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Feedback Control of External MHD Modes using High Speed FPGA Computing on the HBT-EP Tokamak

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with the help of

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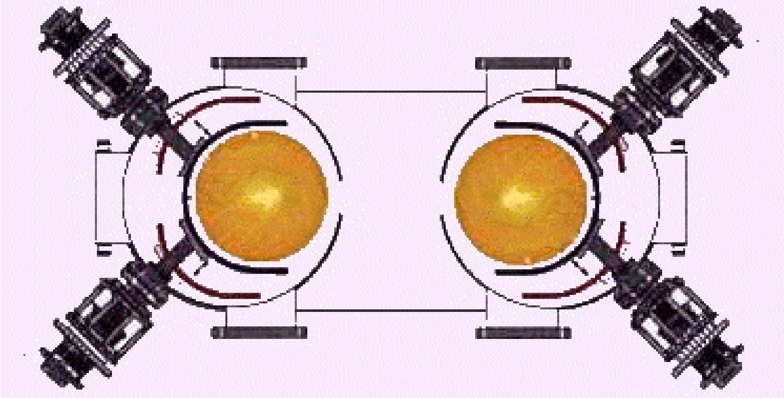
HBT-EP

HBT-EP: a tokamak designed specifically to study effects of conducting walls and explore feedback schemes to improve MHD stability



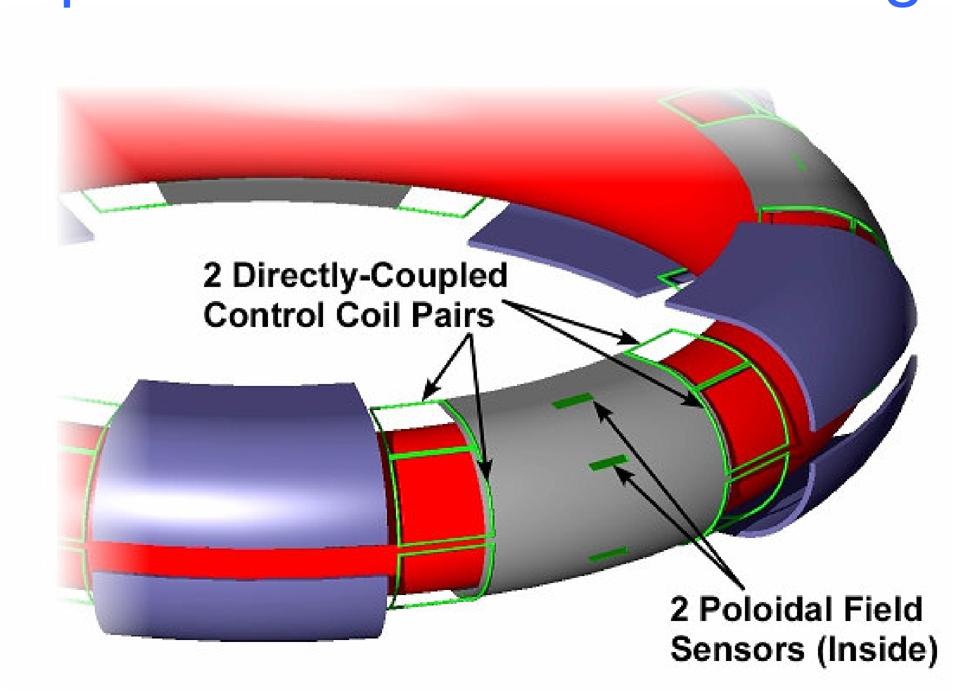
- Moveable conducting shells surround plasma
- Partial passive stabilization by having 50% of shells be highly conducting
- Active feedback through use of electro-magnetic control coils mounted in gaps between shells

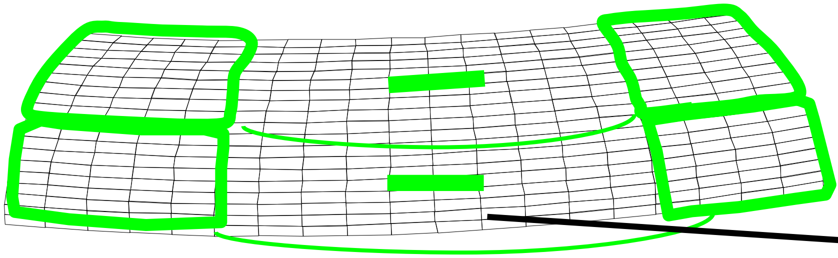
MODE CONTROL: optimized feedback configuration (with aid of VALEN code) enables rapid response, high gain, low noise, robustness

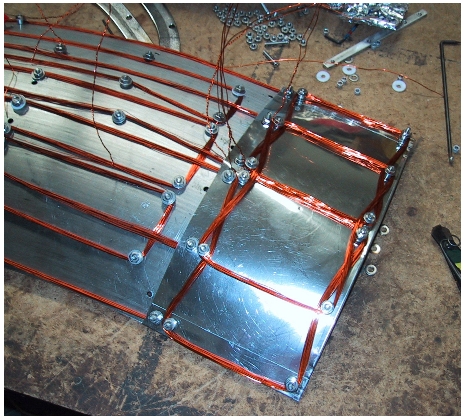
- Control coils couple directly to plasma: mutual inductance with passive conducting shell minimized
- Sensor coils also directly facing plasma, decoupled from passive shells
- Control coils and sensor coils decoupled: radial vs. poloidal magnetic fields

Mode Control:

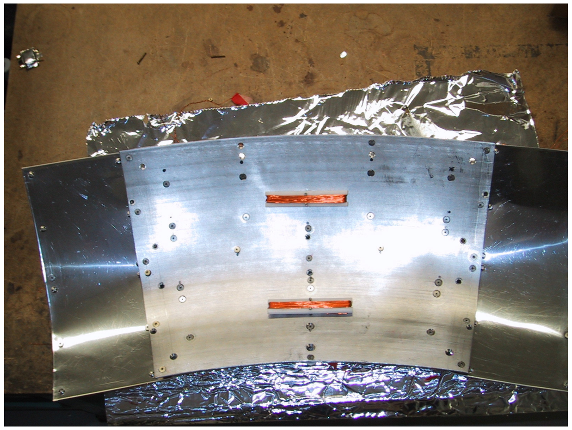
Optimized Feedback Configuration





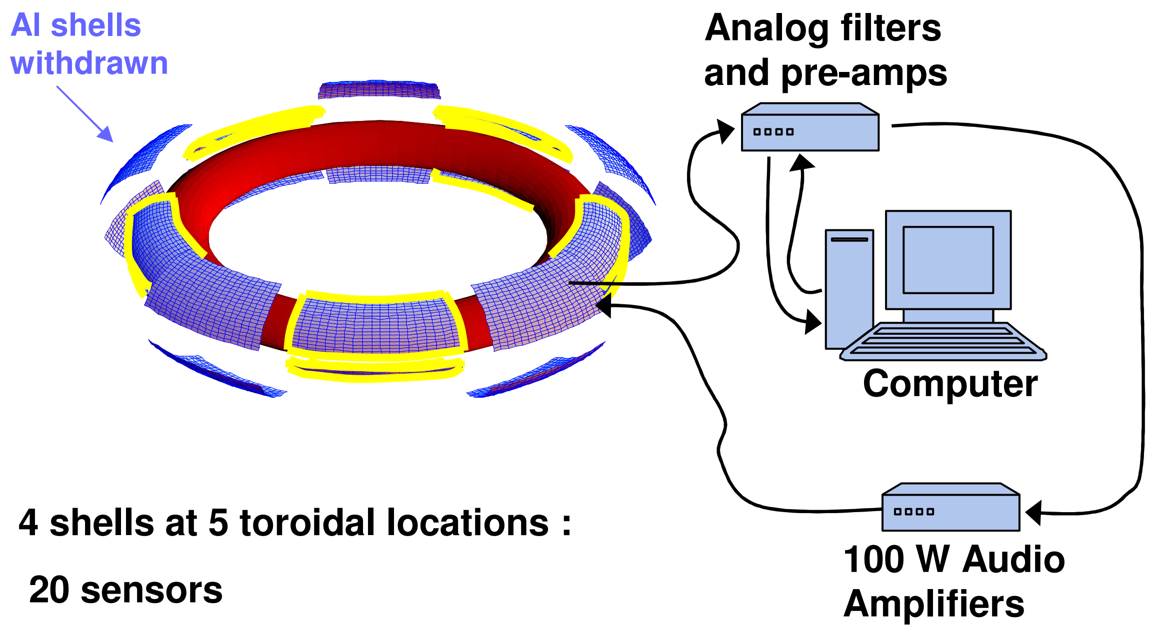


Radial Control Coils



Poloidal Sensor Coils

Mode Control Feedback Implementation



Al shells withdrawn

Analog filters and pre-amps

Computer

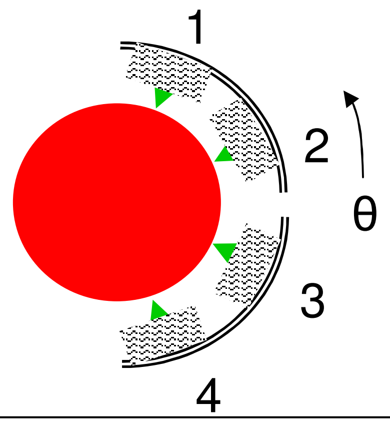
100 W Audio Amplifiers

4 shells at 5 toroidal locations :

20 sensors

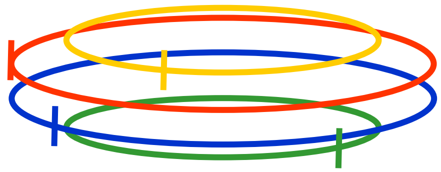
20 pairs of control coils

Sensors and Control Coils grouped according to poloidal angle. Each group performs feedback independently



System latency: 10 μsec, limited by A/D conversion

Each sensor group processed by separate module, with floating toroidal phases



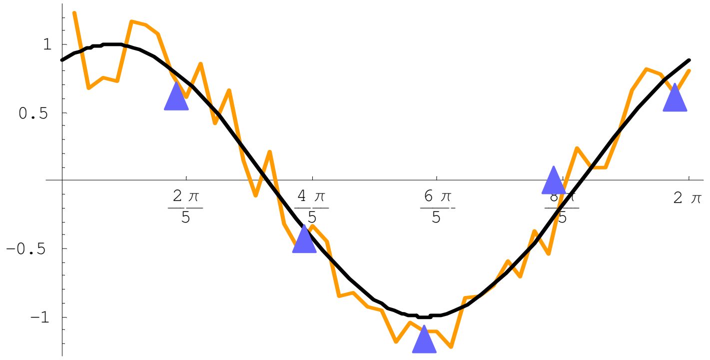
4 independent control loops

Mode Control Feedback Implementation

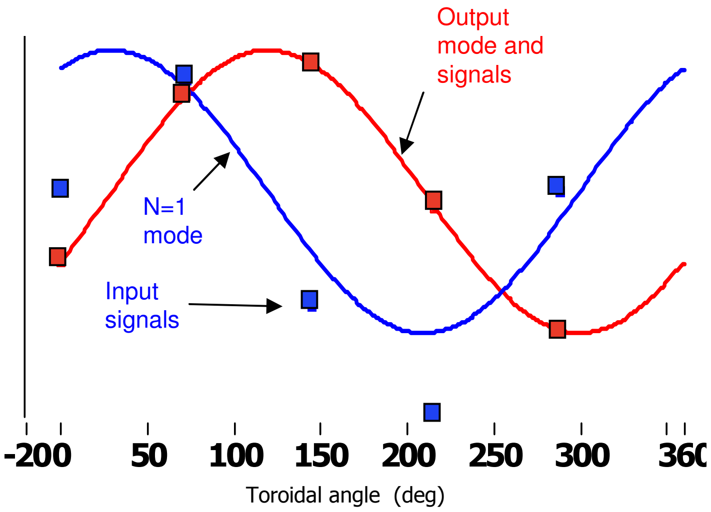
processing of 5 torroidal signals is accomplished with a simple 5x5 matrix multiply operation

$$\vec{\mathrm{S}}_{\mathrm{cntrl}} = \overleftrightarrow{\mathrm{T}} \bullet \vec{\mathrm{S}}_{sens}$$

where $$\overleftrightarrow{\mathrm{T}} = \overleftrightarrow{\mathrm{A}^{-1}} \times \overleftrightarrow{\mathrm{R}} \times \overleftrightarrow{\mathrm{N}} \times \overleftrightarrow{\mathrm{A}}$$

