Limits of RMP ELM suppression in double null plasmas

by

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With

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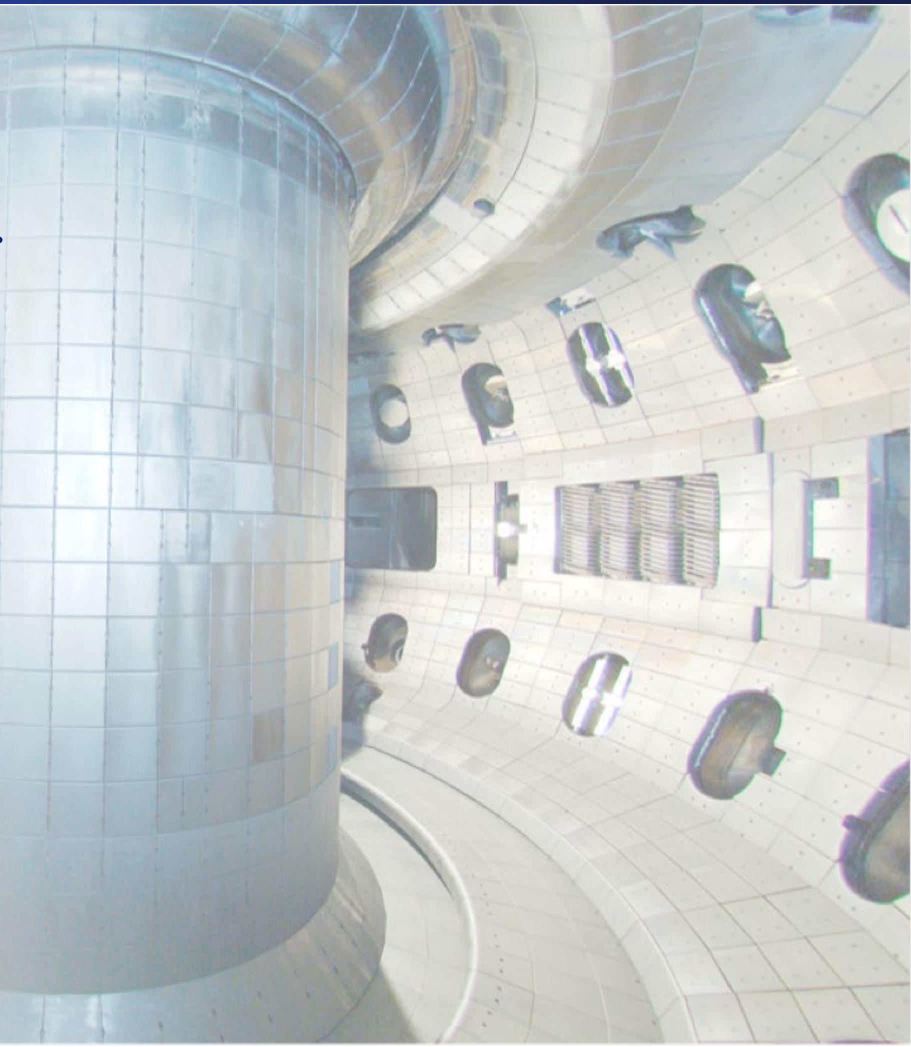

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Motivation

- **Double-null configurations offer additional power handling capability for future machines and stronger shaping for advanced scenarios**
  - Suppressing ELMs remains key challenge regardless of single or double null to avoid divertor material damage
  - Standard H-mode relies on Type I ELMing regime
- **Suppression via resonant magnetic perturbations (RMP) not yet shown to couple to strongly shaped scenarios**
- **Experiments in shapes transition for single to double null performed to:**
  - Explore access to ELM suppression
  - Examine underlying RMP response

Result: Reduction in plasma response on high field side correlates with loss of ELM suppression in double null, suggesting reduction of tearing drive

Hypothesis for RMP ELM suppression

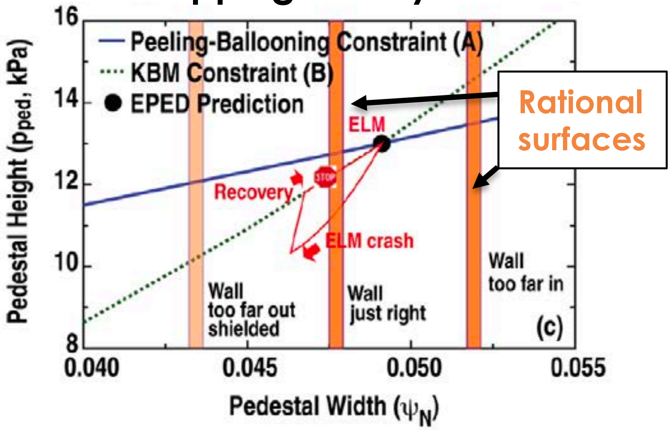
- **Basic premise: ELMs can be suppressed by stopping inward growth of pedestal**

