Optimization of the Plasma Response for the Control of ELMs with 3D fields

By
C. Paz-Soldan[1]

On behalf of
R. Nazikian[2], R. Moyer[3], J. Callen[4], T. Evans[1], N. Ferraro[2], N. Logan[2], B. Lyons[5], X. Chen[1], L. Cui[2], D. Eldon[1], M. Fenstermacher[6], A. Garofalo[1], B. Grierson[2], R. Groebner[1], C. Hegna[4], S. Haskey[2], M. Lanctot[1], C. Lasnier[6], T. Luce[1], G. McKee[4], D. Orlov[3], T. Rhodes[7], M. Shafer[8], P. Snyder[1], W. Solomon[1], E. Strait[1], A. Wingen[8], R. Wilcox[8]

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[8]Oak Ridge National Laboratory

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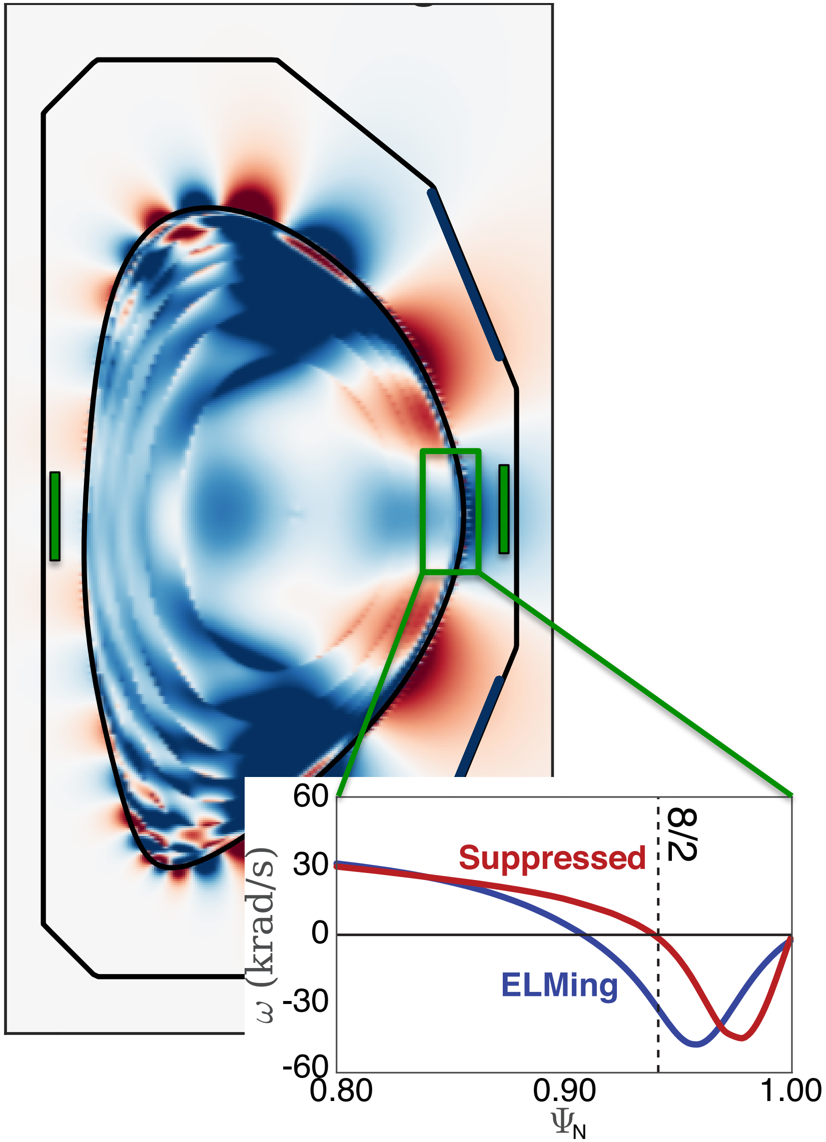

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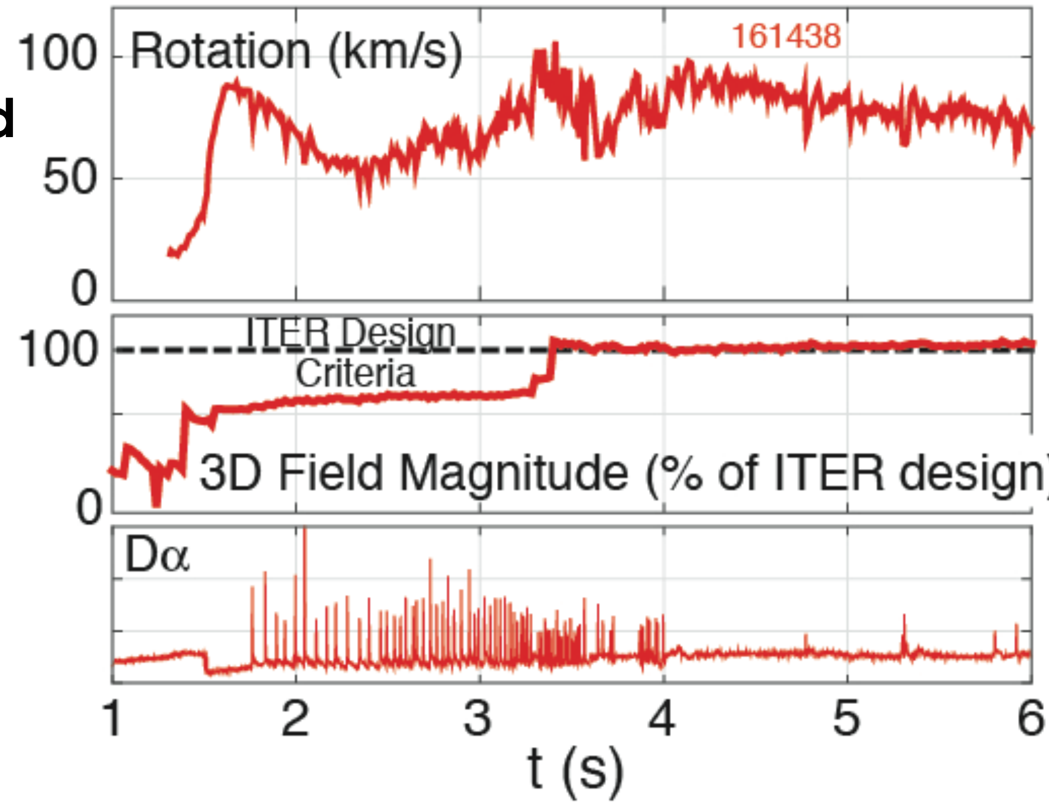
GENERAL ATOMICS

DIII-D demonstrates Edge-Localized Mode (ELM) Control with 3-D Fields in ITER 15 MA Q=10 Conditions

Match ITER shape, I/aB, β_N

- **ELMs suppressed if 3-D field magnitude meets ITER design criteria**

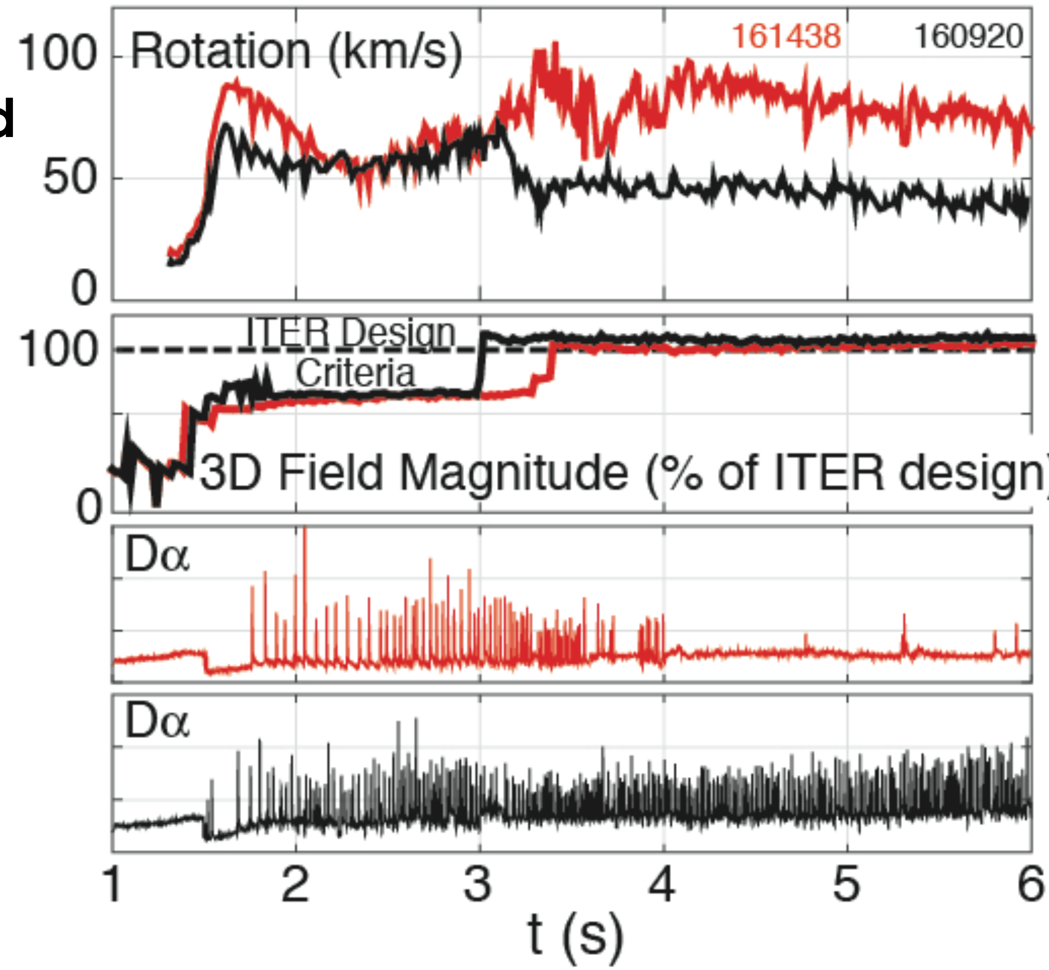


M. Wade et al., Nucl. Fusion 2015

DIII-D demonstrates Edge-Localized Mode (ELM) Control with 3-D Fields in ITER 15 MA Q=10 Conditions

- **ELMs suppressed if 3-D field magnitude meets ITER design criteria**
- **Reducing toroidal rotation causes ELM return**
- **Plasma response must be understood to explain effect and optimize ELM control with 3D fields**

Match ITER shape, I/aB, β_N



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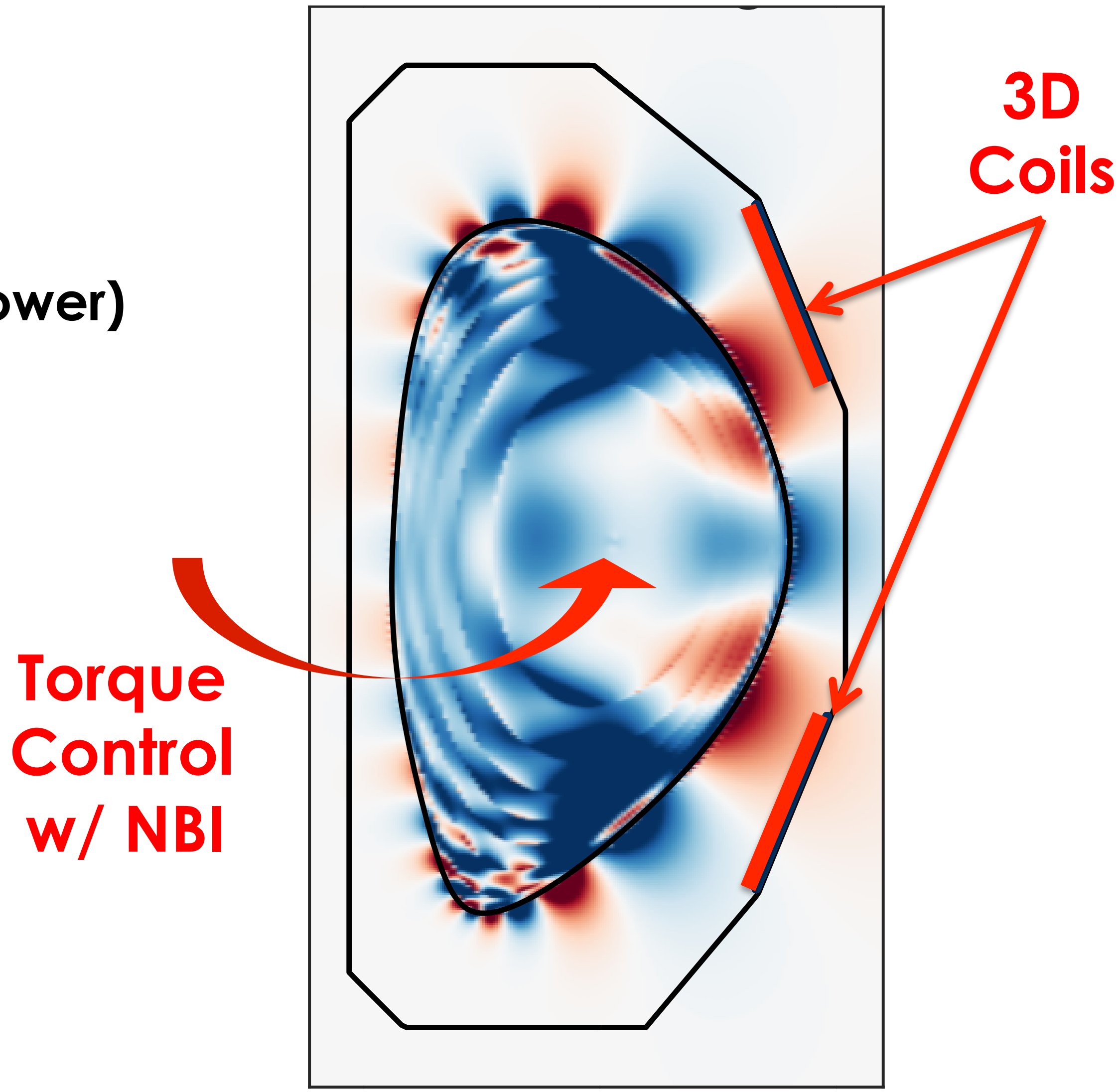
Control of Plasma Rotation and MHD Mode Spectrum Required to Optimize the Plasma Response for ELM Control

