US MHD Workshop, Princeton, Oct 2009

Effect of 3d Fields near the Tearing Beta Limit

by Richard Buttery[1]

with Stefan Gerhardt[2], Rob La Haye[1], Steve Sabbagh[3]

[1]General Atomics, USA.
[2]Princeton Plasma Physics Laboratory, NJ.
[3]Columbia University, NY.

Work funded by the US DOE.

GENERAL ATOMICS

DIII-D NATIONAL FUSION FACILITY

EFDA JET

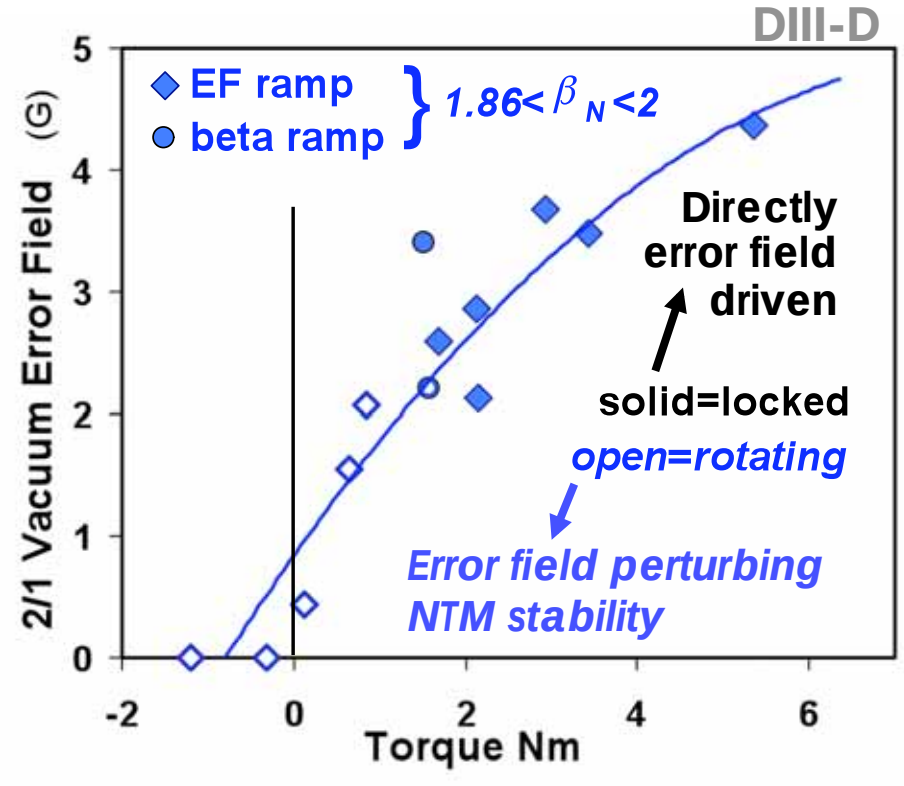
CCFE CULHAM CENTRE FOR FUSION ENERGY

NATIONAL SPHERICAL TORUS EXPERIMENT

PPPL PRINCETON PLASMA PHYSICS LABORATORY

How do Error Fields Interact with Plasma?

DIII-D experiments show <u>resonant</u> error field can act through two mechanisms to drive modes in high β plasmas:



- **Locked modes:**
  - Influenced by proximity to
    - ideal kink beta limit?
    - classical tearing limit?
  - Role of rotation?
- **Rotating modes:**
  - EF perturbing classical or neoclassical stability?
    - Action through rotation or rotation shear?

→*EFs can probe NTM physics*

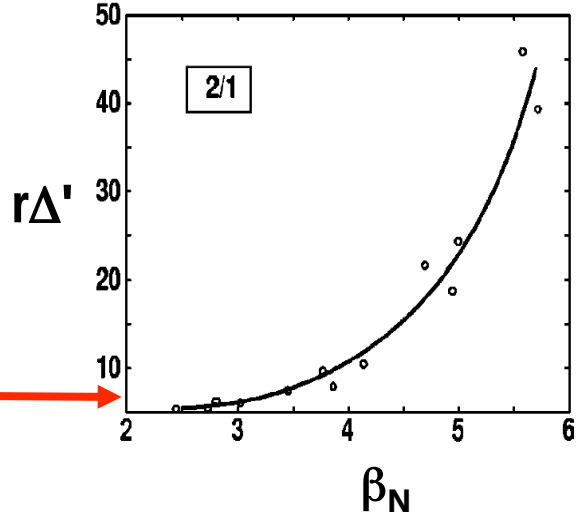
→*Measure error field response & correction requirements…*

2/1 Tearing β Limits May Be Governed by Pole in Δ'
– Introducing dependency on current and flow profiles

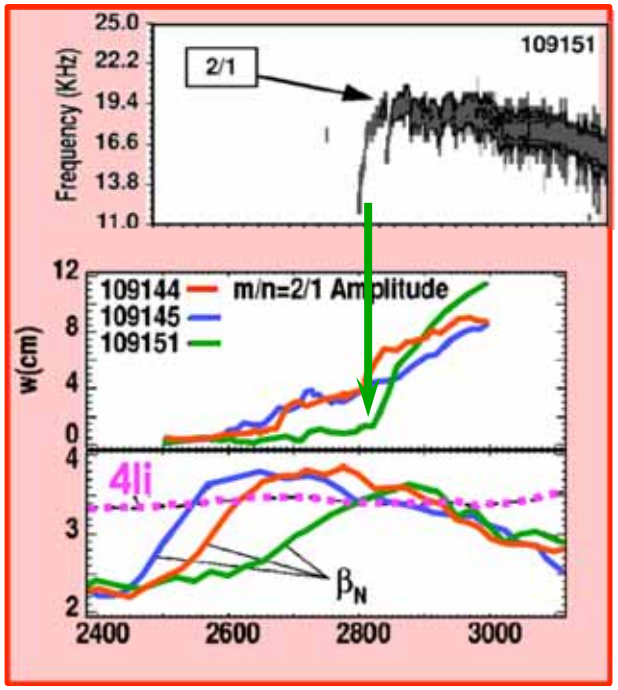
- **Calculations show Δ' rises as ideal β limit approached**

Seedless 2/1 modes observed as β_N crosses ideal no-wall limit

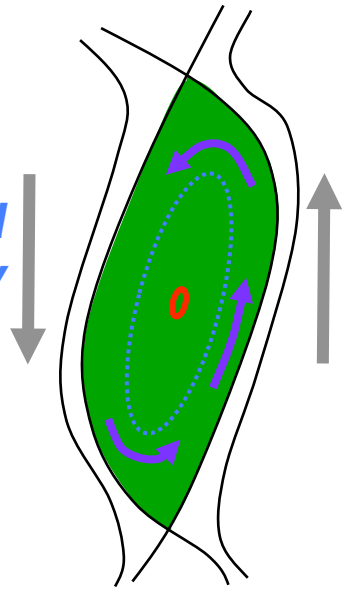
- *Current profile governs baseline Δ' & gives means to raise thresholds*



[Brennan et al, PP10, 1643]



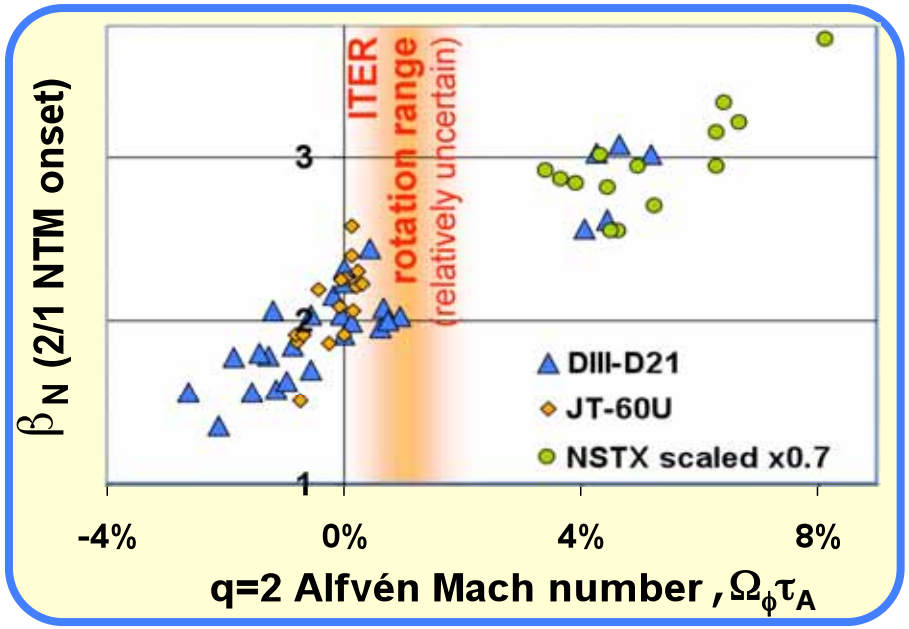
- **Island stability may also be modified by flow shear:**
  - *Viscous coupling distorts island structure changing free energy*