- **Hypothesis: localized penetration of applied 3D magnetic field creates sufficient transport to stop inward pedestal growth**
  - Expected to occur at low rotation ($\Omega_{E\times B}$) aligned with rational surface*
  - Experiments support hypothesis: show suppression when rotation ~0 at top of pedestal

- **Requires: Low rotation at pedestal top aligned with rational surface**

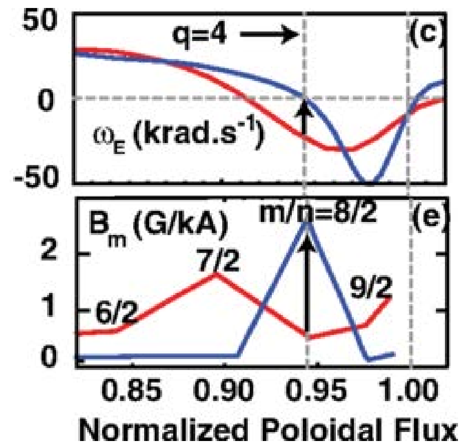
*Ferraro N.M. 2012 *Phys. Plasmas* **19** 056105; Fitzpatrick, R. 2020 Phys. Plasmas **27** 042506; Q.M. Hu *et al* 2020 *Nucl. Fusion* **60** 076001