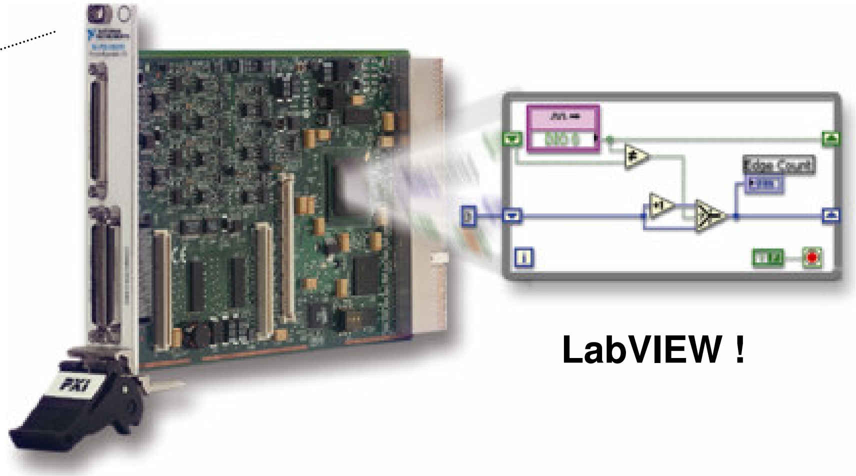


(noisy) Input signals from 5 toroidal locations



Result of calculation for noisy signals transformed with 90° phase shift

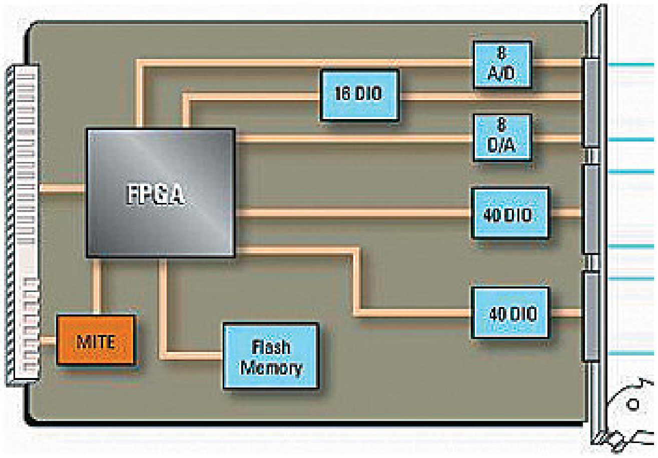
High speed digital signal processing:
National Instruments Real Time Modules



LabVIEW !

Each board provides:

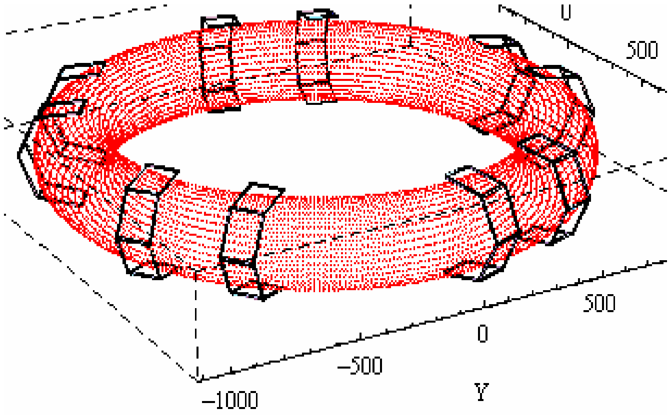
- ✓LabVIEW-configurable Xilinx II FPGA
- ✓8 Independent 16-bit analog inputs, 200 kHz
- ✓8 Independent 16-bit analog outputs, 1 MHz
- ✓96 digital I/O lines
- ✓Onboard flash memory
- ✓Onboard 8 kb RAM
- ✓PXI interface for synchronizing multiple boards



Gain

$$\psi_{m/n} \propto \sin(n\phi - m\theta^*)$$

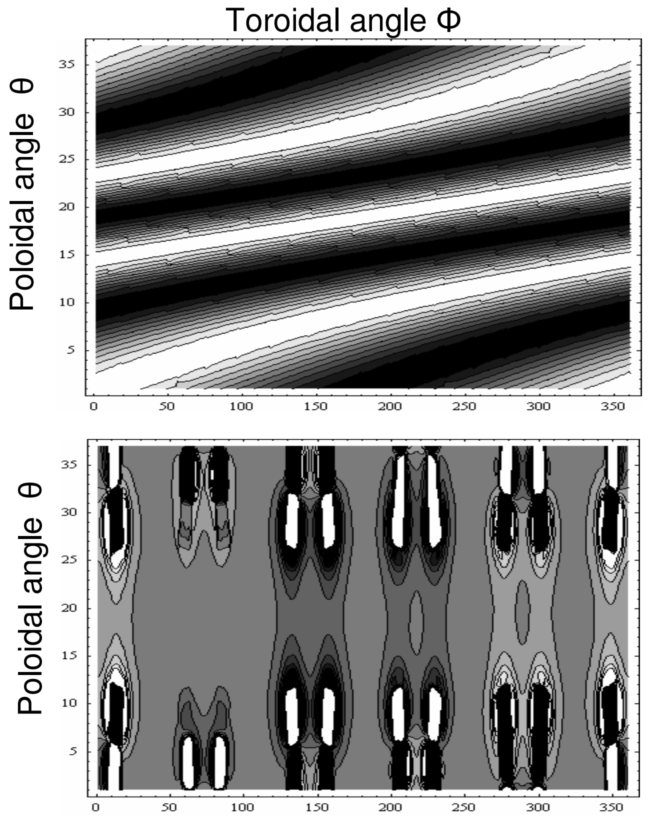
where $\theta^* = \theta - 0.4\sin(\theta)$



$$\mathrm{Gain}_{\mathrm{m/n}} \equiv \frac{\int_{surface} B_{\mathrm{contr}} \cdot \psi_{m/n}}{\int_{surface} B_{\mathrm{plasma}} \cdot \psi_{m/n}}$$

Configuration operates with gain$_{(3/1)}$ ~ 0.2

In principle can be run at 40 times higher gain with amplifier upgrade (measured)



Radial flux produced by plasma and control coils when configured to produce 3/1 mode

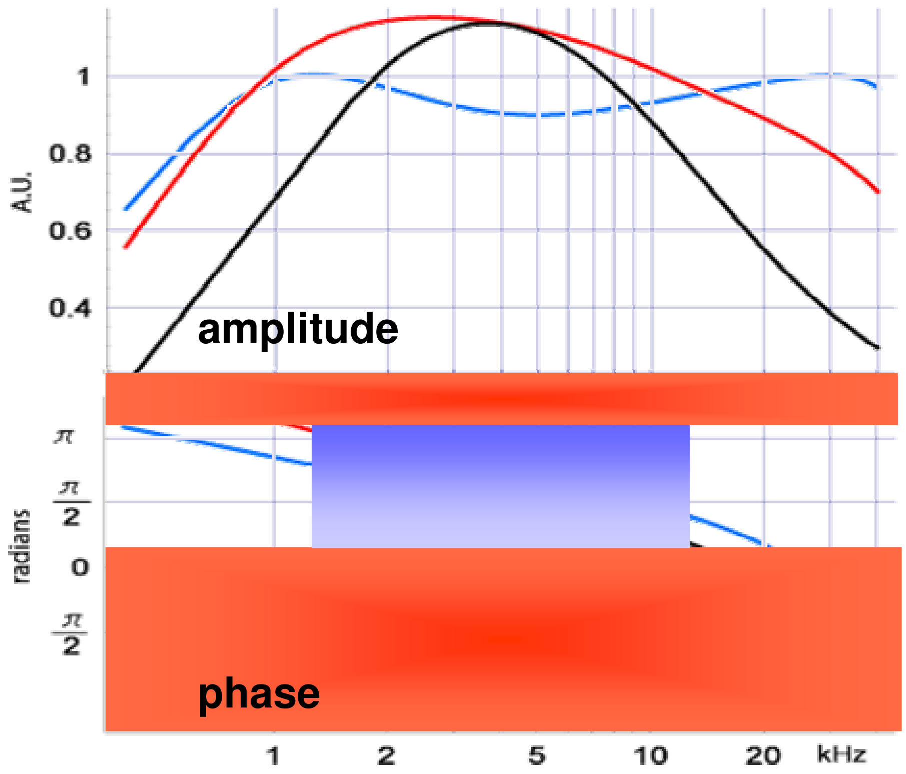
Transfer Functions and their importance for rotating modes

