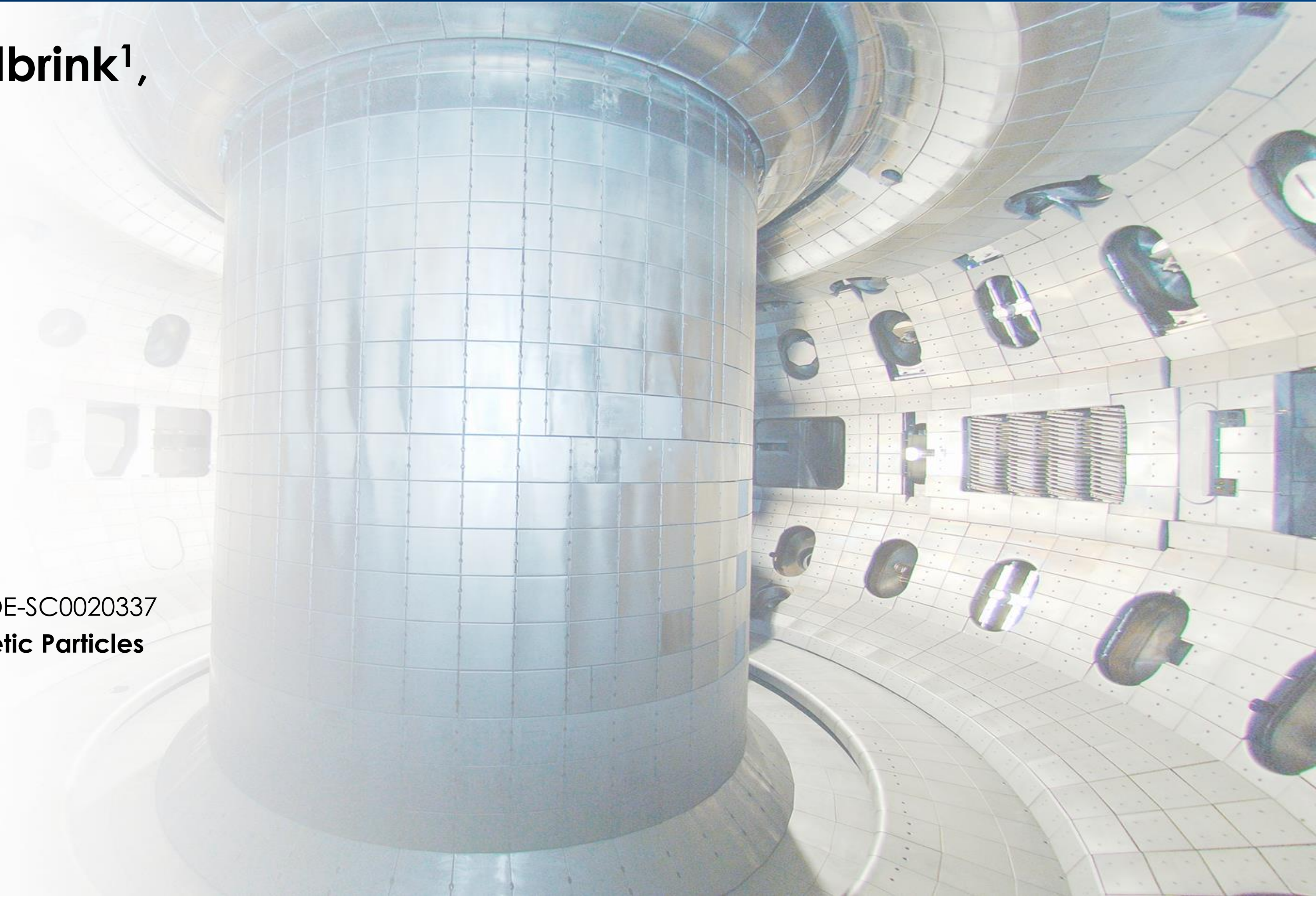
Fast Ion Losses and Plasma Response Induced by Externally Applied Magnetic Perturbations on DIII-D



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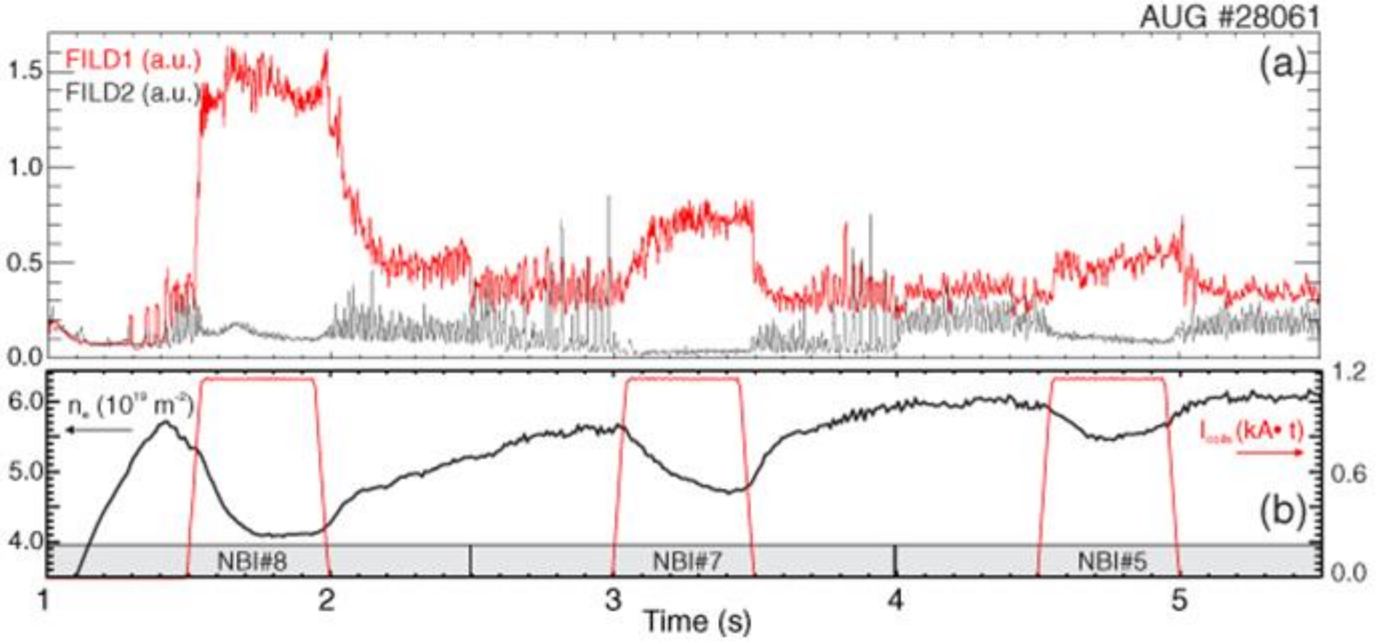
Resonant Magnetic Perturbations (RMPs) used to mitigate ELMs cause fast ion transport

- **3D fields lead energetic particle (EP) orbits to be lost to the vessel walls**
  - Losses from RMPs seen on DIII-D [1], AUG [2], KSTAR [3], and others
- **Losses depend on applied perturbation spectra [4]**
- **Plasma response to external 3D fields can magnify or shield perturbations [5,6]**
  - Response amplitudes often have strong dependence on β_n
- **This study focuses on the effect of β_n on RMPs and EP losses**

