Investigation of MHD Mode Structure in Shaped HBT-EP Plasmas

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Outline

- Introduction
  - Motivation for Shaped Plasma Research on HBT-EP
  - HBT-EP Baseline and New Capabilities
  - Analysis Procedures
- New Challenges with Shaped Plasmas
  - Plasma/Sensor coupling
  - Positional Instability
- Proposed Research Plan
  - Observe Structure and Dynamics of RWM in Shaped Plasmas
    - Natural Structure/Growth Rates
    - RMP Response
- Initial Results
- Summary

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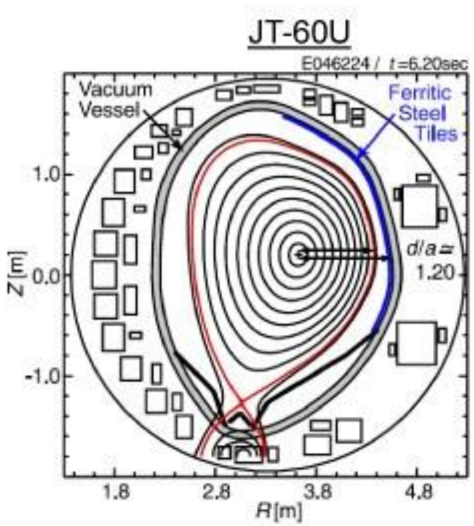
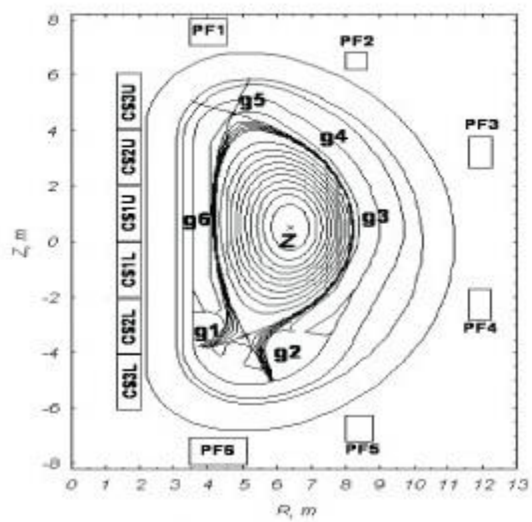
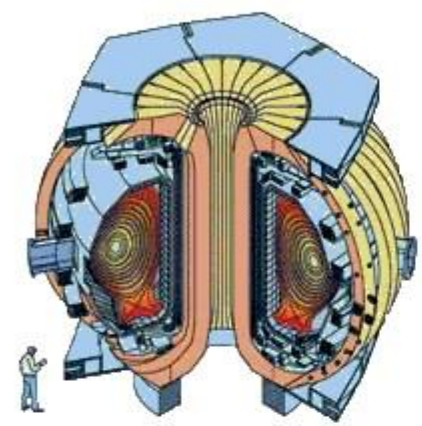
Introduction - Motivation

- A tokamak fusion plasma will need to be shaped
  - Fusion plasma heat load too high for material limiter
    - Exhaust redirected to diverter protects instruments, VV wall
  - Shaping allows access to higher β regimes, easier access to H-Mode

- All present and planned advanced tokamaks are non-circular







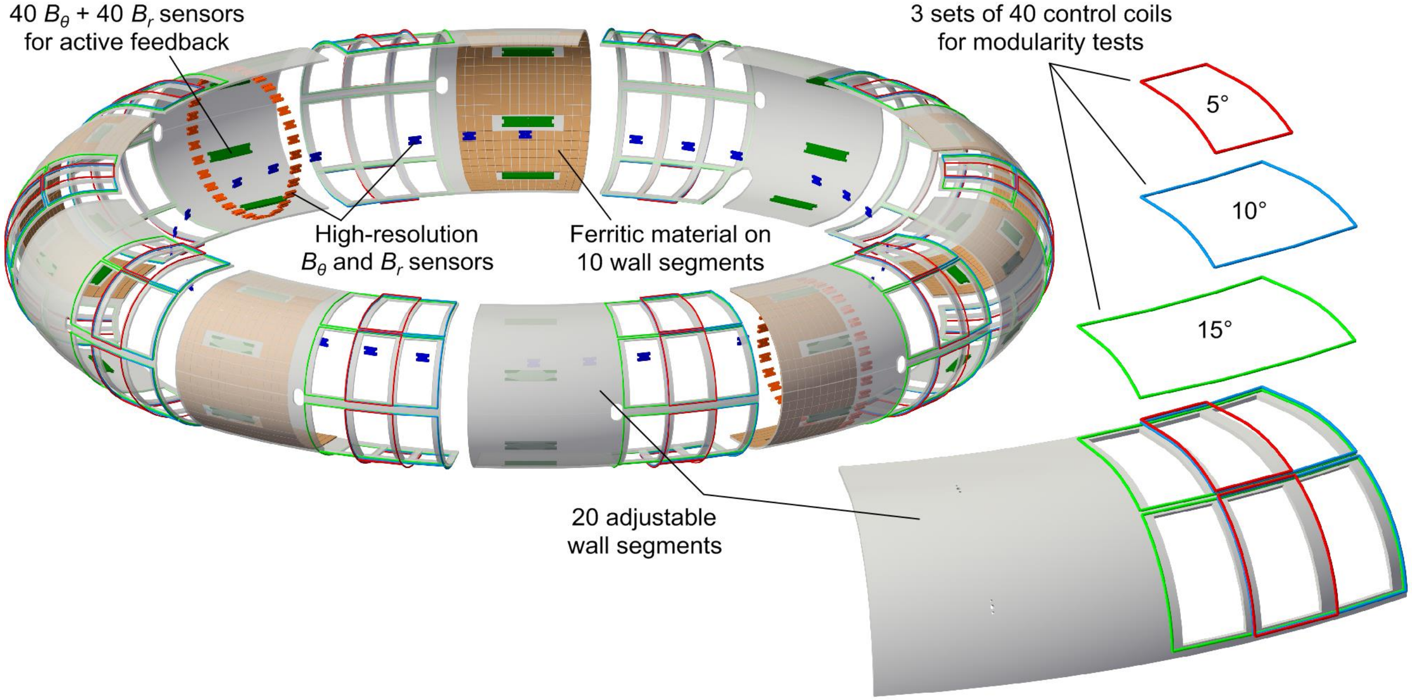
Introduction - Motivation

- A tokamak fusion plasma will need to be shaped
- Kink instabilities potentially limit performance in fusion reactors
- HBT-EP's Mission (in part):
  - To quantify external kink dynamics and multimode response to applied magnetic perturbations… in ways that are ITER and reactor relevant[1]
- HBT-EP is well instrumented to measure external kink modes
  - High resolution magnetic sensors
  - Passive stabilization and active control with flexible configuration
- Shaping HBT-EP's plasmas increases relevancy of kink studies to fusion reactors

[1]HBT-EP Narrative, FY 2011-2013

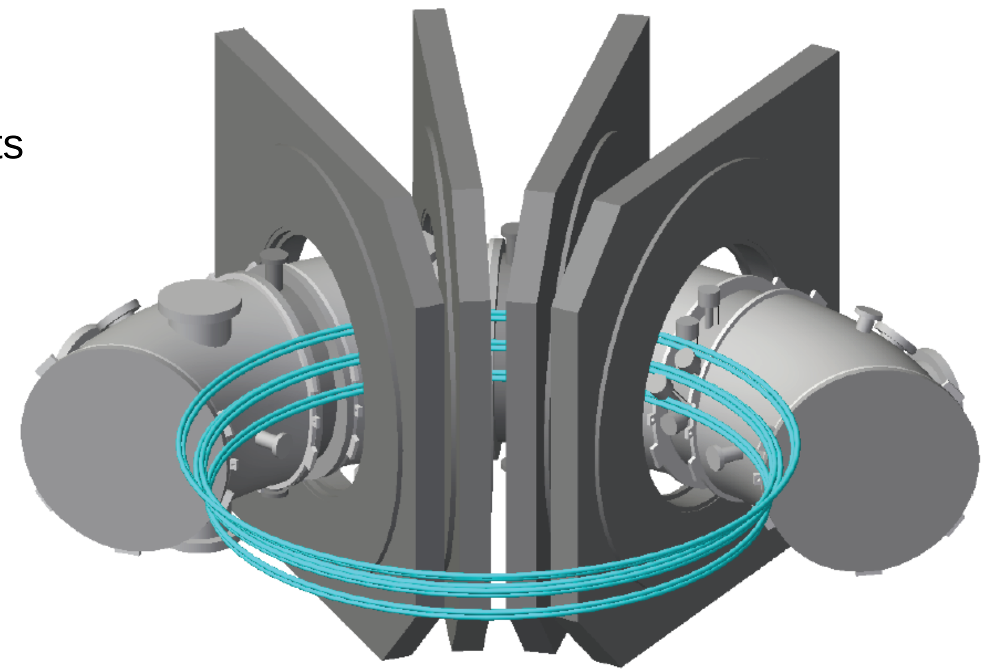
Introduction – HBT-EP Capabilities

- High resolution magnetic sensors
  - 216 total sensors, in 3 arrays, measure radial and poloidal field
- Highly modular passively stabilizing shells
  - 2 independently positionable sets of 10 stainless steel/SS+ferritic walls
- Active control coils
  - 2 coils per shell (of 6) can be independently driven for RMP or feedback



