Recent and Upcoming RWM Experiments on HBT-EP

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Outline

• Motivation for multimode research

• Recent major results
  – Passive multimode measurements
  – Resonant magnetic perturbations (RMPs)

• Upcoming experiments
  – Plasma shaping to enhance multimode spectrum
  – Multimode feedback with GPU-based control
  – Control coil modularity studies
  – Ferritic resistive wall mode
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Motivation: Understand multimode plasma response to 3D magnetic perturbations

• Understanding 3D field effects is important for predicting and optimizing tokamak performance
  – ELM mitigation, error field correction, RWM feedback

• Modular control coils may distort single mode response and lead to non-rigid (“multimode”) behavior
  – Small control coils will couple to other stable or unstable modes (sideband harmonics)
    • Can lead to loss of feedback control, complicate resonant plasma response, and impact plasma performance

• HBT-EP’s mission: Measure and control 3D edge magnetic fields with high detail and accuracy in a tokamak
New adjustable walls and magnetic diagnostics in HBT-EP allow high resolution excitation and detection of plasma modes.

- High-resolution poloidal and radial magnetic field sensors
- 40 poloidal + 40 radial field sensors for active feedback
- 20 adjustable wall segments
- 3 sets of 40 control coils for modularity tests

5°, 10°, 15°
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High resolution space-time measurements reveal complicated mode dynamics

- High-field-side toroidal array
- Diametrically opposed poloidal arrays
Biorthogonal Decomposition (BD) yields empirical basis functions derived from measurements

- Singular Value Decomposition splits fluctuation data into spatial and temporal modes

\[
A = U \Sigma V^T
\]

Fluctuation signals \( \uparrow \uparrow \uparrow \uparrow \quad s_1 \quad s_2 \quad \cdots \quad s_n \downarrow \downarrow \downarrow \downarrow \)

Temporal modes \( \uparrow \uparrow \uparrow \uparrow \quad u_1 \quad u_2 \quad \cdots \quad u_n \downarrow \downarrow \downarrow \downarrow \)

Spatial modes \( \leftarrow \leftarrow \leftarrow \leftarrow \quad v_1 \quad v_2 \quad \cdots \quad v_n \rightarrow \rightarrow \rightarrow \rightarrow \)

where \( u_i \cdot u_j = \delta^i_j \), \( v_i \cdot v_j = \delta^i_j \)

- Traveling waves are decomposed into \textit{sine} and \textit{cosine} components

\[
\cos(n\phi + \omega t) = \cos(n\phi) \cos(\omega t) - \sin(n\phi) \sin(\omega t)
\]

\[
c_1 \cos(n\phi) + c_2 \sin(n\phi) = A \cos(n\phi + \delta)
\]

- BD Technique is robust against sensor gain/alignment errors
High resolution space-time measurements reveal complicated mode dynamics.

Diametrically opposed poloidal arrays

High-field-side toroidal array

70246: Poloidal Field Fluctuations

BD window 3.5-4.0ms
BD analysis shows good separation of rotating modes in HBT-EP discharges

- Unambiguous pairing of 1st (dominant) mode
- 2nd mode pair almost always well defined
- 3rd mode pair is harder to interpret, but is sometimes coherent
The $m/n=6/2$ kink can evolve independently of the $3/1$ mode, implying the need for multimode control.

- Amplitude and phase of the $6/2$ mode do not simply track with the $3/1$ mode.
- Rapid $6/2$ growth is often seen during periods of decreasing $3/1$ amplitude.
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RMPs applied to lock external kink and study mode characteristics

- Static -3/1 radial field is applied near when edge q crosses 3

- Toroidal phase of RMP rapidly changed by 180° ("phase-flip") after 0.5 ms
Three regimes of plasma response are observed when applying 3/1 RMPs

- Large applied fields lead to disruption for $B_r^{3/1}/B_T > 3.5 \times 10^{-3}$
- Linear response is seen for $B_r^{3/1}/B_T < 1.5 \times 10^{-3}$
- For intermediate RMP strength $1.5 \times 10^{-3} < B_r^{3/1}/B_T < 3.5 \times 10^{-3}$,
  - Linear response seen for lower edge q
  - Saturated response seen for higher edge q near the q=3 resonance
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Biased electrode used to change edge plasma rotation and kink mode response

- Natural rotation: $\omega \tau_w \sim 20$
  - Modes rapidly rotate compared to wall time

- Edge biasing induces $E \times B$ flow to change plasma rotation

- Mode can be accelerated or decelerated depending on sign of bias
Plasma response is enhanced and phase-shifted for lower plasma rotation

- RMP applied in the linear response regime, $B_r^{3/1}/B_T = 10^{-3}$
- Phase difference of ~90° for slow versus fast plasma rotation
- Disruptions encountered at smaller applied fields for slower rotating plasmas
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Upcoming experiments will focus on multimode control

- Shaping coil will be installed
  - Multimode spectrum will change

- Multimode feedback with GPU control
  - Fast parallel computations for multimode control

- Coil modularity studies
  - Effect of changing sidebands

- Ferritic resistive wall mode
  - Reactor relevance
Multimode spectrum will be enhanced with installation of shaping coil

- Simple coil geometry will facilitate installation
  - Zero-net-turns to minimize coupling with other coil systems
  - Low self-inductance simplifies bank design
- Small change to plasma boundary is compatible with existing diagnostics and control coils
Active feedback will be done using GPU-based control system

- **Hardware details**
  - Standard Linux host system
  - NVIDIA Tesla M2050 GPU
  - D-TACQ ACQ196 digitizer (input from sensors)
  - Two D-TACQ AO32 boards (output to control coils)

- **Capabilities**
  - 96 analog inputs, 16-bit resolution
  - Fast parallel processing with GPU
    - 448 computing cores, each running at 1.15 GHz
  - 64 analog outputs
    - Latency ~10µs

All components commercially available
Modular control coils allow study of significance of applied field sidebands

Small

Medium

Large
Ferritic wall components will allow study of Ferritic Resistive Wall Mode in a toroidal device

- Cylindrical model* used to estimate the effect of ferritic material on the RWM in HBT-EP

Major results and implications

- Structure of naturally occurring external kink modes is composed of multiple independent eigenmodes: $m/n=3/1$ and $6/2$
  - ITER and other future tokamaks will require multimode active control

- Application of resonant magnetic perturbations to plasmas having a pre-existing saturated $m/n=3/1$ kink exhibit mode locking of the external kink to the applied resonant field
  - Magnitude and phase of the plasma response is dependent on the edge $q$ and plasma rotation
  - Locked plasma response is characterized by linear, saturated, and disruptive regimes, which depend on the edge $q$

- Upcoming HBT-EP experiments will continue to investigate multimode physics and control relevant to future devices, with plasma shaping, GPU-based control, and ferritic wall modes
Plasma responds to resonant component of applied field as the applied helicity is changed

- Control coils used as sensors to determine the natural 3/1 mode structure

- Helicity of external field scanned by changing $m$ for $n=1$ fields
  - Applied field projected onto the natural mode structure to determine resonant component

- Kink response matches the resonant component of the applied field
In the linear regime, kink plasma response is a maximum when near the 3/1 resonance.
Next stage of feedback: Perturbed equilibrium control

• The RWM can be interpreted as a sequence of perturbed equilibria
  – RWM evolves much slower than the Alfvénic force-balance time scale
  – Evolution is caused by changing external fields (i.e. decaying wall currents), and the RWM is a transition of the plasma through different MHD equilibria

• Perturbed equilibrium control:
  – Control a specific 3D state, instead of just imposing axisymmetry or preselecting a rigid perturbation