Influence of Rotation and Error Field on Tearing Stability

in Low Torque ITER-like Plasmas in DIII-D

by

Richard Buttery*, presented by Rob La Haye

with special thanks and considerable input from:

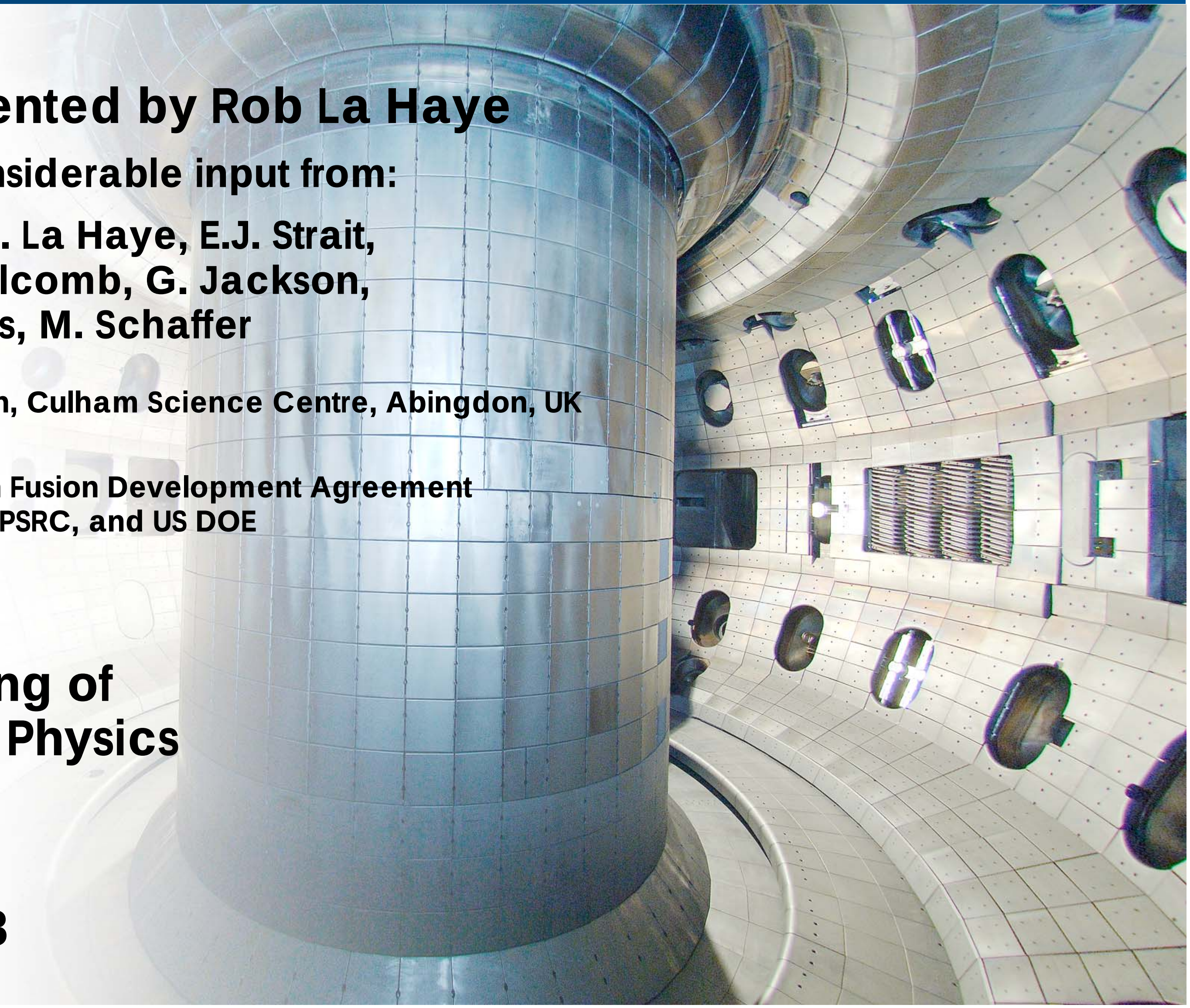
**S. Gerhardt, A. Isayama, R.J. La Haye, E.J. Strait,
J. deGrassie, P. Gohil, C. Holcomb, G. Jackson,
M. Maraschek, H. Reimerdes, M. Schaffer**

* **EURATOM/UKAEA Fusion Association, Culham Science Centre, Abingdon, UK**

**Work conducted under the European Fusion Development Agreement
and jointly funded by EURATOM, UK EPSRC, and US DOE**

**Presented at the
50^{th} APS Annual Meeting of
The Division of Plasma Physics
Dallas, Texas**

November 17-21, 2008



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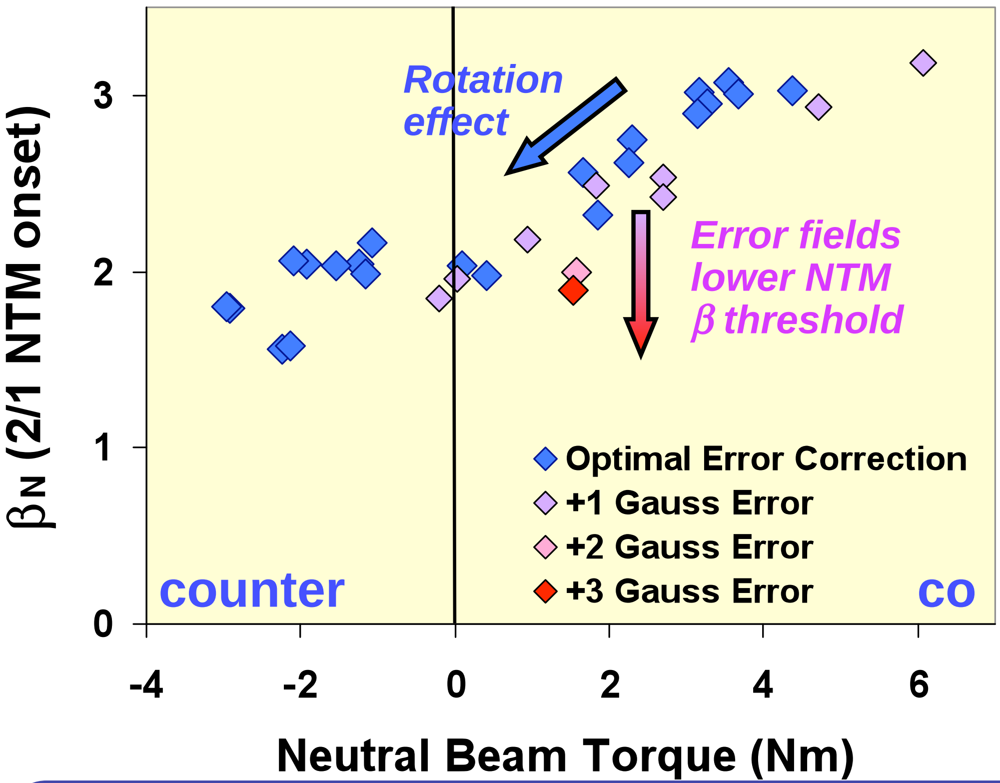
Previous NTM & Error Field Study Raised Many Questions

DIII-D 2006/2007 showed lower rotation has lower 2/1 onset β_N

– *and error fields can lower it further…*



But:

- Is it tearing stability or triggering physics changing?
- Is counter rotation destabilising?
- How do error fields influence thresholds?
  – *especially at low rotation*

Understanding is important:

– Prevalence of 2/1 NTMs

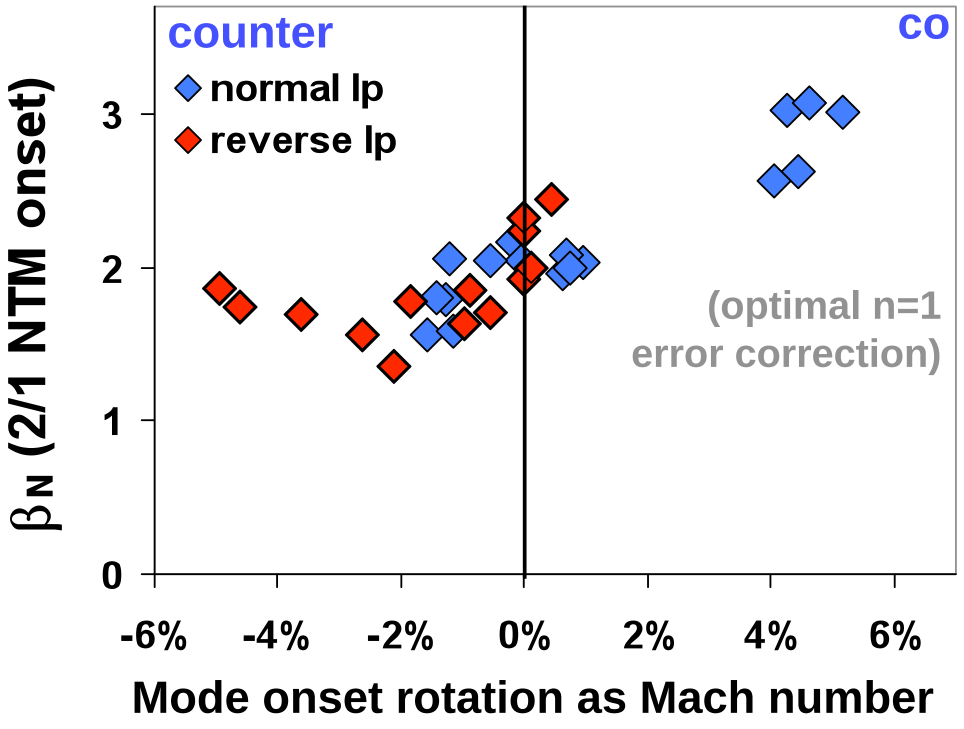
– ECCD control requirements

– Error field correction needs

– Rotation requirements

New DIII-D Normal & Reverse I_P Data Continues Strong Trends

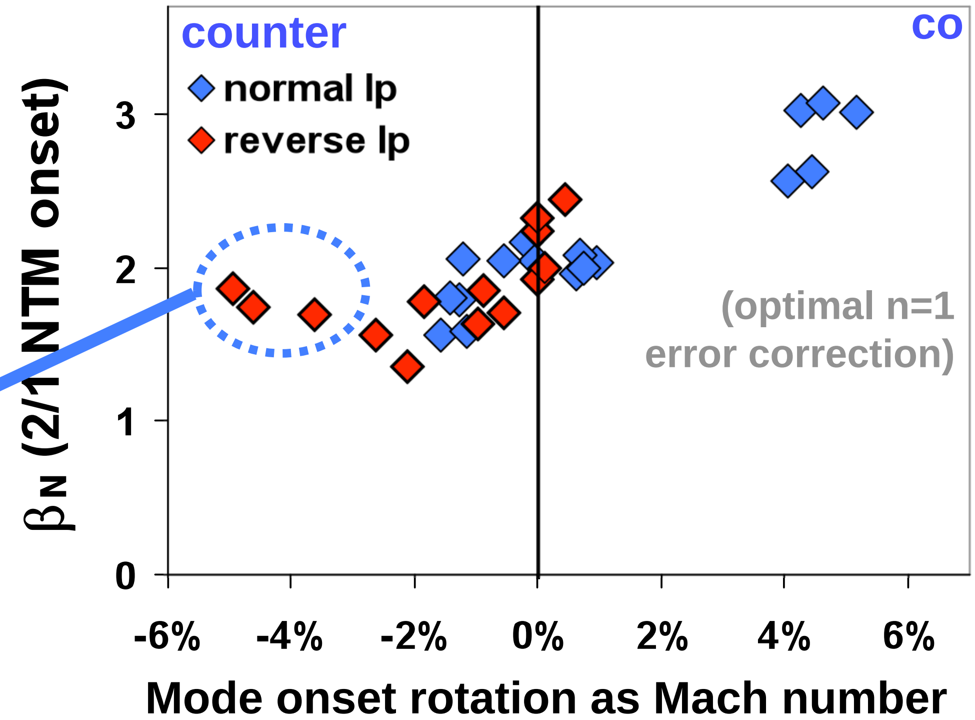
- **Extreme counter torque led to higher β_N thresholds…**

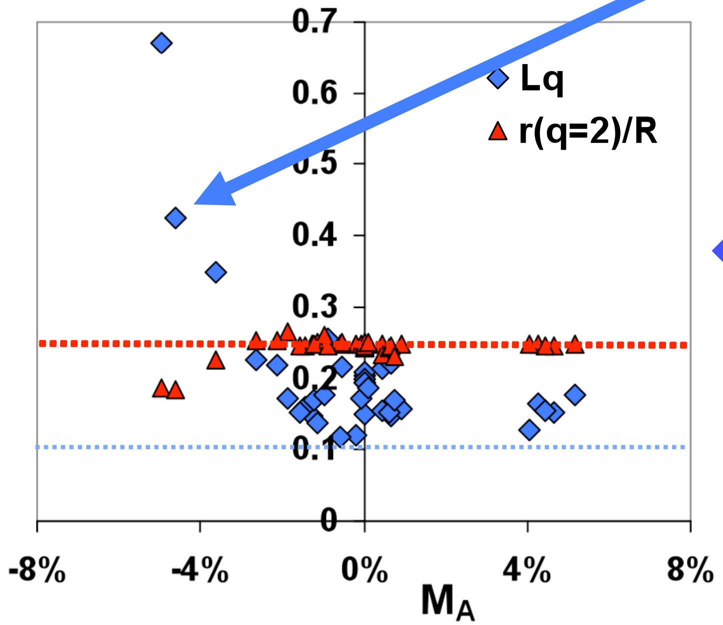


New DIII-D Normal & Reverse I_p Data Continues Strong Trends

– but must remove profile variation from regime change

- **Extreme counter torque led to higher β_N thresholds…**
  - *…a profile effect:*





← *profiles change for reversed I_p*
strong counter rotation (→no ELMs):

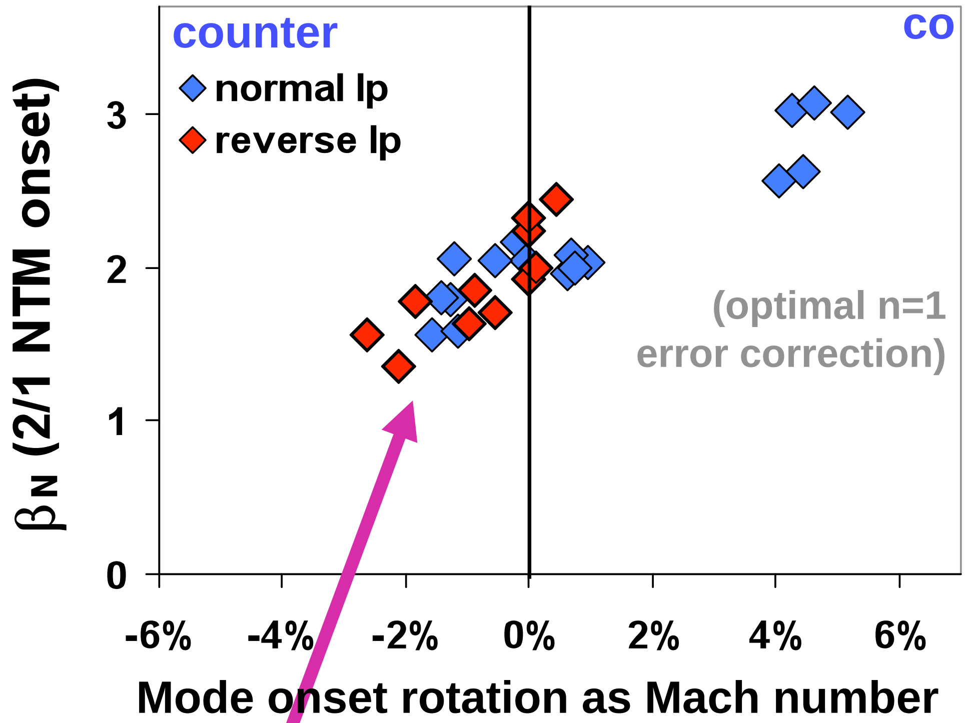
- Core MHD goes away, (no ST or 3/2)
- r(q=2) lower, L_q higher
- Core density peaking (+ no core MSE)