Introduction – HBT-EP Capabilities

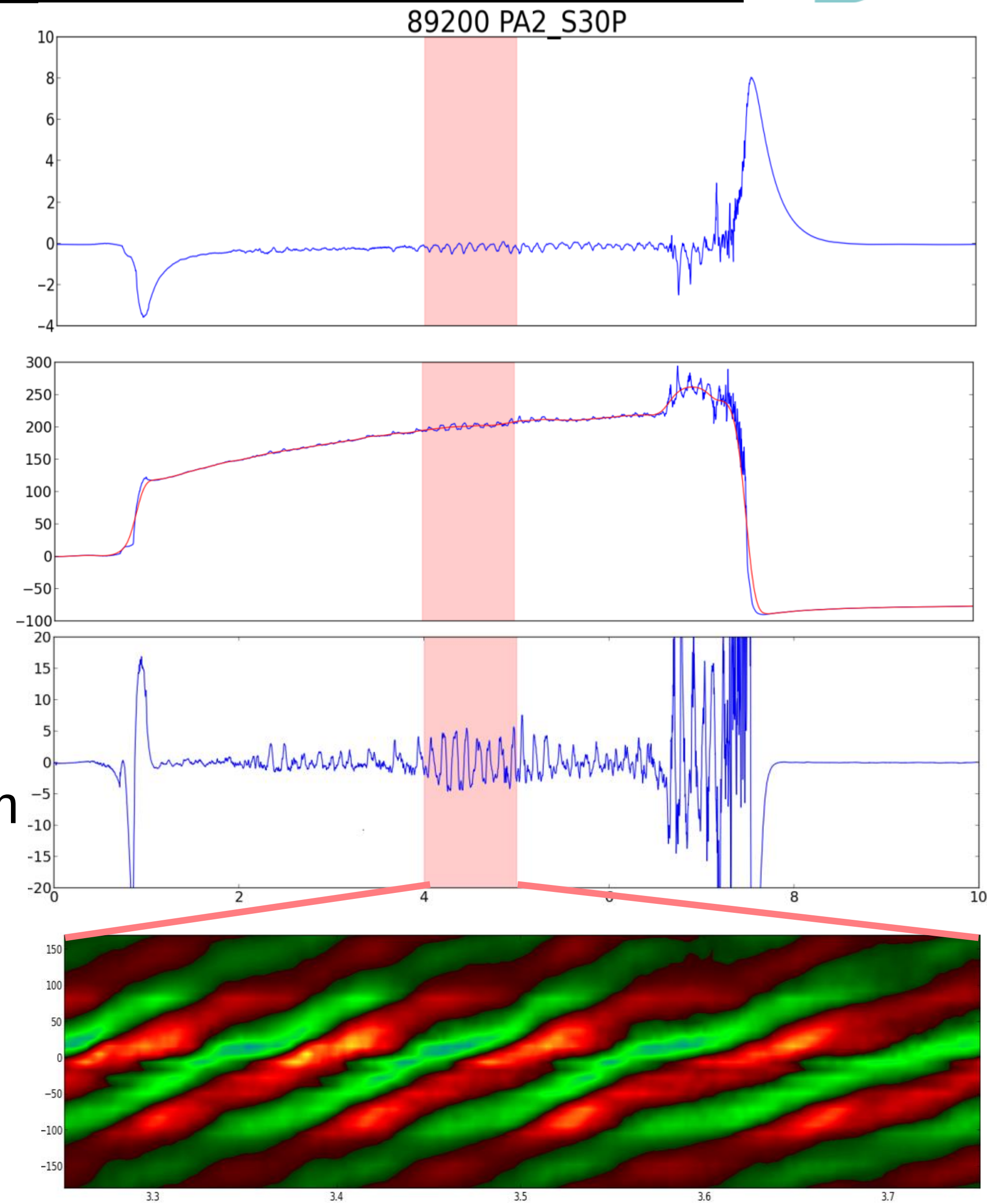
- Zero net turns
  - Center bundle of 4 turns (co-I_p) flanked by 2 bundles of 2 (contra-I_p)
  - All bundles connected in series
    - Low self/mutual inductance
    - Low power supply requirements



- Max current: 7.5 kA / turn
  - Center bundle current: $2 * I_p$
- Arbitrary current/polarity
  - Allows variety of shapes
- Fast startup, sustained current
  - $\tau_{start} < 1ms$
  - $\tau_{peak} > 7ms$ –> $I_{peak} > .9 * \max(I_{max})$

Introduction – Data Acquisition

- Sensors record partially integrated signal
- Signal integrated in software
- Smooth equilibrium fit to data
- Fluctuations separated from signal by subtracting equilibrium
- Fluctuations arranged and contour plotted
  - Dominant mode & frequency often visible by inspection



Biorthogonal Decomposition (BD)

- BD resolves coherent modes from fluctuations
  - Mathematically equivalent to singular value decomposition
  - Coherent traveling modes isolated from fluctuations as degenerate pairs
  - Modes further broken into temporal and spatial components
  - Requires no a priori assumption of mode basis
  - Insensitive to errors in sensor positioning or orientation

$$A = USV^{\dagger} = \begin{pmatrix} | & | & & | \\ a_1 & a_2 & \dots & a_n \\ | & | & & | \end{pmatrix} => \begin{pmatrix} | & | & & | \\ u_1 & u_2 & \dots & u_n \\ | & | & & | \end{pmatrix} \begin{pmatrix} s_1 & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & s_n \end{pmatrix} \begin{pmatrix} - & v_1 & - \\ - & v_2 & - \\ & \vdots & \\ - & v_n & - \end{pmatrix}$$

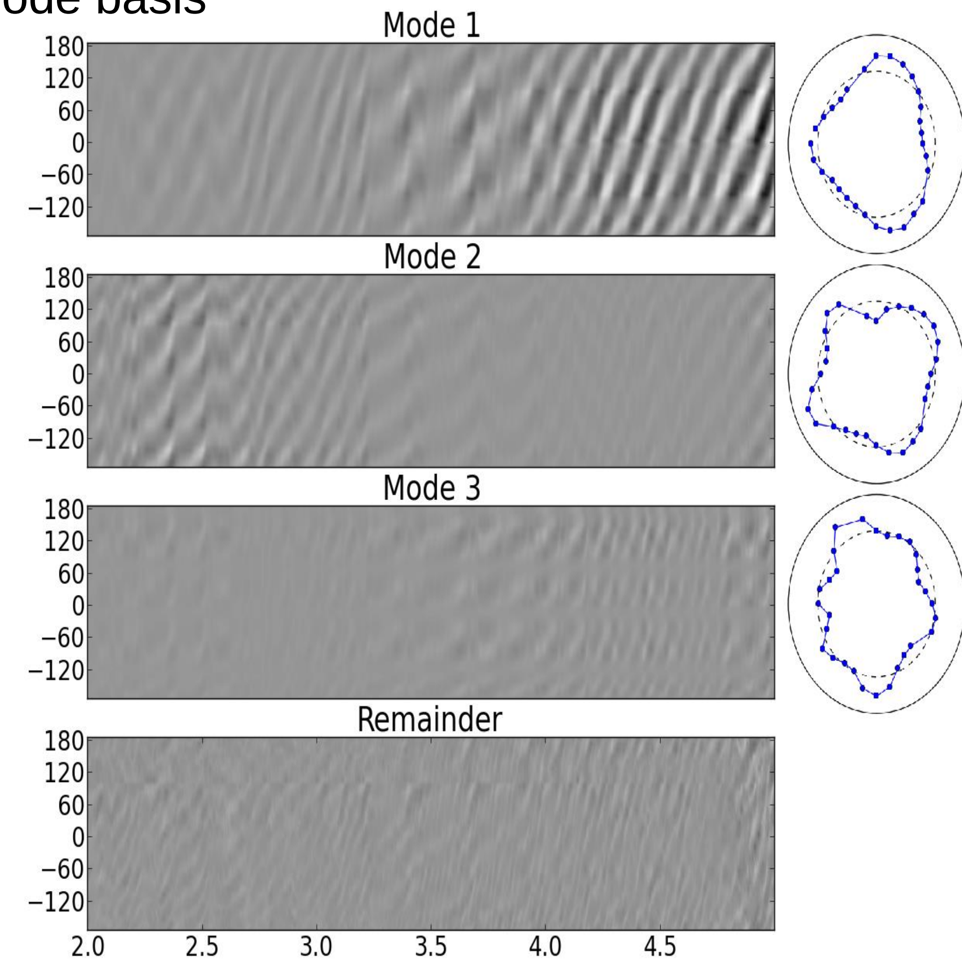
$$v_i \cdot v_j = u_i \cdot u_j = \delta_{i,j}$$