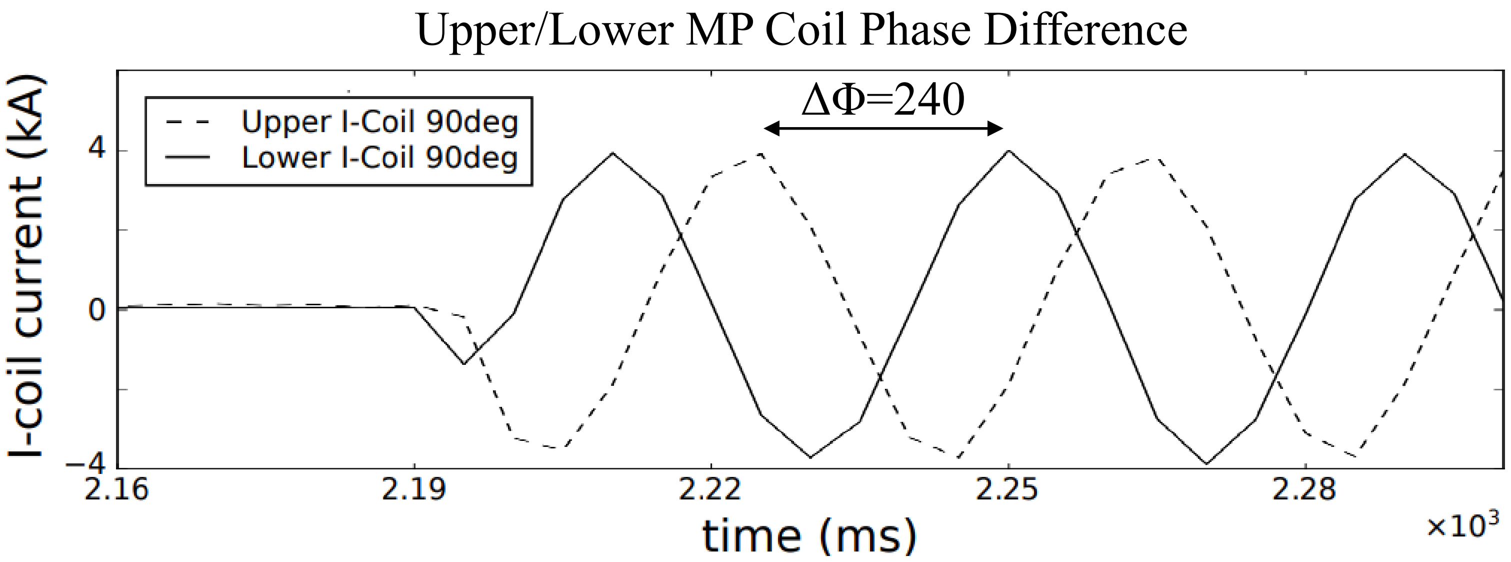


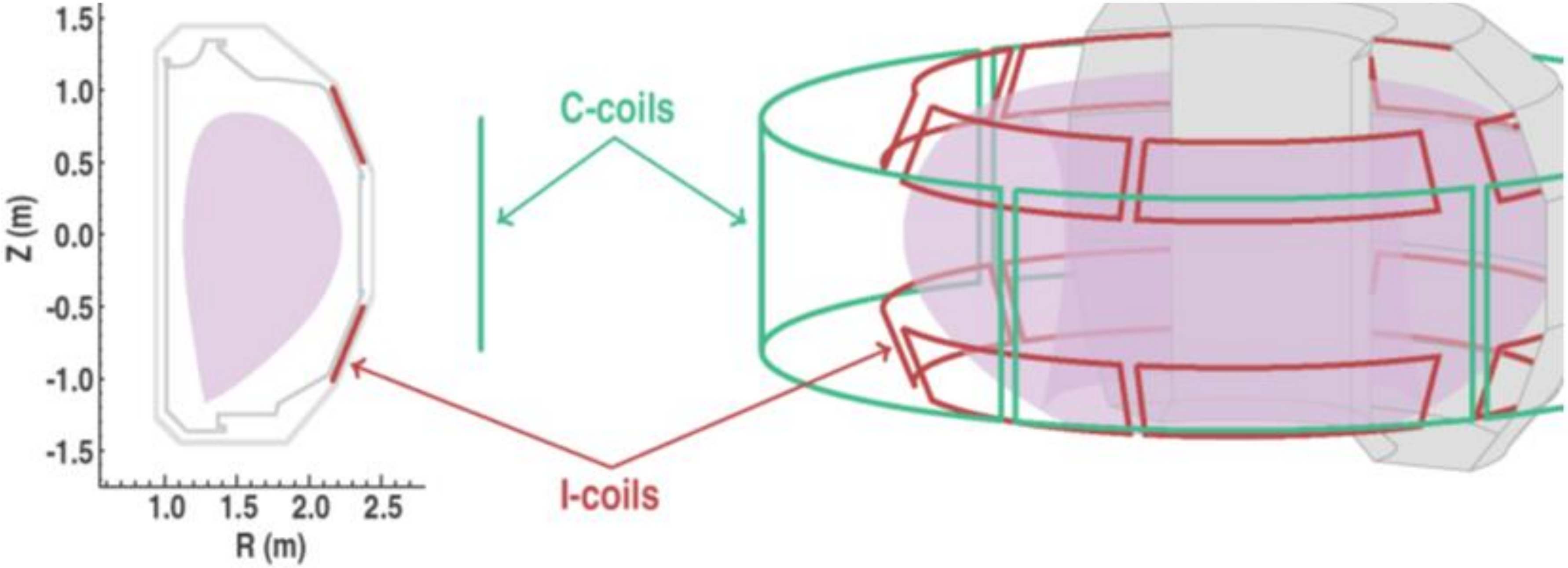
[1] M A Van Zeeland *et al* 2015 *Nucl. Fusion* **55** 073028
[2] M Garcia-Munoz *et al* 2013 *Plasma Phys. Control. Fusion* **55** 124014
[3] K Kim *et al* 2018 *Phys. Plasmas* **25** 122511
[4] K He *et al* 2021 *Nucl. Fusion* **61** 016009
[5] H Reimerdes *et al* 2004 *Phys. Rev. Lett.* **93** 135002
[6] N C Logan *et al* 2016 *Phys. Plasmas* **23** 056110

Outline

- **Background Information**
- **Experimental β_n Scan on DIII-D**
- **Simulations of L- and H-mode Losses**

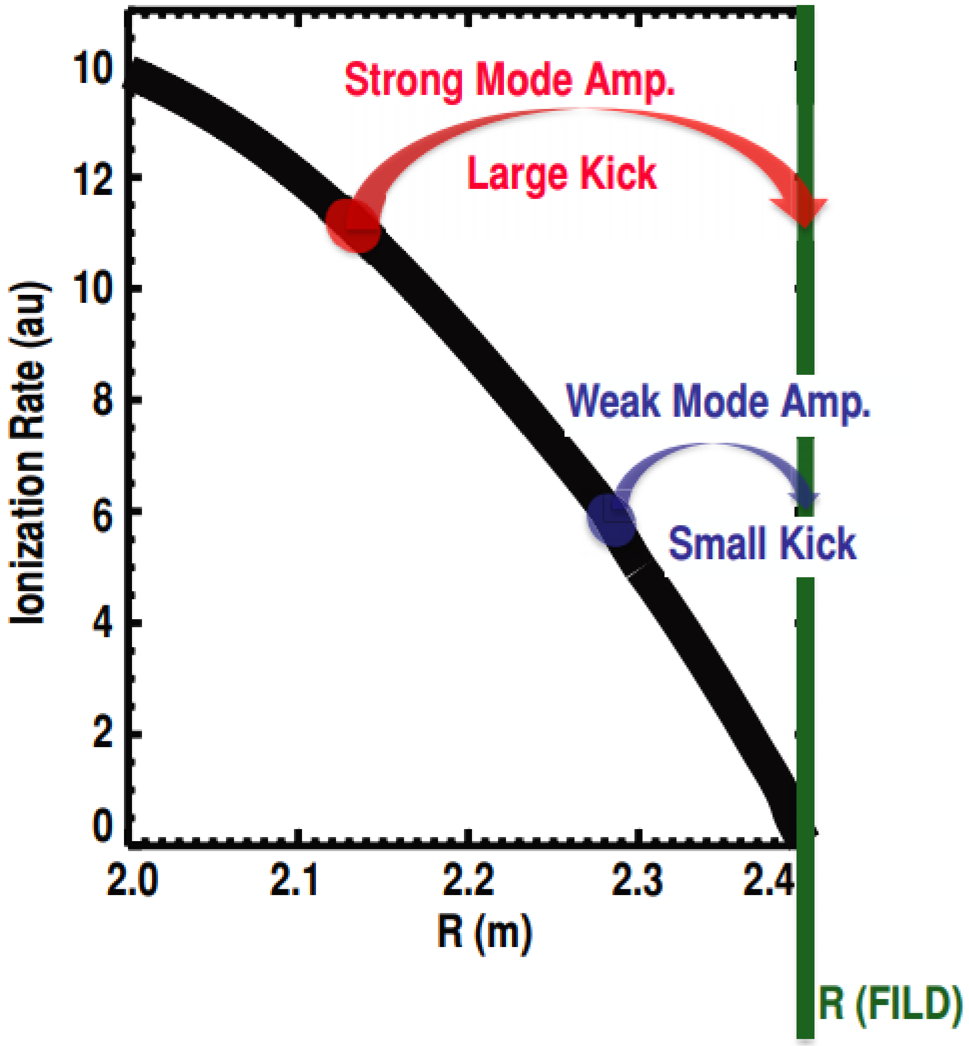
Internal RMP coils on DIII-D operate upper and lower coils independently to include a phase shift





The Light Ion Beam Probe (LIBP) technique [1] uses neutral beam prompt loss to study effects of magnetic perturbations

- **Fast Ion Loss Detectors (FILDs) on DIII-D [2,3] measure losses at the midplane and a slightly lower poloidal location**
- **Beam modulation used to ensure only prompt loss is used in analysis**
- **Method relates loss fluctuations to kick size from perturbation [1]**



[1] X Chen *et al* 2013 *Nucl. Fusion* **53** 123019

[2] R K Fisher et al 2010 Rev. Sci. Instrum. 81 10D307

[3] X Chen et al 2012 Rev. Sci. Instrum. 83 10D707

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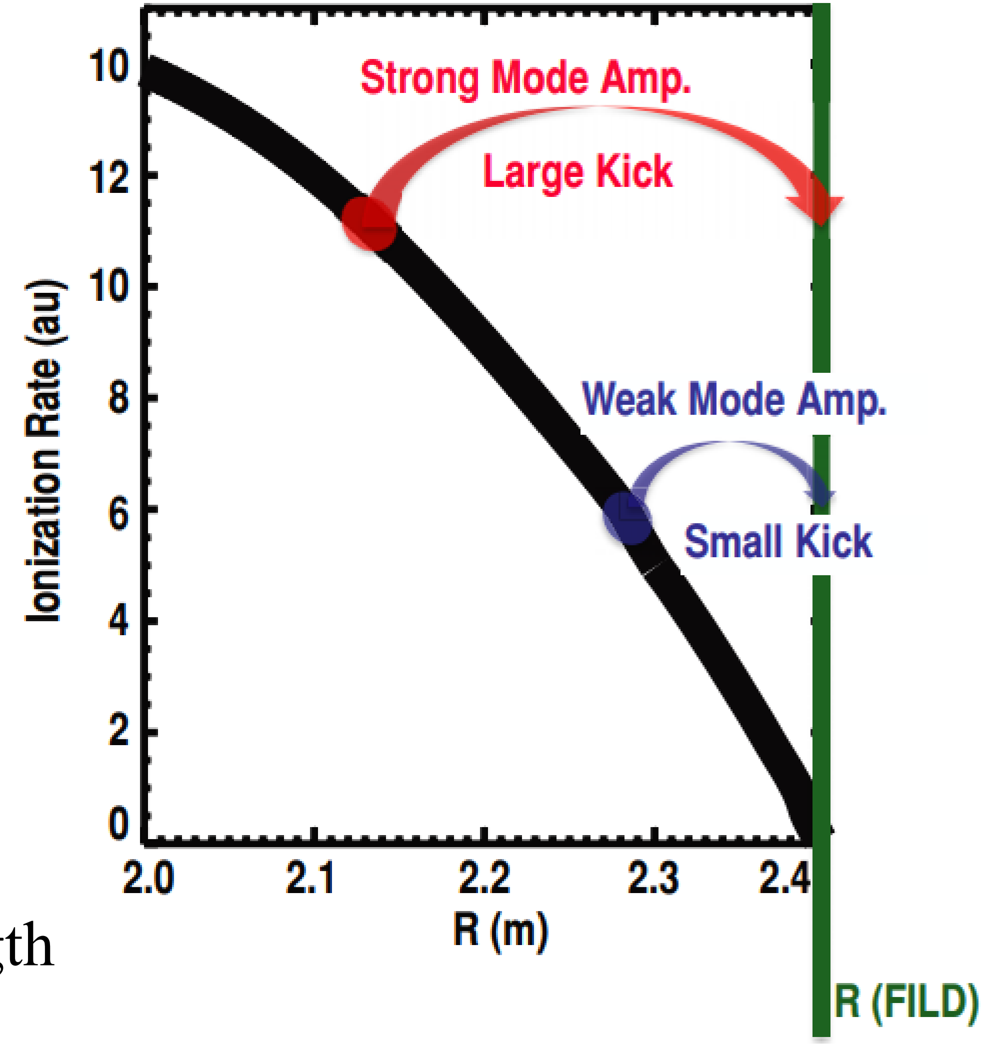
$$\boxed{\xi = \frac{\Delta F}{\bar{F}} \cdot L_i}$$