→ ***Discard 3 most counter points***

New DIII-D Normal & Reverse I_P Data Continues Strong Trends
– but must remove profile variation from regime change

- Extreme counter torque led to higher β_N thresholds…
  - *…a profile effect:*

- **Clear β fall with increasing counter rotation**

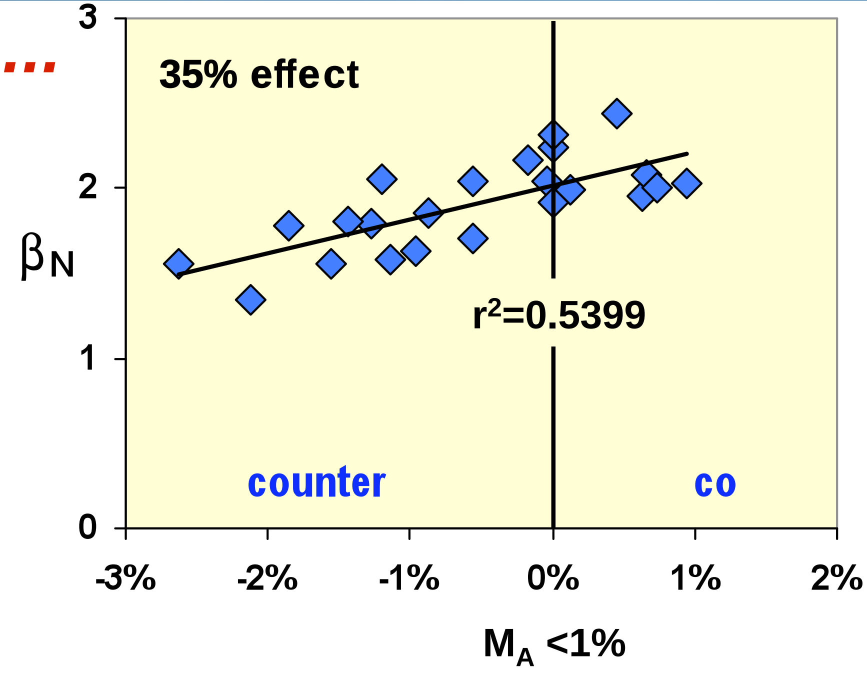


Is remaining counter rotation trend a 'real' effect in underlying tearing physics?

Fall in Threshold with Counter Rotation is a Real Effect...

Consider only low rotation DIII-D data...

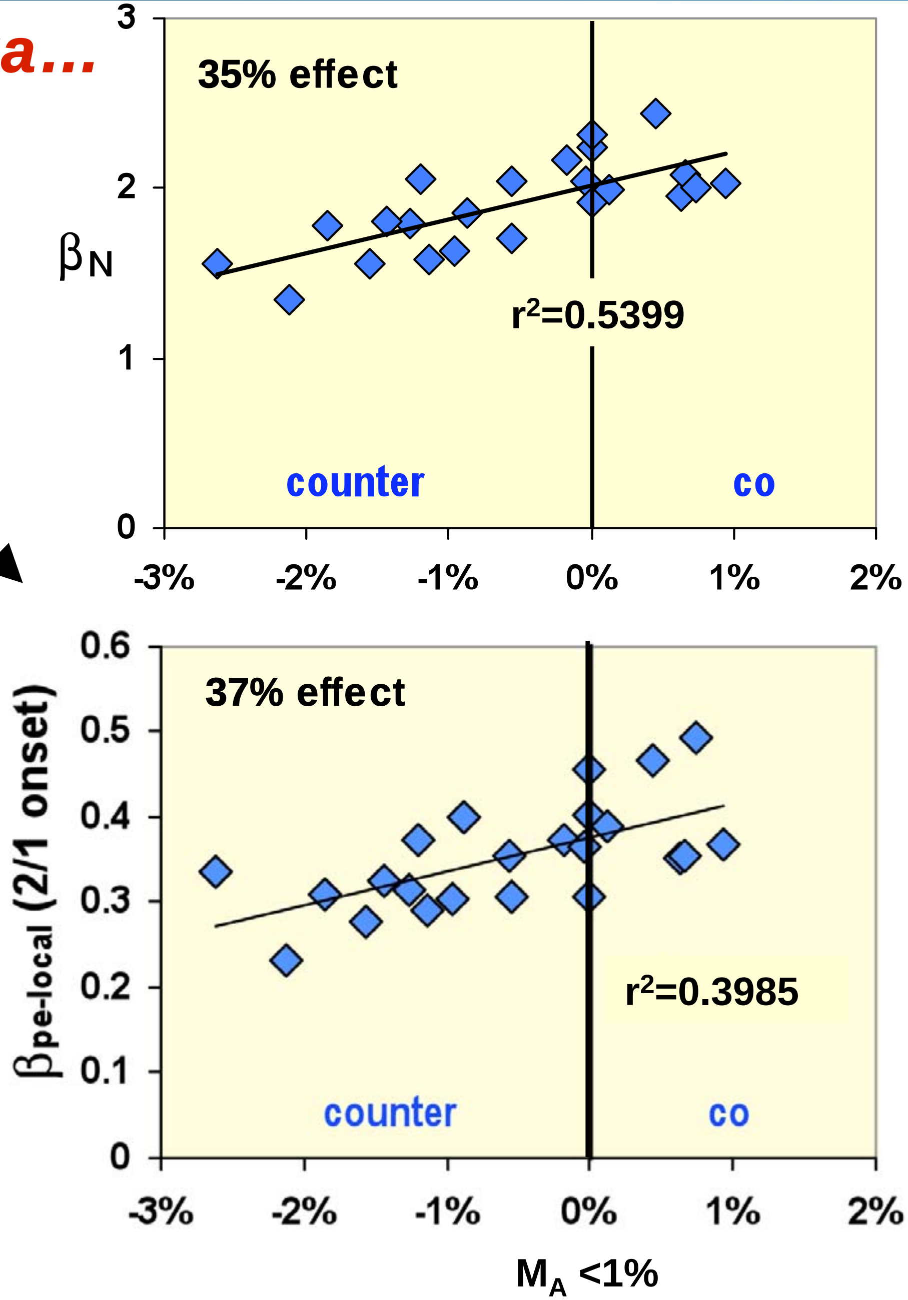
- Clear trend in β_N



Fall in Threshold with Counter Rotation is a Real Effect...

Consider only low rotation DIII-D data...

