Extended magnetohydrodynamic simulations of magnetic perturbations on ASDEX Upgrade

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ELM mitigation by external 3D fields

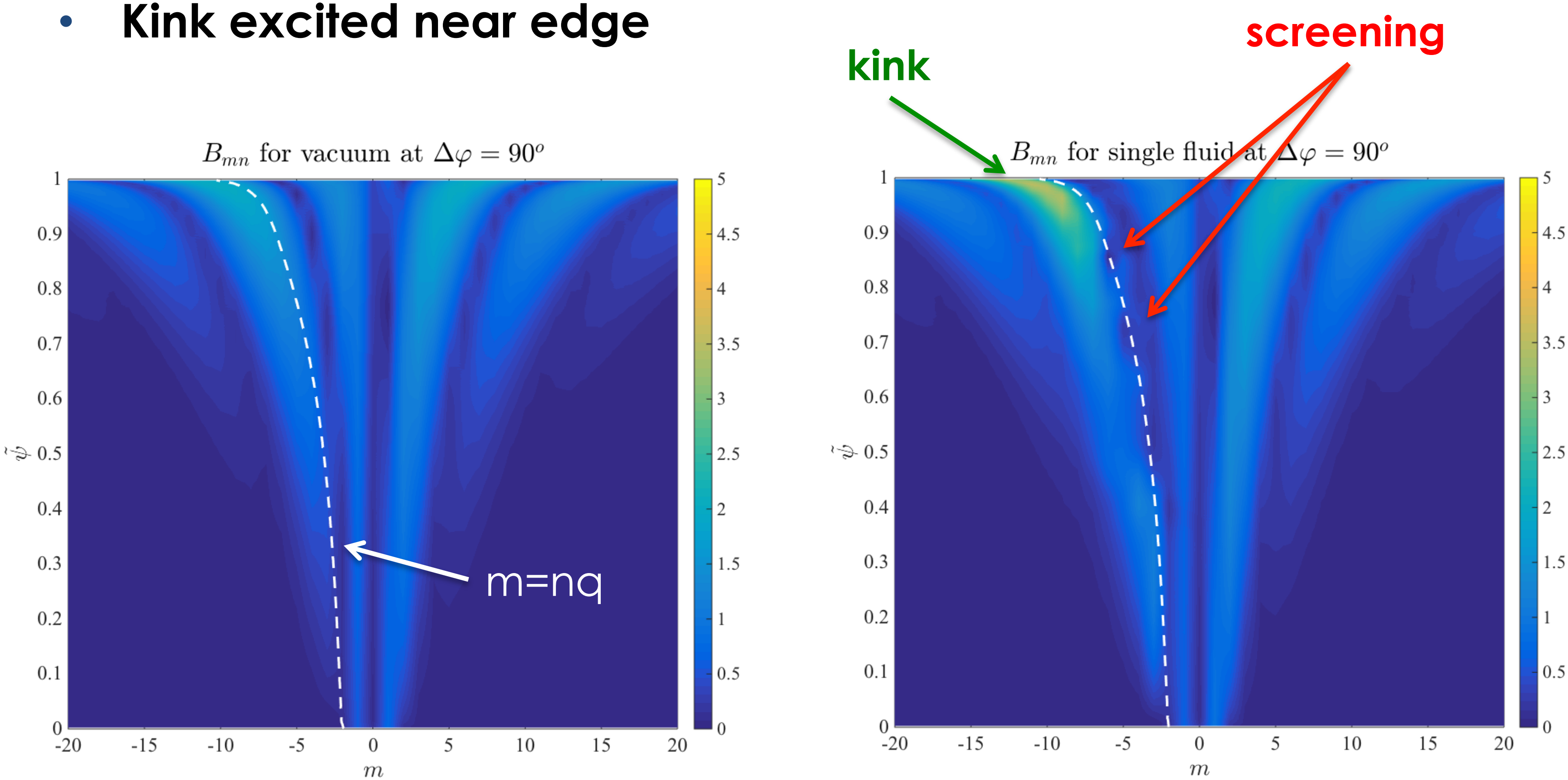
- **DIII-D has demonstrated complete suppression of edge-localized modes (ELMs) using externally-applied 3D magnetic perturbations**
  - Evans, T.E. et al. Nat. Phys. **2**, 419 (2006).
  - Among others
- **Results motivated installation of coils on several machines**
  - ASDEX Upgrade
  - KSTAR
  - MAST
  - NSTX-U
  - ITER (planned)

Theoretical understanding still incomplete

- **Early theoretical work focused on the nature of the applied vacuum field**
  - Resonant perturbations at rational surfaces open islands
  - Overlapping of islands at edge-pedestal boundary produces stochastic fields
  - Increased transport in stochastic layer maintains pedestal height/ width below ELM stability thresholds
- **Recent MHD simulations have demonstrated the importance of including the plasma response**
  - Ideally, resonant fields are completely shielded by plasma currents
  - Resistively, resonant fields can be enhanced by tearing
  - Non-resonant fields excite kink-like deformations with $m>nq$
  - Kink and tearing structures can couple to each other

Screening can shield resonant vacuum field

- **SURFMN-like field decomposition** $\delta B_r(\psi) = \sum_{m,n} B_{mn}(\psi) \exp\left[i\left(m\theta - n\phi\right)\right]$
- **Screening at q=5/2 and q=3 surfaces**
- **Kink excited near edge**



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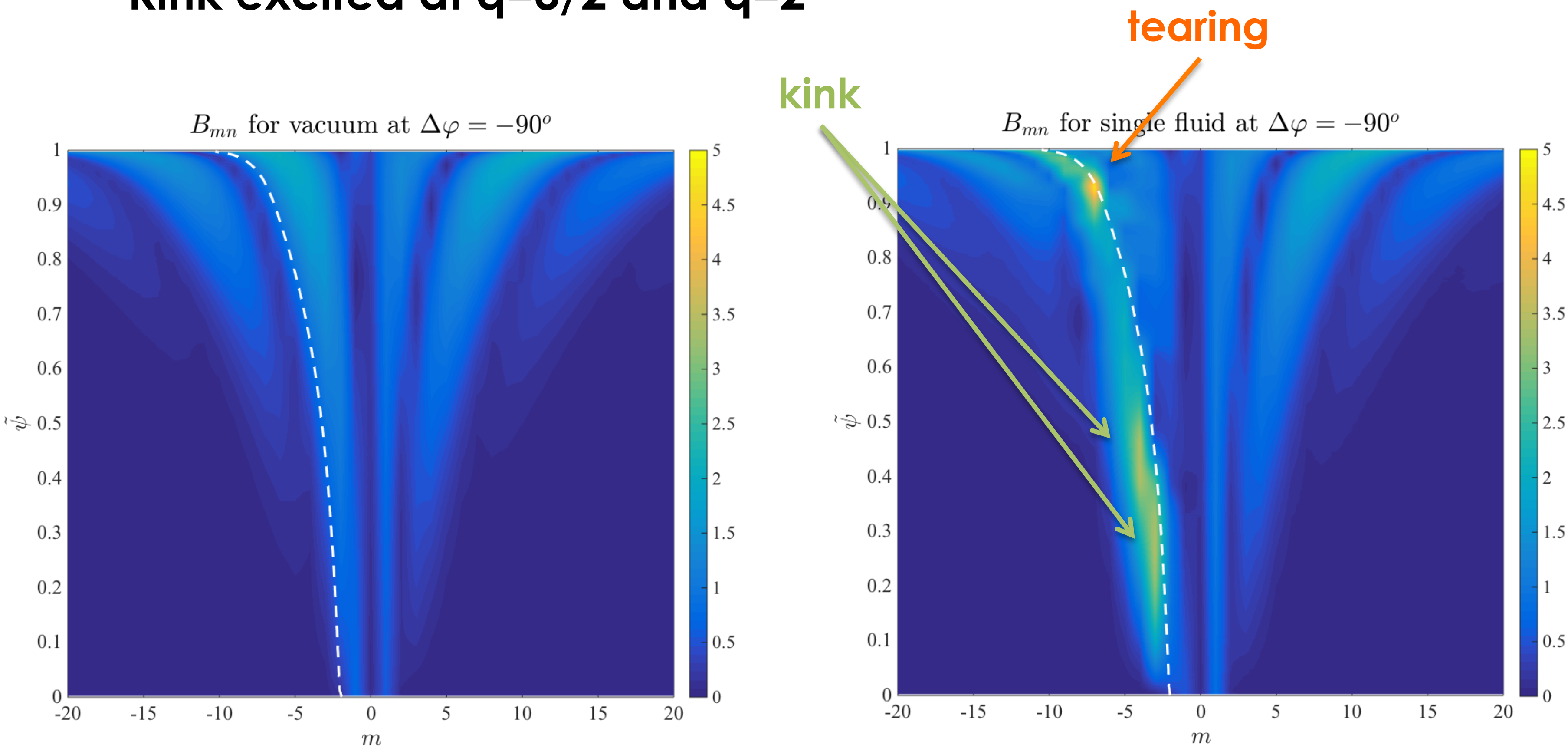
Tearing can amplify resonant vacuum field

