3D Magnetic Structure of Plasmas with an Adjustable Wall Geometry

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with the HBT-EP Group:

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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

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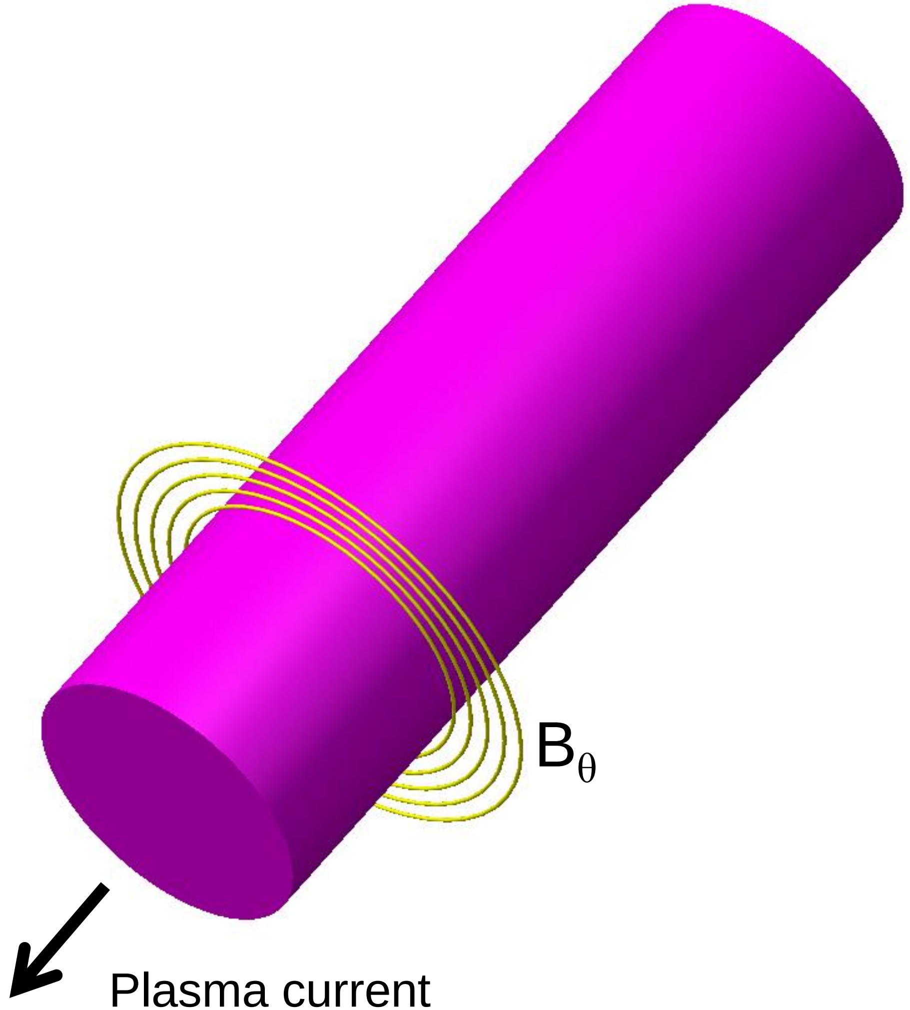
HBT-EP's mission: Measure and control 3D edge magnetic fields with high detail and accuracy

- 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



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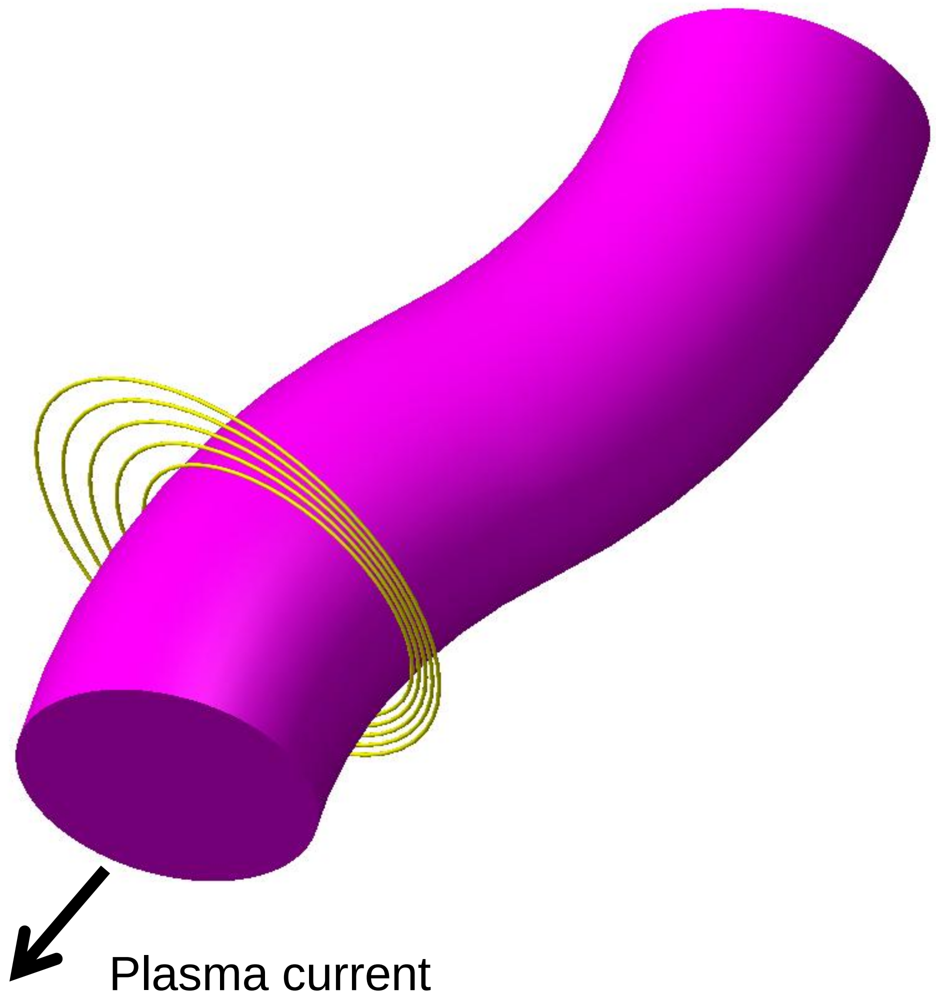

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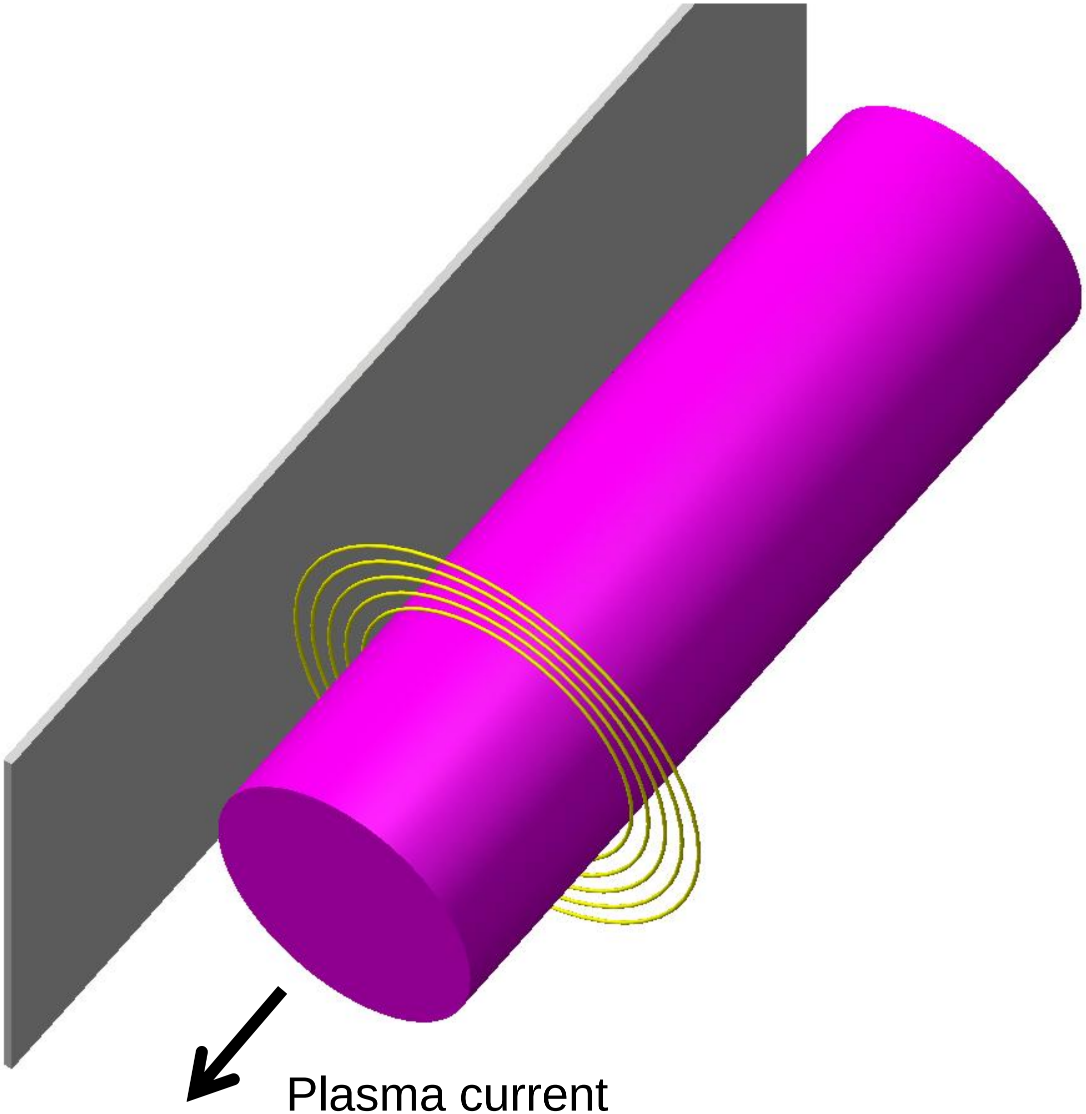