Temporal phase shift equivalent to a spatial phase shift due to mode rotation

Negative feedback only in narrow frequency band

Phase compensation: 2nd order digital filter producing a combination of phase lead/phase lag compensation serves to maintain a relatively constant phase response from 1-20 kHz

Total system transfer functions:



— System transfer w/out compensation

— With “bad” compensator

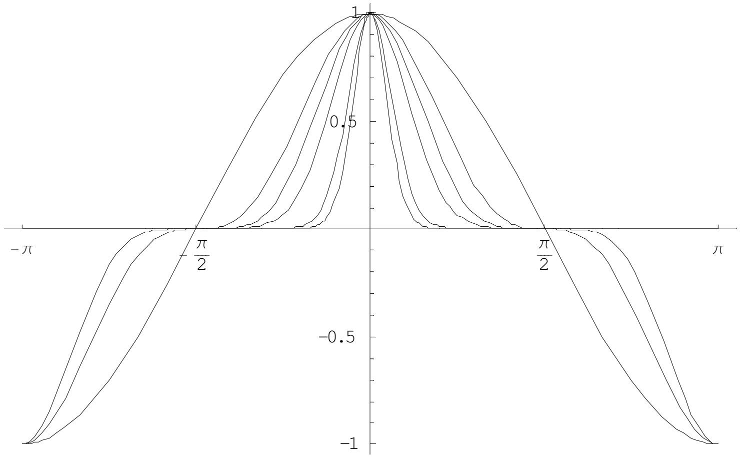
— With good compensator

Optimizing Digital Filter Using Cost Functions

Many cost functions used, among them:

$$C = \frac{A}{A_{\max}} Cos(\Delta\phi), \quad \frac{A}{A_{\max}} Cos^3(\Delta\phi), \quad \frac{A}{A_{\max}} Cos^5(\Delta\phi),$$

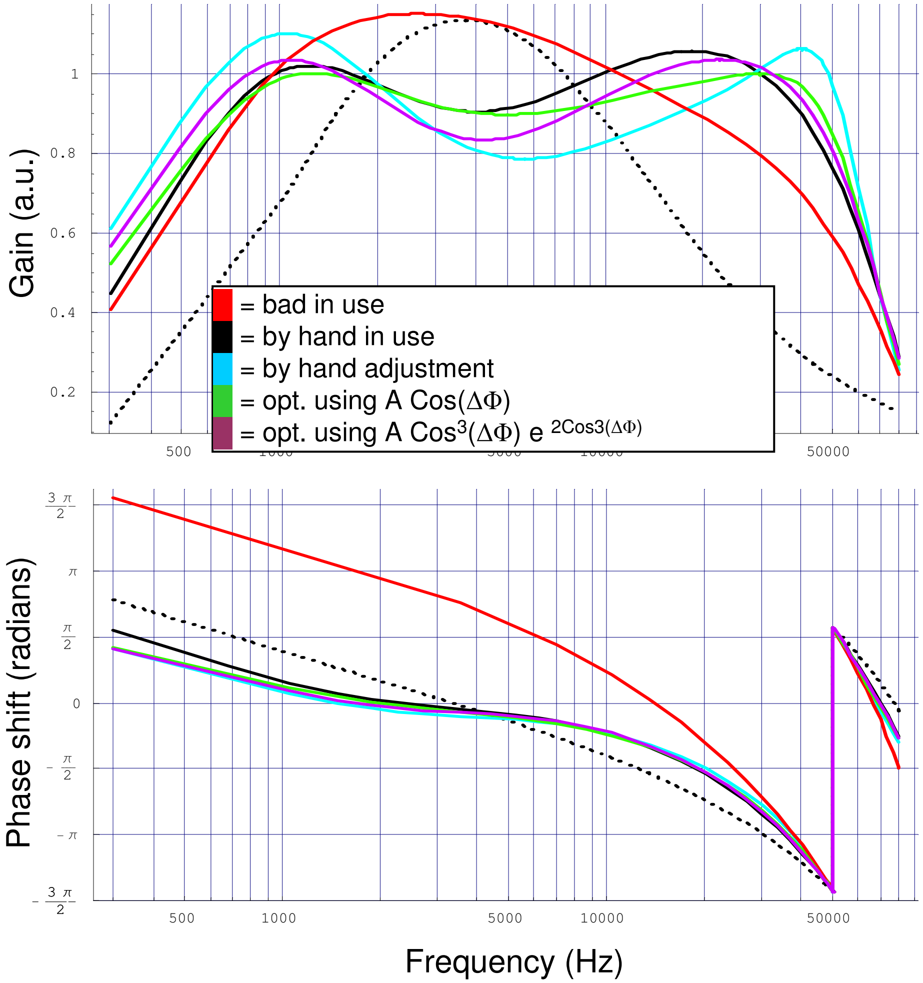
$$\frac{A}{A_{\max}} Cos(\Delta\phi)\cdot e^{2Cos(\Delta\phi)}, \quad \frac{A}{A_{\max}} Cos^3(\Delta\phi)\cdot e^{2Cos^3(\Delta\phi)}$$