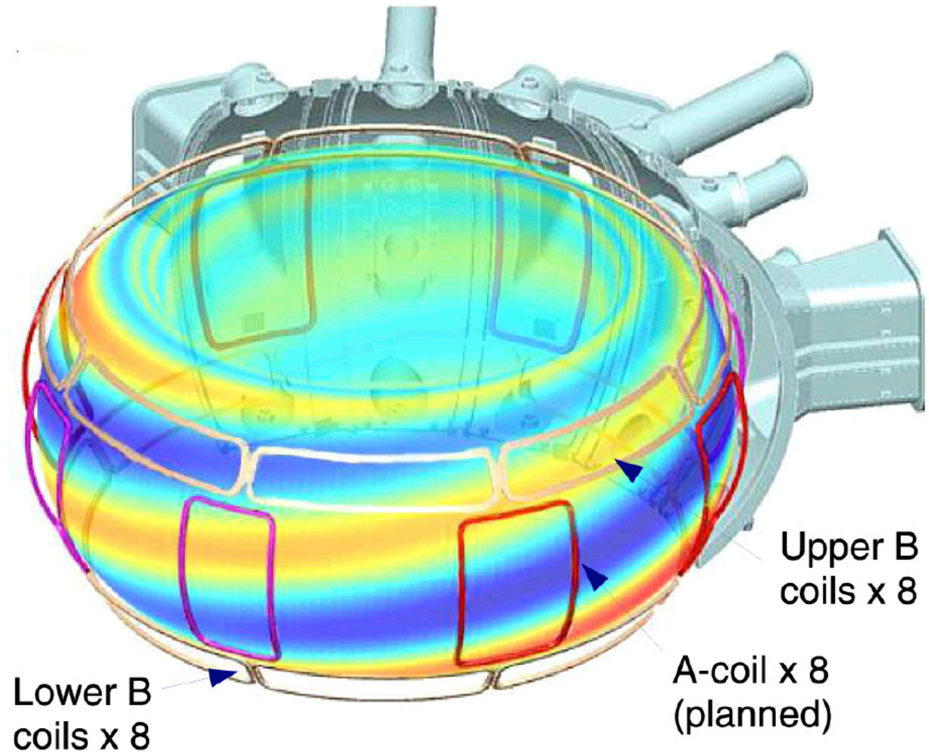
- **SURFMN-like field decomposition** $\delta B_r(\psi) = \sum_{m,n} B_{mn}(\psi) \exp\left[i\left(m\theta - n\phi\right)\right]$
- **Tearing at q=7/2 surface**
- **Kink excited at q=3/2 and q=2**



External field coils on ASDEX Upgrade

- **Two rows of eight in-vessel saddle coils**
- **Toroidal mode number of perturbations up to n=4**
- **For n=2 fields, the differential phase angle (AKA phasing) can be varied between upper and lower coils sets**
  - $\Delta\varphi = \phi_{up} - \phi_{low}$
  - Varies the magnetic pitch angle of the applied field
  - Affects coupling of resonant and non-resonant fields

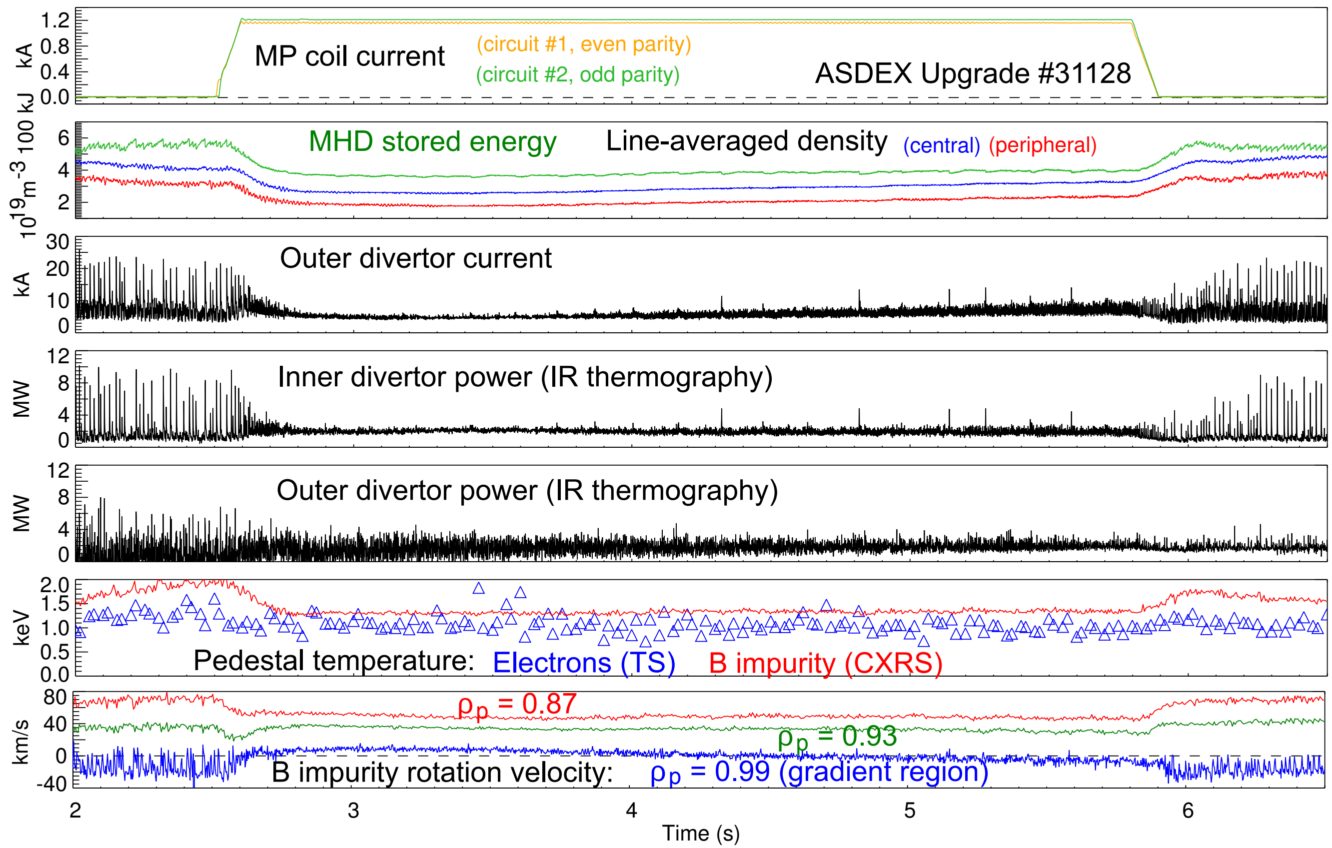
Figure 1 from G D Conway et al 2015 Plasma Phys. Control. Fusion 57 014035



ELMs are mitigated by perturbations on ASDEX Upgrade

- **Peak divertor heat loads decrease**
- **Electron density decreases**

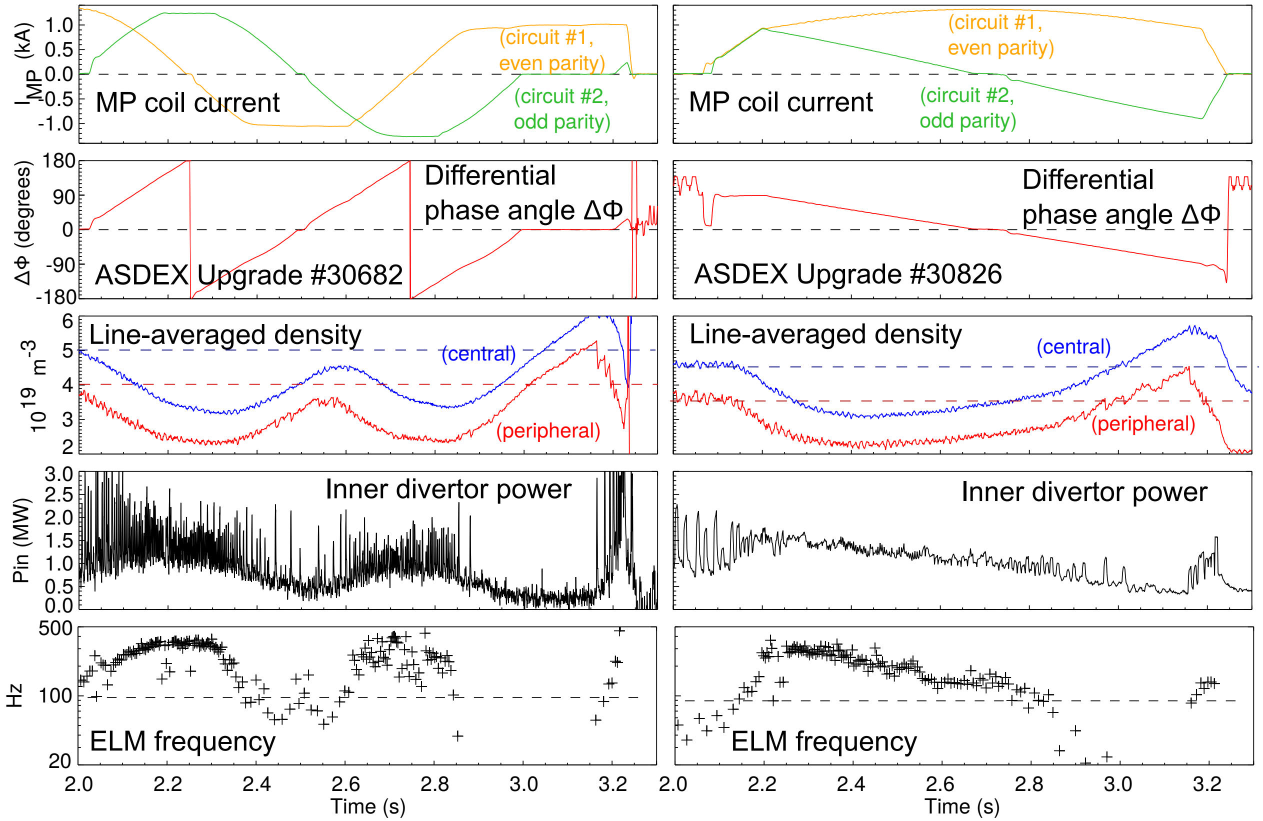
Suttrop, W. et al. EX/P1-23. IAEA FEC 2014.



Phasing affects the magnitude of ELM mitigation

- **Density and ELM frequency are modulated by phasing**
- **Strongest mitigation at minimum density**

Suttrop, W. et al. EX/P1-23. IAEA FEC 2014.