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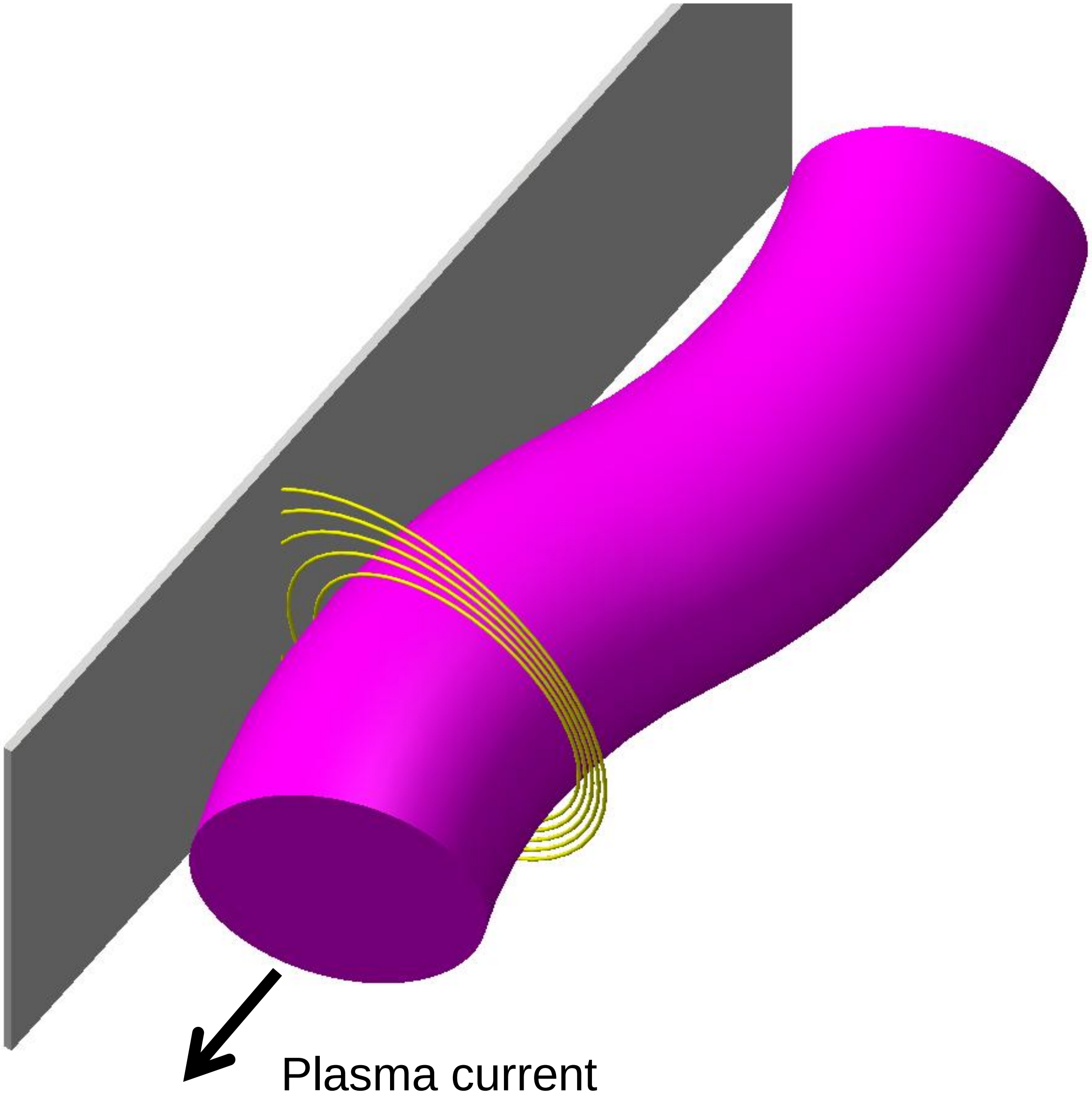

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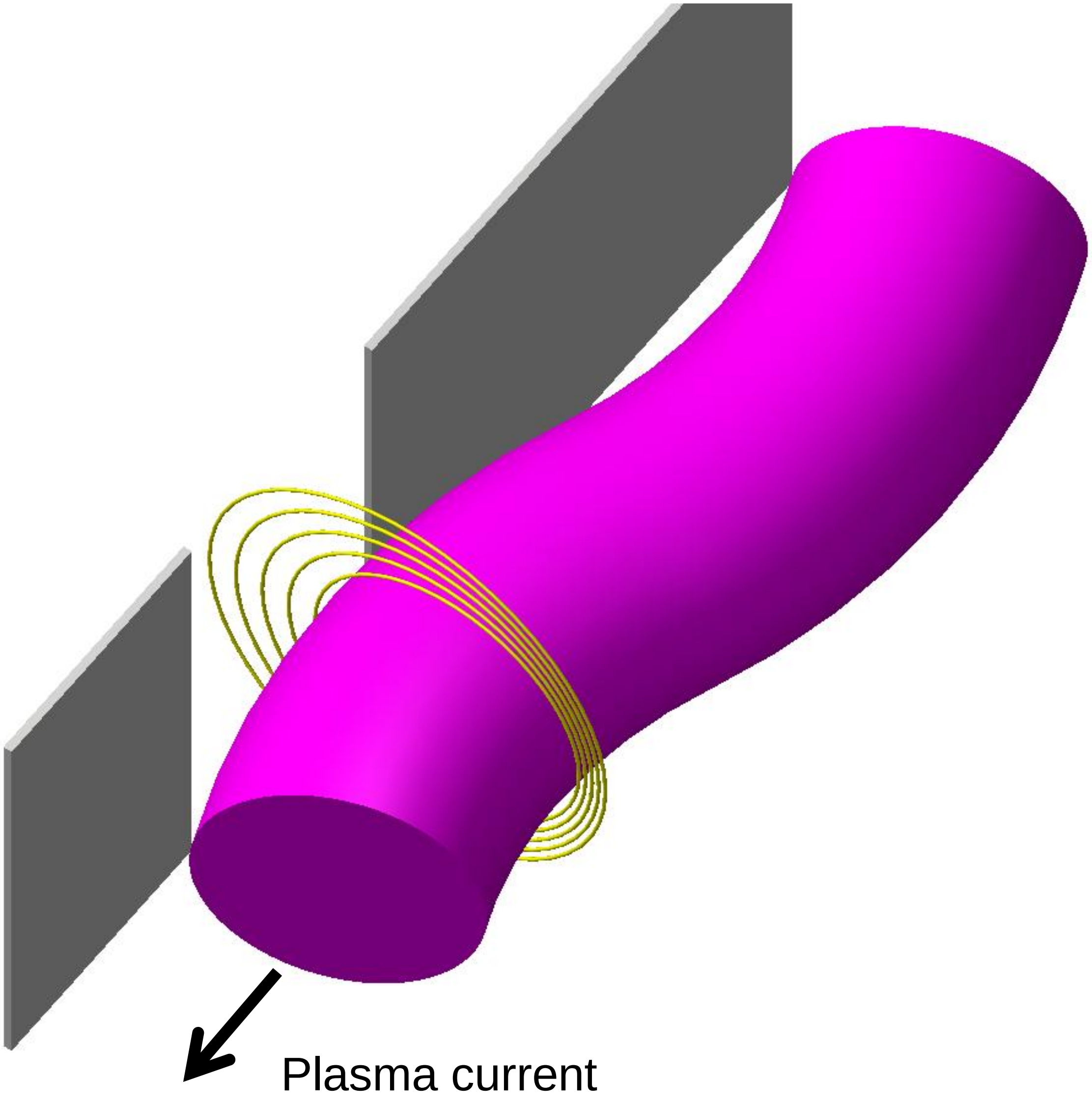

Small wall asymmetries exist in realistic machines

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

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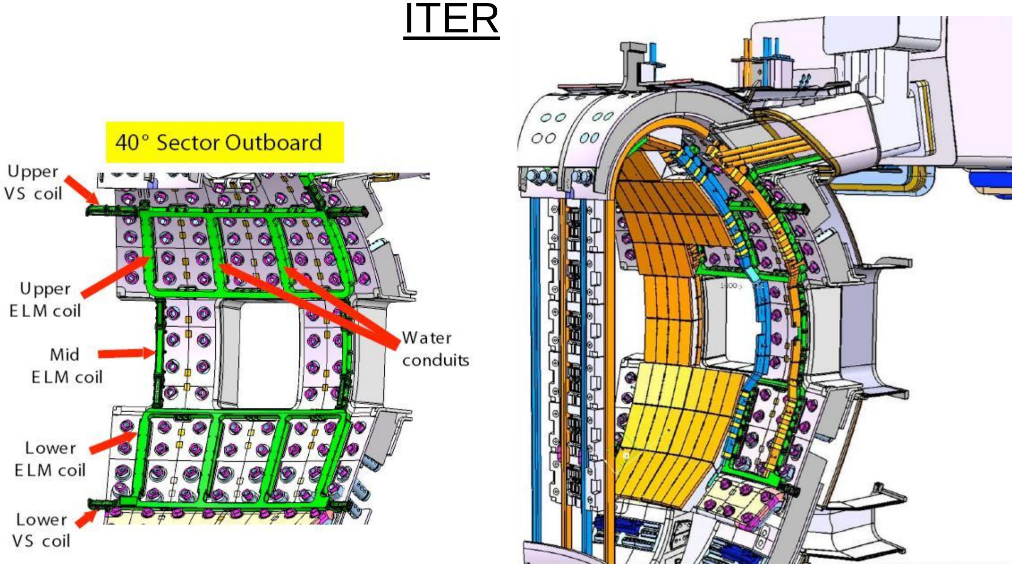
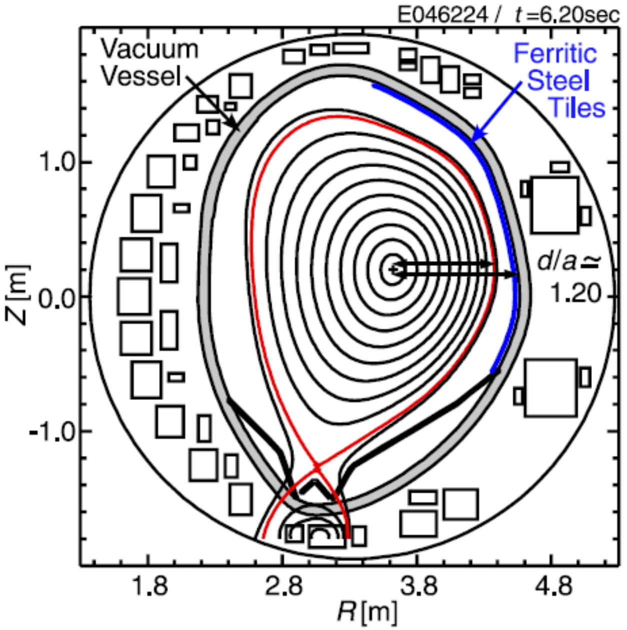


JT-60U



- 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.

