Optimized RWM Control System Design and Initial Experiments on HBT-EP

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HBT-EP MHD Control Strategy

Goal: Understand the basic physics of macroscopic, performance limiting MHD instabilities and their active and passive control.

Use this knowledge to improve the performance of fusion energy systems.

Study physics of these issues in a flexible small machine test bed enviroment with MHD relevant plasmas and apply knowledge gained to larger fusion experiments (DIII-D, NSTX, FIRE, ITER)

Optimized Feedback: Reaching the Ideal Wall Limit

- Theory and modeling tell us that **minimizing the control coil-resistive wall coupling** (mutual inductance) while **increasing control coil-plasma coupling** leads to better feedback performance **(Directly Coupled Coils)**

- And **minimizing sensor coil-control coil coupling** and **feeding back on only the MHD mode** increases performance **(Mode Control)**

- New goal is ***"optimized"*** **system** with both of these features **able to perform at the ideal wall limit**

- **The first experimental test of these ideas is underway on HBT-EP**

*RWM Dispersion Relation with Feedback**

* A. Boozer, Phys. Plasmas 5, 3350 (1998)

Apply Voltage to Control Coil, $V_f(t) = -\frac{L_f}{M_{fp}}[\gamma_w K_p + K_d \frac{d}{dt}]\,\phi_{sensor}$

K_p = Proportional Gain $\quad$ K_d = Derivative Gain

$\gamma_w = R_{wall}/L_{wall}$ $\quad$ $\gamma_f = R_{control\ coil}/L_{control\ coil}$ $\quad$ τ = feedback delay

$$\boxed{a_3\gamma^3 + a_2\gamma^2 + a_1\gamma + a_0 = 0}$$

$$a_0/\gamma_w = -\gamma_f + \gamma_w [\, D(s) + c_f \,] K_p$$

$$a_1 = \gamma_f D(s) + \gamma_w [\, (D(s) + c_f) K_d - 1] K_p$$

$a_2 = D(s)$ $\quad$ $a_3 = \tau D(s)$ $\quad$ $s \propto -\delta W$ instability strength

For Stability all four Coefficients must be Positive

Understanding Ideal Wall Limit Performance

$$D(s) = c[(1+s)/s] - 1 \quad \text{where } c = [M_{pw}M_{wp}]/[L_{mode}L_{wall}]$$

At Ideal Wall β Limit: $D(s_{crit}) = 0$

Feedback Coupling Constant, $c_f = 1 - [M_{pw}M_{fw}]/[L_{wall}M_{fp}]$

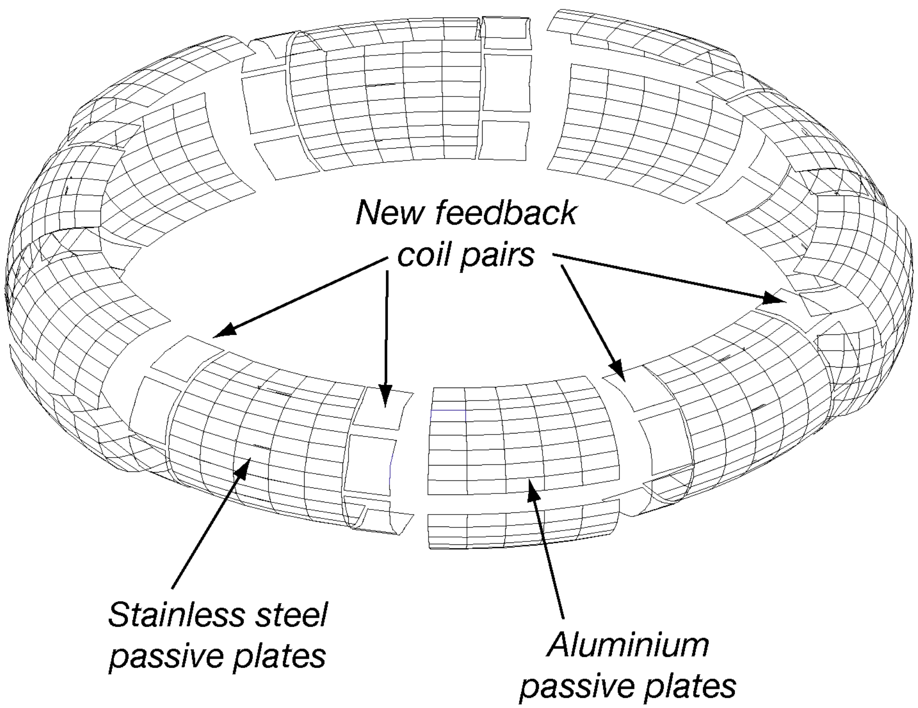
For Feedback to Stabilize up to
Ideal Wall β Limit **c_f must be ≥ 0**

