THE IMPACT OF 3-D FIELDS ON TEARING MODE STABILITY OF H-MODES

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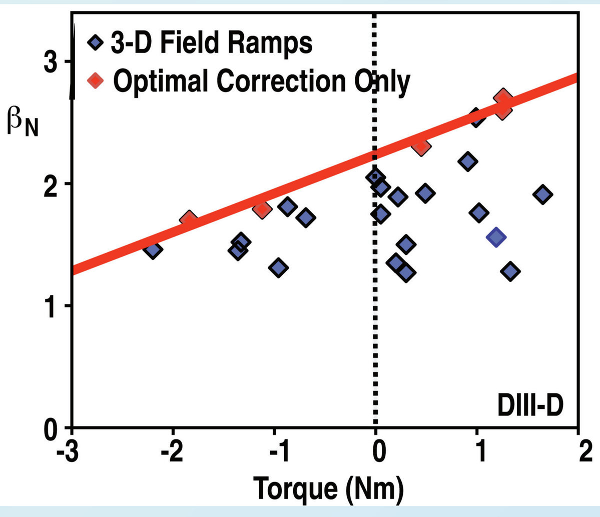
DIII-D NATIONAL FUSION FACILITY — GENERAL ATOMICS

ABSTRACT & CONCLUSIONS

- **New resistive response to 3-D fields** discovered, increasing sensitivity of the plasma to error fields at low rotation in proximity to the H-mode tearing β limit.
- **Action through rotation identified** – either decreasing rotation shear to destabilize naturally unstable rotating mode, or stopping plasma to directly drive a locked mode.
- **New error field threshold scalings** obtained for ITER β_N=1.8 torque free baselines, indicate H mode thresholds lower than previous regime of greatest concern.

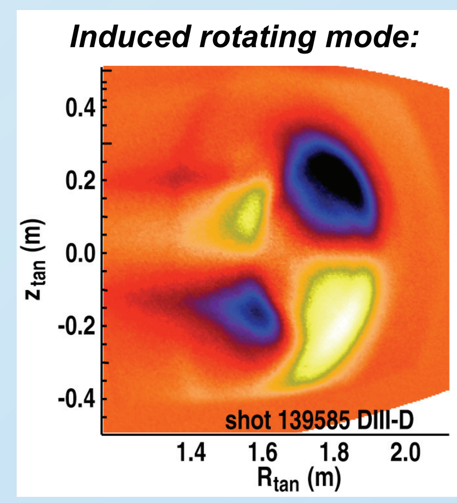
NEW RESISTIVE RESPONSE TO 3-D FIELDS AT LOW ROTATION

n=1 fields ramped until 2/1 mode triggered:



Parameters explored: each point is a shot with parameters held under feedback control while 3-D field is ramped to trigger mode

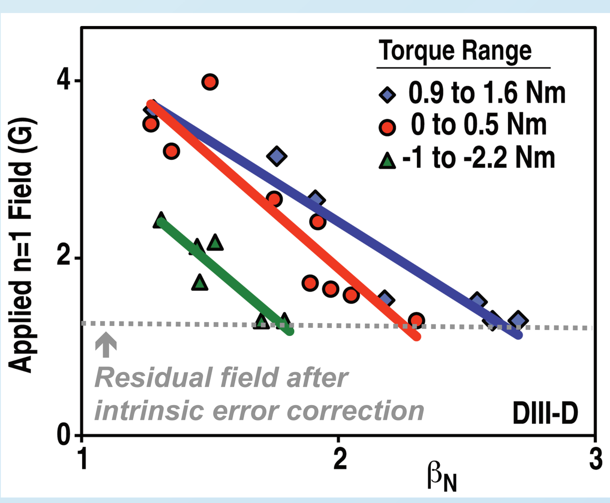
← **Shots run at a range of low torque and β_N**
- Used ITER like SND baselines ELMy H modes with relaxed profiles & sawteeth
- Limit in red imposed by natural tearing limit: $\beta_{N\text{-TM-limit}} = 2.2 + 0.32T_{NBI}$