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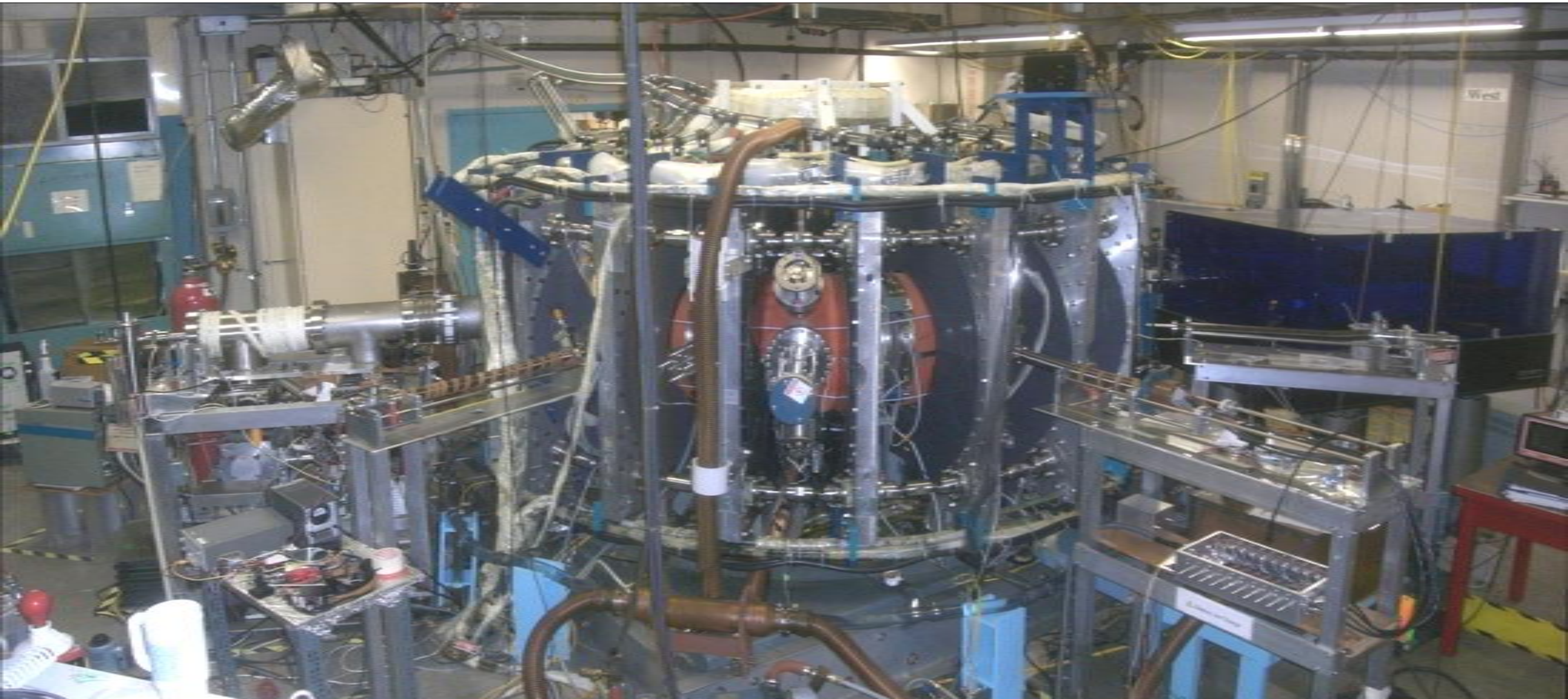
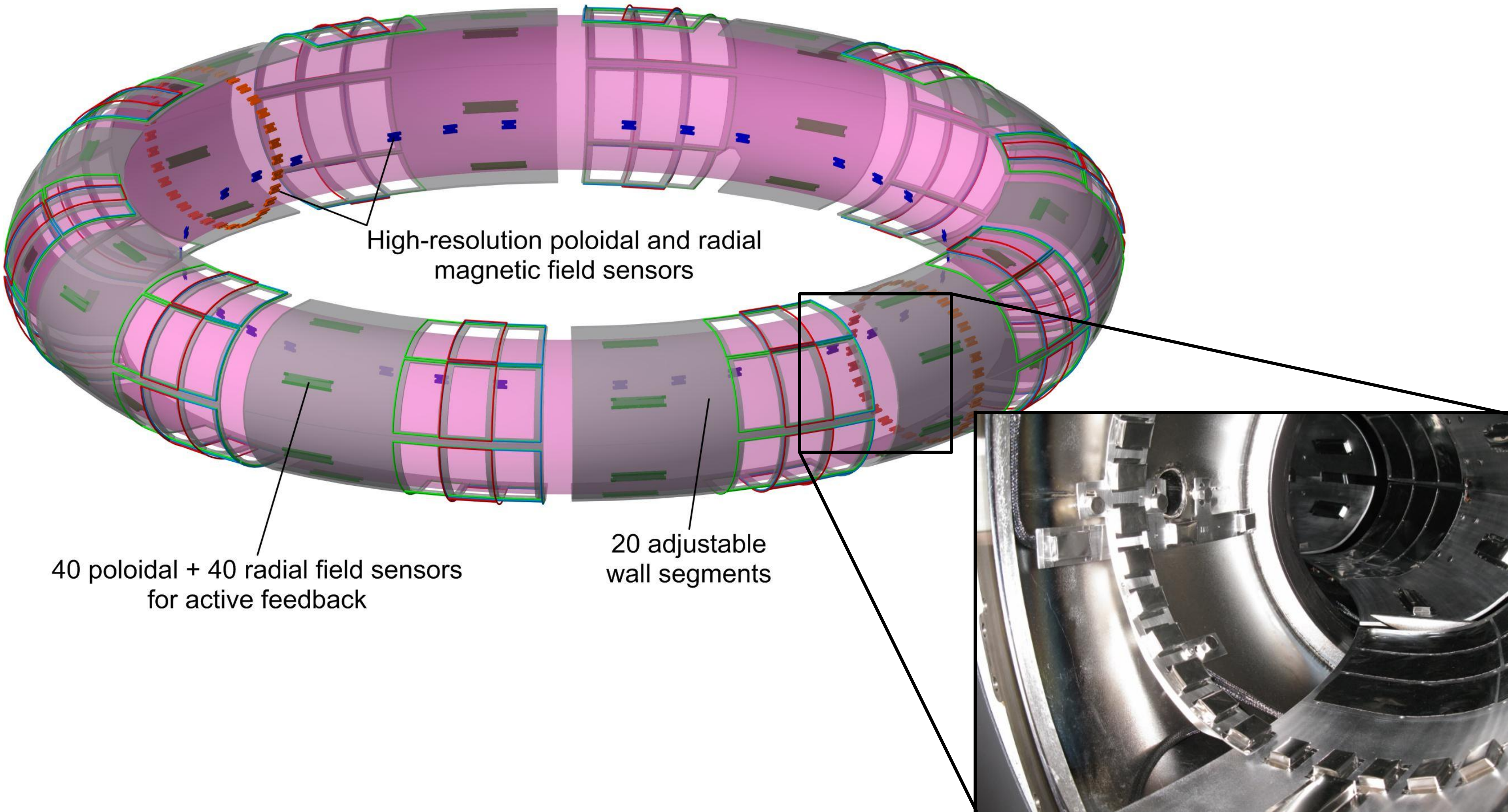
HBT-EP system parameters

Major Radius R_0:	92 cm	Toroidal Field B_T:	0.33 T
Minor Radius:	15 cm	Pulse Length:	5 - 10 ms
Plasma Current I_p:	~15 kA	Electron temperature:	≤ 150 eV

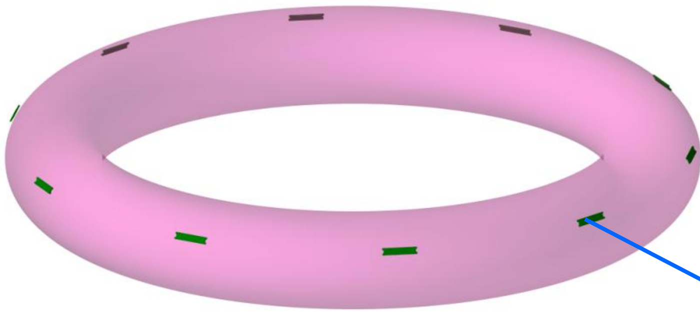


Adjustable walls and magnetic diagnostics in HBT-EP allow high-resolution detection of plasma modes

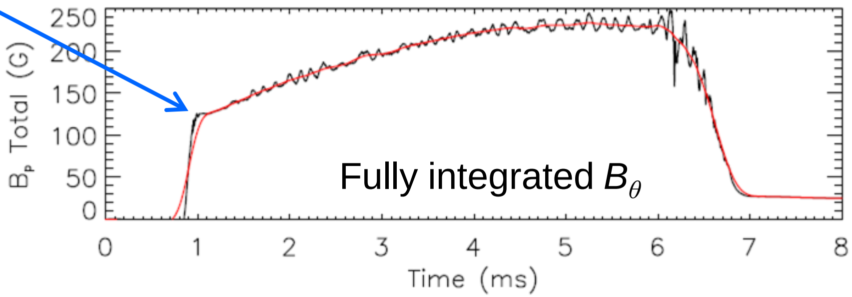
- 236 in-vessel magnetic sensors, 120 active feedback coils



Magnetic pickup coils are used to analyze 3D mode behavior



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



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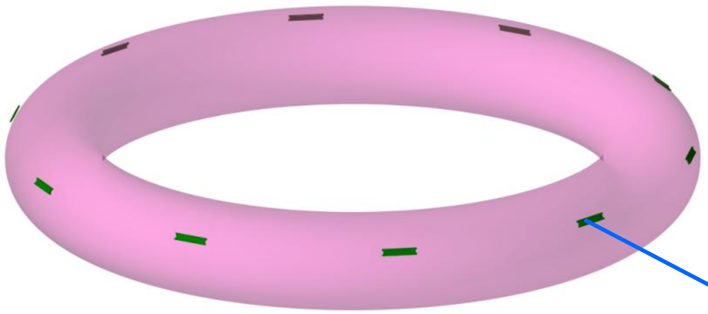

