Uncovering RWM stability limits in tokamaks

By
Jeremy M. Hanson[1]

In collaboration with
H. Reimerdes[2], M. J. Lanctot[3], J. Berkery[1], I. Chapman[4], S.A. Sabbagh[1], S. Haskey[5], G.A. Navratil[1], R. J. Buttery[7], Y. In[6], G. L. Jackson[7], R. J. La Haye[7], Y. Liu[4], M. Okabayashi[8], E. J. Strait[7], F. Turco[1]

1. Columbia University
2. CRPP-EPFL
3. LLNL
4. Euratom/CCFE Fusion Association
5. Australian National University
6. FAR-TECH, Inc
7. General Atomics
8. PPPL

Presented at
16th Workshop on MHD Stability Control
21 November 2011

DIII-D NATIONAL FUSION FACILITY

COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK

Measurements of plasma response to applied perturbations used to understand, control RWM stability

- **Motivation: need to validate theories of RWM stability for ITER, beyond**
  - Resistive wall modes arise from the interaction between an external kink mode and wall eddy currents. RWMs can be ***global, beta-limiting instabilities.***
  - Recent experiments on several devices have shown complex dependence of stability on plasma rotation, ***lack of a critical rotation threshold.***
- **Compare driven response of stable plasma with theory**
  - $\delta B/B < 10^{-3}$ – refer to this state as a *perturbed equilibrium*
- **Ideal MHD describes perturbed equilibria below no-wall beta limit**
  - Large body of measurements consistent with ideal MHD when $\beta < \beta^{no\text{-}wall}$
- **Kinetic modifications to ideal MHD needed above no-wall limit**
  - Evidence for wave–particle interactions uncovered, qualitatively consistent with theory.
  - Off-axs NBI used to probe kinetic damping in recent experiment
- **Direct stability control demonstrated using NBI feedback**
  - Feedback dynamics are linear below no-wall limit.

Outline

1. **Making perturbative measurements of RWM stability**
   – Measure plasma response δB^{plas} to applied fields in stable plasmas

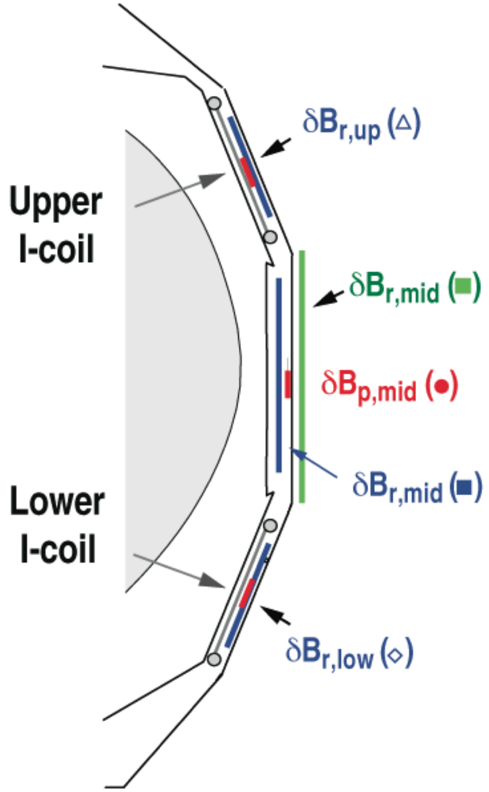
2. **Linking plasma response and ideal MHD theory**
   – Ideal MHD describes experiments for $\beta < \beta^{no\text{-}wall}$, plasma rotation sufficiently high

3. **Uncovering kinetic modifications to ideal MHD**
   – Kinetic modifications important when $\beta > \beta^{no\text{-}wall}$

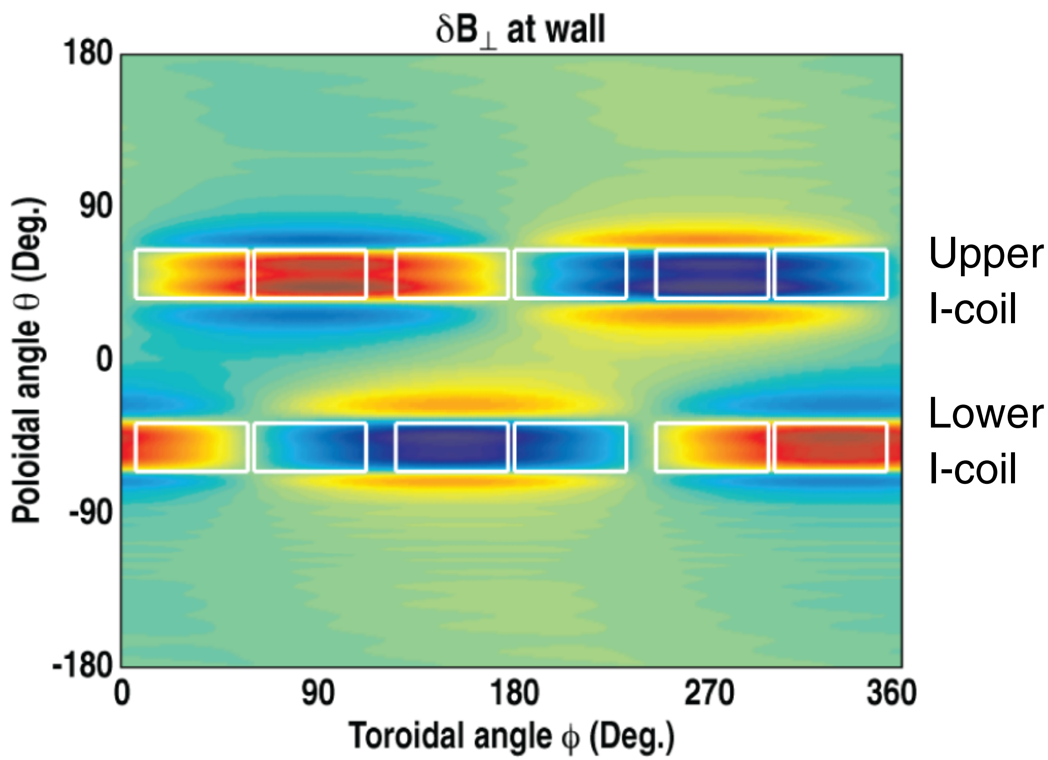
4. **Controlling the proximity to the RWM stability limit**
   – Direct control of RWM stability margin demonstrated using NBI feedback

Perturbative measurements of RWM stability

DIII-D tokamak is well equipped to create and measure perturbed equilibria

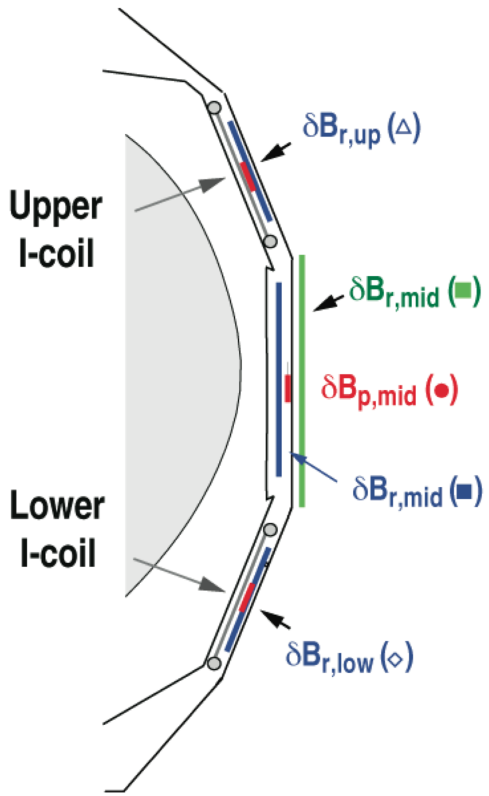


I-coil vacuum field ($\delta B/B_T < 10^{-3}$)

