Linear Ideal MHD Effects on 3D Equilibria in DIII-D

By

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In collaboration with

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COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK

Fusion Energy Sciences

Motivation and Background

- **All toroidal devices have non-axisymmetric (3D) magnetic fields:**

  $\vec{B} = \vec{B}_0 + \delta\vec{B}$

- **3D equilibria must satisfy force balance**
  - Implies the plasma contributes to the total 3D field: $\delta\vec{B} = \delta\vec{B}^{ext} + \delta\vec{B}^{plas}$
  - Linear ideal plasma response model provides an alternative to solving the full force balance equation [Boozer, *Phys. Plasmas*, 1999]

- **Plasma response measurements are an important diagnostic tool for understanding 3D equilibria (critical for model validation)**

- **Validated 3D equilibrium models have applications in**
  - Error field physics
  - Effects of 3D fields on the plasma rotation
  - Stabilization of MHD Instabilities: RWM and **ELM**

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Outline

- Relevance of Linear Ideal MHD Plasma Response Models
- Study of The Plasma Response in ELM Suppressed Discharges
- Summary

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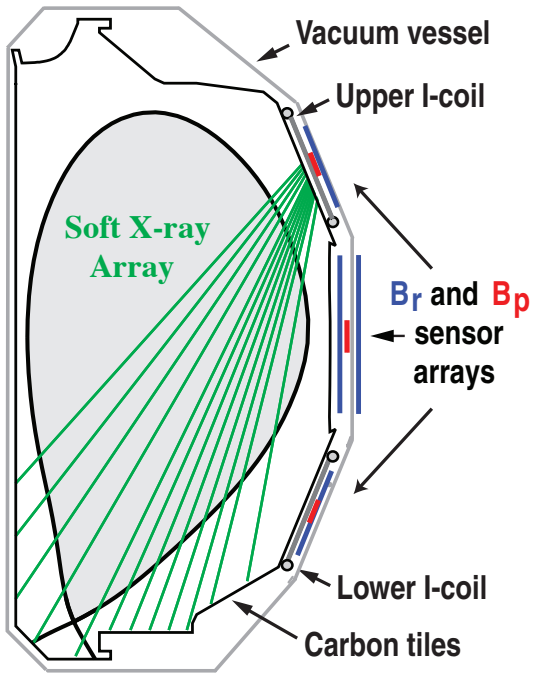
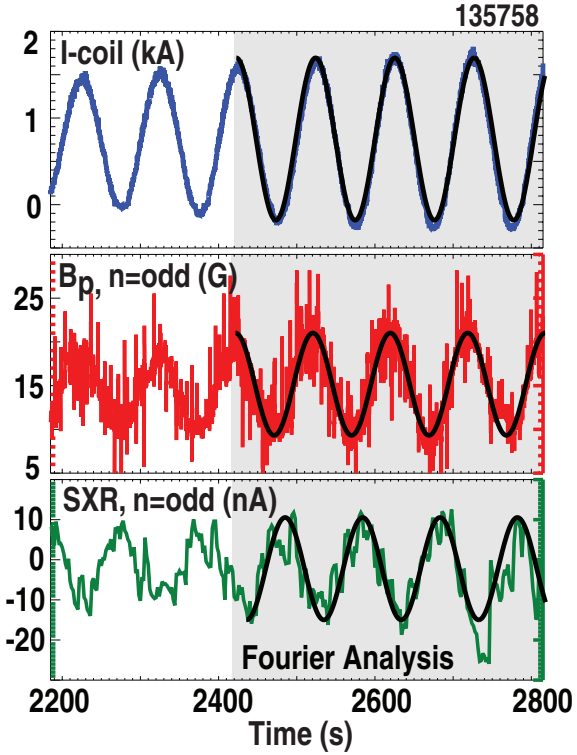
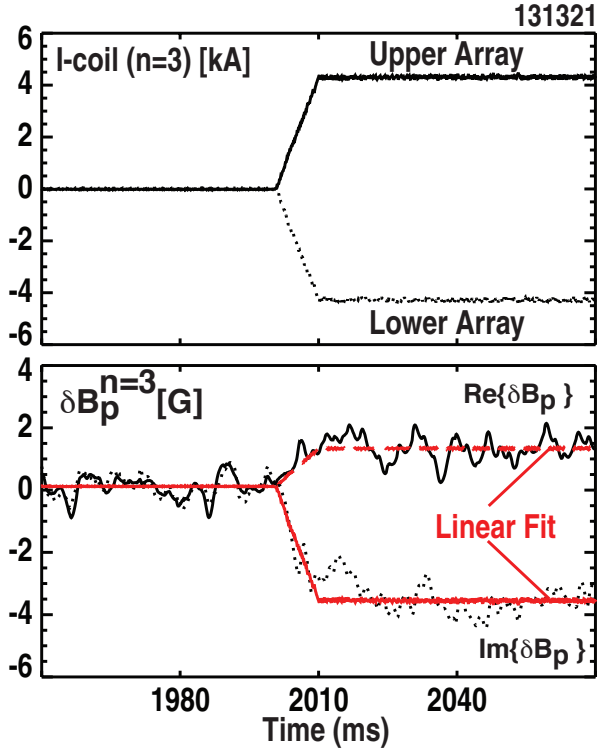
3D Equilibria Are Studied By Probing H-mode Discharges With The Internal Coil (I-coil)

- Toroidal (n) and poloidal (m) spectra of δB^{ext} can be varied (n=1,2,3)
- Toroidally distributed diagnostics resolve the toroidal spectrum of the 3D equilibrium
- Rotating the n=1 external field in the toroidal direction allows synchronous detection of the plasma response







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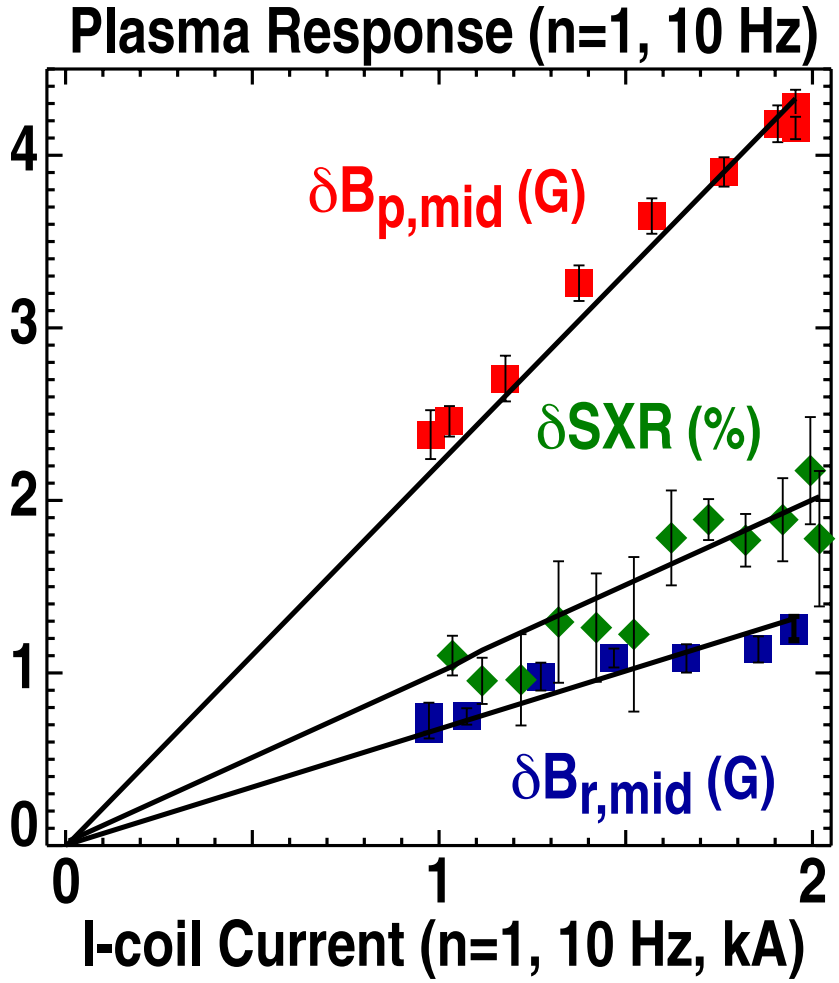
Measured Plasma Response in Rotating Discharges Is Linear in the Applied Magnetic Field



