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XP-10??: RFA Suppression With Different Sensors and Time Scales in NSTX

S. P. Gerhardt, J. E. Menard, S. A. Sabbagh

NSTX Team Review
April 19th, 2010

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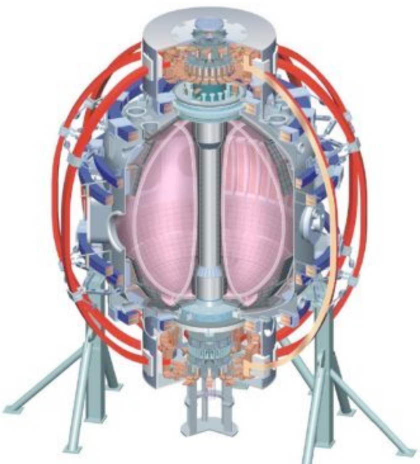

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Overview

- Background:
  - RFA is the amplification of “error fields” by a ***stable*** RWM.
  - The resulting rotation damping can destabilize the RWM.
  - In 2007, JEM utilized RFA to develop a DEFC scheme.
    - XP-701 used B_P sensors only.
  - New compensations have been implemented in real-time, allowing better mode identification using B_R sensors.
- Goals of proposed XP:
  - Determine B_R sensor compensations and FB parameters which are optimal for error field correction.
    - Examine system response to applied n=1 fields.
    - Examine system response to the intrinsic time-varying error field.
    - Attempt to minimize rotation damping and pulse length using B_R feedback.
  - Compare results to DEFC with B_P sensors.
  - Verify appropriate F.B. gain and phase for newly-compensated B_P and B_R sensors, using RFA suppression as a guide.
- Contributes to:
  - MDC-2: Joint experiments on resistive wall mode physics.
  - MS Milestone R(10-1): Assess sustainable beta and disruptivity near and above the ideal no-wall limit.
  - Improved reliability of NSTX operations.

Outline

- New sensor compensations
- Results from previous XPs
- Considerations and shot list for this XP

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New Realtime Sensor Compensations For Improved Mode Identification

- Sensors should measure the n=1 field from the plasma only.
  - Need to "compensate" the i^{th} sensor B_i for other sources of field
  - With proper compensations, vacuum shots produce no signal
- Three compensations now in realtime system

Static
Present From Beginning

$$C_{i,static} = \sum_{j=0}^{NumCoils-1} p_j I_j$$

816 Coefficients

OHxTF
New For 2010

$$f_i = LPF\left(I_{OH} \times I_{TF}; \tau_{OHxTF,i}\right)$$

$$f_i = \frac{f_i}{1+\beta_i f_i}$$

$$\textbf{if } f_i > 0 \textbf{ then } C_{OH\times TF,i} = r_{p,i} f_i$$

$$\textbf{if } f_i < 0 \textbf{ then } C_{OH\times TF,i_i} = r_{n,i} f_i$$

96 Coefficients

AC Compensation For Fluctuating RWM Coil Currents
New For 2010

$$C_{AC,i}(t) = \sum_{j=0}^{5} \sum_{k=0}^{k_{max}} p_{i,j,k} LPF\left(\frac{dI_{RWM,j}(t)}{dt}; \tau_{AC,i,k}\right)$$

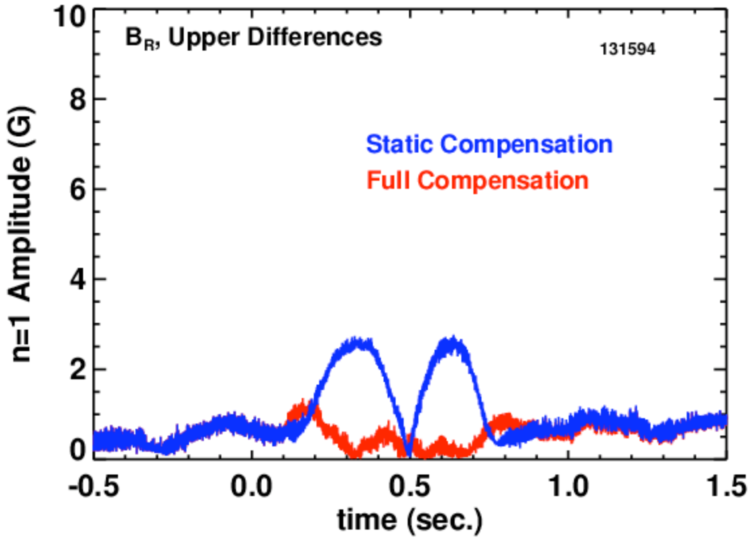
504 Coefficients

Final Field For Plasma Mode Identification

$$B_{i,plasma} = B_i - C_{i,static} - C_{i,OH\times TF} - C_{i,AC}$$

remaining compensation: vessel eddy currents via loop voltages

OH x TF Compensations Important For The B_R Sensors (I)



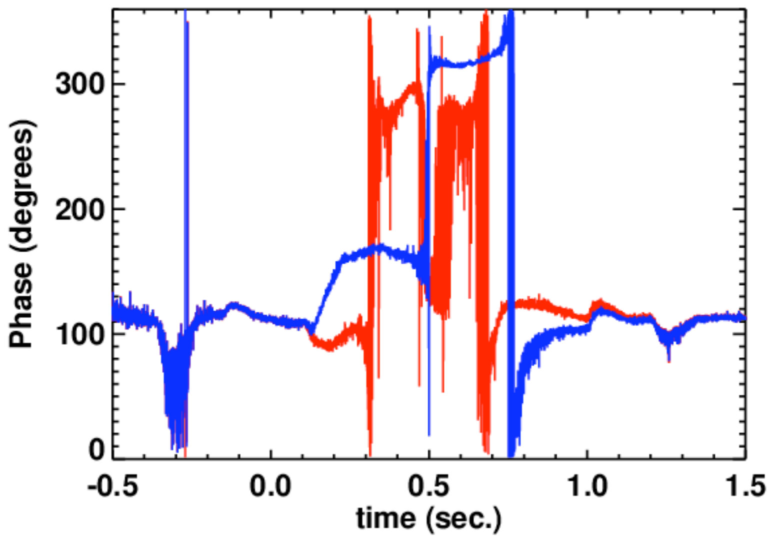
n=1 Amplitude

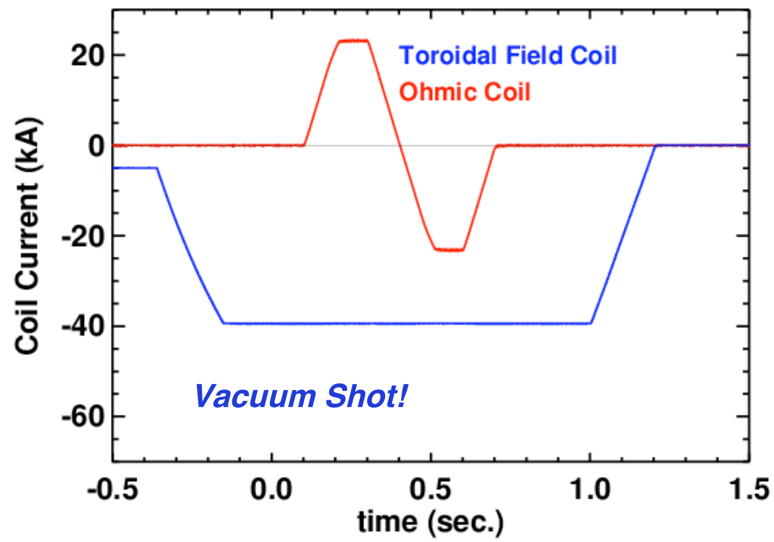
Vacuum Shot

Should not detect anything.

