MHD Workshop, Princeton, Nov 2006:

Influence of delta-prime and rotation on NTM thresholds

R J Buttery

with special thanks and considerable input from:

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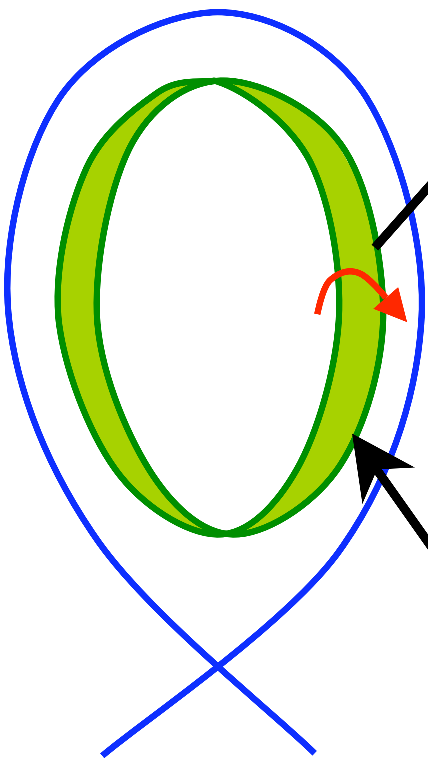
EURATOM/UKAEA Fusion Association,
Culham Science Centre, UK.

Results are preliminary and should not be distributed further

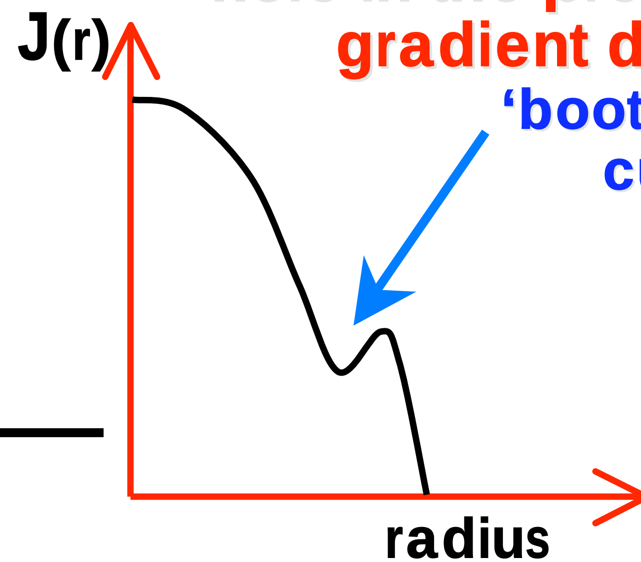
Why do we get NTMs?

Tearing modes are amplified by a bootstrap effect:



good conduction about island → **flattens pressure gradients across the island** → **leaves a helical hole in the pressure gradient driven 'bootstrap' current** → **current perturbation drives island growth**

Needs a trigger to kick the whole process off



NTM threshold dependence

Island growth rate governed by modified Rutherford:

$$\frac{\tau_r}{r}\frac{dw}{dt} = r(\Delta' - \alpha w) + r\beta_P \left[a_{bs}\left(\frac{0.65\,w}{w^2 + w_d^2} + \frac{0.35\,w}{w^2 + 28\,w_b^2}\right) - \frac{a_{GGJ}}{\sqrt{w^2 + 0.2\,w_d^2}} - \frac{a_{pol}\;w}{w^4 + w_b^4}\right]$$

classical tearing

bootstrap

finite island transport

ion banana width

field curvature

ion polarisation currents

small island terms stabilising - lead to minimum size and β for growth

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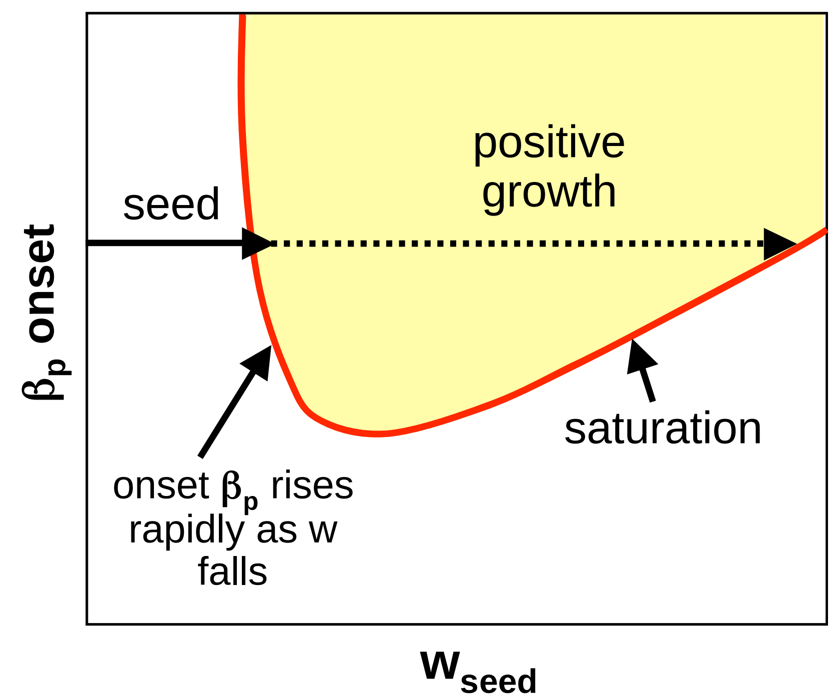
classical tearing · bootstrap · finite island transport · ion banana width · field curvature · ion polarisation currents

small island terms stabilising - lead to minimum size and β for growth

Example: ion polarisation term, $a_{pol} \propto \rho_{i\theta}^2\, g(\nu,\varepsilon)\;\omega\;(\omega_{i*} - \omega)/\omega_{e*}^2$

$$\Rightarrow \beta_{p\text{-}onset} \propto -r_s\Delta' . \rho_{i\theta}^* . \frac{w_{seed}/\sqrt{a_{pol}/a_{bs}}}{[1-a_{pol}/a_{bs}w_{seed}^2]} . g$$

- **Need a seed to trigger mode**
- **Introduces dependencies on ρ^* and other variables…**



Rotation influences on NTM triggering

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- **Decrease the threshold terms**
  - Eg Ion polarisation introduces rotation dependence:

★ **Island streaming through the plasma**

— **polarization drift from ion inertia**

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    - *Depends on rotation in ExB frame of reference*

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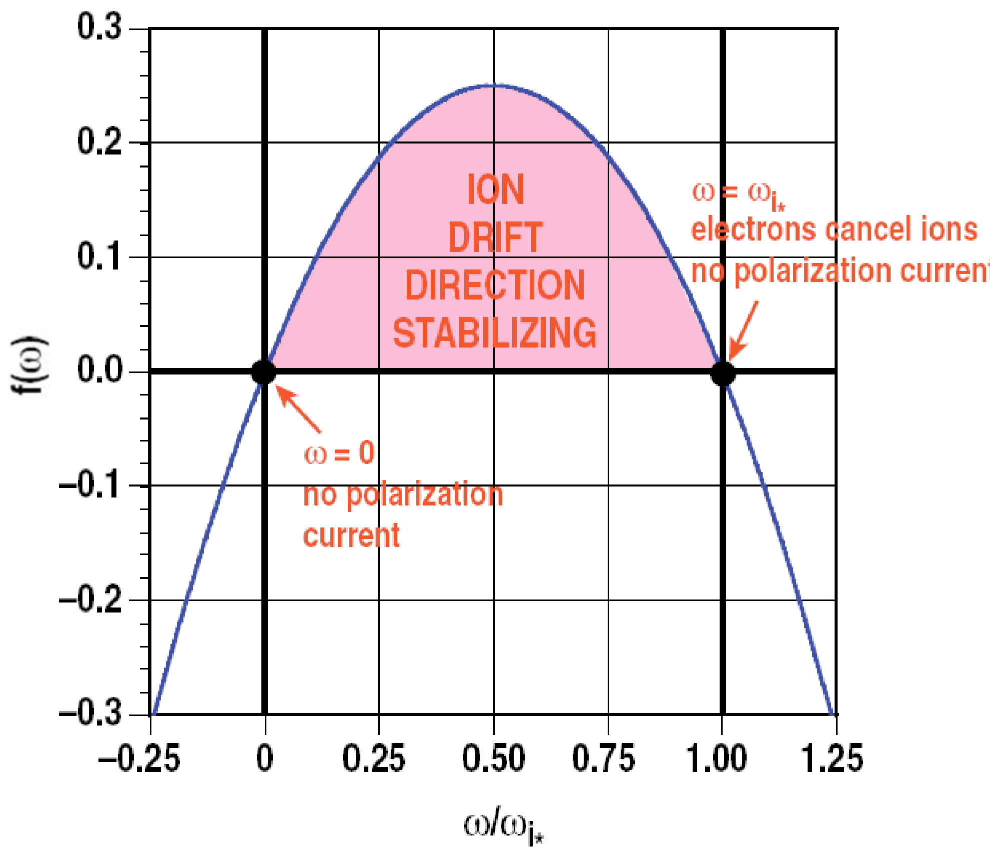

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- **Increase the seeding process…** ***(applies to 2/1 NTM?)***
  – Decreased rotation between resonant surfaces (q=2 cf q=1, 1.5 or edge) enhances mode coupling

Seeding is crucial aspect of β threshold

Seeding depends on complex physics:

$w_{seed}/r \propto$ (MHD size) × (coupling) × (shielding factors)

additional dependence?

β^{γ} (shafranov shift and plasma shape)

$S^{-\alpha}$ ('skin' effect')

Shielding:[1]

- Must overcome resonant response at NTM surface
- Like error field problem:
  - torque induced between surfaces
  - locking required for substantial tearing

→ Rotation will play an important role

1. Hegna et al., Phys Plas 6 (1999) 130

Rotation influences on NTM triggering

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  - Eg Ion polarisation introduces rotation dependence:

$$a_{pol} \propto \rho_{i\theta}^2 \; g(\nu,\varepsilon) \;\; \omega \; (\omega_{i*} - \omega) / \omega_{e*}^2$$

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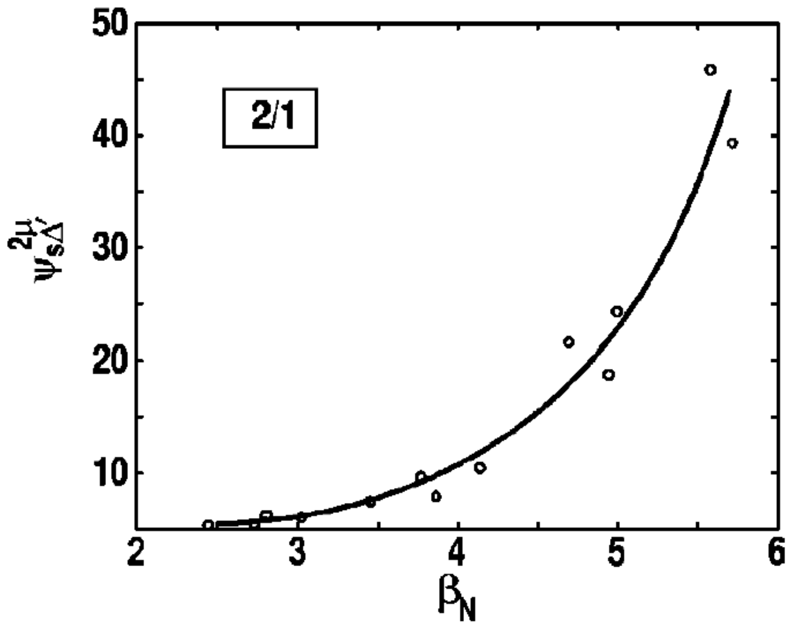
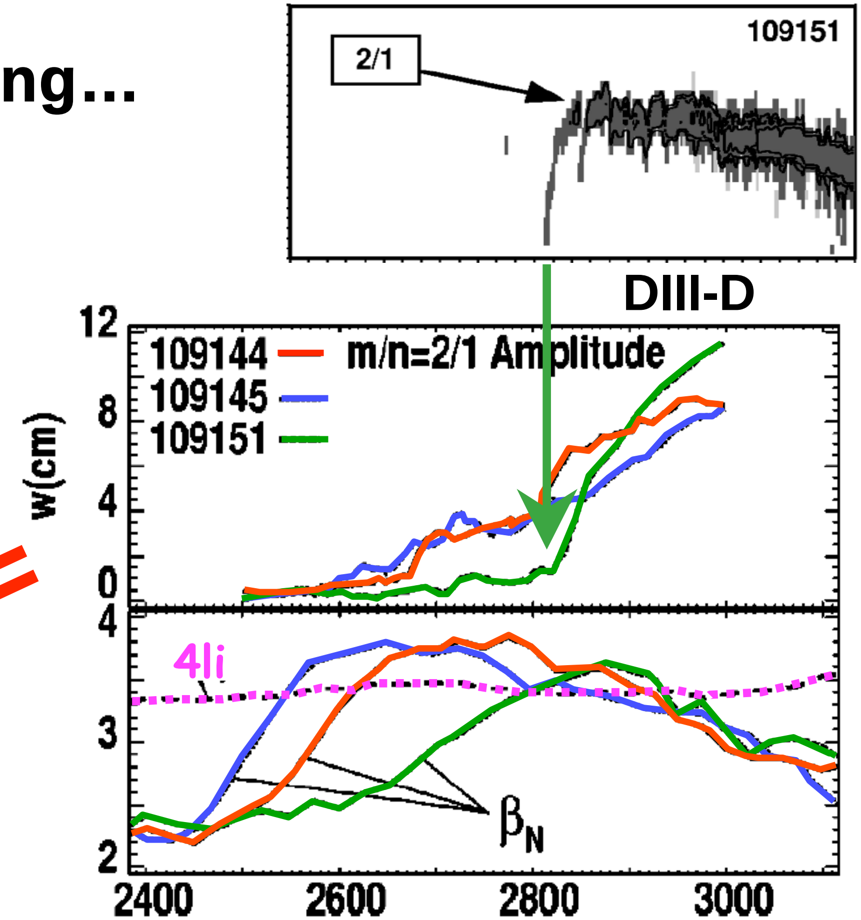
  - Variation in Δ' drives mode onset at high β_N ***- esp. 2/1 NTM?***
    - *Mechanisms for ion polarisation to influence threshold…*

