A New Resistive Response to 3-D Fields in Low Rotation H-modes

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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[4]Columbia University, NY / CRPP Lausanne, Switzerland

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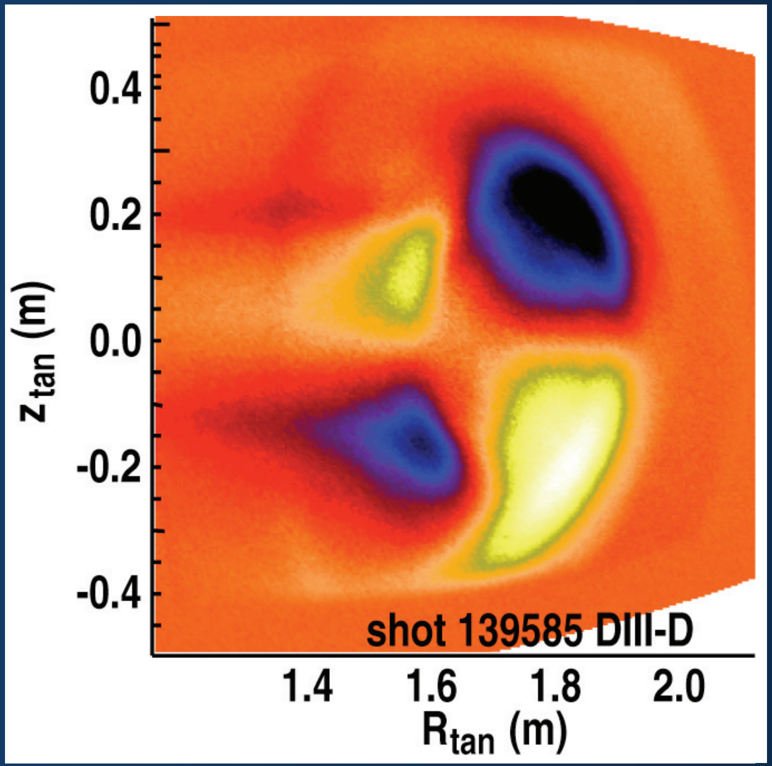

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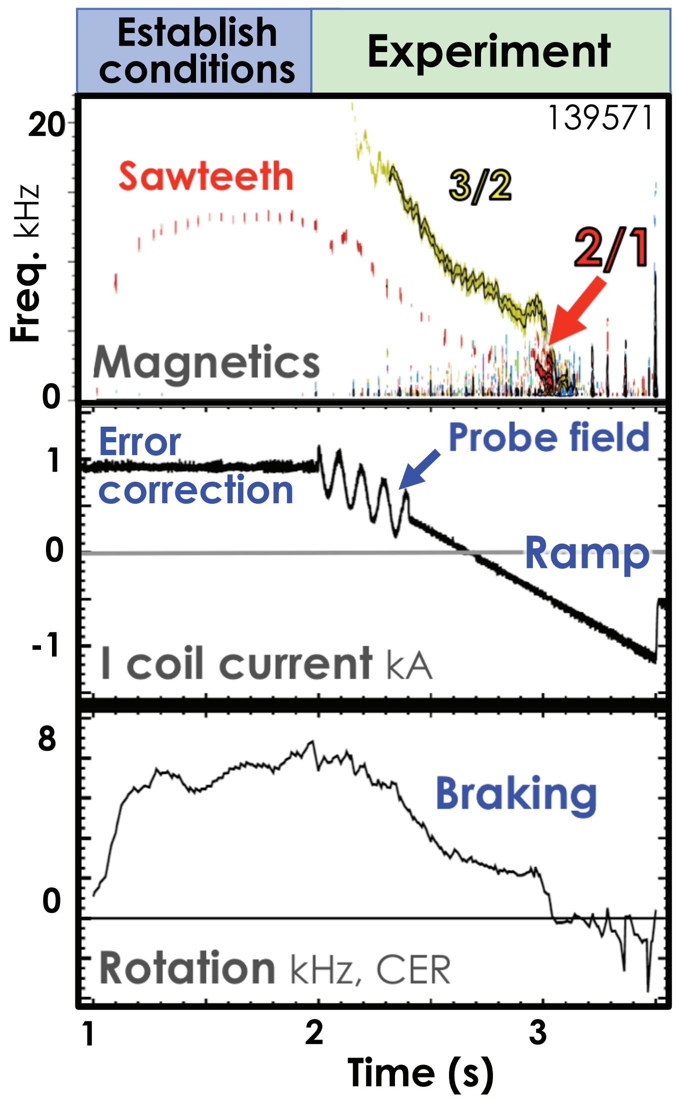
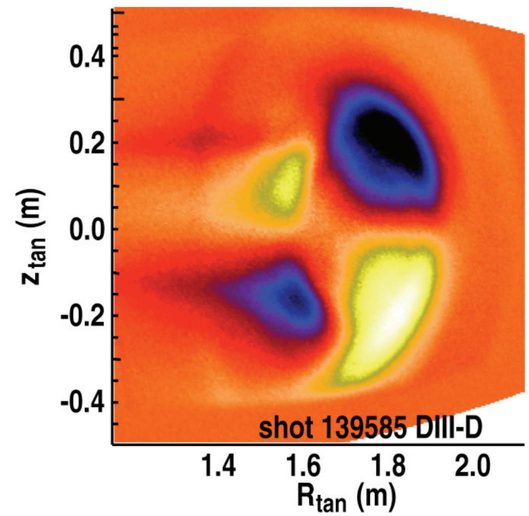
DIII-D NATIONAL FUSION FACILITY

GENERAL ATOMICS

Low Torque H Modes are Susceptible to Error Fields



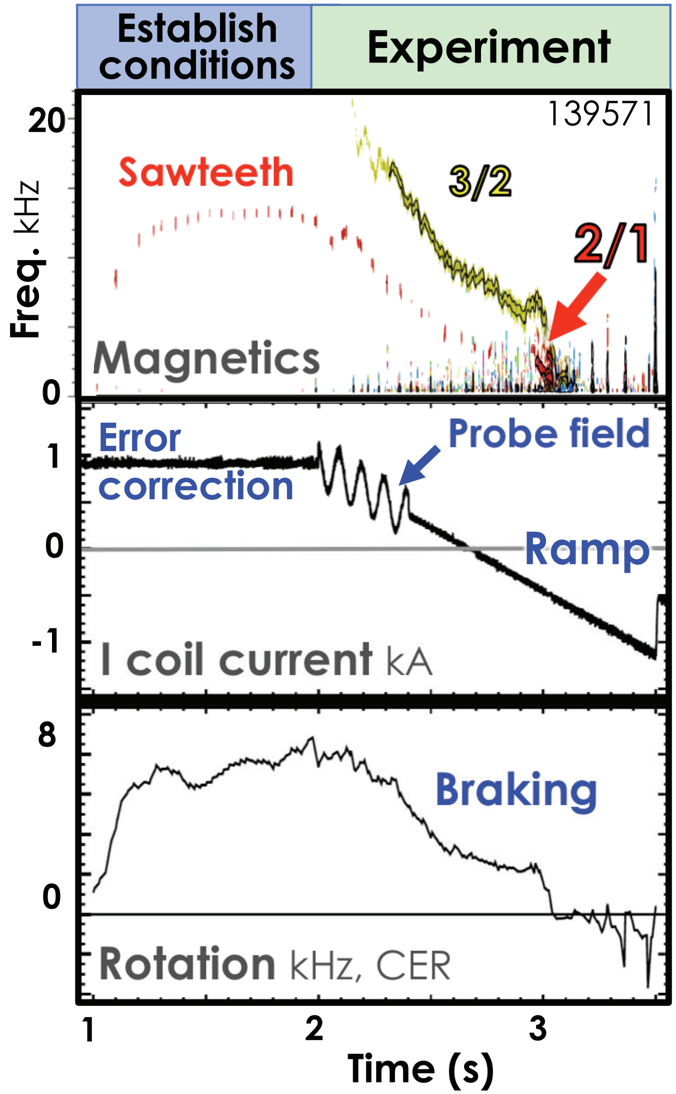
- Applying a *static* error field destabilizes a *rotating* 2/1 tearing mode:



1.8kHz Fourier decomposed fast visible imaging

Feedback control of NBI torque and β_N

Low Torque H Modes are Susceptible to Error Fields



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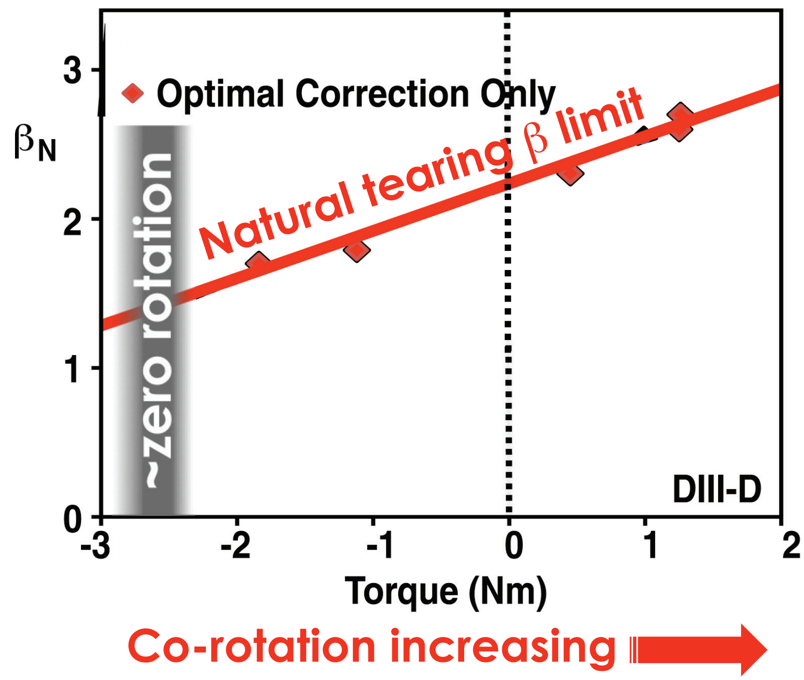
  - Tearing β_N limit falls with rotation:



