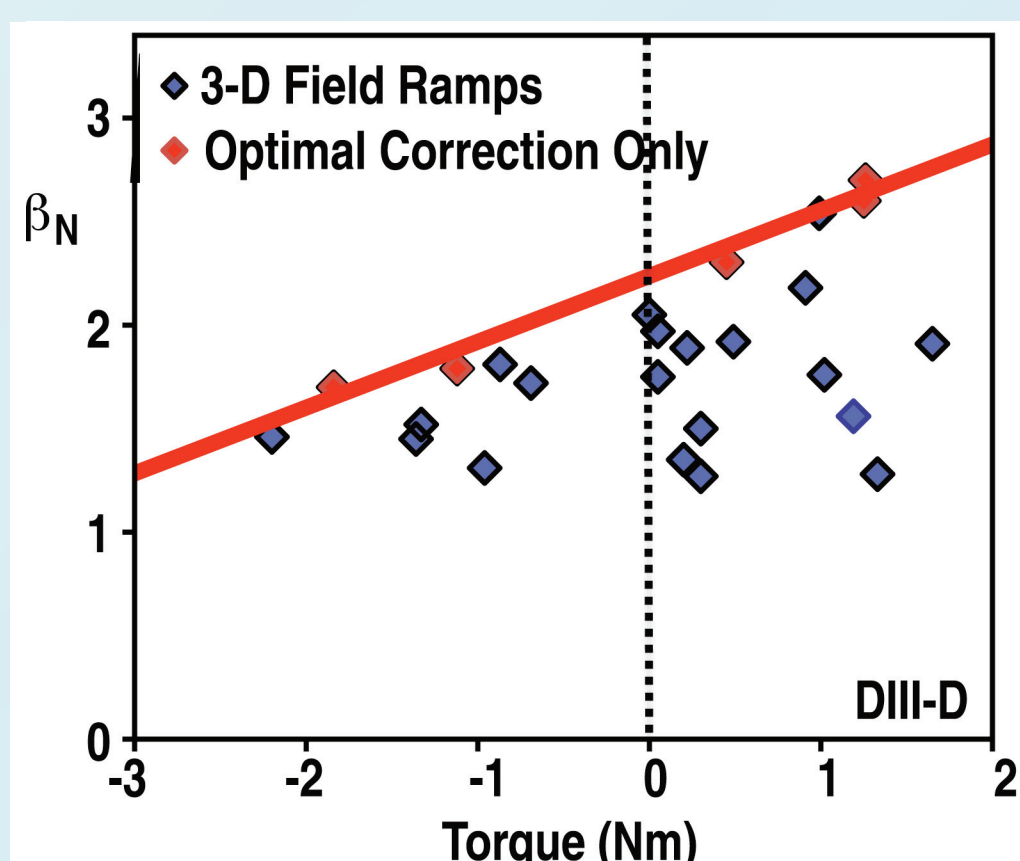


ABSTRACT & CONCLUSIONS

- 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 $\beta_N=1.8$ 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:



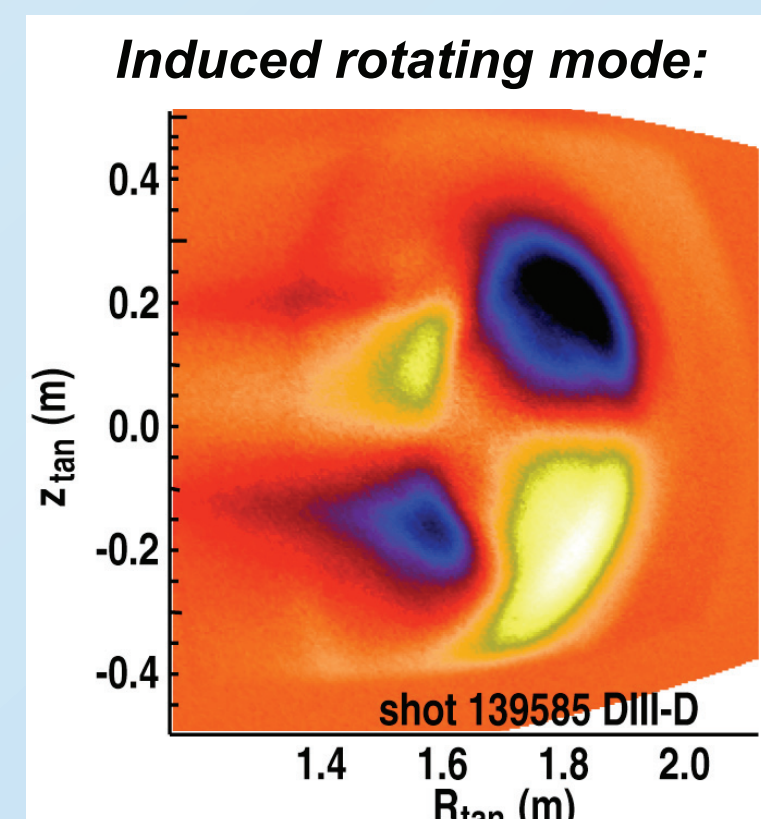
Shots run at a range of low torque and β_N