- **Clear trend in β_N**
- **Similar trend in local β_{Pe}**



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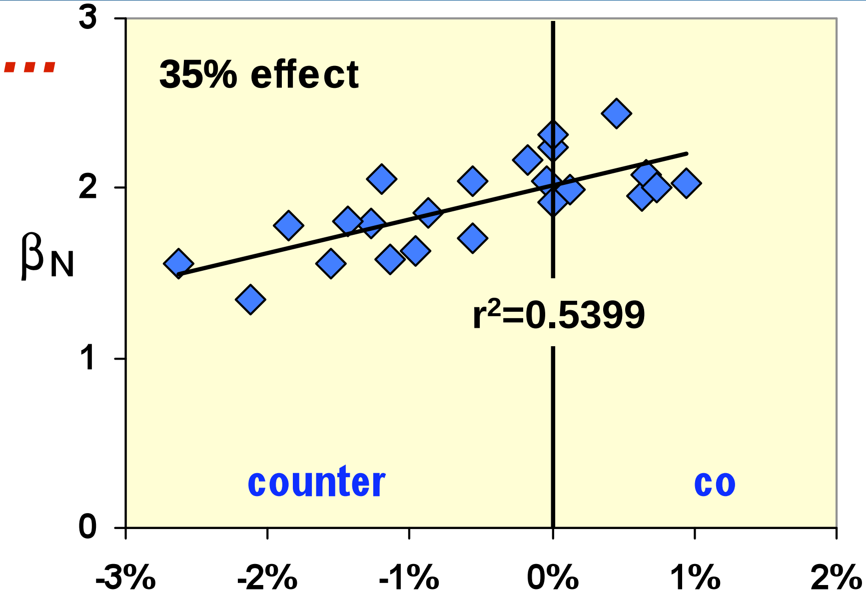
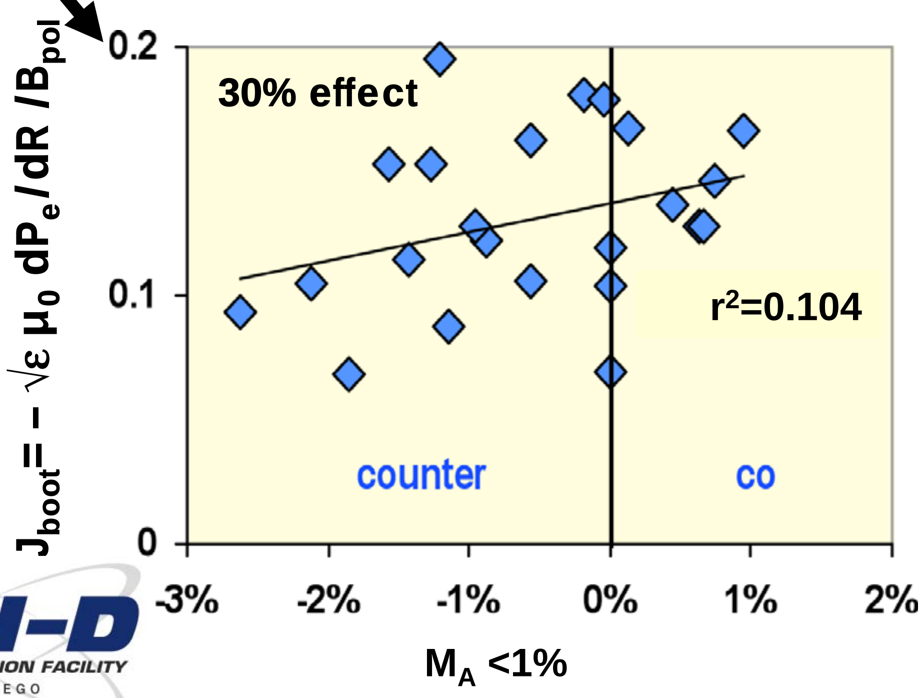
Fall in Threshold with Counter Rotation is a Real Effect

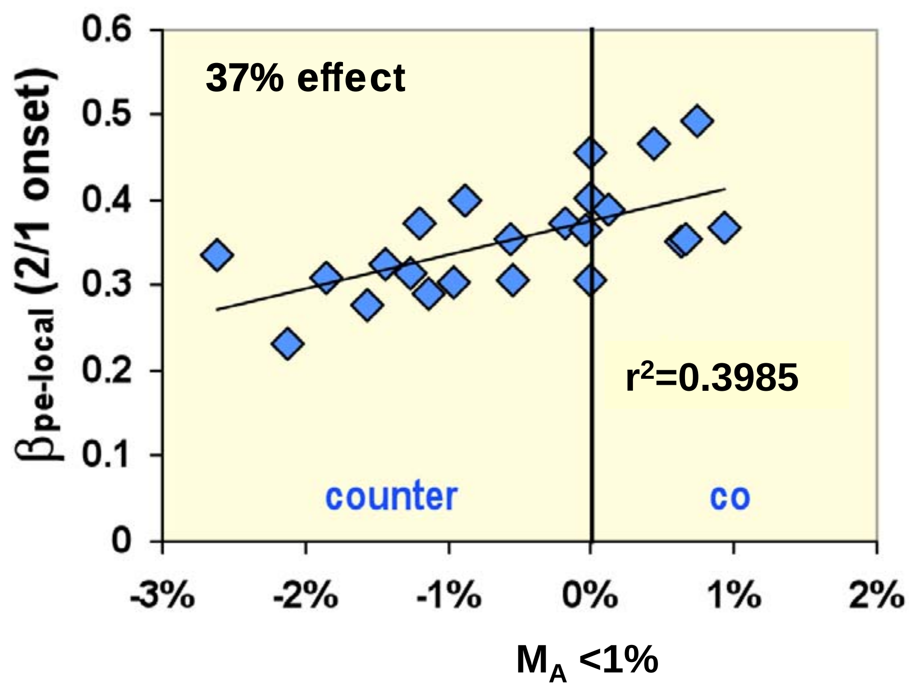
Consider only low rotation DIII-D data…

- Clear trend in β_N
- Similar trend in local β_{Pe}
- …and in bootstrap measure (?)
  - *noisier – more local gradients used*

  (but no trends in profile parameters)







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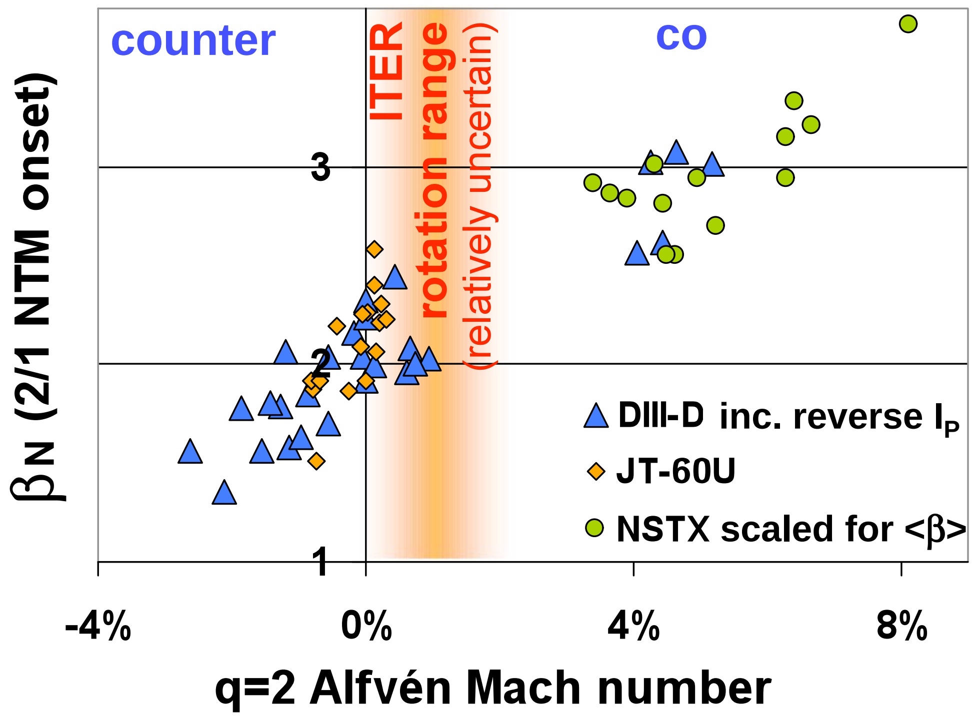
Cross-machine Data Set Confirms Strong Rotation Role

- **DIII-D scans show:**
  - Less Mach → lower β_N limit
  - More counter rotation is destabilising!
- **JT-60U beam mixing shows**
  - Consistent absolute thresholds
  - Similar (but steeper?) rotation effect
- **NSTX n=3 braking shows:**
  - Similar rate of effect at high rotation
  - Similar absolute levels in volume average $\langle\beta_N\rangle$ (NSTX x0.7 factor)