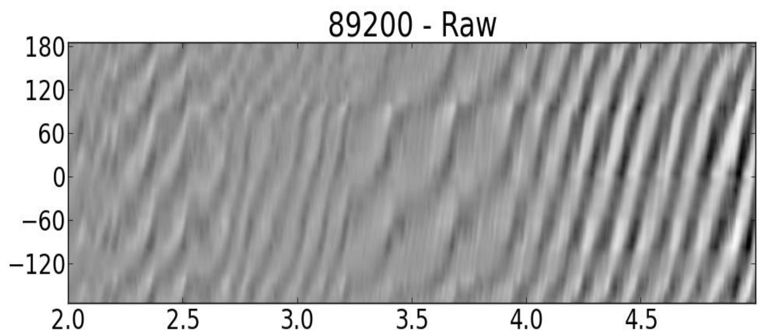
$$\cos(n\varphi + \omega t) = \cos(n\varphi)\cos(\omega t) + \sin(n\varphi)\sin(\omega t)$$

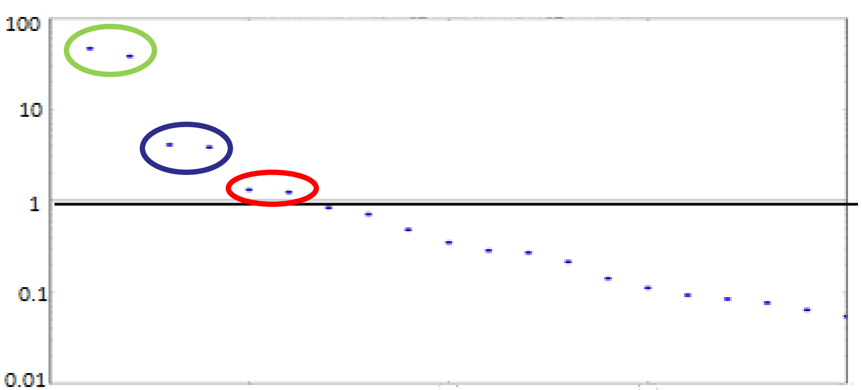
$$f(\theta, \varphi)\cos(n\varphi + \omega t) = f(\theta, \varphi)\cos(n\varphi)\cos(\omega t) + f(\theta, \varphi)\sin(n\varphi)\sin(\omega t)$$

Introduction – Analysis Procedures
Biorthogonal Decomposition

- BD resolves coherent modes from fluctuations
  - Requires no a priori assumption of mode basis
  - Allows discrimination of modes with power ~1% of total fluctuations



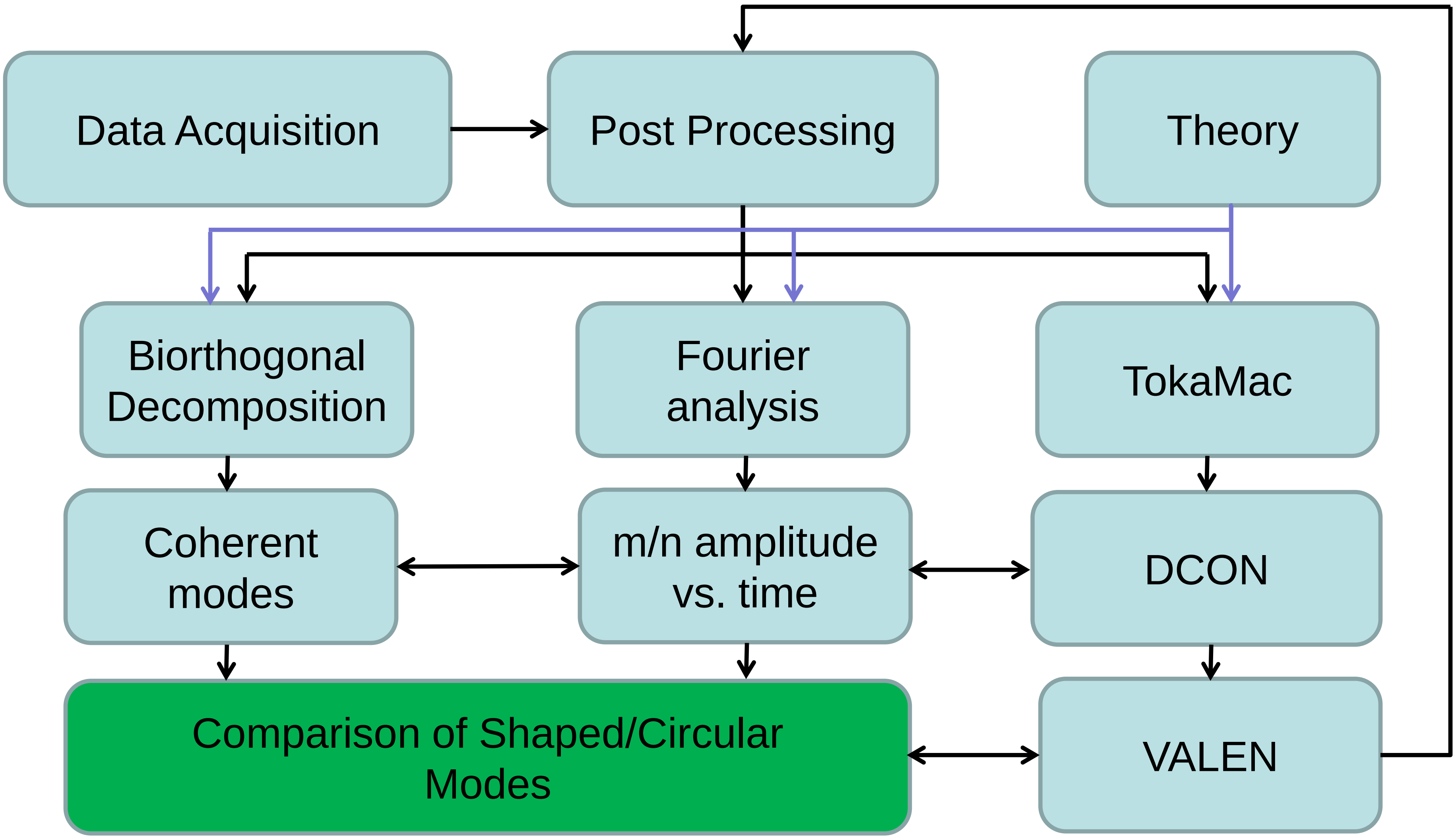




Data Analysis – Modeling

- TokaMac: Grad-Shafranov Equilibrium Solver
  - Provides estimate of LCFS shape and X-point location
    - Assists in shot development
  - Fed direct measurements and empirically constrained estimates
- DCON: Ideal MHD Stability code
  - Fed TokaMac output
  - Predicts MHD mode m-spectra and stability
- VALEN: Resistive model of HBT-EP
  - Transient eddy current response
  - Sensor coupling to mode as function of:
    - LCFS shape
    - Plasma position
    - Rotation Frequency

