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

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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

Match ITER shape, $I/aB$, $\beta_N$
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, $\beta_N$
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 & $E_r$
• 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
• 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

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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

\[
\omega_E \text{ (krad/s)}
\]

B. Lyons et al., PPCF (in review)
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- Model predicts significant 8/2 penetration @ suppression
  - Pedestal expansion stopped before ELM stability limit

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- Substitute ELMing and ELM suppressed rotation profiles
- Model predicts significant 8/2 penetration @ suppression
  - Pedestal expansion stopped before ELM stability limit
- Model predicts shift in HFS response from penetration
  - No effect predicted for LFS
- What about experiment?

B. Lyons et al., PPCF (in review)
Consider back-transition from ELM suppressed state

- Before any ELMs appear
- Zoom in on ms timescale

R. Nazikian et al, NF (in preparation)
Back-transition from ELM Suppression Reveals Rotation and HFS Magnetic Changes on Millisecond Timescale

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- Prompt change in turbulent Doppler shift in ms timescale
  - Indicates rotation change

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• HFS structures shift in Z, $\phi$ immediately (1 ms) after losing ELM suppression

• Qualitative match to model

R. Nazikian et al., NF (in preparation)

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

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- ELMs are suppressed at a critical rotation (NBI torque)
- In ELMing conditions, rotation zero-crossing is at low $\Psi_N$
- $\omega_{\perp,e}$ 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

![Graph showing $\omega_{\perp,e}$ vs $\psi_N$ for q=8/3 and q=9/3 with NBI and 3D fields indicated.](image)
Imposed NBI Torque Effects 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
- Zero-crossing point jumps to next rational surface
  - Does not linger in between
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
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
- Wide variety of pedestal conditions compatible with static $\omega_{\perp,e}$ zero-crossing
- Gradient driven flows balance toroidal rotation spin up

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

- LFS measurements swamped by pressure driven modes

![Graph showing LFS response sensitive to $\beta_N$]
Measurements Find LFS Plasma Response Sensitive to $\beta_N$, HFS Totally Invariant; Collisionality Has Opposite Effect

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- Striking invariance of the HFS response to plasma pressure
  - MHD modeling agrees
- HFS sensitive to pedestal effects like field penetration
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- 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
- Collisionality reduces HFS only
- ITER-relevant collisionality needed for right MHD modes
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
Increasing Core Pressure Works Against Edge Resonant Coupling … Low Collisionality Bootstrap Helps

- **Resonant drive @ core surfaces increased by core pressure**
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- **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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- **Amplifying** modes least stable, beta driven, LFS localized

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

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- **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 $\delta W$
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 overpredicts 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
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 $\beta_{N,\text{ped}}$ increases
- **IPEC** and **MARS-F** agreed for $J_{\text{boot}}$ and core $\beta_N$ trends
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