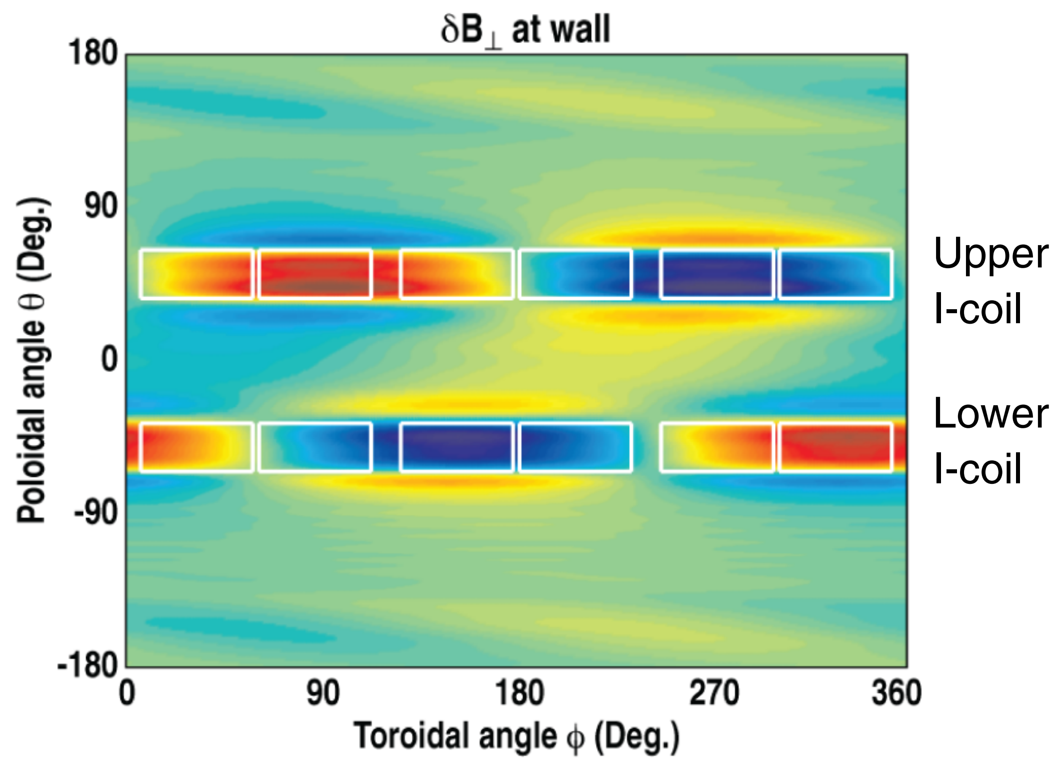


Spectrum of applied I-coil field chosen to resonate with plasma kink mode

DIII-D tokamak is well equipped to create and measure perturbed equilibria

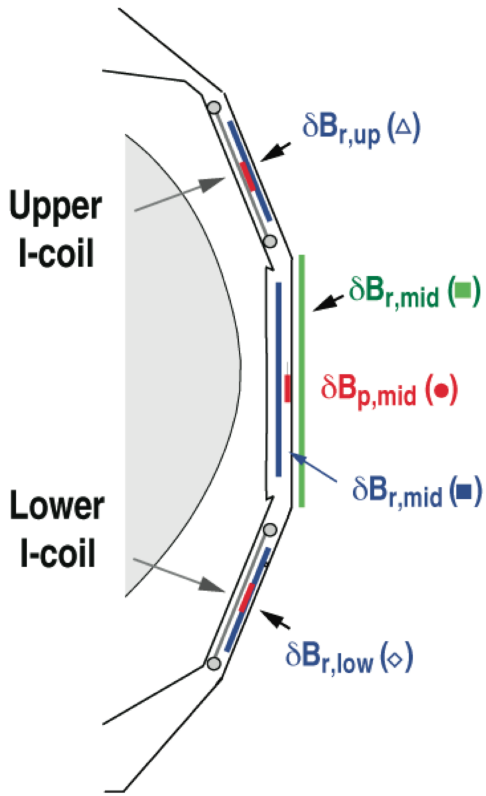


I-coil vacuum field + plasma response

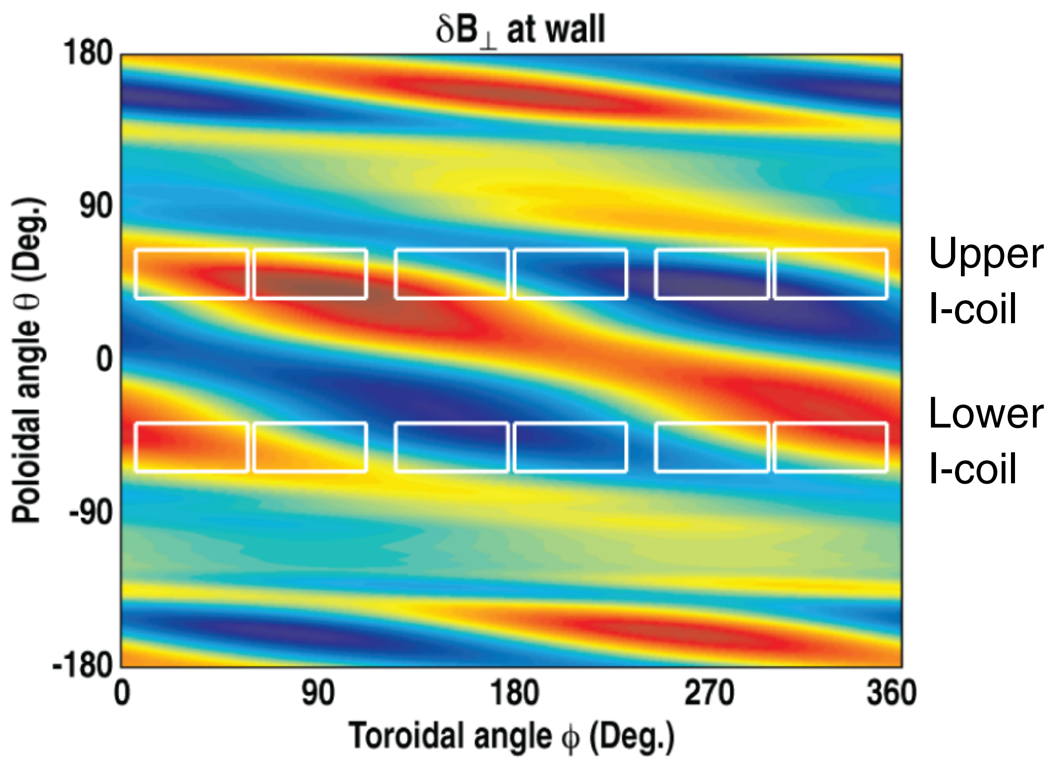


Spectrum of applied I-coil field chosen to resonate with plasma kink mode

DIII-D tokamak is well equipped to create and measure perturbed equilibria

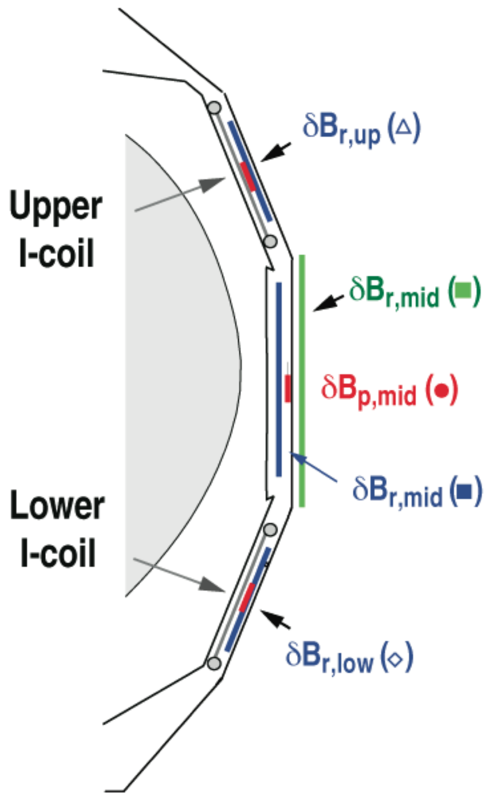


Plasma response to I-coil field

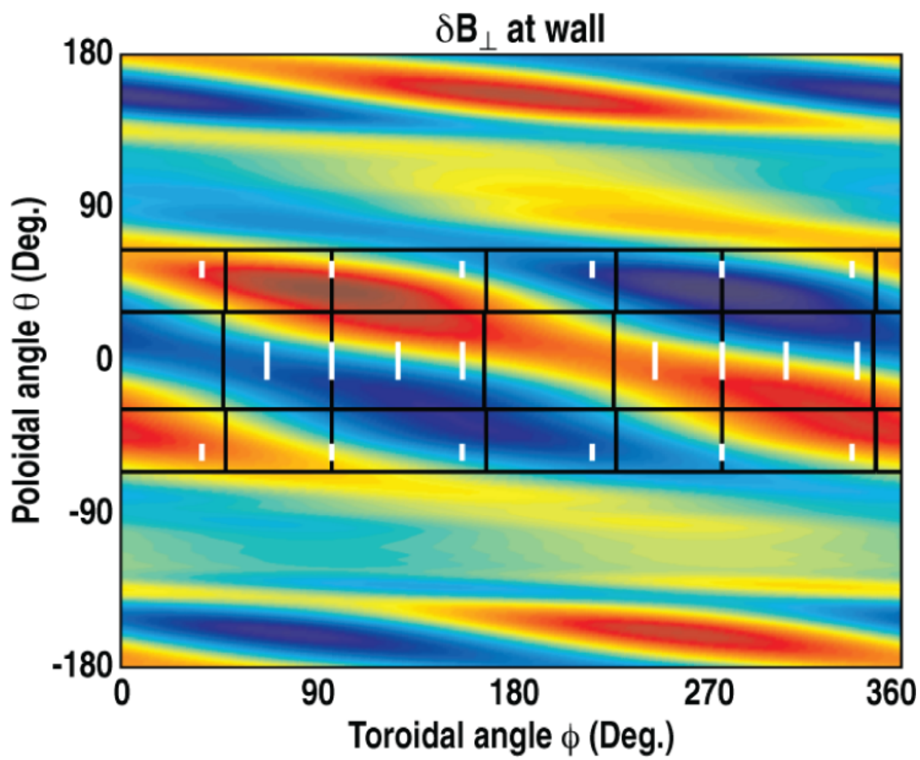


Spectrum of applied I-coil field chosen to resonate with plasma kink mode

DIII-D tokamak is well equipped to create and measure perturbed equilibria



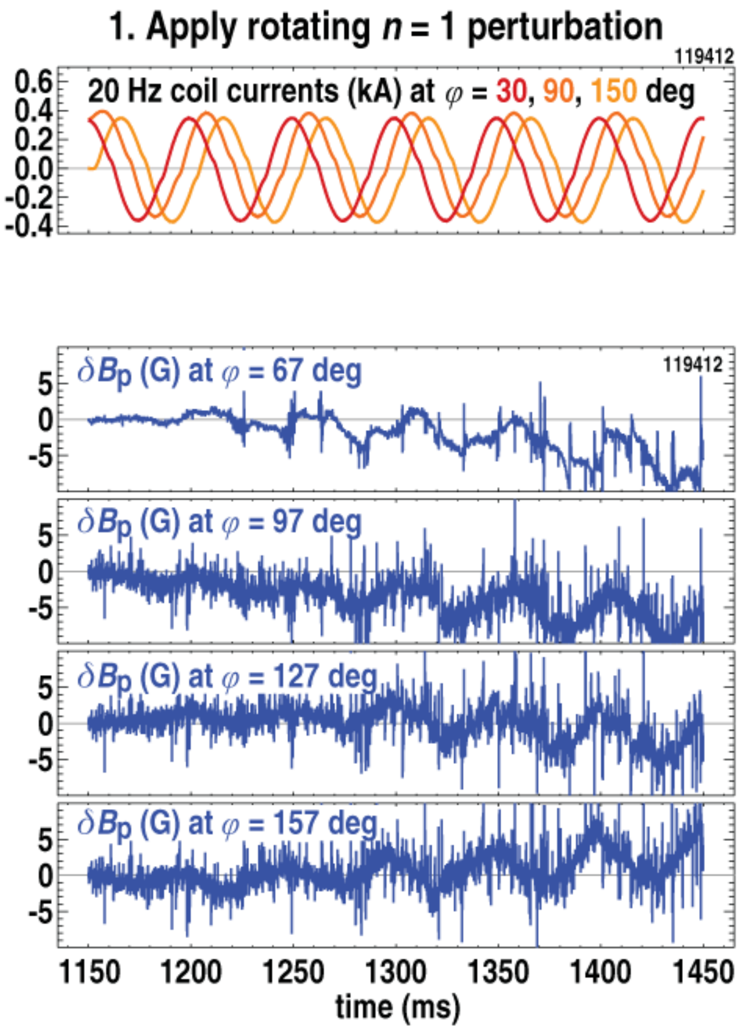
Plasma response to I-coil field



B_r and B_p pickup loops

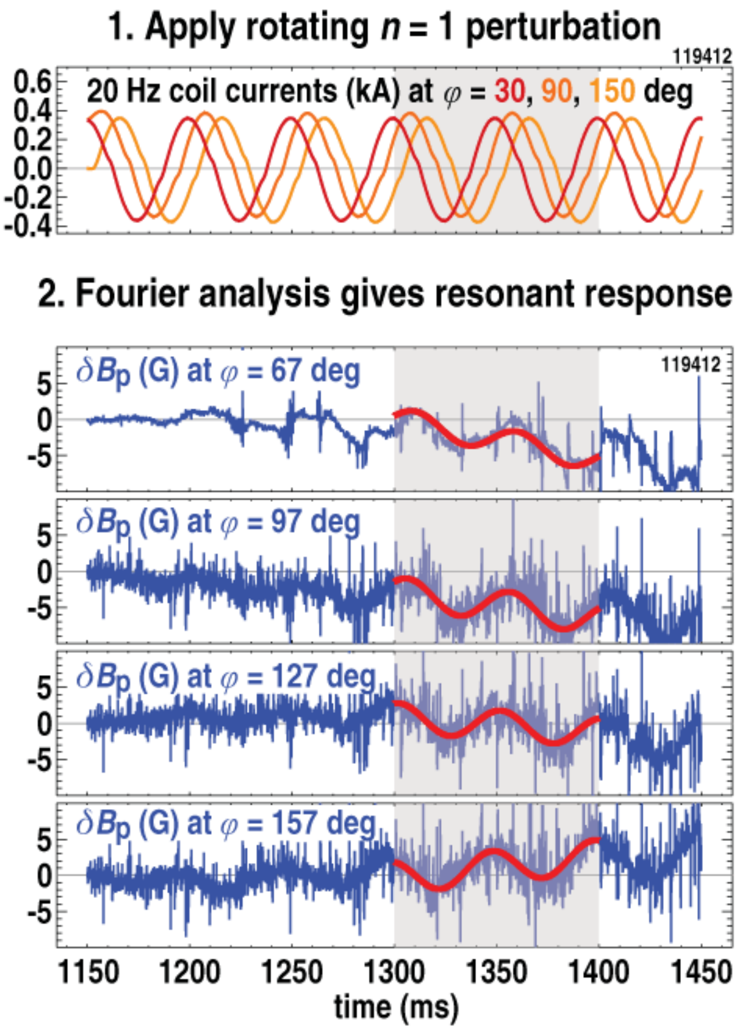
Fits to magnetic measurements yield *amplitude* and *toroidal phase* of plasma response

Single-frequency analysis yields plasma response to applied, rotating perturbation



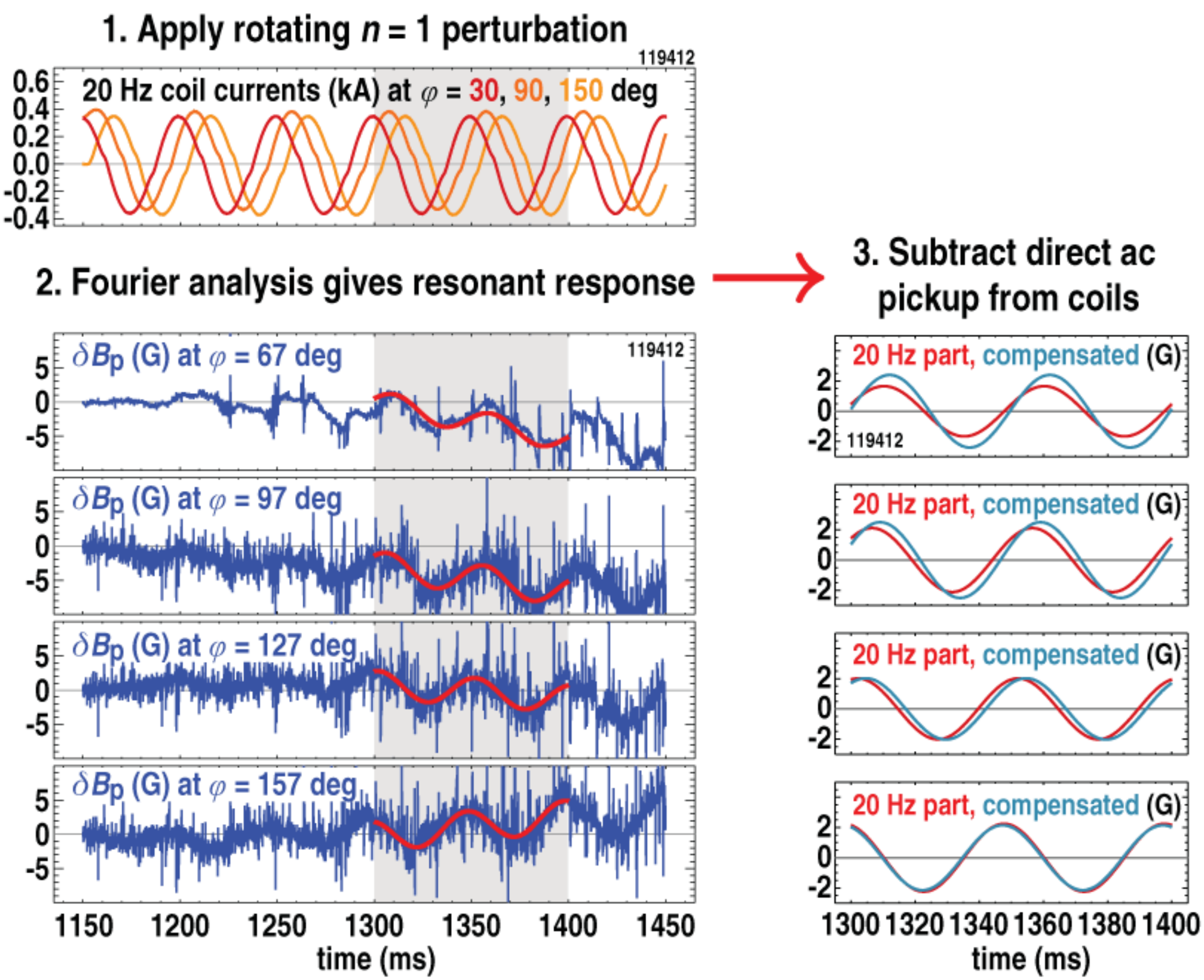
- **Apply rotating perturbation** near natural rotation frequency of RWM, ~20 Hz in DIII-D.