[Buttery et al., IAEA 2008]

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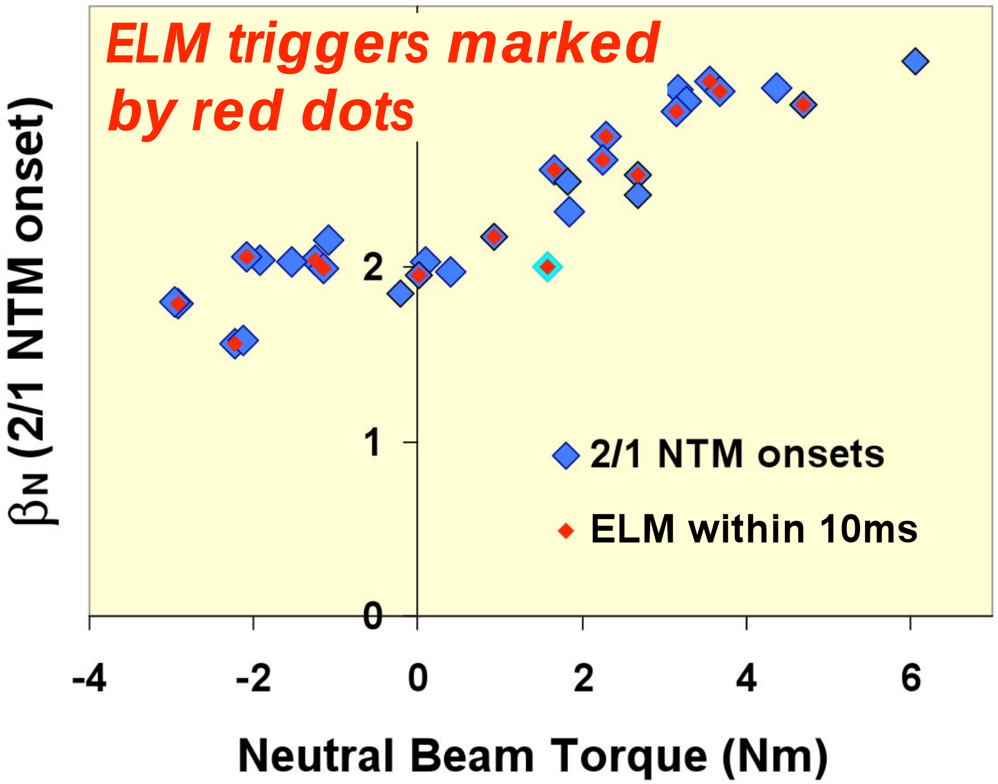
NSTX

ELM Role in 2/1 Triggering Appears Incidental (and No Correlation at all with Sawteeth)

ELMs 'trigger' about half the 2/1 NTMs:

- But trigger has no influence on NTM onset β_N
  - Points lie on trend
  - & trigger type not correlated with rotation

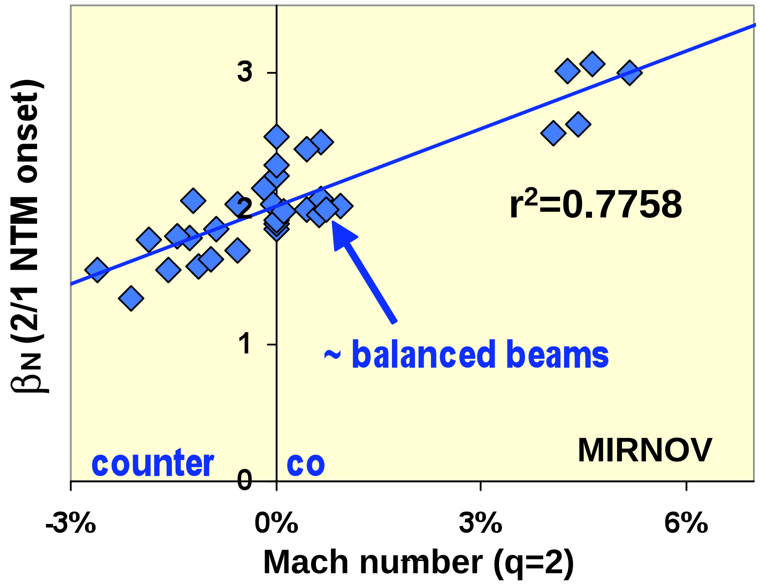


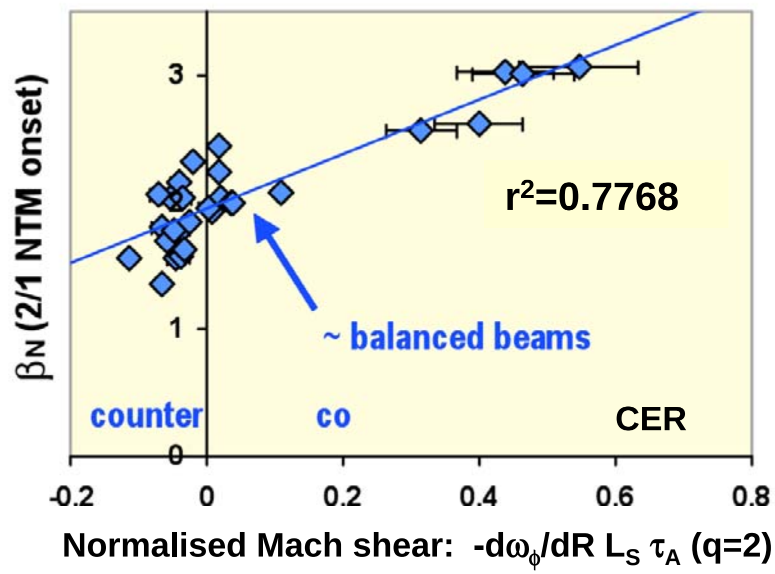
➔ ***NTM onset β is <u>not</u> about "triggered seed exceeding threshold width"*** ←ρ* dependent

- but dictated by changes in the intrinsic tearing stability

Flow Shear Could Play the Stabilising Role

- **Theoretically <u>flow shear</u> impacts intrinsic tearing stability (through Δ′)**
  - But flow and its shear are degenerate in DIII-D
    - → *see NSTX* [1]
    - & see [2] for study of DIII-D saturated modes
  - Note for counter rotation flow shear reverses with respect to magnetic shear





<u>See:</u>

[1]S. Gerhardt poster APS 2008 NP6.00100 We AM

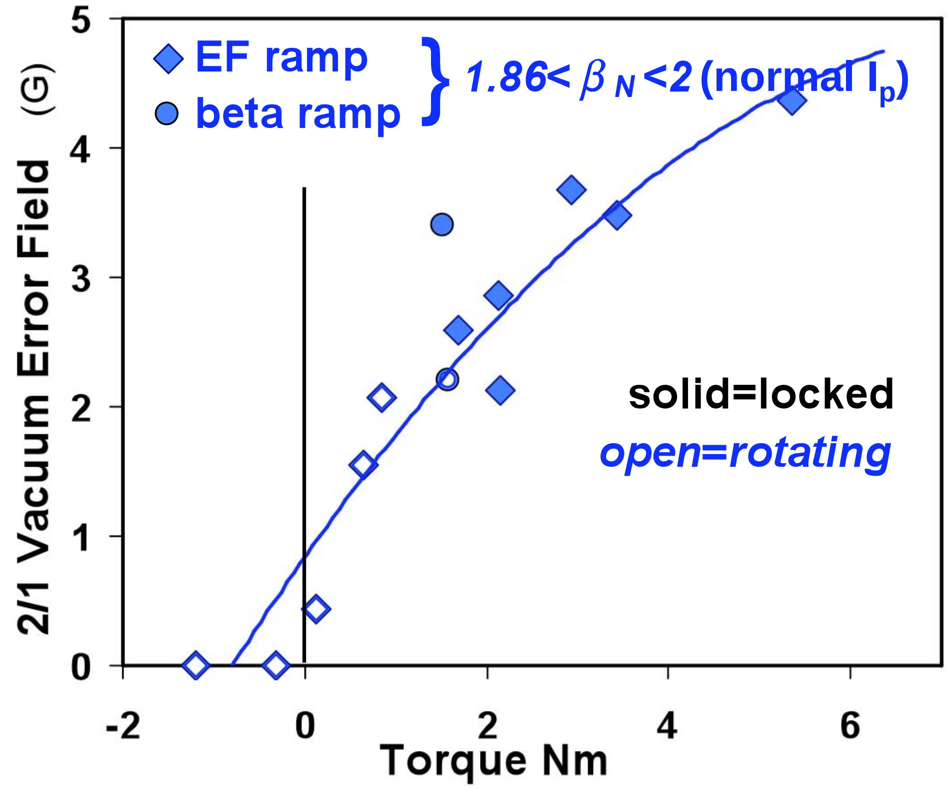
[2]R J La Haye poster APS 2008 JP6.00087 Tu AM

