Extending 3D Magnetic Diagnostics on NSTX-U

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Acknowledgements
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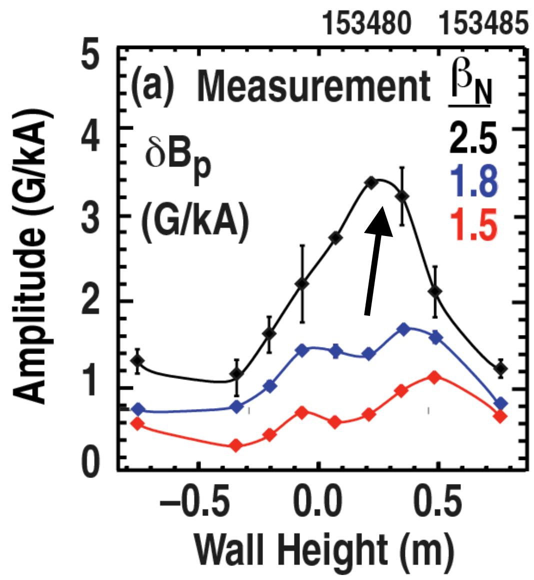
NSTX-U

Conceptual design of new 3D magnetic diagnostics on NSTX-U is being developed as part of GA collaborative research

- **Expanded magnetic sensor set on DIII-D has enabled improved understanding in many areas of 3D physics**
  - Plasma response (including at high beta)
  - RMP ELM suppression
  - Error field sensitivity and optimization
  - 3D magnetic field torques



King, NF 2016

- **GA-NSTXU collaboration leverages experience and tools developed during DIII-D upgrade**

- **Overview of DOE project milestones**
  - M15. Evaluate completeness of existing magnetic diagnostics ☑
  - **M16. Report on conceptual design (in progress)**
  - M17. Report on final physics design
  - M18. Report on frequency response and noise evaluation of new sensors
  - M19. Report on new experimental results with model comparisons

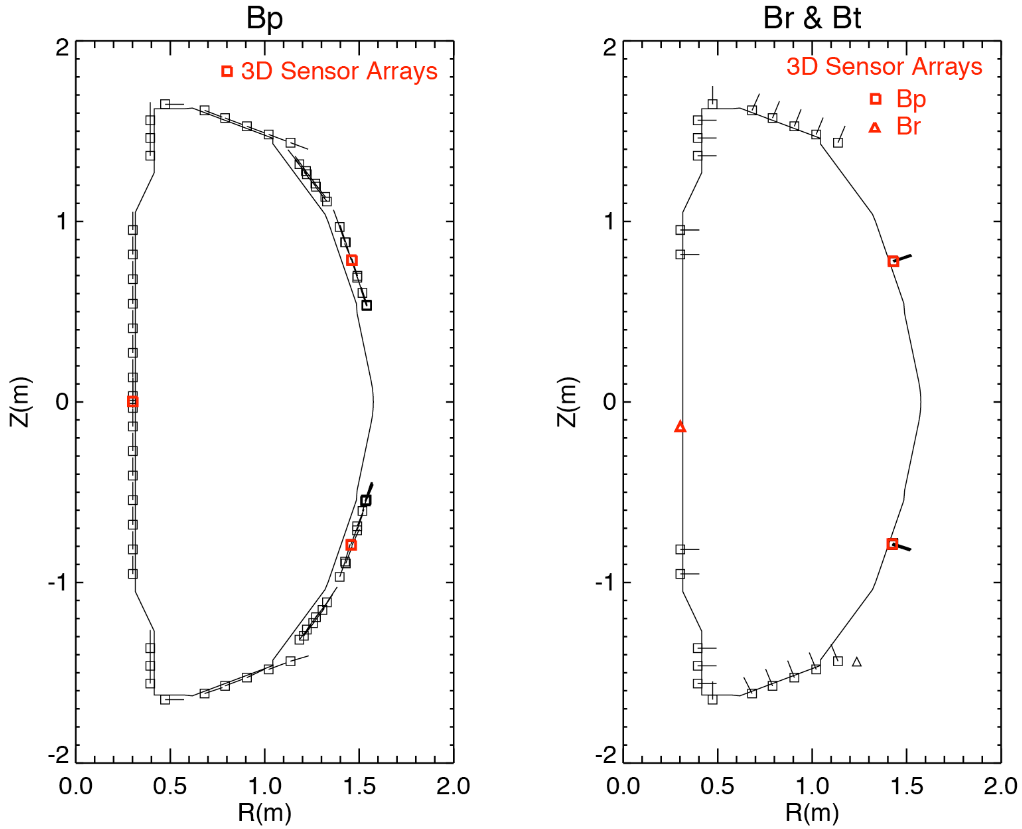
Outline

- **Highlights from Milestone 15 on completeness of existing magnetic diagnostics**
  - Recommendation for instrumenting existing HFS diagnostics
- **Initial analysis of plasma response in NSTX-U with MARS**
- **Remaining steps to complete conceptual design (Milestone 16)**

Physics objectives drive the requirements for non-axisymmetric field measurements (from DIII-D study)

Objectives	Requirements
• **Plasma response (PR) to applied 3D fields** – PR to error fields and RMPs – Direct measurement of EM torque	$n \leq 3, m \leq 15$ $\delta B_p, \delta B_r$
• **Equilibrium reconstruction** – Improve axisymmetric equilibrium reconstruction – Full and perturbed 3D equilibrium reconstruction	$n = 1, m \leq 5$ $\delta B_p, \delta B_r$
• **Unstable plasma modes: low n, low frequency** – Poloidal structure of non-rotating modes n>1 – Poloidal structure of rotating modes	$n \leq 3, m \leq 15$ $\delta B_p, \delta B_r$
• **Unstable plasma modes: high n, high frequency** – Detection of ELM precursors – Energetic particle instabilities	$high\ m, n$ $high\ f \rightarrow \dot{B}_p$
• **Disruption physics** – Runaway electrons & their instabilities	$n = 1, m \leq 5$ $\delta B_p, \delta B_r$

Milestone 15: How NSTX-U 3D magnetic diagnostics are incomplete



- **Six 3D B field arrays exist on NSTX-U**
  - Two 12-sensor B_r & B_p arrays on LFS above and below the midplane (from NSTX)
  - One 12-sensor poloidal field array on HFS midplane (new, not yet instrumented)
  - One 5-sensor B_T array on the HFS just below the midplane (halo current diag.)