Single-frequency analysis yields plasma response to rotating, 3D perturbation

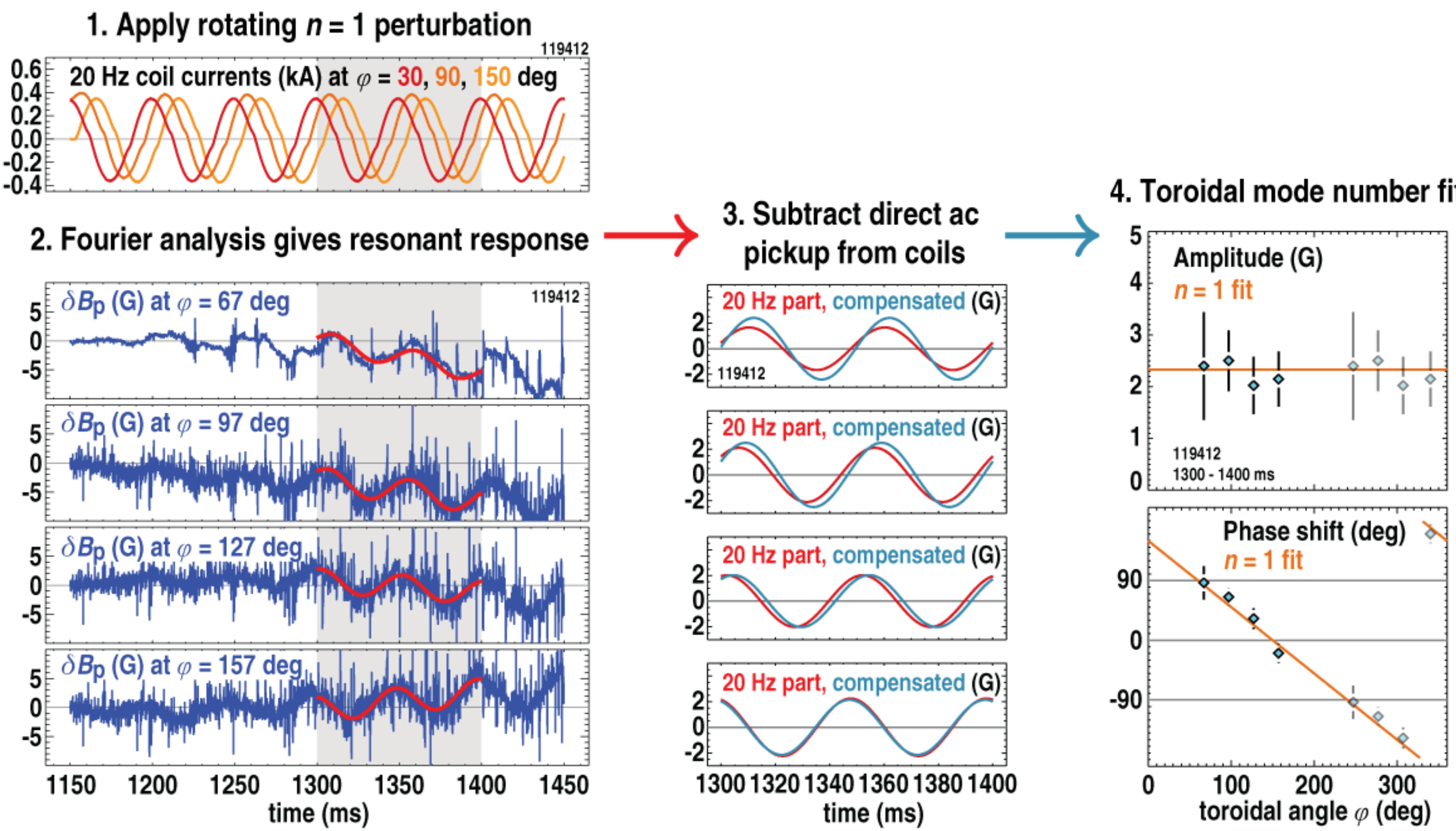


- **Apply rotating perturbation** near natural rotation frequency of RWM, ~20 Hz in DIII-D.
- **Measure response using synchronous detection.** Fourier analyze over a sliding window containing several oscillation periods
- In real-time analysis and feedback, sliding averaging window leads to delay of half the window size, τ_{lag} ~ 100 ms.

Single-frequency analysis yields plasma response to rotating, 3D perturbation

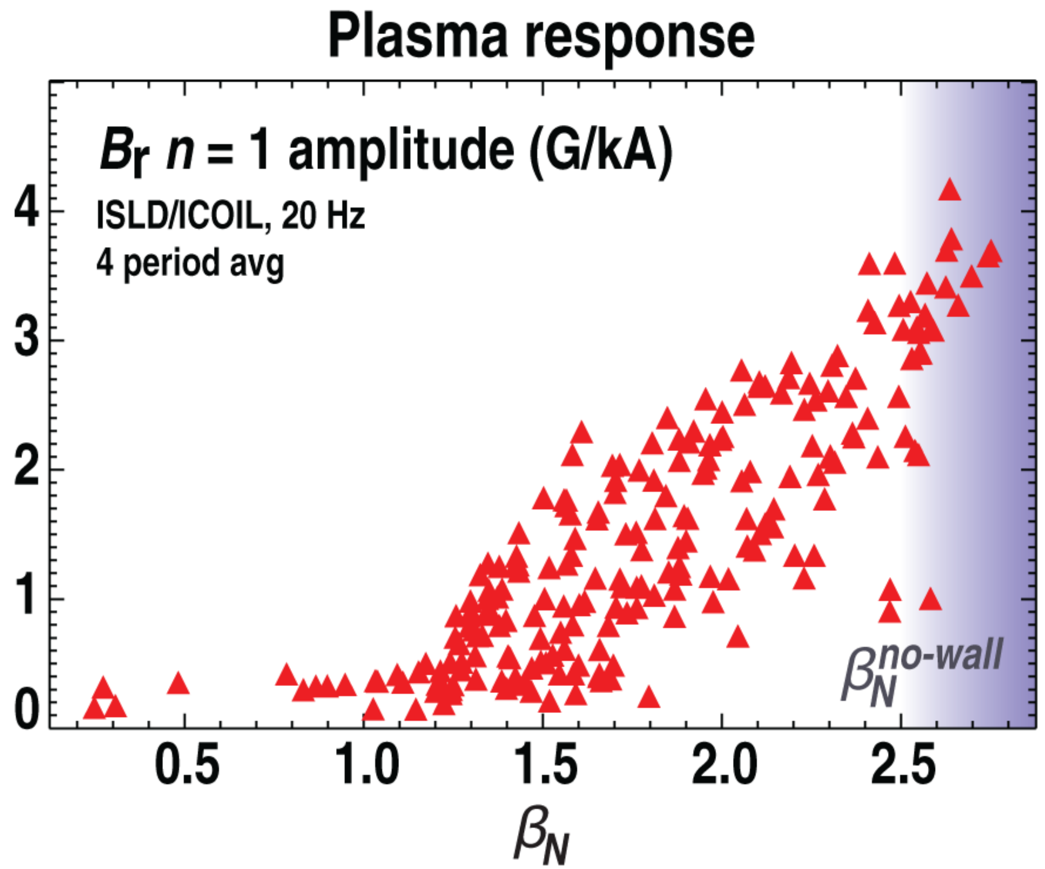


Single-frequency analysis yields plasma response to rotating, 3D perturbation



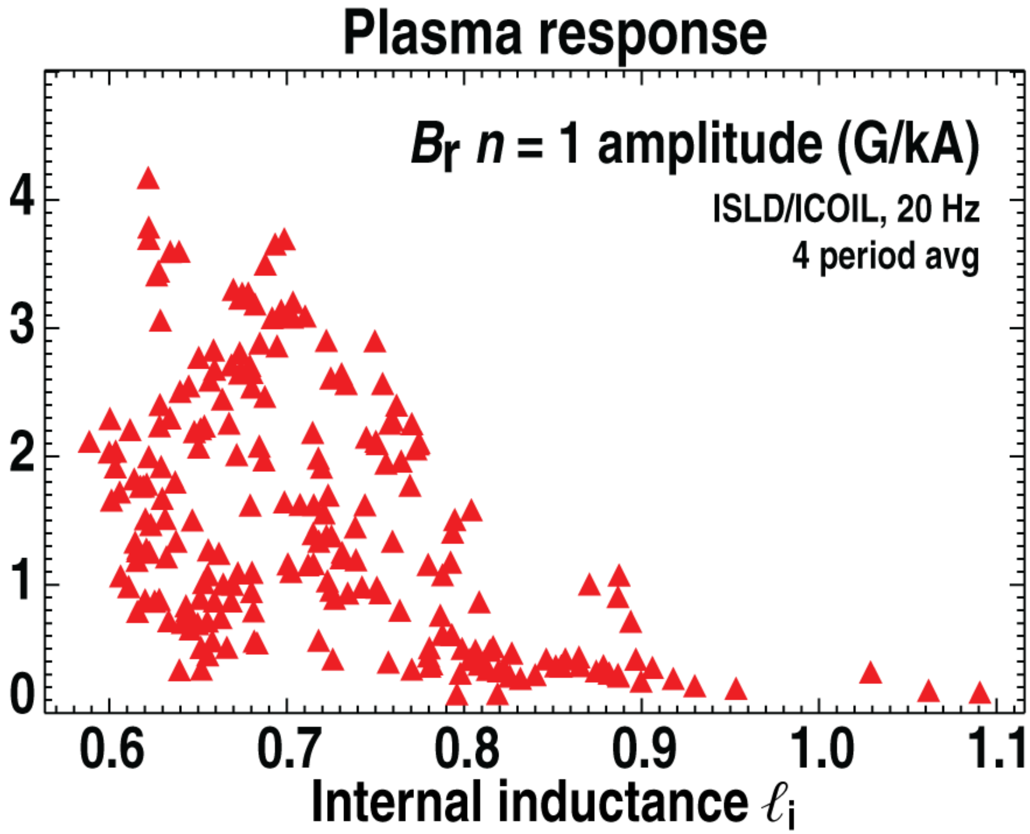
Link between plasma response and ideal MHD theory below no-wall limit

Plasma response dependencies consistent with ideal MHD expectations for RWM stability, below no-wall limit



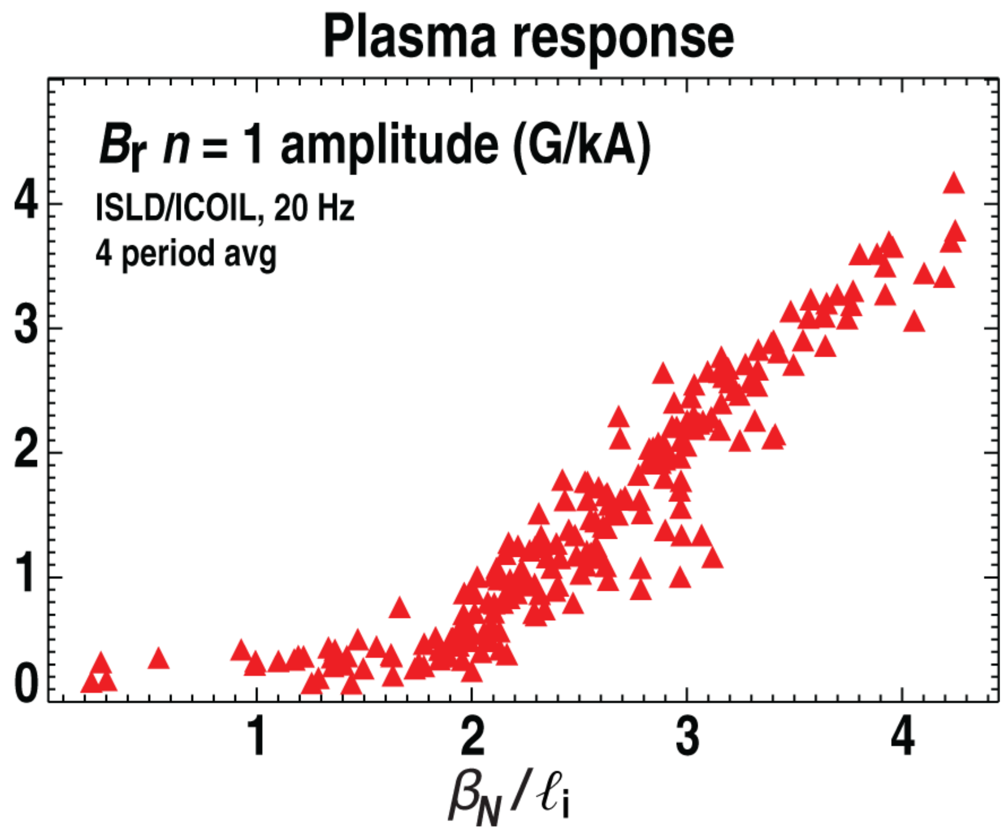
- **Data from 14 shots, obtained during AT scenario development day**
- **Increase of δB^{plas} with β_N widely observed (DIII-D, NSTX, JET)**
  - Some devices/scenarios do exhibit devitations from monotonicity

Plasma response dependencies consistent with ideal MHD expectations for RWM stability, below no-wall limit



- **See inverse dependence on internal inductance** (current profile broadness)
  - Scatter due to wide variations in β_N

Plasma response dependencies consistent with ideal MHD expectations for RWM stability, below no-wall limit