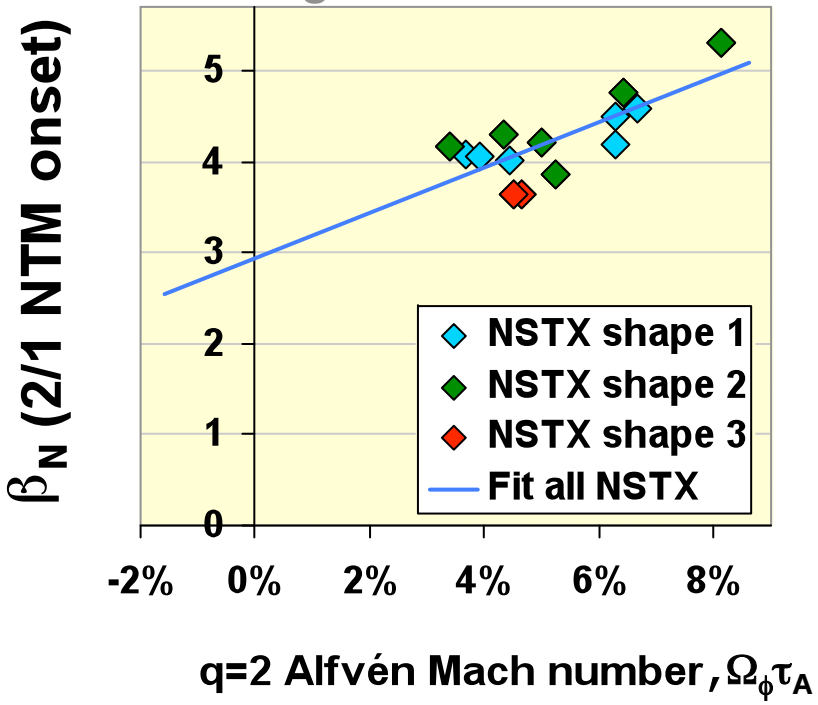
- **Error fields can perturb flows in the plasma**
  - *Response to error fields may depend on plasma stability ← β_N,Δ'*

NSTX Studies Have Shown a Rotation Effect in Error Field Interaction & Impact on NTM β limit

- **n=3 braking showed 2/1 NTM thresholds rise with rotation**
  - **Consistent with rotation trends from beam mixing studies on DIII-D & JT-60U:**



NSTX: n=3 braking perturbs rotating 2/1 NTM beta limit



→ ***How is rotation acting on NTM stability?***

→ ***What are practical error field limits?***

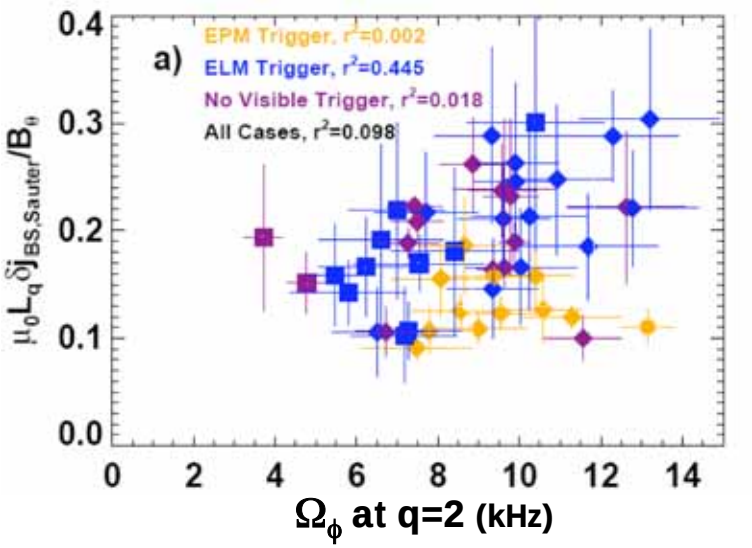
NSTX Database Study Suggested Rotation Acts Through the Local Rotation Shear at the Island

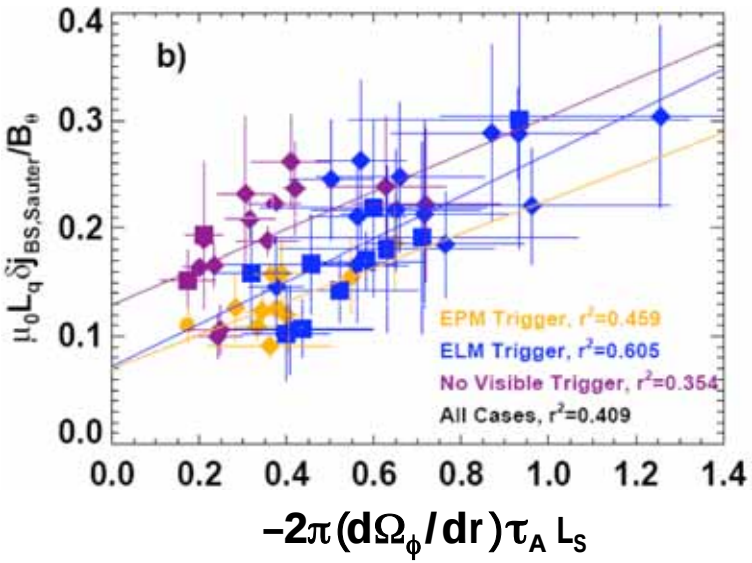
- **Gerhardt analysis[1] compared trends for different types of NTM trigger across NSTX 2007 campaign**
  - **no n=1 braking in this data set**

Goal 2009: Controlled study of error field effect in constant conditions:

  - **Decouple rotation roles further with n=1 and n=3 fields**
  - **Learn about error field interaction**

- ***Achieved reproducible scans by tuning H mode:***
  - **shape, gas, lithium**





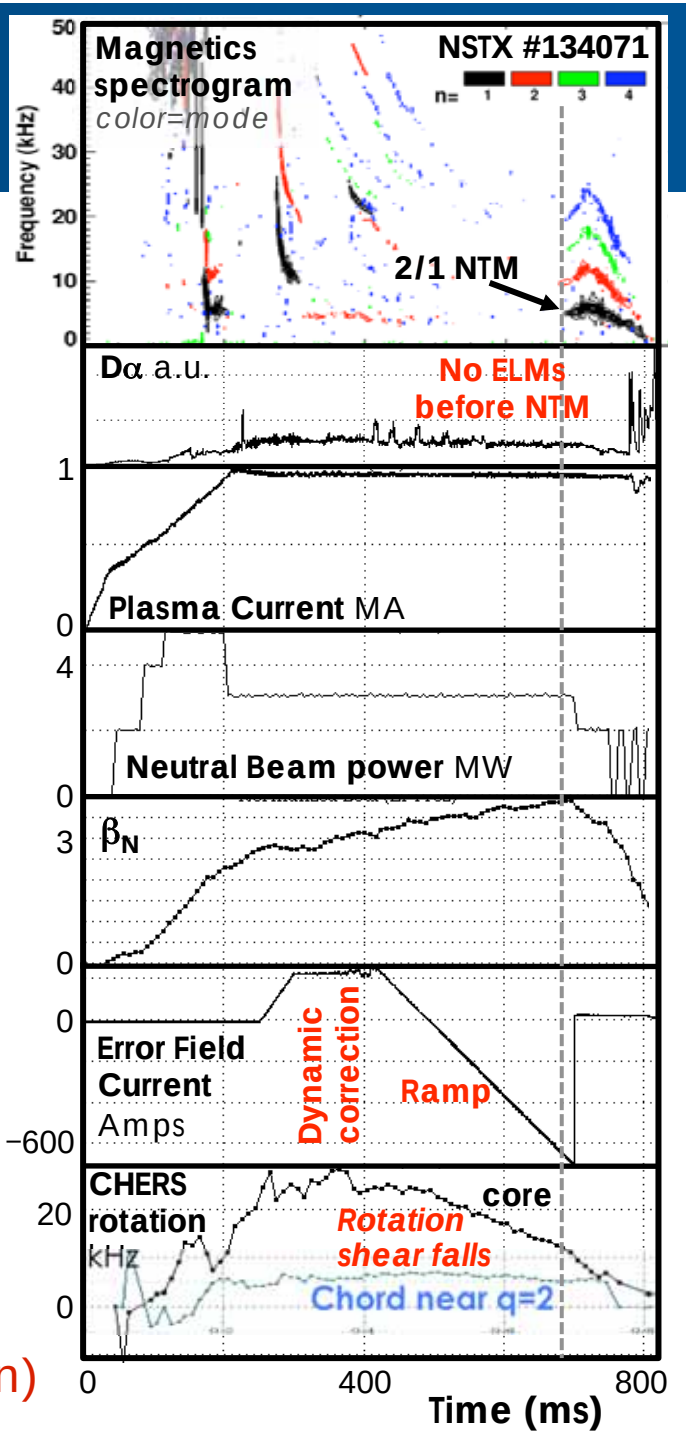
[1S.P. Gerhardt, NF (2009) 032003.]