- **Existing sensors were evaluated in terms of ability to resolve toroidal and poloidal structure of slowly-rotating and DC magnetic fields**
  - Toroidal distribution of sensors in existing arrays sufficient for n<=3 on LFS and HFS
  - Poloidal distribution of sensor arrays insufficient to resolve poloidal structure

Toroidal distribution of sensors in existing arrays sufficient for n<=3 on LFS and HFS

- **Number of sensors in toroidal array determined by number of interesting modes, *k***
  - Required number of sensors to resolve *k* modes is 1+2*(*k*-1), yields n=0 amplitude and n>0 amplitudes & phases

- **Orthogonal measurements for given *n* are obtained for separations of $\delta\phi = 2\pi/n/4$**

n	1	2	3	4	5	6
$\delta\phi$	90	45	30	22.5	18	15

  - Note: Existing Bp, Br sensors are 30 deg apart; Br sensors are 15 deg. wide toroidally
    - High n (>3) measurements likely limited to Bp without new Br sensor design

- **Often sensors must be spaced unequally so as to avoid existing hardware**
  - How does unequal toroidal spacing of probes impact error in inferred amplitude?

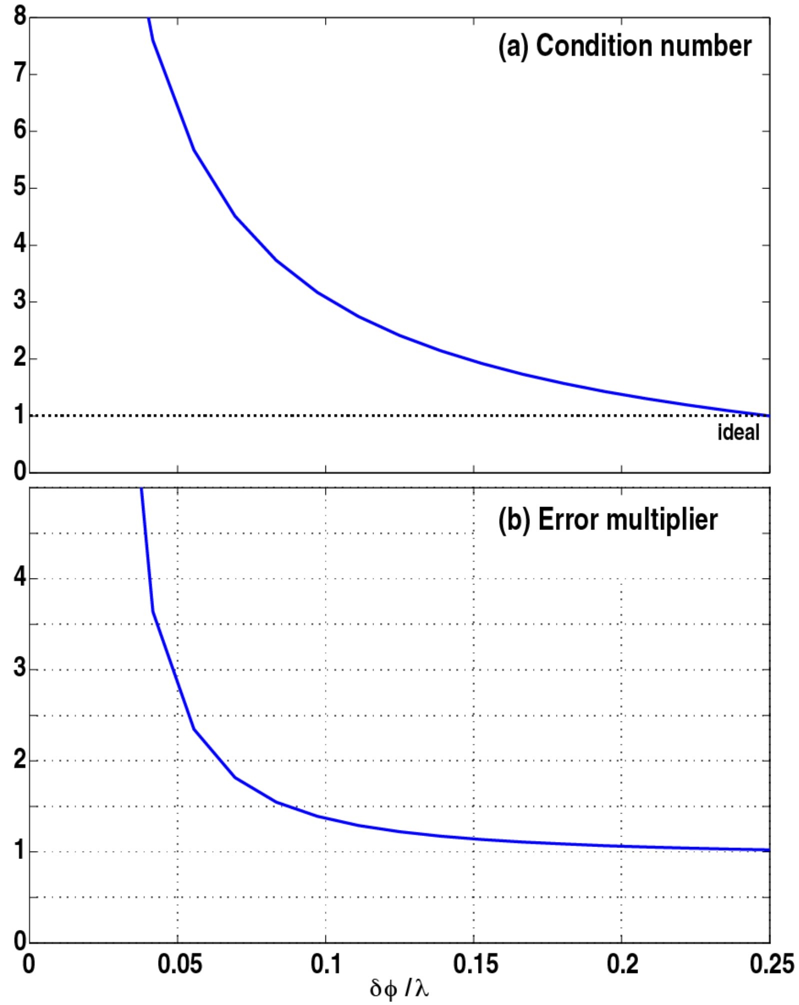
Toroidal location of probes should be selected so as to minimize the condition number of the resulting fit matrix

- **Mode fit coefficients obtained by taking pseudo-inverse of a fit matrix A(n,ϕ)**

$$A_{ij}(n,\phi) = \left[\cos(n_j\phi_i)\ \ \sin(n_j\phi_i)\right]$$

  – Basis sets other than cos,sin are possible

- **Condition number (C) is ratio of the largest singular value of A to the smallest**
  – When C=1, error from fit is no worse than the data ("error multiplier"=1)



