Role of Resonant Magnetic Field Penetration in ELM Suppression and Density Pump-out in DIII-D ITER-like Plasmas

by

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with

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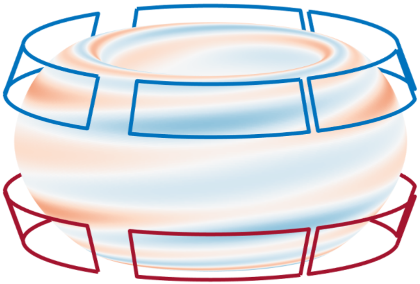
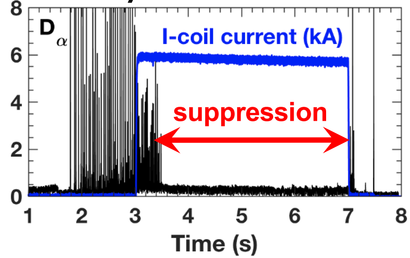
Resonant Magnetic Perturbations (RMPs) Are the Leading Strategy to Control ELMs in ITER

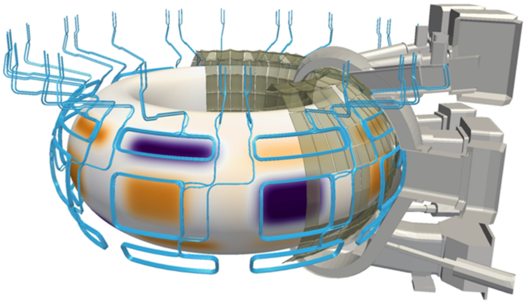
DIII-D 3D coils



Complete ELM suppression by RMPs in DIII-D



ITER 3D coils



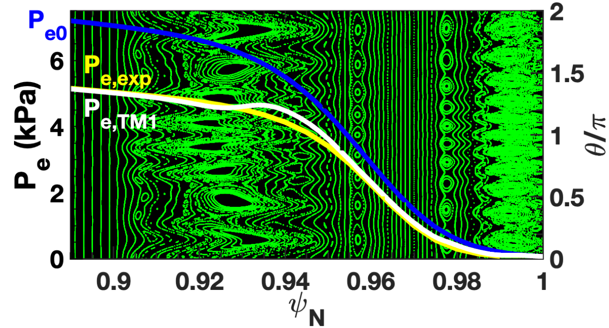
- DIII-D [1] and other tokamaks have achieved ELMs suppression by RMPs
- RMPs have been incorporated to control ELMs in ITER
- However, a quantitative understanding of the mechanism is required to predict and optimize the access conditions for ITER—RMP strength, q_{95} windows etc

In Memoriam to Todd Evans

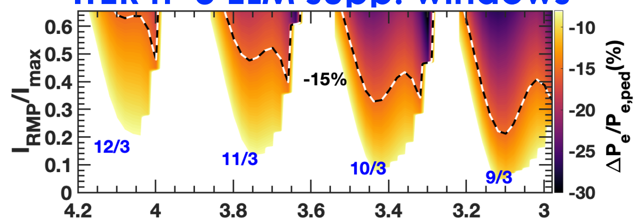
[1] T. E. Evans, et al., PRL **92**, 235003 (2004);
T. E. Evans, et al., NP **2**, 419 (2006);
T. E. Evans, et al., NF **48**, 024002 (2008)

Nonlinear MHD Model Reproduces RMP ELM Suppression Conditions in DIII-D and Predicts ELM Suppression for ITER

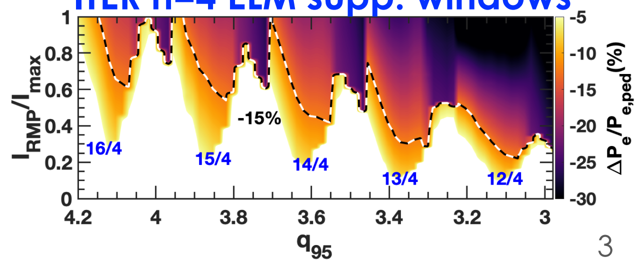
- **Demonstrates that pedestal top islands formation limits height and width of the pedestal to suppress ELM**
- **Reproduces narrow q_{95} windows of ELM suppression by n=3 in DIII-D**
- **Predicts ELM suppression in ITER within its 3D coil capability (I_{max}=90 kAt)**



ITER n=3 ELM supp. windows



ITER n=4 ELM supp. windows



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Outline

- Introduction of nonlinear MHD model
- Role of magnetic island formation in ELM suppression
- Narrow q_{95} windows of ELM suppression, why?
- Wide q_{95} windows of ELM suppression, how?
- Summary

Introduction of nonlinear MHD model

We Use a Suite of Codes to Obtain Quantitative Predictions of Island Formation at the Top of the DIII-D and ITER Pedestal

Experimental parameters and boundary conditions are used

GPEC
3D boundary conditions (vacuum + kink)

KineticEFIT
Kinetic equilibrium & profiles

TRANSP
Transport coefficients (χ_ϕ, χ_e, D_e)

OMFIT

TM1
2-fluids nonlinear MHD modeling

[1]https://omfit.io/publications.html#citing-omfit
[2] J-K. Park and N.C. Logan, POP **24**, 032505 (2017)
[3] J. Breslau, et al., **TRANSP** v18.2 2018
[4] Q. Yu, et al., POP **10**, 797 (2004);

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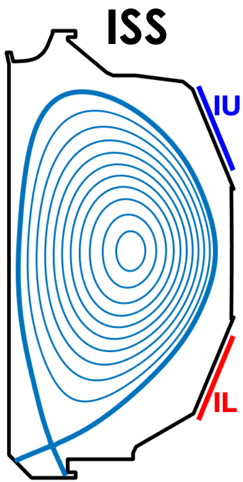
- ✓ TM1 nonlinearly calculates the penetration or screening of RMP
- ✓ TM1 simulates the enhanced parallel transport across the islands
- ✓ TM1 runs efficiently to be able to scan parameter space

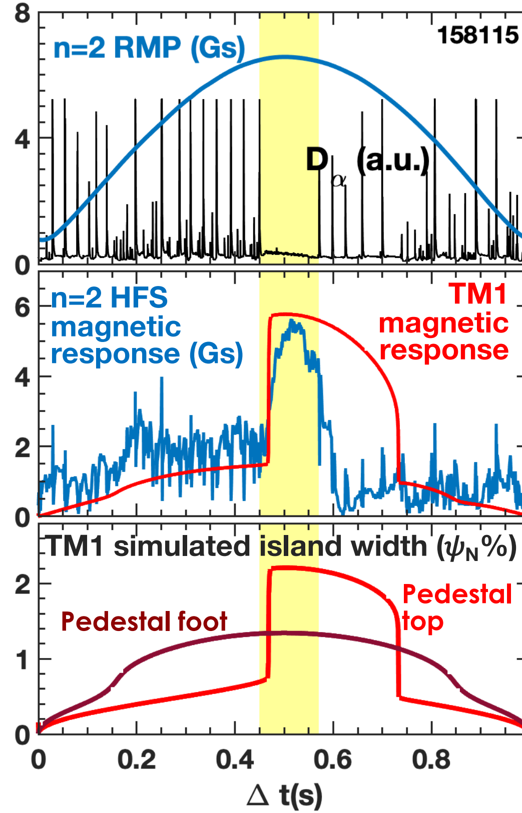
Role of magnetic island formation in ELM suppression

What limits the access conditions for ELM suppression?