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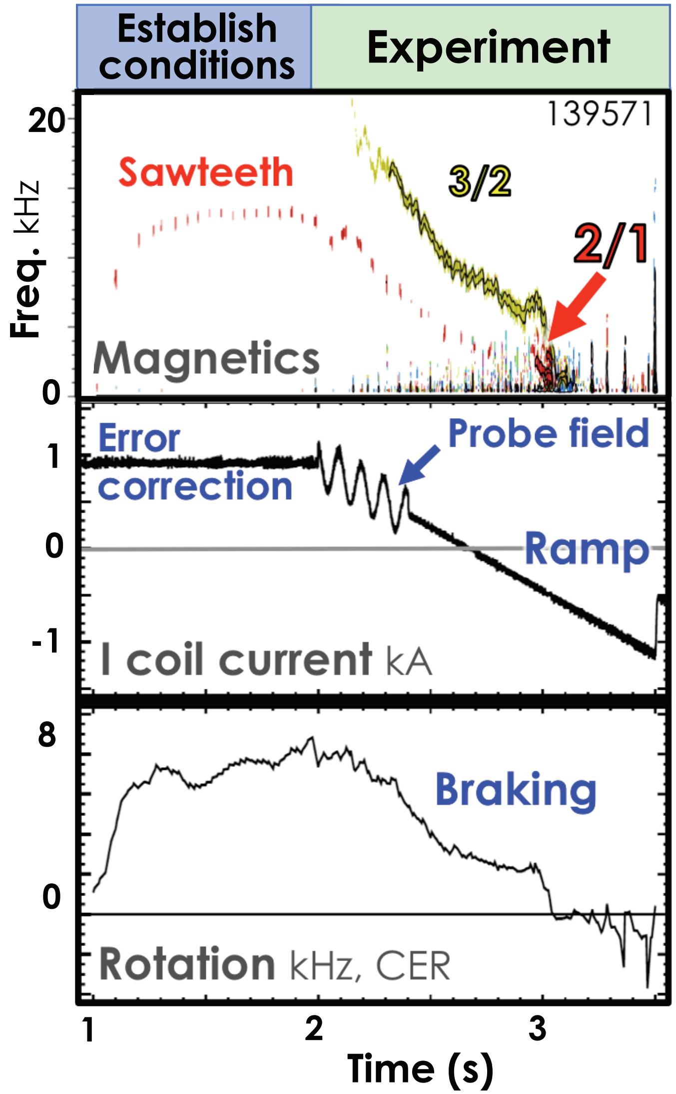
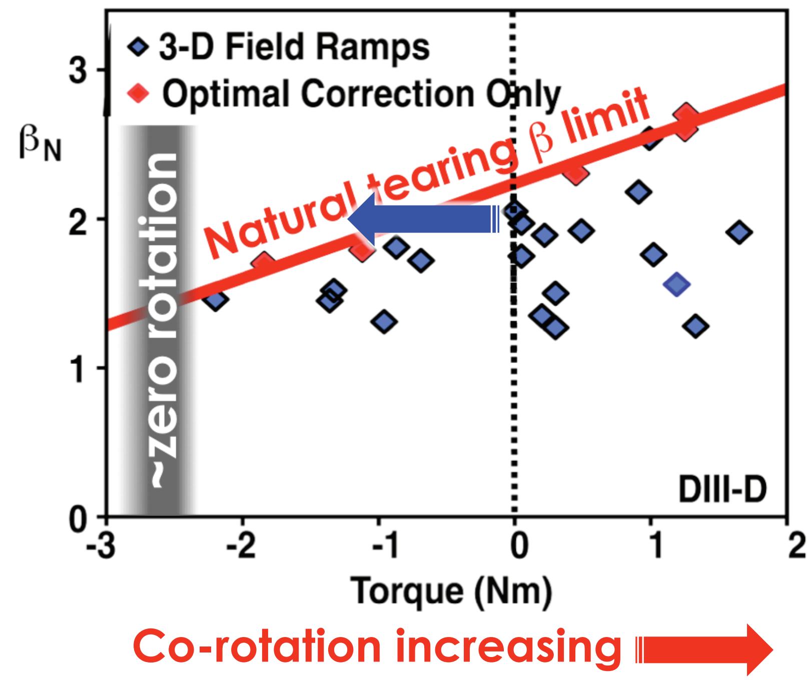
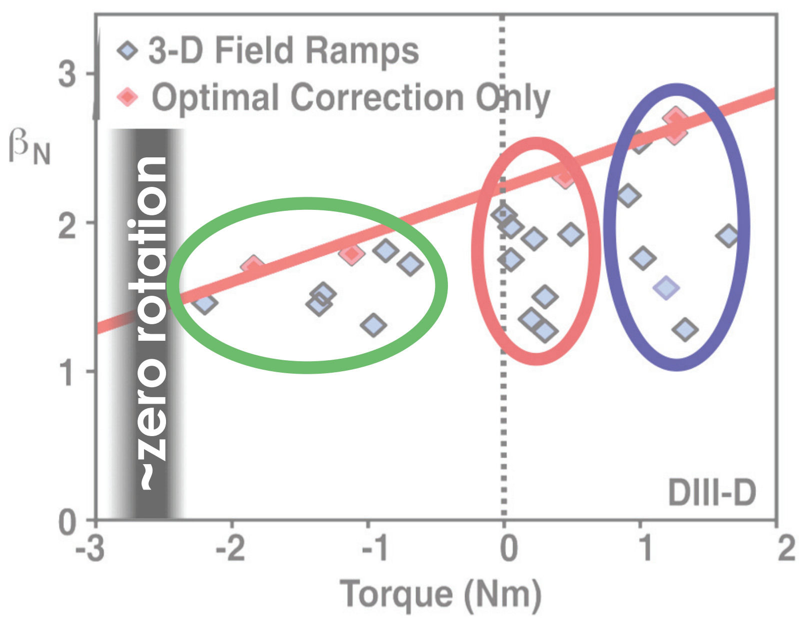


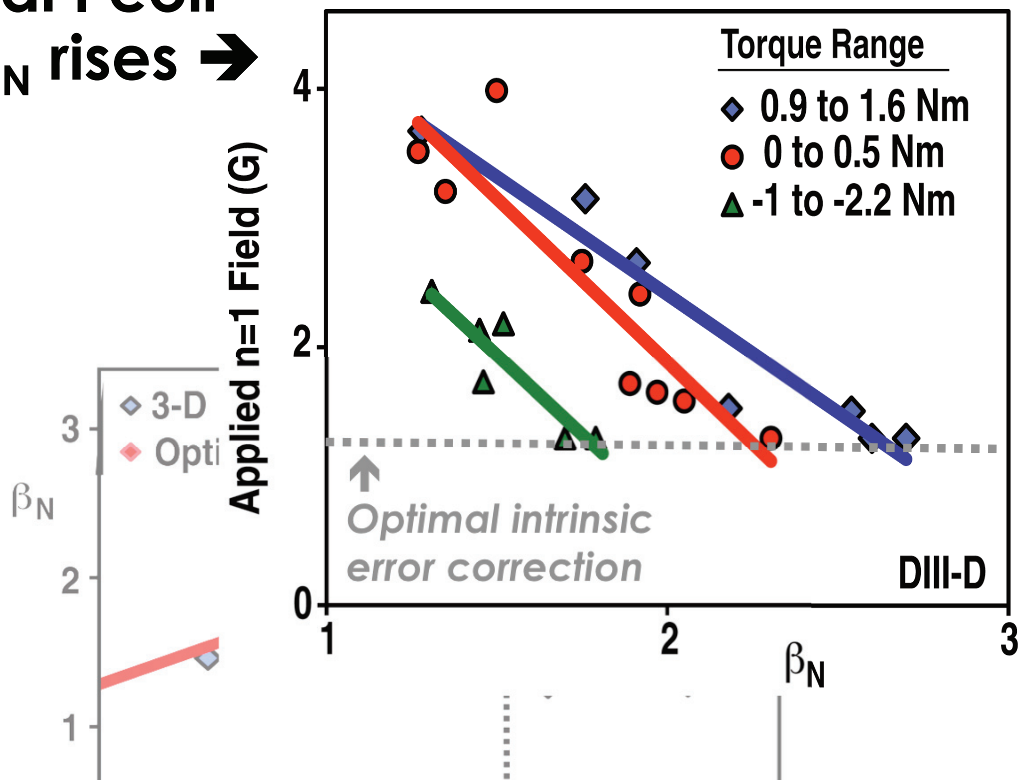
- Applying a *static* error field destabilizes a *rotating* 2/1 tearing mode:
  - Tearing β_N limit falls with rotation
  - Error field brakes plasma, accessing instability → mode grows & locks



