Neoclassical Tearing Mode Control with ECCD and Magnetic Island Evolution in JT-60U

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Neoclassical Tearing Modes (NTMs)
- appear in a high $\beta$ plasma with positive shear
  ITER Standard and Hybrid scenarios
- set achievable beta at $\beta_N < \beta_N$
- sometimes cause disruption

NTM control is important
... In particular, $m/n=3/2$ and $2/1$

Two scenarios for NTM suppression
- Avoidance of onset through $p(r)$ & $j(r)$ control  T. Suzuki et al., EX/1-4Rc
- Active NTM stabilization  This talk

Active control tool:
Electron Cyclotron Current Drive (ECCD)
- Highly localized current drive
- Flexible ECCD location with steerable mirror
NTM stabilization with ECCD in JT-60U

Previous results in JT-60U
• Stabilization with O1 & X2 ECCD
• Stabilization with real-time mirror steering
• Preemptive stabilization
• Simulation with TOPICS code

Remaining issues
• How much is the minimum EC wave power for complete stabilization?
• How much is the allowable misalignment?
• Is modulated ECCD really effective? If yes, how much?

Investigation of \( m/n=2/1 \) NTM is important because it is more dangerous

This talk
• Identification of minimum EC wave power
• Effect of misalignment on NTM stabilization \( m/n=2/1 \)
• Stabilization with modulated ECCD
Typical discharge of m/n=2/1 NTM stabilization

- 2/1 NTM onset at t=5.8s
- Step down of NB power + bal. to ctr injection at 7s
- ECCD from 9.5s

Detailed island structure measurement by ECE diagnostic
Minimum EC-driven current for complete stabilization has been identified in two regimes

- Previous experiments: *overstabilized* i.e. $P_{EC} > P_{EC}^{\text{min}}$

- For efficient stabilization, identification of $I_{EC}^{\text{min}}$ ($\sim P_{EC}^{\text{min}}$) is necessary

<table>
<thead>
<tr>
<th></th>
<th>case 1</th>
<th>case 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_p [\text{MA}]/B_t [\text{T}]$</td>
<td>1.5 / 3.7</td>
<td>0.85 / 1.7</td>
</tr>
<tr>
<td>$\beta_N^{\text{sat}} / \beta_N^{\text{marg}}$</td>
<td>0.9 / 0.4</td>
<td>1.5 / 0.8</td>
</tr>
<tr>
<td>$W_{\text{sat}} / W_{\text{marg}}$</td>
<td>0.12 / 0.06</td>
<td>0.15 / 0.08</td>
</tr>
<tr>
<td>$d_{EC}$</td>
<td>0.08</td>
<td>0.05</td>
</tr>
<tr>
<td>$(j_{EC}/j_{BS})_{\text{min}}$</td>
<td>0.35-0.45</td>
<td>0.2-0.4</td>
</tr>
<tr>
<td>$(I_{EC}/I_{BS})<em>{@W</em>{\text{marg}}}$</td>
<td>0.78</td>
<td>0.27</td>
</tr>
<tr>
<td></td>
<td>($d_{EC}&gt;W_{\text{marg}}$)</td>
<td>($d_{EC}&lt;W_{\text{marg}}$)</td>
</tr>
</tbody>
</table>

* $I_{BS}=2\pi \rho_s W_{\text{marg}} j_{BS} (\rho=\rho_s)$

- Different ECCD deposition width
  - Case 1: $W_{\text{marg}}/d_{EC}=0.75$  Wide ECCD
  - Case 2: $=1.6$  Narrow ECCD

- Future work: extrapolation to ITER
  - Note $W_{\text{marg}}/d_{EC}<<1$ in ITER
More precise alignment of ECCD location is required for narrower ECCD width

- For effective stabilization, ECCD misalignment should be small
- In reality, there is some misalignment

- $W_{\text{sat}}/d_{\text{EC}} \approx 1.5$ for case 1 (wider ECCD), $W_{\text{sat}}/d_{\text{EC}} \approx 3$ for case 2 (narrower ECCD)
- Similar V-shape is obtained by normalizing to $d_{\text{EC}}$
- Allowable misalignment: $|\rho_{\text{EC}} - \rho_{q=2}|/d_{\text{EC}} \approx 0.5$
ECRF system in JT-60U has been upgraded to achieve power modulation at $>\sim 5\text{kHz}$

