3D Magnetic Structure of Plasmas with an Adjustable Wall Geometry

Jeffrey P. Levesque

with the HBT-EP Group:
S. Angelini, J. Bialek, P.J. Byrne, B.A. DeBono, P. Hughes, B. Li, M.E. Mauel, G.A. Navratil, Q. Peng, N. Rath, D. Rhodes, D. Shiraki, and C. Stoafer
Outline

• Introduction
  – 3D fields in tokamaks
  – Why are conducting walls important?
    • Stabilization of the kink instability
  – Motivation for studying the influence of conducting wall geometry

• HBT-EP capabilities
  – Magnetic sensors for measuring mode activity
  – Adjustable wall structure
  – Mode analysis without a pre-defined basis

• Results of changing the HBT-EP wall geometry

• Summary
Outline

• Introduction
  – 3D fields in tokamaks
  – Why are conducting walls important?
    • Stabilization of the kink instability
  – Motivation for studying the influence of conducting wall geometry

• HBT-EP capabilities
  – Magnetic sensors for measuring mode activity
  – Adjustable wall structure
  – Mode analysis without a pre-defined basis

• Results of changing the HBT-EP wall geometry

• Summary
HBT-EP’s mission: Measure and control 3D edge magnetic fields with high detail and accuracy

- Tokamaks are nominally axisymmetric, but small 3D fields arise in practice
  - Finite magnetic coils
  - Coil misalignments
  - Plasma instabilities

- Understanding 3D field effects is important for predicting and optimizing tokamak performance
  - Edge Localized Mode (ELM) mitigation
  - Error field correction
  - Resistive Wall Mode (RWM) feedback
Nearby conducting walls are important for kink mode stability.
Nearby conducting walls are important for kink mode stability
Nearby conducting walls are important for kink mode stability
Nearby conducting walls are important for kink mode stability.
Nearby conducting walls are important for kink mode stability
Small wall asymmetries exist in realistic machines

- Toroidal and poloidal wall asymmetries exist due to ports, insulating breaks, and varying plasma geometries

- Modular walls may distort kink mode structure, and lead to non-rigid (“multimode”) behavior
  - Discrete conducting structures will couple multiple stable or unstable modes through eddy currents. This can lead to loss of feedback control or complicate the plasma response.
Outline

• Introduction
  – 3D fields in tokamaks
  – Why are conducting walls important?
    • Stabilization of the kink instability
  – Motivation for studying the influence of conducting wall geometry

• HBT-EP capabilities
  – Magnetic sensors for measuring mode activity
  – Adjustable wall structure
  – Mode analysis without a pre-defined basis

• Results of changing the HBT-EP wall geometry

• Summary
HBT-EP system parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major Radius $R_0$:</td>
<td>92 cm</td>
</tr>
<tr>
<td>Minor Radius:</td>
<td>15 cm</td>
</tr>
<tr>
<td>Plasma Current $I_p$:</td>
<td>~15 kA</td>
</tr>
<tr>
<td>Toroidal Field $B_T$:</td>
<td>0.33 T</td>
</tr>
<tr>
<td>Pulse Length:</td>
<td>5 - 10 ms</td>
</tr>
<tr>
<td>Electron temperature:</td>
<td>$\leq 150$ eV</td>
</tr>
</tbody>
</table>
Adjustable walls and magnetic diagnostics in HBT-EP allow high-resolution detection of plasma modes

- 236 in-vessel magnetic sensors, 120 active feedback coils
Magnetic pickup coils are used to analyze 3D mode behavior

- Measure $\partial_t B_{r,\theta}$ using pickup coils and integrate to get $B_{r,\theta}$
Magnetic pickup coils are used to analyze 3D mode behavior

- Measure $\partial_t B_{r,\theta}$ using pickup coils and integrate to get $B_{r,\theta}$

- Subtract smoothed signal for individual sensors
Magnetic pickup coils are used to analyze 3D mode behavior

- Measure $\partial_t B_{r,\theta}$ using pickup coils and integrate to get $B_{r,\theta}$

- Subtract smoothed signal for individual sensors

- Contour plot sensor groups
  - Use appropriate window for analysis
HBT-EP plasmas have a variety of coherent 3D mode activity
Singular Value Decomposition gives temporal and spatial modes derived from measurements.