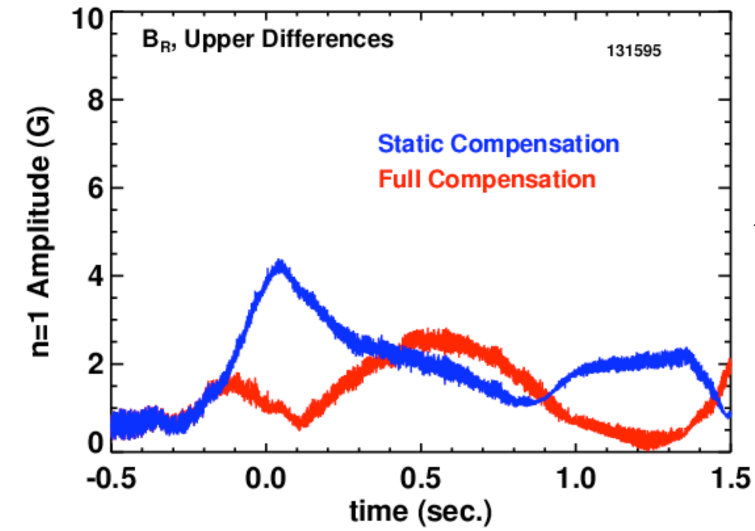
n=1 Phase

Coil Currents





OH x TF Compensations Important For The B_R Sensors (II)



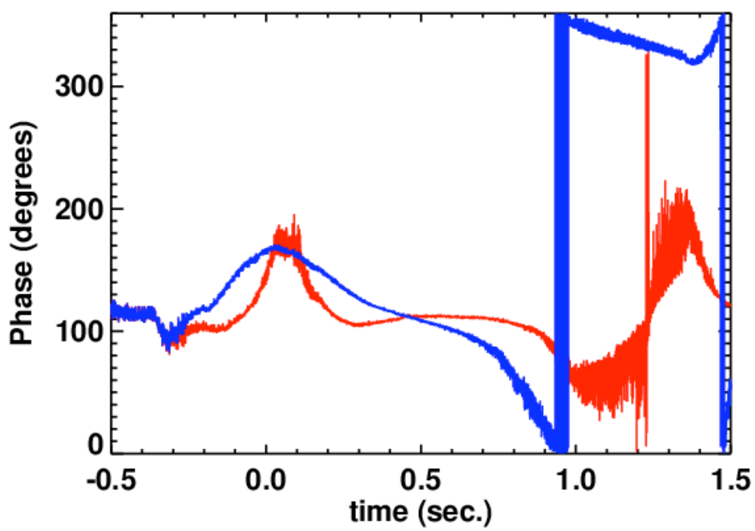
Vacuum Shot

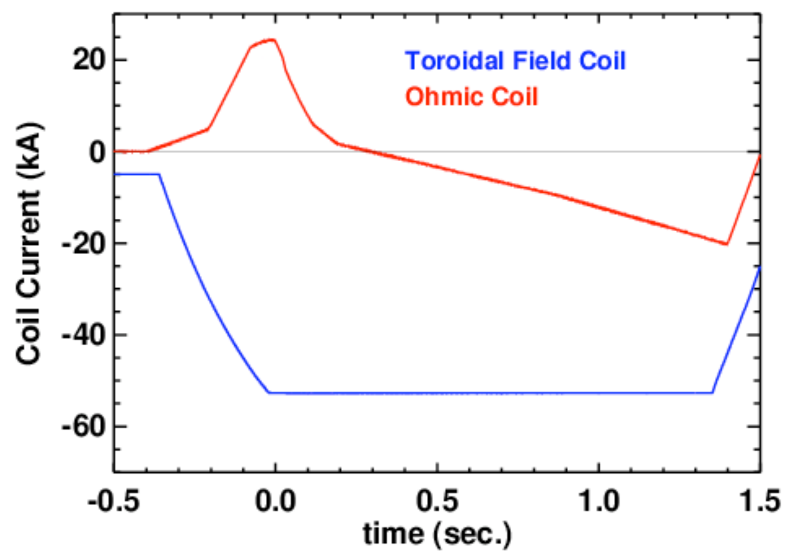
Should not detect anything.

n=1 Amplitude

n=1 Phase

Coil Currents



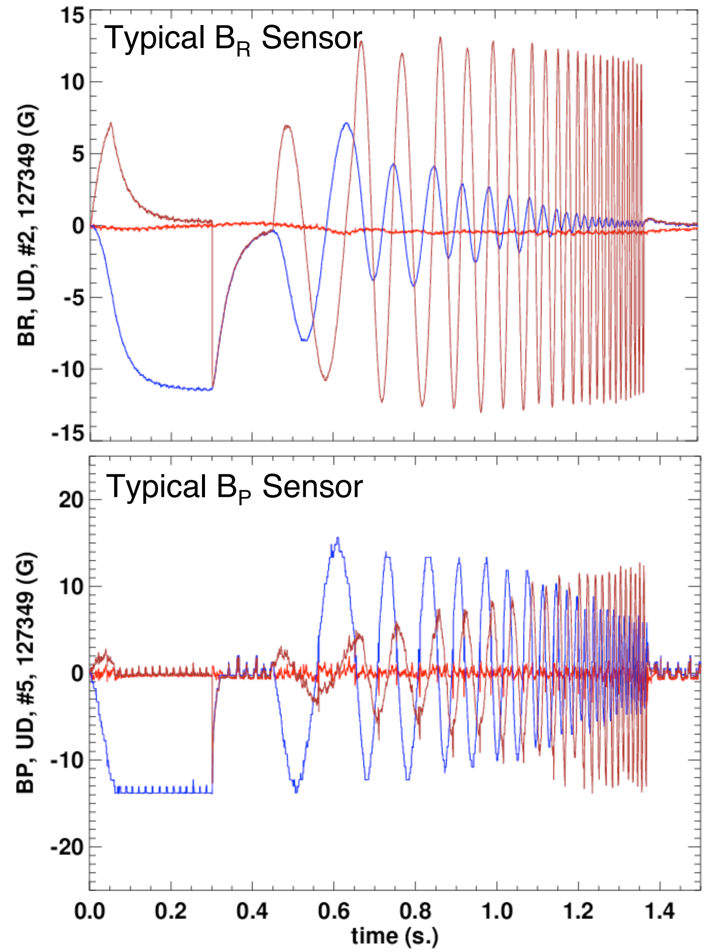


AC Compensations Remove dI_{RWM}/dt Driven Eddy-Current Pickup

$$C_{AC,i}(t) = \sum_{j}^{NumRWMCoils} \sum_{k=0}^{k_{max}} p_{i,j,k} LPF\left(\frac{dI_{RWM,j}(t)}{dt};\tau_k\right)$$

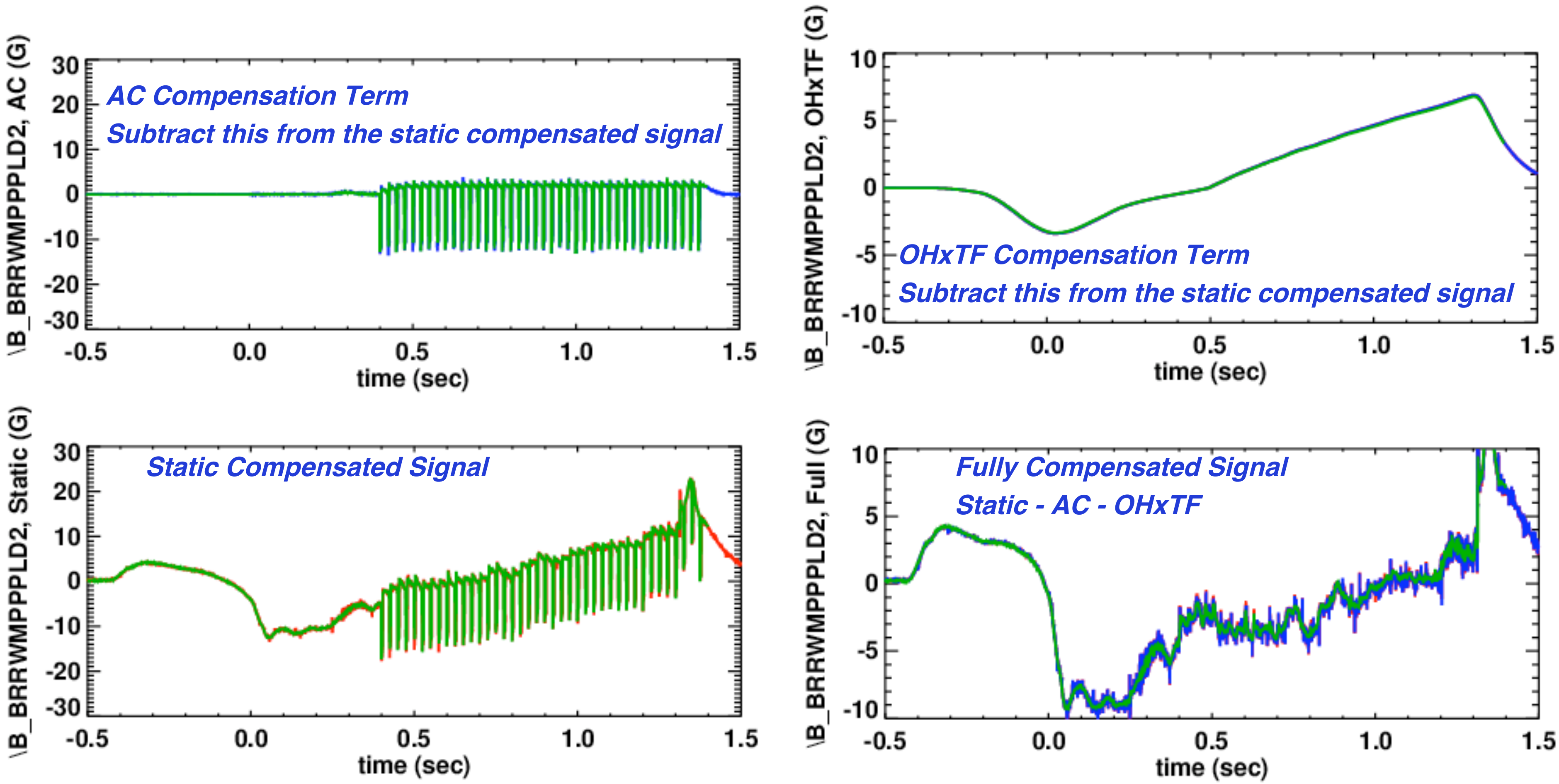
- Sensors should measure the n=1 field from the plasma only.
  - Direct mutual coupling of RWM coil to sensors has always been subtracted off in PCS.
  - Eddy currents due to dI_{RWM}/dt leads to pickup without plasma.
    - *Eddy currents are out of phase with the coil currents.*
- Realtime AC compensations may be useful for:
  - Mode identification during fast feedback.
    - SAS proposal on fast feedback.
  - Mode identification with rapidly changing preprogrammed currents.
    - ELM triggering experiments.
  - Future realtime RFA measurements.