- **Modulated ECCD**: more effective than unmodulated ECCD
  Experimental verification is important for ITER
  Modulation at several kHz is technically challenging

**Progress in modulation**
- NTM stabilization
- Heat wave propagation

**Synchronization with NTM**
- Magnetic probe signal to synchronize with NTM rotation

S. Moriyama et al., FT/P2-26
Frequency tracking was successful

- Modulated ECCD: phasing is required for O-point ECCD
- NTM frequency ~ plasma rotation: change in time
  => Frequency tracking is necessary for accurate phasing
  => Parameters for gyrotron operation were optimized in real time

- Trigger signal was generated as expected while the mode frequency changed from 4.3 to 6.1kHz
- Delay from trigger signal is also taken into account
Stabilization effect is significantly affected by the phase difference between dB/dt and ECCD

- 0° phase difference: stabilization effect
- 90° phase difference: no clear effect
- 180° phase difference: destabilization effect

=> Phasing is important
Detailed phase scan showed that phase error should be smaller for effective stabilization

\[ \tau_{\text{decay}}: \text{minimum at } \sim -10^\circ \]
\[ \Rightarrow \text{O-point ECCD} \]

\[ \text{Allowable phase error: e.g. } \tau_{\text{decay}} < 1.5 \tau_{\text{decay}}^{\text{min}} (\sim 1.8 \text{s}) \]
\[ \Rightarrow |\Delta \alpha| < \sim 50^\circ \]

ECCD efficiency: \( \eta_{\text{EC}} \)

\[ \eta_{\text{EC}} = \int_{-1}^{\infty} j_{\text{EC}}(\Omega) \frac{R(\Omega)}{S(\Omega)} d\Omega \]
\[ R(\Omega) = \int \frac{\cos \alpha d\alpha}{\sqrt{\Omega + \cos \alpha}}, \quad S(\Omega) = \int \frac{d\alpha}{\sqrt{\Omega + \cos \alpha}} \]

Modified Rutherford equation

\[ \frac{dW}{d\tau} = f(W) - \eta(W)g(W) \]
\[ \alpha_c \]

\[ \text{Similar to experiments} \]

JT-60U

Hegna, PoP '97
Perkins EPS '97
Giruzzi, NF '99
Superiority of modulated ECCD to unmodulated ECCD has been demonstrated

- **EC wave power**
  - #3: 0-100% modulation
    O-mode power: 0.49MW
  - #2: 20-100% modulation
    O-mode power: 0.52MW
  - #1: no modulation
    O-mode power: 0.56MW

Similar power: ~0.5MW

- **ECCD location of #1-3: ~same**
  (from ray tracing & F-P code)

- **Island center: ~same**
  (rather toward better alignment)

The difference is mainly due to the difference in ECCD pattern

=> modulated ECCD is more than twice effective
Summary

Active control of \( m/n=2/1 \) NTM with ECCD has been extensively performed in JT-60U

Minimum EC-driven current for complete stabilization
- Range of the minimum required current has been identified in two different regimes
  - \( j_{EC}/j_{BS}=0.35-0.45 \) for \( W_{\text{marg}}/d_{EC}=0.12/0.08 \)
  - \( j_{EC}/j_{BS}=0.2-0.4 \) for \( W_{\text{marg}}/d_{EC}=0.08/0.05 \)

Effect of misalignment on NTM stabilization
- Higher precision of ECCD alignment for narrower ECCD width
- Misalignment \( |\rho_{EC}-\rho_{q=2}|/d_{EC} <\sim 0.5 \) for efficient stabilization

Stabilization by modulated ECCD
- Successful modulation at \( \sim 5kHz \) including phase tracking
- Phasing is important: Phase error \( <\sim 50^\circ \) for >50% degradation
  Consistent with theoretical model
- Modulated ECCD is more than twice effective than CW ECCD
Issues in synchronizing EC wave with NTM: Disturbances by other NTMs, ELMs, ...

- Trigger signal was disturbed at ELM ($f_{\text{ELM}} \ll f_{\text{NTM}}$)
- $\text{dB/dt signal: } 2/1 + 3/2$
- ITER Standard / Hybrid operations: ELMy H-mode & prone to 2/1 + 3/2
  
  => Development of pre-processing scheme is also important