Onset and Suppression of 2/1 NTM in DIII–D

by

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The “spontaneous” 2/1 tearing modes considered here are classically destabilized as the ideal MHD stability limit is approached. These tearing modes become indistinguishable from (island seeded) neoclassical tearing modes after the initial linear growth phase.

Onset phase of spontaneous 2/1 tearing modes can be explained by modified Rutherford equation when the evolution of the linear drive is modelled correctly. NIMROD simulations confirm the importance of the linear drive.

Suppression of an existing 2/1 tearing mode has been achieved in DIII–D using electron cyclotron current drive to replace the “missing” bootstrap current in the island.
PART I: THEORY OF “SPONTANEOUS” TEARING MODE ONSET IS CONFIRMED BY EXPERIMENTAL DATA

\[
\frac{\tau_R}{r} \frac{dw}{dt} = \Delta' \left[ \beta_N(t) \right] r + a_2 \frac{J_{BS}}{J_{||}} L_q \left( \frac{w}{w_d^2 + w^2} + \frac{ww_{pol}^2}{w_b^4 + w^4} \right)
\]

**Classical Drive**

**Neoclassical Drive**

**Polarization Stabilization**

Model uses \( \beta_N(t) \) and \( \Delta'(\beta_N) \) from PEST-III in island evolution equation.
THEORY AND EXPERIMENT AGREE $\beta_N$ AT FIXED ISLAND WIDTH INCREASES WITH $d\beta_N/dt$

Results support hypothesis that $\Delta'$ is increasing with $\beta$ in time, consistent with theoretical model

Polarization parameter is fitted to find $\beta_N$ vs. $d\beta_N/dt$ at mode onset
MODEL REPRODUCES LULL IN ISLAND GROWTH RATES OBSERVED IN EXPERIMENT

- Cutoff in polarization term for $w < w_b$ causes lull
- Resulting phase space plots have low growth rates just after onset
MINIMUM RATE OF HEATING FOR TEARING MODE ONSET
QUALITATIVELY AGREES WITH EXPERIMENT

- Island causes transport, reducing $\beta$ and $\Delta'$, resulting in a lower limit in $d\beta/dt$. 

![Diagram showing the comparison between experimental and model results for $\beta$, $d(\beta/4l)/dt$, and $w/a$.]
DEPENDENCE OF $\beta(w)$ AND $\gamma(w)$ ON HEATING RATE CAPTURED BY NIMROD EXTENDED MHD SIMULATIONS

- **Timescales:** $\tau_R \gg \tau_H > \tau_{MHD}$
- **Thermal anisotropy:** temperature flattening, fast parallel transport included
- **Neoclassical and Polarization Effects** necessary for NTM threshold and low heating rate limit
- For low heating rates, the island growth rate decreases at minimum detected size, reducing ECCD power requirements for stabilization

See poster for additional details
PART II: SUPPRESSION OF 2/1 TEARING MODE USING ECCD TO REPLACE "MISSING" BOOTSTRAP CURRENT

ECCD aimed at q = 2 surface

Island shrinkage optimized when ECCD is centered on 2/1 island

ECCD Launch
2/1 TEARING MODE IS COMPLETELY SUPPRESSED AT $\beta = 3.5\%$ USING CLOSED-LOOP FEEDBACK TO OPTIMIZE ECCD LOCATION

2/1 mode suppressed in hybrid discharge with $\beta_N$ well above ITER baseline scenario

"Target lock" algorithm uses small, rapid variations in $B_T$ to optimize suppression
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CO-CURRENT DRIVE IS NECESSARY TO STABILIZE 2/1 MODE

- Slow $B_T$ scan sweeps 3.0 MW of ECCD past $q=2$ surface

![Graph showing Co-Radial, Counter, ECCD currents and various plasma parameters](image)

- $J_{EC}$ (green)
- $J_{BS}$ (blue)
- $(\rho_{21} - \rho_{EC}) / \delta_{EC}$ (red)
- $W_{21}$ (cm) (green and red)

Mode Locked
Mode Stabilized
MODELLED ISLAND WIDTH FOR CO/RADIAL/COUNTER INJECTION SEPARATES EFFECTS OF ECCD AND $\Delta^\prime$ MODIFICATION

$$\frac{\tau_R}{r} \frac{dw}{dt} = \Delta r + a_2 \frac{J_{BS}}{J_{||}} \frac{L_q}{w} \left[ 1 - \frac{w_{pol}^2}{w^2} \right] - K_1 \frac{J_{EC}}{J_{BS}}$$

- $K_1$ is effectiveness parameter that depends on alignment and ECCD width
- Reduced ECCD power (2.0 MW) results in partial mode suppression

$\left( \rho_{21} - \rho_{EC} \right) / \delta_{EC}$

$W_{21}$ (cm)
Changes in island widths are well reproduced by including co/radial/counter ECCD in modified Rutherford equation.
CO-ECCD MAKES $\Delta'$ MORE NEGATIVE, WHILE COUNTER-ECCD HAS OPPOSITE EFFECT

- Although $\Delta'$ modification is significant, direct current drive in island is main reason for 2/1 tearing mode suppression.
SUMMARY

- Time evolution of linear drive is the key to understanding the growth phase of the 2/1 tearing mode.

- Three physics predictions about the onset phase of the 2/1 tearing mode have been experimentally verified:
  - Increase in growth rate with higher $\beta$.
  - Early lull in island growth.
  - Minimum heating rate for onset of 2/1 mode.

- Complete suppression of 2/1 NTM has been achieved using ECCD at the $q=2$ surface for $\beta_N = 2.8$ ($\beta = 3.5\%$) at 90% of the ideal no-wall stability limit.

- ECCD also appears to modify $\Delta\gamma$ significantly in a direction that complements the direct current drive effect.

- Future experiments will apply early ECCD to avoid 2/1 mode onset.