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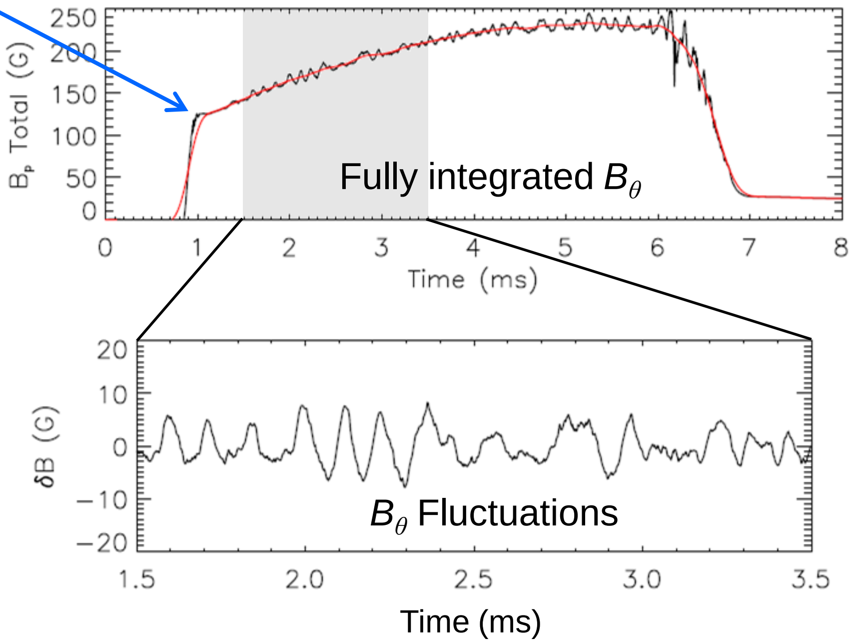

- Subtract smoothed signal for individual sensors

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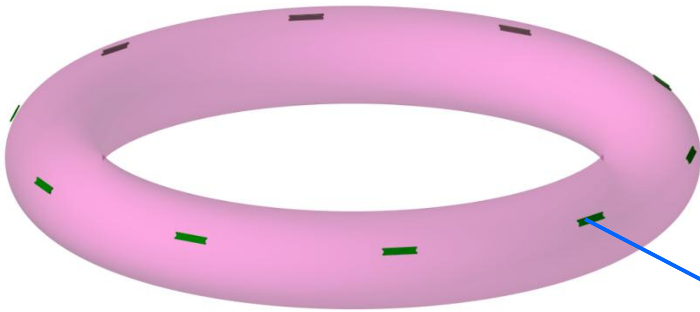
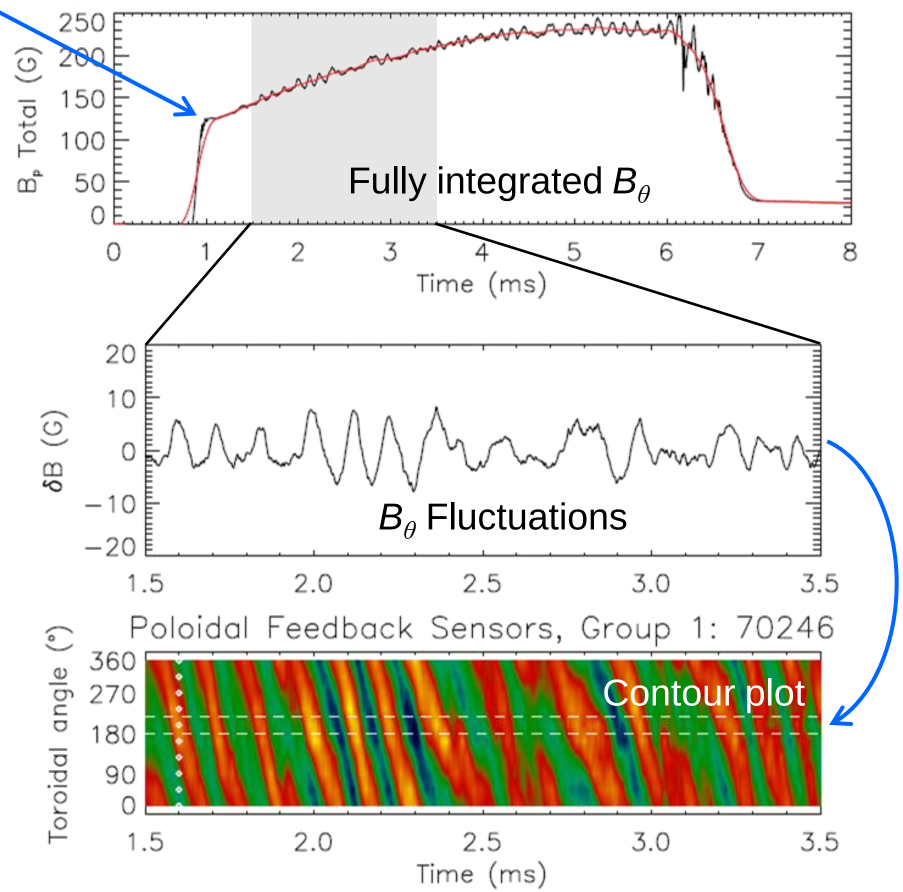


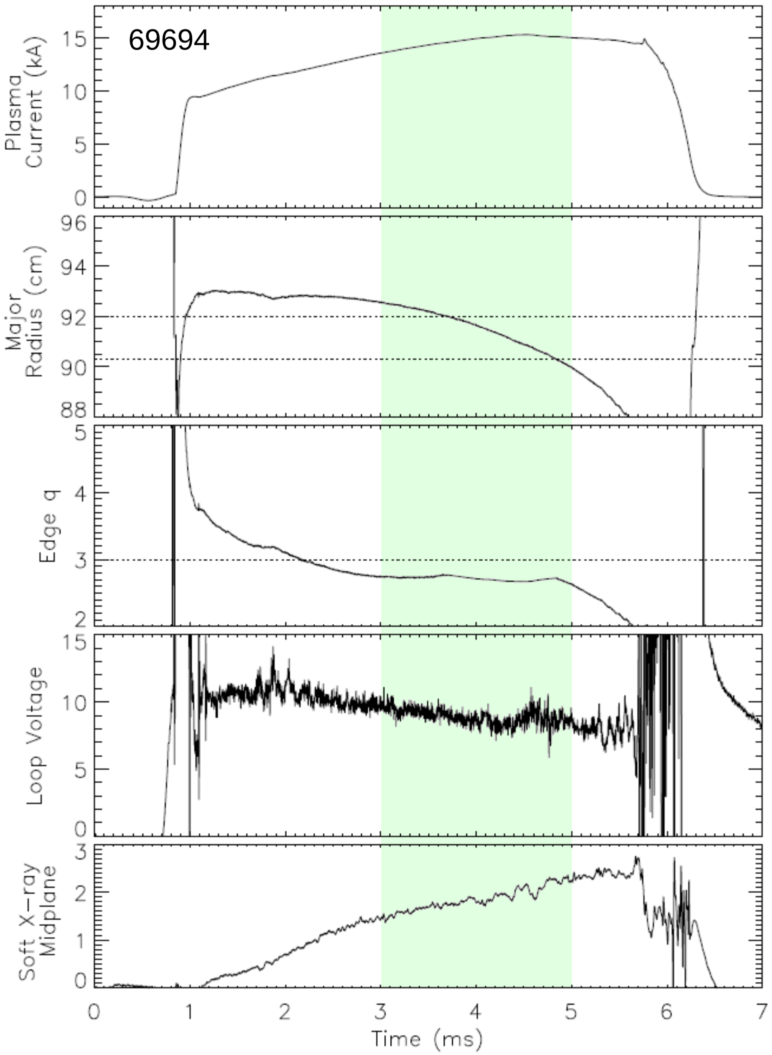
- Measure $\partial_t B_{r,\theta}$ using pickup coils and integrate to get $B_{r,\theta}$

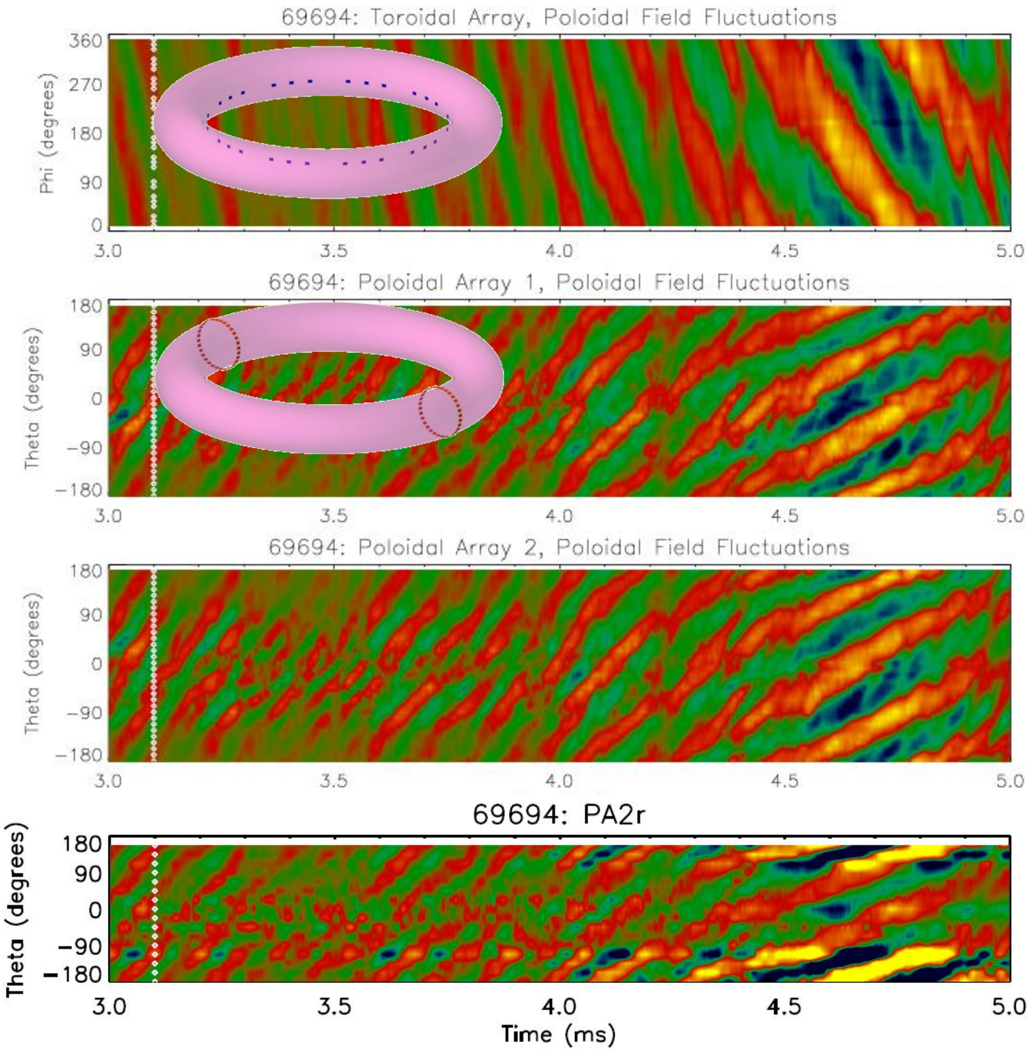
- Subtract smoothed signal for individual sensors