- **Vary n=1 I-coil amplitude at fixed plasma pressure**
  - Use closed feedback control of neutral beam power
- **Plasma response measurements show a <u>linear scaling with I-coil amplitude</u>**
  - Fits include constraint at zero current
  - Correlation coefficients > 0.99

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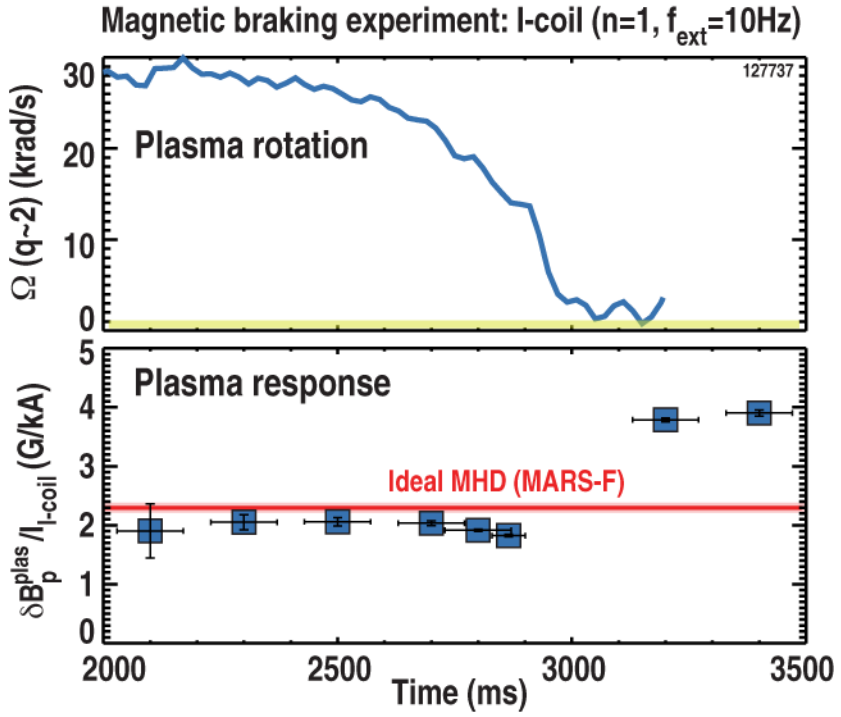
A Linear Response Is Observed As Long As The Plasma Rotation Is Sufficiently Large

- Measure response to *n*=1 I-coil field in magnetic braking experiment
- For "large" rotation
  - δB^{plas} *is* independent of rotation
  - δB^{plas} *is* consistent with ideal MHD



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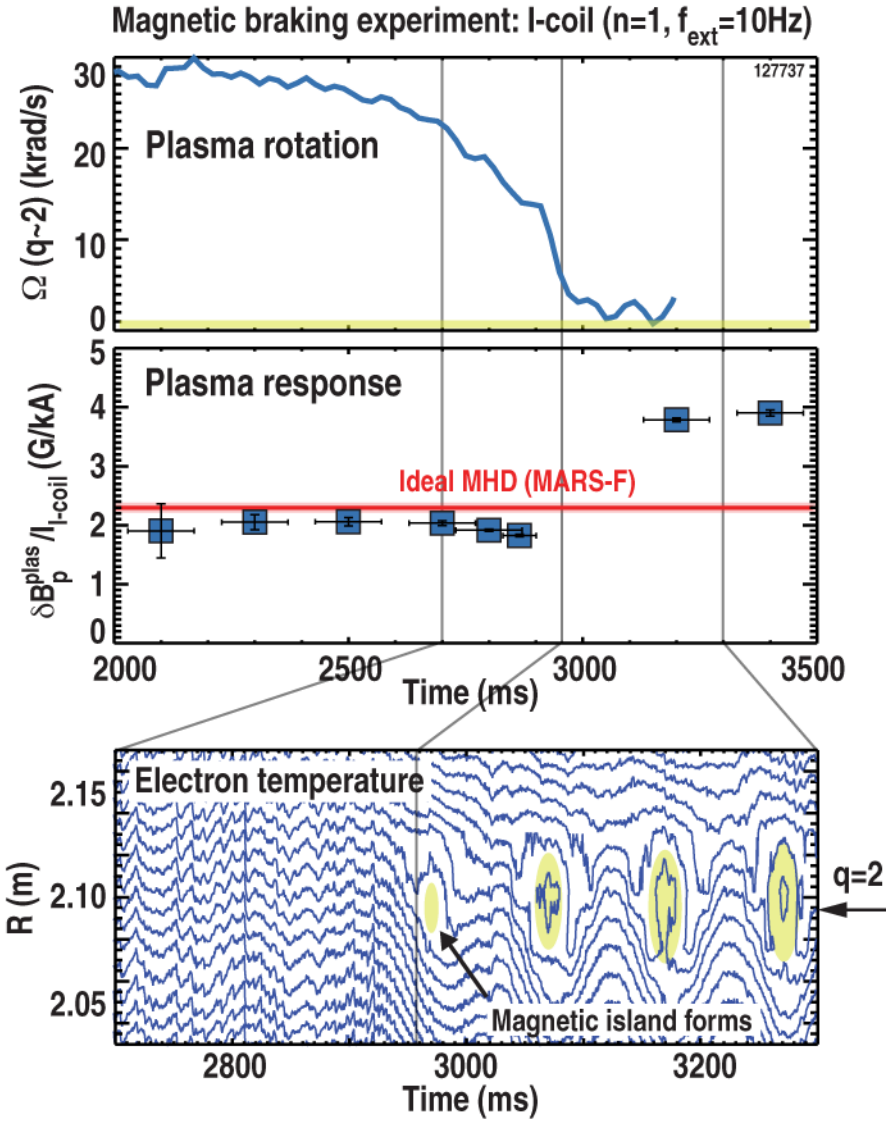