*Fourier decomposed fast camera image of 1.8KHz **rotating** mode induced by **static** n=1 field ramp*

In most cases, a rotating mode is → triggered by the 3-D field ramp
- Magnetic braking decreases rotation shear, lowering underlying tearing stability [1,2]

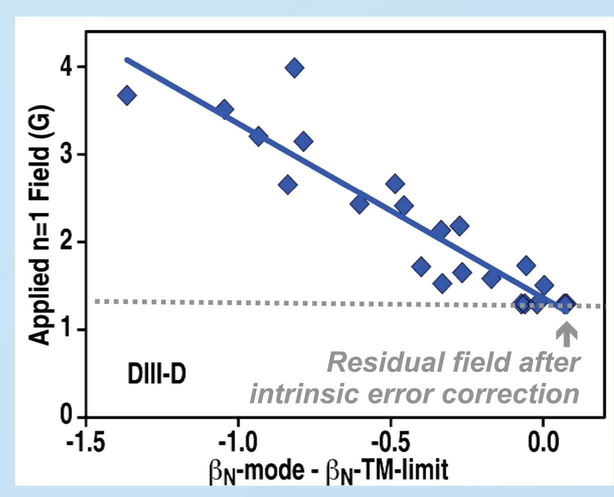
↙ **Threshold field to trigger 2/1 modes shows clear trends:**
- Decreasing threshold (to optimal correction level) as tearing β limit approached
- Decreasing threshold as co- torque and co-rotation fall
  - *Fields plotted include estimated intrinsic error*



n=1 field threshold vs torque and β_N

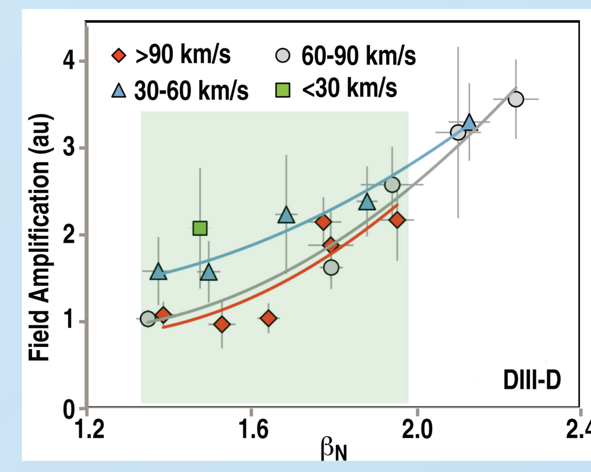
Threshold well fitted by proximity → to natural tearing limit (see above)
- *Is this evidence of a resistive response?*
- **Significant concern for plasmas operating close to tearing b limits**

(Field thresholds are measured in terms of component at plasma boundary that generates plasma response at q=2, including plasma ideal response [3])



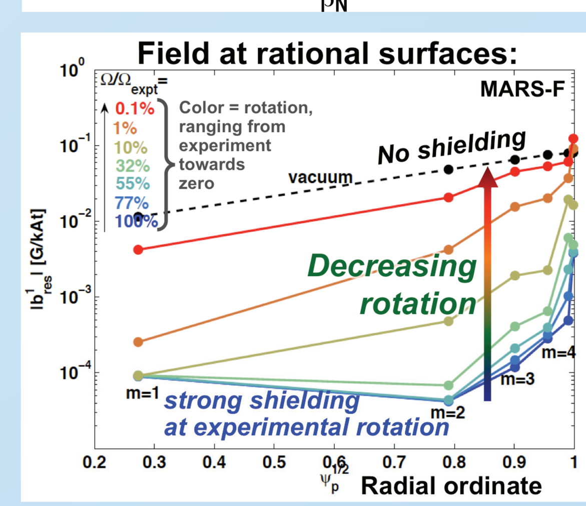
n=1 field thresholds plotted in terms of proximity to NTM β limit