New NSTX Experiment:
Ramp Error Fields to Make Mode

- **Vary ratio n=1:n=3 fields shot to shot**
- **Typically ELMs are small (due to lithium)**
- **No clear NTM trigger in most shots**
  - **'Seedless' – must be Δ' triggered**

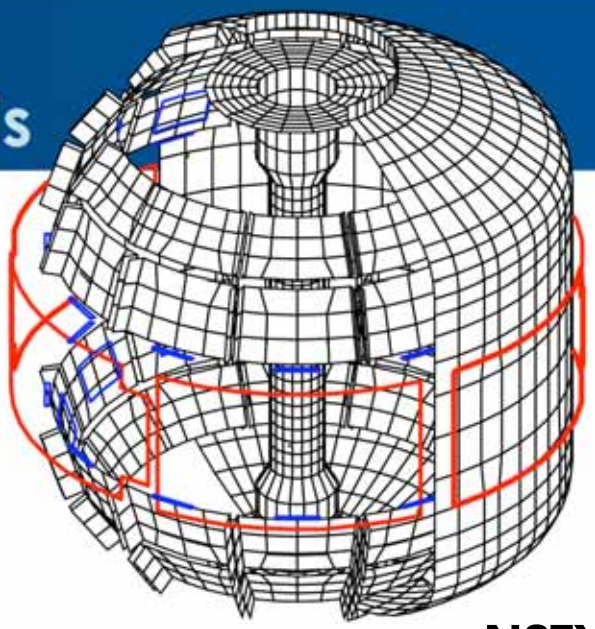
Other shot details:

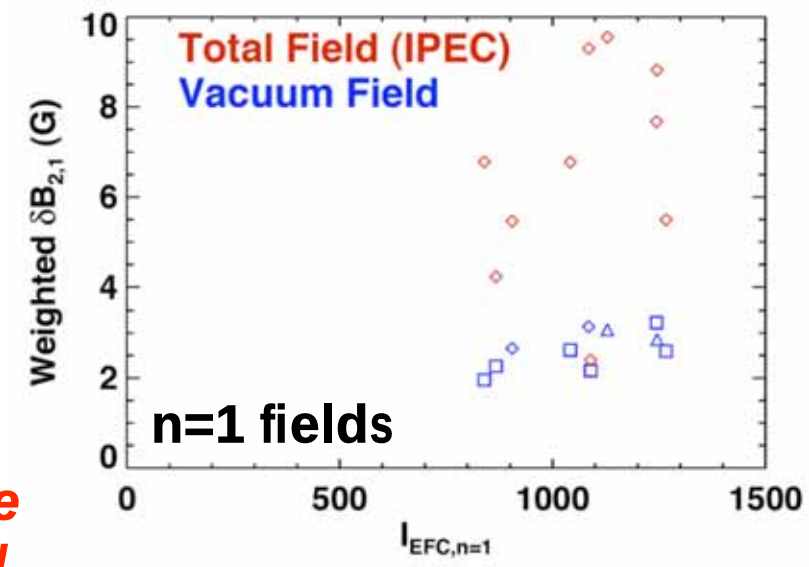
- **Early strong heating for H mode**
- **MHD at 300ms when q=2 appears**
- **Reproducible conditions & front end to eliminate q profile changes shot-shot**
  - From evaporating lithium each shot
- **But note q relaxing towards q=1 (when bad MHD would occur)**
  - (Role of q_{min}=1 with EF under investigation)



Applied Error Fields
Mix of n=1 & n=3 from Midplane Coils

- **n=1 field computed for various shots across the scan:**
  - **Vacuum field is ~2.5G/kA (m=2 n=1 at q=2 surface)**
  - **Including plasma response from other surfaces (IPEC) raises total field at q=2**

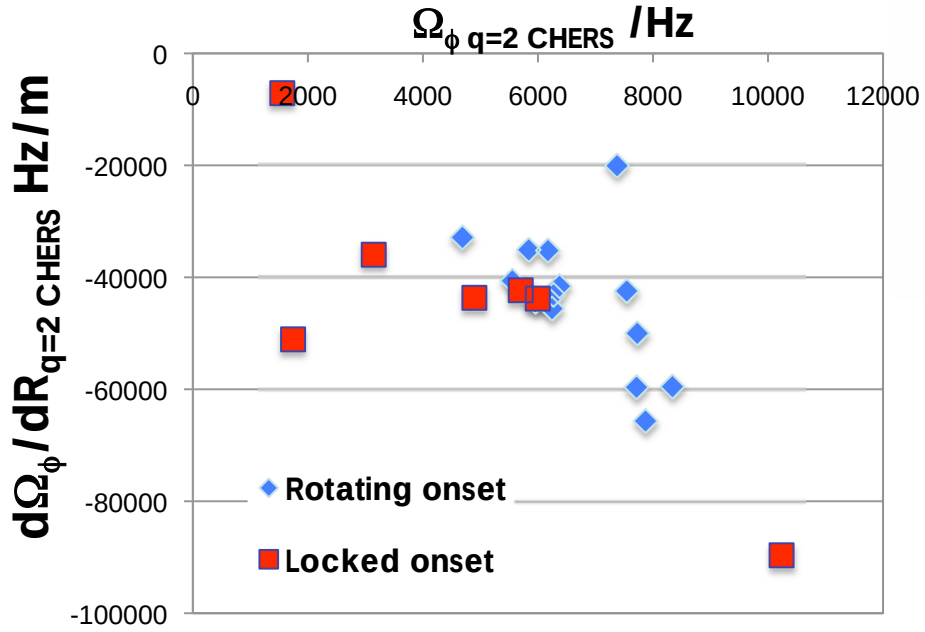


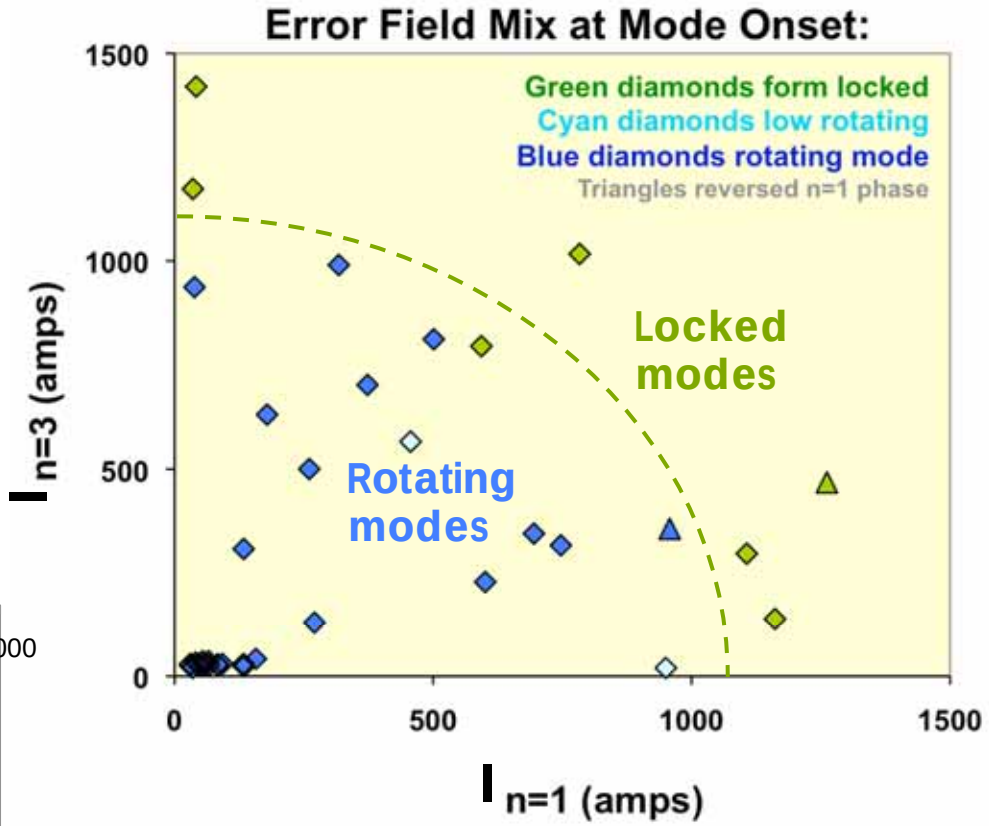


- **n=3: no similar formalism to compare size (as non-resonant)**
  - **Typical surface averaged |B| is a few Gauss**
  - ***But may be best to compare relative magnitudes in terms of coil currents!***
    - *Gives better idea of relative field strengths*