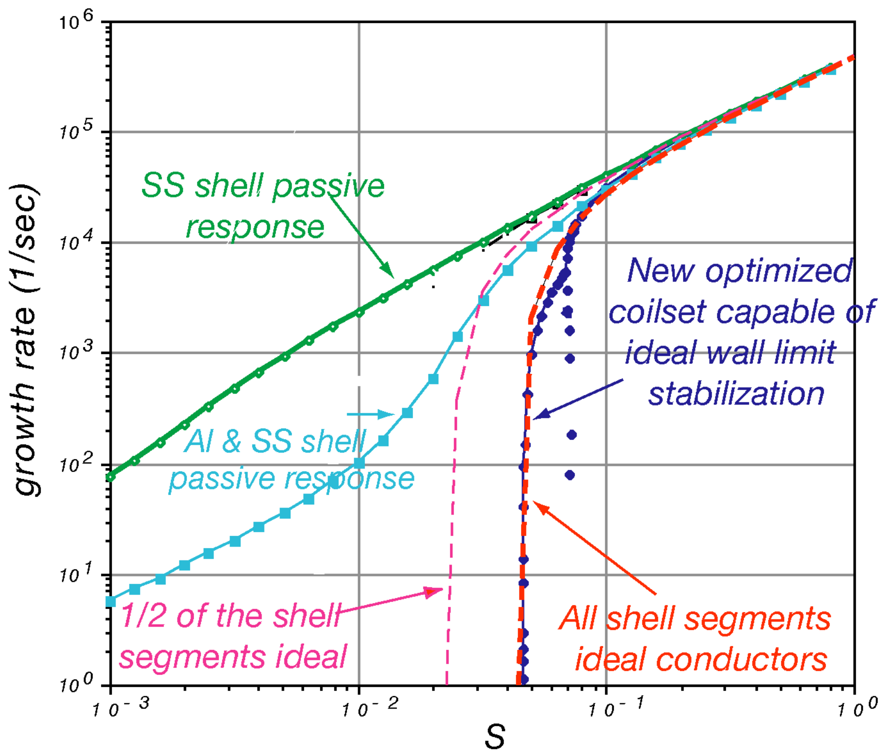
Want small M_{fw} and large M_{fp} to insure **$c_f > 0$**

For Typical "Smart Shell" $M_{wf} > M_{fp}$ and **$c_f < 0$**

VALEN Optimization of HBT-EP RWM Feedback Control

New Control Coils Located in the Gaps Between the Passive Plates with B_p Sensors Predicted to Reach Ideal Wall Limit

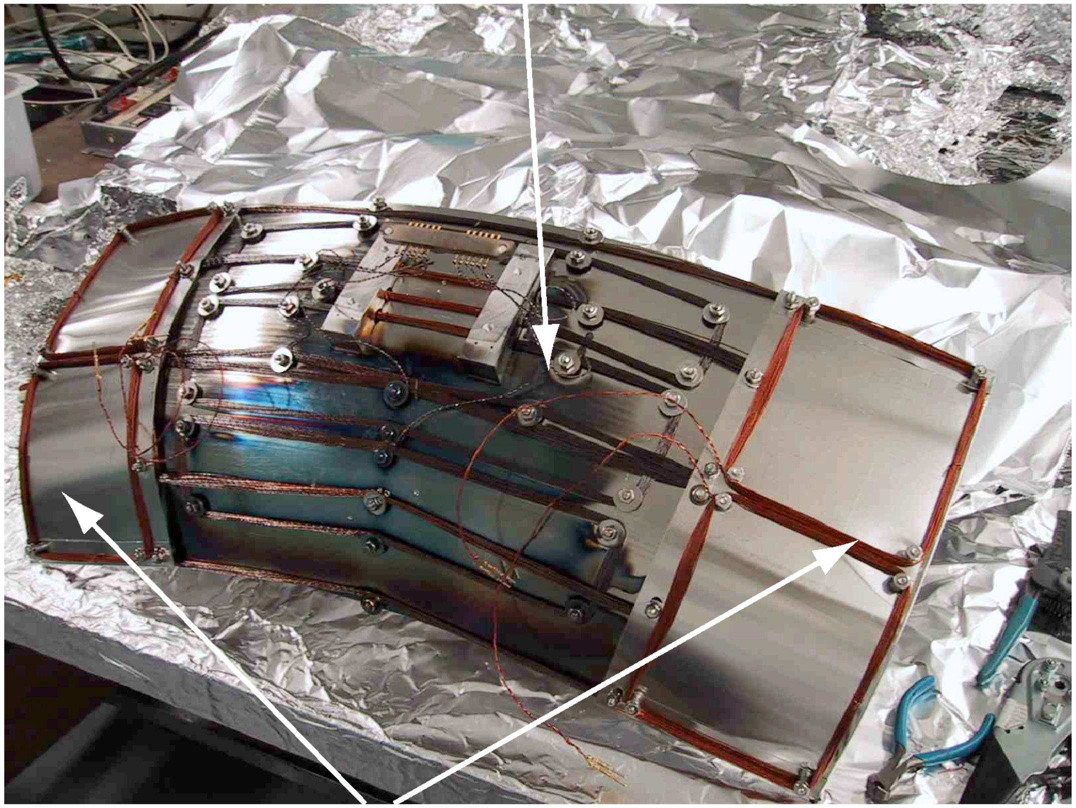




- 20 new control coil pairs at 5 distinct toroidal and 4 poloidal locations on outboard side of tokamak
- 20 new companion B_p sensors on plasma facing side of SS passive plate
- Initial mode control experiments in progress