Analysis of DIII-D ITER-Similar-Shape (ISS) Plasmas With n=2 RMP Shows Bifurcation to ELM Suppressed State at High RMP Amplitude

- **RMP amplitude varies slowly using I-coils**
- **Sudden transition seen to ELM suppression**
- **Correlated with measured plasma magnetic response [1, 2]**



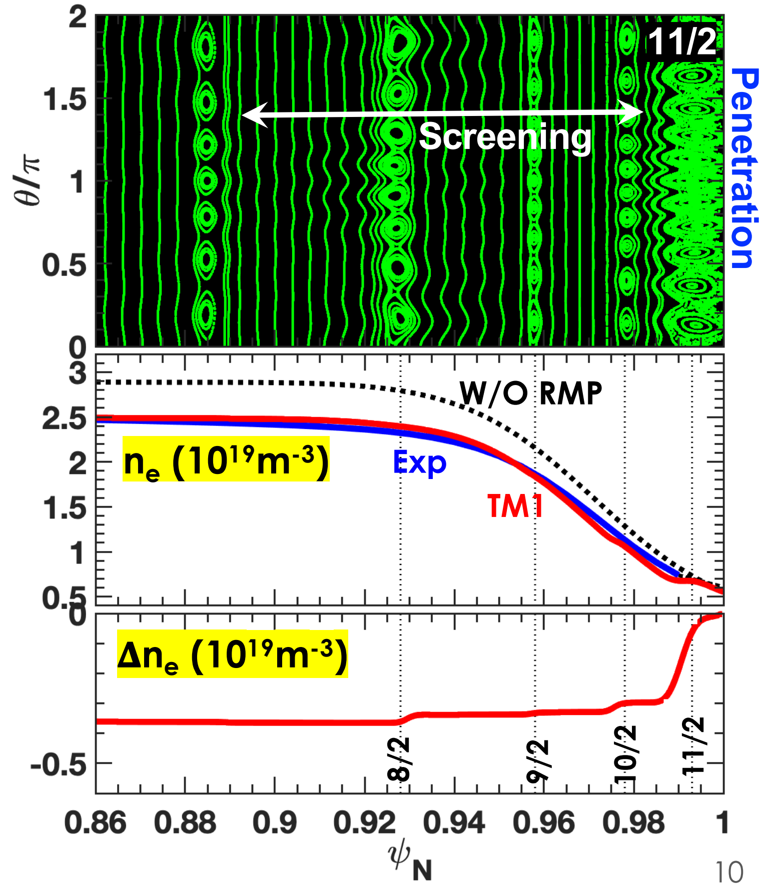


[1] C. Paz-Soldan, et al., PRL **114**, 105001 (2015)

[2] R. Nazikian, et al., PRL **114**, 105002 (2015)

Before ELM Suppression, There is Strong Screening Everywhere Except Pedestal Foot — Produces Density Pump-out

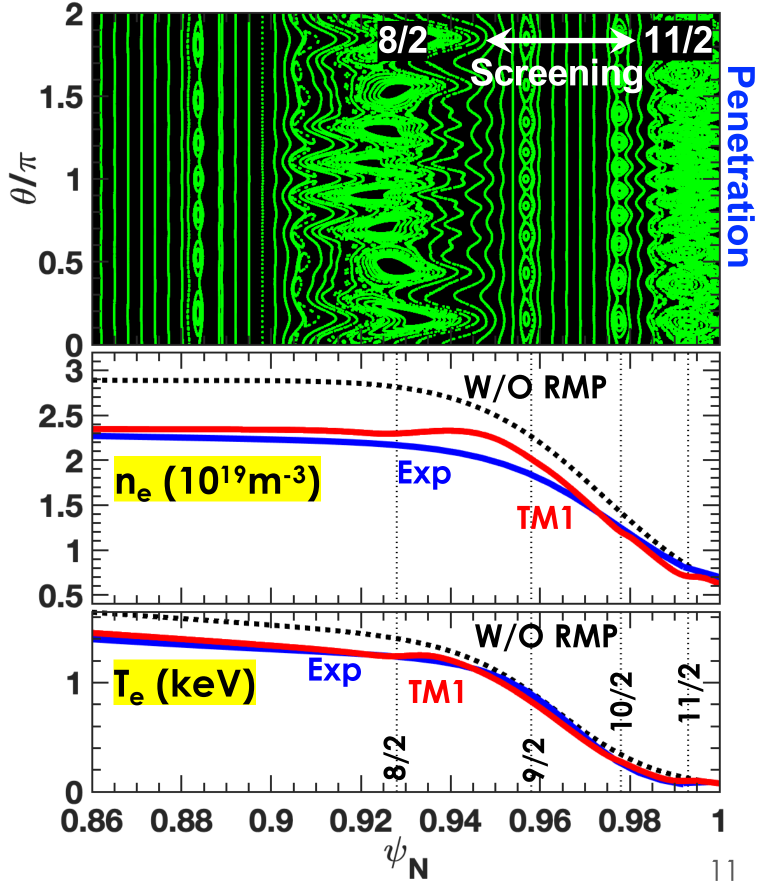
- **11/2 island flattens density at pedestal foot, consistent with experiment**
  - Uses realistic experimental parameters (resistivity)
  - Enhanced parallel transport across the island results in density pump-out



Q. Hu, R. Nazikian, et al., NF **60**, 076001 (2020)

Pedestal-top Field Penetration Further Decreases Pressure to Stabilize Peeling-Ballooning Modes

- **TM1: m/n=8/2 magnetic island forms at top of pedestal**
  - Further decrease density and temperature
  - Discrepancy in pedestal n_e gradient
- **TM1: Strong screening between top and foot of pedestal preserves ETB [1]**



[1] R. Nazikian, Q. Hu, et al., NF **61**, 044001 (2021)

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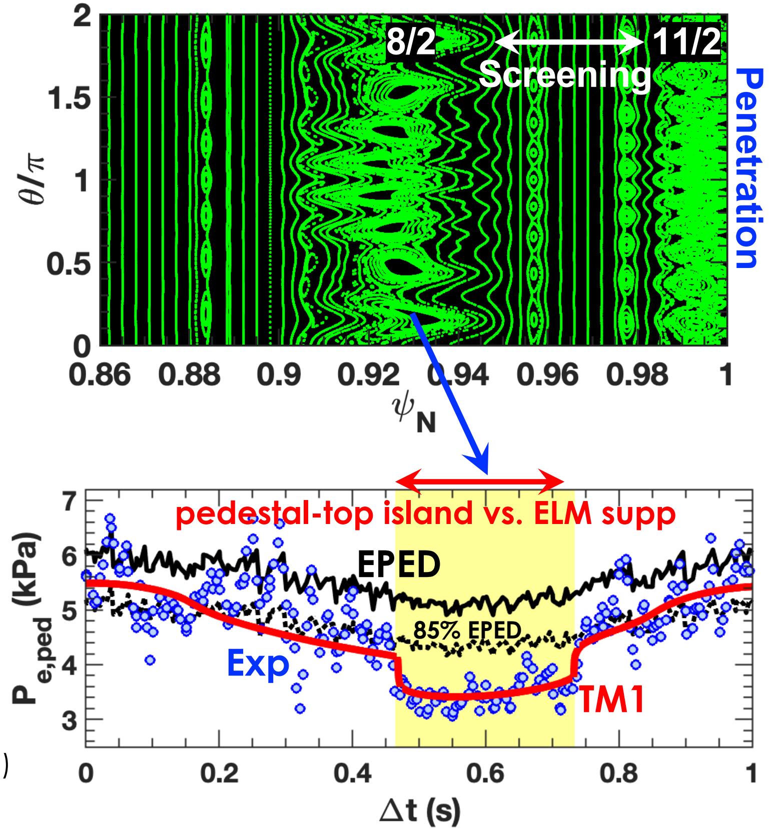
  - Further decrease density and temperature
  - Discrepancy in pedestal n_e gradient
- **TM1: Strong screening between top and foot of pedestal preserves ETB [1]**
- **TM1: Pressure reduction at island onset agrees with experiment**
  - Well below EPED prediction
  - ELITE shows stable to PBMs