Magnetic response to low amplitude 10Hz probing field:



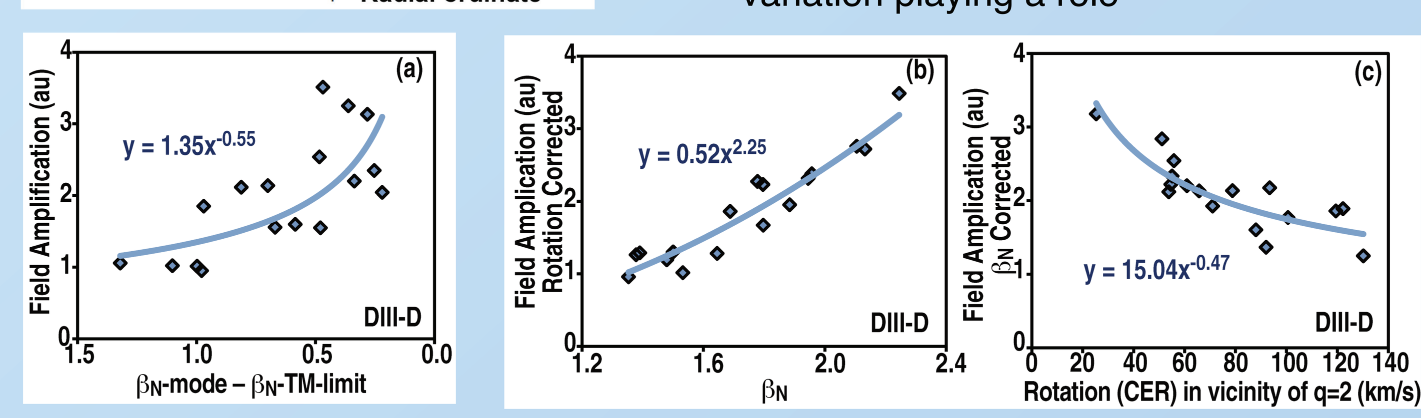
← **Plasma response increases with β_N**
- Could be usual ideal MHD response, increases as kink β limit approached [4]

- **But plasma response also rises as rotation falls** (green shaded region)
  - Ideal MHD response should not be rotation dependent – perfect shielding throughout
  - **Rotation dependence suggests imperfect shielding → resistive response at q=2**
    - *Proximity to tearing instability also an important factor in this response*



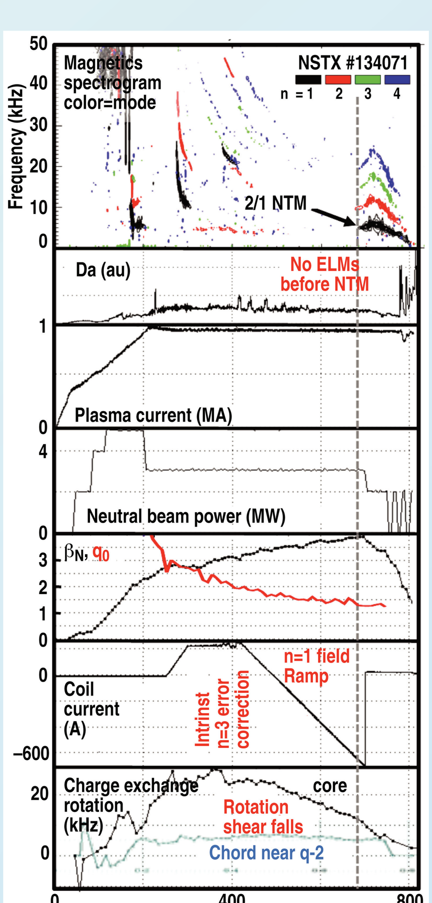
← **Modeling a β_N=1.9 case with the MARS code shows local responses at rational surfaces rises as rotation falls**
- Usual shielding response is weakening