New Experiments Perturbed β Limit with Wide Range of Resonant n=1 & Non-resonant n=3 Fields

- **n=1 and n=3 fields varied up to locked mode limits (◆)**
  - **Locked mode threshold with roughly equal levels of n=1 and n=3 field current**
  - **Wide variation in rotation profile achieved:**

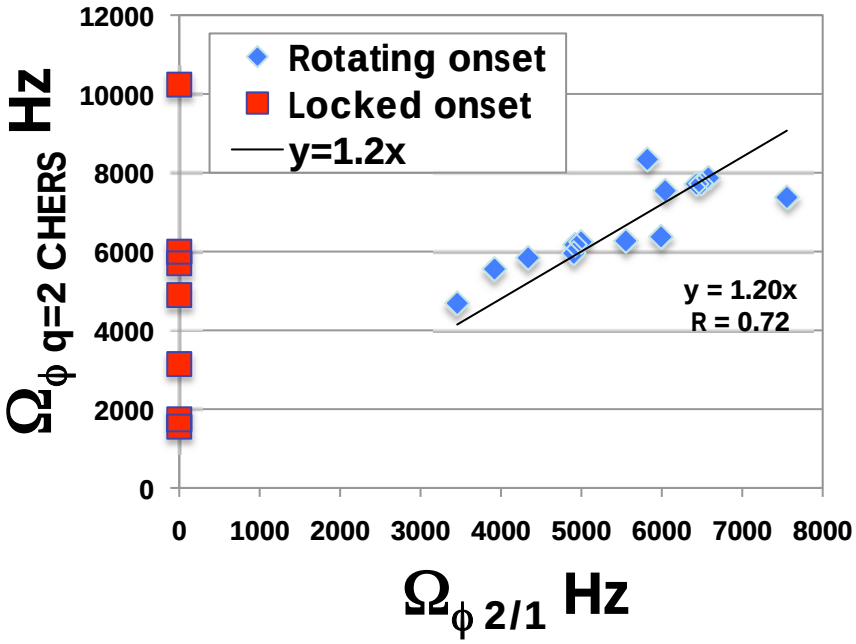


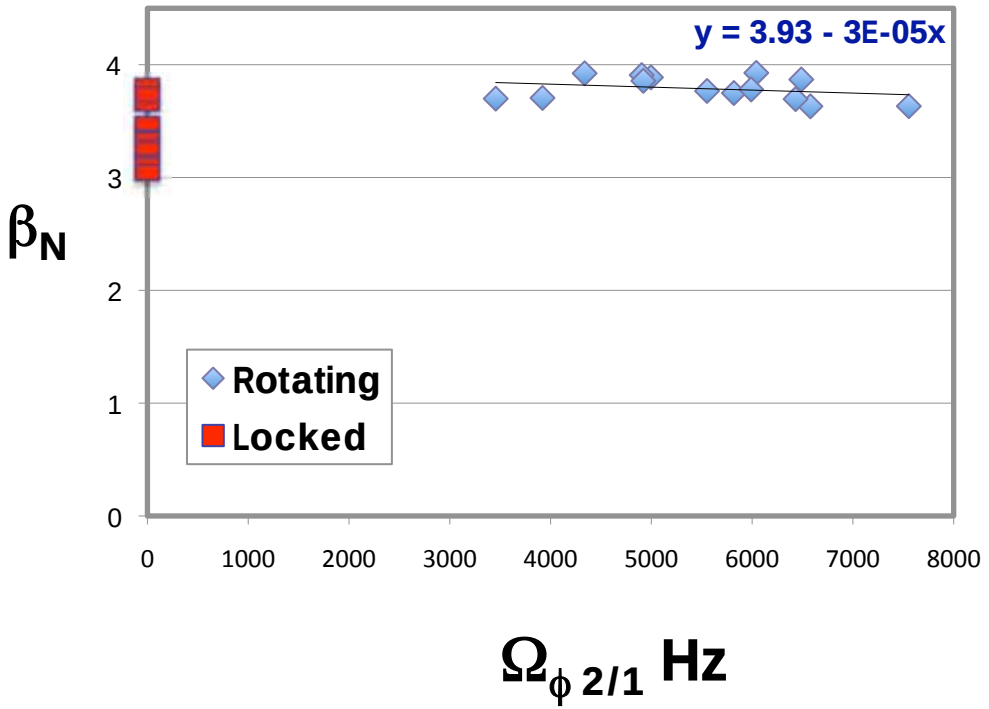


- **Locked modes much slower on CER but not at zero rotation**

Differences in CHERS q=2 and 2/1 mode rotation

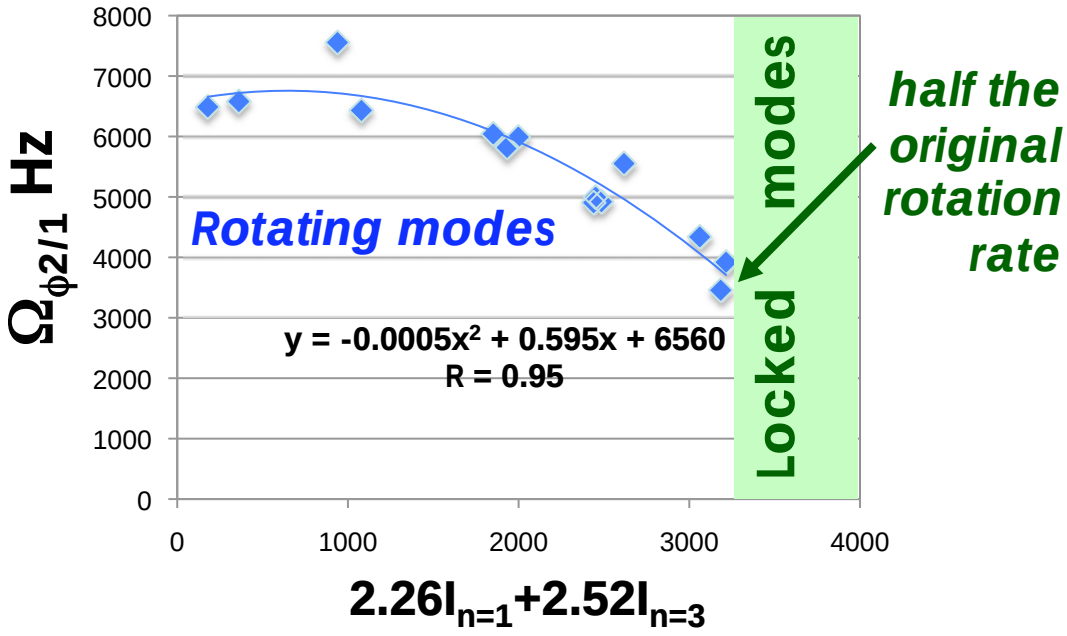
- **Mode forms locked while CHERS shows plasma rotating**
  - **Actual mode onset rotation is lower than CHERS**
    - Coupling to ELMs?
  - **Locked mode stops MHD fluid while plasma still flows**

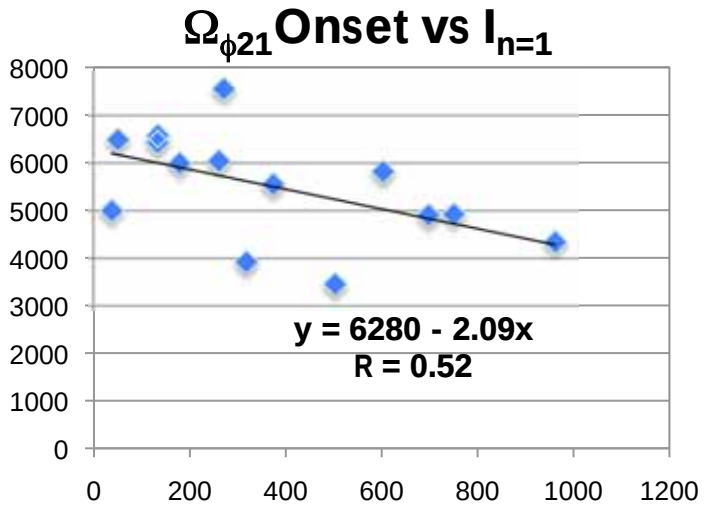


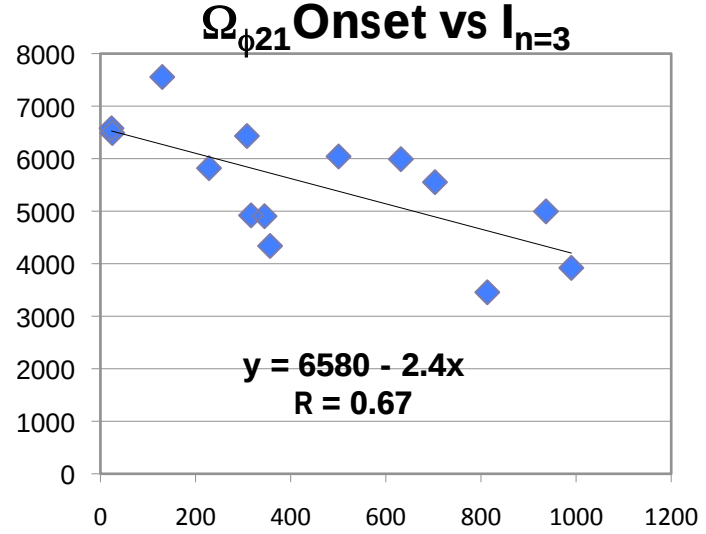


Braking Effect: n=1 & n=3 Contribute Similarly to Braking

- **Both n=1 and n=3 brake plasma**
- **Best fit is combination of similar levels of n=1 and n=3 currents:**
  - $\Omega_{\phi 21}=7500 - (2.26I_{n=1} + 2.52I_{n=3})$
    - ***Good correlation for braking:***