2/1 NTM triggered by Δ' with ideal limit proximity

- **2/1 NTM often with weak/no seeding…**
  - Comes out of noise at high β_N
- **Modelling:**
  - growth driven by "pole" in classical tearing stability, **Δ'**:





[Brennan et al, PP10, 1643]

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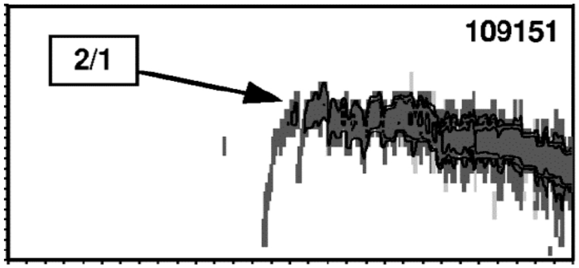

DIII-D

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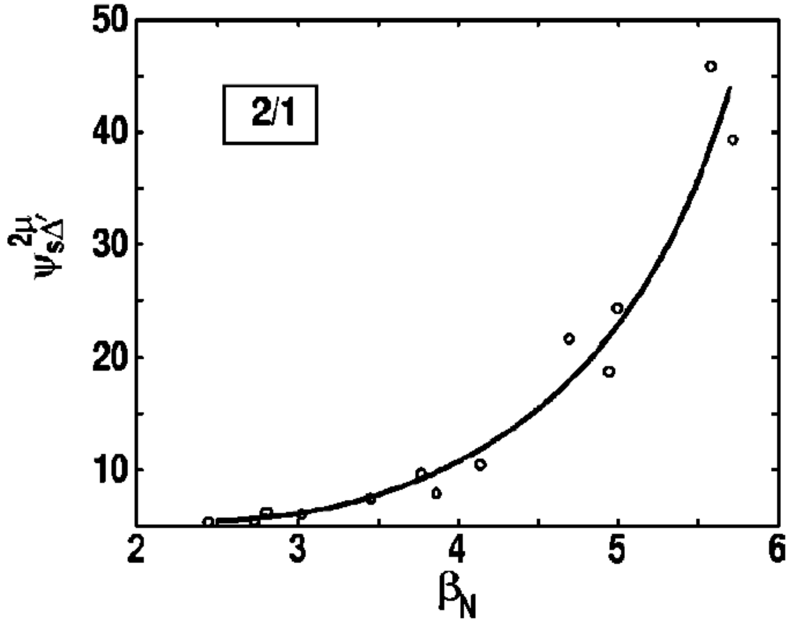

➢ **When Δ' pole overcomes small island stabilisation effects → NTM grows**
  - But the small island stabilisation effects scale with ρ* & rotation

➢ **If ρ* falls or rotation changes small island term can fall**
  ⇒ smaller Δ' rise needed
  ⇒ NTM at lower β_N

Rotation influences on NTM triggering

- **Decrease the threshold terms**
  - Eg Ion polarisation introduces rotation dependence:

$$a_{pol} \propto \rho_{i\theta}^2\ g(\nu,\varepsilon)\ \omega\ (\omega_{i*} - \omega)/\omega_{e*}^2$$

    - *Depends on rotation in ExB frame of reference*
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    - *Mechanisms for ion polarisation to influence threshold…*
  - Rotational wall stabilisation may play a role
    - *Depends on mode rotation in lab frame*

Rotation influences on NTM triggering

- **Decrease the threshold terms** → **Rotation sign/size in Er=0**
  - Eg Ion polarisation introduces rotation depencence:

    $$a_{pol} \propto \rho_{i\theta}^2 \; g(\nu,\varepsilon) \;\; \omega \; (\omega_{i*} - \omega)/\omega_{e*}^2$$

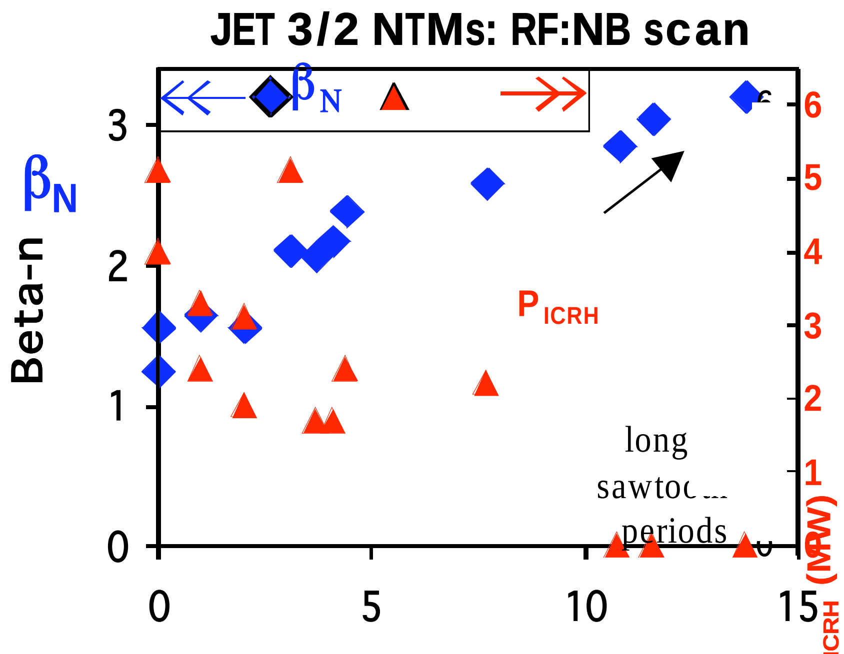
    - *Depends on rotation in ExB frame of reference*
- **Increase the seeding process** → **Differential rotation**
  - Decreased rotation between resonant surfaces (q=2 cf q=1, 1.5 or edge) enhances mode coupling
- **Other drives for the mode** → **Route for other terms**
  - Variation in Δ' drives mode onset at high β_N ***- esp. 2/1 NTM?***
    - *Mechanisms for ion polarisation to vary threshold…*
  - Rotational wall stabilisation may play a role → **Absolute rotation**
    - *Depends on mode rotation in lab frame*

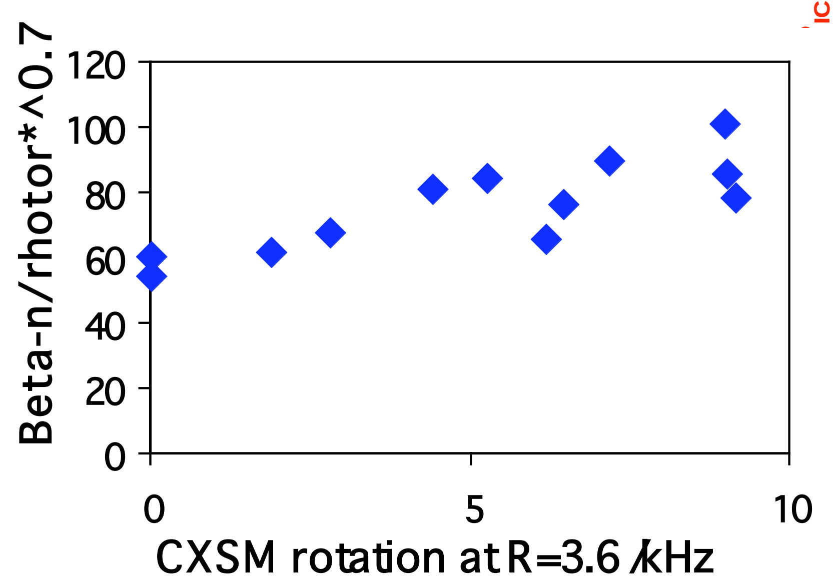
Rotation enters in various ways, making different types of rotation dependency, according to which physics is involved

Experimental studies…

Changing the momentum injection: ICRH:NBI mix at JET

- **Ramp up power for different mixes of ICRH:NBI power**
  - Phase ICRH to avoid large sawteeth
- **Clear result obtained**





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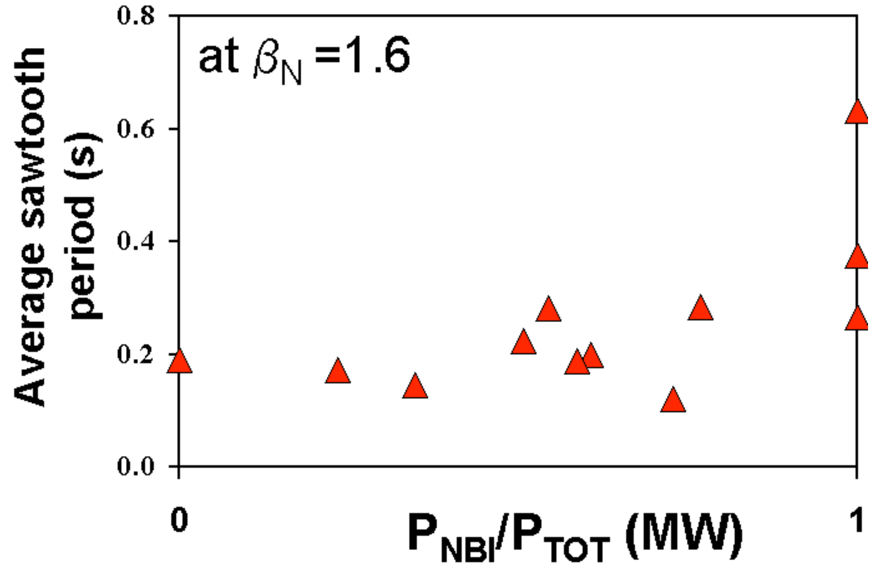

