Understanding and controlling the plasma kink mode response on DIII-D

by
Jeremy M. Hanson[1], A.F. Battey[1], T.C. Luce[2,3], G.A. Navratil[1], E.J. Strait[2], and F. Turco[1]

1. Columbia University
2. General Atomics
3. ITER Organization

Presented at
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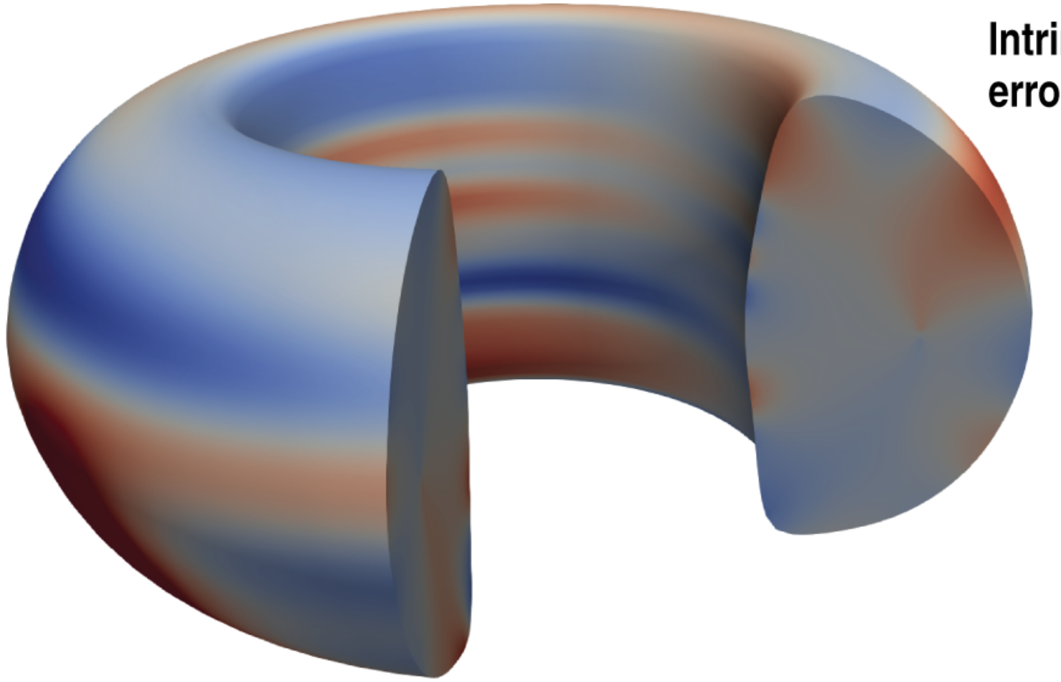
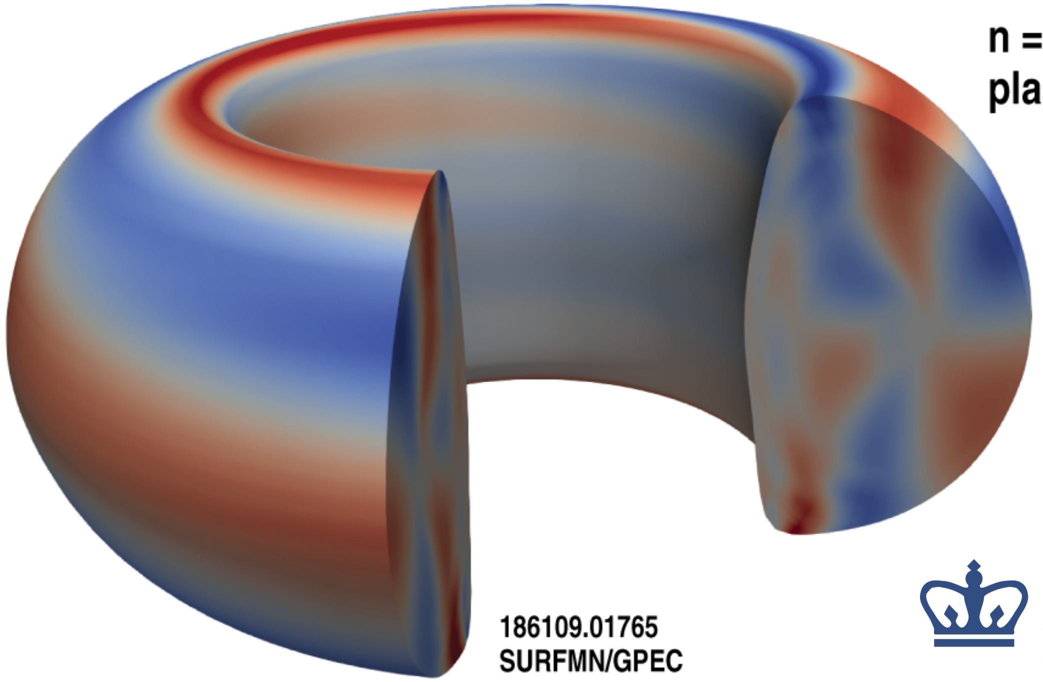




DIII-D NATIONAL FUSION FACILITY

COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK

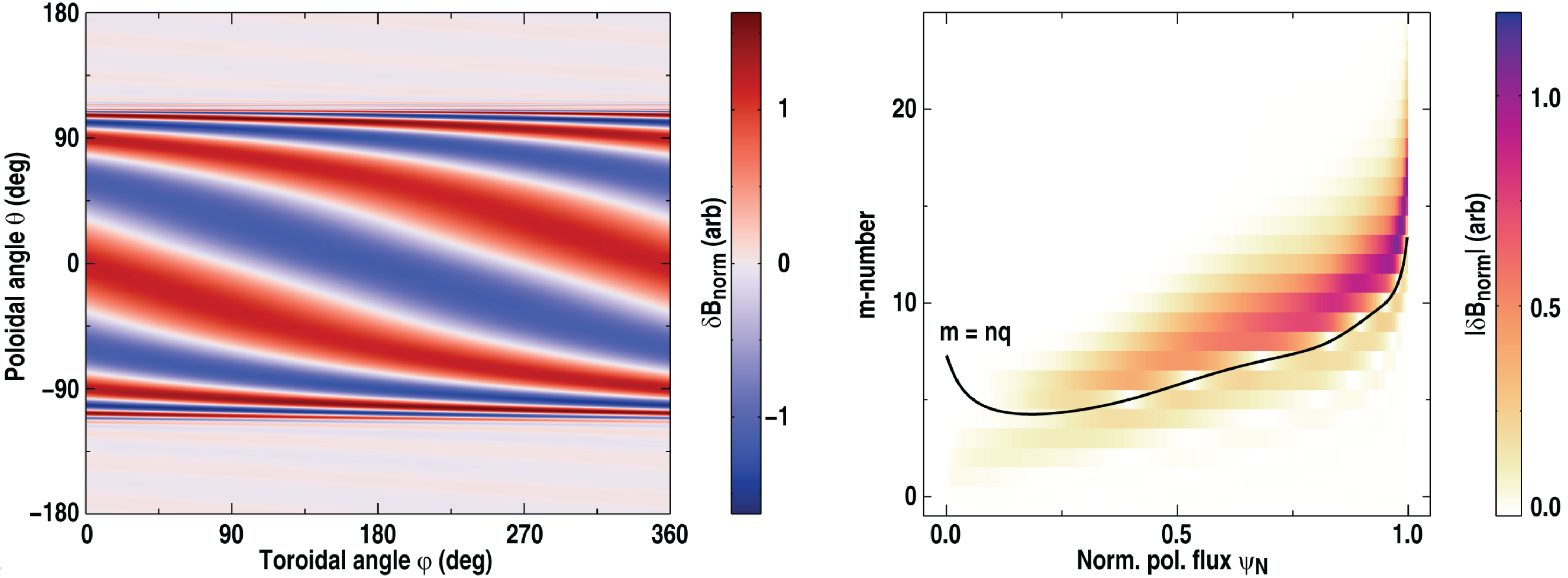
Stable tokamak kink response is useful for model validation and plasma control

The kink mode is a long-wavelength, helical distortion with m > nq

- Often stable but weakly damped ➜ can be driven by applied 3D fields
- Stability boundary sets a key pressure limit

Ideal MHD least-stable n = 1 mode

DCON, 176078, t = 2.45 s



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Stable response is an observable **for simulation comparisons**

- Measure using applied perturbations
- Can be predicted by MHD codes

And a lever **for plasma control**

- Error field correction, ELM suppression

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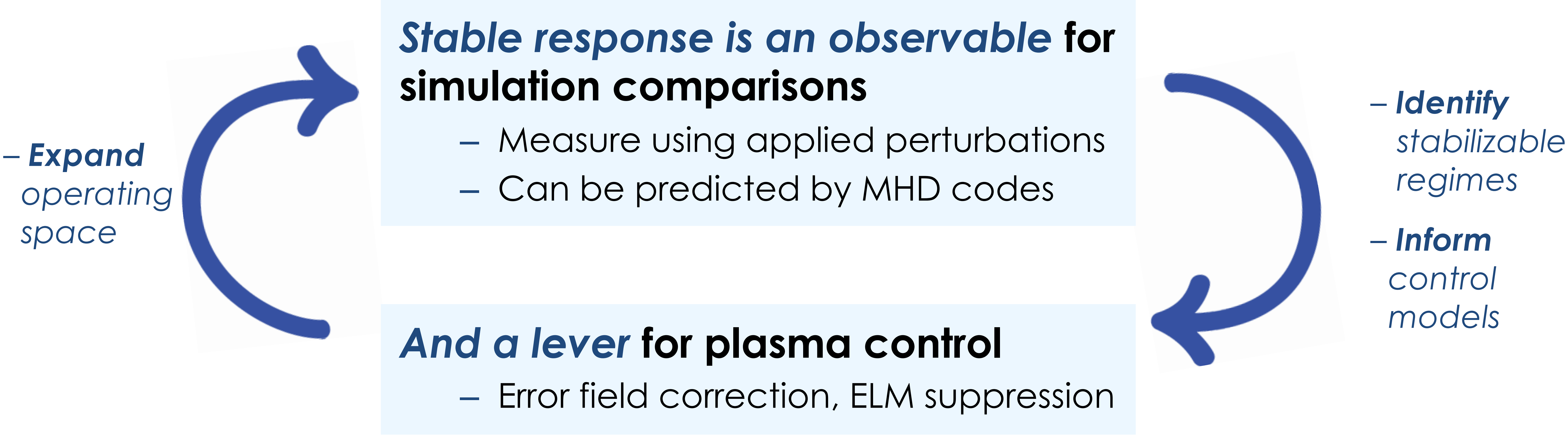

Stable response is an observable **for simulation comparisons**

- Measure using applied perturbations
- Can be predicted by MHD codes

– ***Identify*** *stabilizable regimes*

– ***Inform*** *control models*

And a lever **for plasma control**

- Error field correction, ELM suppression

– ***Expand*** *operating space*

Outline

1. **Background**
   - DIII-D, stable kink excitation, measurements, feedback
2. **Resistive contribution to plasma response at low torque**
   - In the ITER baseline regime
3. **Simulating feedback-controlled error field correction**
   - Integration of error field and MHD response codes

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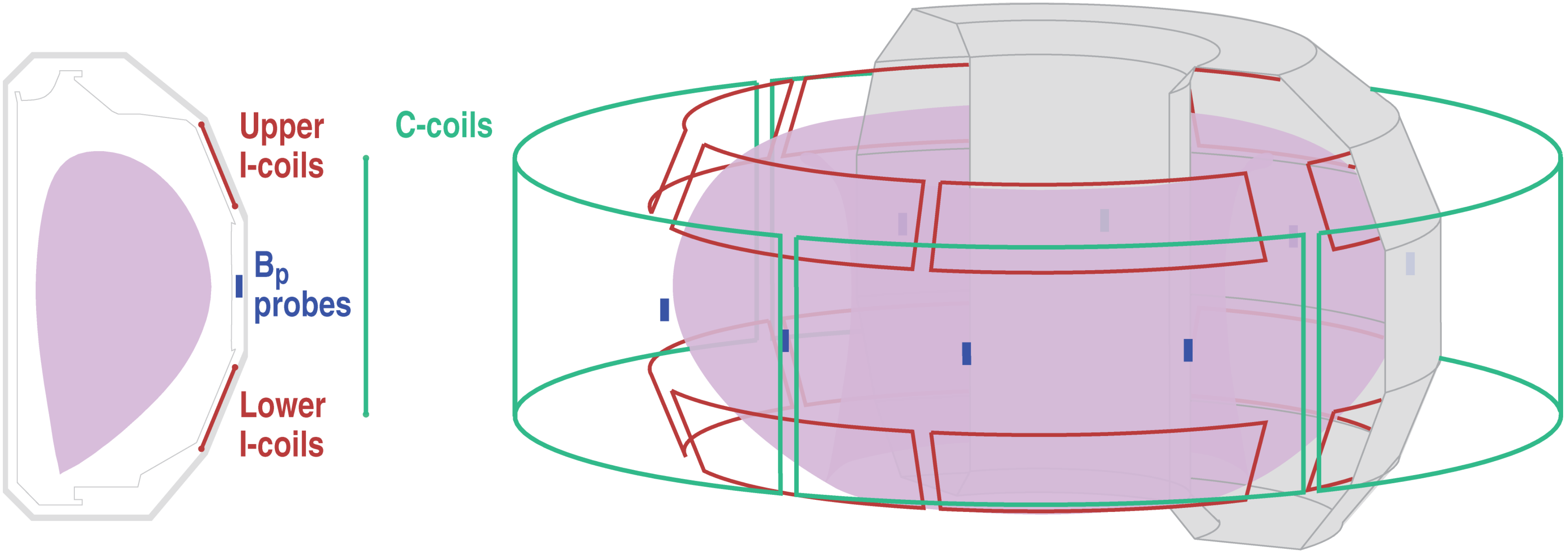
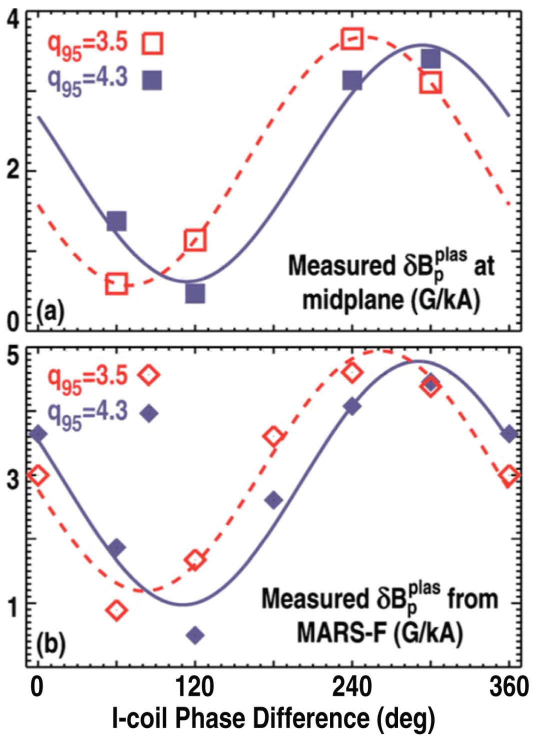
DIII-D is well equipped for 3D response studies



- **12 internal coils (I-coils)** with adjustable lower/upper phasing
- **6 external coils (C-coils)**
- **>100 pair-difference magnetic sensors**
- **Plasma rotation can be controlled** with balanced NBI
- **High disruption tolerance**

Applied 3D fields can be used to excite and control the plasma kink mode

- **Driven stable plasma response consistent with kink mode excitation predictions[1]**
  - Varied poloidal structure of applied field
  - Compared two different q_{95} values



1. MJ Lanctot, *et al.*, *Phys. Plasmas* **17** (2010) 030701.
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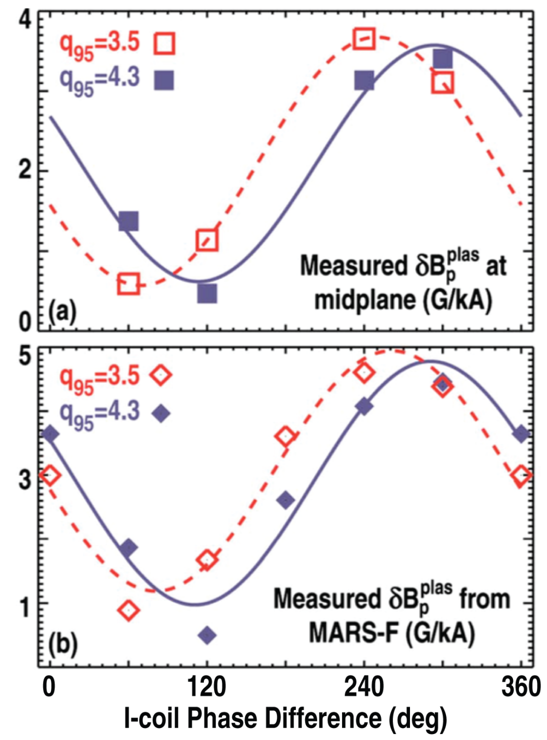
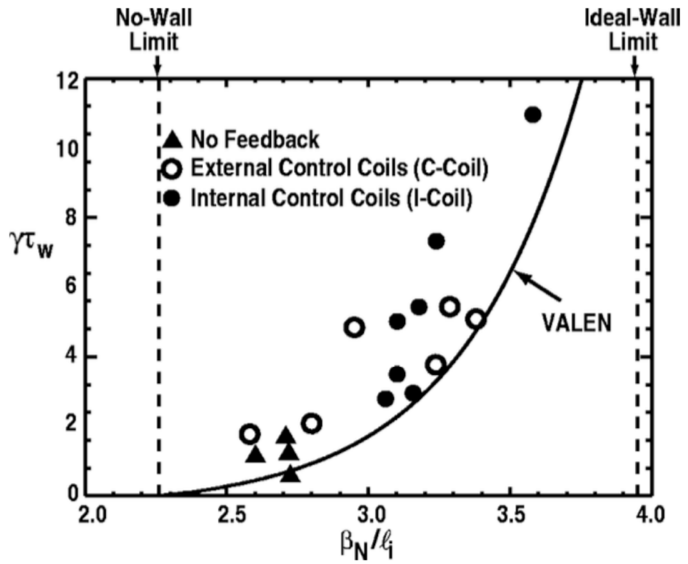


- **Unstable resistive wall mode (RWM) growth rates consistent with simulated dispersion relation**[2]
  - Kink mode interaction with wall eddy currents = RWM
  - Feedback control enables approach to ideal wall β-limit



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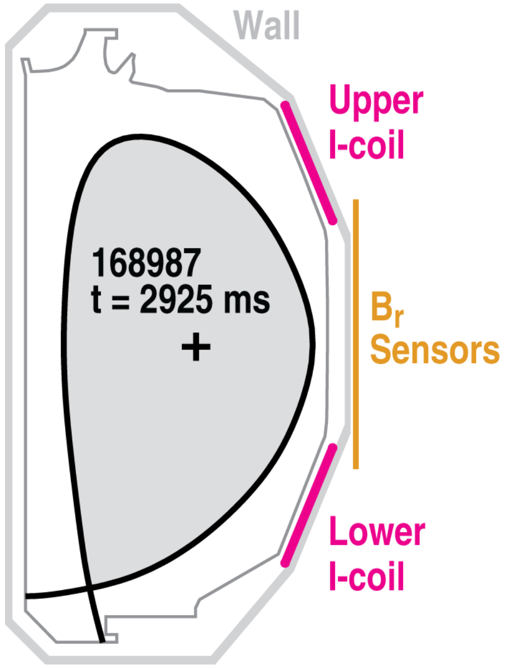
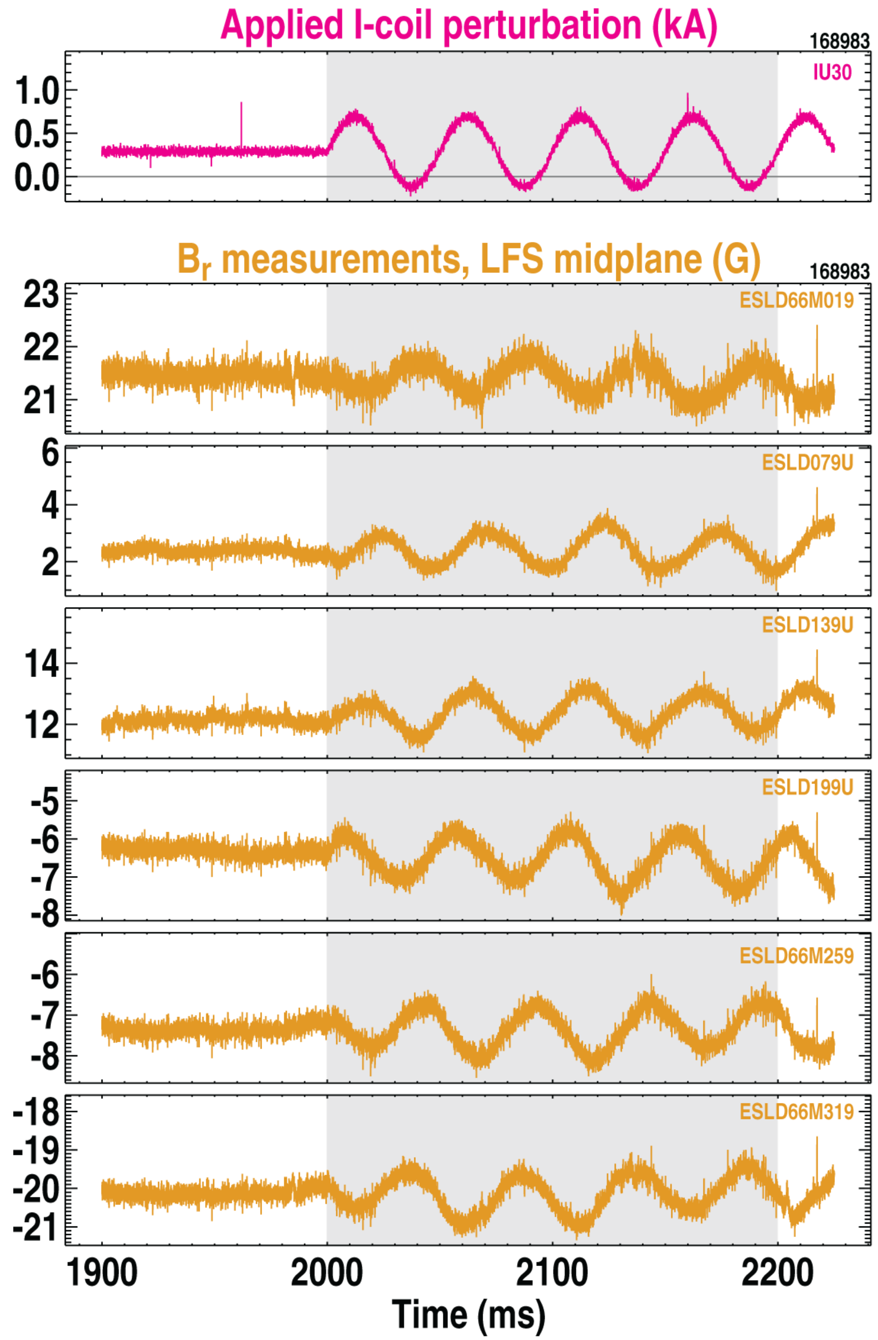
Synchronous analysis yields plasma response to rotating 3D perturbation





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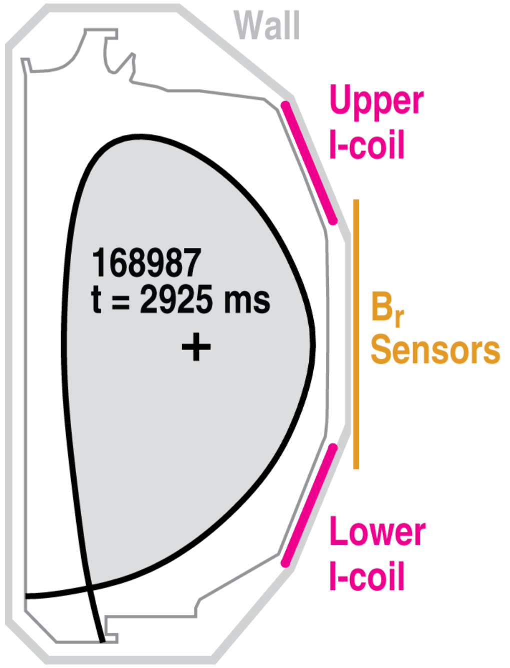

