Excitation and Detection of Plasma Response to 3D Magnetic Fields

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Outline

- Introduction and Motivation
  - What do we mean by 3D magnetic fields, and why are they important?
- The HBT-EP Device
  - Detection of natural plasma modes
  - Active driving of plasma with external fields, and detection of the plasma response
- Summary

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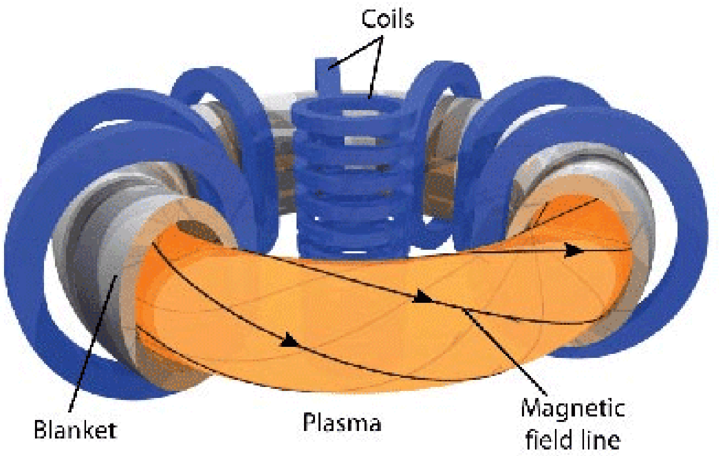
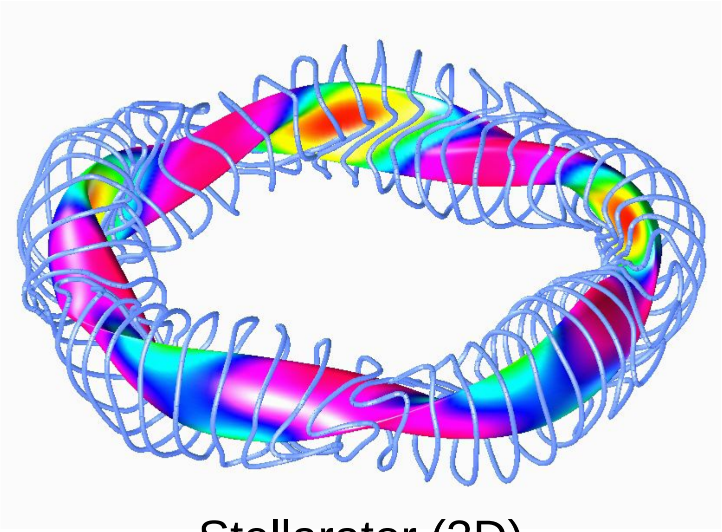
Fusion-relevant plasmas are confined magnetically

- To achieve the conditions necessary for fusion, extremely hot plasmas (~$10^8 K$) must be confined. This requires <u>magnetic confinement</u>
- A tokamak is a toroidal confinement geometry characterized by helical magnetic fields created by a combination of external coils and self-generated fields from plasma current
- The tokamak is an axisymmetric 2D configuration.



Tokamak (2D)

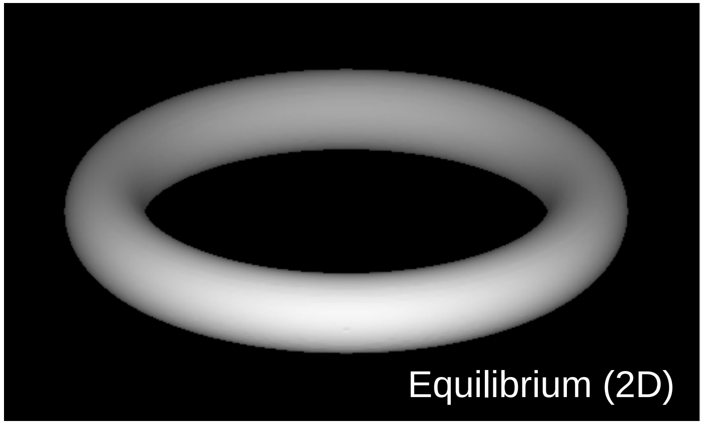


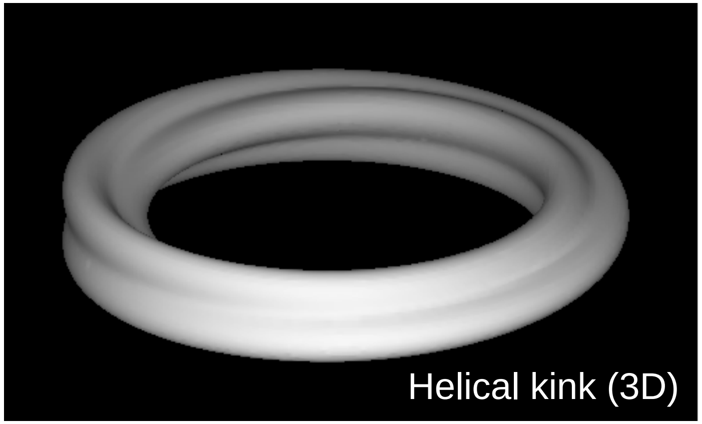
Stellarator (3D)

- Because of its early success, the tokamak is currently the most actively studied confinement concept.

At high beta, tokamak plasmas can spontaneously become 3D

- When the beta (plasma pressure normalized to magnetic pressure) exceeds a critical value, an external kink instability appears, and the plasma becomes 3D





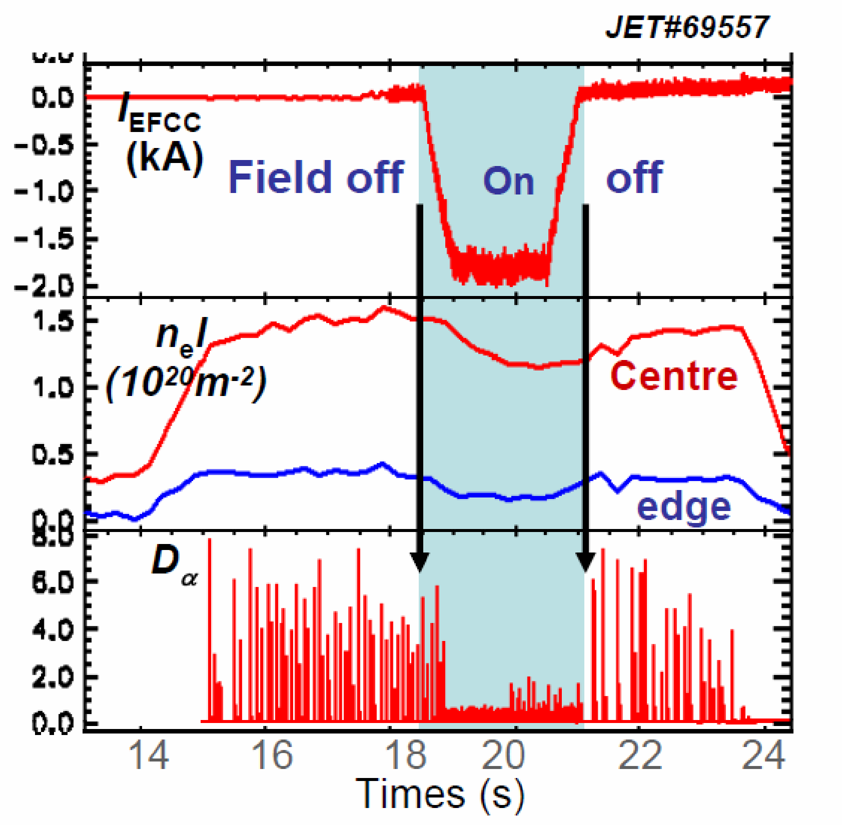
- These perturbations grow exponentially, and often lead to a catastrophic loss of confinement, known as a disruption
- The kink mode can be feedback stabilized by applying an external field of appropriate structure, amplitude, and phase

- The external kink mode places the most stringent beta limit on tokamak plasmas, thus understanding kink mode physics is crucial to the success of a tokamak reactor!