[1] R. Nazikian, Q. Hu, et al., NF **61**, 044001 (2021)

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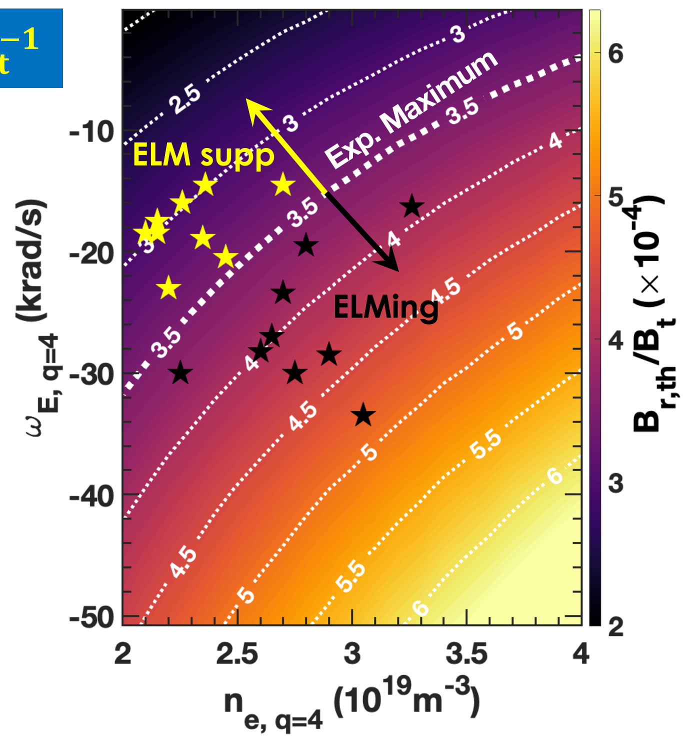
Scaling Law from TM1 Reproduces the Conditions for n=2 ELM Suppression in DIII-D Plasmas

Scaling of pedestal-top penetration threshold

$$B_r/B_t = 3.5\times10^{-2} n_e^{0.7} |\omega_E + \omega_{*e}|^{0.94} B_t^{-1}$$

- Lower n_e and rotation frequency are favorable for ELM suppression in DIII-D [1]
  - Consistent with n=2 database
- This scaling indicates lower penetration threshold in ITER [2] due to the expected low rotation frequency

Contour plot of penetration threshold (color)



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

[2] Q. Hu, R. Nazikian, et al., NF **60**, 076001 (2020)

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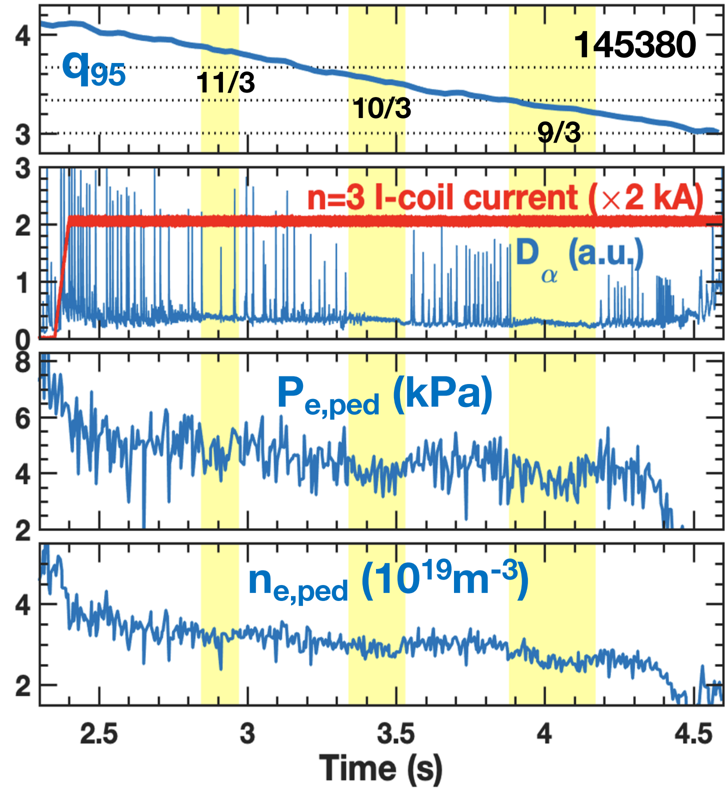
Why narrow q_{95} windows of ELM suppression?

Determined by the location alignment between island and pedestal-top

Multiple Narrow q_{95} Windows of ELM Suppression Seen in DIII-D During Plasma Current Ramp

- ELM suppression for q_{95}~10/3, 9/3
- Windows of ELM suppression Δq_{95}~0.1
- Partial suppression at q_{95}~11/3
- TM1 model can explain partial and full suppression



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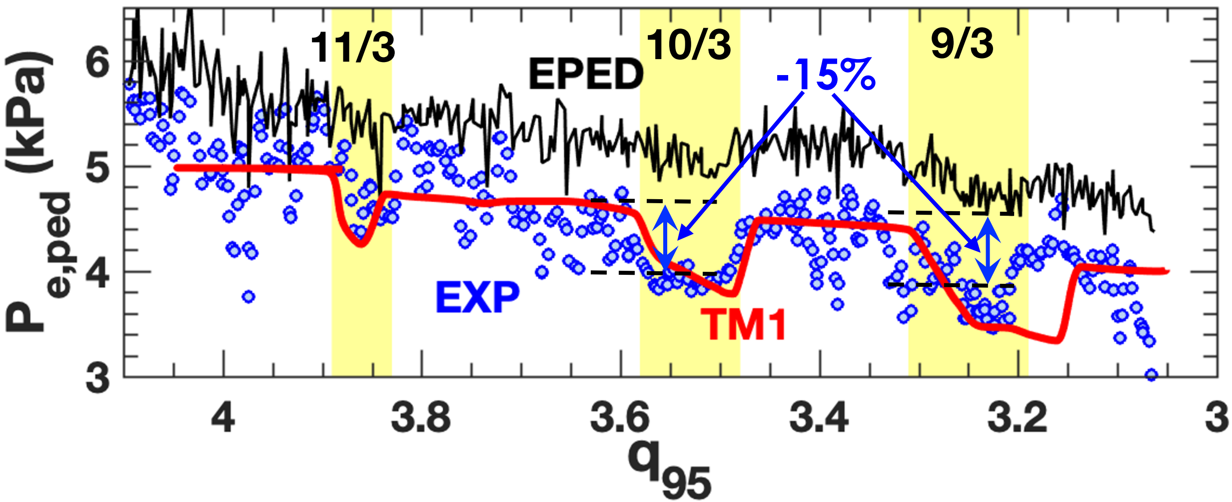
TM1 Reproduces the Experimental Pedestal Pressure Reduction Versus q_{95} Using Measured Profiles and RMP Amplitude