Stopping ELM cycle



Snyder P.B. et al 2012 Phys. Plasmas ***19*** *056115*

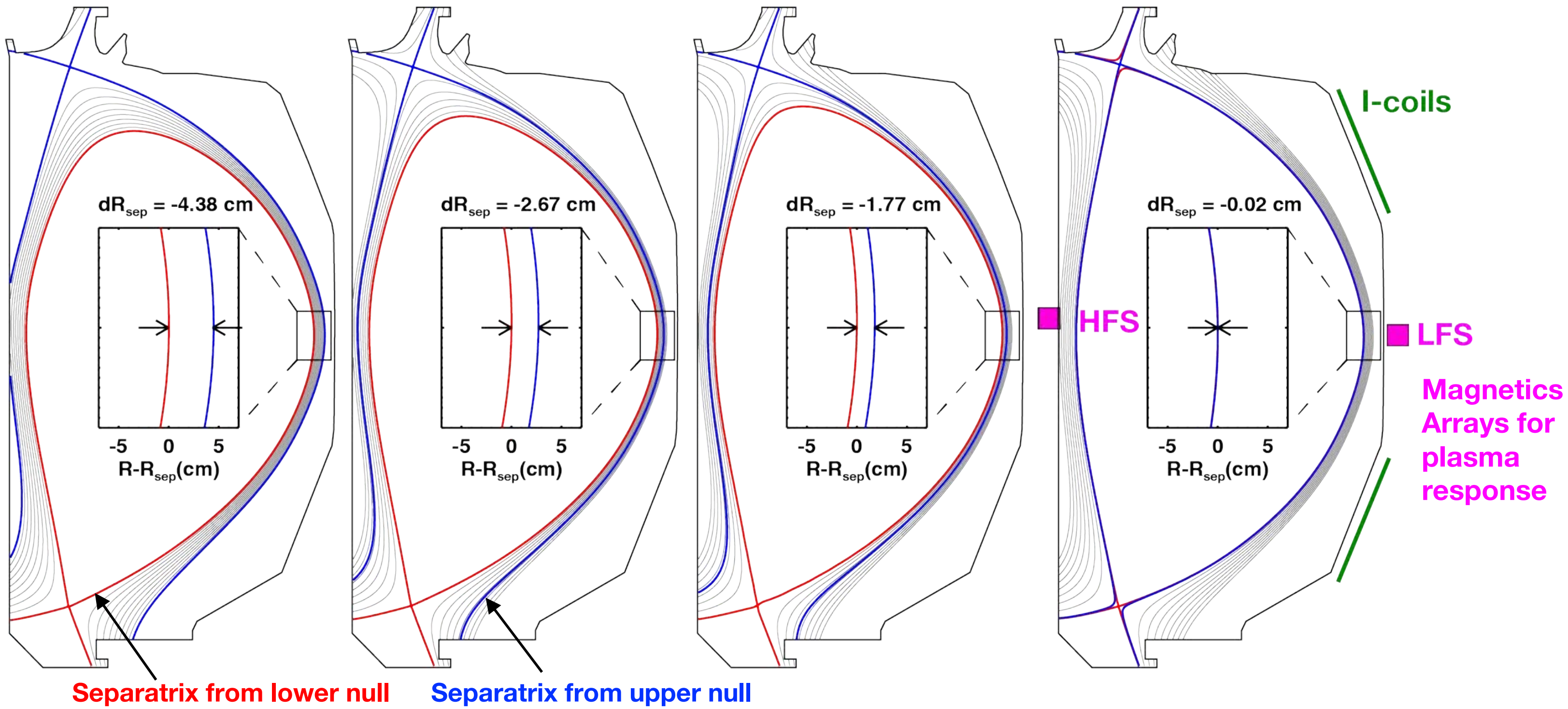
ELMing and suppressed profiles



Nazikian R. et al 2015 Phys. Rev. Lett. ***114*** *105002*

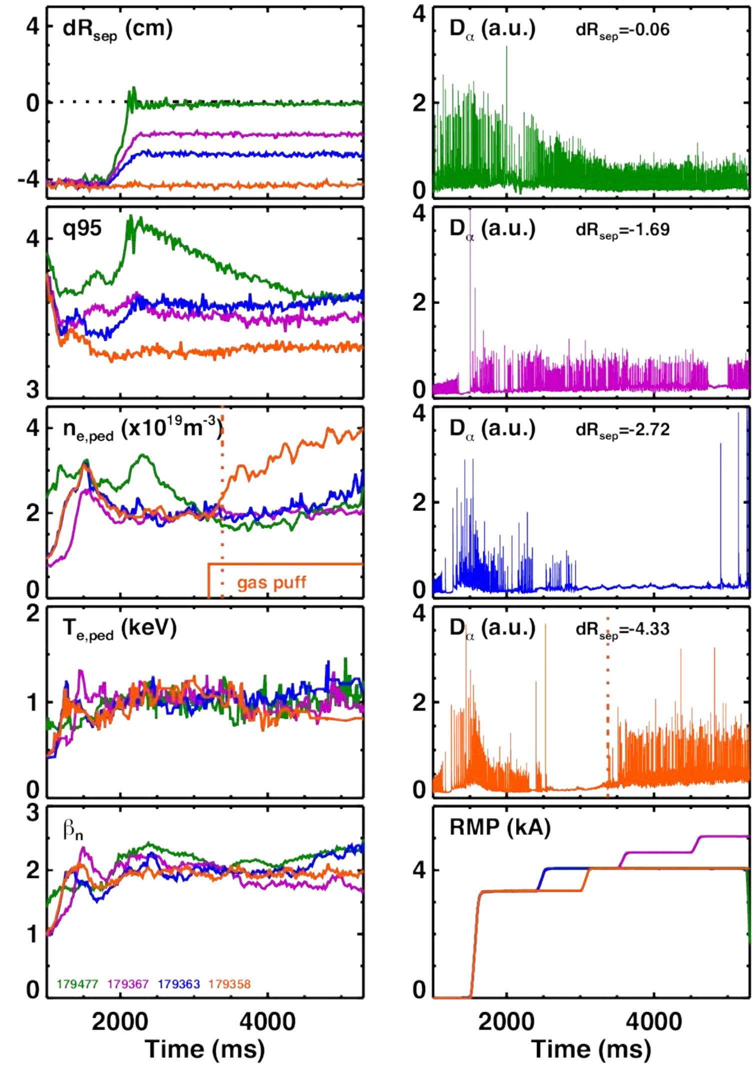
RMP ELM suppression & plasma response examined in shapes transitioning from single null to double null

- **Characterized by separation at midplane of separatrcies, dR_{sep}**
  - Using fixed upper and lower nulls



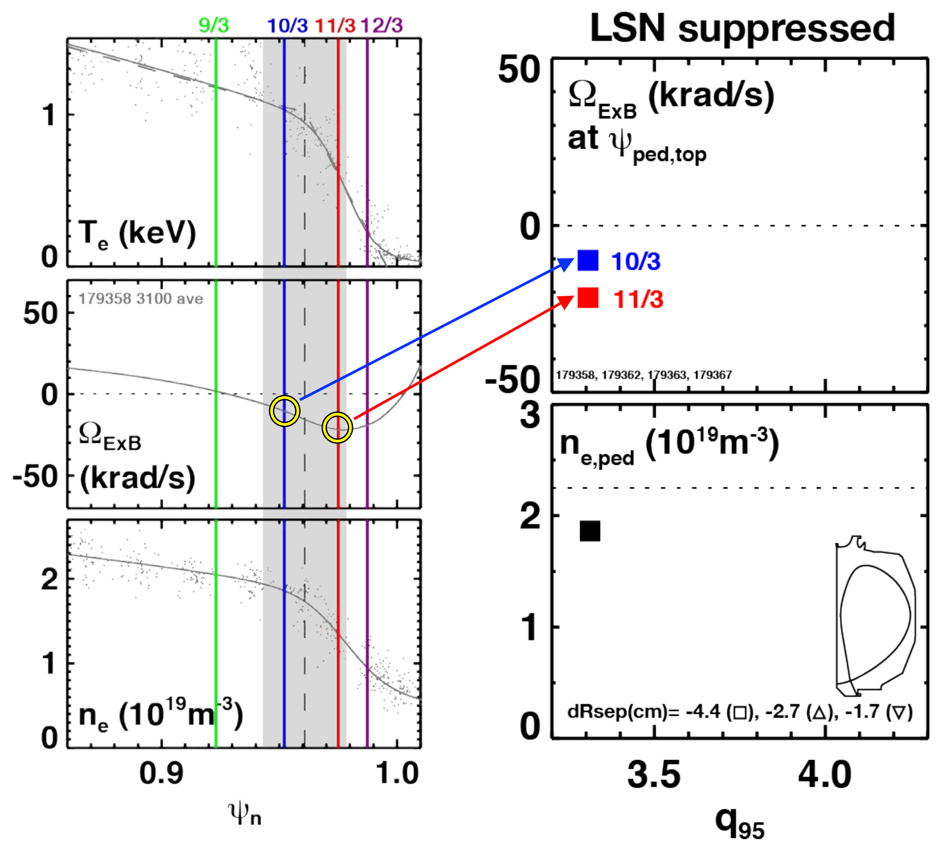
RMP ELM suppression observed in single null, but not double null