3D fields can also prevent instabilities

- In many machines, an instability called the edge localized mode (ELM) causes periodic bursts of energy release resulting in excessive heat loads to components

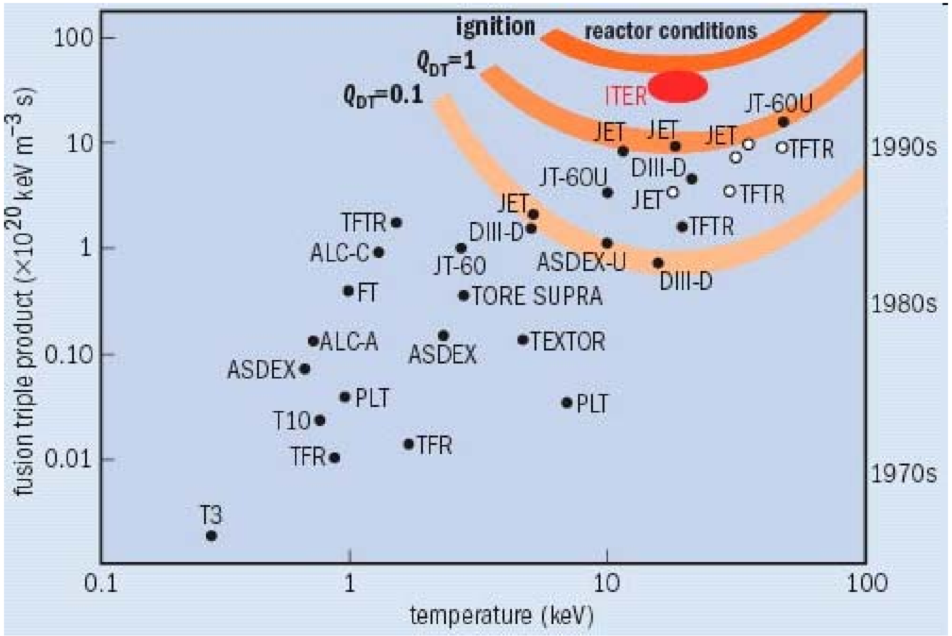
- One possible method of ELM control is the application of 3D fields to keep the plasma away from the stability limits
- The physics of ELM control with magnetic perturbations is not fully understood!



Y.Liang et al., PPCF 2007

Motivation: 3D effects play a crucial role in expanding tokamak operating space

- Understanding of 3D effects allows extension of tokamak operating space and leads to higher performance plasmas



"Fusion research has increased key fusion plasma performance parameters by a factor of 10,000 over 50 years; research is now less than a factor of 10 away from producing the core of a fusion power plant." –ITER Organization

- The physics of plasma interaction with 3D fields is an active area of theoretical and experimental research worldwide!

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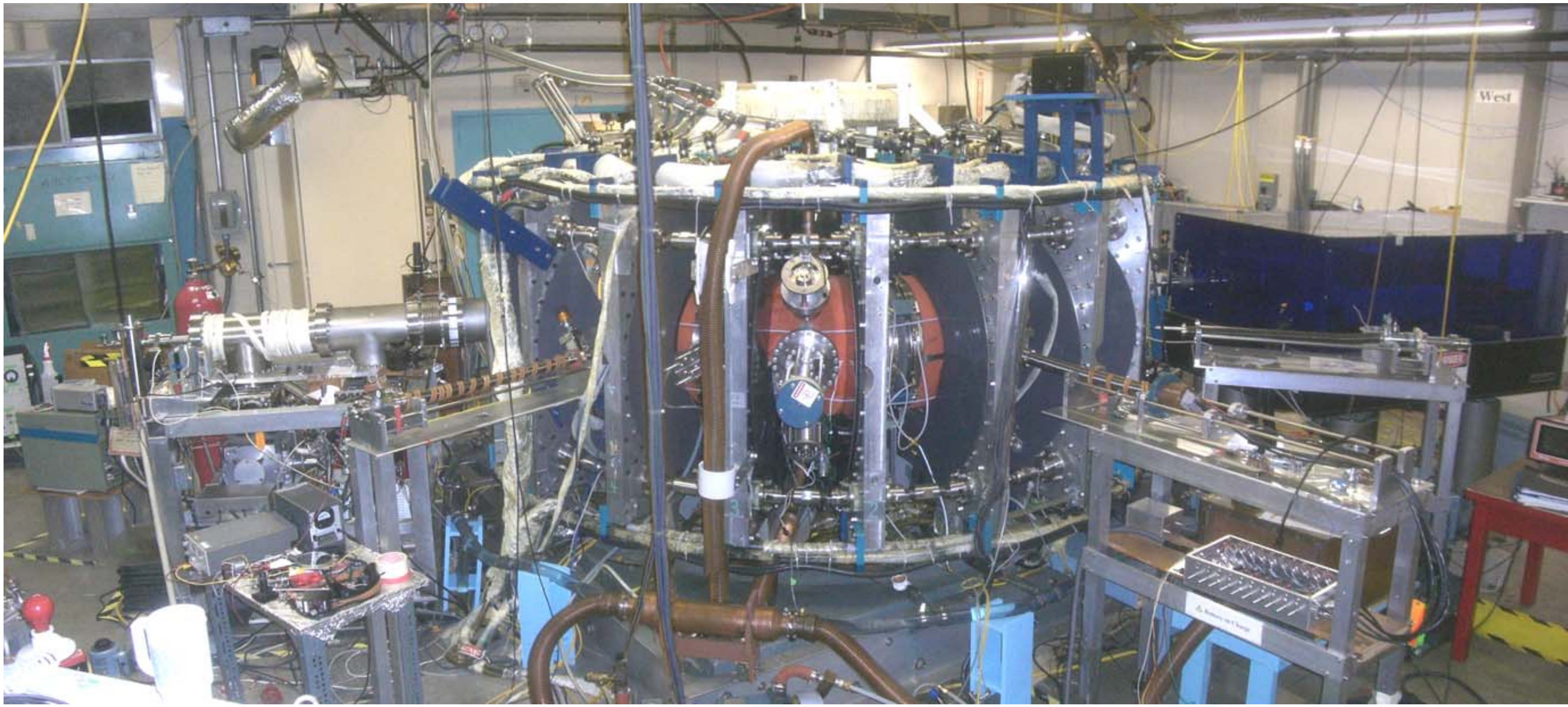
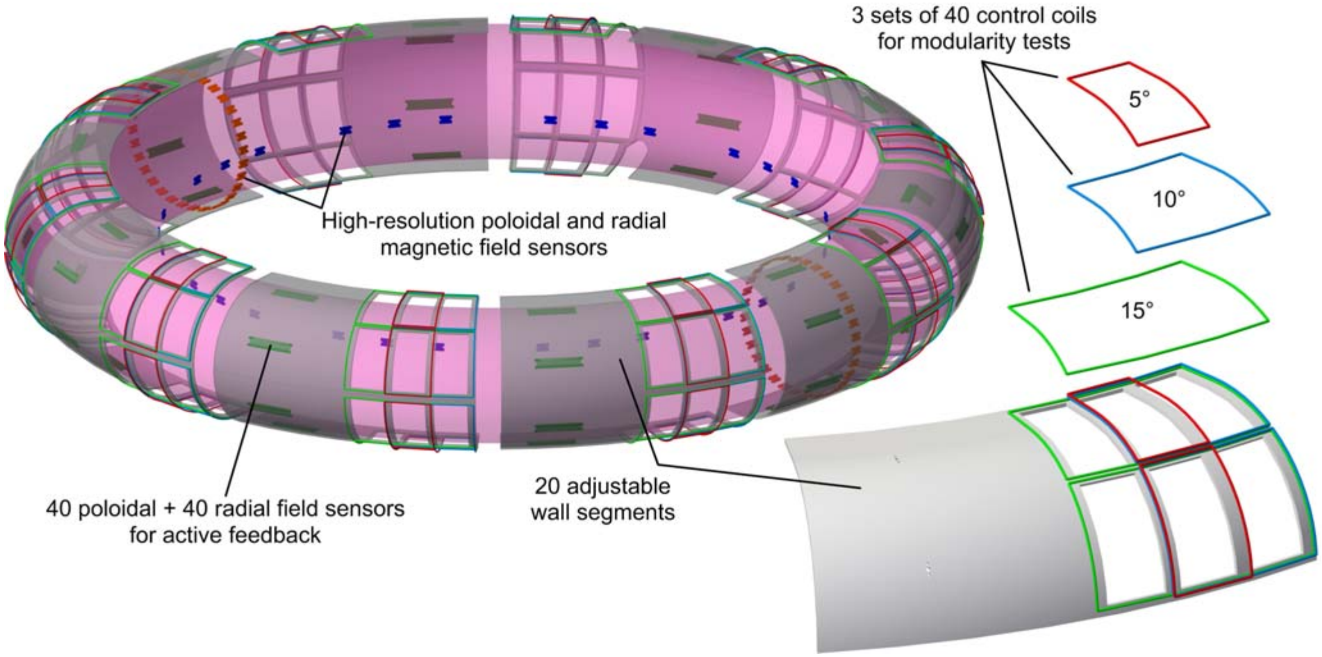
HBT-EP studies the physics and control of beta-limiting instabilities such as the external kink