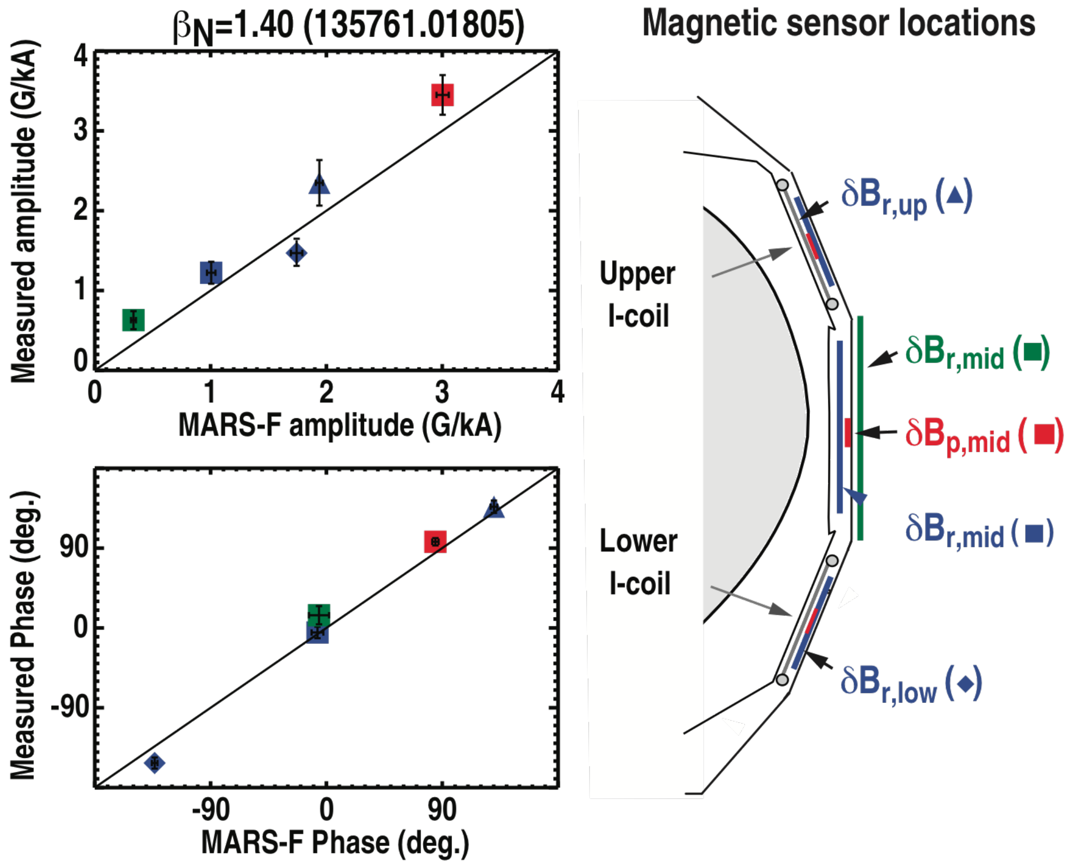


- **Clear dependence of plasma response on β_N/ℓ_i normalization**

Measured plasma response consistent with linear, ideal MHD below no-wall limit

- **Linear ideal MHD calculations (MARS-F) in good agreement with magnetic plasma response measurements**

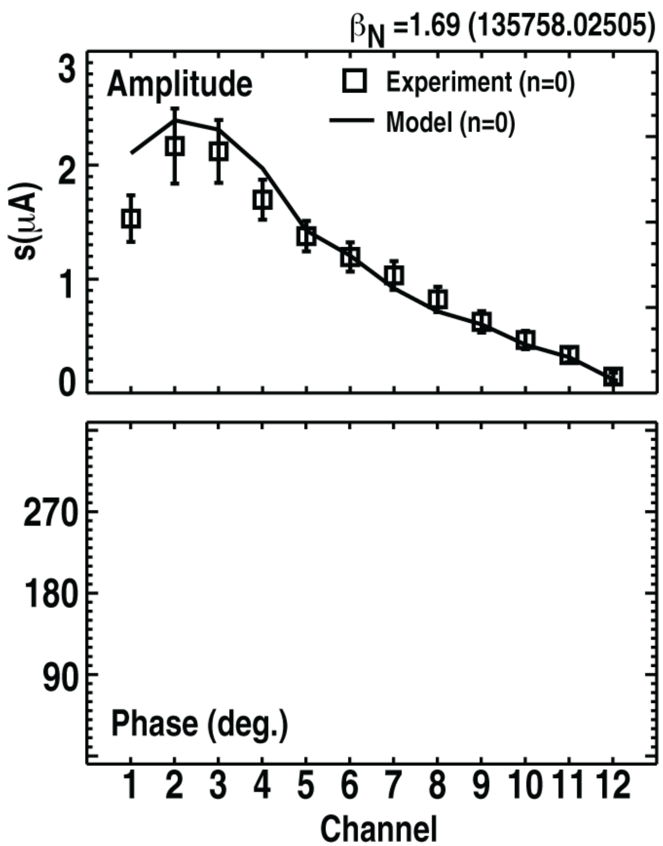
[M.J. Lanctot et al., *Phys. Plasmas* 2010]

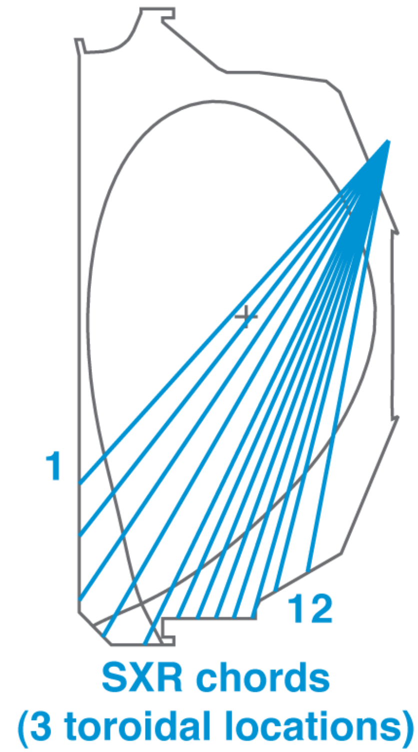


Measured plasma response consistent with linear, ideal MHD below no-wall limit

- **Linear ideal MHD calculations (MARS-F) in good agreement with SXR profile measurements of plasma response**

[M.J. Lanctot et al., *Phys. Plasmas* 2011]

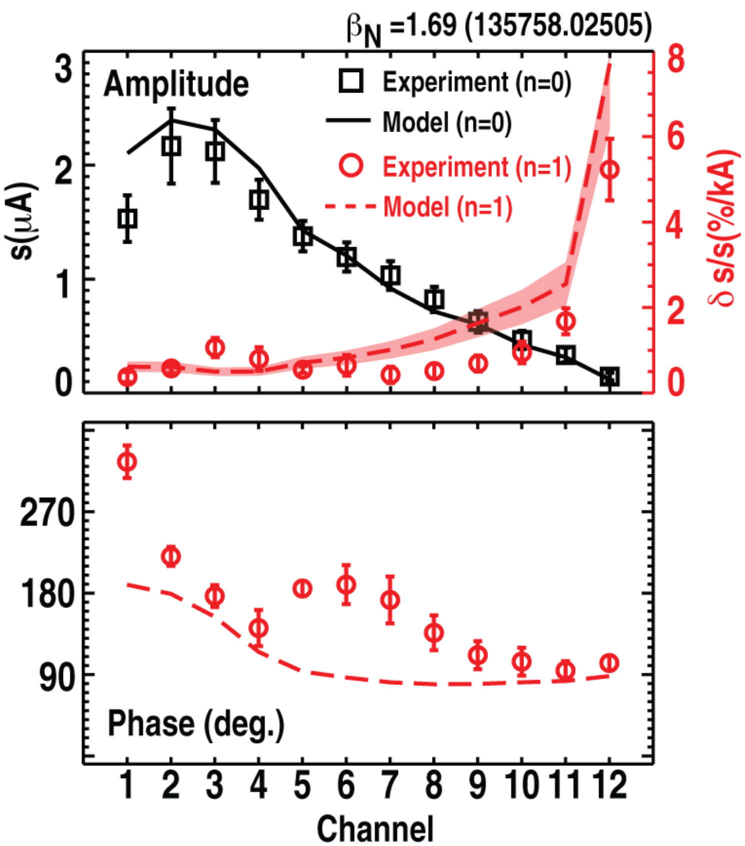


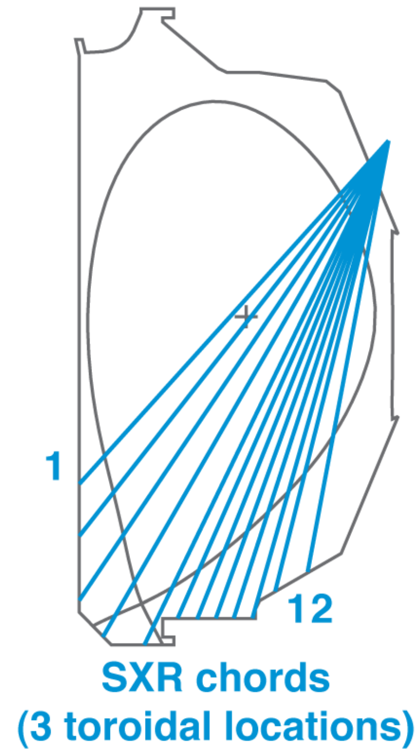


Measured plasma response consistent with linear, ideal MHD below no-wall limit

- **Linear ideal MHD calculations (MARS-F) in good agreement with SXR profile measurements of plasma response**

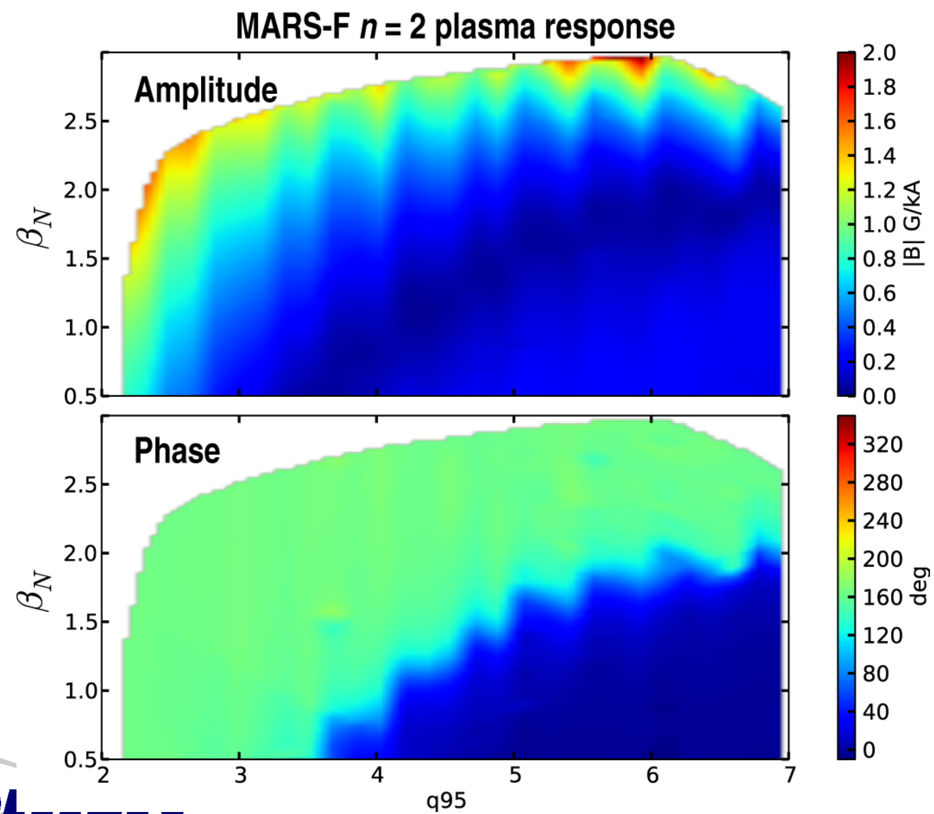
[M.J. Lanctot et al., *Phys. Plasmas* 2011]





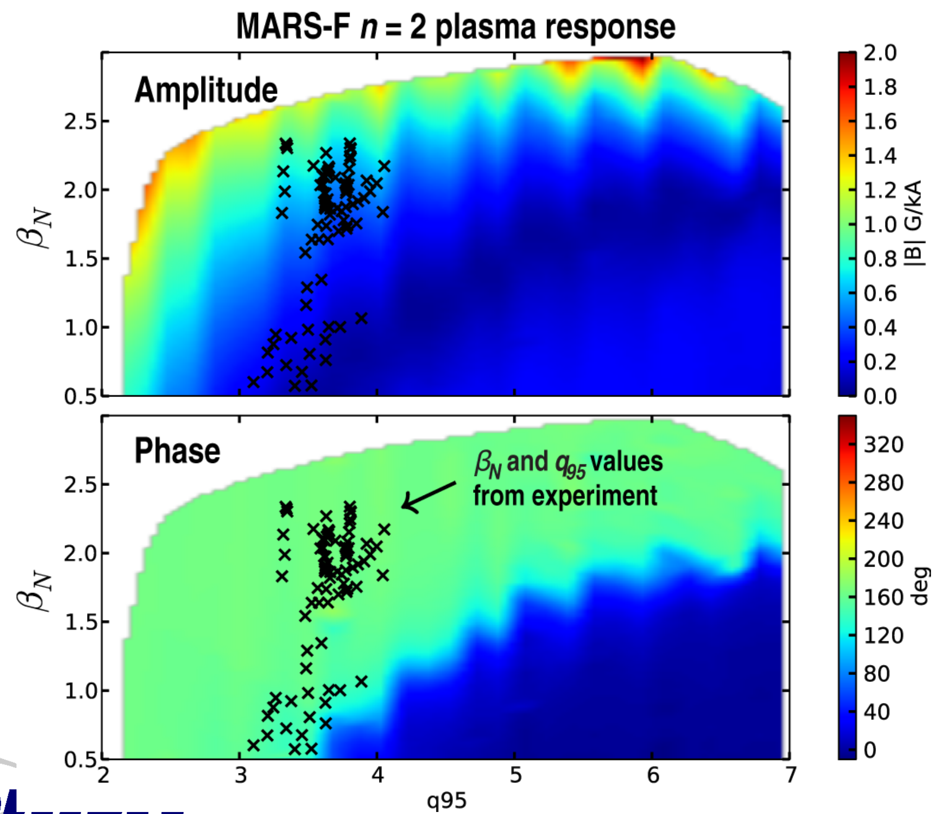
Measurements of n = 2, 3 plasma response compared with linear, ideal MHD