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**

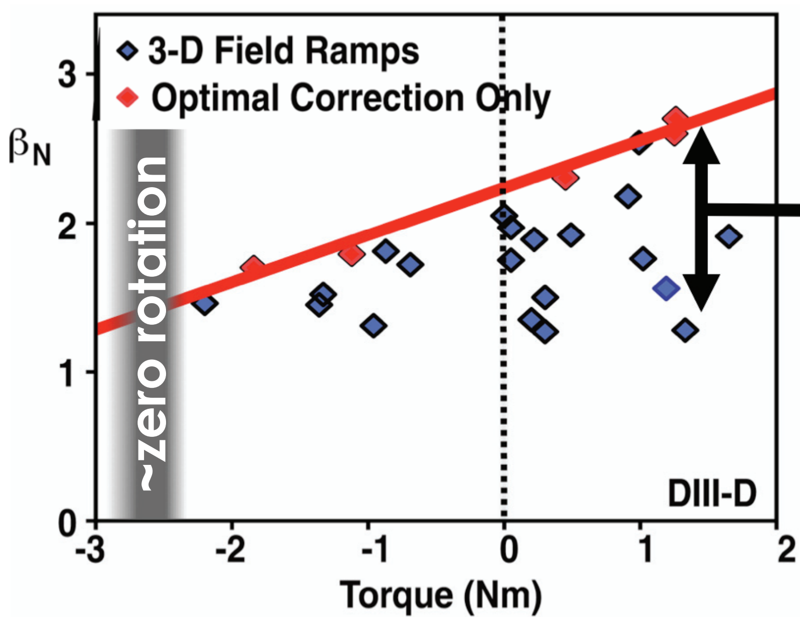


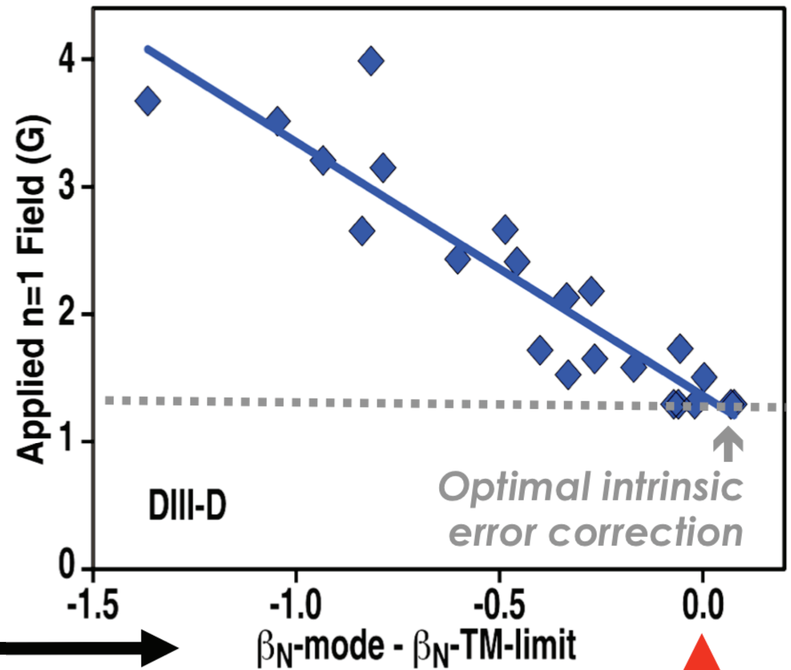


Measure as 2/1 resonant boundary field including ideal response via overlap integral with IPEC dominant mode

Error Field Thresholds Exhibit β and 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:
  - $\beta_{N\text{-TM-limit}} = 2.2 + 0.32T_{NBI}$





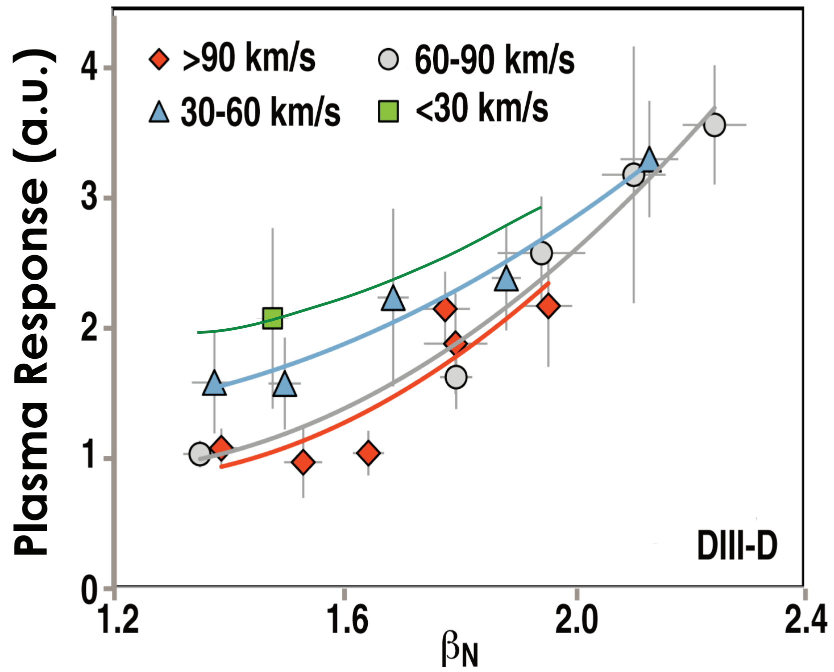
$\beta_{N\text{-TM-limit}}$=2.2 at zero torque

What is nature of plasma response?

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

- β_N dependence → ideal response

Response to 10 Hz probing field



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

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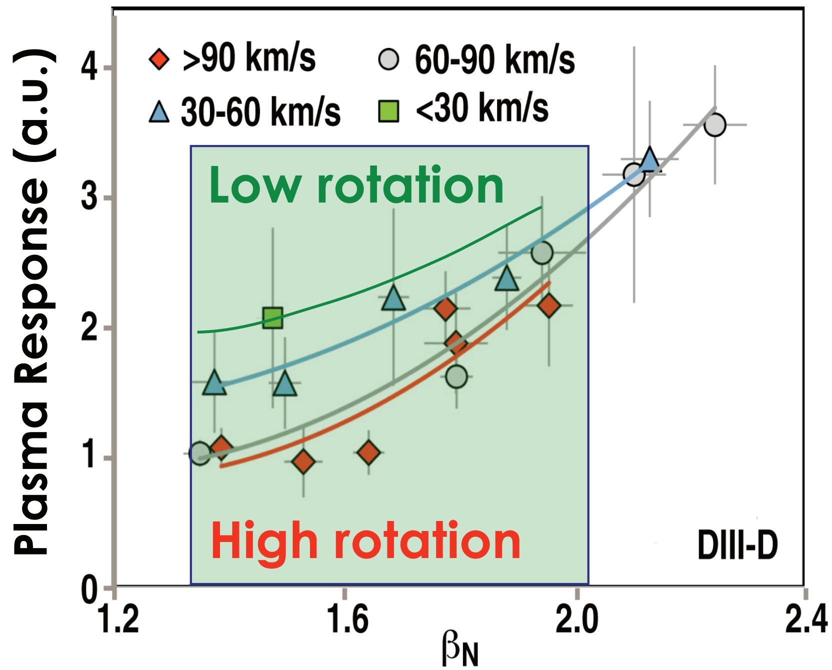

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  - ***Explore with MARS-F modeling…***

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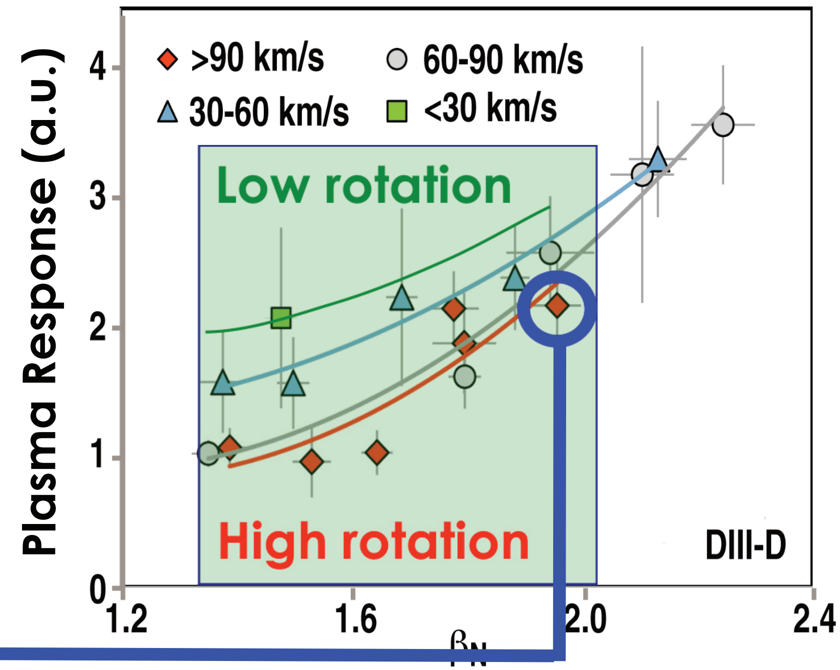
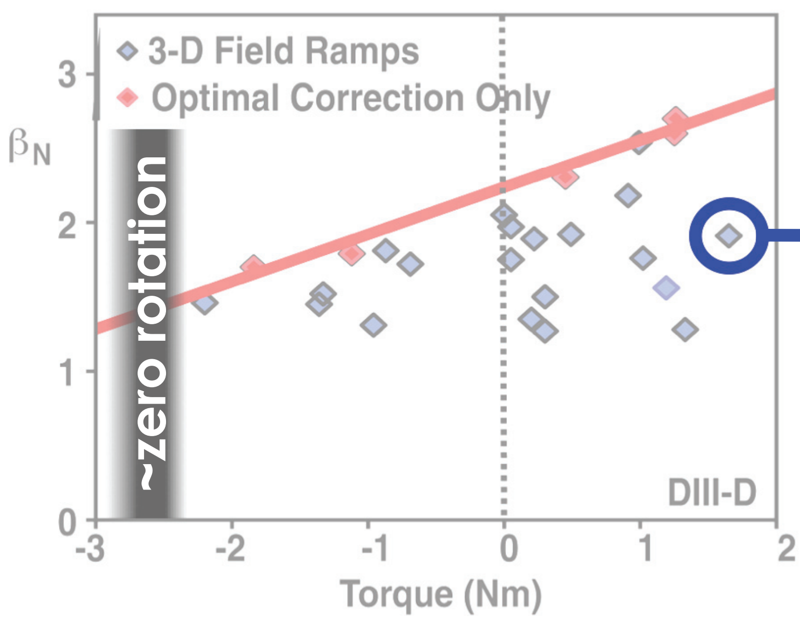