ξ: Orbit diplacement

$\frac{\Delta F}{\bar{F}}$: FILD modulation

L_i: Ionization scale length



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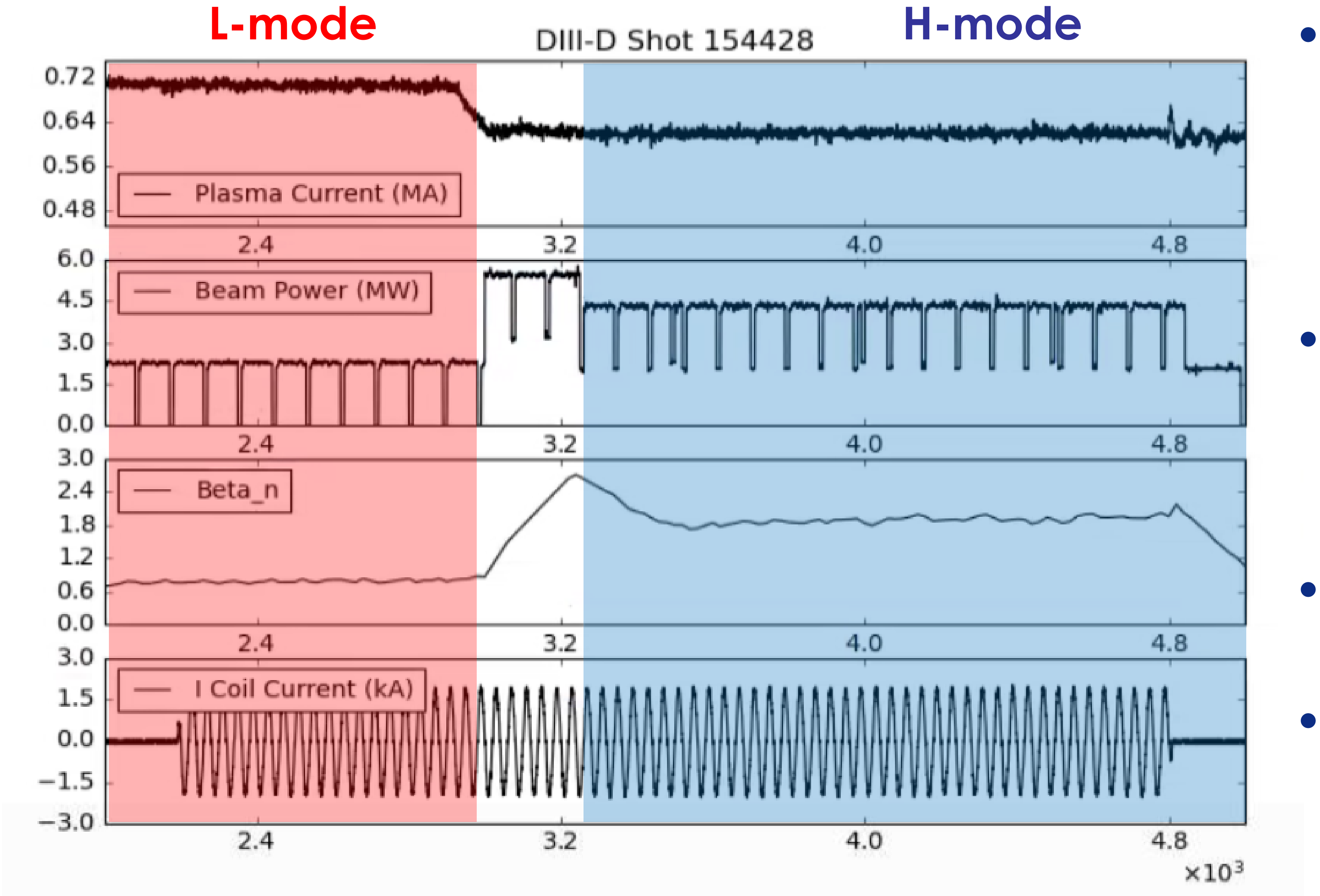
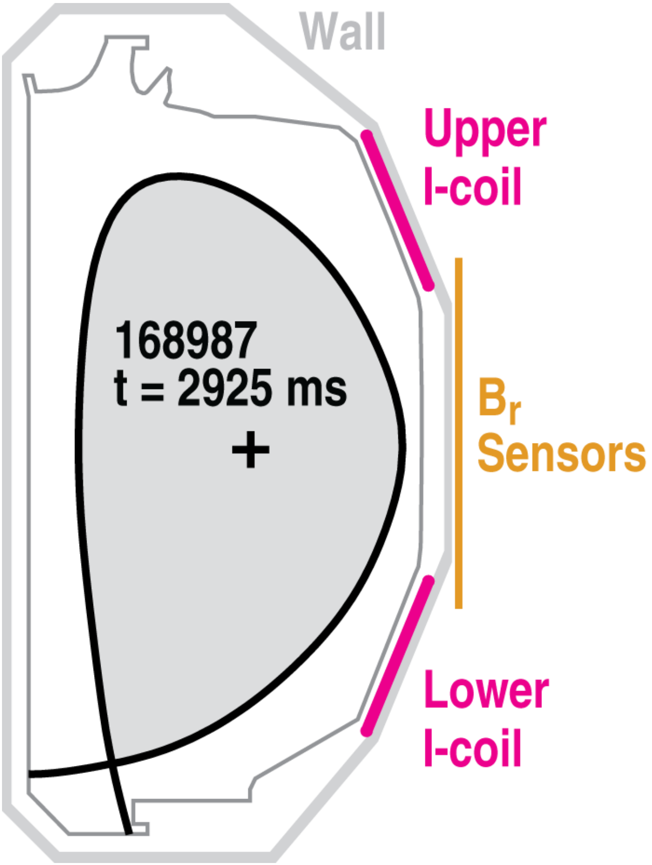
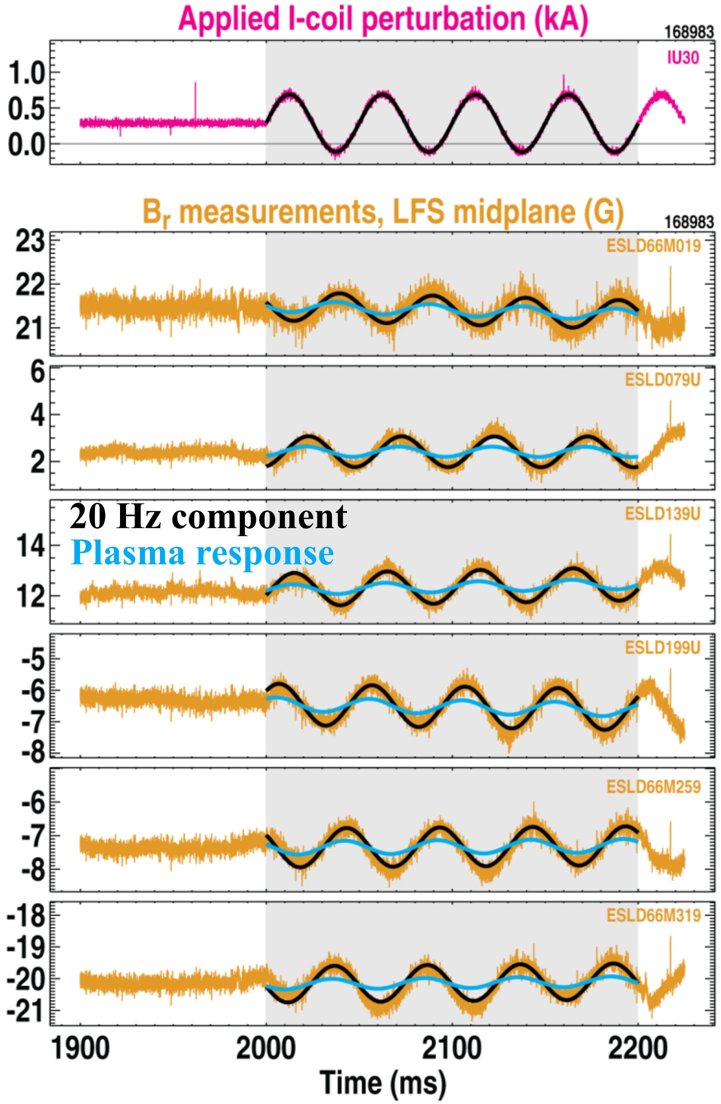
Experiment set up to scan RMP losses over range of β_n

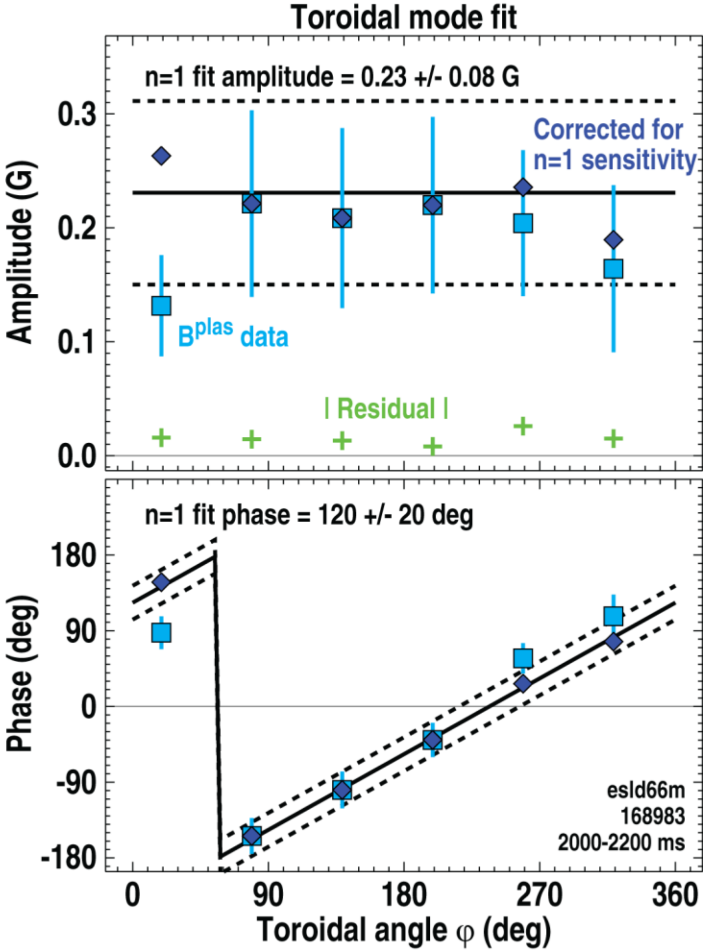


- **Discharges transition from L- to H-mode**
  - Current adjusted to align losses with FILD at L- to H-mode transition
- **RMP coils set in n=1 perturbation with $\Delta\phi = 240$**
  - Other experiments cover more β_n and $\Delta\phi$ values
- **Probing beam (Co-injection) at ~2 MW across transition**
- **Diagnostic loops at midplane measure plasma response**

Synchronous analysis of midplane magnetic probe data measures the plasma's response to the applied RMPs [1,2]



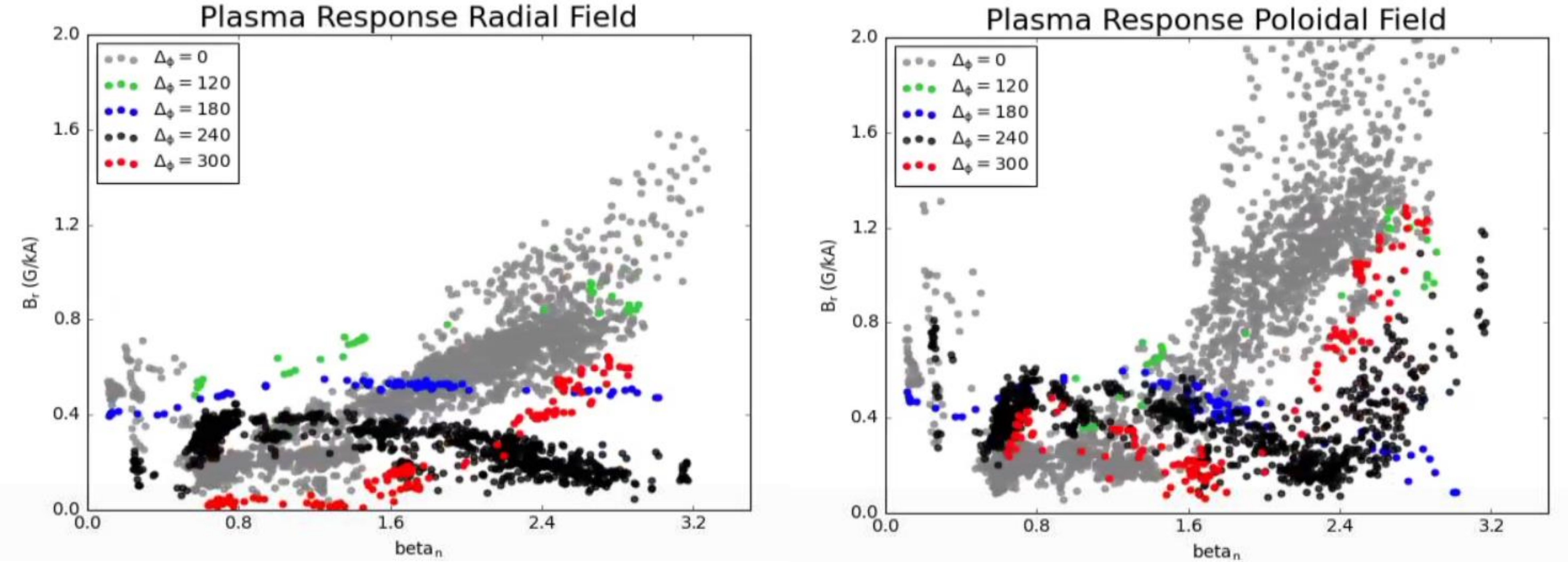




[1] E J Strait 2006 *Rev. Sci. Instrum.* **77** 023502
[2] J M Hanson *et al* 2011 *Nucl. Fusion* **52** 013003