- Used ITER like SND baselines ELMy H modes with relaxed profiles & sawteeth
- Limit in red imposed by natural tearing limit:

$$\beta_{N-TM-limit} = 2.2 + 0.32T_{NBI}$$

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]



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

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

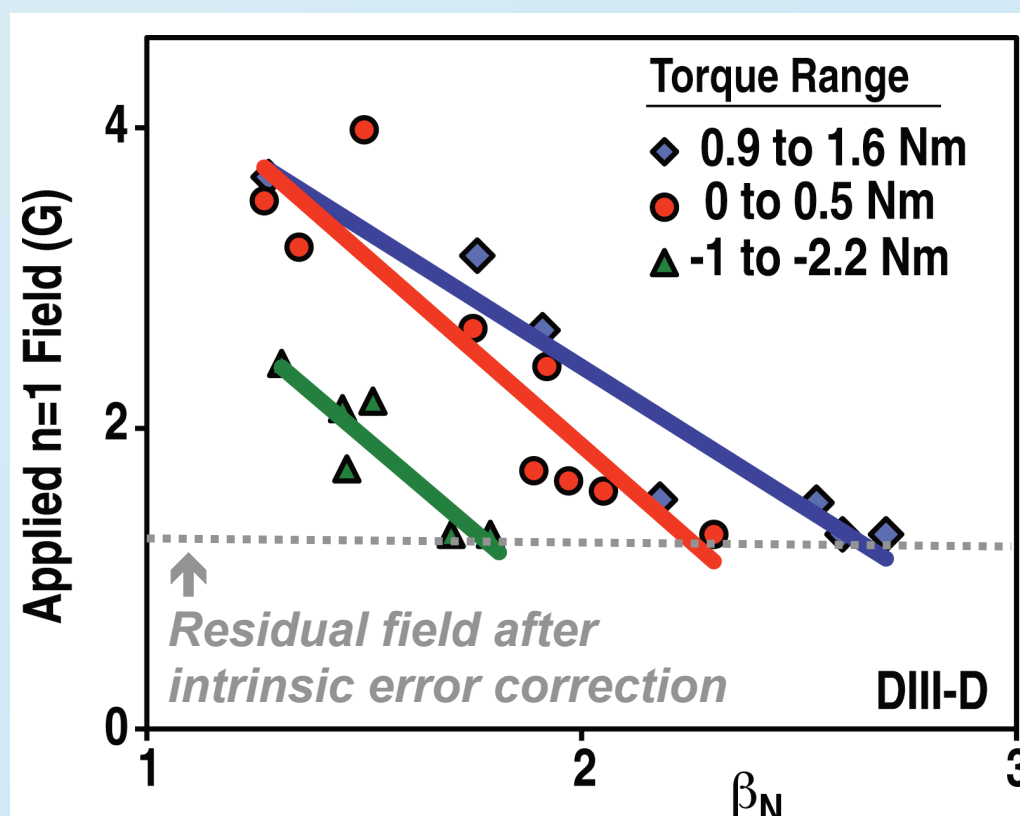
Threshold well fitted by proximity to natural tearing limit (see above)

Is this evidence of a resistive response?