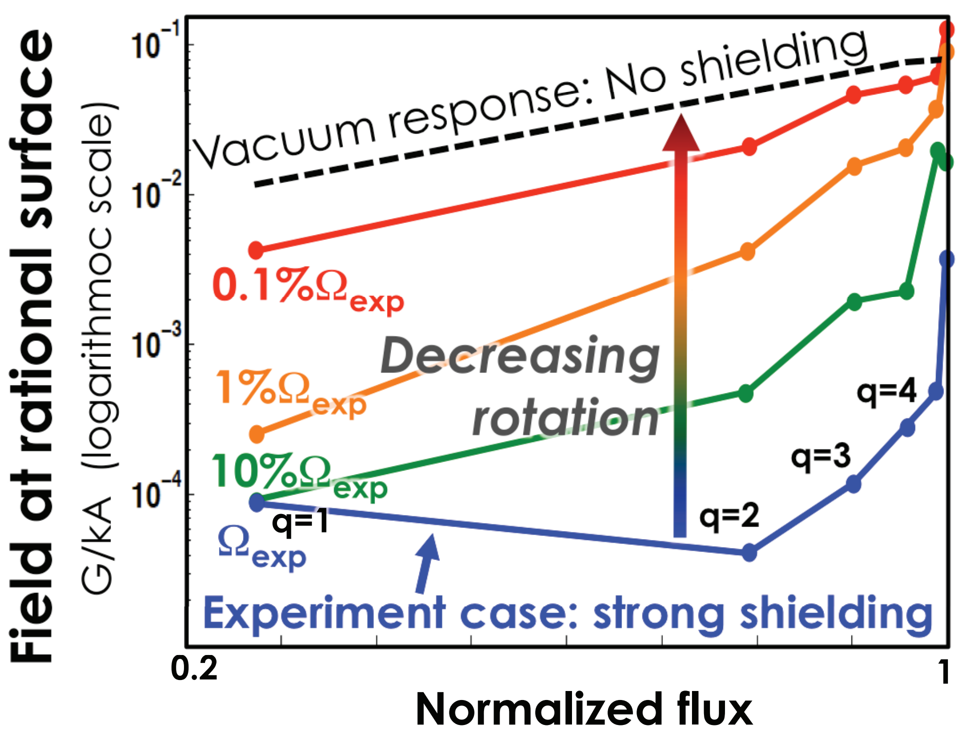
Considered case

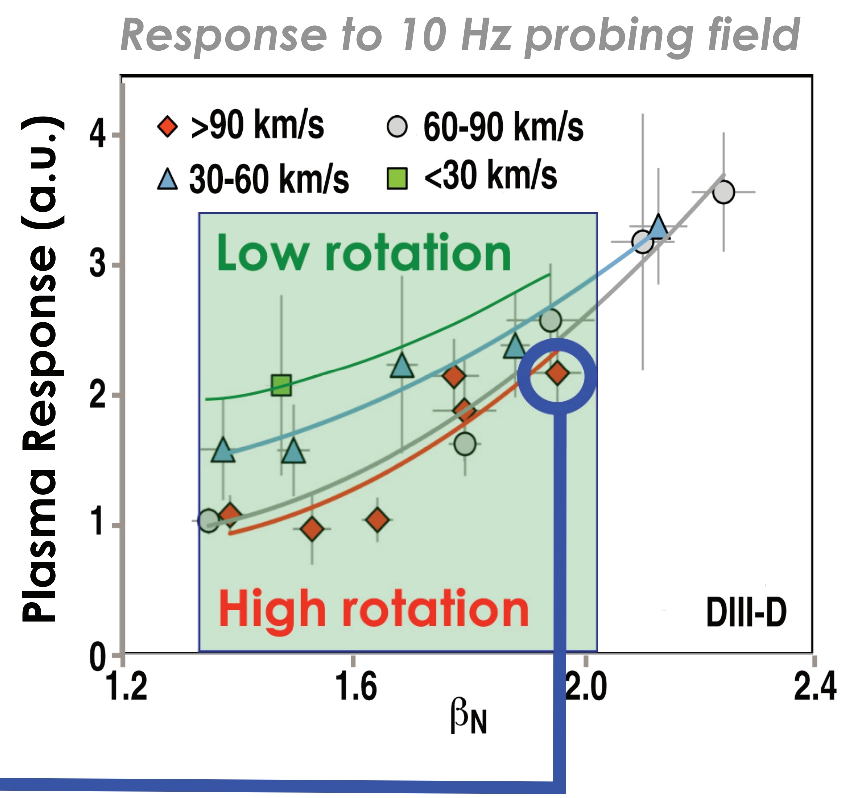
Linear calculation with resistivity

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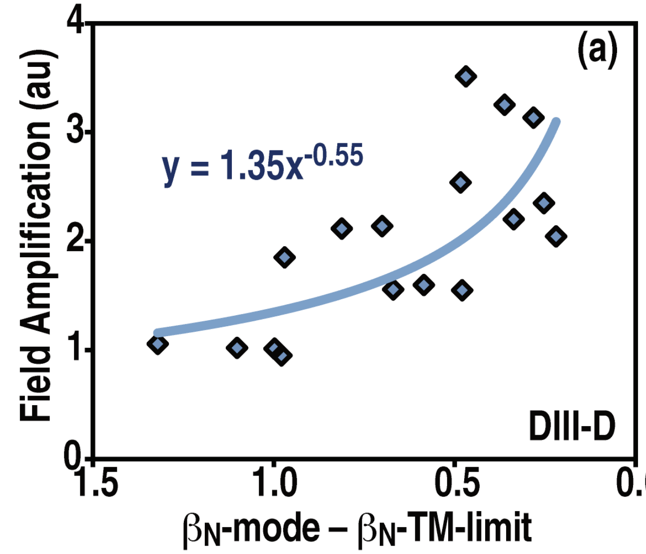
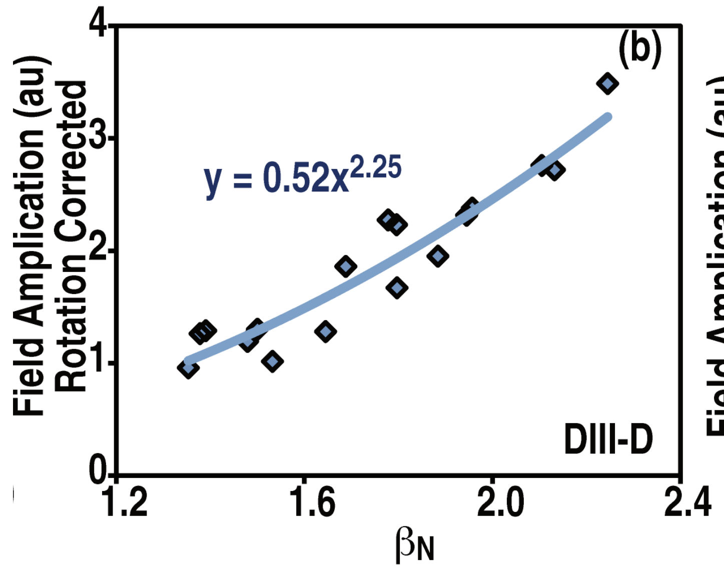
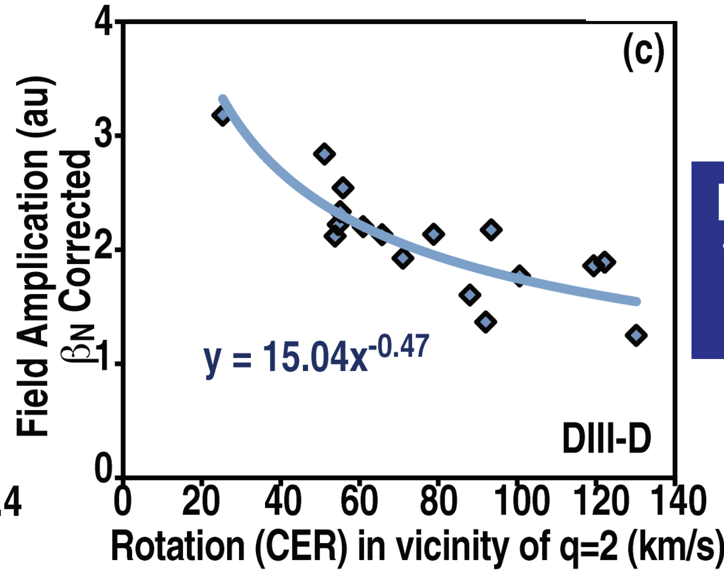
Fitting Confirms "Two Knobs" Needed to Explain Plasma Response – *not simply ideal or resistive*