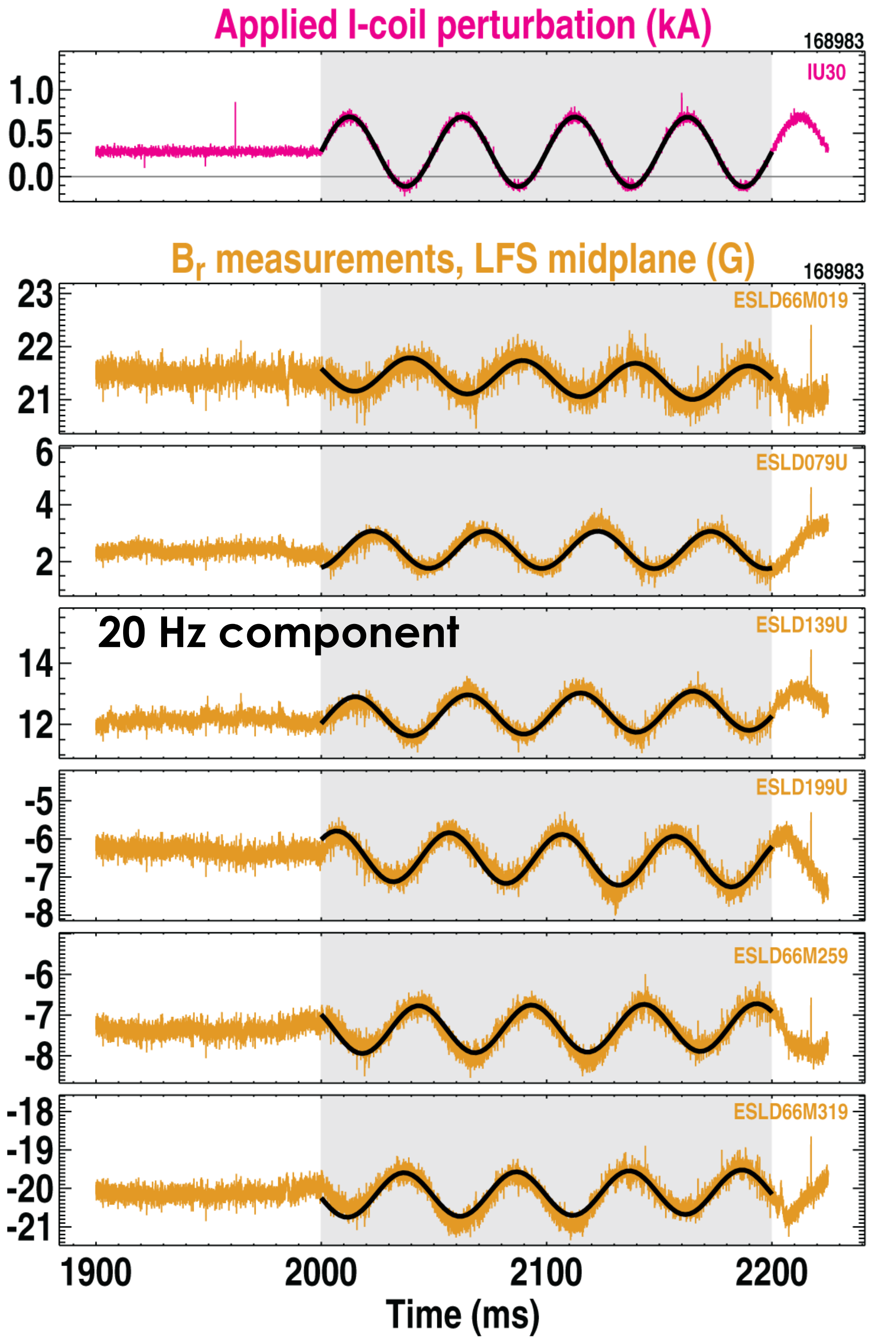

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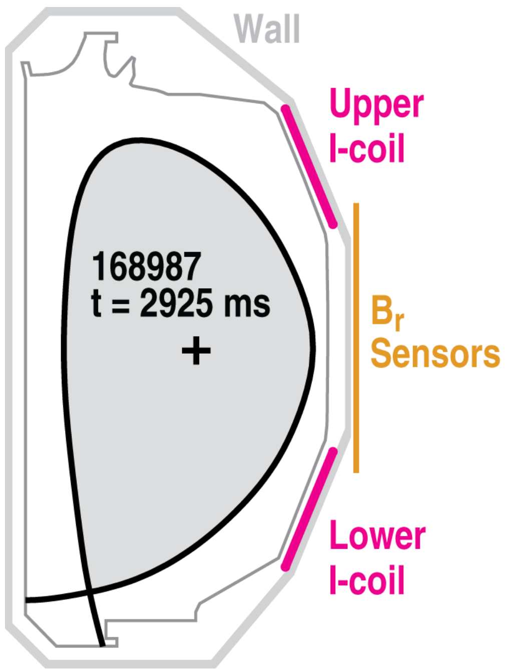

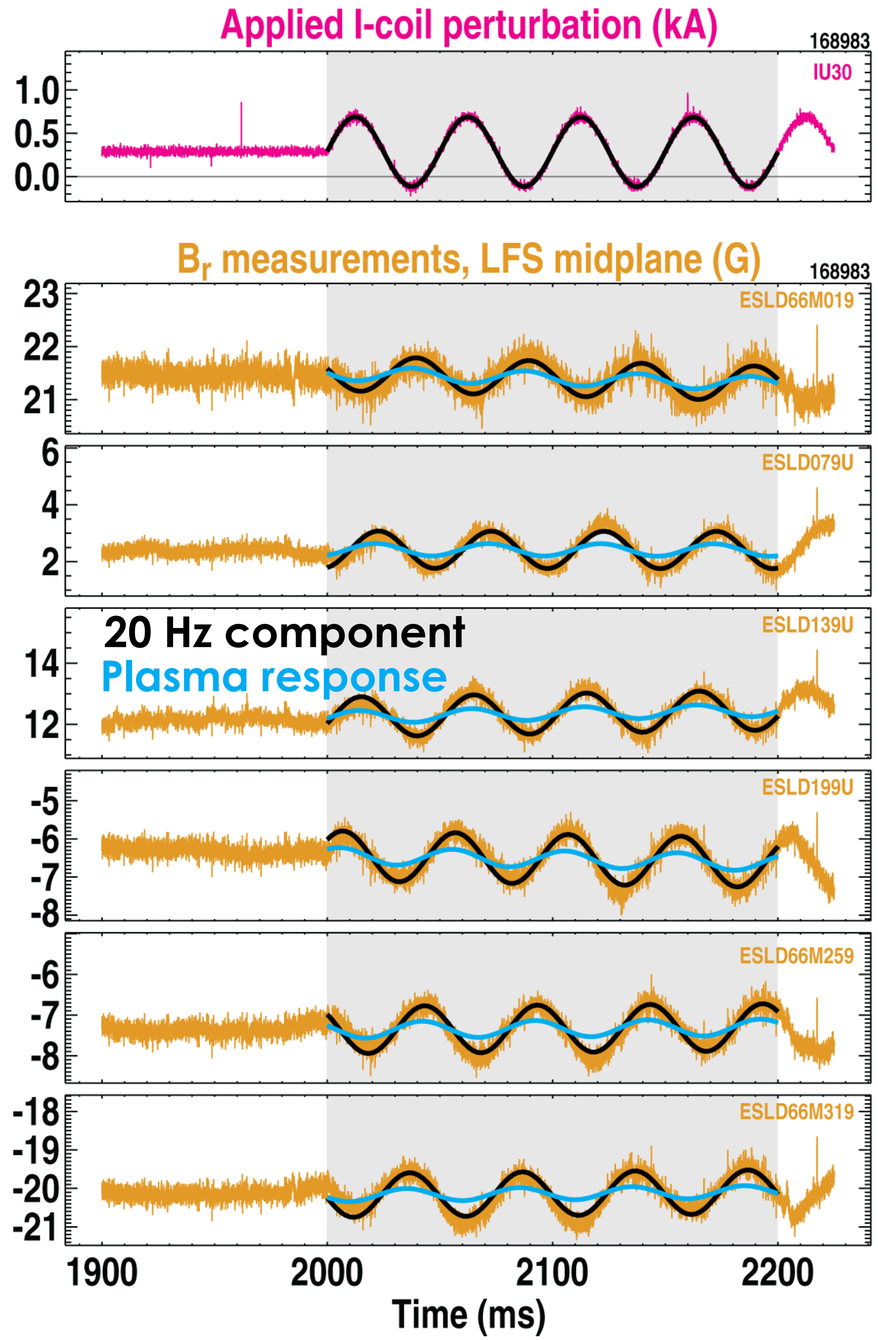

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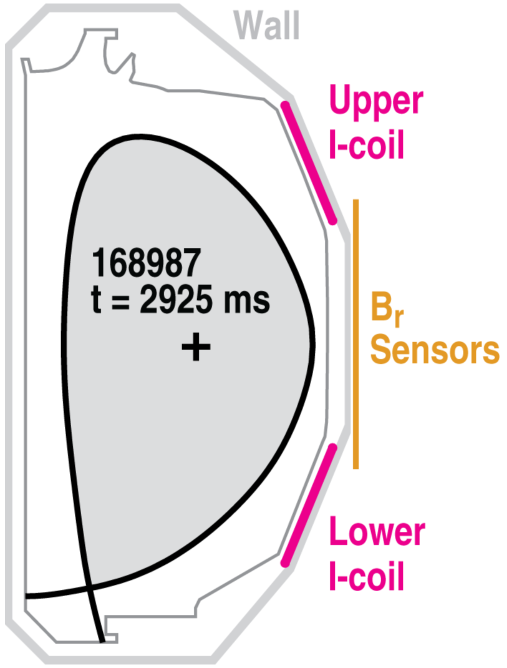
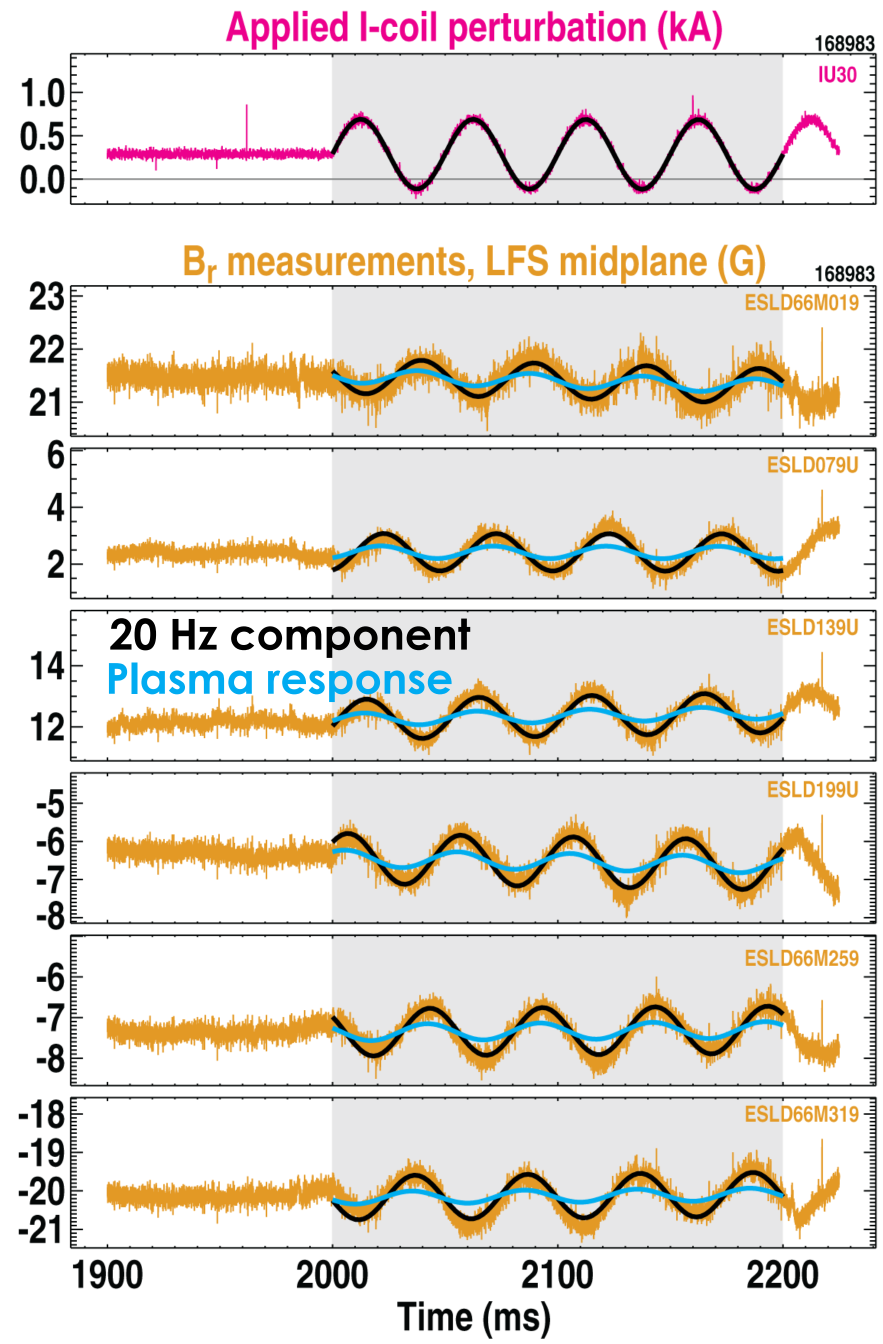
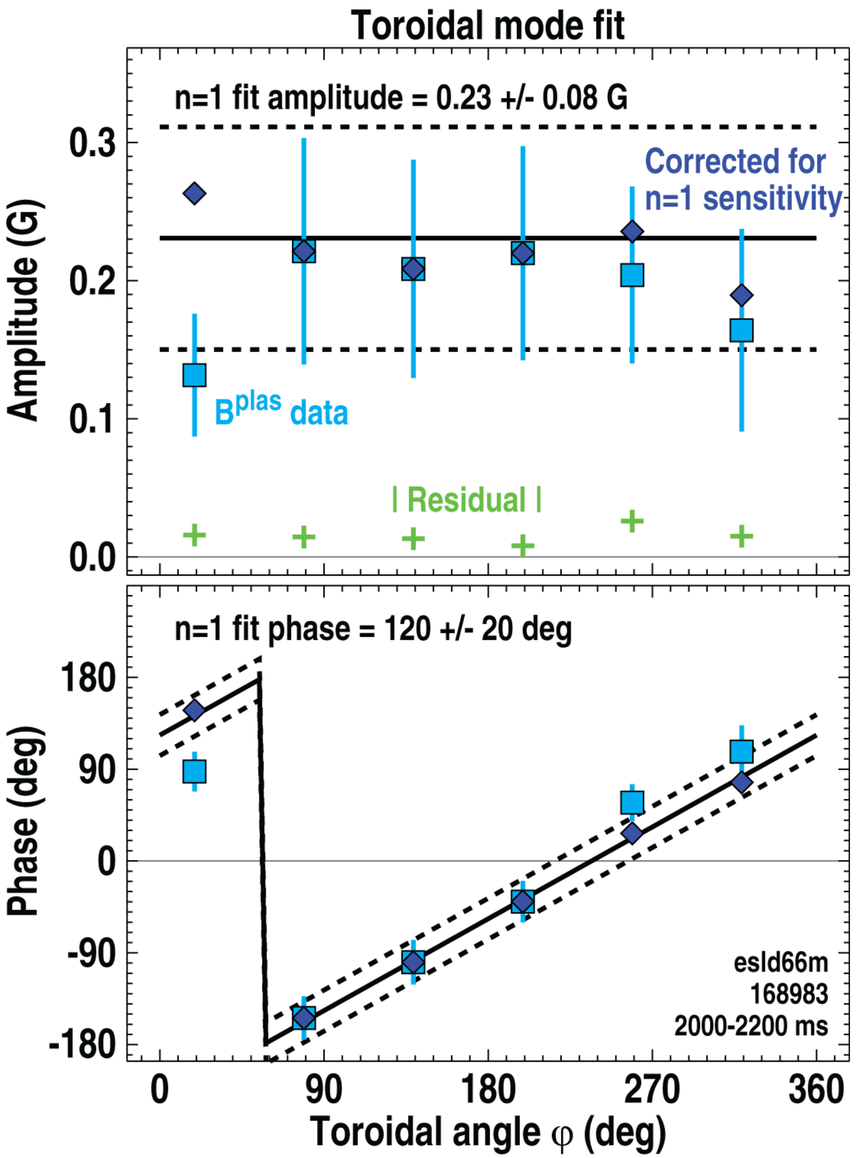




Fit resonances with perturbation *frequency* and *n-number*



Single-mode model describes tokamak n=1 plasma response and kink stability

- **Simple response model has a single mode[1,2]**

$$\tau_{\mathrm{w}} \frac{\mathrm{d}B_s}{\mathrm{d}t} = \gamma \tau_{\mathrm{w}} B_s + M^*_{sc} I_c$$

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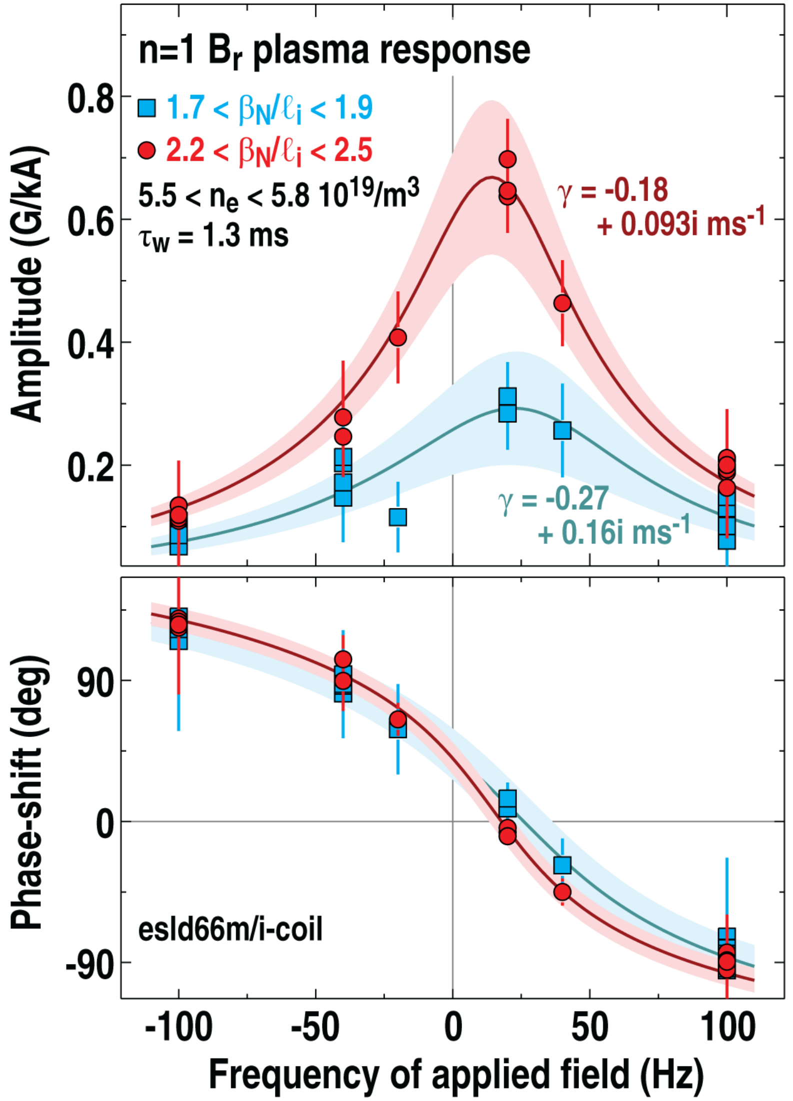
- **In the Fourier domain**

$$\frac{B_{s,\mathrm{plas}}}{I_c} = \frac{B_s - B_{s,\mathrm{vac}}}{I_c} \approx M^*_{sc} \frac{1 + \gamma\tau_{\mathrm{w}}}{(i\omega\tau_{\mathrm{w}} - \gamma\tau_{\mathrm{w}})(i\omega\tau_{\mathrm{w}} + 1)}$$

- **Model consistent with measured n=1 response**
  - Peak at ***resonance*** with mode frequency



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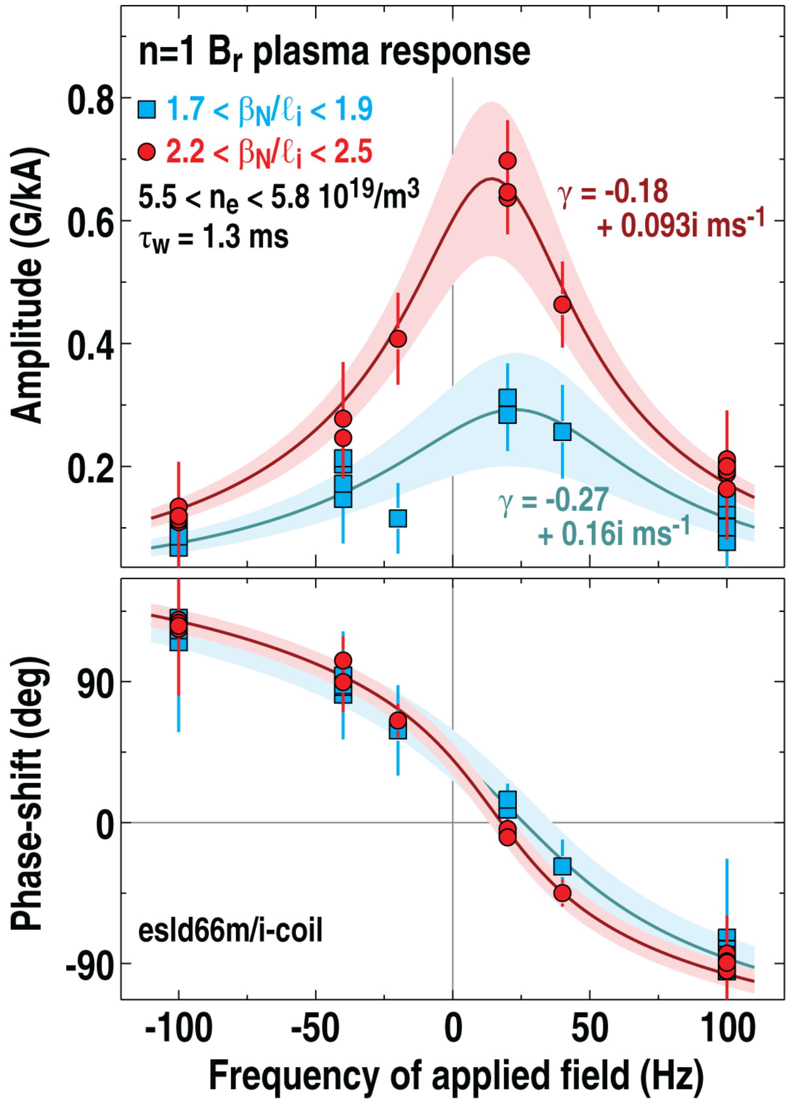
- **Model consistent with measured n=1 response**
  - Peak at ***resonance*** with mode frequency

- **Also compatible with RWM feedback and error field control experiments[3,4]**



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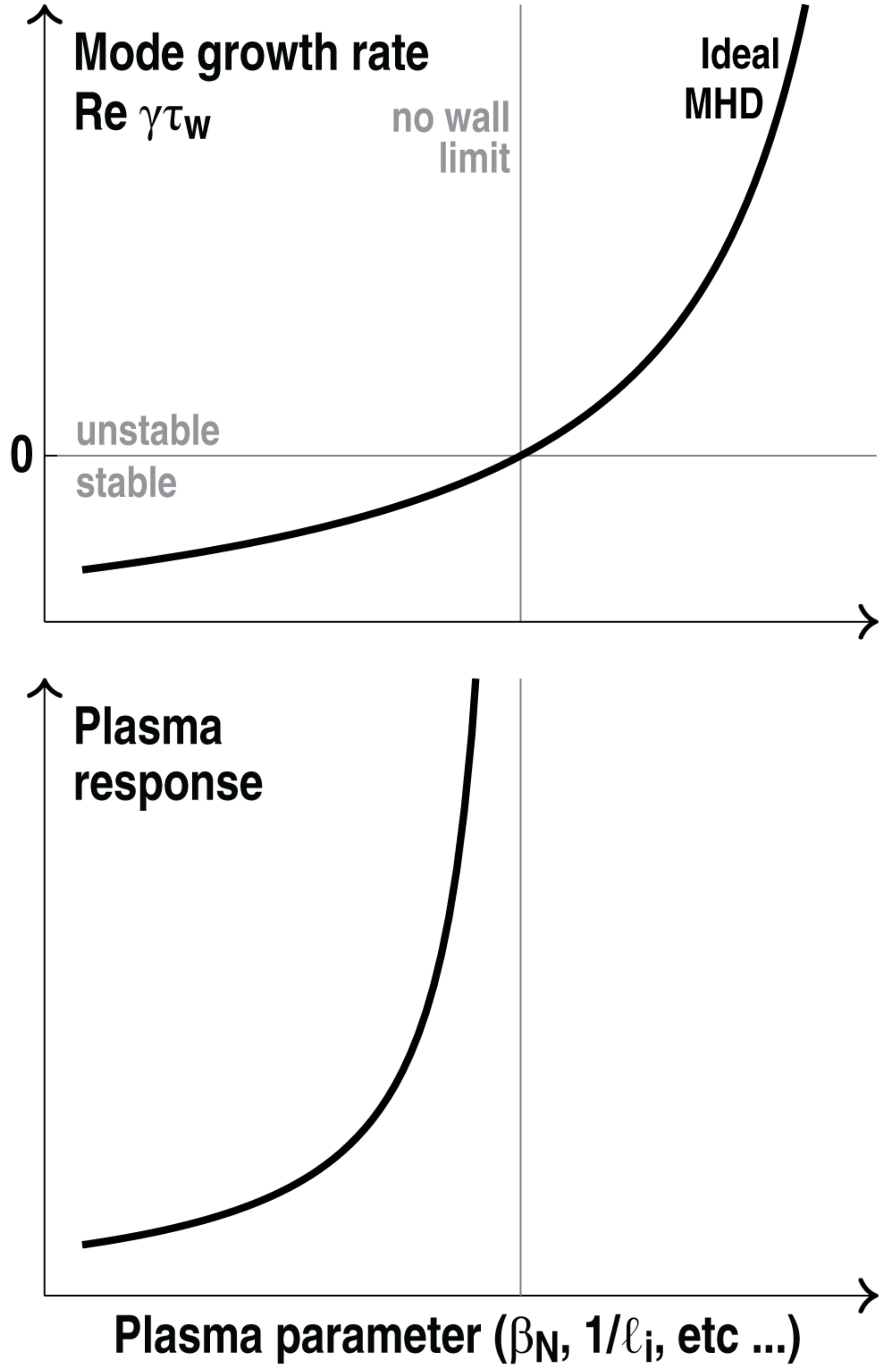
Plasma response depends on mode stability

- **Increasing response indicates approaching stability limit**
  - In ideal MHD this is the no-wall limit