HBT-EP RWM Control Experiments: Optimized Feedback

Old smart shell
feedback system

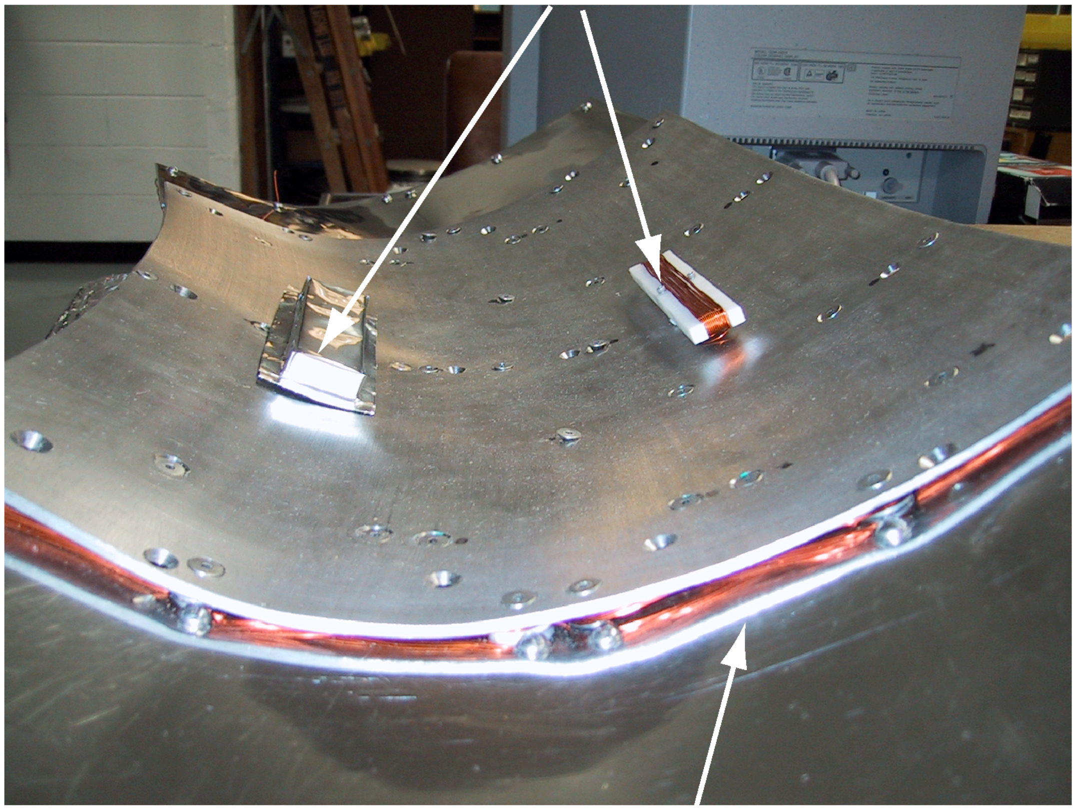


New mode control feedback coils
mounted off of stainless passive plates
installed in 2002

- New control coils mounted on thin 0.25 mm stainless steel shim stock to minimize wall coupling
- New poloidal sensors on plasma facing side of stainless steel plate *(not shown)*
- New mode control experiments have begun by mapping poloidal sensors in toroidal angle 72 degrees to make up B_p sensor to B_r control coil phasing using existing analog circiutry