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



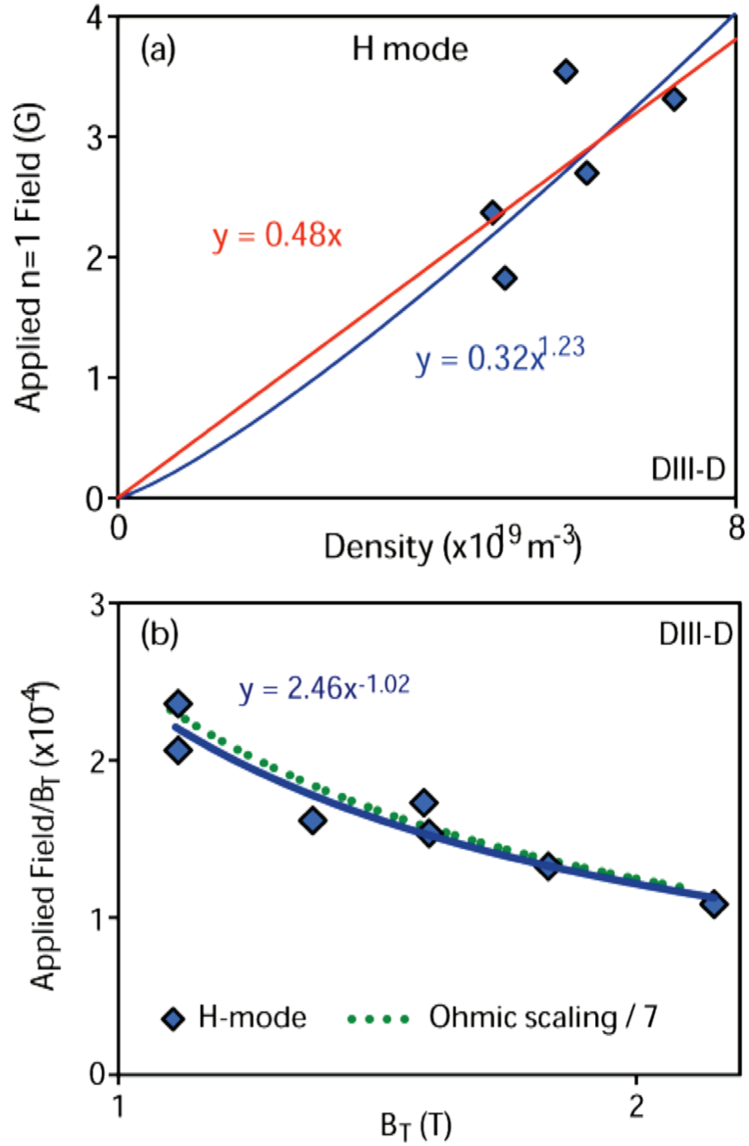


Rotation dependence identified – indicative of resistive response

- **So, low torque H modes exhibit an increased response to 3-D fields due ideal <u>and</u> resistive effects**
  - Ideal: increases with β_N
  - Resistive: decreased screening at low rotation
- **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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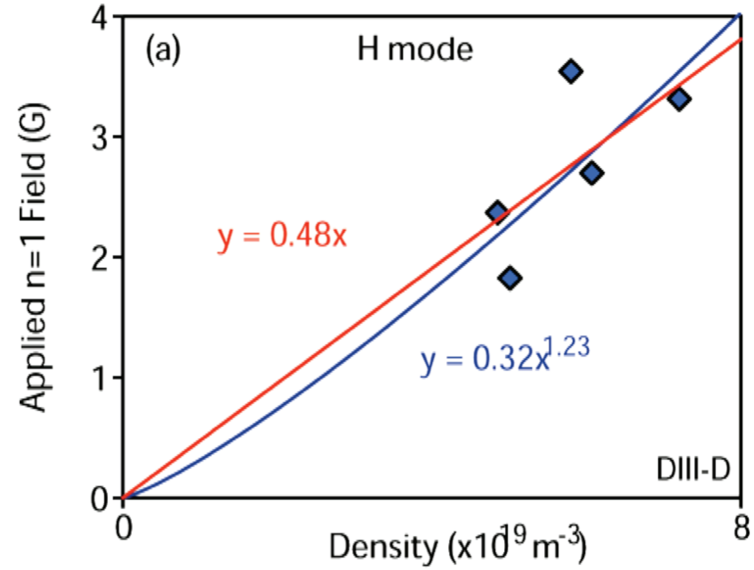
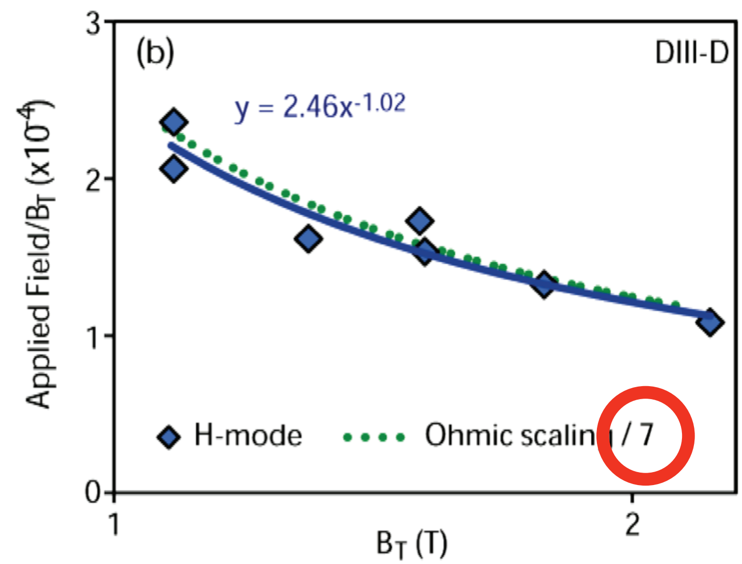
But 7 times lower threshold !

- **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

- **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

Extrapolating to ITER

- **Rotation is key, but not predicted for ITER – how to scale?**
  - Solution: treat rotation as hidden variable in torque-free H modes
    - As for Ohmic regimes – implicit in threshold scalings
    - Possible for ITER H mode, as ITER has low (≈zero) torque
    - Valid provided rotation fn(ρ^*, ν^*, β) does not change from DIII-D range to ITER.
  - Measure scaling with main plasma parameters

- **Use dimensional scaling as for Ohmic plasma:**

$$B_{pen} / B_T \propto n^{\alpha_n} R^{\alpha_R} B^{\alpha_B} q^{\alpha_q} \qquad \{ \times \text{ some fn } (\beta) \text{ if varied}\}$$

  - $\alpha_R = 2\alpha_n + 1.25\alpha_B$ from dimensional considerations, as for confinement ***[Connor and Taylor NF 17 1047]***

To Extrapolate to ITER

- **ITER's error correction system is based on vacuum 2/1 field**
  - Had quoted as this (1.1G/kA in I coils) – but this is not correct physics !
- **Actual q=2 field includes plasma response** → higher harmonics matter
  - IPEC calculates at 3.26G/kA for similar DIII-D plasmas
- **But ITER needs an estimate for tolerable external field – *solution:***
  - IPEC identifies a dominant field component at the boundary:
    - All other components give an order of magnitude lower response
  - **Calculate overlap integral of I coils with this: 1.57G/kA** **(Used this talk)**
    - Provides component of external field that generates q=2 response
  - Other error sources of ITER can be mapped to this with IPEC

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Warning: This is probably incomplete!

- *Experimentally we know structure of field matters:*
  - *DIII-D I coils still leave 60% of field uncorrected*
  - *Likely: response of other surfaces & modes matter (eg q=3, NTV…?)*

Allowing for Intrinsic Error

- **DIII-D I coil cannot correct intrinsic error perfectly**
  - Different harmonic content adds to field
- **Consider fields as distributions of normal magnetic field at boundary:**
  - Intrinsic error composed of two components: $B_E = B_{EN} + B_{EA}$
    - B_{EN} 'non-aligned' has zero overlap with I coil
    - B_{EA} aligned part – adds linearly = –ve I coil field for optimal correction
  - Torque ~ B^2 ~ $(B_I - B_{Ioptimal})^2 + B_{EN}^2$
    - Deduce B_{EN} from density limits with no I coil & optimal I coil correction
      - Density limit scales as |B| ~ √T
      - Ratio of density limits of 0.61 gives B_{EN} = 0.61 $B_{Ioptimal}$
- ***Consistently captures threshold between zero & optimal I coil correction, and the asymptote to high I coil current***
  - ***Though variations in harmonic content with mix may alter this further***

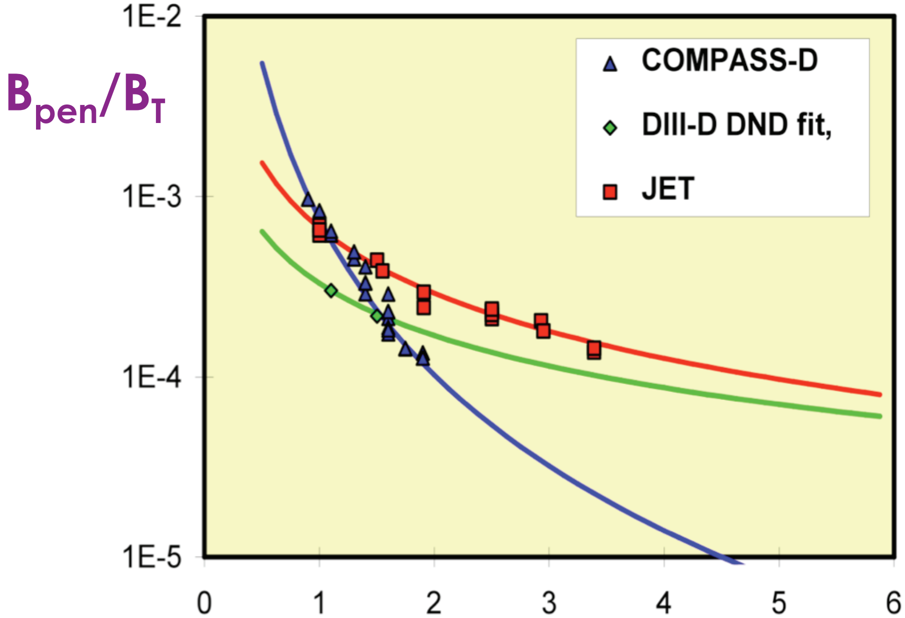
Key Physics – later…

- **Error field effects are about ideal <u>and</u> resistive responses**
  - Ideal governs how fields permeate a rotating plasma
    - Screening currents prevent tearing
    - Drives kink distortion – increases with beta
  - Local resistive response ultimately will always manifest itself as field progresses towards penetration threshold
    - Resistive response governs criteria for mode formation
- **Resistive response critically dependent on further parameters**
  - Lower rotation → less screening → increased tearing & greater torque at rational surfaces
  - Δ', by definition, governs plasma tearing response to residual field