- Significant concern for plasmas operating close to tearing β limits

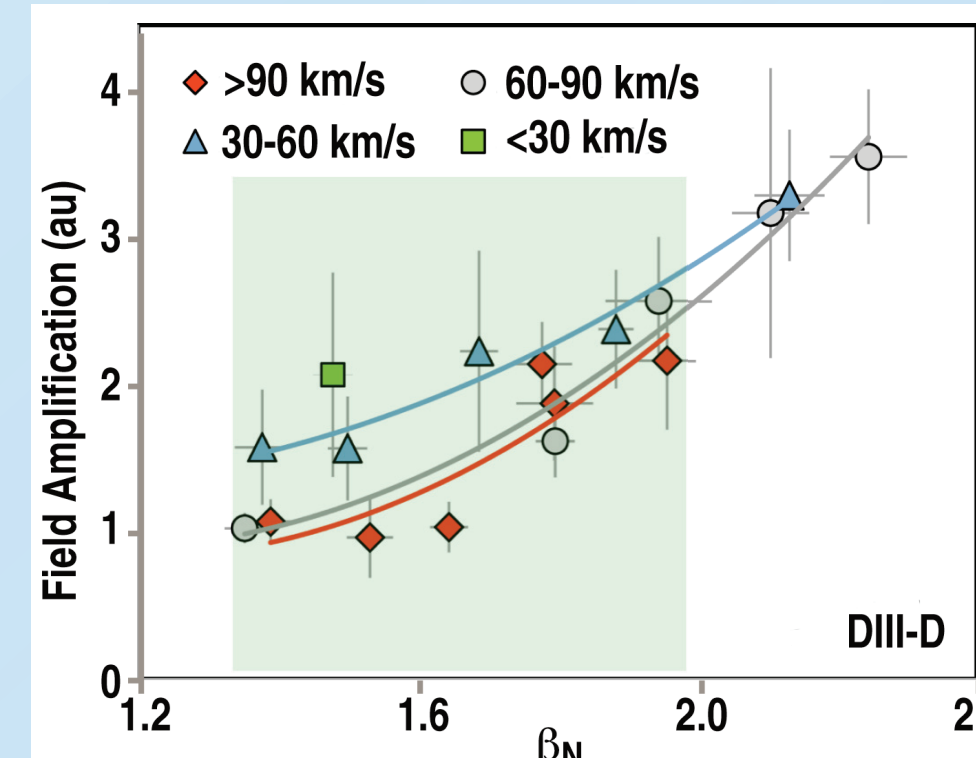
(Field thresholds are measured in terms of component at plasma boundary that generates plasma response at $q=2$, including plasma ideal response [3])

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



$n=1$ field threshold vs torque and β_N

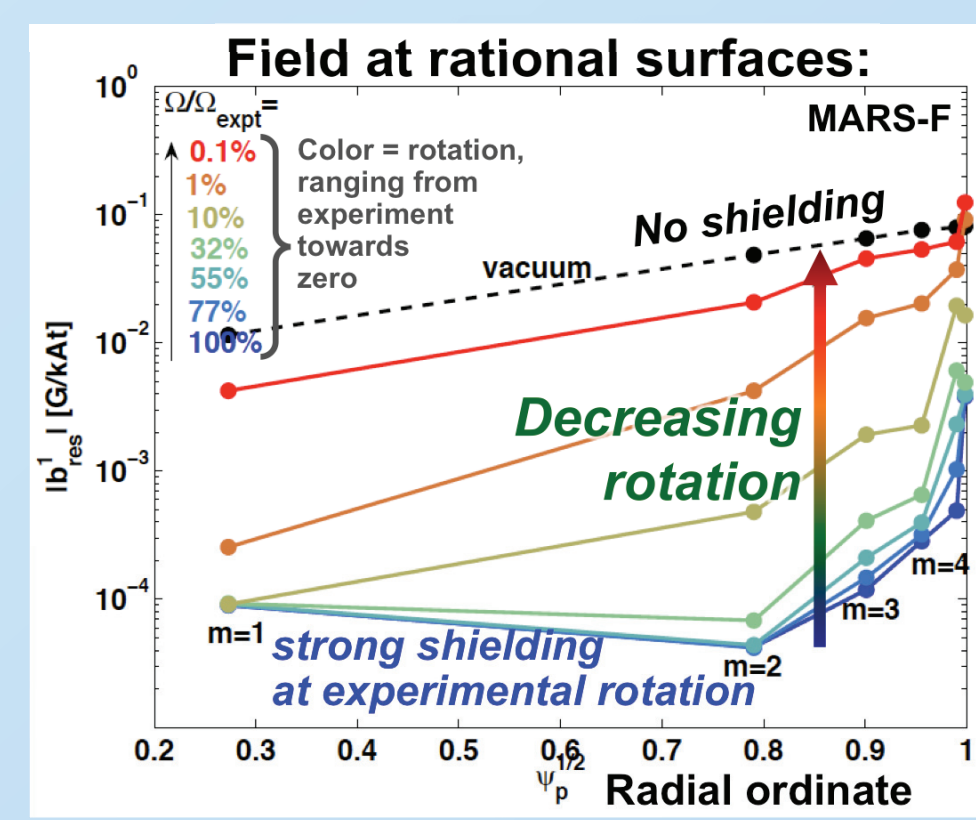
Magnetic response to low amplitude 10Hz probing field:



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 \rightarrow resistive response at $q=2$
- Proximity to tearing instability also an important factor in this response

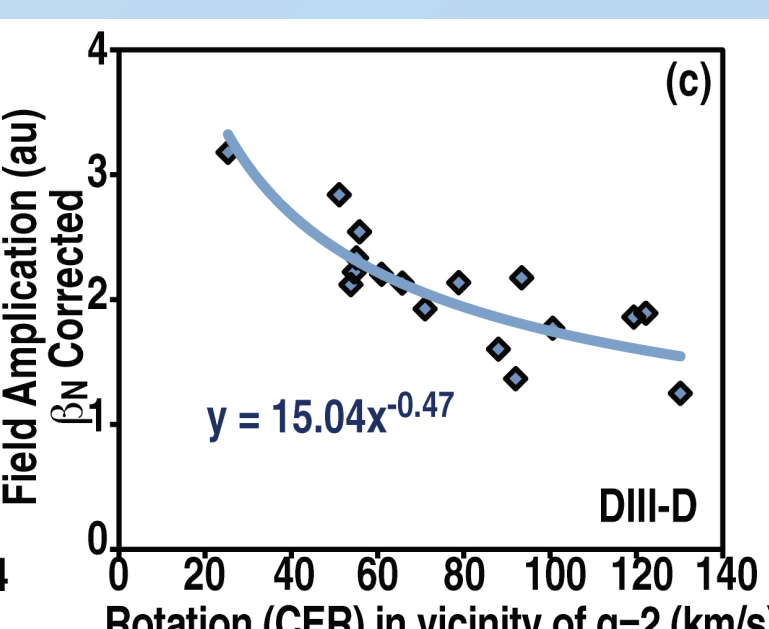
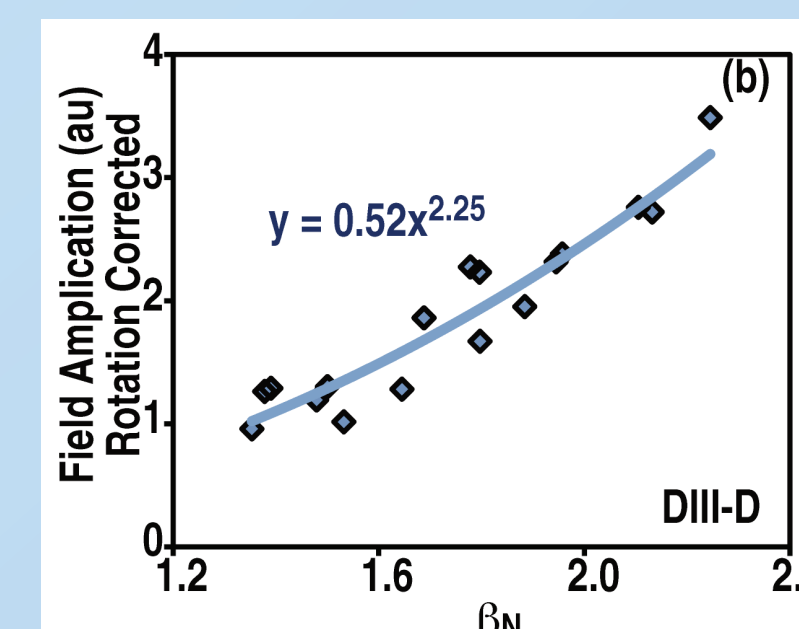
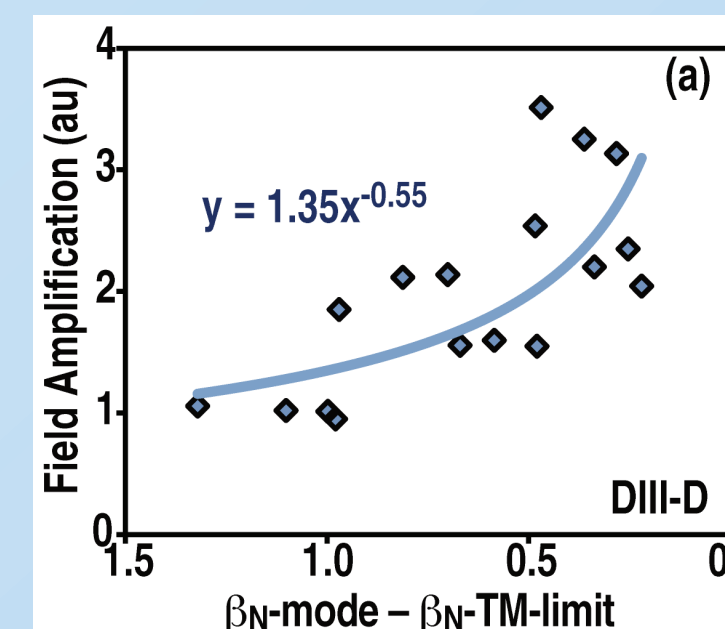