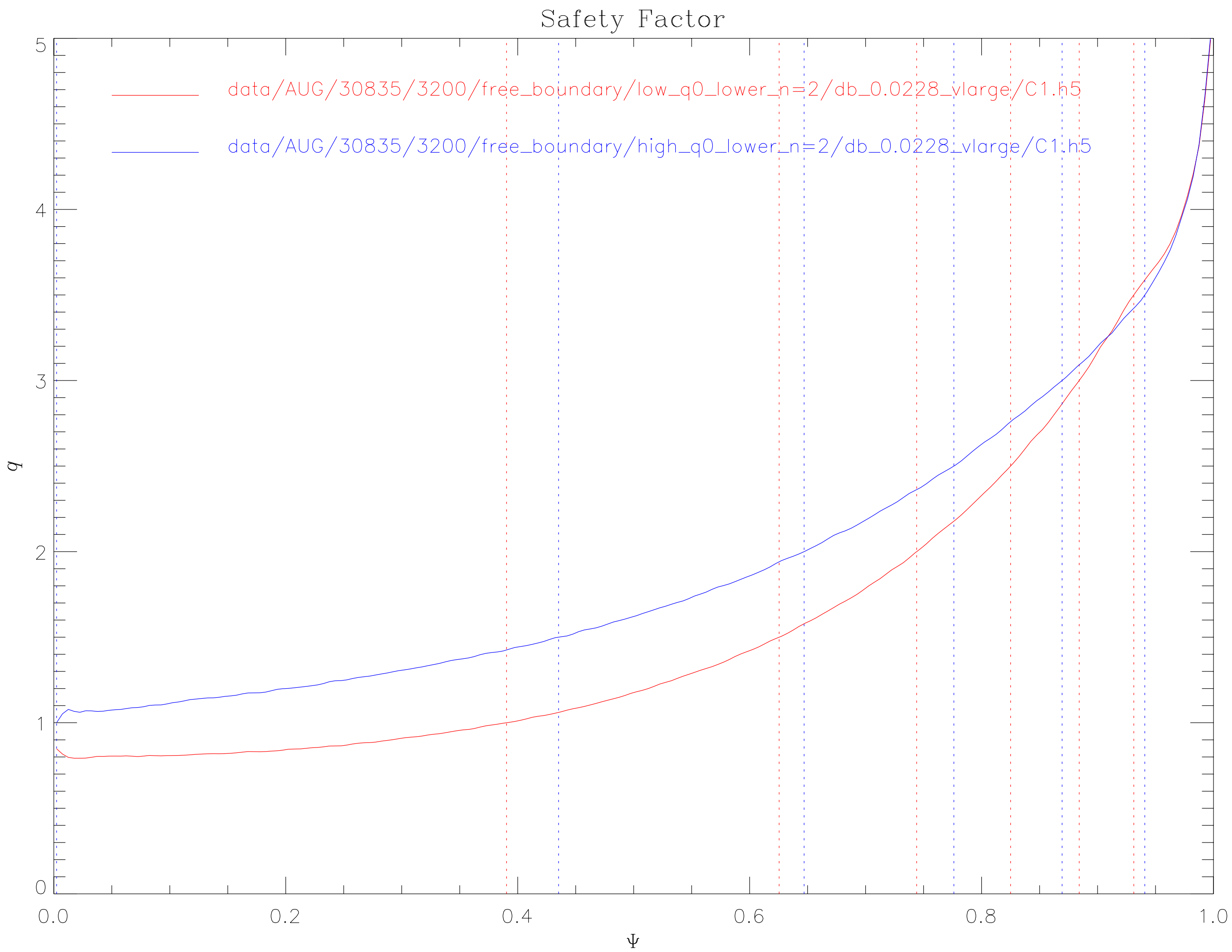
MHD simulations of ASDEX Upgrade shot 30835

- **Good ELM mitigation observed with n=2 fields in 30835 and similar shots**
- **Four phasings have been studied with MARS-F and VMEC**
  - $\Delta\varphi = 30^\circ$: Optimum vacuum resonance
  - $\Delta\varphi = 90^\circ$: Strongest ELM mitigation
  - $\Delta\varphi = -90^\circ$: Classical, non-stationary ELM-free phase
  - $\Delta\varphi = -150^\circ$: Optimum non-resonant field (ELM mitigation observed)
- **We've used M3D-C[1] to examine this shot**
  - Time-independent analysis
  - Six equally-spaced phasings from -150 to 150
  - Not quantitative validation work
    - Not comparing to measured field data
    - Only examining qualitative trends/correlations

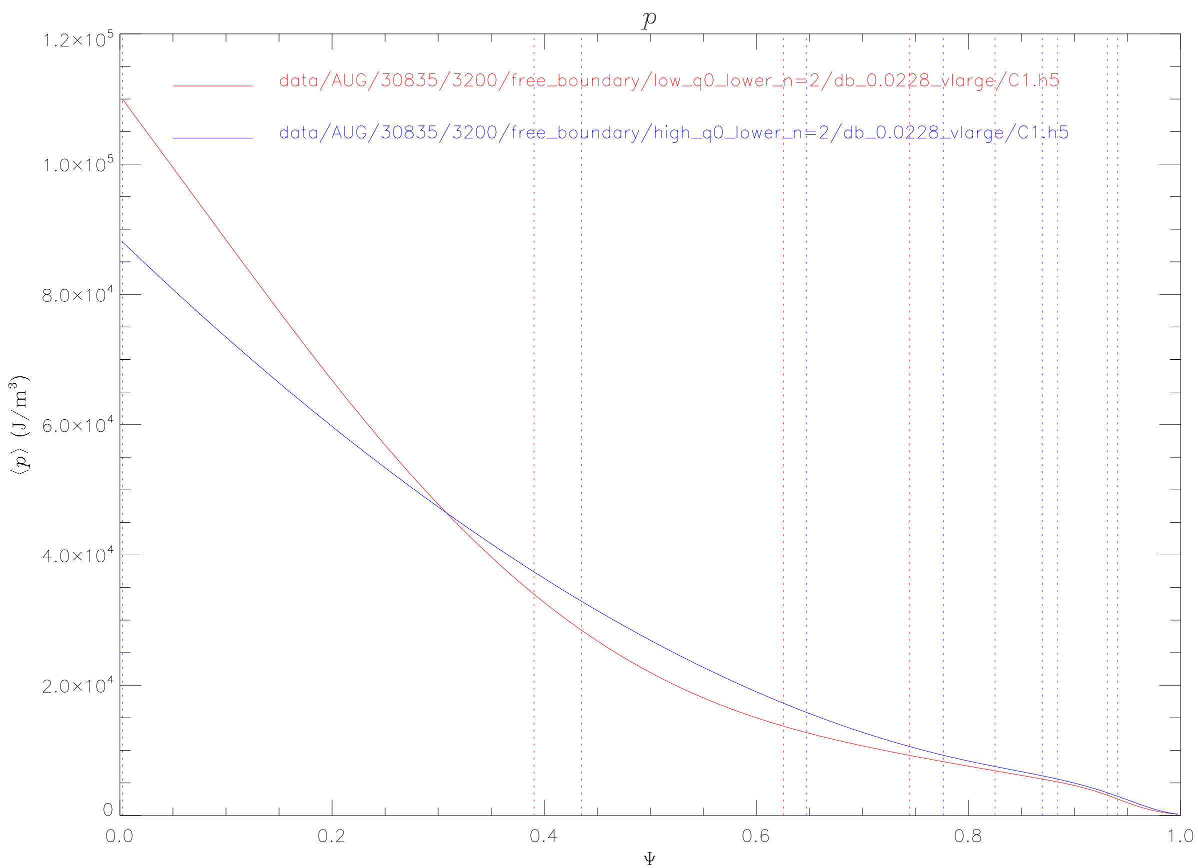
Key parameter varied

- **Two safety factor profiles**
  - Same shot, different equilibrium reconstructions
  - $q_0<1$: Unstable 1/1 and 2/2 modes
  - $q_0>1$: Stable equilibrium
- **Single- vs. two-fluid**
  - Single-fluid sensitive to ion rotation profile
  - Two-fluid allows for separate ion and electron rotation
- **Superconducting vs. resistive wall**

Safety factor profiles



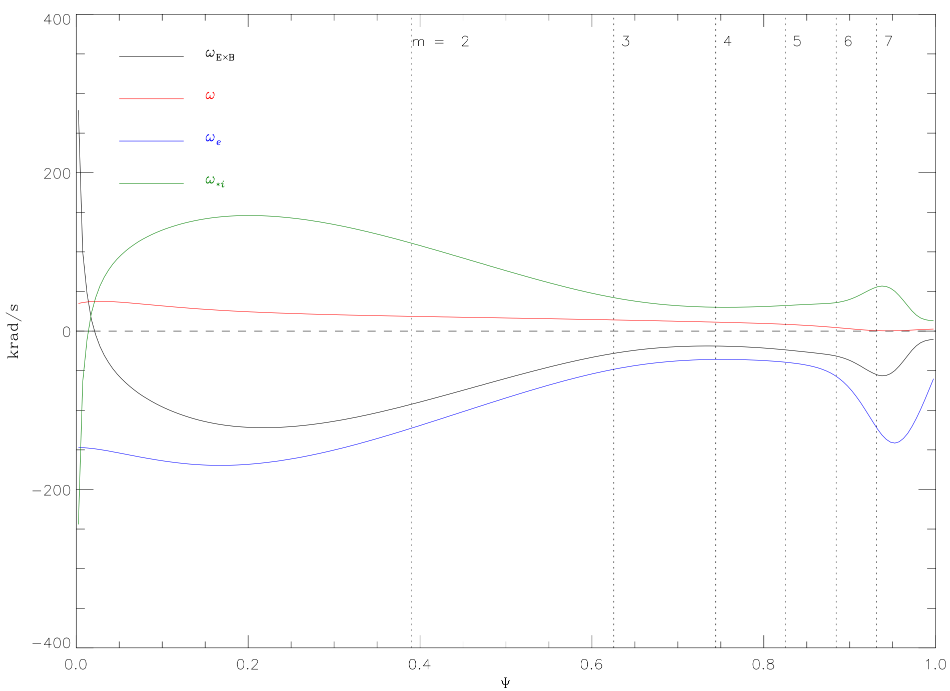
Pressure profiles



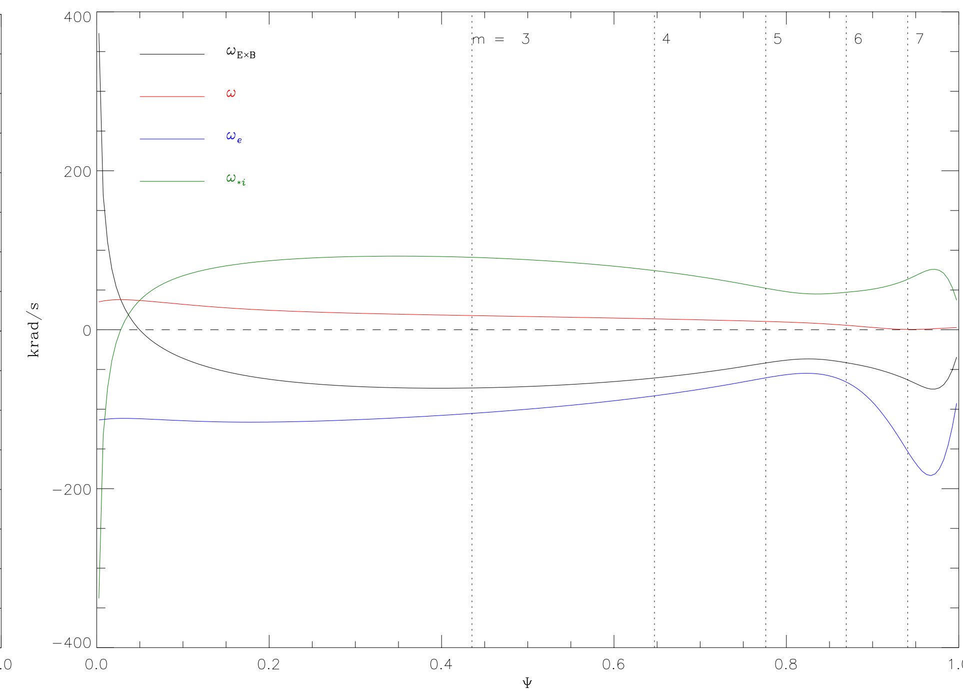
- **We'll often look at** $\tilde{\psi} \approx 0.93$
  - Near top of pedestal
  - Very close to q=7/2 surface