Error Fields Assist Medium β_N Tearing Mode Formation

Hold β_N~1.9 and vary torque from shot to shot: then ramp error field

- ◆ Error field threshold falls with torque
- ◇ But rotating modes at low torque!
  - *Intrinsic tearing stability is being modified…*

    …by rotation perturbation?



(◆Similar to advanced scenario observations of Reimerdes: PO3.00011)

Error Fields Assist Medium β_N Tearing Mode Formation

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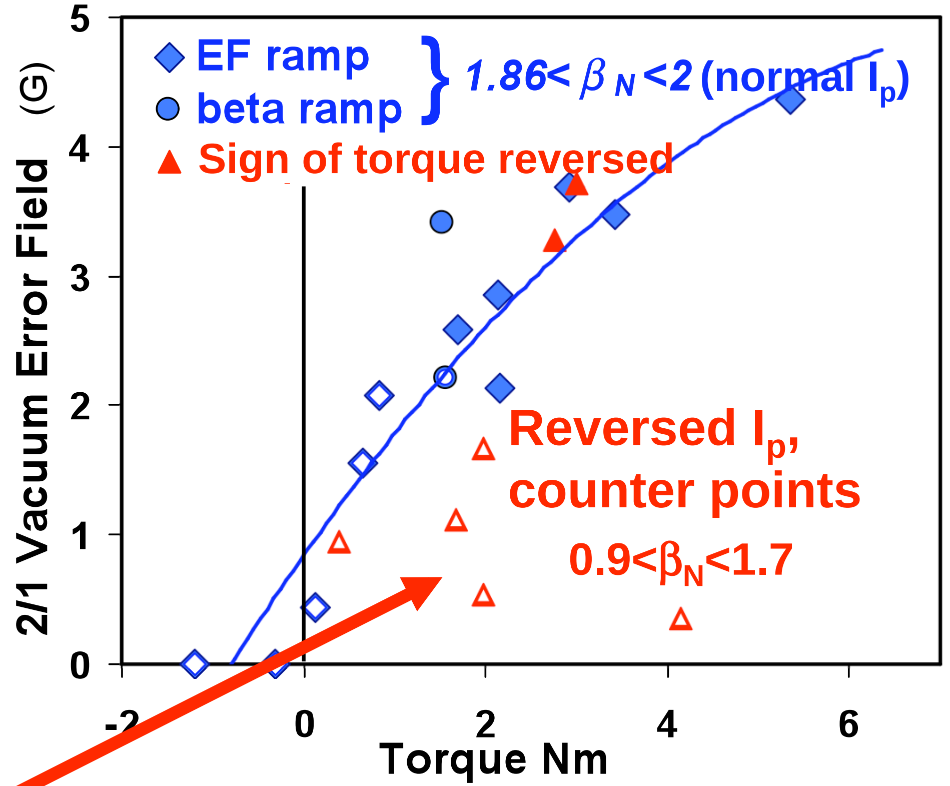

Compare with counter torque (△)

– *Error field thresholds are lower! (Could not operate at β_N ~1.9)*

- *Despite __higher__ natural mode rotations (not shown) and __lower__ β_N values for counter torque modes*

Conclusions

- DIII-D database extensions confirm strong role of rotation in tearing mode stability:
  - Increased counter rotation <u>lowers</u> β_N thresholds
    - A challenge to theory!
  - Behaviour related to changes in intrinsic tearing stability
    - Does this change predictions of a ρ^* dependence?
  - Trends seem validated by observations on other devices
    - $\langle\beta_N\rangle$ and Alfvén Mach number are the relevant parameters
- Error fields have strong effect at low torque and modest β_N
  - and demonstrate asymmetry between co and counter rotation
  - ITER baseline point just stable with modest co-rotation and good EF correction?

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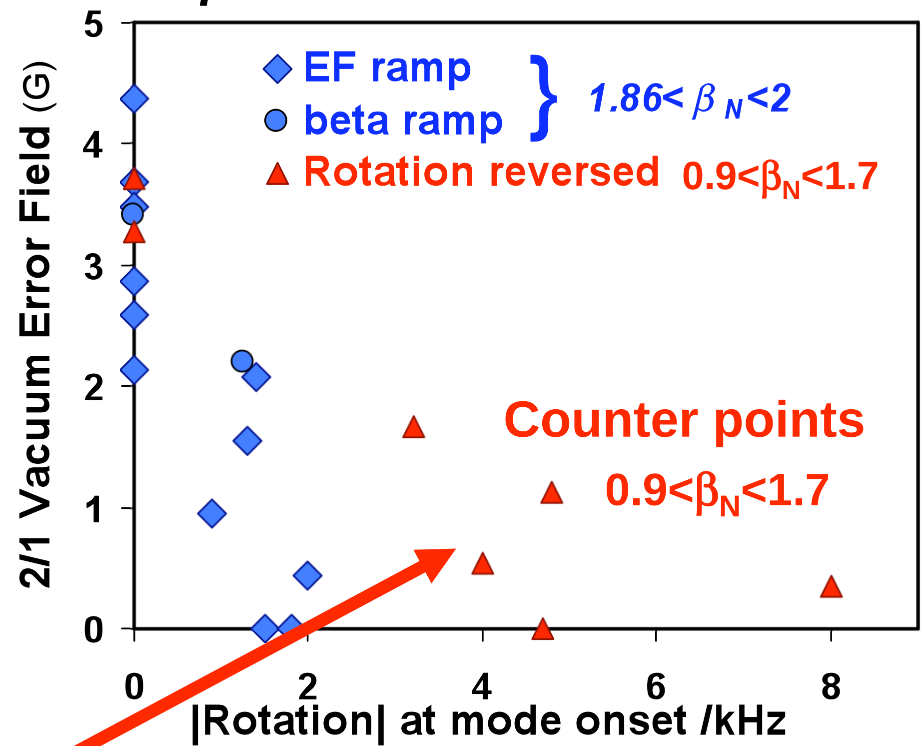
Error Fields Assist Medium β_N Tearing Mode Formation

Hold β_N~1.9 and vary torque from shot to shot:

- Error field threshold falls with torque
- But rotating modes at low torque!
  - *Intrinsic tearing stability is being modified…*

    …by rotation perturbation?

