Recent and Upcoming RWM Experiments on HBT-EP

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,
D.A. Maurer, G.A. Navratil, Q. Peng, N. Rath, D. Rhodes, D. Shiraki, and C. Stoafer

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in the City of New York

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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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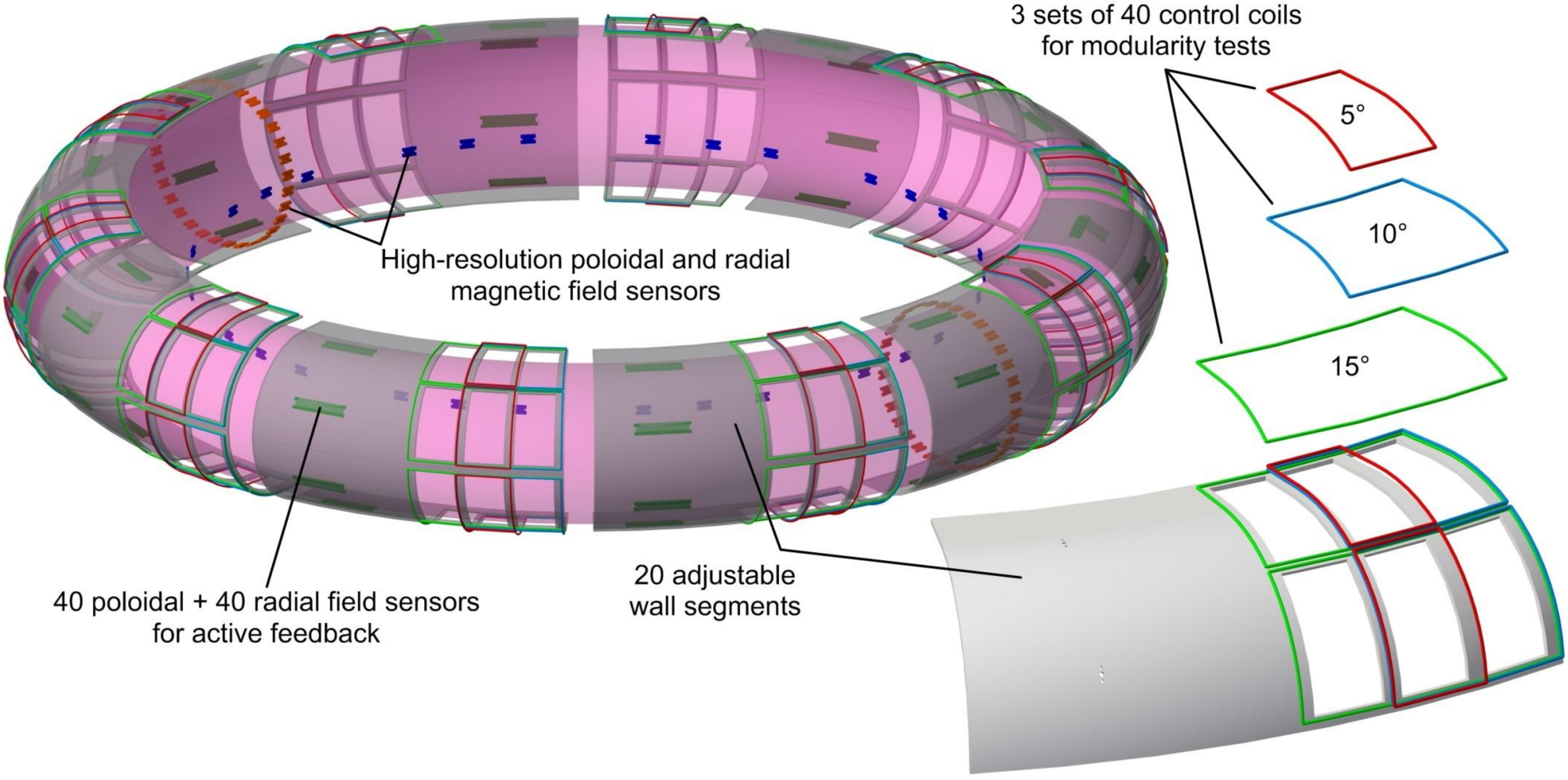
Motivation: Understand multimode plasma response to 3D magnetic perturbations

- 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



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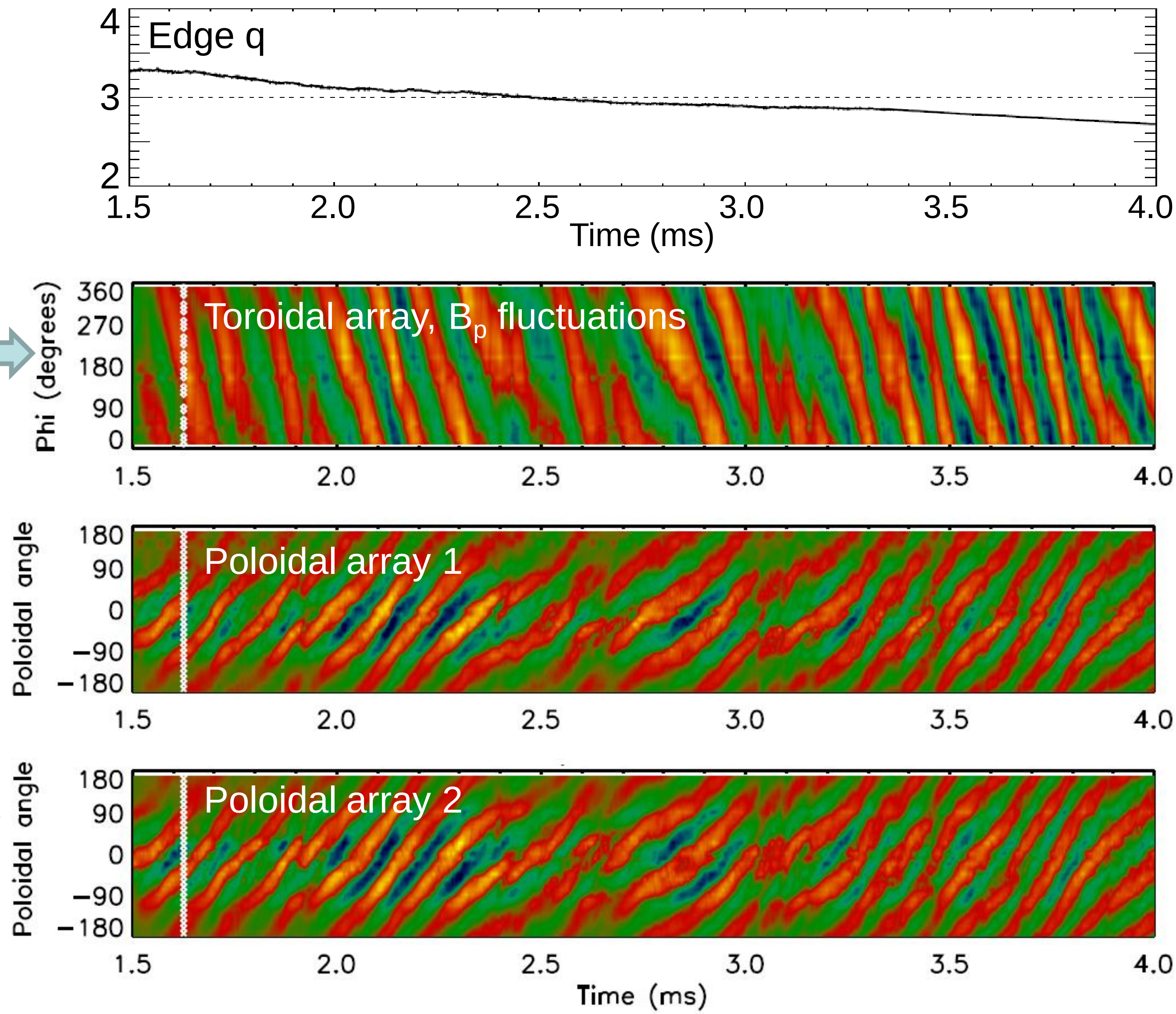
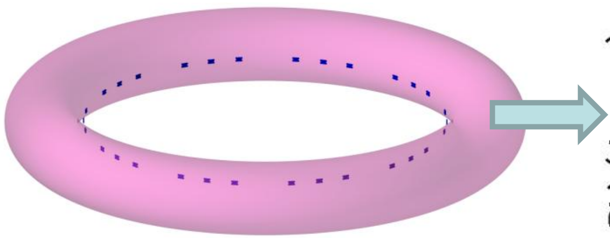
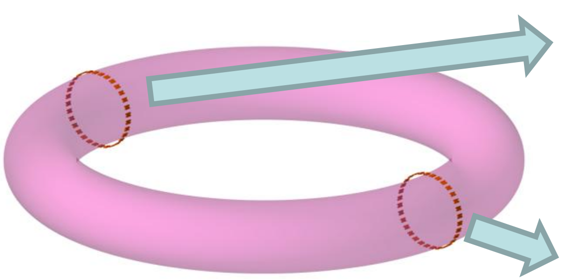
High resolution space-time measurements reveal complicated mode dynamics