Rotation profiles

Low q_0



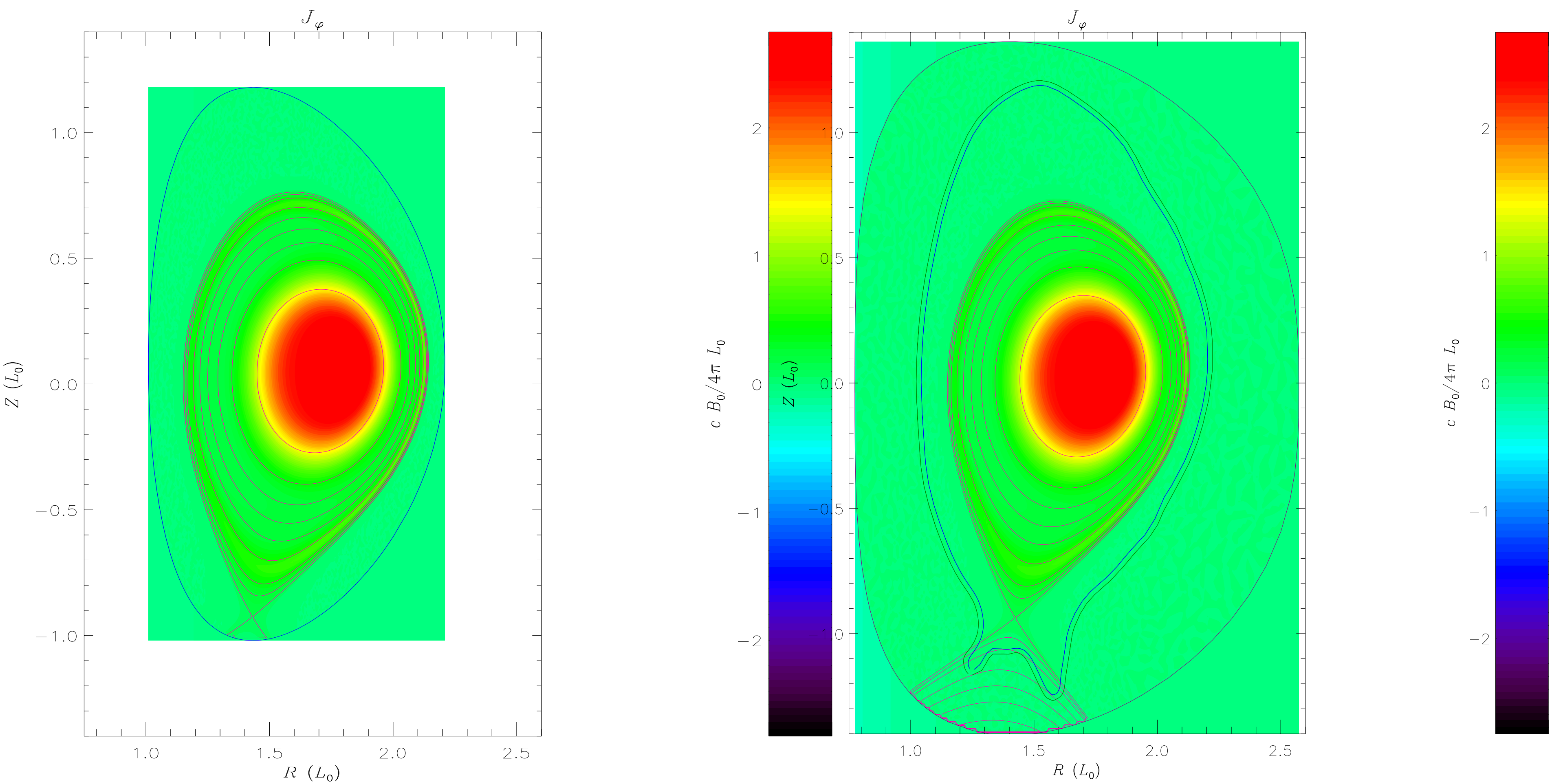
High q_0



- Same ion rotation but diamagnetic changes due to pressure
- No ion rotation, but strong electron rotation, at q=7/2

Domains used

Superconducting wall | Resistive wall



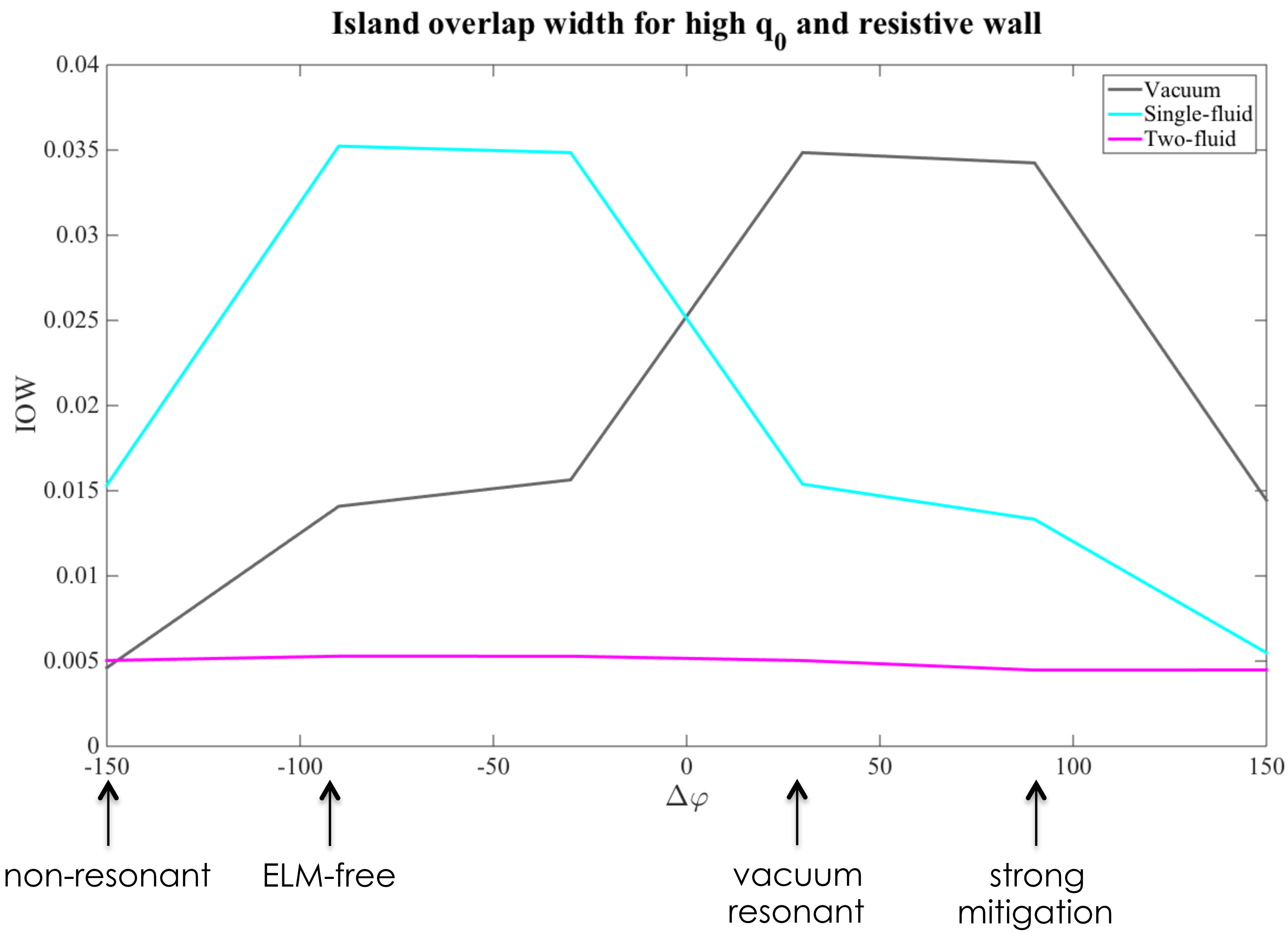
Metrics examined

- **Island overlap width**
  - $\tilde{\psi}$ distance from edge to first location where islands don't overlap
  - Generally a discontinuous function
- **Chirikov parameter:** $\sigma\left(\frac{\tilde{\psi}_{m+1}+\tilde{\psi}_m}{2}\right) = \frac{1}{2}\frac{w\left(\tilde{\psi}_{m+1}\right)+w\left(\tilde{\psi}_m\right)}{\tilde{\psi}_{m+1}-\tilde{\psi}_m}$
- $|\delta B_r|^2$
  - At pedestal top: $\tilde{\psi} \approx 0.93$
  - In core: $\tilde{\psi} \approx 0.12$
  - Total integrated
- B_{mn}
  - Full SURFMN-like plots