Reward and penalty for phase deviation from phase shift at center frequency

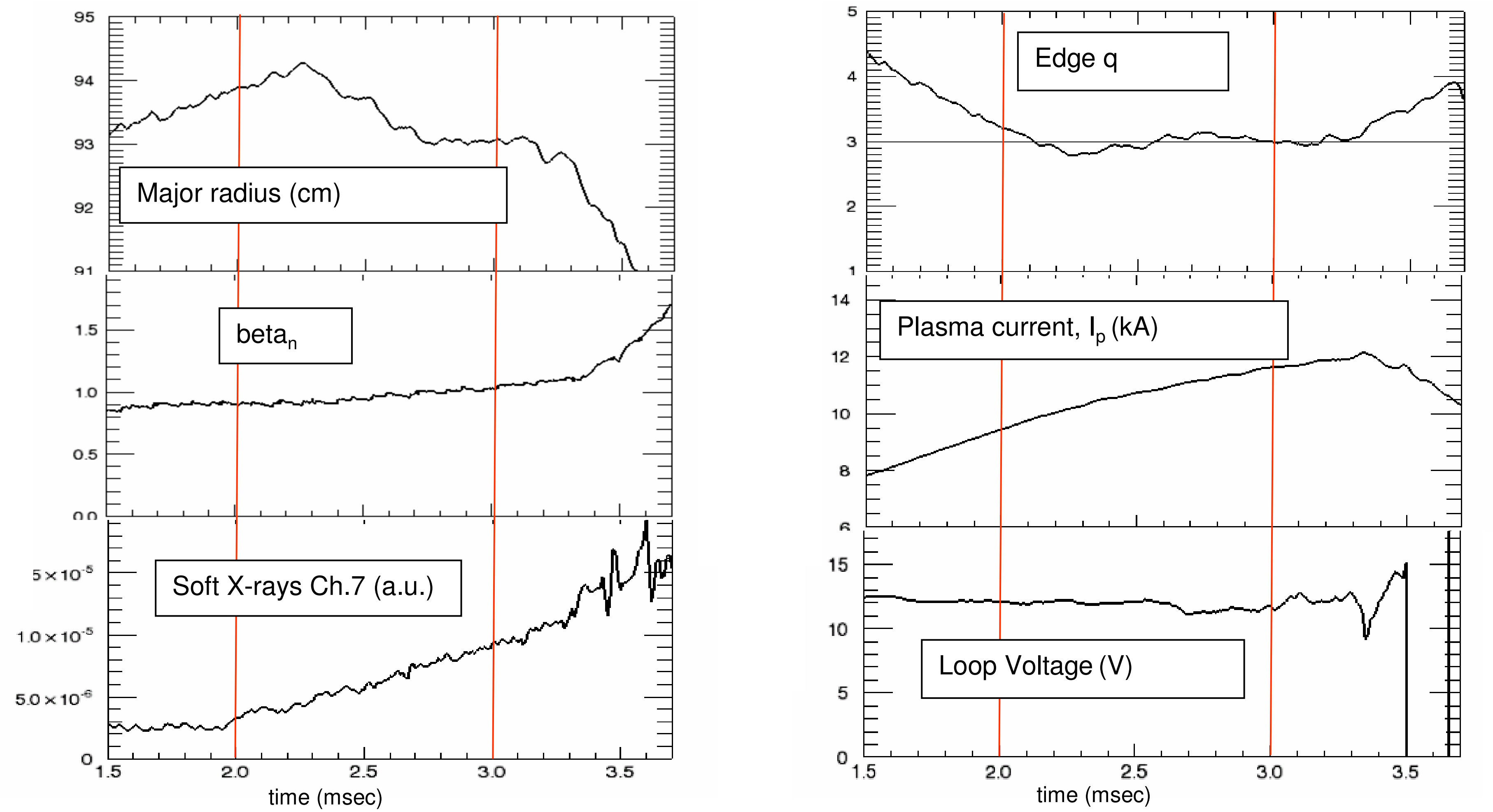
Results were almost identical

Total system transfer functions:



Plasma Parameters

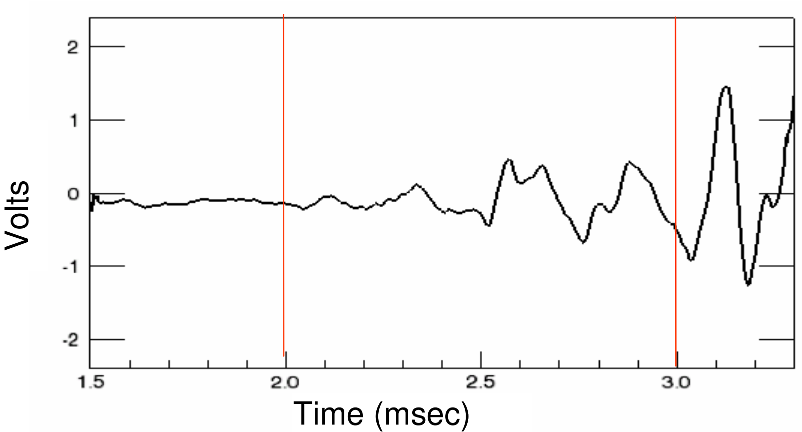
- sustained current ramp (2 MA/s) brings q* down rapidly, simultaneously broadening current profile
- edge q remains near 3 to excite edge-localized, current-driven external kink instabilities
- shot consistently developed MHD modes (growth time ~300 μsec) when the q* = 3 surface was located just exterior to the plasma



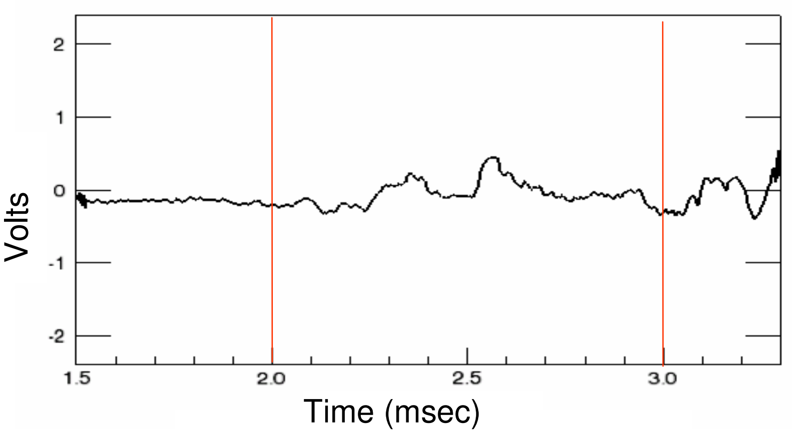
Shot# 44256

Plasma Parameters

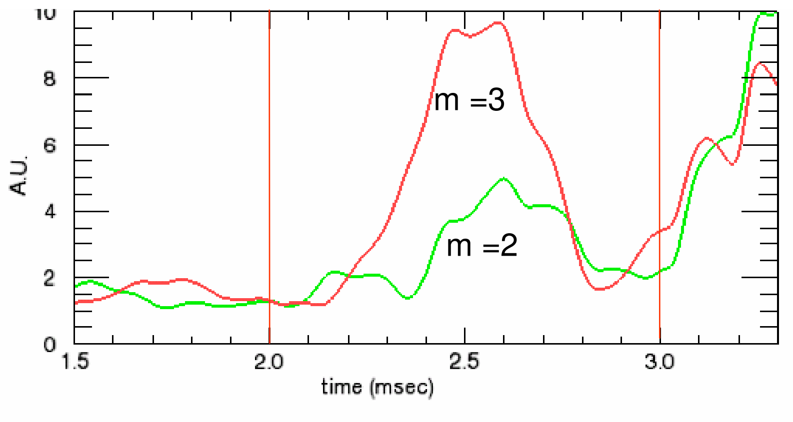
- Shot consistently developed 3/1 MHD modes (growth rate ~300 μsec) when the q* = 3 surface was located just exterior to the plasma.