Blue: Full Pickup
Brown: Direct Pickup Only Subtracted (Previously in PCS)
Red: Fully Compensated (Now in PCS)



New Sensor Compensation Fully Implemented in PCS "miu" Algorithm (I)

Red: Calculations in idl, from Jon's routines
Blue: Calculations in idl, in a form appropriate for PCS (streamlining a bunch of loops)
Green: Archived PCS Calculations



New Sensor Compensation Fully Implemented in PCS "miu" Algorithm (II)

Red: Calculations in idl from Jon's routines

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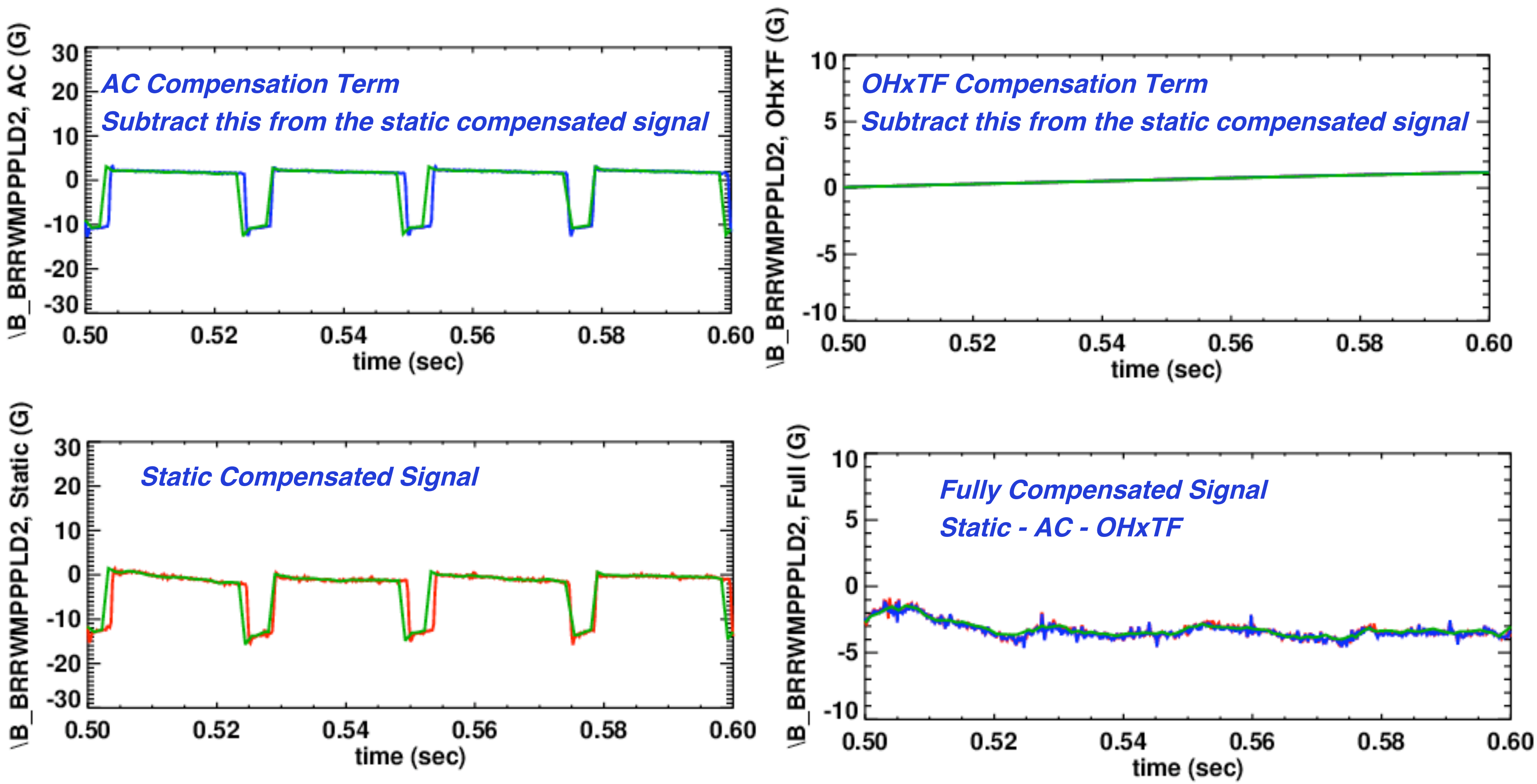
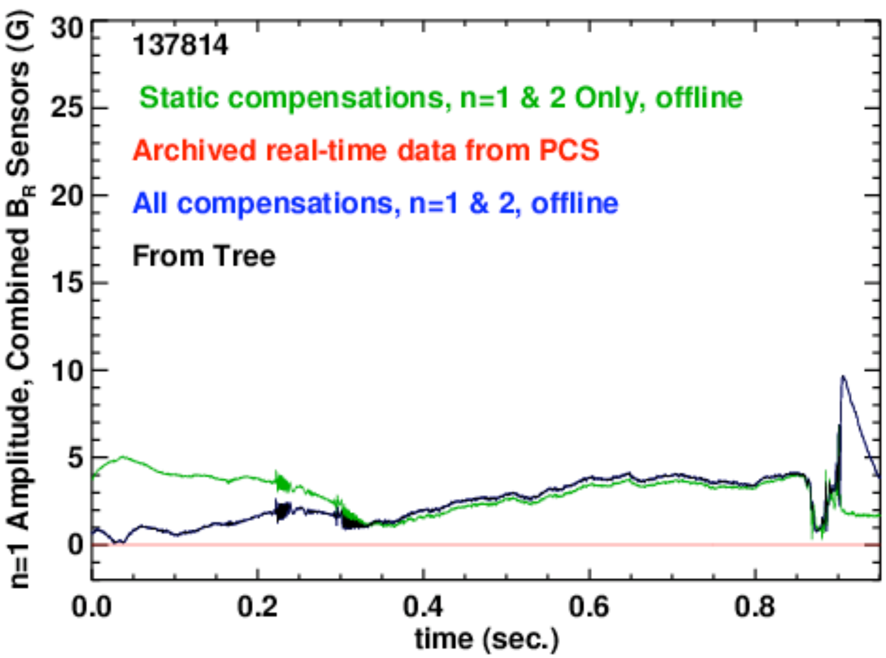
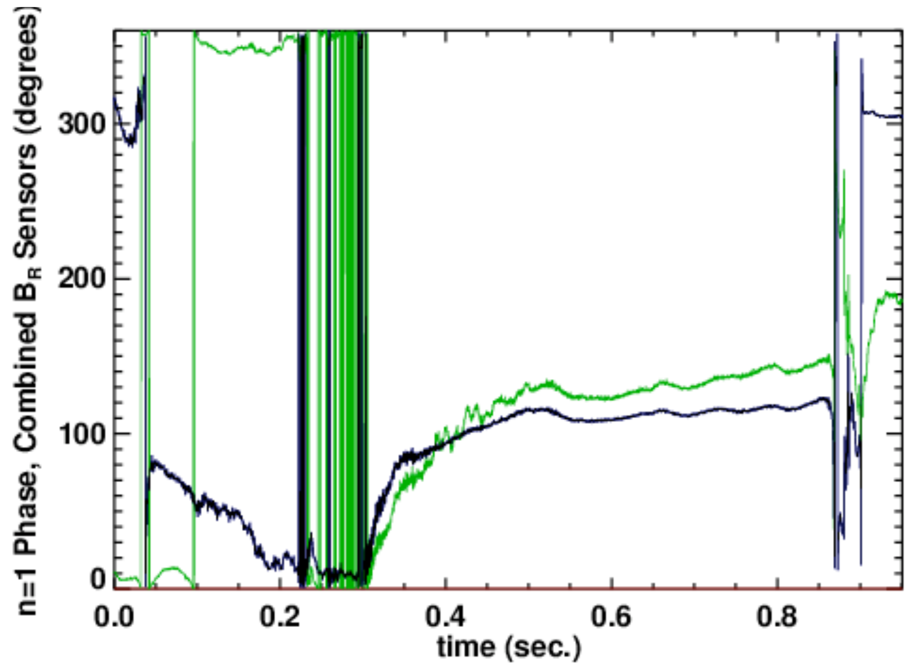