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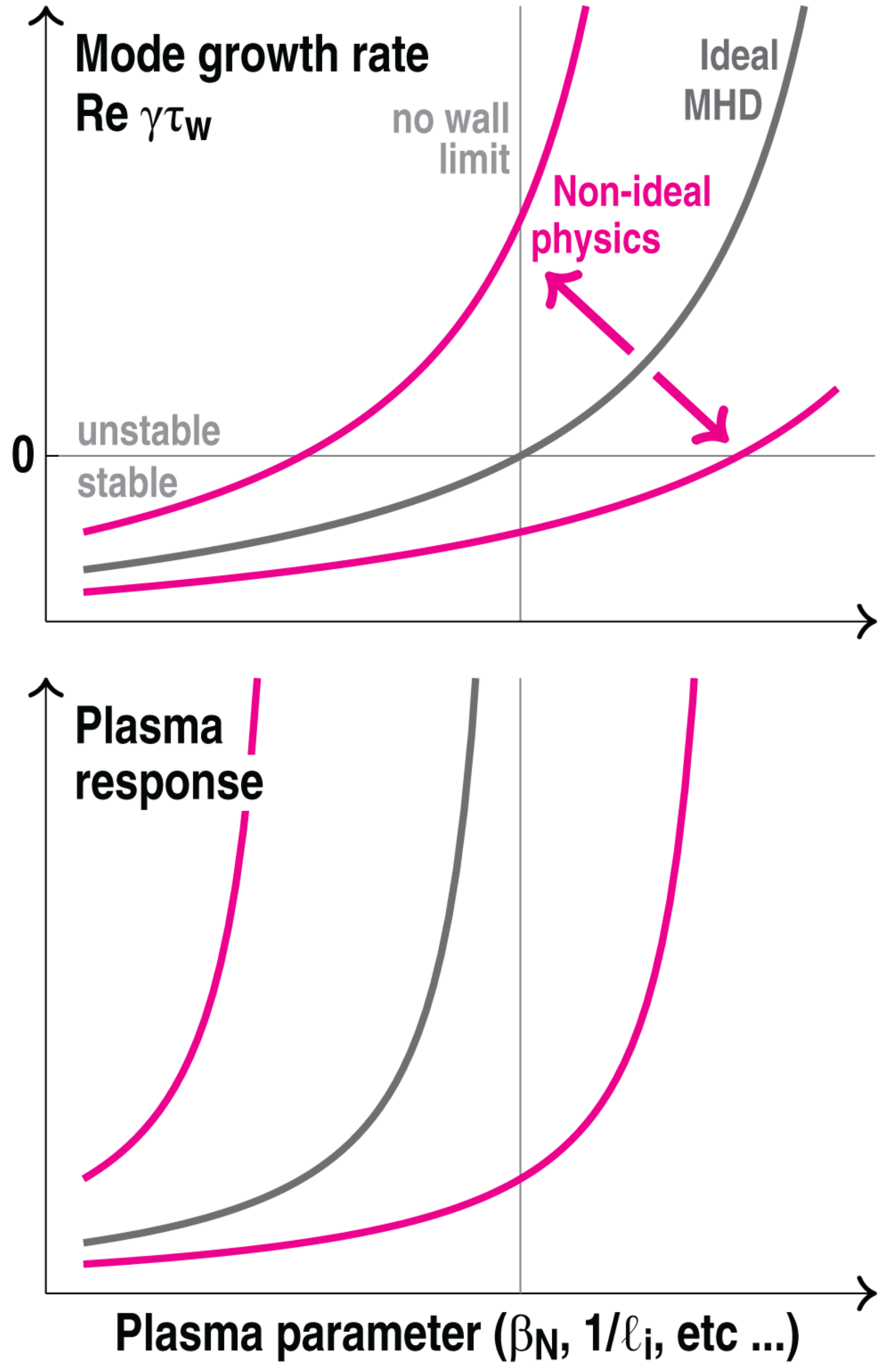
- **Non-ideal physics modifies limits and response**

- **Response is a useful tool for stability control and model validation**



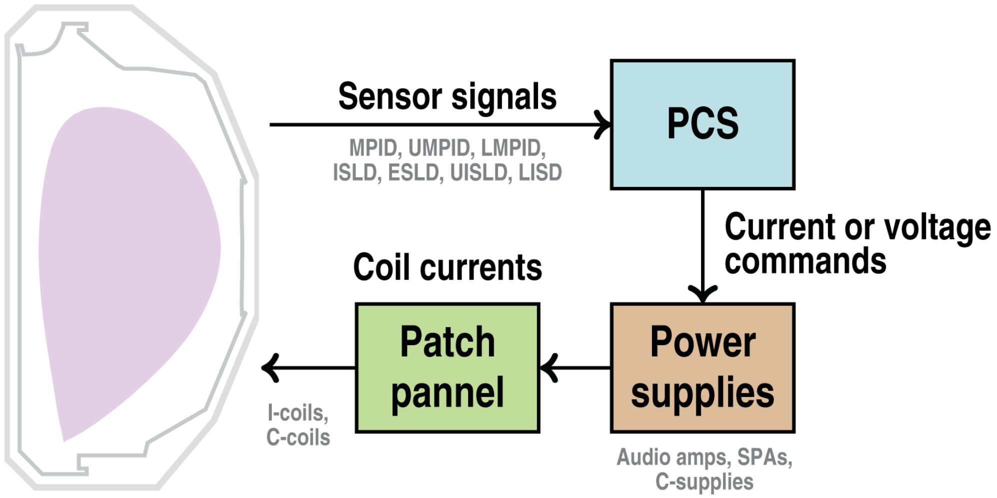
Magnetic feedback enables error field optimization

- **Measure perturbed field with magnetic sensors, feed back with 3D coils**

- **Feedback optimizes error field correction**
  - Sum with feedforward correction derived from Ohmic COMPASS scans

- **Important for sensitive plasmas**
  - **High β_N** ➜ strong plasma response, possible unstable RWMs
  - **Low input torque** ➜ locking likely

3D control system



Sensor signals

MPID, UMPID, LMPID, ISLD, ESLD, UISLD, LISD

PCS

Current or voltage commands

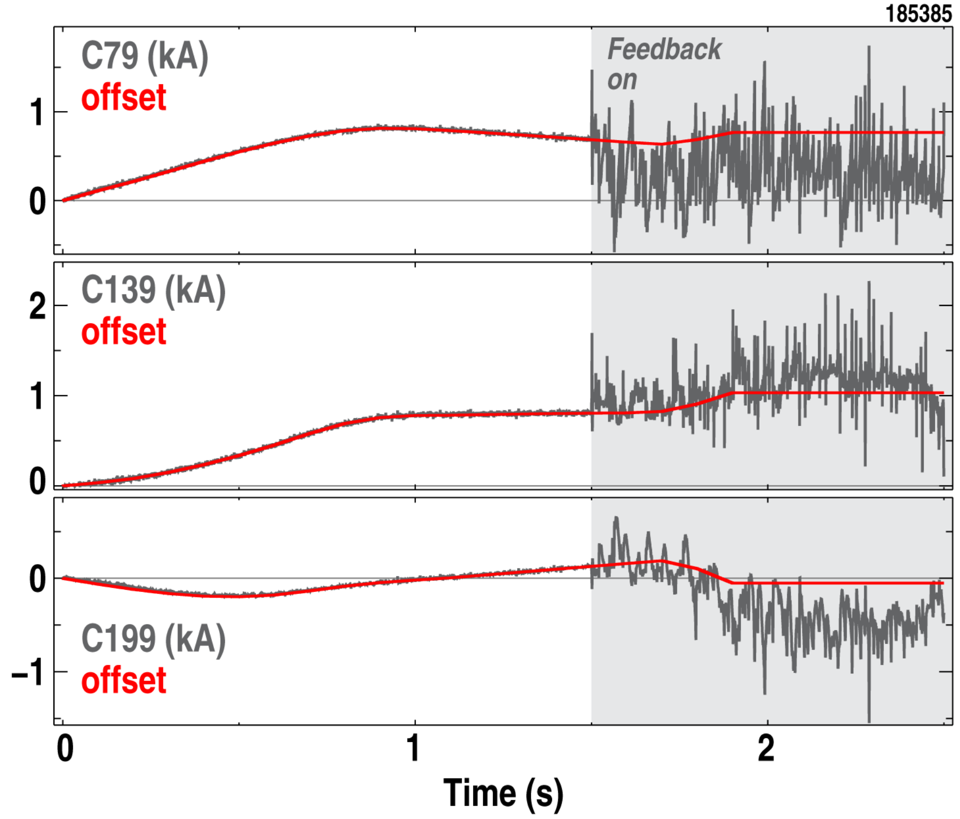
Power supplies

Audio amps, SPAs, C-supplies

Coil currents

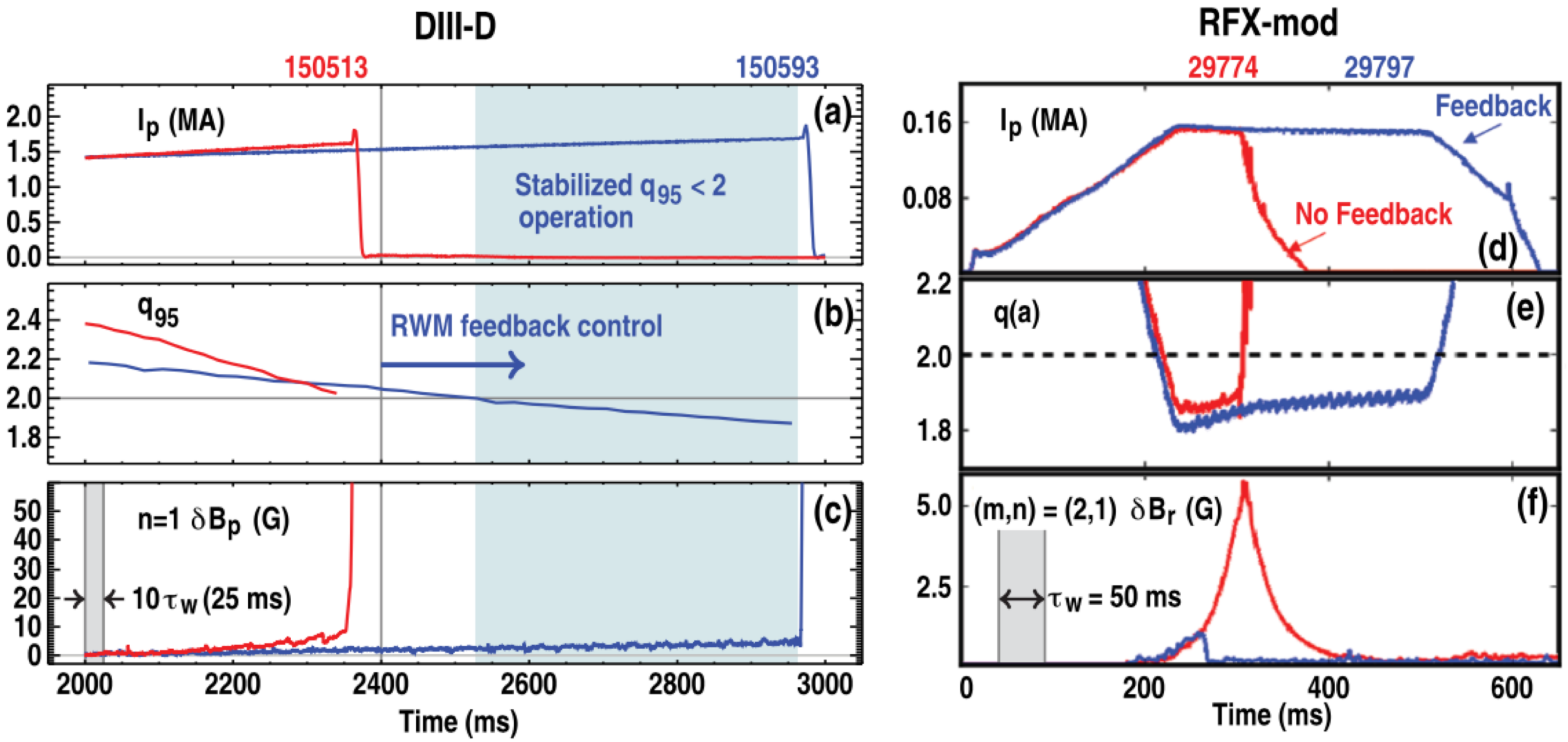
Patch pannel

I-coils, C-coils

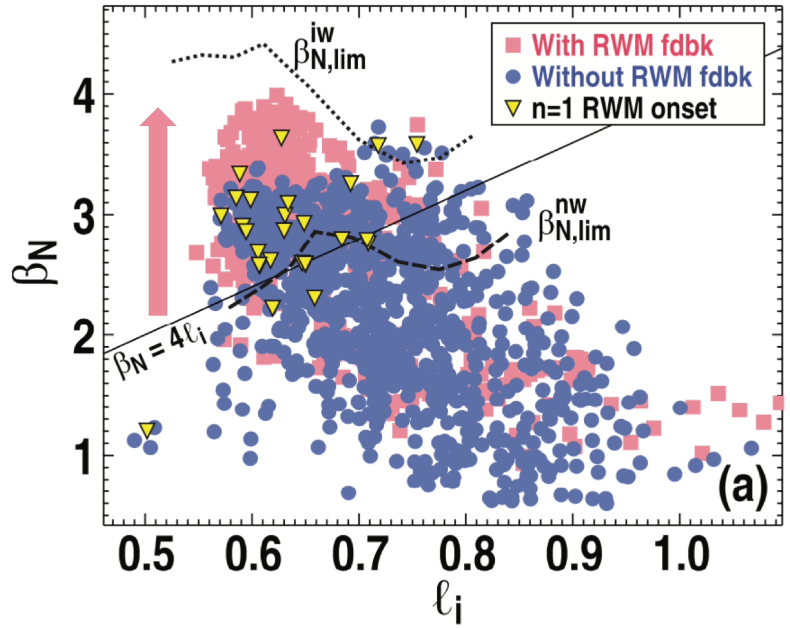


Magnetic feedback helps expand the tokamak operating space

- **To below q_{edge} = 2**
  - In DIII-D and RFX-MOD[1]



- **To higher β_N**
  - In DIII-D high-q_{min} scenario[2]



1. JM Hanson, *et al.*, *Phys. Plasmas* **21** (2014) 072107.
2. JM Hanson, *et al.*, *Nucl. Fusion* **57** (2017) 056009.

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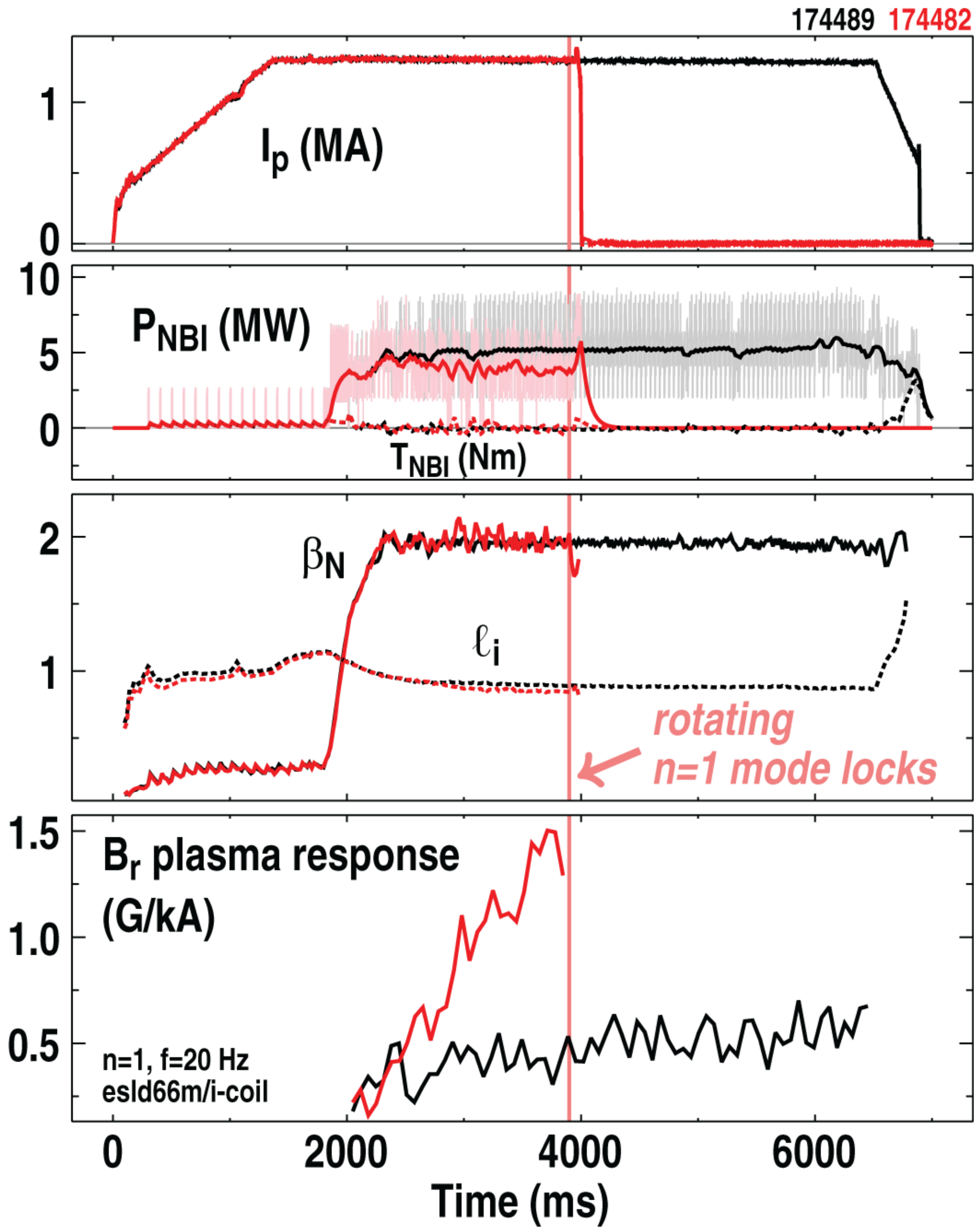
DIII-D ITER baseline demonstration discharges present stability challenge

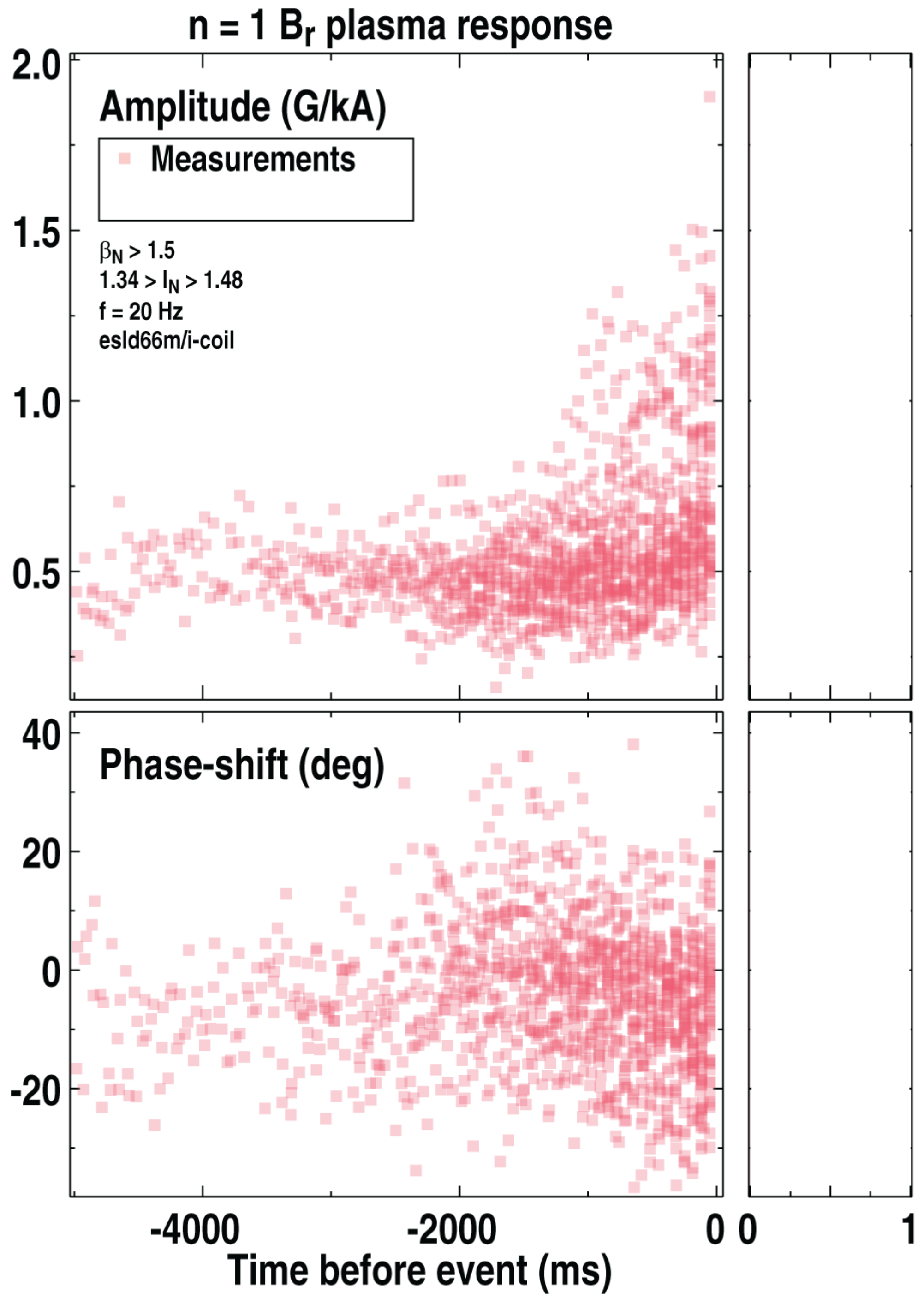
- **Combination of low torque, low q_{95}≈3 and H-mode edge leads to stability challenges**[1]
  - Below ideal MHD limits, *but* …
  - … current profile shape near q=2 and 3 ➜ tearing
- **Low frequency plasma response increase prior to tearing mode locking**



[1] F. Turco, *et al.*, *Nucl. Fusion* **58** (2018) 106043.

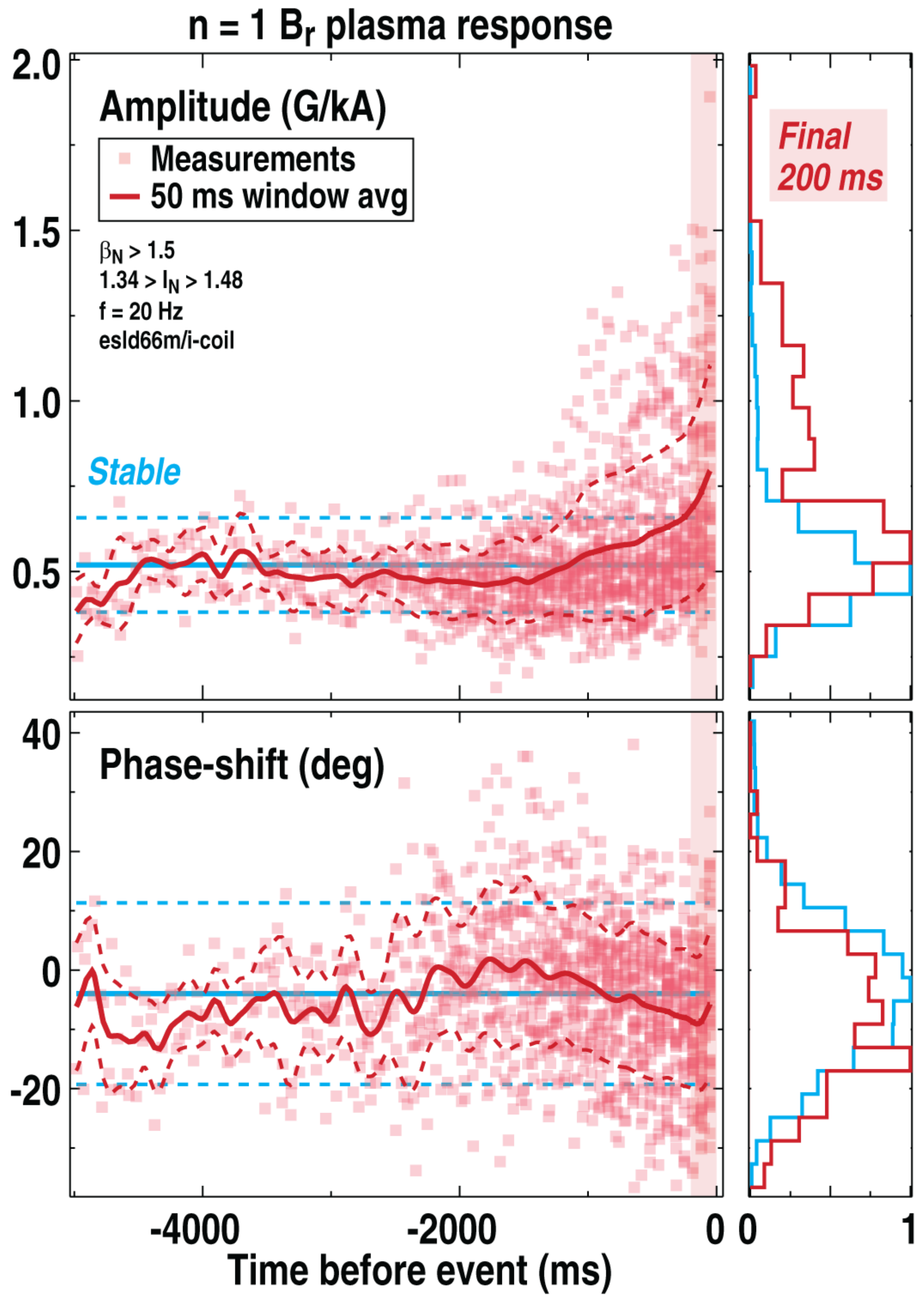
Many shots exhibit response increase before locking

- **Compare time-evolutions of 52 discharges with n=1 locking events**



Many shots exhibit response increase before locking

- **Compare time-evolutions of 52 discharges with n=1 locking events**
- **Average evolution shots increasing response amplitude**
  - Exceeds baseline of 60 stable shot
- **Not all cases show increased response**
  - β_N influences response but not TM stability in this regime[1]
  - Modes sometimes lock more quickly than 100 ms response timescale



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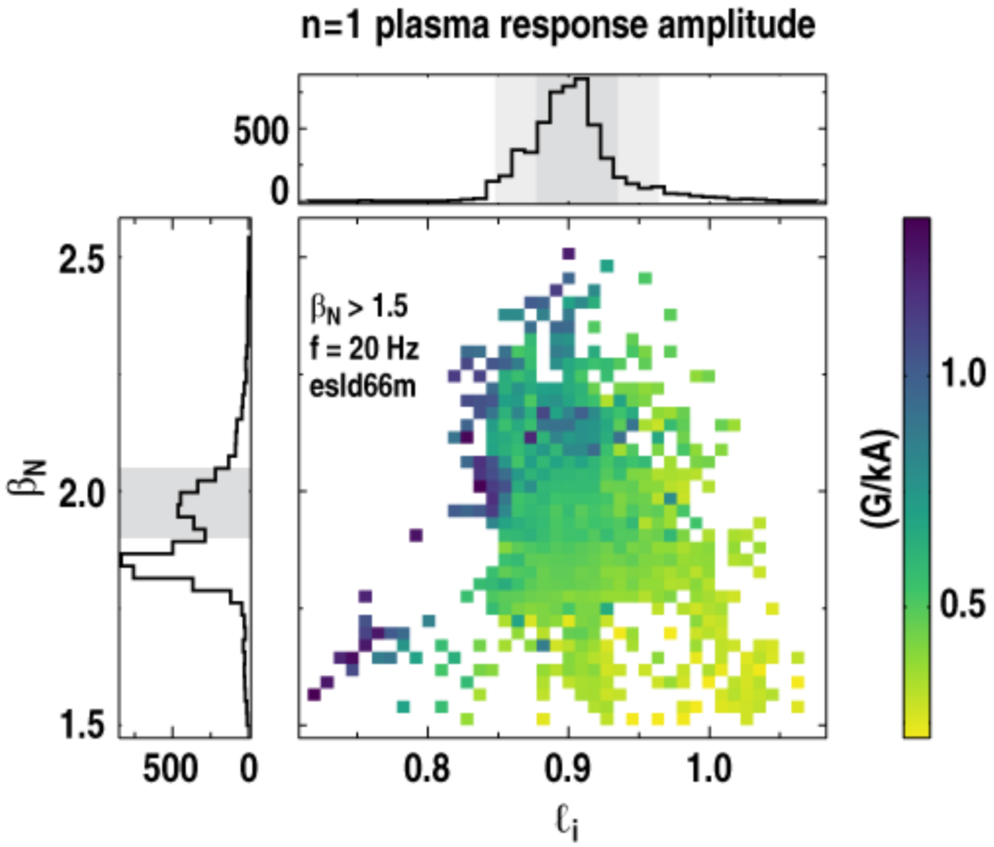
Plasma response is sensitive to MHD equilibrium