New Mode Control Sensors Mounted on Plasma Facing Side of Stainless Steel Shells

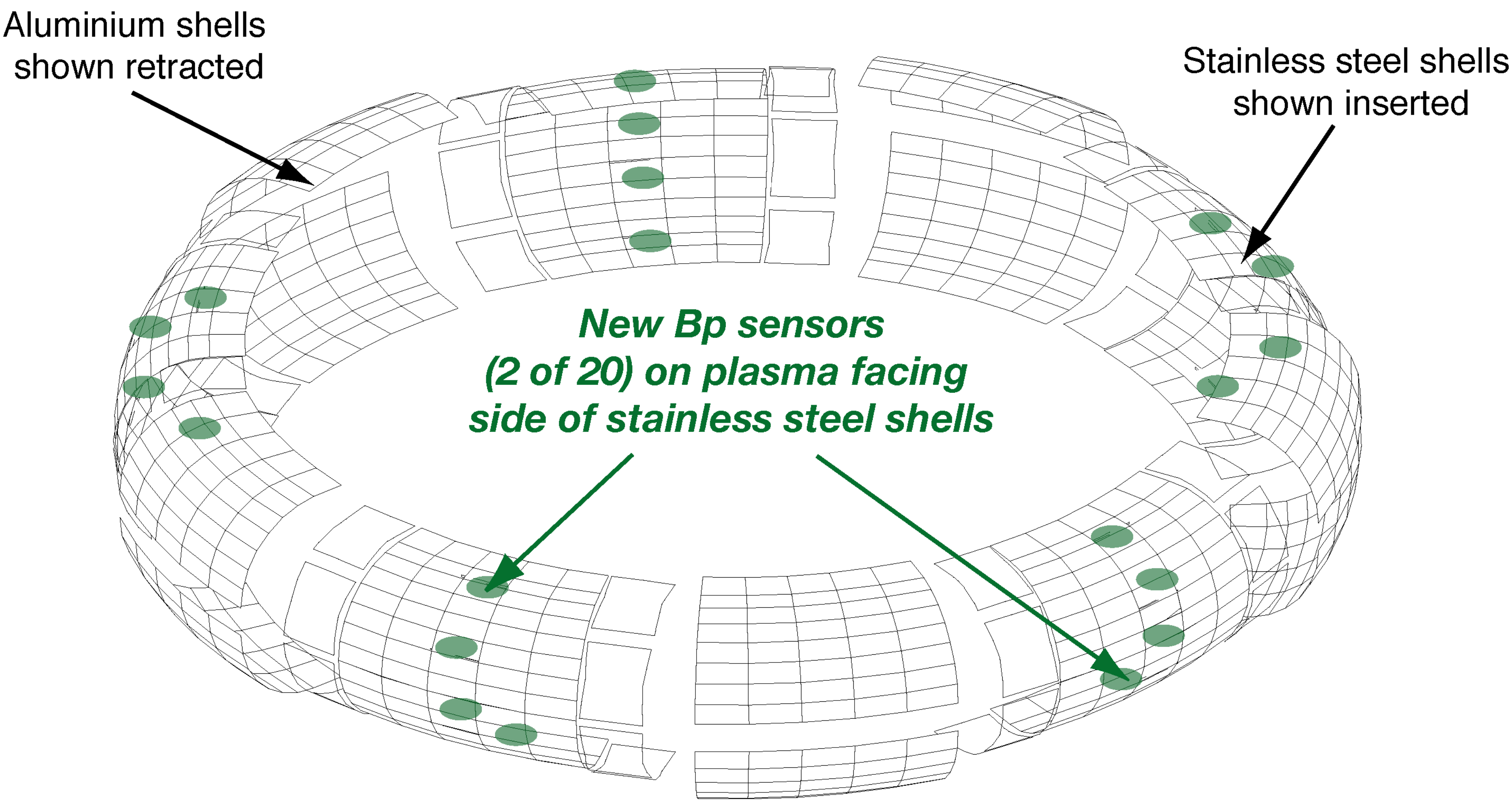
New B_p sensors
(electrostatic shield on one shown)



Back of stainless steel shell with old smart shell coils

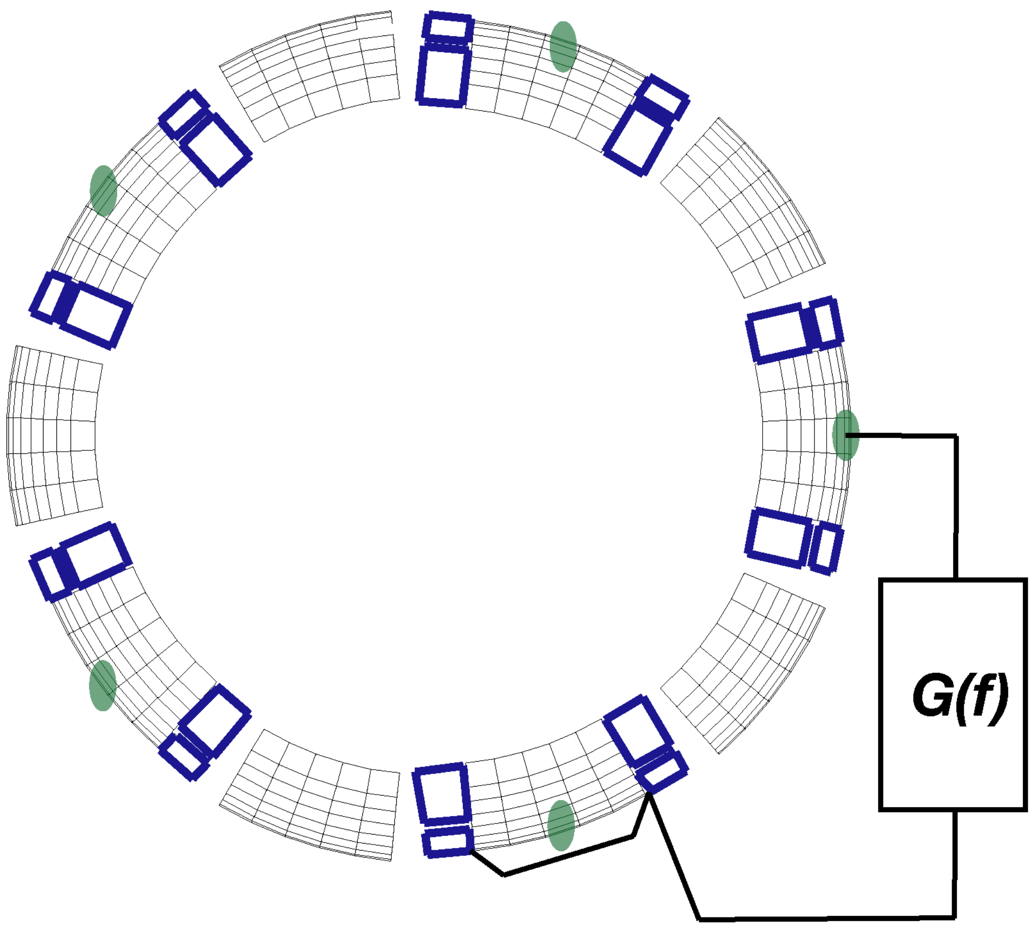
- Twenty new B_p sensors mounted plasma facing side of shell. Gives detection of kink fluctuations essentially on the plasma surface
- Fifteen turns on teflon form
- $L_{sensor}=12\mu H$
  $R_{sensor}\sim 1\Omega$

