CONTROL OF NEOCLASSICAL TEARING MODES IN DIII–D

by

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Acknowledgments to
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Comparison of nested surfaces and $m=3$ ($n=2$) tearing mode islands

- Reinforces "seed", a destabilizing effect at high beta

Helically perturbed bootstrap current (Qu and Callen 1985)

- "Seed" island from another MHD instability
- Pressure is flattened in island O-point, but not in X-point
- O-point and X-point $J_{bs}$ differ; $\delta J_{bs} \approx \varepsilon^{1/2} \delta \nabla p/B_\theta \propto \beta_\theta/w$

- Reinforces "seed", a destabilizing effect at high beta
CONTROL OF NEOCLASSICAL TEARING MODES

- Stabilized by replacing “missing” bootstrap current in O-point of island
  - Off-axis radially localized electron cyclotron current drive (ECCD)

- Control is to position peak $j_{\text{ECCD}}$ on island
  - Real-time feedback of optimum position
  - Complete $m/n=3/2$ NTM suppression — in presence of continued sawteeth
  - Beta raised after NTM stabilization

- Inhibited by interfering with the fundamental helical harmonic of perturbed pressure
  - Non-resonant helical field of different helicity

- Control is to apply $n = 3$ field from C-Coil
  - $m/n=3/2$ NTM avoided until $n=3$ field turned off
CO-ECCD CAN REPLACE THE “MISSING” BOOTSTRAP CURRENT AND STABILIZE THE NEOCLASSICAL TEARING MODE

\[ \frac{\tau_R}{r} \frac{dw}{dt} = \Delta \dot{r} + \epsilon^{1/2} \left( \frac{L_q}{L_p} \right) \beta_\theta \left[ \frac{rw}{w^2+w_d^2} - \frac{rw_{pol}^2}{w^3} - \frac{8qr\delta_{ec}}{\pi^2w^2} \left( \frac{\eta j_{ec}}{j_{bs}} \right) \right], \]

- NTM amenable to complete suppression because \( \dot{w} < 0 \) for \( w \leq w_{pol} \)
- ECCD must be within island
  - no effect for \( \Delta R \gtrsim \delta_{ec} \)

\[
\eta = \eta_0 e^{-[5\Delta R/3\delta_{ec}]^2/(1+2\delta_{ec}^2/w^2)}
\]

- m/n = 3/2
- \( \beta_\theta = 0.9 \)
- \( \Delta \dot{r} = -3 \)
- \( r = 0.36 \text{ m} \)
- \( \epsilon^{1/2} = 0.5 \)
- \( L_q/L_p = 1.5 \)
- \( w_{pol}/r = 0.05 \)
- \( \delta_{ec}/r = 0.08 \)
- \( \eta_0 = 0.4 \) (no mod)
- \( \Delta R/\delta_{ec} = 0 \)
SUPPRESSION OF m/n=3/2 NTM BY OFF-AXIS ECCD

(ELMy H–mode with sawteeth)

Resources:

(1) lower cryopump to improve current drive

(2) up to 4 gyrotrons injecting up to 2.3 MW for 1 to 2 s

(3) PPPL & GA co–ECCD steerable launchers

T.C. Luce
F01.005
OPTIMUM LOCATION OF ECCD IS FOUND
BY SWEEPING TOROIDAL FIELD

- Toroidal field was ramped down to scan ECCD past the island
- Alignment within ±1 cm is required
- $j_{ECCD} > j_{BS}$ is satisfied (TORAY-GA)
  - 2 gyrotrons for $\approx$ 1 MW injected

C. Petty
FO1.002

R. Prater
RP1.022
OPTIMUM CAN ALSO BE FOUND WITH FLATTOP TOROIDAL FIELD ADJUSTMENT

- Before ECCD, \( \gamma \equiv -I \frac{\partial B_{\theta,32}}{\partial t} \frac{dI B_{\theta,32}}{dt} \approx 0 \)
- Upon ECCD, initially \( \gamma \propto J_0 \exp \left[-(5\Delta R/3\delta_{ec})^2\right] \), \( \delta_{ec} \equiv \delta_{FWHM} \)

TORAY–GA predicts 2.7 cm

\( \beta_N \approx 1 \text{ MW} \)

\( w/r = 7 \text{ cm}/36 \text{ cm} \)

\( n=1 \text{ MIRNOV (G)} \)

