2007 Error Field Workshop, Orlando, Florida

What is the rotation dependence of error field thresholds?

R J Buttery[1]

T.C. Hender[1], R. J. La Haye[2], T. Scoville[2]

and the DIII-D and JET teams.

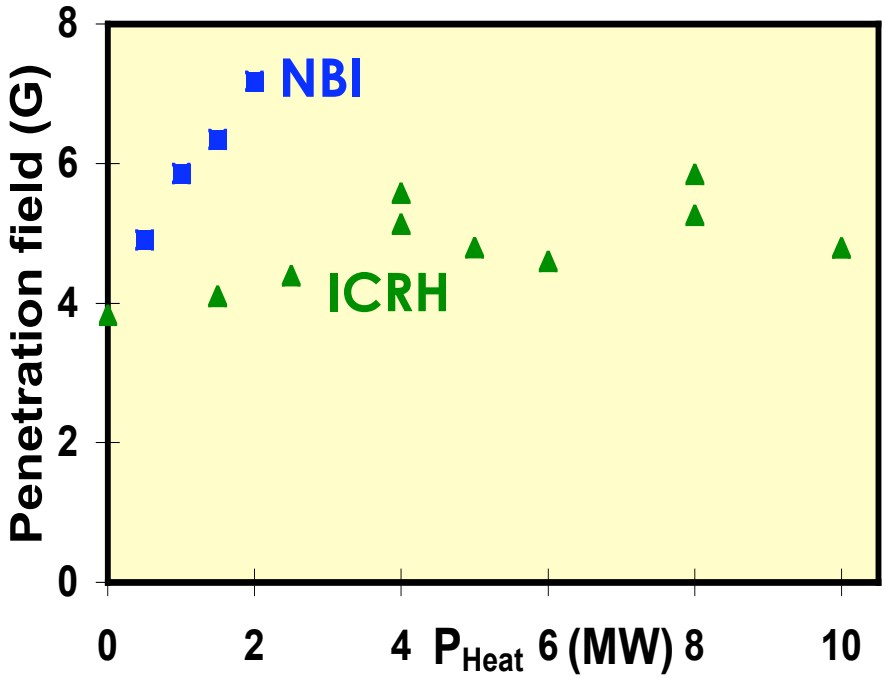
[1]EURATOM/UKAEA Fusion Association, Culham Science Centre, UK.
[2]General Atomics, San Diego, USA

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

NTM/TM triggering – Error Field role

- **Error fields act to brake rotation and then drive tearing**
  - Criteria for mode based on error field torque overcoming plasma rotation to allow tearing to accelerate
  - threshold scales as $B_{pen} \sim B_T \, \omega_0 \, t_A \, (t_{rec} / t_v)^{1/2} \sim \omega_0$ *(visco-resistive) or may be* $\omega_0^{0.5}$ *(ideal viscous)*
  - ω_0 is 'natural' MHD fluid rotation

- **Increased rotation raises thresholds**
  - So modes not a problem in most co NB plasmas
  - …but a concern if you cancel fluid rotation? ($\omega_0 = 0$)

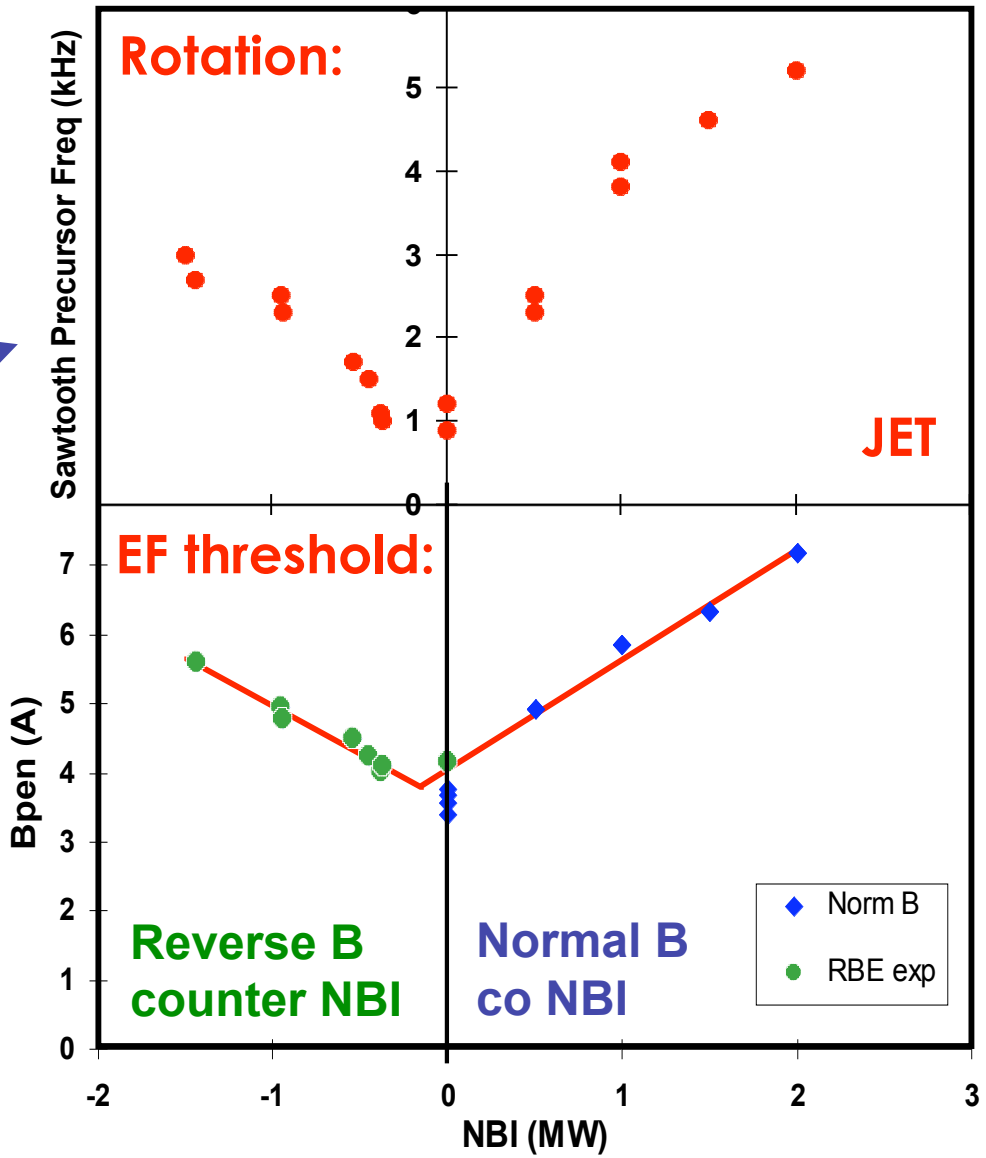


…although finer NBI scans give some encouragement at low rotation

Momentum injection varied with neutral beams on JET:

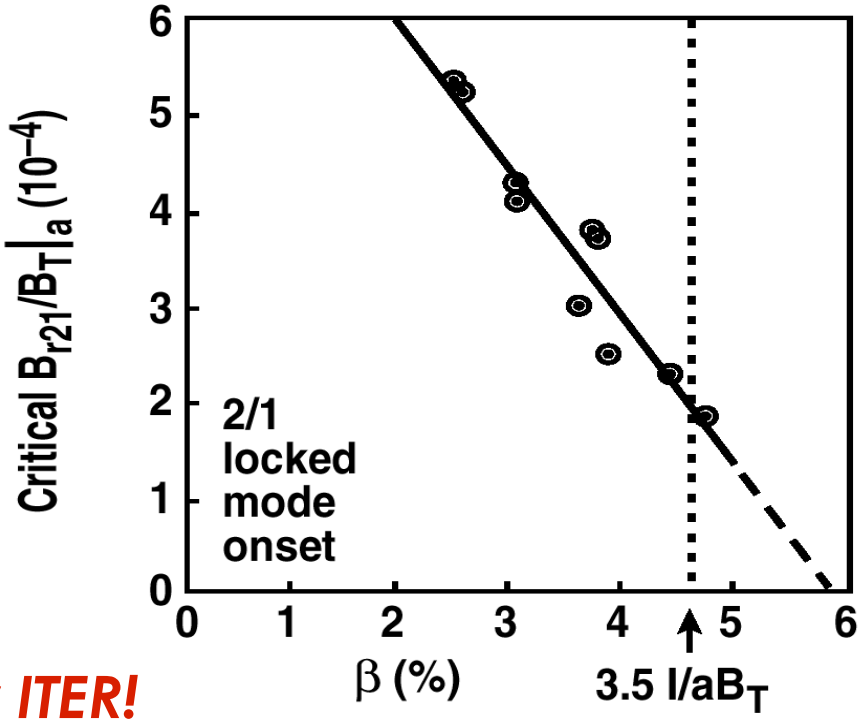
- Error fields ramped to induce locked mode
- Despite considerable range in **plasma rotation**…
- …Error field **threshold** variation is modest
  - 'Sweet spot' with very low threshold not found…
- ***Contrasts with traditional EF theory:***

$$B_{pen} \sim B_T \, w_0 \, t_A \, (t_{rec} / t_v)^{1/2}$$



But error fields role may be worse at high beta

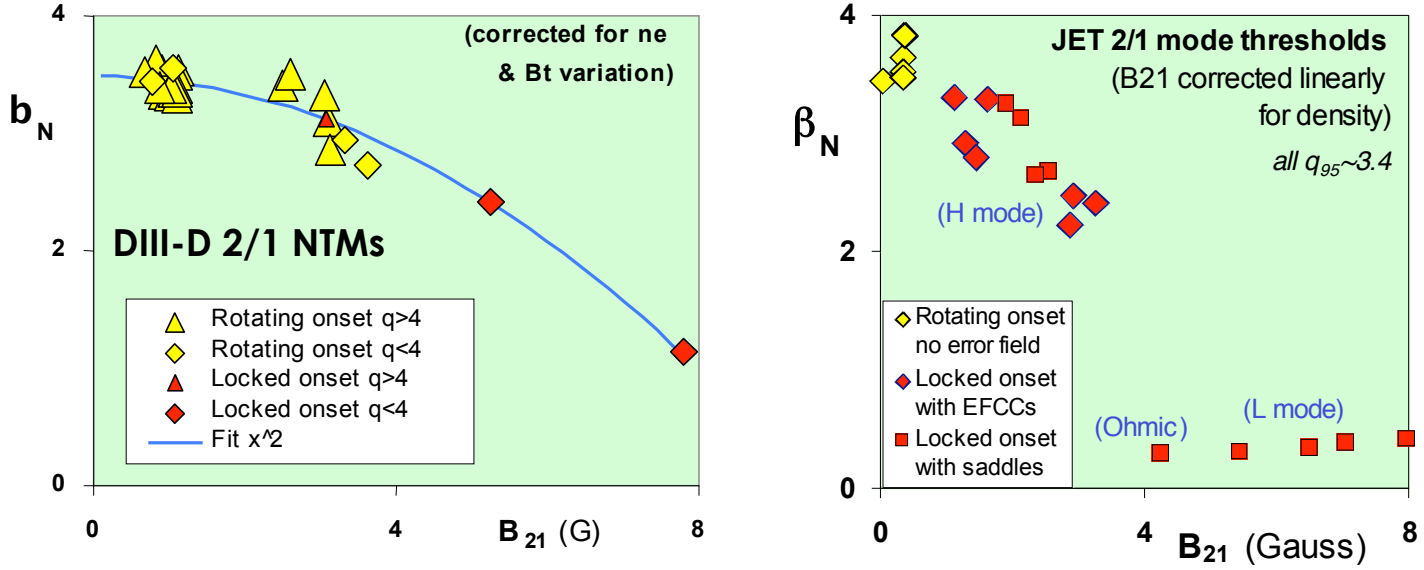
- **At high beta, error fields couple more strongly to the plasma**
  - Increased resonant response brakes plasma rotation
  - Decreased locked mode threshold [La Haye 1991]



- ***This poses a double concern for ITER!***
  - Rotation braking by error field may further perturb NTM stability physics
  - Lower rotation may lower EF thresholds further at high b