Actuators:

- NBI torque (@ fixed power)
- 3D coils (n=2 or n=3)



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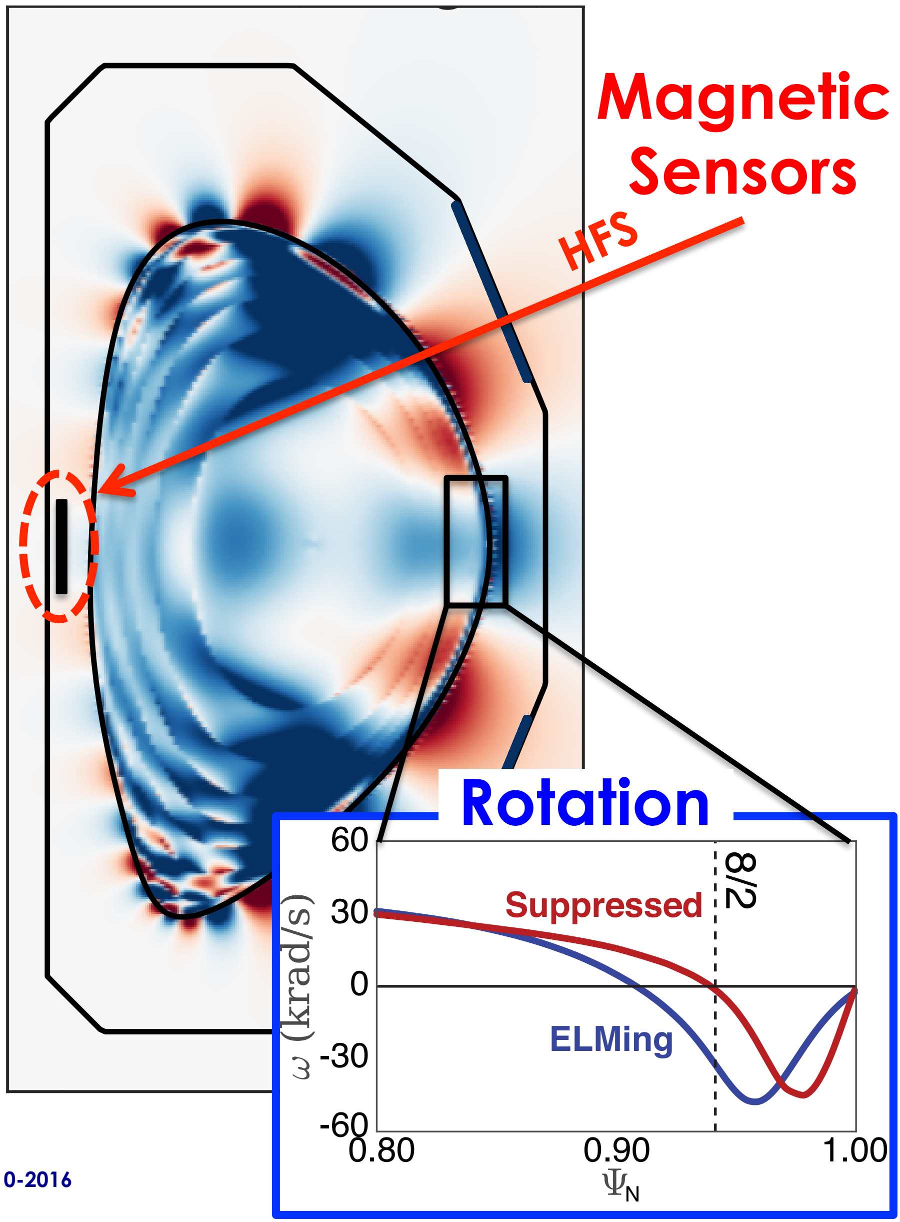
Diagnostics:
- High-field side (HFS) magnetics
- Plasma rotation & E_r



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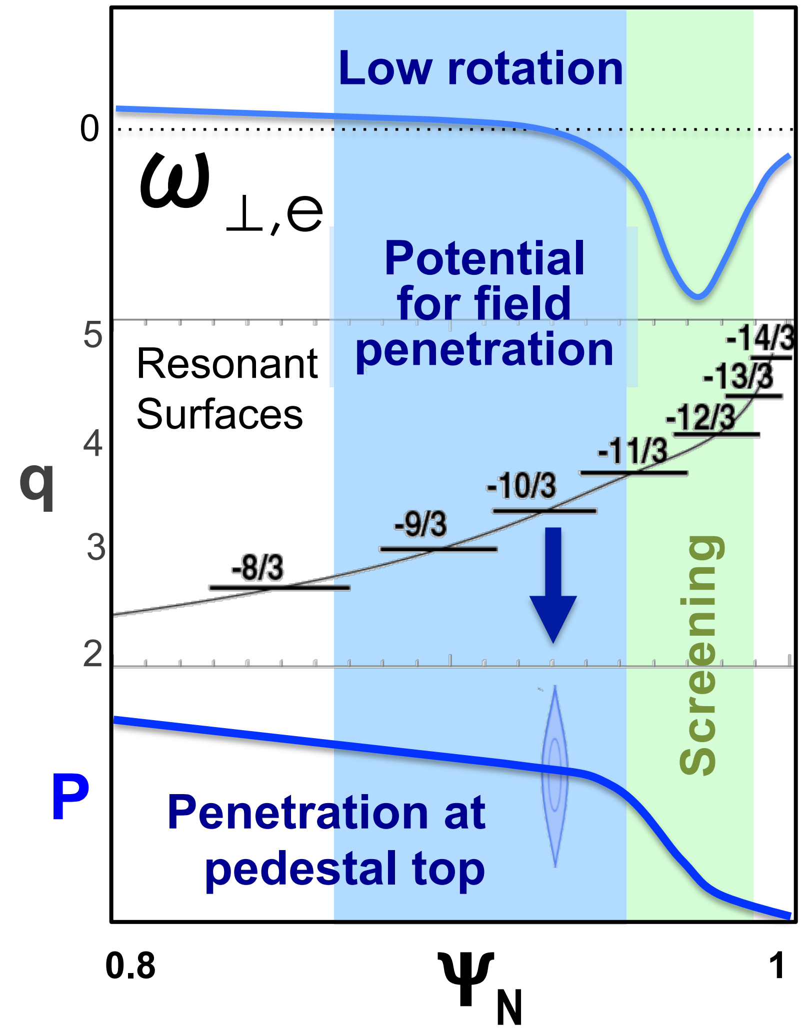
Control of Plasma Rotation and MHD Mode Spectrum Required to Optimize the Plasma Response for ELM Control

- **Hypothesis: 3D fields drive resonant field penetration at pedestal top to restrict its width**
  - → Prevents ELM instability

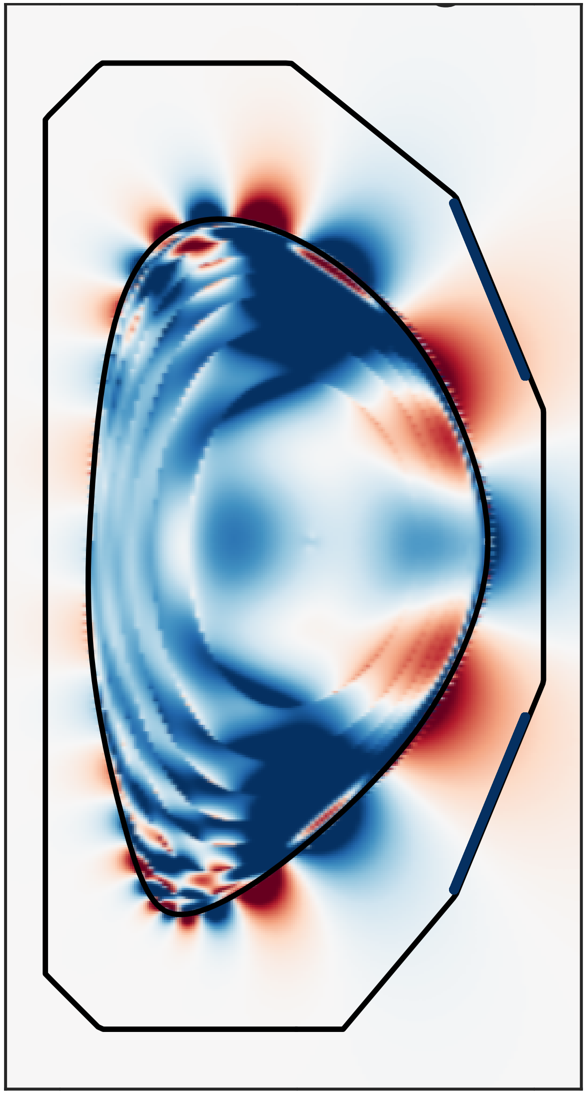
- **Requires co-alignment of:**
  - 3-D field (Resonant Drive)
  - Low $\omega_{\perp,e}$ rotation region
  - Resonant surface
  - …at the pedestal top



P. Snyder et al., Phys. Plasmas 2012

Control of Plasma Rotation and MHD Mode Spectrum Required to Optimize the Plasma Response for ELM Control

- **Observations validate resonant field penetration as optimization criterion**
- **Penetration requires optimized electron rotation profile**
- **Resonant drive can be optimized by 2D equilibrium conditions and 3D spectrum**



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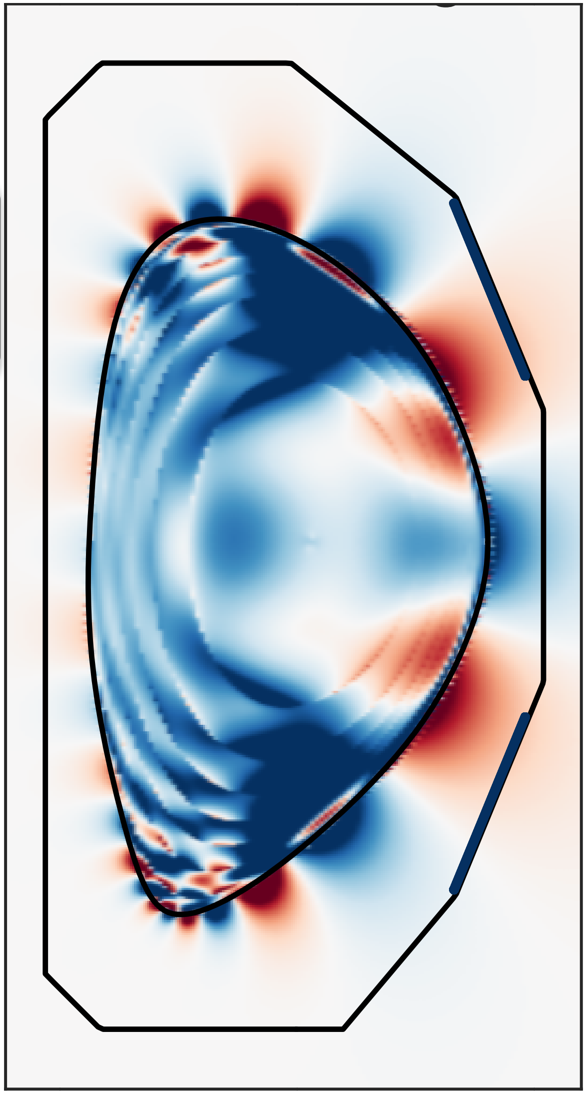
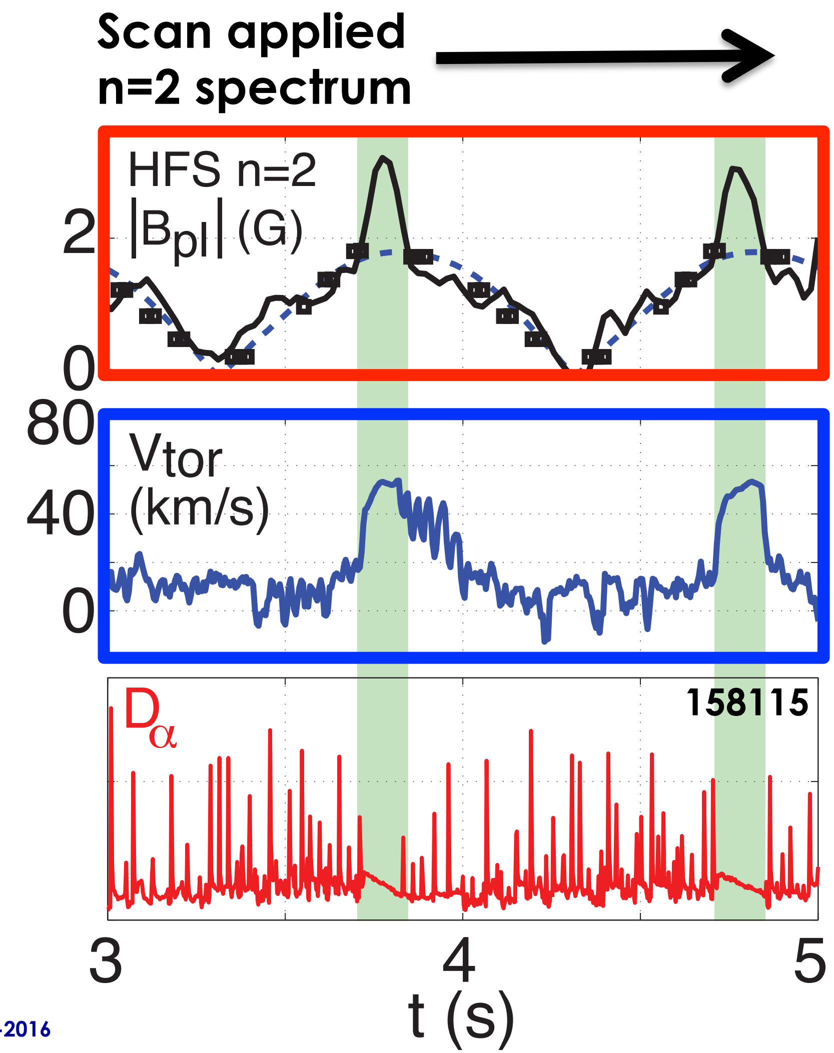