Introduction – Analysis



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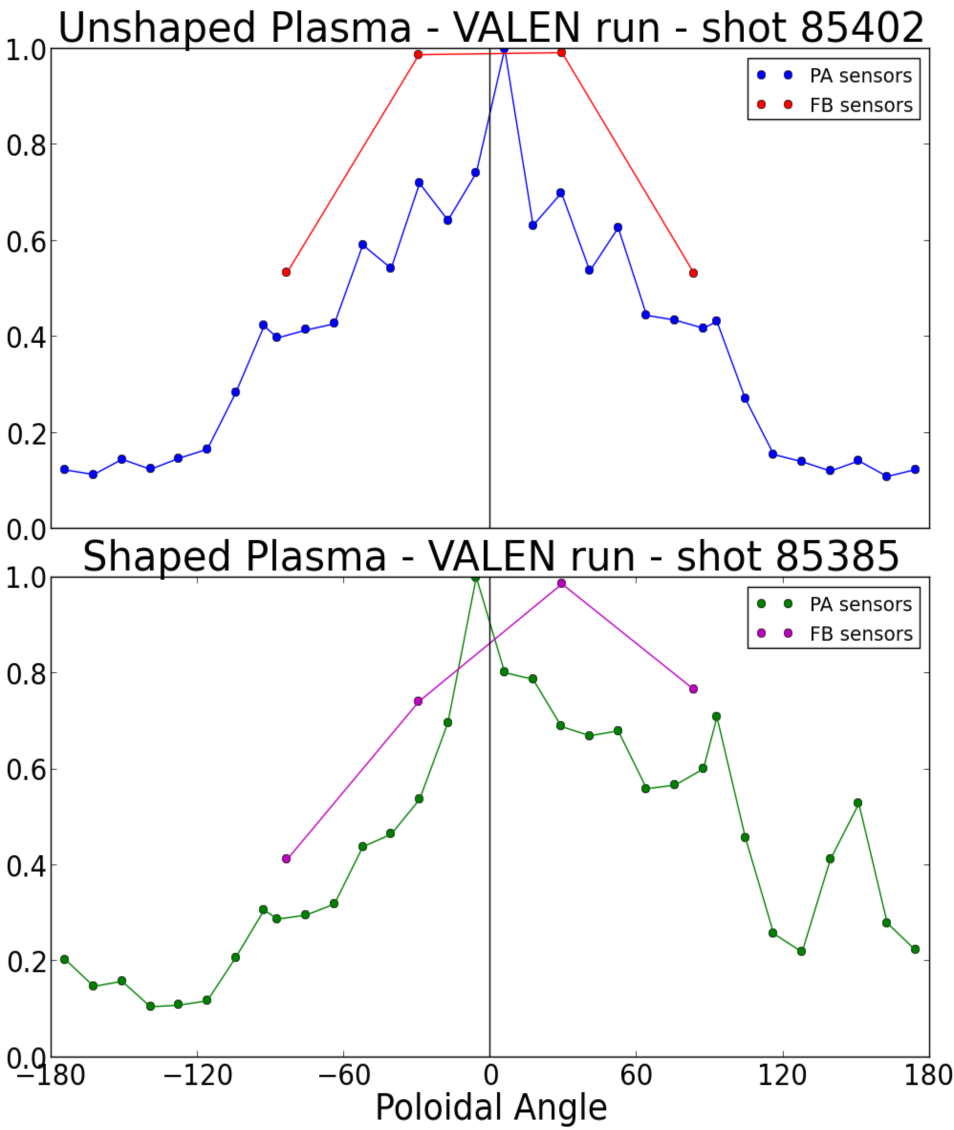
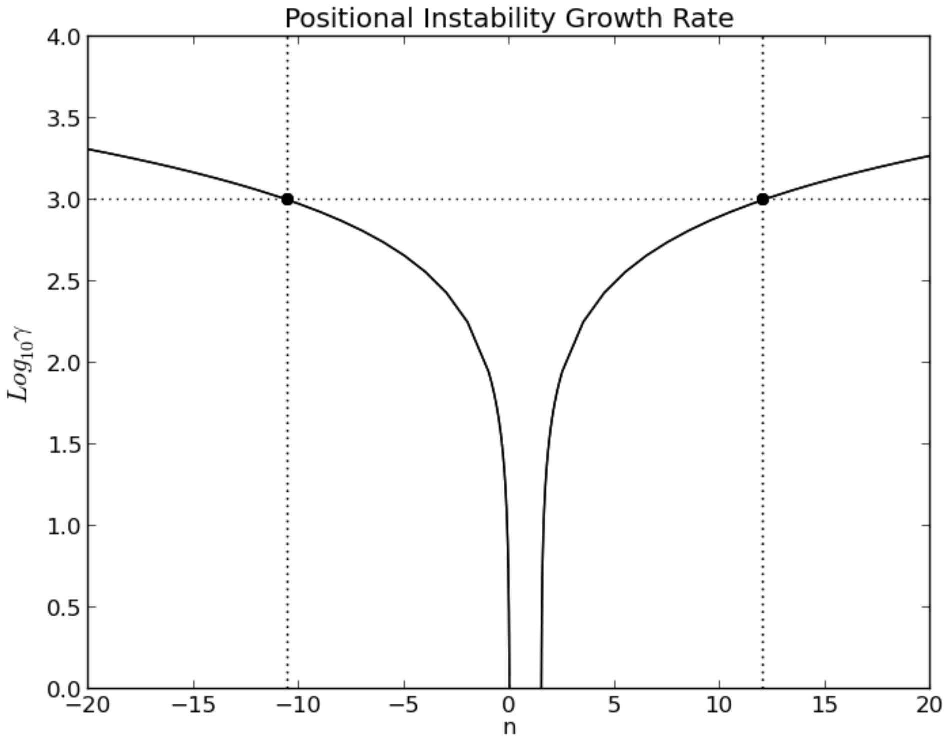
New Challenges – Plasma Sensor Coupling

- Sensors, control coils designed for centered, circular plasma
- Coupling to shaped plasma/mode will vary poloidally
- VALEN can be used to predict coupling at each sensor/coil
  - More accurate measurement of plasma modes
  - Resonant field vs control coil current maximized
  - Novel method, can be applied to circular plasmas as well



New Challenges

- Vacuum fields designed for centered, circular plasma
  - Shaping destabilizes plasma positionally
  - Theory[2] predicts passive stabilization of plasma position
    - Growth time reduced to scale longer than plasma lifetime
  - Real shaped plasmas observed to persist for multiple ideal growth times



[2]A. Fukuyama, Japanese Journal of App. Phys. Vol 14, No. 6 (1978), 871-877

New Challenges

- Shaped plasma displaced upwards
  - Complicates Equilibrium Reconstruction
  - Poloidal arrays to be used as up/down Rogowski
  - Algorithm under development, will require good vacuum field subtraction
    - VALEN modeling of eddies
    - FFT response functions
    - Single pole model
    - Linear multiple subtraction

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Proposed Research

- Explore structure and dynamics of RWMs in shaped geometry

- How are the natural modes affected by shaping?
  - Saturated amplitude, mode shape, stability w/ different LCFS?
  - Growth rate, stability, disruptivity w/ weaker shell coupling?