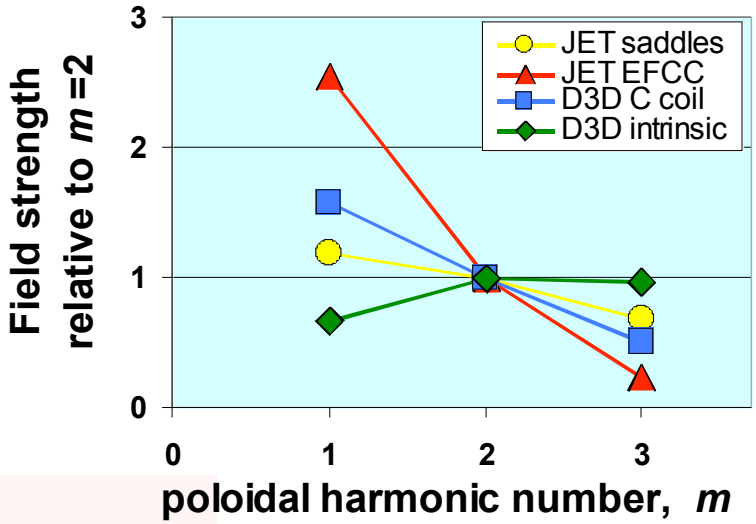
Error fields help trigger tearing modes at high beta

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



- **Note difference in locking behaviour**
  - JET: error field rapidly brake plasma and cause locked modes
    - Interplay of b_N accessible and error field amplitude
  - DIII-D: zone of **rotating** mode onset with decreased b thresholds
    - Not error field penetration, but changes to NTM stability physics
  - ***How will this manifest with low torque injection?***

Differences in DIII-D/JET error field effects lie in harmonic mix



D3D **standard** and **JET-like** shapes

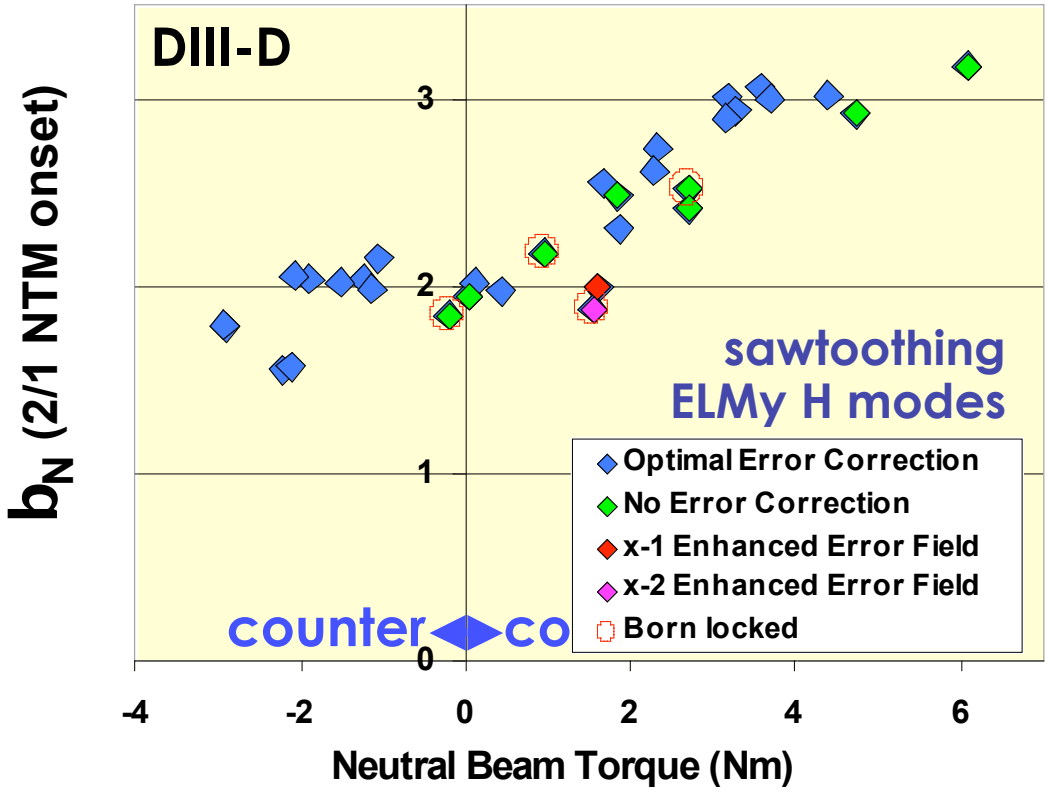
JET shape

- **JET error fields have more 1/1 field**
  - Increased braking may explain locking
- **DIII-D 100% co beam scan used C coils**
  - Some uncertainty in intrinsic error
    - Esp with JET shape
- **DIII-D ~30% net co beam scan used I coils**
  - Very low m=1, more m=3

New studies using DIII-D beam balancing…

DIII-D beam balancing studies

2/1 NTM b_N thresholds fall as net torque is reduced:

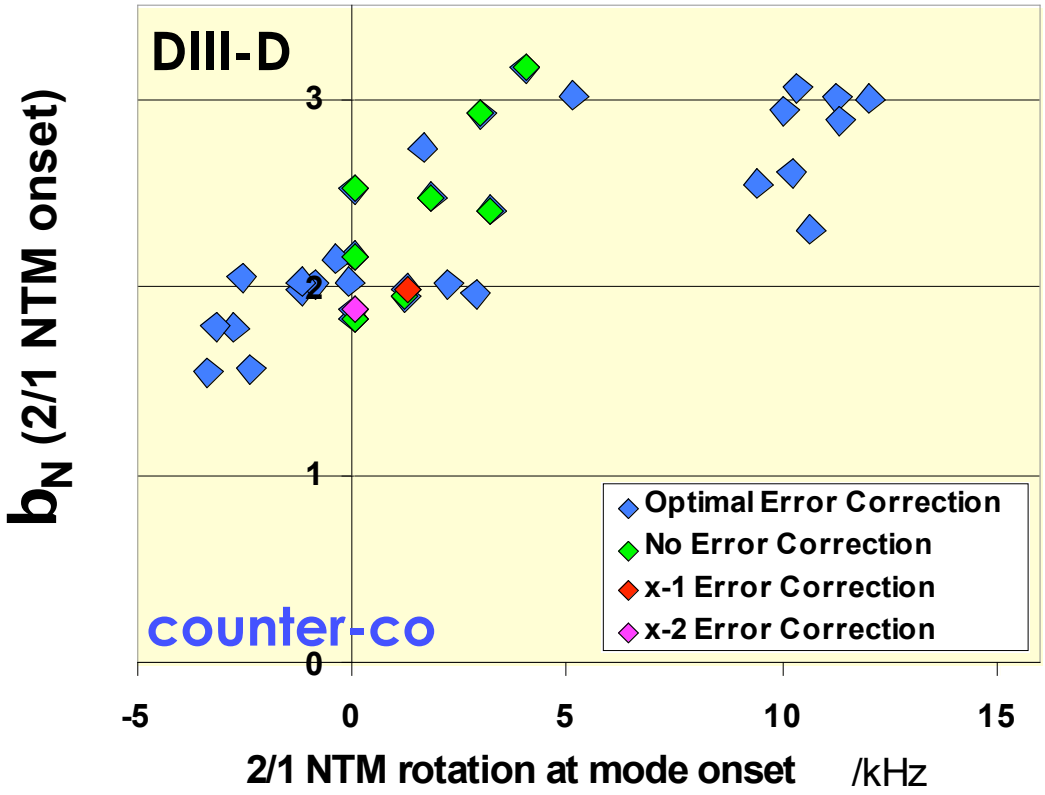


Error field seems to drop threshold slightly

- but effect not highly pronounced…
- and modes usually form rotating…

Trend confirmed in initial mode rotation speed

2/1 NTM b_N thresholds fall as net torque is reduced:

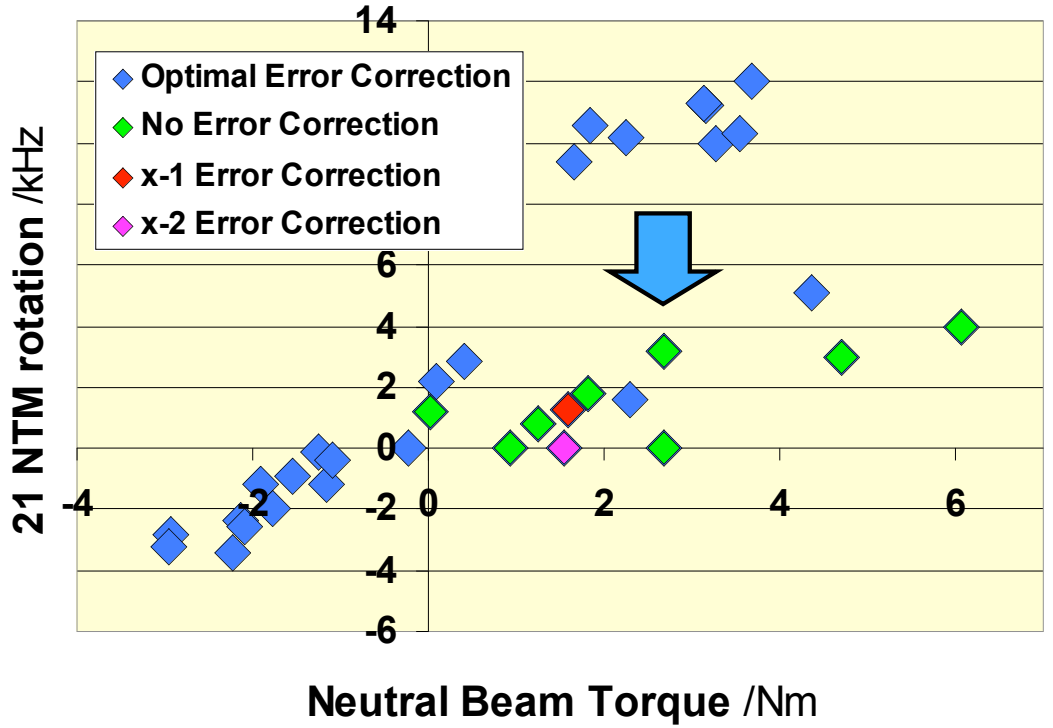


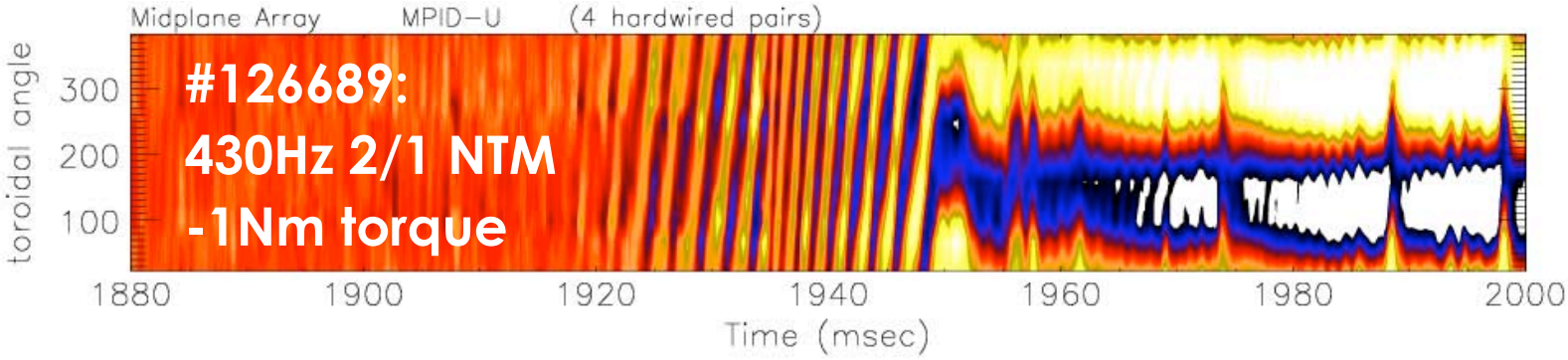
Error field seems to drop threshold slightly

- but effect not highly pronounced…
- and modes usually form rotating…
- ***Error fields act to brake plasma…***