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

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

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

Fluctuation signals — Temporal modes — Spatial modes

$$\text{where} \qquad \mathbf{u}_i \cdot \mathbf{u}_j = \delta^i_j, \qquad \mathbf{v}_i \cdot \mathbf{v}_j = \delta^i_j$$

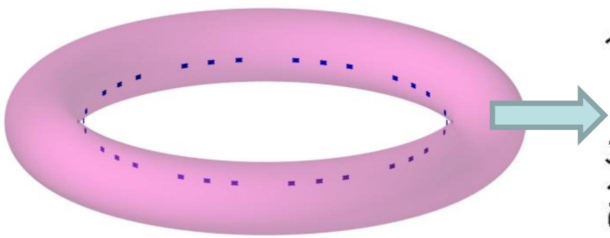
- Traveling waves are decomposed into *sine* and *cosine* components

$$\cos(n\phi + \omega t) = \underbrace{\cos(n\phi)}_{\text{Spatial}}\ \underbrace{\cos(\omega t)}_{\text{Temporal}} - \underbrace{\sin(n\phi)}_{\text{Spatial}}\ \underbrace{\sin(\omega t)}_{\text{Temporal}}$$

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

- BD Technique is robust against sensor gain/alignment errors

High resolution space-time measurements reveal complicated mode dynamics



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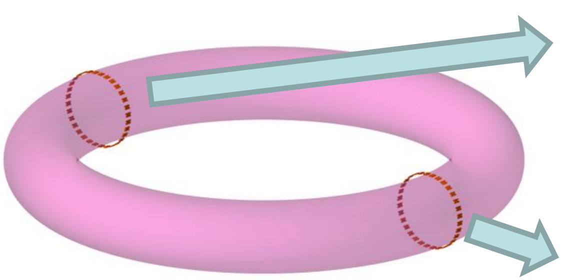