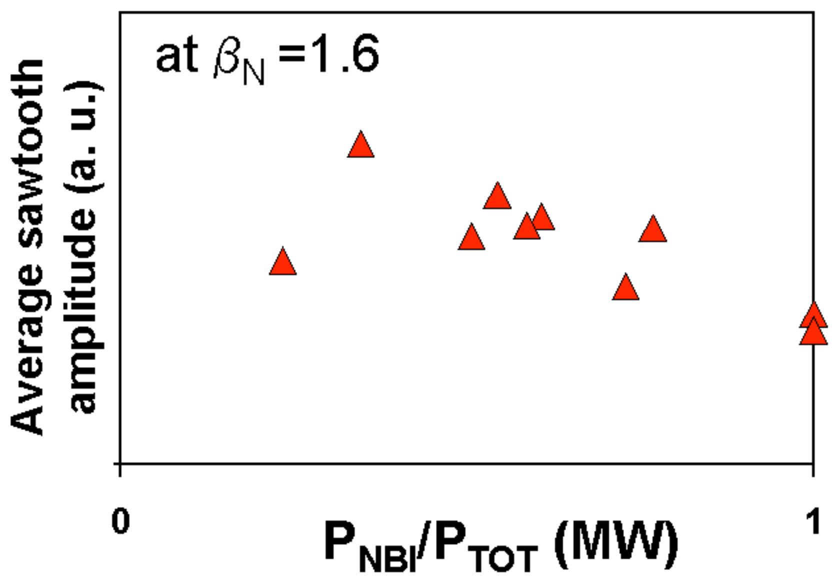

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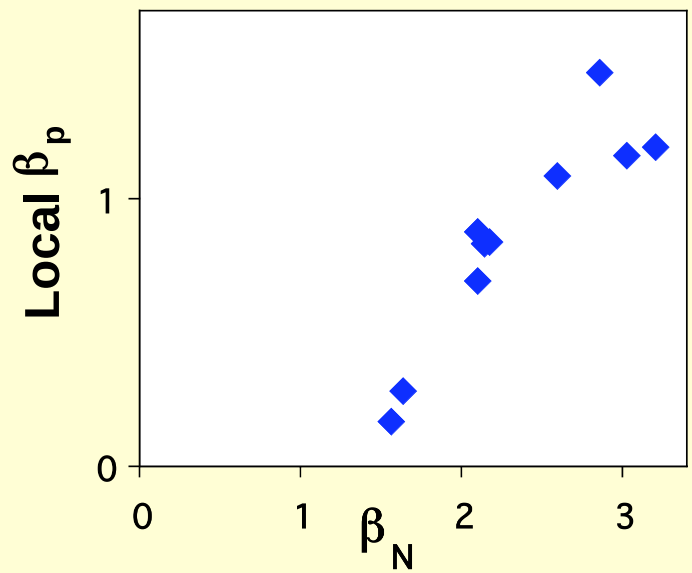
  - But still use of ICRH gives additional variations
    - in sawteeth
    - and profiles
- ***Need to do something more controlled…***

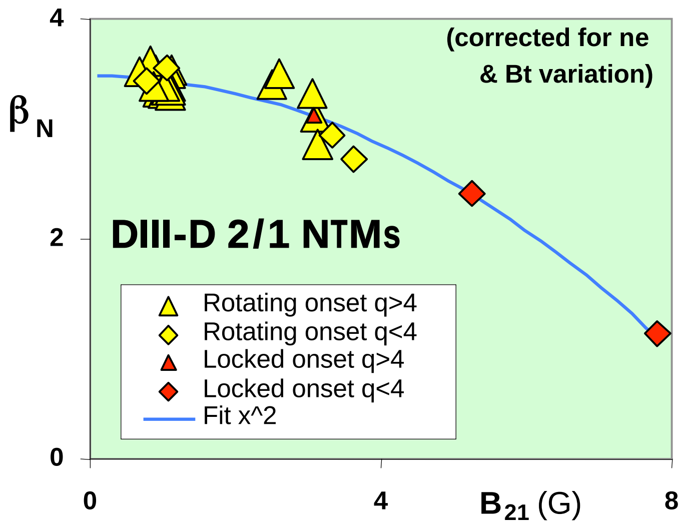
Mapping $\beta_N \rightarrow$ local β_P:

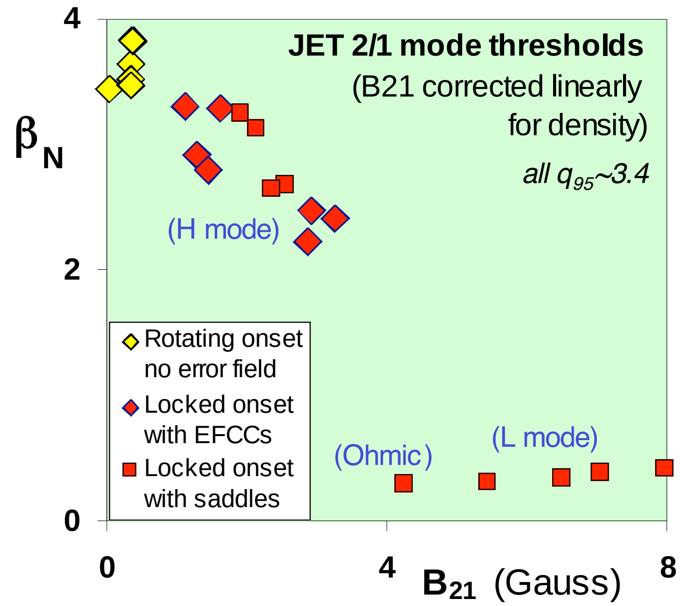


→ Profile changing

Rotation and error fields play key role in tearing mode behaviour

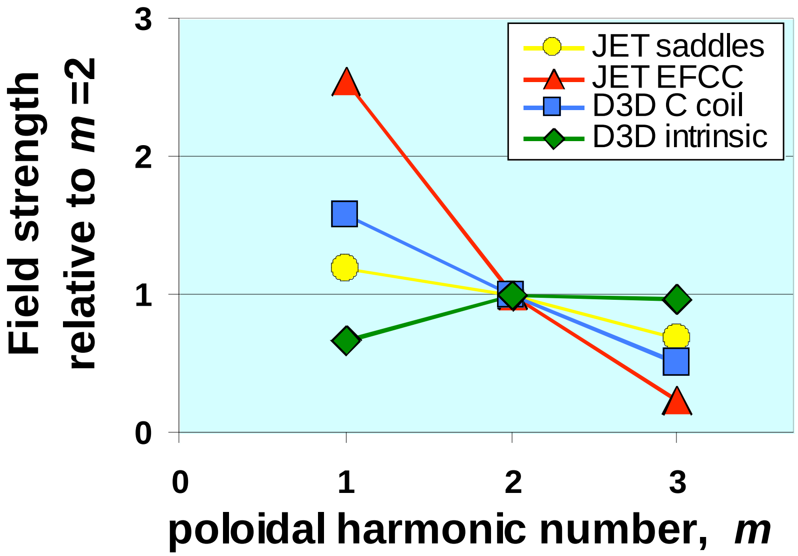
- **DIII-D and JET show a lowering of 2/1 NTM thresholds with increased error field:**





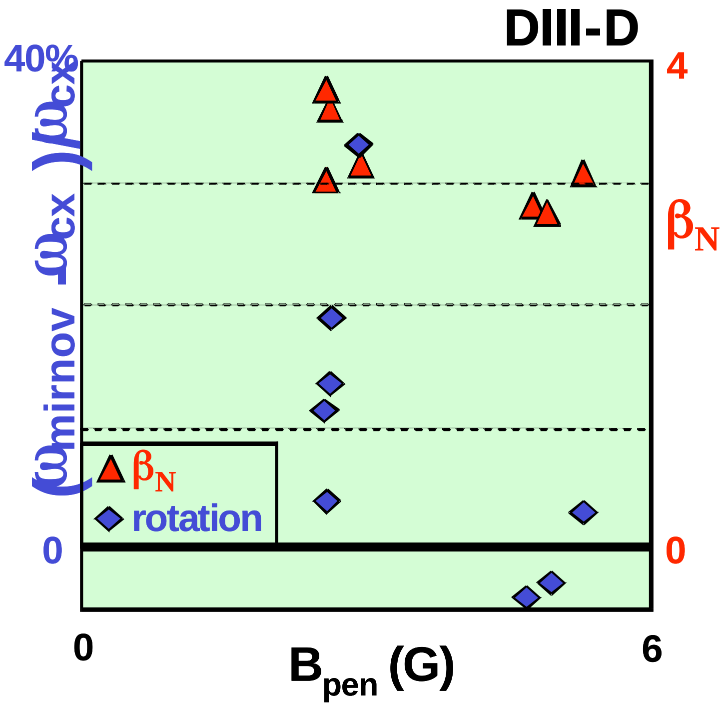
- **This is likely to act through braking of the plasma rotation**
  - Decreased magnetic shielding
  - Changes to NTM physics terms (eg ion polarisation)
  - Direct magnetic braking leading to error field penetration

Trends in error field-NTM data indicating rotation role



- **JET error fields have more 1/1 field**
  - Increased braking

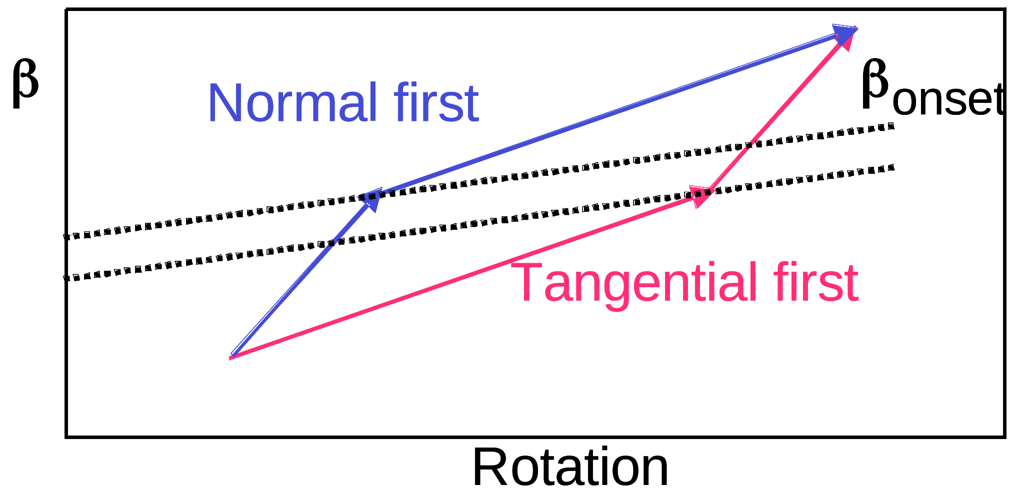
- **DIII-D data also shows fall in mode rotation in CX frame**
  - Suggests rotation in Er=0 falling
  - Indicative of ion polarisation current role



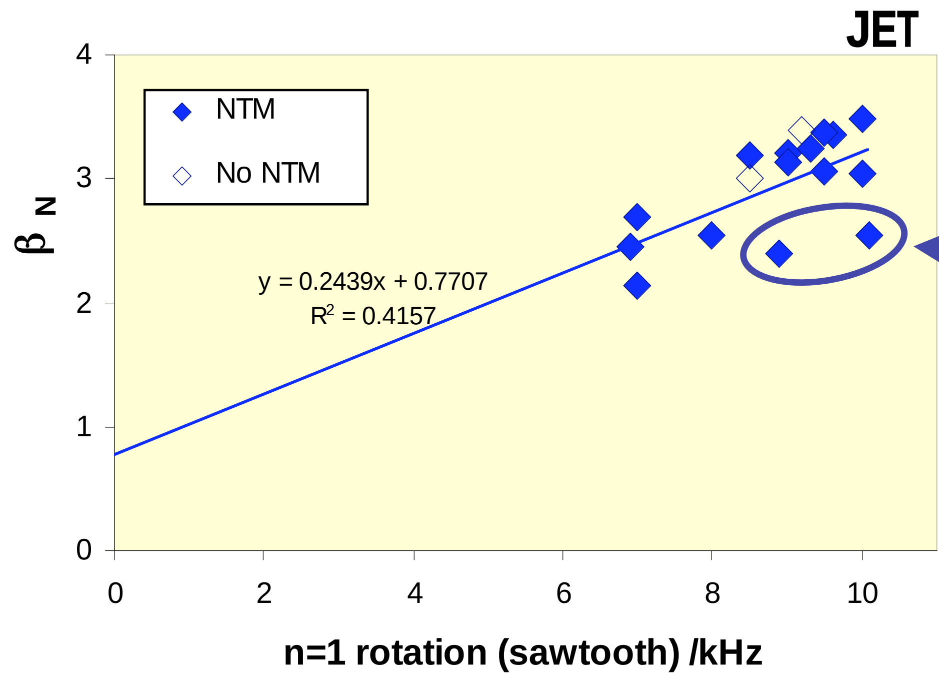
➢ ***Explore role of rotation directly…***

Experiments to vary momentum injection: for 3/2 NTM on JET

- **JETs "tangential" and "normal" beams inject different levels of momentum,**
  - ***Induce 3/2 NTM by ramping up power with different beam mixes***