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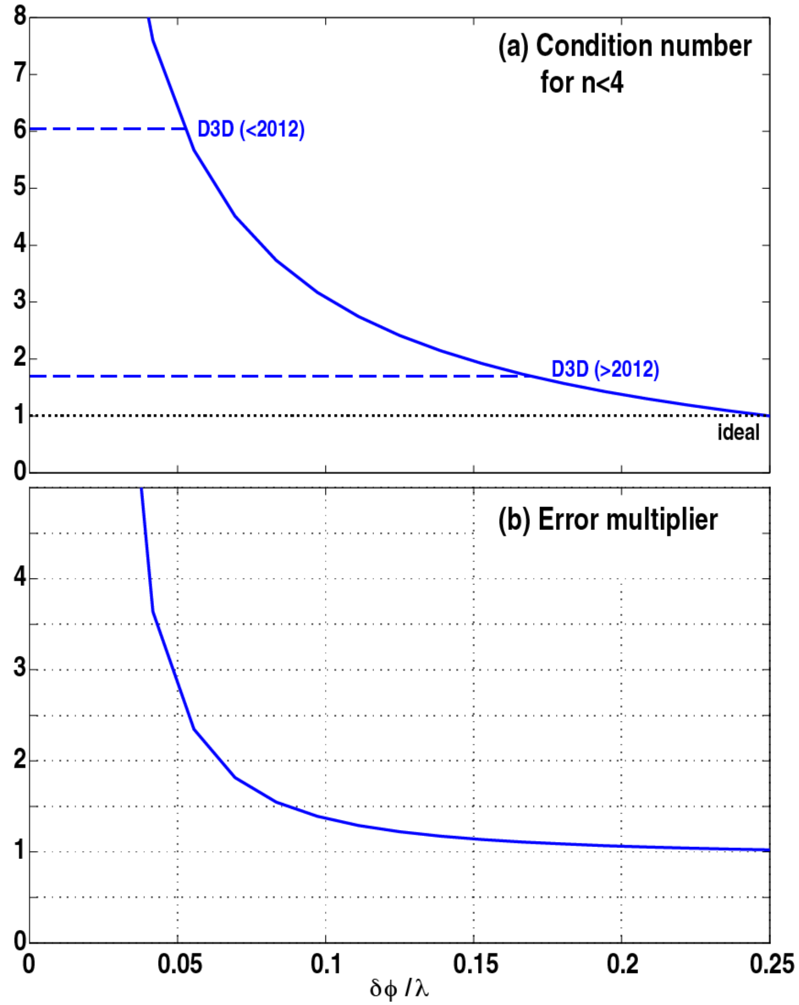
- **Condition number & error multiplier increase as sensors deviate from ideal spacing** ($\delta\phi/\lambda$=0.25)
  – Compute for fit matrix A(n<4)



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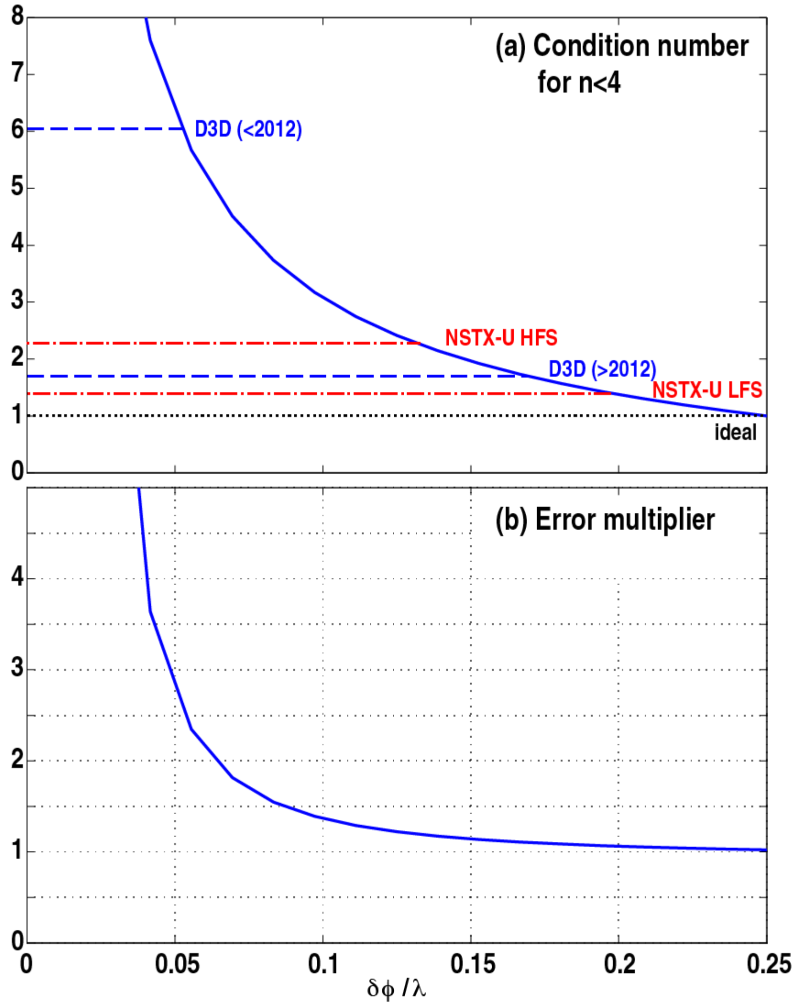
- **Condition number & error multiplier increase as sensors deviate from ideal spacing** (δϕ/λ=0.25)
  – Compute for fit matrix A(n<4)
  – Existing NSTX-U arrays nearly as good or better than DIII-D upgrade (assuming same noise level)



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Initial design recommendation: Instrument Bp array on HFS

- **Bp sensor array on HFS should be instrumented as soon as possible**

- **New data would be extremely valuable**
  - Measure plasma response amplitude to validate models being used in design
    - Existing models mainly validated at low edge q
  - Document existing noise characteristics to inform toroidal spacing question
  - Assess if existing sensor design is adequate

- **If MARS prediction (next section) correct and general, then it is unlikely additional probes will be installed on the centerstack**
  - Sensor amplitudes are relatively small: <1 G/kA

- **Discussion: Is it possible to pursue this project in parallel with the PF coil repair?**
  - Propose we delay discussion until end of talk

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- **Initial analysis of plasma response in NSTX-U with MARS**
- Remaining steps to complete conceptual design report (Milestone 16)

Critical questions for analysis of plasma response in NSTX-U

- **Where on the wall is the plasma response localized?**
- **Is there sufficient field amplitude on the centerpost?**
- **Is there sufficient field amplitude at the Sensor “B” position?**
- **Which field components should be measured?**
- **What are the ideal probe dimensions?**
- **How many probes are needed to resolve the local poloidal wavenumber?**
- **How does the response amplitude and structure scale with plasma parameters?**