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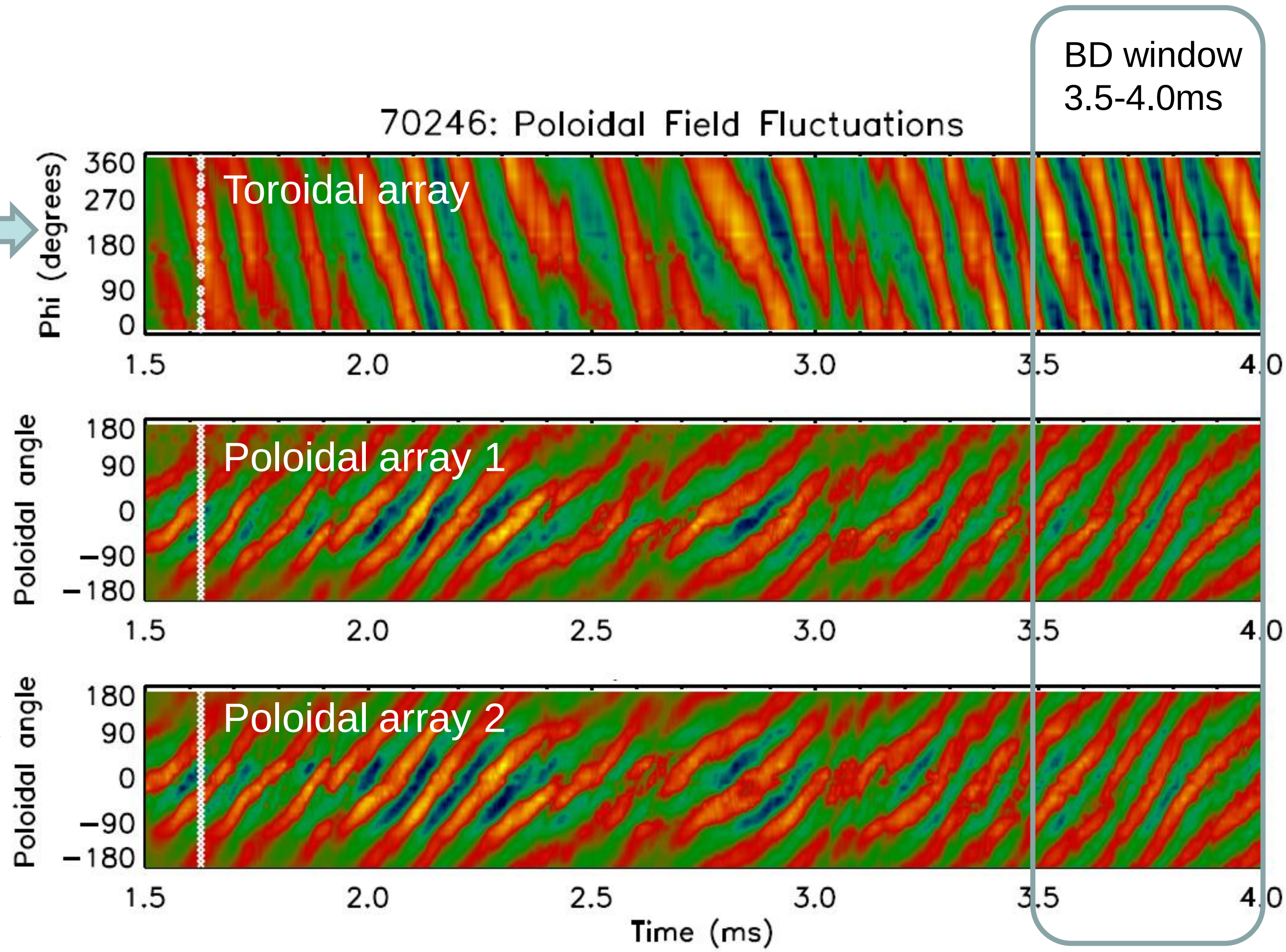
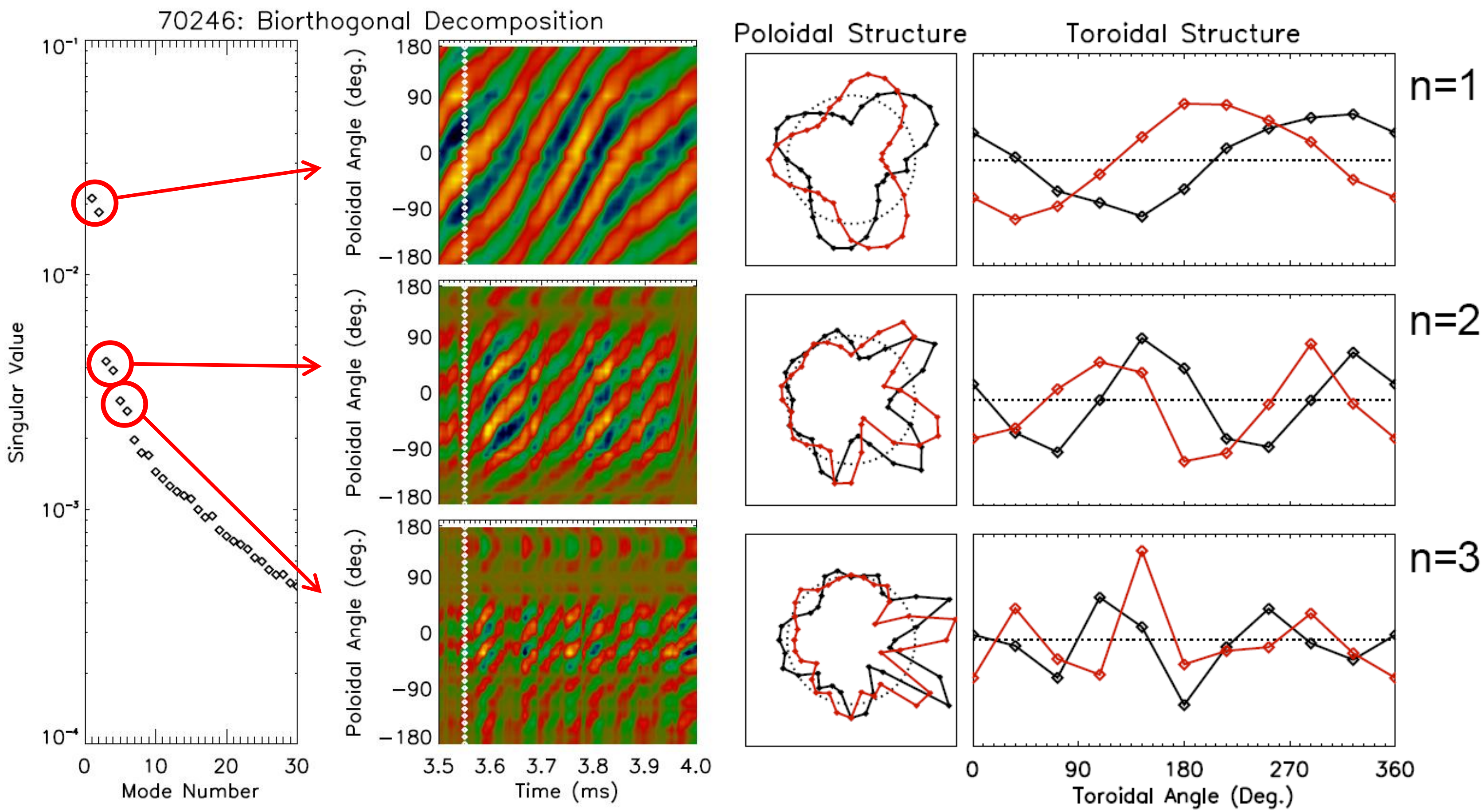
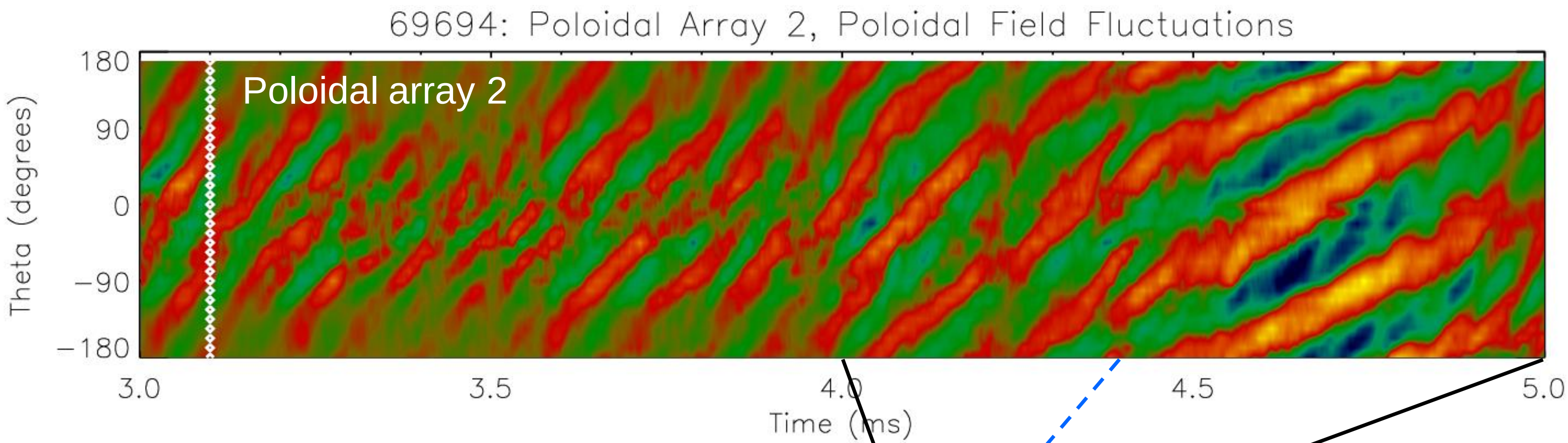


BD analysis shows good separation of rotating modes in HBT-EP discharges

- Unambiguous pairing of 1st (dominant) mode
- 2nd mode pair almost always well defined
- 3rd mode pair is harder to interpret, but is sometimes coherent

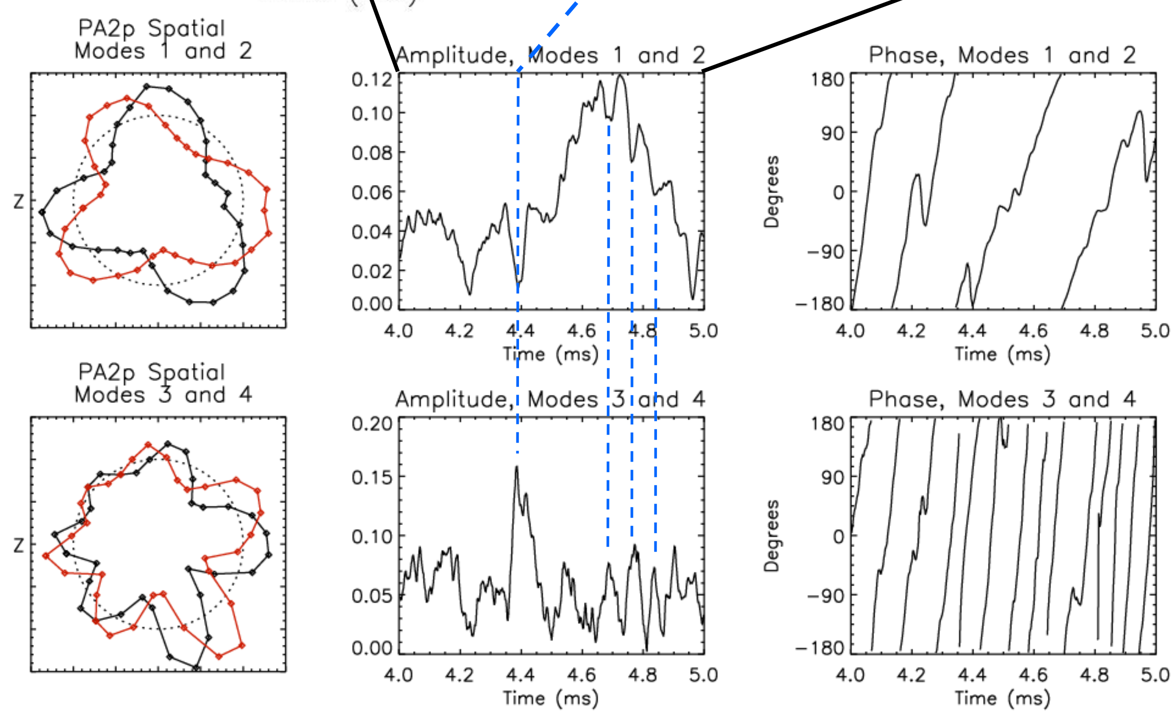


The m/n=6/2 kink can evolve independently of the 3/1 mode, implying the need for multimode control