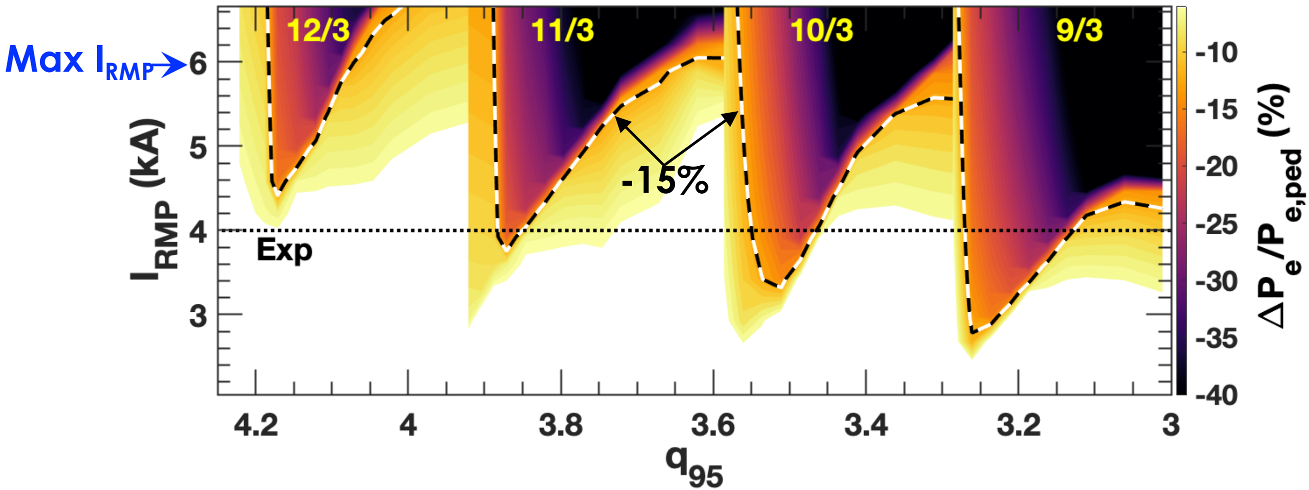
Pedestal pressure versus q_{95} from experiment, TM1 and EPED



- **ELM suppression coincides with localization of narrow islands to the top of the pedestal**
  - $P_{e,ped}$ drops ≥15% during ELM suppression compared to ELMing

TM1 shows that ELM Suppression Threshold is Satisfied for m/n = 9/3, 10/3, Marginal for m/n=11/3, as Observed in Experiment

Predicted n=3 q_{95} windows represented by pedestal pressure



- TM1: Contour plot of pressure reduction vs RMP coil
  - q_{95}~3.2, 3.55, 3.85 and 4.15 determined by 9/3, 10/3, 11/3 and 12/3
  - q_{95} width sensitive to RMP strength and distance~0.33 (1/n)

Q. Hu, R. Nazikian, et al., PRL **125**, 045001 (2020)

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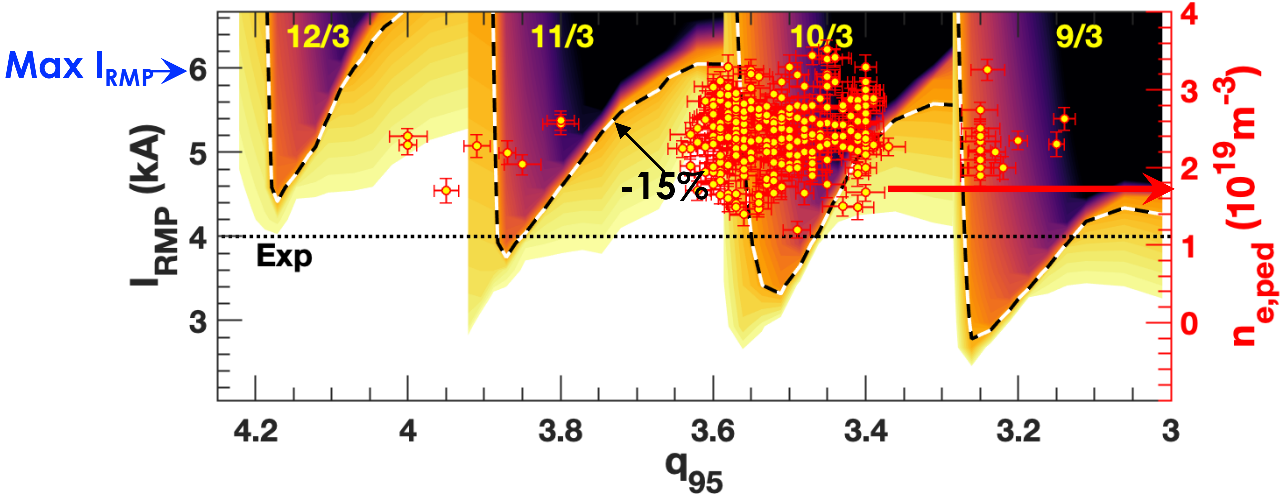
n=3 q_{95} windows comparison between TM1 simulation and DIII-D database



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  - q_{95} width sensitive to RMP strength and distance~0.33 (1/n)
  - Consistent with DIII-D n=3 database in q_{95} vs $n_{e,ped}$ space

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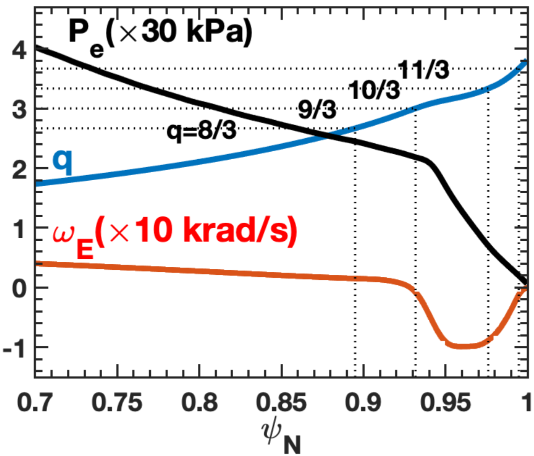
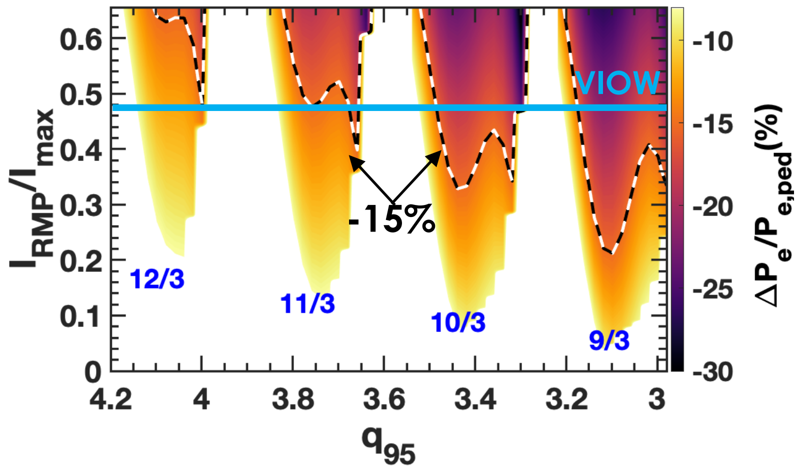
TM1 Prediction Shows Similar q_{95} Windows for ITER Q=10 Plasma and the Required RMP Strength is Within the Capability of ELM Control Coils