Modeling a $\beta_N=1.9$ case with MARS code shows local responses at rational surfaces rises as rotation falls

- Usual shielding response is weakening

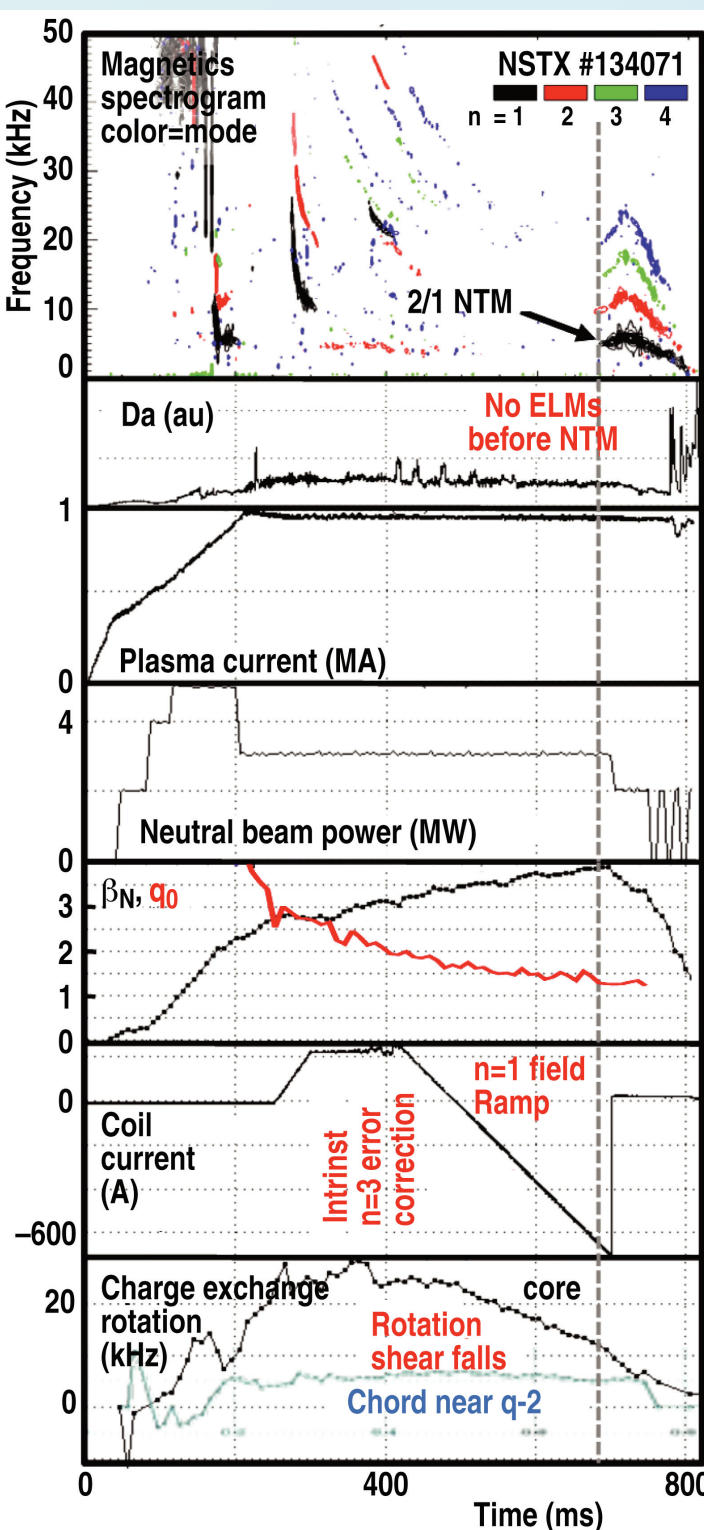
Field amplification not simply a function of proximity to tearing limits

- A 2-D fit in β_N and rotation is better \downarrow
- 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