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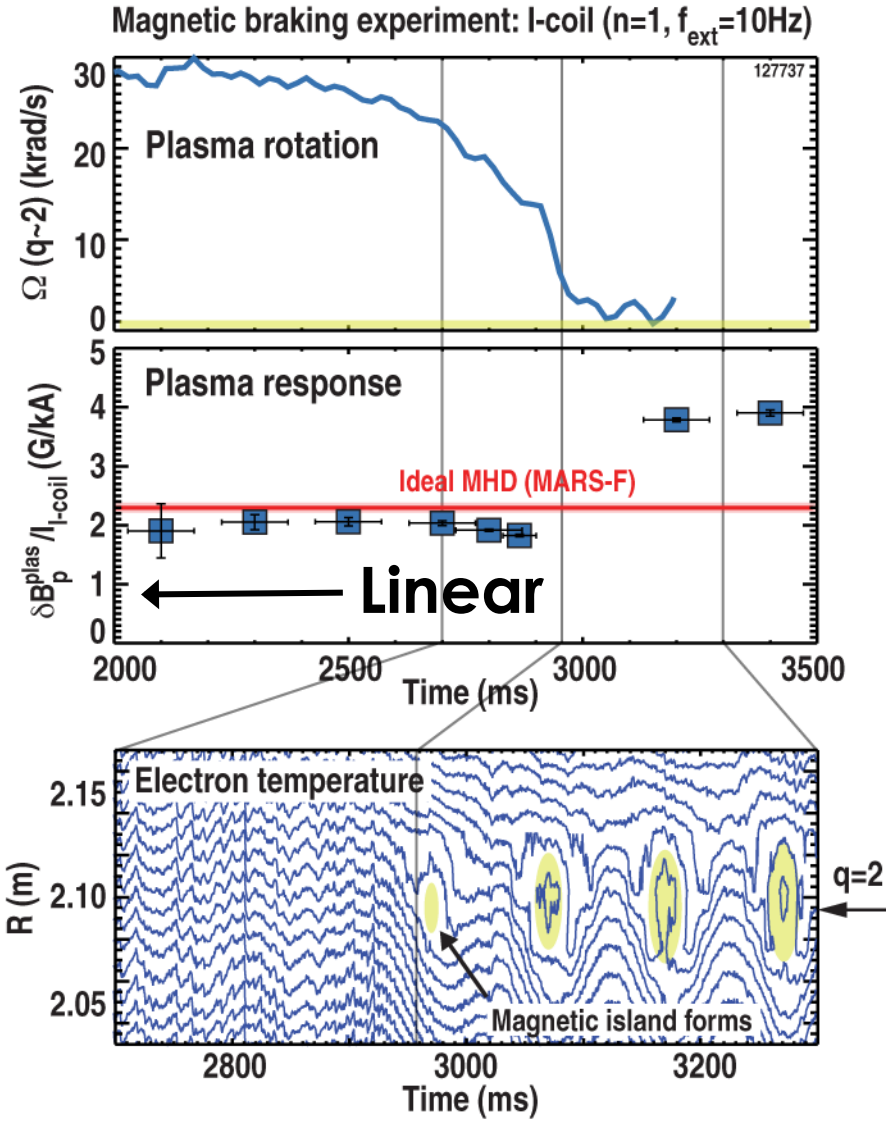
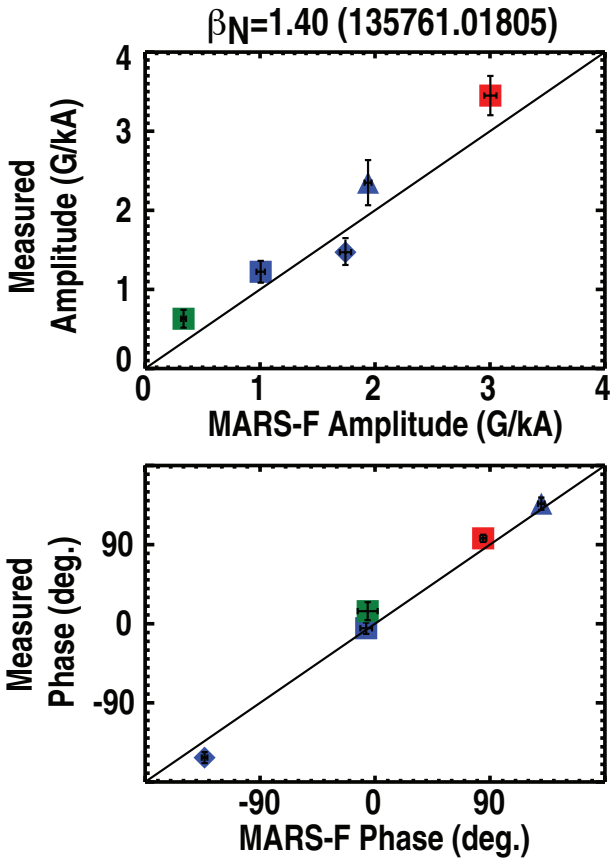
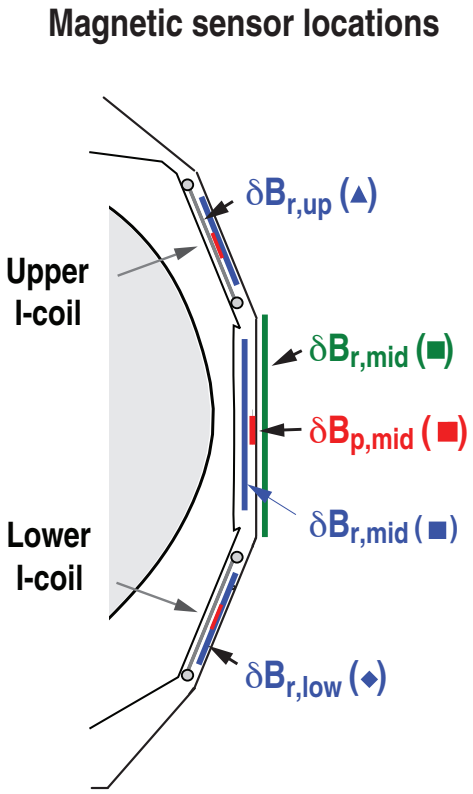
- Recent focus has been on the linear response prior to island formation



Linear Ideal MHD Theory Gives a Quantitative Description of 3D Equilibria

- **Probe plasma with 10 Hz n=1 field at fixed plasma pressure**
- **Linear ideal MHD calculations (MARS-F*) based on detailed equilibrium reconstructions are in good agreement with experiment**
  [*Liu et al, *Phys. Plasmas* 2000]



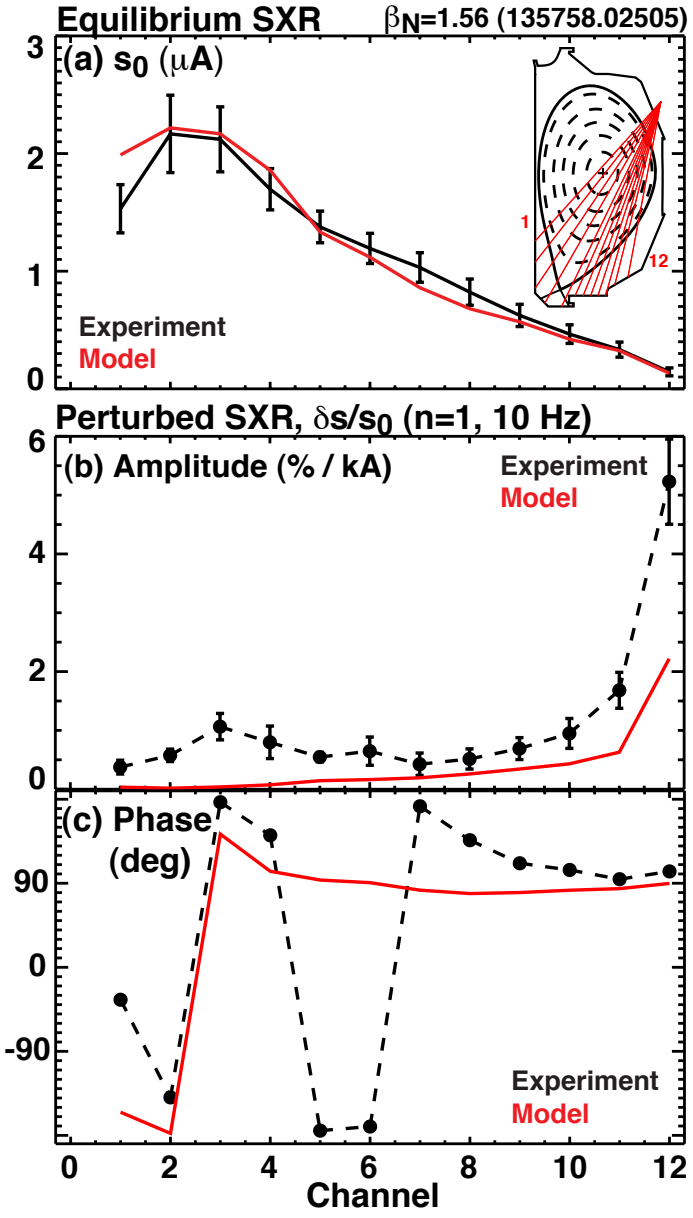


M.J. Lanctot et al, *Phys. Plasmas* 2010

However, Plasma Response Structure Derived From Soft X-ray Identifies a Need For Additional Studies

- **Probe plasma with rotating n=1 I-coil field**
- **Model of n=0 emissivity agrees with measurements**
- **Amplitude of n=1 component largest near plasma edge**
  - Island structures not observed in phase
- **Model of the n=1 soft x-ray measurements underestimates response amplitude (~2x)**
  - Assumes $\delta S(\psi) = -\xi_n \cdot \nabla S(\psi)$
  - Includes only carbon VI impurities
  - Neglects non-thermal emission

