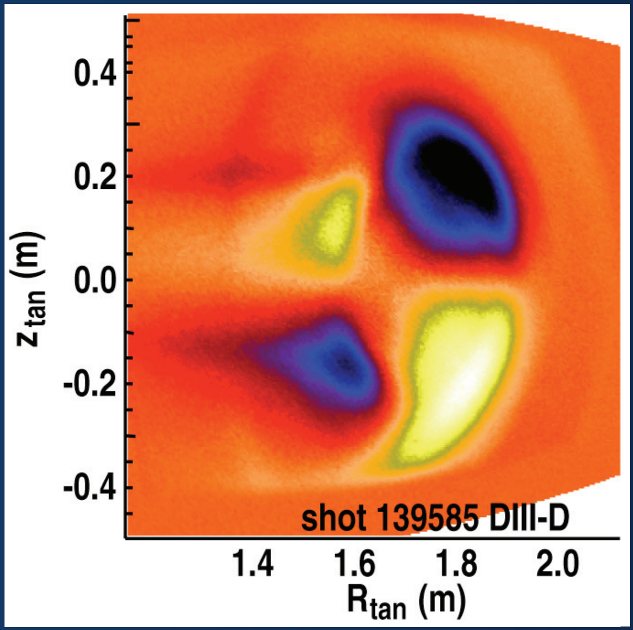
MHD Control Workshop, November 2010

Error Field Thresholds in H Mode Plasmas



by Richard Buttery[1]

with Rob La Haye[1], Yueqiang Liu[2], Bob Pinsker[1], Jong-kyu Park[3], Holger Reimerdes[4], Ted Strait[1], and the DIII-D research team.

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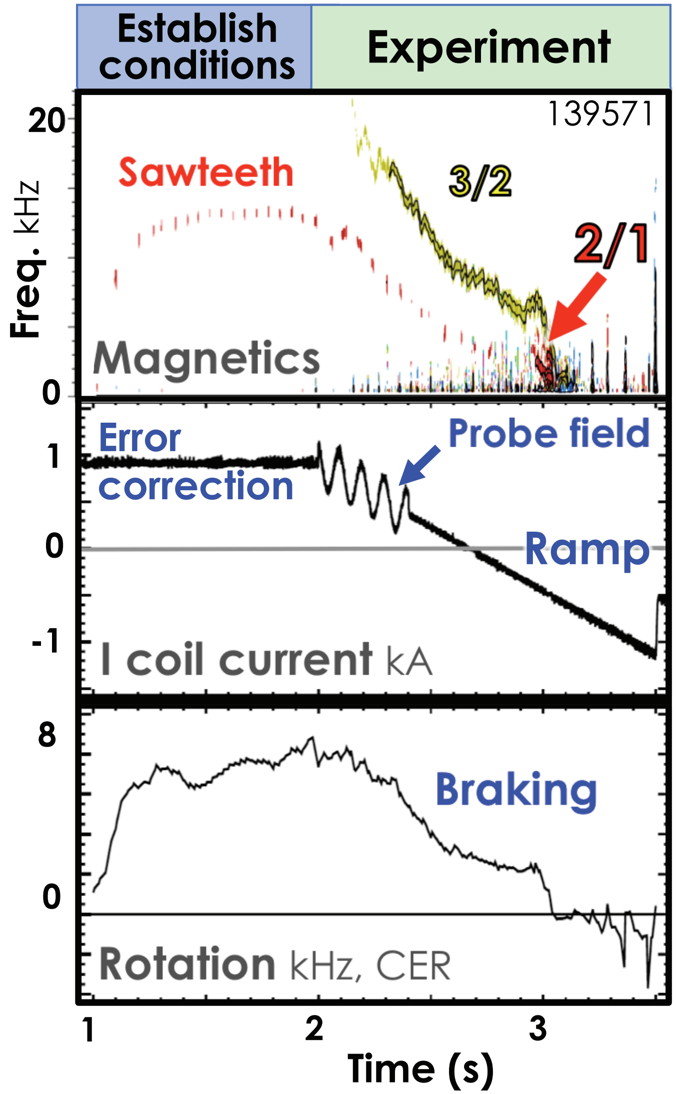
[2]Culham Centre for Fusion Energy, UK
[3]Princeton Plasma Physics Laboratory, NJ.
[4]Columbia University, NY / CRPP Lausanne, Switzerland.

Work funded by the US DOE.

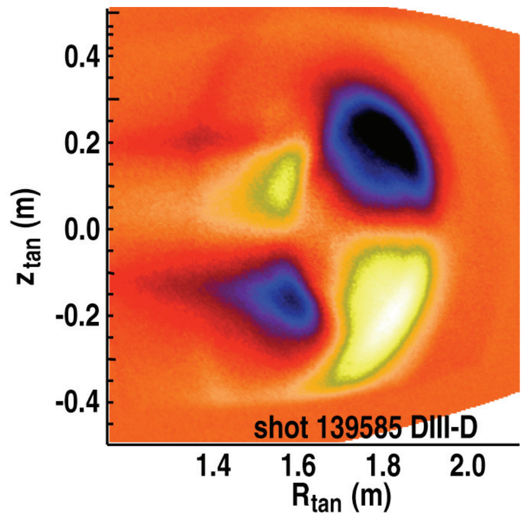
DIII-D NATIONAL FUSION FACILITY

GENERAL ATOMICS

Low Torque H Modes are Susceptible to Error Fields



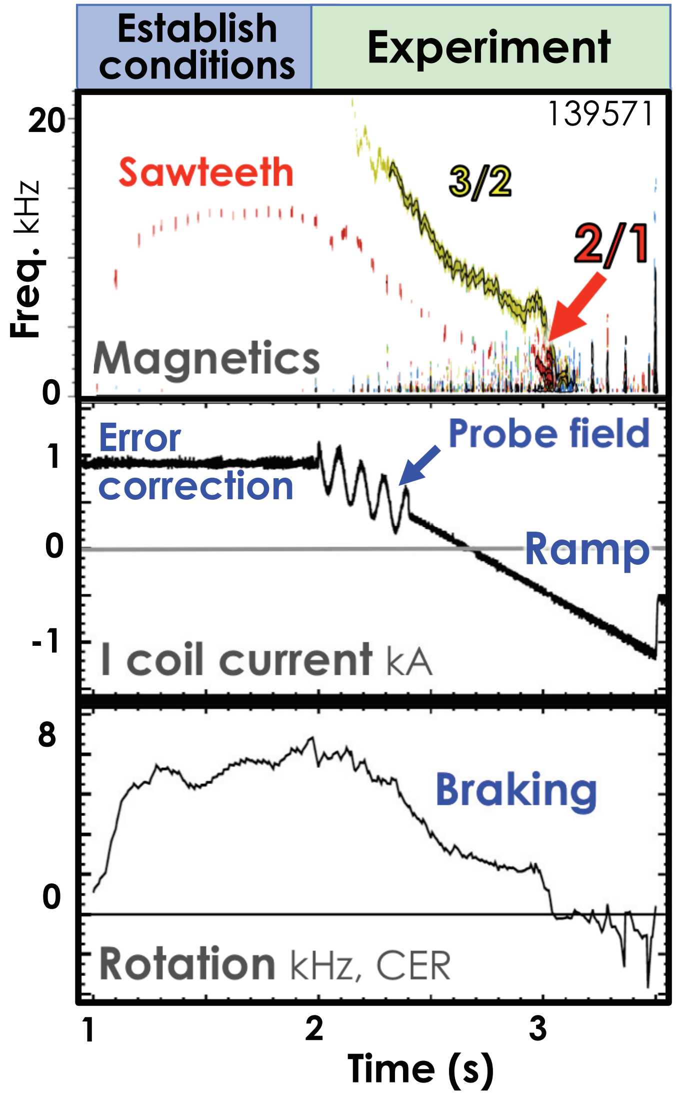
- Applying a *static* error field destabilizes a *rotating* 2/1 tearing mode:



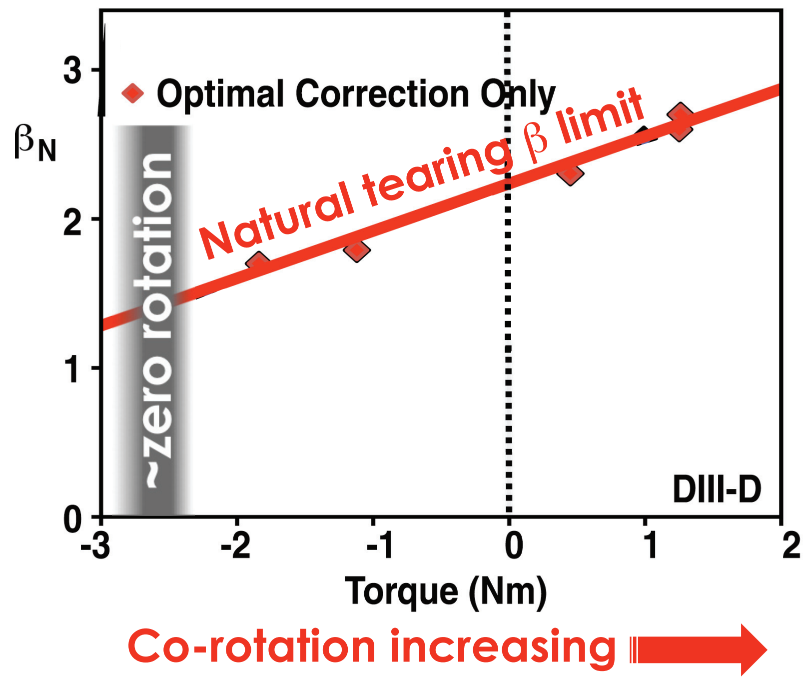
1.8kHz Fourier decomposed fast visible imaging

Feedback control of NBI torque and β_N

Low Torque H Modes are Susceptible to Error Fields



- Applying a *static* error field destabilizes a *rotating* 2/1 tearing mode:
  - Tearing β_N limit falls with rotation:



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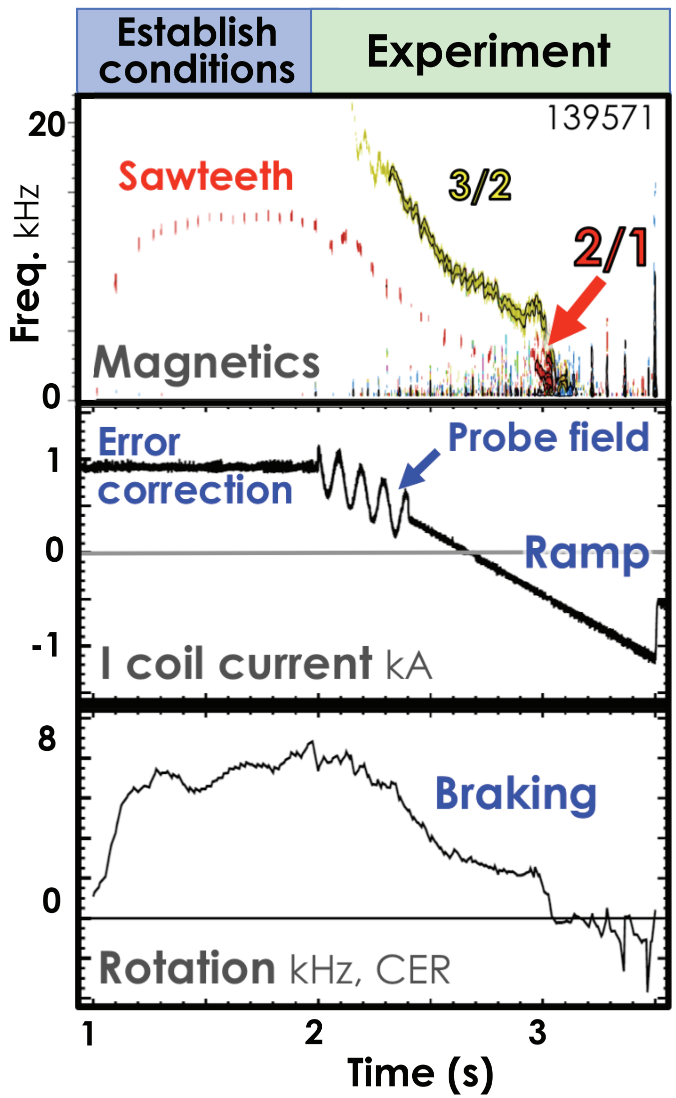
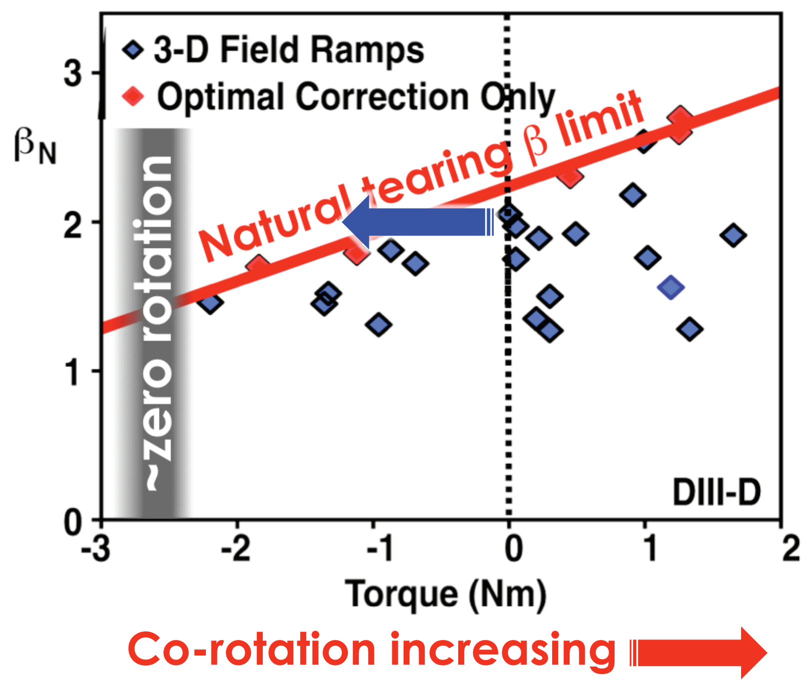
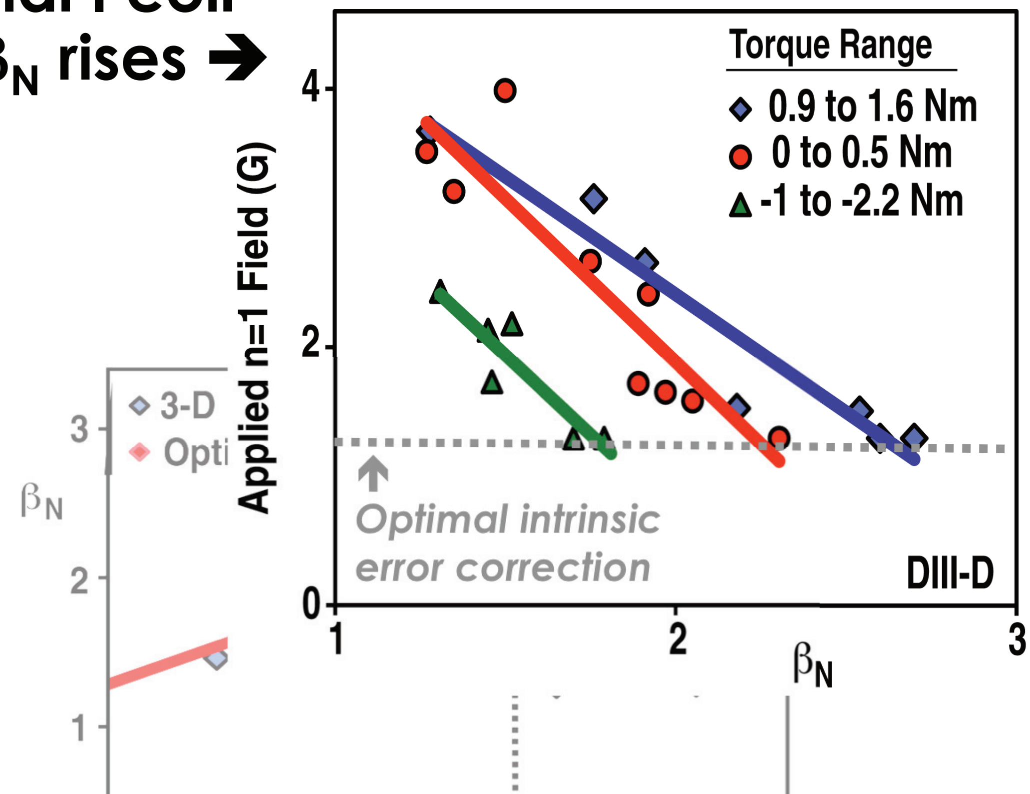