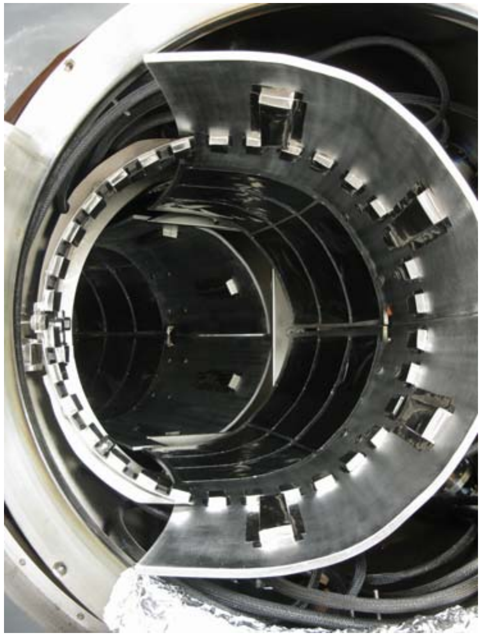


Typical Parameters

Major Radius:	92*cm*	Electron Temperature:	100-150*eV* (~10^6*K*)
Toroidal Field:	0.33*T*	Densities:	$10^{19}m^{-3}$
Plasma Current:	10-15*kA*	Pulse Length:	10*ms*

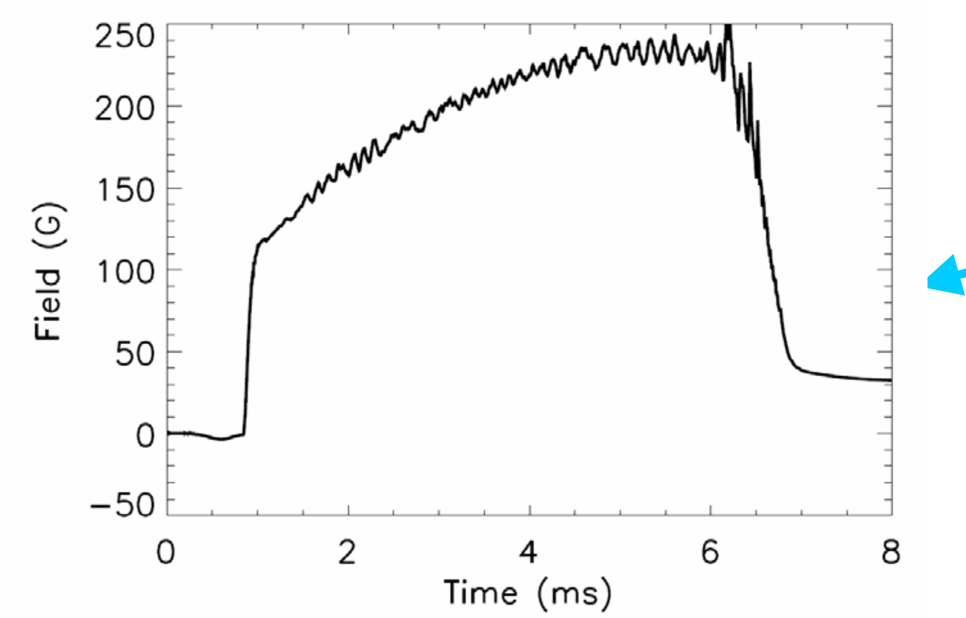
HBT-EP is designed for detailed measurements of 3D effects

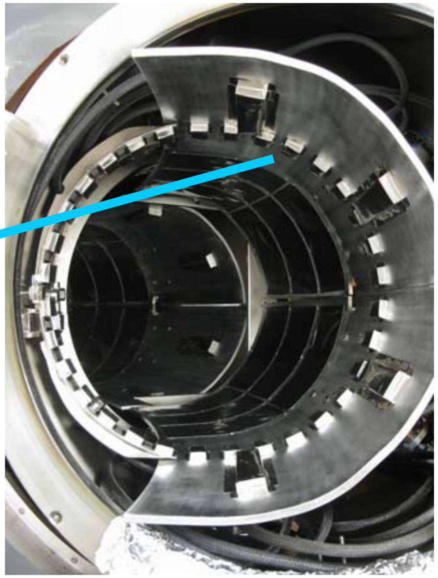




- The modular control coils and large number of magnetic sensors allows the high-resolution, high-accuracy excitation and detection of plasma response to 3D external fields

Magnetic sensor arrays give detailed picture of the 3D fields





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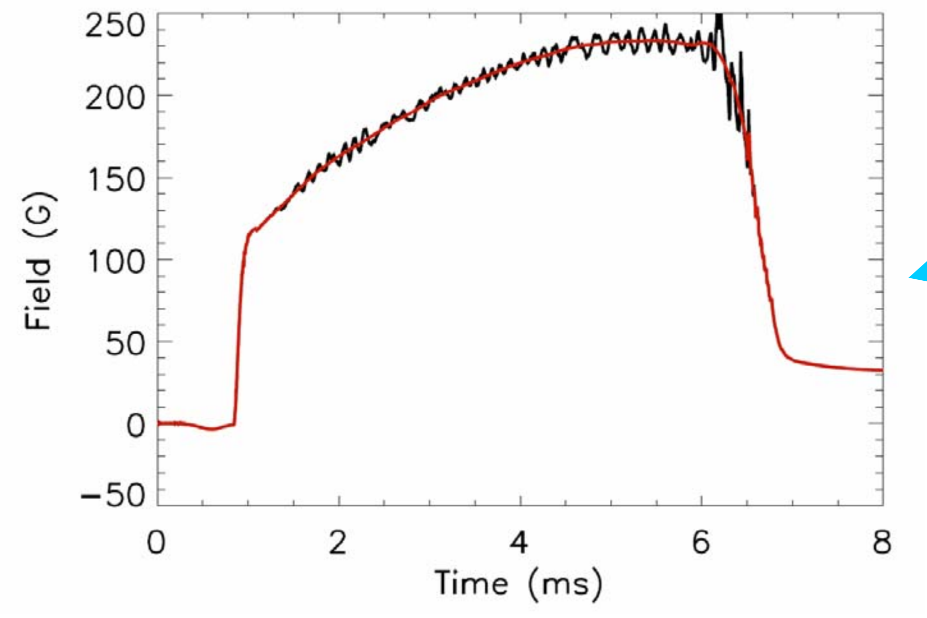