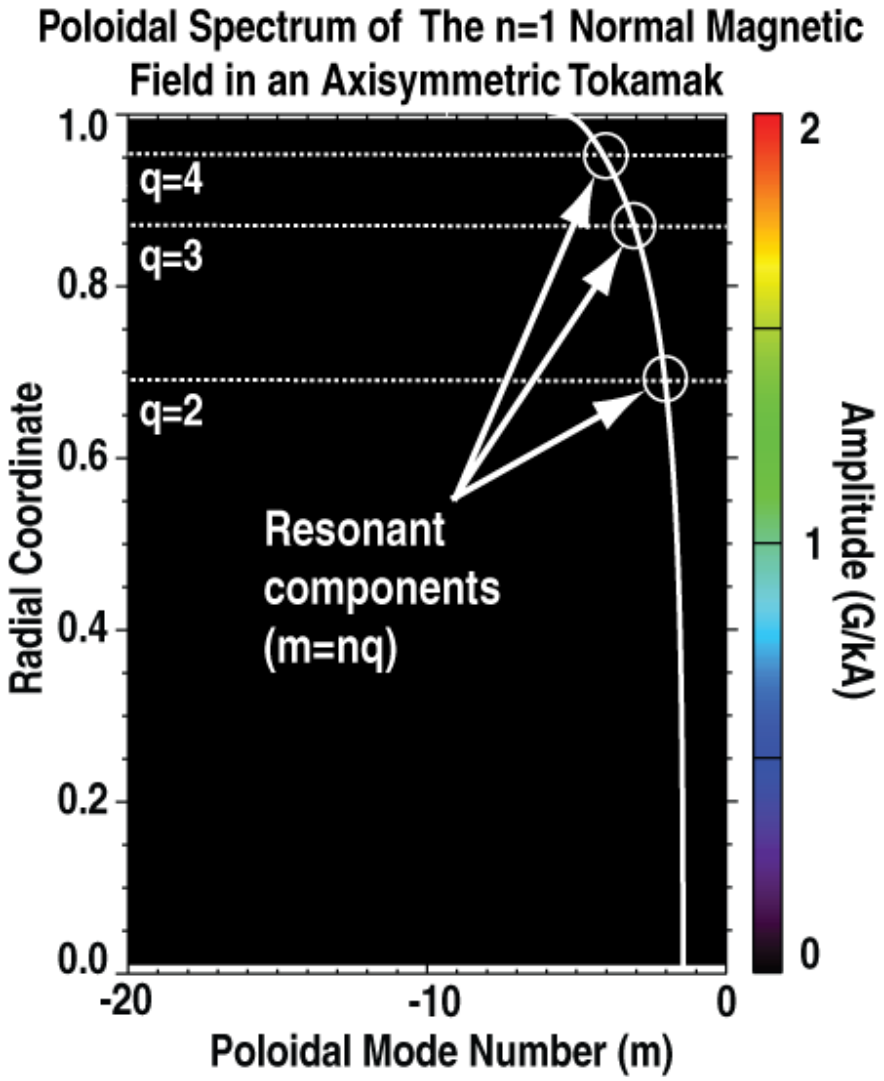
- **Need local internal plasma response measurements of basic plasma parameters for more direct test of models**



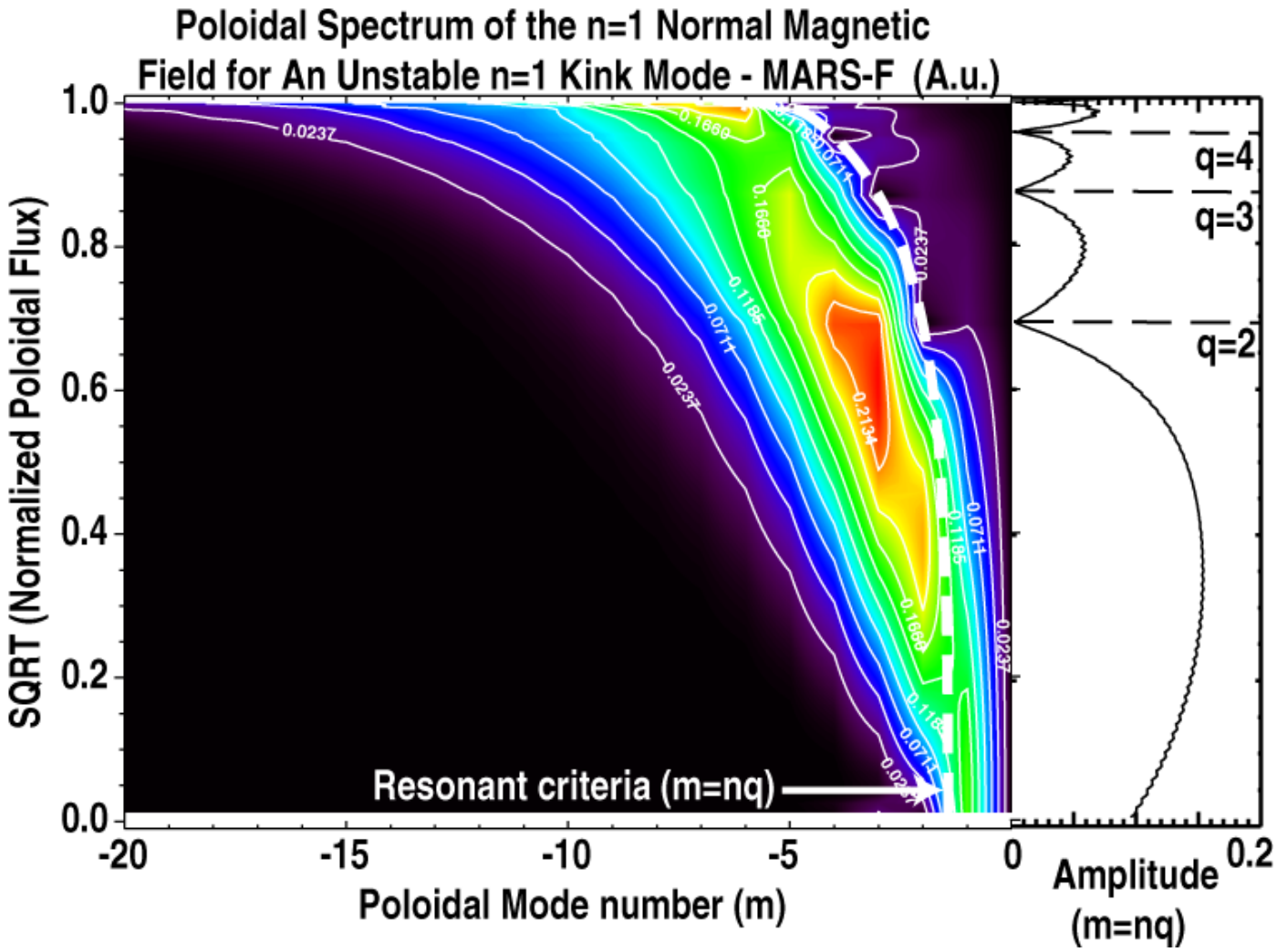
Outline

- Overview of Previous Results
- **Study of The Plasma Response in ELM Suppressed Discharges**
- Summary

In Ideal MHD, Pitch Resonant Magnetic Fields Can Drive Screening Currents At the Rational Flux Surfaces



Helical 3D Fields May Also Couple The Global Kink Mode Which Has Extensive Poloidal Mode Coupling