- **Suppression accessed with $n_{e,ped} \leq 2.5$**
  - Gas puff to increase density after pump-out shows transition to ELMing at $n_{e,ped} = 2.5$
- **Marginal suppression at $dR_{sep} \sim 1.77$**
  - Triggered by sawtooth
- **Double null case shows similar pedestal conditions, but no suppression**



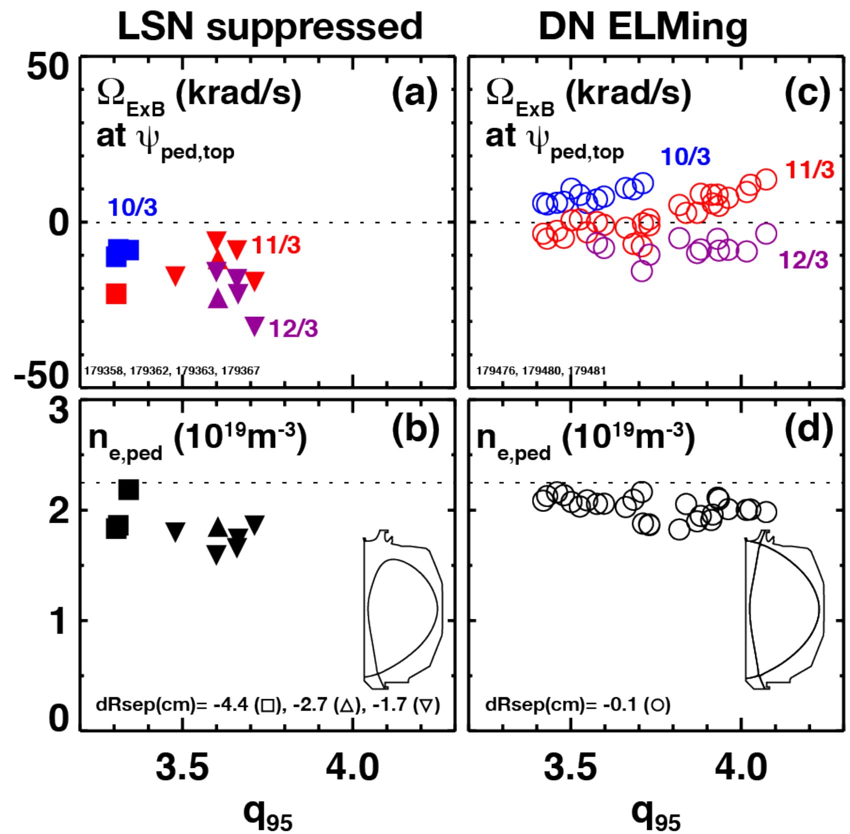
$\Omega_{\mathrm{E\times B}}$ at rational surfaces examined over range of q_{95}, dR_{sep}

- **Analysis uses T_e profile for pedestal top, $\psi_{ped,top}$**
  - Determined by intersection of linear fit through steep gradient and pedestal top
- **$\Omega_{\mathrm{E\times B}}$ evaluated at rational surfaces within $\pm 2\%$ $\psi_{ped,top}$**
  - Using kinetic EFITs



RMP suppression access conditions met in double null where ELM suppression obtained in LSN

- **Low $\Omega_{E\times B}$ flow at pedestal top collocated with rational surfaces in ELM suppressed conditions**
  - 9/3 surface at lower q95
  - 10/3 surface at higher q95
- **ELM suppression conditions established in DN, but suppression not observed**
  - $|\Omega_{E\times B}| < 10 krad/s$ near the pedestal top in DN--tighter range than in LSN
  - lower value of than the highest value suppressed in LSN