Plasma response is suppressed at higher β_n up to a threshold for poloidal field in $\Delta\phi = 240$ spectrum

- **Previous results from DIII-D show that plasma response can have a significant effect on NBI loss levels [1]**



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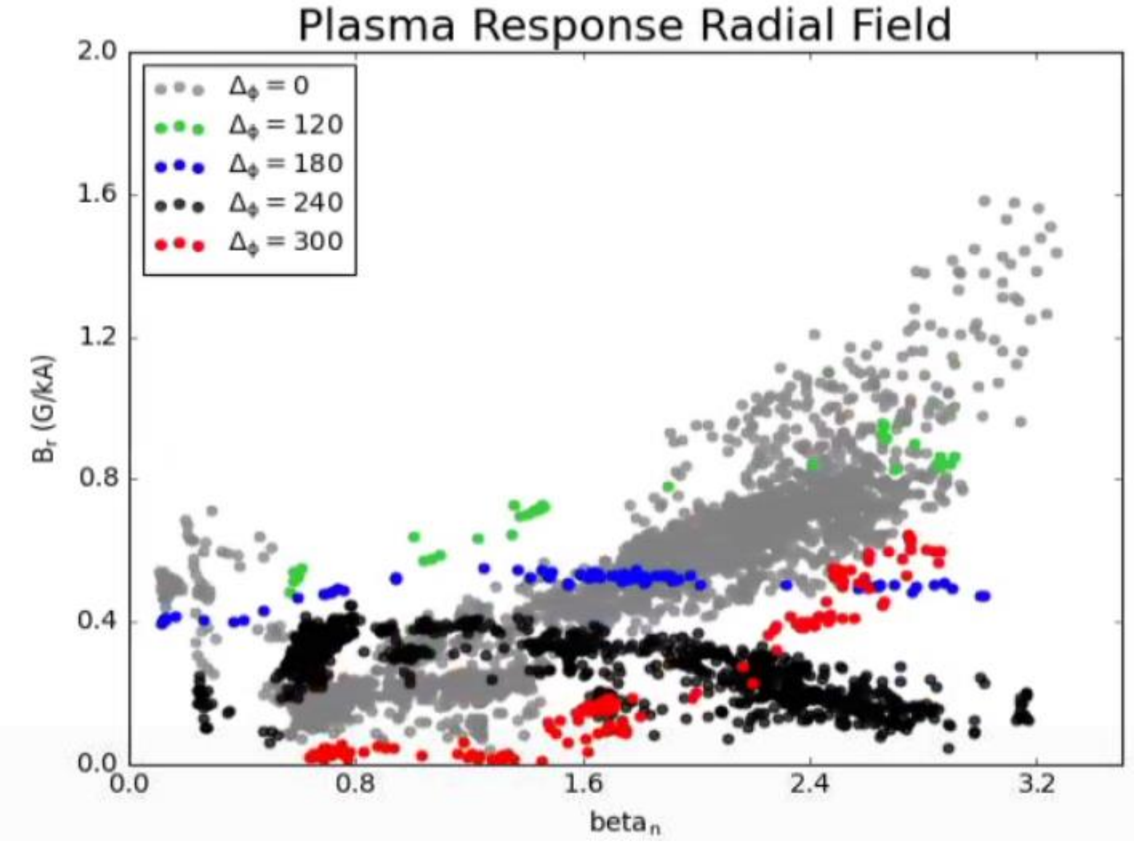

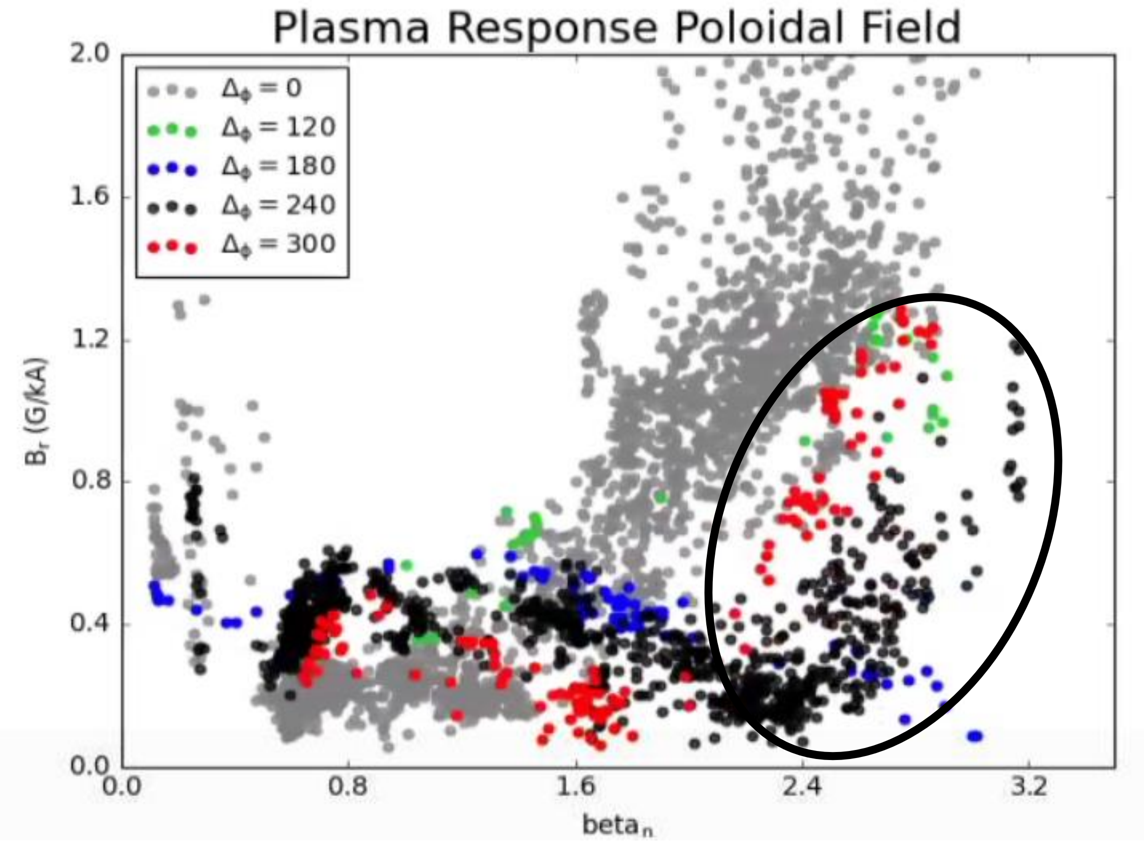

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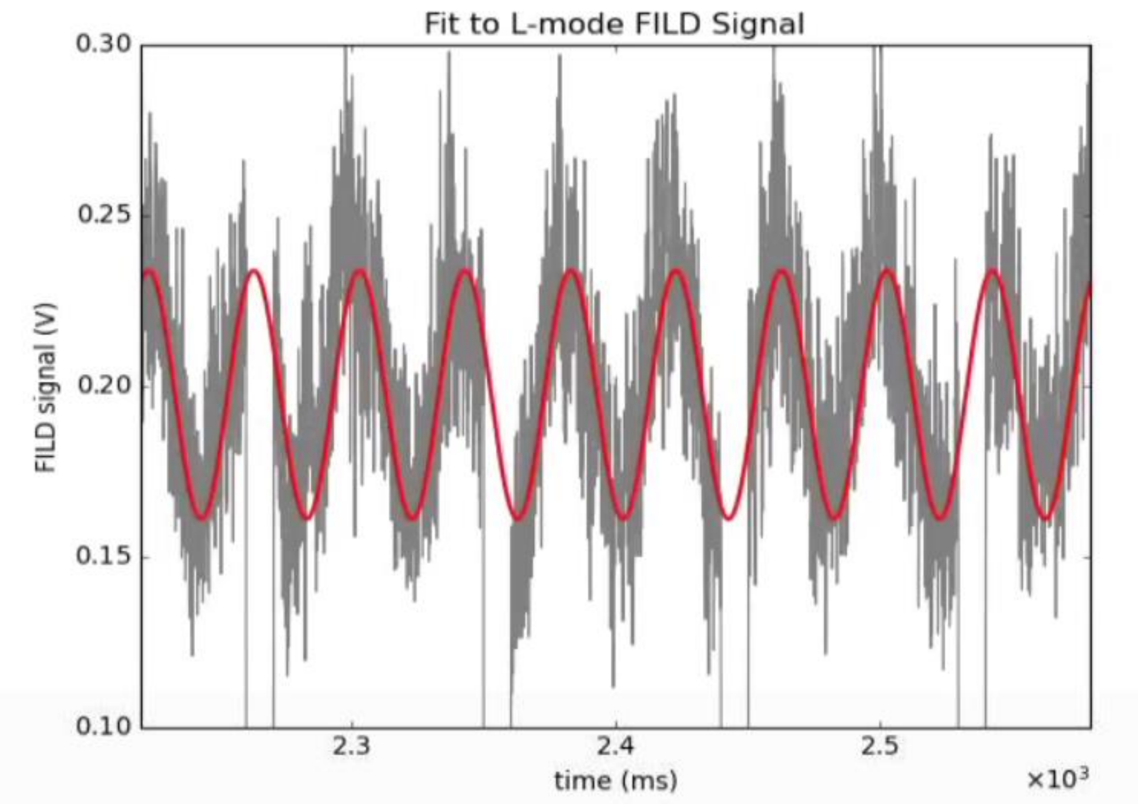
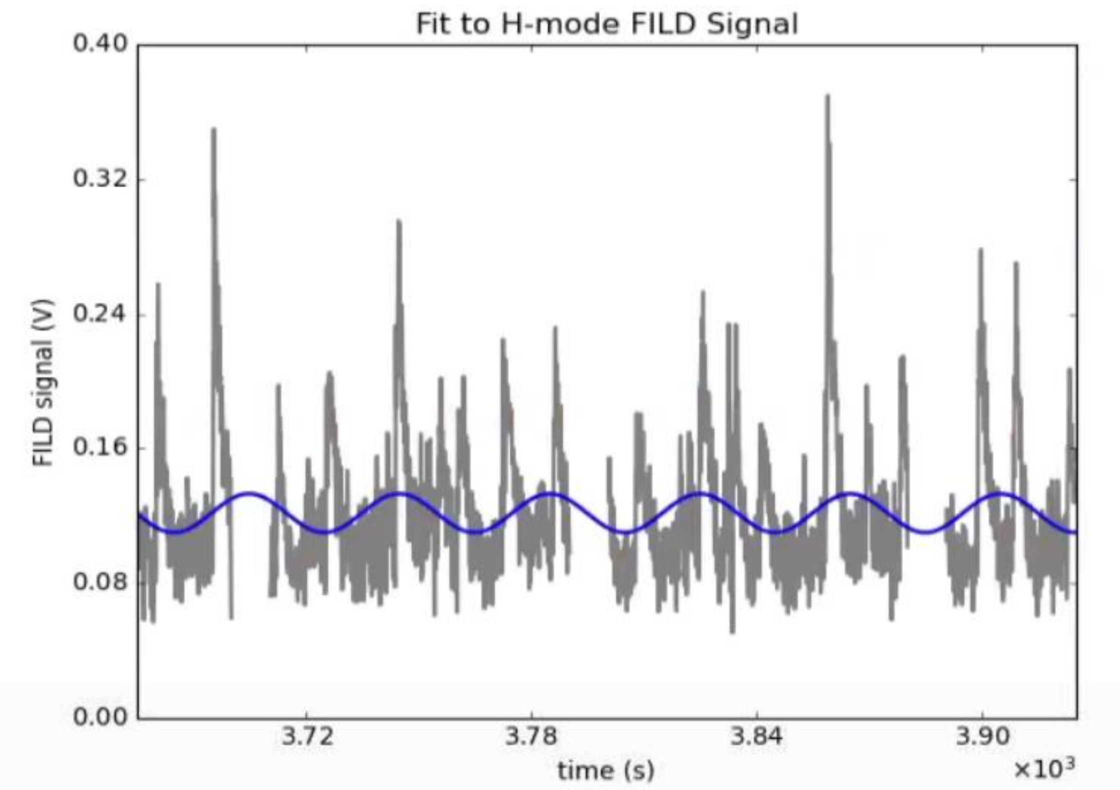
ELM subtraction allows for sinusoidal fitting of FILD data in H-mode analysis