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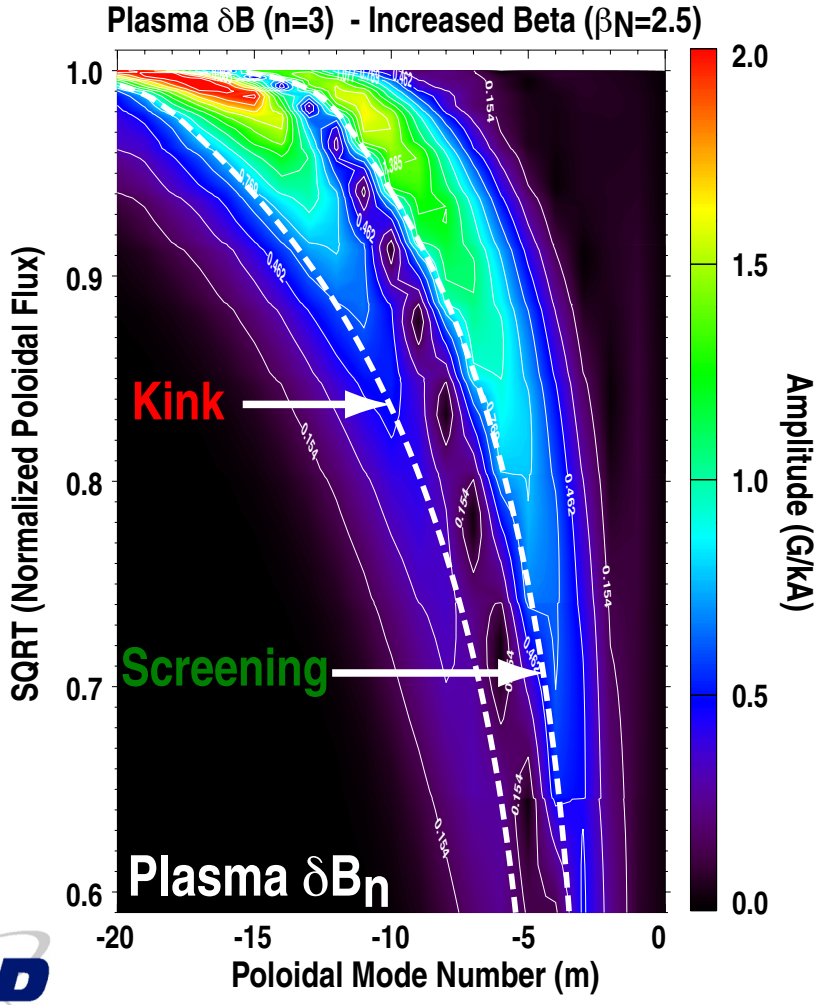
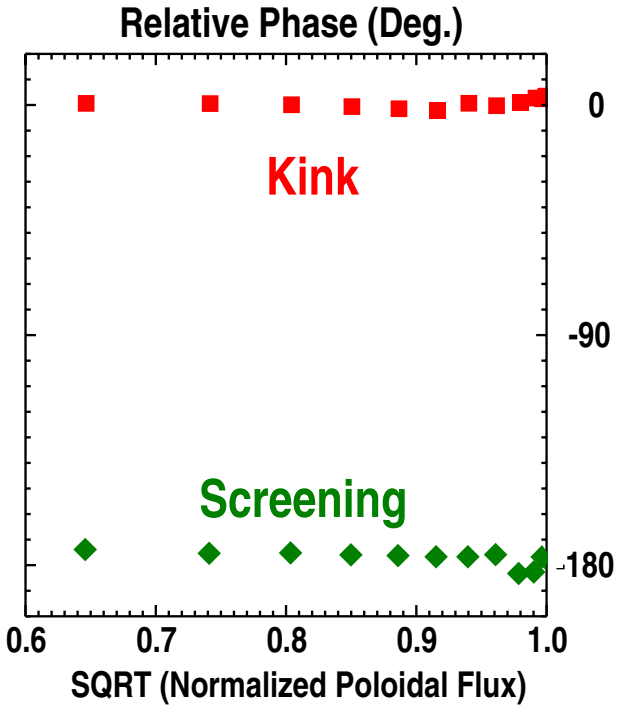
Phase of the Plasma δB Shows Screening Field Decreases the Local Field While δB Increased By Kink Mode Excitation

- Plasma δB calculated for n=3 even parity field applied to ITER-shaped DIII-D equilibrium (q_{95}=4.0)





➜ Indicates the Potential For The Superposed Field To Vanish

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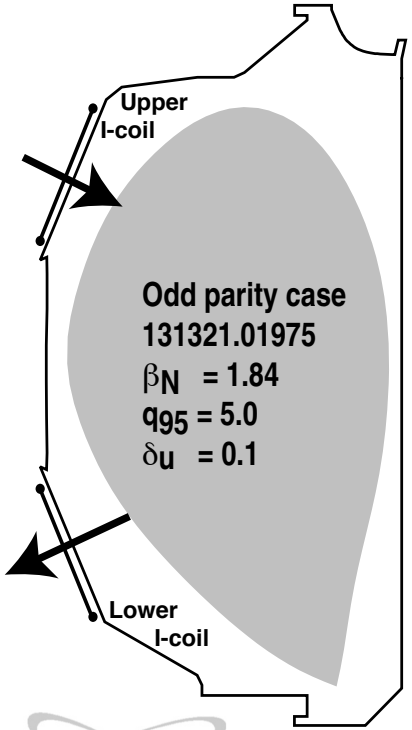
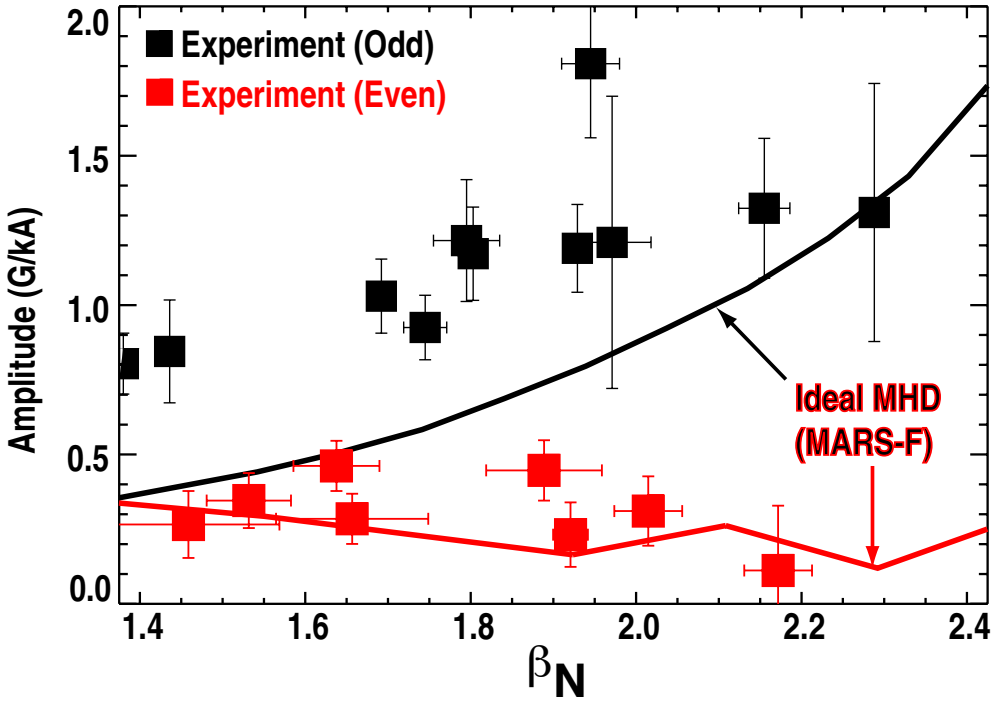
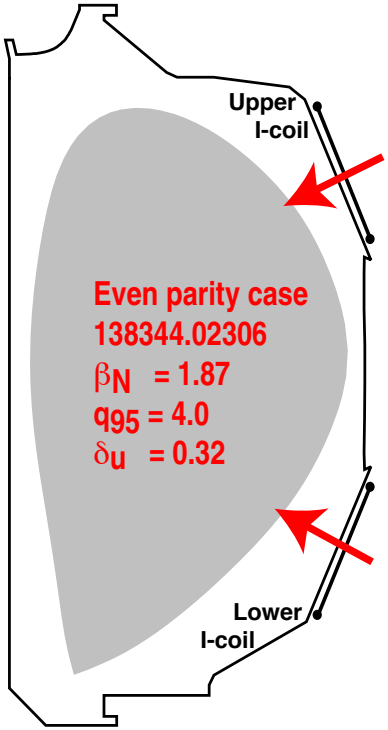
Measured Response To n=3 Even Parity I-coil Field Shows Plasma δB Is Near Zero At the Midplane