Compensations Result in ~40º Shift in Phase of B_R Detected EF

Static Compensations, as in the old algorithm.

All Compensations





More About the New "miu" Algorithm

- Provides identical "outputs" as the present mid algorithm
  - Mode amplitude and phase from B_P, B_R, & B_P+B_R sensors.
  - Fully interchangeable with the mid algorithm for RWM control.
- Allows separate re-zeroing times for B_R and B_P sensors.
  - Old mid algorithm had a single common re-zeroing time.
- Has switches to turn off the new compensations.
  - "static only"
  - "static +AC"
  - "static+OH×TF"
  - "static+AC+OH×TF
- All compensation coefficients are read from the model tree.
  - Many new nodes open in the model tree in September.
- Archives many many internal calculations for comparison to off-line.
- Prepares sensor data for the state-space controller.

"miu" was used on Friday the 16th without incident.

Outline

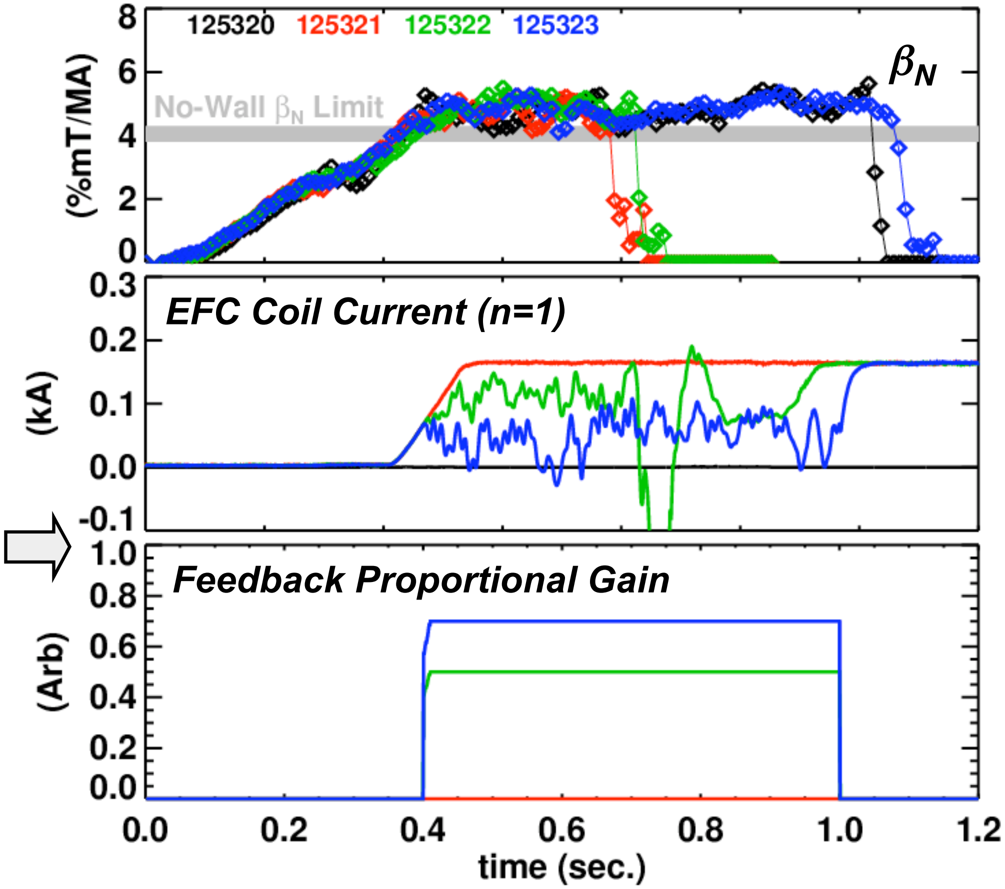
- New sensor compensations
- Results from previous XPs
- Considerations and shot list for this XP

2007 Experiment Had a Phase Scan…
…and a Gain Scan

- **Pre-programmed n=1 EF correction requires a priori estimate of intrinsic EF**
- Detect plasma response → **EF correction using *only feedback on RFA***

RFA Suppression Algorithm

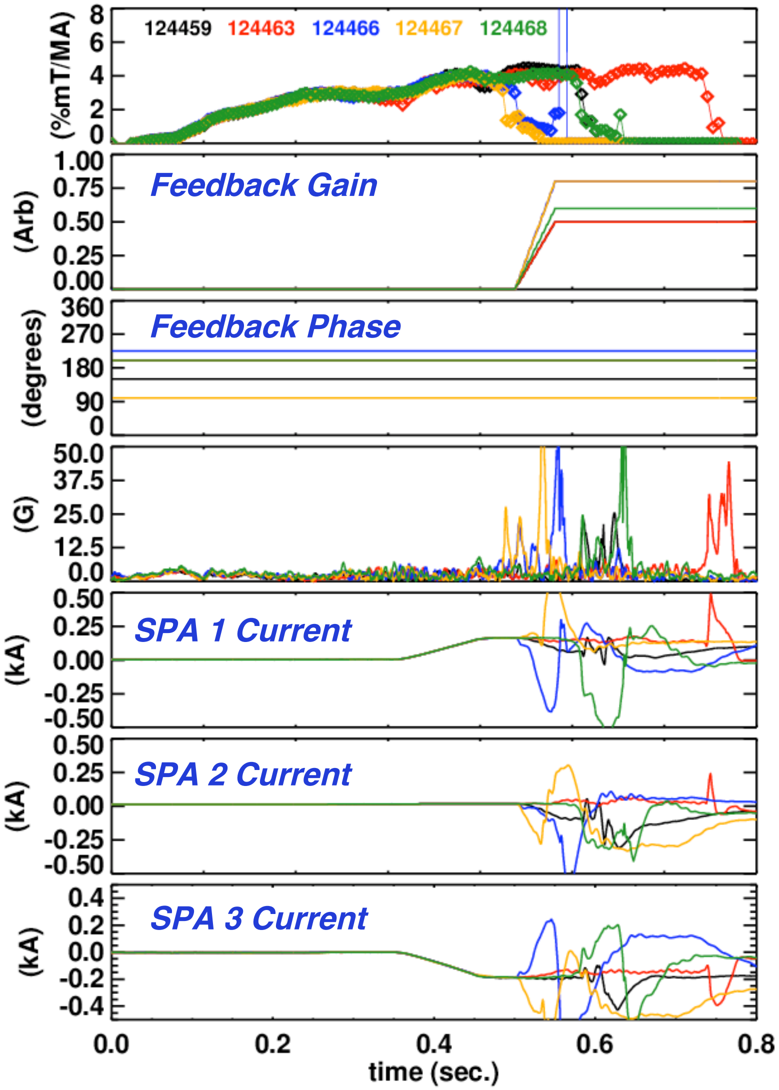
- **Use discharge with rotationally stabilized RWM.**
- **Deliberately apply n=1 EF in order to reduce rotation, destabilize an RWM.**
- **Find feedback phase that reduces the applied n=1 currents (B_P sensors).**
  - **Direct coil-sensor pickup is removed.**
- **Increase the gain until currents are nearly nulled and plasma stability is restored.**