New Poloidal Sensor Coils on HBT-EP for Mode Control Feedback



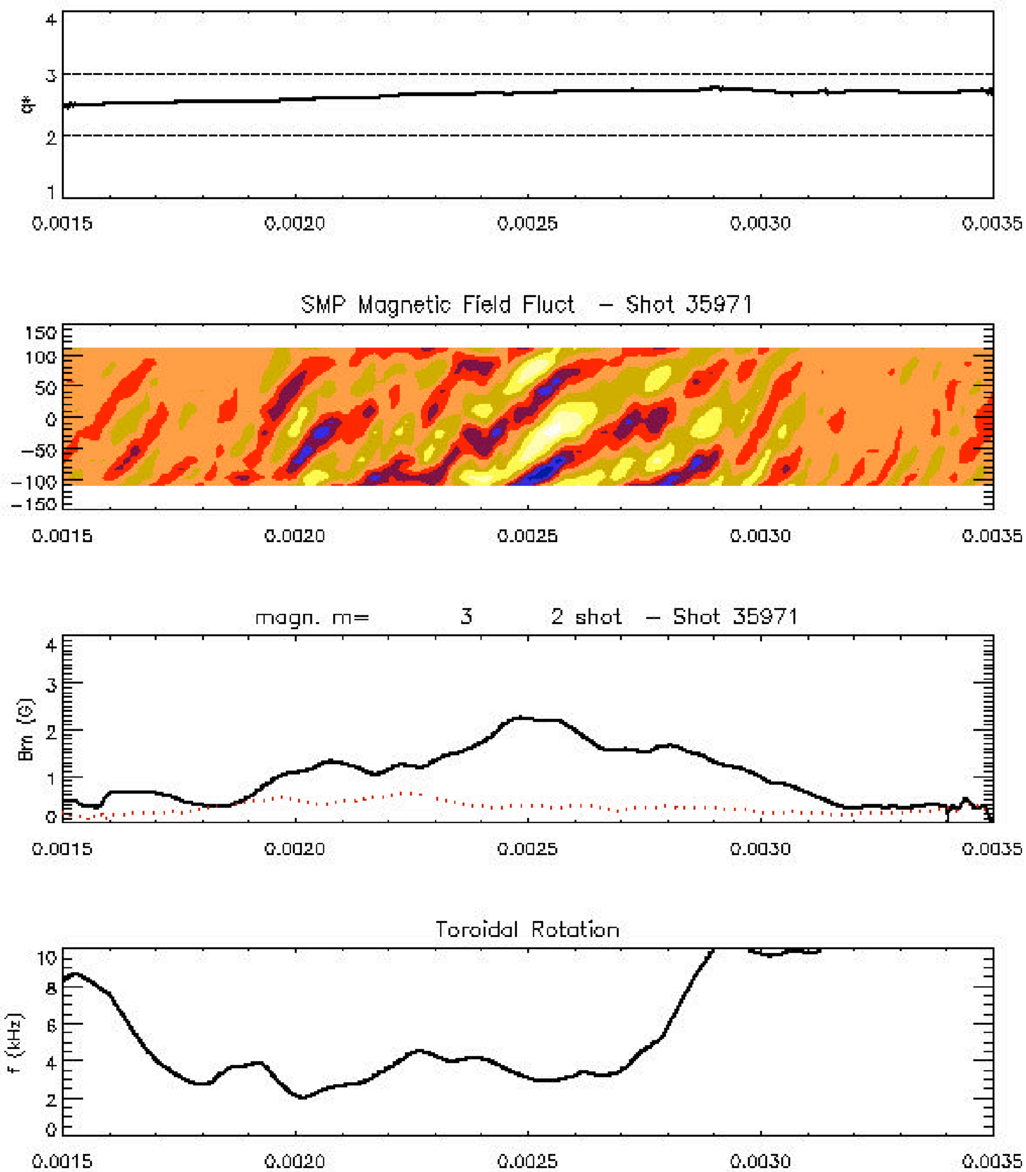
- ***Plasma mode detection essentially on the unperturbed plasma surface***