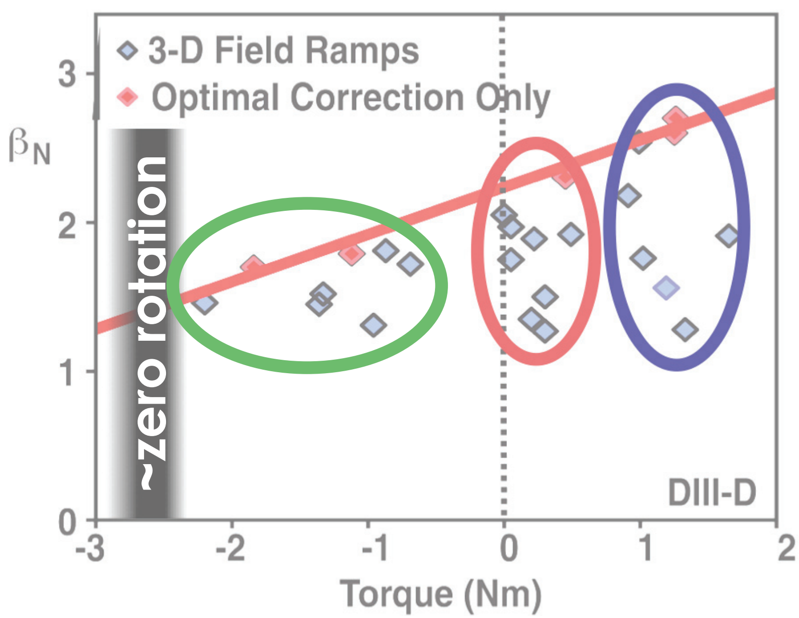
- Applying a *static* error field destabilizes a *rotating* 2/1 tearing mode:
  - Tearing β_N limit falls with rotation
  - Error field brakes plasma, accessing instability → mode grows & locks



Error Field Thresholds Exhibit β <u>and</u> Torque Dependence

- **Field thresholds reach optimal I coil correction level of 1.3G as β_N rises ➔**
- **Torque dependence**

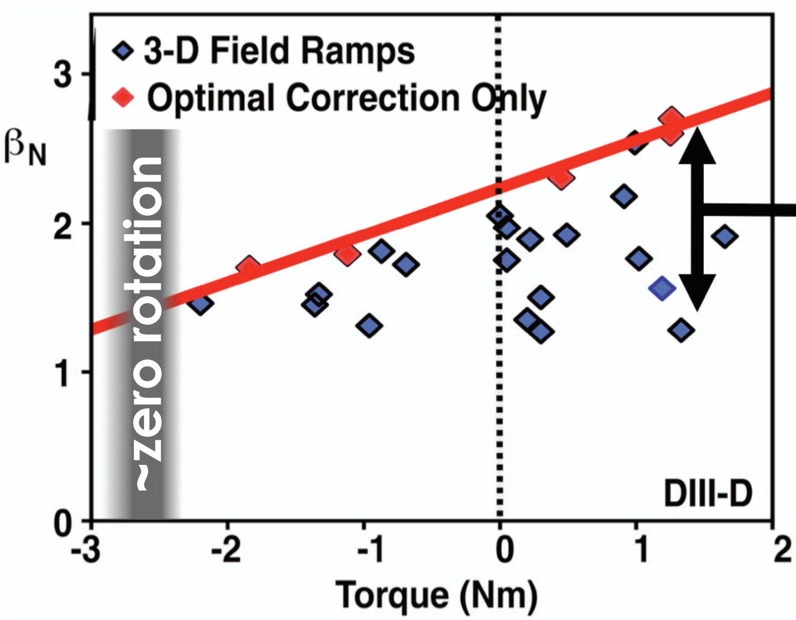


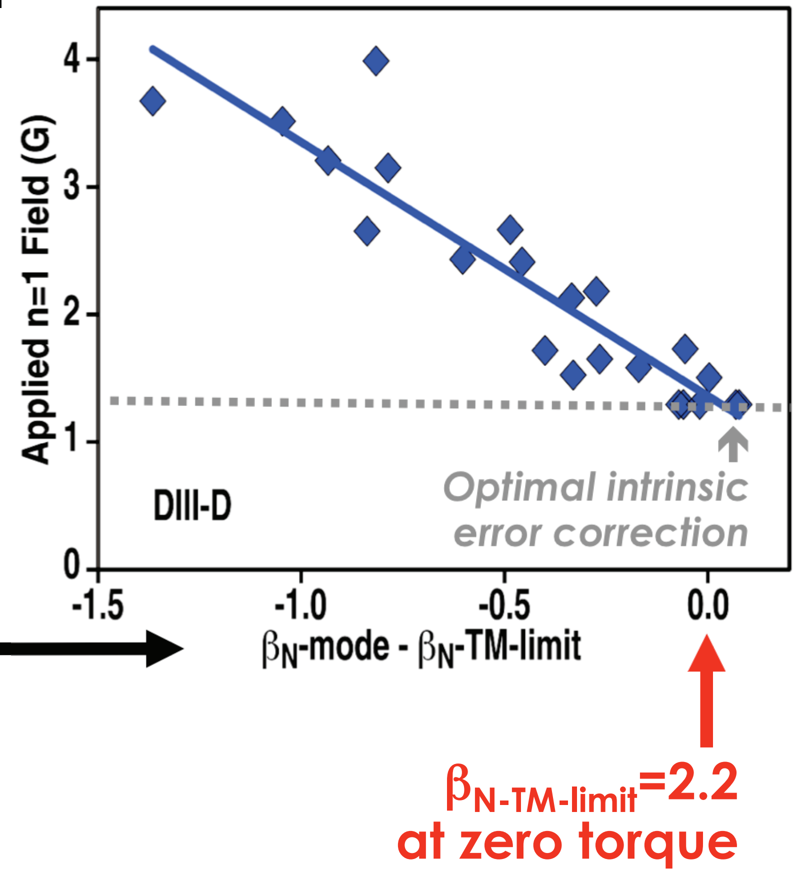


Measure field as 2/1 resonant boundary field including ideal response via overlap integral with IPEC dominant mode

Error Field Thresholds Exhibit β <u>and</u> Torque Dependence

- **Field thresholds reach optimal I coil correction level of 1.3G as β_N rises**
- **Torque dependence**
  - ***Explained by proximity to → natural tearing β limit:***
  - $\beta_{N\text{-}TM\text{-}limit} = 2.2 + 0.32T_{NBI}$



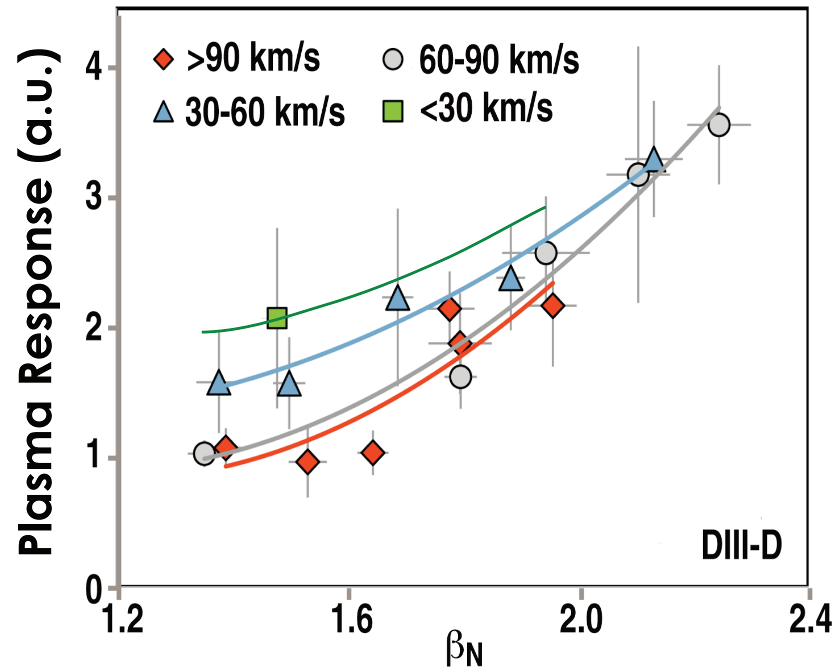


What is the nature of the plasma response?

