Active MHD Spectroscopy: A Tool for Plasma Stability Studies

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Overview

• Motivation

• What is active MHD spectroscopy?

• Some history

• Application to the resistive wall mode

• Simple single mode model

• Antenna and detection systems

• Flux amplification experiments

• Summary
MHD activity is a performance limiting factor in all devices

<table>
<thead>
<tr>
<th>Stellarator</th>
<th>Tokamak</th>
<th>ST</th>
<th>RFP</th>
<th>FRC/Spheromak</th>
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<tbody>
<tr>
<td>B provided by external currents</td>
<td>B provided by plasma currents</td>
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Develop new ways to diagnose and study MHD instabilities

- How can we study MHD modes?

  Passively: Wait and measure a modes properties and effects

  Actively: Find an appropriate driving force and excite the mode
What is Active MHD Spectroscopy?

- Active MHD spectroscopy is the probing of plasma stability with magnetic perturbations used to excite MHD modes and then measure their effect on plasma response.

- Excitation source: saddle coil array of antennas.

- Detection system: pickup coils, ECE, SXRs, reflectometry, …
Why is Active MHD Spectroscopy Useful for Laboratory Plasmas?

- It can be used to study many MHD instabilities relevant to IC concepts and toroidal plasmas in general:
  - TAEs
  - Kink/Resistive wall modes
  - Tearing modes/magnetic islands
  - Ballooning (?)
  - ELMs (?)
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  - ELMs (?)
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- What Can Be Studied About These Modes? Answer: It depends upon the particular mode.
  - Map out dispersion relations
  - Real time dynamics
  - Rotational and damping effects
  - Mode coupling
  - Others…
Some History…

Term introduced by Goelblood  [1993 PPCF 35 B277]

TAE excitation and damping on JET by Fasoli  [1995 PRL 75 645]
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Long history of applying low frequency and mode number magnetic perturbations to study tearing modes in tokamaks and RFPs

Established Examples:

- Error field locked tearing modes (DIII-D and Compass)\(^1\)
- Tearing mode phase instability and rotational effects (HBT-EP)\(^2\)
- Induced tearing mode rotation and mode coupling effects (RFX)\(^3\)

New Example: Resistive wall mode spectroscopy

HBT-EP antenna and detector system

- Passive stabilization of fast ideal kinks with Al segments
- Active feedback control of RWM using coils on SS segments

Dynamics and excitation of RWM with external coils

Thick (1 cm) Al Segments
Poloidal Field Sensor Array
Thin (2 mm) SS Segments
30 Overlapping Control Coils

30 channel programmable digital waveform generator
Amplifiers provide up to 2G of resonant field at the plasma surface
DIII-D has versatile sets of antennas and detectors

Experimental setup:

**Antennas:** 6 external (C-coils) and 12 internal saddle coils (I-coils), controlled by fast switching power supplies.

Static or rotating magnetic field with large overlap with RWM structure at the wall.

**Detectors:** Toroidal arrays of saddle loops (and poloidal field probes) above, on and below the midplane. Frequency dependent vacuum coupling to I-coil is measured.
Single mode model

- Evolution equation:
\[ \frac{d\psi_w}{dt} - \gamma_o \psi_w = \gamma_w \psi_c \]

- Natural growth (or damping) rate:
\[ \gamma_o = -\frac{\gamma_w}{1 - c} \left( 1 - \frac{1}{1 - \bar{s}} \right) \]

- Stability parameter:
  - \( \bar{s} < 0 \) stable
  - \( \bar{s} = 0 \) marginal stability
  - \( \bar{s} > 0 \) unstable

- Flux Amplification Factor:
\[ A_{RFA} = \frac{\psi_w - \psi_w^{vac}}{\psi_w^{vac}} = c \frac{1 + s}{(-s)} \]

- Stable plasma: \( A_{RFA} > 0 \)  

Plasma amplifies the wall flux

Nonrotating plasma: $\gamma_o$ is a real number

Consider a step function turned on at $t = 0^+$ with $\psi_c = 1$

Step Response: $\psi_w(t) = \frac{\gamma_w}{\gamma_o} \left( 1 - e^{\gamma_o t} \right)$

Natural Damping rate determined by the decay rate of the response or its asymptotic amplitude
Rotating plasma: \( \gamma \) becomes complex, \( \gamma = \gamma_r + i\omega_r \)

Rotation and dissipation do two things

- Can stabilize the mode \(^1,2\)
- RWM acquires a real frequency

Step response now becomes:

\[
\psi_w \propto \left[ 1 - e^{\gamma_r t} \left( \cos(\omega_r t) - \frac{\omega_r}{\gamma_r} \sin(\omega_r t) \right) \right]
\]

As the RWM approaches marginal stability, \( \gamma_r \to 0 \), large oscillations might be observable in the plasma response.

