Locked mode entrainment with synchronized ECCD deposition

by

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General Atomics

Wednesday November 9, 2016
Outline

• Introduction
• Mode entrainment
  • Preemptive entrainment
  • Feedback controller
  • Mode phase control
• Electron cyclotron current drive (ECCD) deposition
  • Deposition location
  • Mode amplitude evolution
• Conclusions and future work
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Modeling fixed-width mode dynamics under influence of torques

\[ I \frac{d^2 \phi}{dt^2} = T_{wall} + T_{EF} + T_{RMP} + T_{TM} + T_{visc} + T_{NBI} \]

**E.M. Torques on Island**

**Non-E.M. Torques**

![Diagram showing 2/1 magnetic island with I-coils and C-coils](image)
Simulation of mode dynamics with some simplifying assumptions

- **Simplified equation of motion**

\[ I \frac{d^2 \phi}{dt^2} = T_{wall} + T_{EF} + T_{RMP} \]

- **Condition for smooth entrainment**

\[ 0 = T_{wall} + T_{RMP} \]

\[ T_{wall} = - \frac{[2\pi R B_R(b) r_{mn}^{2m-1}]}{\mu_0 b} \left[ \frac{r_{mn}}{b} \right]^{2m-1} \frac{\Omega \tau}{1 + (\Omega \tau)^2} \]

\[ T_{EF} = -\pi^2 R^2 m \frac{a}{r_{mn}} I_{EF} B_R(a) \sin[n\phi(t)] \]

\[ T_{RMP} = -\pi^2 R^2 m \frac{b}{r_{mn}} I_{RMP} B_R(b) \sin[n\phi(t) - n\phi_{RMP}(t)] \]
Critical steady entrainment frequency depends on island width and coil current

- Max frequency at which smooth entrainment is possible
  - Increases with coil current
  - Decreases with island width

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Upon locking, neoclassical tearing modes quickly grow and often cause disruption.

If the mode is never actually allowed to lock, perhaps it is less detrimental to the plasma.

Can a pre-existing rotating perturbation be used to prevent mode locking?
Mode locks directly to preemptive, feed forward rotating RMP

Rotating phase:
fast signal lost at 2514 ms
n1rms = 17G
n1freq = 1.04 kHz

Locked to rotating RMP phase:
slow signal found at 2516 ms
freq = 70 Hz

Used 3.6 kA in I-coils, rotating at 70 Hz
Proportional-integral controller for mode phase as implemented in DIII-D

\[ \Phi_{\text{error}} = \Phi_{\text{ref}} - \Phi_{\text{mode}} \]

\[ \Phi_{\text{correction}} = \text{PI control (} \Phi_{\text{error}} \text{)} \]

\( \Phi_{\text{reference}} \) requested

\( \Phi_{\text{mode}} \) from magnetic signals

reference

mode

Choi/MHD Workshop/Nov. 2016
Proportional-integral controller for mode phase as implemented in DIII-D

\[ \Phi_{\text{error}} = \Phi_{\text{ref}} - \Phi_{\text{mode}} \]

\[ \Phi_{\text{correction}} = \text{PI control} \left( \Phi_{\text{error}} \right) \]

\[ \Phi_{\text{RMP}} = \Phi_{\text{mode}} + \Phi_{\text{corr.}} \]

Limit to \( \Phi_{\text{mode}} \pm 90^\circ \) for max torque

\( \Phi_{\text{reference}} \)

requested

\( \Phi_{\text{mode}} \)

from magnetic signals

\( \alpha_{\text{mode}} \)

max torque

\( \text{RMP} \)
Proportional-integral controller for mode phase as implemented in DIII-D

\[
\Phi_{\text{error}} = \Phi_{\text{ref}} - \Phi_{\text{mode}}
\]

\[
\Phi_{\text{correction}} = \text{PI control (}\Phi_{\text{error}})\]

\[
\Phi_{\text{RMP}} = \Phi_{\text{mode}} + \Phi_{\text{corr}}.
\]

Limit to \(\Phi_{\text{mode}} \pm 90^\circ\) for max torque

Applied to coils
Experimental results on DIII-D match well with simulation

- When RMP was applied, successful demonstration of controller’s ability to prescribe phase and entrain at 20 Hz
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Verifying ECCD deposition timing and location

- at 2810 ms, $\Phi_{LM} = -72^\circ = 288^\circ$ (peak $B_R$ at outboard mid-plane)
- at same time, at poloidal angle of 135°, X-point is also at ~285°
- Toroidal deposition of ECH power is between 251° to 299°
- $\Phi_{LM} = \Phi_{ECCD}$ implies X-point deposition
Modulated ECCD in phase with island obtained amplitude modulation, but not full suppression

- Mode amplitude decreases as soon as ECCD is switched on
- but grows again when ECCD is in ‘off’ state
Changing relative phasing gives different behaviour

a) Nominal O–point deposition

<table>
<thead>
<tr>
<th>Time (ms)</th>
<th>3060</th>
<th>3090</th>
<th>3120</th>
<th>3150</th>
<th>3180</th>
</tr>
</thead>
<tbody>
<tr>
<td>LM amp [G]</td>
<td>0</td>
<td>2</td>
<td>4</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>ECH Power [MW]</td>
<td>0</td>
<td>2</td>
<td>4</td>
<td>6</td>
<td>8</td>
</tr>
</tbody>
</table>

b) Nominal X–point deposition

<table>
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c) Nominal X–to-O points transition

<table>
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<th>Time (ms)</th>
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<th>4830</th>
<th>4860</th>
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<tbody>
<tr>
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Ray-tracing code shows ECCD radial misalignment

- Result from EFIT02 for shot 166567 at 2805 ms
Modeling mode amplitude with MRE (work in progress)

- Attempting to match observed results with modified Rutherford equation predictions
- will include all relevant terms from the MRE

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

- Previous work simulates mode dynamics and interaction with applied RMP at DIII-D

- Entrainment of 2/1 islands, both preemptively and in feedback, was demonstrated

- ECCD can be synchronized to be deposited only in the island O-point, which is expected to increase mode suppression efficiency
Future work

- Continue to study mode amplitude evolution under modulated ECCD, using coherent averaging technique to suppress noise

- Improve the controller to apply RMP with varying amplitude, fixed at 90° from mode phase

- Extend controller to higher frequency (~100 Hz), which will include real-time compensation for wall shielding on mode phase measurement