Critical questions for analysis of plasma response in NSTX-U

- **Where on the wall is the plasma response localized?**
  - Not on HFS
- **Is there sufficient field amplitude on the centerpost?**
  - Likely marginal. Amplitude is <1 G/kA for n=1
- **Is there sufficient field amplitude at the Sensor "B" position?**
  - Yes. Amplitude is similar to existing sensors
- **Which field components should be measured?**
- **What are the ideal probe dimensions?**
- **How many probes are needed to resolve the local poloidal wavenumber?**
- **How does the response amplitude and structure scale with plasma parameters?**

This work focused on existing MARS analysis at high betaN by Wang and Park

- **NSTX-U Target: 2 MA, 0.9T**
  - g.142301C94_2MA_bN5.5_q6.9
- **Coil configurations:**
  - Midplane coil, Upper and lower NCC coil
- **This work looked at magnetic sensor set:**
  - NSTXU sensors + Midplane(HFS,LFS) + Sensor "B"

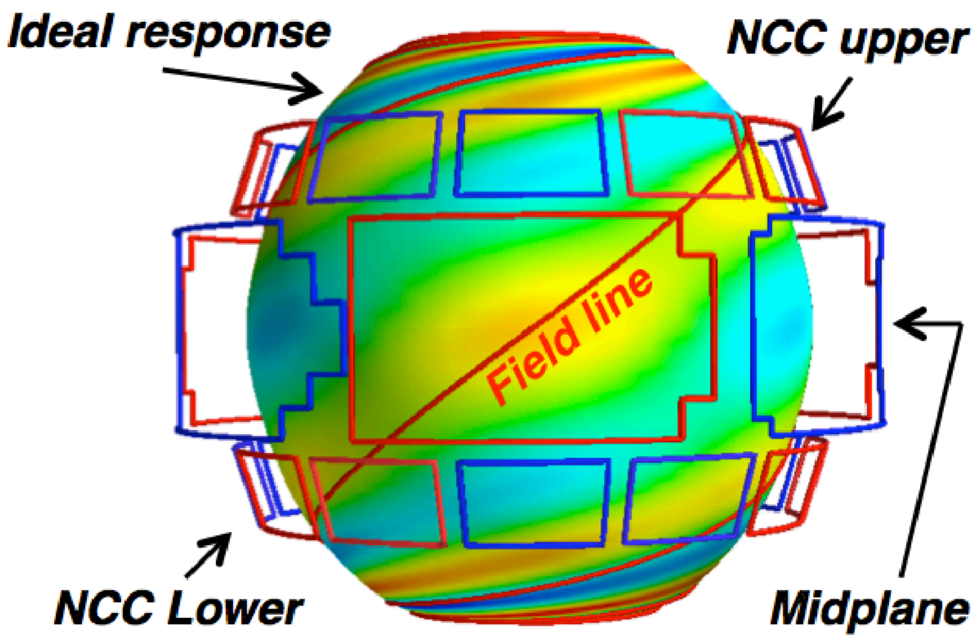
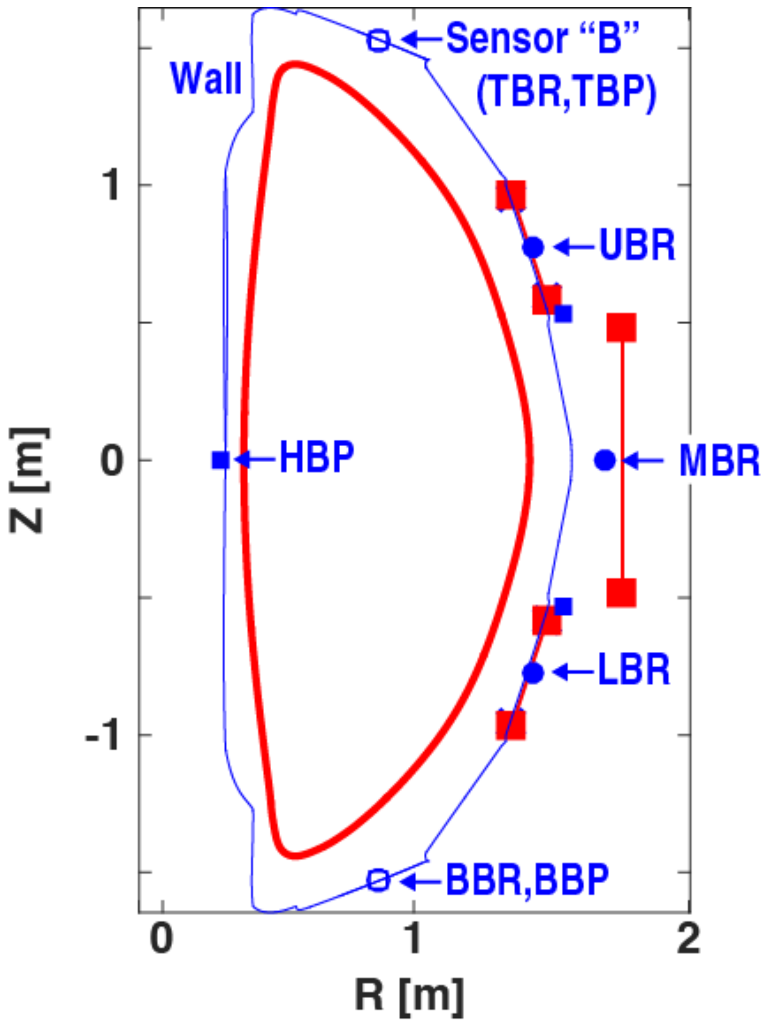
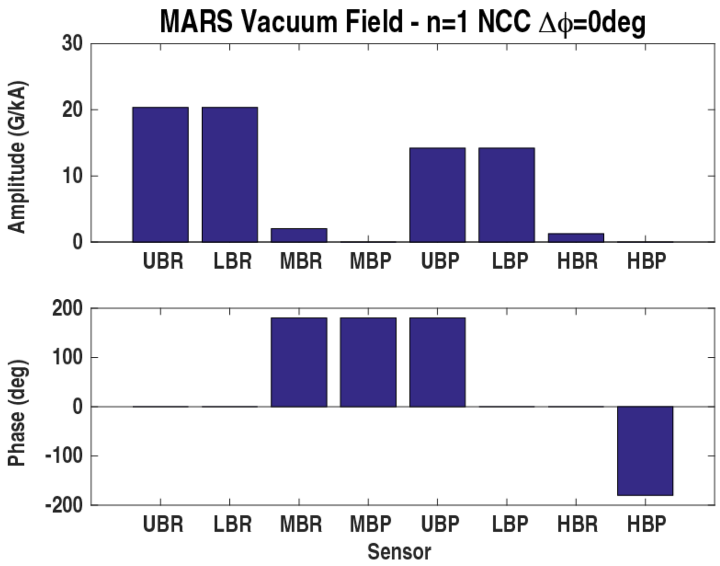