↙ **Field amplification not simply a function of proximity to tearing limits**
- A 2-D fit in β_N and rotation is better ↓
- Likely ideal and resistive response variation playing a role



3-D fields induce tearing more readily in plasmas that are close to natural tearing instability with low rotation – in part due to a new resistive response: imperfect shielding at q=2

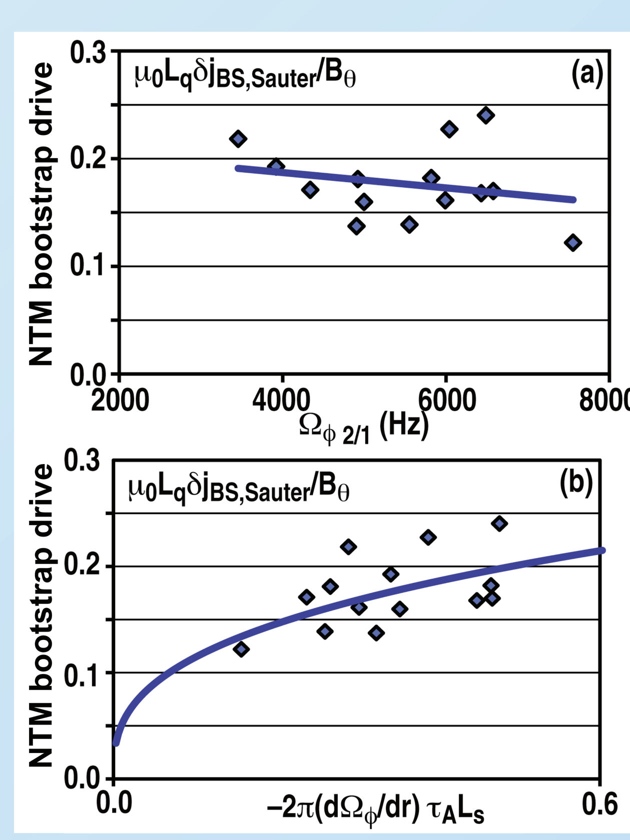
ACTION OF 3-D FIELDS IDENTIFIED THROUGH ROTATION ON NSTX



Typical discharge in NSTX

← **Field ramps applied with profiles, β_N and q_0 evolving**
- Profile evolution helps deconvolve rotation from rotation shear effects
- Vary n=1:n=3 ratio to explore physics

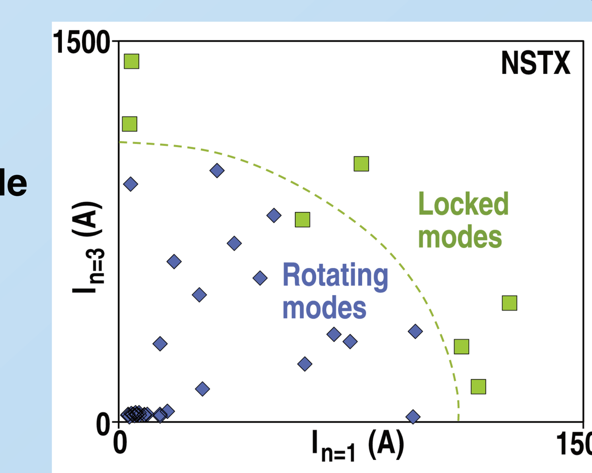
Action of fields on Modes
- **Slow field ramps: mode induced close to → natural tearing limit → mode forms rotating**
  - Thresholds plotted in terms of NTM bootstrap drive (as profiles are evolving, β is not a good proxy)
  - Effect correlates with rotation shear parameter better than rotation – *consistency, not proof* ↘
  - Braking changes underlying tearing mode stability
    - *As previously observed for NTM [4]*
- **Faster field ramps access mode sooner, with more field and lower NTM drive**
  - *See right →→*