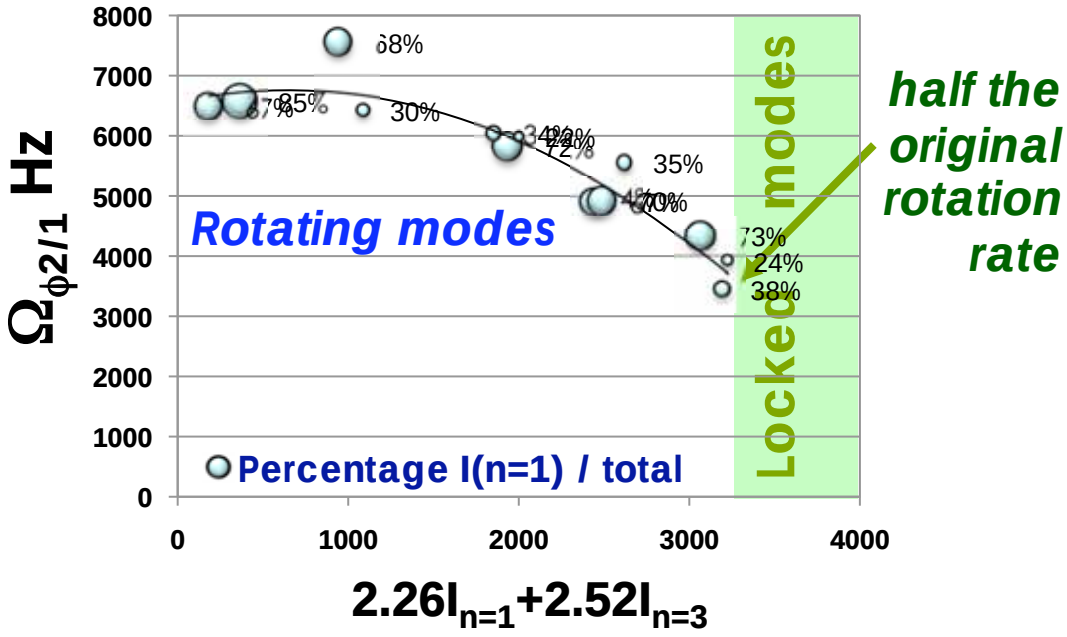


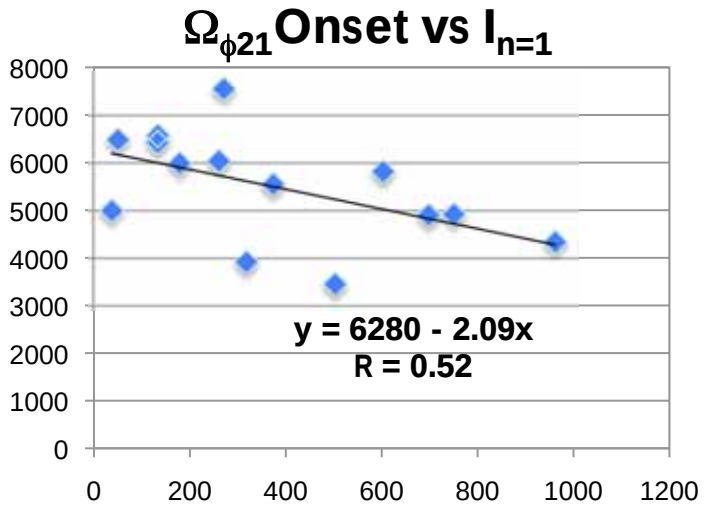


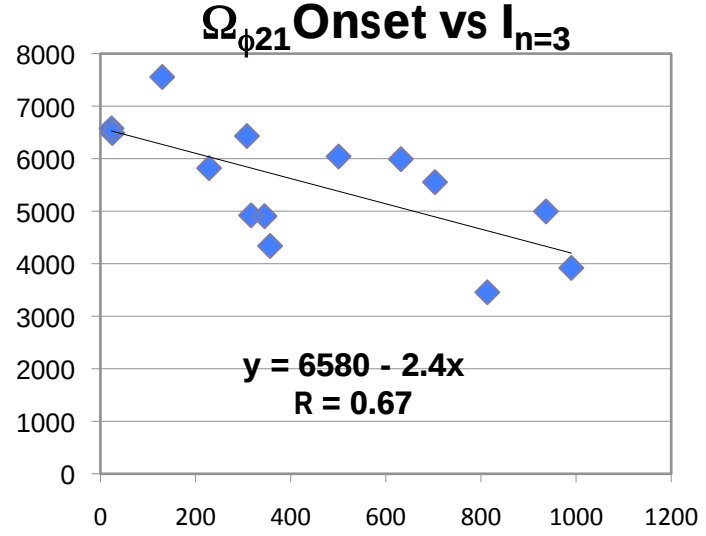
✓ ***Matches Fitzpatrick theory: Penetration at half natural rotation rate.***

Braking Effect:
n=1 & n=3 Contribute Similarly to Braking *& LM threshold*

- **Both n=1 and n=3 brake plasma**
- **Best fit is combination of similar levels of n=1 and n=3 currents:**
  - $\Omega_{\phi 21}=7500 - (2.26I_{n=1} + 2.52I_{n=3})$
    - ***Good correlation for braking:***