m = 3 Rogowski coil pick up

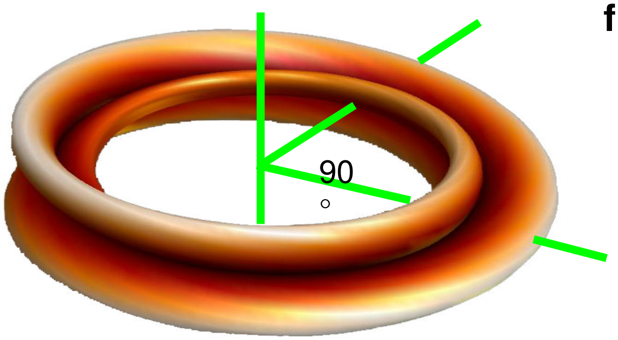


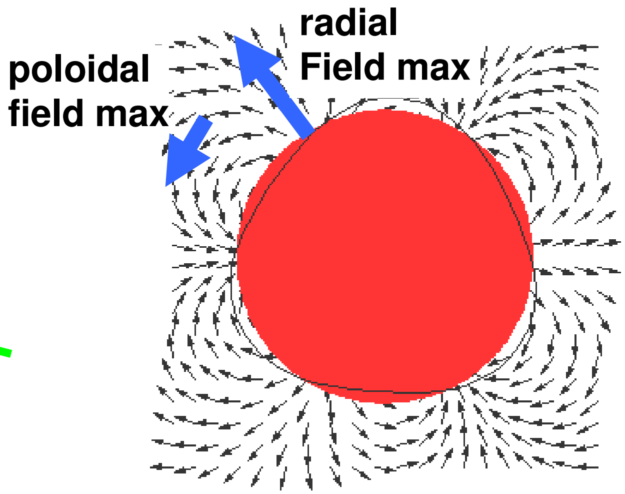
m = 2 Rogowski coil pick up



Mirnvov array: m = 3, m = 2 decomposition

3/1 External Kink Mode Structure:



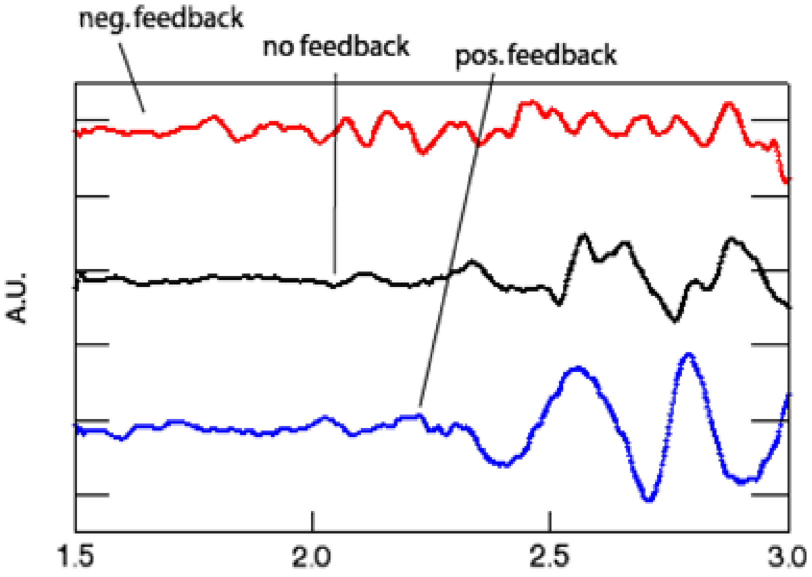


For any n = 1 mode, maximum poloidal and maximum radial perturbed magnetic fields are toroidally 90° out of phase

(Since poloidal phase of sensor/contr. coils floats, all m numbers dealt with)

Feedback expected to be effective when c-coil currents are 90° toroidally phase shifted with respect to sensor B-field phase

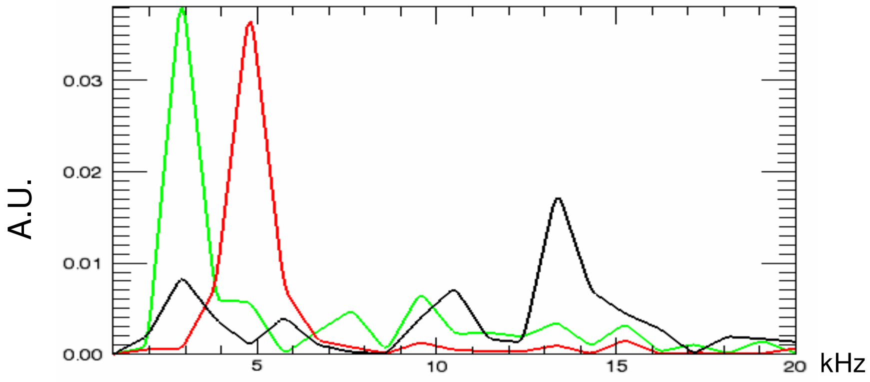
This is the case as observed in m = 3 Rogowski signals during feedback: Suppression (red) and excitation (blue) of m = 3 mode depend on toroidal phase shift of feedback system (black is natural mode, no feedback)



Measuring Feedback Effectiveness:

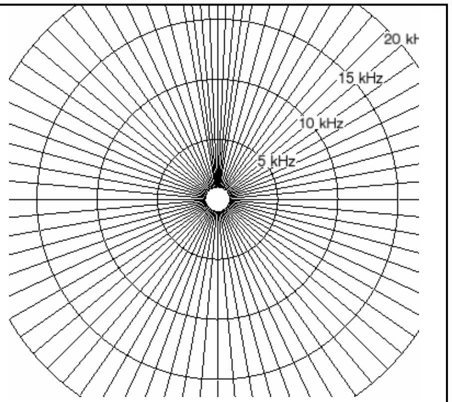
Analysis of a m = 3 Rogowski Coil Signal

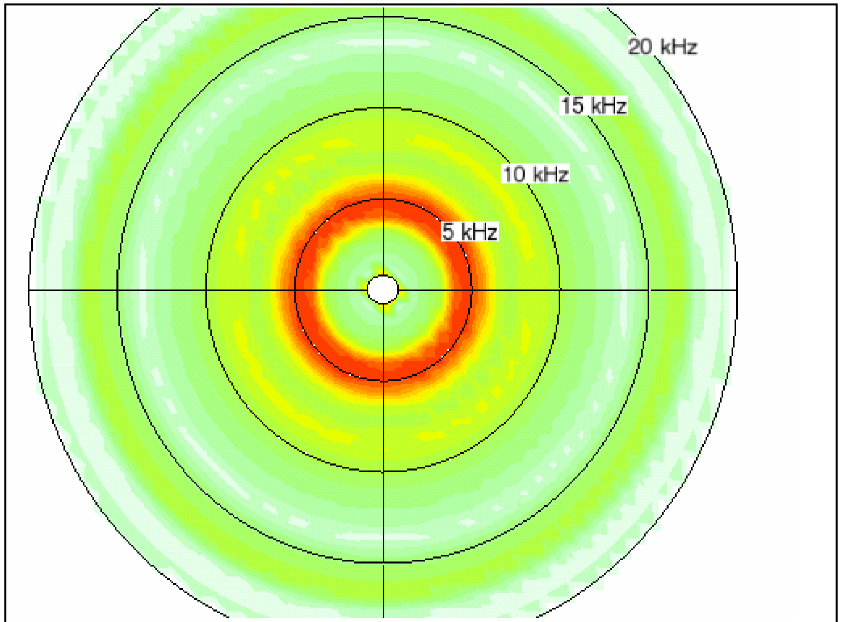
Signals from t = 2 to 3 msec are Fourier analyzed to get mode amplitude at frequencies from 1-20 kHz



m = 3 mode amplitudes at various frequencies for three different sample shots (black, green w. feedback)

148 discharges with identical parameters were run. Toroidal phase between control and sensor signals is rotated in small increments between shots.