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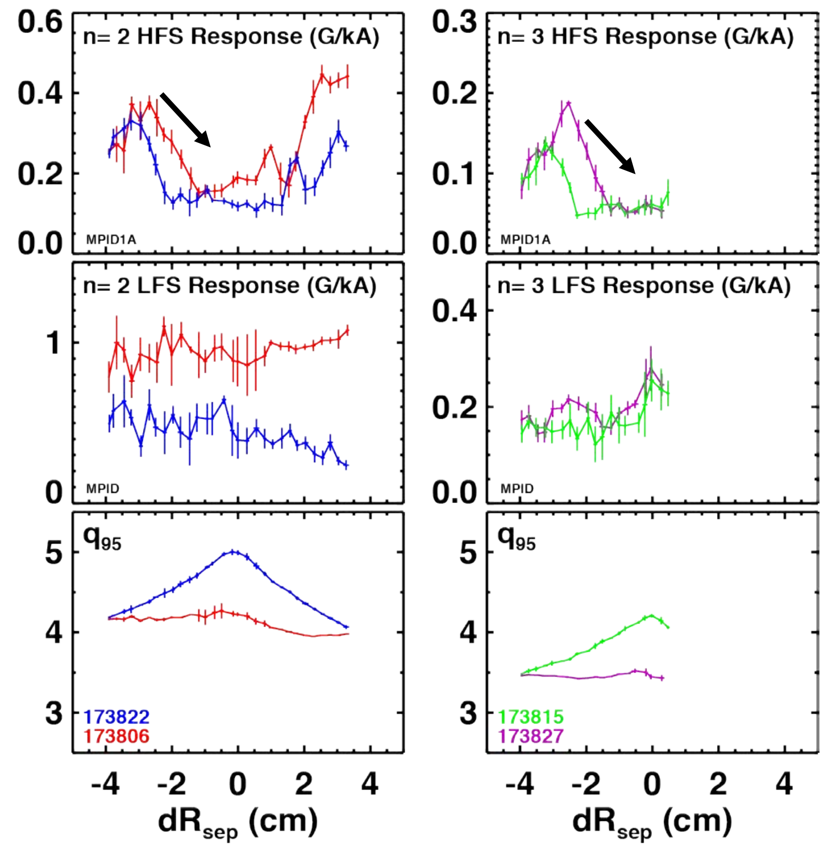
Plasma response on high-field side drops toward DN while low field side remains constant

- **Drop in HFS response occurs at values of $|dR_{sep}| < 3$ cm**
  - Not a divertor effect: heat flux balance changes $|dR_{sep}| < 1$ cm
  - Increases transitioning to USN

- **Drop in HFS response approaching DN observed over range of q_{95}, applied n (n=2,3)**
  - Drops at larger $|dR_{sep}|$ for higher q95

Plasma response measurements

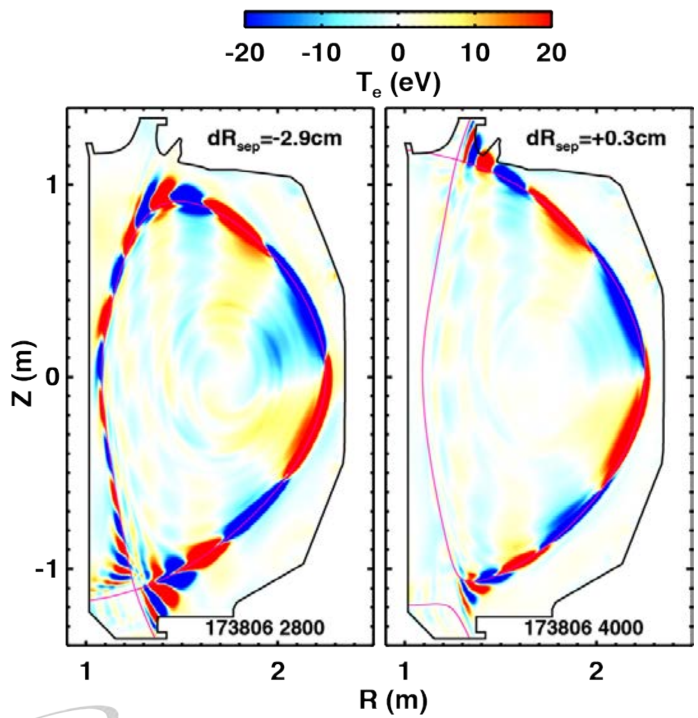


terminated early due to power supply issues experienced

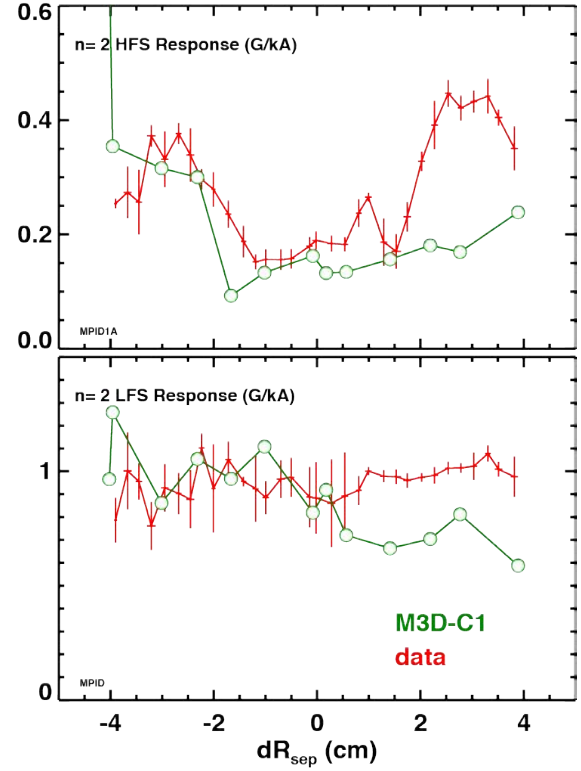
Linearized single-fluid MHD modeling captures similar trend with drop in HFS plasma response