\( n=2 \text{ MIRNOV (G)} \)

\( \delta_{FWHM} = 3.8 \pm 0.8 \text{ cm} \)

TORAY–GA predicts 2.7 cm

\( \Delta R \text{ (cm) from Variation of Toroidal Field and thus } 2f_{ce} \text{ Location, Shot-to-Shot} \)
ΔR “Blind Search” when mode (3/2 island) amplitude exceeds threshold

- Move plasma major radius (and island) “rigidly” (ΔR_{step} = 1 cm)

- Detect alignment of ECCD current deposition with island (“sweet spot”) by sufficient change in mode amplitude over the “dwell” time (100 ms)

- If mode decays at > threshold rate, continue to dwell. If not, continue search (or “jitter” . . . )

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RP1.010

Δ_{SURF} = 2.3 cm

Island moved wrt 2f_{ce} resonance

ECH
f=110.0 GHz
facet ang=11.0 deg
tilt ang=66.0 deg
REAL-TIME CONTROL OF MAJOR RADIUS FOR ECCD SUPPRESSION
(m/n = 3/2 NTM, 3 GYROTRONS, 1.5 MW, 3000 TO 4800 ms)

PCS reset at 4500 ms
No PCS optimization
Search
Dwell
NTM restrikes on a sawtooth crash
PCS optimization starting from $\Delta R \approx -2$ cm
#106654
#106642

SAN DIEGO
DIII-D NATIONAL FUSION FACILITY
REAL-TIME CONTROL OF MAJOR RADIUS FOR ECCD SUPPRESSION
(m/n = 3/2 NTM, 3 GYROTRONS, 1.5 MW, 3000 TO 4800 ms)
**PLASMA CONTROL SYSTEM REAL-TIME FEEDBACK**

**NTM CONTROL VARIES TOROIDAL FIELD IN RESPONSE TO MODE AMPLITUDE**

- $\Delta B_T$ “Blind Search” when mode (3/2 island) amplitude exceeds threshold

- Adjust toroidal field and location of $2f_{ce}$ ($\Delta B_T = 0.01 \text{T} \Rightarrow \Delta R \approx 0.9 \text{ cm}$)

- Detect alignment of ECCD current deposition with island (“sweet spot”) by sufficient change in mode amplitude over the “dwell” time (100 ms)

- If mode decays at > threshold rate, continue to dwell. If not, continue search (or “jitter” . . . )

\[
\Delta B_T = 0.018 \text{ T} \quad \Rightarrow \quad \Delta R \approx 1.6 \text{ cm}
\]

2 $f_{ce}$ resonance moved wrt island
REAL-TIME CONTROL OF TOROIDAL FIELD FOR ECCD SUPPRESSION

(m/n = 3/2 NTM, 3 GYROTRONS, 1.5 MW, 3000 TO 4000 ms)

PCS optimization starting from $\Delta B_T \approx 0.02T \approx \Delta R = 1.8$ cm

#107390

Dwell

Search

No PCS optimization

#106642
RAISING $\beta_N$ AFTER ECCD SUPPRESSION OF m/n = 3/2 NTM

- $\beta_N$ raised 60% (20% above onset level)
- mode restrikes as q=3/2 moves radially by 2 cm off ECCD

$\Delta R_{3/2}=2$ cm due to high $\beta$ Shafranov shift

n=2 RMS (G)

n=1 RMS (G)

$\beta_N$
EXTERNAL HELICAL FIELD OF DIFFERENT HELICITY CAN DECREASE NTM PRESSURE PERTURBATION

\[ \frac{\tau_R}{r^2} \frac{dw}{dt} = \Delta' + \frac{\varepsilon^{1/2} L_q}{L_p} (\frac{\beta_\theta}{w}) \left[ \frac{w^2}{w^2 + w_d^2} - \frac{w_{pol}^2}{w^2} \right] \]

with \( w_d \approx (L_s/k_\theta)^{1/2} (\chi_\perp/\chi_\parallel)^{1/4} \)

effect of cross-field transport “washing out” helically perturbed bootstrap current — if \( w^2 < w_d^2 \)

- Non-resonant, static, \( n = 3 \) helical field
- \( |\vec{b}| = |B_{rmn}/B_T| \) can be up to \( 2 \times 10^{-3} \) from C–Coil
- \( \vec{b} \) interferes with helical \( \nabla p \) of NTM
- \( \vec{b} \) acts similar to increasing cross-field “washing out”

\[ w_d \to w_{do}^* \left( 1 + \frac{|\vec{b}|^2}{4 \chi_\perp/\chi_\parallel} \right)^{1/4} \]