ITER Q=10 equilibrium is used



Predicted n=3 q_{95} windows for ITER



- ITER Q=10 15MA equilibrium and RMP configuration [1] are used
- n=3 q_{95} windows are predicted with RMP coil current less than half of the full capability (I_{max} = 90 kAt):
  - Threshold current is lower than VIOW prediction [2]
  - Narrower q_{95} windows compared to DIII-D

[1] L. Li, Y. Q. Liu, et al, NF **59** 096038 (2019)
[2] T.E. Evans, et al, NF **53** 093029 (2013)

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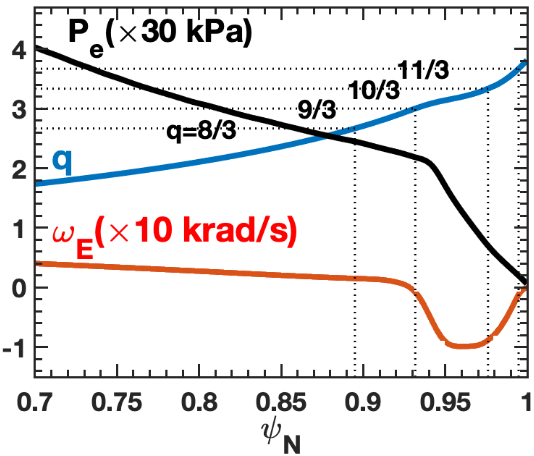

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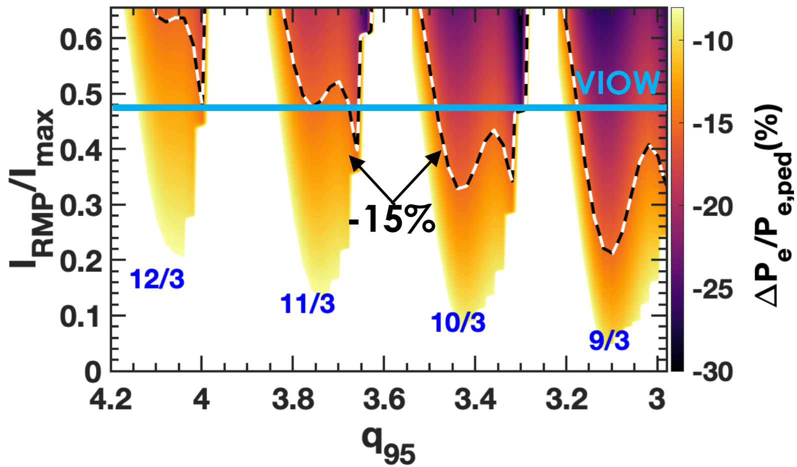
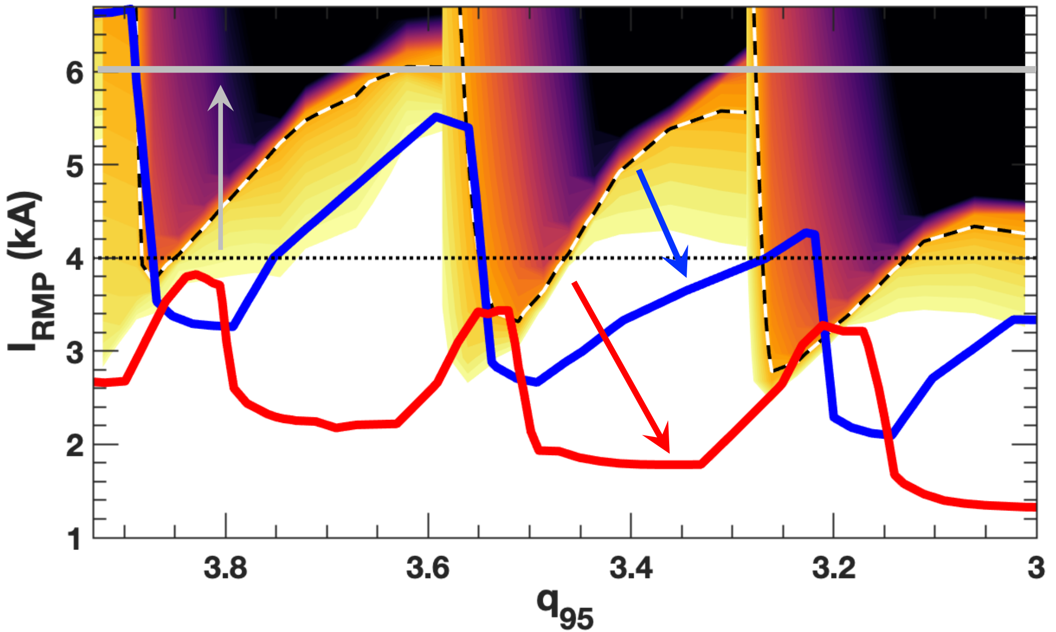


- **Challenge**: ELM suppression with narrow q_{95} windows does not provide effective operational flexibility for ITER
- **How can we expand the q_{95} windows of ELM suppression?**

[1] L. Li, Y. Q. Liu, et al, NF **59** 096038 (2019)
[2] T.E. Evans, et al, NF **53** 093029 (2013)

How to expand the narrow q_{95} windows to enable operation flexibility?

Prediction from TM1: q_{95} Windows will Expand if RMP Level Increases or Threshold for Penetration Decreases



DIII-D ISS plasmas

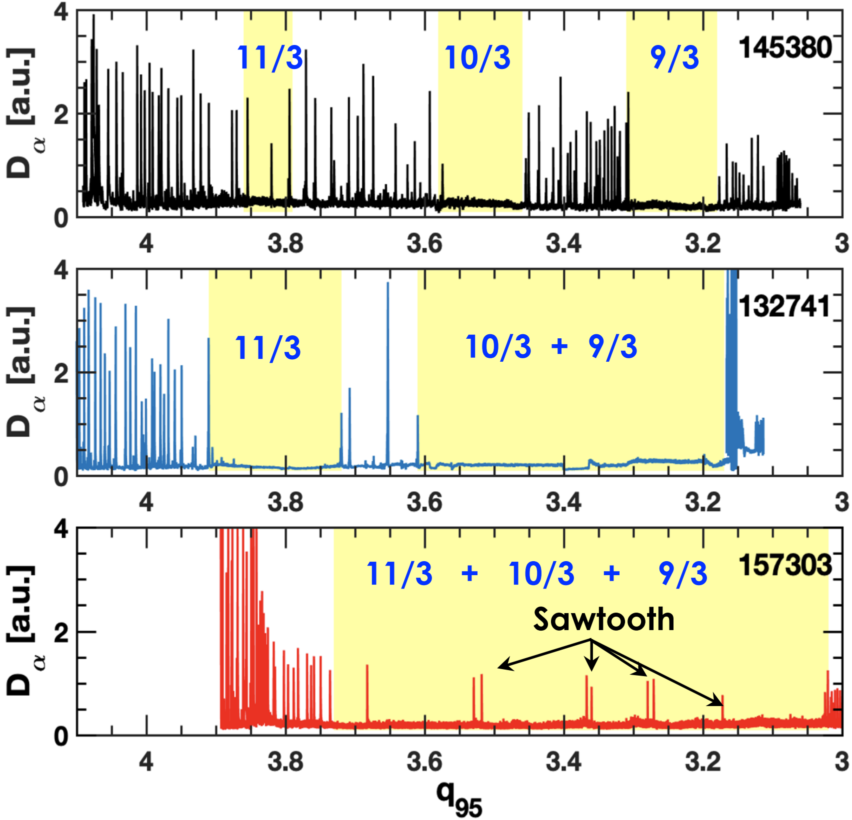
$n_{e,ped}/n_G = 0.35$

$n_{e,ped}/n_G = 0.25$

$n_{e,ped}/n_G = 0.15$

- **Raise the RMP amplitude**
- **Or lower the density to expand and merge q_{95} windows**
  - **Lower density** or rotation