Error fields act to brake plasma

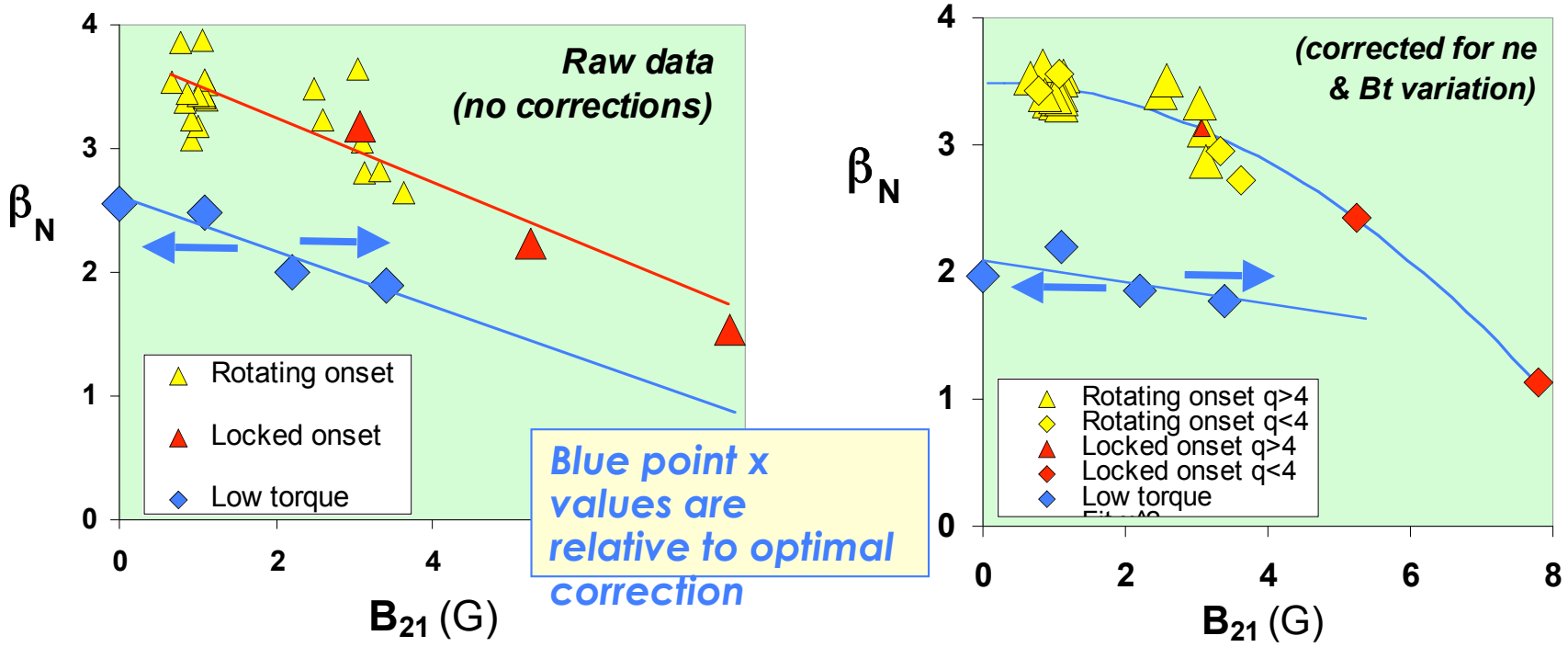
- **Error fields slow plasma rotation and lower NTM b thresholds**
- **But do not directly drive locked modes**
  - Most low torque cases start in rotating state





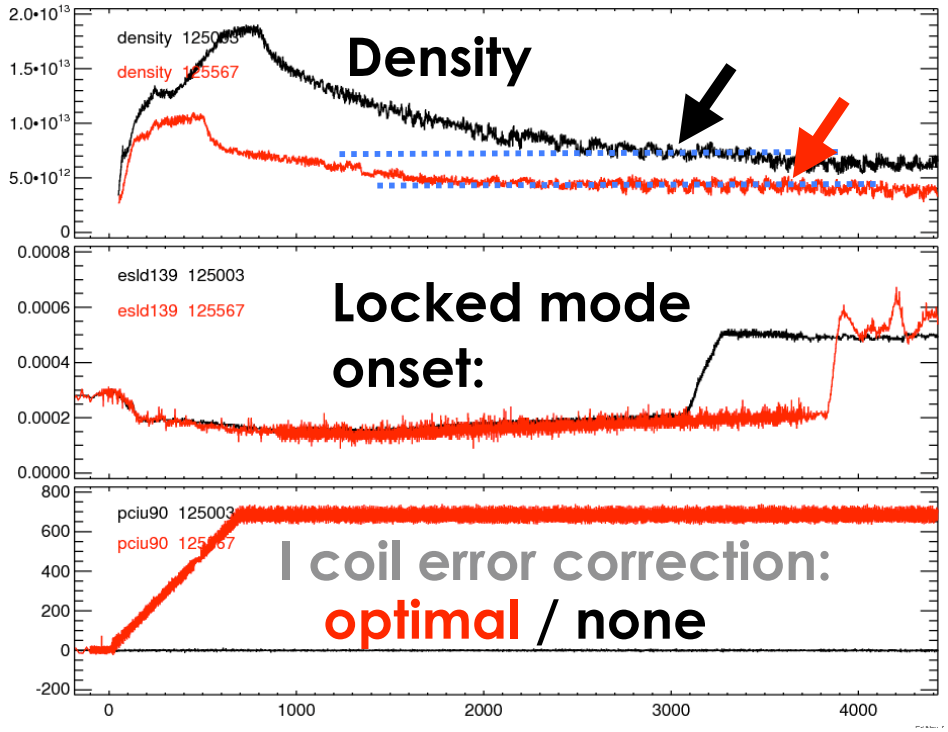
Comparison of low and high torque: *no increased error sensitivity*

- **Compare previous all co-scan with points at ~+1.7Nm torque**



- Note some uncertainty in intrinsic error - ***treat as an unknown…***
- Low torque points use I coils; high torque points use C coils
- ***But gradients clearly similar or weaker than high torque points***