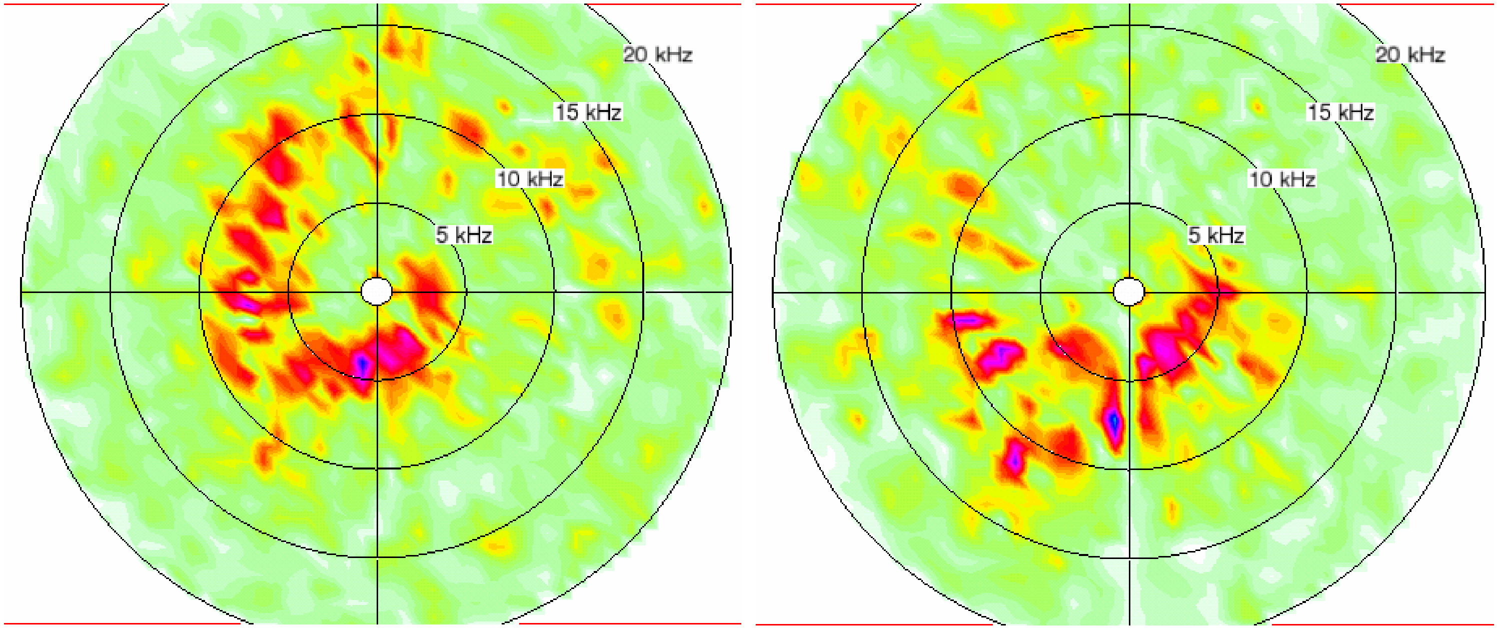
0 Color scheme for all contour plots (a.u.) **1**

Natural (no feedback) mode (average of 3 shots), shown for all angles for comparison with feedback shots (phase not defined in case of no feedback)

Results with Two Kinds of Transfer Functions:

a) “Bad” compensator resulted in steep phase shifts as function of frequency. The result is that the system, while suppressing the natural mode at some phase angles, will always excite a mode at some other frequency

b) When phase shifts are kept constant, feedback suppresses kink modes when toroidal phase is set for control fields to oppose plasma fields



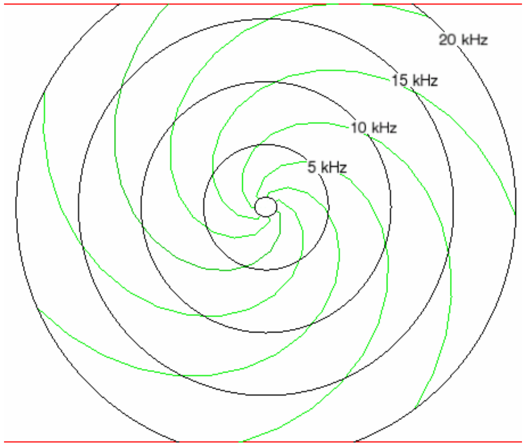
a) Amplitude of m = 3 Rogowski signal vs. frequency and target phase angle with steep frequency dependent phase transfer function

b) Amplitude of m = 3 Rogowski signal vs. frequency and target phase angle with effective phase compensation

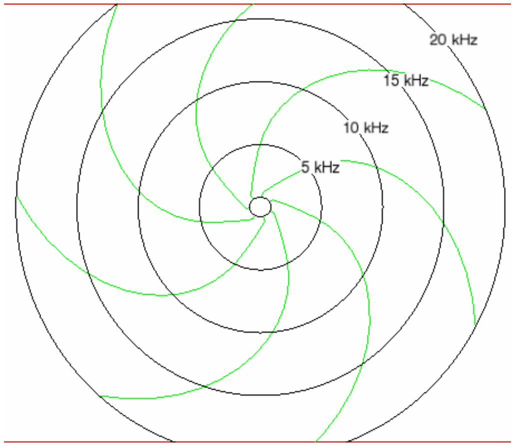
Taking transfer function phase shifts into account in the analysis: Phase shift in time is equivalent to a phase shift in space

Frequency-phase mapping of transfer function phase shifts illustrates phase margin limitations of feedback

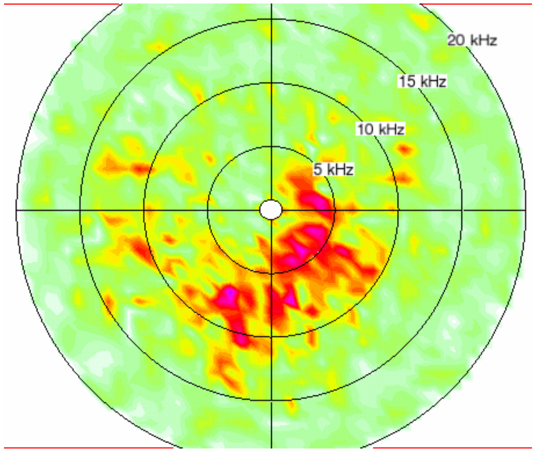
One can undo the mapping and plot mode amplitude vs. true toroidal phase angle for each frequency. The result shows that the mode does look like what one expects: The poloidal and radial fields are 90° out of phase. The two datasets look almost identical