3/2 NTM rotation dependence

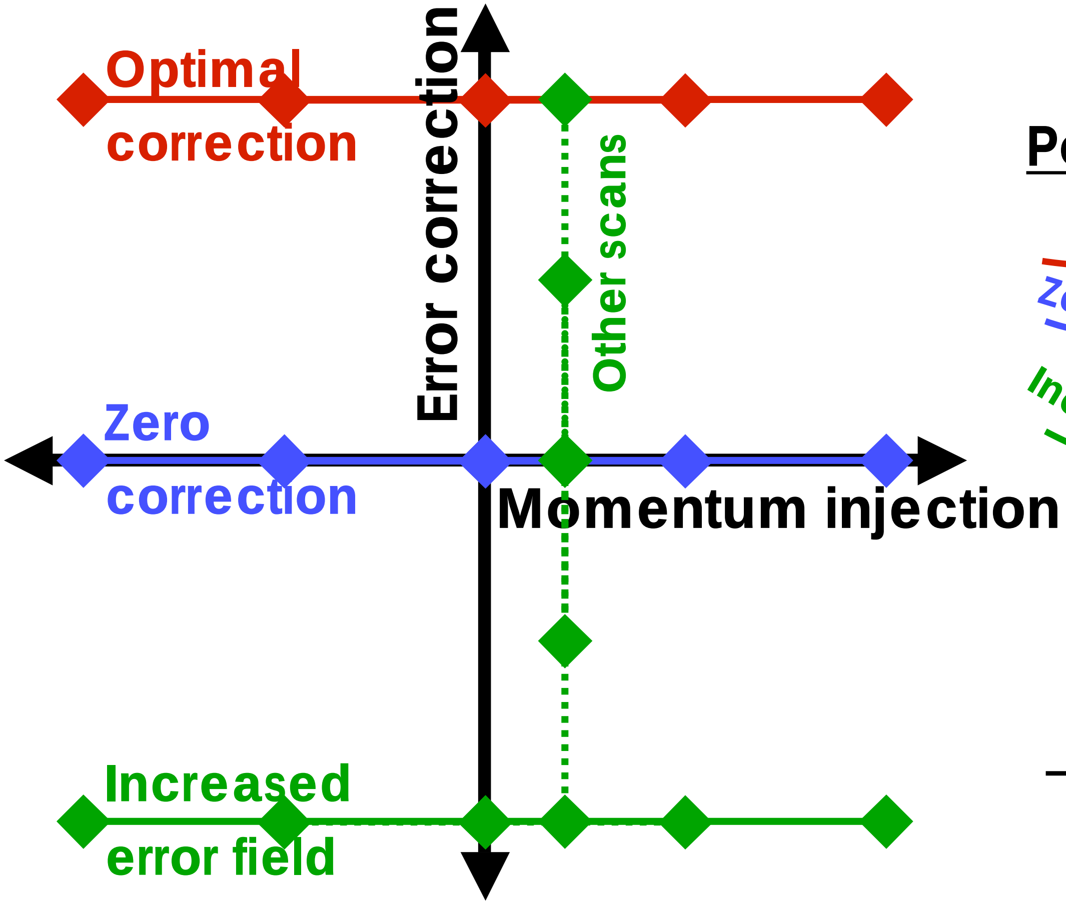


- **A trends is apparent across the plot**
  - *but some outliers violate this trend*
  - *due to natural variation in sawteeth and NTM from slight changes in NBI & density waveforms*

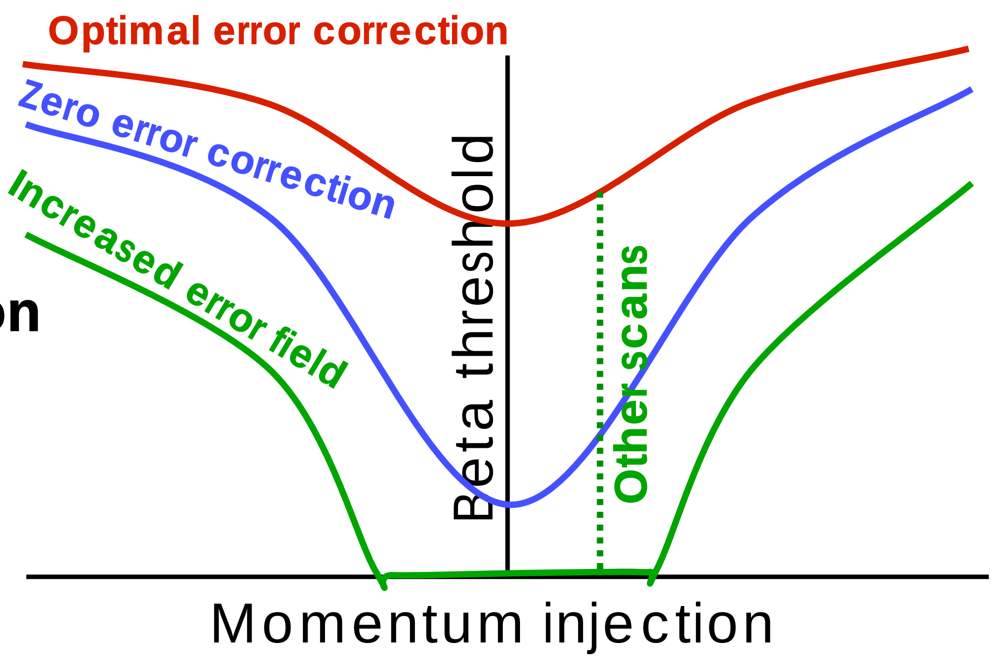
- **Nevertheless this extrapolates to low thresholds for a self-heated plasma such as ITER**
  - *Motivates further studies with balanced beams…*

Torque scan experiment on DIII-D

- **Perform β ramps at ~fixed co:counter dependence**
- **Vary co:counter mix and error field between shots:**

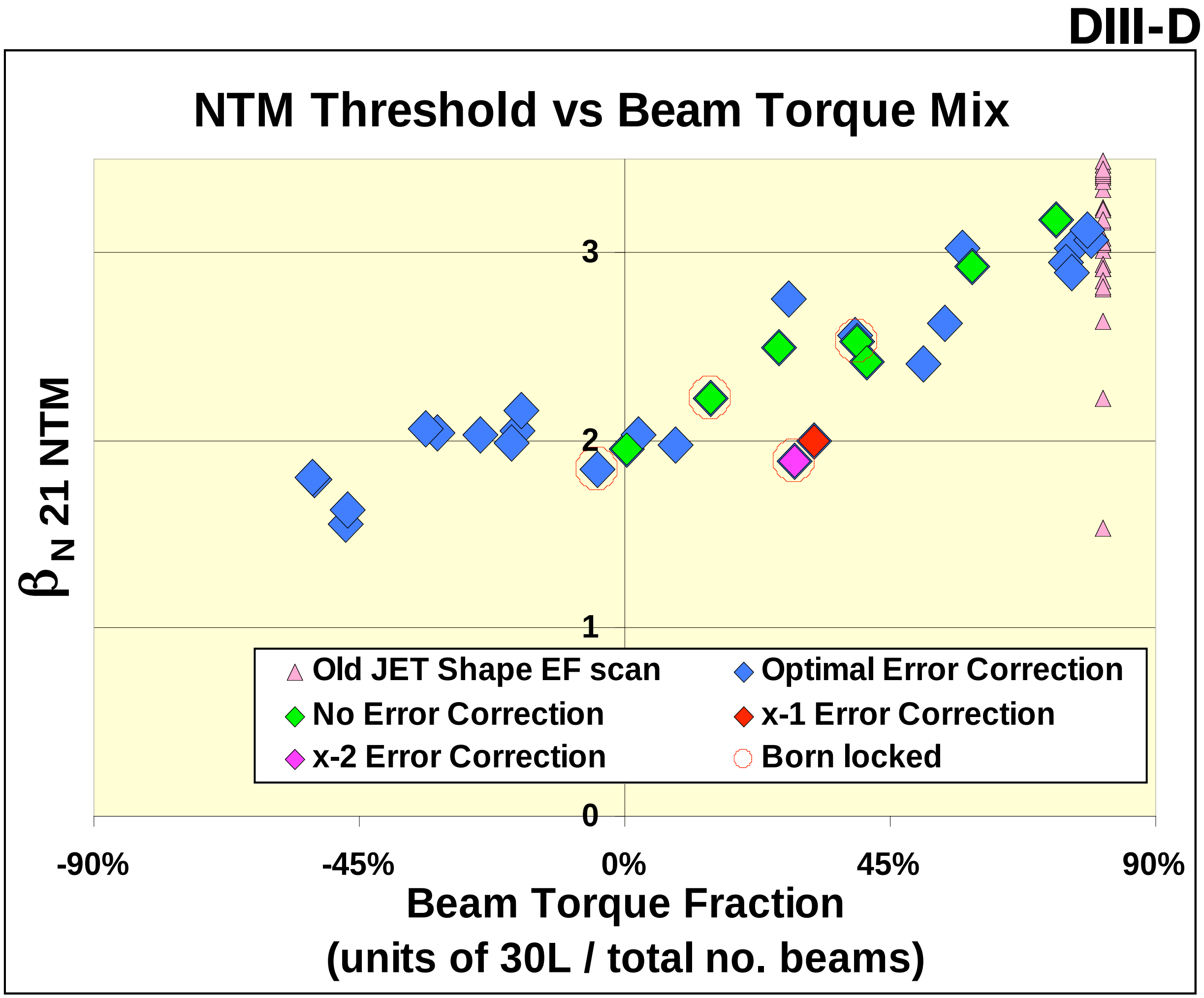


Possible results?:



Clear trend observed

Plot in terms of co:counter mix:

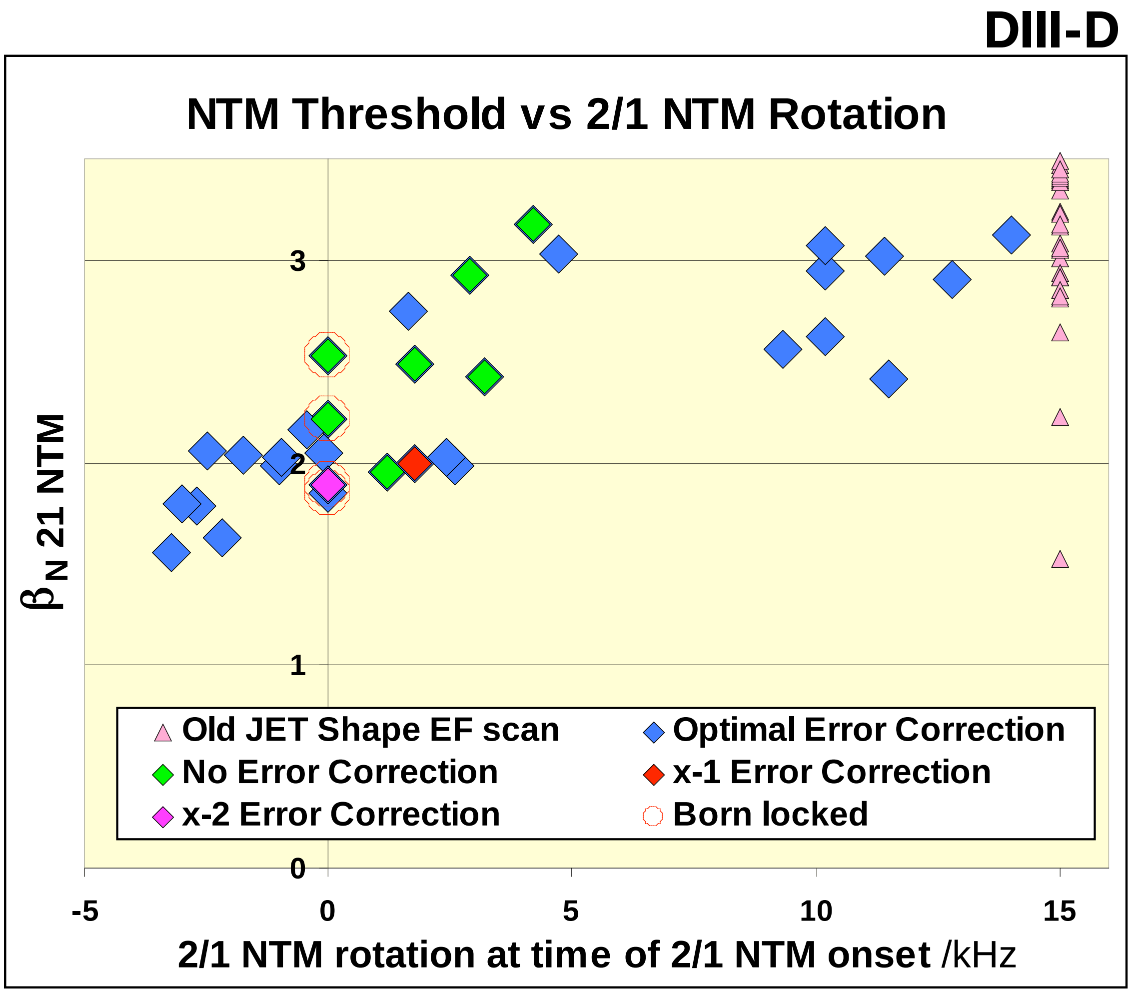


- **Threshold falls with co-torque fall**
- **Lower still with net counter injection**
- **Error fields only modest effect**