Experiments in DIII-D Observed Wider q_{95} Window of ELM Suppression at Lower Density with 50% Pressure Reduction



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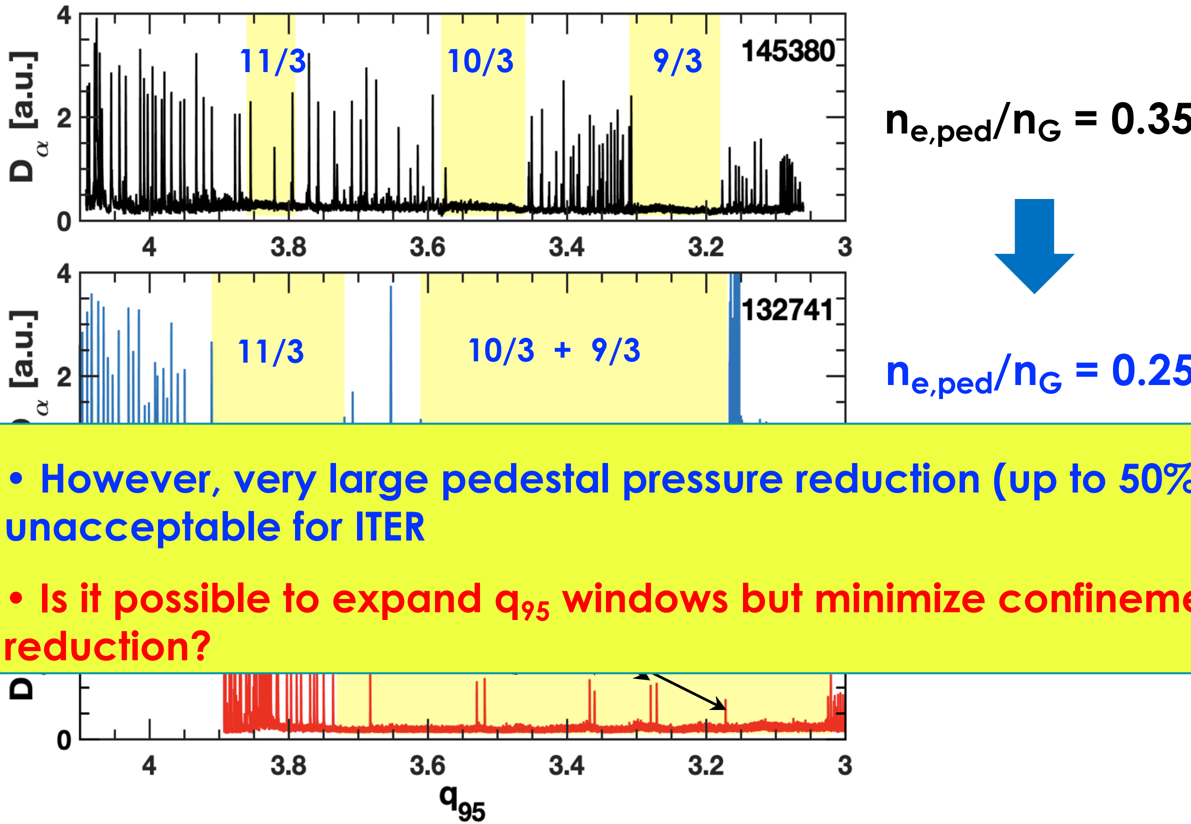

- However, very large pedestal pressure reduction (up to 50%) unacceptable for ITER
- Is it possible to expand q_{95} windows but minimize confinement reduction?

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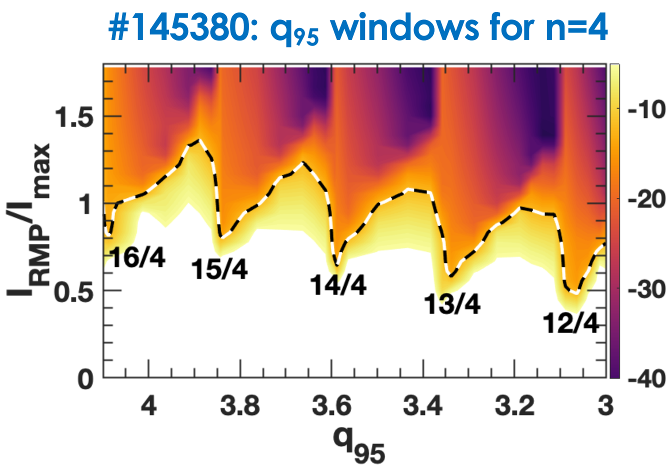
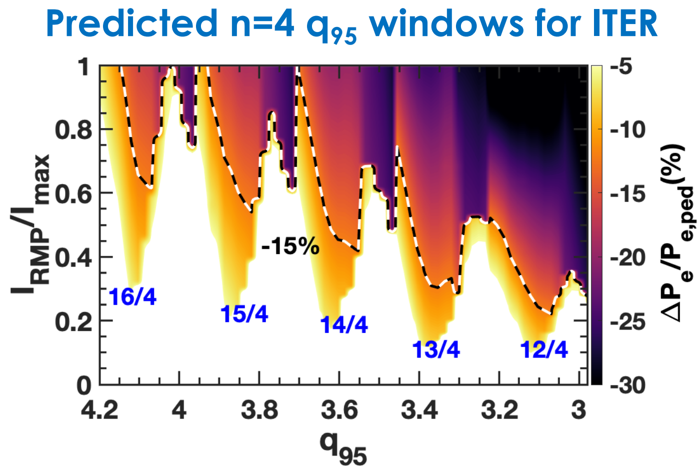
TM1 Simulation Predicts Wide q_{95} Windows of ELM Suppression with Less Pressure Reduction for n=4

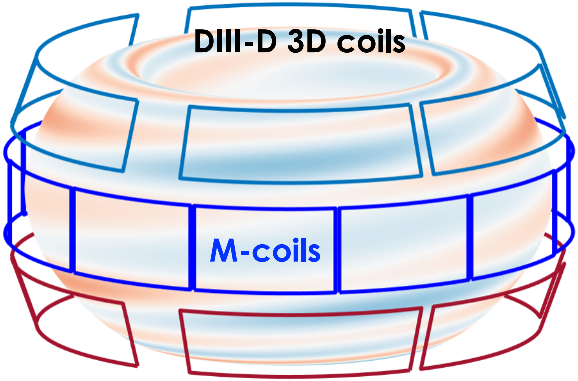


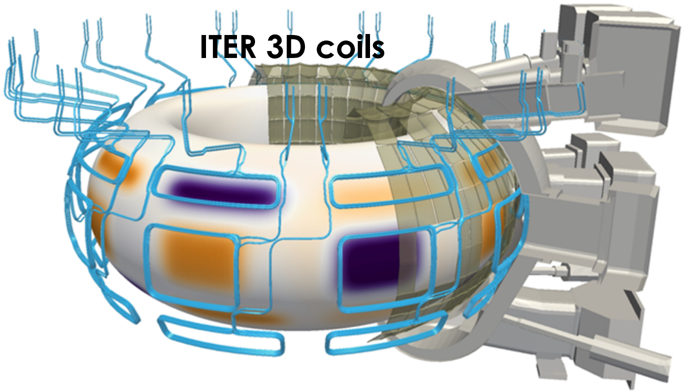


- **Closer q_{95} windows for n=4 RMPs**
  - More rational surface enhances field penetration
  - Less pressure reduction (~20%)
- **Wide q_{95} ELM suppression windows by n=4 RMP in DIII-D and ITER**
  - Full capability of 3D coils **(I_{max} = 90kAt)** in ITER will enable wide q_{95} ELM suppression