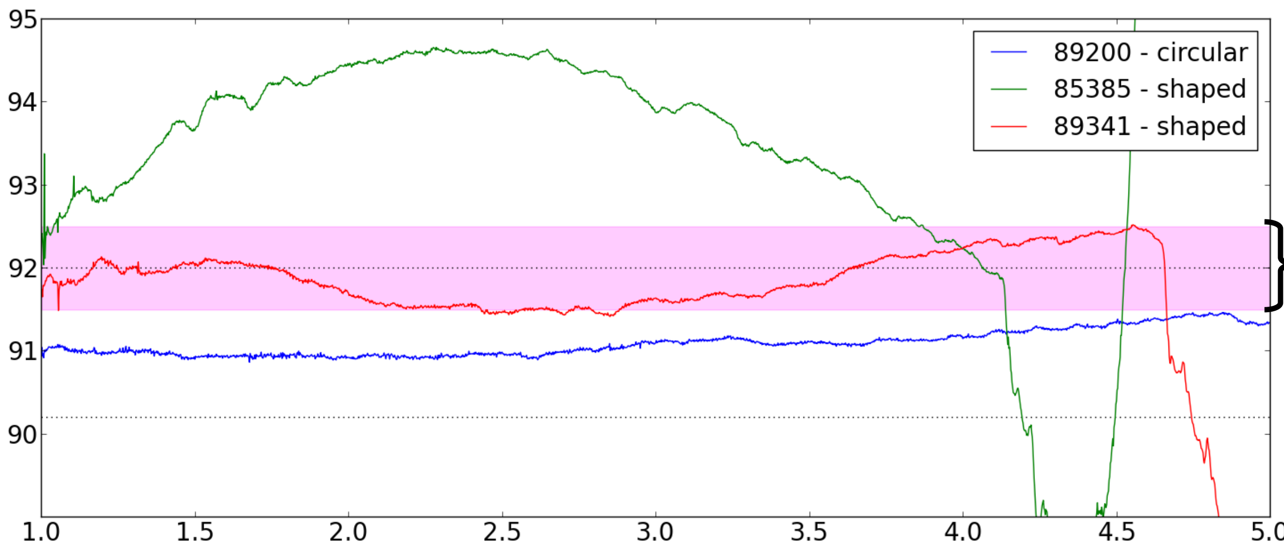
- How is the natural multimode spectrum affected by shaping?
  - Relative strengths of dominant/subdominant BD modes
    - Generally n = 1 vs n = 2

- How does a shaped plasma respond to RMPs?
  - Changes to RFA/disruptivity?
  - Changes to resonant helicity?
  - Coupling to sidebands?

Proposed Research – Shot Development

- Ensuring diversion requires deliberate equilibrium development
  - I_p, MR, VF, OH, and SH affect equilibrium and shaping degree
  - MR strongly affected by all other values
    - Location of plasma in chamber has implications for mode measurements

- Want to develop diverted, centered, MR-steady plasma
  - Diverted: represents a break from previous limited operation
  - Centered: strongest possible coupling to all sensors/control coils
  - MR-steady: allows use of BD across long time windows



Outboard: ease of diversion
Well centered: good coupling
MR-steady: $v_{plasma} \leq .5$cm/ms

Proposed Research – Natural Modes

- Grow database of shots w/ static, diverted, well coupled equilibrium

- Observe modes
  - As measured by sensors & segregated by BD/Fourier analysis
  - As predicted by TokaMac/DCON

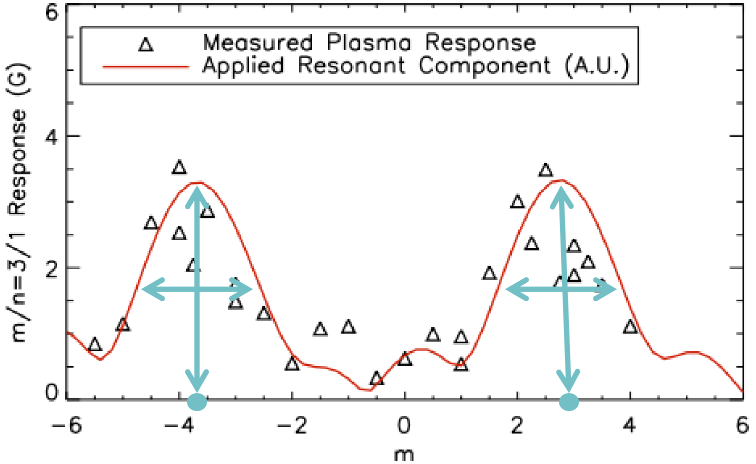
- Compare modes
  - Computationally: Through DCON
  - Experimentally: Through sensors & BD/Fourier
    - Naïve – Direct comparison
    - VALEN – Eliminates effects of boundary shape and position
  - Look at shape, amplitude, q_{edge}, growth rates
    - Dominant mode
    - Subdominant mode(s)
    - Correlation between modes

Proposed Research - RMPs

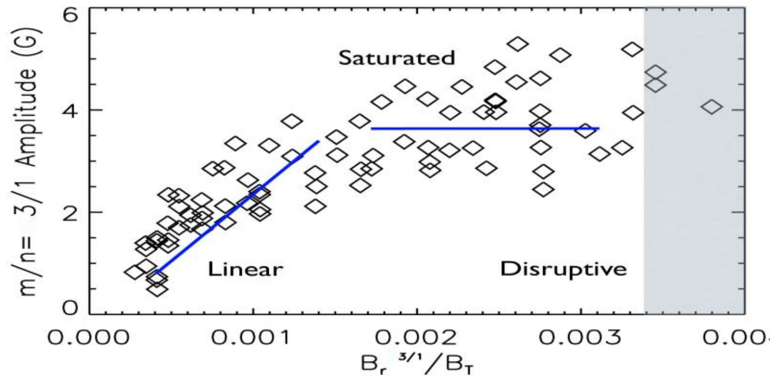
- RMP response: covariance between control coil current and measured field:

$$\frac{\int B(t)I(t)\,dt/\int dt}{\sqrt{\int I(t)I(t)dt/\int dt}}$$

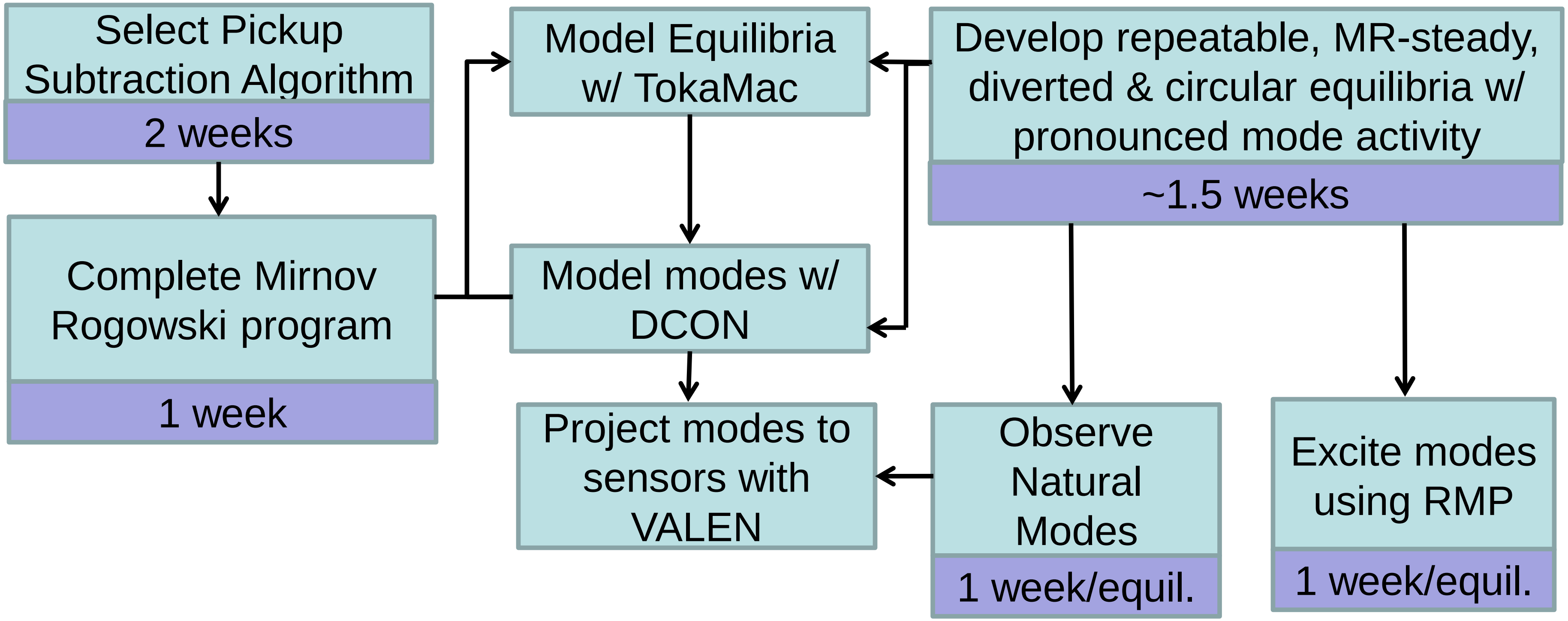
- Observe spectrum of response
  - Will the same modes couple to the same RMP in shaped/circular plasmas?
  - Will the response peaks be in the same location / the same width?