Fast Changes in Rotation Profiles and HFS Magnetics are Found at Entry to the ELM Suppressed State

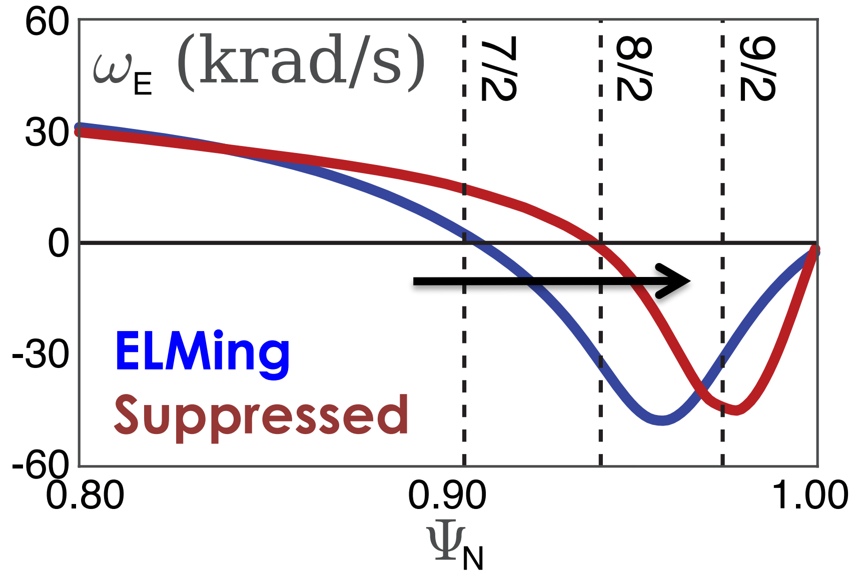
- **Use n=2 field to scan applied spectrum and ease diagnosis**
- **Bifurcation into ELM suppression impacts high-field side magnetic response and toroidal rotation**
- **Changes occur together on a fast (10 ms) time scale**



C. Paz-Soldan et al., PRL 2015
R. Nazikian et al., PRL 2015

MHD Modeling Shows Magnetic Response Changes Expected Purely from Field Penetration at Pedestal Top

- **Model with resistive single-fluid MHD (M3D-C1)**
- **Substitute ELMing and ELM suppressed rotation profiles**



B. Lyons et al., PPCF (in review)

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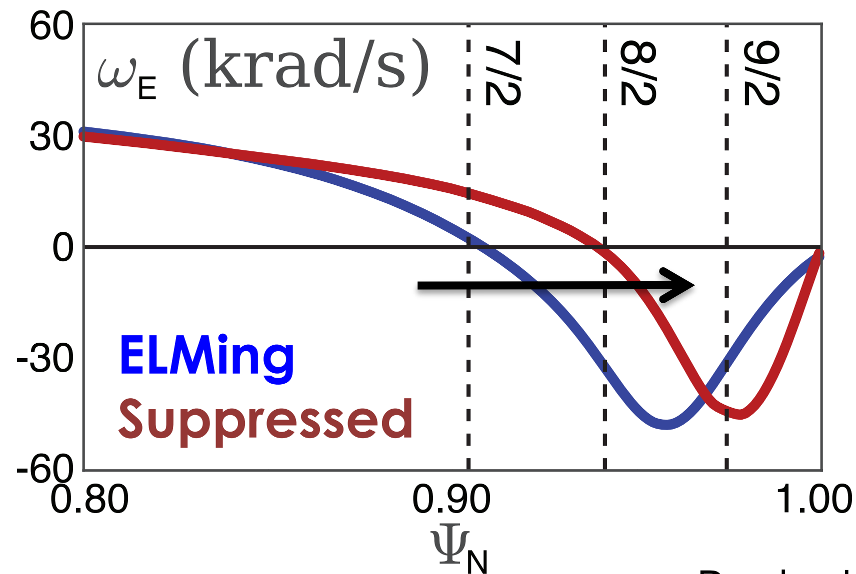
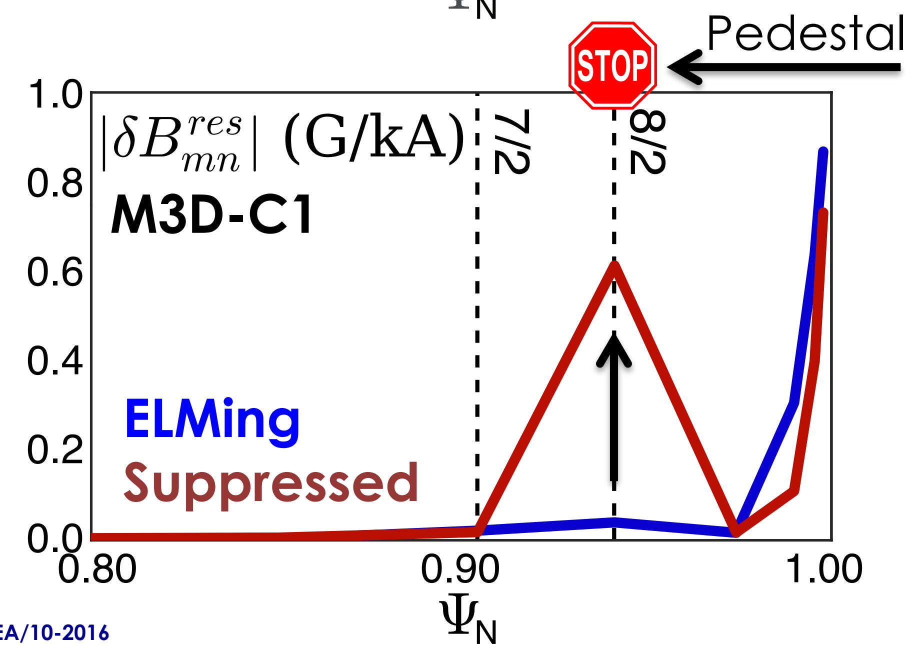
  - Pedestal expansion stopped before ELM stability limit





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- **Model predicts significant 8/2 penetration @ suppression**
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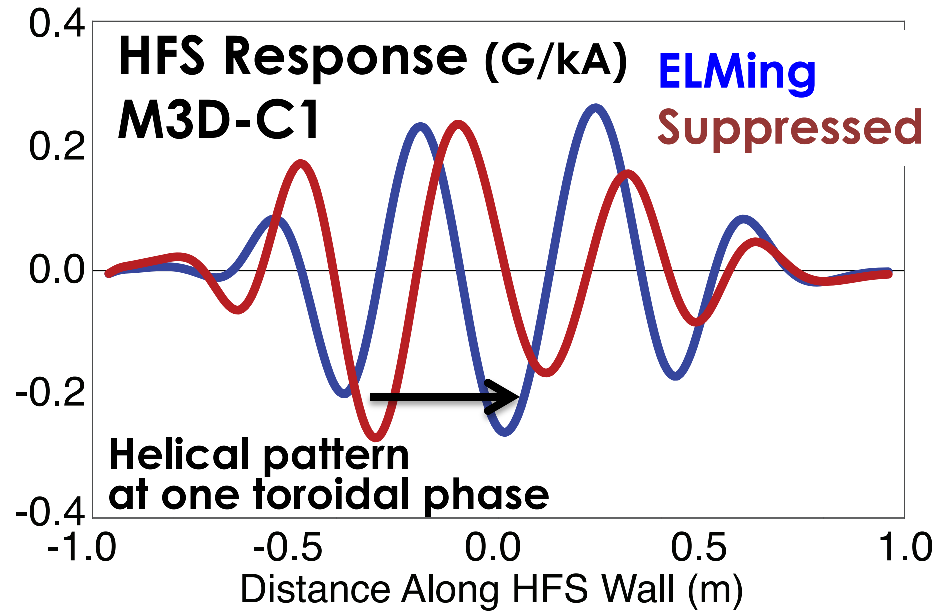
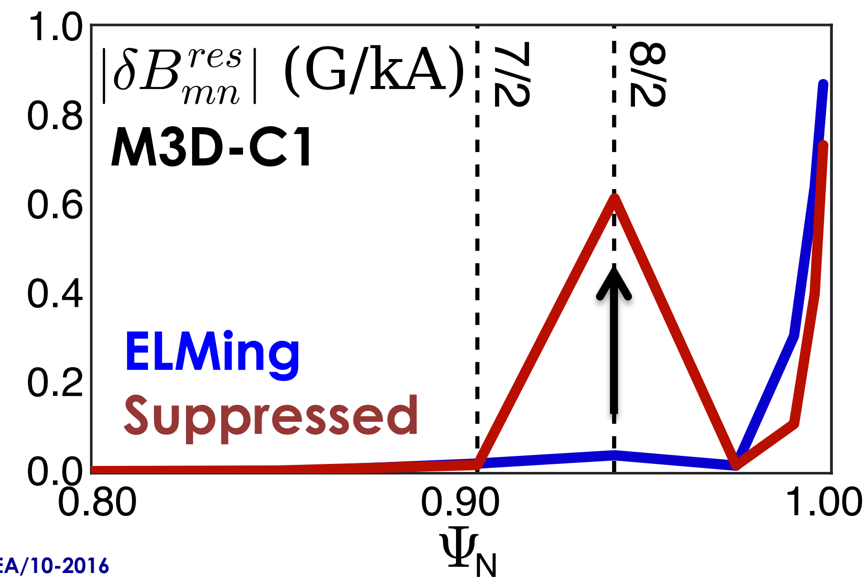
- **Model predicts shift in HFS response from penetration**
  - No effect predicted for LFS
- **What about experiment?**





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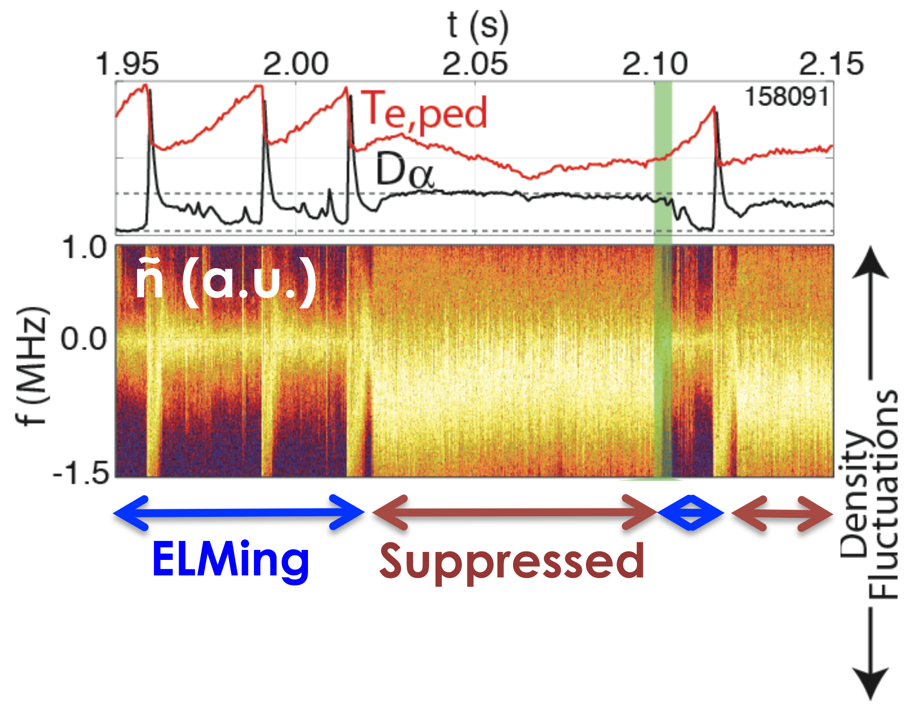
Back-transition from ELM Suppression Reveals Rotation and HFS Magnetic Changes on Millisecond Timescale

- **Consider back-transition from ELM suppressed state**
  - Before any ELMs appear
  - Zoom in on ms timescale