- Modeling uses M3D-C1 to solve resistive MHD response
- Modeling matches data transitioning from LSN to DN
- Strong reduction of perturbation along HFS

Simulated T_e perturbation



Comparison of synthetic to measured plasma response



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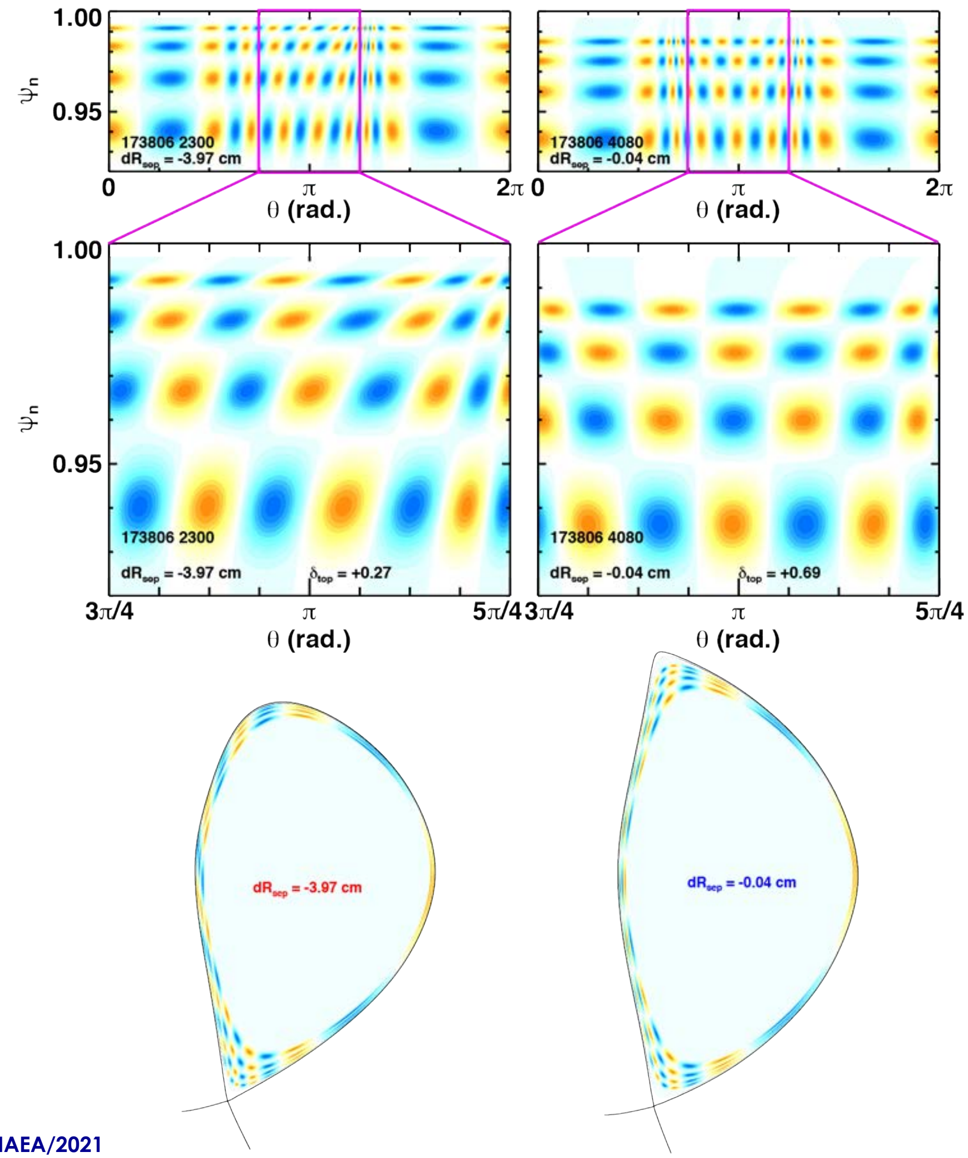
Simplistic explanation: presence of second null increases interference of modes driven on LFS to HFS

- **Assume simple field-aligned mode structure for pedestal modes m=8-11**
  - $A\cos(nq\theta_{PEST})$
- **LFS response is stronger and driven directly while HFS relies on the connection from the LFS around the upper X-point**