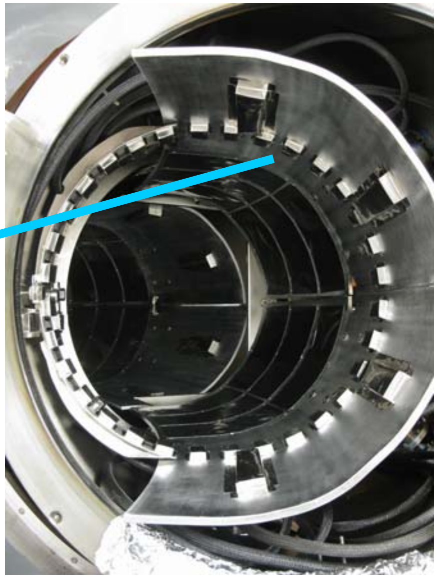

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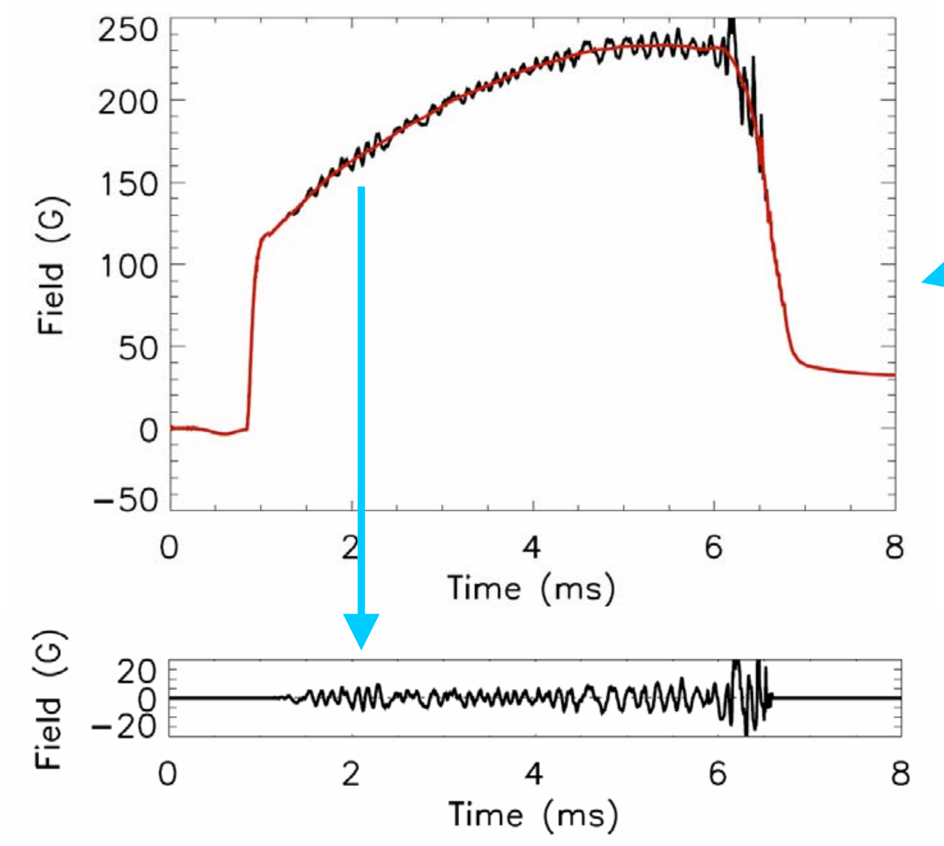

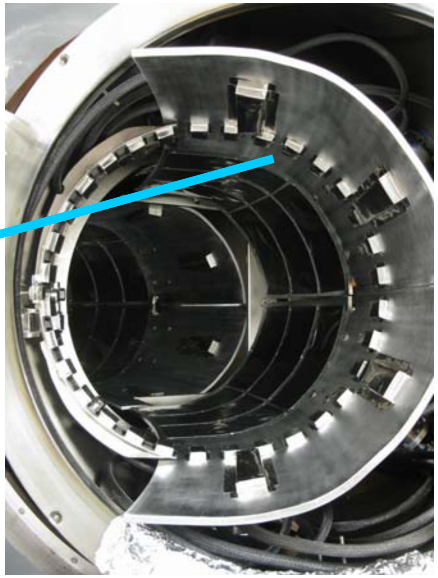

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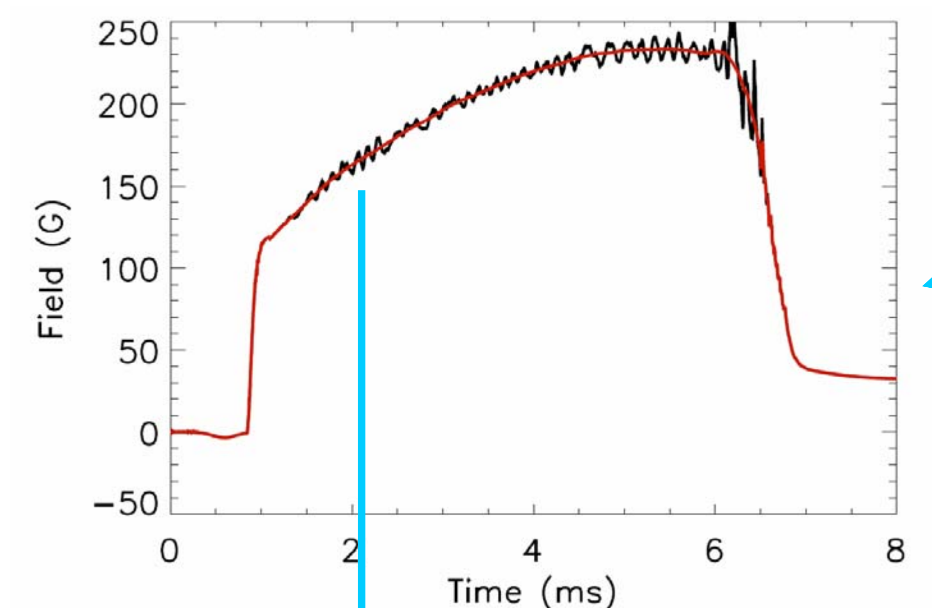
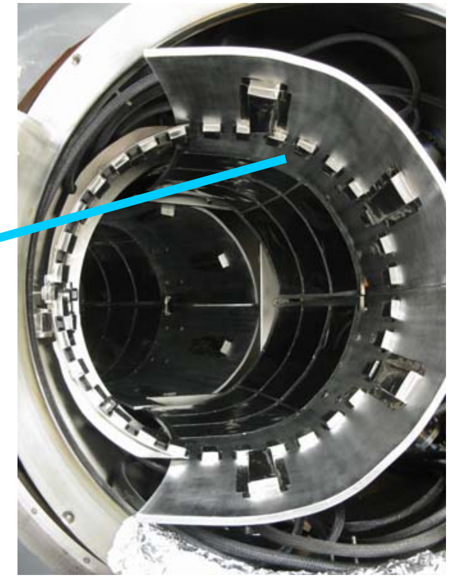
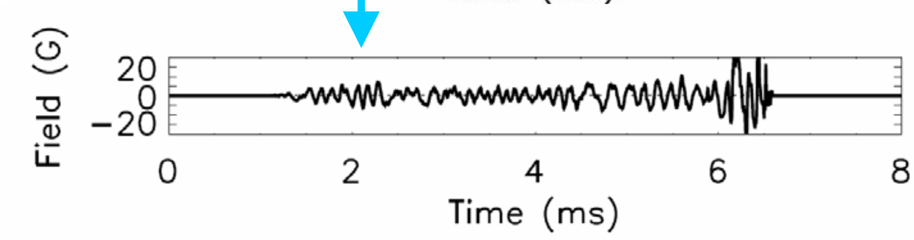
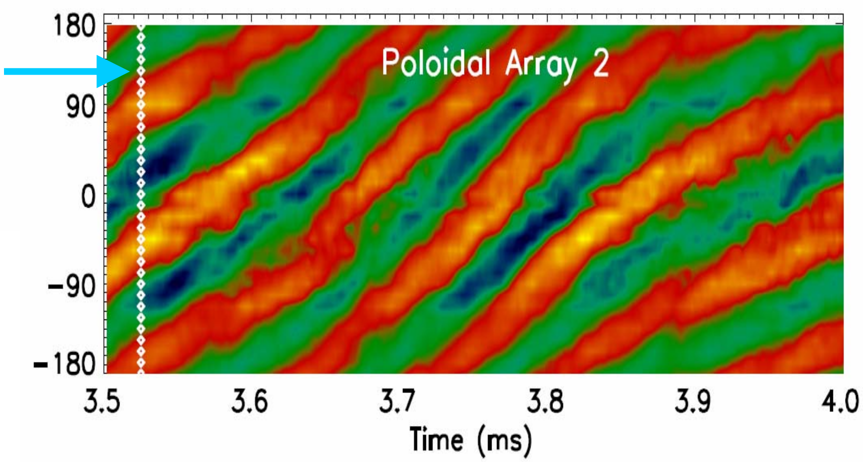
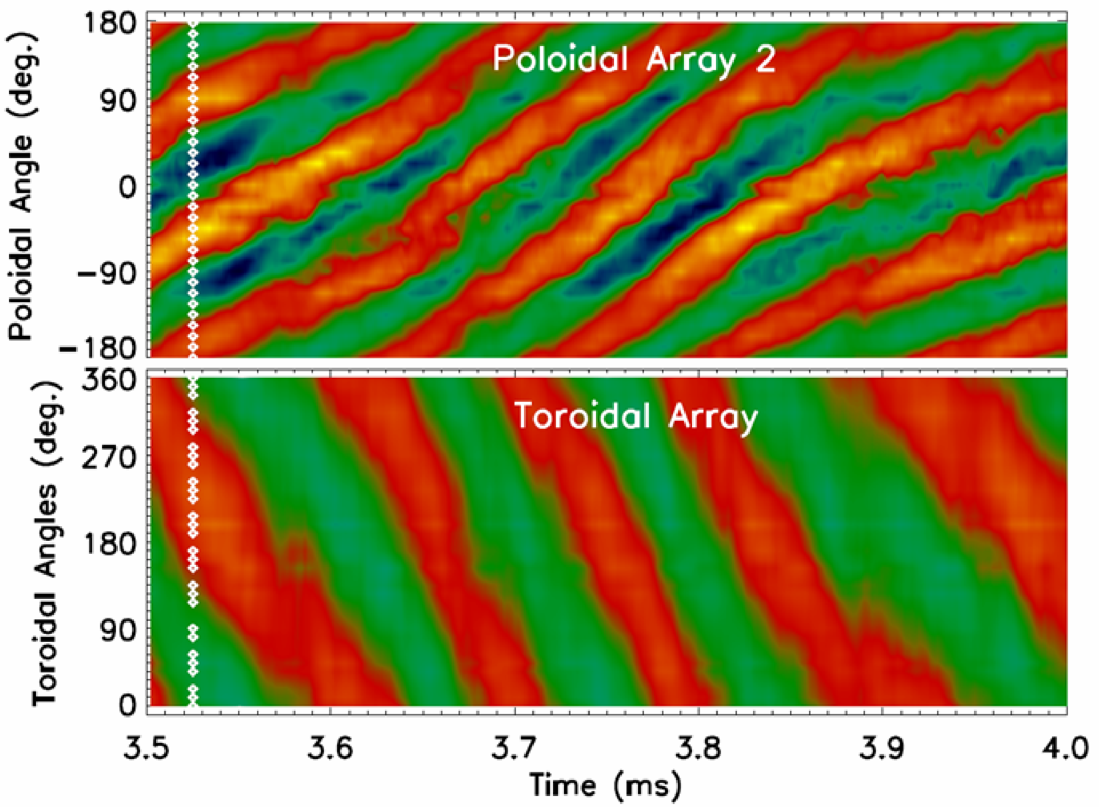