- **But are hidden variables changing?...**

Clear trend observed

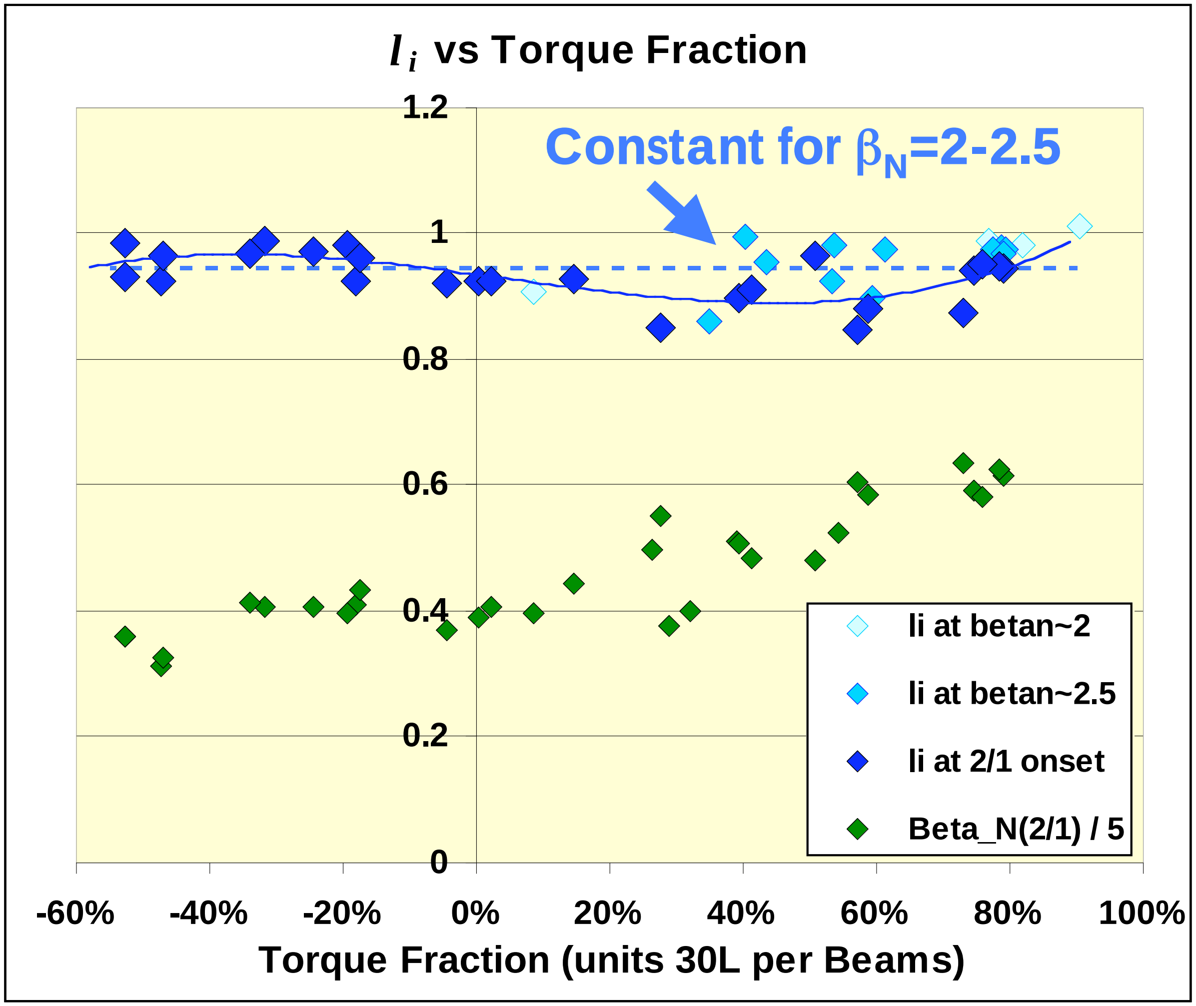
- **Trend born out in terms of rotation**



Current profiles are fairly steady at given β_N

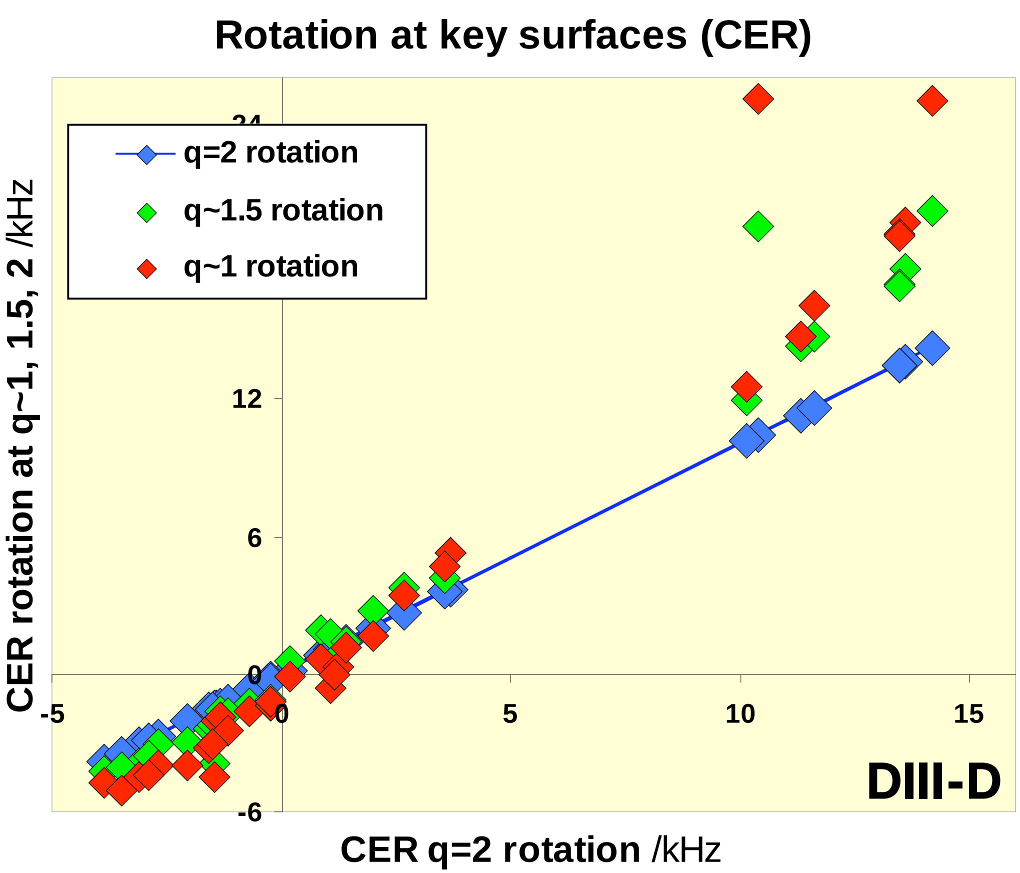
- **No significant variation in li**
  - Dependence at NTM onset due to variation in β_N
  - Still checking out detailed MSE EFIT profiles:
    - Er correction for MSE
    - Kinetic EFITs for extreme points…

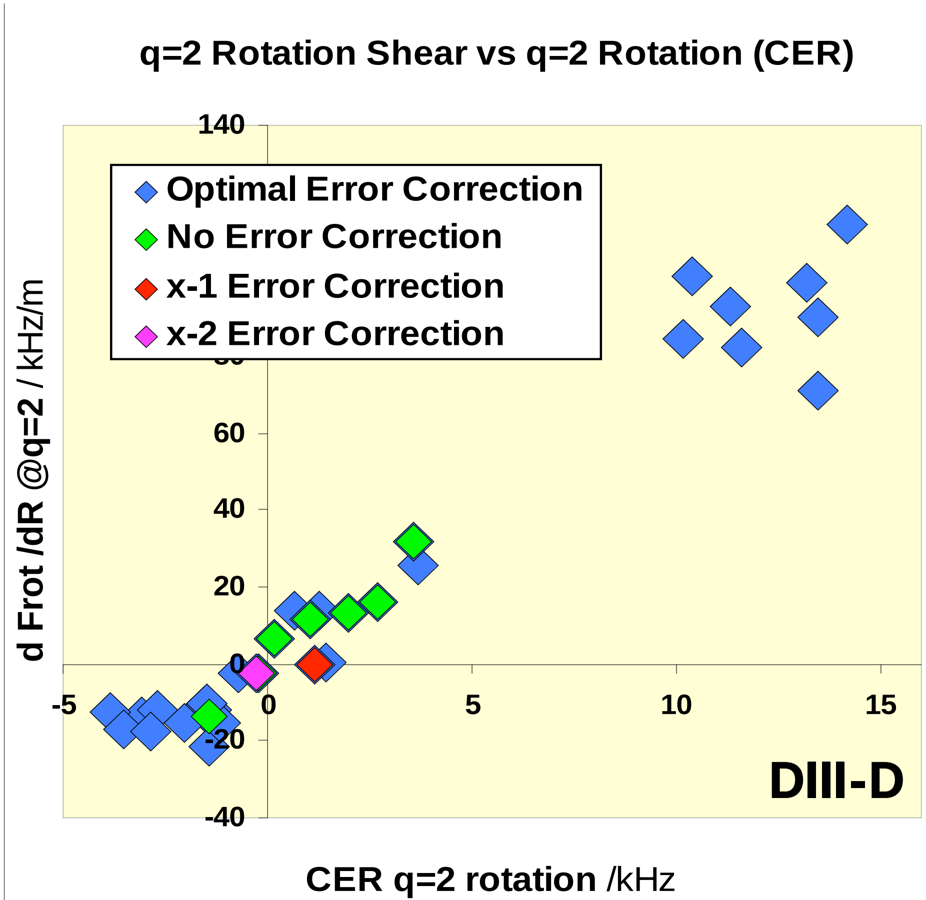
DIII-D



Rotation profiles

- **Some variability - but remain sheared, even for counter**



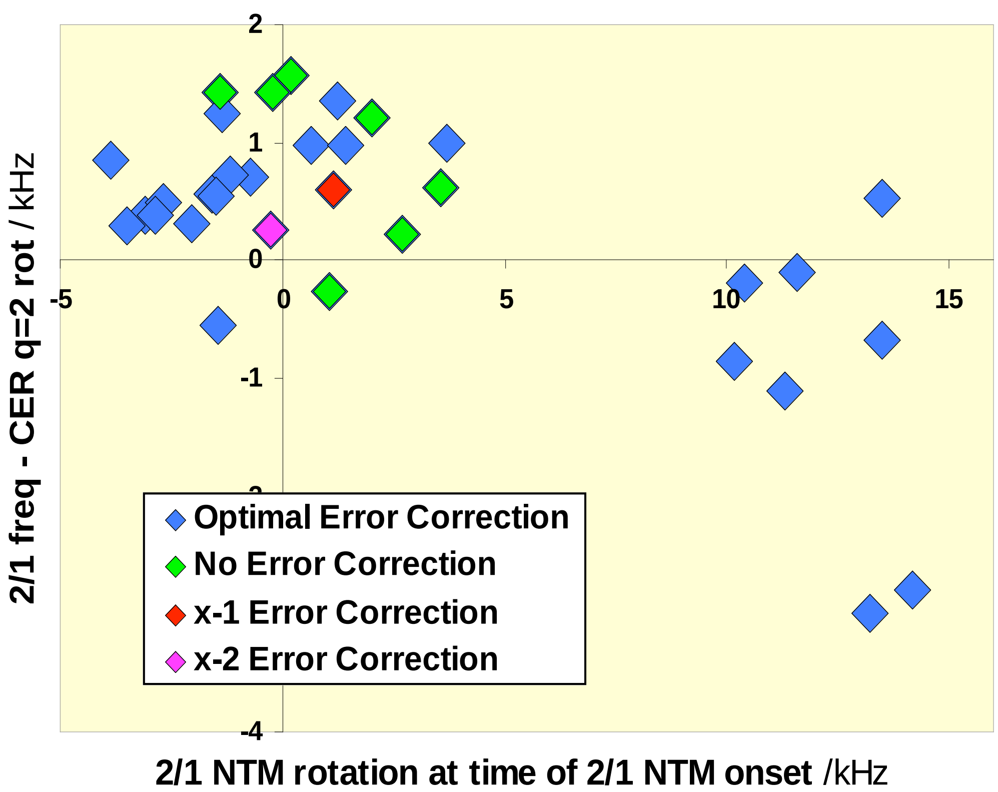


- **Suggests low counter thresholds are not simply due to lower |rotation| (wall effect) or rotation shear (coupling)**