- Observe magnitude of response
  - Is response greater or less?
  - Are multiple modes unstable?
  - Is the saturated level higher or lower?
  - Is the plasma more disruptive?



Proposed Research – Workflow/Timeline



Look for effects on:
Natural Modes: Mode Shape, Saturated Amplitude, Growth rates
Driven Modes: Mode Response, Disruptivity, Resonant Helicity/bandwidth

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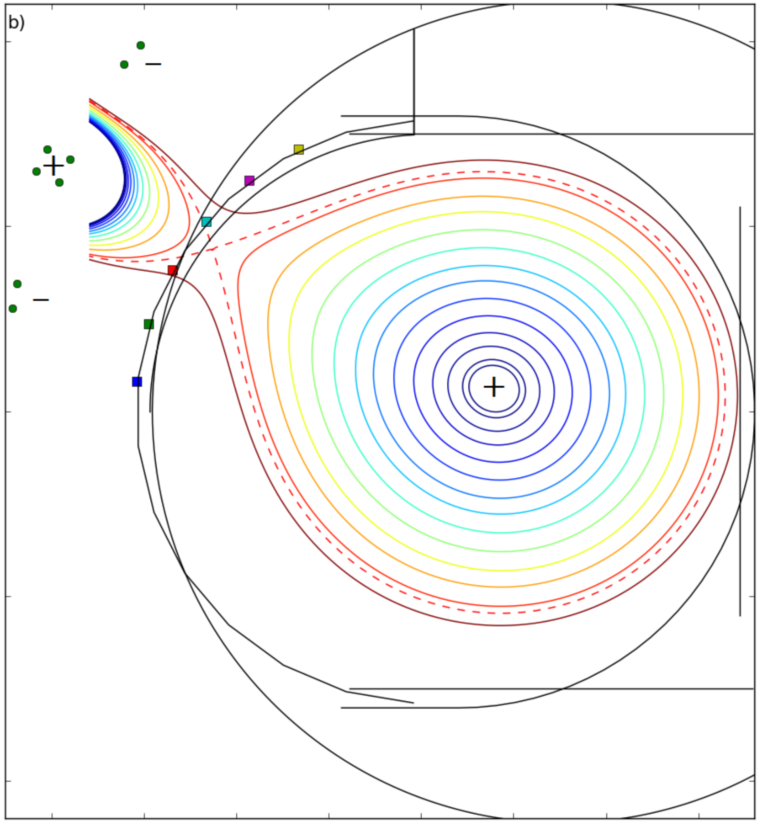
Initial Results

- Shaping Coil has been constructed and installed on HBT-EP
  - Allows investigation of a wide array of shaped configurations
  - Diverted operation has been demonstrated for first time in HBT-EP (Shot 85385)
  - Near-X point sensors poorly coupled
    - Due to plasma MR
- Shot development in process
  - Well centered, MR-steady, high I_{sh} shots under development (Shot 89341)

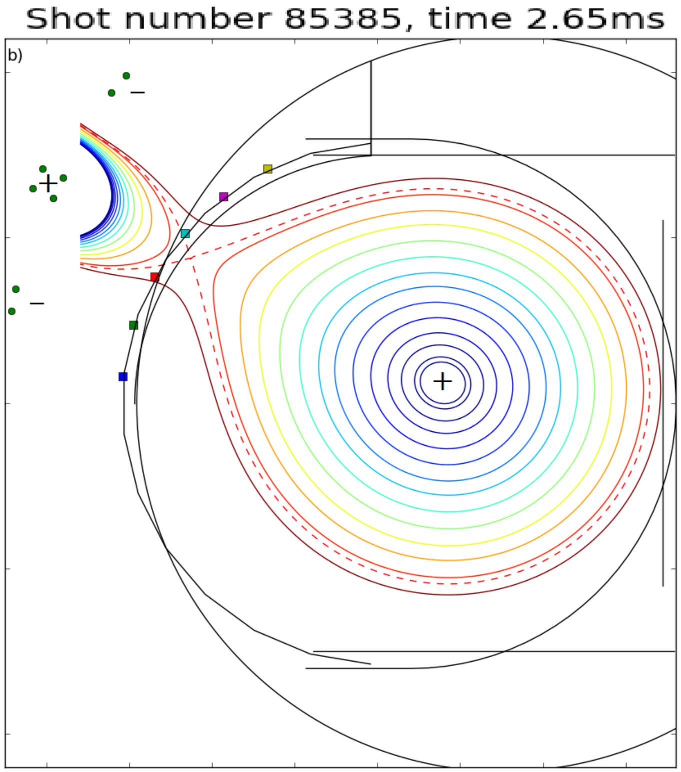
Shot number 85385, time 2.65ms

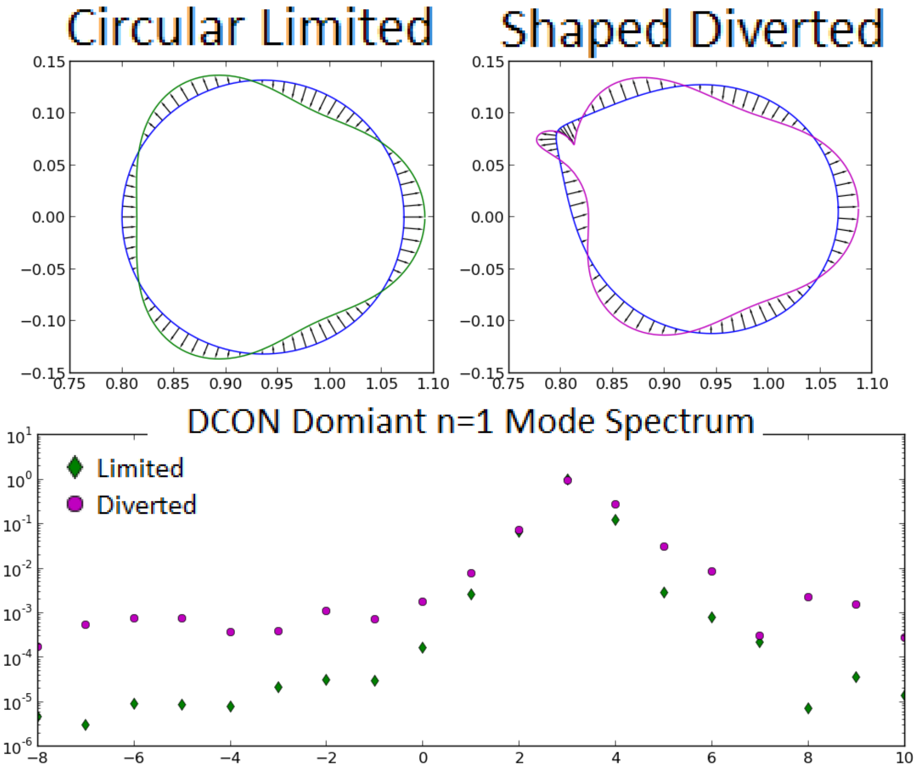


Initial results – Modeling/Simulation

- Equilibrium Reconstruction: TokaMac used to confirm diversion
  - Direct measurements of near-x point field confirm diversion