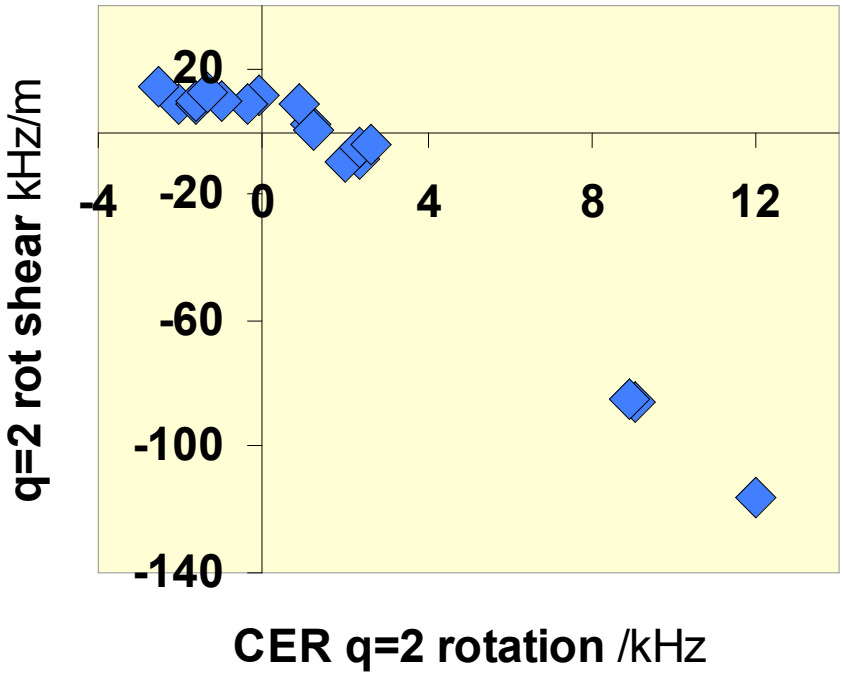
(Density ramp down gives estimate of intrinsic error)



- **Optimal I coil correction accesses 42% lower density**
  - I coil field applies 1.1G of 2/1 field in our study
  - Intrinsic error is of order 1.5G of 2/1 field
  - *This is approximate - ignores sideband completely*

Is there much higher rotation shear? …*not really*

- **Co and counter beams may deposit differently, so balancing may make profile sheared…**
  - Could help make plasma more resilient to tearing?

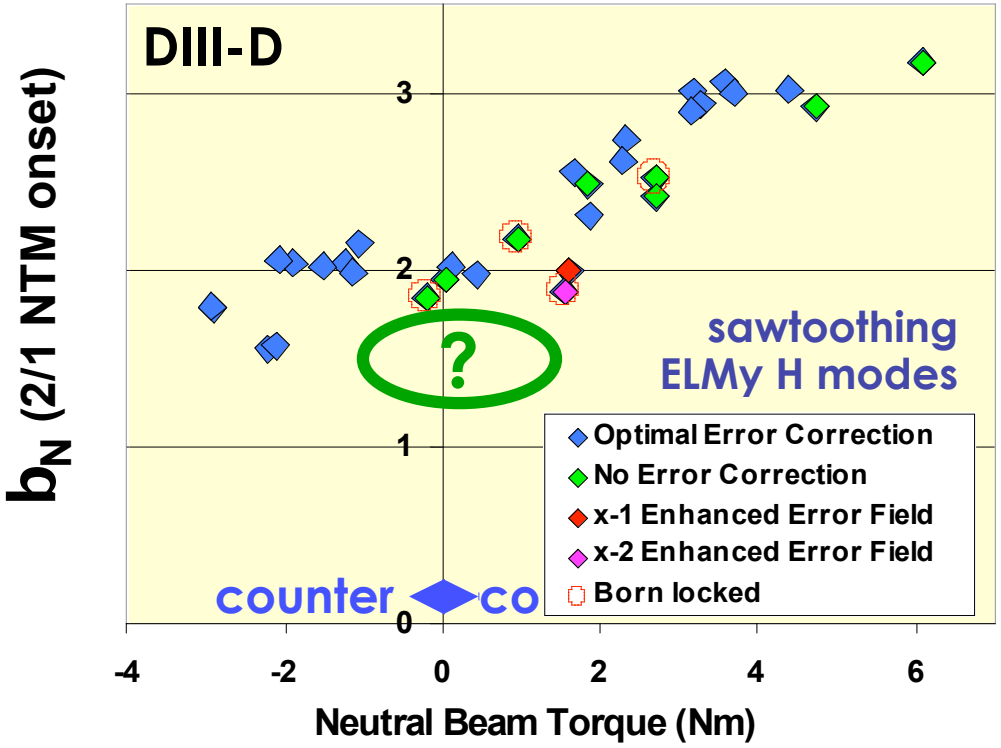


Summary

- **Theory: Error fields expected to induce modes more readily at low rotation**
  - Experiment: some evidence for this but not the expected linear dependence
- **New torque scan experiment reveals 2 surprising things**
  - No region of where modes systematically form locked
  - Error fields have modest effect on TM thresholds
- **Questions:**
  - Are medium b_N plasmas somehow more stable to EF modes?
  - Is torque balancing introducing rotation shear?
  - Is rotation dependence in EF theory linear?

Key Question

Key area of parameter space to explore:



These areas should be explored experimentally…

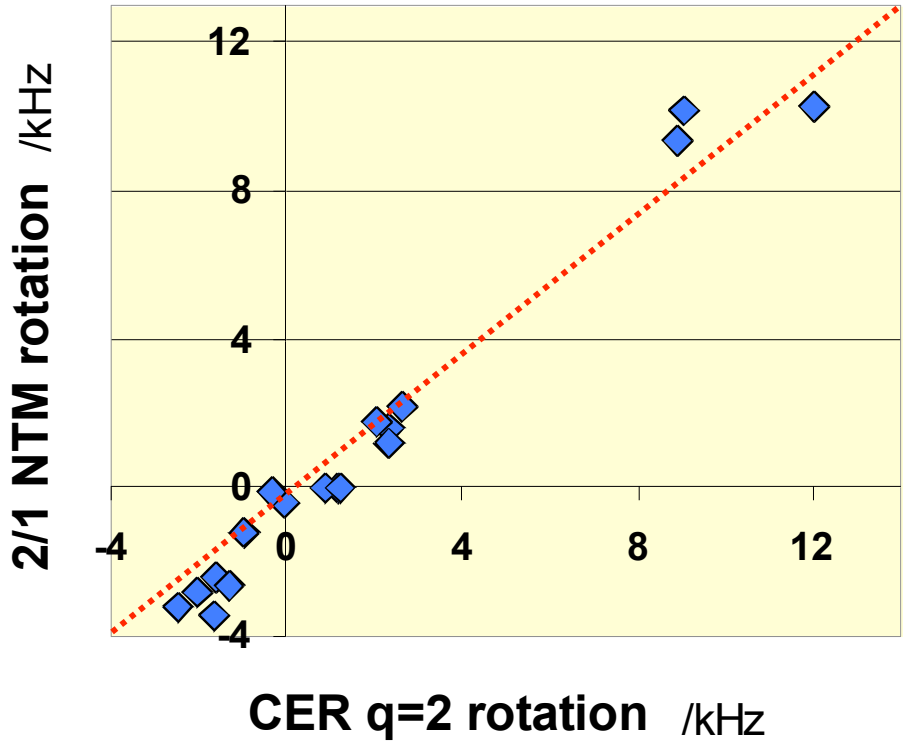
Is low torque really <u>not</u> sensitive to EFs?

- Vital question for ITER operational limits
- And real puzzle for theorists!
  - *Perhaps there is no sweet spot where zero rotation gives zero threshold?*