- **Probe plasma with static n=3 fields using odd and even parity**

- **Measurements and modeling (MARS-F) show plasma δB at midplane**
  - Increases with β_N for odd parity field
  - Decreases with β_N for even parity field







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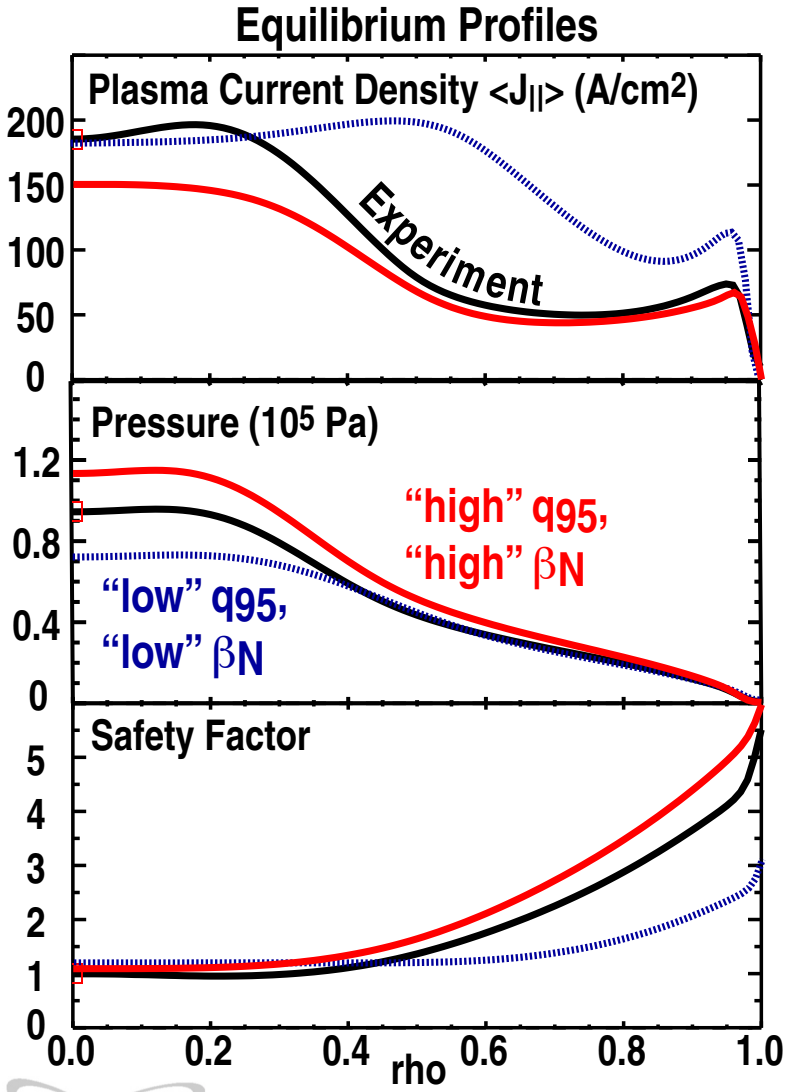
Numerical Plasma Response Study Was Conducted In The Parameter Space Relevant For ELM Suppression



- **"Kinetic" equilibrium reconstruction of an ITER shaped DIII-D plasma was modified using CORSICA Grad-Shafranov solver** [*J.A. Crotinger et al, LLNL Report UCRL-ID-126284]
  - $1.0 < \beta_N/\ell_i < 3.0$
  - $2.5 < q_{95} < 4.5$
  - $q_0 > 1.05$

- **Linear Ideal MHD model (MARS-F) used to calculate plasma response to n=3 even parity I-coil field ("RMP")**
  - Neglect rotation

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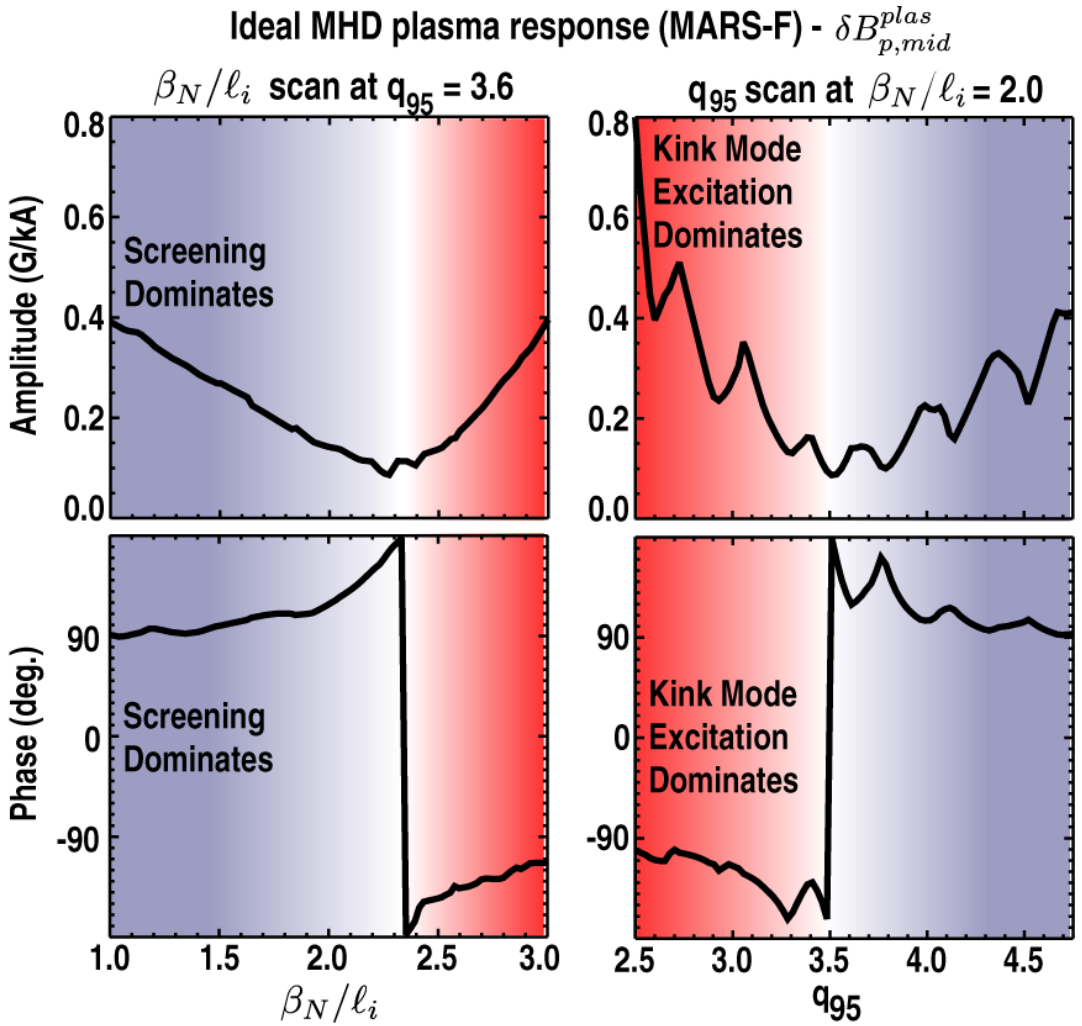
Numerical Study Shows Even Parity Field Excites The Kink Mode At High Plasma Beta and Plasma Current



- **Kink Mode Excitation becomes dominant when**
  - Kink mode becomes less stable at higher β_N
  - Largest harmonics of δB^{ext} exceed nq and couple to the kink mode