R. Nazikian et al, NF (in preparation)

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- **Prompt change in turbulent Doppler shift in ms timescale**
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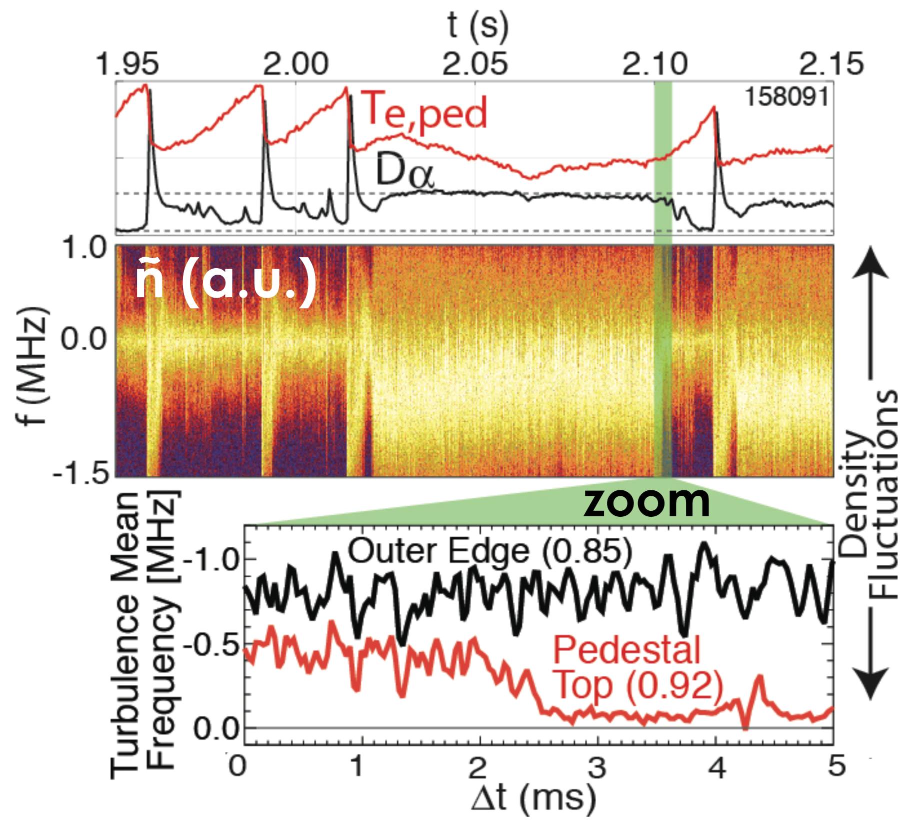

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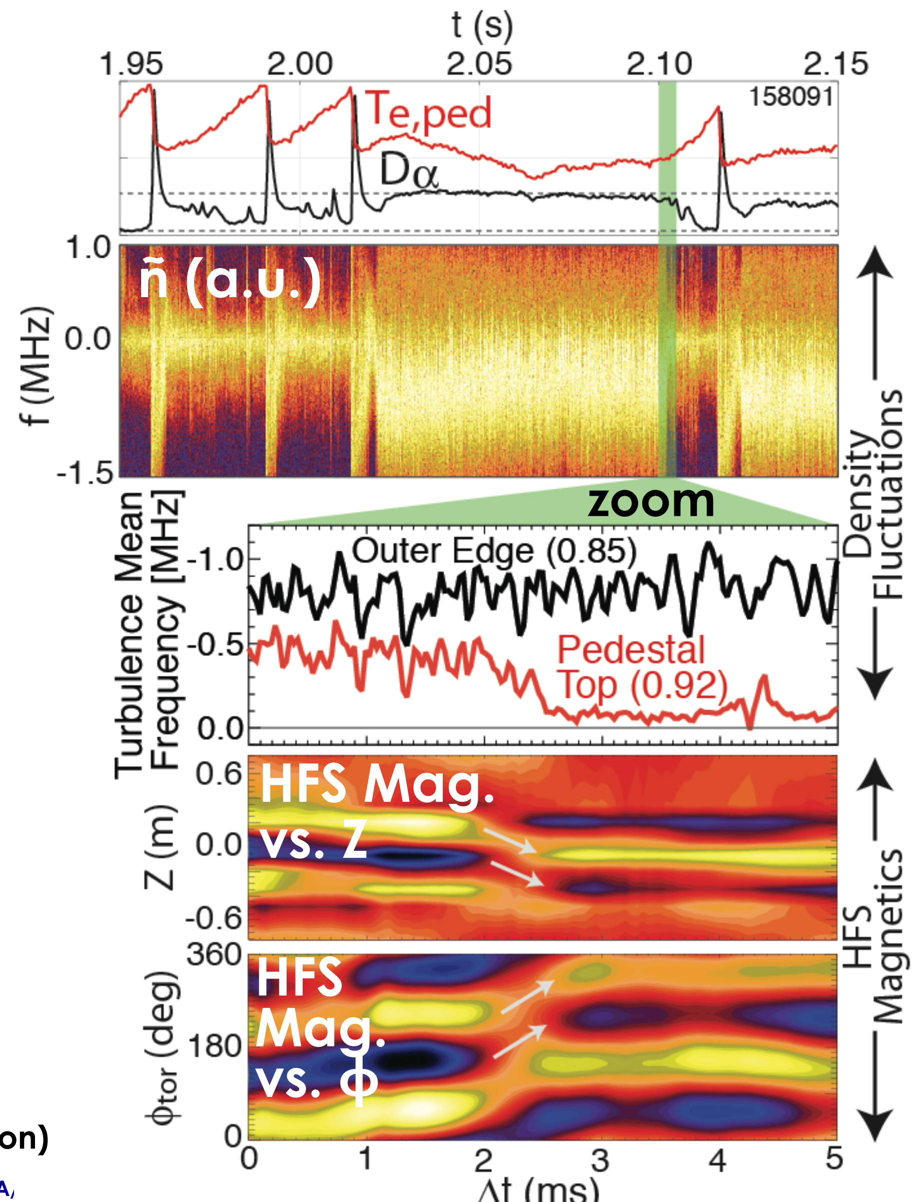
- **HFS structures shift in Z, φ immediately (1 ms) after losing ELM suppression**

- **Qualitative match to model**



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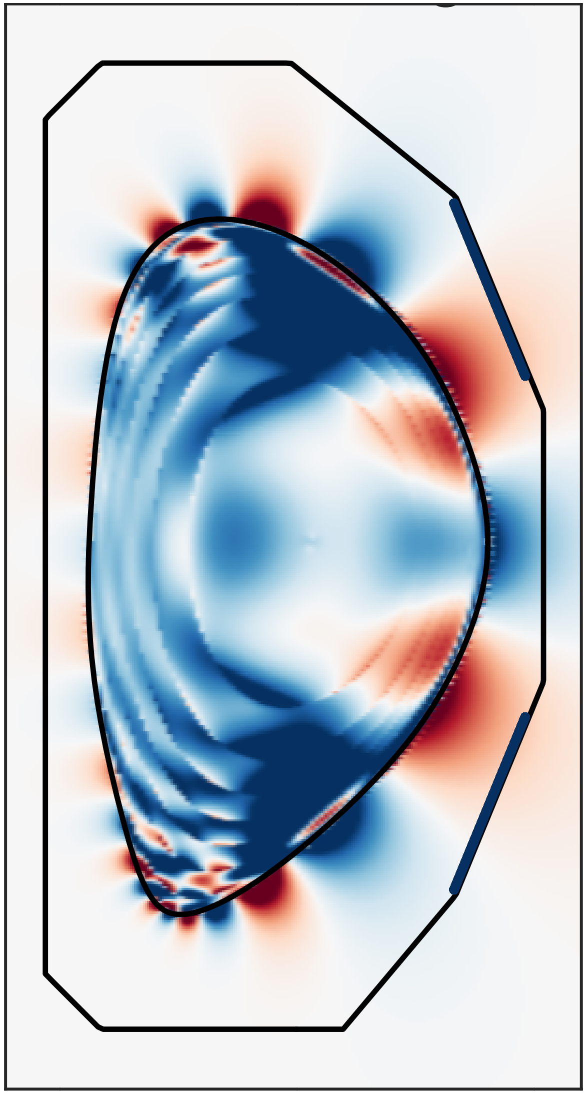
Control of Plasma Rotation and MHD Mode Spectrum Required to Optimize the Plasma Response for ELM Control

- **Observations validate resonant field penetration as optimization criterion**

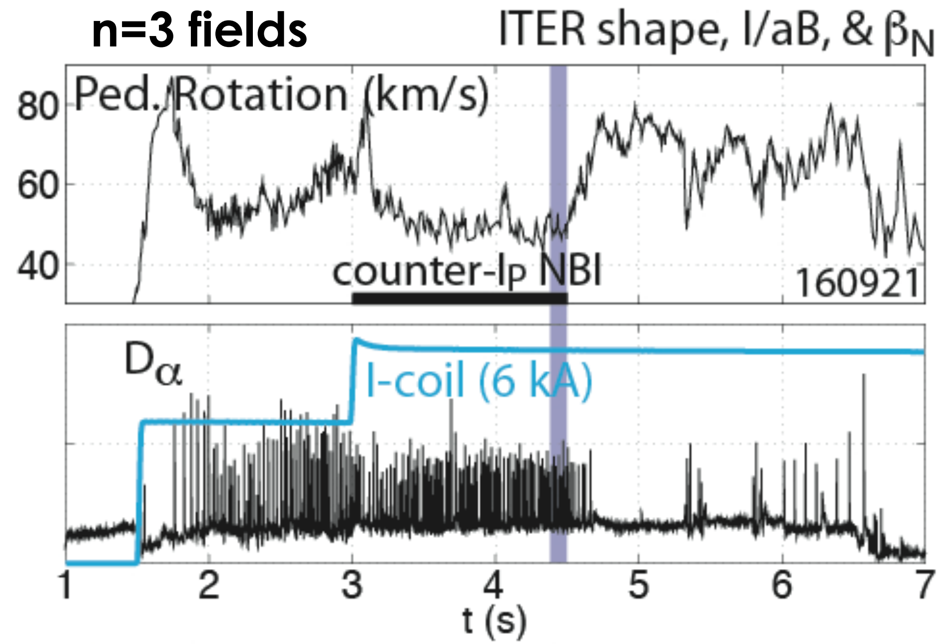
- **Penetration requires optimized electron rotation profile**
  - Torque dependence
  - Performance recovery

- **Resonant drive can be optimized by 2D equilibrium conditions and 3D spectrum**



Rotation Zero-crossing Model Can Explain Why Elms Only Suppressed Above Critical Value of Rotation

- **ELMs are suppressed at a critical rotation (NBI torque)**



R. Moyer et al., APS-DPP 2016

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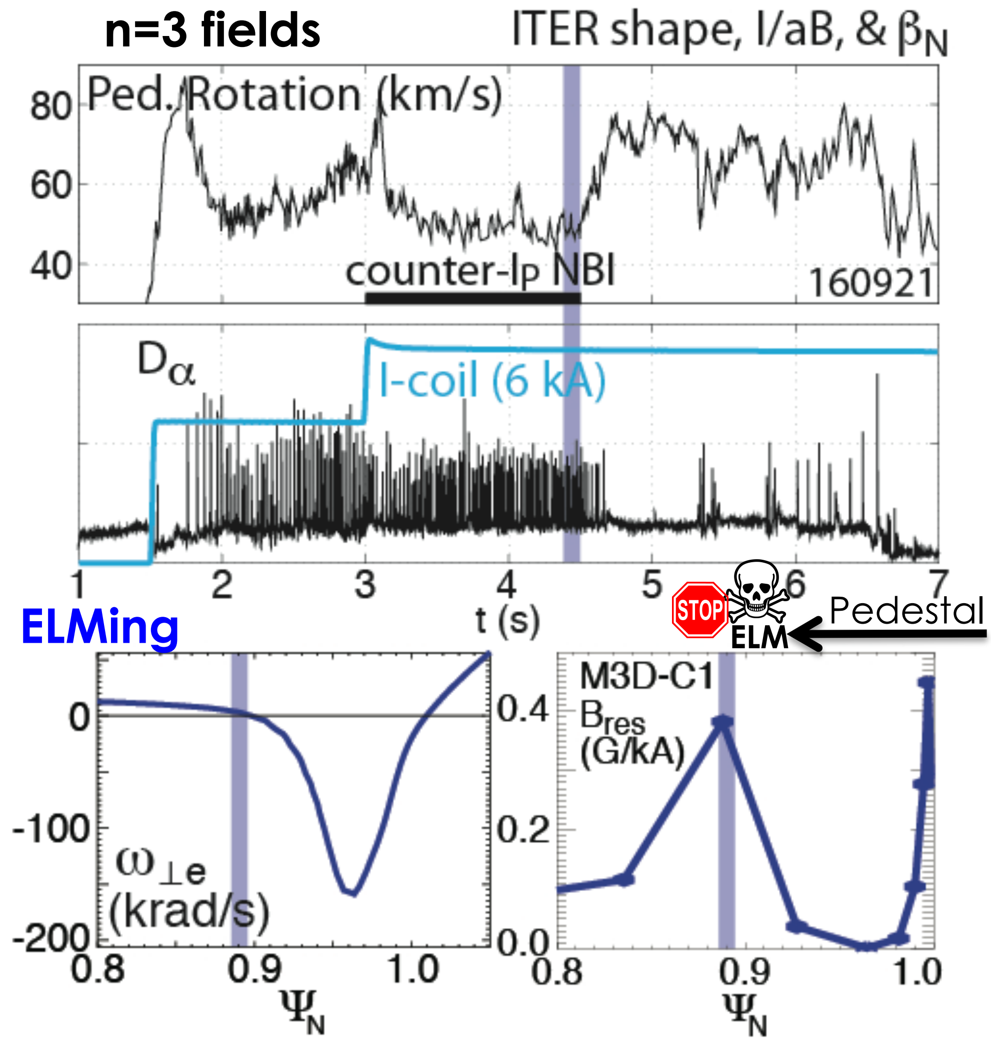

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Rotation Zero-crossing Model Can Explain Why Elms Only Suppressed Above Critical Value of Rotation