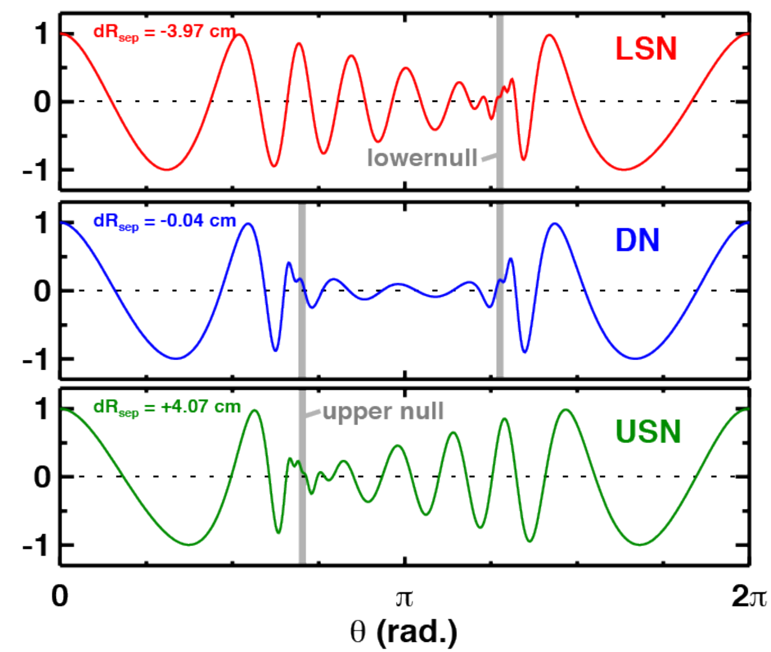
Summation of modes can be used to conceptually understand the interference

- **Interference strongest near null**

- **Moving away from the single null along the HFS (decreasing θ in LSN and increasing θ in USN), the summed amplitude increases and interference decreases**

- **Between the two nulls in DN**
  - reduction reflecting out-of-phase structure

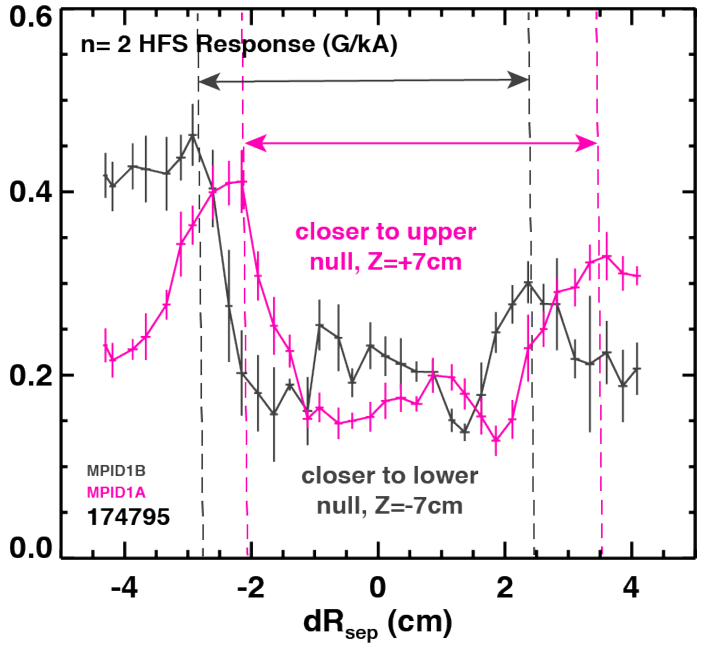
Radial summation of field-aligned modes



Proximity to null impacts drop in HFS response

- **HFS response closer to dominant null drops first**
  - Utilizing magnetics arrays above and below midplane on HFS
- **Transitioning from LSN to DN**
  - the HFS response below the midplane (and closer to the lower null) starts to reduces before the array above the midplane (and further from the lower dominant null)
- **Transitioning from USN to DN**
  - the HFS response closer to the upper null drops before the response further from the upper null

HFS response measured above and below midplane



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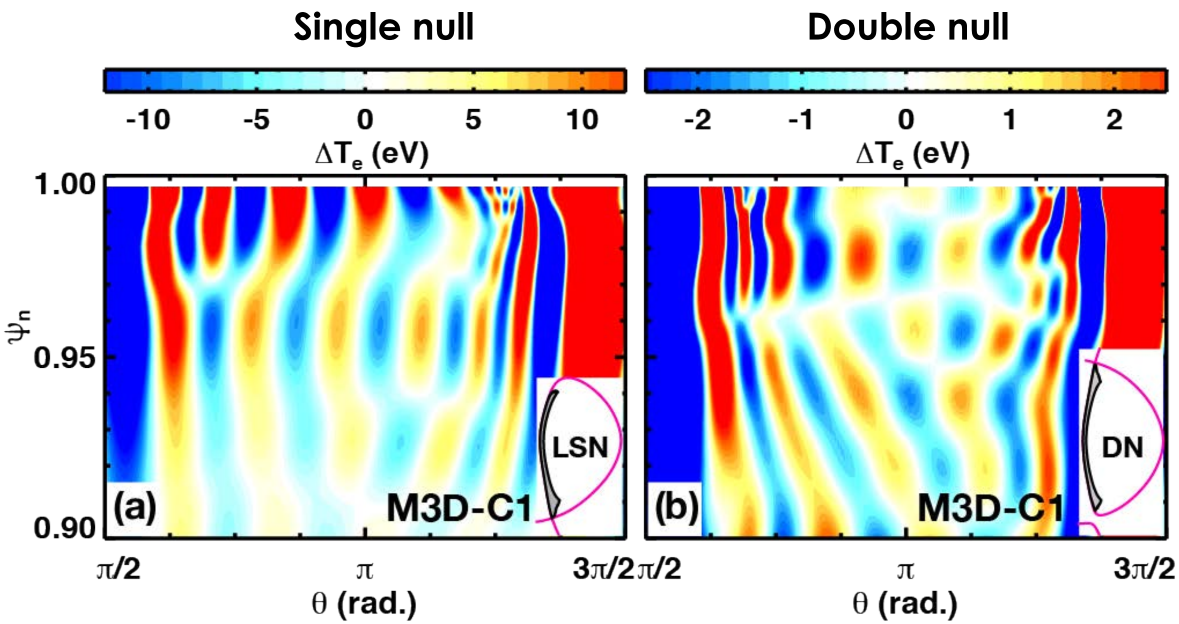
M3D-C1 modeling confirms basic field aligned structure patterns in LSN and DN