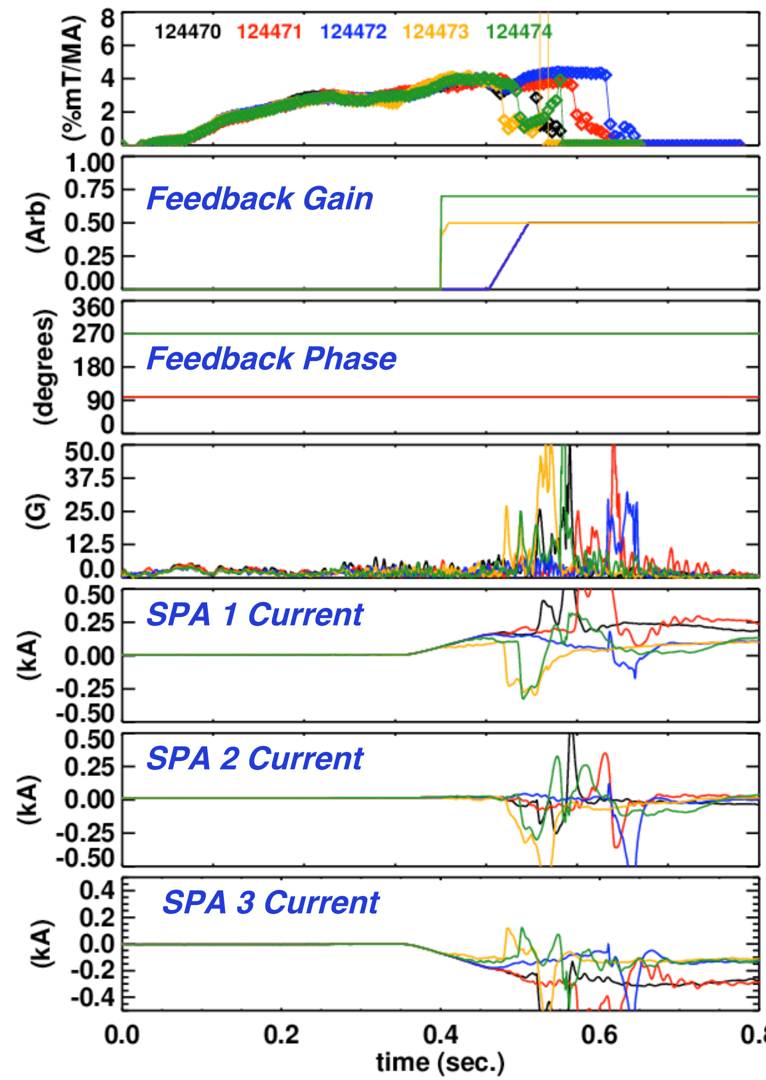
→ *Use same gain/phase settings to suppress RFA from intrinsic EF **and** any unstable RWMs*

2007 Experiment Had a Phase Scan…
…and a Gain Scan

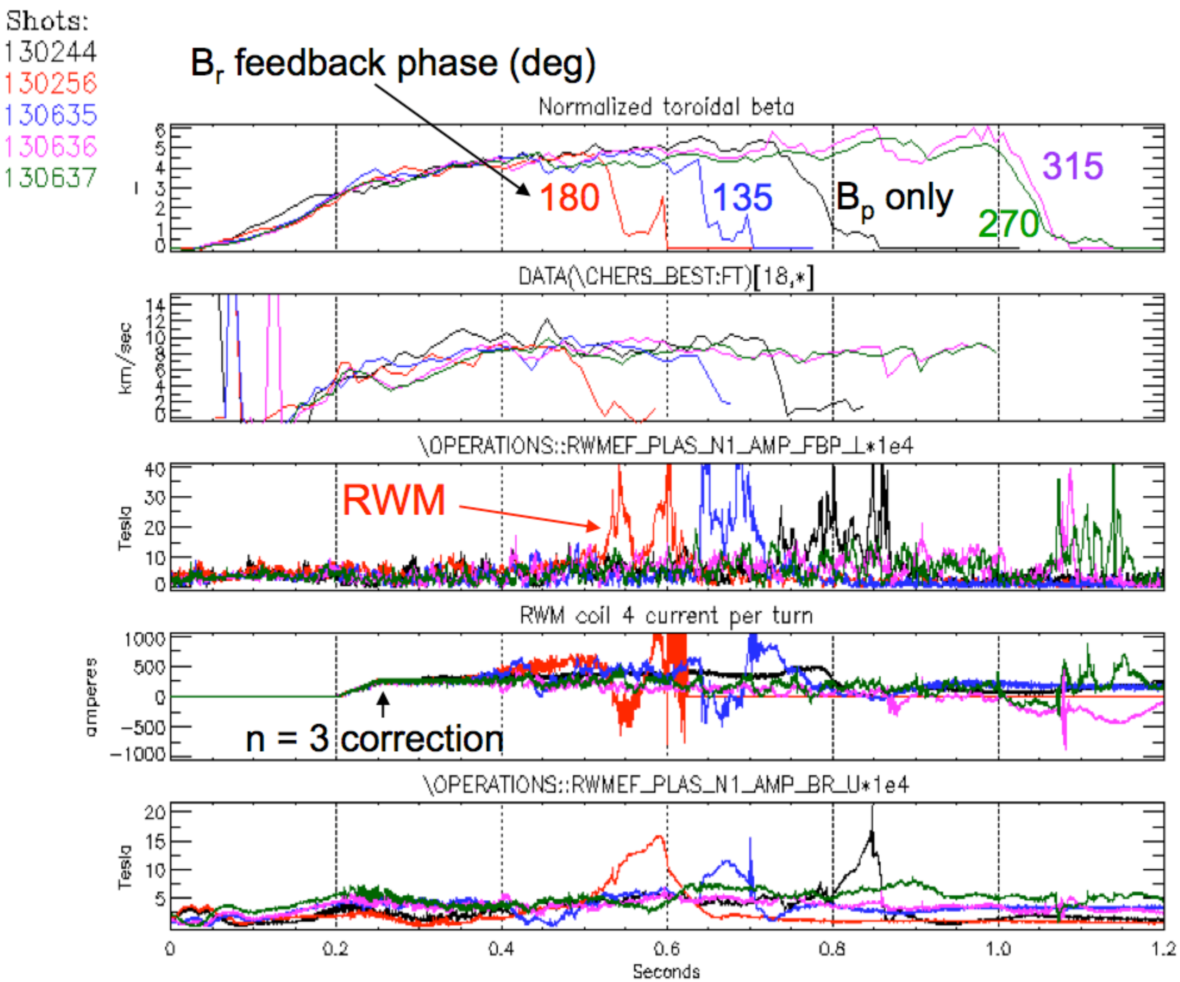
Upper B_P Sensors



"Combined" B_P Sensors



2008 Also Had Feedback Attempt With B_R Sensors

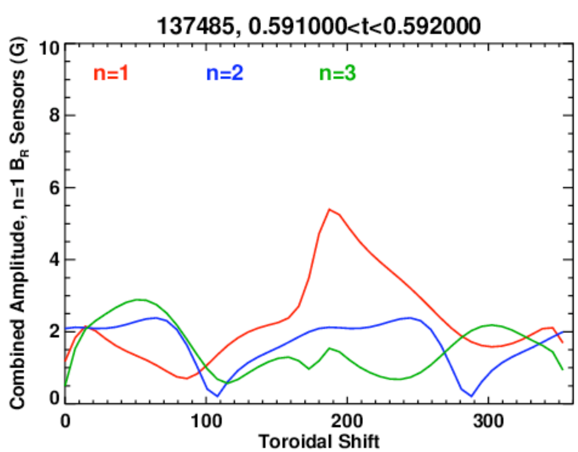


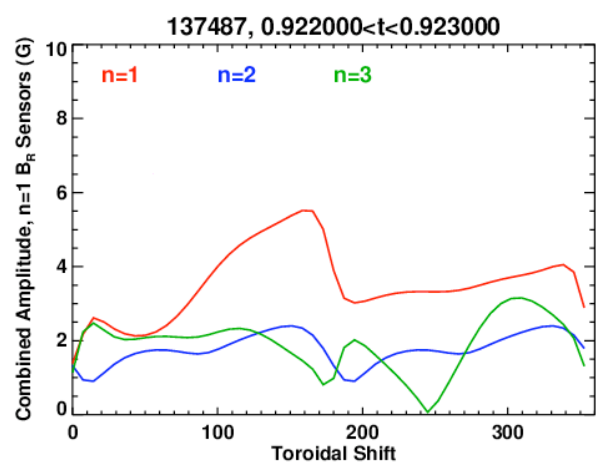
XP-802, Sabbagh et al.