- 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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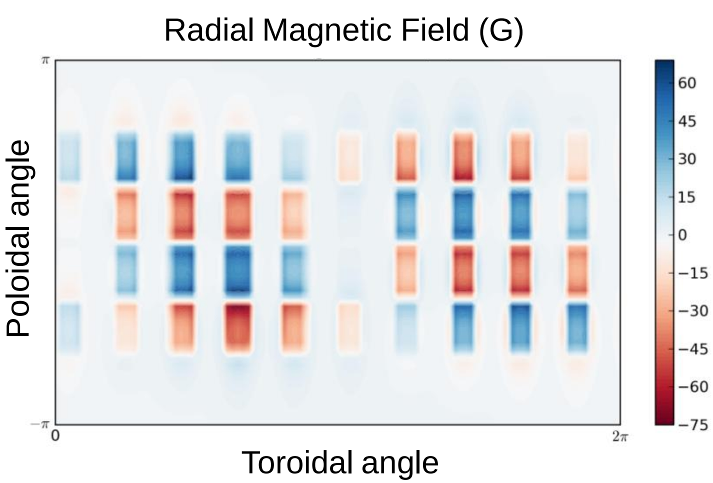
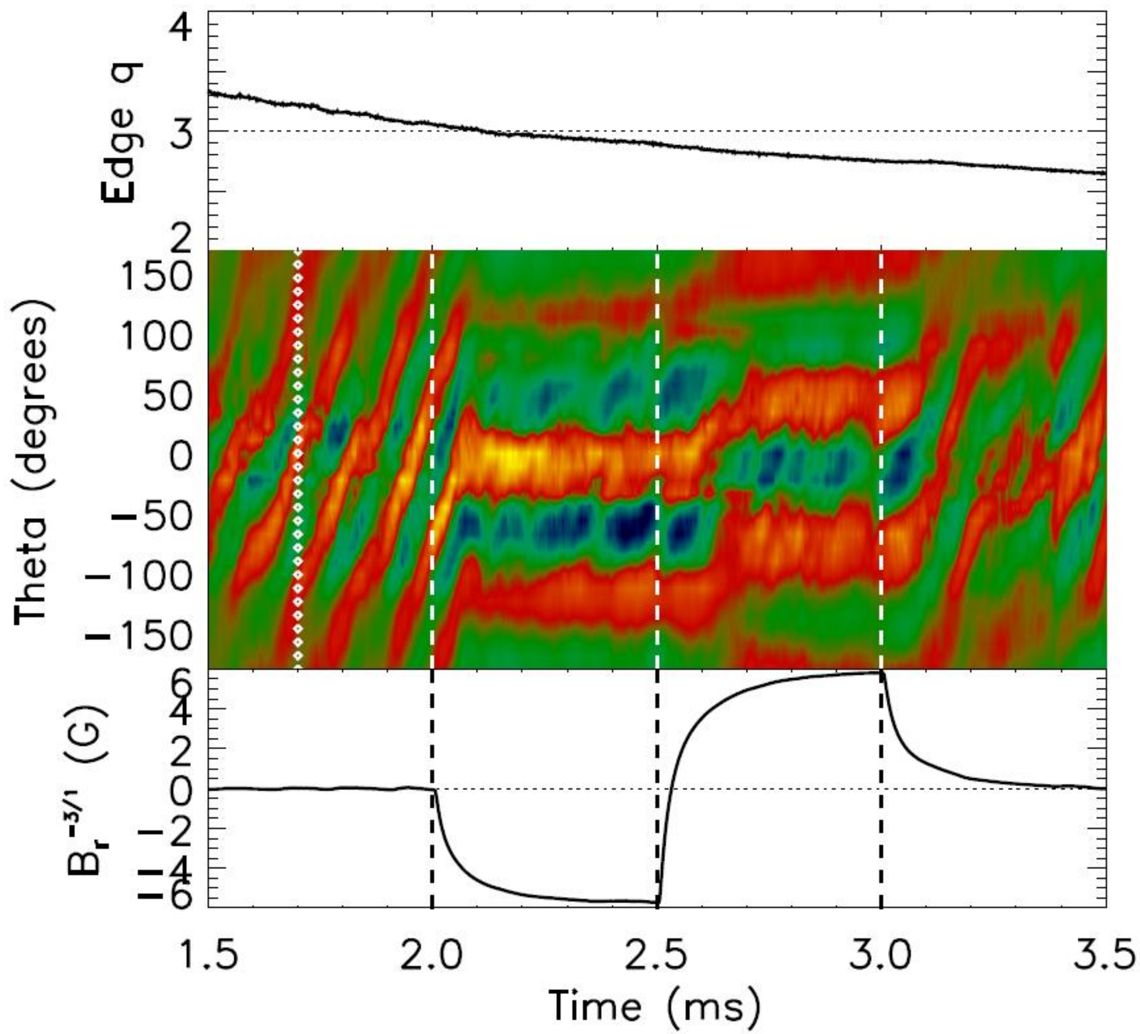
RMPs applied to lock external kink and study mode characteristics

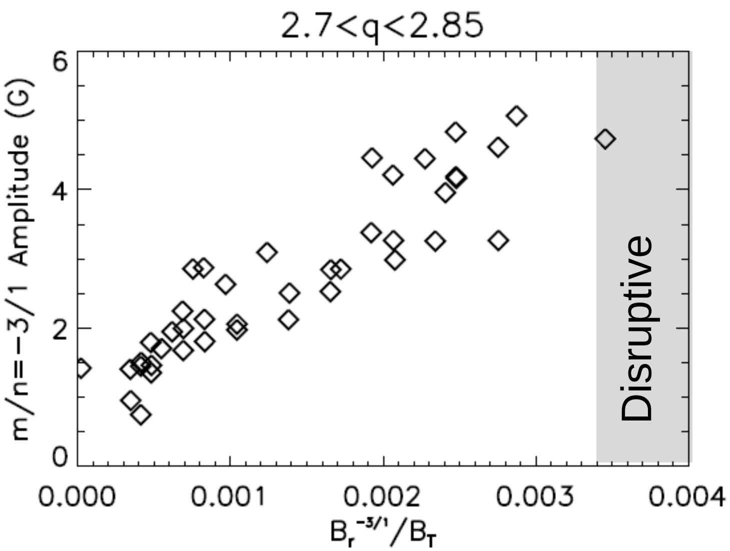
- Static -3/1 radial field is applied near when edge q crosses 3