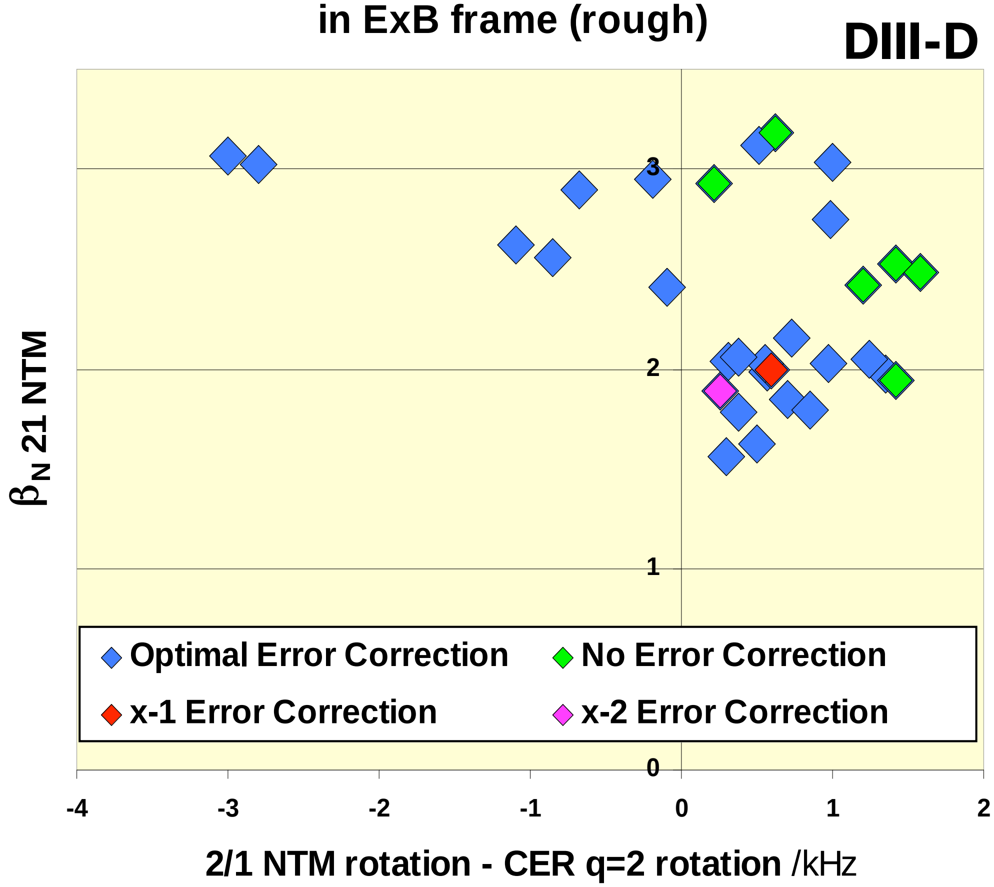
Ion polarisation current variation? Rotation in ExB frame (rough)

- **Some trend in mode rotation in ExB frame**

Rough ExB rotation vs q=2 Rotation



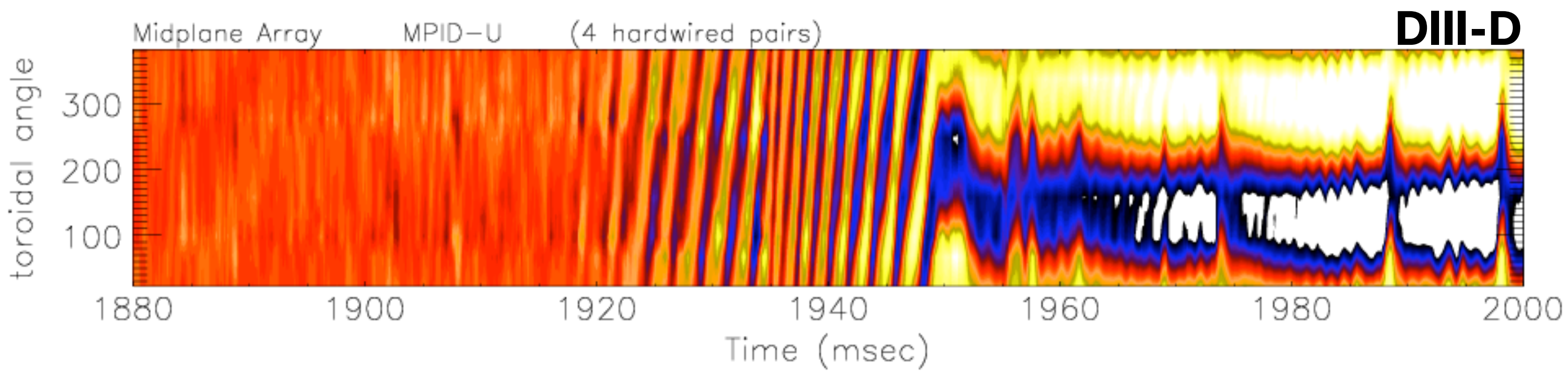
NTM Threshold vs mode rotation in ExB frame (rough)



– ***Preliminary – detailed CER fits underway with corrections for atomic physics and other rotation contributions***

Even at low torque get rotating modes

- **At -17% torque, 2/1 born at just 430Hz in counter direction**
  - (3/2 mode rotation just 1kHz, cf usual ~30 with balanced beams)



  - A number of near balanced shots exhibit this behaviour
    - ***Even those where error field correction has been reversed and has led to lower β thresholds!***

➢ **Not simple error field penetrations**

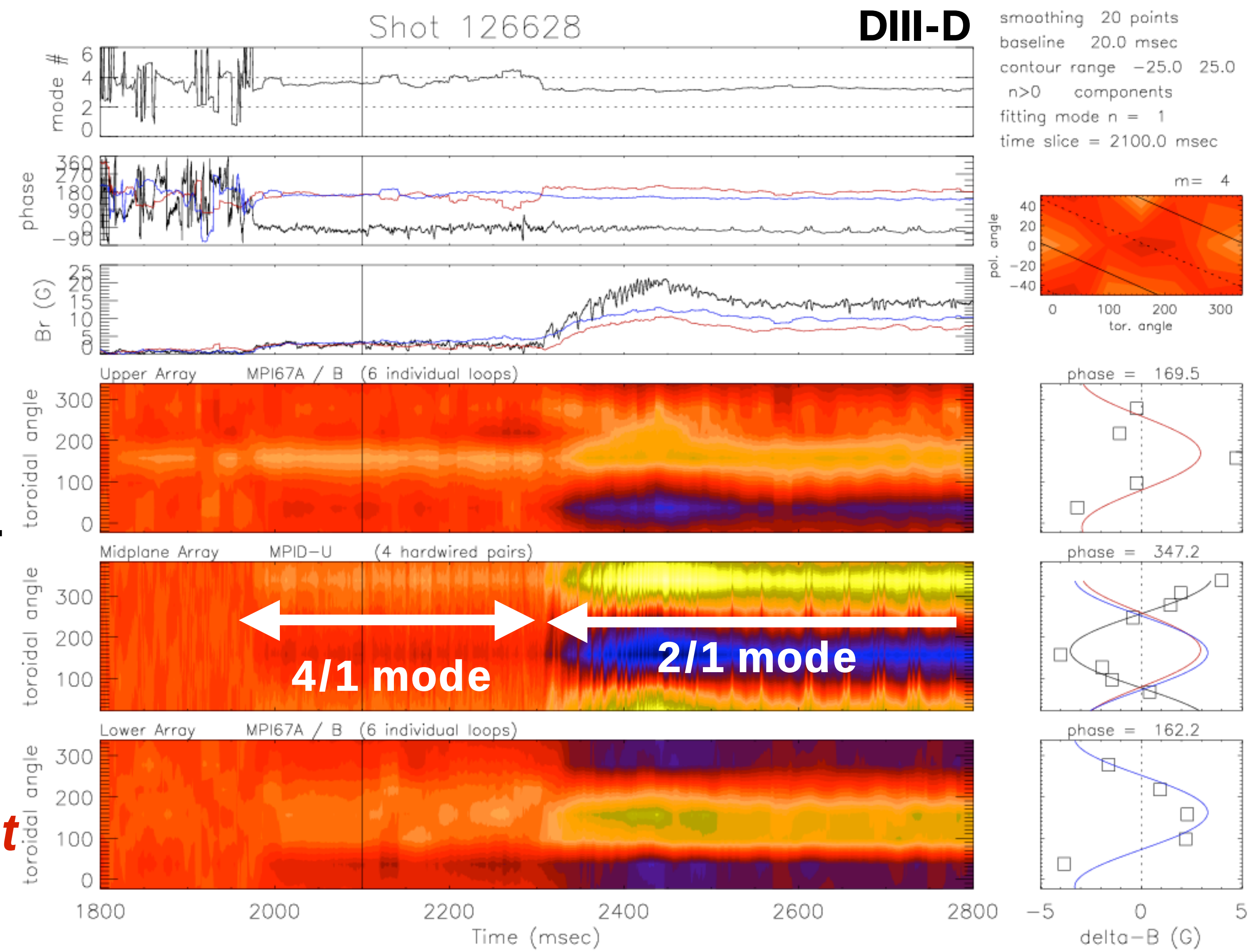
  - Error field acting through changes to NTM stability
  - *…as in previous error field scan experiments*

Conclusions

- **A range of experiments indicate NTM onset β's fall with rotation**
  - ***poses a concern for ITER which needs to be investigated further***
- **A number of effects may be coming into play**
  - Decreased shielding
  - Error field drive
  - Changes in Ion Polarisation
  - Reduced wall stabilisation
- **Strongest, cleanest effect seen for 2/1 NTM in beam mix exps**
  - ***One third fall in threshold to β_N~2***
  - ***Threshold continues to fall with increasing counter rotation!***
    - Suggests seeding not governed by mode coupling and not predominantly controlled by wall interaction
    - Favours Δ' model of seeding with ion polarisation current variation
  - ***Error fields also lower thresholds by plasma braking***

These results are preliminary, and we are still checking some key aspects of behaviour in more detail.