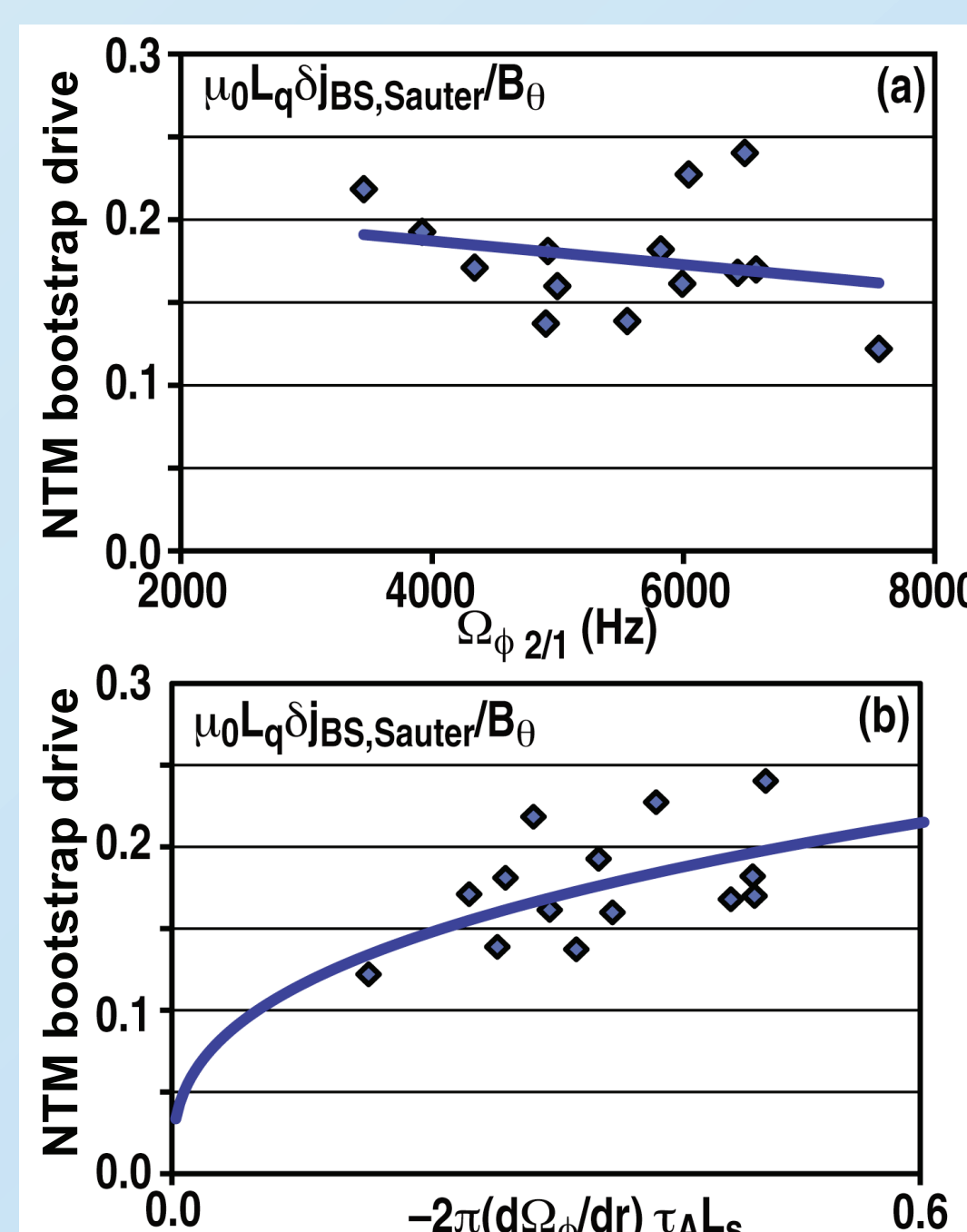
Action of fields on Modes

Slow field ramps: mode induced close to natural tearing limit \rightarrow 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 \downarrow
- 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