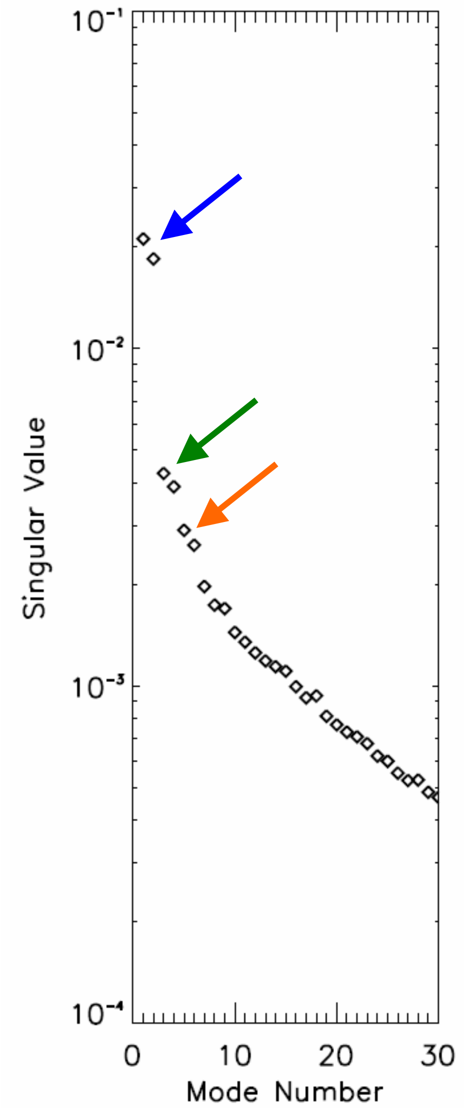






High-resolution measurements of natural fluctuations can be decomposed into independent plasma modes

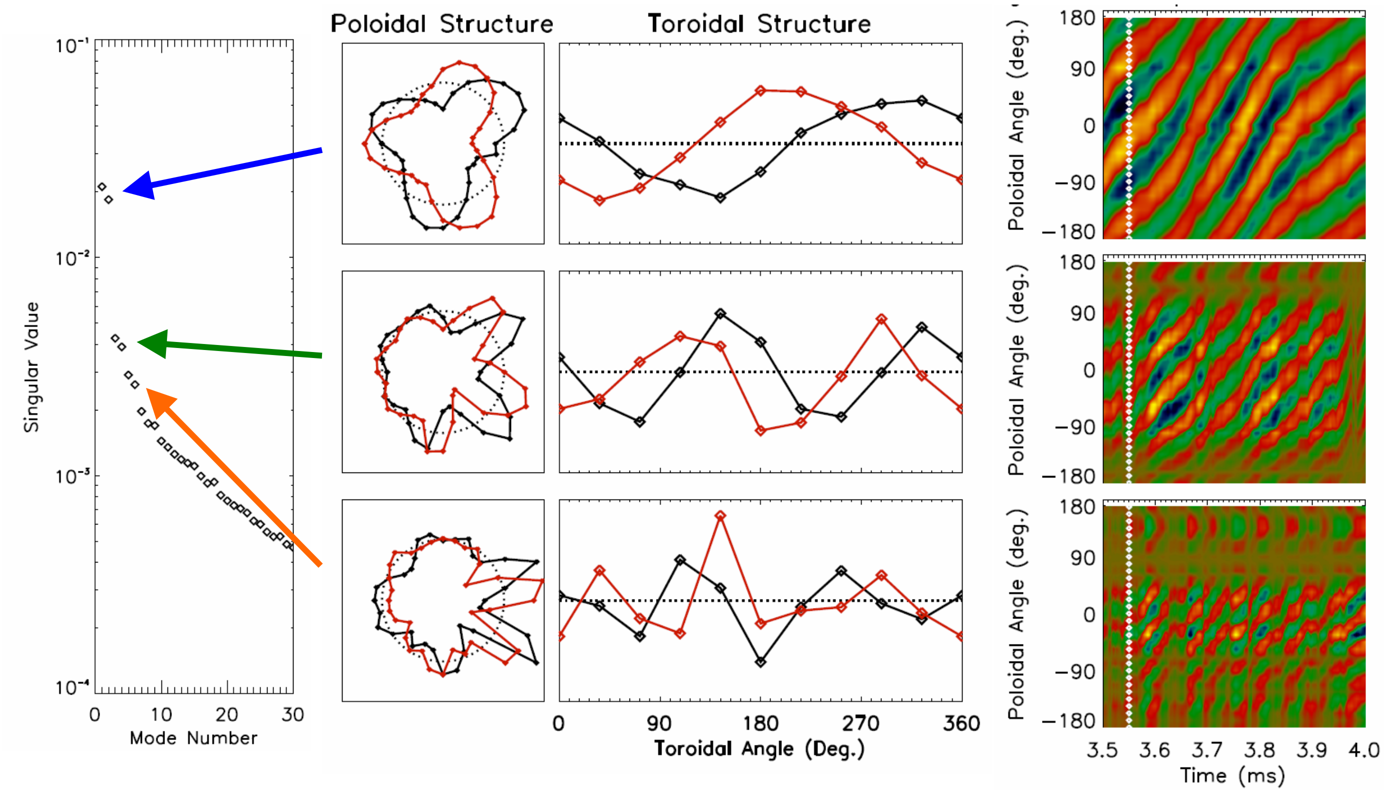




- A Singular Value Decomposition of the data matrix decomposes the signal into a strongly ordered series of orthogonal plasma modes