Results

- **Phasing dependences of island overlap and Chirikov parameter**
  - Little difference between single-fluid and two-fluid
  - Generally do not correlate with ELM suppression
- **Total integrated magnetic perturbation**
  - Dominated by core modes in low-q_0 cases
  - Mixes core and edge modes in high-q_0 cases
- **Magnetic perturbations at pedestal top**
  - Single-fluid
    - Generally do no correlate with ELM suppression
    - Superconducting wall, low-q_0 case has peculiar phasing dependence
  - Two-fluid
    - Seem to do much better
    - Electron rotation suppresses spurious tearing mode at pedestal top
    - Dominated by edge kink-like structure

Island overlap widths



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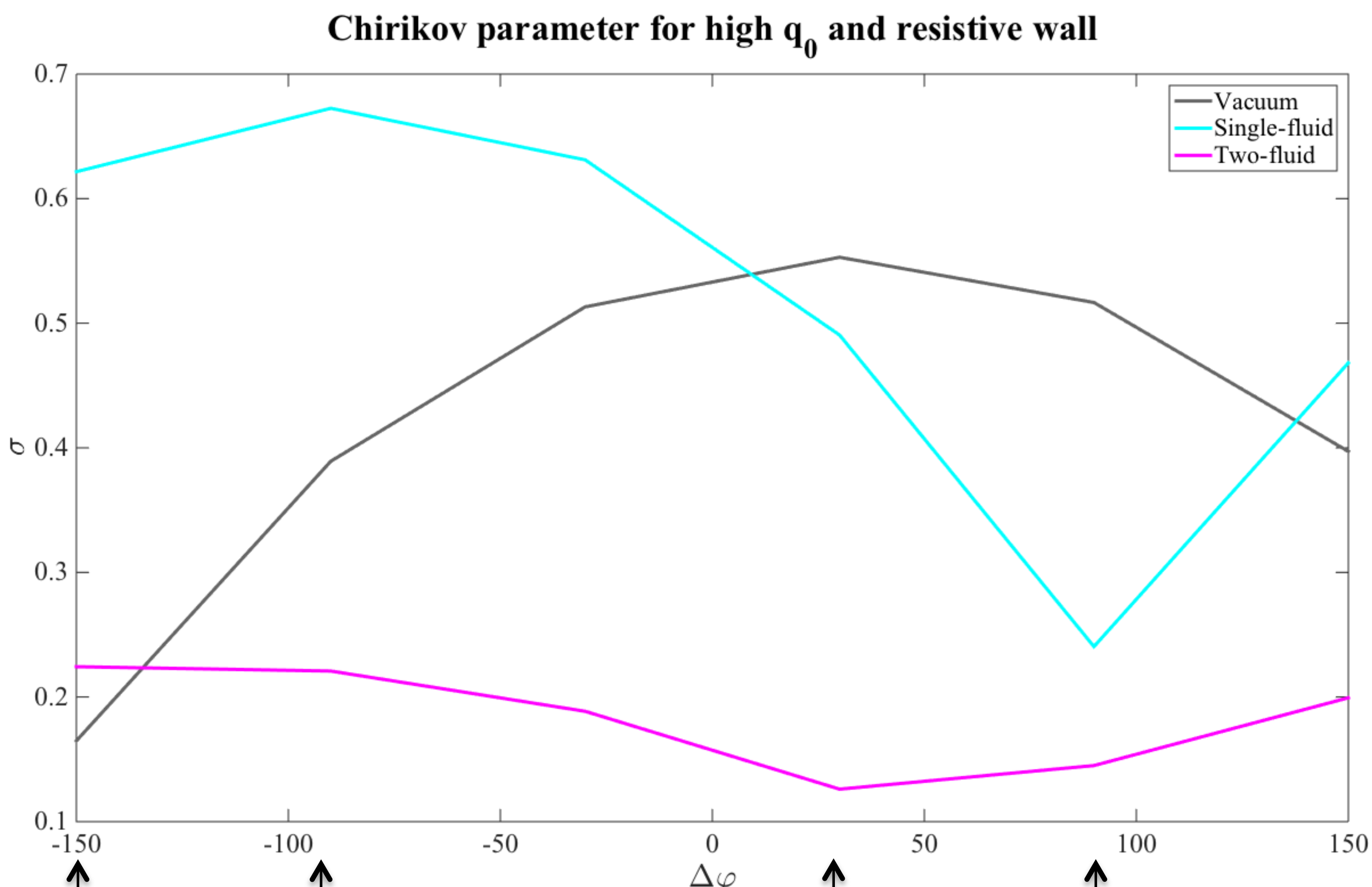
Chirikov parameter at pedestal top



non-resonant ELM-free vacuum resonant strong mitigation

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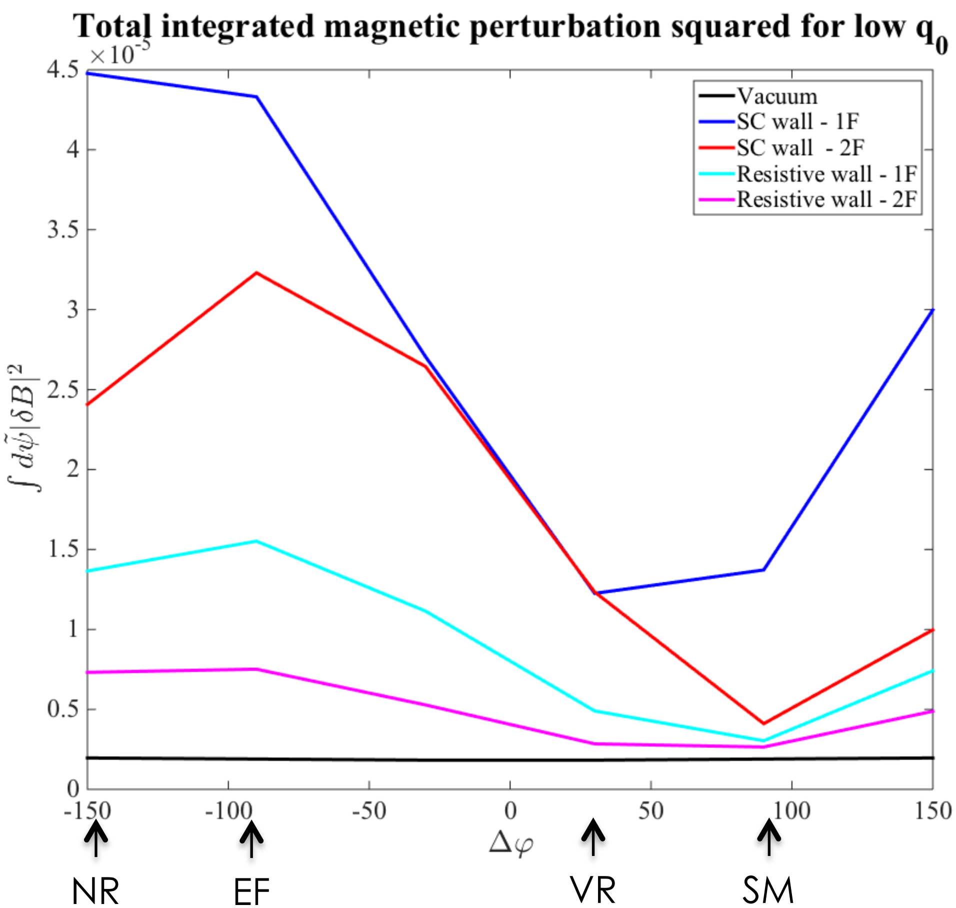
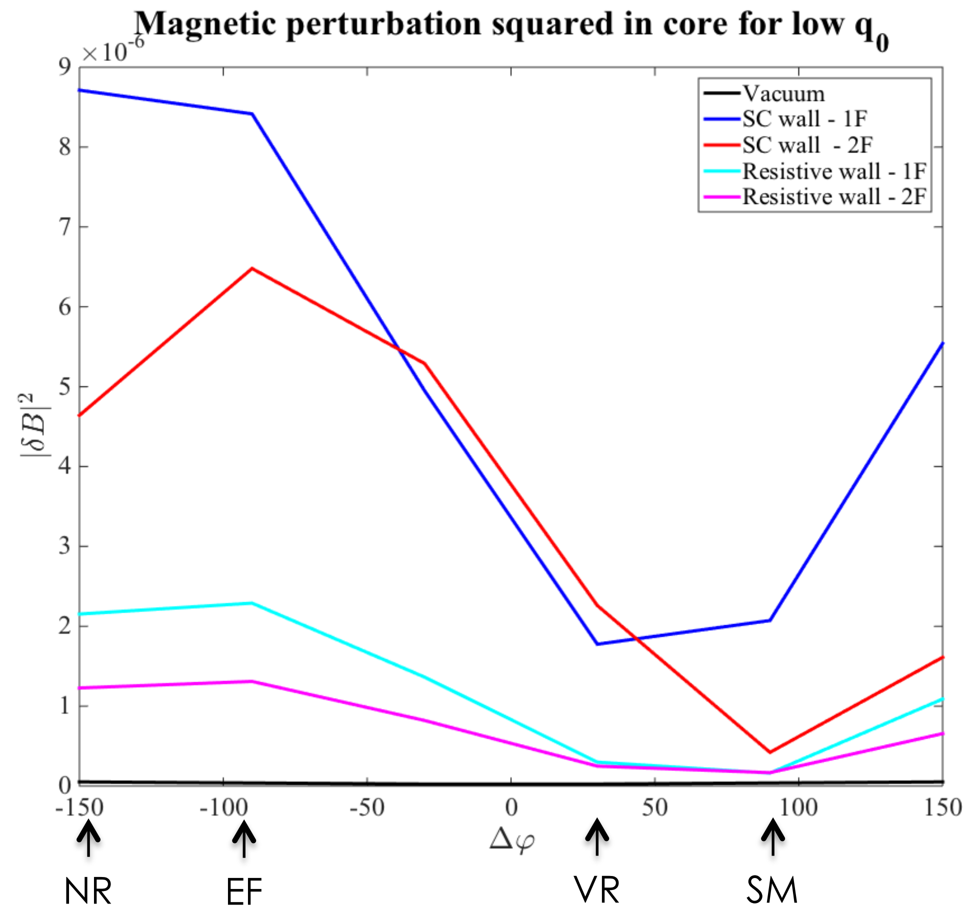
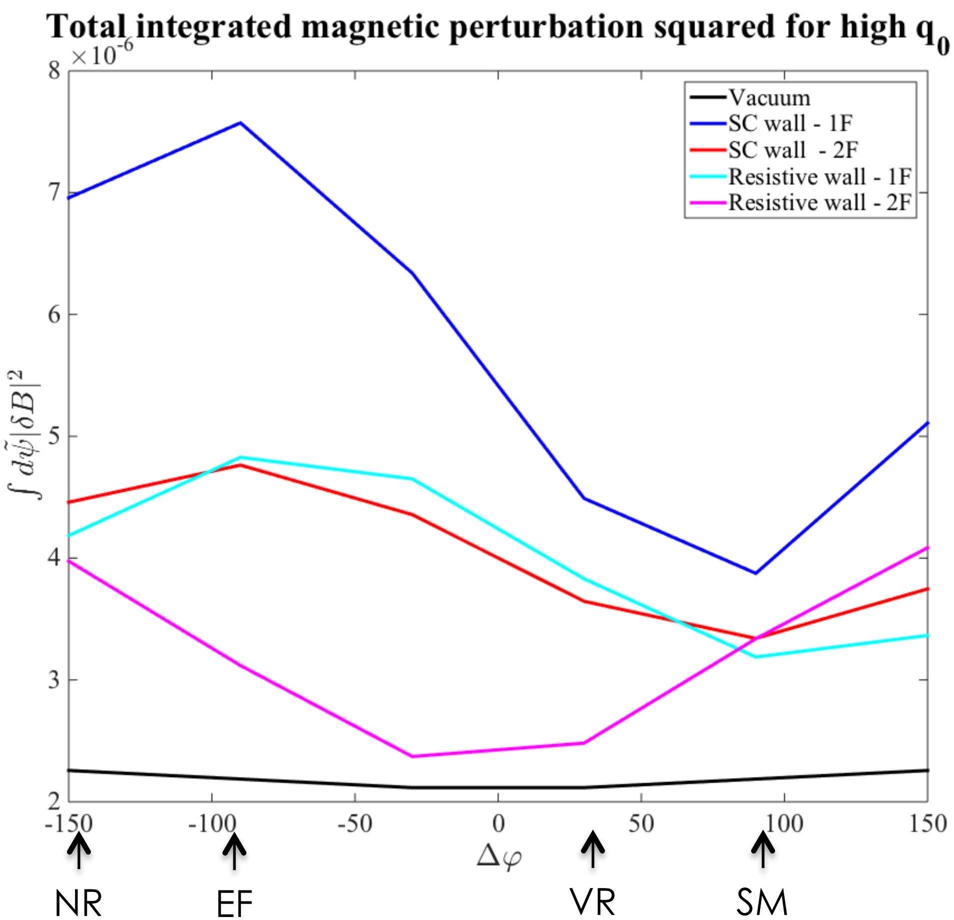
Total integrated magnetic perturbation for low q_0