Re-plot vs mode onset rotation:



Compare with counter torque (Δ)

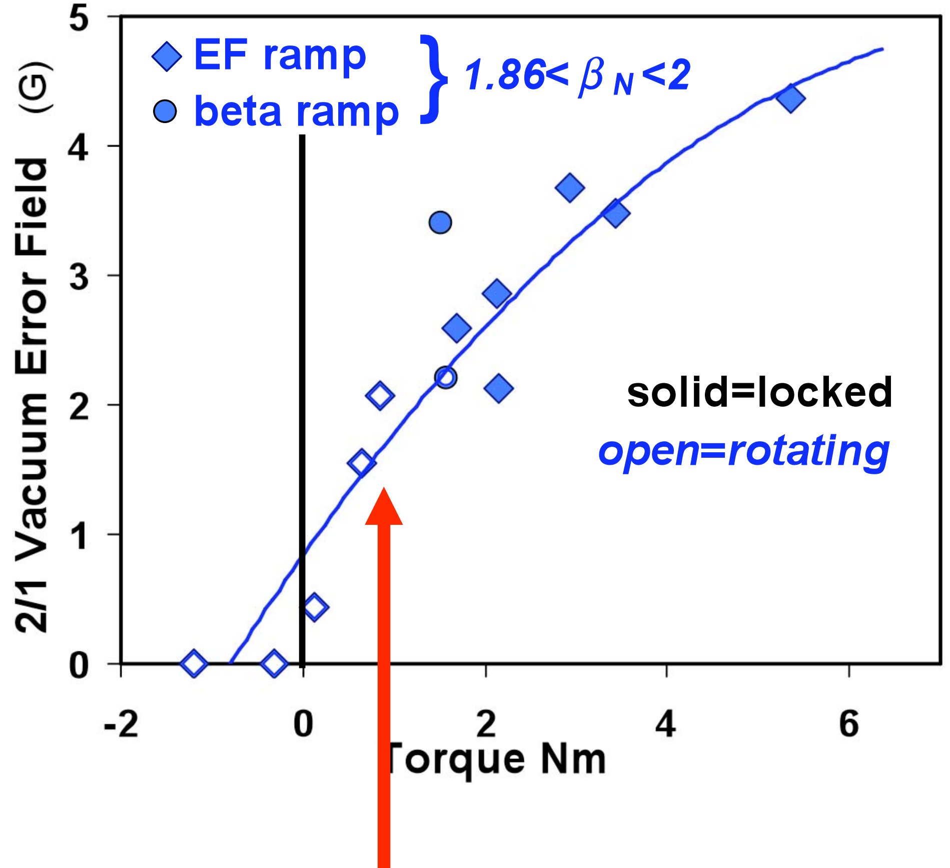
- *Error field thresholds are lower!*
  - *Despite **higher** natural mode rotations and **lower β_N** values for counter torque modes*
    - *Is this an asymmetry in the effect of rotation on island stability?*
    - *Does proximity to intrinsic tearing limit raise error sensitivity?*

Error Fields Assist Medium β_N Tearing Mode Formation

Hold β_N~1.9 and vary torque from shot to shot:

- Error field threshold falls with torque
- But rotating modes at low torque!
  - ***Intrinsic tearing stability is being modified...***

    ...by rotation perturbation?



ITER relevant torques/rotations just stable with good error correction:

$\delta B_{21}/B_T < 1.10^{-4}$

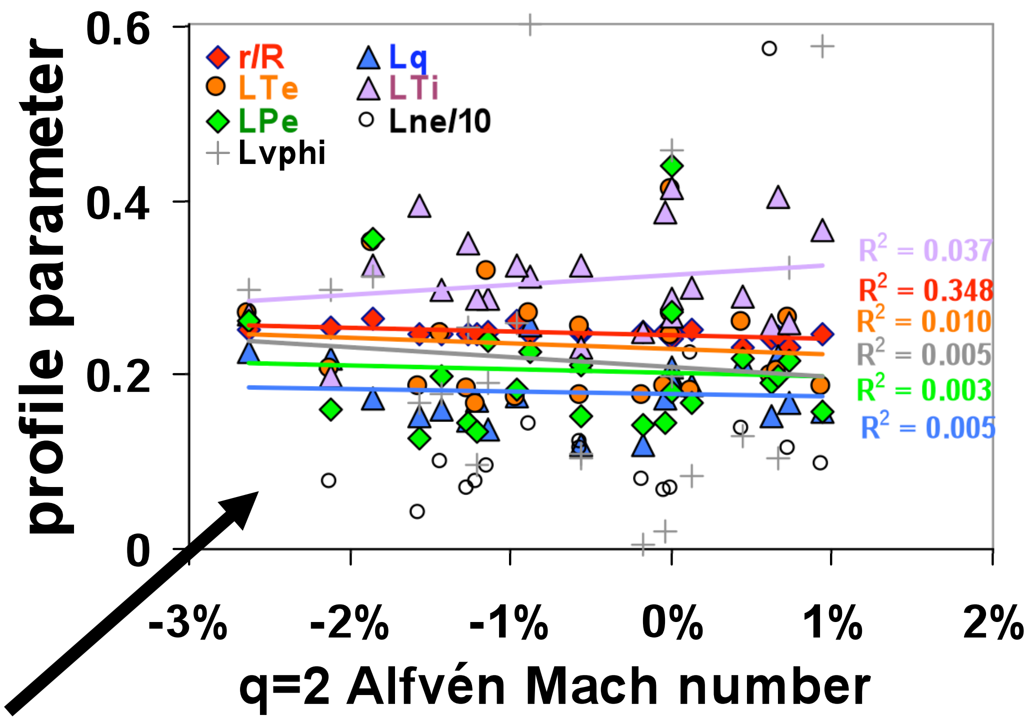
DIII-D Negative Trend with Counter Rotation is Real Effect

Consider only low rotation DIII-D

- Clear trend in β_N
- Similar trend in local β_{Pe}
- And in 'rough bootstrap' term
  - *Q. Is there a profile effect going on, or just increasing noise with more gradient terms?*

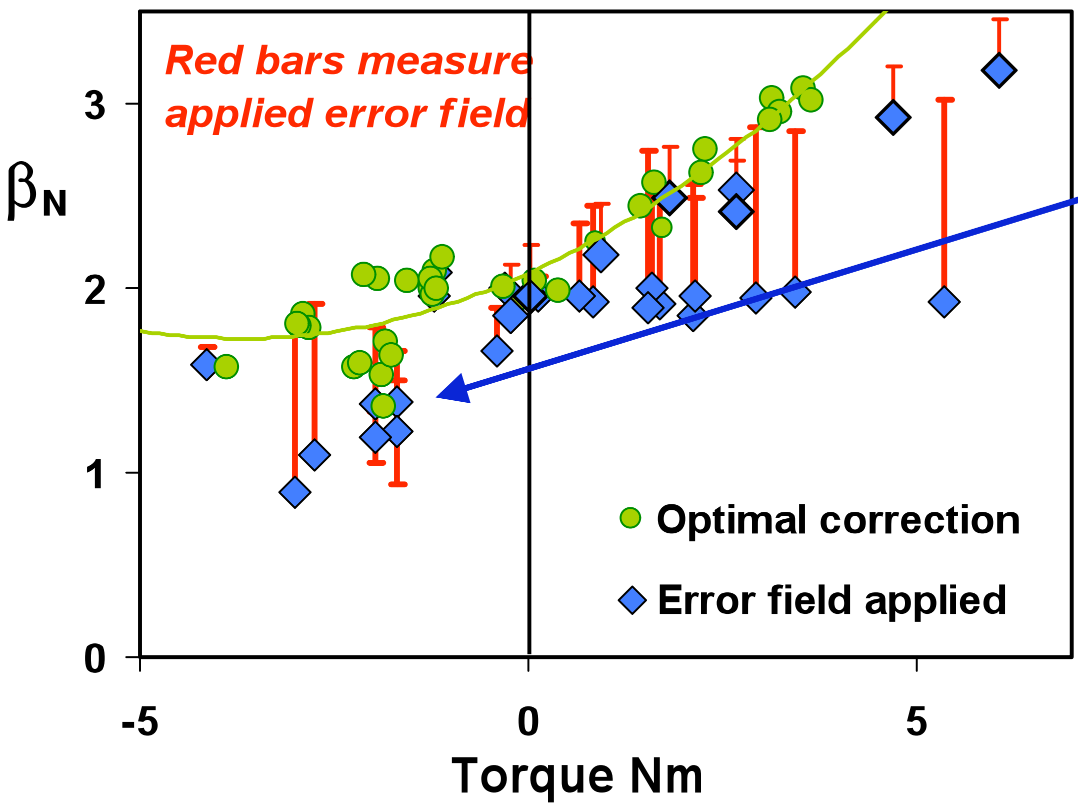
ANSWER:

- *Profiles show no systematic variations or trends with rotation*
  - **Local β_{Pe} dependence on rotation carries over to NTM drive…**
  - ***Effect lost in J_{BS} mainly due to noise***



Amount of Error Field Needed Depends on Proximity to NTM Limit at a Given Torque?