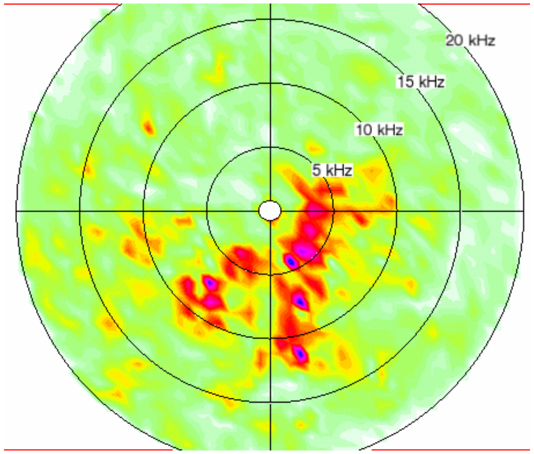
a) Map of bad compensator



b) Map of good compensator



a) Data obtained with bad compensator unraveled

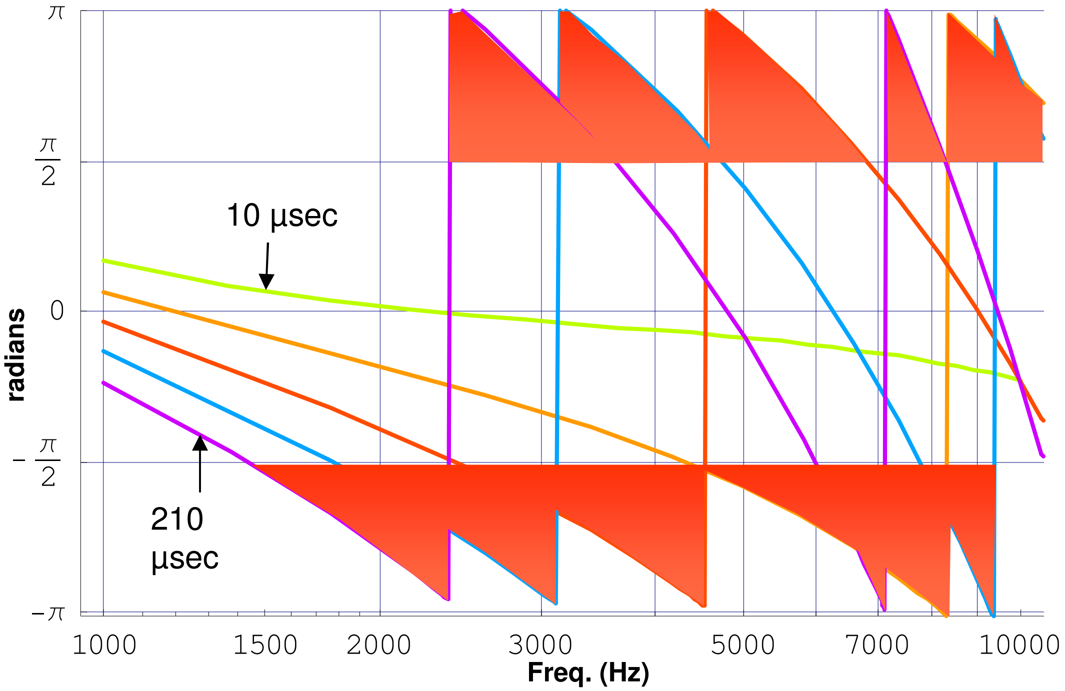


b) Data obtained with good compensator unraveled

The Effect of Latency

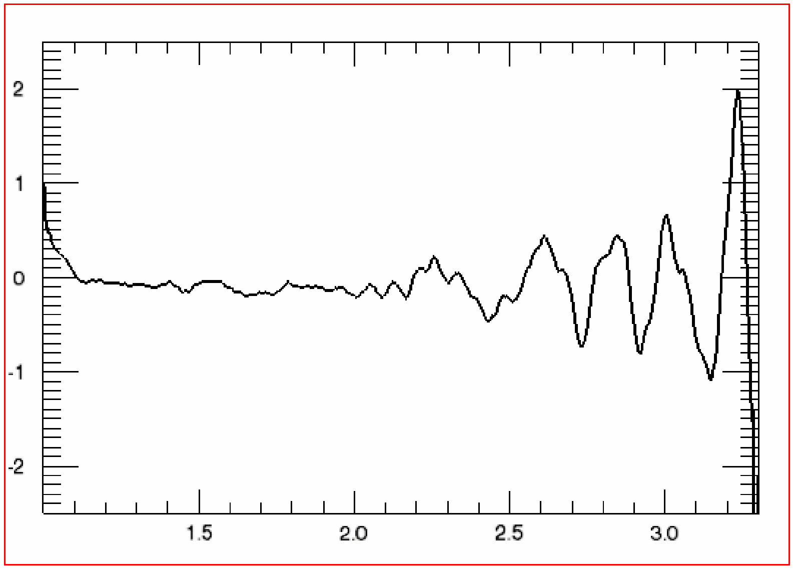
- **For stability of system, latency must be less than characteristic growth time of any instability**
- **Latency also adds phase shifts to the transfer function of the system, especially pronounced at high frequencies (when mode rotation period becomes comparable to latency period)**

Experiments performed where system latency was increased by programming a delay into the feedback algorithm. Results show that latency is an important component in the design of a digital feedback system

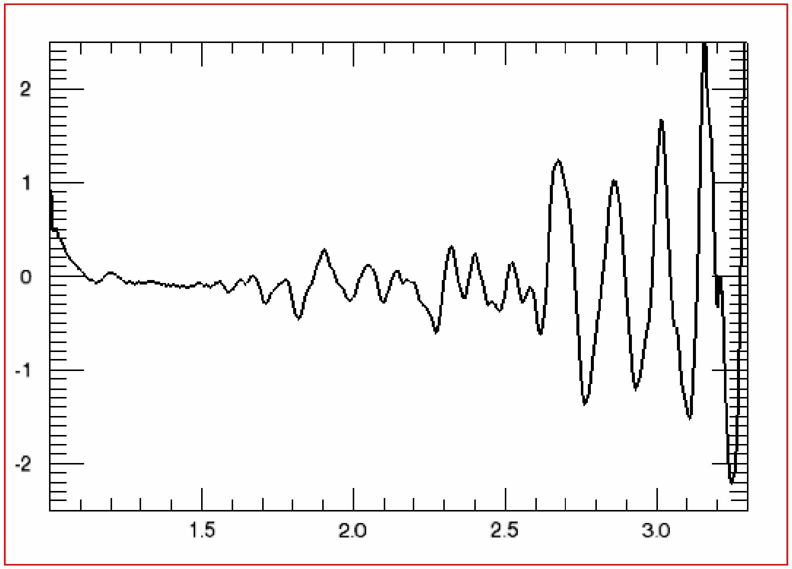


Phase response of feedback system with latency settings: 10, 60, 110, 160, and 210 msec

Latency data:



m =3 from shot #43312 (no feedback)



m=3 from shot #43305, 60 μsec latency

↑

Latency adds phase shift, phase shift drives mode at higher frequency

Conclusions:

- **Low cost, high speed, versatile & user-friendly mode control system operating on HBT-EP**
- **VALEN predicts gain is sufficient to stabilize external kink up to ideal limit**
- **Feedback very effective when lead/lag compensation provides relatively flat transfer function phase shifts**

Future work:

- **Investigate mode rigidity & gain effects**
- **Experiment with feedback in no-rotation limit (biased electrode)**
- **Connect poloidal groups, add complexity to algorithm (Kalman filter?)**
- **Act on n = 2 modes**