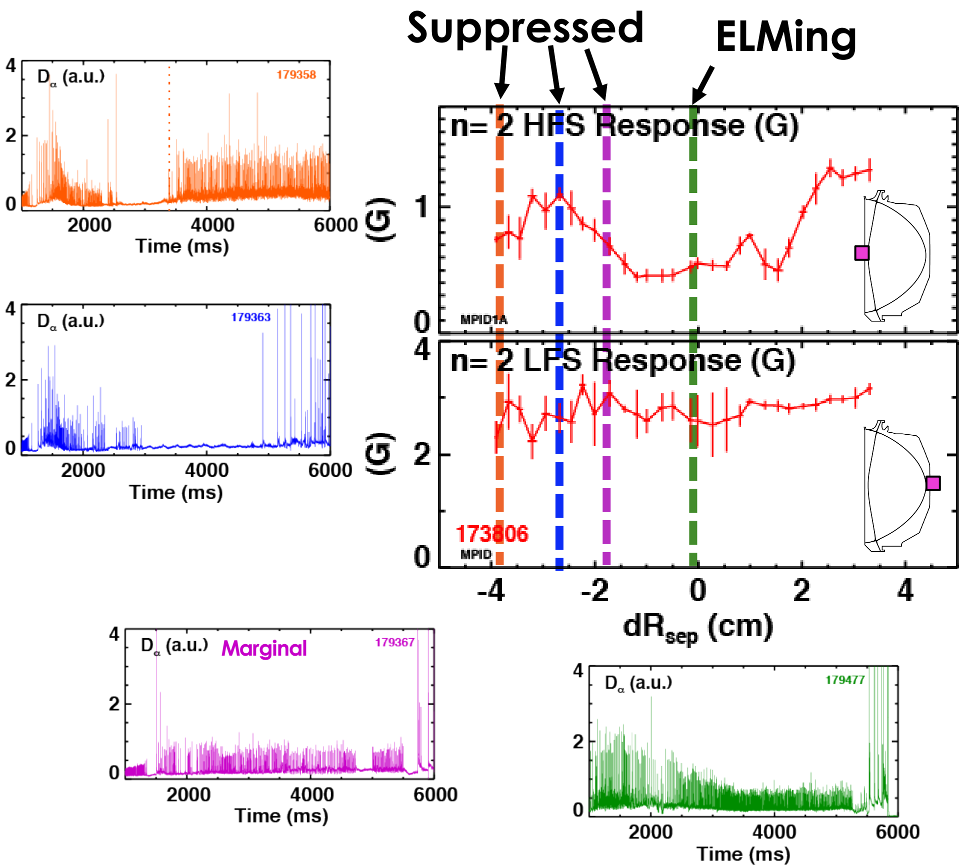
- T_e **is aligned with the magnetic field making this a good way to examine the mode structure**
  - LSN HFS ΔT_e is relatively in phase radially
  - DN HFS ΔT_e is both much smaller in amplitude (note ΔT_e range different for each chase) and radially out-of-phase



Lack of high-field side response correlates with loss of ELM suppression

- **Hypothesis: High-field side response likely represents tearing response when driven from LFS**
  - Previously observed by varying applied field pitch*

- **Speculation: when geometric shaping inhibits tearing response, pedestals are no longer limited by local penetration**



*Paz-Soldan C. et al 2015 Phys. Rev. Lett. **114** 105001

Summary: Magnetic up/down asymmetry has strong impact on plasma response and ELM suppression

- **ELM suppression not observed in double null configurations**
  - despite achieving similar $\boldsymbol{n_{e,ped}}$ and co-alignment low-flow at resonant surface near pedestal top
- **Measurements show 3D response on HFS response drops toward double null**
  - MHD modeling shows similar picture to that found in experiment and agrees well in magnitude with magnetics data
  - This can be understood by the role of a secondary X-point influences mode structure
- **Consistent with using HFS response as a proxy for local tearing drive responsible for ELM suppression by stopping inward growth of pedestal**