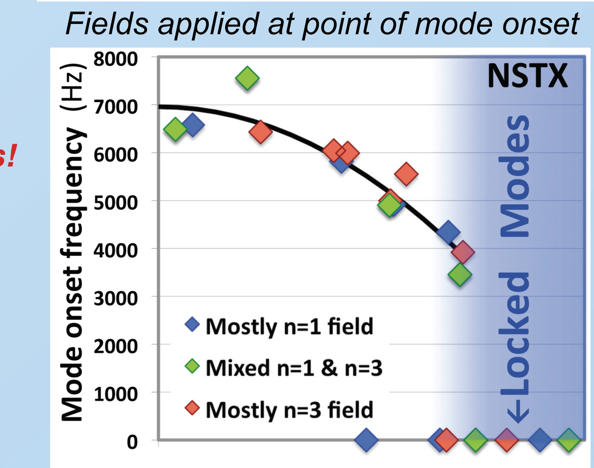
Threshold scaling of rotating 2/1 NTM induced with various n=1 and n=3 braking fields applied

Action of n=1 & n=3 fields on rotation:

- **Both types of field see a transition from → rotating to locked mode onset at high amplitude**
  - Surprising as n=3 braking is non-resonant
    - *Should tolerate low levels of rotation*
- **Both types of field give similar, progressive ↘ braking effect on q=2 rotation**
  - Here plotted against a 2-D best fit of dependence: $W_{21} = 6958 - (2.26I_{n=1} + 2.58I_{n=3})$
- **Transition to locked mode at ~50% rotation**
  - Similar to resonant error field penetration expected for Ohmic plasmas [5] – ***but here also with n=3 fields!***
- **Suggests: n=1 fields primarily act through *non-resonant* braking**
  - Opens the door to *resonant braking* from applied or residual 3-D field, once rotation lowered
- ***Threshold for both types of mode can be considered one in terms of rotation***
  - Reminiscent (but modification) of the Fitzpatrick torque balance penetration model [6]



