Recent locked mode control experiments on DIII-D using non-axisymmetric coils

by
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DIII-D
NATIONAL FUSION FACILITY

COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK
Motivation

• Essential part of “MHD Control for Steady State Burning Plasmas” is locked mode (LM) control

• Future burning plasma devices will operate at low torque

• Ability to reliably predict and avoid, or if necessary deal with, mode-locking needed
LM control strategies will involve non-axisymmetric coils

- Control of island phase with non-axisymmetric coils is an important tool in LM control
  - Volpe, PoP 2008

- Experiments needed to:
  - Improve our modeling of the interaction between 3D fields and rotating/locked islands
  - Continue development of LM control strategies
Non-axisymmetric coils used on DIII-D for locked mode control

- I-coil and C-coil $n=1$ arrays apply resonant torques on magnetic islands

- Two experiments in 2013:
  - Low frequency limit
    - Further develop island torque balance models
  - High frequency limit
    - Prevent mode-locking for disruption avoidance

2/1 magnetic island
Non-axisymmetric coils used on DIII-D for locked mode control

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Island dynamics described by toroidal torque balance

- Island torque balance: \[ T(I) + T(C) + T(EF) + T_{NR} = \frac{L}{t} \]
  - Resonant
  - Non-resonant

- For LM, total torque = 0

- **Resonant torques** due to \( j \times B \) interaction of island currents and 3D fields

- **Non-resonant torques** can include viscosity, beam torques, NTV
2013 EFC experiment on DIII-D studied LM torque balance in detail

- Combined experiment with EF penetration studies in Ohmic discharges ($\beta_N \approx 0.2$)

1. Ramp currents until EF penetrates
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1. Ramp currents until EF penetrates
2. Measure dynamics of resulting LM as function of 3D fields

- High safety factor ($q_{95} \approx 4$) provides non-disruptive islands
- No beam torques, eddy currents negligible
- Independent estimate of EF in same discharges
Island evolution measured in detail

- LM phase measured over multiple C-coil trajectories
- Independent measure of EF from mode onset thresholds
Island evolution measured in detail

- LM phase measured over multiple C-coil trajectories
- Independent measure of $\text{EF}$ from mode onset thresholds
Island evolution measured in detail

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Ohmic EF penetration LMs do NOT satisfy resonant torque balance

- LM phase measured over multiple C-coil trajectories
- Independent measure of EF from mode onset thresholds

- Interpretation: Non-resonant torques are important!
Simplified phasor analysis of measured island dynamics

- Both the island and 3D fields each characterized by $n=1$ phasor

- **Island** evolution denoted by $j$ ($n=1$ component of magnetics signals)

- **3D field** denoted by $B$ ($n=1$ component of applied field and EF)

- Resonant interaction of island and 3D fields described by $j \times B$
Non-resonant torques determined empirically, from island torque balance

- Assuming LM is in torque balance, total torque is zero

- Can solve for non-resonant torques: $T_{NR} = -j \times B$

- Empirically find: $T_{NR} = \alpha |j|^2$
  - As reported by Strait et al. (2011)

- Direction of $T_{NR}$ is in electron diamagnetic drift direction
Non-resonant torque has simple interpretation

- **Resonant torque balance:**
  \[ j \times B = 0 \]

  - Result: island locks to 3D field

- **With non-resonant torque:**
  \[ j \times B + T_{NR} = 0 \]

  - Result: island deviates from 3D field by
    \[ \Delta \varphi = \sin^{-1} \left( \frac{-T_{NR}}{|j| |B|} \right) \]
Saturated island amplitude gives complete model of LM dynamics

- Saturated island amplitude found to scale as:
  $$|j| = \beta |B| + \gamma$$

- Complete model of LM dynamics:
  $$j \times B + \alpha |j|^2 = 0$$
  $$|j| = \beta |B| + \gamma$$  \((\text{Fit from data})\)

- Model depends only on applied field, $B$

- Different dependences of resonant, non-resonant torques on $B$ lead to interesting behavior
Torque balance including non-resonant term in good agreement with measurements

- Non-resonant term modifies predicted LM dynamics
- Measured island phase in good agreement with full torque balance model