- **Several sinusoidal fits are applied in the time ranges of interest for error estimation**
- **Simplified ELM detection model allows for determining average ELM signal in FILD data**
  - Not all ELMs are able to be removed, leading to larger errors than L-mode analysis
- **Beam modulation used for background subtraction**

ELM subtraction allows for sinusoidal fitting of midplane FILD data in H-mode analysis



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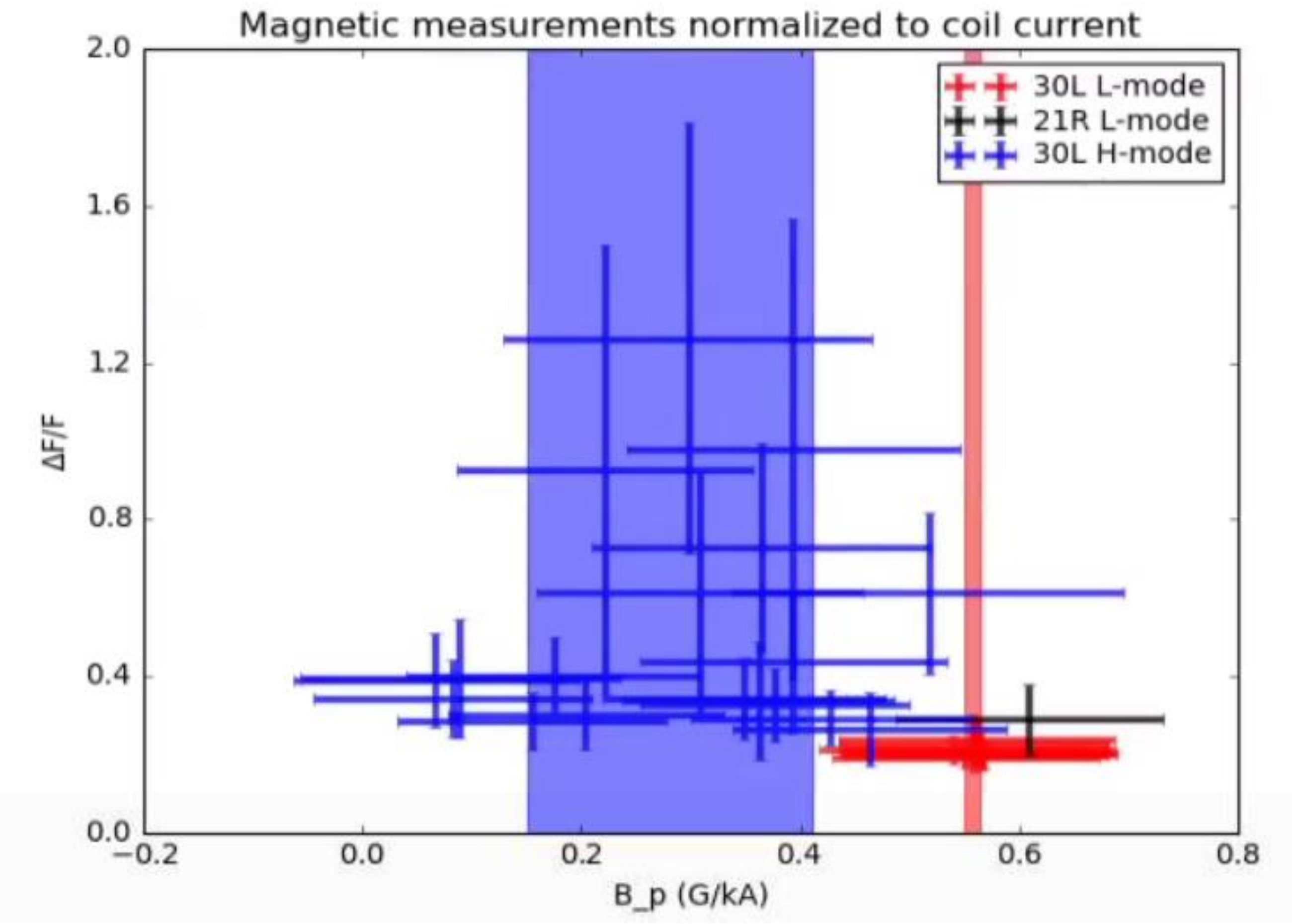
Shielded plasma response in H-mode doesn't suppress $\Delta F/\bar{F}$

- **Comparing 30L L-mode and H-mode:**
  - 62% increase in $\Delta F/\bar{F}$ from L- to H-mode
  - 34% decrease in B_r from L- to H-mode
  - 50% decrease in B_p from L- to H-mode
- **Consistent with simulations of RMP induced EP losses on EAST [1]**
  - Found plasma response shielding reduced magnetic island size, but large fast ion orbits see enough of the field to be lost



[1] K He *et al* 2021 *Nucl. Fusion* **61** 016009

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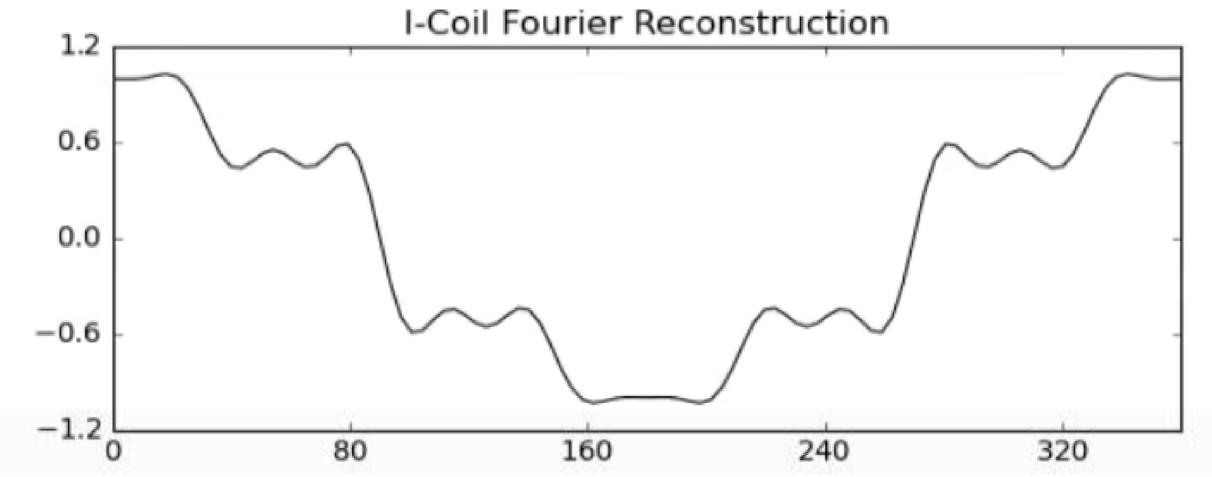
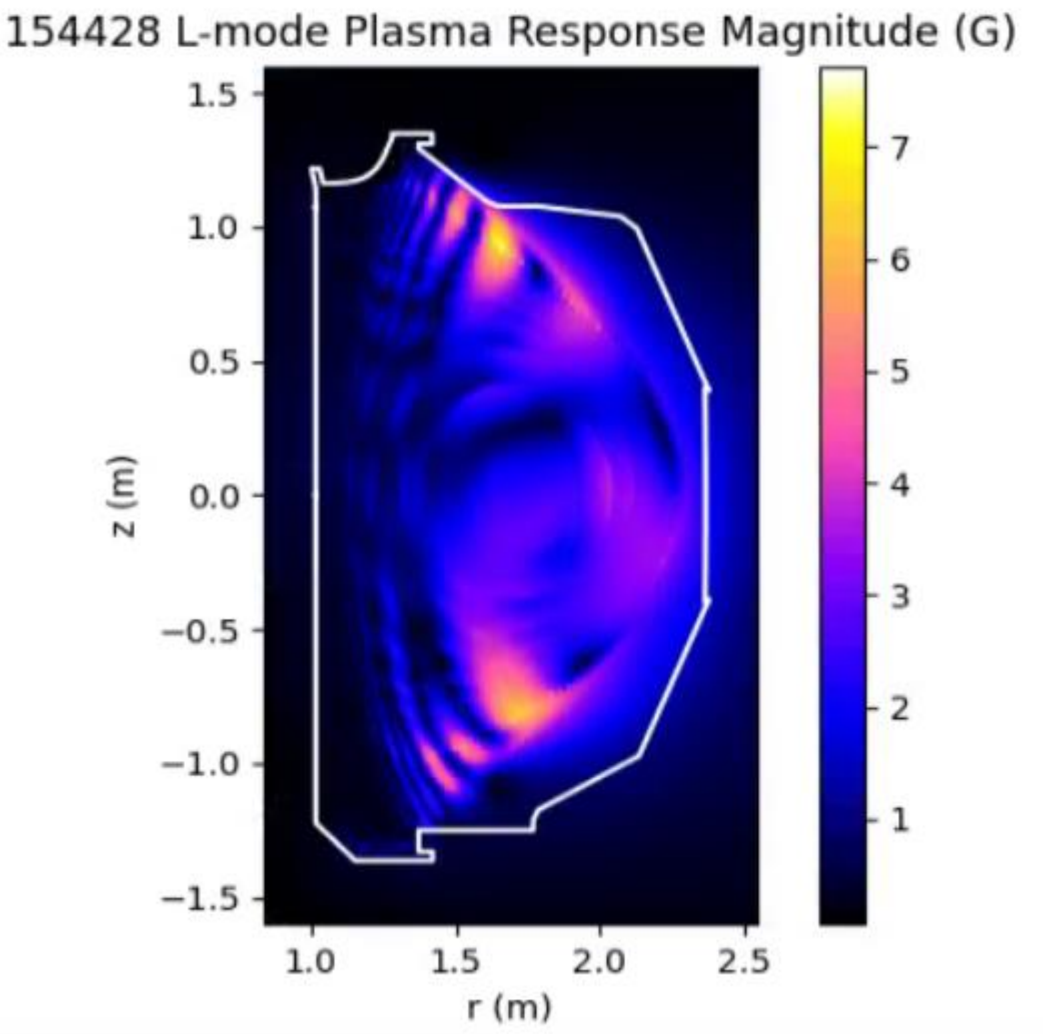
Experimental RMPs are recreated to simulate experimental conditions