See m=4 locked modes in some low rotation cases, as core rotates



Plasma rotation stopped with 2/1 locked mode onset

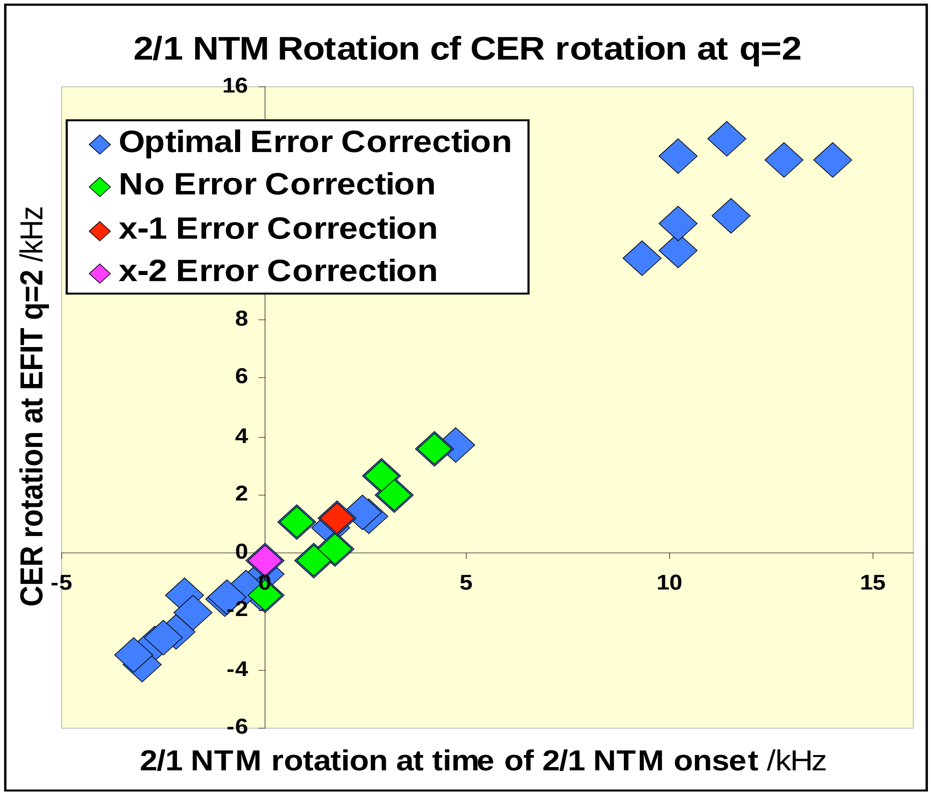
- *But not while 4/1 locked mode present*

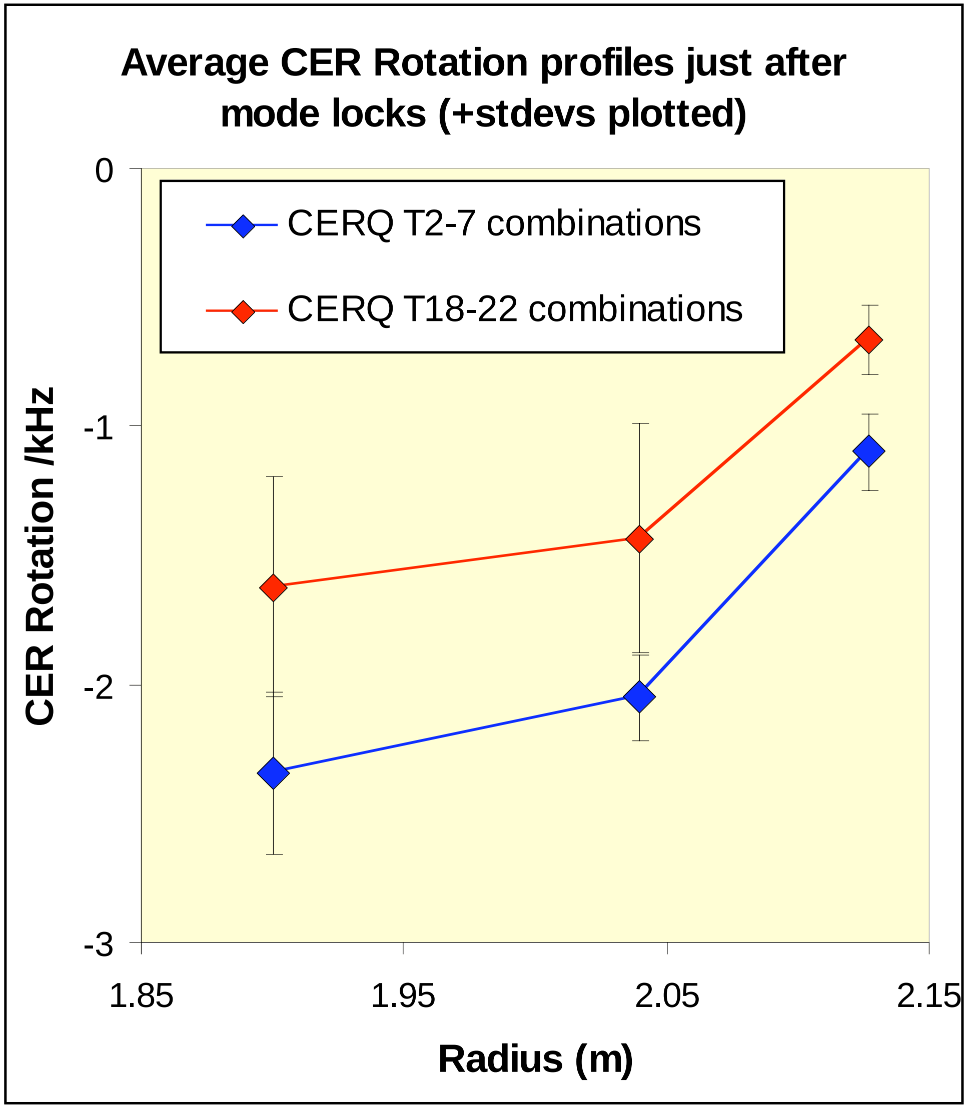
➤ *Potential for n=1 ELM control with sub-critical error field?*

Reserve slides...

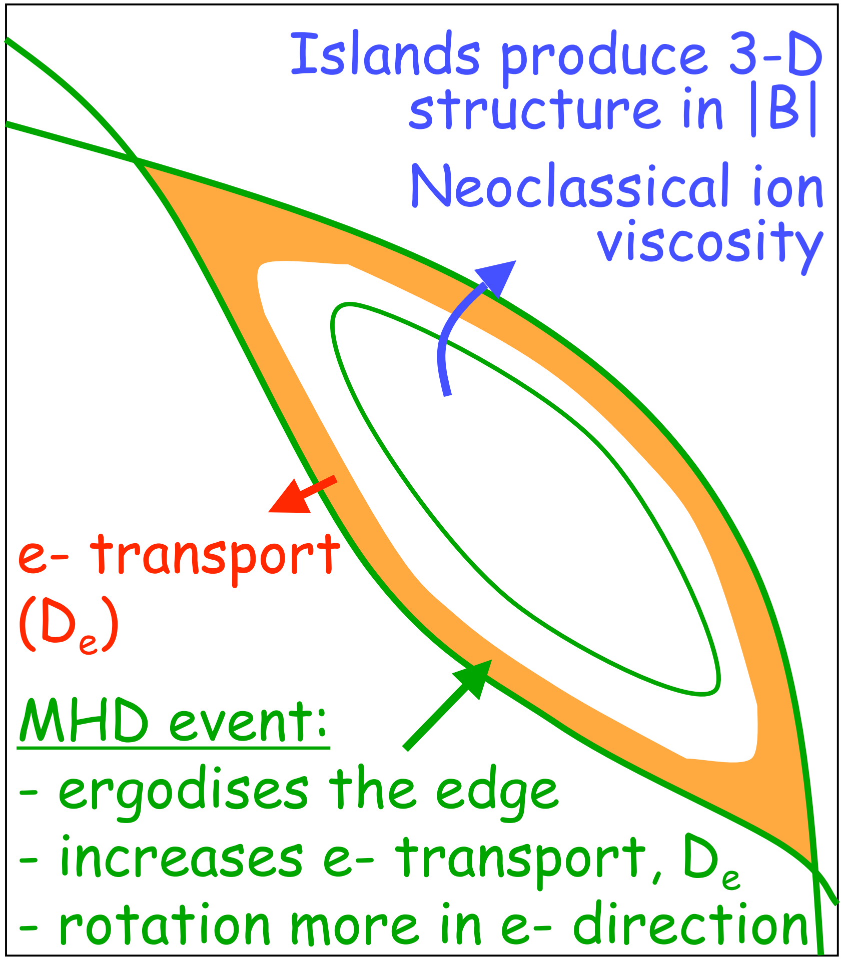
Locked mode

- **Locked mode always forms with negative CER rotation**
  - Tallies with offset between mode and CER rotation
  - *Diamagnetic rotation…*



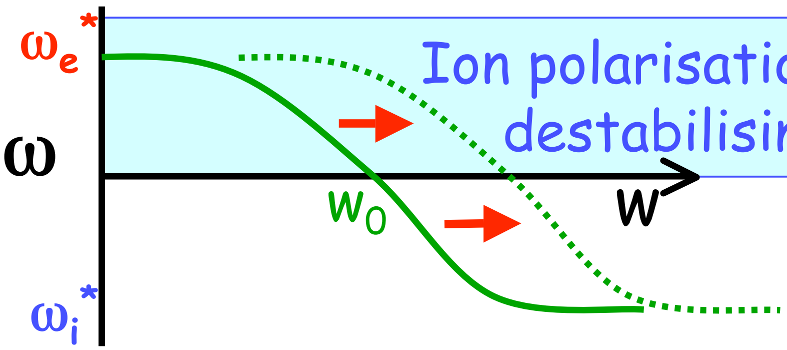


- **Ion polarisation effects depend on island rotation -** $a_{pol} \sim \omega(\omega - \omega^*_I)$



[Hegna, Bull.Am.Phys.Soc.48, 280]

Rotation from balance of ion and electron dissipation:



– naturally leads to small islands via ion polarisation effects

– higher e-dissipation raises $w_0 \sim (D_e)^{0.5}$

- *Does not require frequency matching between MHD modes and the island*
- *May explain error field effects*

LHCD in low field regimes

- **LHCD is a potentially efficient tool for driving current**
  - and useful perturbative tool to explore the role of Δ'
    - Expect effect on tearing modes:

$$\frac{\tau_r}{r}\frac{dw}{dt} = r\Delta' + a_{bs}\frac{r\beta_P}{w}\left[\frac{1}{1+w_d^2/w^2} + \frac{w_{pol}^2}{w^2}\right]$$

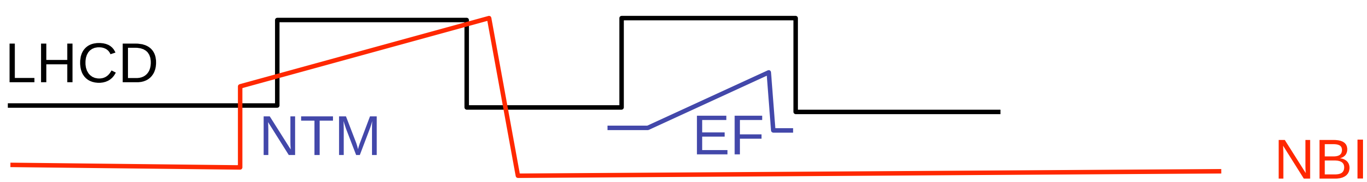
Small island effects

LHCD drives axi-symmetric currents, modifying overall tearing stability

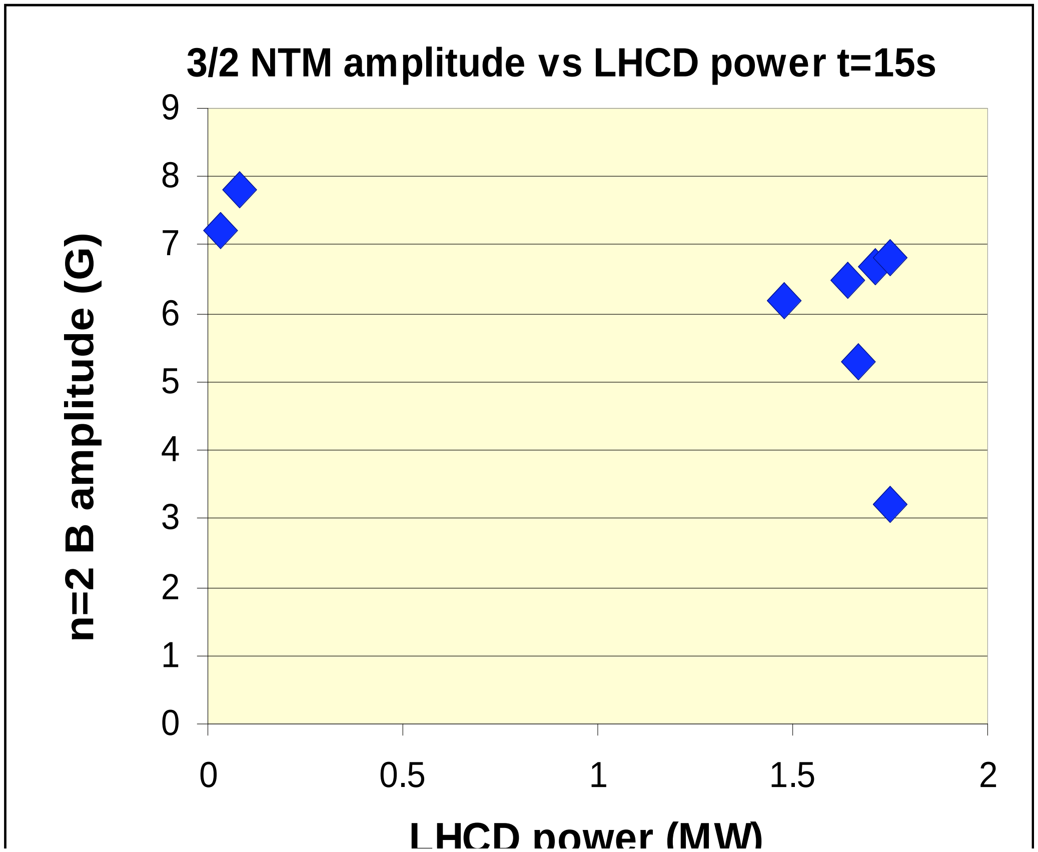
Bootstrap drive overcomes natural tearing stability

