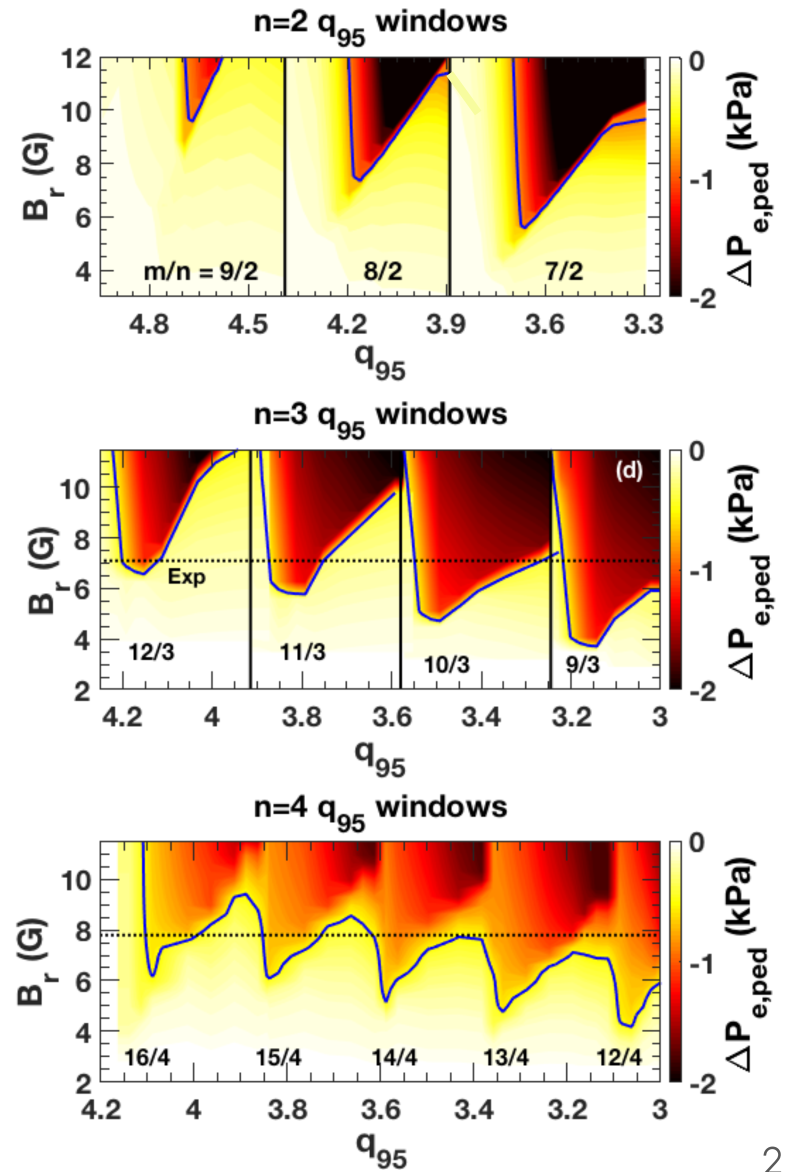
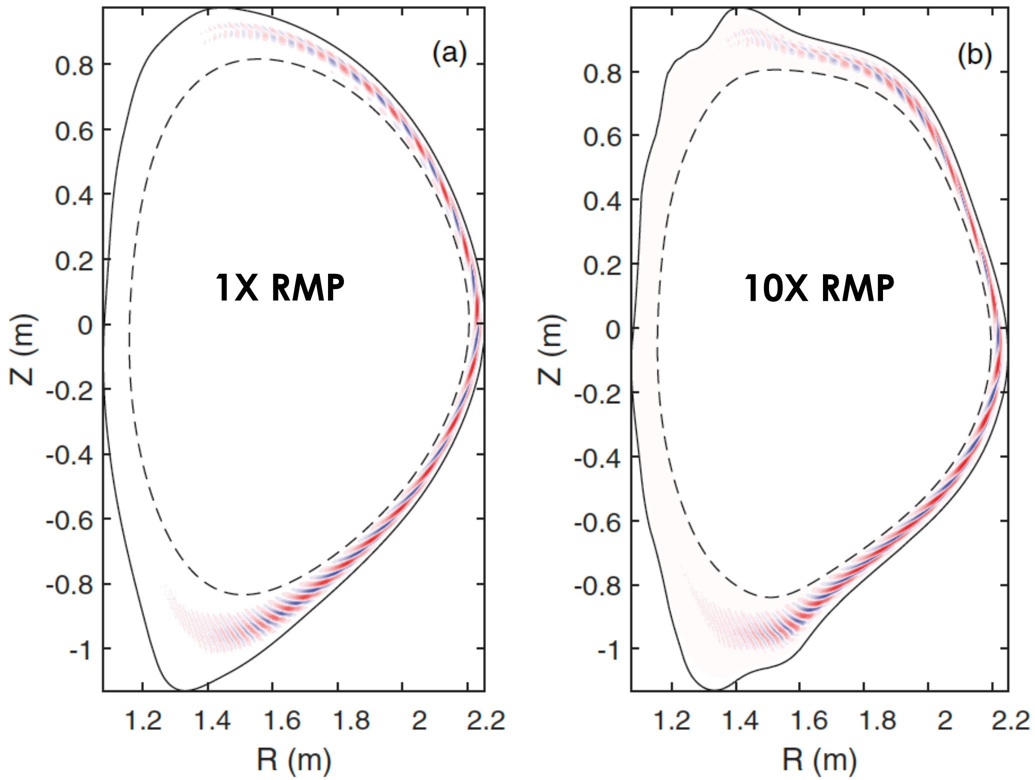
Summary: Why there are q_{95} windows