Q. Hu, R. Nazikian, et al., PRL **125**, 045001 (2020)

DIII-D and ITER can Explore ELM Suppression at Higher Toroidal Mode Number





- **New DIII-D M-coils [1] will enable exploring ELM suppression at n=4, 5, 6**
- **ITER ELM control coils (9 coils each row) are able to run at n=4, 5**

[1] D.B. Weisberg, et al., NF **59**, 086060 (2019)

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Summary: Nonlinear MHD Model Reproduces RMP ELM Suppression Conditions in DIII-D and Predicts ELM Suppression for ITER

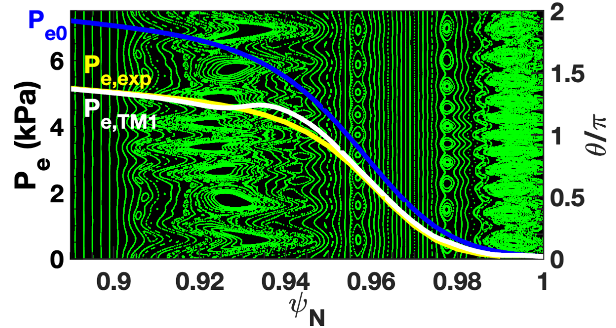
- **Demonstrates that pedestal top islands formation limit height and width of the pedestal to suppress ELM**
  - Explains dependence on rotation and density

- **Reproduces narrow q_{95} windows of ELM suppression at n=3 in DIII-D**
  - Lowering density expand q_{95} windows

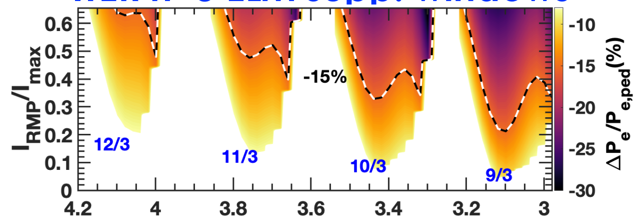
- **Predicts ELM suppression in ITER within its 3D coil capability (90kAt)**
  - n=3 q_{95} windows similar to DIII-D
  - wide n=4 q_{95} windows

Q. Hu, R. Nazikian et al., NF **60**, 076001 (2020)

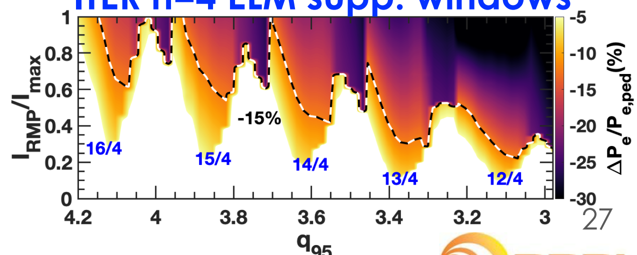
Q. Hu, R. Nazikian et al., PRL **125**, 045001 (2020)



ITER n=3 ELM supp. windows



ITER n=4 ELM supp. windows



Nonlinear Two-fluid TM1 is Used to Simulate Island Formation and Transport due to RMP

- Cylindrical, circular cross-section geometry model

$$\frac{d\psi}{dt} = E - \eta j + \Omega(\nabla_{||} n_e + \nabla_{||} T_e)$$ Ohm's law

diamagnetic drift

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

$$\rho \frac{d}{dt} \nabla^2 \phi = \vec{e_t} \cdot (\nabla\psi \times \nabla j) + \rho\mu\nabla^4\phi + S_m$$ Perpendicular motion equation

$$\frac{dn_e}{dt} = \frac{\omega_{ce}}{v_e} \nabla_{||} j - \nabla_{||}(n_e u) + \nabla \cdot (D_\perp \nabla n_e) + S_n$$ Electron continuity equation

ion polarization current

$$\frac{3}{2} n_e \frac{dT_e}{dt} = \frac{\omega_{ce}}{v_e} T_e \nabla_{||} j - T_e n_e \nabla_{||} u + n_e \nabla \cdot (\chi_{||} \nabla_{||} T_e) + n_e \nabla \cdot (\chi_\perp \nabla_\perp T_e) + S_e$$ Energy transport equation

Sources are time-independent

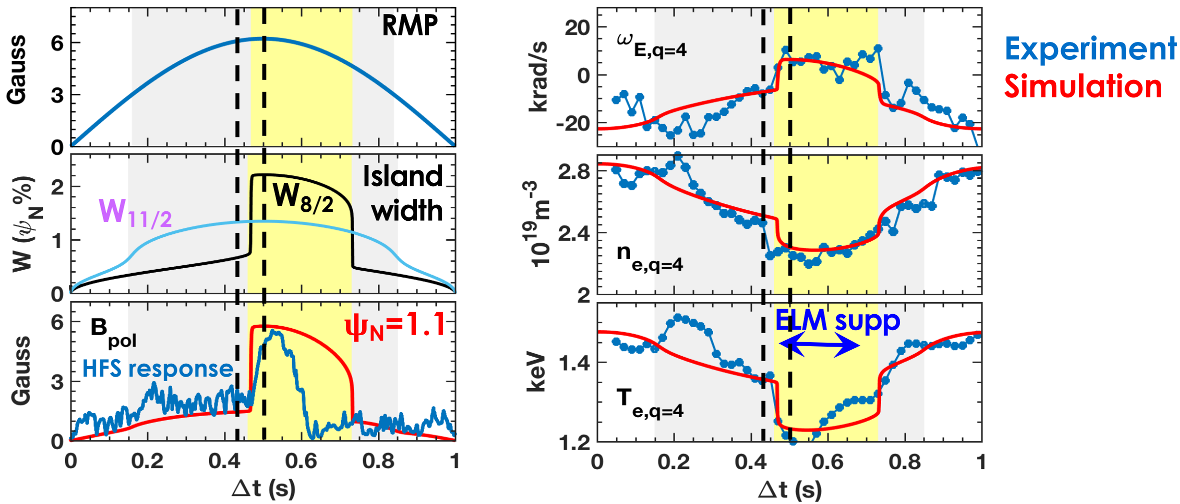
Q. Yu, et al., POP **10**, 797 (2004); Q. Yu, et al., NF **51**, 073030 (2011)

Cylindrical Model is Relevant for RMP Effect on Edge Plasma in DIII-D and KSTAR Low-collisionality Plasmas

- Gyrokinetic simulation shows that 3D field effect on ballooning stability is negligible in low-collisionality ITER similar shape (ISS) plasmas [1]
- Gyrokinetic simulation shows that kink response causes little neoclassical transport [2]
- Helical boundary condition provided by full toroidal code GPEC includes kink response [3]
- Toroidal mode coupling at nonlinear stage is weak [4] due to 1) much small and separate islands, 2) strong flow shear between rational surfaces

[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)
[4] Q. Yu, et al., NF **59**, 106053 (2019)