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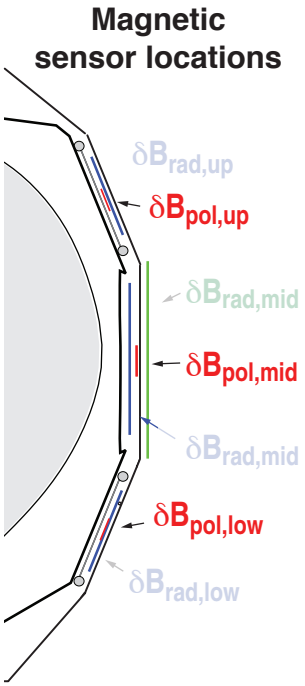
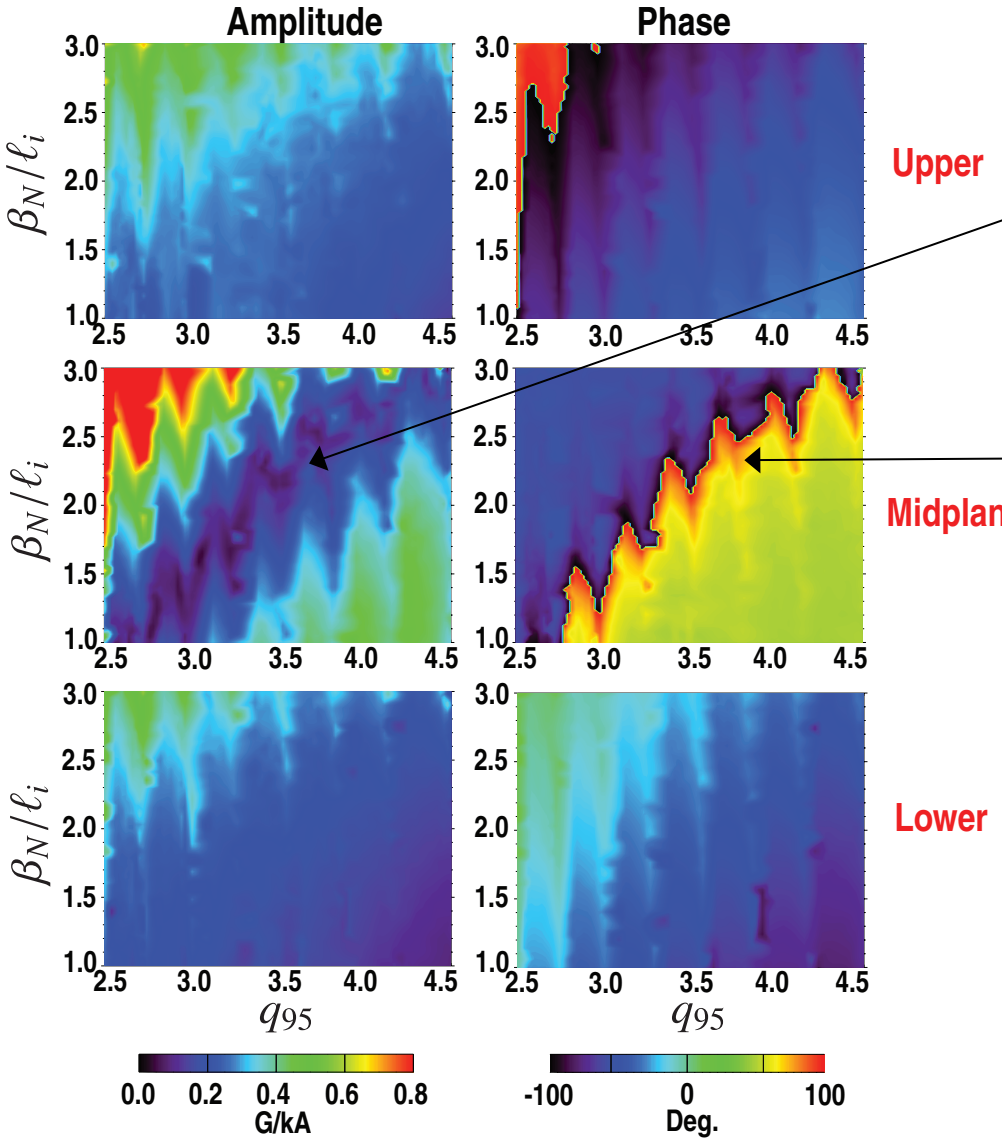
At Midplane, Poloidal Field (n=3) Attains a Minimum; Poloidal Field Increases with β_N, I_p Above/Below Midplane





- Location of minimum depends on β_N, q_{95}
- Strong shift in phase of plasma response at minimum
- No minimum observed above/ below midplane
- Similar trends observed in radial field at saddle loop locations

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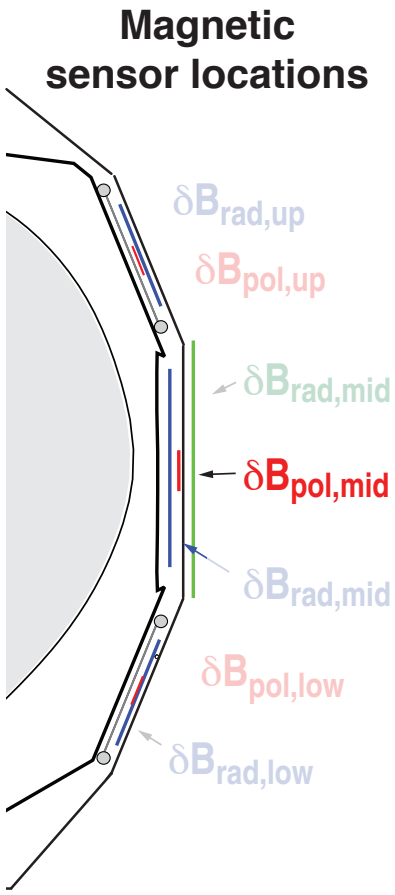
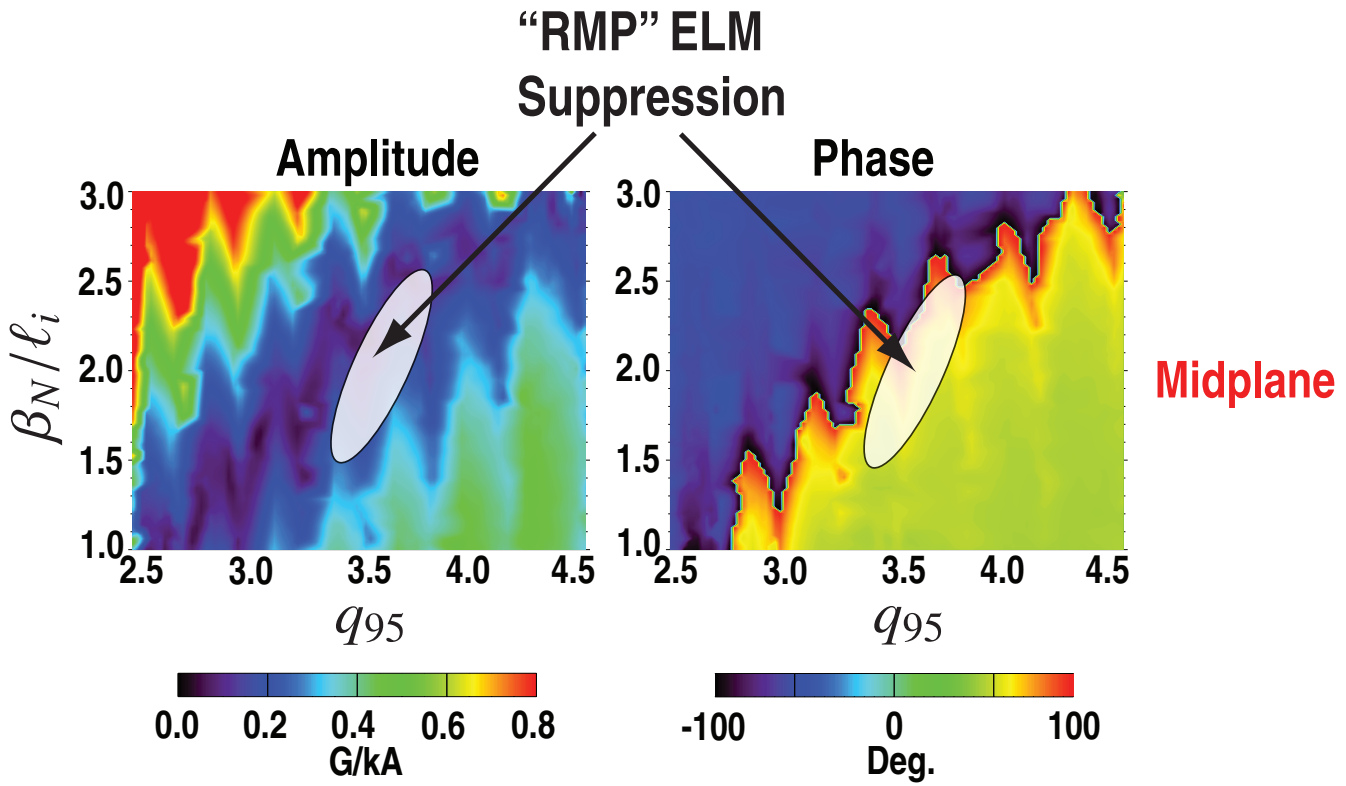
ELM Suppression By "RMP" Is Observed When Calculated Plasma δB Attains a Minimum at Midplane