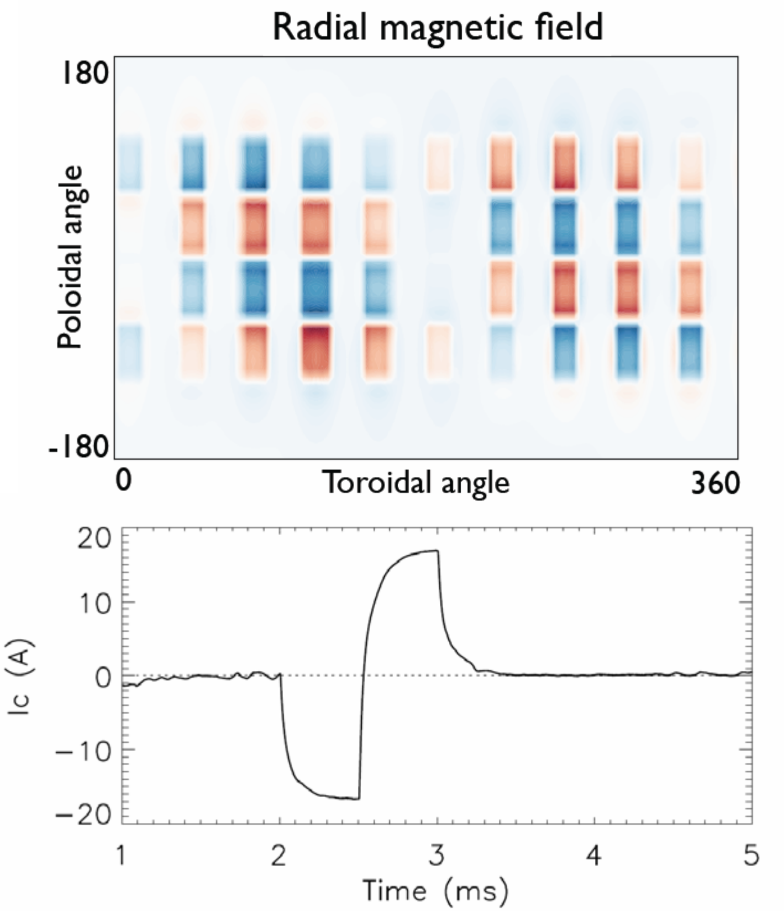
$$A = U\Sigma V^{\dagger} = \sum \sigma_i \mathbf{u}_i \otimes \mathbf{v}_i$$

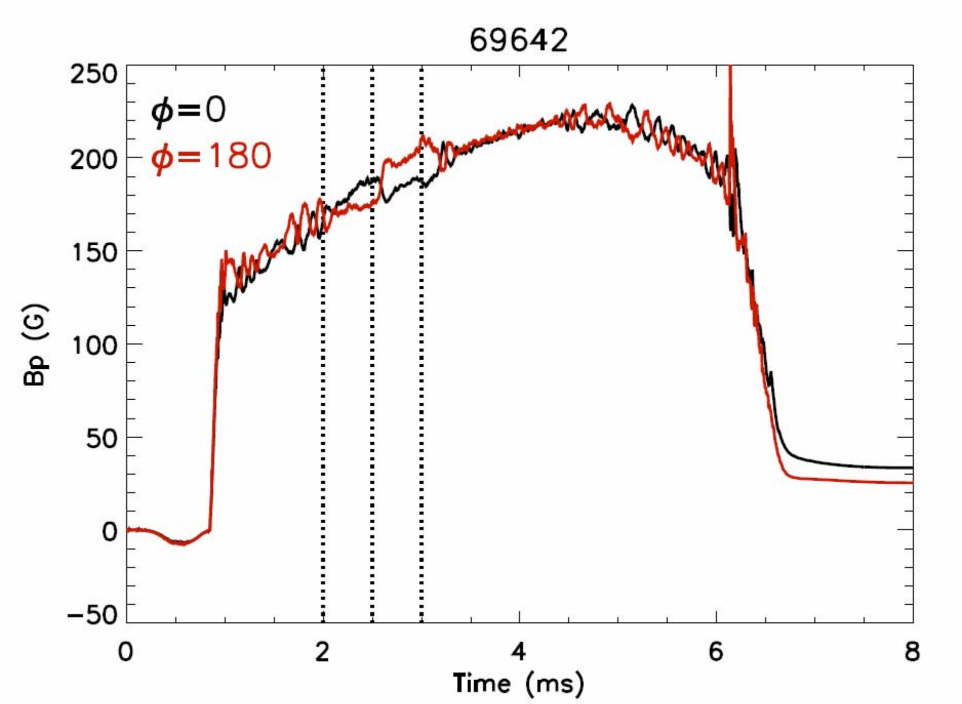
A rich spectrum of natural modes is observed from passive measurements of HBT-EP plasmas



- The dominant mode structure that we measure is a 3/1 helix, followed by a 6/2, and ?/3 helix at much lower amplitude. These are modes that resonate with the helicity of the equilibrium field
- These are independently evolving modes which must be simultaneously controlled in a feedback scheme!

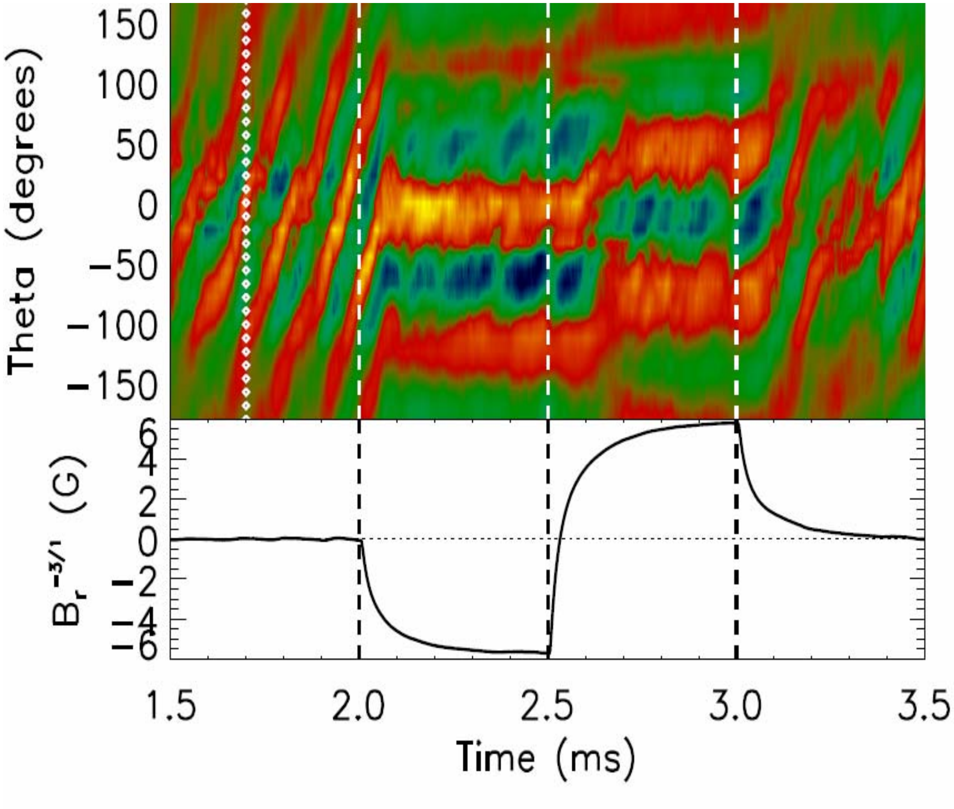
Plasma can also be probed with an external magnetic perturbation applied by control coils





- We use a helical magnetic perturbation that reverses sign midway through the pulse (a "phase-flip")
- Allows easier detection of the plasma response over a slowly evolving equilibrium