Magnetic Probing Data & Modeling Suggest Both Ideal and Resistive Responses Occurring

- β_N dependence → ideal response

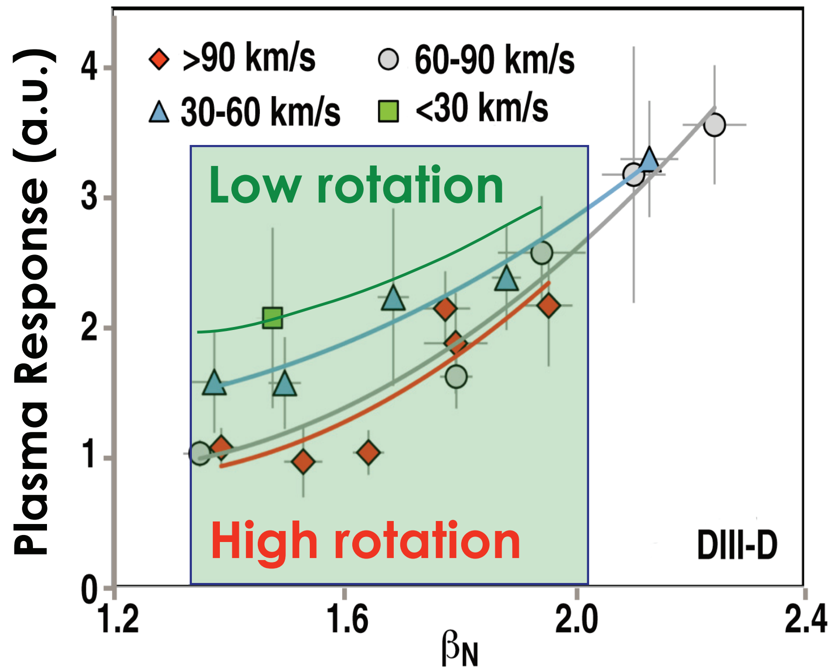
Response to 10 Hz probing field



Magnetic Probing Data & Modeling Suggest Both Ideal <u>and Resistive</u> Responses Occurring

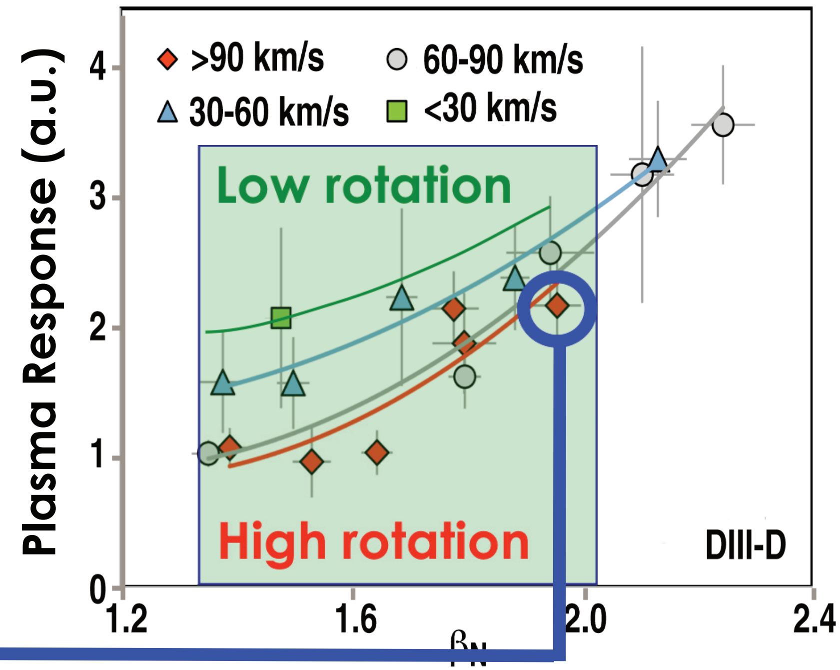
- β_N dependence → ideal response
- **Rotation dependence → resistive?**
  - Break down of screening response?

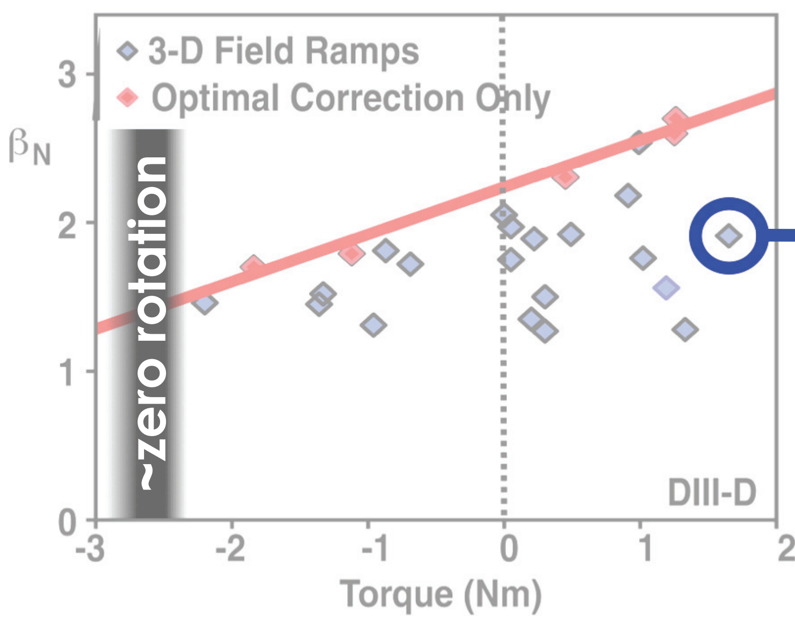
Response to 10 Hz probing field



Magnetic Probing Data & Modeling Suggest Both Ideal and Resistive Responses Occurring

- β_N dependence → ideal response
- **Rotation dependence → resistive?**
  - Break down of screening response?
  - ***Explore with MARS-F modeling…***



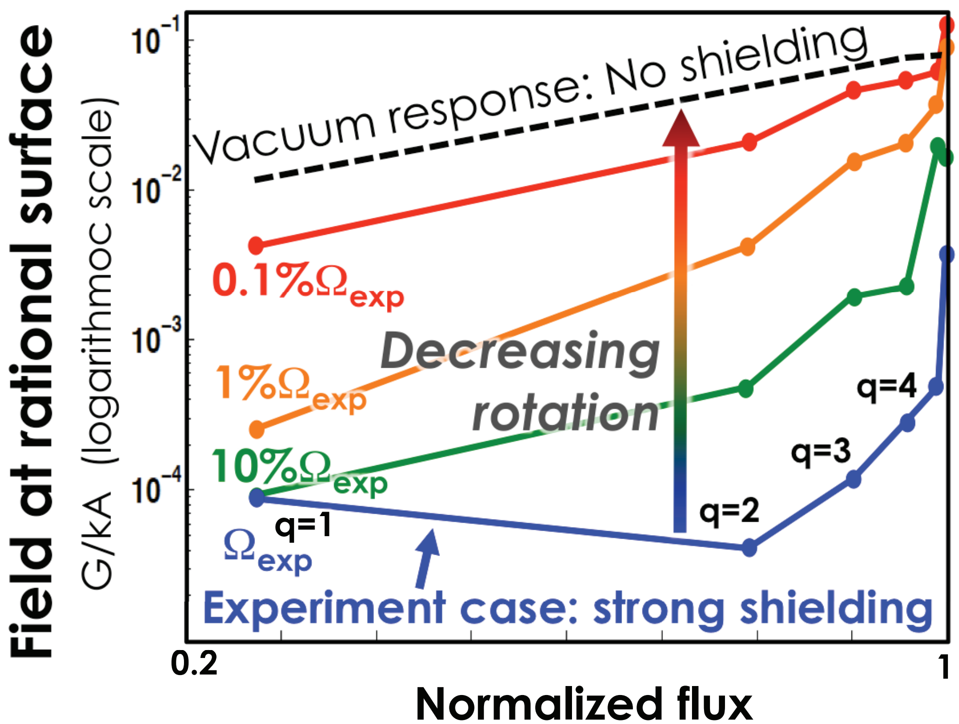


Linear calculation with resistivity

Many thanks to Y Liu

Magnetic Probing Data & Modeling Suggest Both Ideal and Resistive Responses Occurring

- β_N dependence → ideal response
- Rotation dependence → resistive?
  - Break down of screening response?
  - *Found to be an effect in MARS-F:*