Q. Yu et al PRL (2001)

\( m/n = 3/2 \)
\( r = 36 \text{ cm} \)
\( w_{pol} = 1.8 \text{ cm} \)
\( \Delta r = -3 \)
\( \varepsilon^{1/2} \frac{L_q \beta_\theta}{L_p} = 0.675 \)
\( \chi_\perp/\chi_\parallel = 2 \times 10^{-8} \)

\( \tau_R \frac{dw}{dt} \)

\( w_d = 1.0 \text{ cm}, |\vec{b}| = 0 \)
\( \text{saturated } w \propto \beta_\theta \)

\( w_d = 3.0 \text{ cm}, |\vec{b}| = 2 \times 10^{-3} \)
n = 3 FIELDS FROM C–COIL

- **n = 3 helical field** is predominantly non-resonant \((m/n \leq q_0 \approx 1)\)
  - Fourier analysis on hi-lited surface
  - 4 turn coils, +5000, −5000, +5000, amps etc.

- **n = 3 radial field** “ripple” fall-off with minor radius is gradual
  - \(\sum B_{rm3} \text{ vs } R-R_{surf}\)
  - \(\sum B_{rm3} \text{ vs } R-R_{surf}\)

- n = 3 left hand (right hand is similar)

\[
\begin{array}{c|c}
\text{m} & B_{mn} \text{ (G)} \\
\hline
0 & 0 \\
1 & 15 \\
2 & 10 \\
3 & 5 \\
4 & 2 \\
5 & 0 \\
\end{array}
\]

- n = 3 on midplane \((\theta = 0^\circ)\) at \(\phi = 79^\circ\)

\[
\begin{align*}
q & \approx \frac{3}{2} \\
q & \approx 2 \\
r & = a
\end{align*}
\]

\[
\begin{array}{c|c}
R-R_{surf} (cm) & \text{G} \\
\hline
0 & 0 \\
10 & 50 \\
20 & 100 \\
30 & 50 \\
40 & 0 \\
50 & 0 \\
60 & 0 \\
\end{array}
\]
n = 3 NON-RESONANT HELICAL FIELDS APPLIED TO m/n = 3/2 NTM

- NTM not suppressed
  \[ |\vec{b}| = \frac{B_{r3\text{eff}}}{B_{T0}} \approx 1.6 \times 10^{-3} \]

  S. Günter
  F01.006

- Plasma rotation slowed

\[ 2 \times \text{ION TOR. ROT. @} q=3/2 \]
● Consistent with n=3 ripple drag like TTMP

\[ f = \frac{f_0 - f_{\tau M}}{(1 + C_3 B_{r3eff})^2} \]
\textbf{NTM inhibited}

\begin{itemize}
  \item \( l_{bl} = \frac{B_{r3eff}}{B_{To}} \approx 1.6 \times 10^{-3} \)
  \item Hysteresis makes \( l_{bl} \) more effective for small seed islands
\end{itemize}

\( n = 3 \) \textbf{NON-RESONANT HELICAL FIELDS APPLIED BEFORE} \( m/n = 3/2 \) \textbf{NTM}

\( \delta J_{bs} \propto \frac{\beta_\theta}{w} \frac{w^2}{w^2 + w_d^2} \)

\( l_{bl} = 0 \)

\( 1 \times 10^{-3} \)

\( 2 \times 10^{-3} \)

Seed

Saturated

3/2 \textbf{NTM onset as} \( n = 3 \) field ramped off
CONCLUSIONS ON CONTROL OF NTMS IN DIII–D

- Precise location of off-axis ECCD is needed for effective suppression
  - achieved by either $\Delta R$ or $\Delta B_T$ real-time control “search and suppress”
    - in presence of continued sawteeth
    - control requires pre-existing mode

- Beta can be raised above the initial NTM onset level
  - Shafranov shift moves $q = 3/2$ radially off the optimum
  - future work is real-time PCS alignment of $j_{ec}$ on $q = 3/2$ in absence of NTM

- Large $n = 3$ helical fields can inhibit NTM onset
  - large island suppression ineffective
  - plasma rotation strongly damped