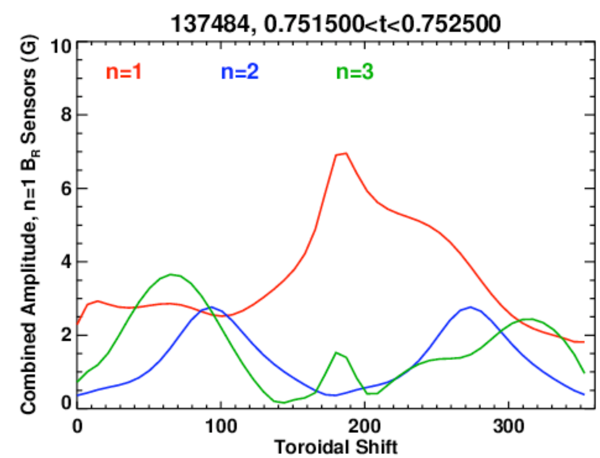
- Combined $B_P + B_R$
- B_R feedback phases around ~290º appear to be useful.
- B_R feedback gains of 0.7 appeared stable.
- Time average applied-field phase of ~290-320º is not well aligned to the known OHxTF correcting phase of ~30-40º.
- Compensated B_R sensors detect OHxTF with phase of ~110º.
  - Implies that a good feedback phase would be 150º.
- Use this result as guidance for the XP.

Recommended B_P Spatial Phase Does Not Change, but B_R Phase of 180° Is Recommended.

- Find time in discharge when there is likely to be a dominant n=1 mode.
  - Just after an n=1 mode stops rotating and locks to the wall.
  - Large RWM.
- Find spatial phase that maximizes the n=1 amplitude.
- For B_P sensors, spatial phase of 150-180° is the clear winner.
- Appears to be an optimum for B_R sensors around 180 as well.
  - XP-802 used 0° B_R spatial phase for feedback, while off-line analysis presently uses 250°.



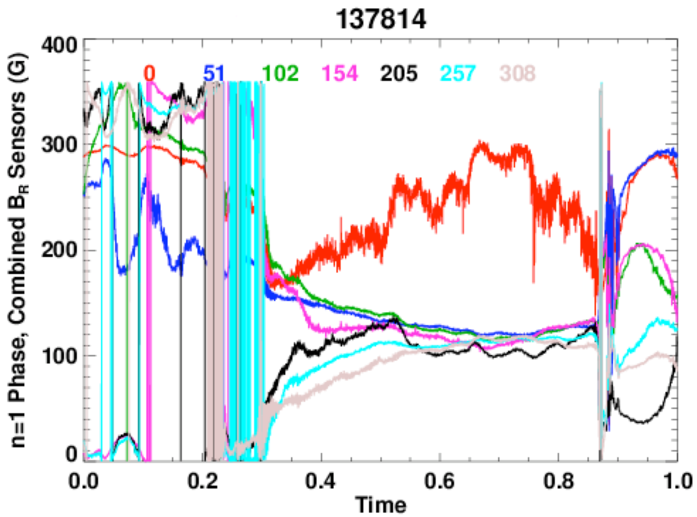


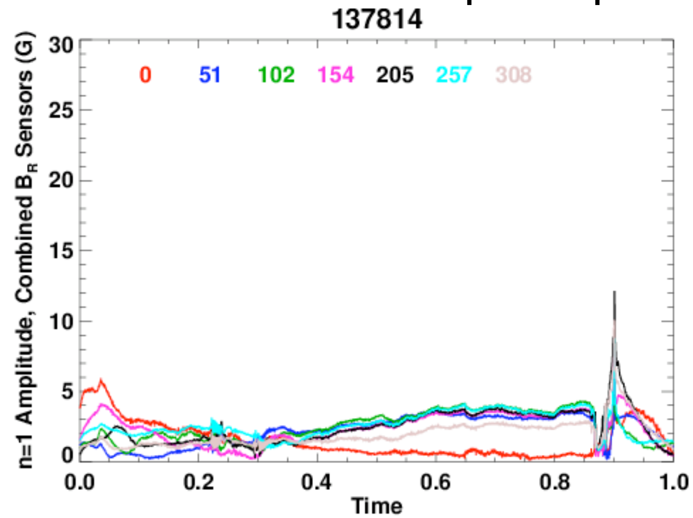


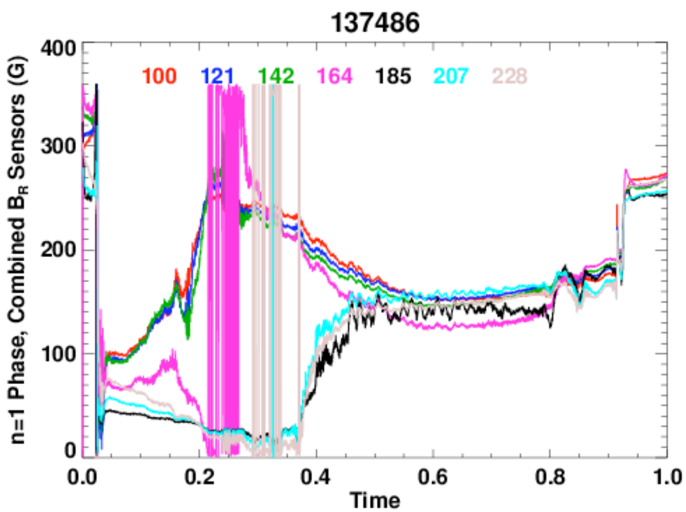
Use this spatial phase (180°) when generating the mode-ID matrix for realtime control

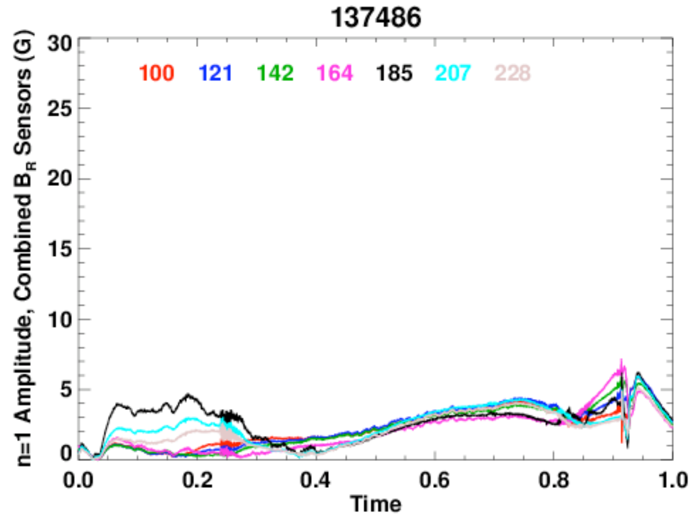
Can Also Determine the Spatial Phase from RFA Response

- Pick long-pulse discharge with steady n=1 perturbation detected in the B_R sensors.
- Study amplitude and phase response was as a function of the “spatial phase”.









Outline

- New sensor compensations
- Results from previous XPs
- Plan for this XP

Experimental Plan (I)

3.0: Off-line testing

The miu algorithm should be tested sufficiently before running the XP that all bugs are eliminated.

3.1: Sensor compensation test:

In the days leading up to the running of this XP, the following coil-only shots should be taken

Type	Example Shot #	Shot for XP
TF only	137505, 137732	
TF + Simple Bipolar OH	137648	
TF + Plasma like OH waveform	137650	

3.2: Development of reference shot (3 shots)

3.2.1 Load ~800 kA, B_T=0.45 T discharge, fiducial shape. Use beta-control to achieve β_N~5.5. Discharge should suffer rotation collapse and RWM. Note that XP-701 used 1 MA and 0.44 T, while nice 800 kA high-β shots from J. Berkery's XP (133775) used 0.39 T.

3.2.2 If rotation collapse and RWM do not occur, then repeat discharge with either:

i) Increased power and β_N.

ii) Adding ~300 A of steady-state n=1 field (SPA-1 @ 300 A, SPA-2 @ 300 A, and SPA-3 @0 A). This adds to the intrinsic EF.