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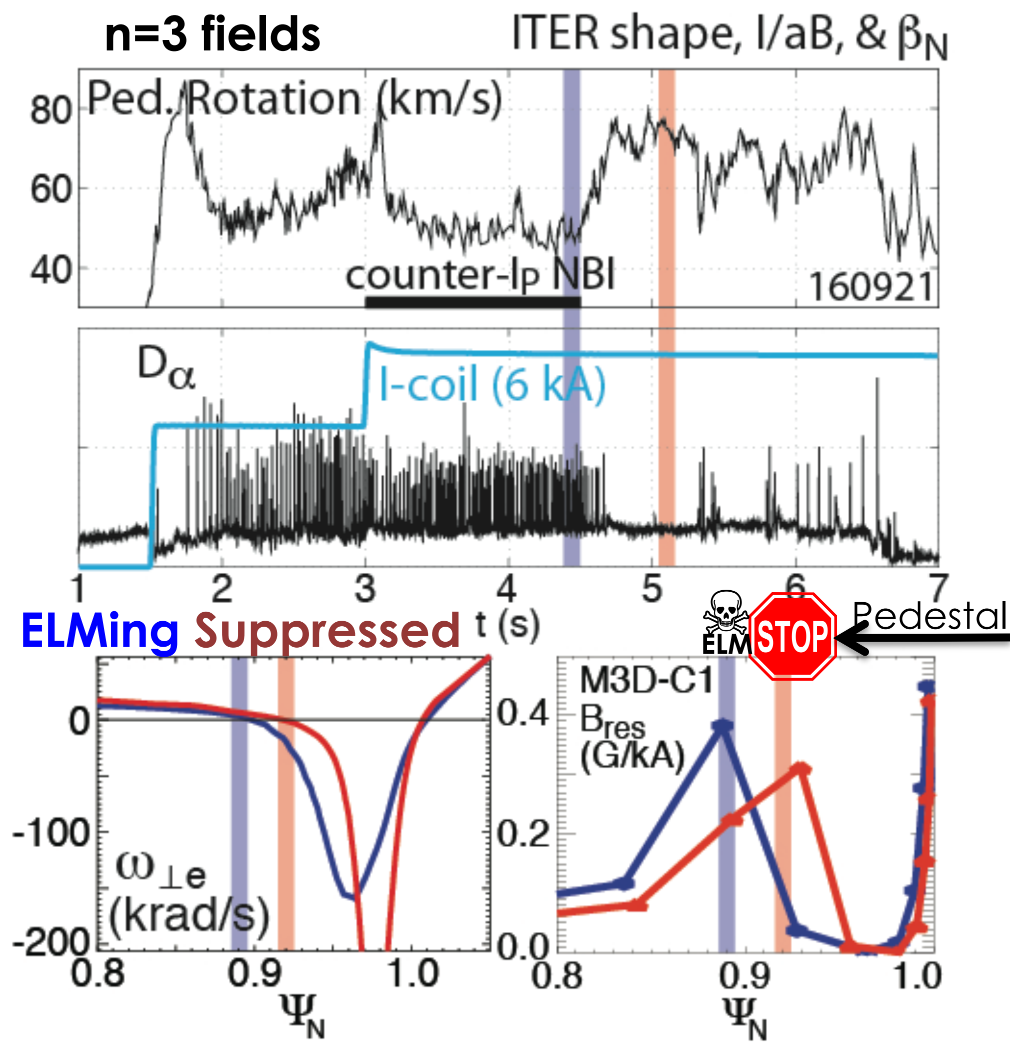
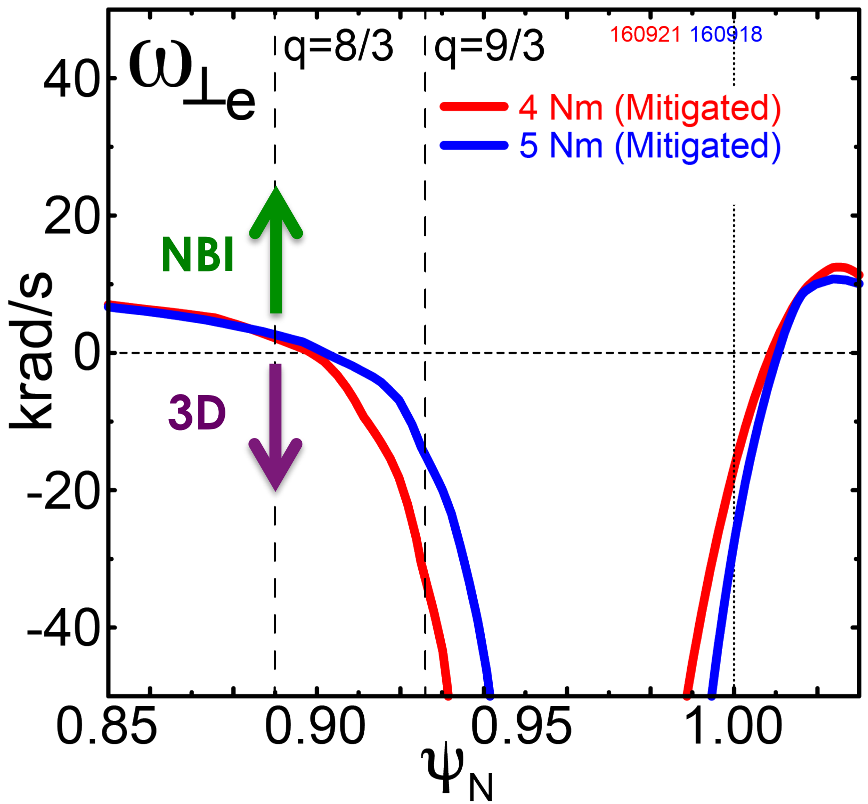
- **In ELMing conditions, rotation zero-crossing is at low Ψ_N**
- **$\omega_{\perp,e}$ zero crossing moves out as NBI torque increased**
- **Field penetration moves out, constricting pedestal width**



R. Moyer et al., APS-DPP 2016

Imposed NBI Torque Affects Inner Boundary Condition … but $\omega_{\perp,e}$ Depends on Local Resonant Torques

- **3D field torque at rational surface key in balance**
- **NBI torque can be insufficient to unlock rational surface**



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Imposed NBI Torque Effects Inner Boundary Condition … but $\omega_{\perp,e}$ Depends on Local Resonant Torques

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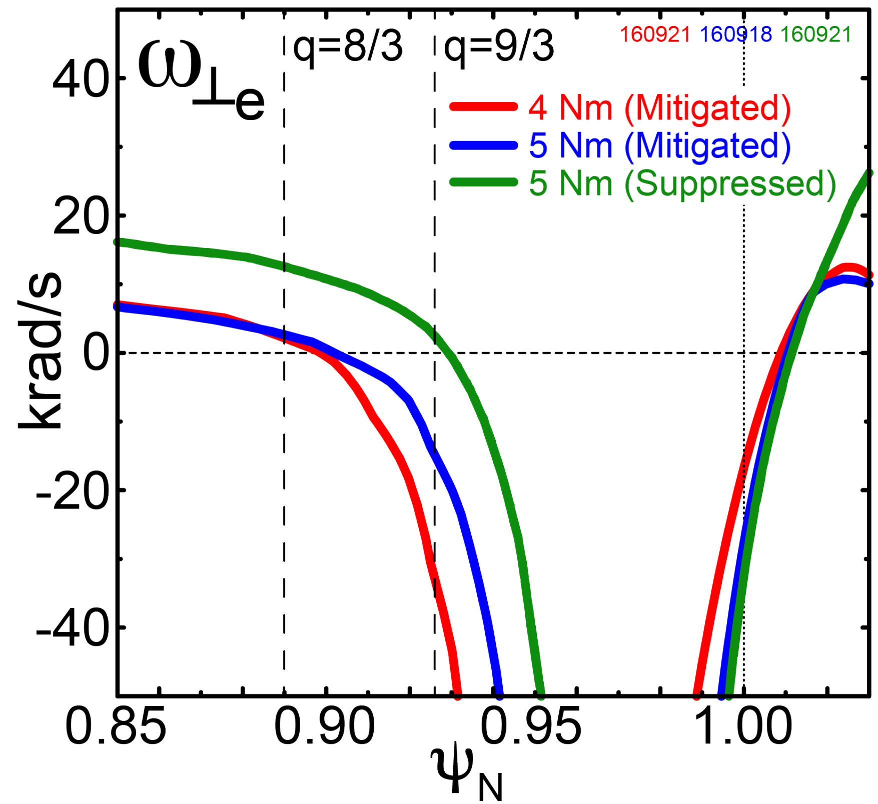
- **NBI torque can be insufficient to unlock rational surface**
- **Zero-crossing point jumps to next rational surface**
  - Does not linger in between



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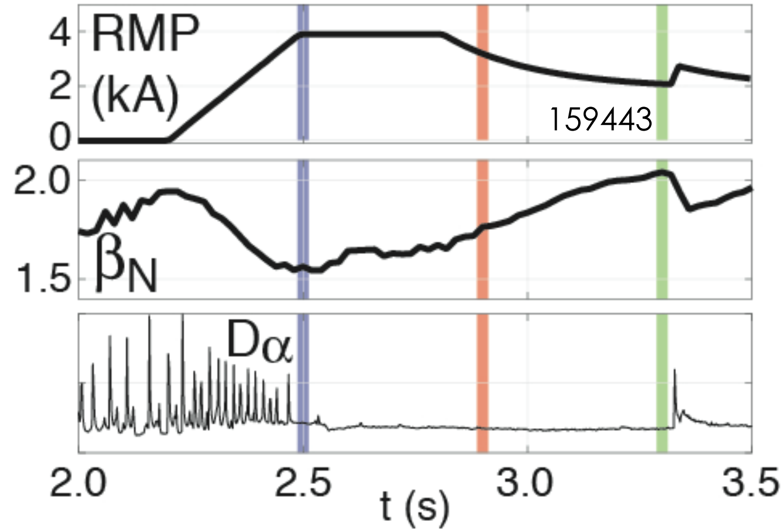
Resonant Torques Can Maintain Locked $\omega_{\perp,e}$ as 3D Coil Current Reduced – Enabling Confinement Recovery

- **Once 3D field penetrates can reduce coil current: hysteresis!**
- **Confinement recovered before ELMs return @ back-transition**



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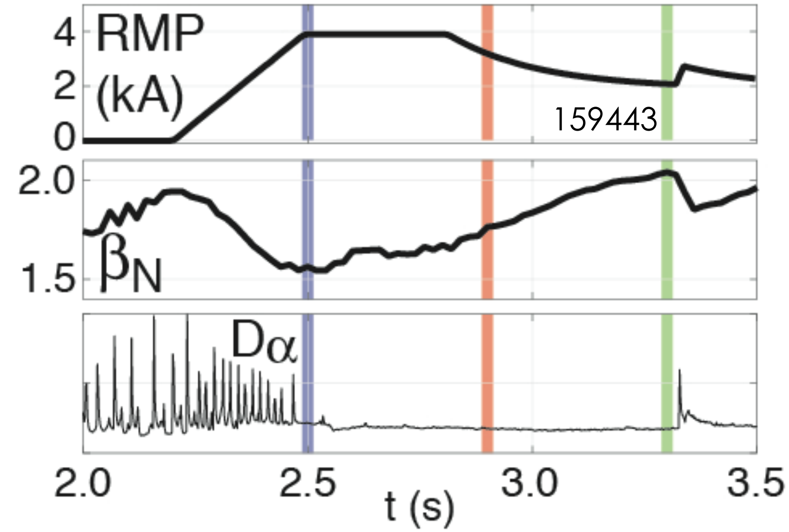
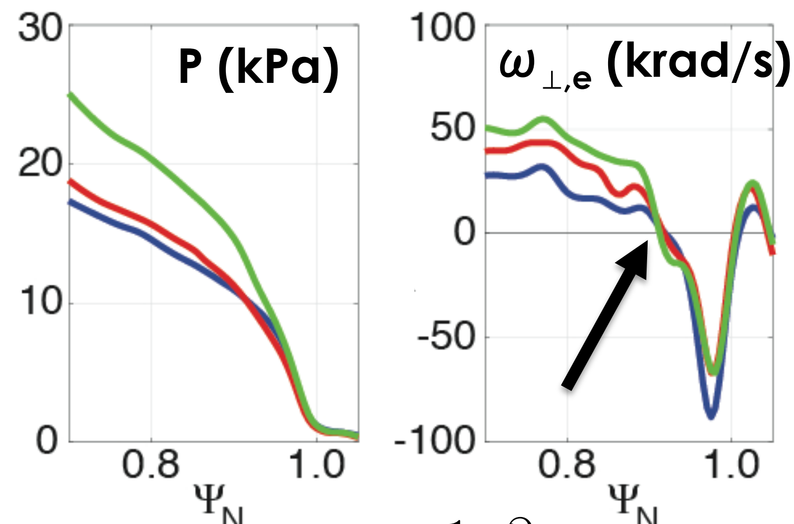
- **Wide variety of pedestal conditions compatible with static $\omega_{\perp,e}$ zero-crossing**
- **Gradient driven flows balance toroidal rotation spin up**





$$\omega_{\perp,e} = \omega_E + \frac{1}{n_e}\frac{\partial p_e}{\partial \Psi}$$