Initial Gap Coil and Poloidal Field Sensor Feedback Loop Configuration



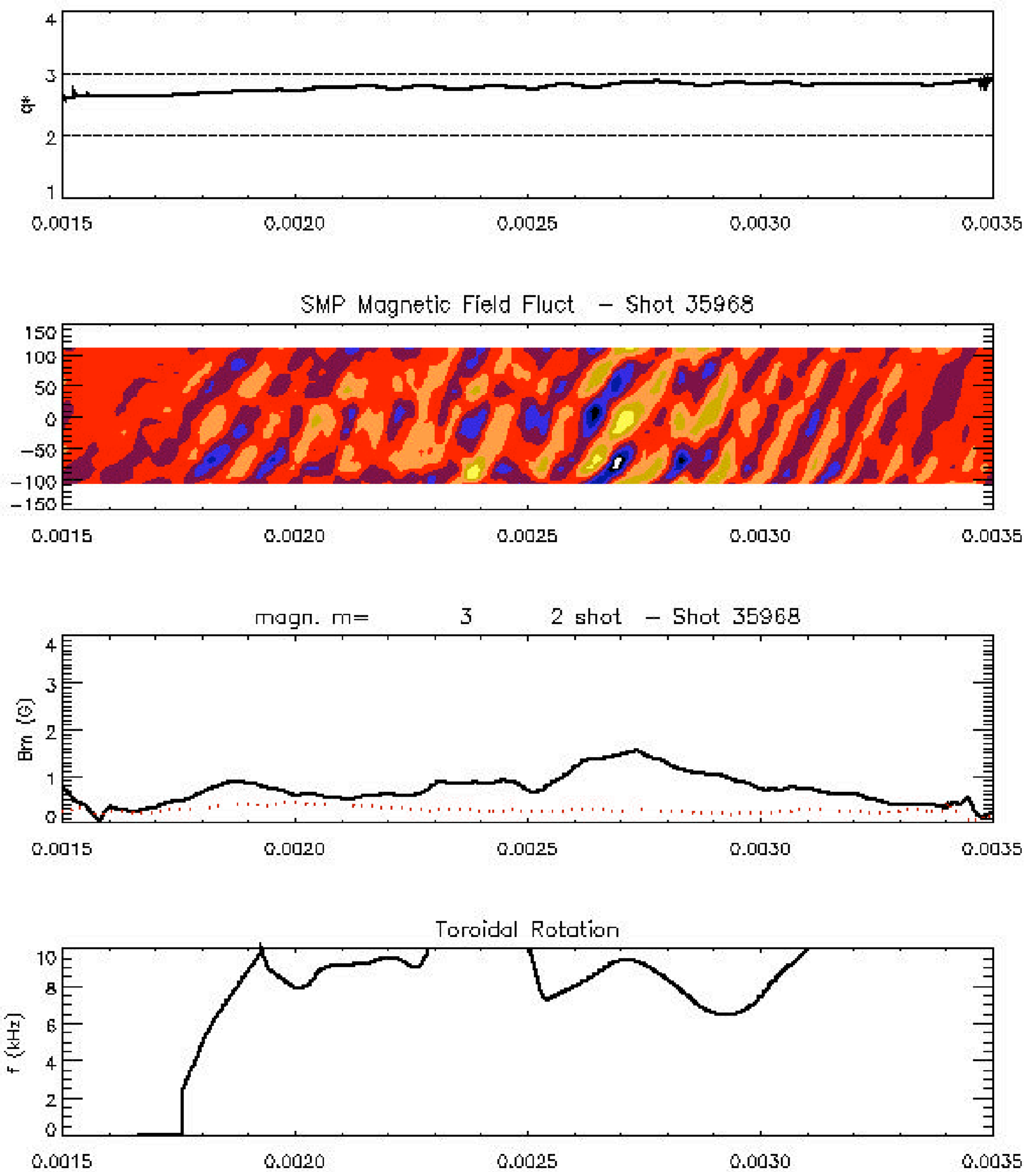
- Have implemented a simple SISO system for initial studies
- B_p sensors mapped toroidally as shown
- Allows initial experiments to use existing "smart shell" closed loop circuitry
- Mapping toroidally provides sensor-feedback coil decoupling (mode control operation)