Low rotation and Δ' stability is the region expected for ITER

How Rotation is Buried in Extrapolation to Next Steps

- **Plasma rotation & torque are key determinants of field threshold**
  - H modes: usually driven rotation; ITER rotation uncertain
  - Ohmic regimes: no injected torque, self generated rotation
    - Rotation then becomes a hidden variable, implicitly varying
    - ***Adopt same approach for torque free H modes***



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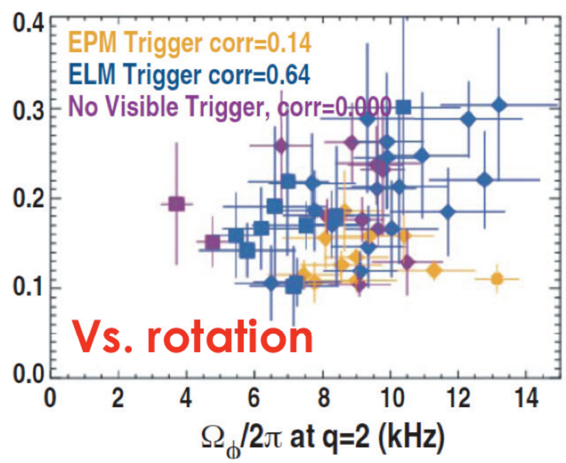
But COMPASS-D behaved differently…

Tearing Stability is a Concern at Low Rotation

Tearing β limits fall with rotation

– *Interpreted as rotation shear changing tearing stability Δ':*

$$\frac{\mu_0 L_q \delta j_{BS,\,Sauter}}{B_\theta} \left(\approx \frac{\varepsilon^{1/2} L_q \beta_{\theta e}}{2L_{pe}} \right)$$



Bootstrap drive at NTM onset

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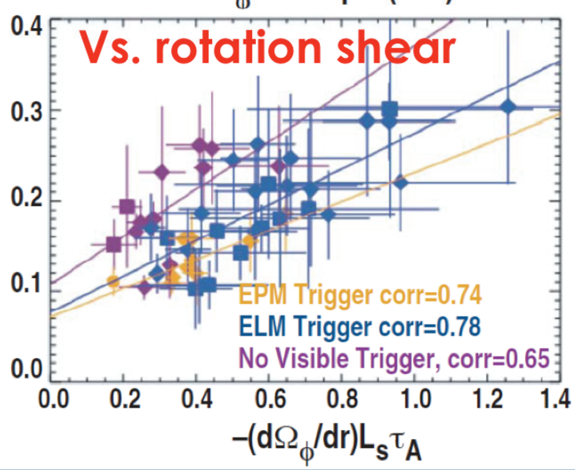
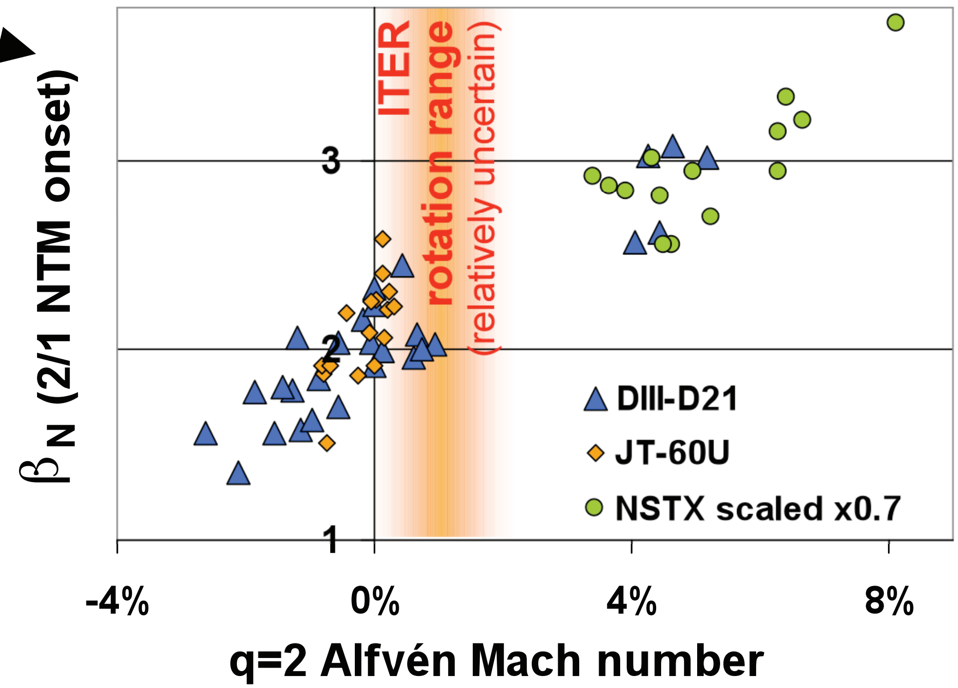




Rotation shear provides correlation in 'No visible trigger' cases and improves correlation in triggered cases

[Gerhardt, NF 2009, Buttery IAEA 2008, La Haye PoP 2009]

Error Field Threshold is All About Plasma Response and Rotation

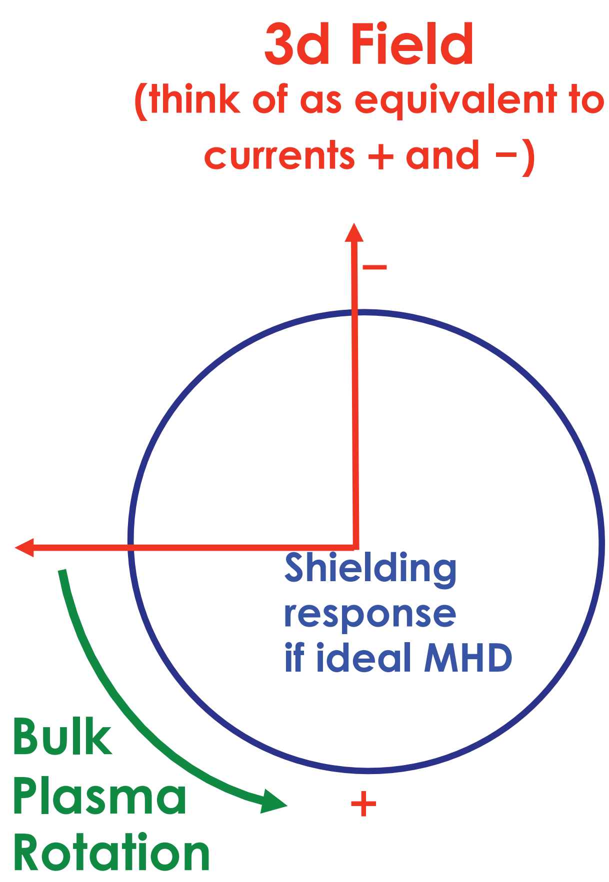
- **Apply small field:**
  → Plasma rotation leads to shielding currents
  → But residual plasma response → small island forms
  - Response depends on tearing stability, $1/\Delta'$, and rotation
  - Island couples viscously to bulk plasma, slipping past
    → **viscous torque** depends further on rotation and viscosity

  → EM torque between island and 3d field
  - Self consistent high shielding nearly suppressed state with $\pi/2$ to EF
- **Increase field:**
  → Response grows → Increased torque → Island phase to EF closes
  → Island bigger still → Increased response…
  - ***Eventually reach bifurcation as braking enables more tearing & torque***

[Fitzpatrick NF 1993]

Plasma Rotation Leads to Shielding of 3-D Fields

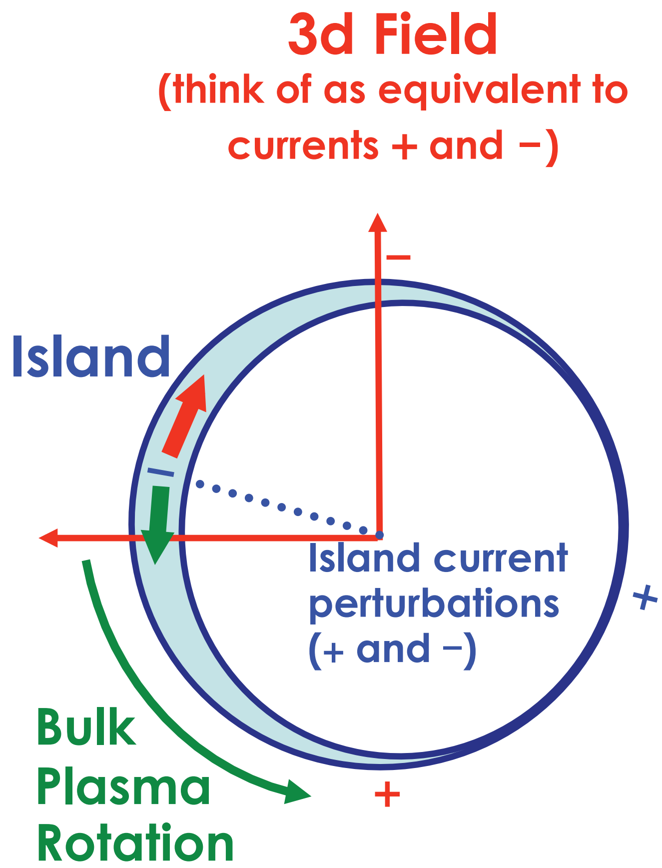
Image currents inhibit tearing response



[Fitzpatrick NF 1993]