- **Examine large ITER demo shot dataset**
  - 148 shots with $\beta_N > 1.5$, $I_N \approx 1.4$
  - 5525 100 ms time-intervals

- **Sensitivity to β_N and ℓ_i suggests ideal MHD link**



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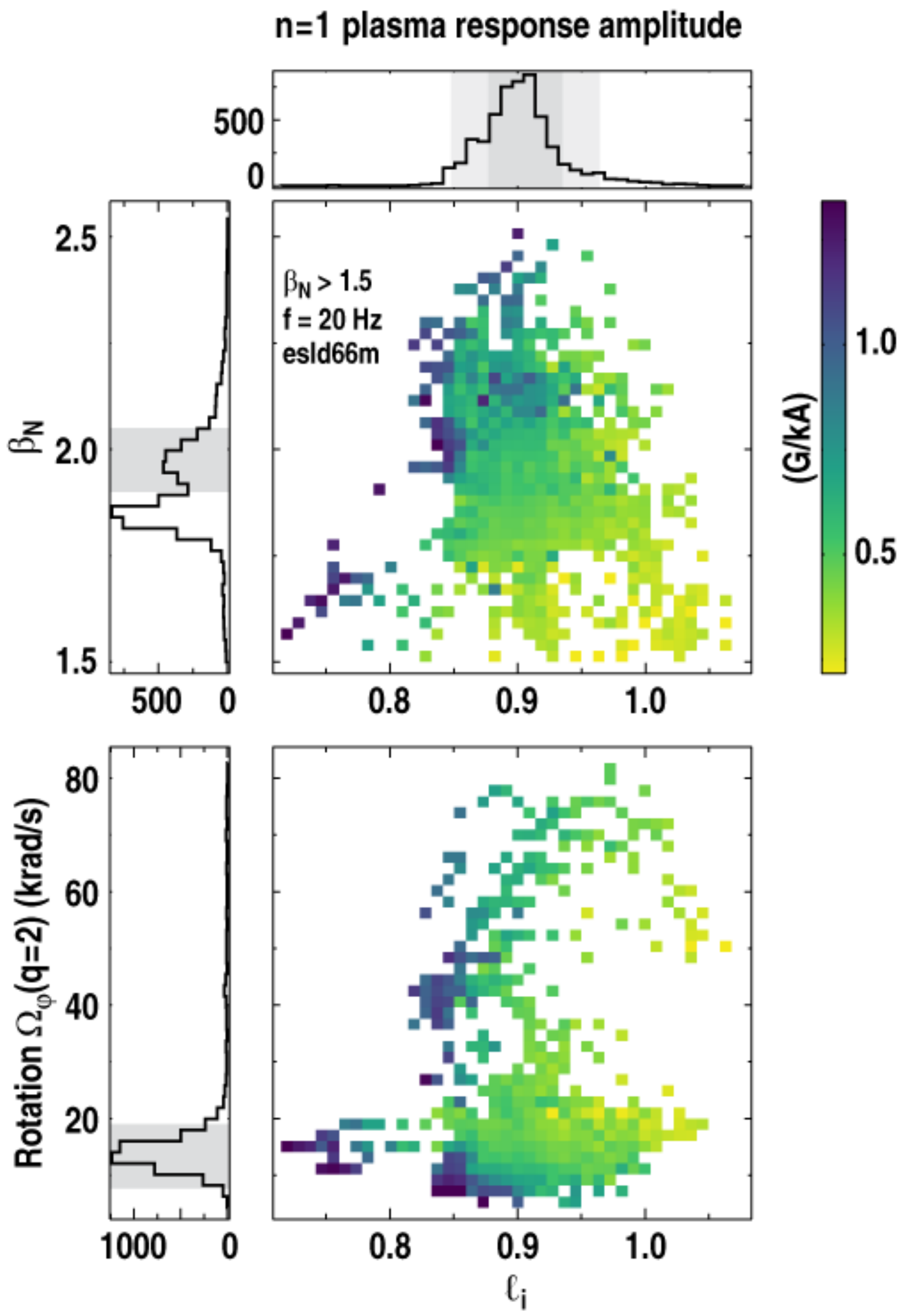

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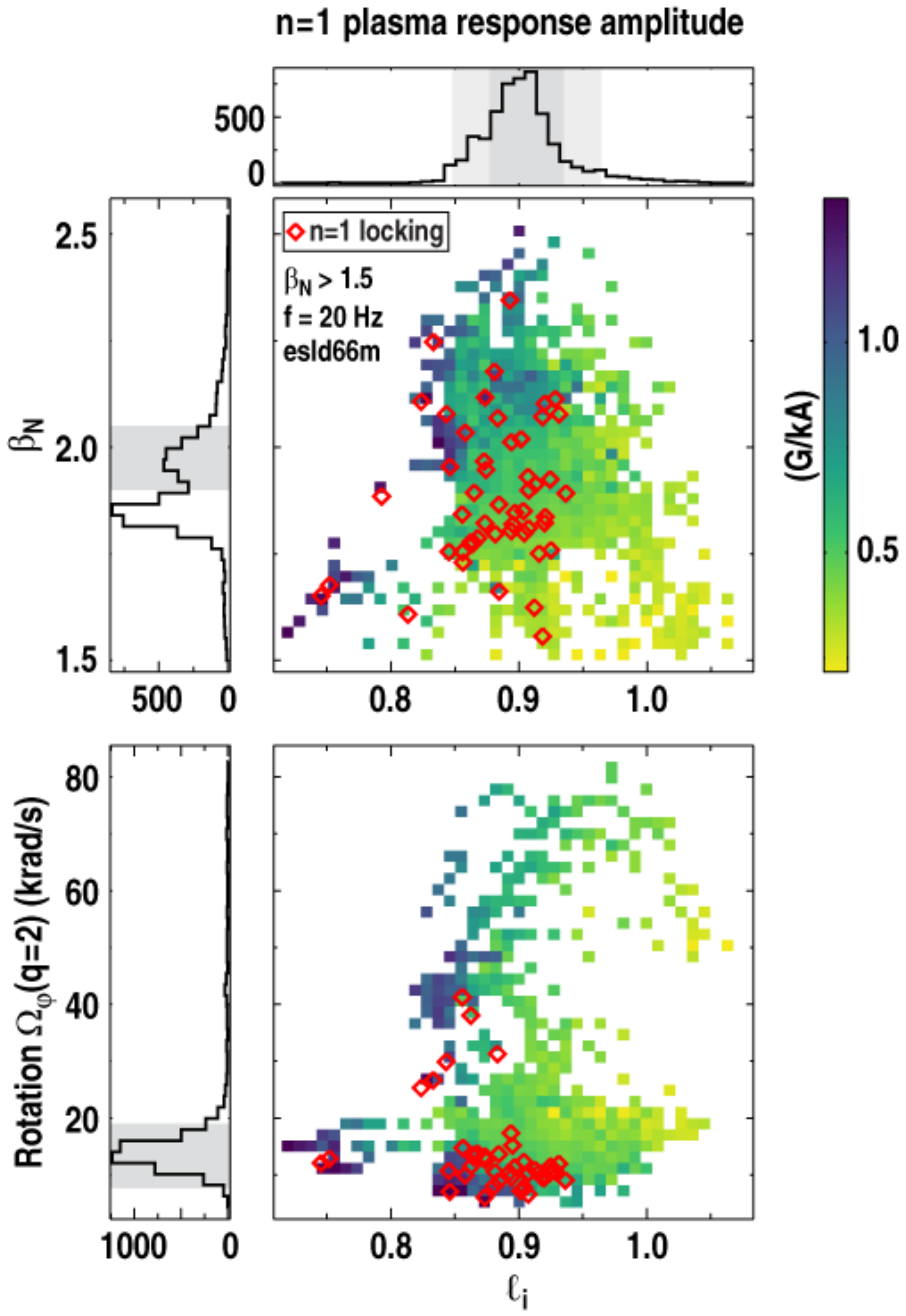
- **Sensitivity to β_N and ℓ_i suggests ideal MHD link**
- **Strongest response at low ℓ_i and low rotation**
- **Higher incidence of locking in this regime**
  - 52 n = 1 mode locking events
  - All followed by disruption, sometimes at reduced I_p



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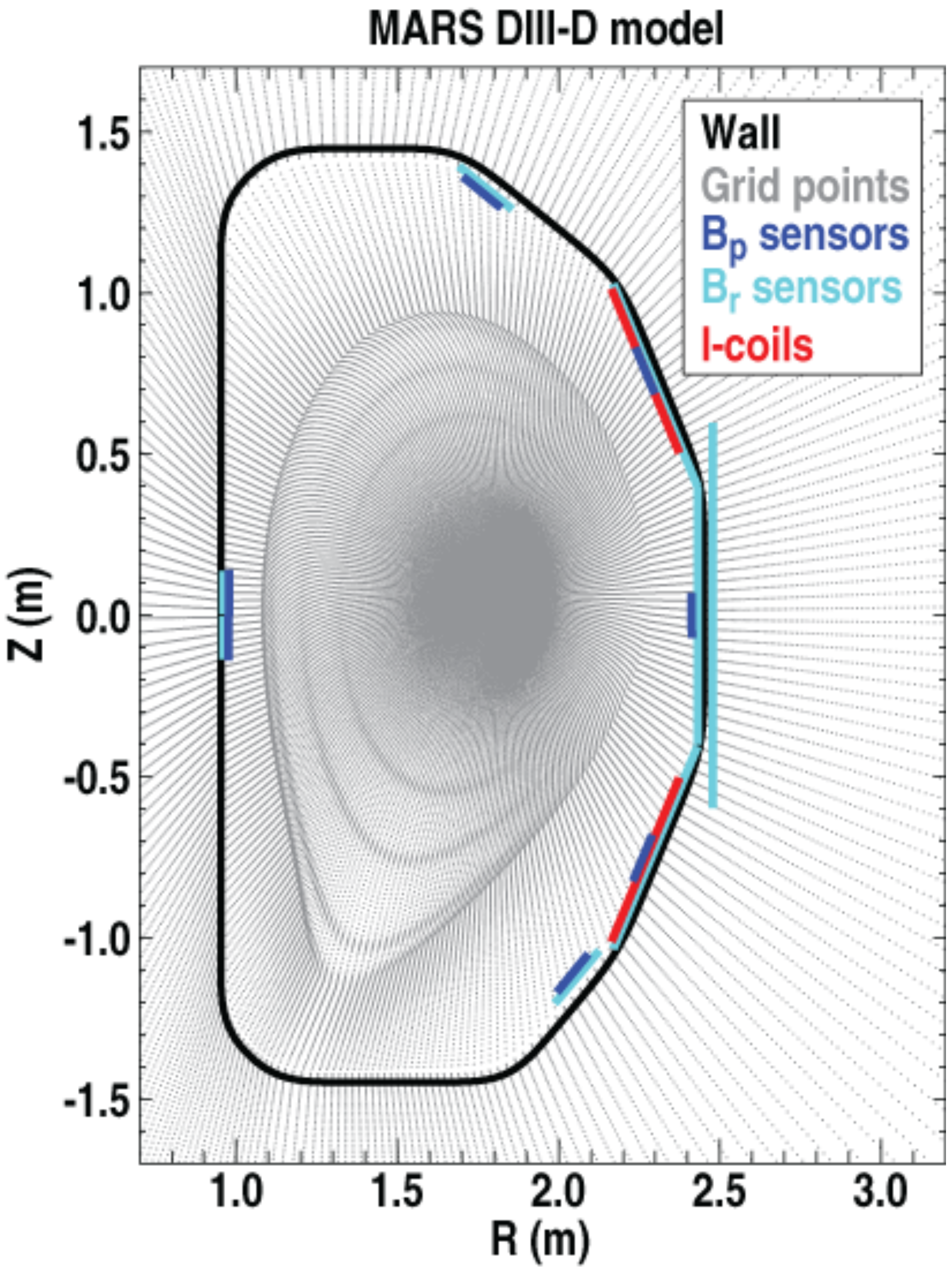
MARS-F code simulates toroidal mode plasma response

- **MARS-F solves linearized, perturbed MHD model with resistive wall and coils**[1]
  - Solves for perturbed field over a large domain
  - Can apply rotating perturbations with coils
  - Compare with magnetic sensor measurements by averaging predictions over sensor locations

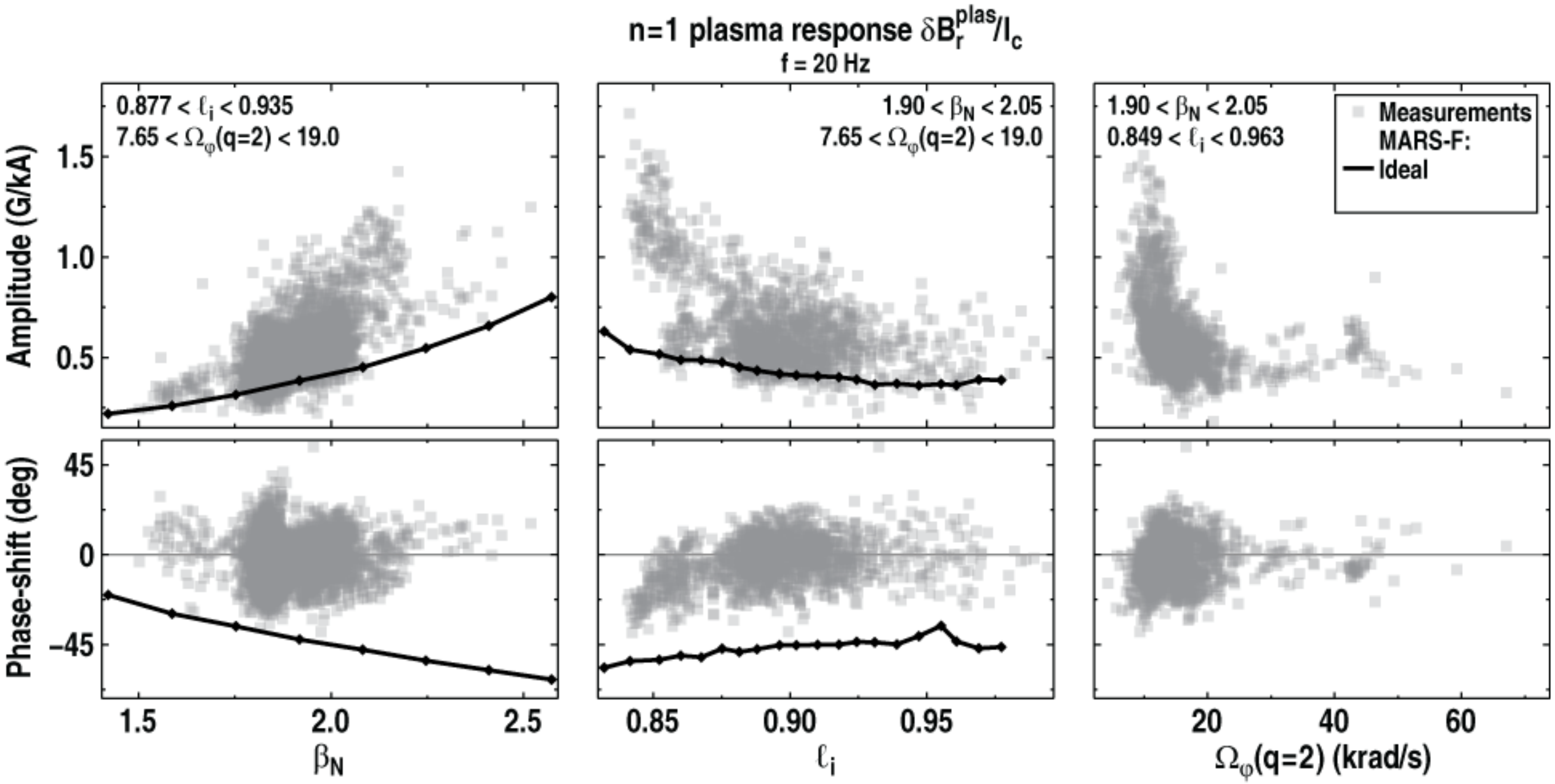
- **A variety of plasma physics contributions can be included**
  - Plasma rotation
  - Single-fluid resistivity
  - Kinetic contributions



[1] Y. Liu, *et al.*, *Phys. Rev. Lett.* **84** (2000) 907.

Resistive response simulations compatible with experimental dependencies

- **Ideal MHD qualitatively consistent with β_N and ℓ_i dependencies**



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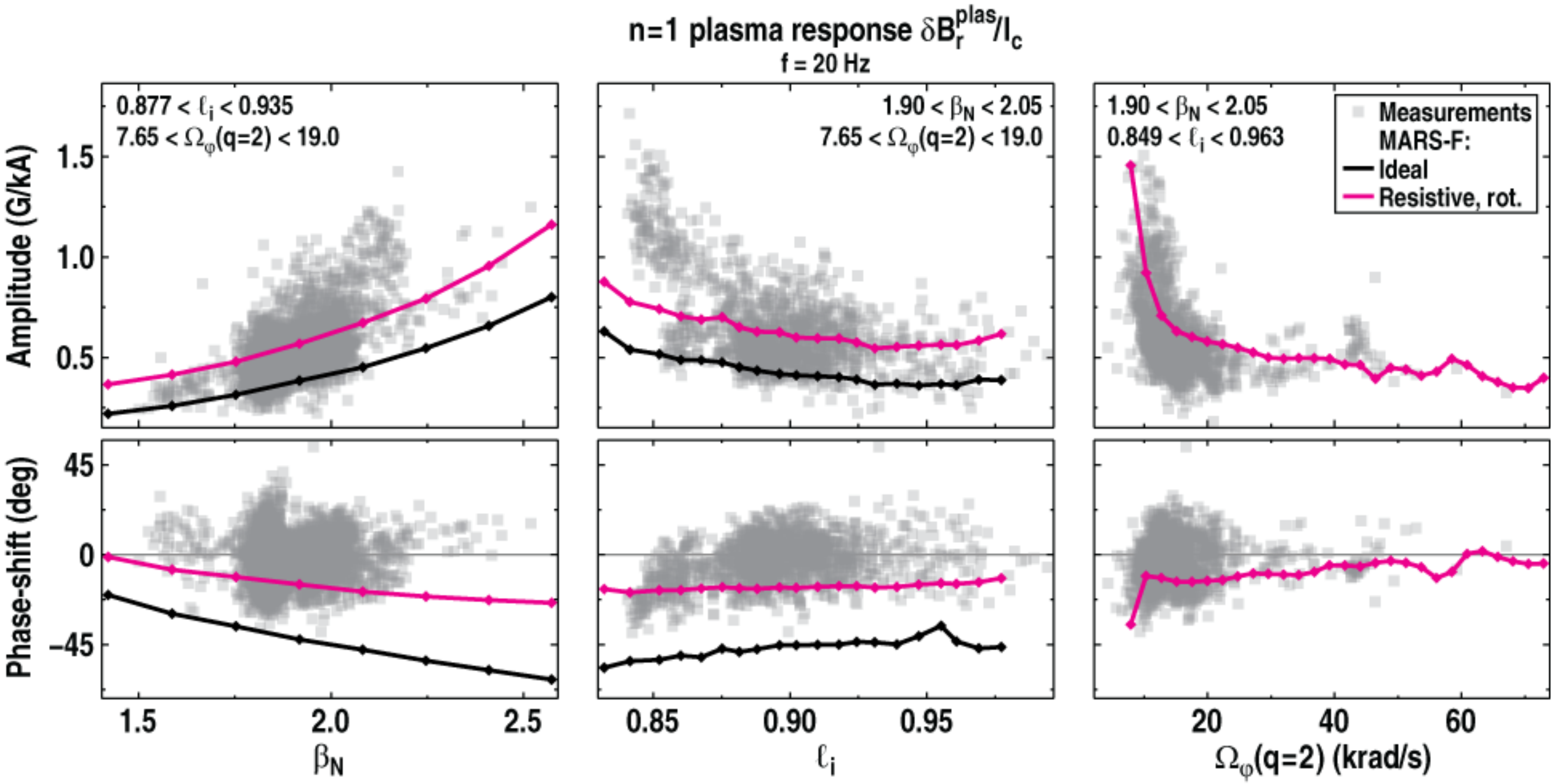
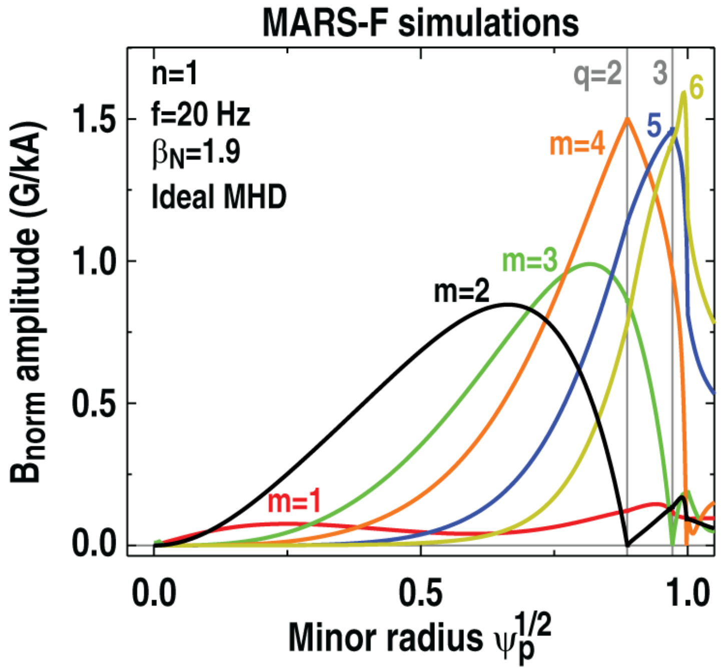


- **Including resistivity and rotation improves agreement**
  - Modeling consistent with large change at low rotation

Resistive simulations show enhanced resonant response

- **Ideal MHD: pitch-resonant fields screened at rational surfaces**



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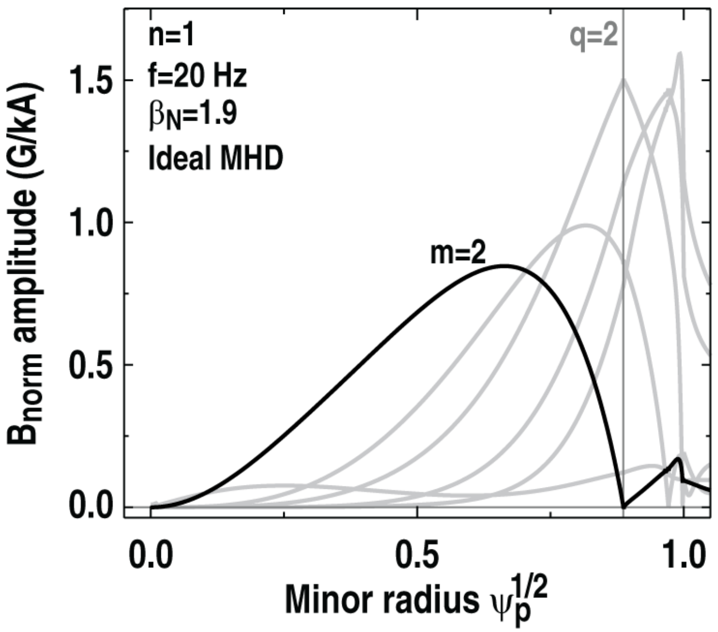
MARS-F simulations



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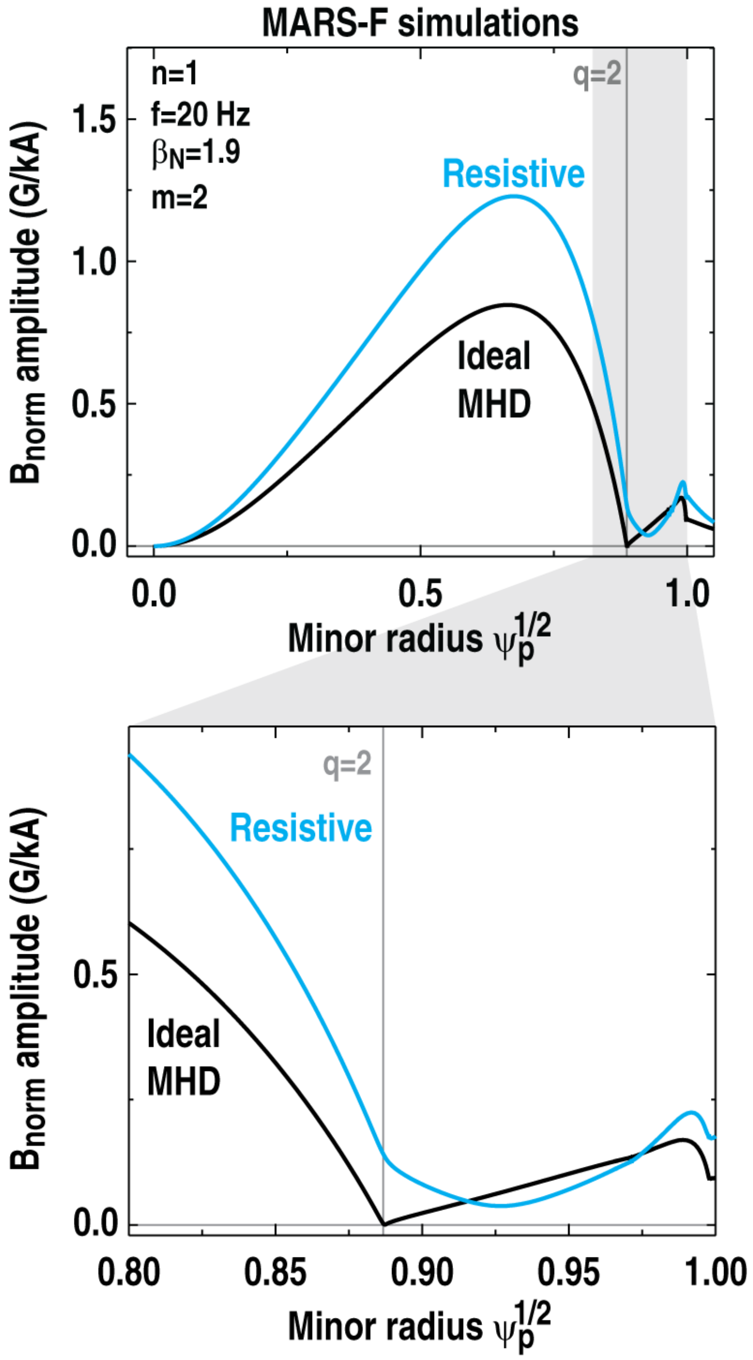
  - Permitting non-zero resonant components