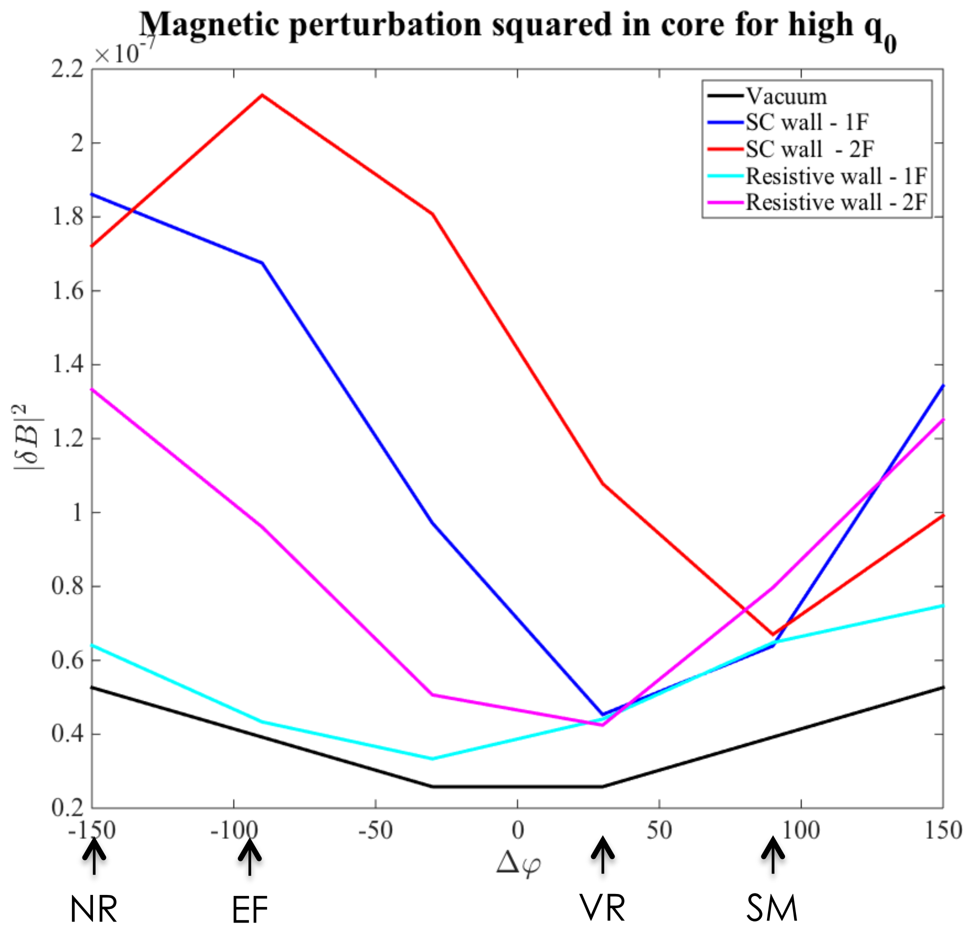




- **Phasing and relative magnitudes agree well**
- **Poor correlation with ELM suppression**

Total integrated magnetic perturbation for high q_0





- **Non-negligible contribution from edge modes**
- **Phasing varies a bit & relative magnitude varies substantially**