- **M3D-C1[1] calculates both the vacuum 3D fields and plasma response**
  - Includes n=1,5,7,11,13 to reconstruct physical coils
- **Magnetic response in H-mode roughly 10% lower near wall at midplane**





[1] N M Ferraro 2012 Phys. Plasmas 19, 056105

[2] J Varje et al 2019 arXiv:1908.02482

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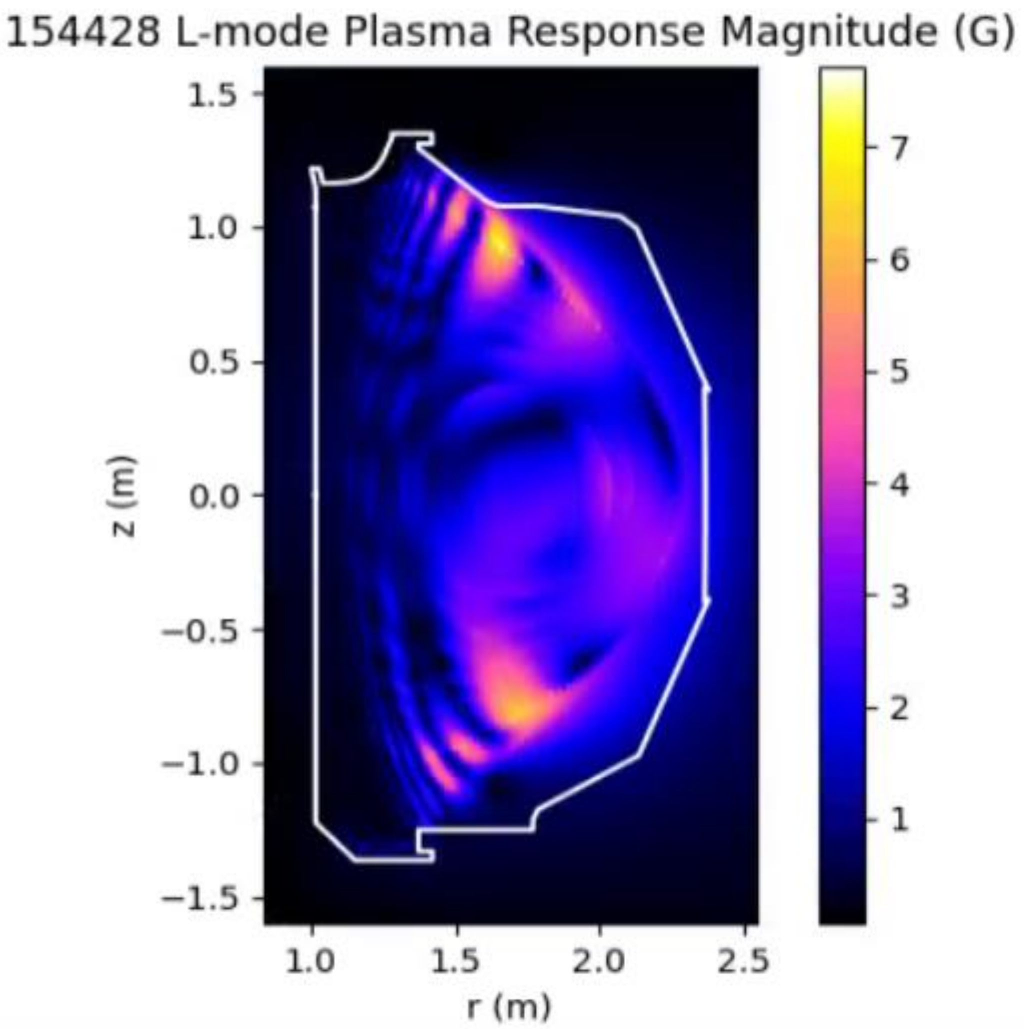
- **Beam distribution of markers followed through fields in ASCOT5 [2]**
  - Beam deposition distribution followed for a full poloidal orbit (prompt loss)
  - Simulate in 2D before 3D to filter out ions lost by the equilibrium fields



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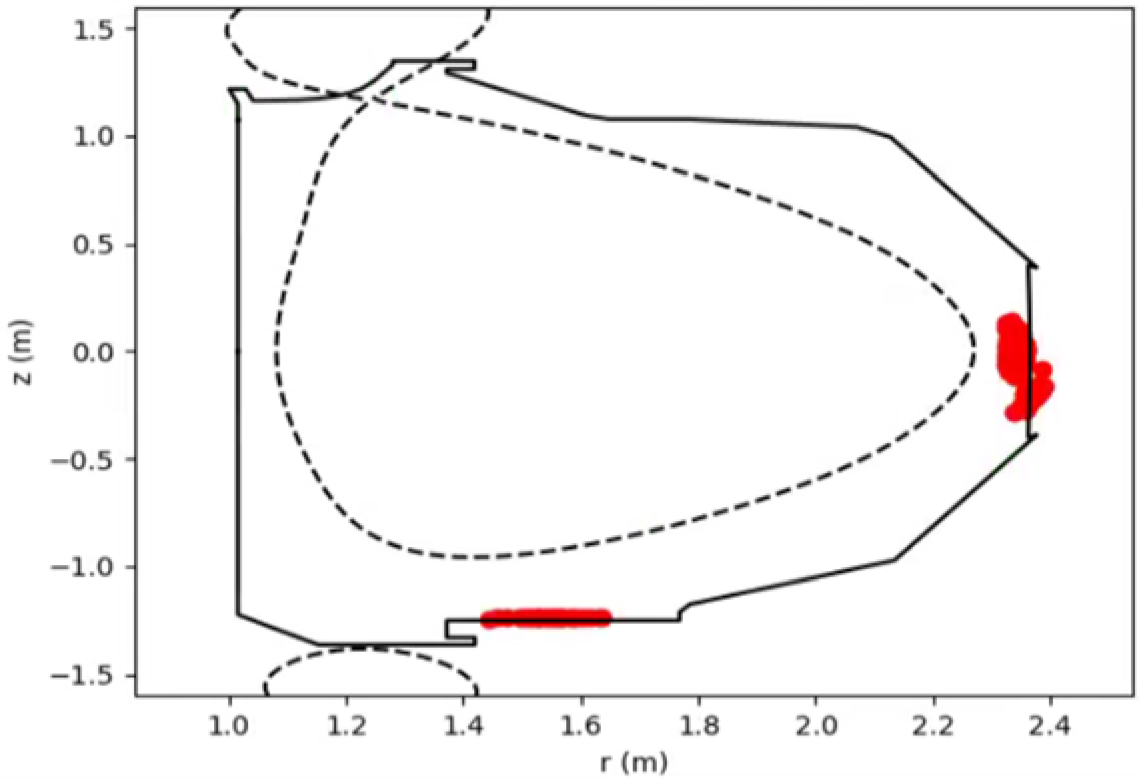
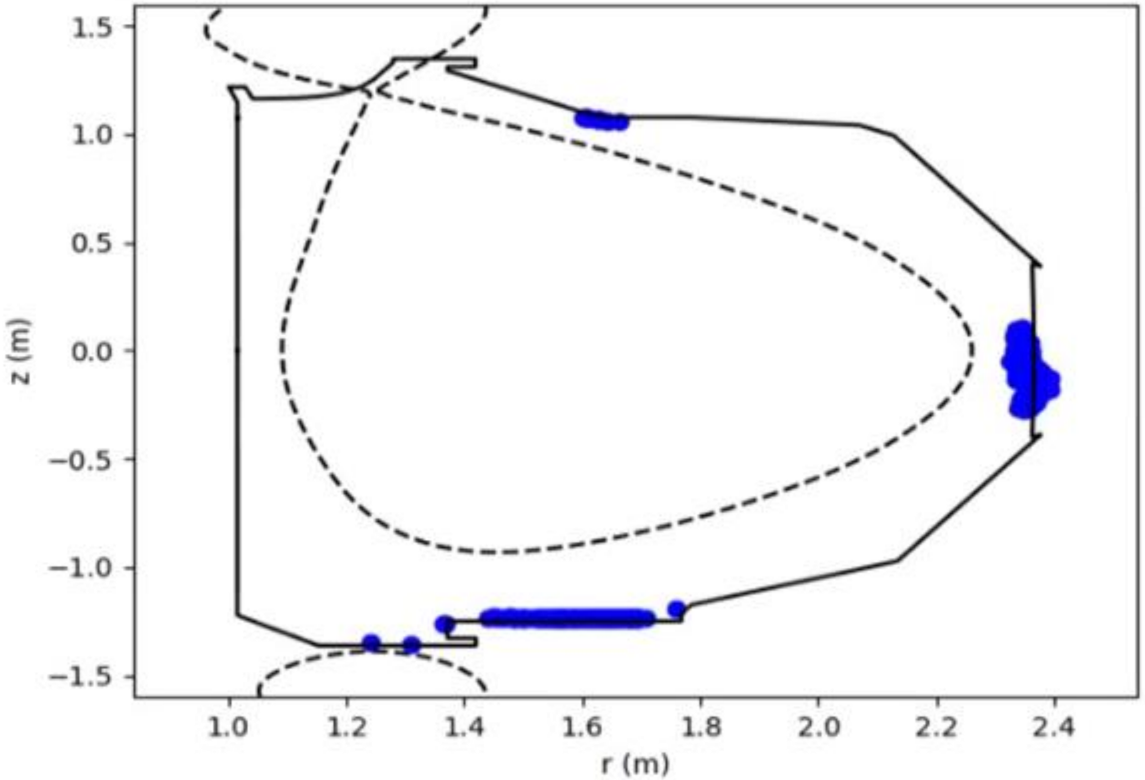
RMP induced losses are concentrated in outer midplane ports and at the vessel floor

- **Similar loss patterns seen in simulations on EAST [1]**
  - EAST losses to low field side are found to be resonant with the RMP