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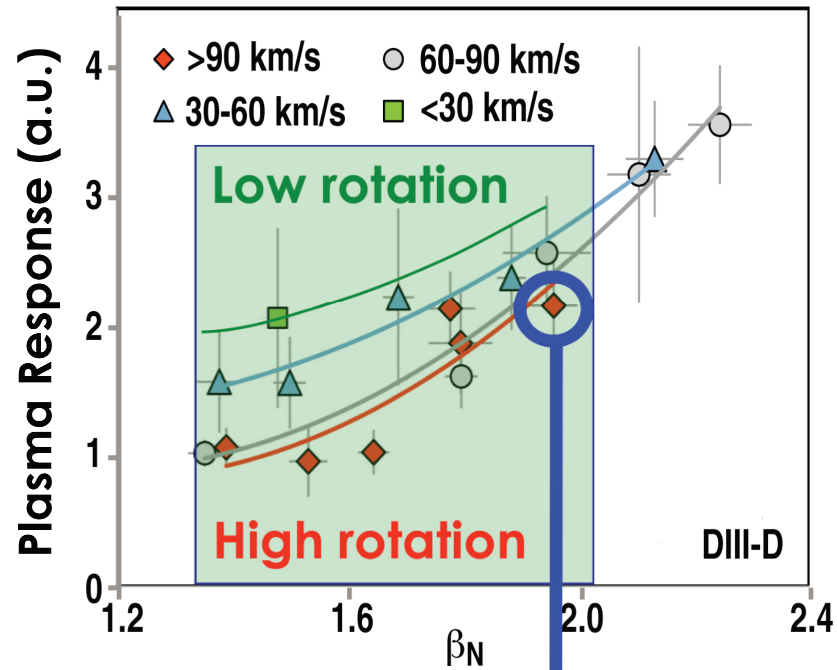

Linear calculation with resistivity

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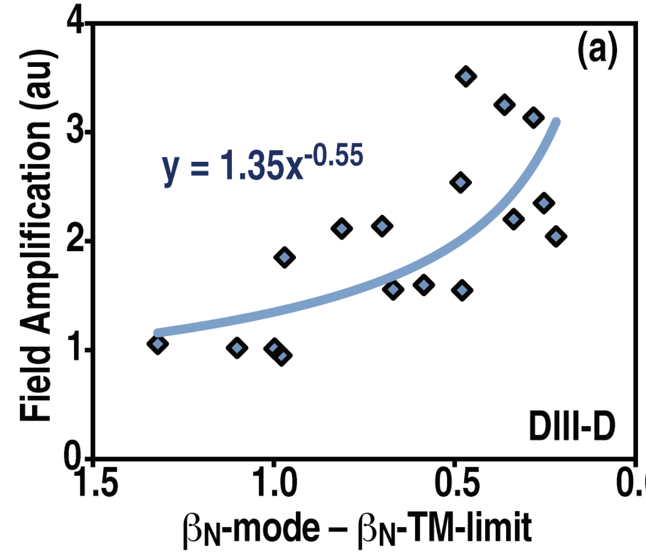
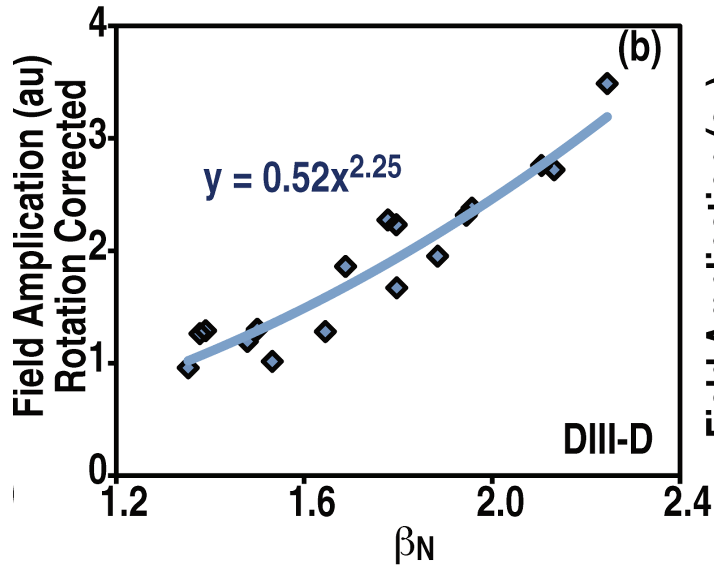
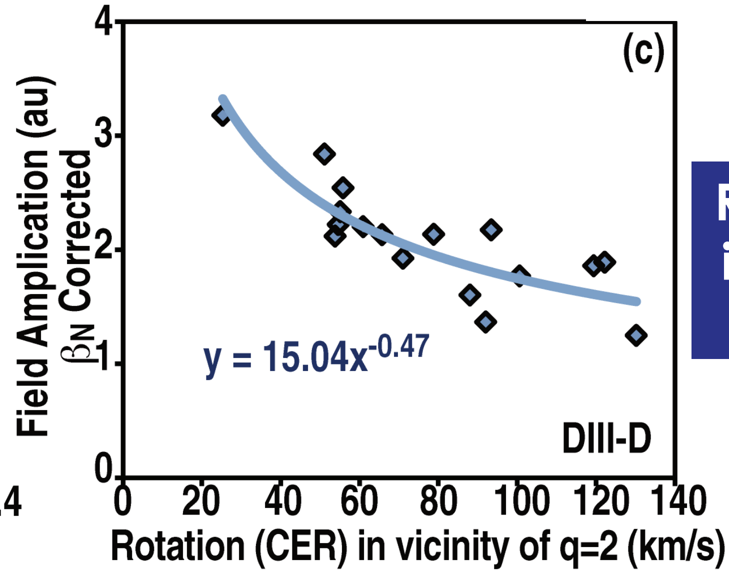
Fitting Confirms "Two Knobs" Needed to Explain Plasma Response – *not simply ideal or resistive*



- Simple 1-D fit of response to tearing ➔ limit proximity does not do good job
- 2-D fit shows β and rotation response needed





Rotation dependence identified – indicative of resistive response

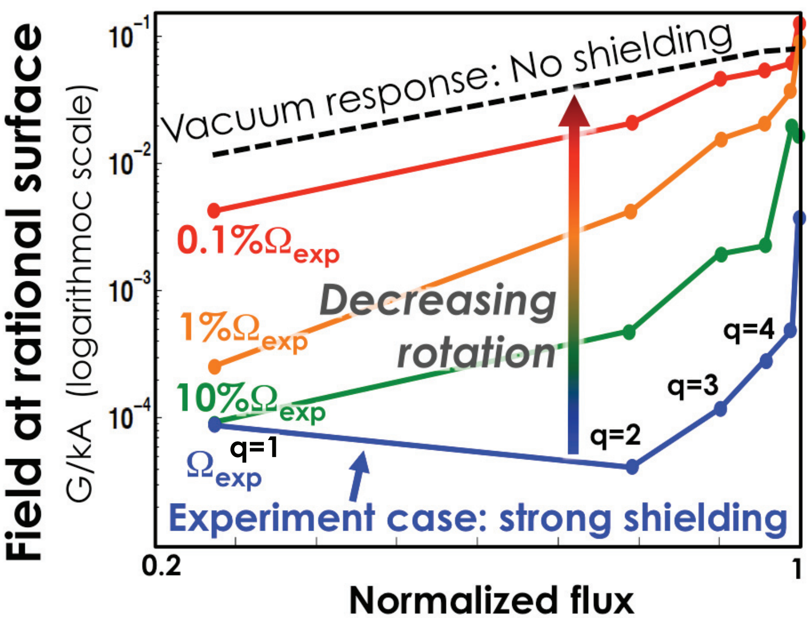
Understanding the plasma response…

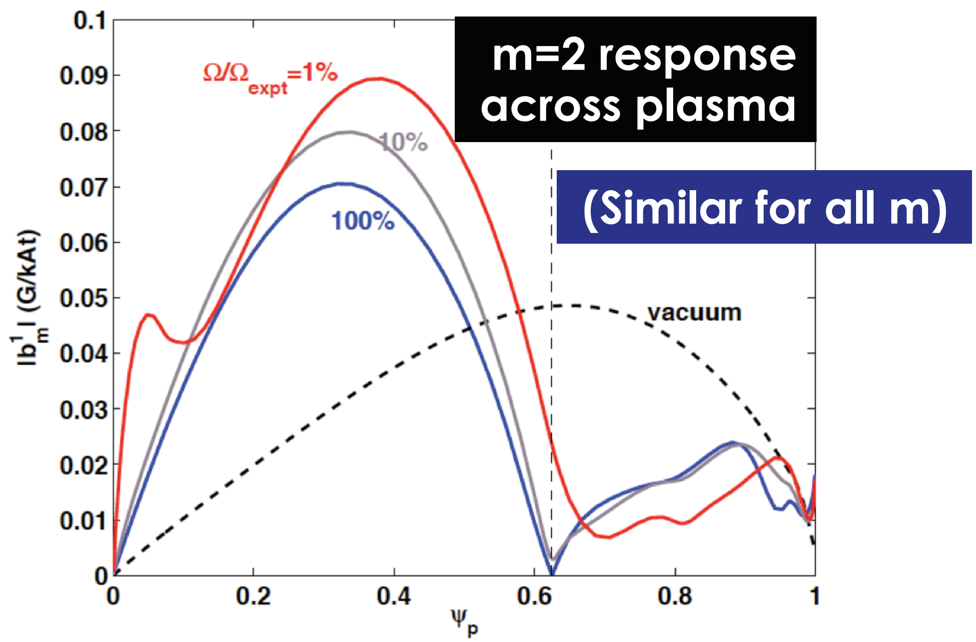
– MARS-F modeling:

- ***Is this about proximity to tearing β limit at low rotation?***

MARS-F Shows Local q=2 Response with Rotation but Global Response is Weak

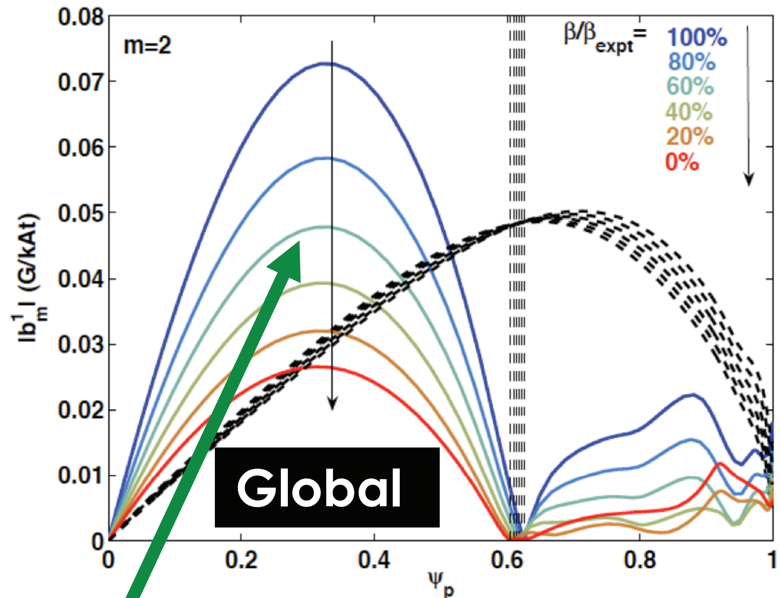
- **Magnetic probing results would require larger response across plasma to give observed x2 at sensor**
    - *Is this just an artifact of linear nature of calculation?*
  - Non-linearly: breakdown of shielding will raise torque, change phase of response, and give more amplification
    - *Note all MARS modeling linear in next few slides…*

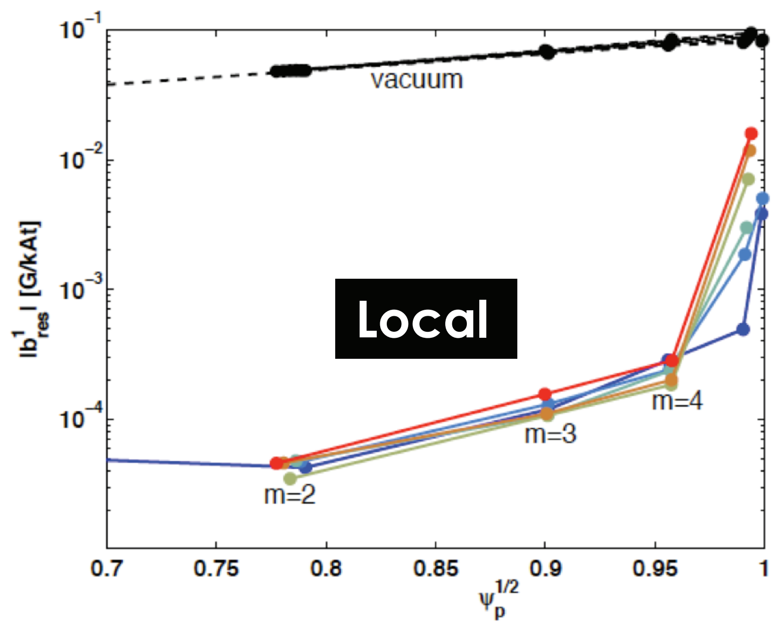




Beta Dependence in Response is the Expected Linearity in the High Rotation Base Case…

- **Global response just scales with β**
- **Local residual field remains tiny**
  - Strong shielding maintained at the high rotation of these points



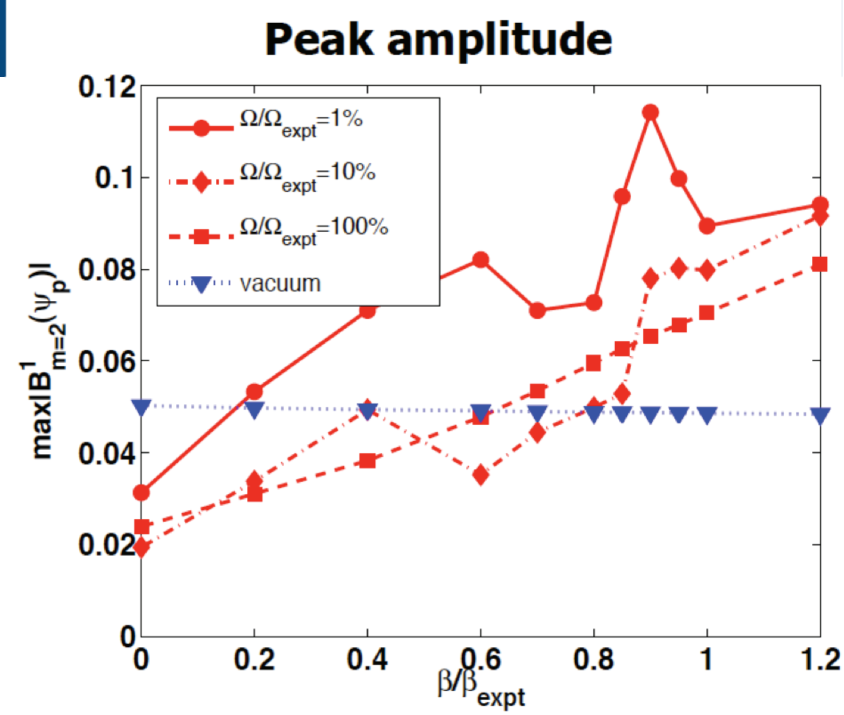


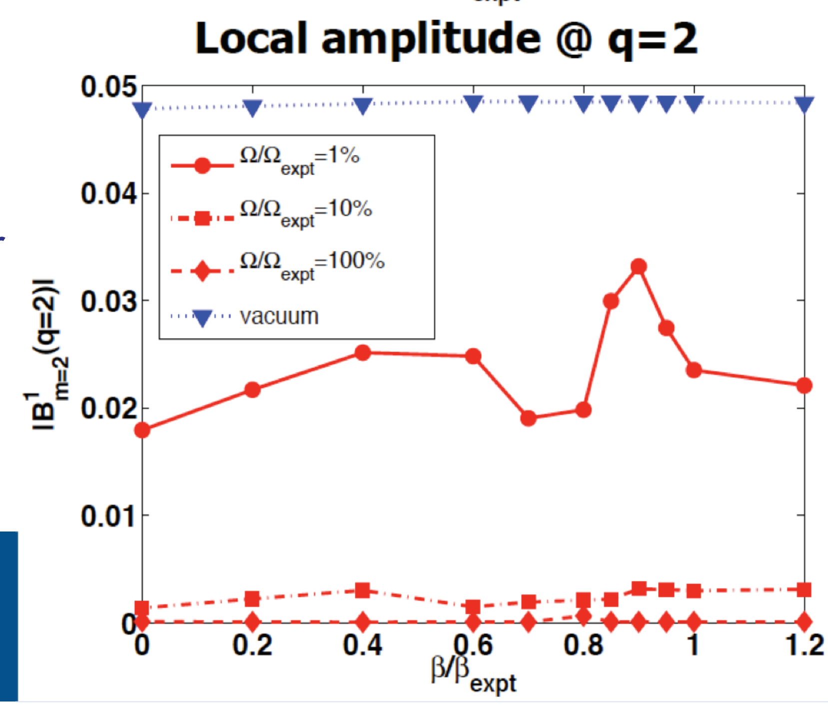
Note peak values – used next slide

But β Resonances Observed Close to Tearing β Limit if Rotation Dropped

- **Peak of response across plasma:**
  - Linear at high rotation (- - -)
  - Peaks near tearing β limit at low rotation (——)