Plasma response to step-like magnetic perturbations
Plasma response is easily measured

- Measure plasma response as the approach to marginal stability is changed

- When \(q^*<3\) the plasma response is resonant and amplifies the external field.

- When \(q^* >3\) the plasma response is not amplified

- The saturated amplitude of the plasma response varies weakly with edge \(q^*\)

- The inferred damping rates are \(\sim 0.2\) ms

Plasma response measurements allow characterization of dissipation magnitude

- Large flux amplification near marginal stability damped by large dissipation
- Experimental observation of flux amplification on HBT-EP requires high dissipation factor in model $-\nu_d \tau_w \sim 90$
- Previous tearing mode experiments observed high viscous dissipation in HBT-EP (E.D. Taylor et al., Phys Plasmas, 2002)

- Modeled with the FA equations$^{1,2}$

Plasma Flux Amplification Consistent with Model for Observed Range of Rotation

- Rapidly rotating plasmas damp flux amplification.
- Experimental observation of plasma flux amplification on HBT-EP consistent with model for observed range of natural RWM rotation (3-8 kHz)
Plasma flux amplification to applied step perturbations observed above the no-wall limit on DIII-D

Plasma response to constant tone burst magnetic perturbations
Probe plasma stability with a rotating magnetic field

Lower single-null target plasma with co-injected NBI heating.
- $\Box$ above no-wall stability limit $\Box_N > 2$ (~2.4 $li$).
- Broad current profile with $q_{\text{min}} > 1$ and good wall coupling.

**Experiment:**
Use internal coil (I-coil) to apply a rotating resonant field

$$B_{w,\text{ext}} = M_{wc} \cdot I_C \cdot e^{i\Box_{ext}t}$$

while main stability parameters ($\Box_N$, $li$, $v_{\text{rot}}$) are kept constant.

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As shown in the graph, the plasma rotation $R=2.12\text{m} (\text{km/s})$ with $B_{w,\text{ext}}$ causing RWM instability when $v_{\text{rot}}$ drops below $v_{\text{crit}}$. 
Plasma response peaks for an externally applied field rotating in the direction of the plasma rotation

- Largest response for $f_{\text{ext}}$ between 10 and 20Hz (fraction of the inverse wall time in the direction of the plasma rotation).

\[ \beta_N = 2.40 \pm 0.1 \sim 1.15 \times \beta_{\text{no-wall}} \]
Frequency response yields measurement of $g_0$

Fit measured $A_{RFA}$ to predicted $\square_{ext}$ dependence:

$$A_{RFA} = \frac{1 + g_0 t_{ext}}{i g_0 t_{ext} \square_{w} g_0 \square_{w}}$$

- Largest response for $f_{ext}$ of a fraction of the inverse wall time.
- Good agreement indicates that the single-mode models are applicable.
- Fit yields measurement of $g_0$.

Plasma response to
“phase flip”
magnetic perturbations
RWM Simulations indicate transient plasma response is enhanced by applying phase flips

- Transient oscillations excited after the phase flip dissipate on time scale of $1/\gamma_r$
- And oscillations are enhanced and give a direct measure of $\gamma_r$ as marginal stability is approached
Plasma response to “phase flip” perturbations shows decreased damping as marginal stability is approached

- Plasma response damping time is measured to increase as marginal stability is approached
- Measured frequency is ~ 7 kHz
- Real time detection of the approach to marginal stability

Shilov et al. (2004) PoP
Measured RWM damping times consistent with model predictions

- Damping Time for Low Rotation
- Damping Time for High Rotation
- Model Damping Rate

Damping time (ms)

3/1 flux soak-through time
Summary and Conclusions

• Active spectroscopy is a useful tool for MHD studies

• Technique applied to the RWM

• Flux amplification measurements are able to quantify:
  -- Effects rotation and dissipation
  -- Damping rate and frequency stable modes
  -- Approach to marginal stability