- When the plasma response is near zero $\delta B \approx \delta B^{ext}$





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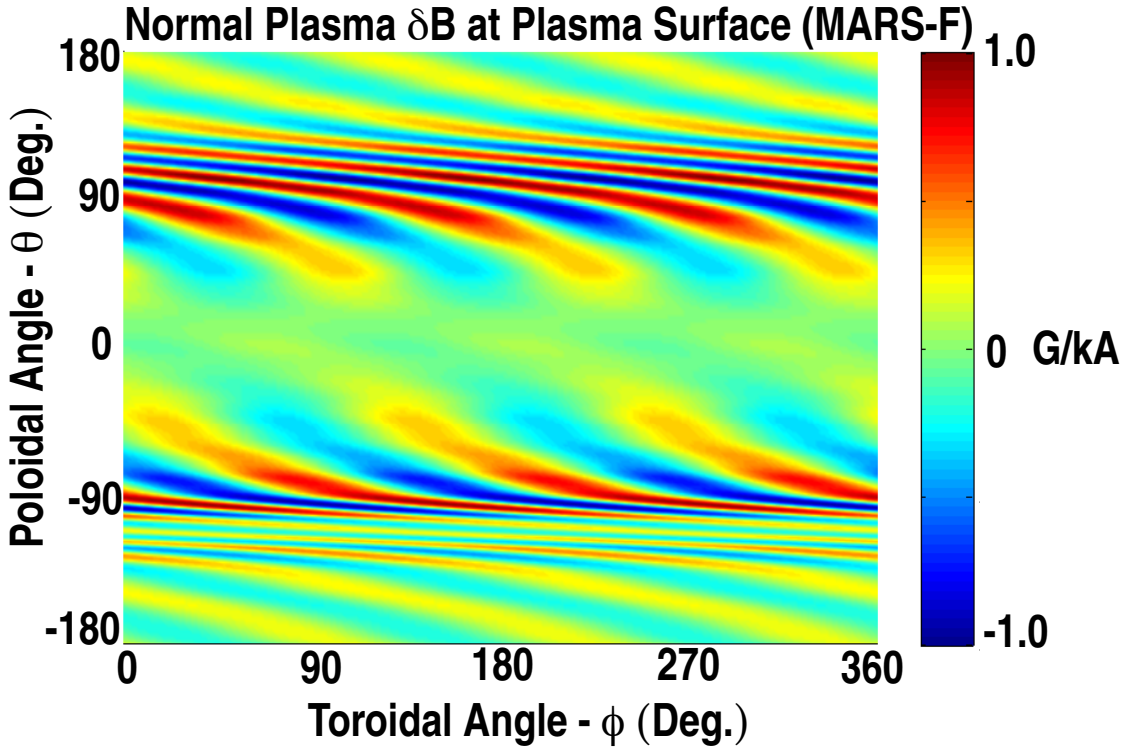
Calculated Plasma Response Is Also Near Zero At the Plasma Surface

- **Suggests a vanishing plasma response over a narrow poloidal region (allowing the external field to penetrate in bad curvature region?)**

- **May be consistent with observation that ELM suppression correlates with a minimum width for island overlap in the edge region**
  [Fenstermacher et al, Phys. Plasmas, 2008]



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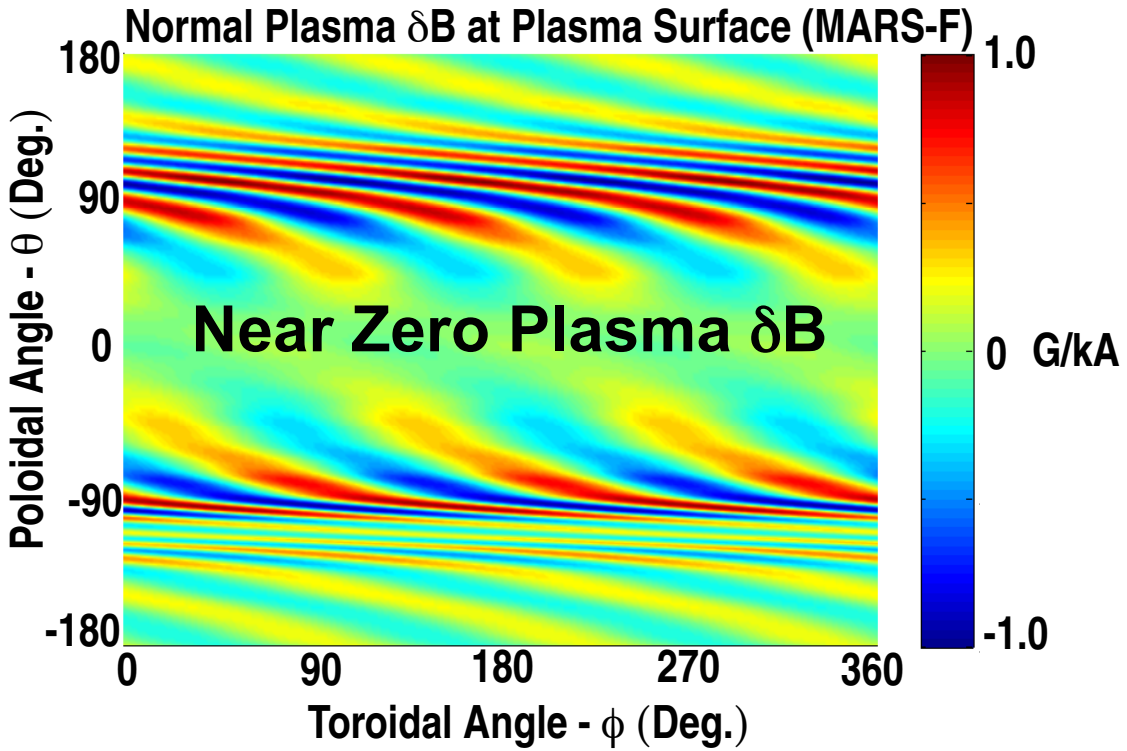
- **Future experiments will focus on further tests of modeling results**
- **Comparisons in other scenarios are planned**
- **Result should be investigated using more complete physics models**



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Summary

- **Linear Ideal MHD Theory Gives a Quantitative Description of The External Magnetic Plasma Response Over a Wide Range of β_N**
  - Up to ~ 80% of the ideal MHD no-wall limit
  - Response is linear in the applied magnetic field and β_N
  - Response is independent of rotation as long as the rotation is sufficiently large to prevent formation of magnetic islands
  - Internal measurements are needed to test linear ideal MHD models

- **Linear Ideal MHD Identifies Two types of Response fields:**
  "Resonant field screening" and "Kink mode excitation"

- **Numerical Plasma Response Study Identifies a Possible Correlation Between the Plasma Response and ELM Suppression By "RMP"**

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