- **Well separate islands produce q_{95} windows**
- **The simulated q_{95} windows agree with DIII-D experiments**
- **q_{95} windows merge at 50% above threshold**
- **Higher-n RMP easier to generate wide q_{95} with less pressure reduction**
- **Next step: Extend predictions to ITER**



Backup slides

3D field effect on ballooning stability is negligible in low-collisionality ITER ISS plasma in GTC simulations



- **GTC simulation shows negligible 3D field effect on ballooning stability**

I. Holod, *et al*., Nucl. Fusion **57**, 016005 (2017)

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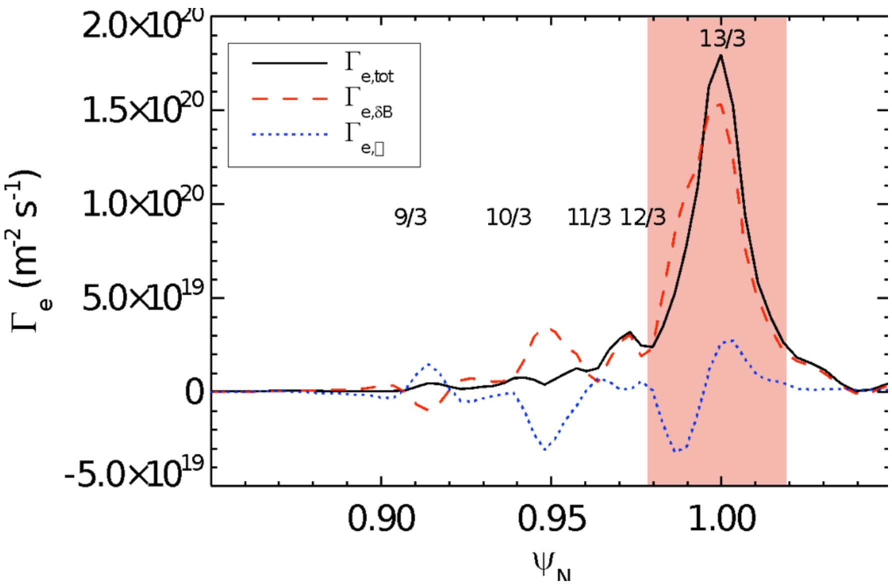
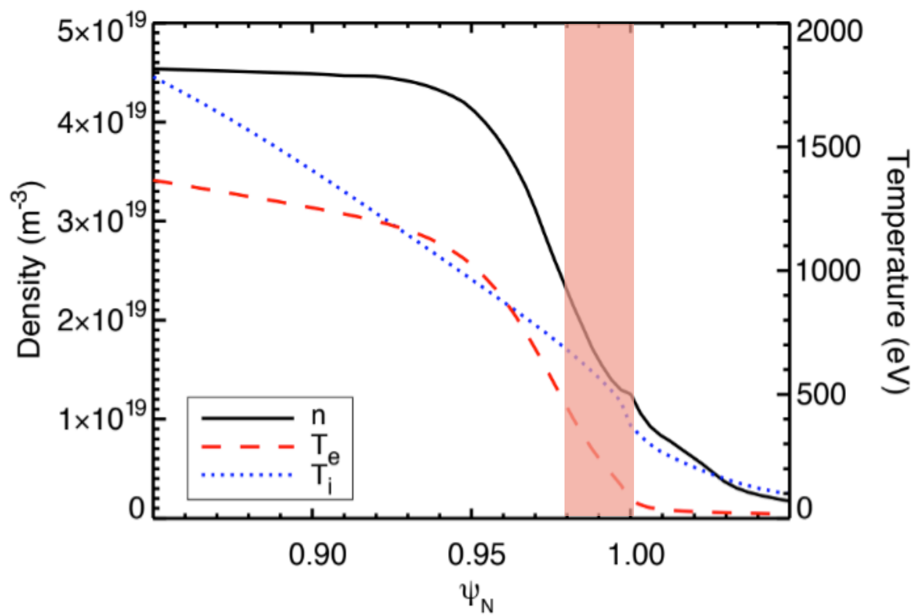
RMP-driven non-turbulent collisional transport strongest at the foot of the density pedestal in XGC simulations

Courtesy of R. Hager

- **XGC simulation with M3D-C1 screened n=3 RMP field**
  - Increased particle flux near the separatrix (mainly parallel transport along the stochastic magnetic field near the separatrix)
  - Flattened density profile visible after ~0.6 ms





R. Hager et al Nucl. Fusion **59** 126009 (2019)

Resonant effect causes two order larger particle flux than NTV effect

- **Resonant effect causes much stronger particle flux compared to non-ambipolar particle flux**

  ?Shot 158115 at 3.65 s (before ELM suppression)