Image: Park NCC White Paper



MARS-F post-processing tools updated to analyze results from MARS-Q

- **Consider n=1 field from upper & lower NCC coils, $\Delta\phi$=0 deg**
  - No wall or plates in calculation: Should be valid for DC or slowly rotating fields
- **Compute sensor averaged fields**
  - See maximum of ~20 G/kA-t near NCC coils



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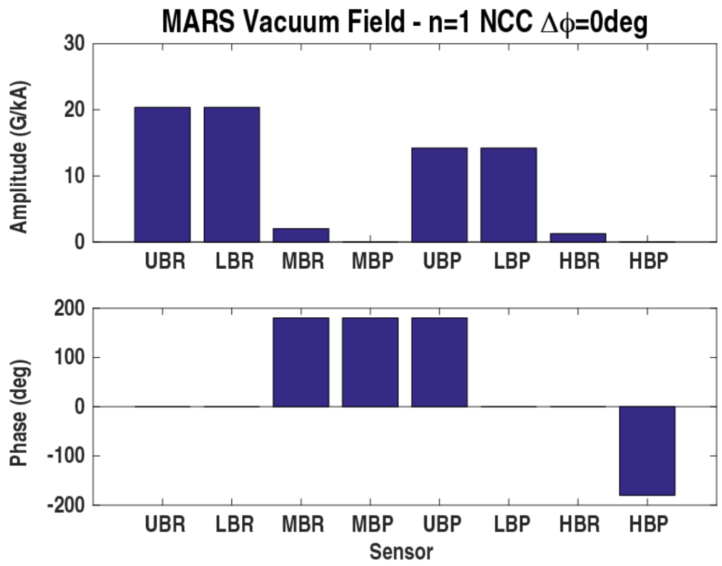
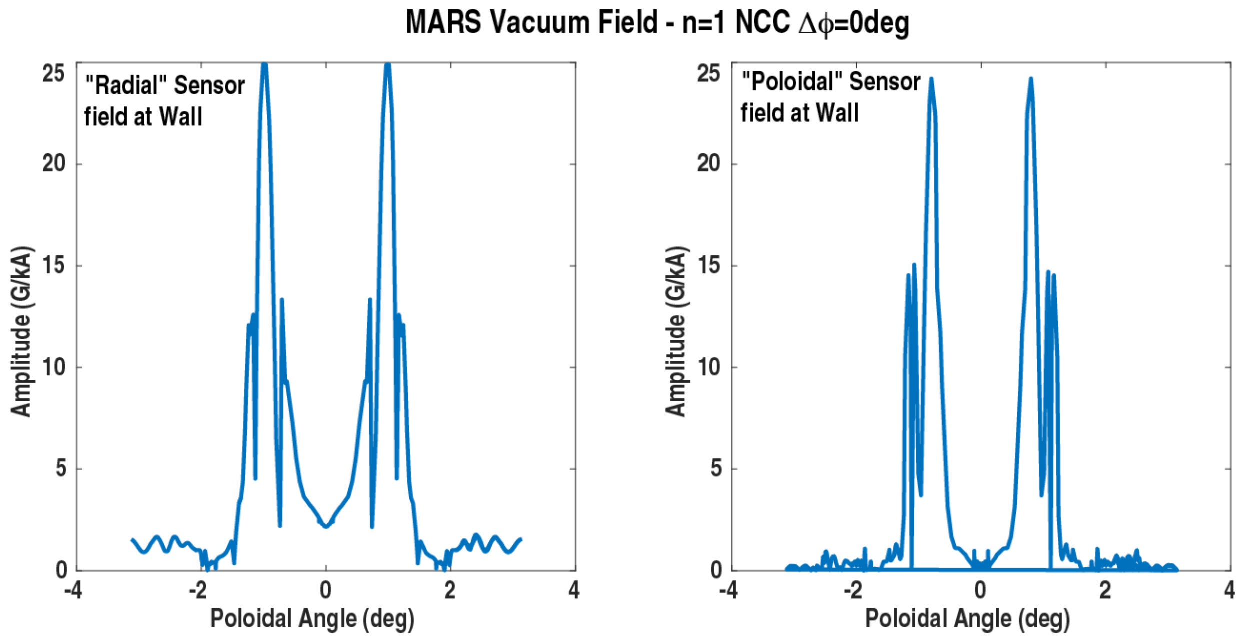
- **Compute sensor averaged fields**
  - See maximum of ~20 G/kA-t near NCC coils
- **Compute fields at wall for "radial" and "poloidal" field sensors**
  - Probe oriented along wall; Fine structure near sharp corners is artifact (will improve)
  - Peak field is ~25 G/kA-t in front of coils (similar level as DIII-D I-coils)