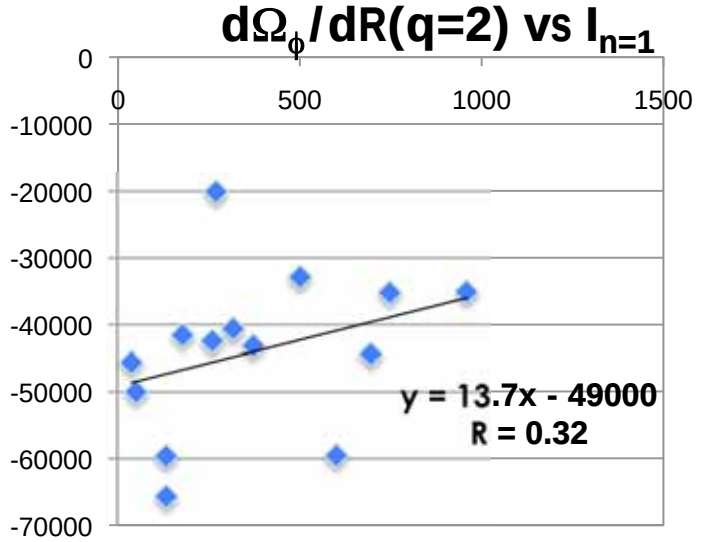


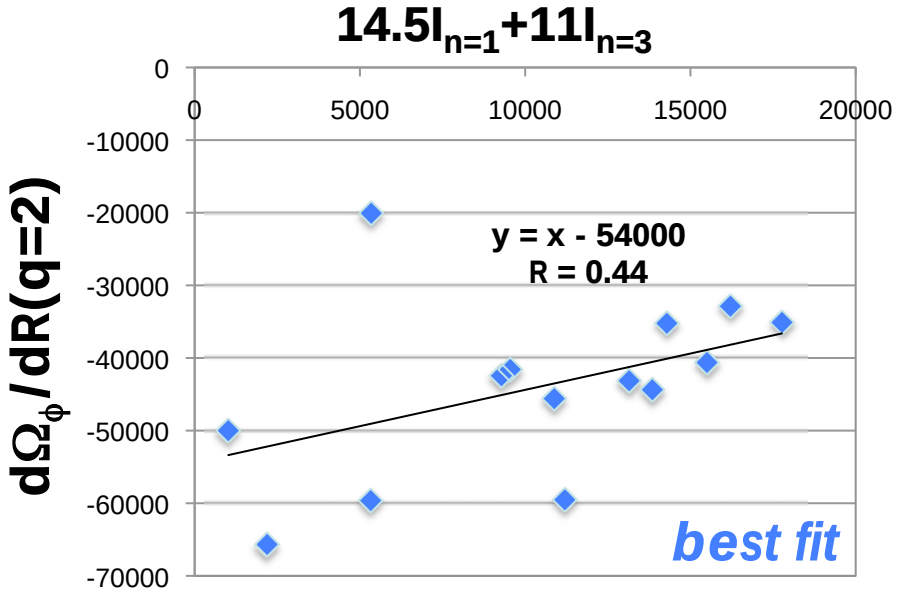


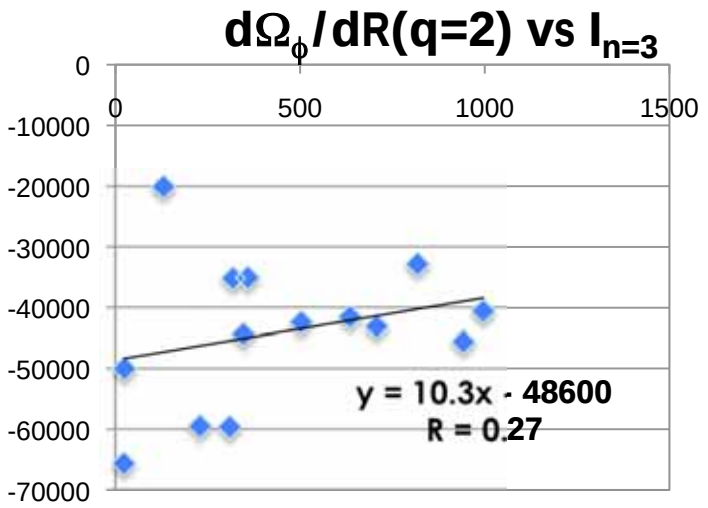
✓ ***Fitzpatrick theory: Kind'a odd this works for n=3 – shouldn't?***

Rotation Shear Much More Variable Over The Scan – *provides opportunity to decouple from rotation trend*

- **Rotation shear more scattered than simple dependence on n=1 & n=3**
  - **Although both forms of braking reduce rotation shear – *best fit:***
    - $d\Omega_{\phi 21}/dR = -54000 - (14.5I_{n=1} + 11I_{n=3})$
  - **Can decouple rotation shear from rotation effects – *which governs NTM?***

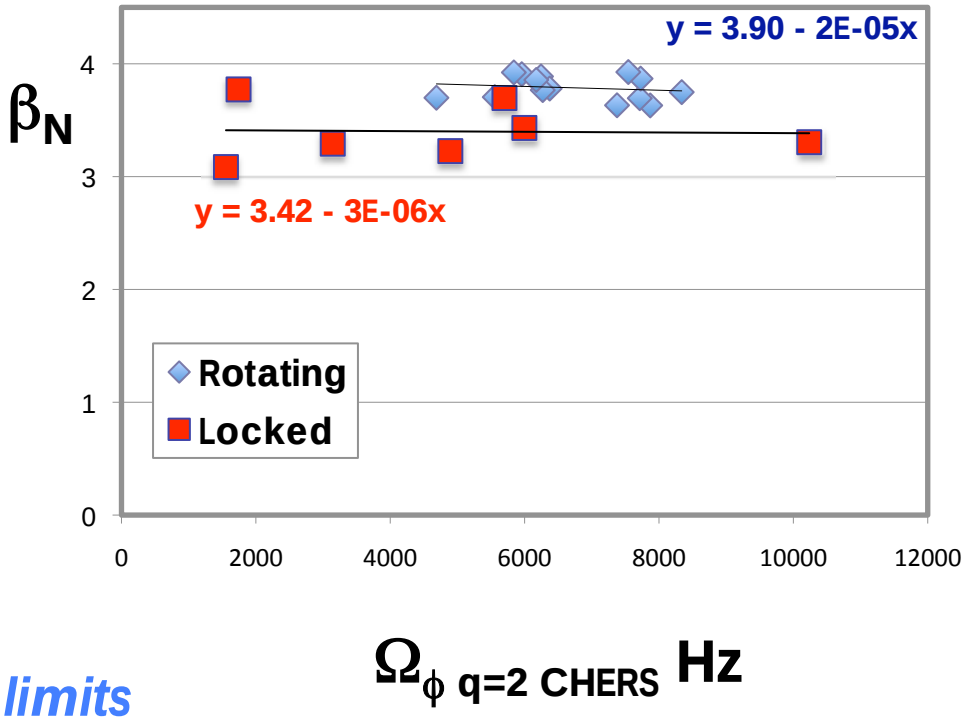






Mode Forms at Lower β_N when Locked

- **Locked mode threshold is 0.5 lower in β_N**
  - May be partly confinement reduction
  - stripped out for rest of this analysis (J-KP analyzing locked mode physics[1])



- **Rotating mode shows no rotation dependence!**
  - *Generally below no-wall β_N limits*
  - ***But need to look at drives in local parameters & understand what we really varied***
    - ***How does braking impact rotation and mode drives?***

[1Poster: PP8.00051, Jong-Kyu Park]

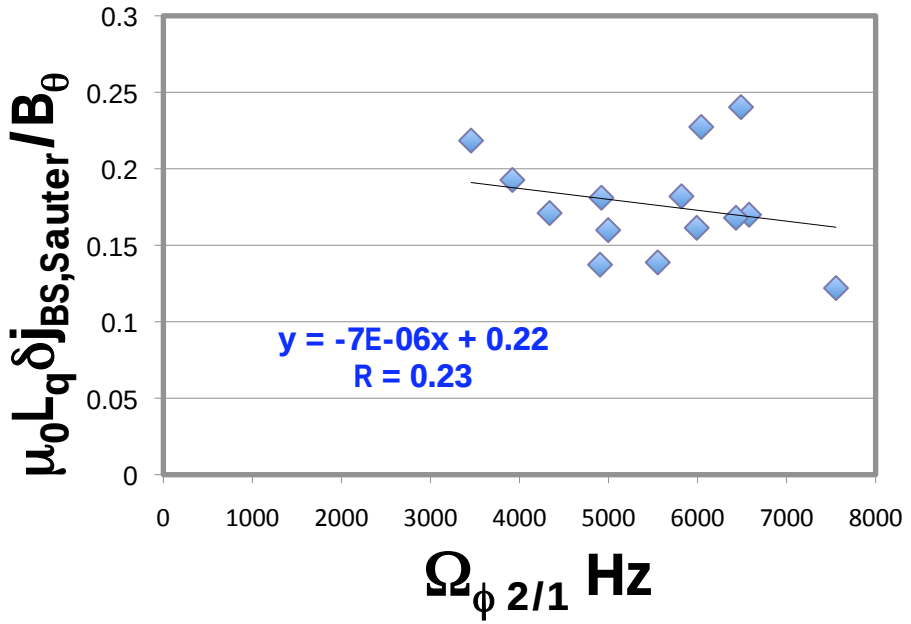
Bootstrap Drive Measure of NTM Threshold Suggests Dependence Through Rotation Shear

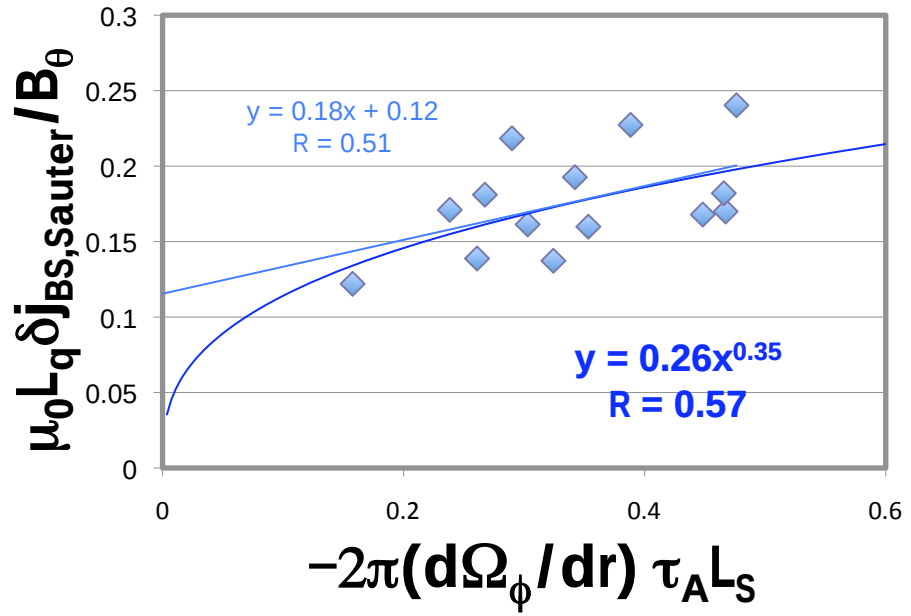
- **No measurable trend with rotation!**
- **Weak positive correlation with normalized rotation shear**
  - **Lowest thresholds at low rotation shear**
  - **Highest thresholds at high rotation shear**
  - **Best 'fit' is power law**