- Contour plot sensor groups
  - Use appropriate window for analysis

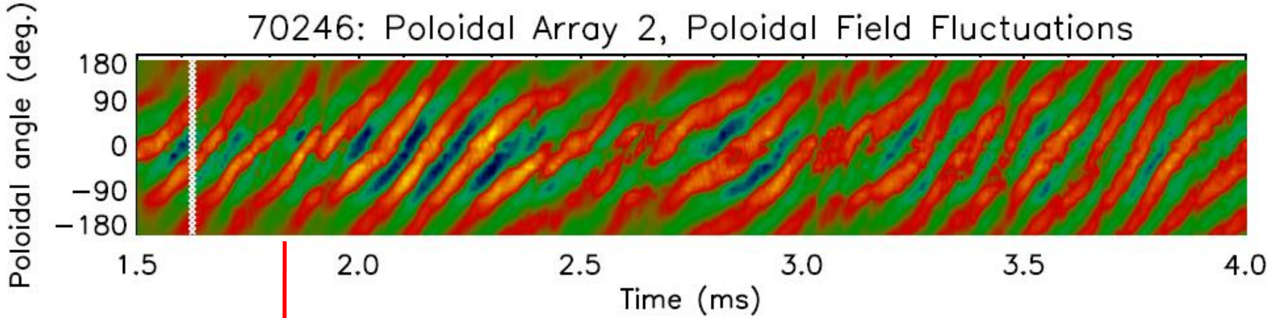


HBT-EP plasmas have a variety of coherent 3D mode activity





Singular Value Decomposition gives temporal and spatial modes derived from measurements



$$A = U\Sigma V^{\dagger}$$

with

$$\mathbf{u}_i \cdot \mathbf{u}_j = \delta_i^j, \quad \mathbf{v}_i \cdot \mathbf{v}_j = \delta_i^j$$

(transpose)

$$\begin{pmatrix} \uparrow & \uparrow & & \uparrow \\ \mathbf{s}_1 & \mathbf{s}_2 & \cdots & \mathbf{s}_n \\ \downarrow & \downarrow & & \downarrow \end{pmatrix} = \begin{pmatrix} \uparrow & \uparrow & & \uparrow \\ \mathbf{u}_1 & \mathbf{u}_2 & \cdots & \mathbf{u}_m \\ \downarrow & \downarrow & & \downarrow \end{pmatrix} \begin{pmatrix} \sigma_1 & & & \\ & \sigma_2 & & \\ & & \ddots & \\ & & & \sigma_n \end{pmatrix} \begin{pmatrix} \longleftarrow & \mathbf{v}_1 & \longrightarrow \\ \longleftarrow & \mathbf{v}_2 & \longrightarrow \\ & \vdots & \\ \longleftarrow & \mathbf{v}_n & \longrightarrow \end{pmatrix}$$

Fluctuation signals | Temporal modes | Singular values | Spatial modes

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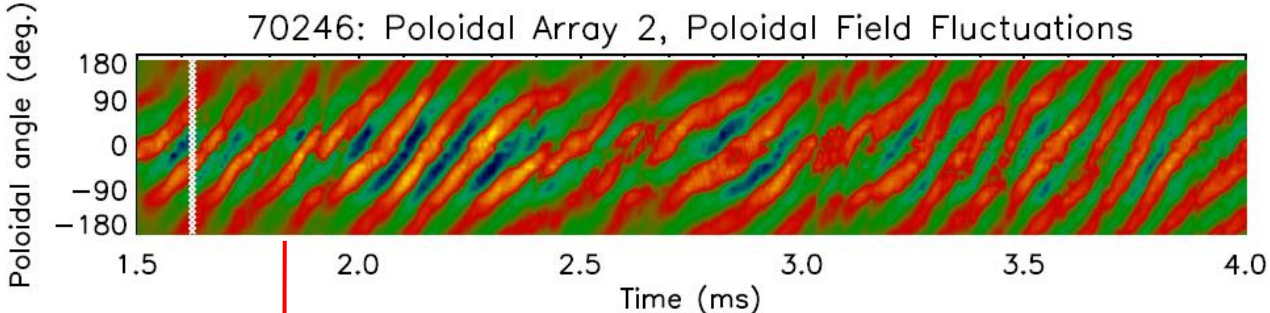

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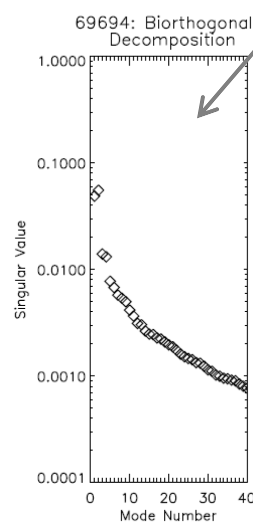
Fluctuation signals — Temporal modes — Singular values — Spatial modes



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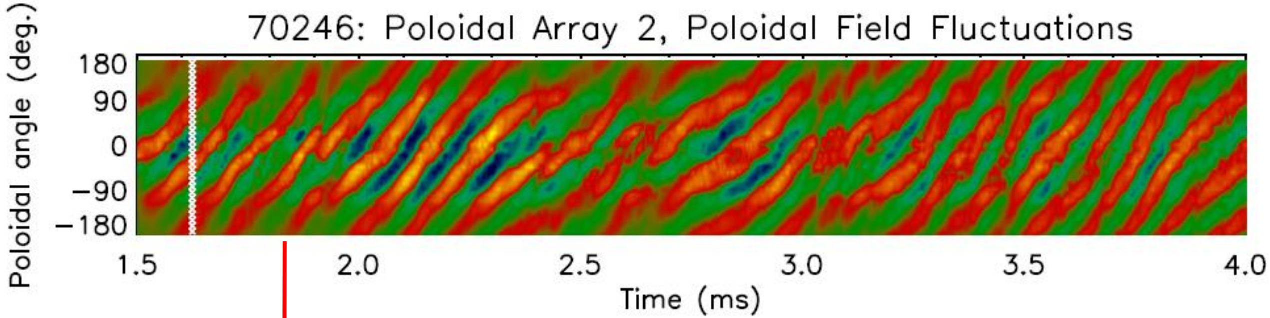

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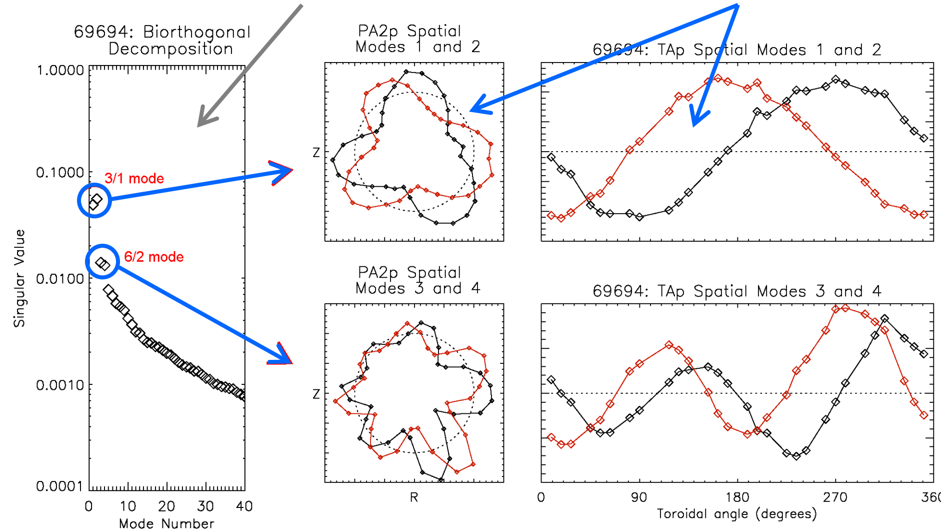
Fluctuation signals

Temporal modes

Singular values

Spatial modes



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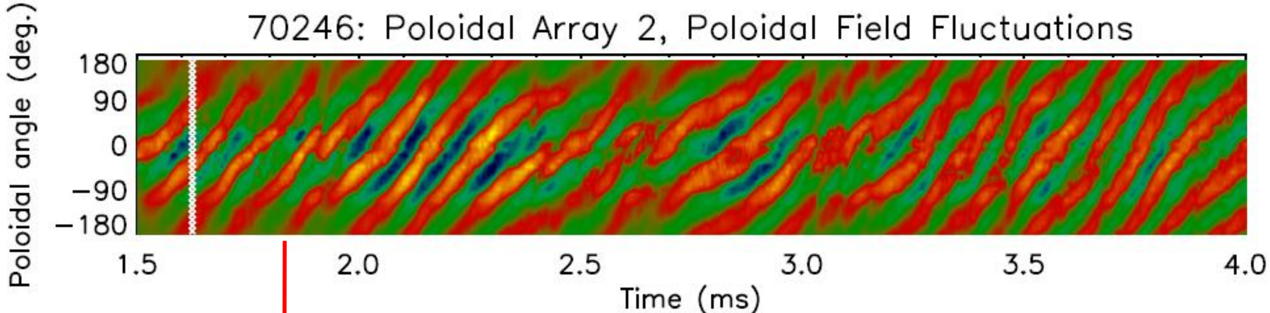