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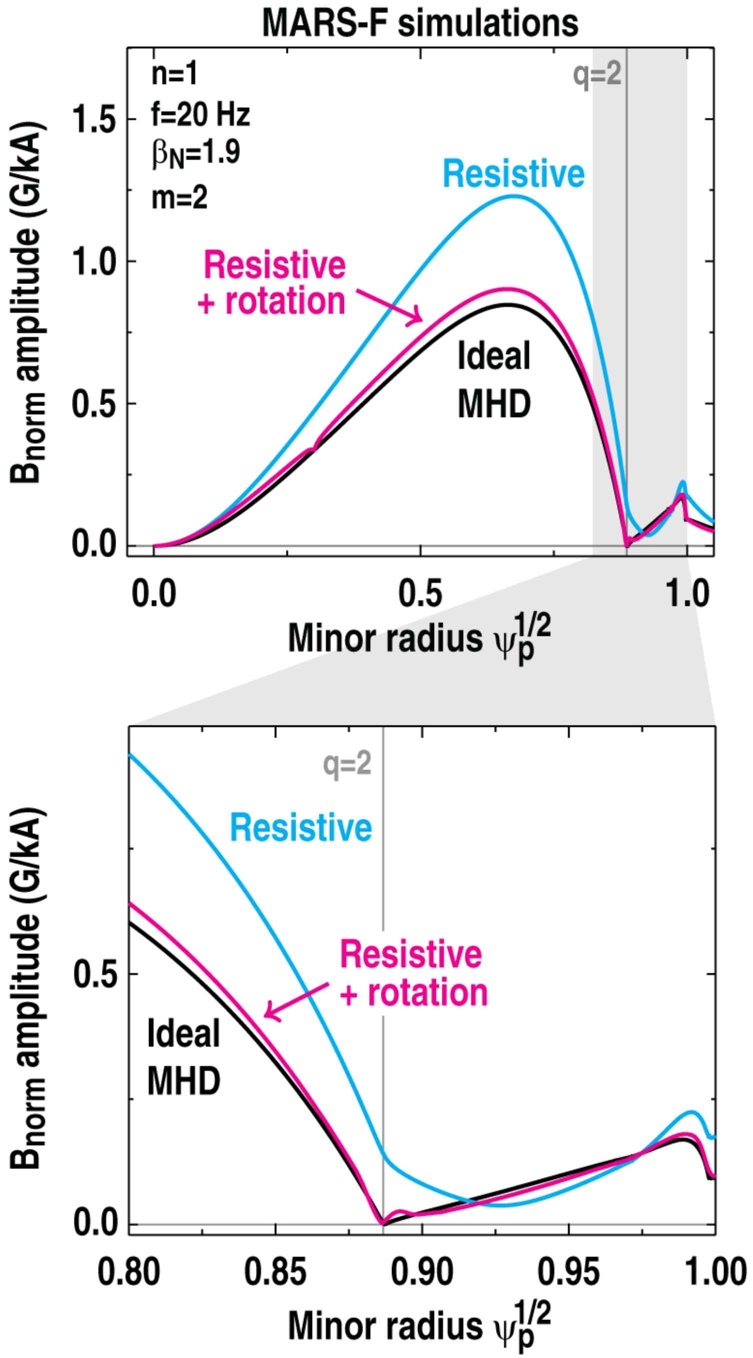
- **Plasma rotation helps restore screening**



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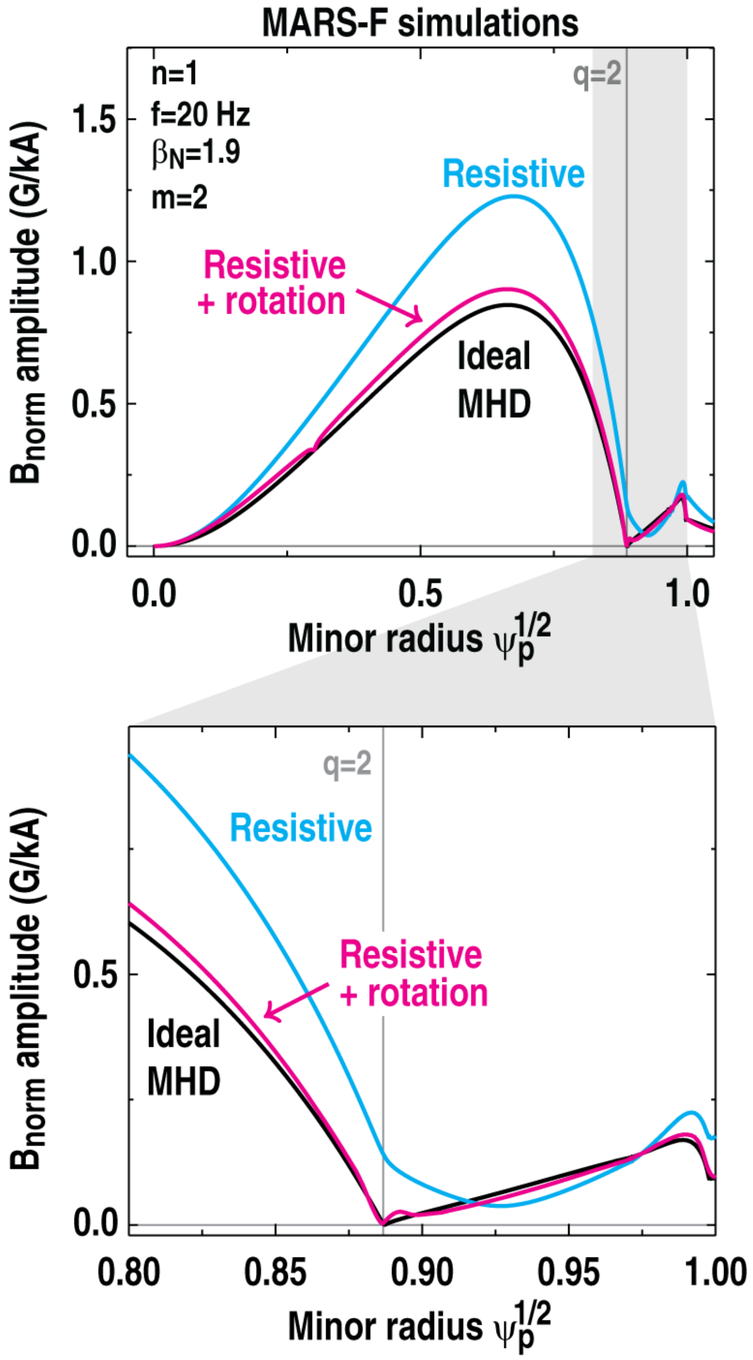
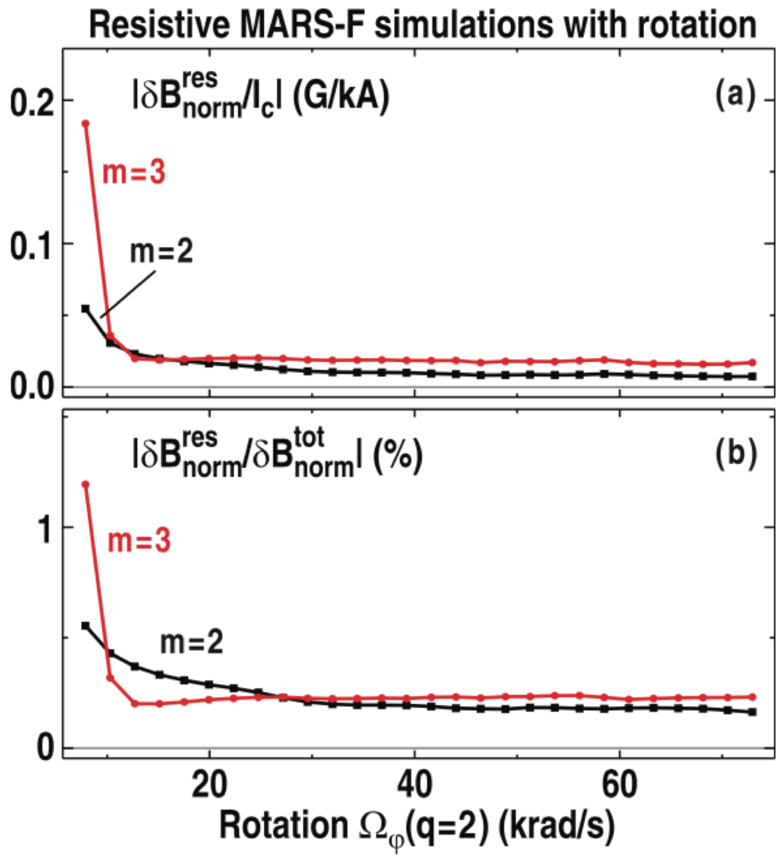


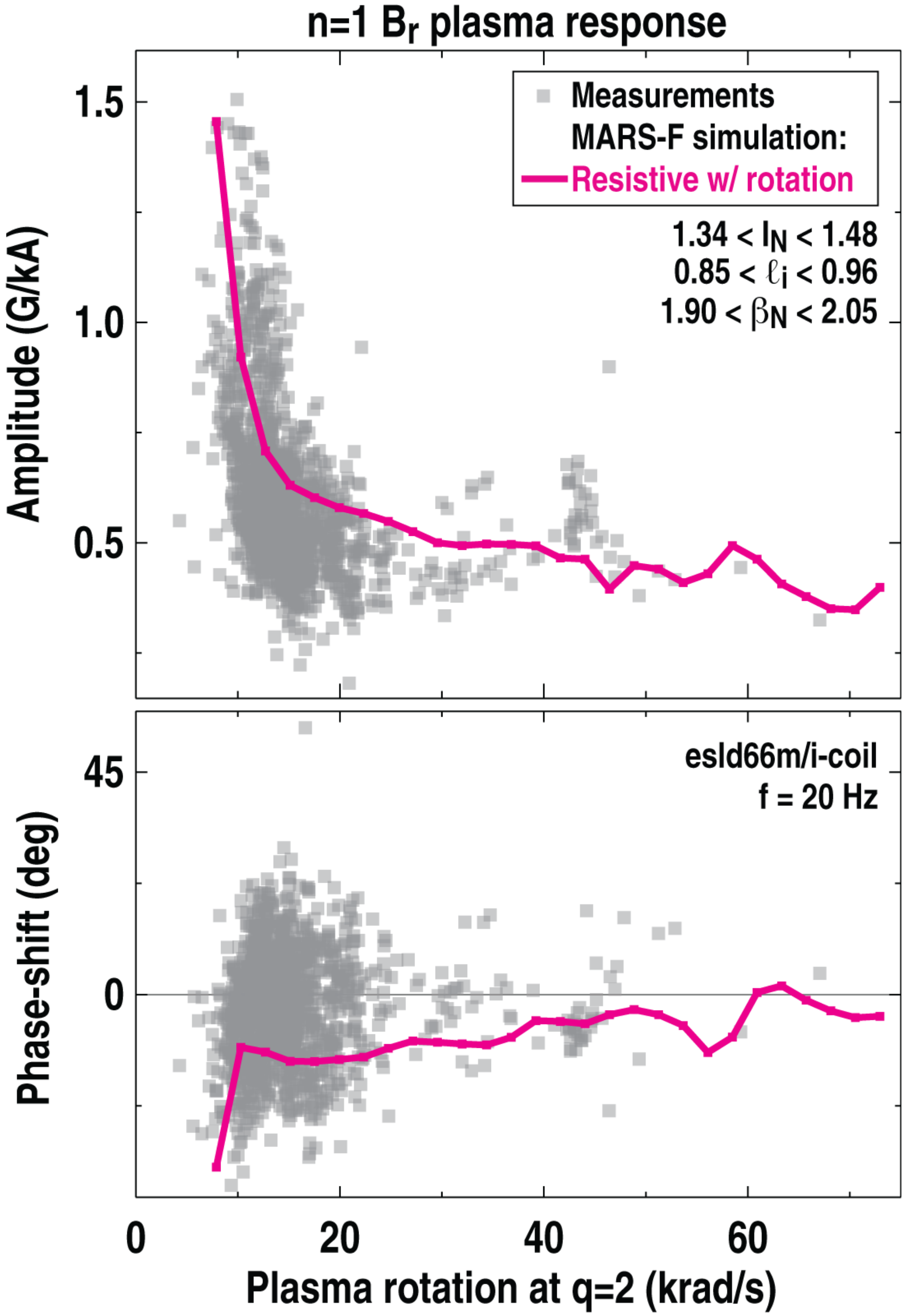


- **Resonant fields increase strongly at low rotation**[1]

[1] JM Hanson, *et al., Phys. Plasmas* **28** (2021) 042502.

What have we learned about the transition to locking?

- **Is the applied perturbation driving tearing?**
  - Simulations show resonant field increase …
  - … but q = 2 surface rotates faster than perturbation: ≈1 kHz vs 20 Hz
  - This regime has (2,1) stability and locking issues even without perturbations[1]



[1] F. Turco, *et al.*, *Nucl. Fusion* **58** (2018) 106043.
[2] F. Turco, *et al.*, *Nucl. Fusion* **64** (2024) 076048.

What have we learned about the transition to locking?

- **Is the applied perturbation driving tearing?**
  - Simulations show resonant field increase …
  - … but q = 2 surface rotates faster than perturbation: ≈1 kHz vs 20 Hz
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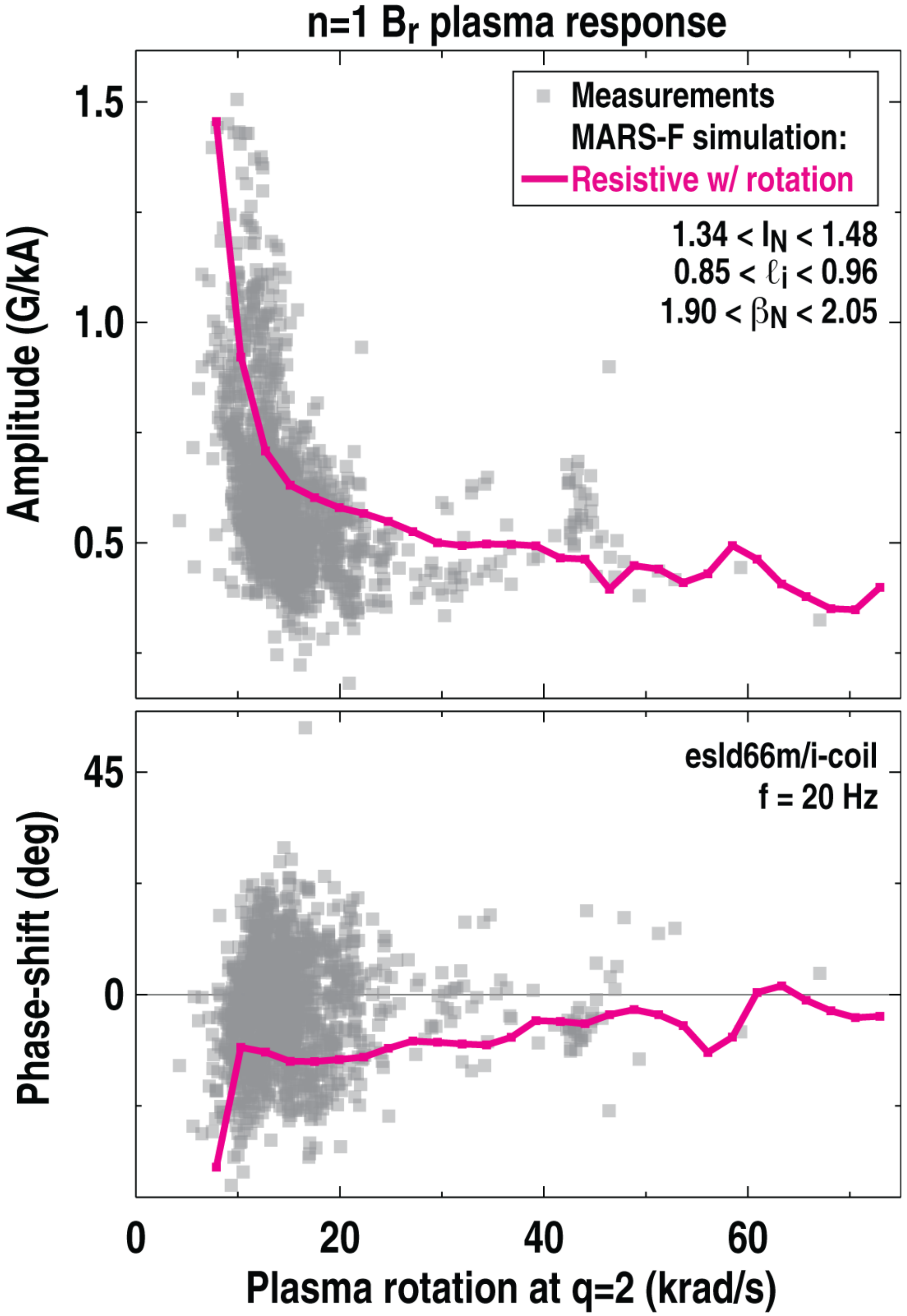
- **Kink stability weakens at low rotation**
  - Below no-wall limit, so don't expect instability
  - But increasing error field amplification likely contributes to locking and disruption



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[1] F. Turco, *et al.*, *Nucl. Fusion* **58** (2018) 106043.

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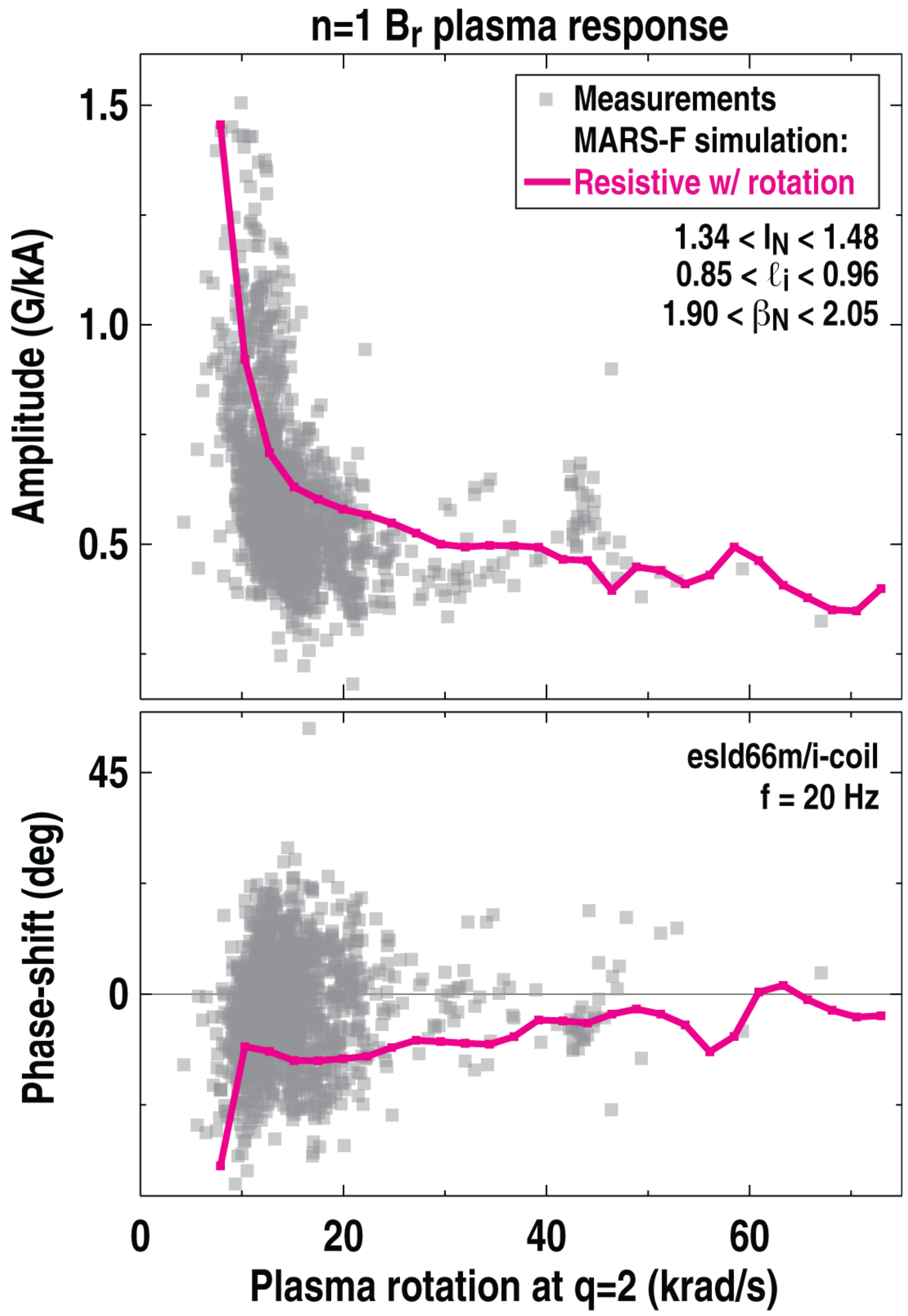
- **Kink stability weakens at low rotation**
  - Below no-wall limit, so don't expect instability
  - But increasing error field amplification likely contributes to locking and disruption
- **Ultimate solution:** current profile optimization for (2,1) tearing stability[2]



[1] F. Turco, *et al.*, *Nucl. Fusion* **58** (2018) 106043.
[2] F. Turco, *et al.*, *Nucl. Fusion* **64** (2024) 076048.

Outline

1. **Background**
   - DIII-D, stable kink excitation, measurements, feedback

2. **Resistive contribution to plasma response at low torque**
   - In the ITER baseline regime

3. **Simulating feedback-controlled error field correction**
   - Integrate error field and MHD response codes

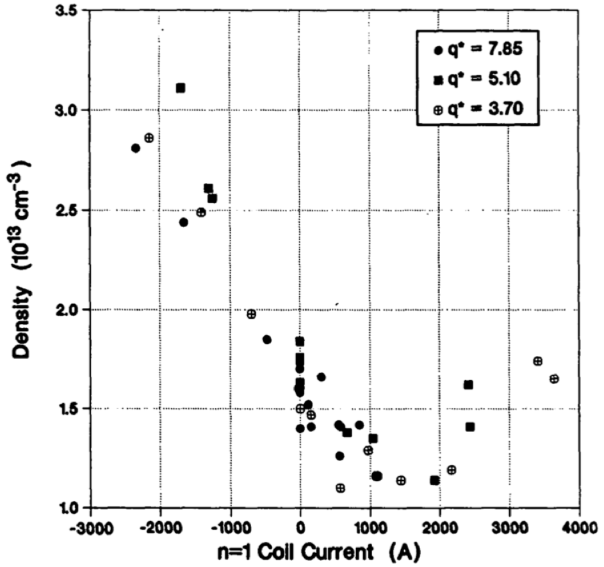
Correcting plasma error field response improves tokamak performance

- **Small equilibrium coil deviations from axisymmetry lead to field errors**
  - Implicated in MHD instability onsets and locking
  - Observed in many tokamaks
  - Critical threshold $\delta B/B_0 \sim 10^{-4}$

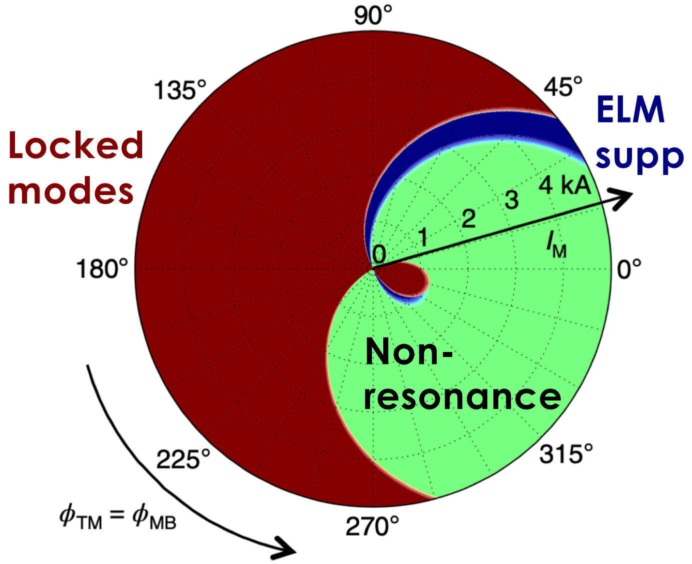
- **Low density locked mode threshold improved with applied n=1 field**[1]
  - Attributed to error field correction

- **Now understand that managing 3D field can have many benefits**
  - Rotation optimization[2], ELM suppression[3] …

DIII-D Low density locked mode threshold[1]



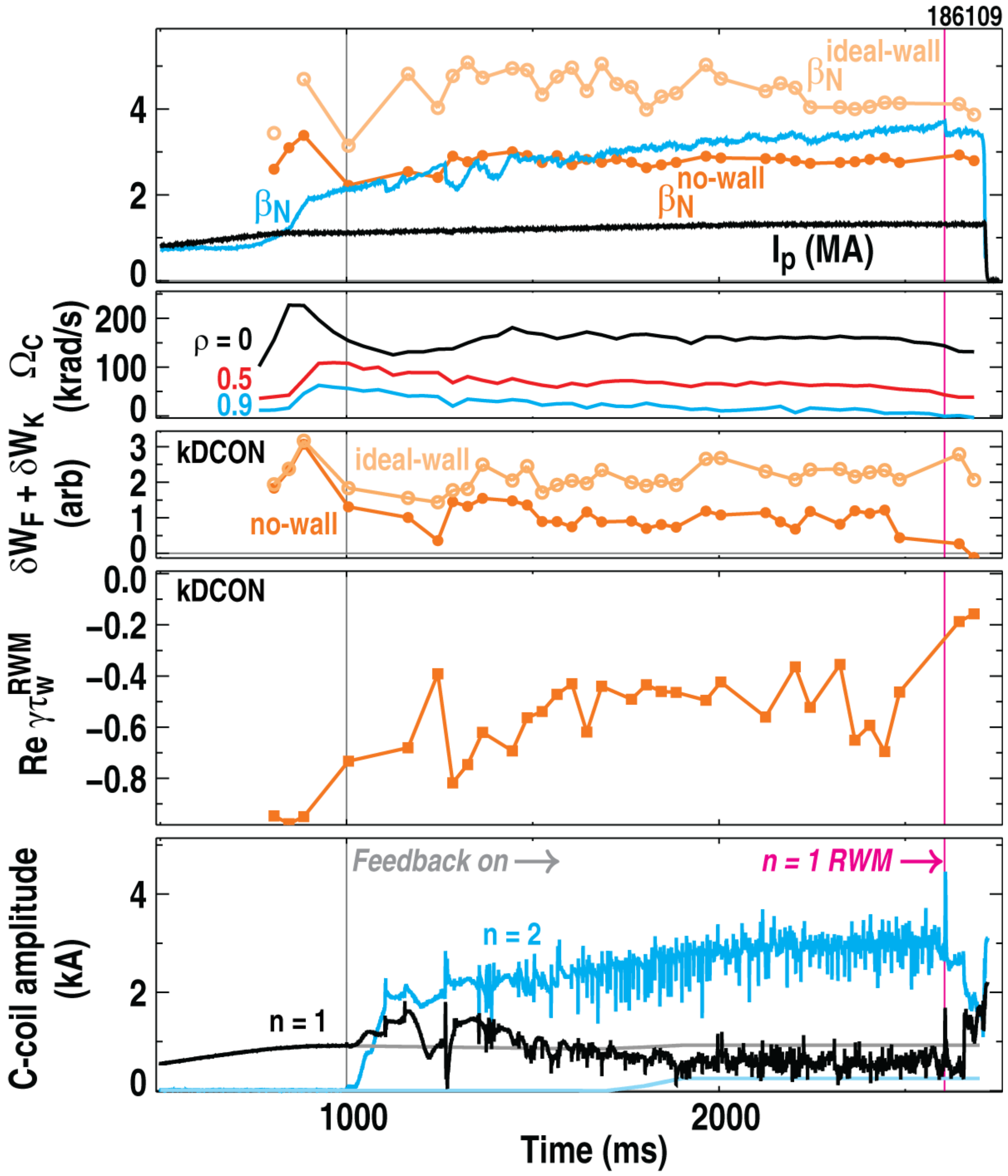
KSTAR simulated 3D operating window[3]



1. JT Scoville, *et al.*, *Nucl. Fusion* **31** (1991) 875.
2. AM Garofalo, *et al.*, *Nucl. Fusion* **42** (2002)1335.
3. J-K Park, *et al.*, *Nature Phys.* **14** (2018) 1223.