This correlation in the 'most noisy' parameters suggest physics is right:

  - ***Rotation impact is through shear changing Δ'***

- **No correlation if fit β_N instead**
- **Fit vs rotation & rotation shear offers little improvement**





Conclusions on Rotation & Error Fields

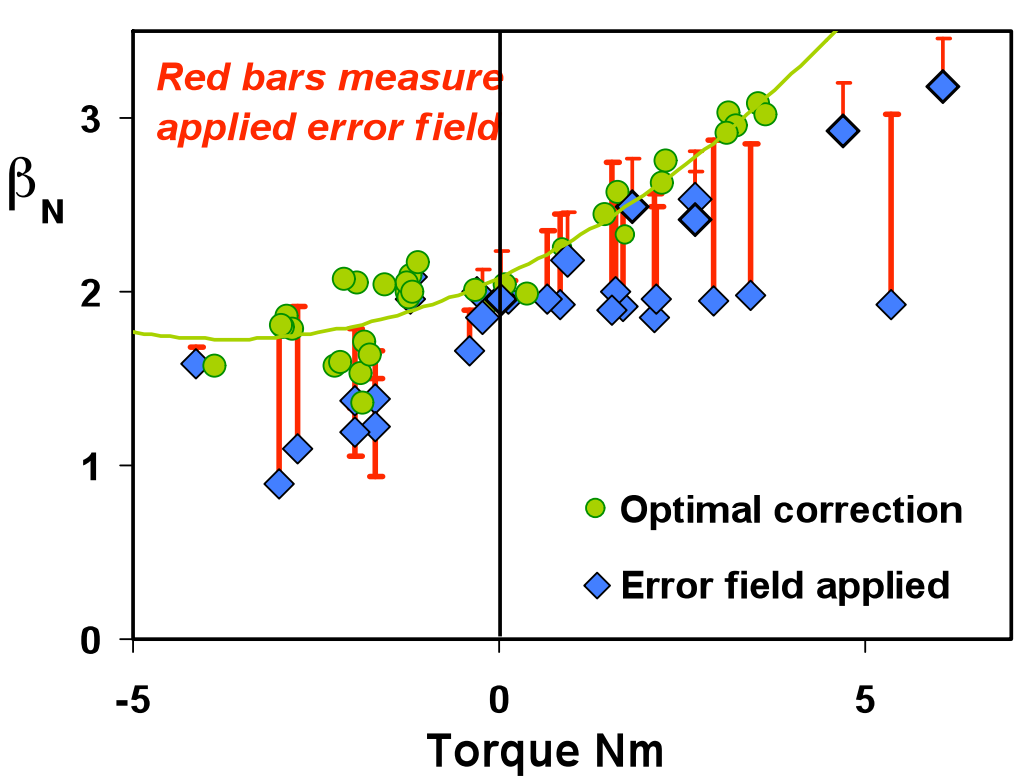
- **NTM threshold dependence on rotation comes through flow shear impact at the rational surface**
  - **Confirms previous database study in controlled conditions**
  - **Correlations with rotation completely stripped out!**
    - ***Suggests changes to inherent plasma stability at the tearing resonant surface play an important role in determining mode onset***
- **Threshold between rotating & locked mode regime at half natural plasma rotation – *for n=1 & n=3 fields!***
  - **Locked modes above this (à la Fitzpatrick)**
- **Locked mode cases exhibit confinement degradation *before* mode onset, and have a lower β_N limit**
- **Both n=1 resonant braking and n=3 non-resonant braking have similar effects on plasma and mode**

Work in progress – some points to think about…

New DIII-D experiments to look at Δ' role

Error field interact with tearing β limit. How?

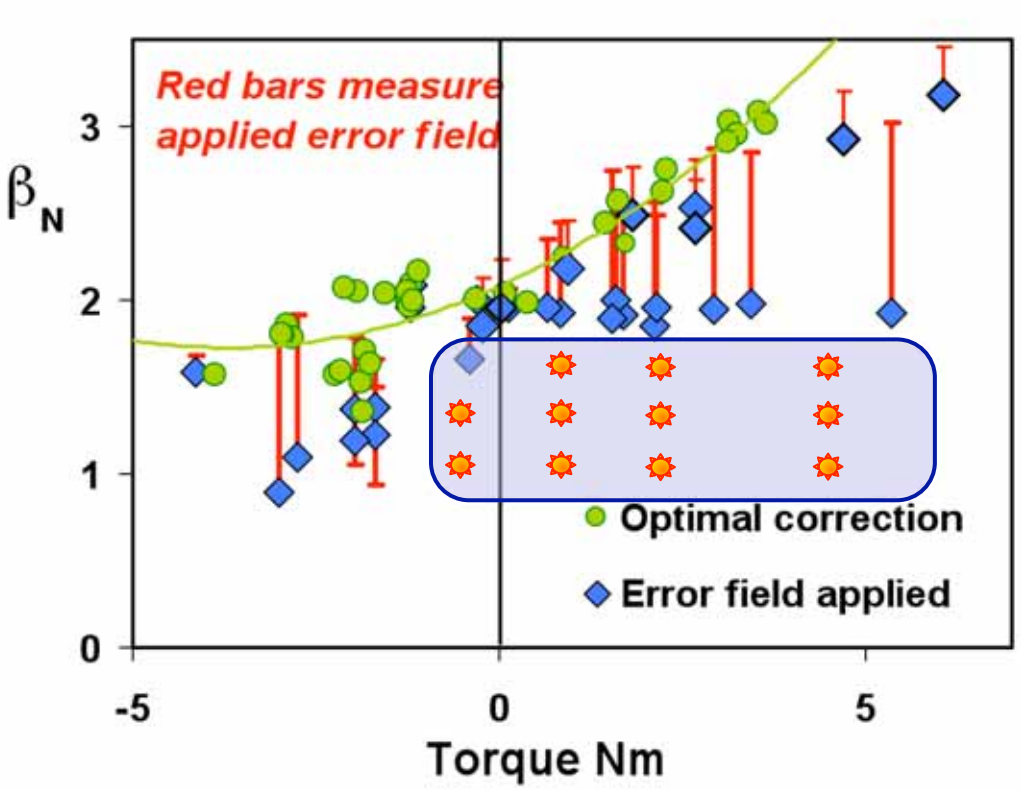
Compare TM β limits with EF cases:



- **Error field required scales as ~ proximity in β to TM limit**
- **But effect through:**
  - **EF response changes?**
    - With proximity to ideal or tearing limit?
  - **Changes in underlying NTM stability?**
  - **Simple torque balance physics?**

Error field interact with tearing β limit. How?

Compare TM β limits with EF cases:

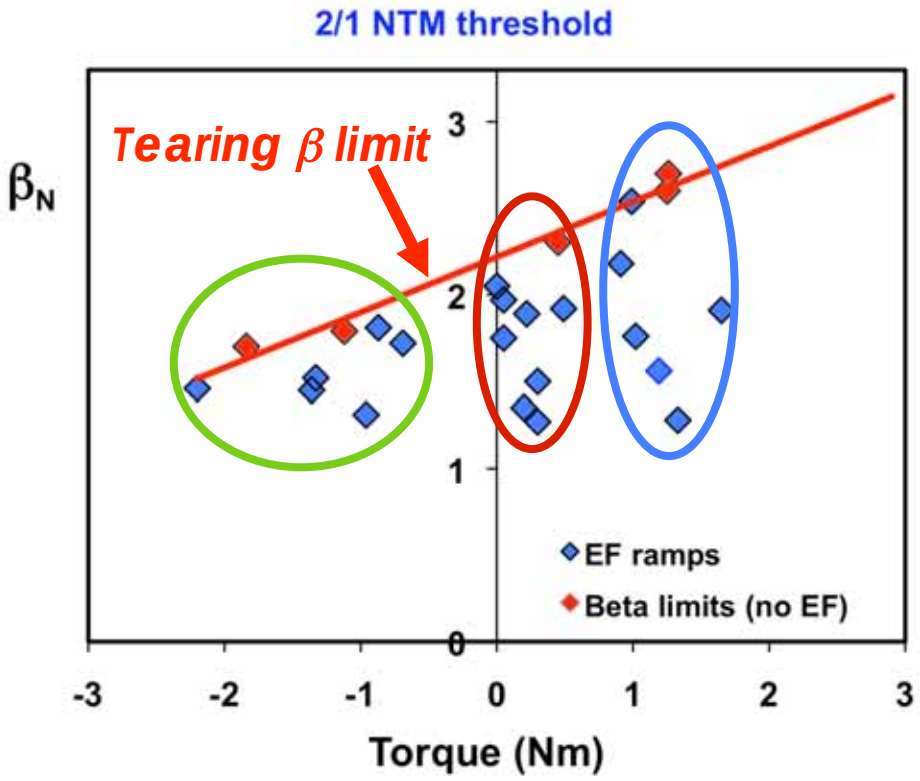


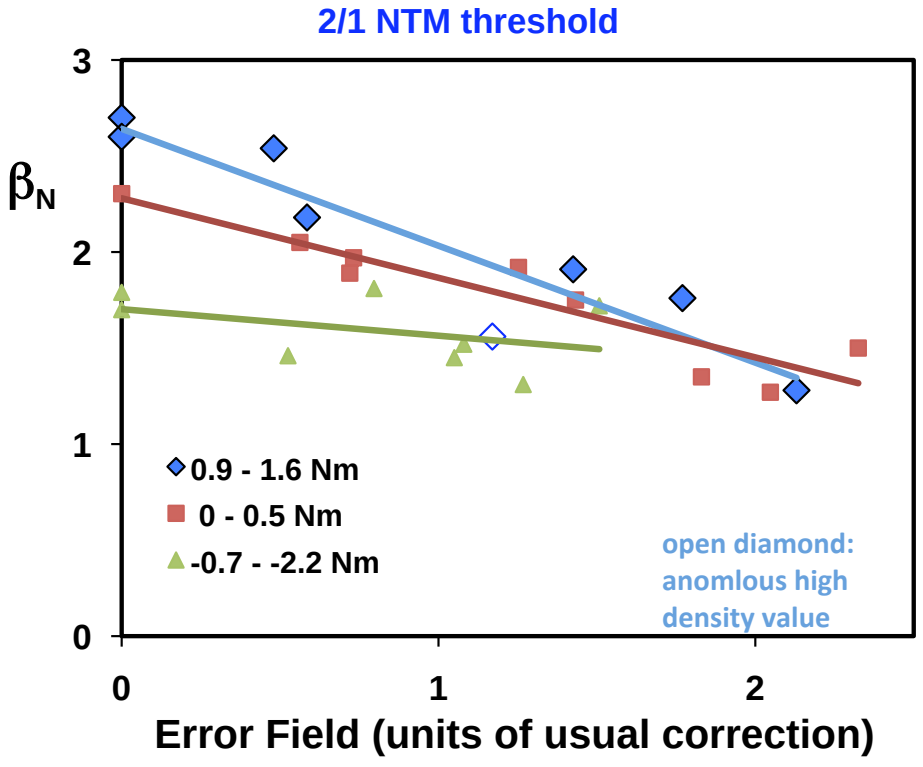
- **Error field required scales as ~ proximity in β to TM limit**
- **But effect through:**
  - **EF response changes?**
    - With proximity to ideal or tearing limit?
  - **Changes in underlying NTM stability?**
  - **Simple torque balance physics?**

New scans to probe this…

New Studies on DIII-D Just Executed
– should get at question of EF response vs Δ'

- **Achieved broad scan of torque and β_N**
  - **Measured EF response close to and far from tearing β limit (red)**
  - **Clear responses and variations observed**

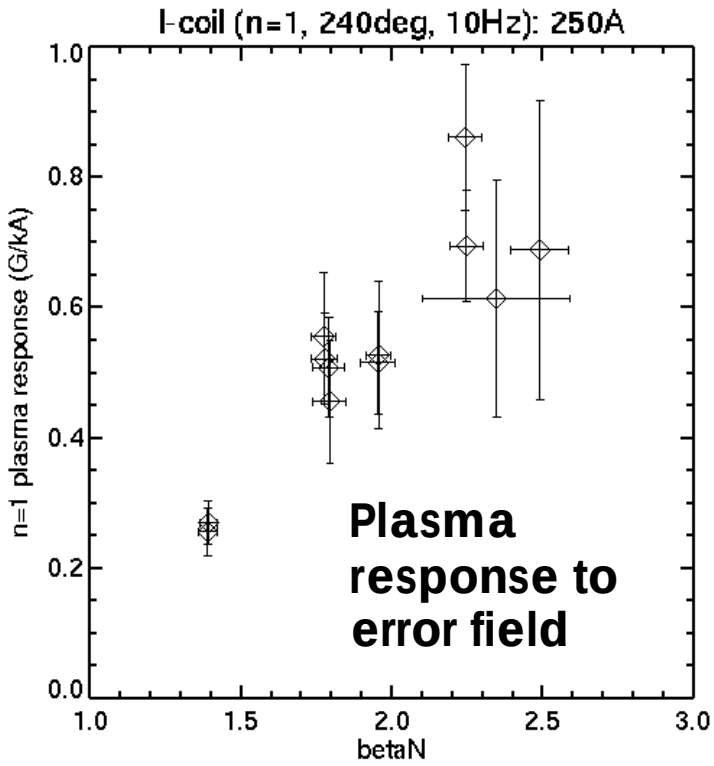




  - **Less error field needed to access mode with counter torque**
    - Is this a rotation or a proximity to Δ' effect - see in EF response… (tba)

Clear variation in EF response with β_N
…still analysing out torque dependence

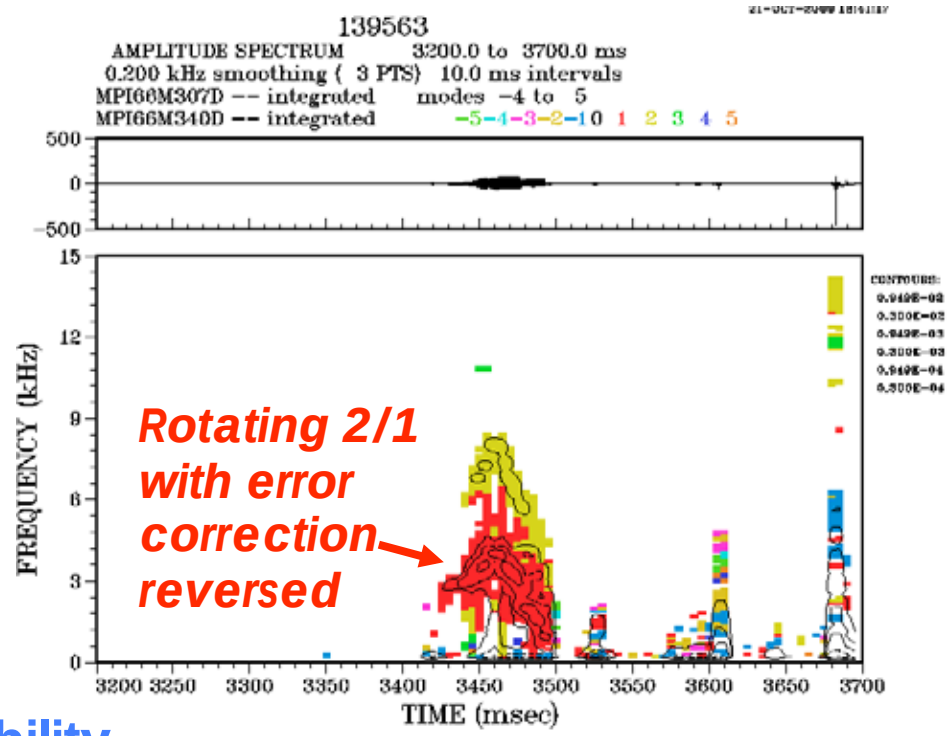
- **Clearly error fields elicit strong response**
  - **Magnetic response increases**
  - **Not looked at all data yet! (just high co torque scan)**



Clear variation in EF response with β_N

...still analysing out torque dependence

- **Clearly error fields elicit strong response**
  - **Magnetic response increases**
  - **Not looked at all data yet! (just high co torque scan)**
- **In all cases error field lead to rotating mode!** ⟶
  - **Even with lots of error field**
  - **Error fields perturbing NTM stability**
    - Presumably through rotation shear
    - Is there an increased magnetic response as tearing β limit neared?



We still don't know H Mode Scalings for Error Field Thresholds

Still outstanding:

Need to move on to extrapolation implications & physics tests

- Density scan
- Lower q_{95}
- TF scan

- **Torque balance of H mode beam driven plasma will be fundamentally different from Ohmic plasma:**
  - Ohmic plasmas will have some natural rotation which scales with Bt and ne – built into Ohmic scalings
  - Rotation scales differently with Bt and ne in H mode?
    - *If so (likely!) then EF threshold will scale differently!*