Experimental Plan (II)

3.3: Phase and Gain Scan with B_R Sensors (10 shots)

3.3.1 Starting with a gain of 1, execute scan over B_R feedback phase and gain, as per the following table. Monitor pulse length (disruptivity) and rotation sustainment as a function of feedback phase.

Shot	Feedback Phase	Feedback Gain	
	270	1	
	90	1	
	180	1	
	360	1	

3.3.2: Repeat best case with OHxTF compensations turned off. Look for a reduction in the plasma rotation and/or increased disruptivity.

Experimental Plan (III)

3.4: Phase and Gain Scan with B_P Sensors (8 shots)

Starting with a gain of 1, execute scan over B_R feedback phase and gain, as per the following table. Monitor pulse length (disruptivity) and rotation sustainment as a function of feedback phase.

Shot	Feedback Phase	Feedback Gain	
	270	1	
	90	1	
	180	1	
	360	1	

Experimental Plan (IV)

3.5: Compensation of the Intrinsic EF **(5 shots)**

If the cases in 3.2 and 3.3 used 3-D fields from the RWM coils, not the intrinsic EF, then repeat the best case for each sensor combinations with the intrinsic EF only. Repeat the B_R feedback case with the OHxTF compensation turned off. Also try a case with B_P+B_R combined using the best settings for each. Be sure that discharge lasts into the phase of large intrinsic EF.

3.6: Time Dependent RFA Suppression: **(4 shots)**

Pick best RFA suppression scheme from 3.3 & 3.4. Add an n=1 traveling wave of various frequencies, likely with 1 kA amplitude. System should suppress the traveling waves.

TW Amp	TW Freq	Sensor Polarity	F.B. Gain	F.B. Phase	Shot
1kA	20				

Readiness…

- miu algorithm has been tested with plasma shots, doesn't crash PCS, produces reasonable results.
  - B_R sensors agree very well with similar off-line compensations, but haven't yet entered a matrix for the B_R sensors.
    - no mode amplitude and phase comparisons have been done.
  - B_P sensors have some small differences between online and off-line.
    - Leads to different phases when the n=1 modes are very small.
- Beta-control works and is apparently ready to go.
- XP could probably run with the 1-LITER system, but would be much better with 2.

Physics Operations Request

Brief description of the most important operational plasma conditions required:

High-β, long-pulse fiducial like discharge will be utilized. Confinement should be good enough to achieve β_N~6 with 6 MW input power with I_P~800 kA.

The new "miu" algorithm should have been tested and fully qualified. Also, control of the plasma β via neutral beam modulation may be incorporated.

Previous shot(s) which can be repeated:

Previous shot(s) which can be modified: Any high-κ, high-δ fiducial like discharge.

Machine conditions *(specify ranges as appropriate, strike out inapplicable cases)*

I_{TF} (kA): **0.4-0.44 T** Flattop start/stop (s): **Longest consistent with I^2t on the coil.**

I_P (MA): **800-900 kA** Flattop start/stop (s): **Longest possible**

Configuration: **Limiter / DN / LSN / USN**

Equilibrium Control: **Outer gap / Isoflux** (rtEFIT) **/ Strike-point control** (rtEFIT)

Outer gap (m): **10-15 cm** Inner gap (m): ~5 Z position (m): ~-2 cm

Elongation: **2.3-2.4** Triangularity (U/L): **0.5/0.75** OSP radius (m): high-δ

Gas Species: **D** Injector(s):

NBI Species: **D** Voltage (kV) **A: 90** **B: 70-90** **C: 70-90** Duration (s):

ICRF Power (MW): **0** Phase between straps (°): Duration (s):

CHI: **Off** Bank capacitance (mF):

LITERs: On Total deposition rate (mg/min): **20 total from two evaporators**

LLD: No Temperature (°C): **Unheated**

EFC coils: On Configuration: **Odd**

Diagnostic Checklist

Note special diagnostic requirements in Sec. 4

Diagnostic	Need	Want
Beam Emission Spectroscopy		
Bolometer – divertor		
Bolometer – midplane array	√	
CHERS – poloidal		√
CHERS – toroidal	√	
Dust detector		
Edge deposition monitors		
Edge neutral density diag.		
Edge pressure gauges		√
Edge rotation diagnostic		
Fast cameras – divertor/LLD		
Fast ion D_alpha - FIDA		
Fast lost ion probes - IFLIP		
Fast lost ion probes - SFLIP		
Filterscopes		√
FIReTIP		
Gas puff imaging – divertor		
Gas puff imaging – midplane		
Hα camera - 1D		
High-k scattering		
Infrared cameras		
Interferometer - 1 mm		
Langmuir probes – divertor		
Langmuir probes – LLD		
Langmuir probes – bias tile		
Langmuir probes – RF ant.		
Magnetics – B coils	√	
Magnetics – Diamagnetism		√
Magnetics – Flux loops	√	
Magnetics – Locked modes		
Magnetics – Rogowski coils	√	
Magnetics – Halo currents		√
Magnetics – RWM sensors	√	
Mirnov coils – high f.		
Mirnov coils – poloidal array		
Mirnov coils – toroidal array	√	
Mirnov coils – 3-axis proto.		

Note special diagnostic requirements in Sec. 4

Diagnostic	Need	Want
MSE	√	
NPA – E‖B scanning		
NPA – solid state		
Neutron detectors	√	
Plasma TV	√	
Reflectometer – 65GHz		
Reflectometer – correlation		
Reflectometer – FM/CW		
Reflectometer – fixed f		
Reflectometer – SOL		
RF edge probes		
Spectrometer – divertor		
Spectrometer – SPRED		
Spectrometer – VIPS		
Spectrometer – LOWEUS		
Spectrometer – XEUS		
SWIFT – 2D flow		
Thomson scattering	√	
Ultrasoft X-ray – pol. arrays		√
Ultrasoft X-rays – bicolor		
Ultrasoft X-rays – TG spectr.		
Visible bremsstrahlung det.		
X-ray crystal spectrom. - H		
X-ray crystal spectrom. - V		
X-ray tang. pinhole camera		

Backup

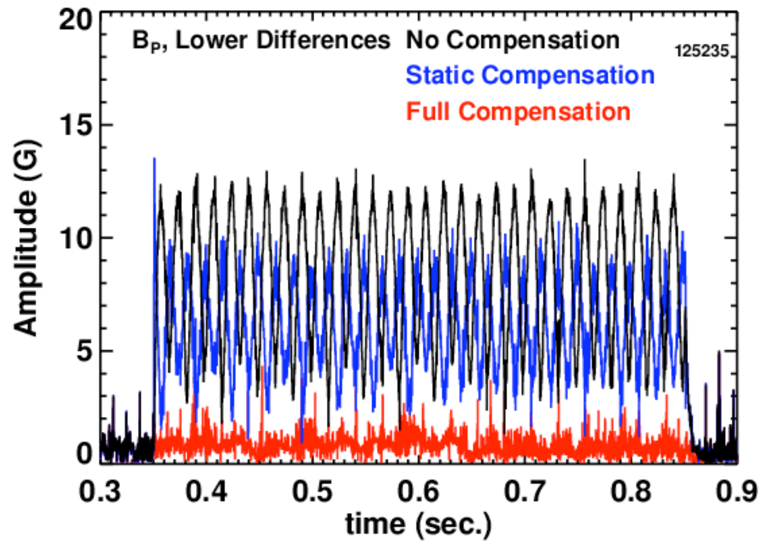
Goals For Proposed Experiment

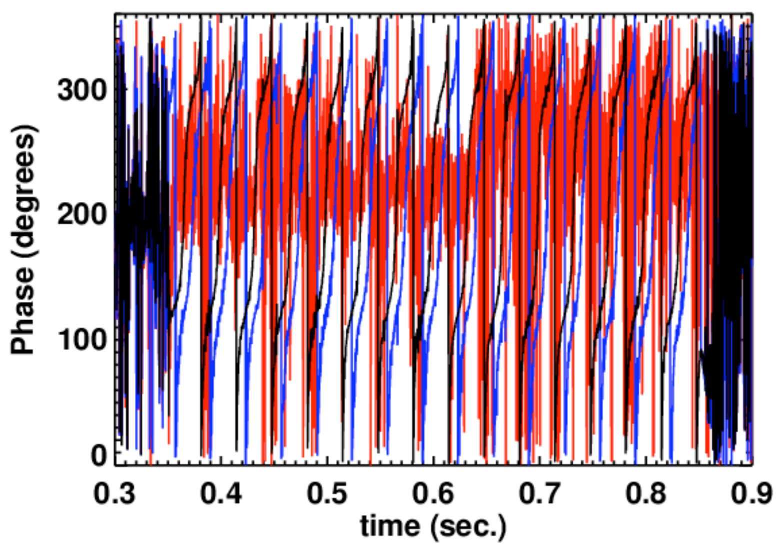
- Qualify B_R sensors for error field correction.
  - Determine the optimal phase shift and gain for DEFC.
    - Can start with results from Steve's XP in 2008
  - Determine if OHxTF sensor compensation is necessary…or beneficial…or irrelevant.
  - Fast feedback is out of scope

- Determine if one or the other sensor type is better for correction:
  - Reduced fluctuations in the FB coil current?
  - Improved rotation sustainment?
  - Higher gain?