Advanced tokamak discharge reaches stability limit with n=1 + n=2 feedback control

- **β_N ramped to 3.8, above ideal n=1 no-wall limit[1]**
- **Born-locked n=1 mode before disruption**
  - Growth time: 1 ms ≈ τ_w
  - Coincides with approach to kinetic MHD marginal point



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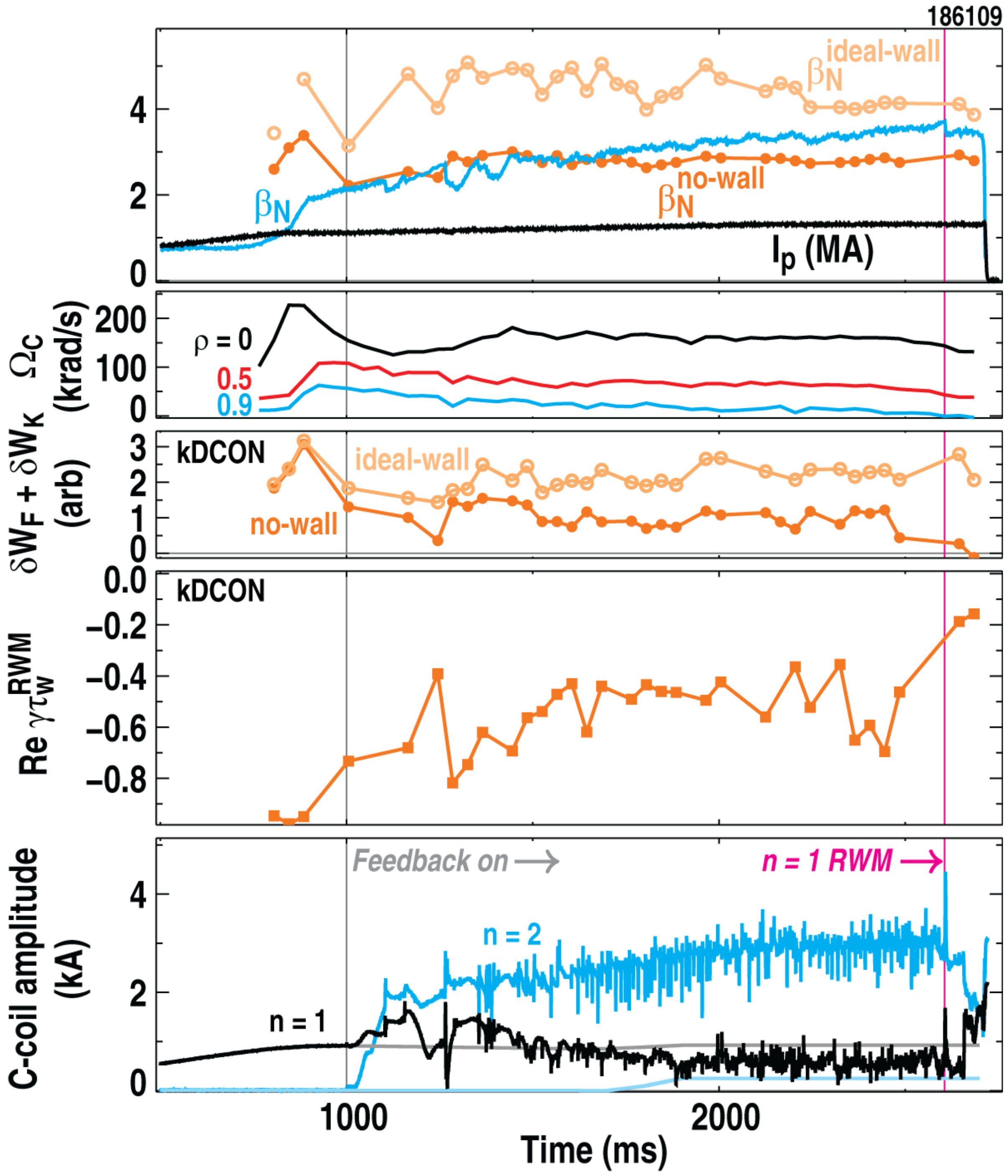
- **n=1 + n=2 C-coil feedback**
  - Fast RWM control and EF correction
  - Baseline evolution indicates EF response



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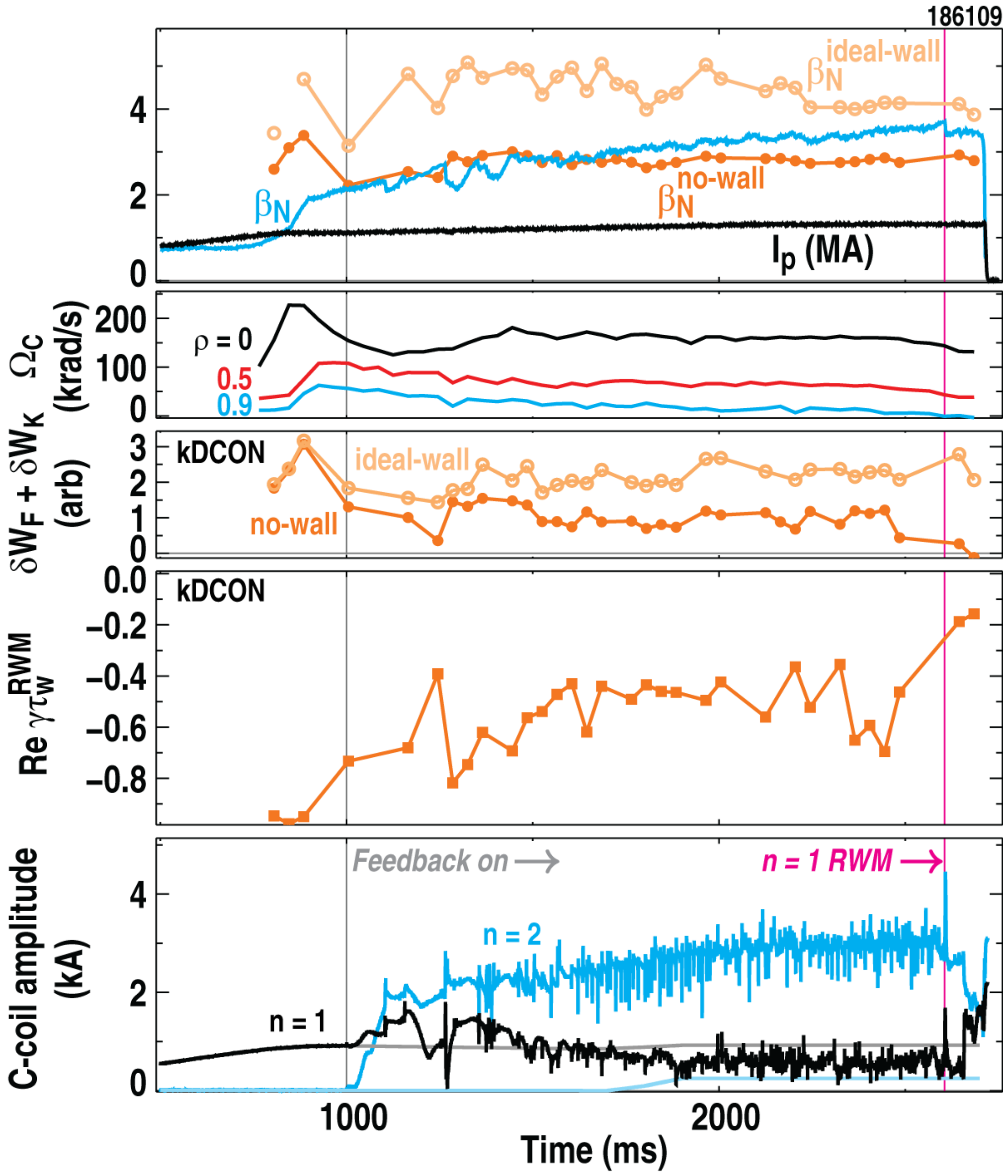
  - Fast RWM control and EF correction
  - Baseline evolution indicates EF response

- ***Can we understand what the feedback did?***



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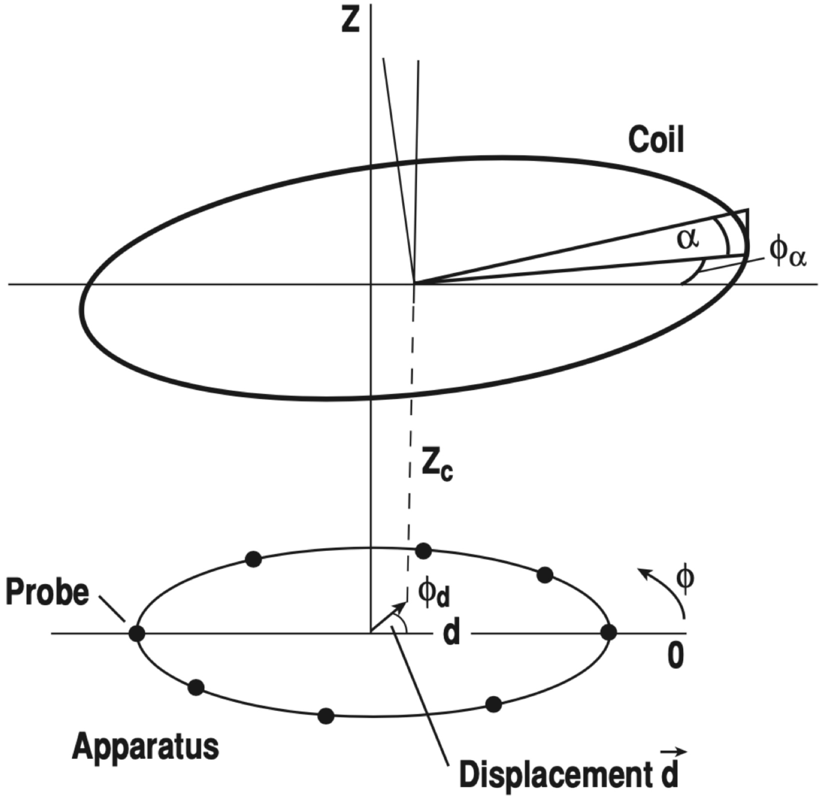
1. AF Battey *et al.*, *Nucl. Fusion* **63** (2023) 066025.

Recent developments enable error field correction simulations

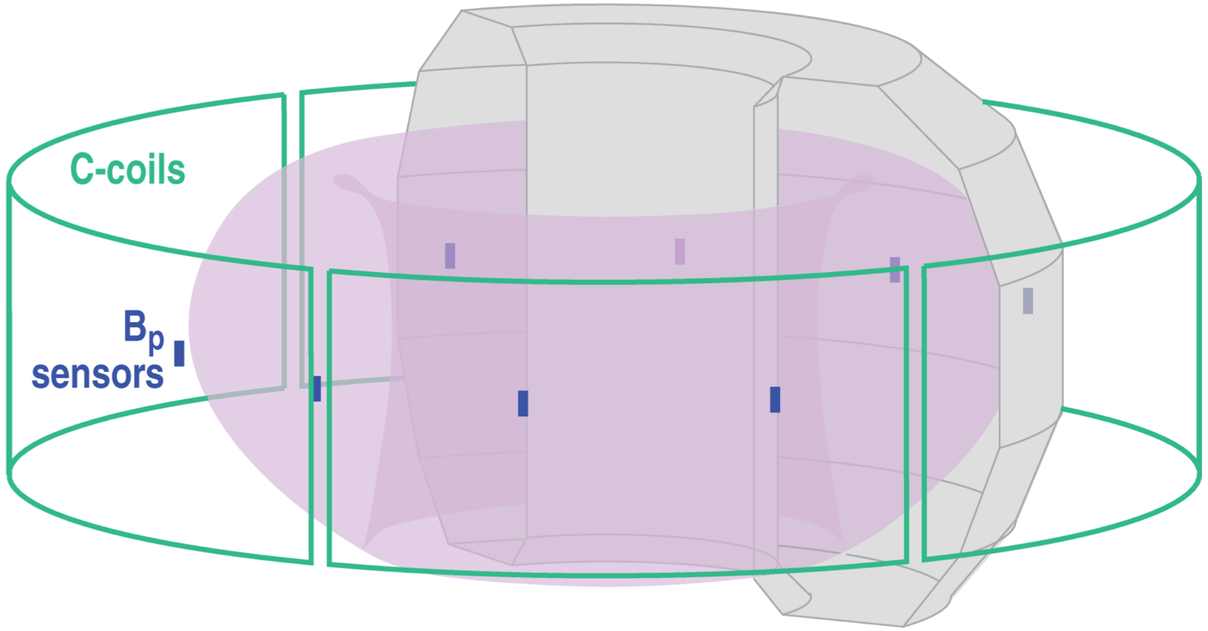
- **DIII-D n=1 and n=2 EF source model is well established[1]**
  - Based on in-vessel coil asymmetry measurements
- **Can simulate plasma response with DCON[2]/GPEC[3]**
  - Critical to include: ***plasma selects EF harmonics***
  - ***Ideal MHD + kinetic model*** allows stable response prediction above no-wall limit
- **Idea: apply codes to simulate DIII-D high β feedback**
  - Multi-harmonic plasma response "collapsed" into single-mode model

Perturbed coil and measurement apparatus[1]



1. JL Luxon, *et al.*, *Nucl. Fusion* **43** (2003) 1813.
2. AH Glasser, *Phys. Plasmas* **23** (2016) 072505.
3. J-K Park and NC Logan, *Phys. Plasmas* **24** (2017) 032505.

Simplifying assumptions lead to tractable model for feedback error field correction



1. **Single toroidal arrays of coils and sensors, single-n**
   - Represent toroidal modes with complex scalars B_s or I_C
   - Consistent with toroidal mode fitting in feedback algorithm

2. **Fields are small enough that plasma response is linear**
   - Perturbed fields proportional to applied coil currents $B_s = A_{SC} I_C$
   - Not always true: EF can change plasma rotation, changing A_{SC}

3. **Plasma response is fast relative to equilibrium time scale**
   - Response time $\tau_W \approx 2.5$ ms << $\tau_E \approx 100$ ms
   - Leads to time-independent model

Model equations are straightforward[1]

- **Sensor mode has vacuum and plasma response contributions, from intrinsic EF and coils**

$$B_s = B_s^{\mathrm{EF,v}} + B_s^{\mathrm{EF,p}} + (A_{sc}^{\mathrm{v}} + A_{sc}^{\mathrm{p}})I_c$$

- **Proportional gain feedback law as in real-time algorithm**

$$I_c = G_{cs}B_s$$

- **Feedforward commands, sensor baselining, and sensor vacuum compensation also included**
  - But omitted here for simplicity

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[1] H. Reimerdes, *et al.*, *Fusion Sci. Tech.* **59** (2011) 572.

Solving yields predicted coil currents and sensor fields

- **Closed loop solution**

$$I_c = \frac{G_{cs}}{1 - A_{sc}G_{cs}} B_s^{\mathrm{EF}}, \quad \text{with } B_s^{\mathrm{EF}} = B_s^{\mathrm{EF,v}} + B_s^{\mathrm{EF,p}} \text{ and } A_{sc} = A_{sc}^{\mathrm{v}} + A_{sc}^{\mathrm{p}}$$

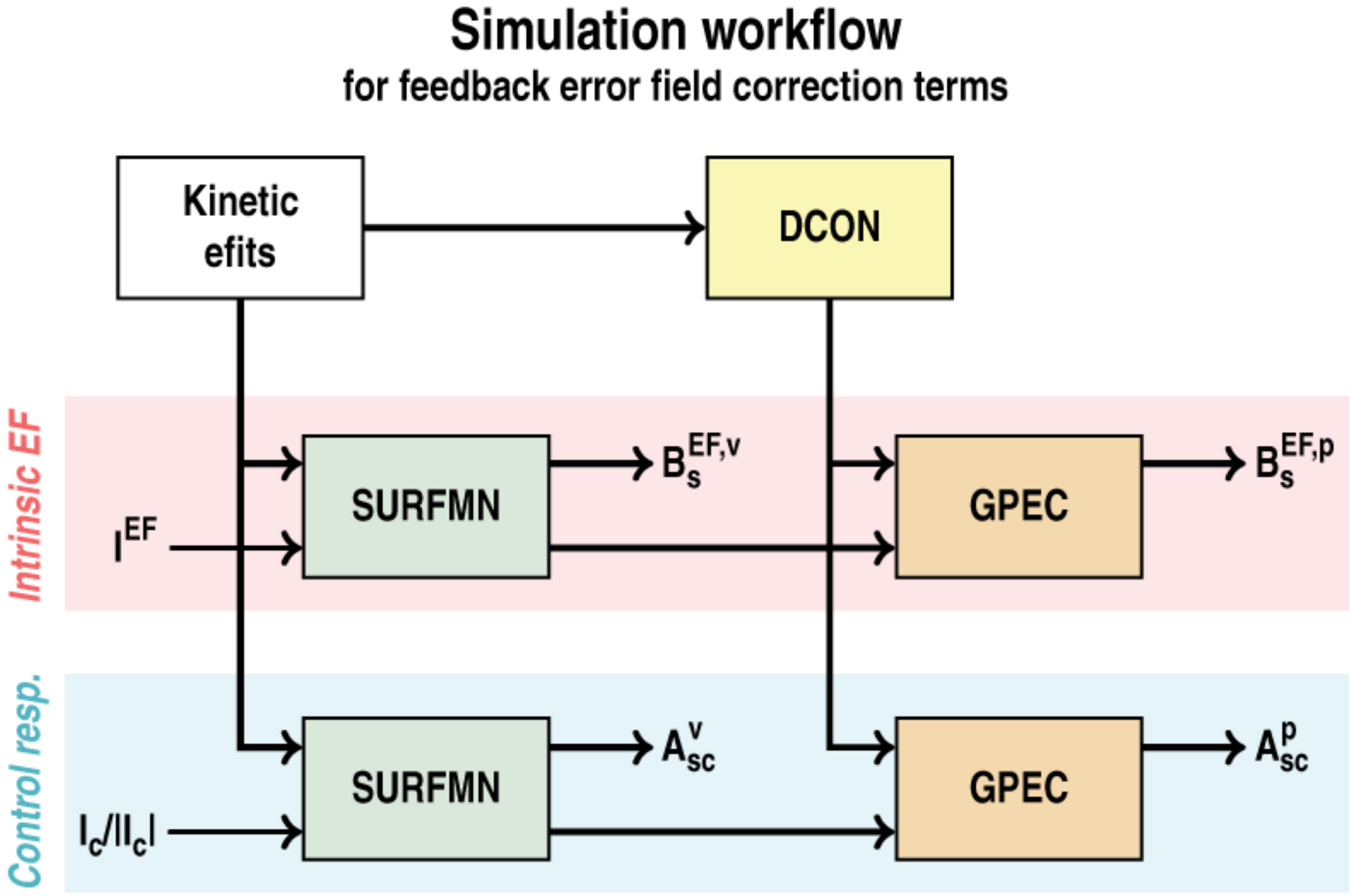
$$B_s = \frac{1}{1 - A_{sc}G_{cs}} B_s^{\mathrm{EF}}$$

- **Infinite gain limit yields "optimal" current for nulling EF sensor field**

$$I_c^{\mathrm{opt}} = -\frac{1}{A_{sc}} B_s^{\mathrm{EF}}$$

Modular simulation codes enable flexible workflow

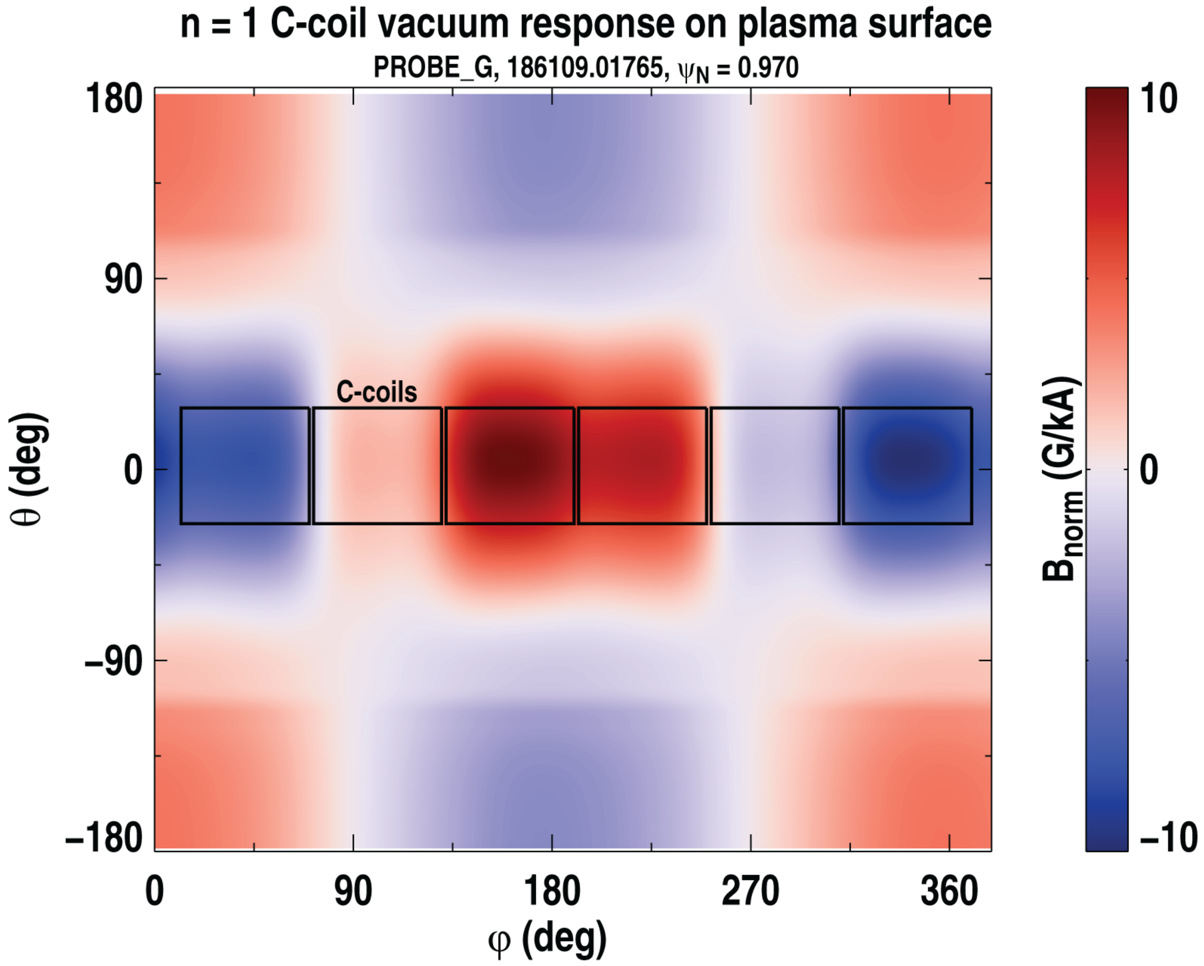
- **SURFMN:** 3D vacuum fields, given coil currents[1]
- **DCON:** MHD mode spectrum and stability[2]
- **GPEC:** MHD spectrum response to 3D fields[3]

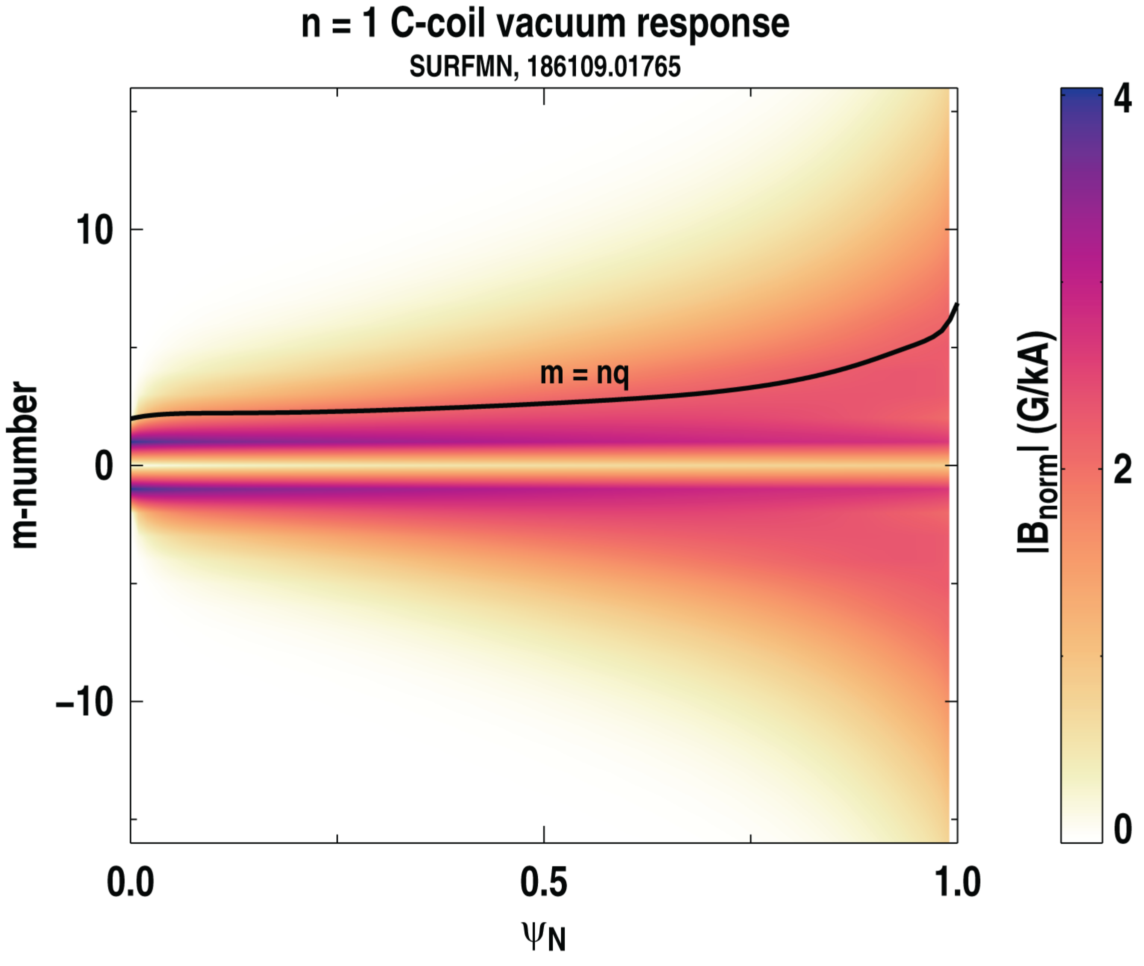


- **Exploit model linearity**
  - Fields from different code runs can be summed
  - Extract amplification terms A_{sc} with unit amplitude coil currents
  - Sensor fields from integrals over sensor areas

1. MJ Schaffer, *et al.*, *Nucl. Fusion* **48** (2008) 024004.
2. AH Glasser, *Phys. Plasmas* **23** (2016) 072505.
3. J-K Park and NC Logan, *Phys. Plasmas* **24** (2017) 032505.