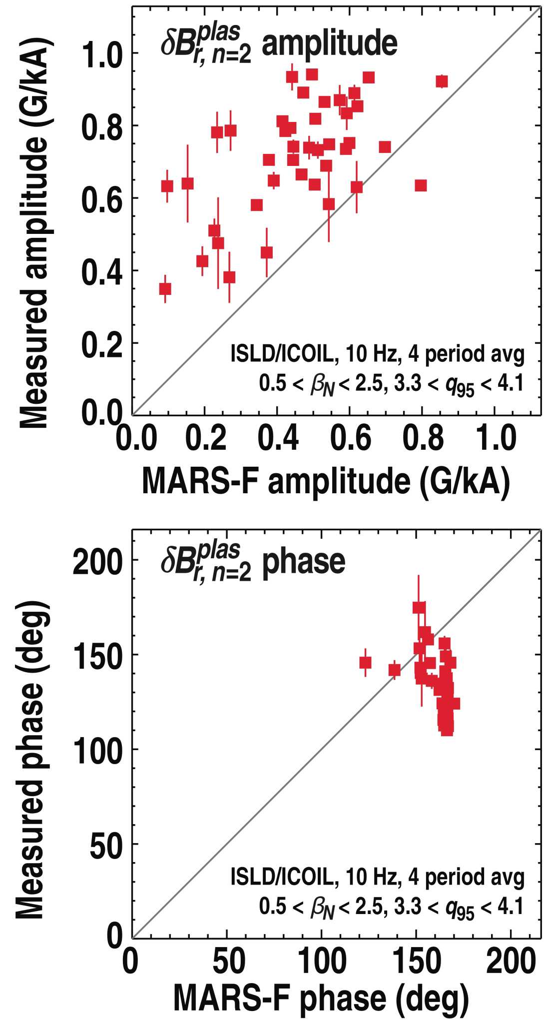
- **Plasma response to ac n = 2 perturbations predicted for a range of β_N, q_{95} values using MARS-F**



Measurements of n = 2, 3 plasma response compared with linear, ideal MHD

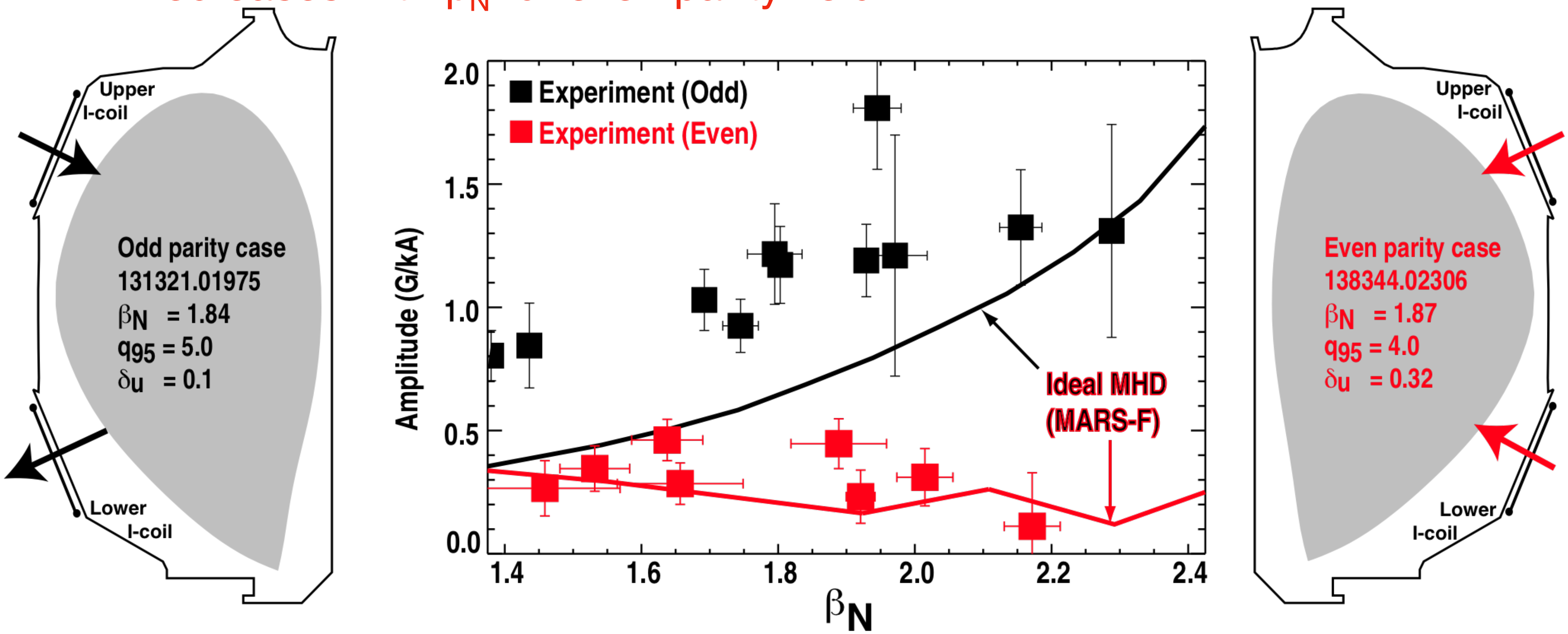
- **Plasma response to ac n = 2 perturbations predicted for a range of β_N, q_{95} values using MARS-F**
- **Preliminary comparison with experiment yields qualitative agreement**





Measurements of *n* = 2, 3 plasma response compared with linear, ideal MHD

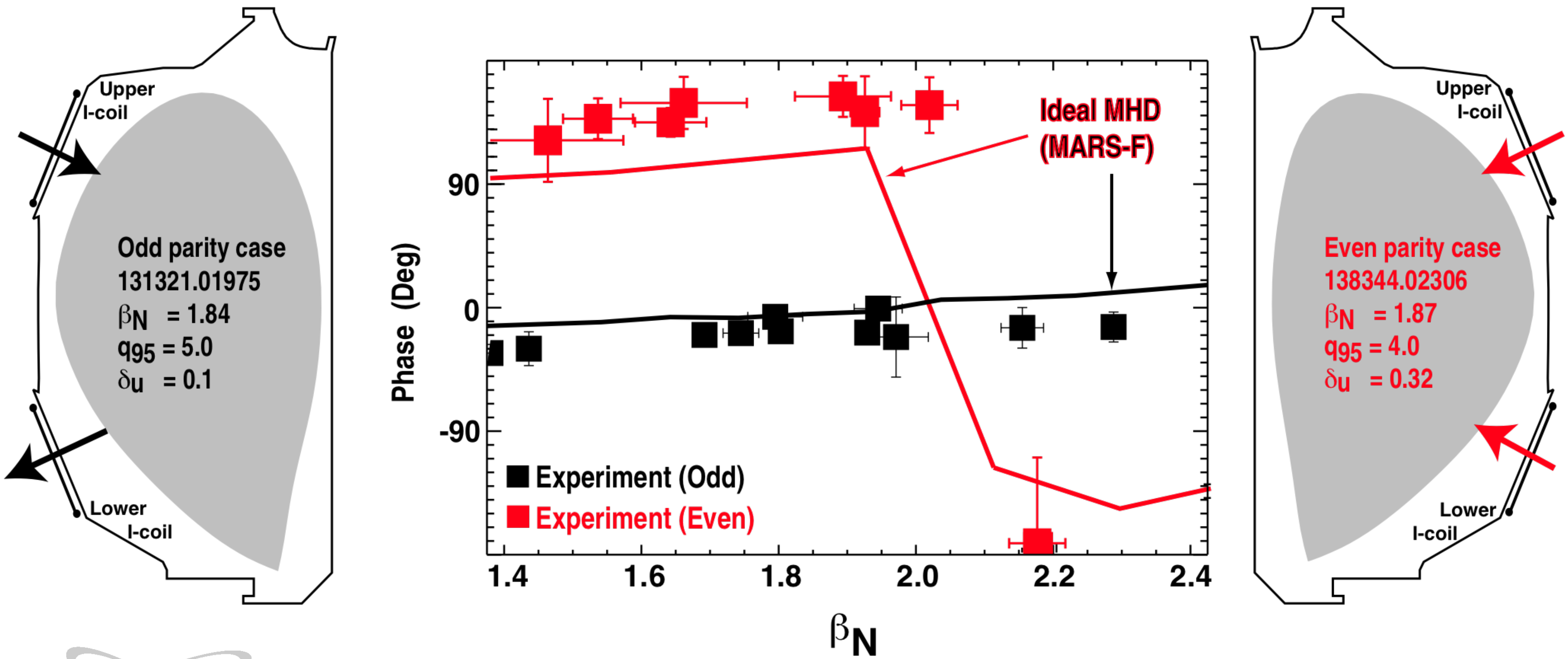
- **Probe plasma with static n=3 fields using odd and even parity**
- **Measurements and modeling (MARS-F) show plasma δB at midplane**
  - Increases with β_N for odd parity field
  - Decreases with β_N for even parity field



[Lanctot, *et al., Phys. Plasmas* 2011]

Measurements of $n = 2, 3$ plasma response compared with linear, ideal MHD

- **Measured <u>phase</u> of even parity response field drifts by 60° with β_N in agreement with linear ideal MHD model**
  - Odd parity phase is relatively constant

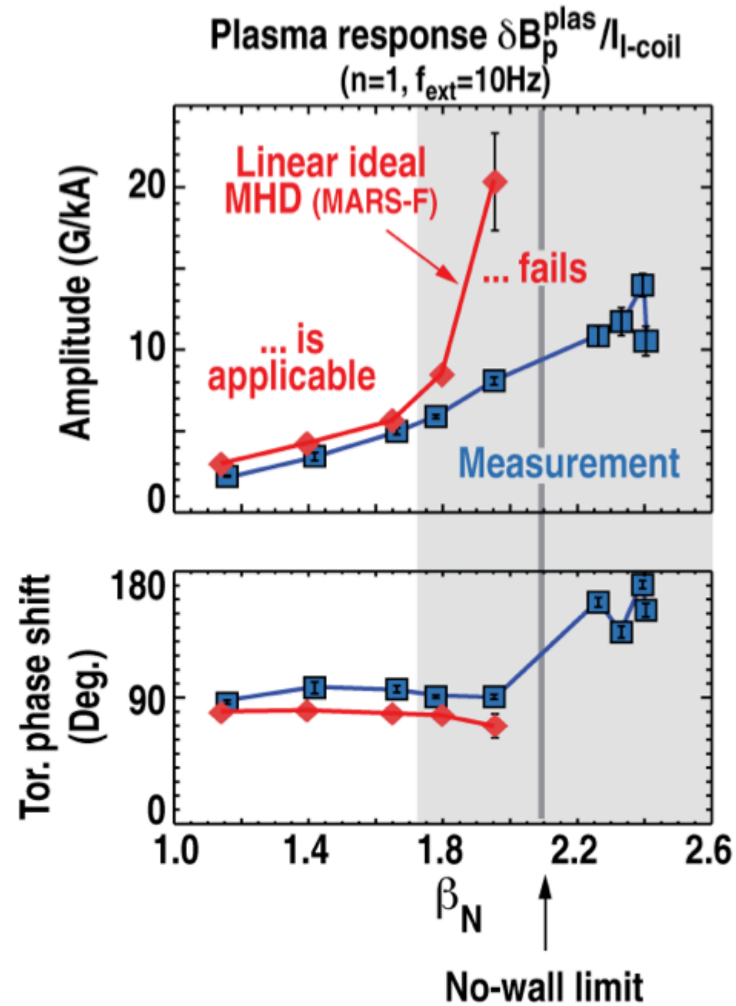


[Lanctot, *et al., Phys. Plasmas* 2011]

Linear, ideal MHD sufficient to predict plasma response below the no-wall limit

- **Scan of β_N dependence of $n = 1$ plasma response reveals limitation of linear ideal MHD**
  - Ideal MHD works for $\beta < 0.8\ \beta^{nw}$
  - Diverges near no-wall limit
  - Predicts instability above no-wall limit

- **Progress in describing observed stability above no-wall limit with kinetic modifications to ideal MHD energy principle**