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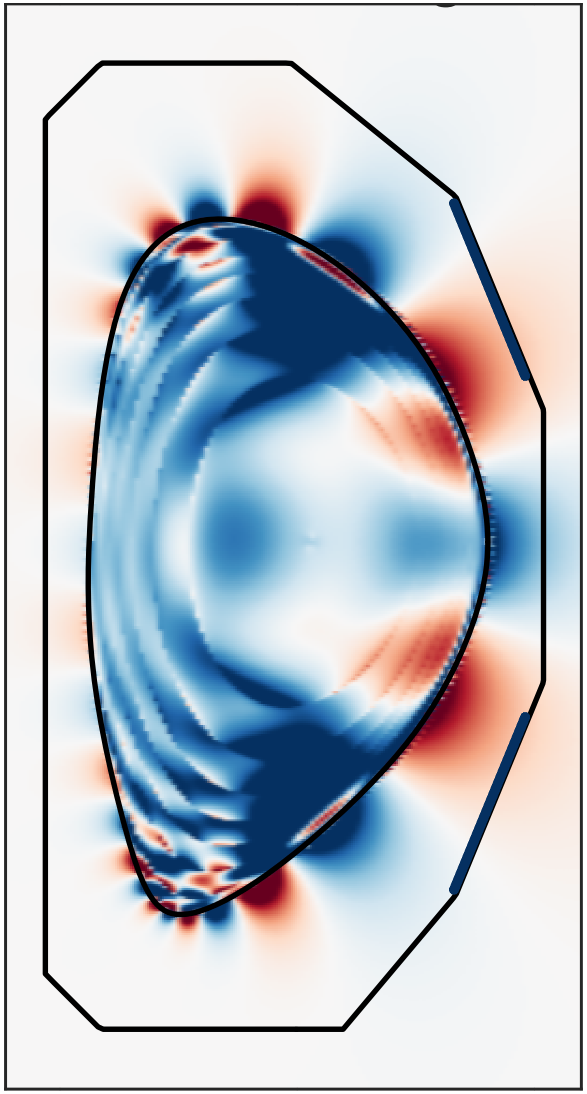
Control of Plasma Rotation and MHD Mode Spectrum Required to Optimize the Plasma Response for ELM Control

- **Observations validate resonant field penetration as optimization criteria**
- **Penetration requires optimized electron rotation profile**
- **Resonant drive can be optimized by 2D equilibrium conditions and 3D spectrum**
  - Role of beta, collisionality
  - 3D spectrum optimization



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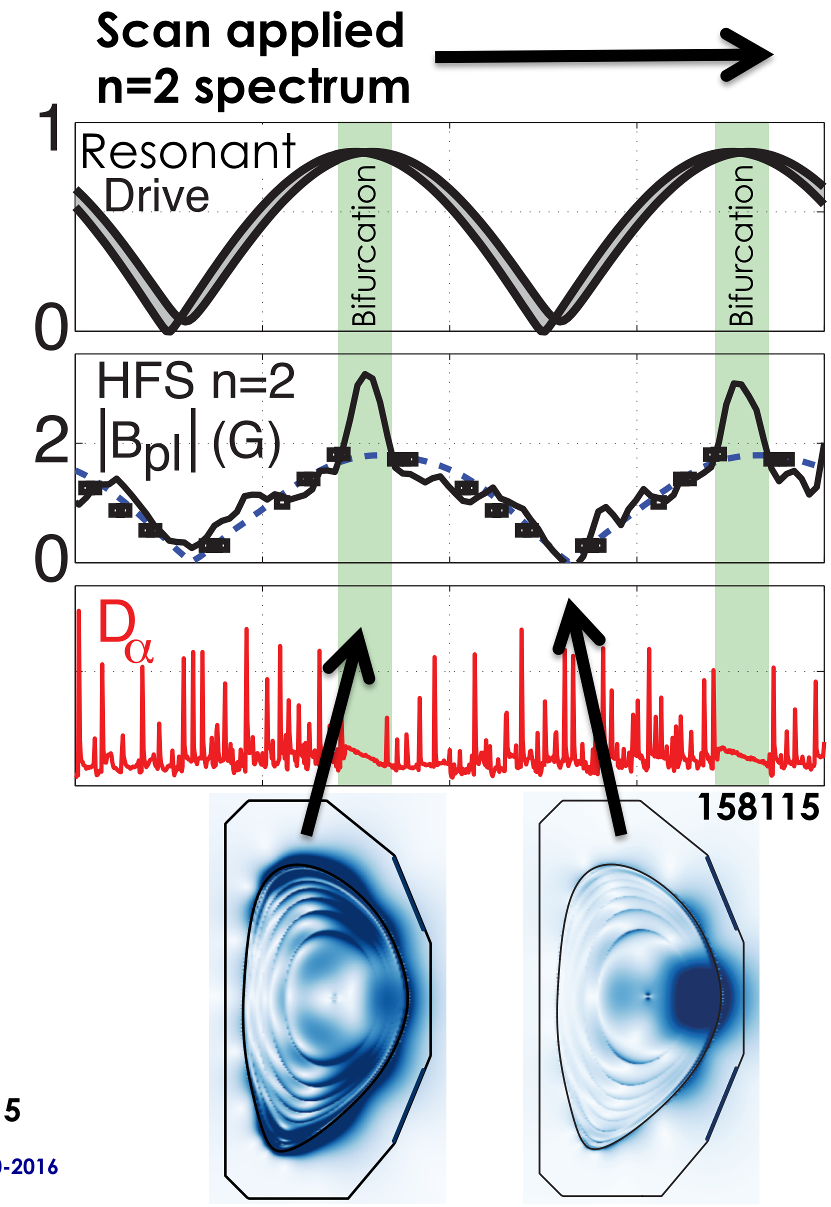
Varying Applied Spectrum Demonstrates Correlation of ELM Suppression with HFS (+ Top/Bottom) Response

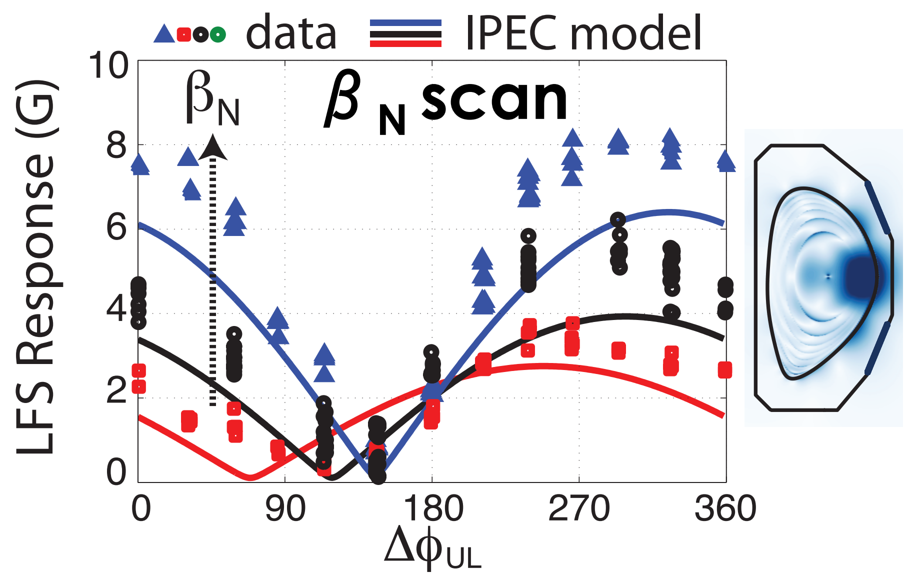
- **Plasma response during ELM suppression largest on high-field side (HFS) + top / bottom**
- **Low-field side (LFS) uncorrelated with ELM suppression**



C. Paz-Soldan et al., PRL 2015

Measurements Find LFS Plasma Response Sensitive to β_N

- **LFS measurements swamped by pressure driven modes**

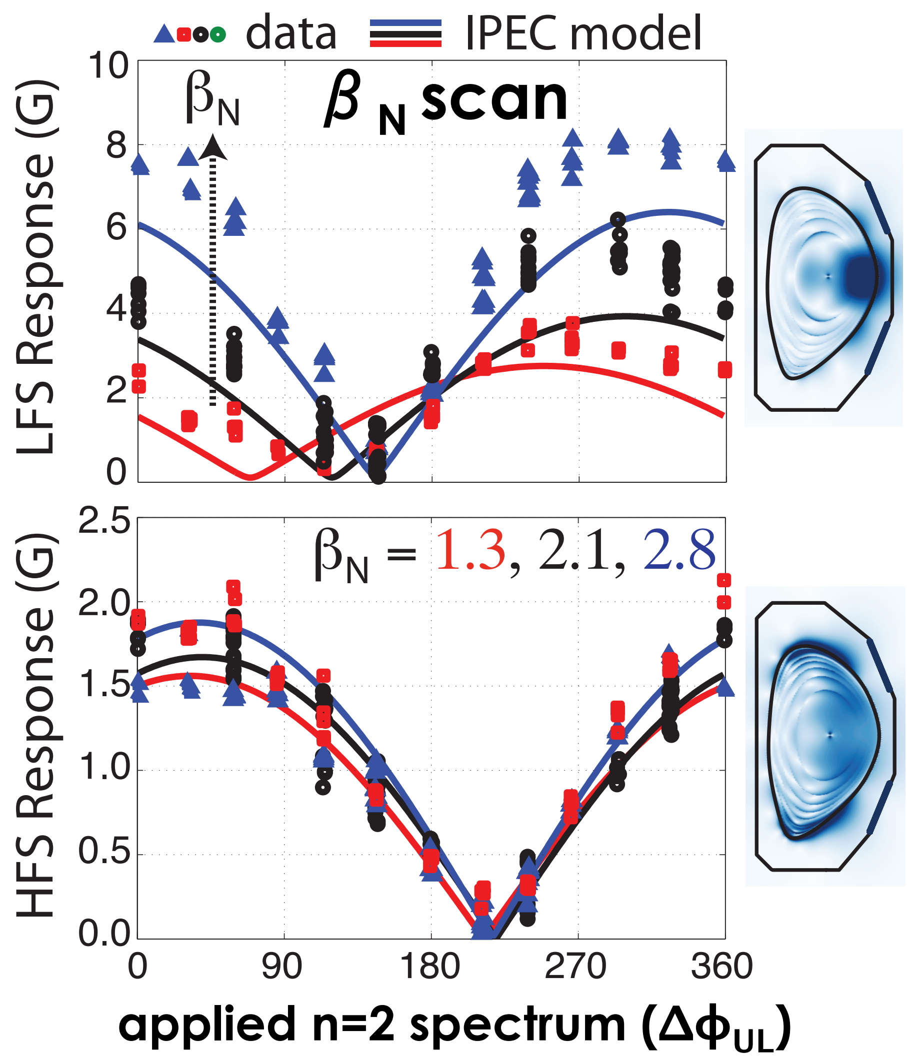


applied n=2 spectrum ($\Delta\phi_{UL}$)

C. Paz-Soldan et al., NF 2016

Measurements Find LFS Plasma Response Sensitive to β_N, HFS Totally Invariant; Collisionality Has Opposite Effect

- **LFS measurements swamped by pressure driven modes**
- **Striking invariance of the HFS response to plasma pressure**
  - MHD modeling agrees
- **HFS sensitive to pedestal effects like field penetration**



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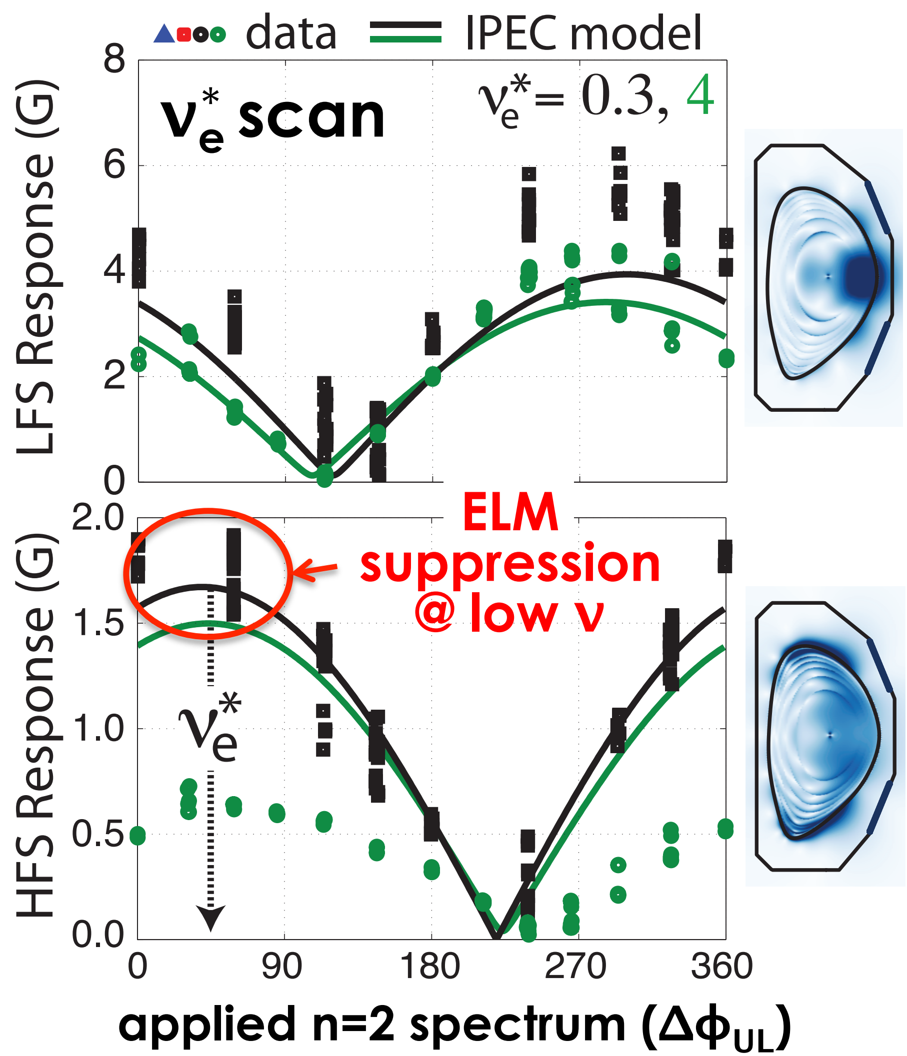
- **HFS sensitive to pedestal effects like field penetration**
- **Collisionality reduces HFS only**
- **ITER-relevant collisionality needed for right MHD modes**