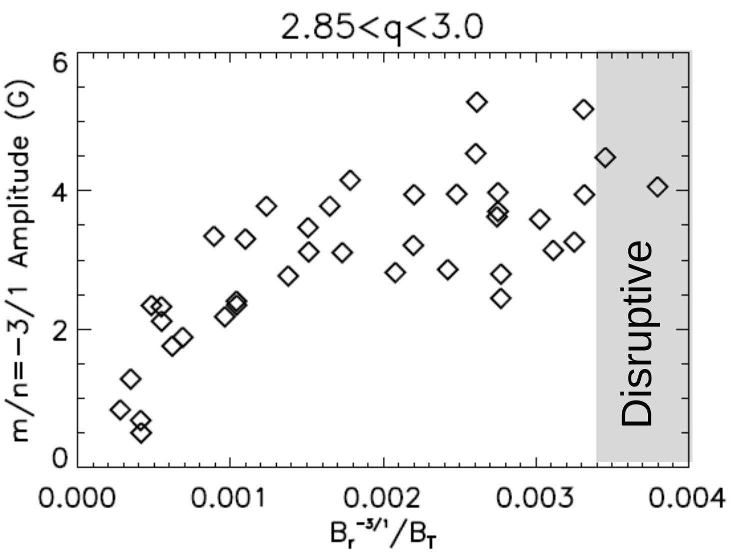
- Toroidal phase of RMP rapidly changed by 180° (“phase-flip”) after 0.5 ms





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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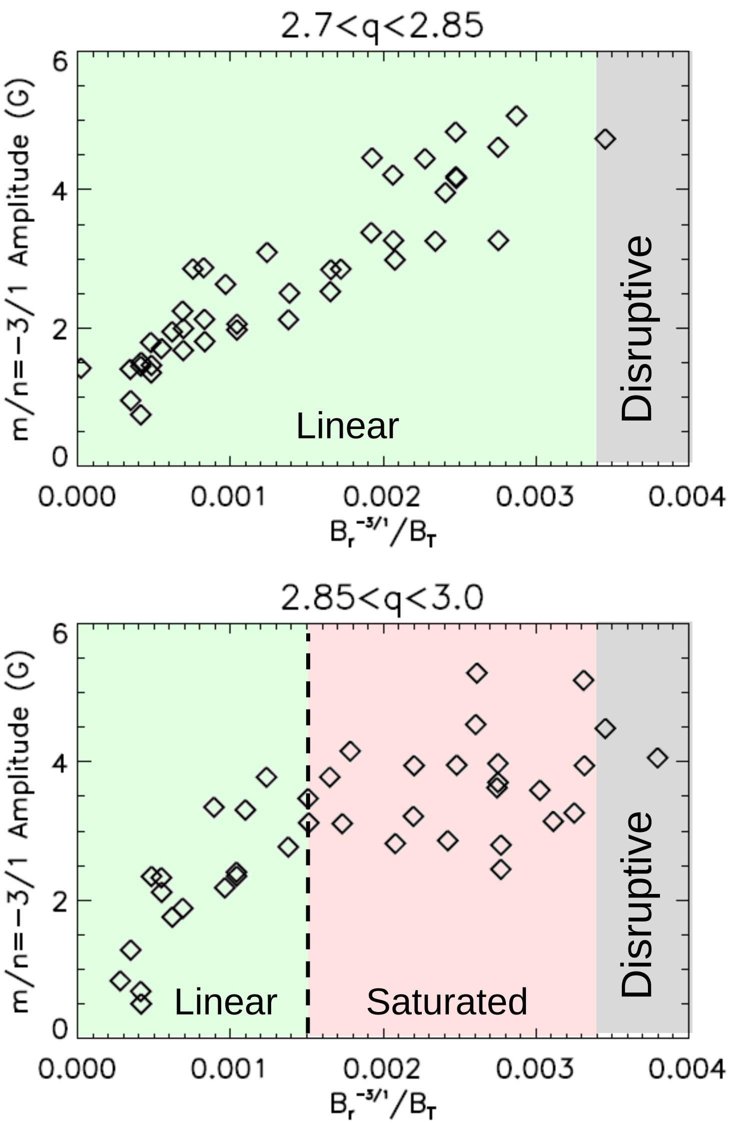

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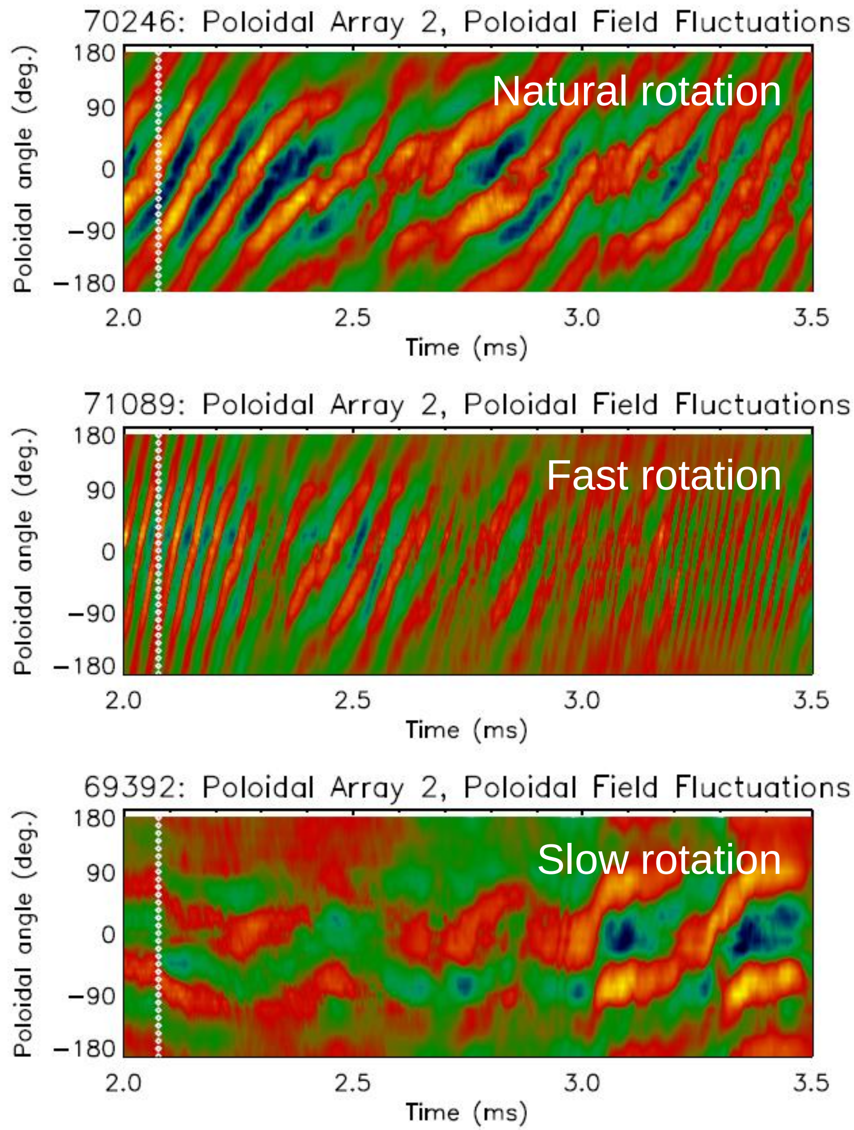
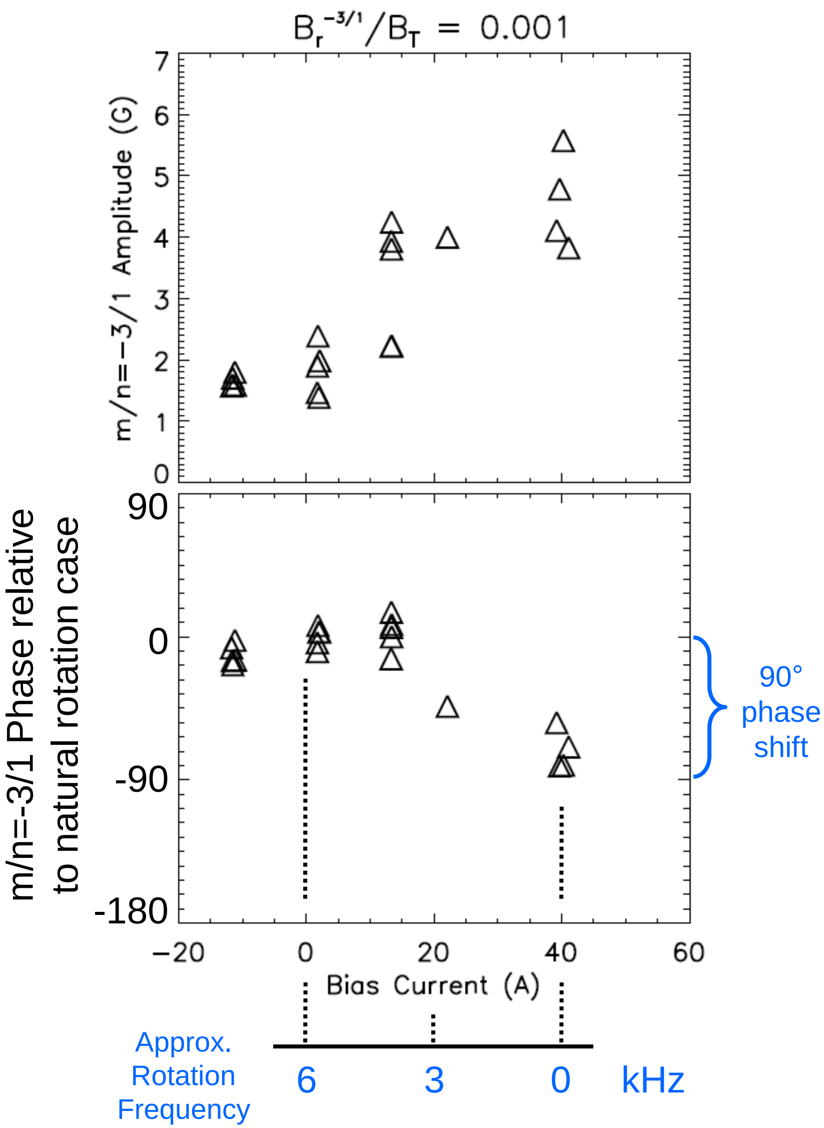
Biased electrode used to change edge plasma rotation and kink mode response