Electron diamagnetic drift

Resonant torque only (Model)
Torque balance including non-resonant term in good agreement with measurements

- Non-resonant term modifies predicted LM dynamics
- Measured island phase in good agreement with full torque balance model

Electron diamagnetic drift

With non-resonant torque (Model)

No solution
Torque balance including non-resonant term in good agreement with measurements

- Non-resonant term modifies predicted LM dynamics
- Measured island phase in good agreement with full torque balance model

With non-resonant torque (Model + measurements)

No solution
Torque balance including non-resonant term in good agreement with measurements

- Non-resonant term modifies predicted LM dynamics
- Measured island phase in good agreement with full torque balance model

With non-resonant torque (Model + measurements)

No solution

LM (measured)
Interpretation of non-resonant torque

- EF penetration LM exists in the lab frame

- Natural tearing mode frame in these Ohmic discharges is electron diamagnetic frame

- Non-resonant torque acts to push island toward its natural frame of reference
Summary (1st half): LM torque balance model advanced through detailed measurements

- EF penetration LMs in Ohmic discharges observed to experience non-resonant torques

- Non-resonant torque scales as square of perturbed field of island

- Torque balance incorporating non-resonant term able to quantitatively predict LM dynamics
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2/1 magnetic island

I-coils

C-coils
Rotating RMPs used to prevent mode-locking in high beta DIII-D discharges

- Rotating perturbations have been used to drive mode rotation
  - ATC (1974)
  - DITE (1990) ~5 kHz
  - TEXTOR (2005)
  - J-TEXT (2013) 5 kHz

- Usually at higher tearing mode frequencies

- This work: mode entrainment after (or near) mode-locking
Resonant interaction with rotating field can sustain mode rotation up to 300 Hz ($\Omega \tau_w \approx 6$)

- **Without control:** 2/1 NTM grows and locks, causing beta collapse and major disruption
Resonant interaction with rotating field can sustain mode rotation up to 300 Hz ($\Omega \tau_w \approx 6$)

- **Without control:** 2/1 NTM grows and locks, causing beta collapse and major disruption

- **Rotating $n=1$ I-coil field** “entrains” slowing island

- **Entrainment up to 300 Hz** ($\Omega \tau_w \approx 6$) demonstrated

- **Loss of entrainment** under study
Magnetics array analysis and ECE diagnostic confirm entrainment and spin-up of 2/1 mode

- Magnetics arrays analyzed for modal shapes (eigspec code)
- $m/n=-2/-1$ mode tracks I-coil frequency
- ECE phase inversion observed across $q=2$ surface, synchronous with I-coil
Modest improvement in confinement observed during entrainment

- 300 Hz corresponds to $\approx 4 \text{ km/s}$ at outboard $q = 2$ surface

- Density and beta both drop after loss of entrainment

- Beam power constant, so changes in beta correspond to changes in confinement
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Improved confinement due to formation of small edge pedestal

- Profiles show confinement increase due to edge behavior

$q=2$

![Graph showing confinement increase](image)
Details of entrainment loss needs study

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- Similar RMPs, differing lengths of entrainment
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- Entrainment lost while constantly rotating RMP applied
- Similar RMPs, differing lengths of entrainment
- Entrainment depends not just on coil currents/frequency
- Critical current may exist, but other factors (MHD events?) also important
What happens after loss of entrainment?

- After entrainment is lost, 2/1 island appears to slowly counter-rotate (~8 Hz)
  - Based on ECE

- Phase-difference evolves as frequency ramped
  - No correction for wall effects

- Is this a bifurcation of torque balance?
Open questions remain regarding effective mode entrainment

- Necessary currents probably exist, but are there necessarily sufficient currents?

- Would this change with feedback control vs. open-loop?

- What causes the island to “unlock” from rotating RMP?

- Is there an optimal entrainment frequency, or is faster always better?
Summary (2nd half): Rotating RMPs entrain slowing 2/1 islands to prevent mode-locking

- Entrainment up to $\Omega \tau_w \approx 6$ demonstrated

- Loss of entrainment due to factors other than coil currents, which are not yet understood

- Entrainment at 100 to 300 Hz has measurable effect on confinement