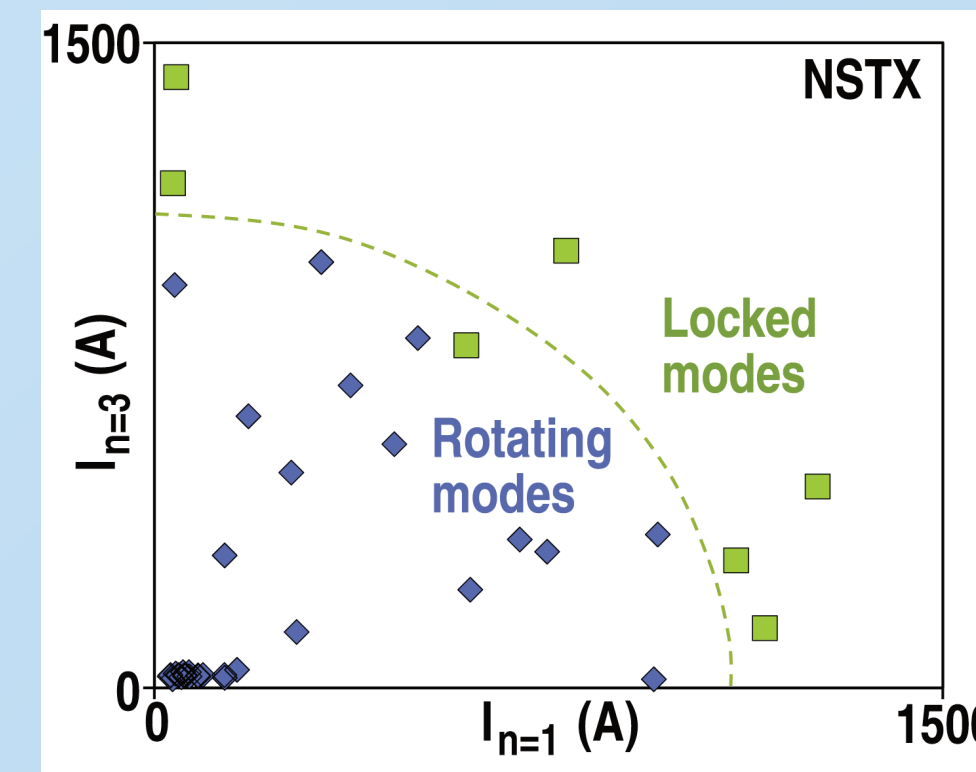
See right \rightarrow



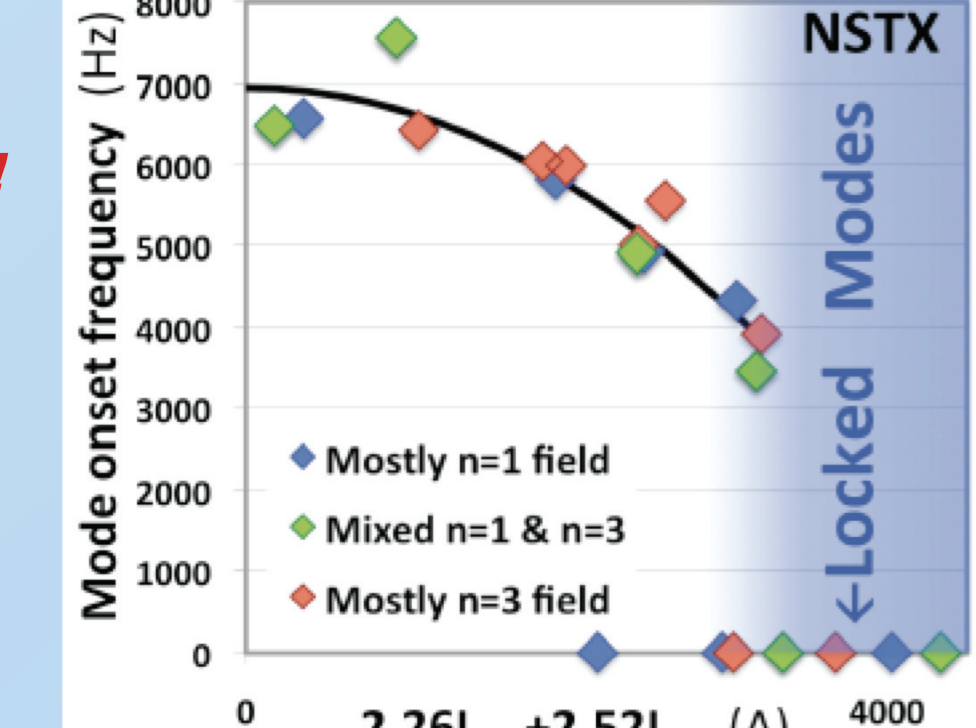
Threshold scaling of rotating 2/1 NTM induced with various $n=1$ and $n=3$ braking fields applied

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: $\Omega_{21} = 6958 - (2.26I_{n=1} + 2.52I_{n=3})^2$
- Transition to locked mode at $\sim 50\%$ 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 \rightarrow 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