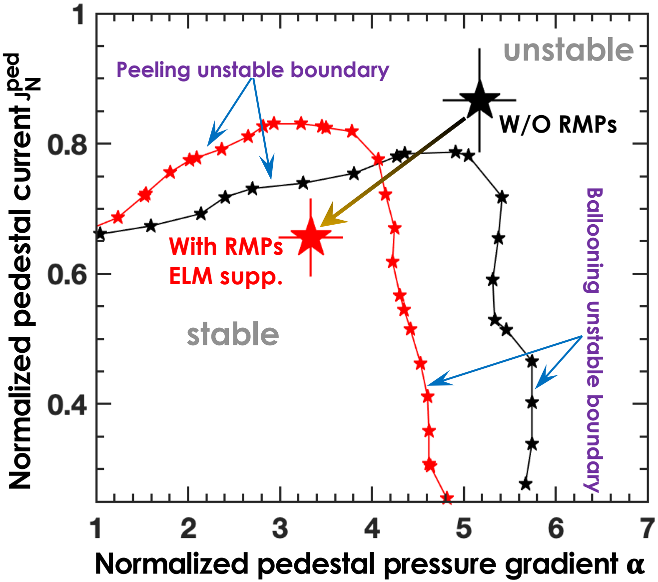
TM1 Simulation Shows Field Penetration at Both the Foot and Top of Pedestal, and Strong Screening in Between



- Resonant field penetration has a low (high) threshold at the foot (top) of pedestal
- Simulations are consistent with experimental changes at the top of the pedestal

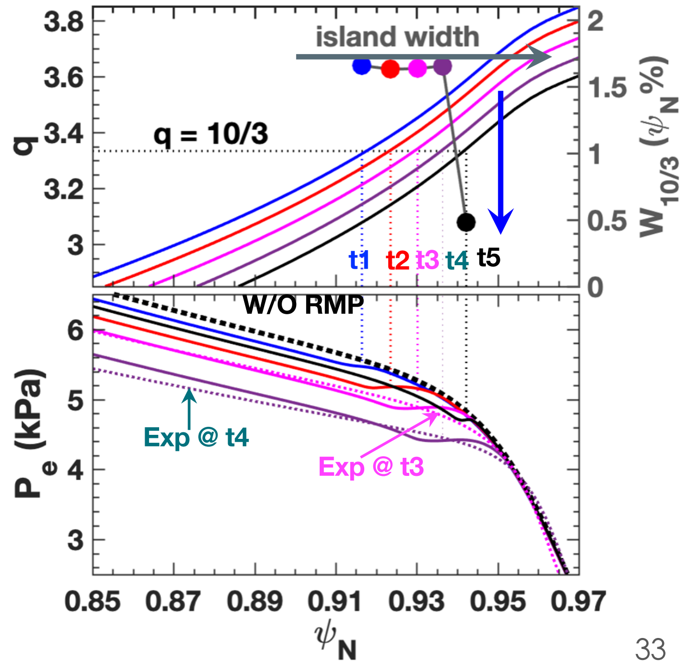
ELITE Confirms the RMP-Assisted ELM-free with Normalized Growth Rate Residing Inside the PBM Stable Region

- **Initial profiles W/O RMP resides inside the PBM unstable region**
- **RMP-assisted ELM-free resides inside the PBM stable region**



Magnetic Island Formation Causes Sufficient Pedestal Pressure Reduction only When it Aligns to the Pedestal Top

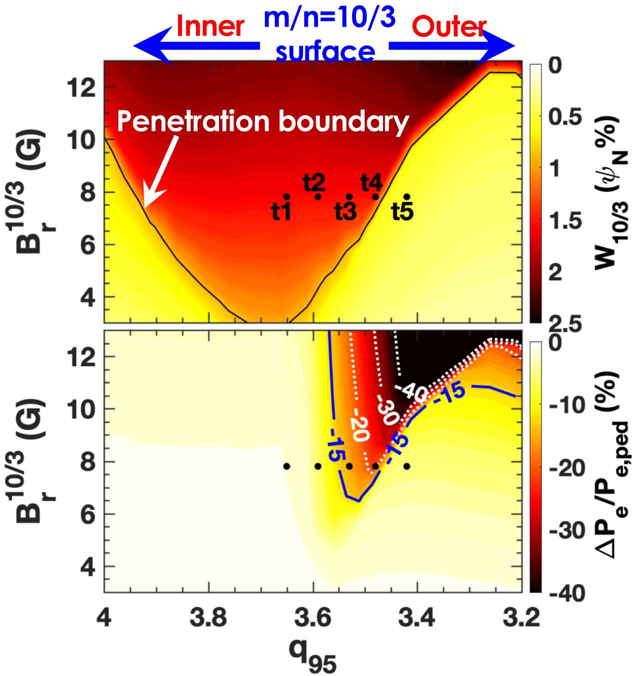
- **The alignment of pedestal-top islands formation leads to narrow q_{95} windows**
  - 10/3 RMP penetrates at from t1 to t4, shielded at t5
  - Stronger reduction in pedestal pressure for t3 and t4
  - TM1 simulated pressure profile consistent with experiment (t3, t4)



Only Well Aligned Island Formation Leads to Enough Reduction in Pedestal Pressure

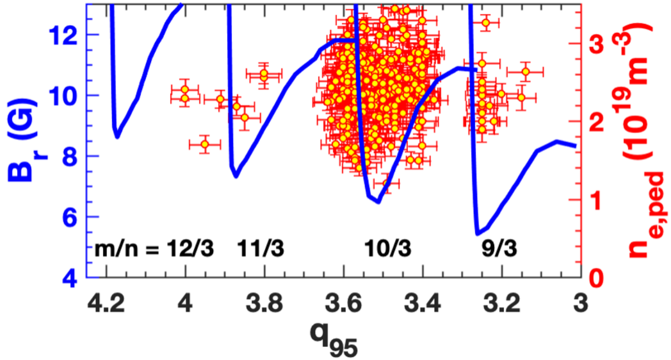
- **m/n=10/3 island must be close to the top of pedestal to sufficiently reduce pedestal pressure and suppress ELM**
  - An island too far in can't reduce pedestal pressure
  - Stronger RMP is required to trigger an island too far out

Q. Hu, R. Nazikian, et al., PRL **125**, 045001 (2020)



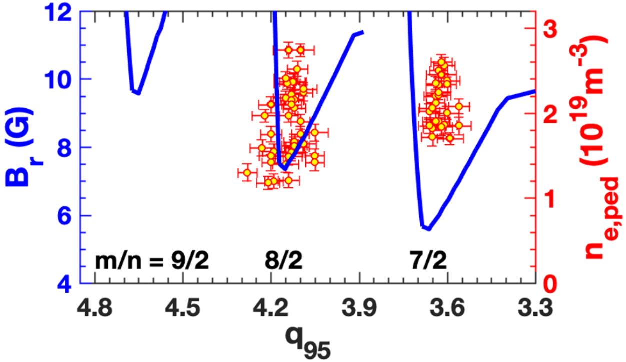
TM1 Simulations Unraveling the q_{95} Windows for DIII-D n=3 and 2 RMP ELM Suppression Observed for Many Years

Comparison of n=3 q_{95} windows between TM1 and DIII-D ISS database



For n=3: q_{95}~3.1-3.3,3.4-3.65, 3.8-4

Comparison of n=2 q_{95} windows between TM1 and DIII-D ISS database



For n=2: q_{95}~3.7, 4.2,4.7

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