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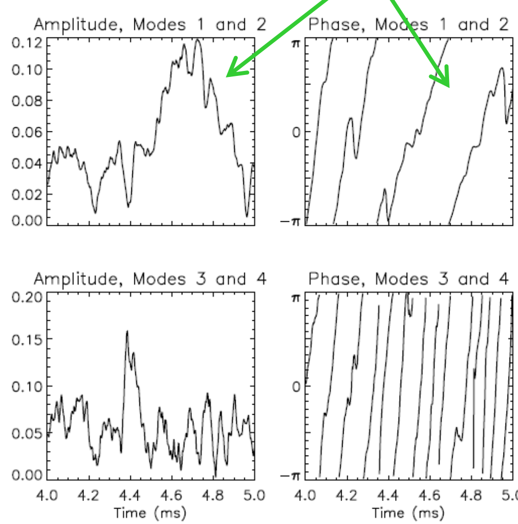
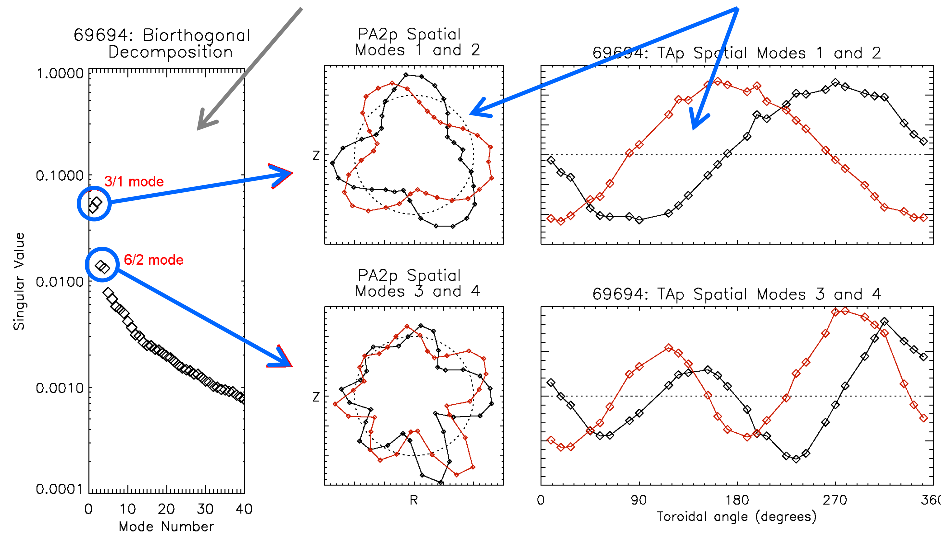
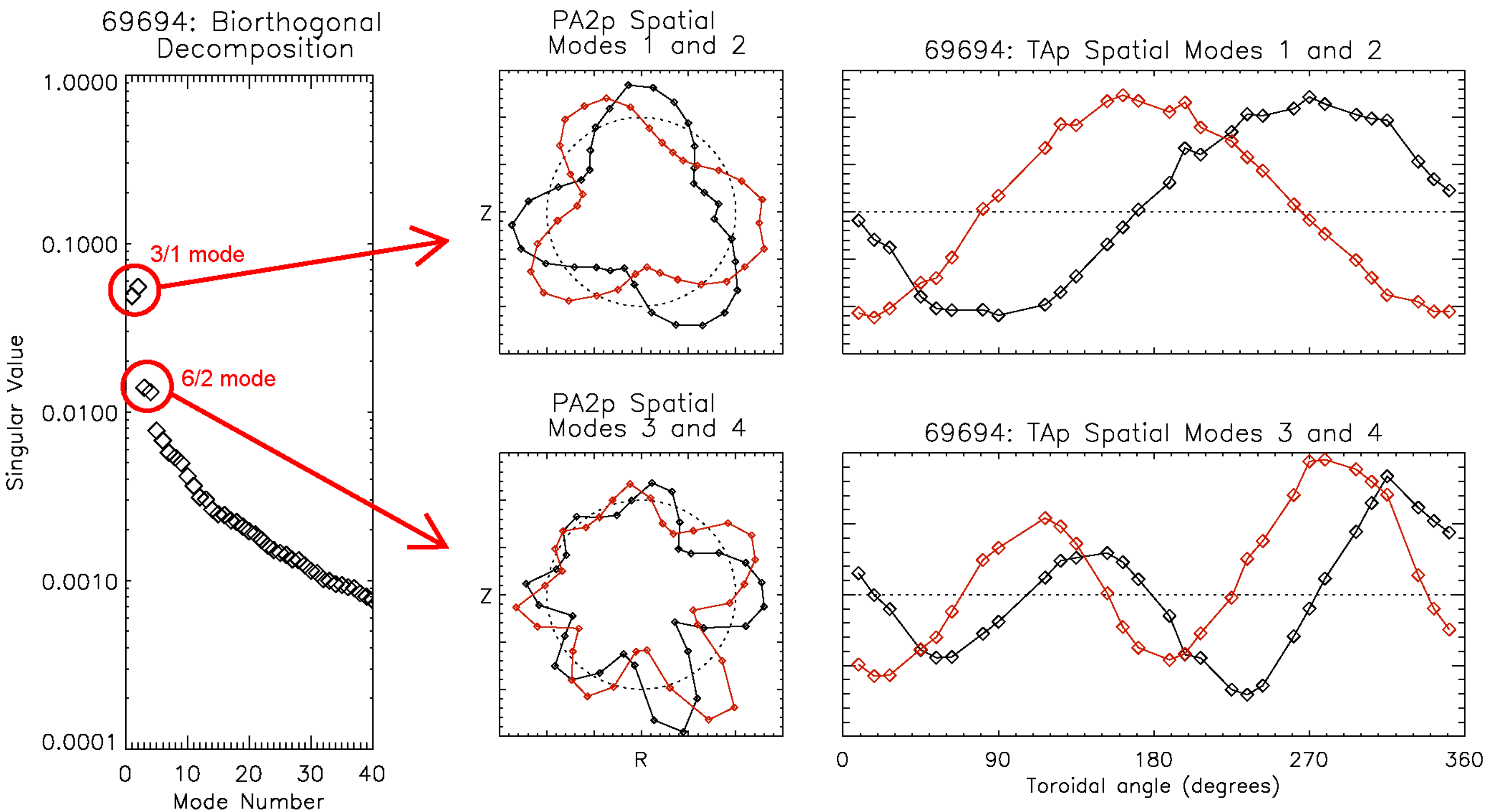
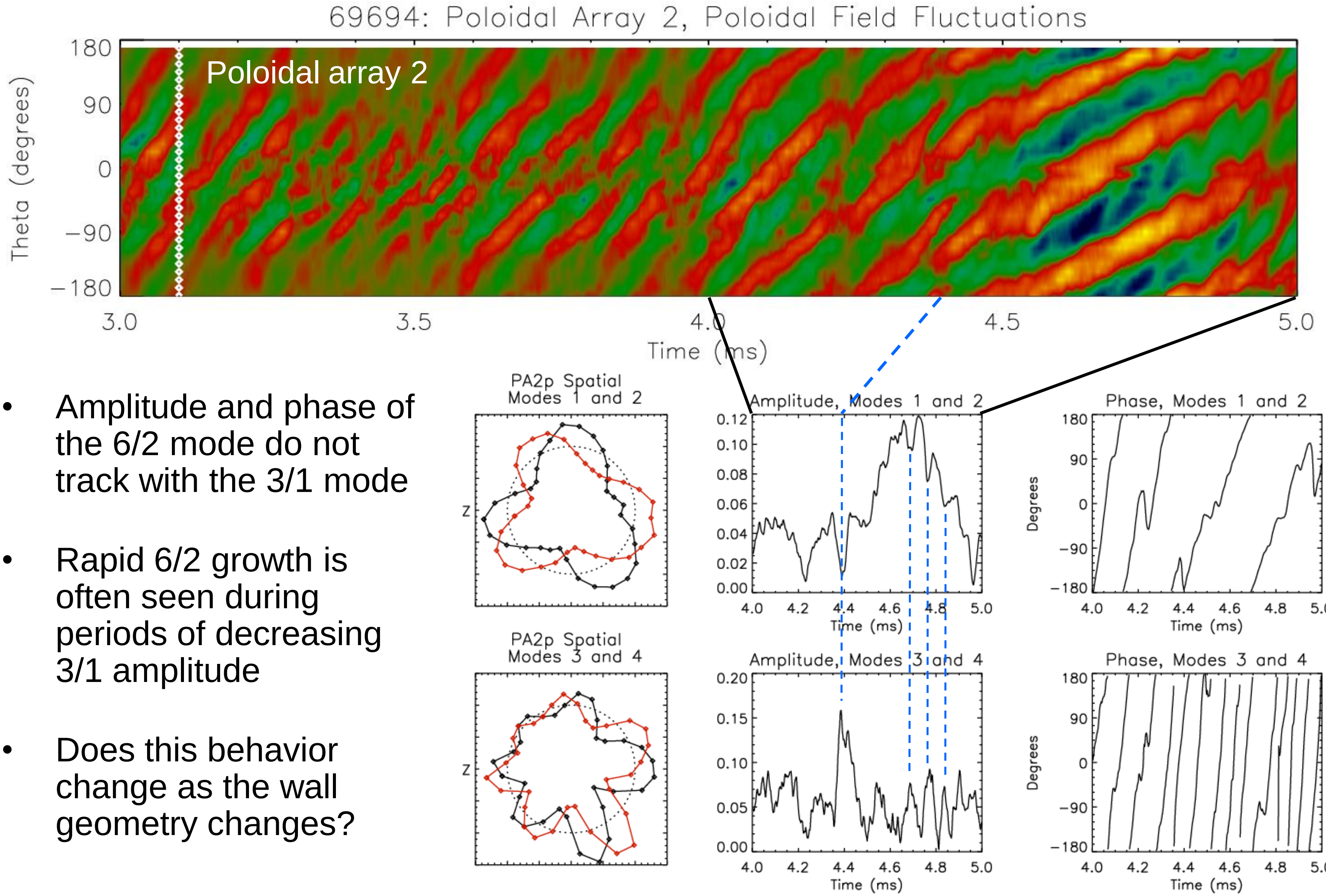




Example shot with edge “safety factor” ~ 2.7 has clear m/n=3/1 and 6/2 modes



The m/n=6/2 kink can evolve independently of the 3/1 mode, implying the need for multimode feedback control

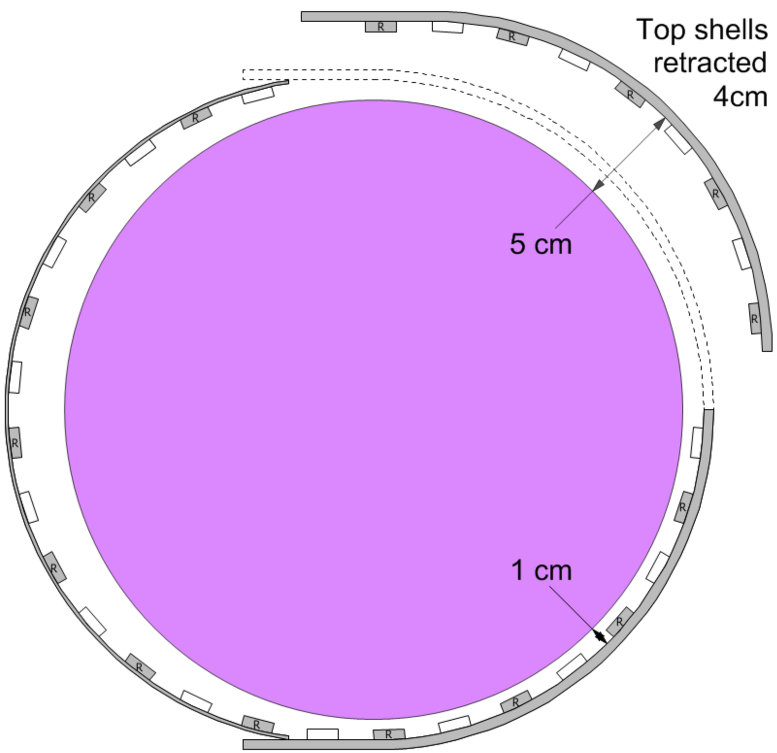


- Amplitude and phase of the 6/2 mode do not track with the 3/1 mode
- Rapid 6/2 growth is often seen during periods of decreasing 3/1 amplitude
- Does this behavior change as the wall geometry changes?