Additional material…

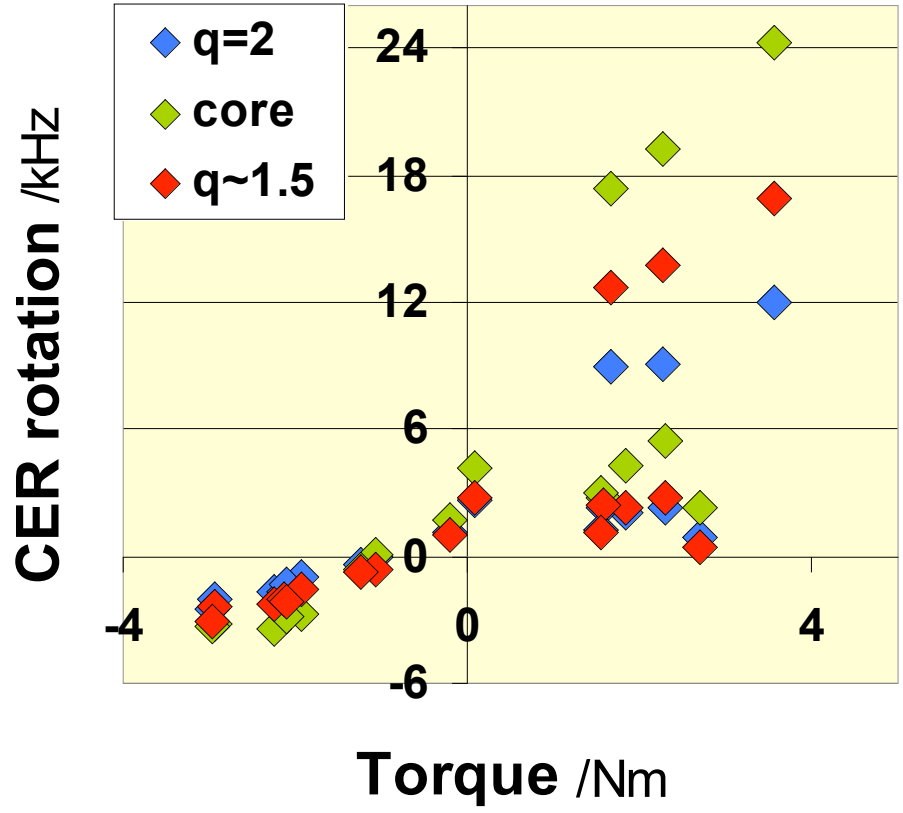
Mode rotation

- **Mode born slightly slower than CER carbon rotation**

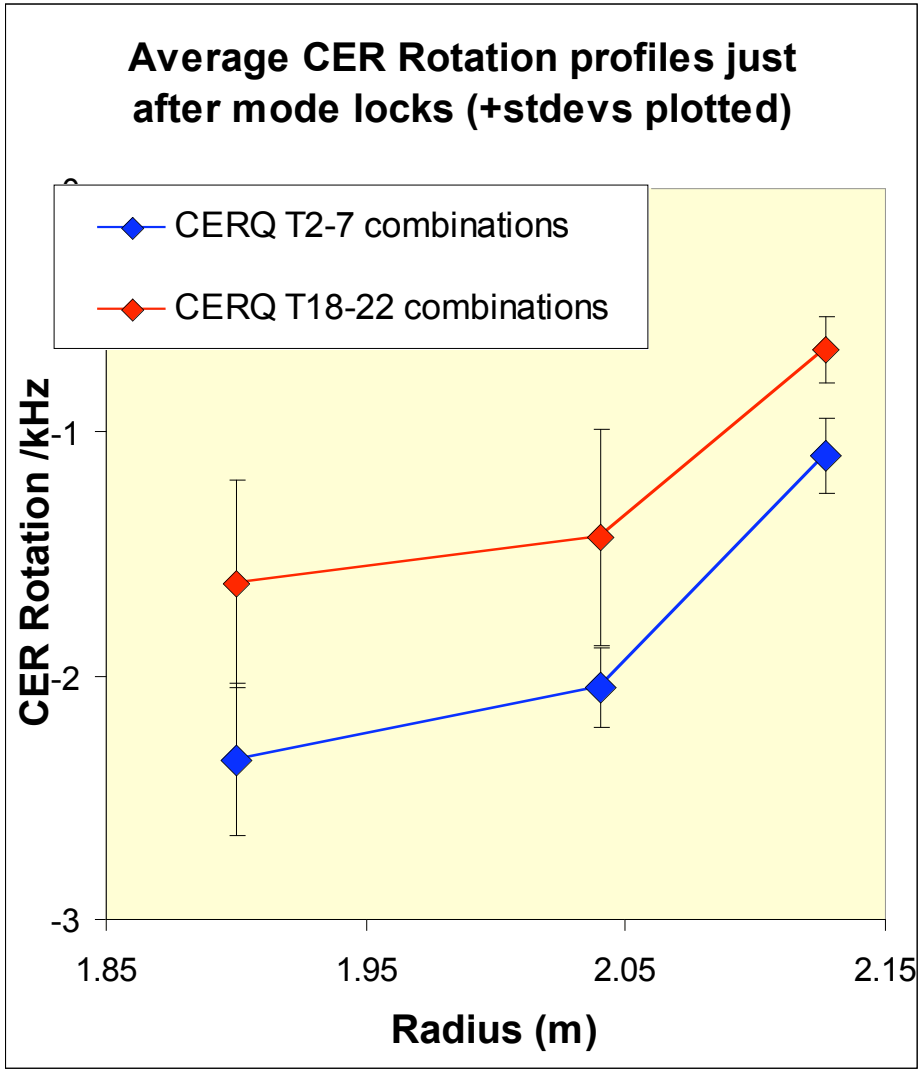


Torque cf rotation

- **Note offset due to intrinsic plasma rotation**



CERq measure at locked mode

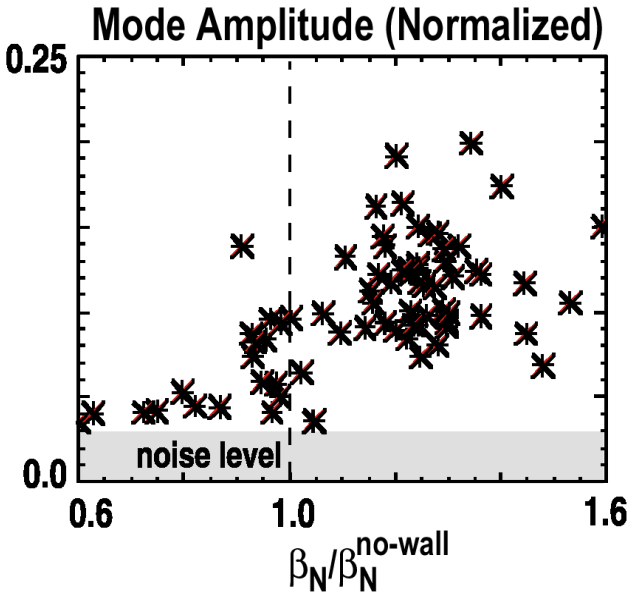


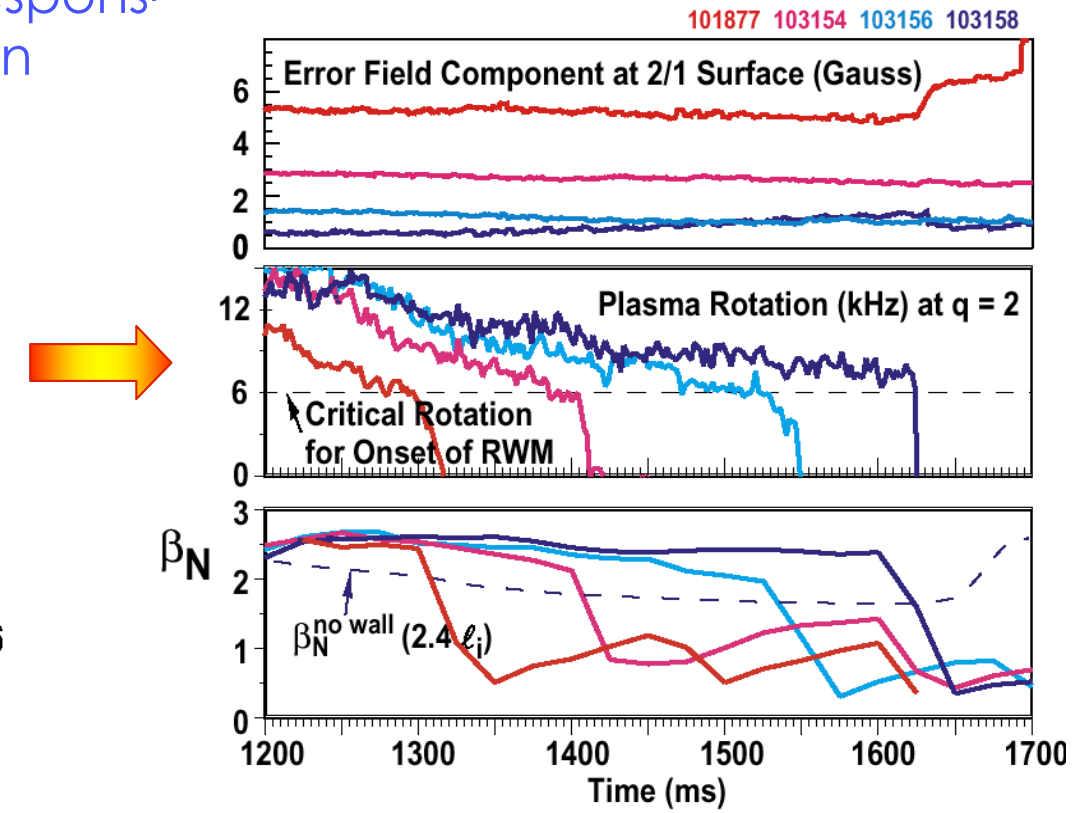
Error field physics raises further concern

- **Modes form when resonant surface is braked by resonant response to EF to ~half it's natural frequency**
  - tiny static island induced by EF
  - viscous forces try to keep bulk plasma rotating slipping about island
    - this opposes island growth
  - torque exerted through island and viscosity by EF brakes plasma
  - if rotation slows enough, island can grow, increasing torque and bifurcating to a locked mode state
  - threshold scales as $B_{pen} \sim B_T \omega_0 \tau_A (\tau_{rec} / \tau_v)^{1/2}$
    - ω_0 often taken to be electron diamagnetic rotation
- **Expect cancelling natural q=2 rotation should lower thresholds**
  - *didn't see in normal B operation on JET so look in reverse B...*

But error field role may be worse at high beta

- **At high beta, error fields couple more strongly to the plasma**
  - Increased resonant response brakes plasma rotation





[Strait et al., IAEA 2002]