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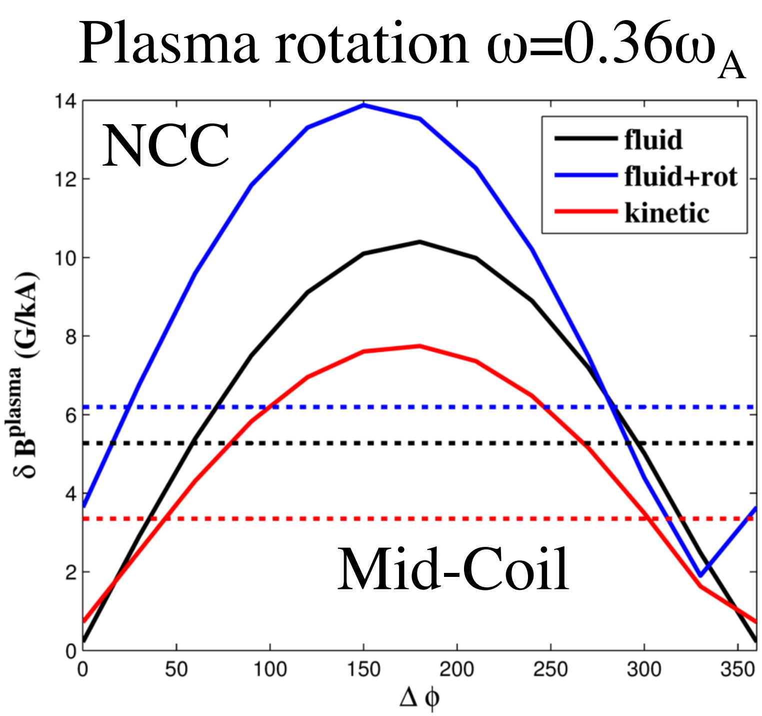
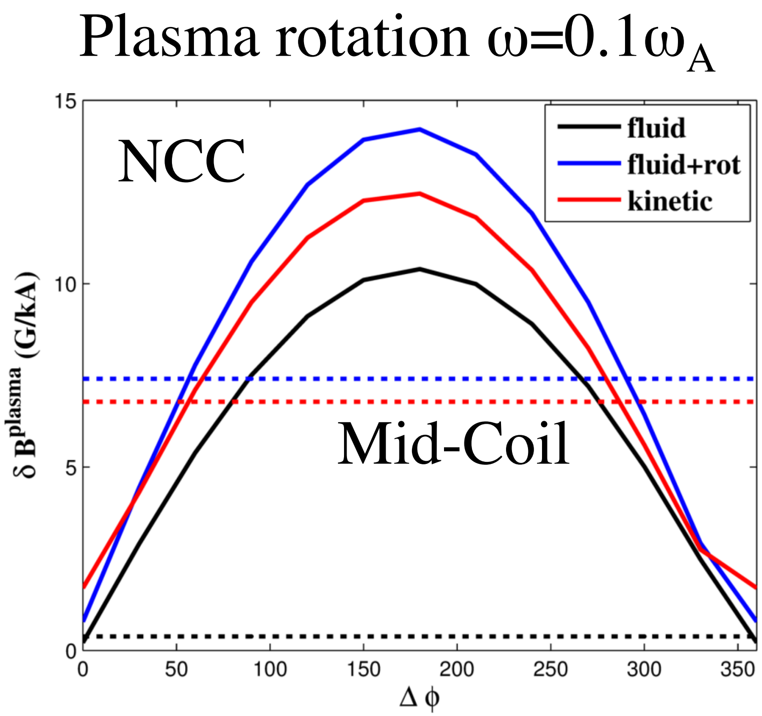
Previous analysis shows single peak in response on LFS magnetics

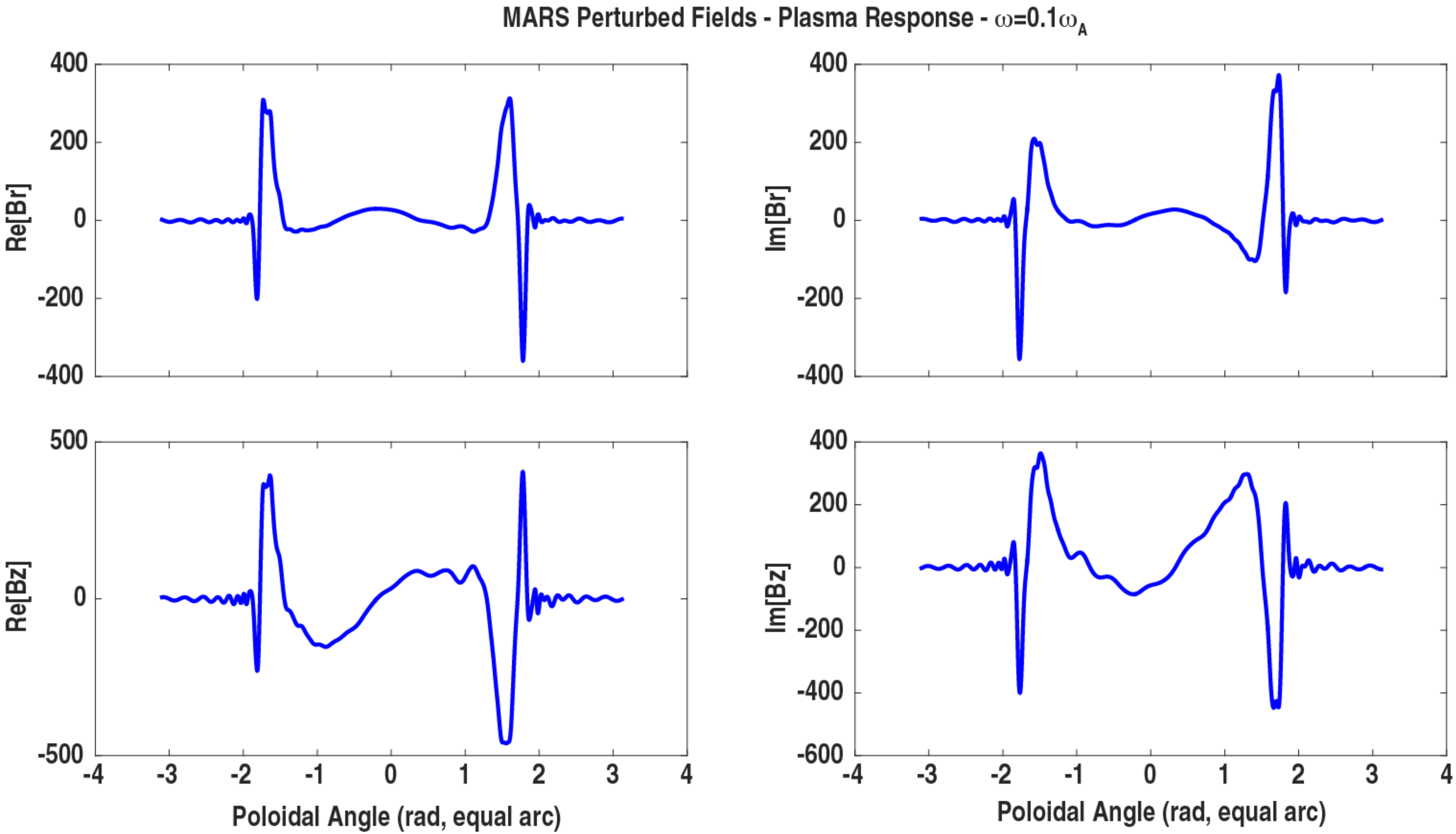
- **Scan of Δϕ for n=1 shows single peak in response**
  - Maximum (minimum) occurs at Δϕ= 150 (330) deg for q95=6.9
- **Rotation modifies kinetic response**
  - Amplitude is damped as rotation increased (consistent with increased stability)