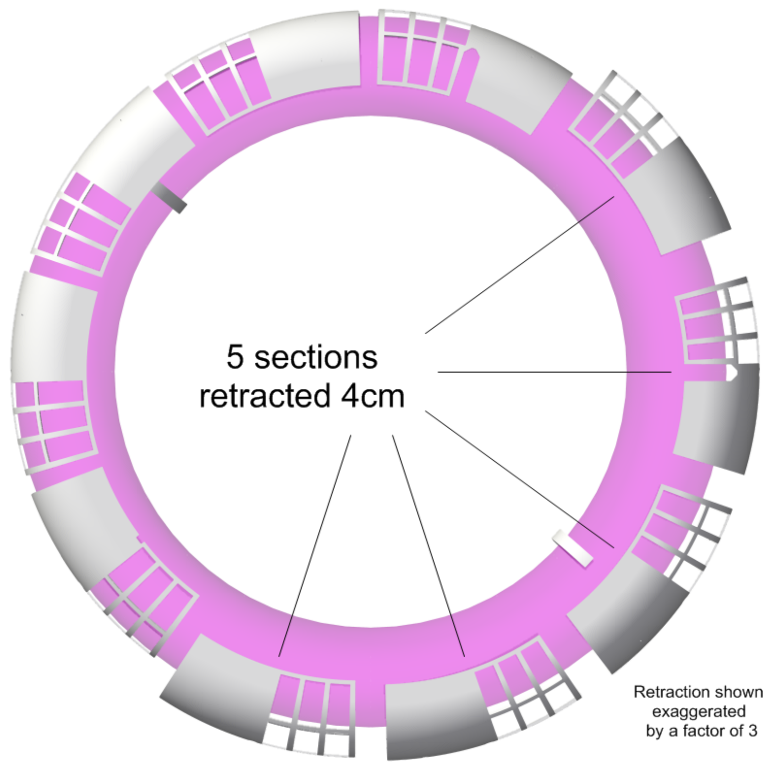
Conducting wall asymmetries may change coupling between multiple kink modes

- 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

Poloidal Asymmetry



Toroidal Asymmetry

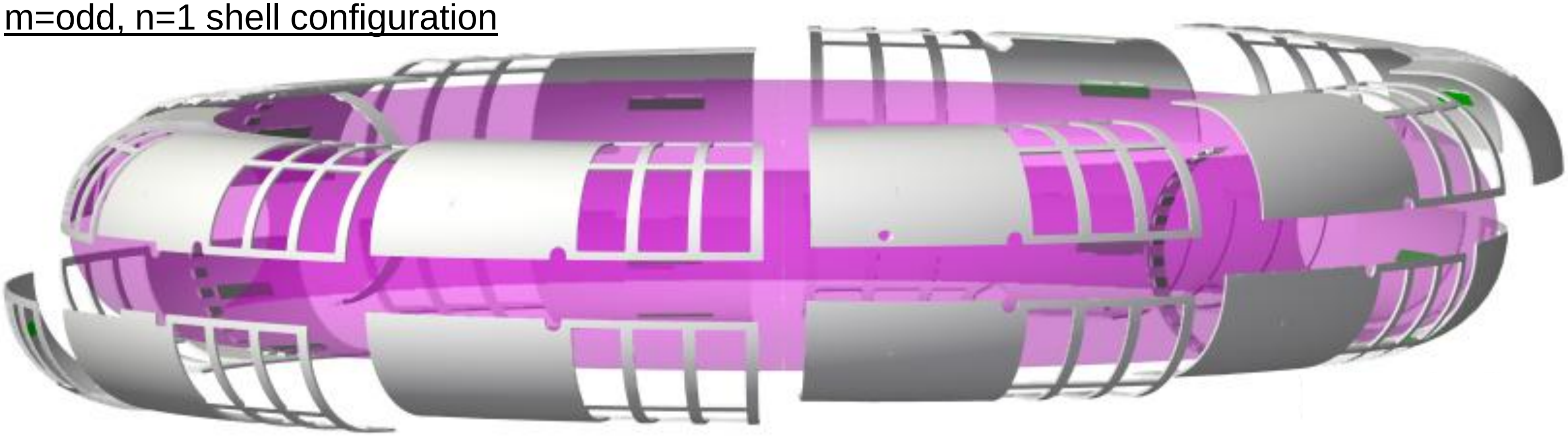


Conducting wall asymmetries may change coupling between multiple kink modes

- 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



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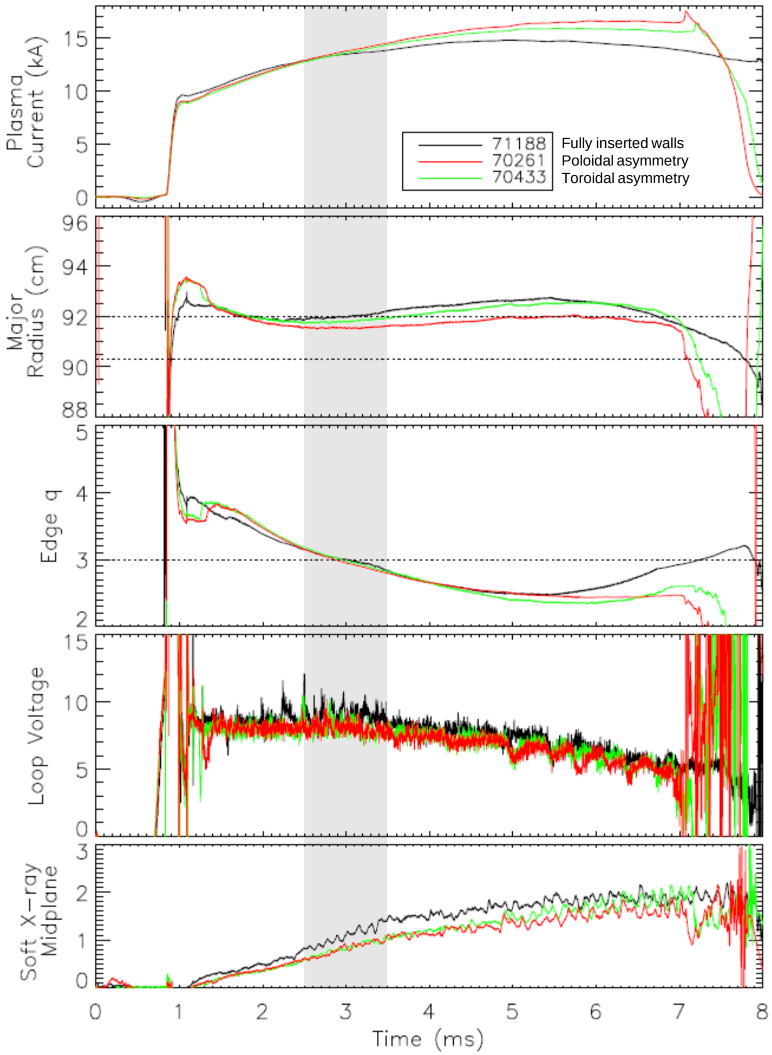
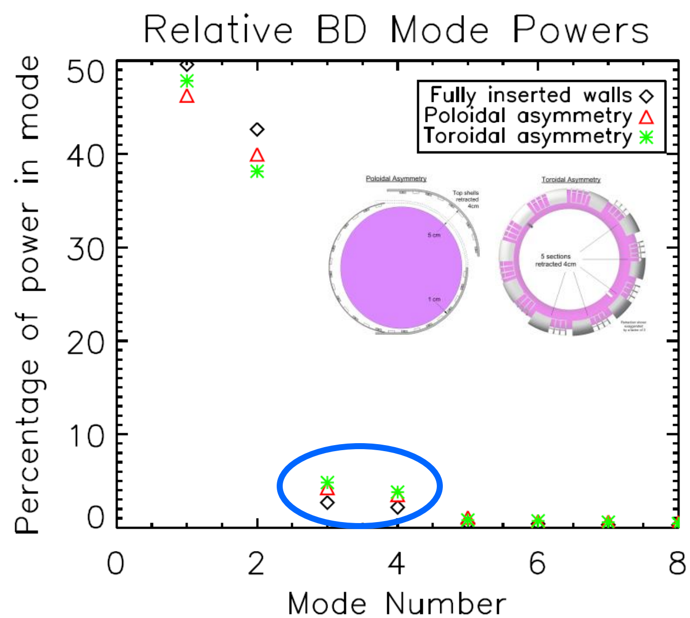
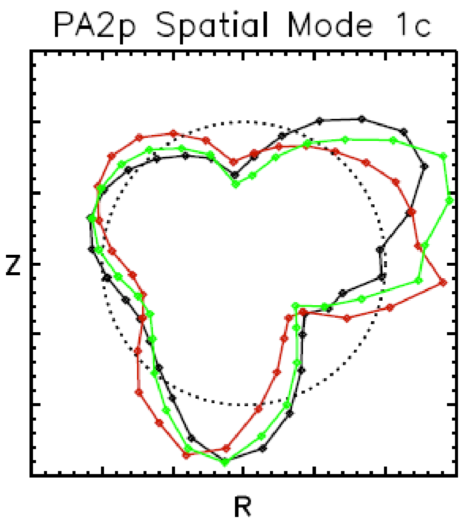
Multimode spectrum is enhanced by changing the wall geometry