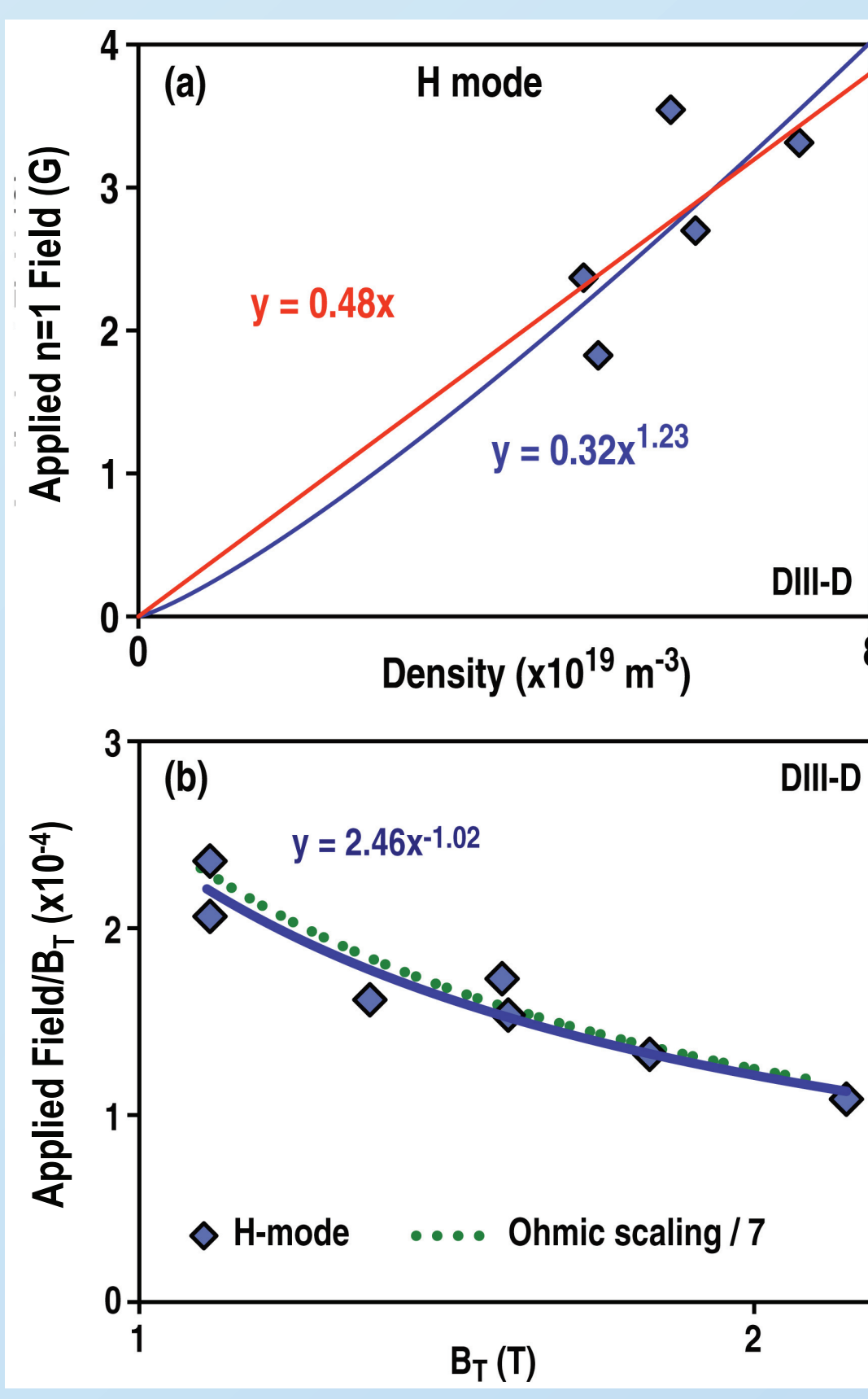
Scalings follow dimensionless scaling law: $B_{pen}/B_T \sim R^{\alpha_R} n_e^{\alpha_n} B_T^{\alpha_B}$

- 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 $\beta_N=1.8$ \rightarrow 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 beam torque ITER-like SND at β
 - 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 \uparrow
 - 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:
- $$\frac{B_{pen}}{B_T} = (1.72 - [\beta_N - 1.8]) \times \frac{(n_e / 10^{20} m^{-3}) (R / 6.2m)^{0.725}}{(B_T / 5.3T)^{1.02}} \times 10^{-4}$$
- 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