Courtesy of Z. Wang

Perturbed field is small and high m at the plasma surface on the HFS



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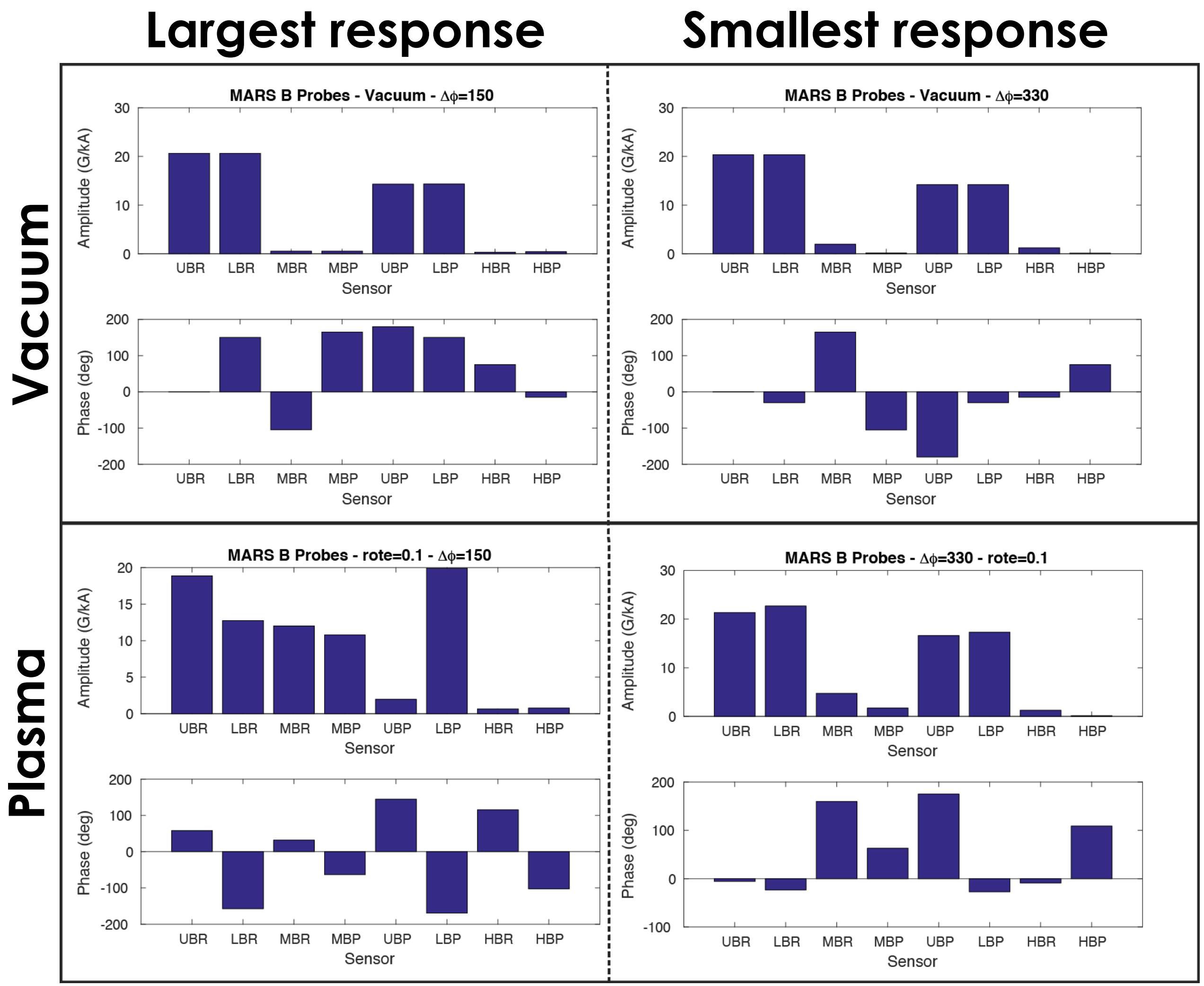
Expected changes in response from MARS at the midplane requires sub-Gauss detection capability at 1kA coil current