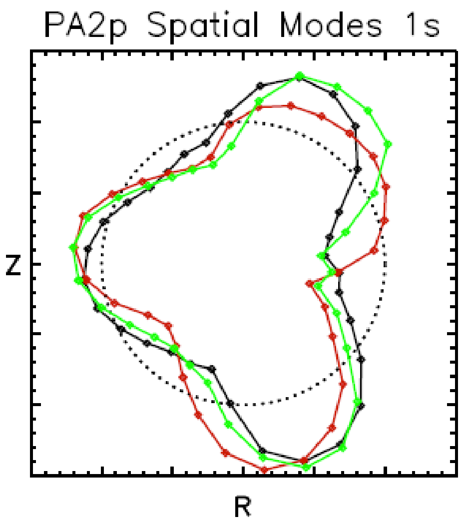


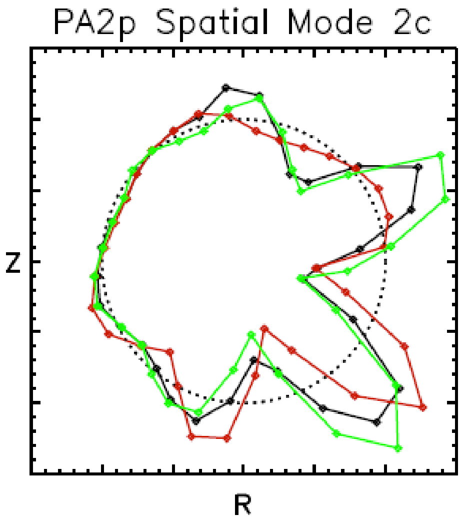


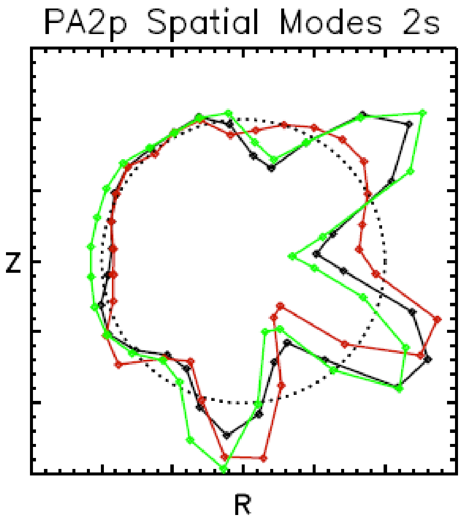
- With several wall sections retracted, power in the second mode pair (modes 3 and 4) is more significant than when shells are fully inserted
- Results strongly depend on equilibrium
  - Need more shots for statistics

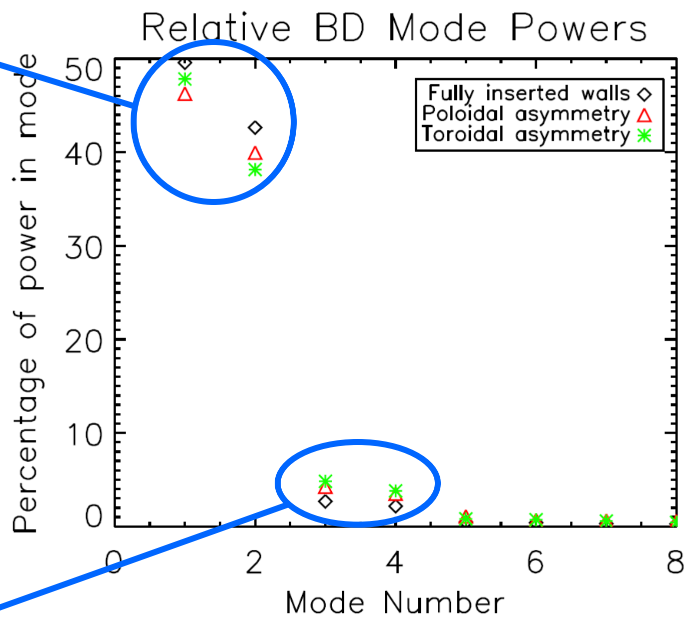
Spatial mode structure is similar for the different wall geometries





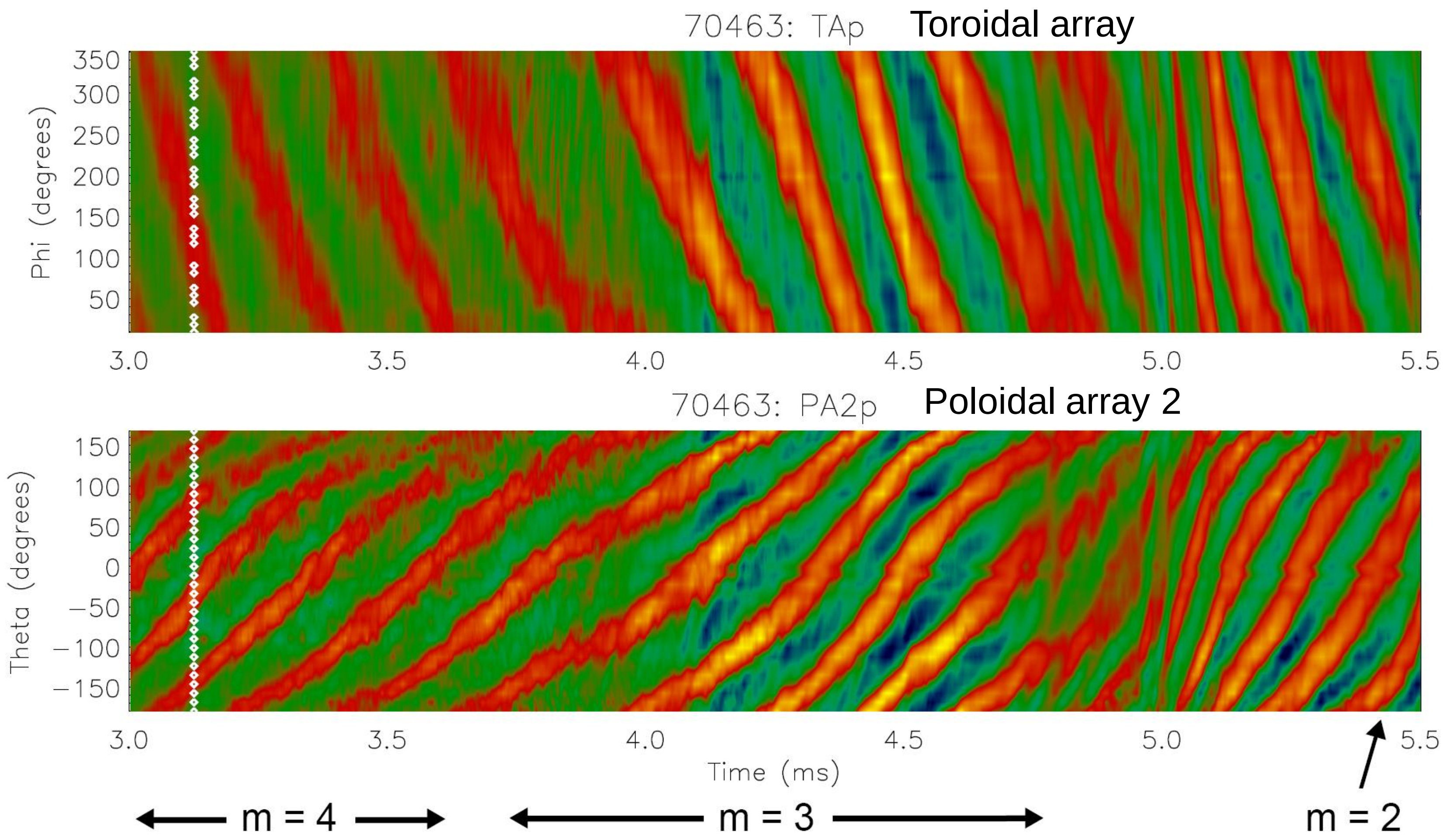




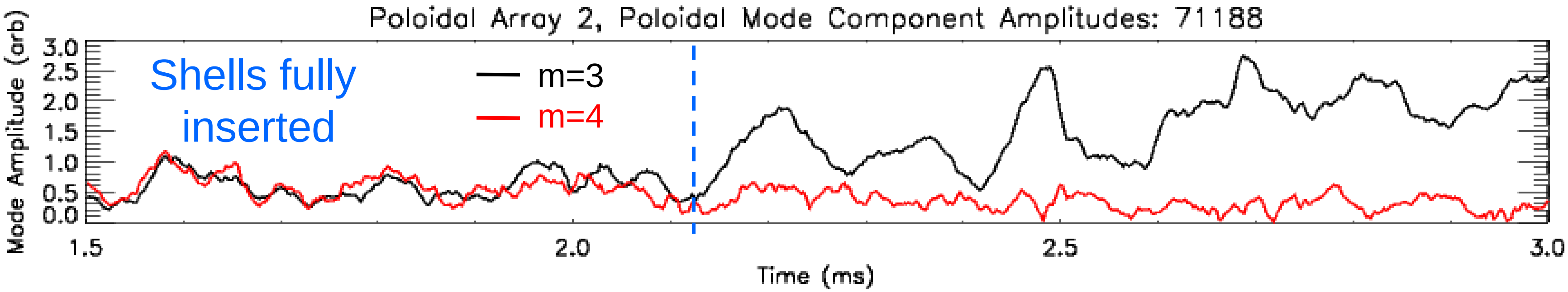


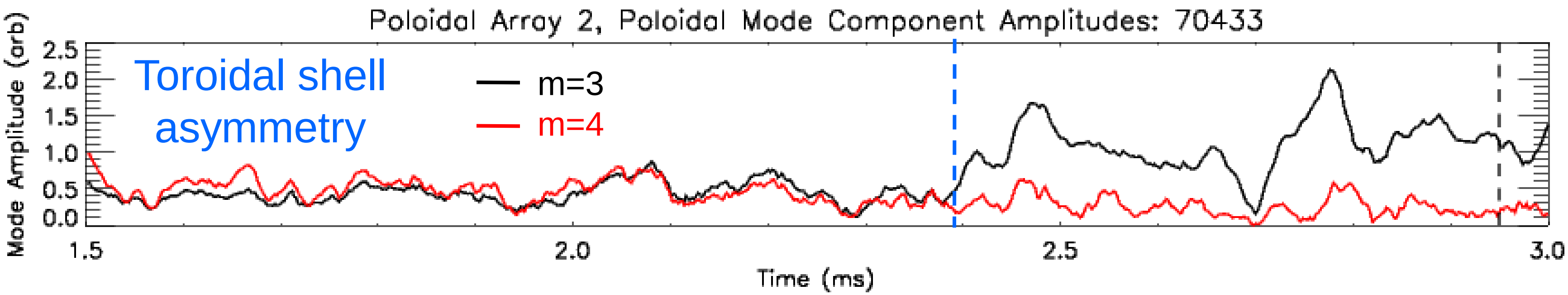
Dominant m-number transitions have been seen for shells fully inserted and asymmetrically retracted

- Toroidal asymmetry, 3 sections retracted:



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

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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