- **Local q=2 response behaves similarly**
  - Proximity to tearing β limit changes plasma response due to partial breakdown of screening at low Ω
  - But global response hints at broader resonance close to tearing limit





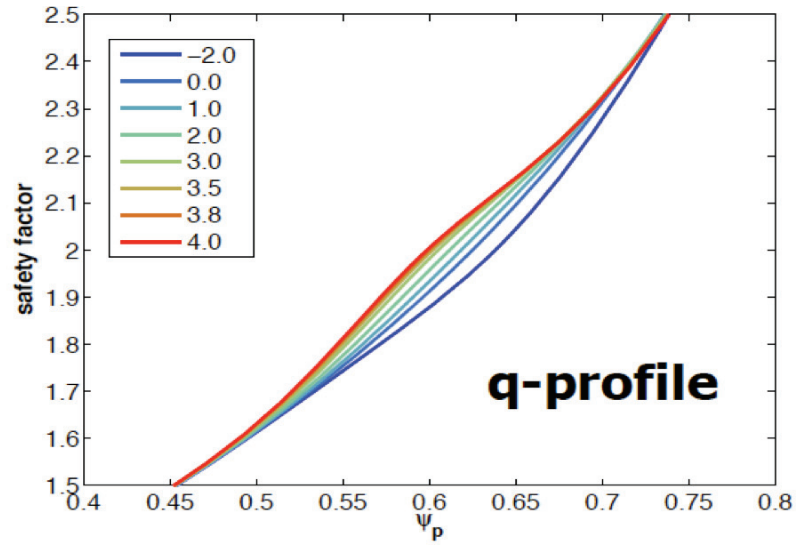
Is Delta-Prime Important?

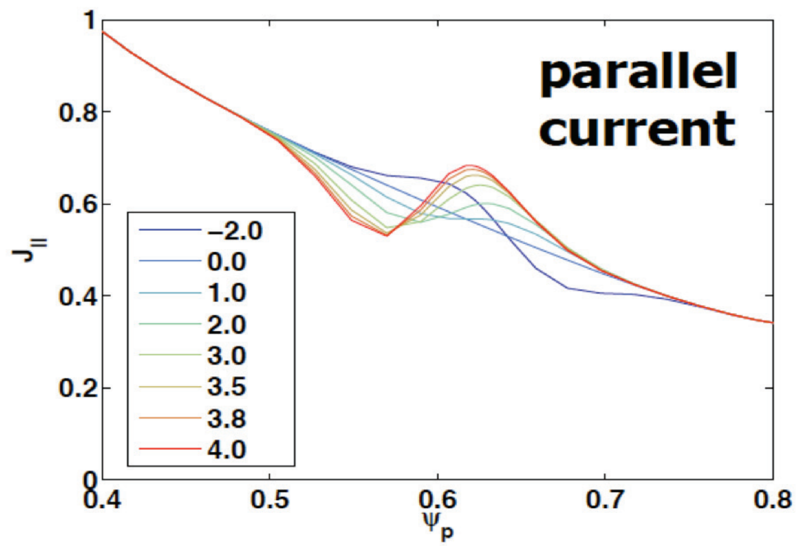
Test with current profile changes:

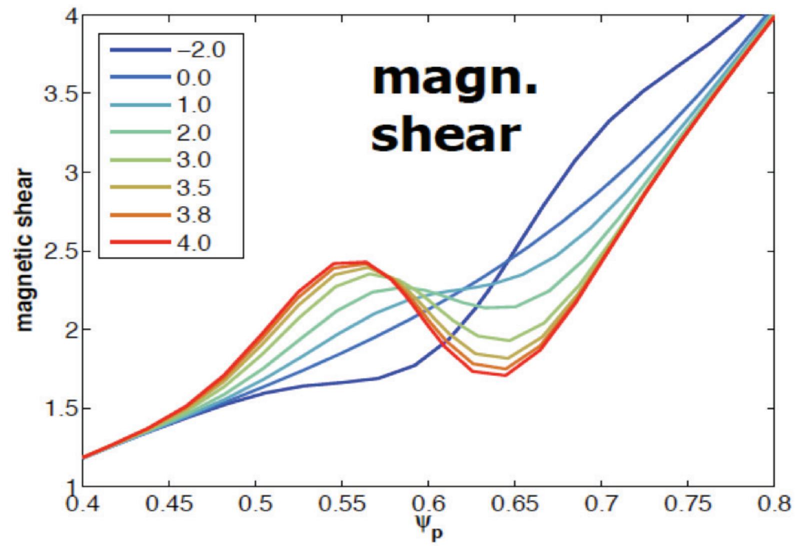
$$J_{\|}^{new} = J_{\|} - aJ_{\|q=2}^{'}(x - x_{q=2})\exp\left[-\left(\frac{x - x_{q=2}}{b}\right)^2\right]$$

$$x = \sqrt{\psi_p}$$

Fix b=0.05, varying a ➔
local variation of current density shear

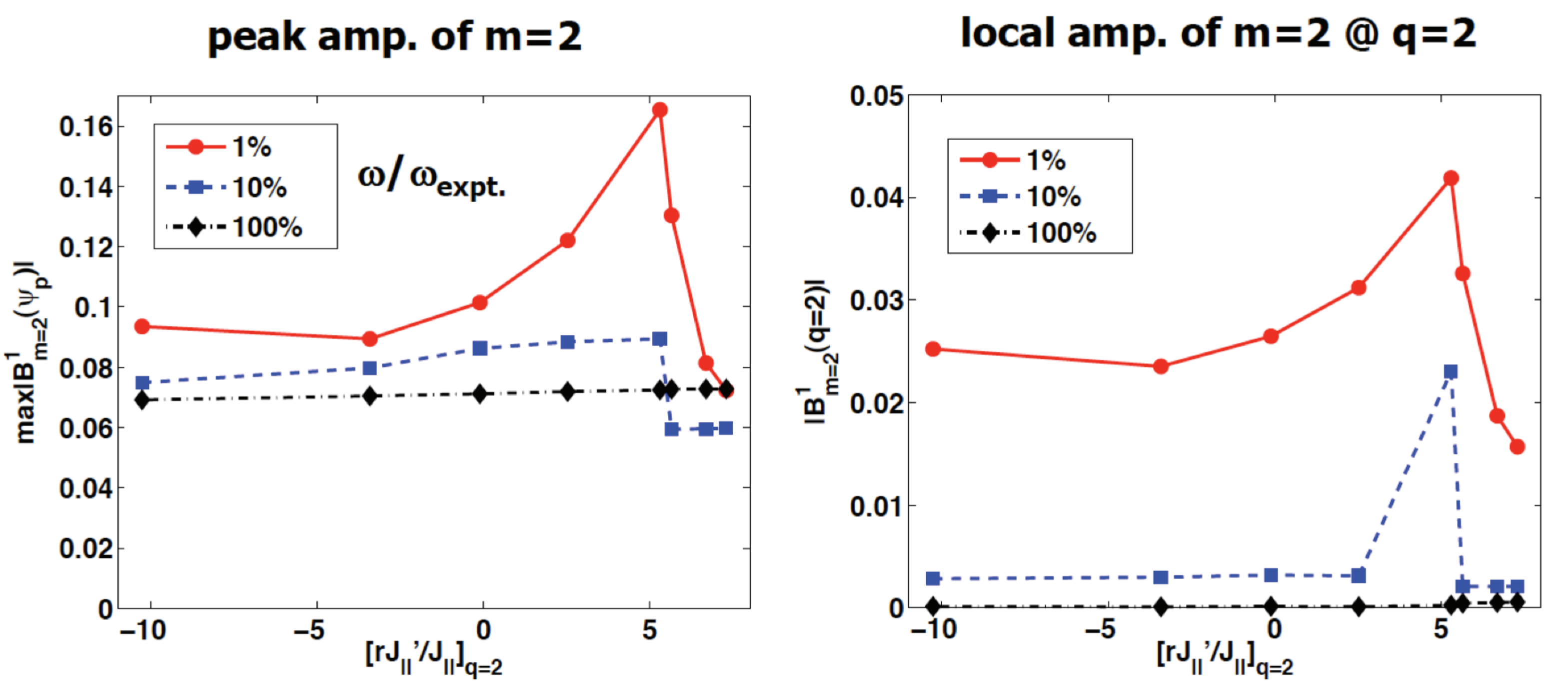






Plasma Response to Current Profile Change

- **High rotation once again insensitive to changes**
- **But low rotation opens the door to plasma response as screening breaks down**
  - As expected [Fitzpatrick] current profile & rotation matter in the tearing resistive response