L-mode RMP Loss Hit Locations



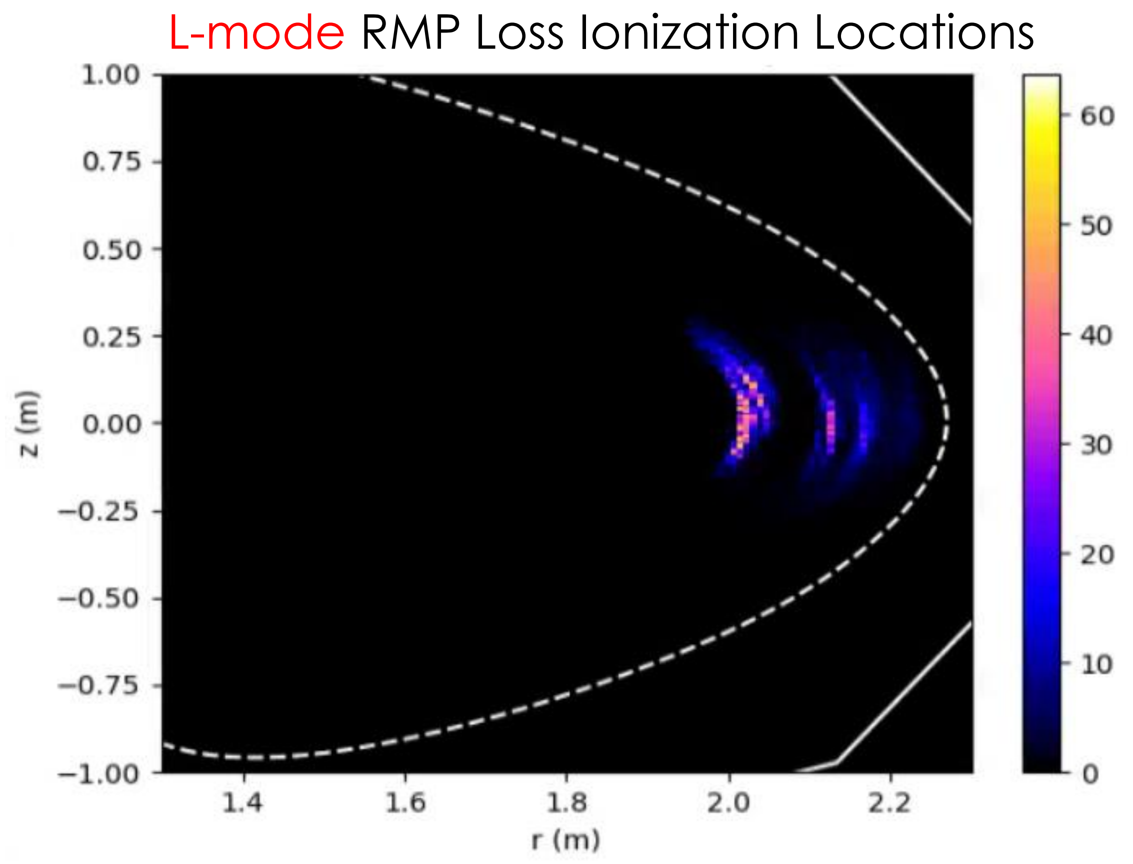
H-mode RMP Loss Hit Locations

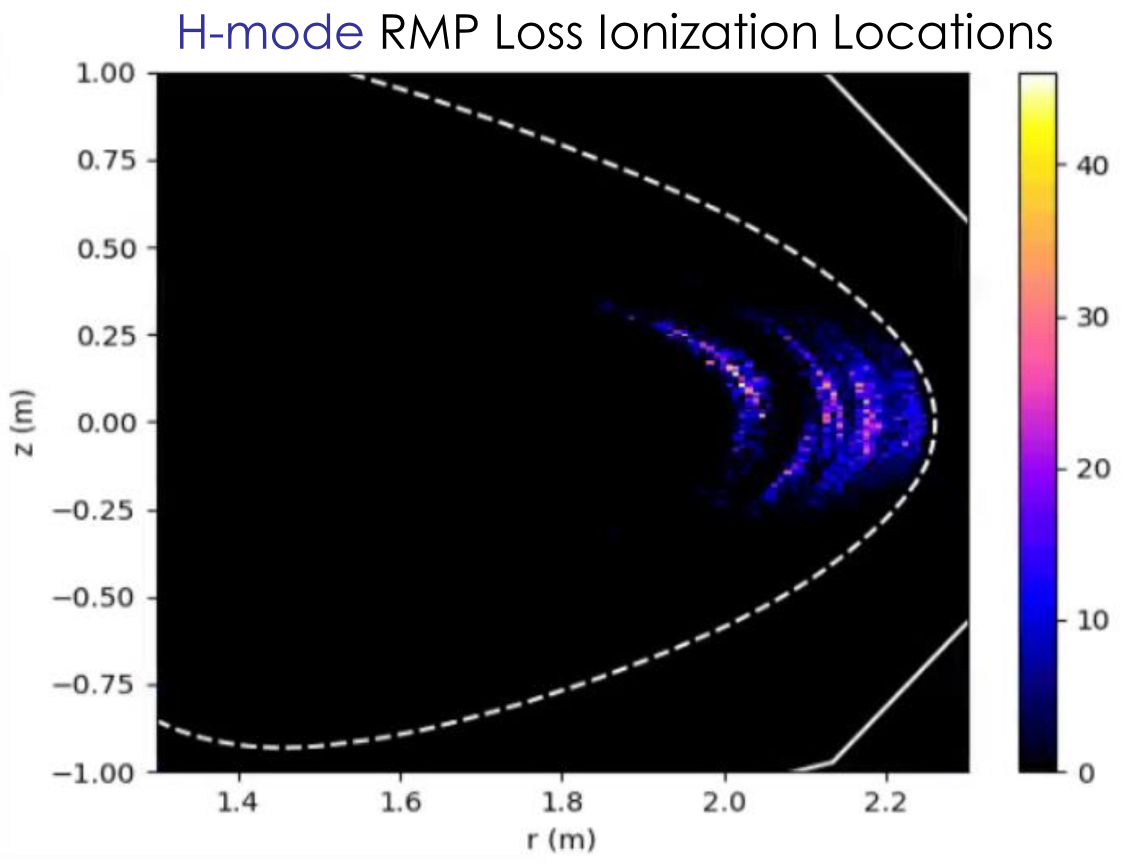


[1] K He *et al* 2021 *Nucl. Fusion* **61** 016009

RMP induced losses are concentrated in outer midplane ports and at the vessel floor

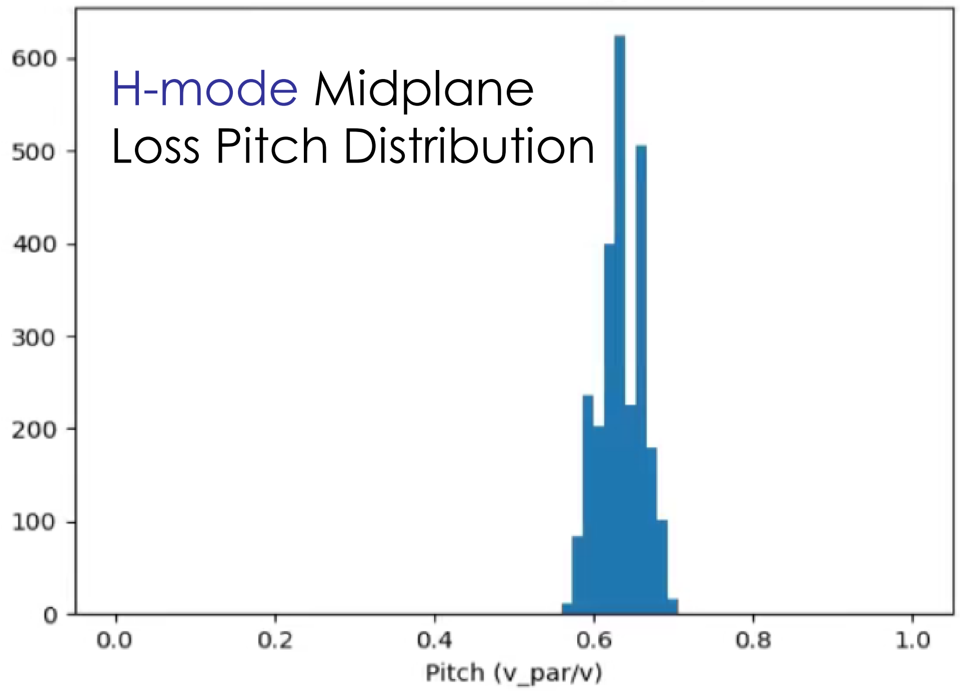
- **Birth locations indicate a large particle displacement due to RMP that does not decrease in H-mode**