Full data set gives an interesting picture:



- **Error fields 'close the gap' in β_N with NTM β_N limit (o)**
  - *note low β_N points needing little error field to lower $\beta_{N\text{-onset}}$ further*
- ***Is this a new error field amplification effect?***
  - Brought on by proximity to classical tearing?
  - Or asymmetry in rotation influence?

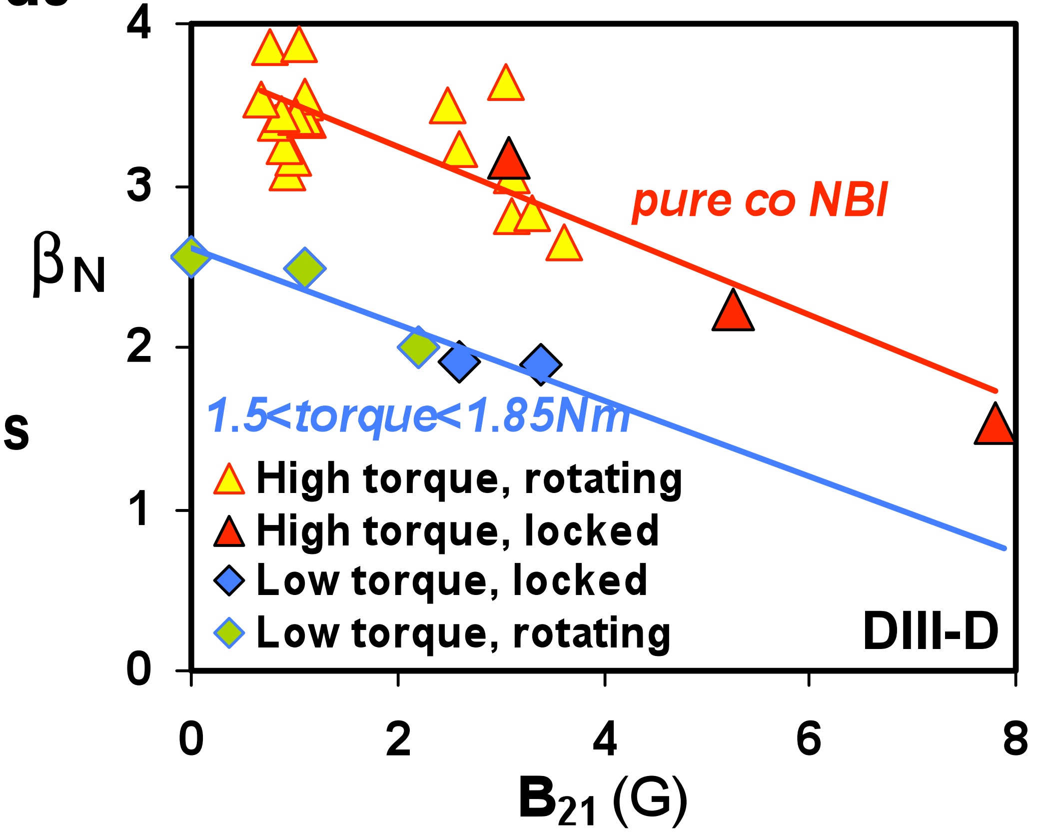
- ***More points needed in low β_N near balanced region to extrapolate ITER sensitivity***

Amount of Error Field Needed Depends on Proximity to NTM Limit at a Given Torque?

- β_N threshold falls as error fields increase

  or equivalently

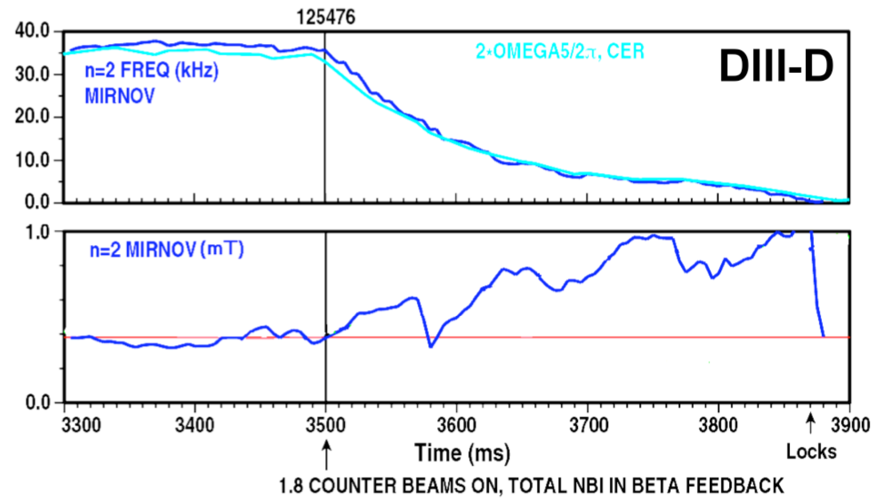
- Error field sensitivity increases at high β_N & low rotation
  - *Should it?*
    …shielding still strong?



- ***Suggests revised error field correction requirements required for ITER at baseline and hybrid operating points***

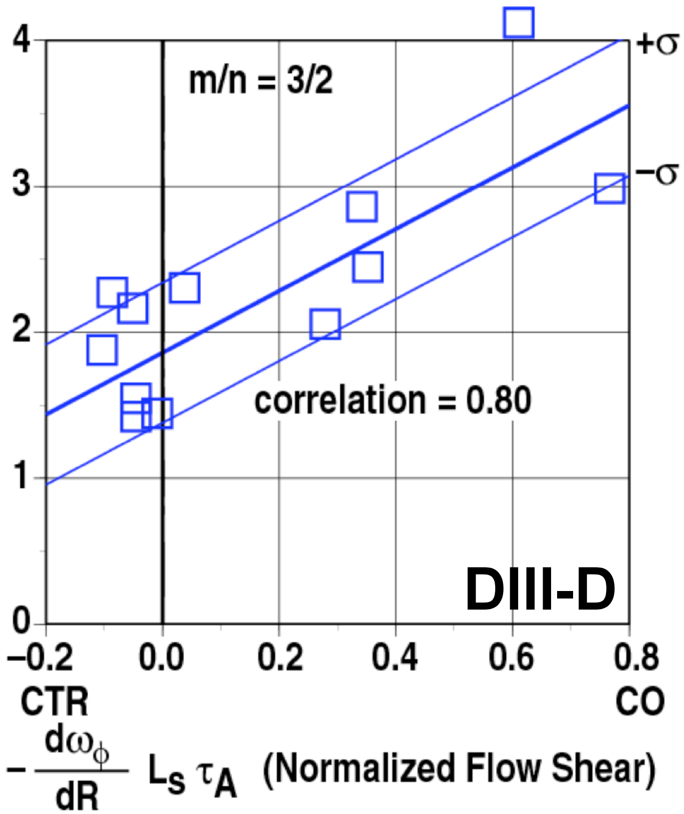
Saturated 3/2 Behaviour Shows Rotation Improves Intrinsic Stability

- **Islands get bigger as rotation falls→**
  - *Calculate matching Δ' from modified Rutherford eqn:*



$$-r\Delta' = \frac{\varepsilon^{1/2}\beta_{\theta e}L_q r_s}{w\,L_{pe}}$$

(Helically Perturbed Bootstrap Term in MRE)



- **Fits show mode less stable at low rotation**
  - Larger w (note 1/w term)
- **Not clear if rotation ^1 or ^2**
  - ...or if sign dependence