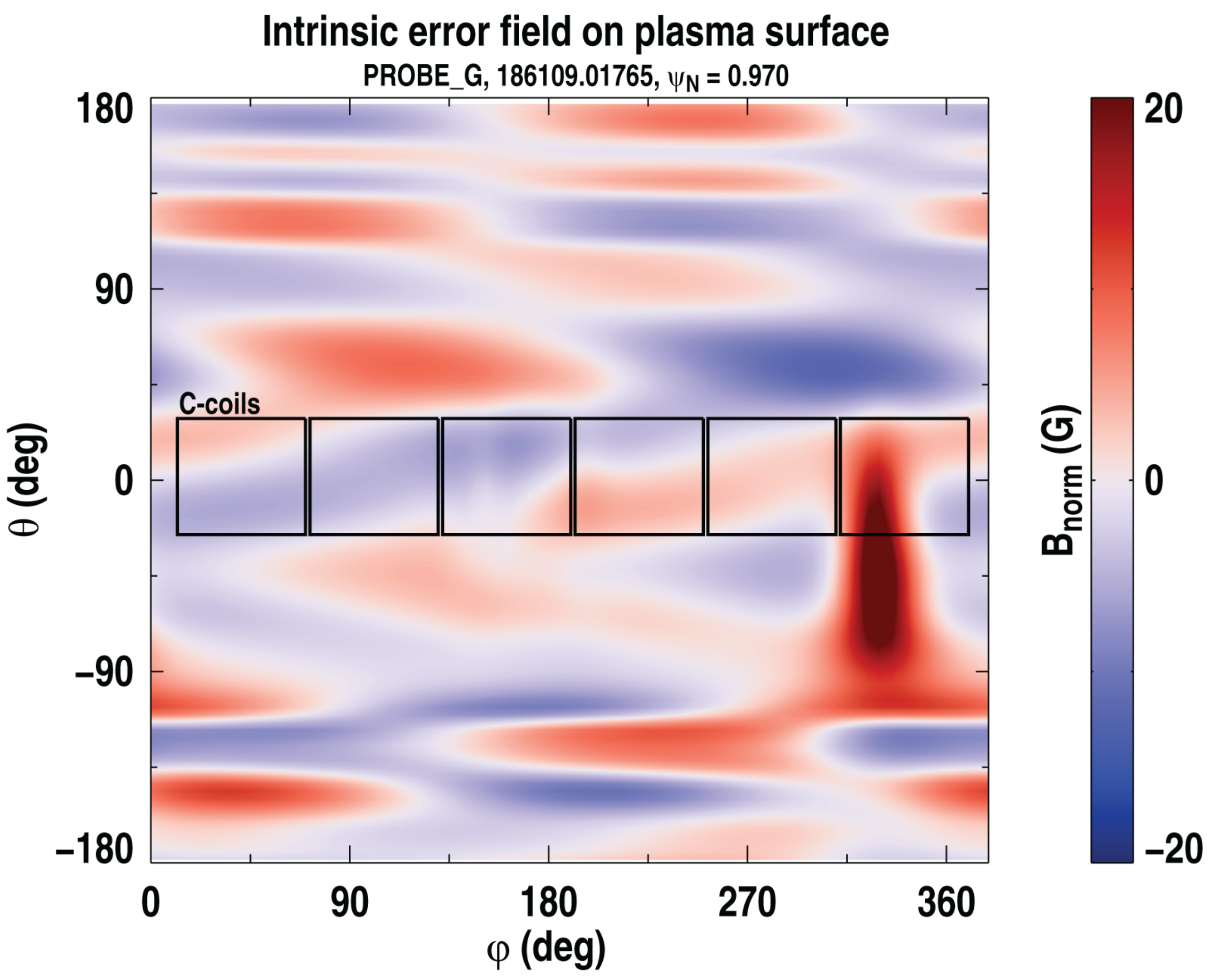
C-coil n=1 vacuum field has a broad m-spectrum

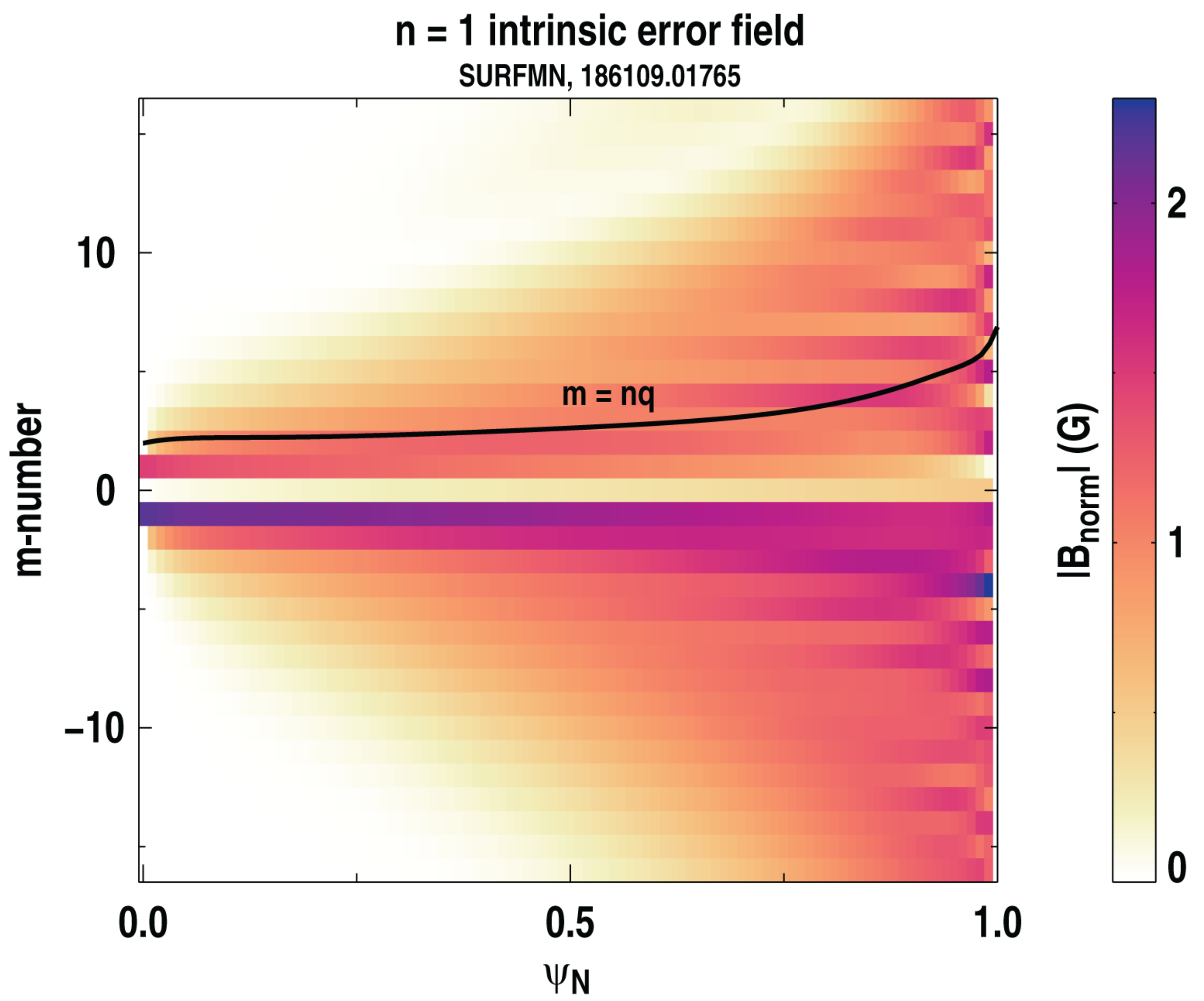




- **SURFMN predicts n=1 C-coil perturbation can couple to pitch-resonant and nonresonant harmonics**

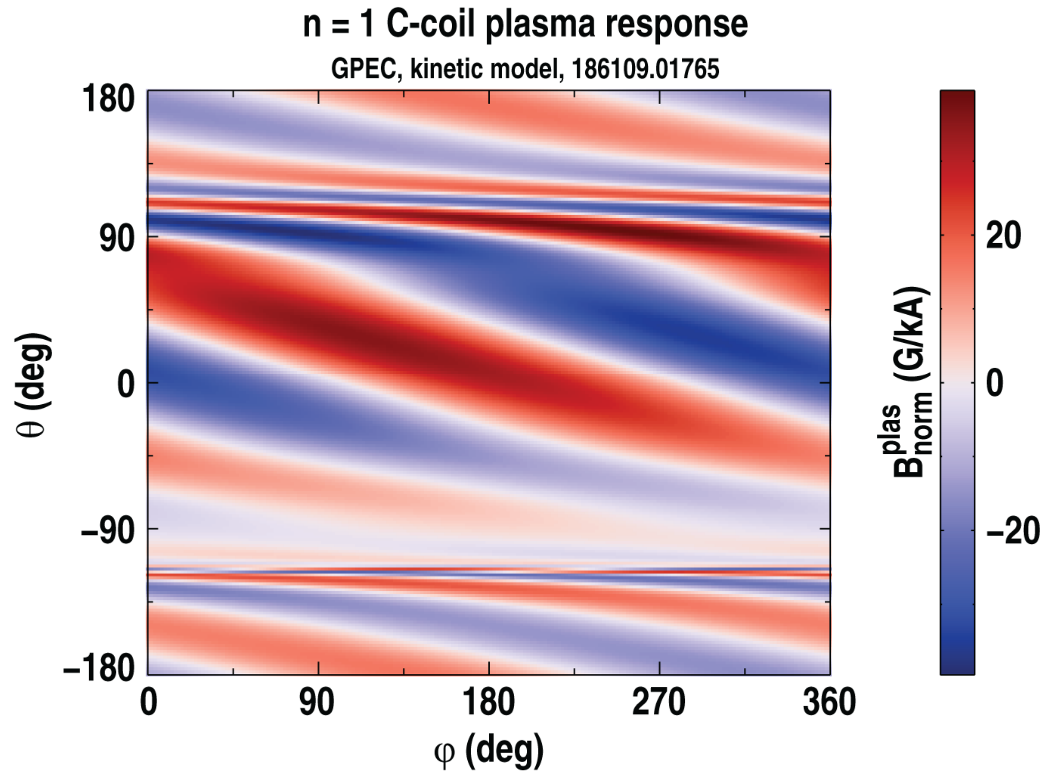
Intrinsic error field spectrum is also broad





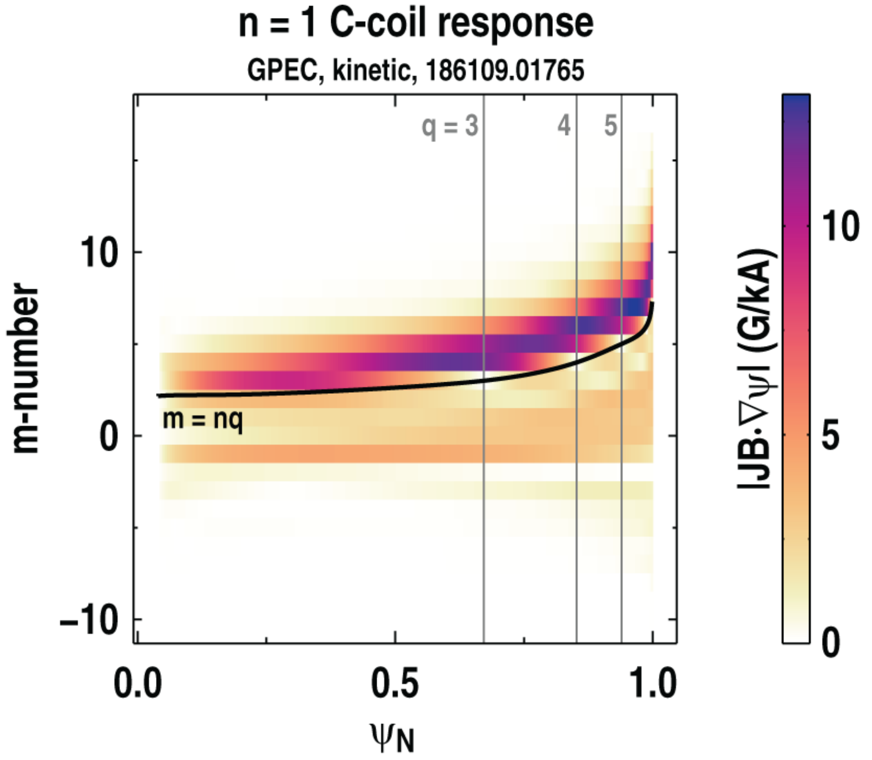
- **SURFMN predicts broad intrinsic error field spectrum**
  - Anti-resonant peak in right-handed plasma

Kink-like plasma response to C-coil field predicted



n = 1 C-coil plasma response

GPEC, kinetic model, 186109.01765



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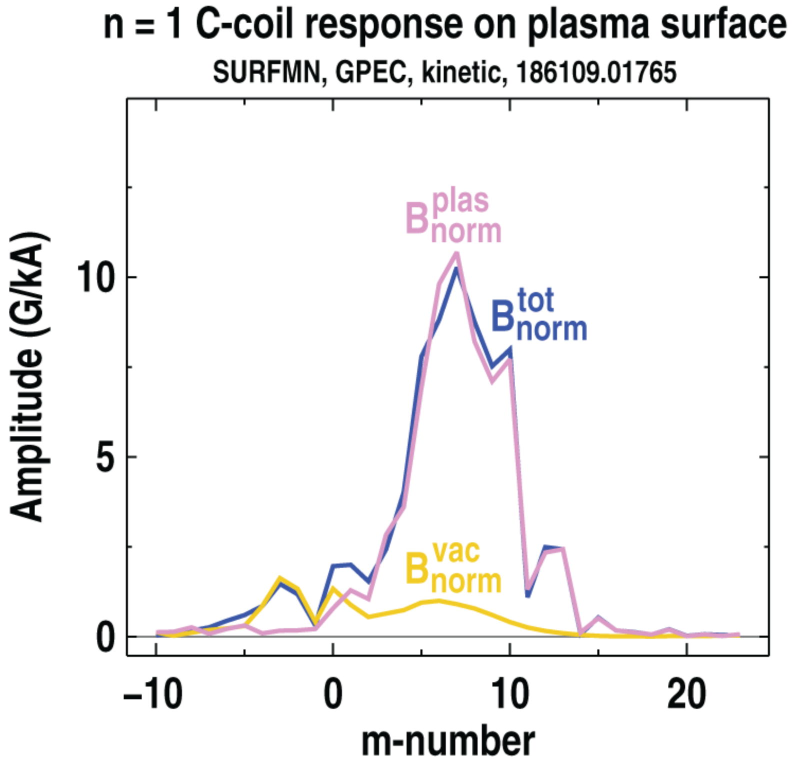
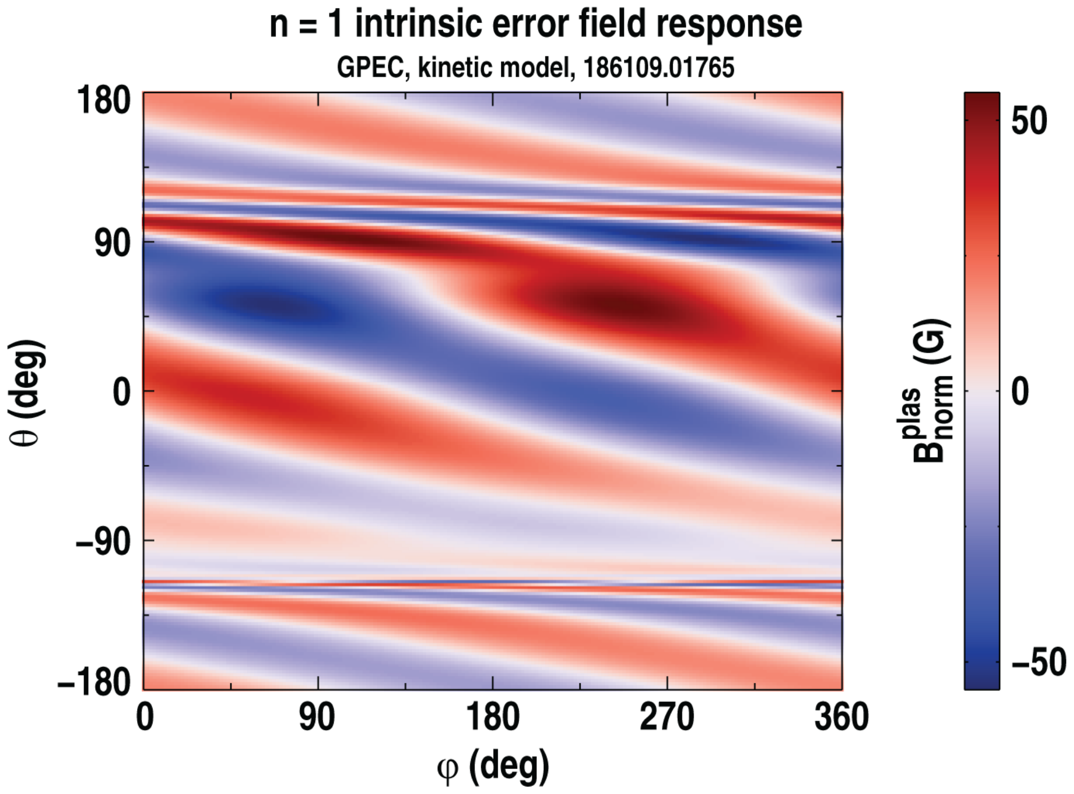


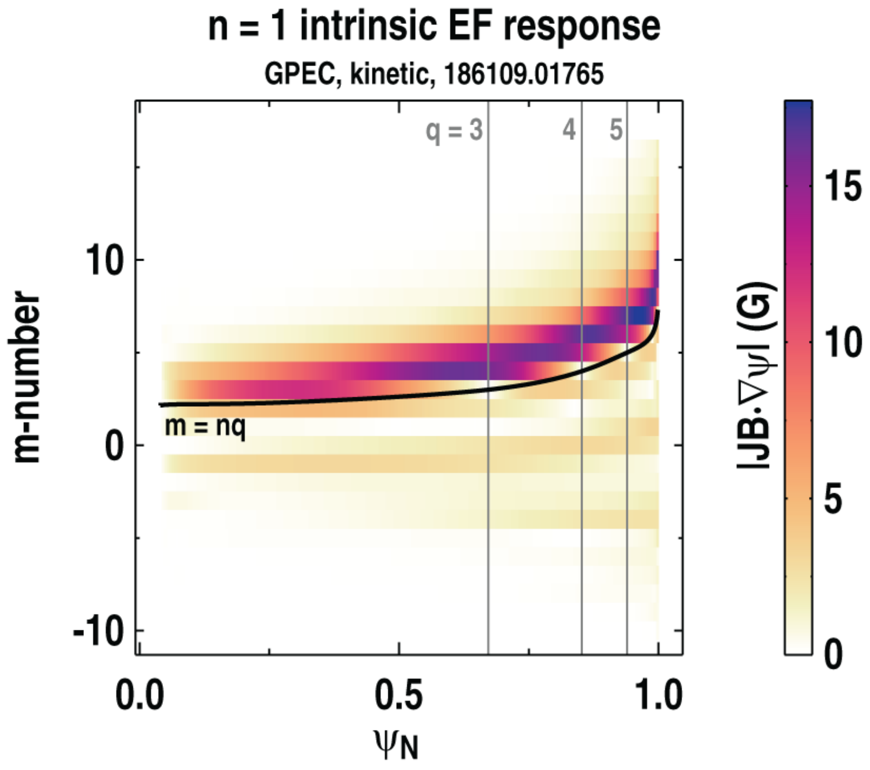
n = 1 C-coil response on plasma surface

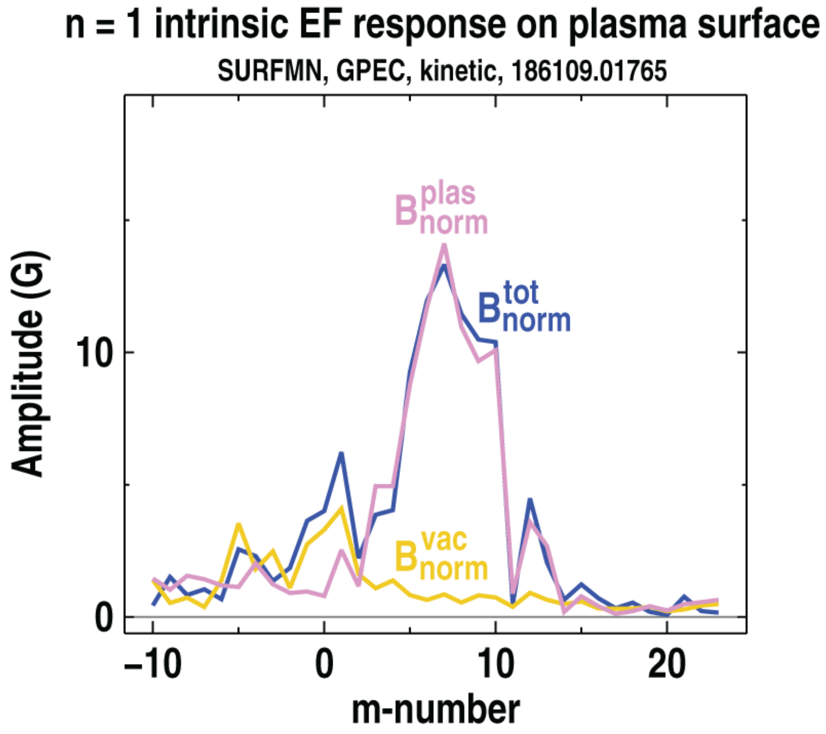
SURFMN, GPEC, kinetic, 186109.01765

- **Plasma response dominates** over vacuum field

Intrinsic error field response prediction is also kink-like

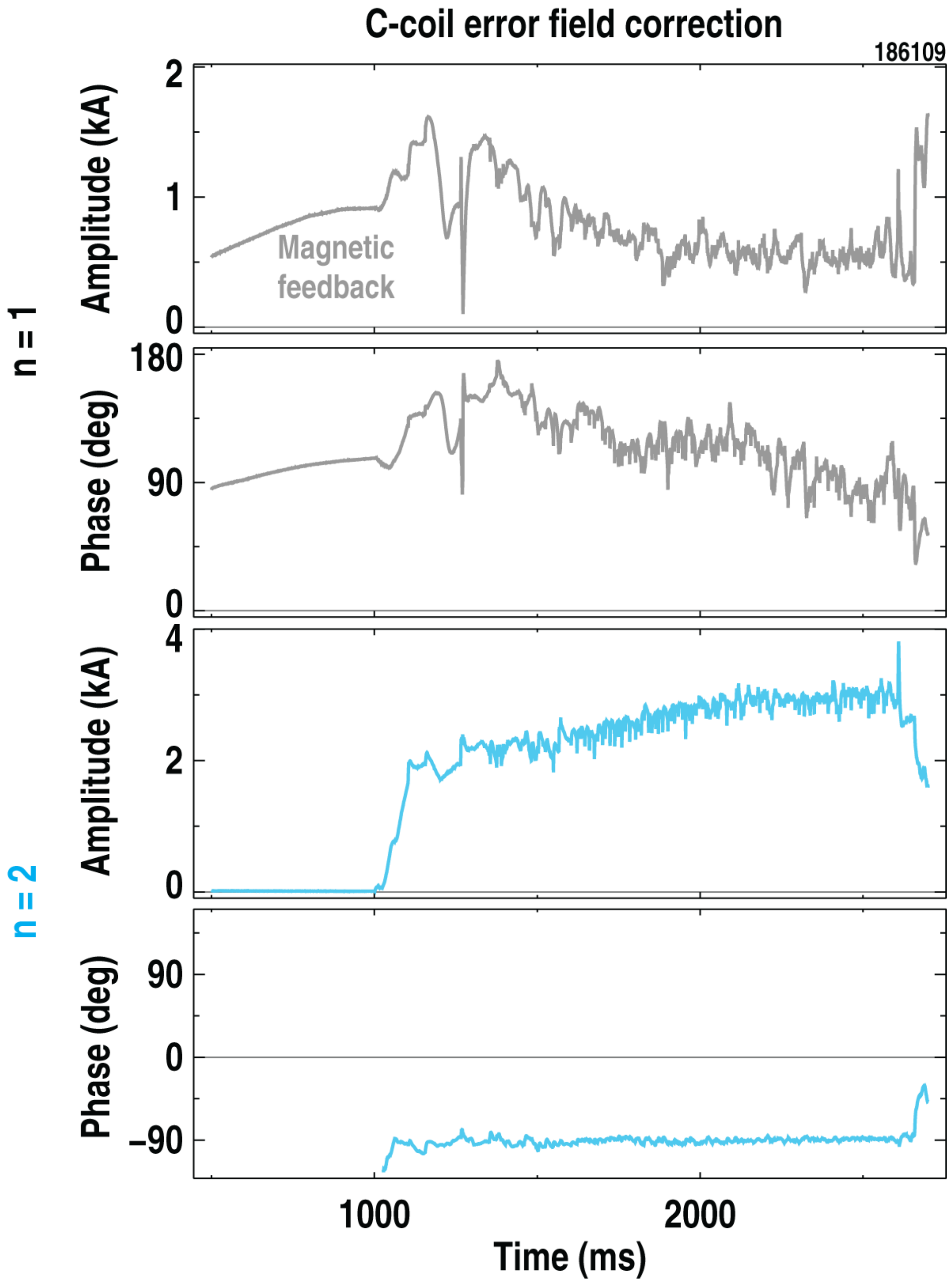






- Coils that couple to the plasma kink mode should be excellent for error field control