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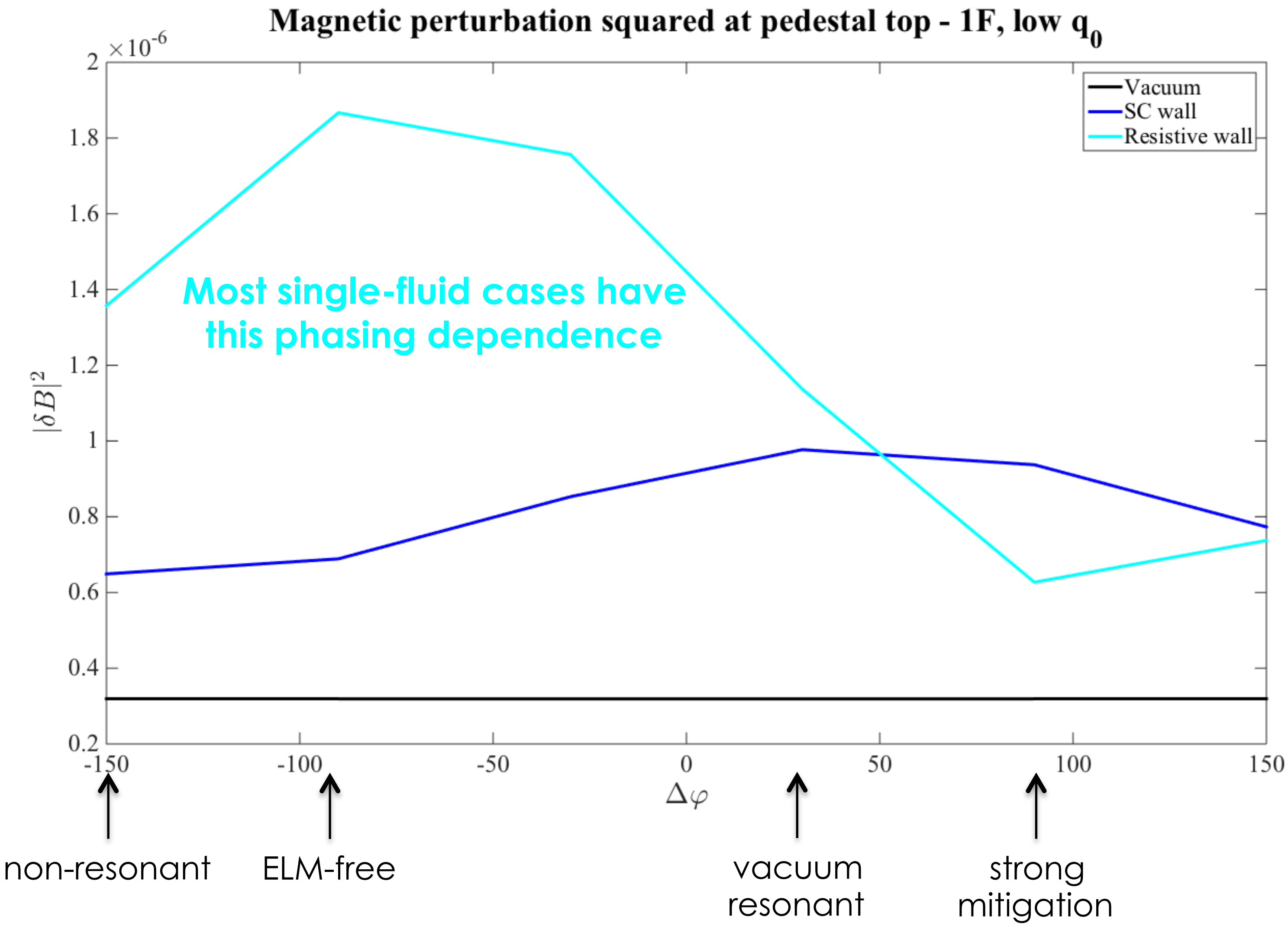
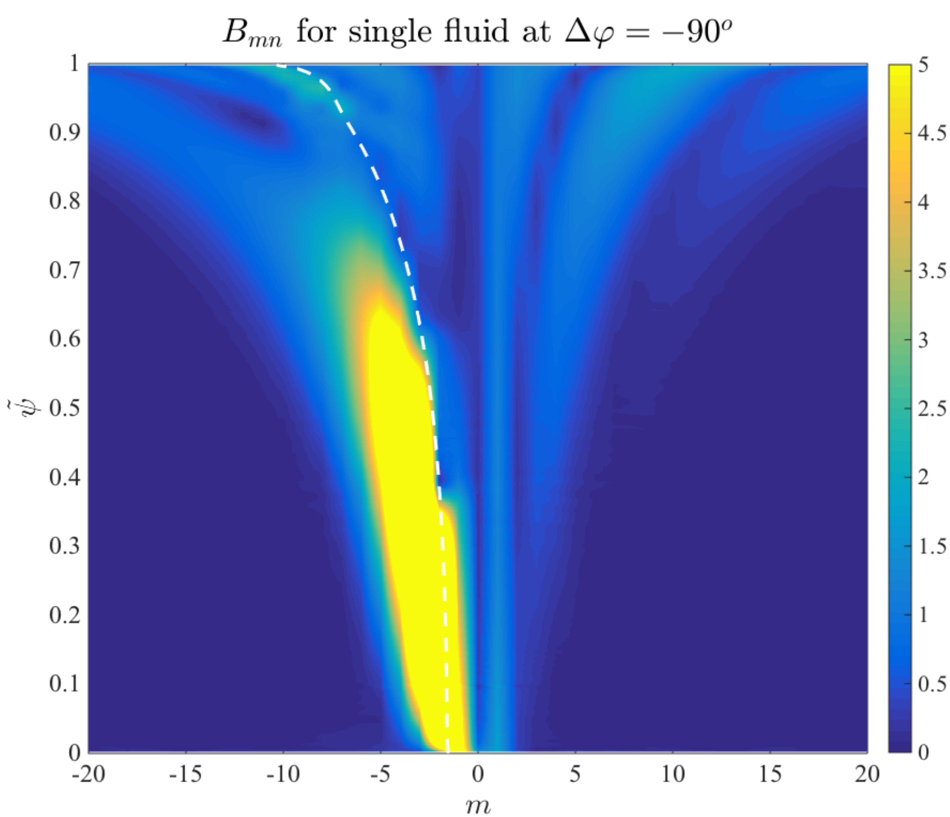
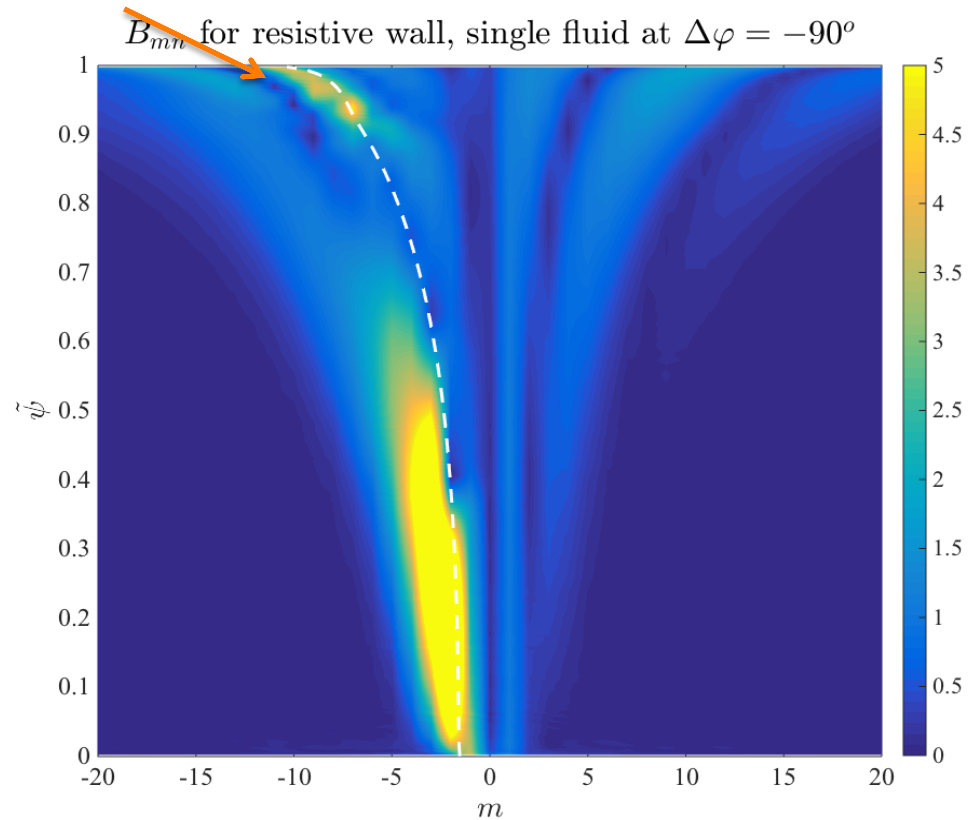
Wall type important for single-fluid, low q0 case



Close, superconducting wall can suppress modes

Resistive wall allows
for enhanced tearing





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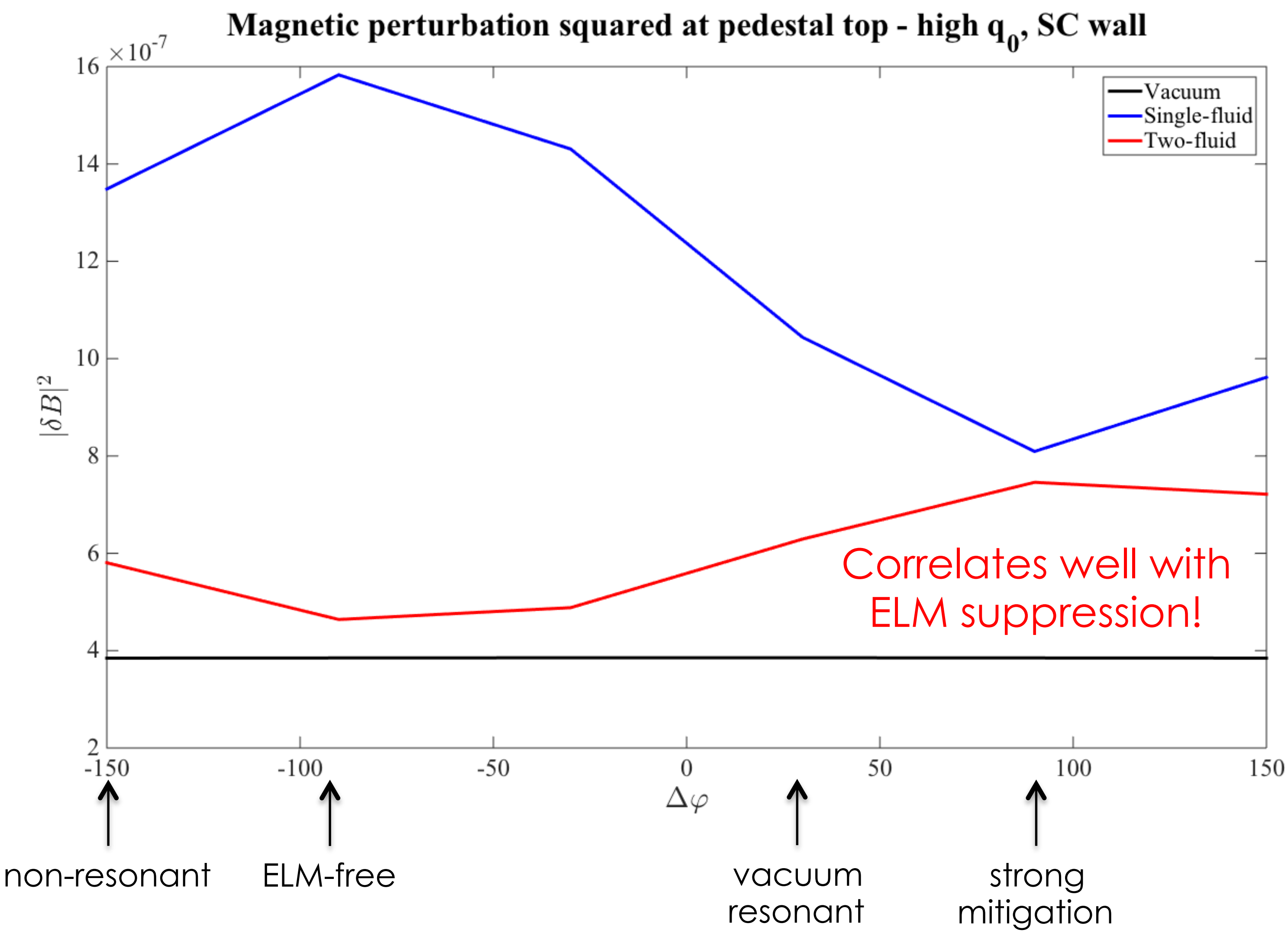
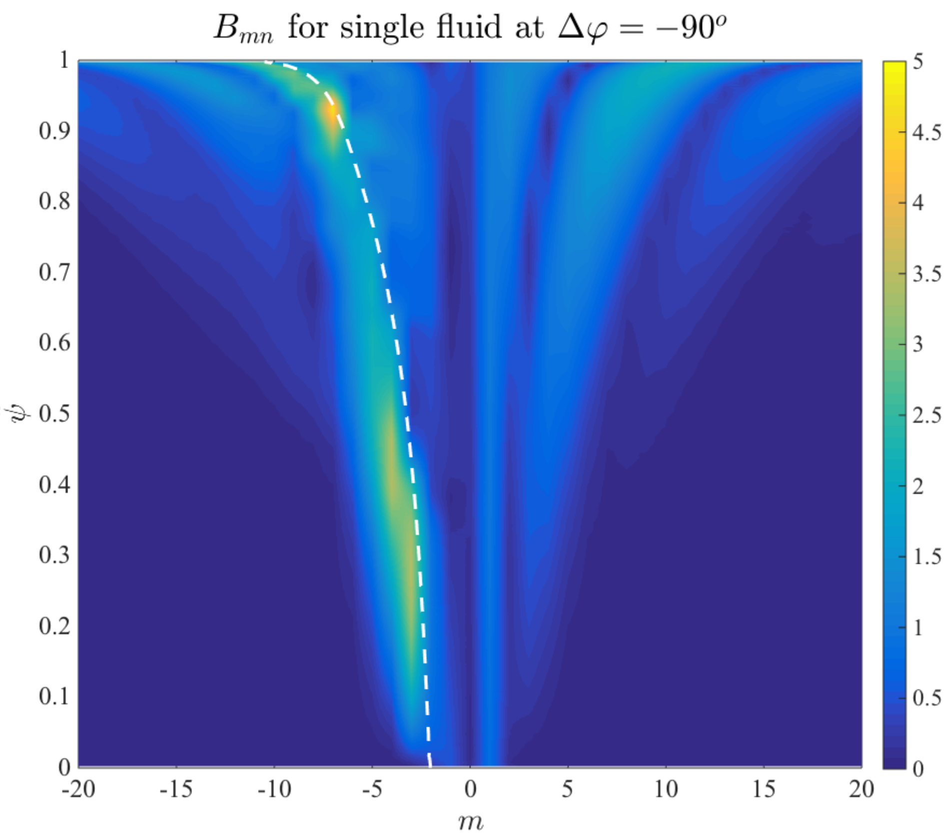
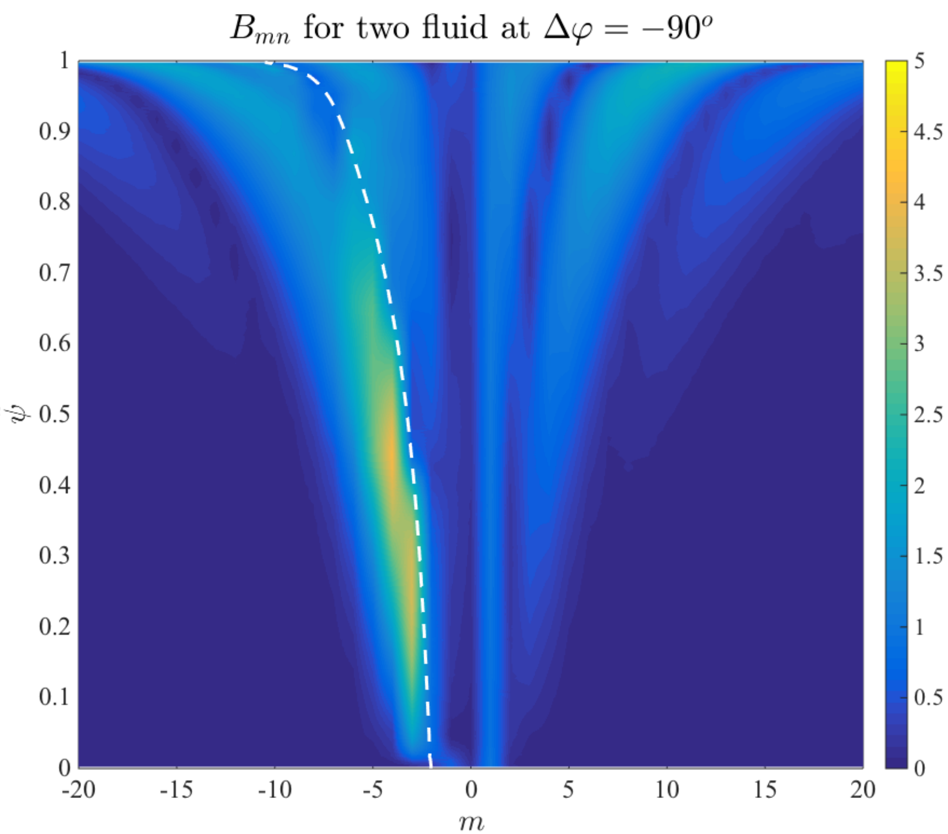
Two-fluid cases have different phasing dependence



