Influence of Rotation and Error Field on Tearing Stability in Low Torque ITER-like Plasmas in DIII-D

by

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Previous NTM & Error Field Study Raised Many Questions

DIII-D 2006/2007 showed lower rotation has lower 2/1 onset $\beta_N$
- 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
• Extreme counter torque led to higher $\beta_N$ 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 $\beta_N$ thresholds...
  - ...a profile effect:

  profiles change for reversed $I_p$
  strong counter rotation ($\rightarrow$ no ELMs):
  - Core MHD goes away, (no ST or 3/2)
  - $r(q=2)$ lower, $L_q$ higher
  - Core density peaking (+ no core MSE)
  $\rightarrow$ Discard 3 most counter points
New DIII-D Normal & Reverse Ip Data Continues Strong Trends
- but must remove profile variation from regime change

- Extreme counter torque led to higher $\beta_N$ thresholds...
  - ...a profile effect:

- Clear $\beta$ 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 $\beta_N$

![Graph showing a linear relationship between $\beta_N$ and $M_A < 1\%$ with a $r^2 = 0.5399$ correlation.](image)
Fall in Threshold with Counter Rotation is a Real Effect...

Consider only low rotation DIII-D data...

- Clear trend in $\beta_N$
- Similar trend in local $\beta_{Pe}$
Fall in Threshold with Counter Rotation is a Real Effect

Consider only low rotation DIII-D data...

- Clear trend in $\beta_N$
- Similar trend in local $\beta_{Pe}$
- ...and in bootstrap measure (?)
  - noisier - more local gradients used
  (but no trends in profile parameters)

$$J_{\text{boot}} = \sqrt{\varepsilon_0} \frac{dP_e}{dR} / B_{\text{pol}}$$

$37\%$ effect

$$35\% \text{ effect}$$

$$r^2 = 0.5399$$

$$30\% \text{ effect}$$

$$r^2 = 0.104$$

$$37\% \text{ effect}$$

$$r^2 = 0.3985$$

MA $< 1\%$
Cross-machine Data Set Confirms Strong Rotation Role

- **DIII-D scans show:**
  - Less Mach $\rightarrow$ lower $\beta_N$ 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]
ELMs ‘trigger’ about half the 2/1 NTMs:

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

$\rightarrow$ NTM onset $\beta$ is not about “triggered seed exceeding threshold width” $\leftrightarrow \rho^*$ dependent

- but dictated by changes in the intrinsic tearing stability
Flow Shear Could Play the Stabilising Role

- **Theoretically flow shear impacts intrinsic tearing stability (through $\Delta'$)**
  - 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

See:
1. S. Gerhardt poster APS 2008 NP6.00100 We AM
2. R J La Haye poster APS 2008 JP6.00087 Tu AM
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?

\[ \beta_N \approx 1.9 \text{ and vary torque from shot to shot then ramp error field} \]

\[ \begin{align*} \text{Error field threshold falls with torque} \\
\text{But rotating modes at low torque!} \\
\text{Intrinsic tearing stability is being modified...} \\
\text{...by rotation perturbation?} \end{align*} \]
Hold $\beta_N \sim 1.9$ 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?

Compare with counter torque ($\Delta$)

- Error field thresholds are lower! (Could not operate at $\beta_N \sim 1.9$)
  - Despite **higher** natural mode rotations (not shown) and **lower** $\beta_N$ values for counter torque modes
Conclusions

• DIII-D database extensions confirm strong role of rotation in tearing mode stability:
  - Increased counter rotation lowers $\beta_N$ thresholds
    • A challenge to theory!
  - Behaviour related to changes in intrinsic tearing stability
    • Does this change predictions of a $\rho^*$ 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 $\beta_N$
  - and demonstrate asymmetry between co and counter rotation
  - ITER baseline point just stable with modest co-rotation and good EF correction?
Reserve slides...
Hold $\beta_N \approx 1.9$ 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?

Compare with counter torque (Δ)
- Error field thresholds are lower!
  - Despite higher natural mode rotations and lower $\beta_N$ 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?
Hold $\beta_N \sim 1.9$ 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 $\beta_N$
- Similar trend in local $\beta_{Pe}$
- 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 $\beta_{Pe}$ 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 $\beta_N$ with NTM $\beta_N$ limit ($\circ$)
  - note low $\beta_N$ points needing little error field to lower $\beta_N$-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 $\beta_N$ near balanced region to extrapolate ITER sensitivity
Amount of Error Field Needed Depends on Proximity to NTM Limit at a Given Torque?

• $\beta_N$ threshold falls as error fields increase
  
or equivalently

• Error field sensitivity increases at high $\beta_N$ & 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 $\Delta'$ from modified Rutherford eqn:

\[ -r \Delta' = \frac{\sqrt{\varepsilon x} L_q r_s}{w L_{pe}} \]

(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