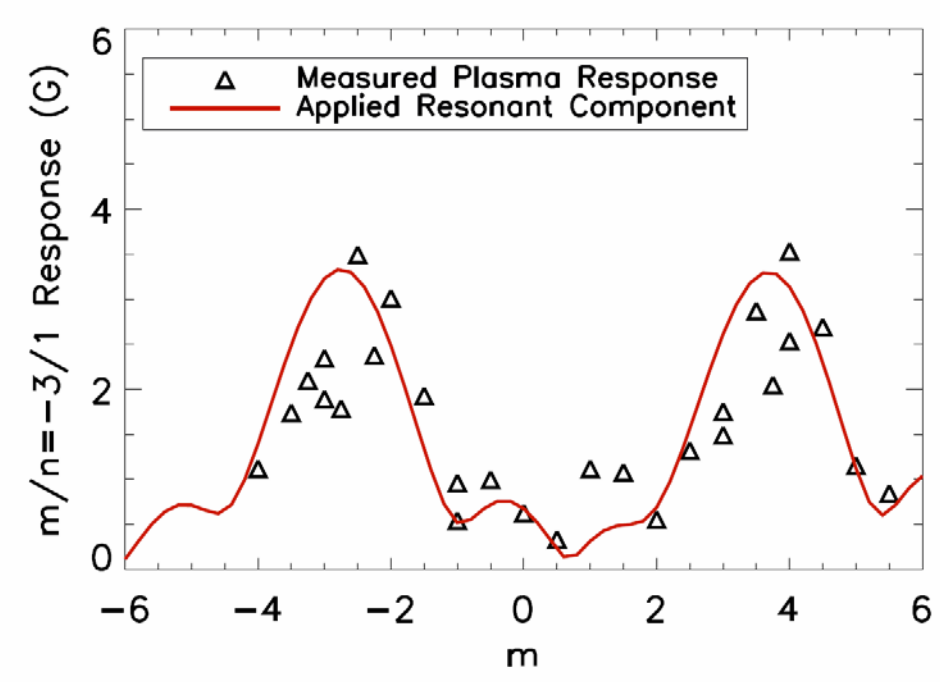
Plasma response to a resonant phase-flip perturbation is easily detected



- When the applied magnetic perturbation is resonant, the plasma strongly amplifies this perturbation. This is called resonant field amplification (RFA)
- The plasma's paramagnetic response is clearly seen in the first half of the perturbation, followed by a change in the sign of the response when the fields are flipped

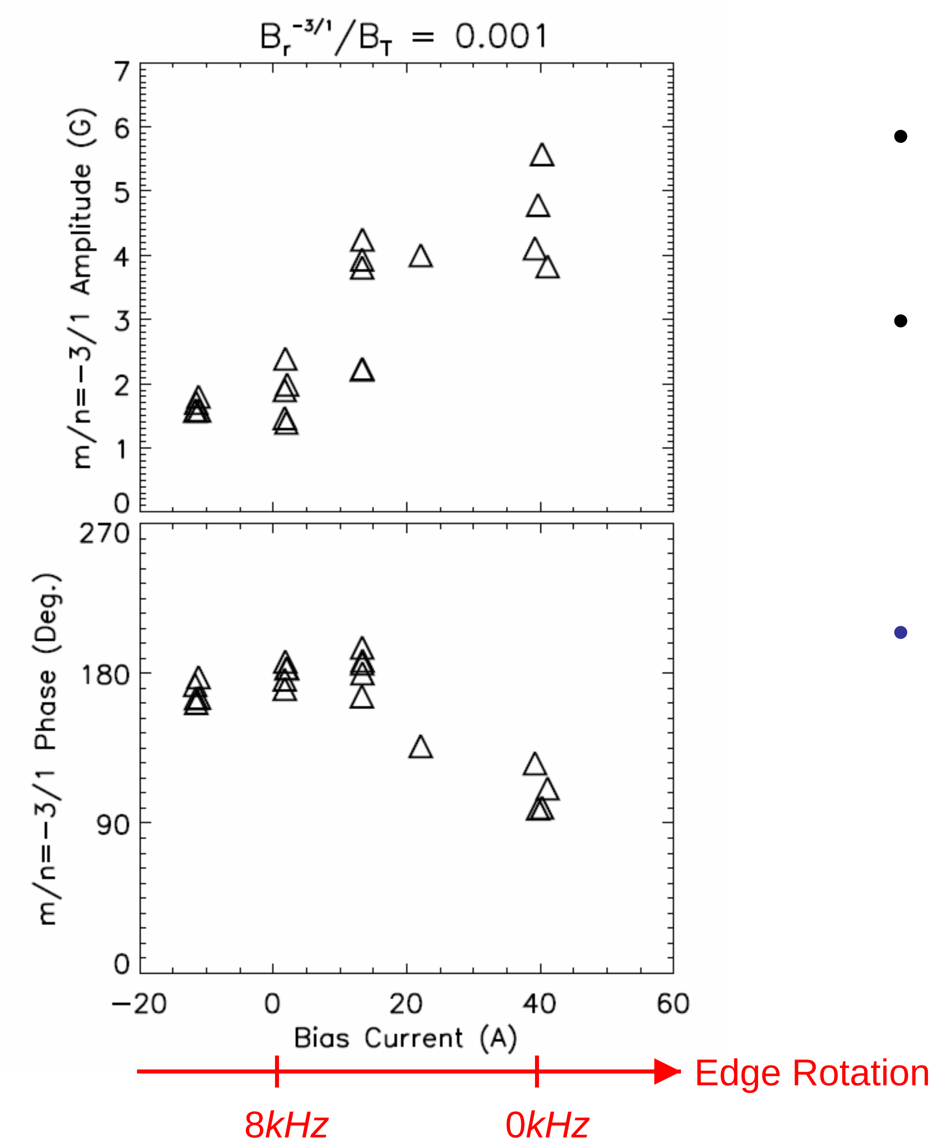
Varying the applied field spectrum demonstrates resonant amplification

- The external field spectrum is continuously varied, with coil current in the i,jth coil equal to: $$Ic_{ij} = A\cos(m\theta_i + \varphi_j)$$



- The plasma response is proportional to the amplitude of the resonant 3/1 component in the applied perturbation, even though the total field is constant.
- When the applied field is non-resonant, the plasma simply ignores the field!

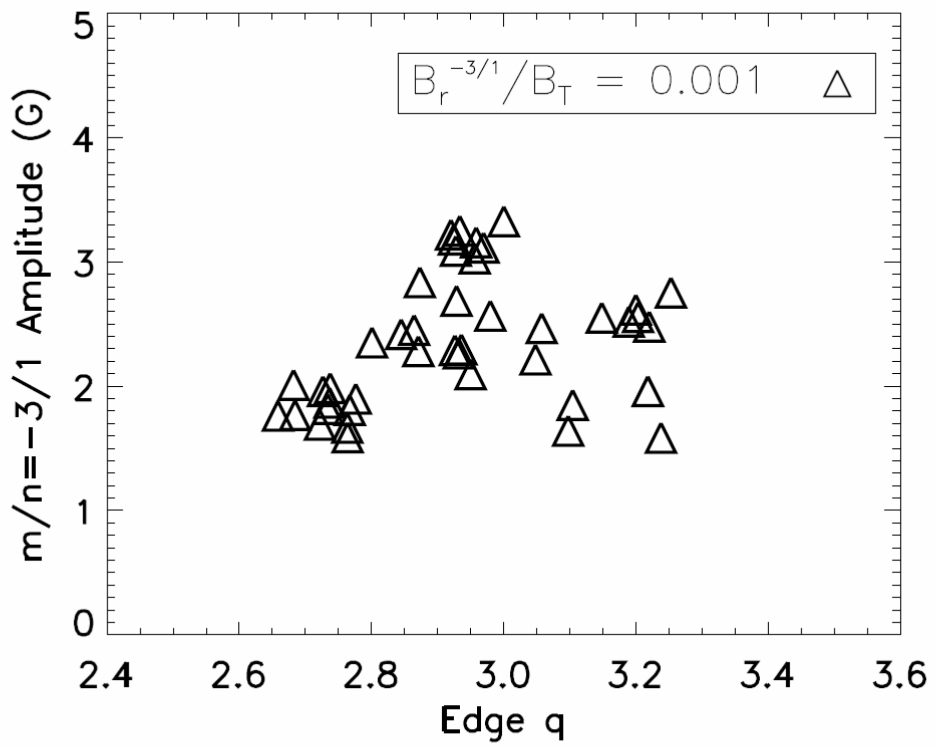
Plasma response increases dramatically as edge rotation is varied with edge biasing



- A biased probe is inserted in the plasma to induce *ExB* flow and change the plasma rotation
- The natural edge plasma rotation of 4-8*kHz* can be slowed to near zero rotation with about 40*A* of bias current

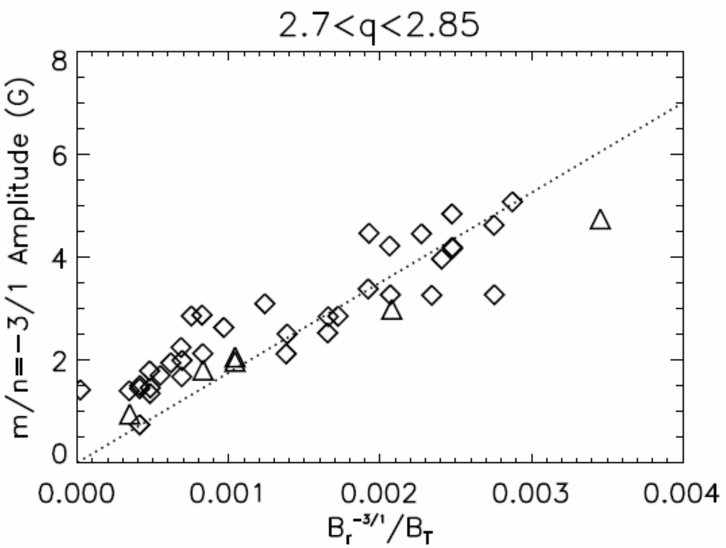
- At low rotation, plasma response is increased by a factor of three!