Shielding is Imperfect –
Residual Island Depends on Rotation & Δ'

- ➔Torque balance established between viscous drag and EM torque on island



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Island Torque Balance and 'Penetration' Depend on Plasma Response and Rotation

Less 3d Field

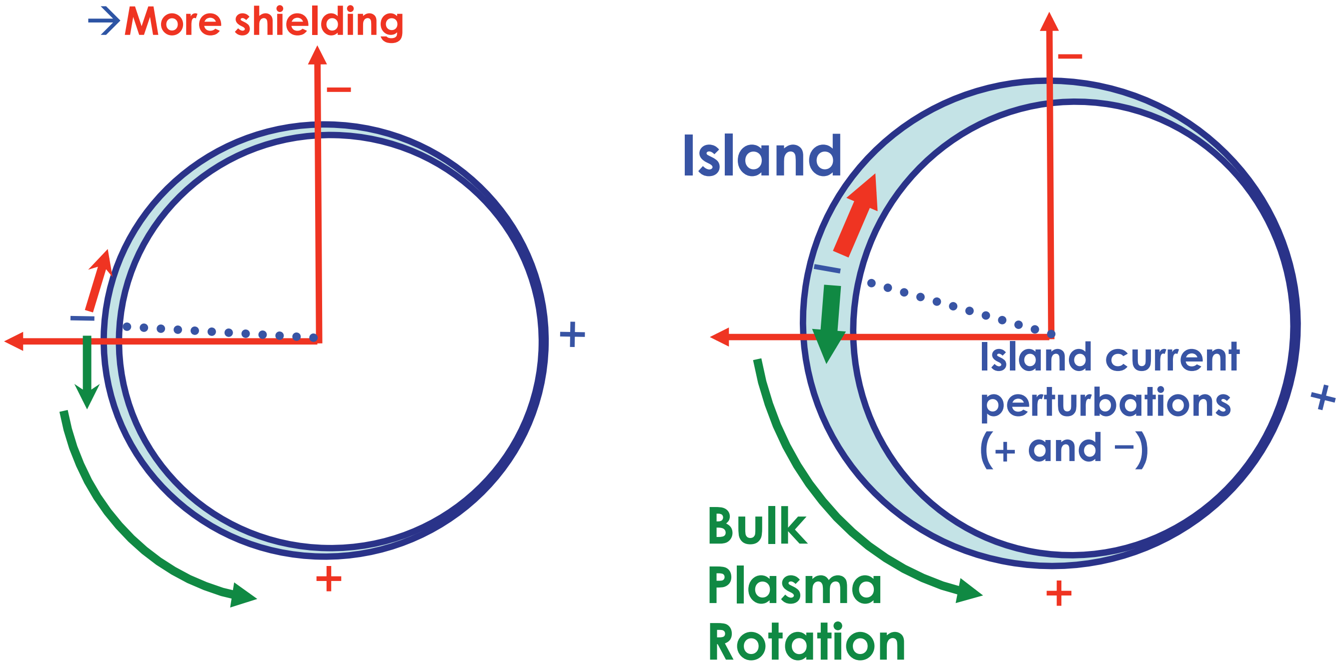
→Less torque,

→Viscosity wins

→More shielding

3d Field

(think of as equivalent to currents + and −)



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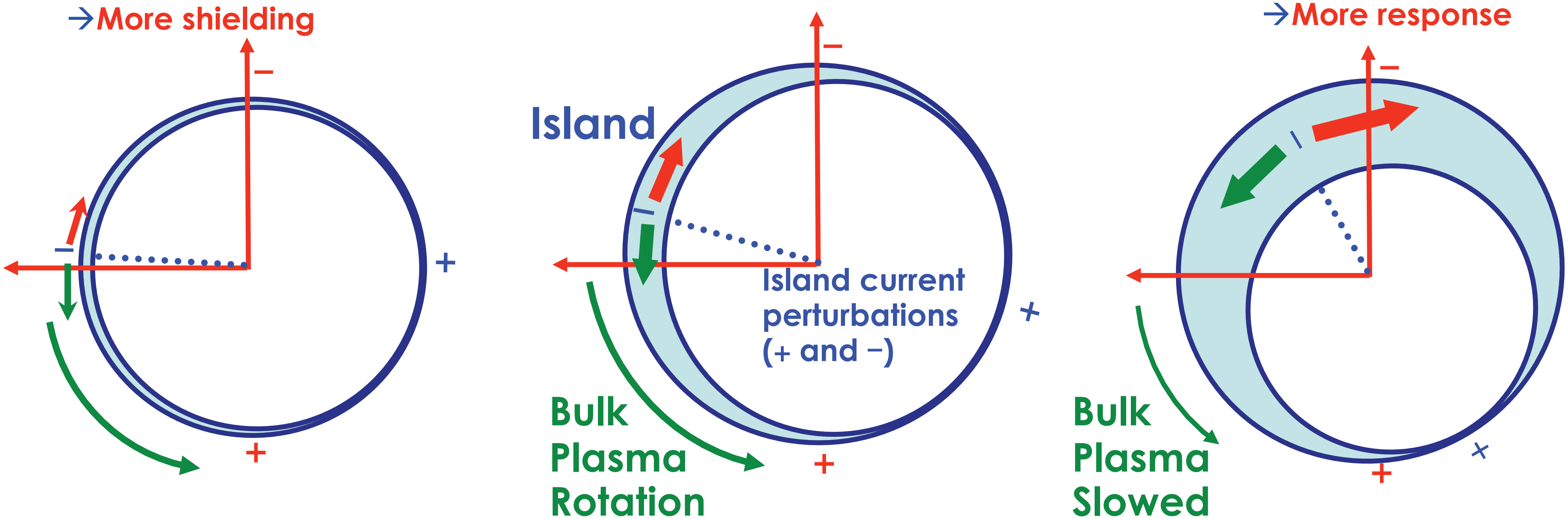

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Island Torque Balance and 'Penetration' Depend on Plasma Response and Rotation

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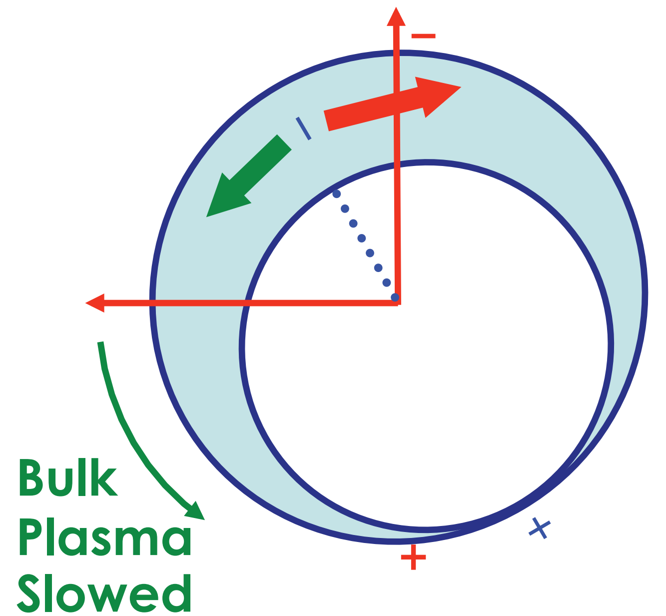
→Ultimately bifurcates to locked state, as phases align, island grows & couples strongly to field.