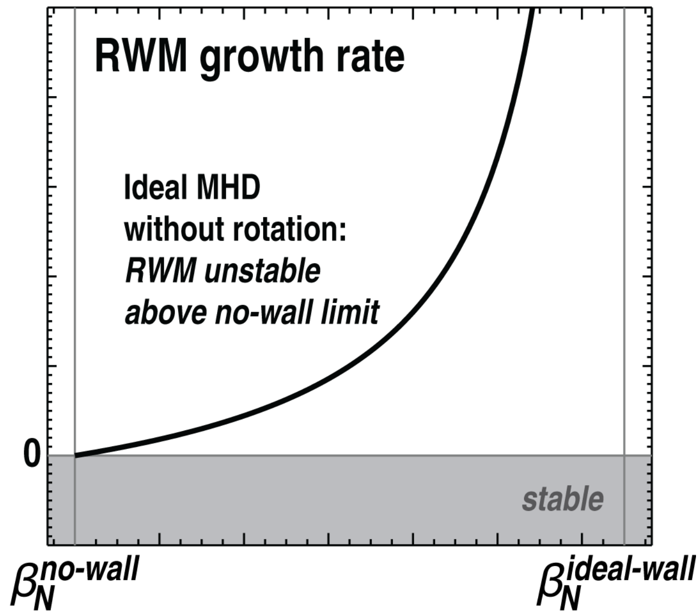
[Lanctot, *et al., Phys. Plasmas* 2010]

Uncovering kinetic modifications to ideal MHD

Kinetic wave-particle damping leads to enhanced RWM stability above no-wall limit

- **Ideal MHD energy principle modified to include kinetic damping physics**
  [Hu and Betti, PRL, 2004].

$$\gamma\tau_w = -\frac{\delta W_{nw}}{\delta W_{iw}}$$

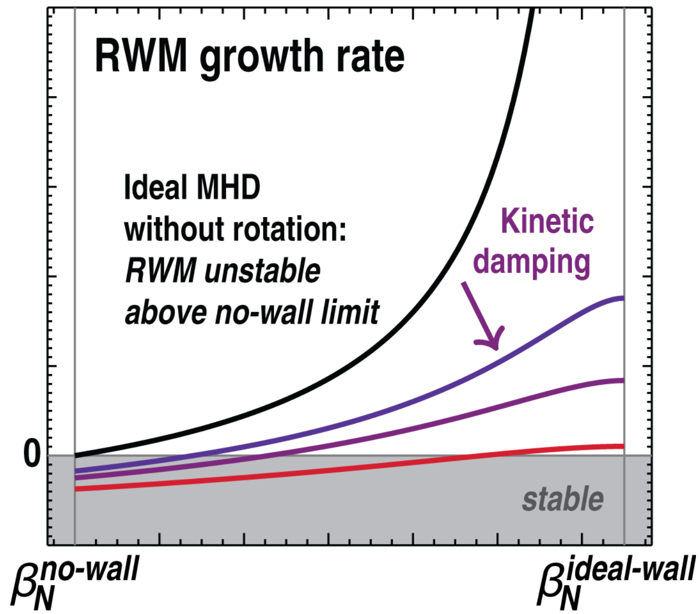


Kinetic wave-particle damping leads to enhanced RWM stability above no-wall limit

- **Ideal MHD energy principle modified to include kinetic damping physics** [Hu and Betti, PRL, 2004].

$$\gamma\tau_w = -\frac{\delta W_{nw}}{\delta W_{iw}} \rightarrow -\frac{\delta W_{nw} + \delta W_K}{\delta W_{iw} + \delta W_K}$$

$$\delta W_K = \frac{1}{2}\int \vec{\xi}_\perp \cdot \vec{\nabla} \cdot \tilde{P}_K d\vec{v}$$

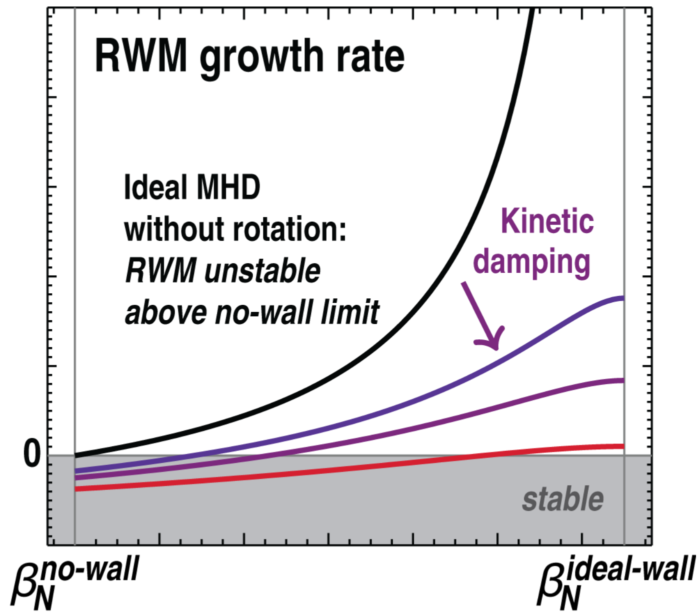


Kinetic wave-particle damping leads to enhanced RWM stability above no-wall limit

- **Ideal MHD energy principle modified to include kinetic damping physics**
  [Hu and Betti, PRL, 2004].

$$\gamma\tau_w = -\frac{\delta W_{nw}}{\delta W_{iw}} \rightarrow -\frac{\delta W_{nw} + \delta W_K}{\delta W_{iw} + \delta W_K}$$

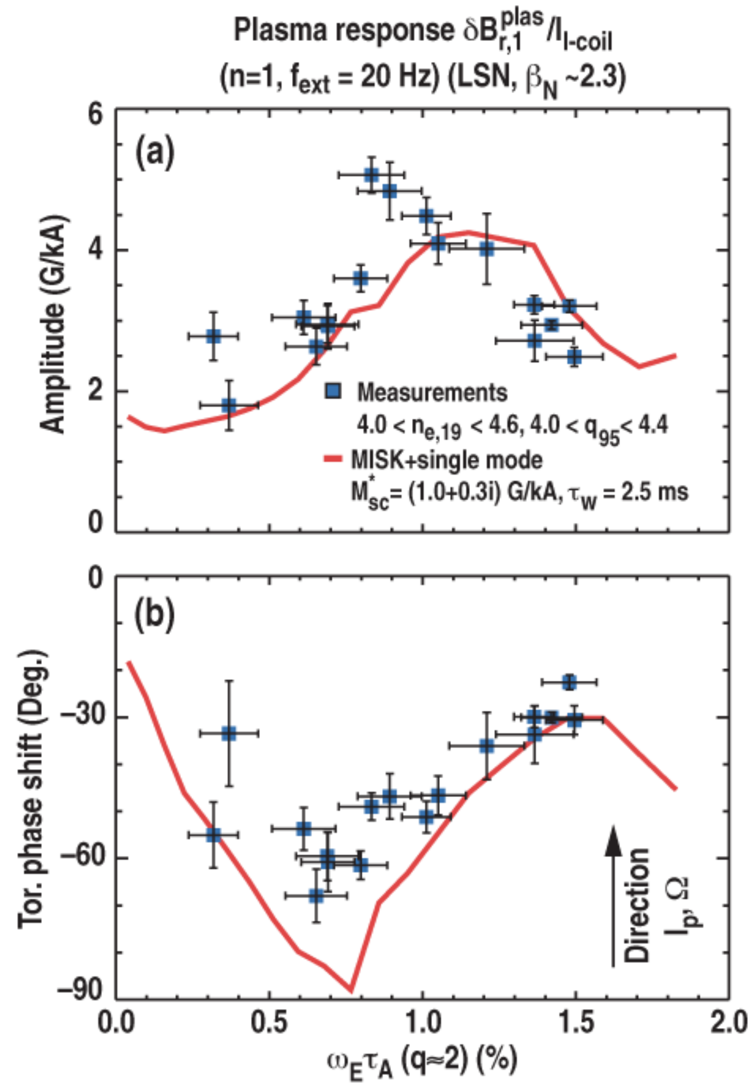
$$\delta W_K = \frac{1}{2}\int \vec{\xi}_\perp \cdot \vec{\nabla} \cdot \tilde{P}_K d\vec{v}$$



- **Kinetic energy principle δW_K allows for energy exchange between RWM and kinetic particle populations:**
  - Resonances between motion of ***trapped particles*** and ***plasma rotation***
  - ***Non-resonant*** effects that depend on alignment of distribution function gradients and the RWM eigenfunction
  - Several codes incorporate this physics: MISK, HAGIS, MARS-K

Kinetic RWM stability effects investigated in stable plasmas above the no-wall limit

- Measurements of ***plasma response*** to slowly rotating *n* = 1 perturbations used to compare theory and experiment
- ***Rotation scan*** revealed evidence of ***trapped particle resonances*** in DIII-D; complemented NSTX work on the RWM stability threshold



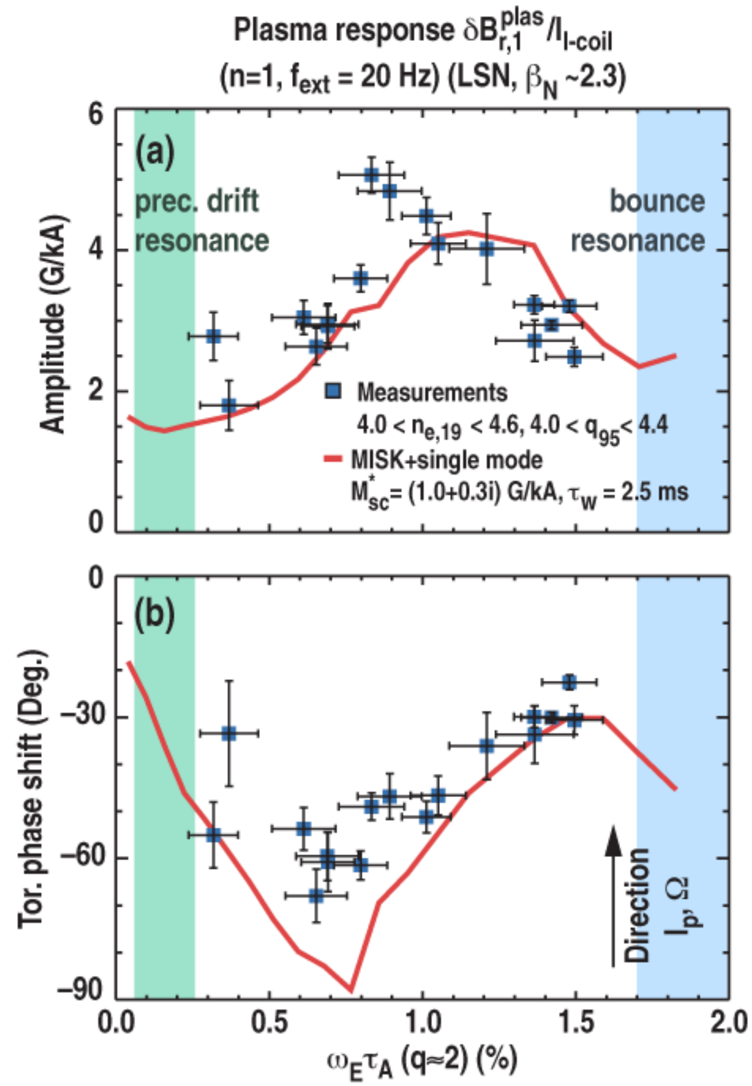
[Berkery, *et al*, PRL, 2010]

[Reimerdes, *et al*, PRL, 2011]

Kinetic RWM stability effects investigated in stable plasmas above the no-wall limit

- Measurements of ***plasma response*** to slowly rotating $n = 1$ perturbations used to compare theory and experiment

- ***Rotation scan*** revealed evidence of ***trapped particle resonances*** in DIII-D; complemented NSTX work on the RWM stability threshold



[Berkery, *et al*, PRL, 2010]

[Reimerdes, *et al*, PRL, 2011]

DIII-D NATIONAL FUSION FACILITY

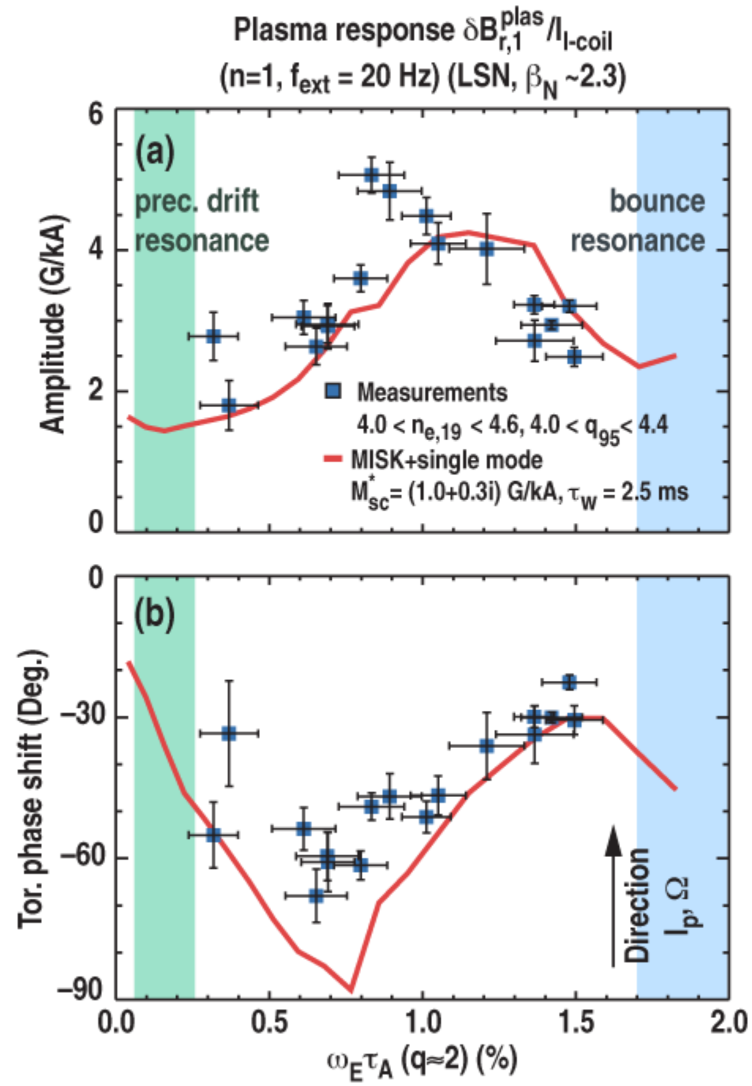
Kinetic RWM stability effects investigated in stable plasmas above the no-wall limit