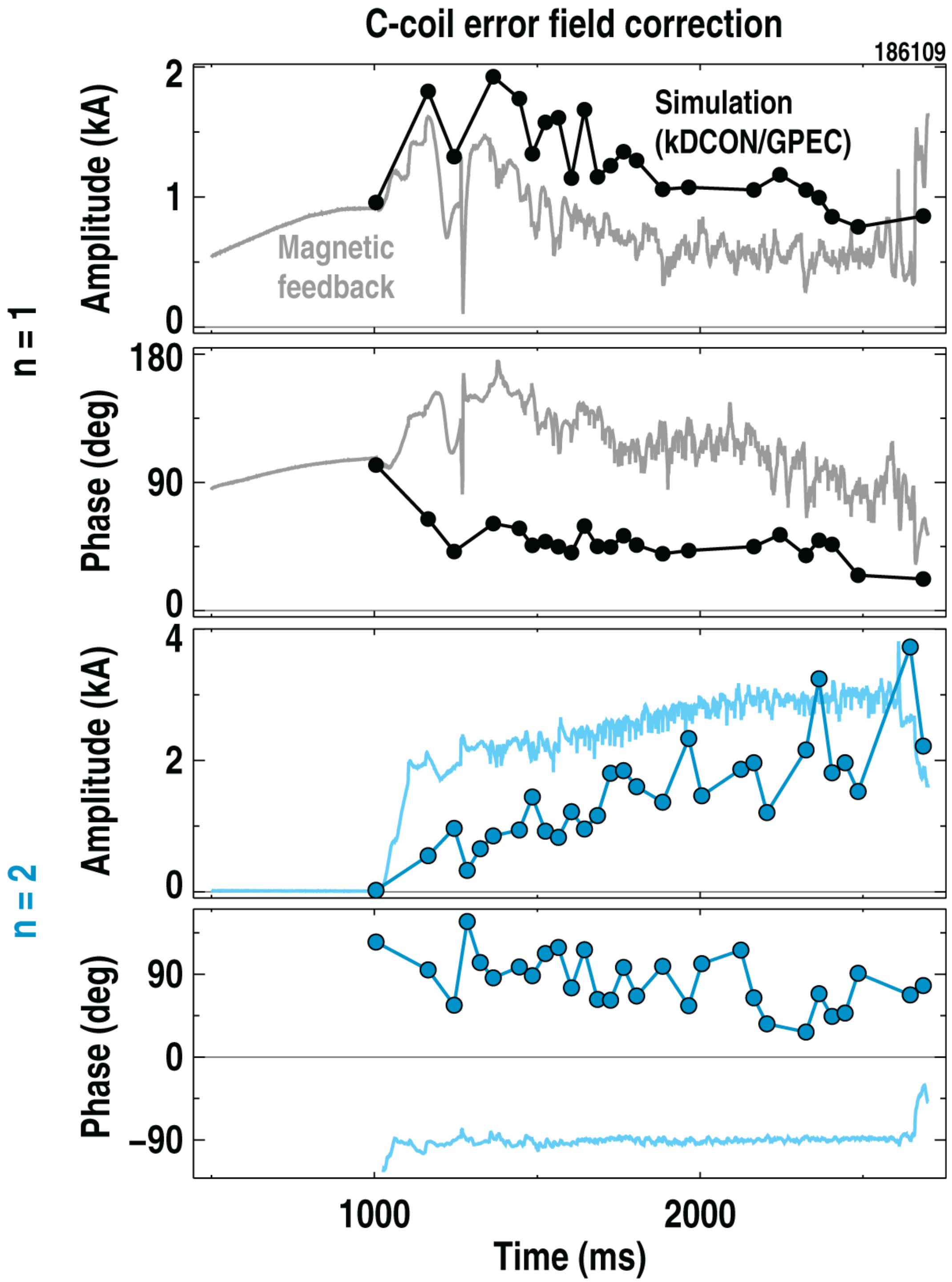
Can simulations predict feedback baseline evolution?



Can simulations predict feedback baseline evolution?

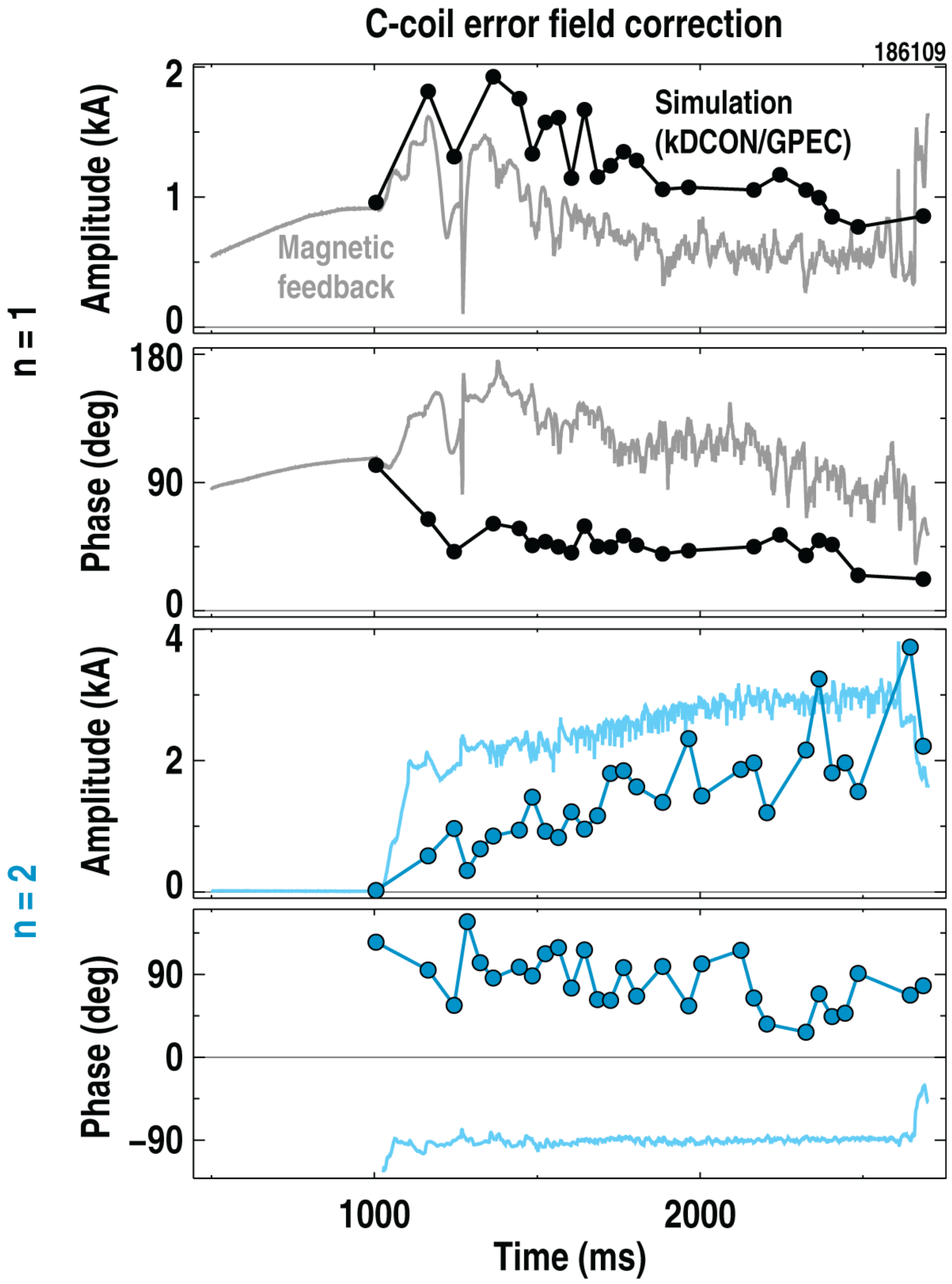
- **Predict n=1 amplitude to within 50%, phase to within 90°**

- **n=2 predictions are more scattered**
  - Large phase disagreement



Can simulations predict feedback baseline evolution?

- **Predict n=1 amplitude to within 50%, phase to within 90°**
- **n=2 predictions are more scattered**
  - Large phase disagreement
- **Several possible explanations for discrepancies**
  - Sub-optimal feedback? *shot did exhibit rotation braking and instability*
  - EF source model inaccuracies?
  - Plasma response calculation? *180 phase shift would be surprising*



Conclusions

- **Kink mode response is a key observable for validating simulations and lever for plasma control**
  - Easily driven with applied 3D fields

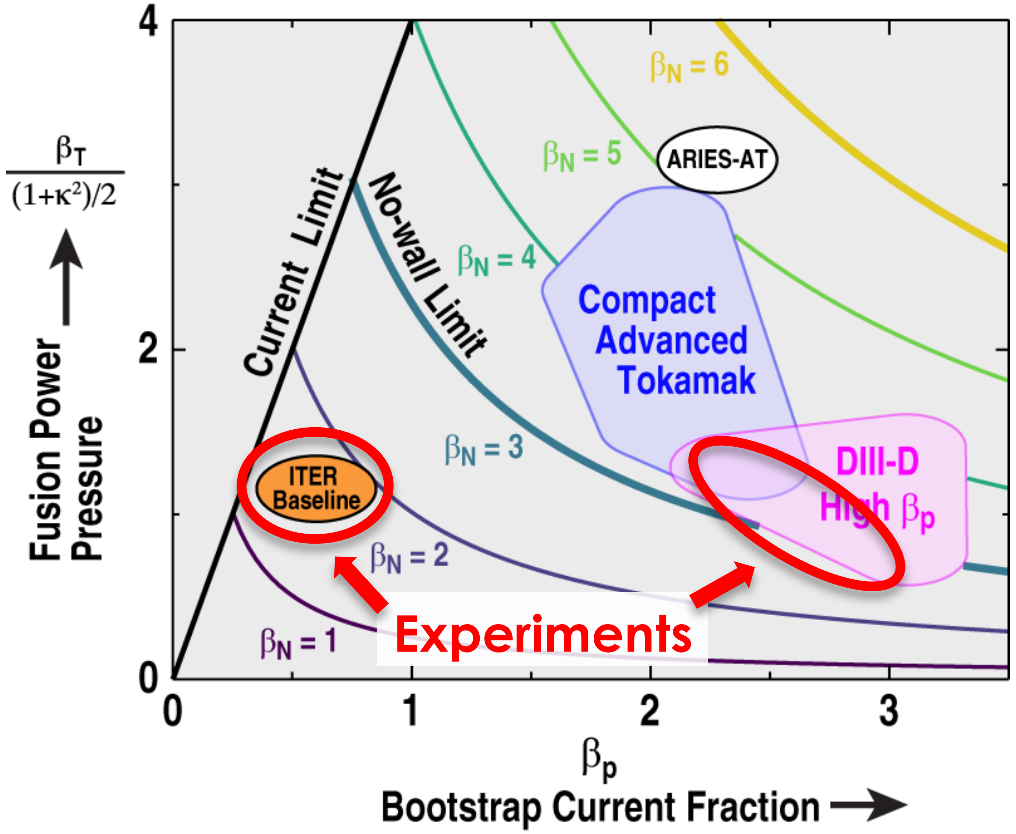
- **Resistive response linked to mode locking in low-torque regime**
  - Measurements consistent with resistive MHD simulations
  - Simulations show weakening shielding at rational surfaces as rotation slows

- **New simulations facilitate error field correction predictions**
  - Link error field source model with plasma response simulation
  - Validation effort ongoing

Extra slides

DIII-D can explore different operating regimes of interest for fusion

- **High current scenarios have good confinement, but high current drive need**
  - Example: ITER baseline scenario (IBS)[1]
  - Peaked current profile ➜ high no-wall limit
- **Increasing β_p is associated with higher bootstrap and non-inductive fractions**
  - Higher degree of profile self-organization[2]
  - Broad current profile ➜ high with-wall limit[3]
  - Advanced tokamak candidate for compact fusion pilot[4]
- **Stability challenges differ, will show results from different regimes**



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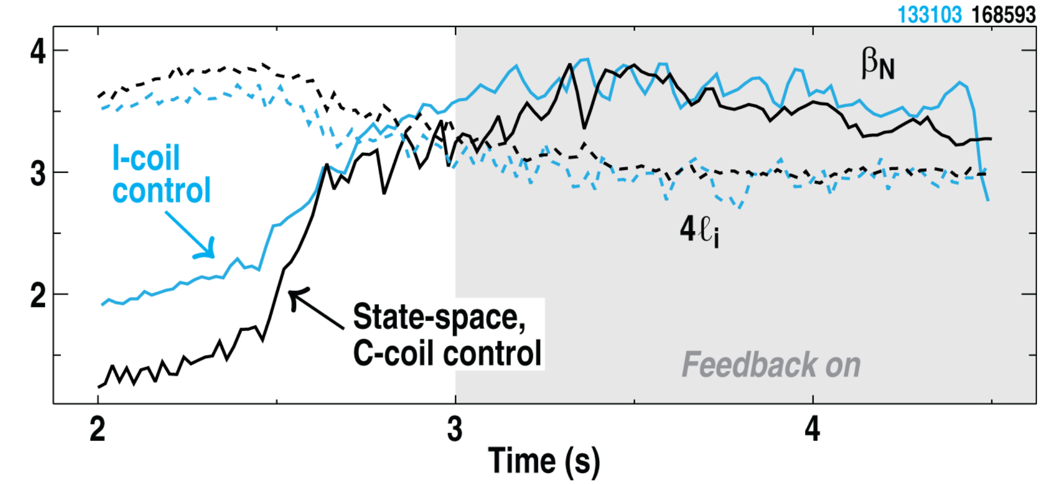
1. EJ Doyle, *et al.*, *Nucl. Fusion* **50** (2010) 075005.
2. PA Politzer, *et al.*, *Nucl. Fusion* **48** (2008) 075001.
3. JM Hanson, *et al.*, *Nucl. Fusion* **57** (2017) 056009.
4. RJ Buttery, *et al. Nucl. Fusion* **61** (2021) 046028.

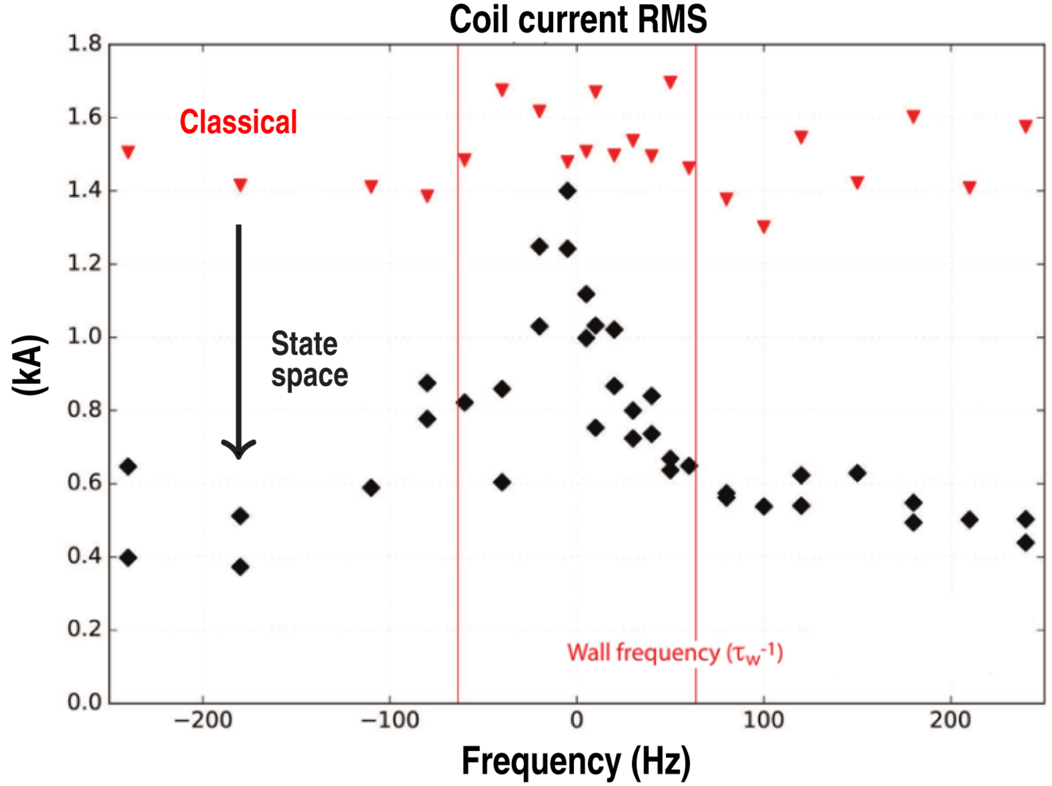
Simulations inform control strategies

- **Evaluated state-space control approach[1]**
  - Incorporating reduced-order VALEN model

- **Accessed $\beta > \beta^{\text{no-wall}}$ using external coils**

- **Led to reduced power requirement**
  - Compared with proportional gain

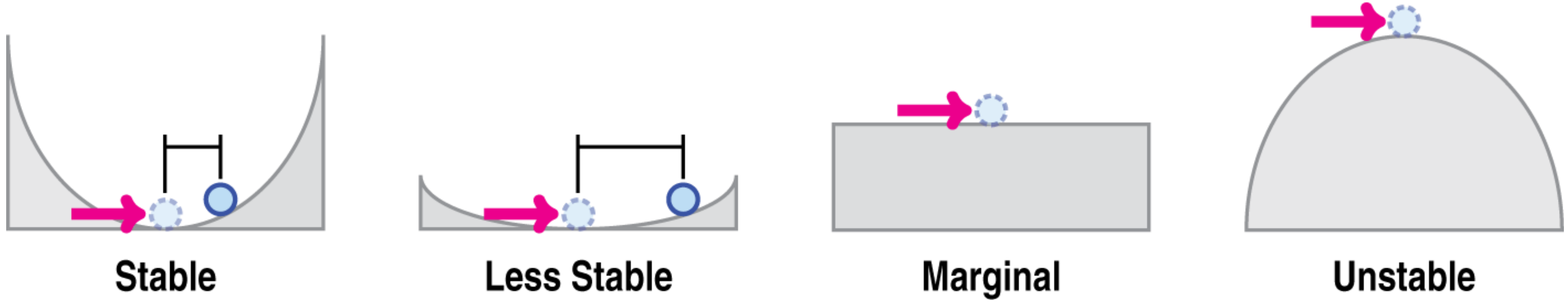




[1] M. Clement, *et al.*, *Nucl. Fusion* **58** (2018) 046017.

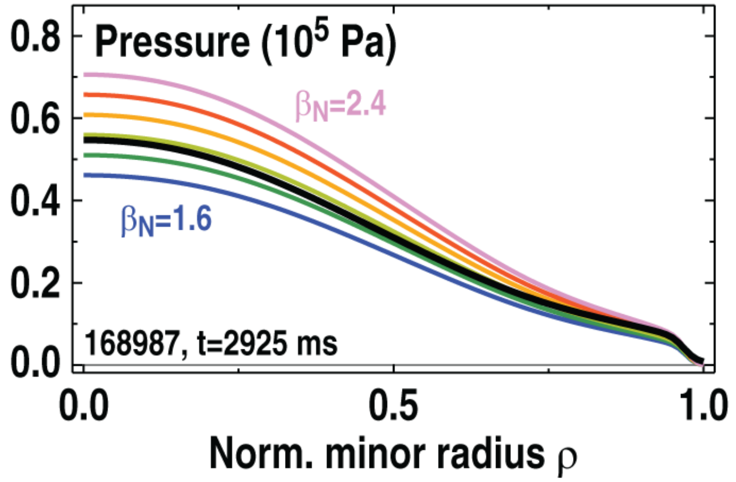
Perturbative experiments can help assess stability

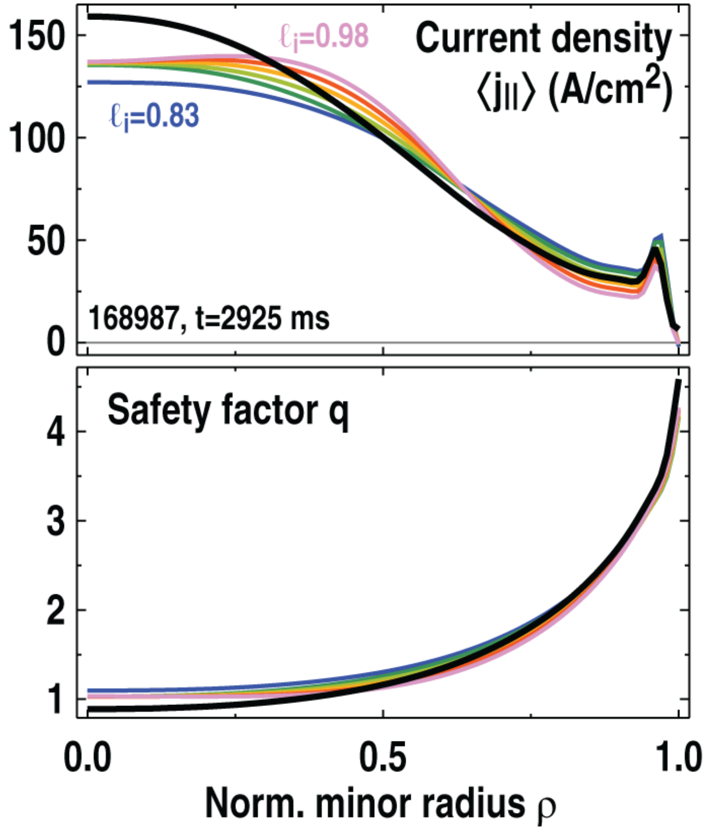
- **Consider a family of mechanical systems**

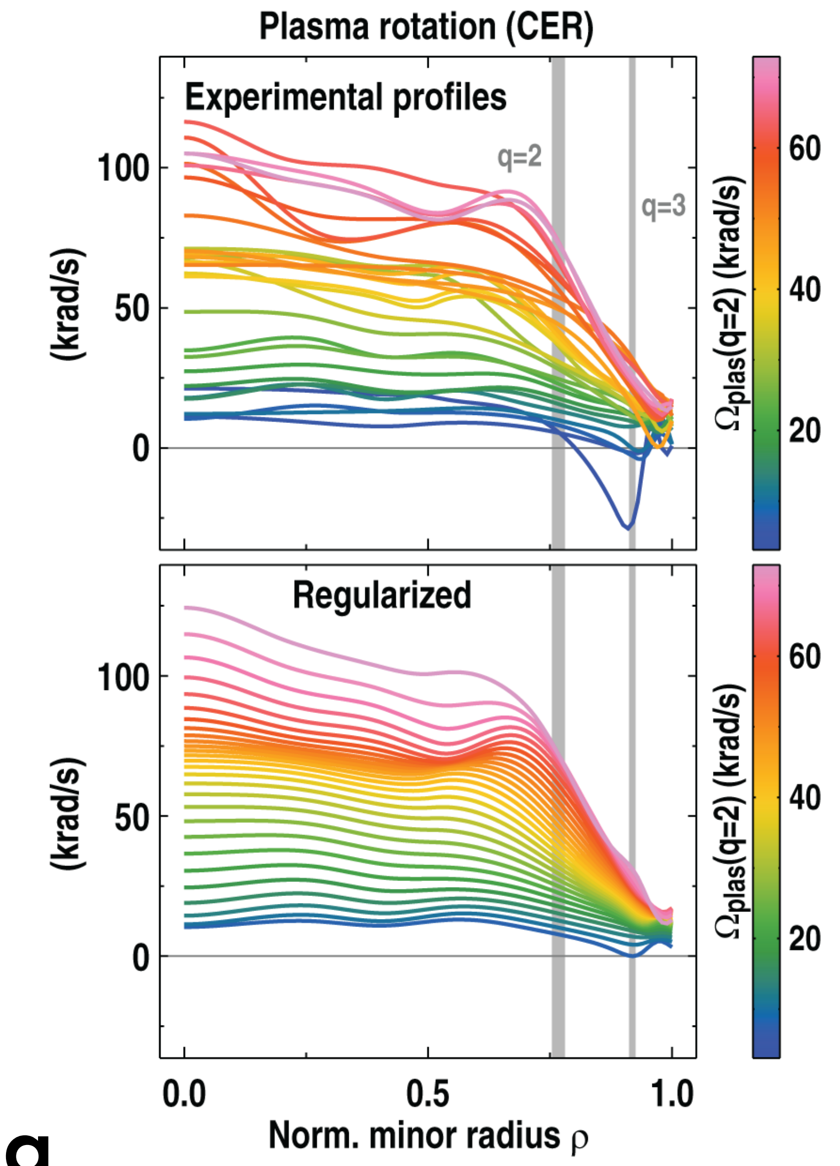


- Apply a ***small perturbation***
- If the system is stable, we can ***measure a finite response***
- ***Response contains information*** about the proximity to marginal

Profile variations allow investigations of β_N, ℓ_i, and rotation dependencies







- **Pressure and current profile variations created by scaling a single equilibrium**
- **Rotation profile variations created by interpolating experimental profiles**