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

with

\[ u_i \cdot u_j = \delta_i^j, \quad v_i \cdot v_j = \delta_i^j \]

Fluctuation signals

Temporal modes

Singular values

Spatial modes
Singular Value Decomposition gives temporal and spatial modes derived from measurements.

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

with

\[ u_i \cdot u_j = \delta^{ij}, \quad v_i \cdot v_j = \delta^{ij} \]

Fluctuation signals

Temporal modes

Singular values

Spatial modes

70246: Poloidal Array 2, Poloidal Field Fluctuations
Singular Value Decomposition gives temporal and spatial modes derived from measurements.

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

with

\[ u_i \cdot u_j = \delta^i_j, \quad v_i \cdot v_j = \delta^i_j \]
Singular Value Decomposition gives temporal and spatial modes derived from measurements.

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

with

\[ u_i \cdot u_j = \delta_i^j, \quad v_i \cdot v_j = \delta_i^j \]
Example shot with edge “safety factor” \( \sim 2.7 \) has clear \( m/n=3/1 \) and \( 6/2 \) modes.
The \( m/n=6/2 \) kink can evolve independently of the \( 3/1 \) mode, implying the need for multimode feedback control.

- Amplitude and phase of the \( 6/2 \) mode do not track with the \( 3/1 \) mode.
- Rapid \( 6/2 \) growth is often seen during periods of decreasing \( 3/1 \) amplitude.
- Does this behavior change as the wall geometry changes?
Conducting wall asymmetries may change coupling between multiple kink modes

- Different eddy-current patterns may couple stable/unstable modes
- A “non-rigid” kink structure means that the shape of instabilities could change as plasma pressure increases
Conducting wall asymmetries may change coupling between multiple kink modes

- Different eddy-current patterns may couple stable/unstable modes
- A “non-rigid” kink structure means that the shape of instabilities could change as plasma pressure increases

- VALEN code can simulate behavior with different wall configurations to maximize coupling of specific modes through eddy-currents

m=odd, n=1 shell configuration
Outline

• Introduction
  – 3D fields in tokamaks
  – Why are conducting walls important?
    • Stabilization of the kink instability
  – Motivation for studying the influence of conducting wall geometry

• HBT-EP capabilities
  – Magnetic sensors for measuring mode activity
  – Adjustable wall structure
  – Mode analysis without a pre-defined basis

• Results of changing the HBT-EP wall geometry

• Summary
Multimode spectrum is enhanced by changing the wall geometry

- With several wall sections retracted, power in the second mode pair (modes 3 and 4) is more significant than when shells are fully inserted.

- Results strongly depend on equilibrium
  - Need more shots for statistics
Spatial mode structure is similar for the different wall geometries.
Dominant m-number transitions have been seen for shells fully inserted and asymmetrically retracted

- Toroidal asymmetry, 3 sections retracted:
  
  ![Toroidal array](image1)
  
  ![Poloidal array 2](image2)
Transition from \( m=4 \) to \( m=3 \) mode occurs later for the toroidally asymmetric case.

- Shell geometry appears to affect mode transitions.
- More shots are needed to study statistical significance.
  - Plasma equilibria were slightly different.
Outline

• Introduction
  – 3D fields in tokamaks
  – Why are conducting walls important?
    • Stabilization of the kink instability
  – Motivation for studying the influence of conducting wall geometry

• HBT-EP capabilities
  – Magnetic sensors for measuring mode activity
  – Adjustable wall structure
  – Mode analysis without a pre-defined basis

• Results of changing the HBT-EP wall geometry

• Summary
Summary

• Small 3D magnetic fields significantly affect tokamak performance

• HBT-EP is able to measure 3D edge magnetic fields in high detail
  – Multimode interactions have been observed

• Conducting wall structures around plasmas can influence the presence of various 3D field components
  – More run-time with wall asymmetries in HBT-EP will provide insight into the importance of wall geometry