- Natural rotation: $\omega\tau_w \sim 20$
  - Modes rapidly rotate compared to wall time
- Edge biasing induces *E x 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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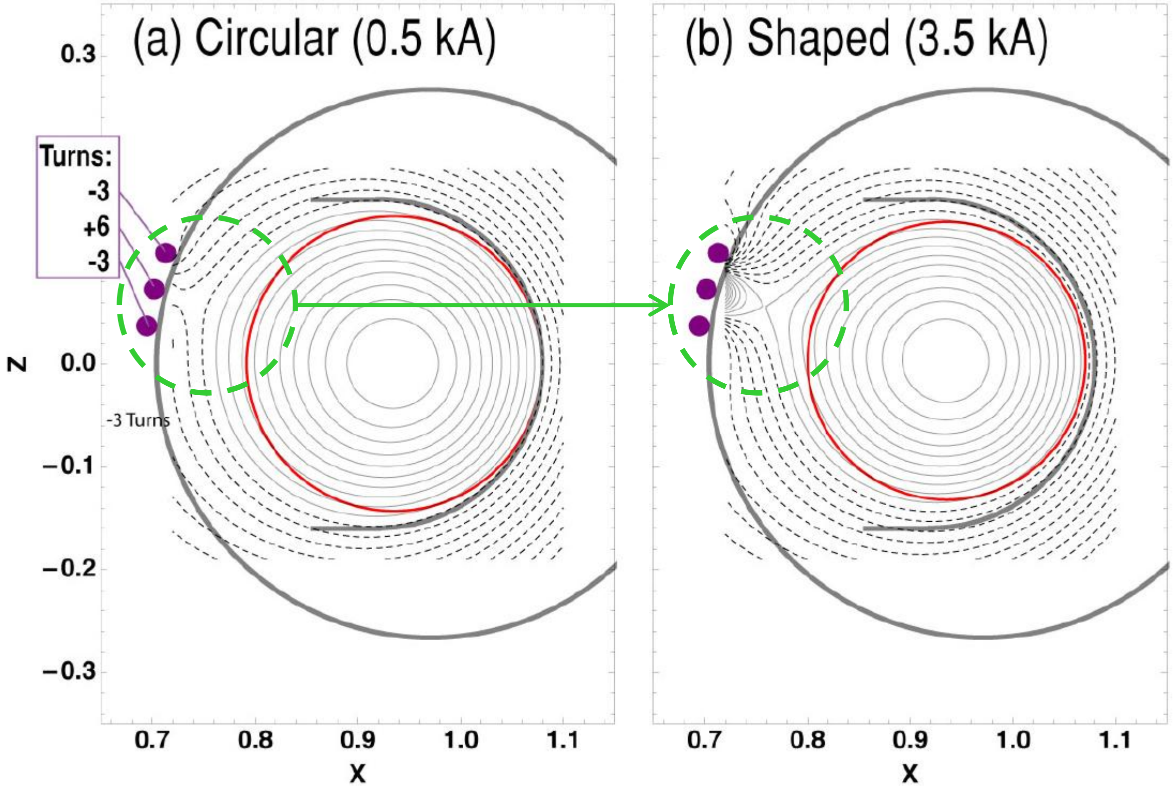
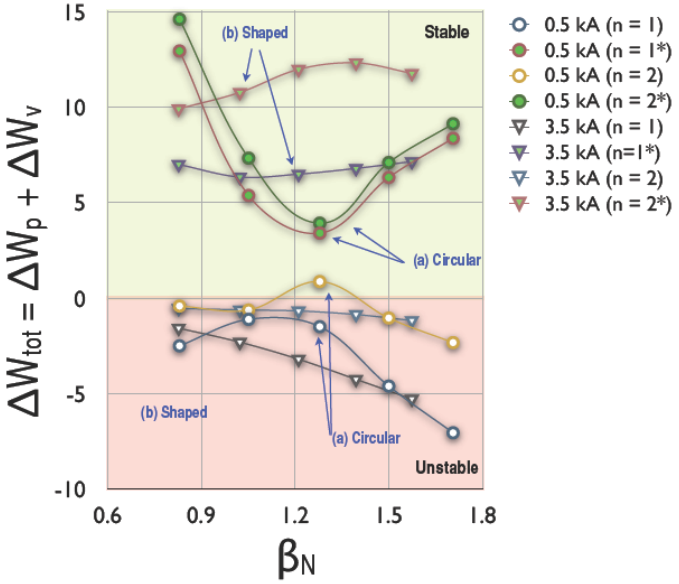
Upcoming experiments will focus on multimode control

- 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





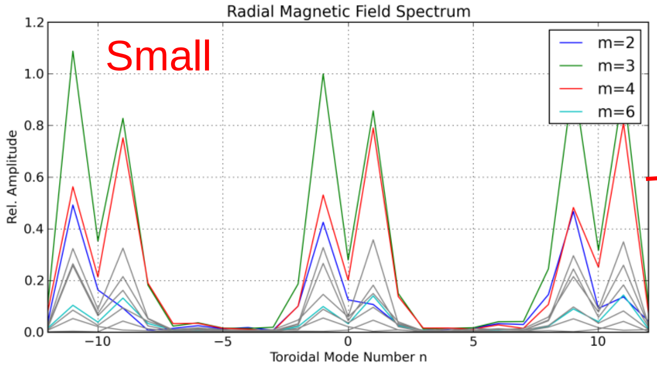
Active feedback will be done using GPU-based control system