C. Paz-Soldan et al., NF 2016

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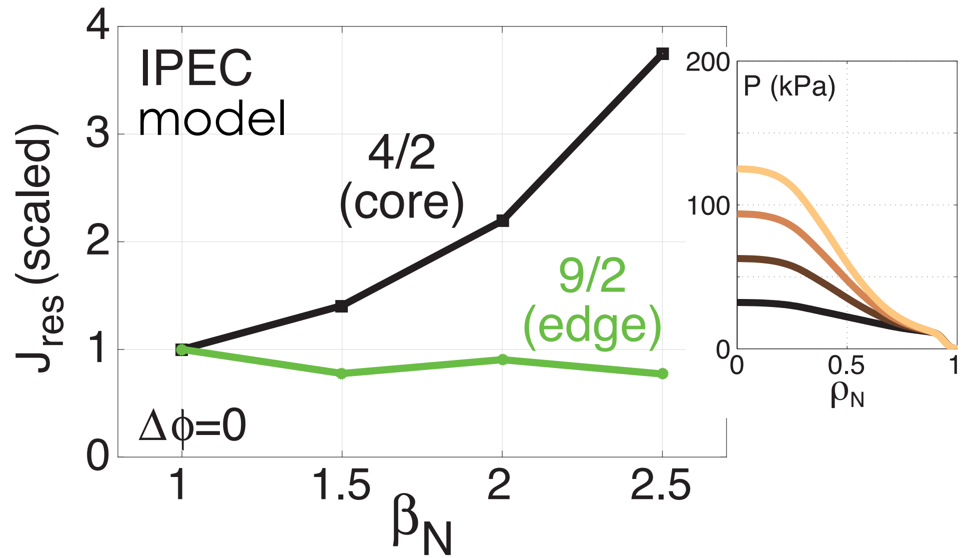
Increasing Core Pressure Works Against Edge Resonant Coupling

- **Resonant drive @ core surfaces increased by core pressure**
  - Opposite for edge surfaces



Increasing Core Pressure Works Against Edge Resonant Coupling … Low Collisionality Bootstrap Helps

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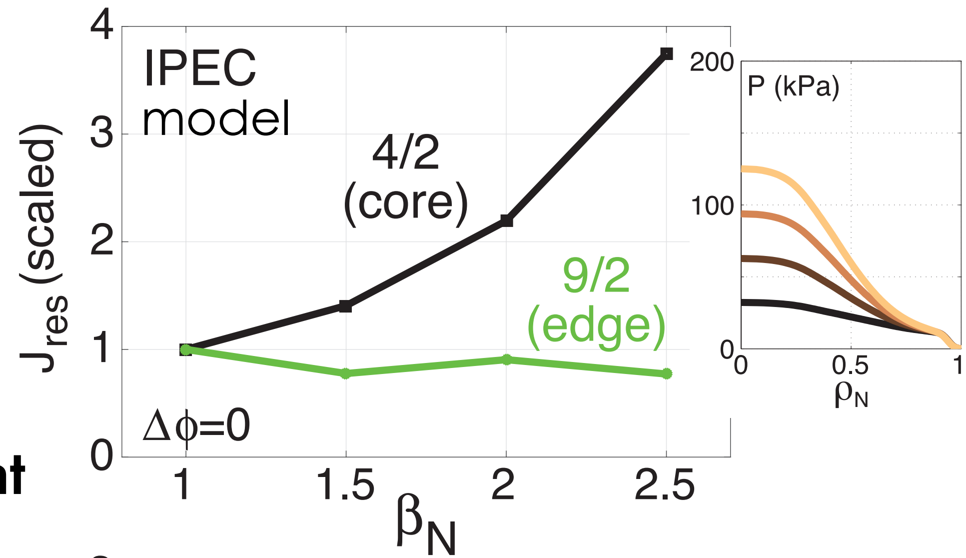
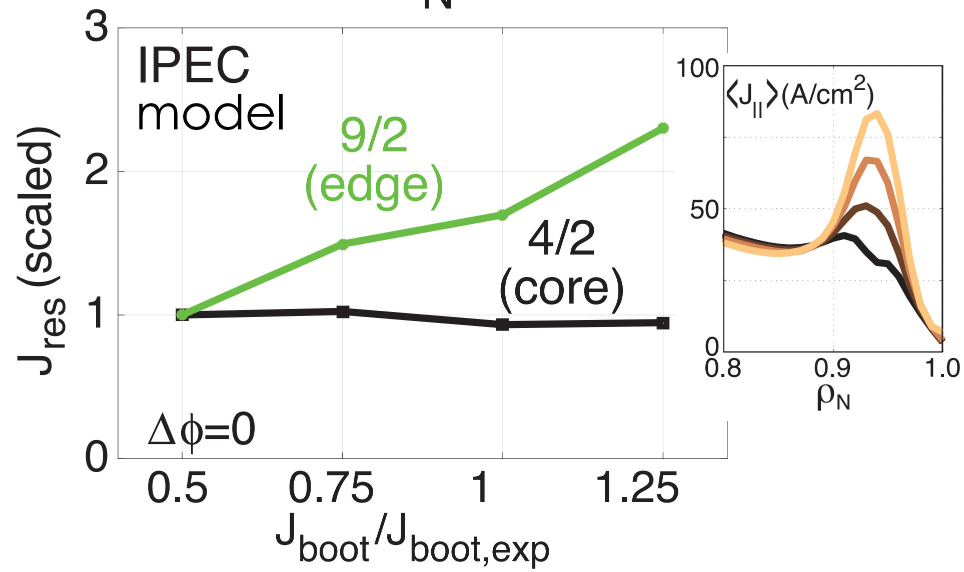
- **Resonant drive @ edge increases with bootstrap current**
  - Path for low collisionality to assist ELM suppression





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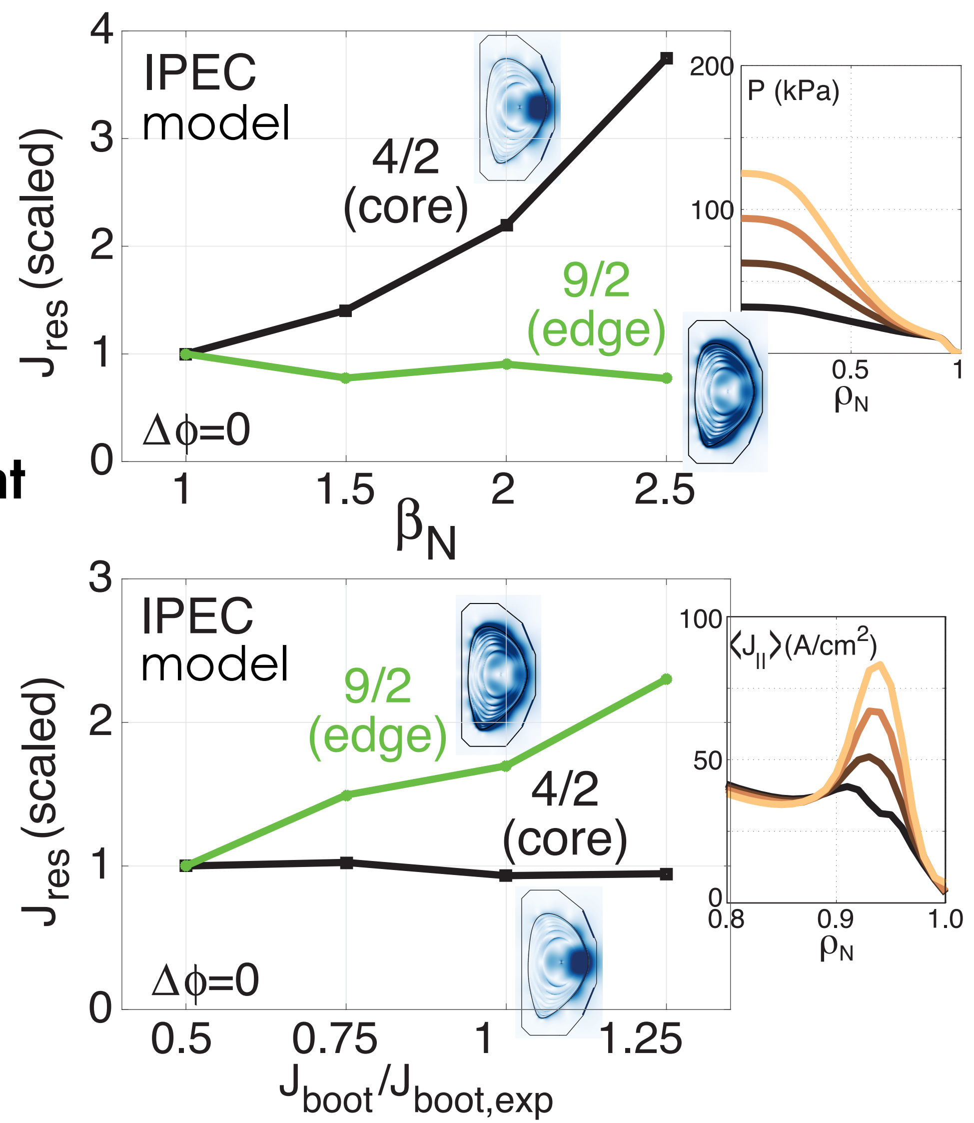
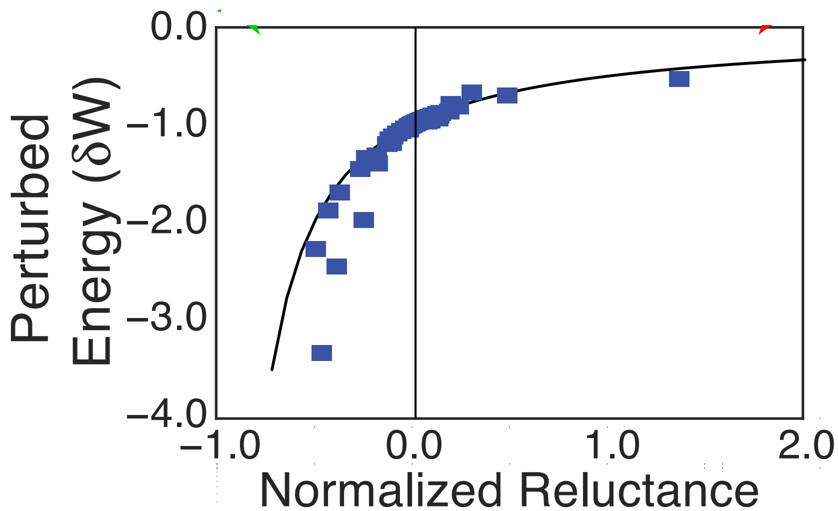
  - Path for low collisionality to assist ELM suppression
- **Consistent with magnetic LFS & HFS measurement trends**



New Reluctance Basis for Categorizing MHD Modes Demonstrates How to Drive Resonant Field Most Stably

- **Reluctance basis sorts MHD modes by magnitude and sign of the plasma response**



N. Logan et al., PoP 2016

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- **Reluctance basis sorts MHD modes by magnitude and sign of the plasma response**
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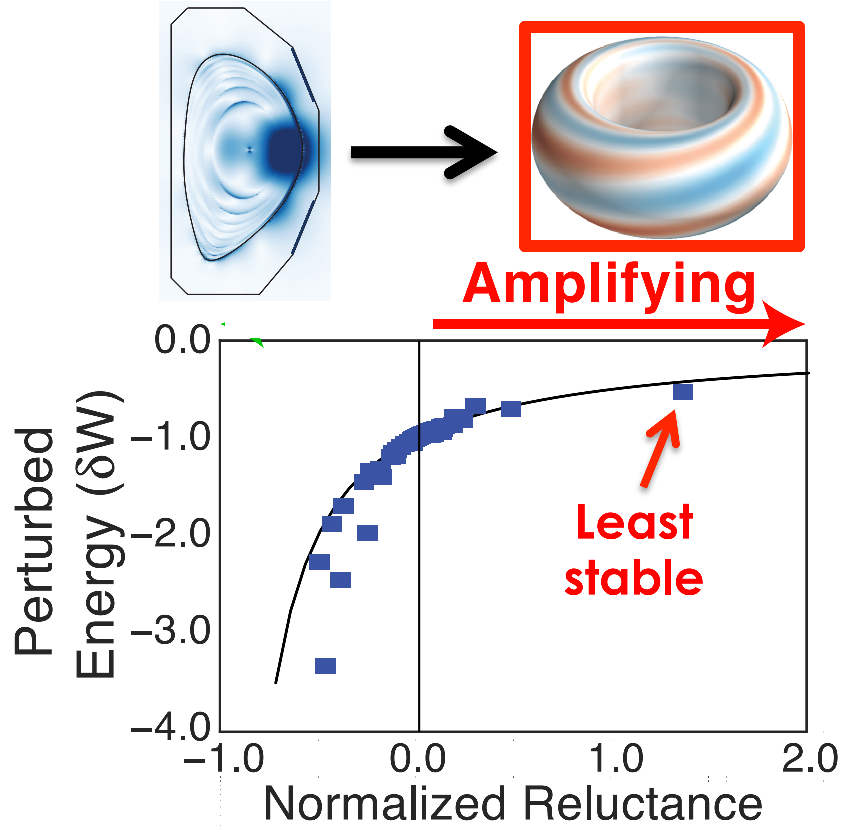