- Consider plasma response at midplane sensors at Δϕ's for max and min response

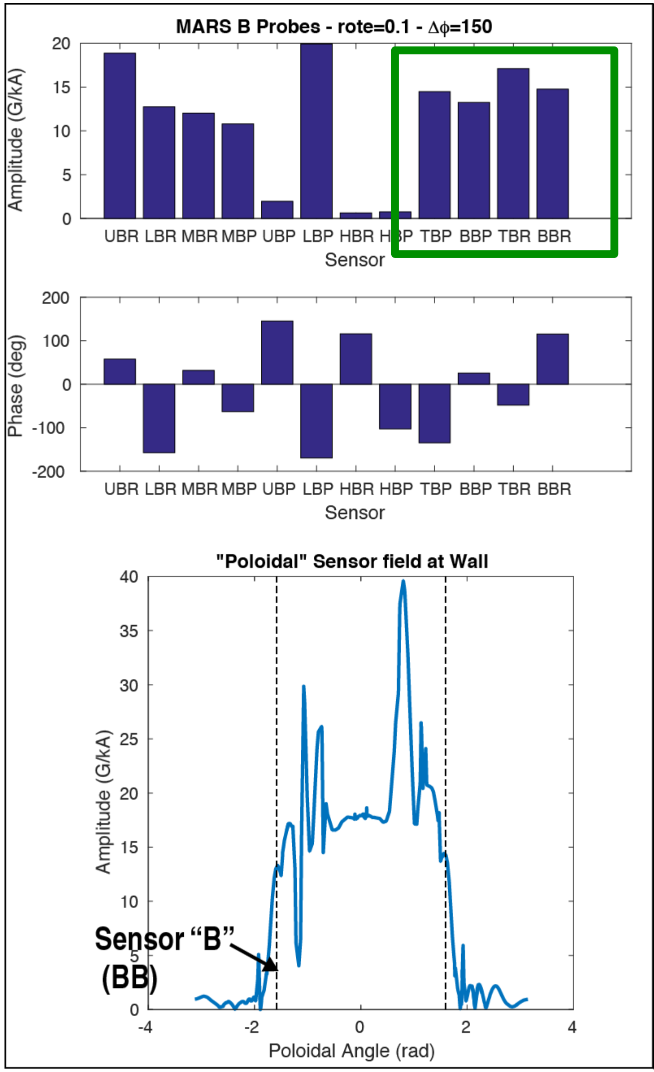
	Δϕ	|HFS/LFS|	|HFS| (G/kA-t)
BR	150	0.04	0.45
	330	0.05	0.14
BP	150	0.08	0.85
	330	0.04	0.08

- HFS response is <10% of LFS
- HFS amplitudes are <1 G/kA

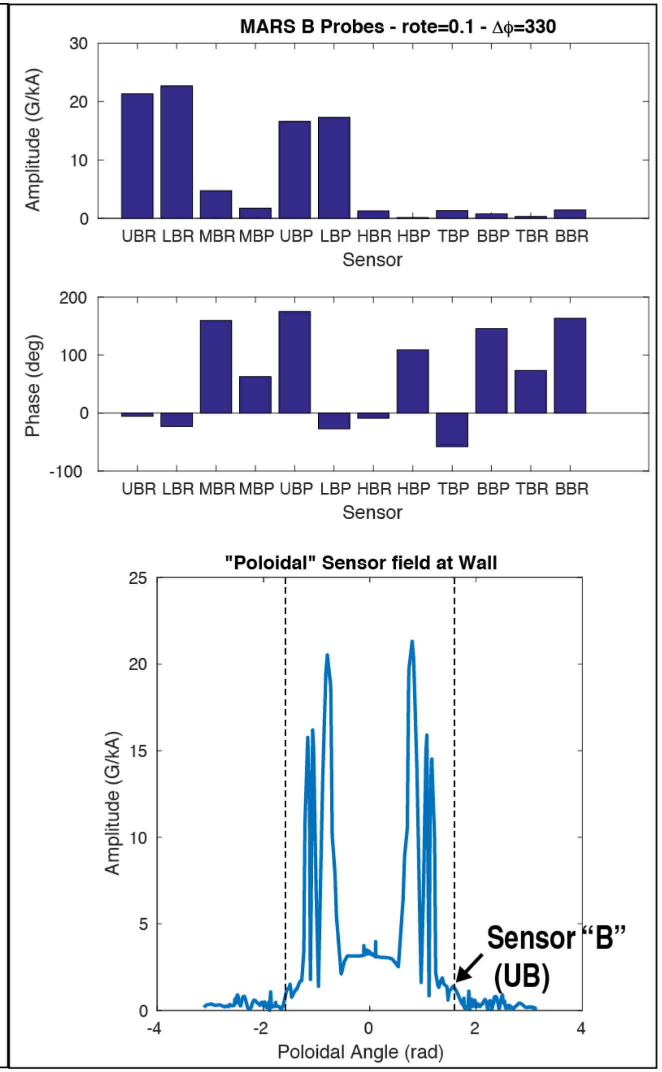
In contrast, field amplitudes at Sensor “B” position are comparable to existing signal amplitudes for strong coil-plasma coupling

- **Sensor “B” position estimate taken from Sabbagh slides**
  - (R,Z) = (0.87,+/-1.53)
- **Sensor “B” located near the edge of the range of poloidal angles with a strong response field**
- **Result is consistent with RWM feedback studies by Columbia team**
  - Plasma response is driven stable RWM
  - Further study of field on top/bottom in progress

Largest response



Smallest response



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- **Consider other plasma equilibria to determine if any targets have strong HFS response. In particular, extend study to n>1 applied fields.**

- **Complete detailed study of probe positions on top/bottom**

- **Other remaining questions**
  - Which field components should be measured?
  - What are the ideal probe dimensions?
  - How many probes are needed to resolve the local poloidal wavenumber?
  - How does the response amplitude and structure scale with plasma parameters?

Discussion

- **Is it possible to pursue instrumentation of HFS Bp array in parallel with the PF coil repair?**
  - Even if HFS signal levels too small to measure, hardware can be used for other new sensors