- **But at low fields JET's LHCD is operating below cut off**
  - Wave undergoes multiple reflections, broadening $n_{//}$ & leading to deeper penetration
  - Code to calculate this under construction & needs data

Explore effect in heated NTM phase and Ohmic error field phase:



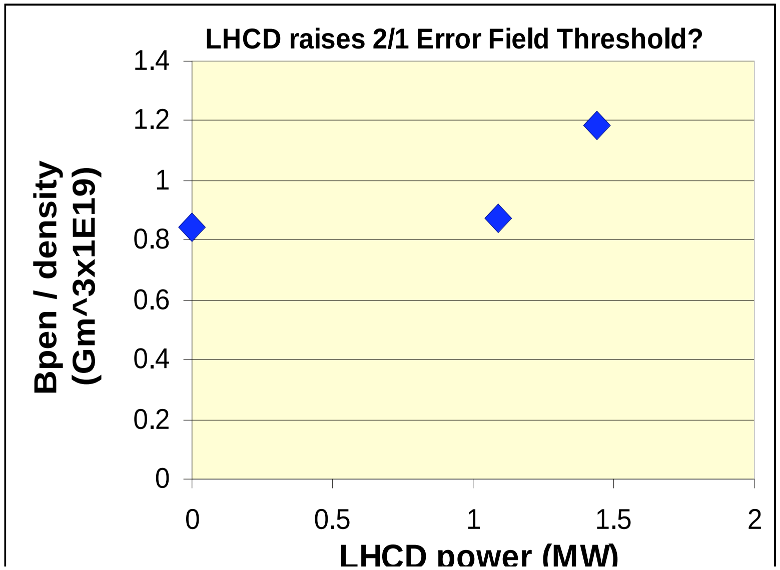
LHCD on a saturated 3/2 NTM

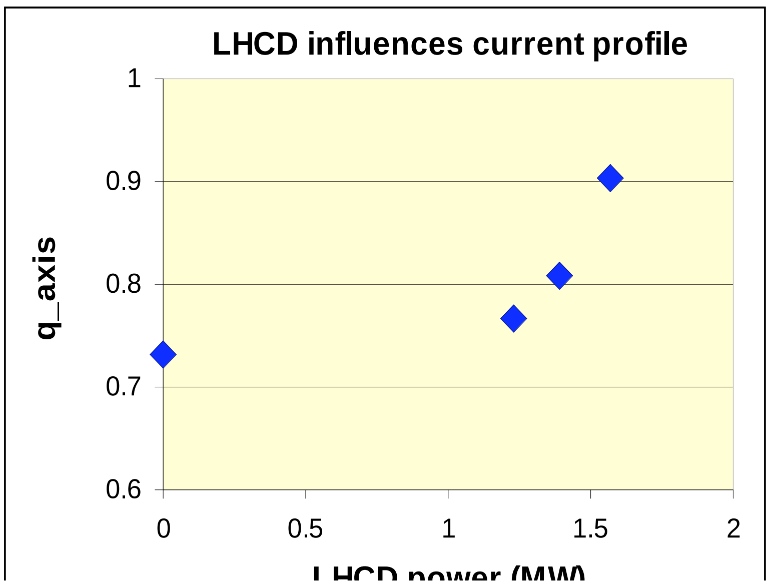


- **Significant effect on saturated 3/2 amplitude**
  - Mode size falls 15-60% with LHCD
- **Increased LHCD power would be interesting**
  - May be at tipping point for mode
- **MSE data not optimised for these discharges**

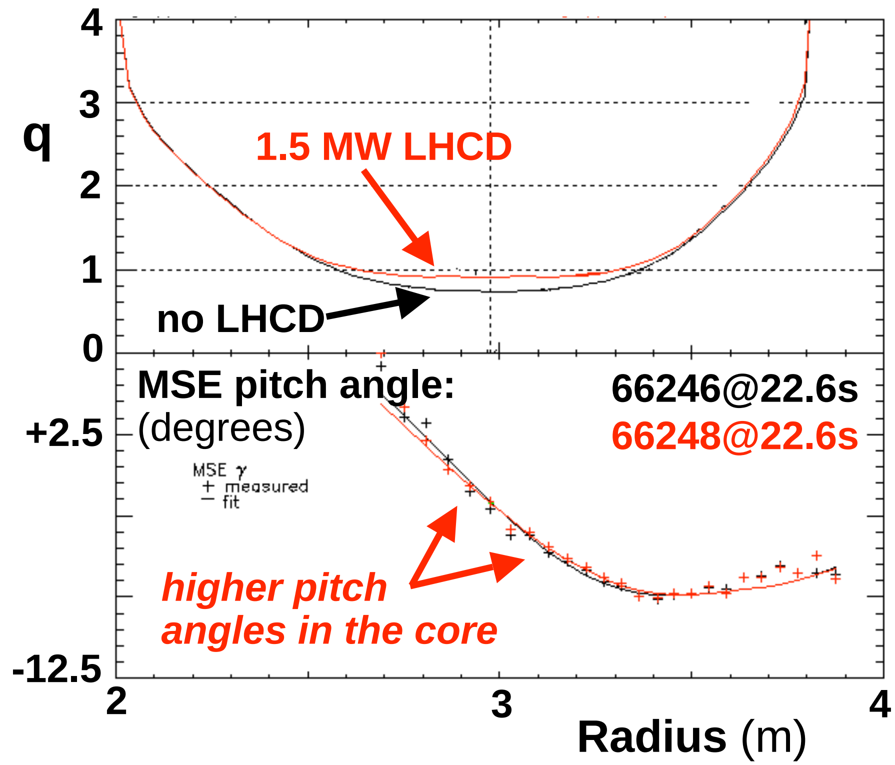
- ***Further data with more LHCD and optimised settings for MSE needed***

LHCD on 2/1 error field threshold in lower density phase of discharge





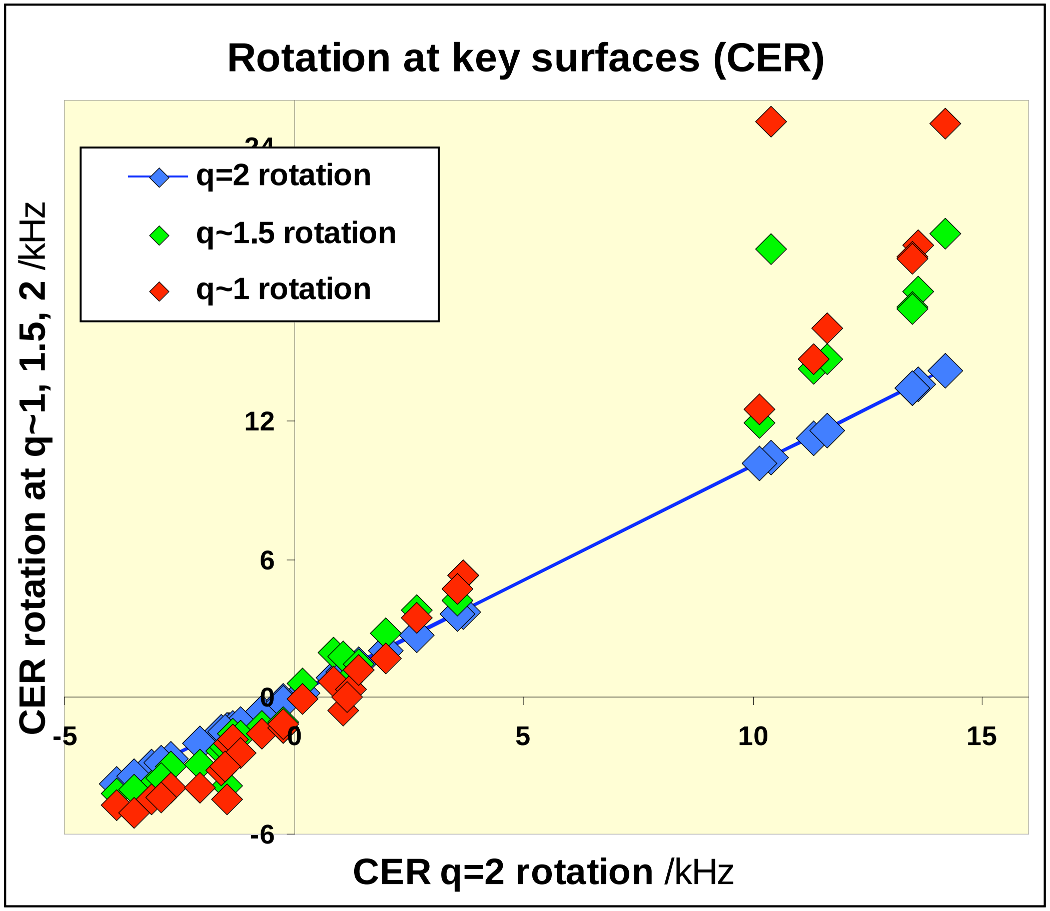
- **Not really a clear effect on the error field thresholds...**
- **But indications of a systematic effect on the current profile:**

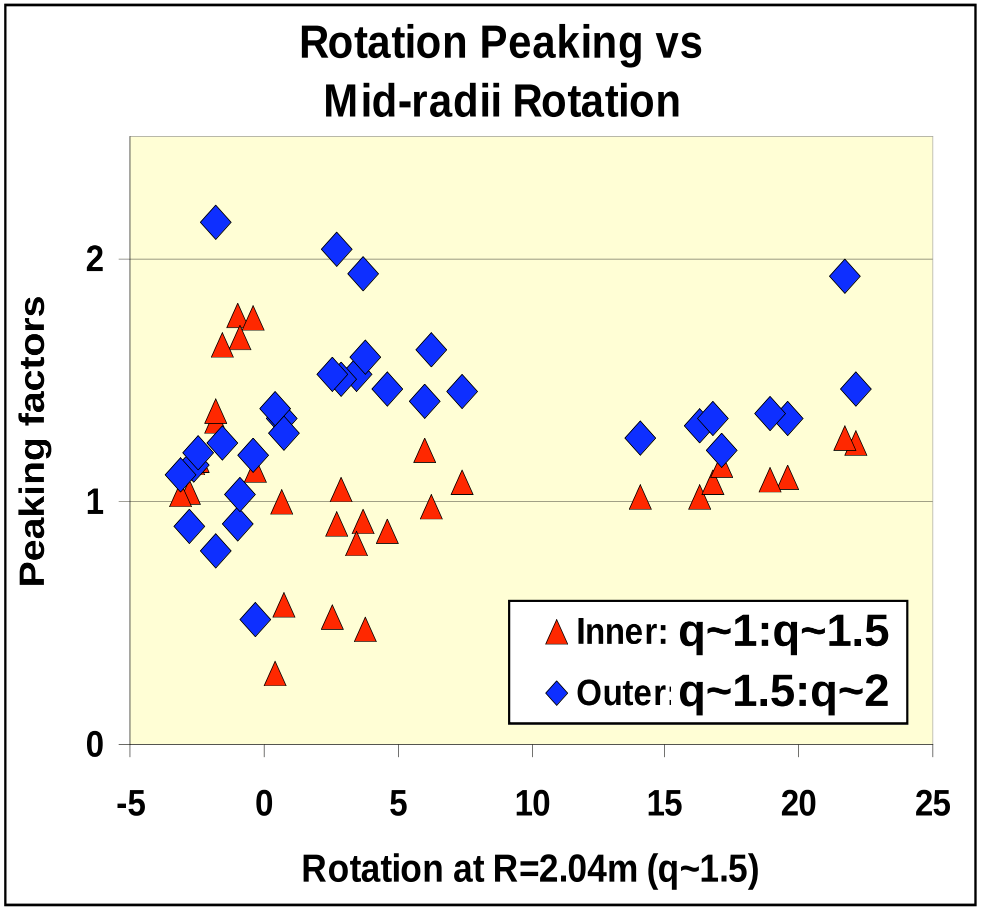


Rotation profiles

- **Some variability but remain sheared, even for counter**

DIII-D





- **Suggests low counter thresholds are <u>not</u> simply due to lower |rotation| (wall effect) or rotation shear (coupling)**