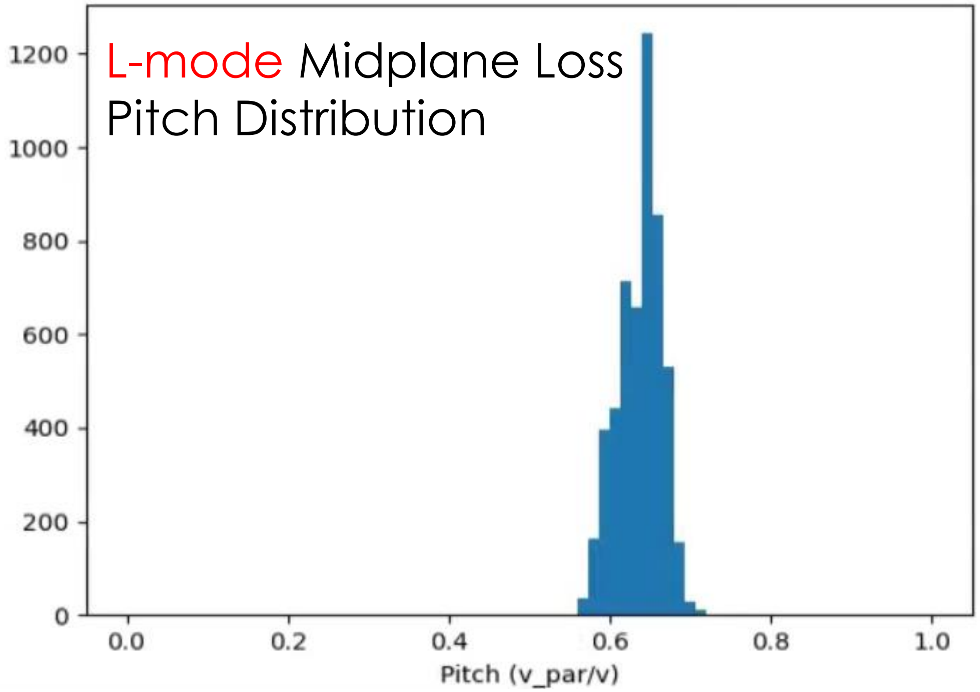




Simulated losses align with measurements from FILDs

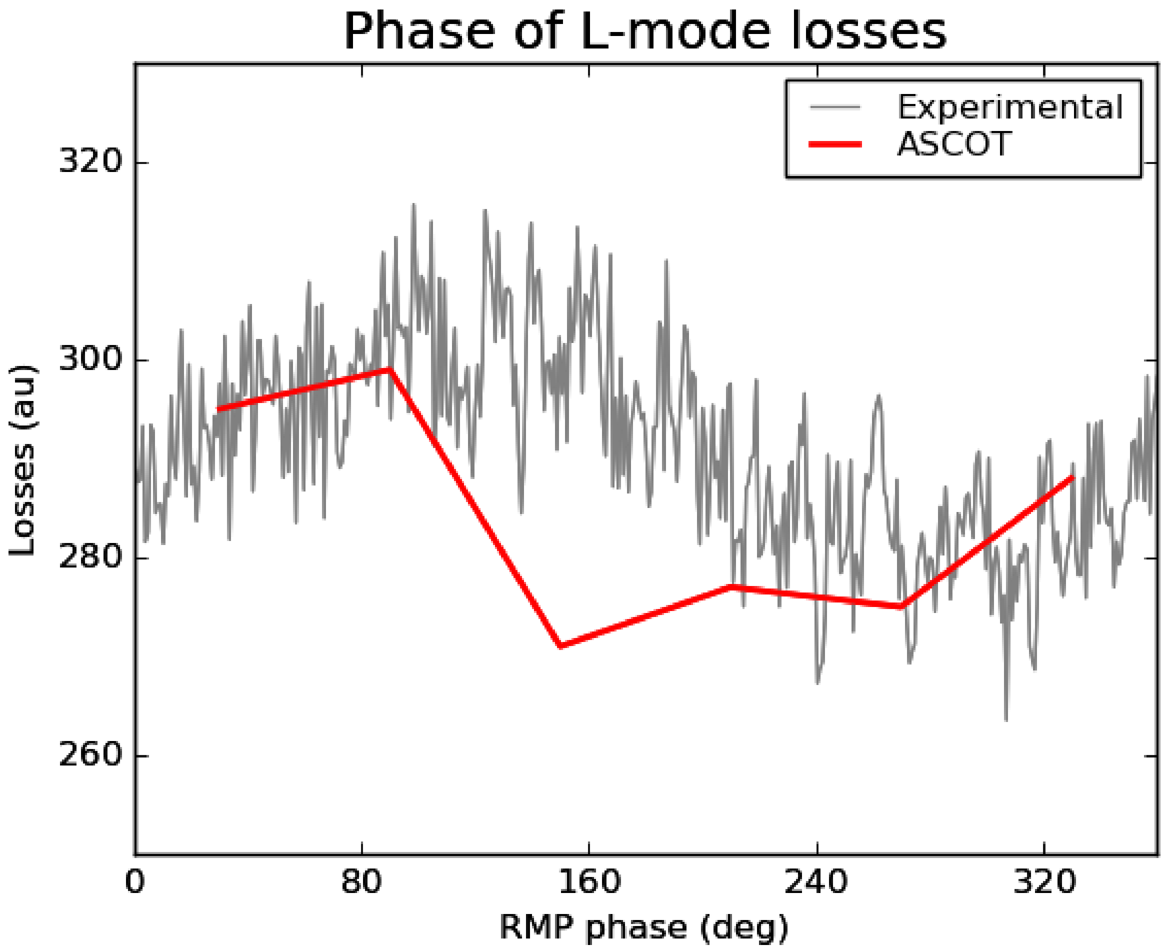
- **Both L- and H-mode losses seen in experiment entered FILDs with pitch angles around 0.6, which is consistent with the simulated losses at the midplane**





Simulated losses align with measurements from FILDs

- **Both L- and H-mode losses seen in experiment entered FILDs with pitch angles around 0.6, which is consistent with the simulated losses at the midplane**
- **Phase of L-mode losses with respect to coil currents is slightly shifted (~40 degrees) with respect to experiment**



Summary

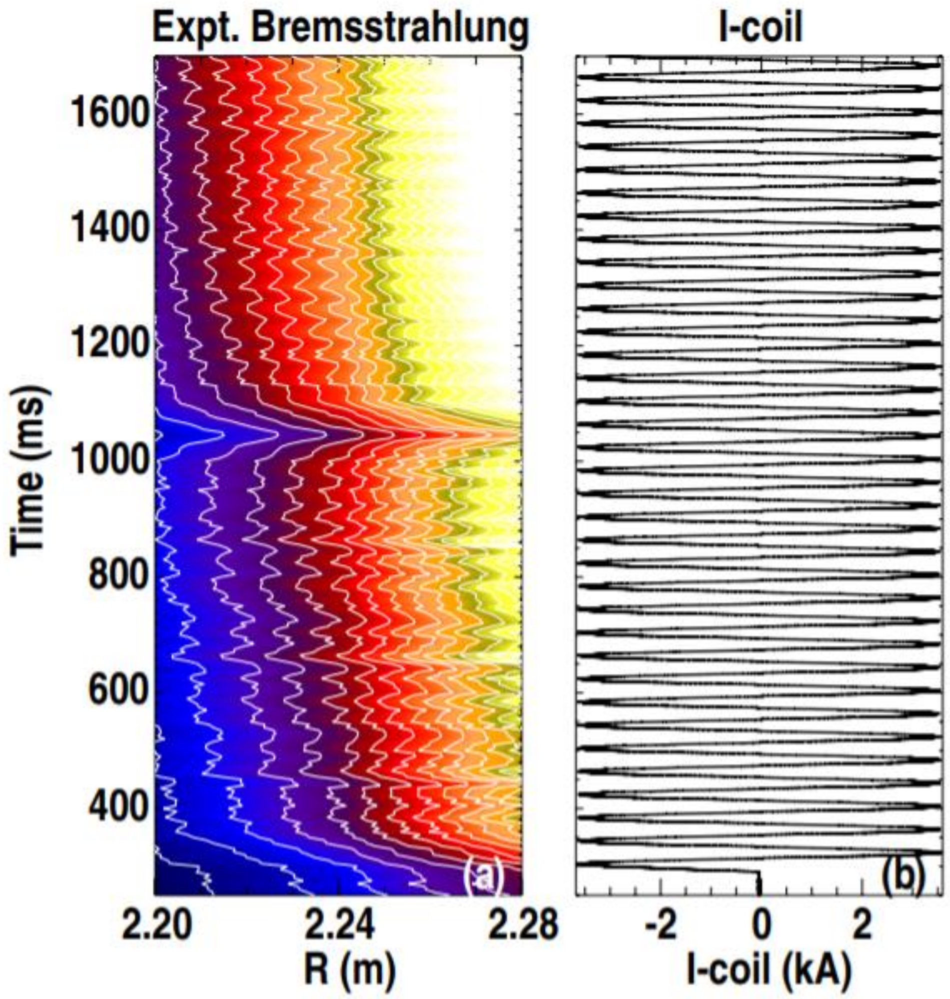
- **DIII-D experiments show suppression in plasma response to n=1 $\Delta\phi = 240$ RMPs in H-mode**
  - At very high β_n, the poloidal field begins to rapidly increase for nearly all RMP spectra
- **Fast ion kick size is not diminished as midplane plasma response decreases**
  - Agrees with theory that large orbit sizes allow for fast ions to be affected and lost to RMPs over a wide range of plasma response levels [1]
- **Simulations of DIII-D experiments find that losses from co-injected NBI are concentrated at the outer midplane in diagnostic ports and at the vessel floor**
- **Losses impacting the midplane are born well inside the LCFS**

[1] K He *et al* 2021 *Nucl. Fusion* **61** 016009

BACKUP SLIDES

Density fluctuations due to RMPs do not have a significant effect on losses in these shots

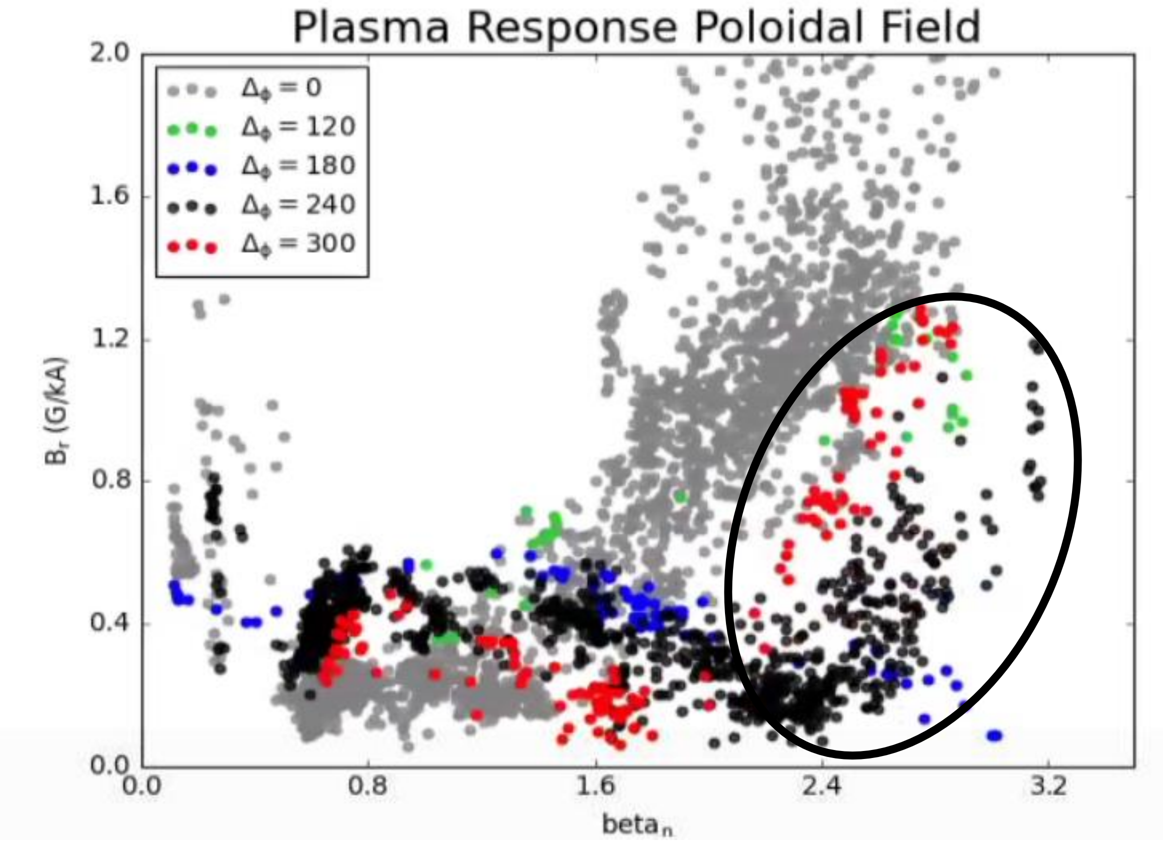
- **Previous modelling of n=2 RMPs on DIII-D have found fluctuation in losses due to perturbed edge densities within the level o statistical noise [1]**
  - This was with edge fluctuation on order 1cm
- **Density fluctuations effect strongest at high gradient edge**
  - Ions well within LCFS not strongly affected



[1] M A Van Zeeland *et al* 2014 *Plasma Phys. Control. Fusion* **56** 015009

Features in the plasma response measurements

- **Plasma response expected to be strongest when applied poloidal spectrum couples with kink mode structure [1]**
  - Coupling also depends on q95, which may be important in shielding effect
  - Amplification and shielding components may be separate [2]
- **Lack of β_n threshold in B_r may be due to geometry of measurement coils**
  - Radial coils surround midplane ports, while small poloidal coils are more like point measurements



[1] M J Lanctot *et al* 2010 *Physics of Plasmas* **17** 030701
[2] N C Logan *et al* 2016 *Phys. Plasmas* **23** 056110

DIII-D FILDs act as magnetic spectrometers for lost ions

- **CCD camera framerate of ~100Hz can be used to determine phase space of losses, but the PMT data is better for fitting to 25 Hz data**
  - Especially true for H-mode, where ELM subtraction is necessary
- **Losses in these experiments were only collected in the midplane probe for the co-Ip injected beams**
  - Signal was seen in the lower probe