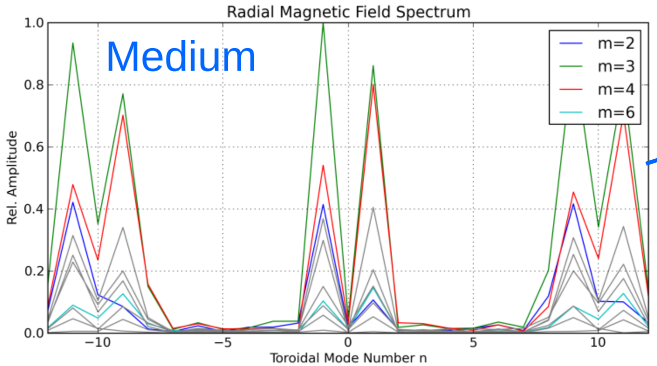
- Hardware details
  - Standard Linux host system
  - NVIDIA Tesla M2050 GPU
  - D-TACQ ACQ196 digitizer (input from sensors)
  - Two D-TACQ AO32 boards (output to control coils)

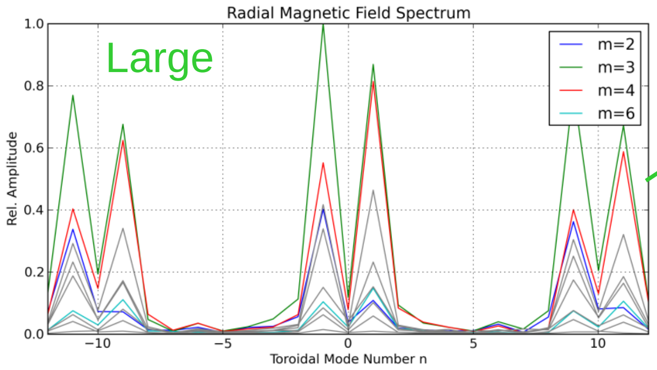
All components commercially available

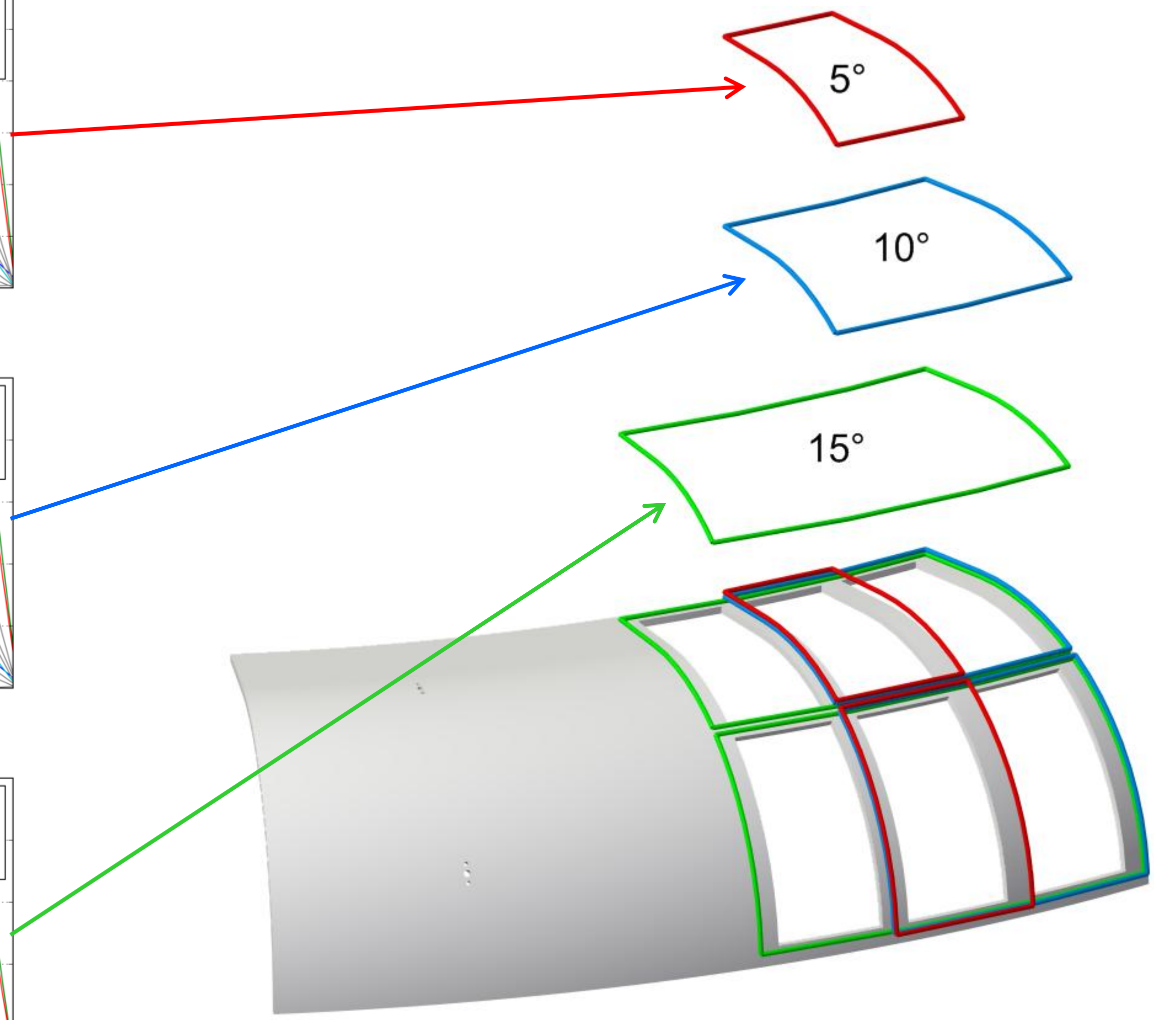
- Capabilities
  - 96 analog inputs, 16-bit resolution
  - Fast parallel processing with GPU
    - 448 computing cores, each running at 1.15 GHz
  - 64 analog outputs
  - Latency ~10μs