Fields applied at point of mode onset

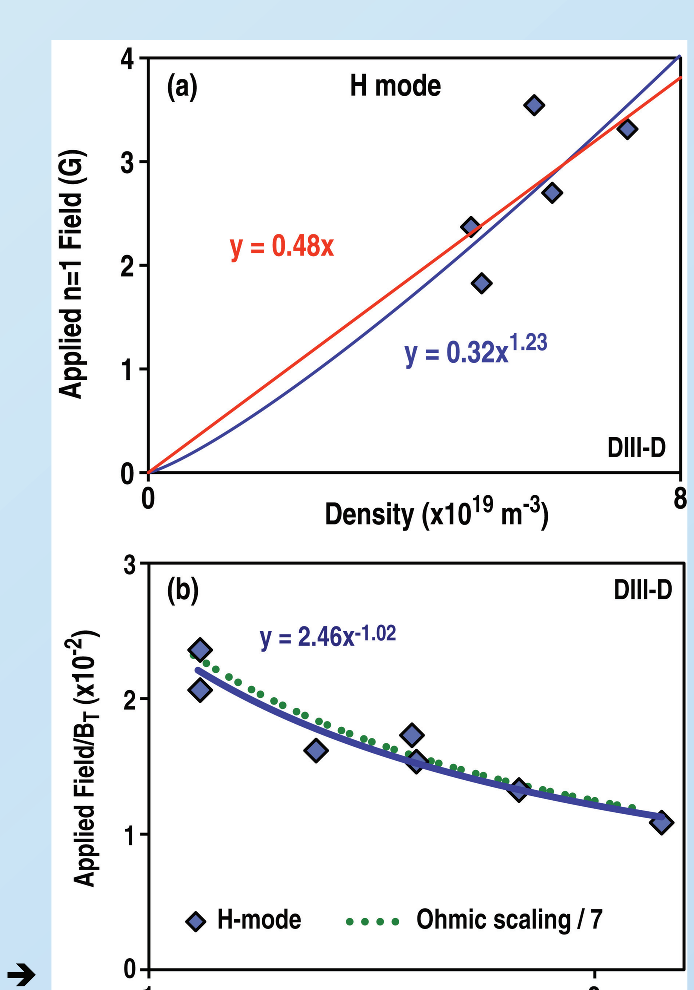


Birth frequency of 2/1 mode vs best fit against n=1 & n=3 fields

NEW CROSS MACHINE ERROR FIELD THRESHOLD SCALING IN TORQUE FREE H-MODES IDENTIFIED FOR ITER

ANSATZ: Consider mode onset (either rotating or locked) as a criteria to achieve sufficient braking → extrapolate field mode trigger thresholds in a similar manner to Ohmic error field thresholds [7]
- For given profiles and β_N

- **Ohmic error field scalings treated rotation as a hidden variable**
  - Self-generated by the plasma, implicit in scalings
  - Similar assumption can be made for torque-free H-mode:
    - *Regime of relevance to future devices like ITER*
- **Scalings follow dimensionless scaling law:** $B_{pen}/B_T \sim R^{\alpha_R} n_e^{\alpha_n} B_T^{\alpha_B}$
  - Machine size scaling from dimensional constraint: $\alpha_R = 2\alpha_n + 1.25\alpha_B$
- **Important to re-assess scalings in H-modes:**
  - Intrinsic rotation may scale differently in H-modes compared to Ohmic regimes, changing field threshold scaling
  - Proximity to NTM stability and birth of rotating mode changes physics further potentially reducing amount of braking needed to trigger modes
- ***Readily studied on DIII-D using balanced beam injection…***



Error field threshold scaling in DIII-D ITER baseline-like torque free H modes at β_N=1.8 →
Also plotted: original (ITER design basis) Ohmic error field scaling prediction for these parameters.

EXPERIMENTS:

← **Executed on DIII-D to measure n=1 field threshold to trigger modes in zero neutral torque ITER-like SND at β_N=1.8**
- Elevated q_{95} to avoid disruptions & enable other mode control studies
- Density and toroidal field varied shot to shot
  - *Generally the mode formed rotating, as in top section* ↑

- **Scalings broadly consistent with Ohmic plasmas:**
  - Linear density scaling (though more data needed)
  - Inverse B_T scaling
  - **But from 7 times lower baseline!**
    - *Interpreted as increased sensitivity from proximity to natural tearing limits, as well as β related increased ideal response*

- **Combine data to obtain new error field threshold scaling for ITER:**

$$\frac{B_{pen}}{B_T} = \left(1.72 - [\beta_N - 1.8]\right) \times \frac{\left(n_e/10^{20}m^{-3}\right)\left(R/6.2m\right)^{0.725}}{\left(B_T/5.37\right)^{1.02}} \times 10^{-4}$$

- Threshold of 1.4×10^{-4} in DIII-D extrapolates to 1.7×10^{-4} in ITER
  - Significantly lower even than low density Ohmic limit prediction: 2.9×10^{-4}
- ***Merits careful consideration of ITER error field correction strategy***

References: [1] R. J. Buttery et al., Phys. Plas. 15 (2008) 056115; [2] R.J. La Haye et al., Phys. Plas. 17 (2010) 056110; [3] J.-K. Park et al., Phys. Rev. Lett. 99 (2007) 195003; [4] H. Reimerdes et al., Nucl. Fus. 49 (2009) 115001. [5] S.P. Gerhardt et al., Nucl. Fus. 49 (2009) 032003; [6] R. Fitzpatrick, Phys. Fluids B (1991) 644 & Nucl. Fus. 33 (1993) 1049; [7] R.J. Buttery et al., Nucl. Fus. 39 (1999) 807.

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