- Measurements of ***plasma response*** to slowly rotating $n = 1$ perturbations used to compare theory and experiment

- ***Rotation scan*** revealed evidence of ***trapped particle resonances*** in DIII-D; complemented NSTX work on the RWM stability threshold

- Ratio of $\boldsymbol{\beta_{fast} / \beta_{thermal}}$ investigated in MAST using ***density scans***

- Recent DIII-D experiment: use ***off-axis NBI*** to impact ***trapped ion fraction***



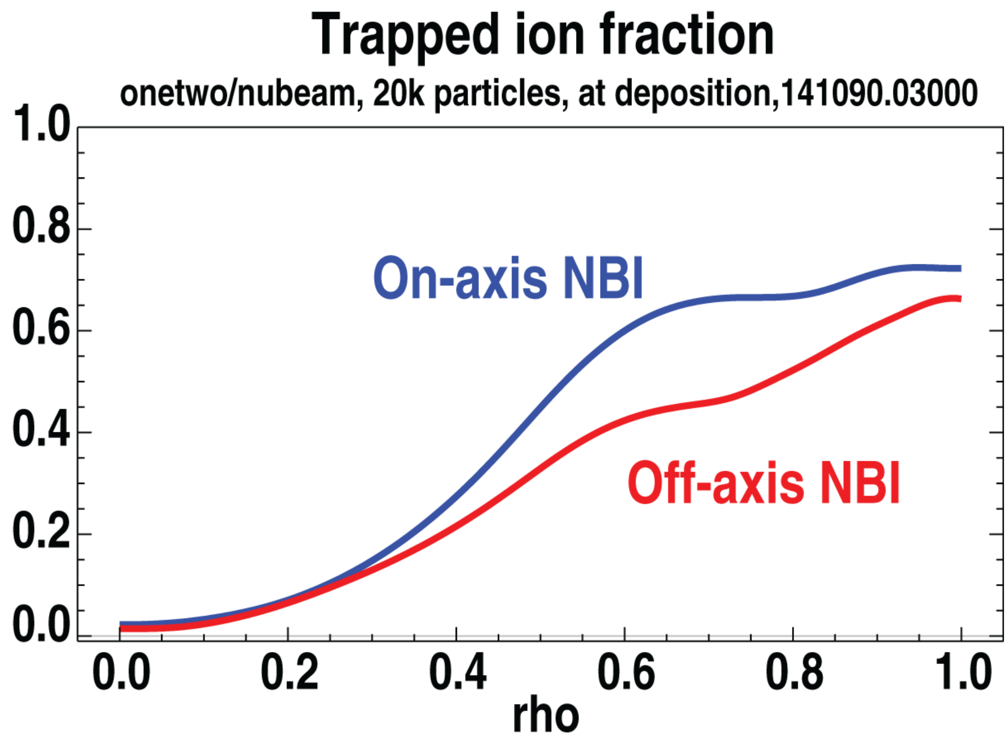
[Berkery, *et al*, PRL, 2010]

[Chapman, *et al*, PPCF, 2011]

[Reimerdes, *et al*, PRL, 2011]

DIII-D NATIONAL FUSION FACILITY

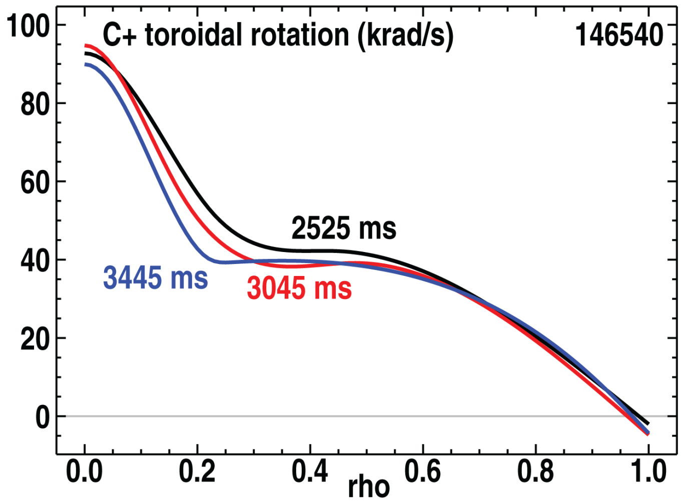
Off-axis NBI expected to decrease RWM stability

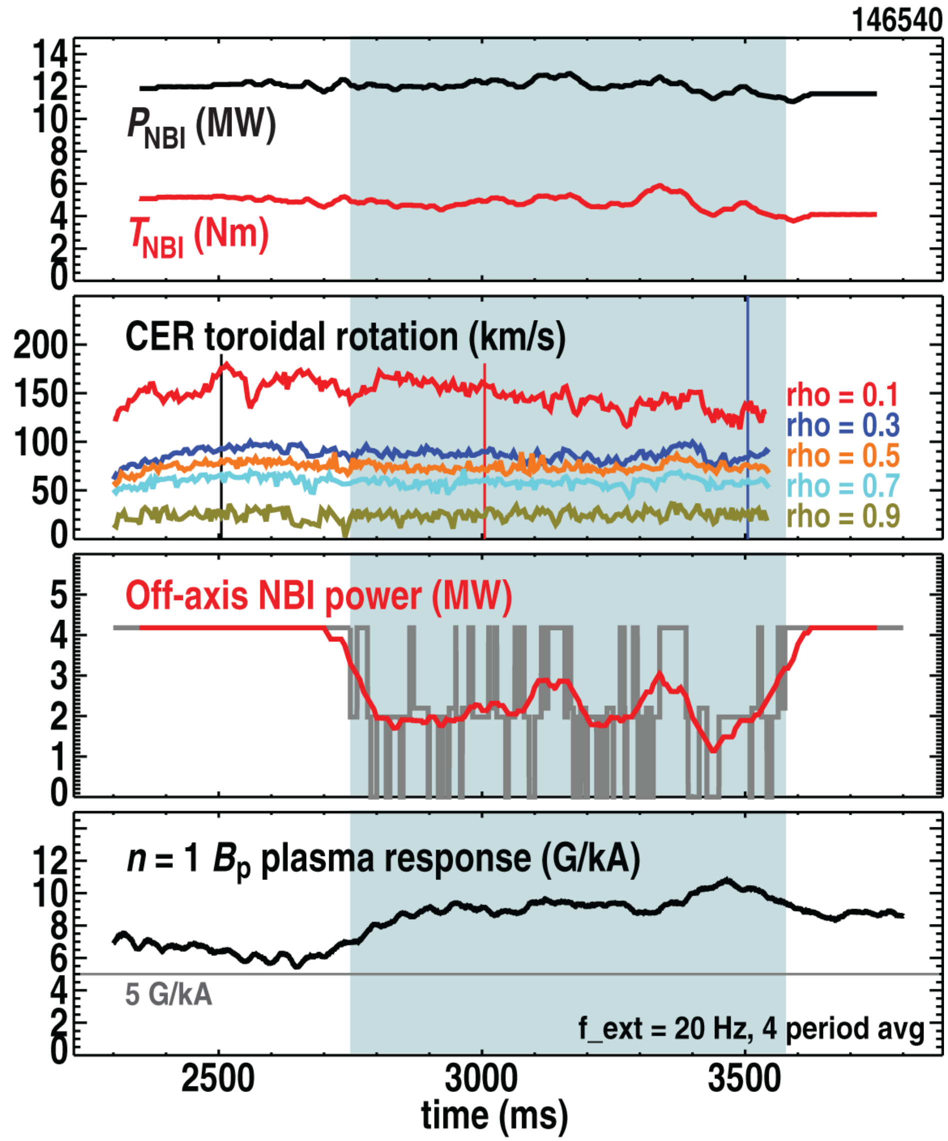


- **Transport modeling: reduced trapped ion fraction with off-axis NBI**, due to more favorable alignment of injection angle with field line pitch.
- **Reduced RWM stability expected with off-axis NBI**; stabilizing effect of passing particles expected to be localized near resonant surfaces, small.

Off-axis NBI leads to *increased* RWM stability

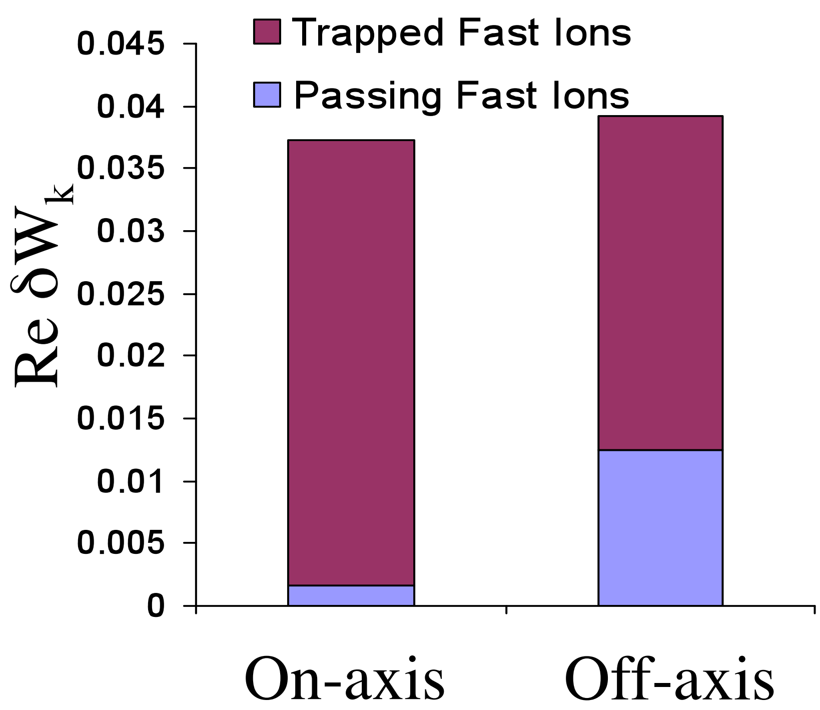
- **Off-axis NBI power modulated at constant β_N, ℓ_i, density**
  - Minor variations in rotation profile
- **Plasma response *increases* with *decreased* off-axis power**
  - Opposite of expectation from considerations of trapped ion fraction





Including finite orbit width effects results in enhanced damping of RWM with off-axis NBI

– TRANSP predicts fast ion distribution function
– HAGIS evolves interaction between fast ions and RWM

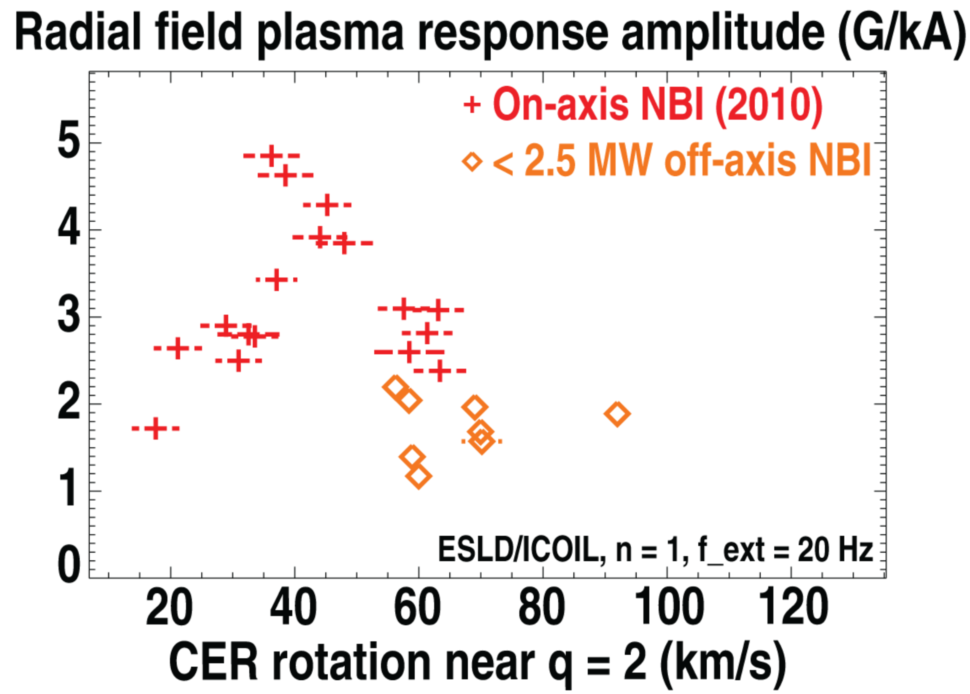


– Scanned radial peak of distribution function using simplified model for F_h

– Passing fast ion damping sensitive to location of peak of F_h with respect to rational surfaces