Modular control coils allow study of significance of applied field sidebands



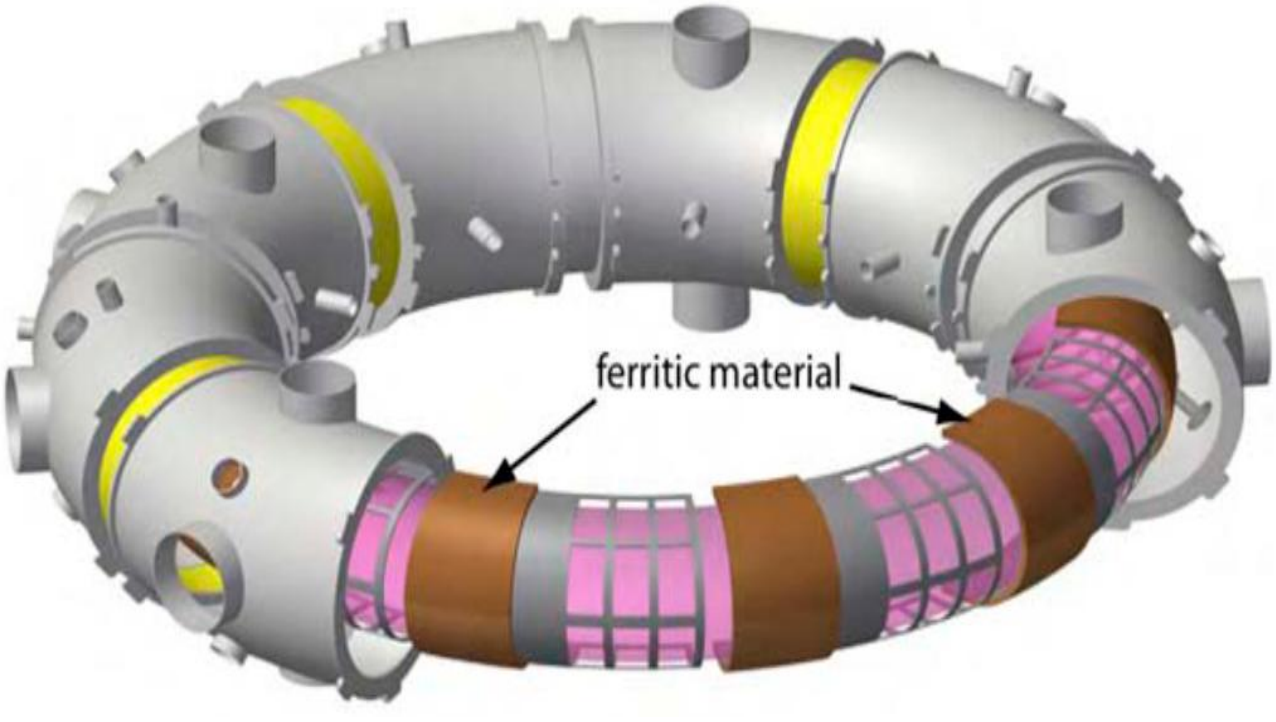






Ferritic wall components will allow study of Ferritic Resistive Wall Mode in a toroidal device

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



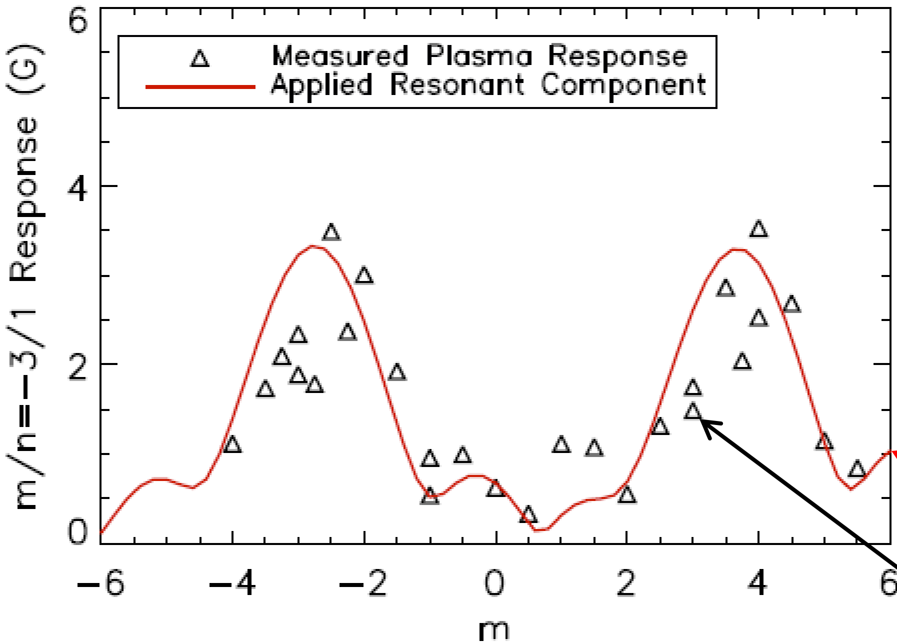
* Kurita *et al.*, Nucl. Fus., **43**, 949 (2003)

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

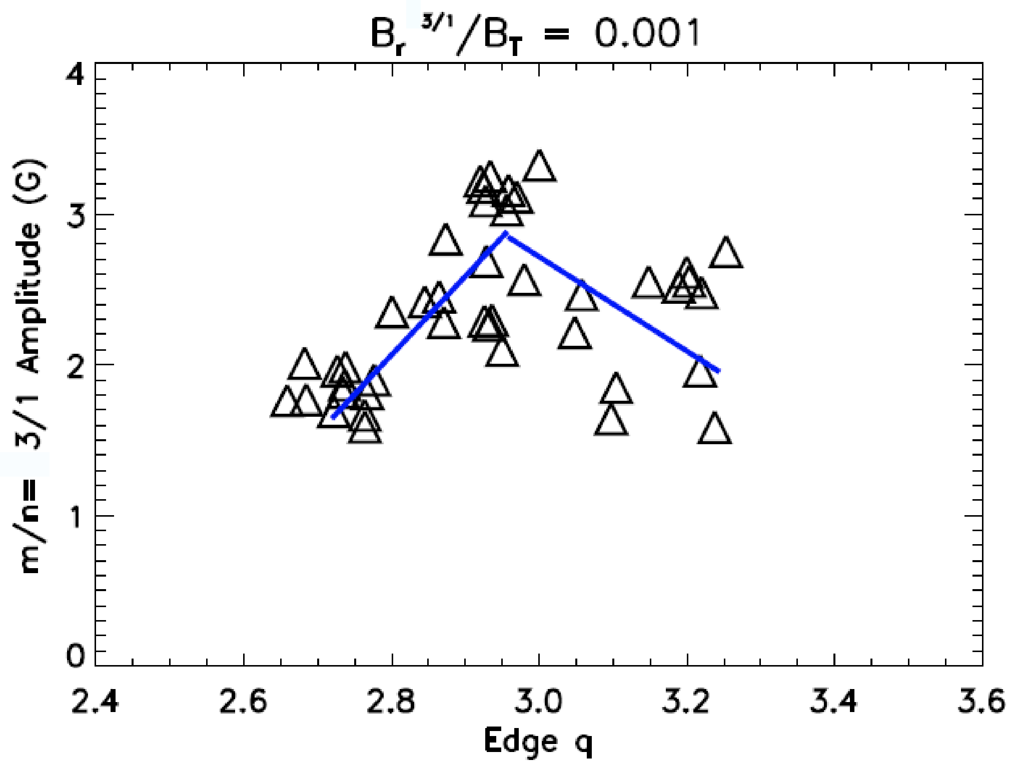
EXTRA SLIDES

Plasma responds to resonant component of applied field as the applied helicity is changed



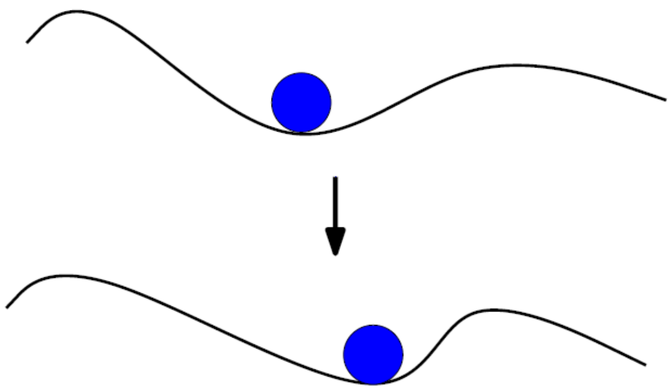
- Control coils used as sensors to determine the natural 3/1 mode structure
- Helicity of external field scanned by changing *m* for *n*=1 fields
  - Applied field projected onto the natural mode structure to determine resonant component
- Kink response matches the resonant component of the applied field

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