Lack of single-fluid rotation allows for spurious tearing





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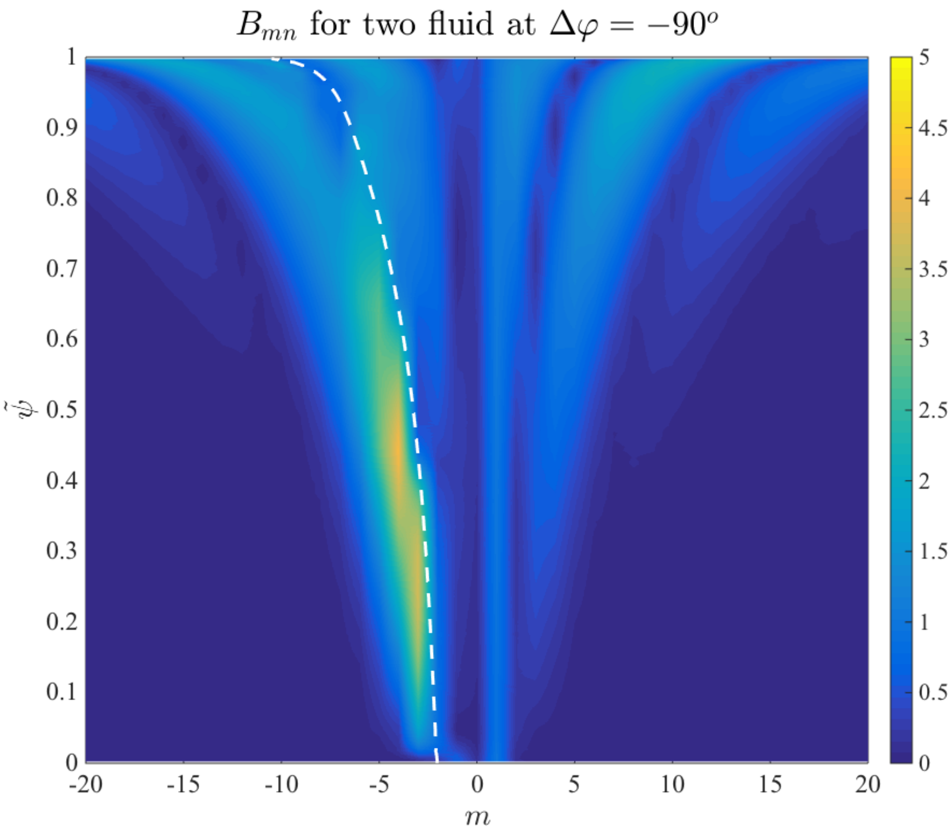
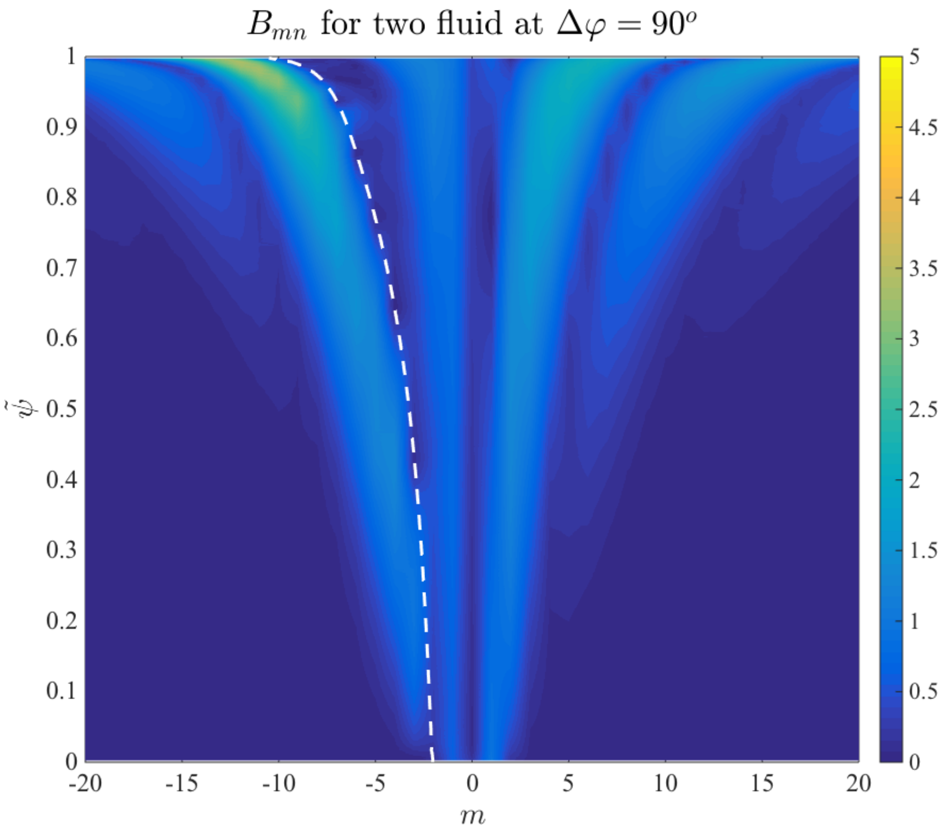
Edge kink strongest where ELM mitigation observed





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Conclusion

- **ELM mitigation on ASDEX Upgrade appears to be governed by non-resonant, kink-like structures in the edge**
  - Metrics that use resonant fields only fail to capture this
  - Magnitude of perturbation at pedestal top does a good job
- **Details of equilibrium and physics models are important**
  - Strong electron rotation and lack of ion rotation highlight importance of two-fluid effects
    - Spurious tearing (possibly driven by core modes?) in single-fluid runs produces poor correlations with observed ELM mitigation
    - Two-fluid effects suppress tearing in edge and allow kink-like structure to dominate
  - Safety factor profiles
    - Important in core where profile varies substantially
    - Some effect on response magnitude, but not phasing, at pedestal top
  - Superconducting wall can suppress physical modes recovered by resistive wall simulations

Future work

- **Make direct comparisons to results from MARS-F and VMEC**
- **Perform quantitative validation with ASDEX Upgrade experimental results**
- **More simulations of ASDEX Upgrade and DIII-D discharges**
  - Past DIII-D results already showed importance of electron rotation
    - Wade, M.R. et al. Nucl. Fusion. **55** 023002 (2015).
    - Varied rotation with co- and counter-NBI
    - ELM suppression observed in shots with zero electron rotation at pedestal top, allowing for tearing there
    - Observed only ELM mitigation in shots where there is electron rotation in the edge
  - Perhaps better ELM mitigation or suppression is/could be observed on ASDEX Upgrade in shots where electron rotation is driven in edge?

- **Additional slides**

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