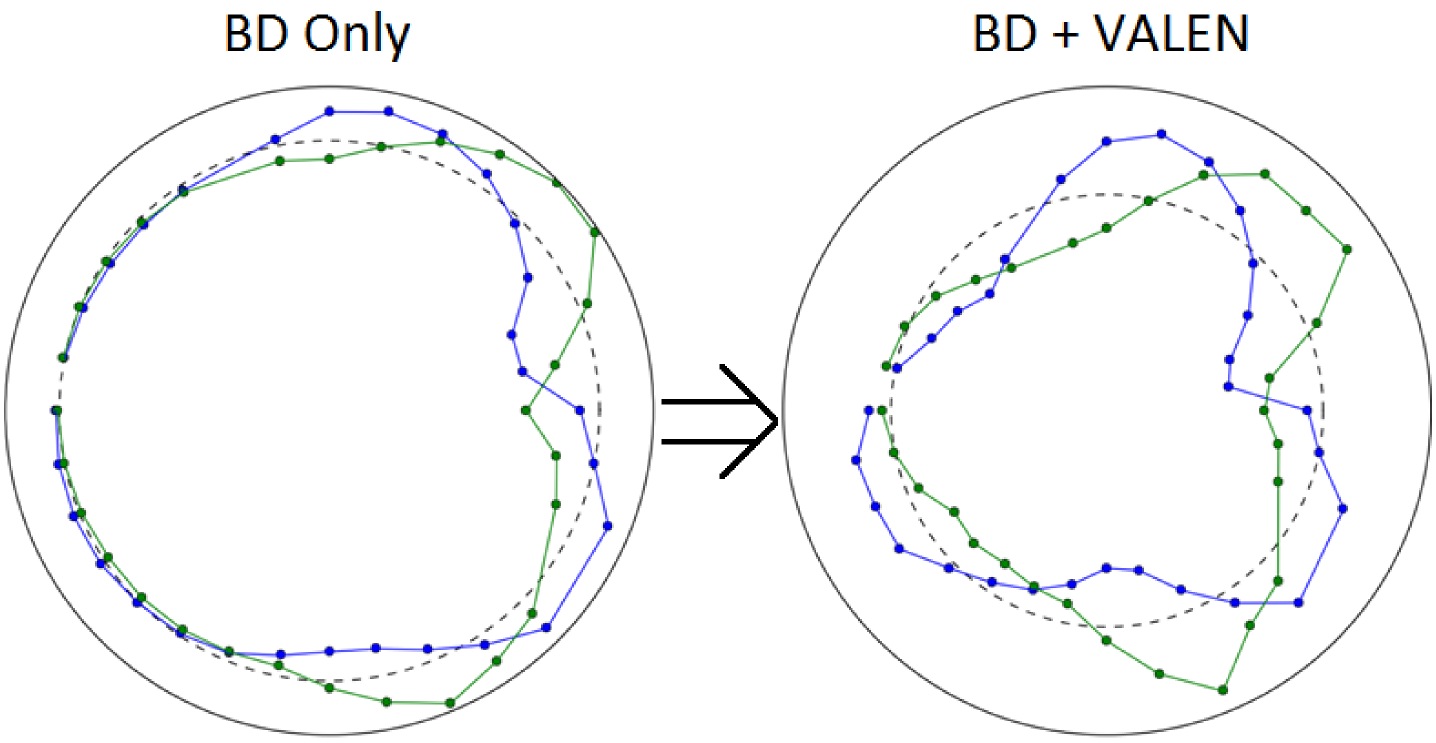
- Mode Energetics and Shape: DCON has predicted modifications to poloidal shape of mode
  - Much broader m spectrum





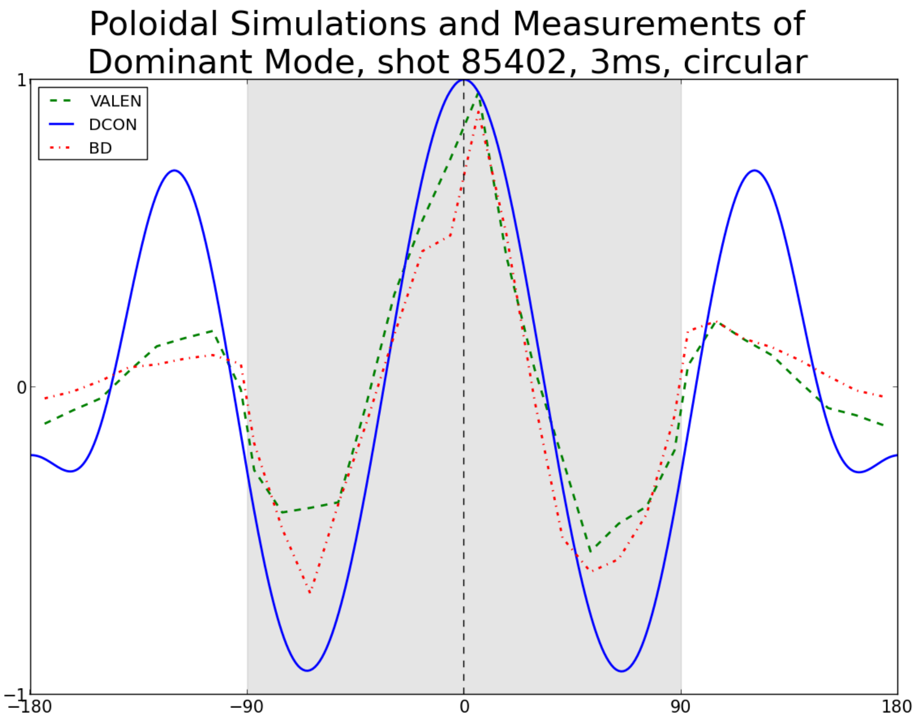
Initial Results – VALEN

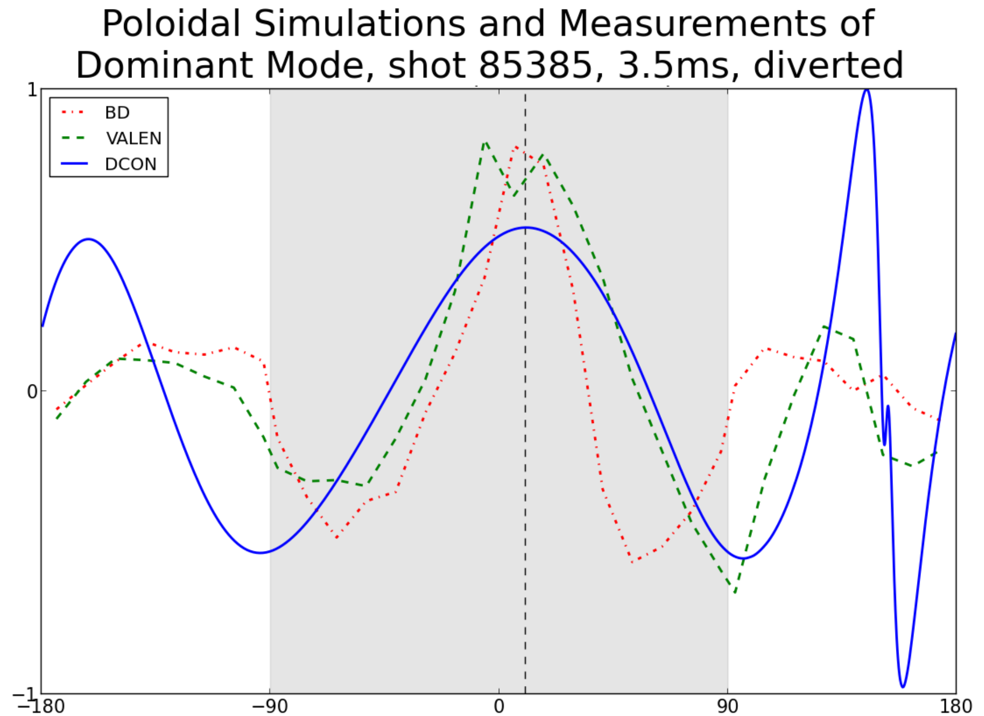
- VALEN used to predict coupling at each sensor/coil
  - More accurate measurement of plasma modes
  - Requires accurate equilibrium reconstruction
  - Want repeatable plasma to limit number of reconstructions