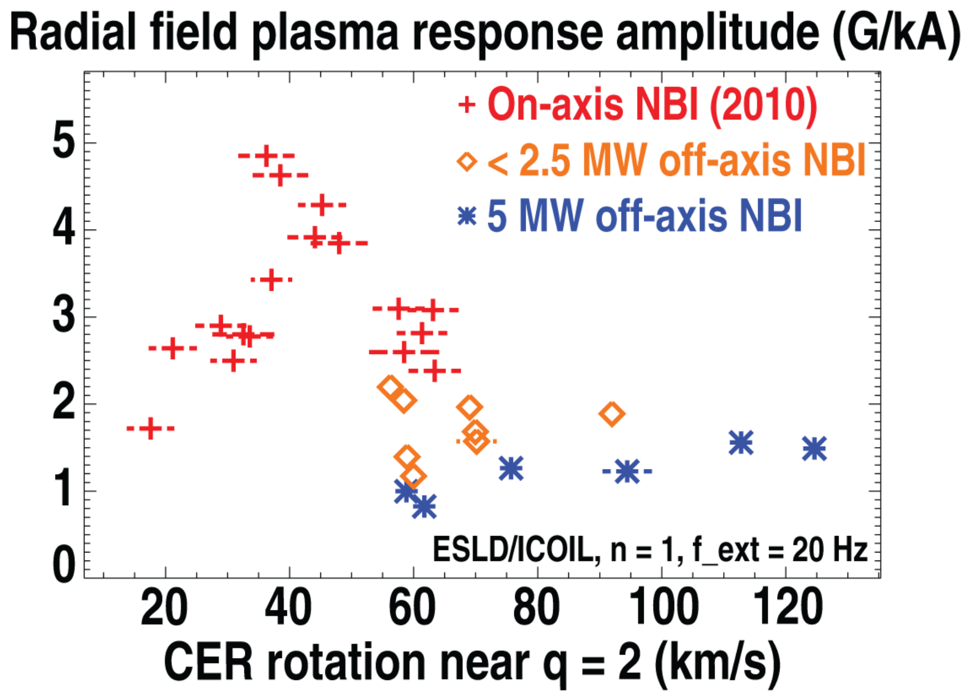
Stabilizing effect of off-axis NBI observed over a range of rotation

- Existing 2010 dataset extended to higher rotation



Stabilizing effect of off-axis NBI observed over a range of rotation

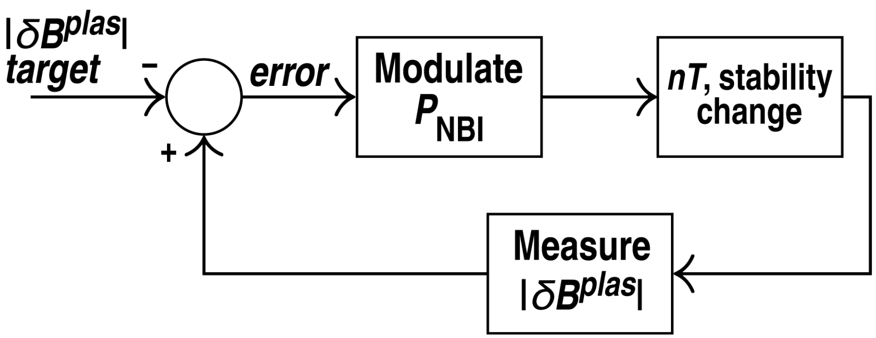
- **Existing 2010 dataset extended to higher rotation**
- **See ~50% *reduction* in plasma response amplitude with 5 MW off-axis NBI, at intermediate rotation.**



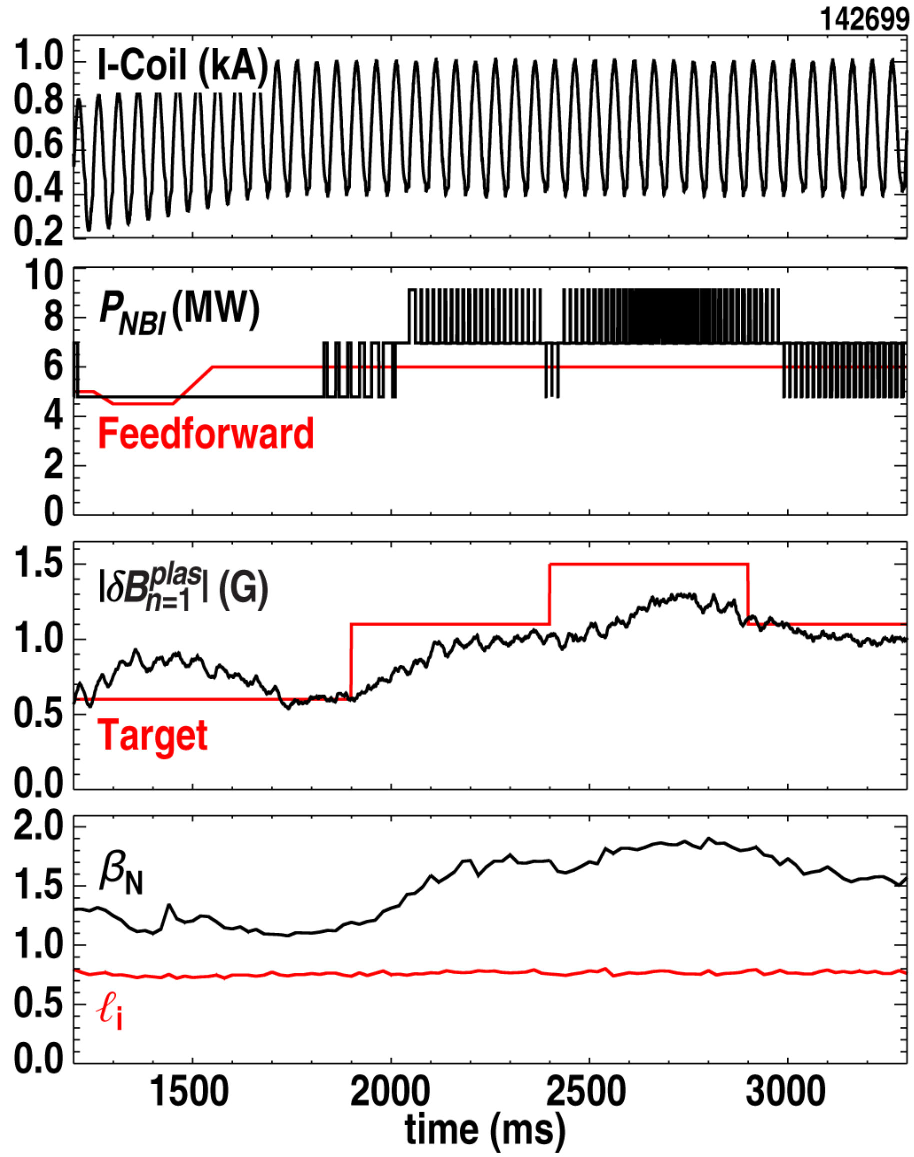
- **Continued damping at increased rotation qualitatively consistent with theoretical expectations.**
- **Resonances with additional bounce frequency harmonics encountered as rotation increases.**

Controlling proximity to the RWM stability limit

RWM stability directly controlled with NBI for first time



- **Plasma response measurement input** to NBI control algorithm
- **Plasma response settles to a value near the target** on a timescale close to τ_E ~ 100 ms.
- **β_N changes linearly with plasma response amplitude – expected below no-wall limit.**



Observed δB^{plas} dependencies suggest 2 parameter dynamical model

- Consider a model of the form

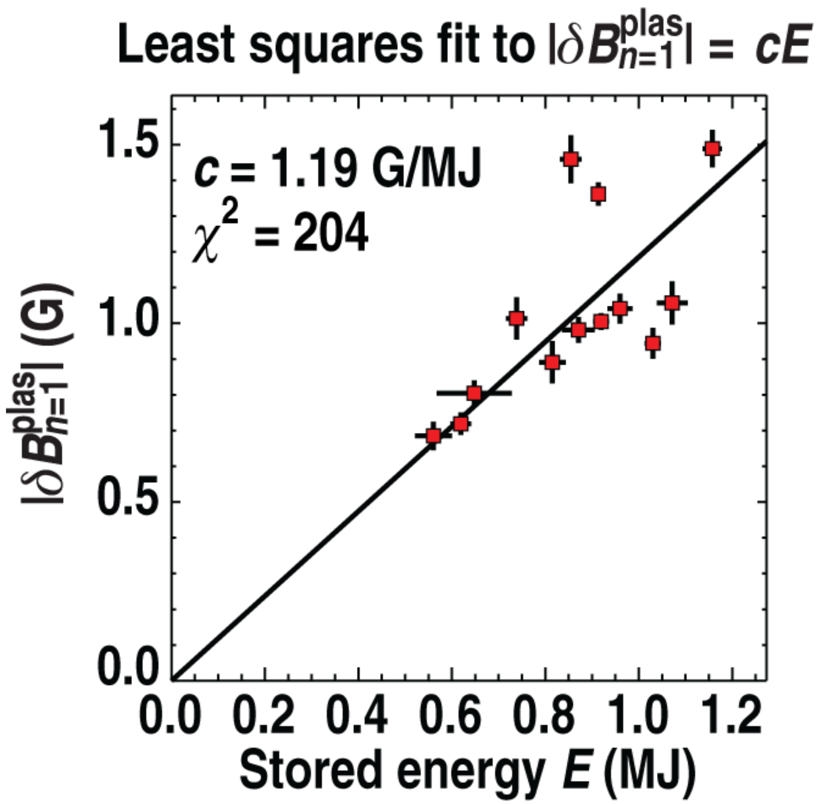
$$\frac{\mathrm{d}}{\mathrm{d}t}|\delta B^{\mathrm{plas}}_{n=1}| = -\frac{1}{\tau}|\delta B^{\mathrm{plas}}_{n=1}| + cP_{\mathrm{NBI}}.$$

- 2 parameters can be estimated by fitting experimental data
  - Time-constant τ
  - Beams coupling coefficient c

- Equivalent to a model* for the plasma stored energy E, if

$$\tau = \tau_{\mathrm{E}} \quad \text{and} \quad |\delta B^{\mathrm{plas}}_{n=1}| = cE = c\frac{I_{\mathrm{p}}B_{\mathrm{t}}}{2\mu_0 a}\beta_{\mathrm{N}}$$

- Expect this scaling to work for constant I_p, B_t, a.



*J. T. Scoville, et al., *Fusion Eng. and Design* **45**, A367 (2003)

Time-constant obtained from fit to steady-state limit

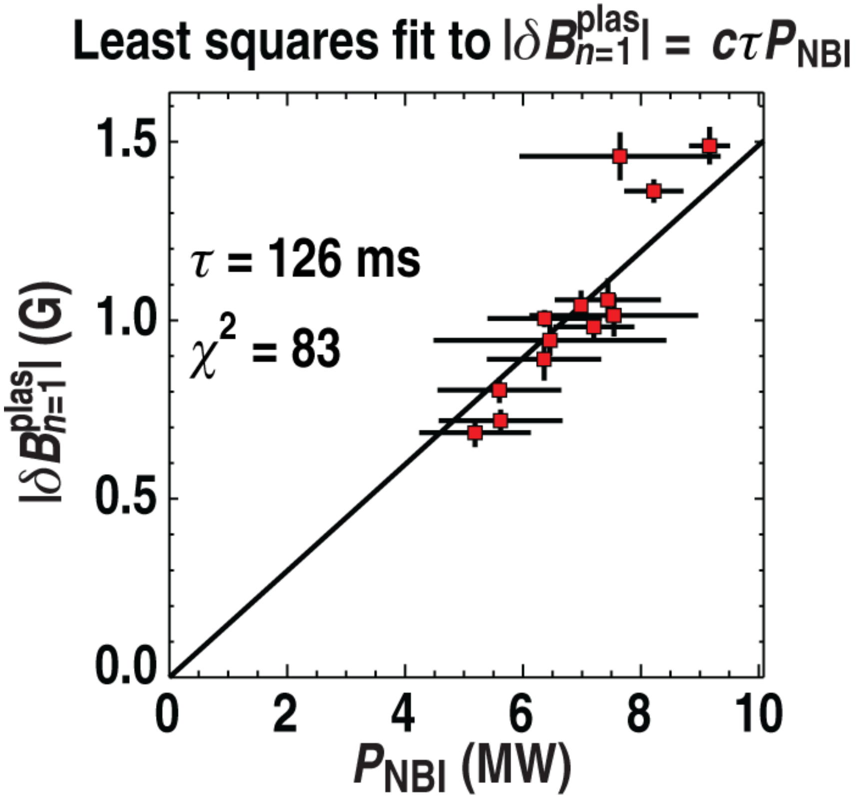
- In the steady state limit, obtain

$$|\delta B^{\mathrm{plas}}_{n=1}| = c\tau_{\mathrm{E}} P_{\mathrm{NBI}}.$$

- So time constant can be obtained from least squares fit if *c* is known.

- These linear relationships will not necessarily hold at high β_N above the no-wall limit.

- However, super-linear dependence of $|\delta B^{\mathrm{plas}}|$ with β_N suggests that a linear controller would naturally avoid the RWM's true marginal stability point.



Conclusions

- **Ideal MHD describes perturbed equilibria below no-wall beta limit**
  - Large body of measurements consistent with ideal MHD at low $\beta < \beta^{nw}$
  - Magnetic (n = 1, 2, 3) and SXR profile measurements (n = 1) compared with theory
- **Kinetic modifications to ideal MHD needed above no-wall limit**
  - Experimental evidence for wave – particle interactions uncovered, qualitatively consistent with kinetic theory.
  - Off-axis NBI used to probe kinetic damping in recent experiment, lead to increased damping of RWM
  - New data obtained for comparisons with theory.
  - Preliminary calculations indicate finite ion orbit width effects may be important
- **Direct RWM stability control demonstrated using NBI feedback**
  - Linear feedback dynamics obtained below no-wall limit
  - Possible solution for maximizing β while avoiding unstable RWM
  - Challenges expected above no-wall limit: rotation, kinetic effects impact feedback linearity