Slowly Growing RWM Observed When q* < 3



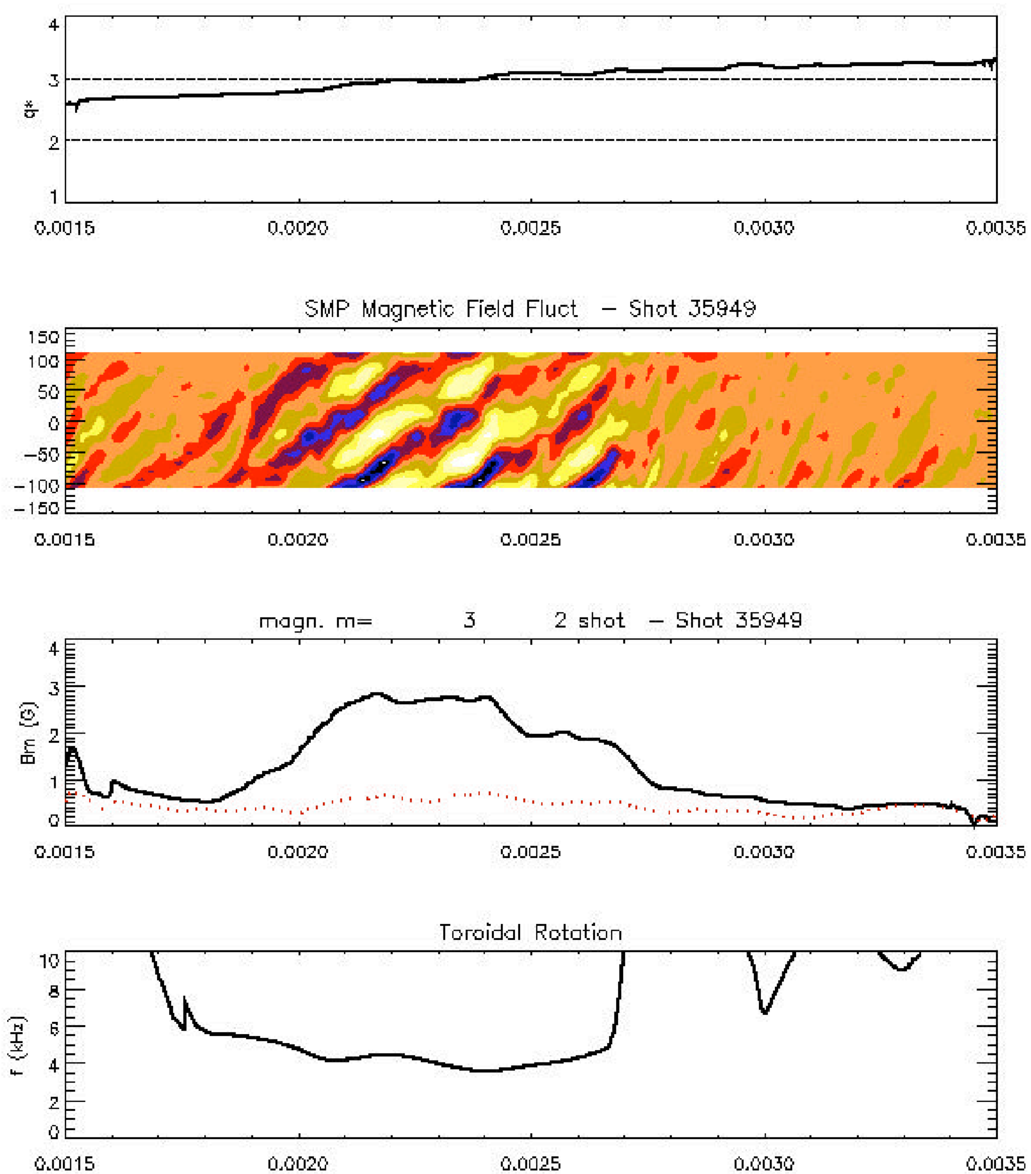
- New target plasma developed with quasi-stationary burst of RWM
- Plasmas formed using "rapid formation" technique with *q**<3 initially.
- Transient burst of RWM observed as *q** slowly ramps toward *q**=3 during plasma evolution
- Observed MHD mode has basic characteristics of RWM: mode frequency ~ $1/\tau_w$ mode growth rate ~ $1/\tau_w$