Initial Results - VALEN

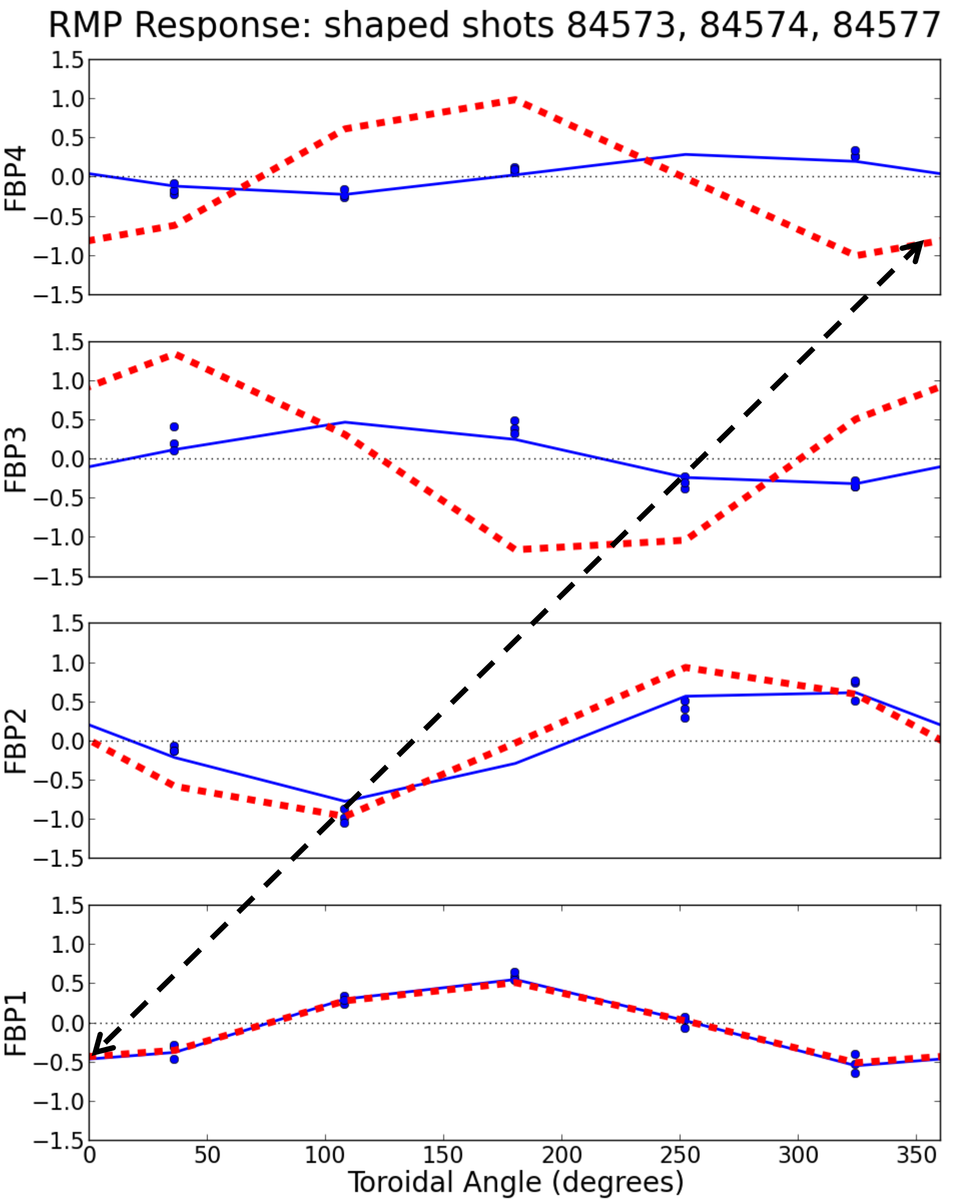
- VALEN's mode-field-at-sensor agrees well for circular plasma
  - Discrepancy between DCON and BD reduced significantly
- More work required for shaped plasmas
  - Better equilibrium and larger shot database





Initial Results – RMP Response

- 3 similar shaped shots w/ m/n = 3/1 RMP applied
- Data and n=1 fit to data in blue, n/m 3/1 response in red
- Poloidal variation of amplitude seen, as predicted by VALEN
  - Strongest coupling to RMP seen at upper midplane
  - Predicted to be strongest at lower midplane
- Significant phase shift seen
  - Suggests poloidal spectrum not just pure m=3



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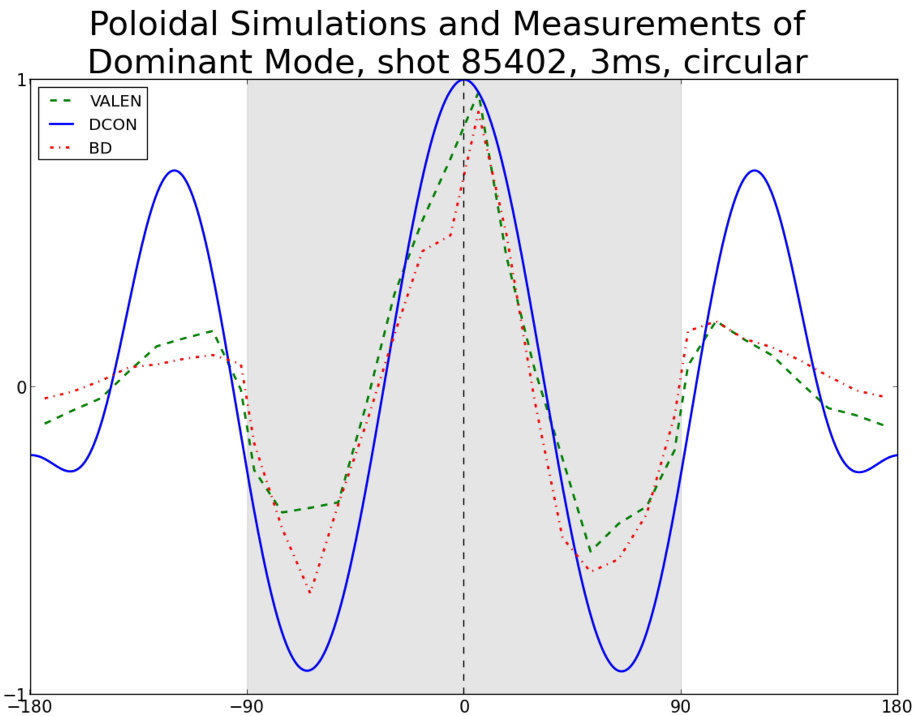
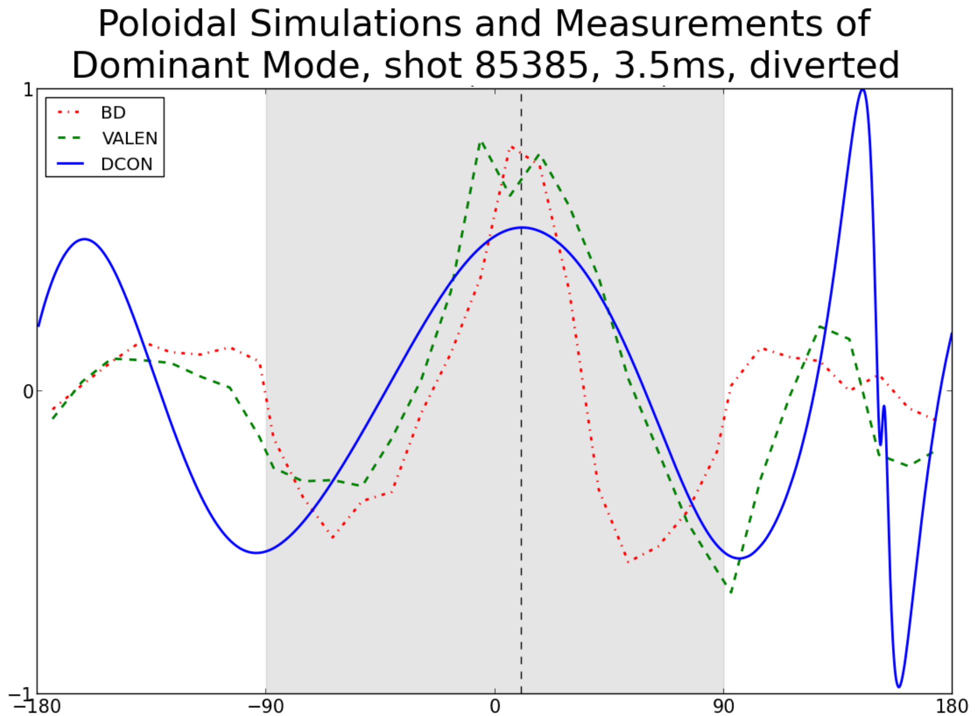
- This thesis will investigate:
  - A novel method for tying the output of MHD codes to direct measurements via VALEN
  - The structure of resistive wall modes as the plasma boundary is shaped in various ways, including full diversion
  - The growth rate and disruptivity of these modes as compared to circular plasmas
  - The response of shaped plasma RWMs to RMPs

Introduction – Analysis Procedures

- Mode Measurements: BD (previously discussed)
- Experiment/Simulation Connection: VALEN
  - Inputs:
    - DCON modes, mode rotation speed
    - HBT-EP conducting structures, sensor location/orientation





Introduction – Analysis procedures

- Plasma equilibria solved for using TokaMac
- Equilibria <u>ideal</u> stability modeled in DCON (edge = $\Psi_{99.5}$)
- Sensor pickup forward modeled using VALEN
- Actual measurements decomposed to coherent modes via biorthogonal decomposition