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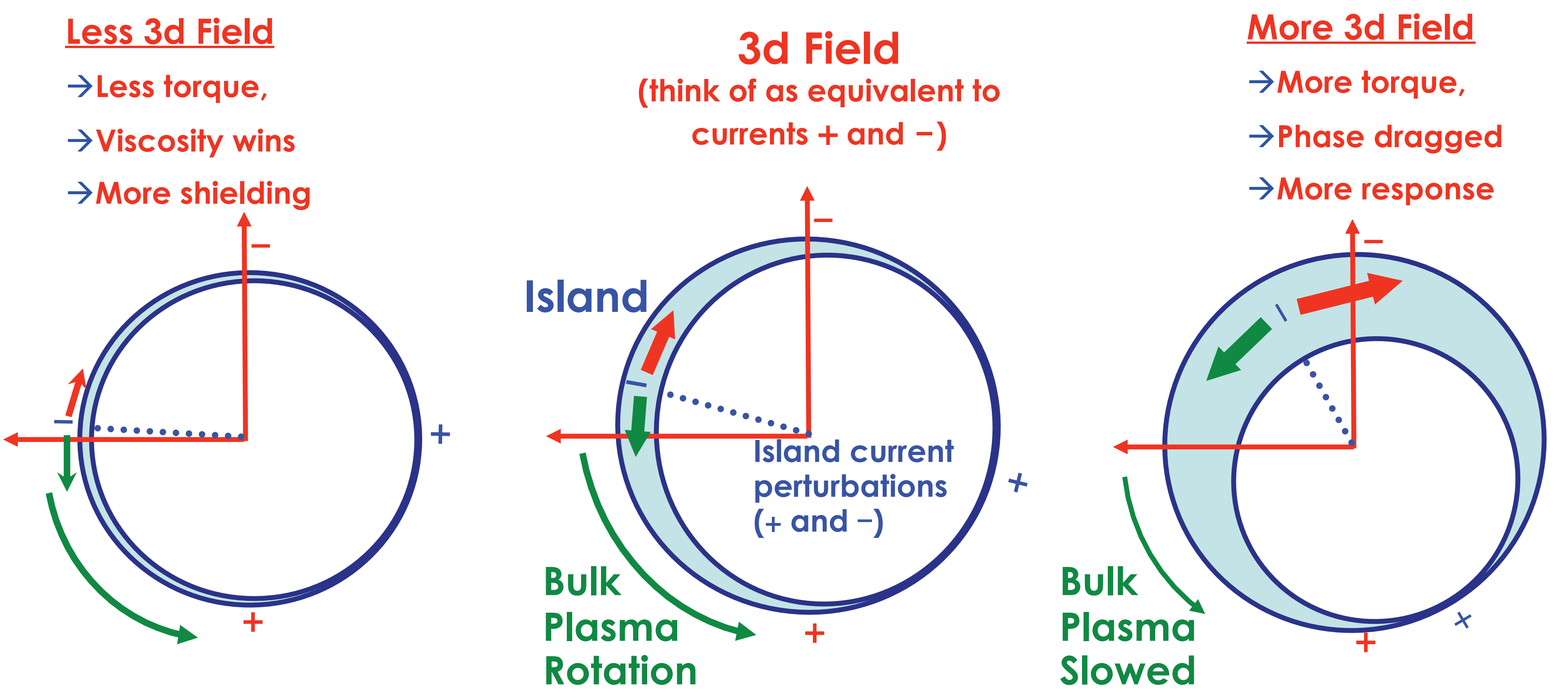
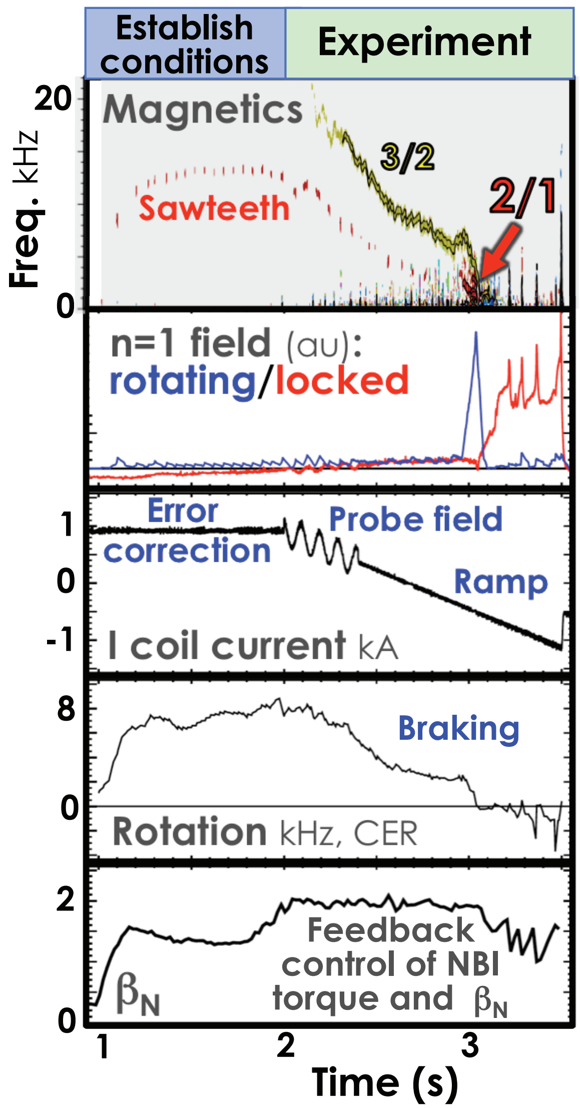


Island response depends on how easy it is to drive tearing instability → $1/\Delta'$
& how much plasma forces it out of phase with 3d field → τ_V and ω

[Fitzpatrick NF 1993]

Low Torque H Modes are Susceptible to Error Fields



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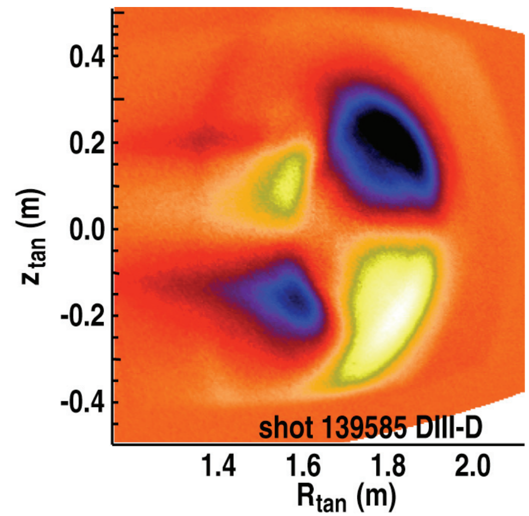

1.8kHz Fourier decomposed fast visible imaging

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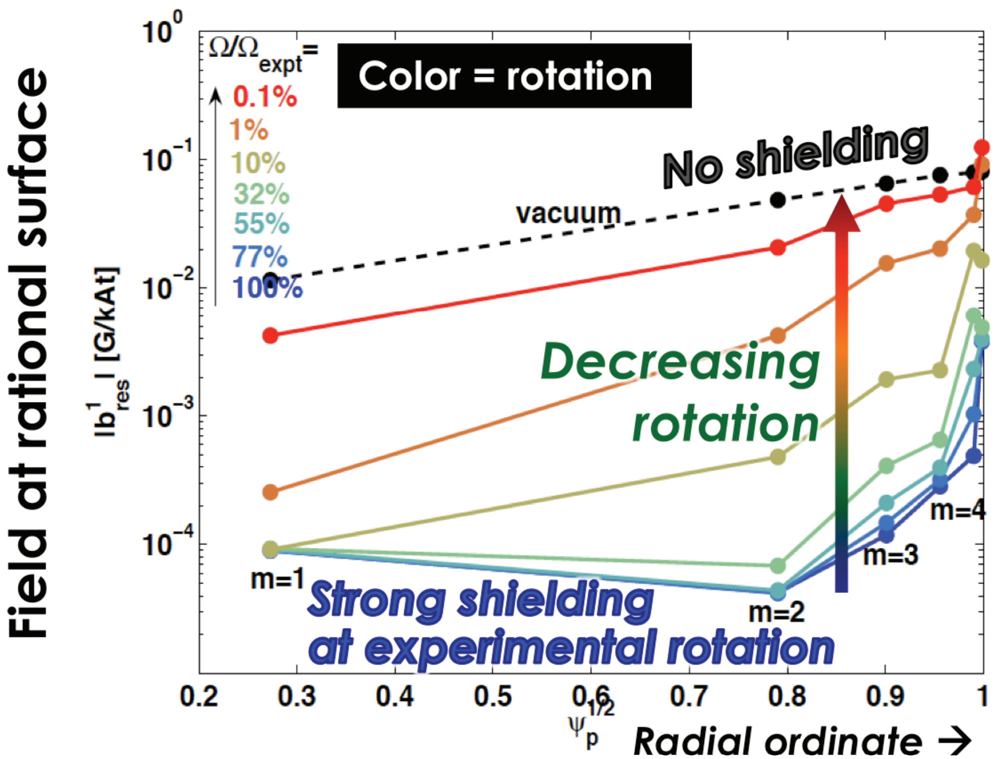
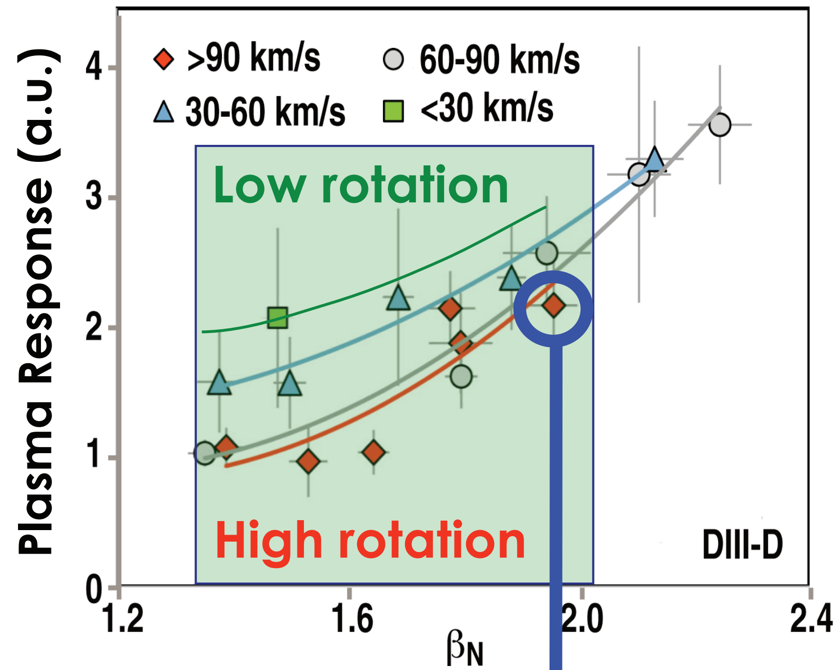


Response to 10 Hz probing field



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