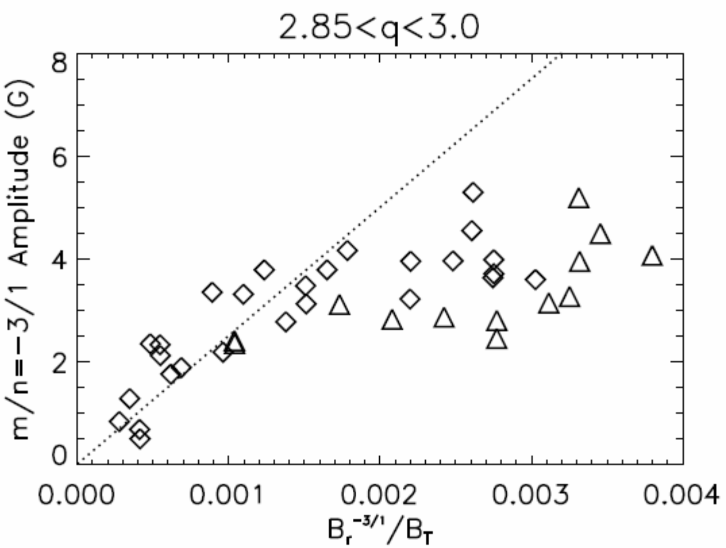
Plasma helicity scan demonstrates resonance



- Plasma response measured as a function of the equilibrium field helicity (edge q) shows a resonance near q=3
- In HBT-EP, edge q is essentially a measure of stability

Three regimes of plasma response observed as phase-flip amplitude is varied

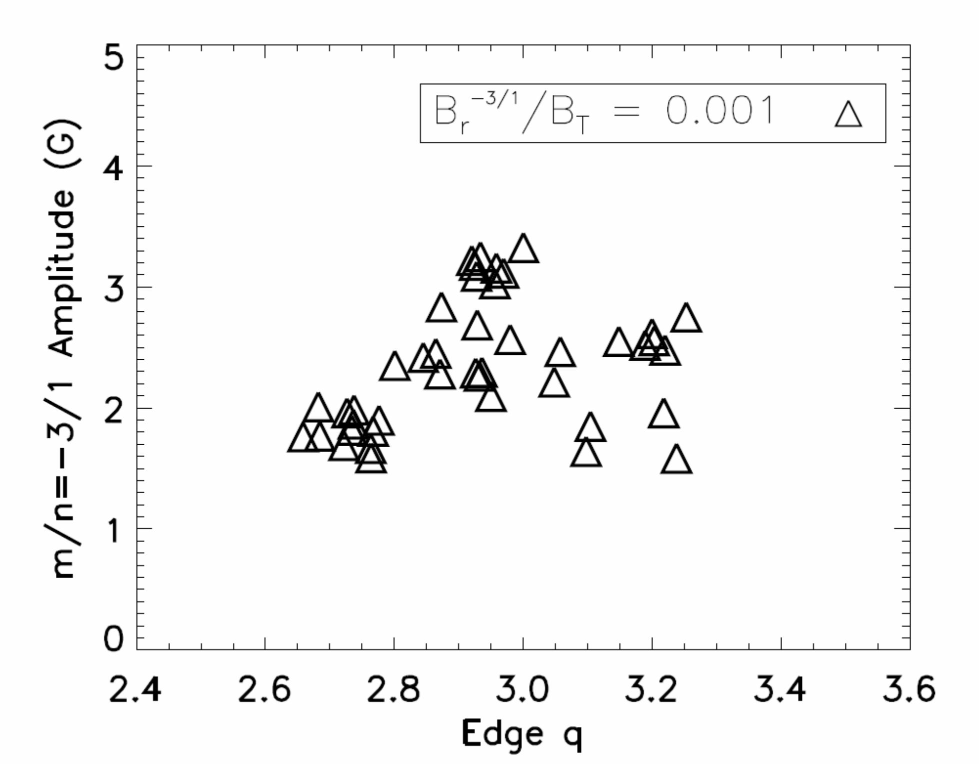




- Three regimes of plasma response are observed:
  - I. Linear regime
  - II. Saturated regime
  - III. Disruptive regime (>30A)

- Plasmas always disrupt for large perturbations
- The saturated regime is only observed near resonance (*q*~3)
- The slope of the linear response is higher near *q*~3 (see *q* scan results)

Detailed q scan at two amplitudes confirm saturated response near resonance



- Away from resonance (q<2.85), doubling the perturbation doubles the response, i.e. linear response
- Near resonance (q~3), the response remains the same, i.e. saturation

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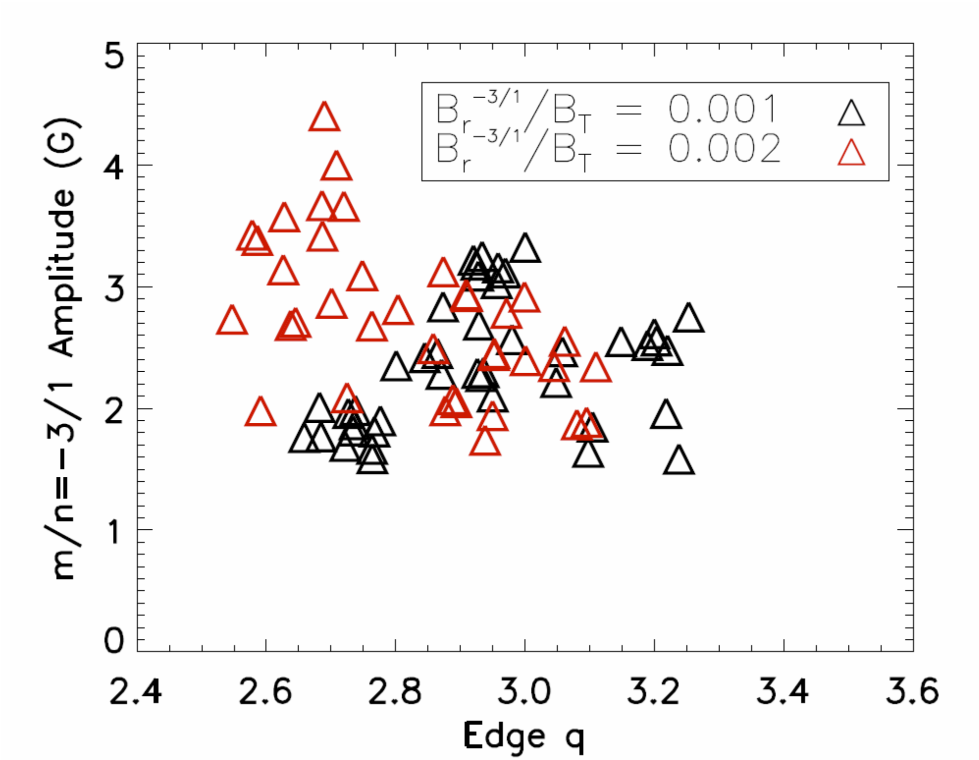

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Summary

- 3D effects are important in expanding tokamak performance to the levels required for a fusion reactor
- HBT-EP is designed to clearly detect these effects, with unprecedented detail
- Passive measurements of natural rotating modes shows a rich spectrum of multiple independent modes
  - This implies the need for “multimode control” in future fusion reactors
- Probing the plasma with magnetic perturbations results in a large resonant field amplification (RFA)
  - RFA measured as a function of various plasma parameters provides information about the plasma and its stability properties