N. Logan et al., PoP 2016

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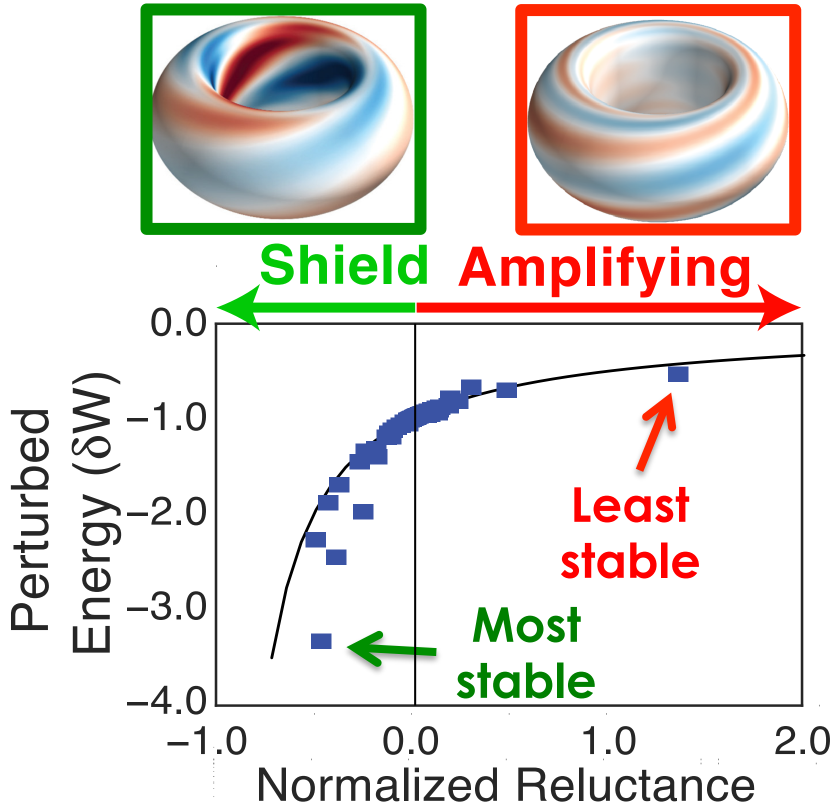
- **Reluctance** basis sorts MHD modes by magnitude and sign of the plasma response
- **Amplifying** modes least stable, beta driven, LFS localized
- **Shielding** modes most stable, beta insensitive, on HFS+LFS



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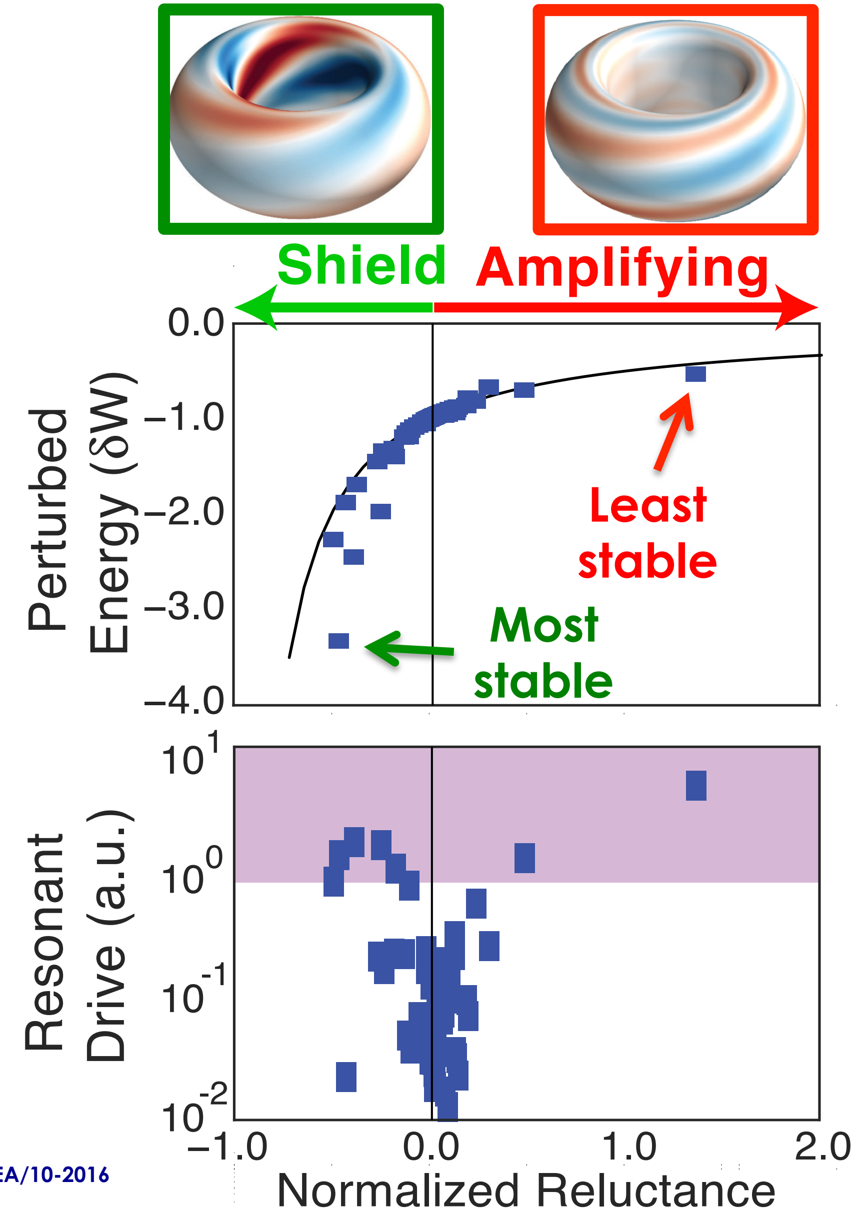
- **Reluctance basis sorts MHD modes by magnitude and sign of the plasma response**
- **Amplifying modes least stable, beta driven, LFS localized**
- **Shielding modes most stable, beta insensitive, on HFS+LFS**
- **Both can drive significant resonant field and control ELMs**
- **3D spectrum that couples to only shielding modes shows path to more stable ELM control**



N. Logan et al., PoP 2016

Control of Plasma Rotation and MHD Mode Spectrum Required to Optimize the Plasma Response for ELM Control

- **Consistency of field penetration with access to ELM suppression validates optimization criteria presented**

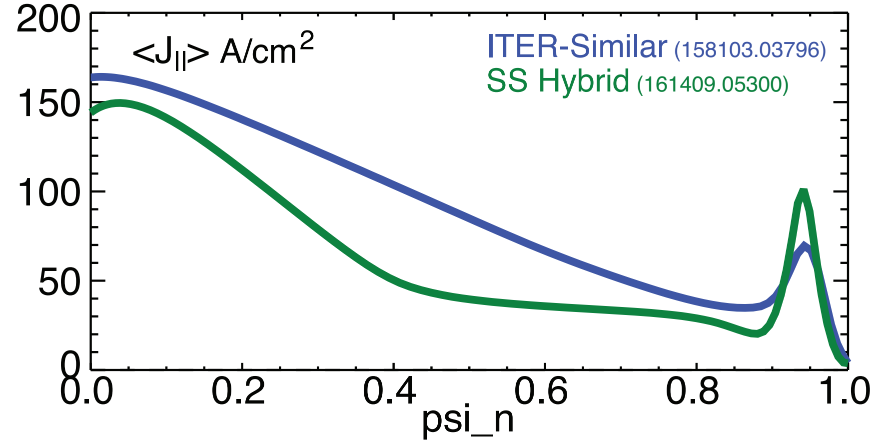
- **Penetration requires optimized electron rotation profile**
  – Good: Wide optimization space enabling performance recovery
  – Bad: Potential torque thresholds require careful extrapolation to ITER

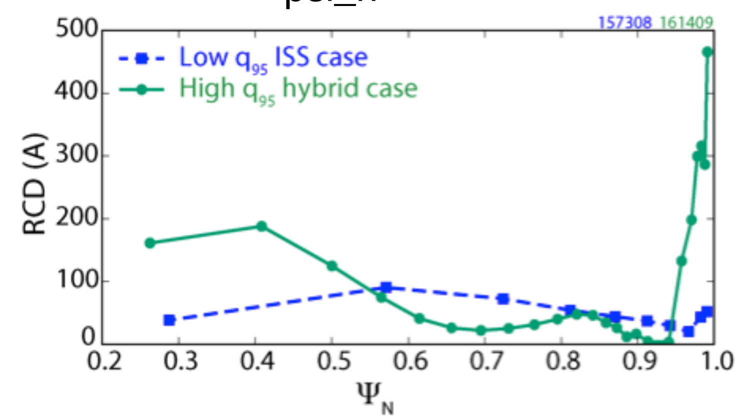
- **Resonant drive optimized by 2D equilibrium and 3D spectrum**
  – Bootstrap current increases edge resonant drive, core beta does not
  – Shielding modes can drive resonant fields without increasing δW

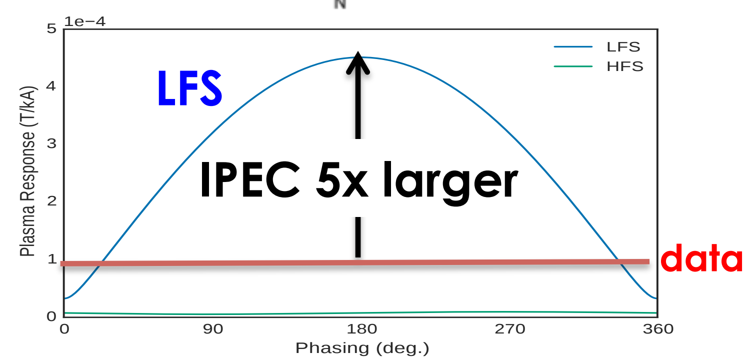
Bonus Slides

Comparison to SS Hybrid Case Reveals Different Radial Structure Likely Due to Large Bootstrap Current

- **SS hybrid least-stable n=3 mode is more edge-localized**
- **Speculate: broad J-profile and bootstrap causes edge-localization of resonant drive**
  – Despite positive reluctance / large LFS signal
- **Ideal MHD modeling over-predicts core/LFS drive by 5x due to beta ~ no wall limit**
  – Kinetic modeling underway
  – HFS sensors blind due to small spatial size of m ~ 20 structures







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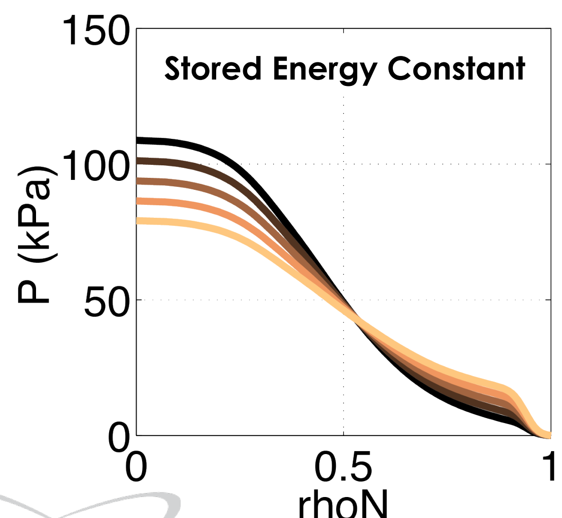
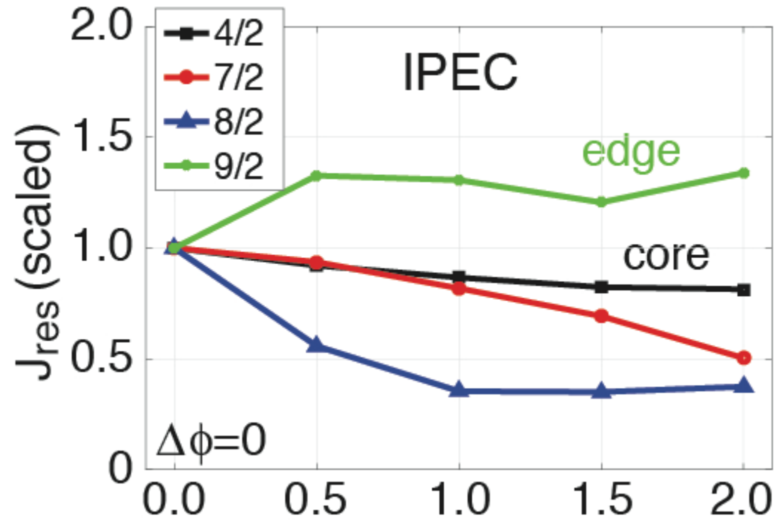
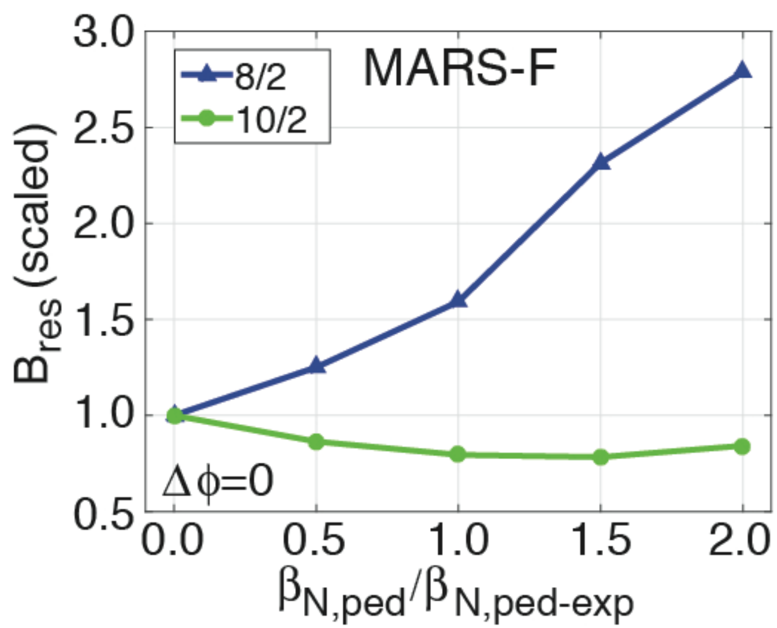
Modeling Disagrees on Ability of Pedestal Pressure at Fixed Stored Energy to Increase Resonant Drive

- **MARS-F shows significant effect at pedestal-top**
- **IPEC shows weak or counter-effect as $\beta_{N,ped}$ increases**
- **IPEC and MARS-F agreed for J_{boot} and core β_N trends**







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