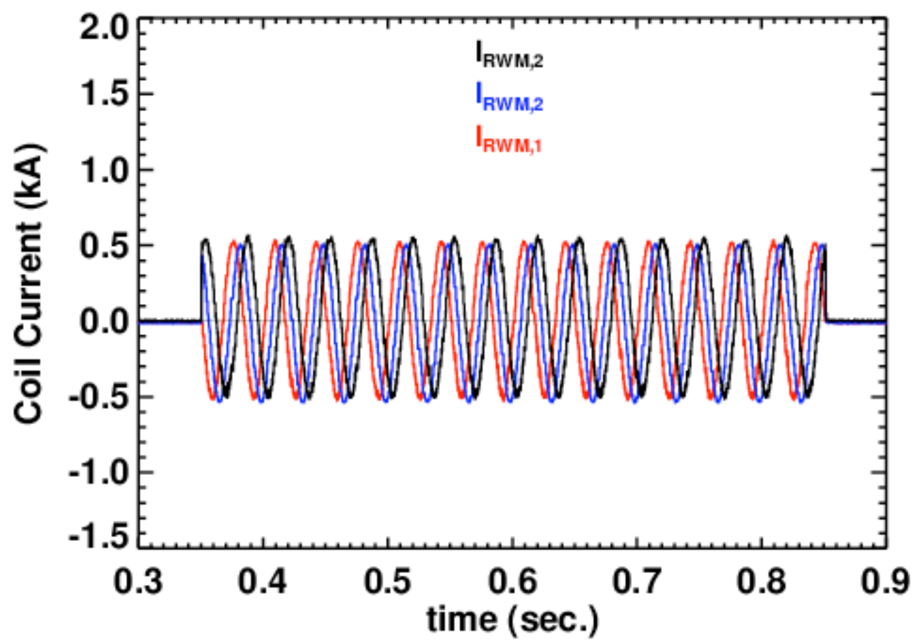
- Examine β-dependence of FB response.

AC Compensations Can Be Important For



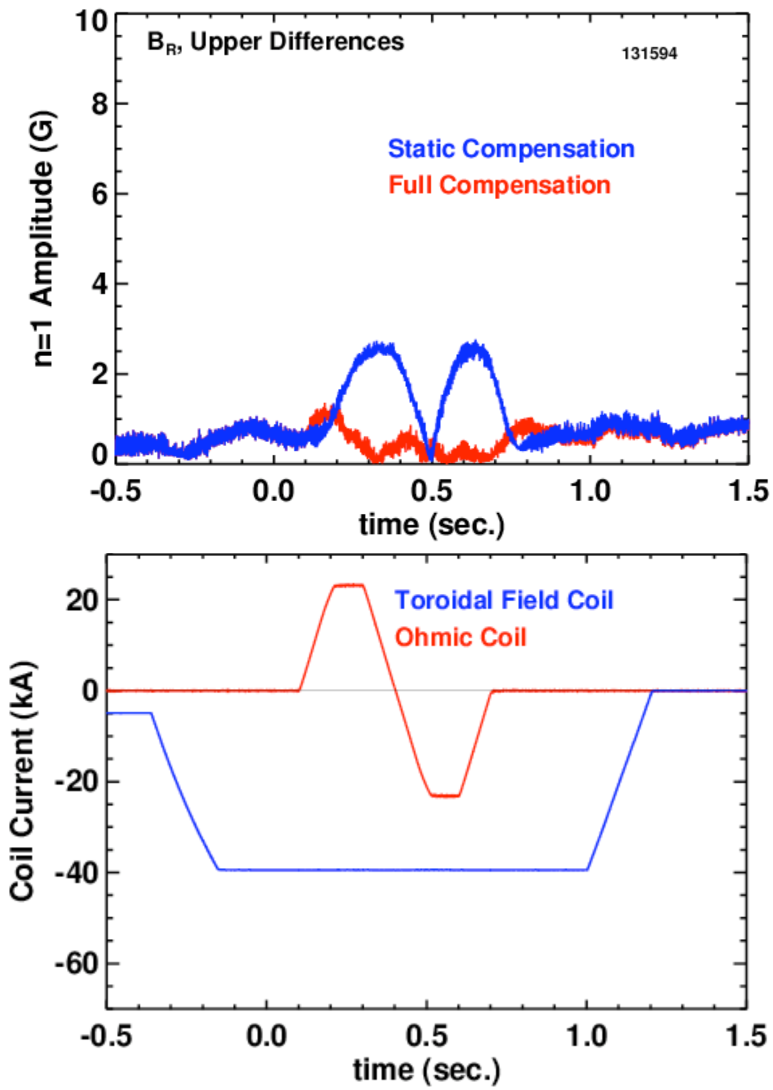


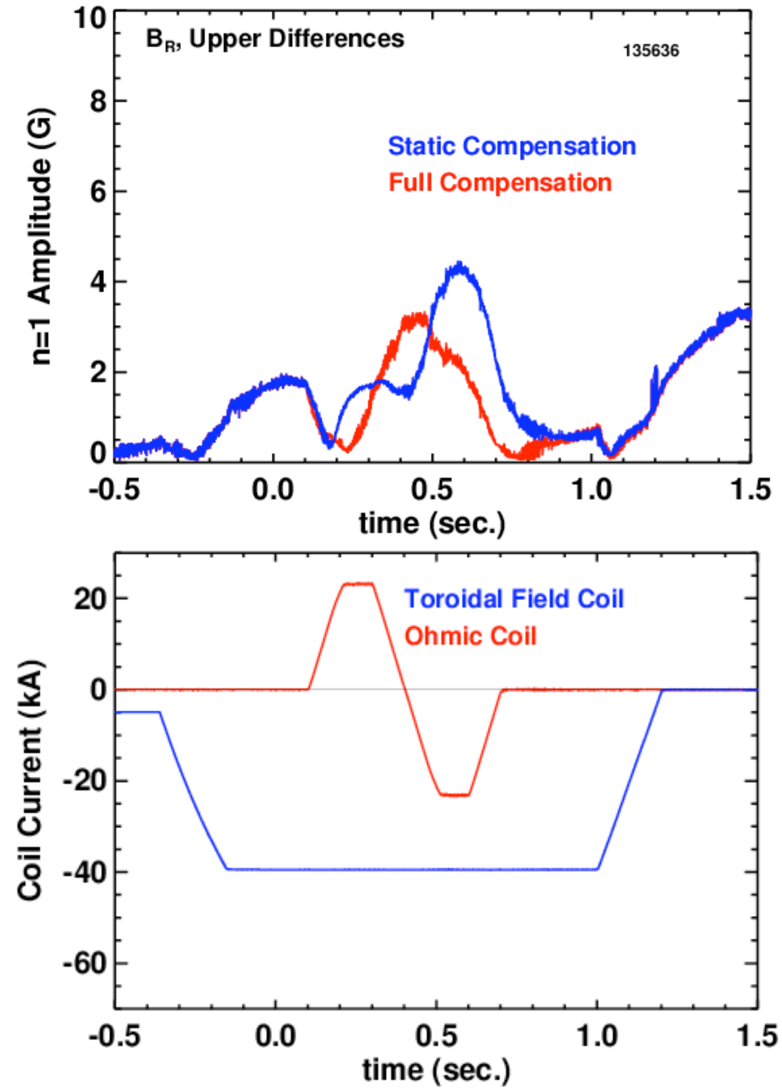
- Large amplitude modulation in signal with static compensation



Need to Keep a Careful Eye on Compensations Through the Run

Beginning of Run | *End of Run*





Other Stuff

- Lithium
  - LITER at ~200 mg/shot
  - No LLD
- Diagnostics
  - Profile diagnostics
  - RWM detection
- Analysis
  - MSE reconstructions.
  - DCON for proximity to ideal stability limits.
  - Intrinsic EF and detailed RWM sensor analysis.