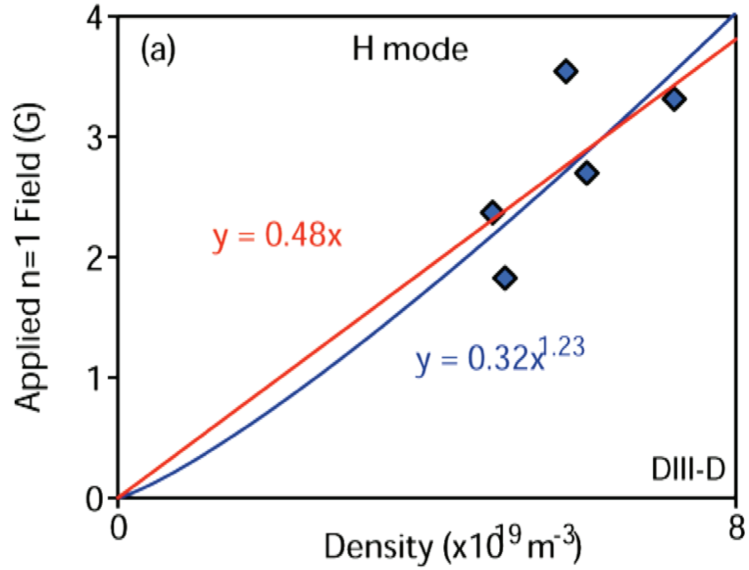
Moving on…

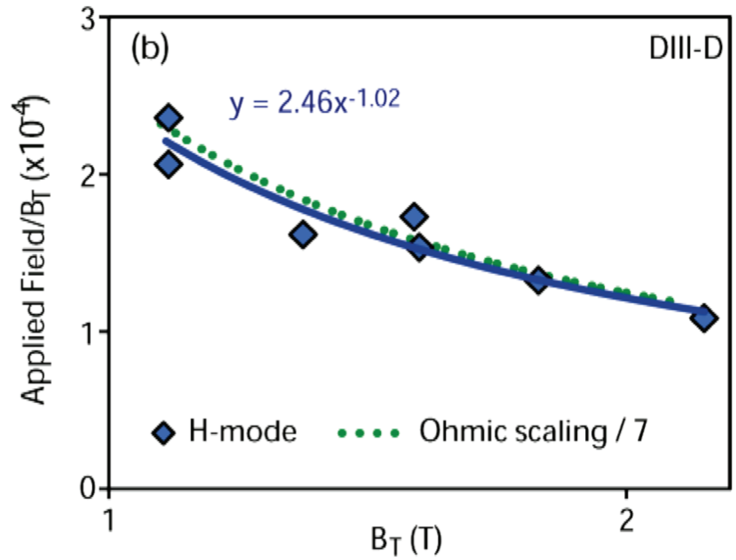
- **So, low torque H modes exhibit an increased response to 3-D fields due ideal and resistive effects**
  - Ideal: increases with β_N
  - Resistive: decreased screening at low rotation
    - Opens door to parameters governing tearing effects like Δ'
- **This brakes the plasma to access natural tearing instability**
- ***What does this imply for error field sensitivity & tearing mode β limits in devices like ITER?***

Extrapolate to ITER by Measuring Density and B_T Scaling of Threshold in Torque Free H-modes

- **ITER baseline-like SND at β_N=1.8** *(but q_{95}~4.3)*
  - ITER heating systems low in torque
    - 'torque-free' reasonable approximation
  - Enables rotation to be treated as hidden variable

- **H mode scalings broadly consistent with previous Ohmic scalings…**
  - Linear in density (within error bars)
  - Inverse with B_T





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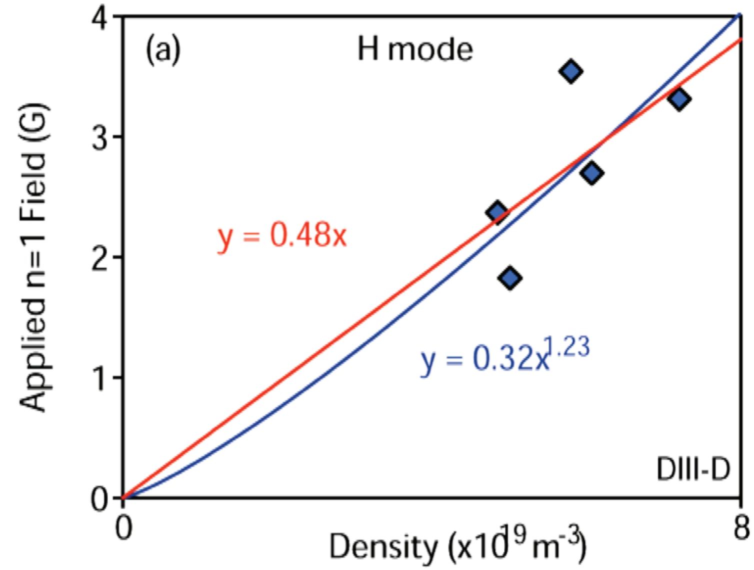
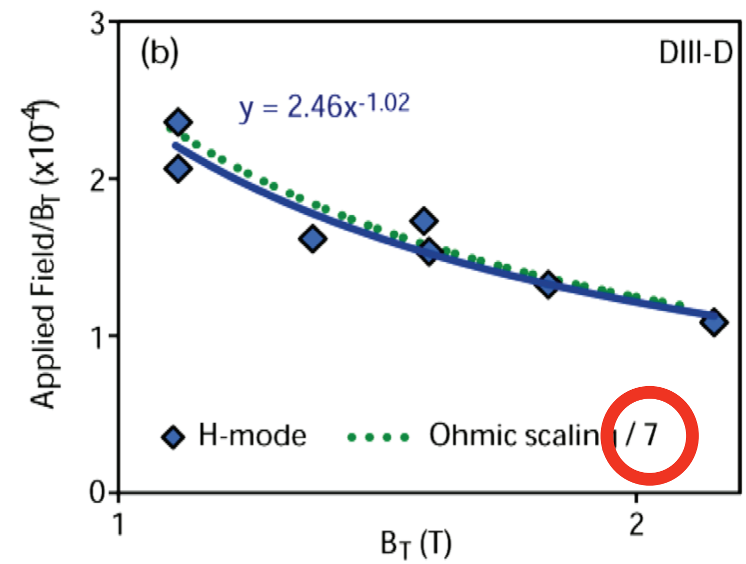
But 7 times lower threshold !

- **As expected of course:**
  - Increased ideal & resistive response
  - More braking to trigger mode





New ITER H mode Error Field Threshold Scaling

Infer size scaling from dimensional invariance to obtain:

$$\frac{B_{pen}}{B_T} = \left(1.72 - [\beta_N - 1.8]\right) \times \frac{\left(n_e / 10^{20} m^{-3}\right)\left(R / 6.2m\right)^{0.725}}{\left(B_T / 5.3T\right)^{1.02}} \times 10^{-4}$$

- **DIII-D threshold of 1.4x10^{-4} scales to 1.7x10^{-4} in ITER**

- **Lower than projections for ITER low density Ohmic phase**
  - Ohmic threshold of **2.9x10^{-4}** for I-coil-like fields in these variables

Note: ITER was designed to minimize m=1,2,3 fields

- *We now understand m=4-8 are key harmonics driving ideal response*

Important to re-evaluate ITER's error field and its correction in the relevant parameters for the ITER baseline scenario

Conclusions

- **Plasma resistive response becomes important in low torque H modes close to tearing stability limits**
  - Error fields open the door to tearing β limit via braking & a decrease of resonant screening
- **New threshold scalings predict error fields are a major concern for torque free H modes, even at low β_N**
  - Implications for ITER & future low rotation devices
  - Manipulating q profile and rotation will help