Suppression of RWM Amplitude Is Observed



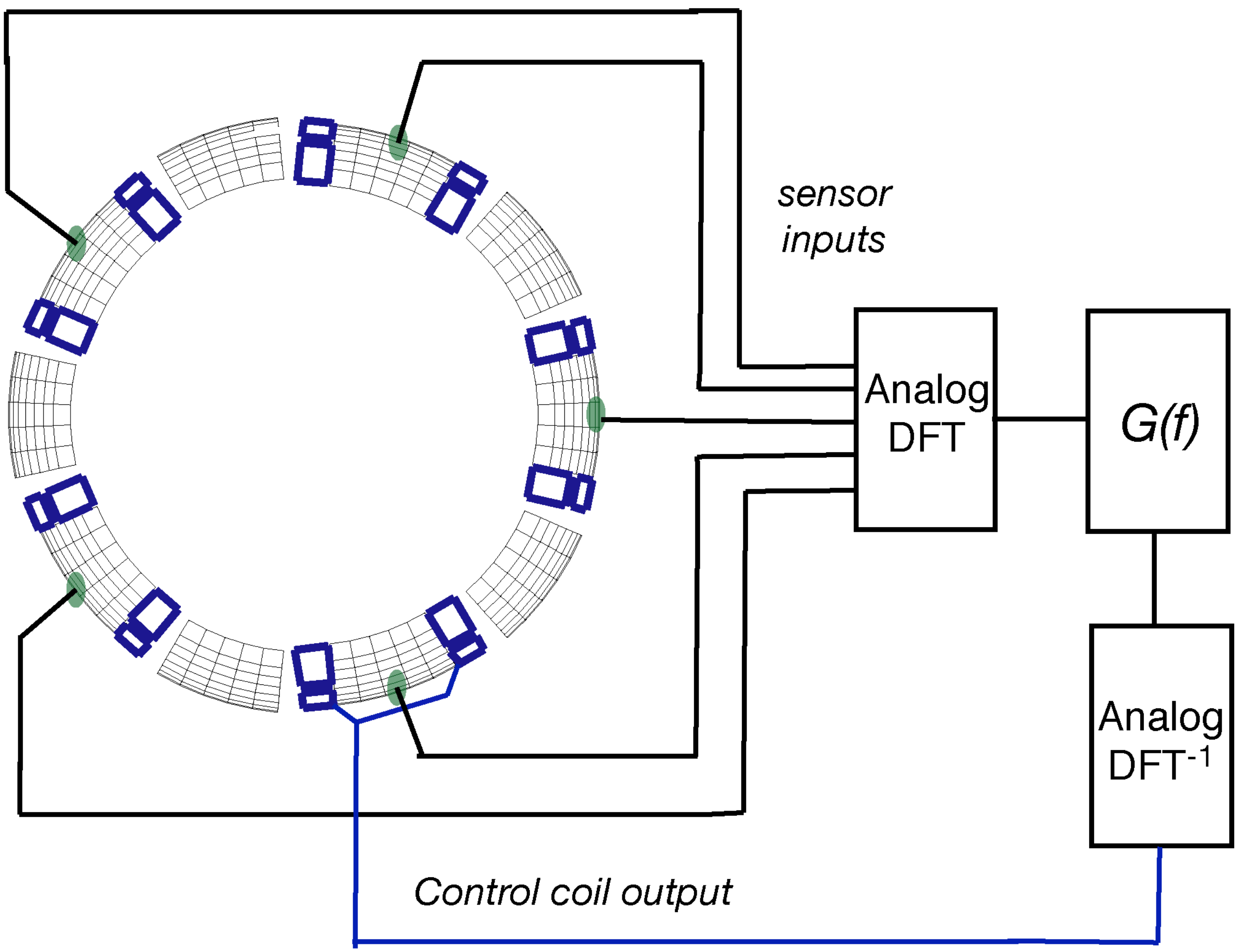
- New mode control feedback applied applied to target mode described above
- Feedback loop configured using smart shell analog board in SISO configuration
- Poloidal sensors at a given toroidal angle used as feedback signal for radial control coils +/- 72 degrees adjacent
- Simple Feedback loop suppressed mode amplitude

Mode Growth is Observed with Alternate Phasing



- Feedback phase changed by 144 degrees from previous suppression phase observed above
- Large amplitude mode driven by feedback phasing
- Mode grows so large minor disruption induced q evolution altered slightly
- Starting development of n=1 MISO control loop circuitry

New Poloidal Field Sensor Feedback Loop Configuration Being Designed



- New MISO analog processer for real time n=1 feedback being designed
  (D. Holly, U. Wisc. PLP1050)

- Five sensors at a given poloidal angle will be summed with appropriate weights to generate sin and cos n=1 signals. These will be recombined to drive a given control coil at that poloidal angle

$$V_{out}=[DFT^{-1}][GAIN][ROT][DFT]V_{in}$$

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HBT-EP Summary

- Built new 40 element (20 series pairs) directly coupled coil set
- Installed 20 new poloidal field sensors for mode control feedback system
- Operated new coils in SISO configuration for preliminary experiments
- Observed RWM suppression/growth with new feedback coil phasing using “smart shell” analog board

HBT-EP Next steps

- Implement new MISO n=1 analog feedback controller
- Demonstration of RWM suppression at ideal wall limit
- Start new digital MHD control system layout