U.S. DEPARTMENT OF ENERGY | Office of Science

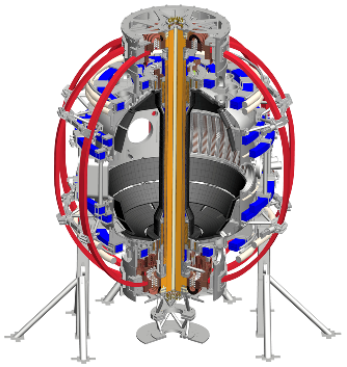
NSTX-U

PF-1aU Summary

Stefan Gerhardt
Devon Battaglia, Dan Boyer, Jon Menard, Clayton Myers

NSTX-U Team Meeting
PPPL, MBG Auditorium
7/29/2016

PPPL



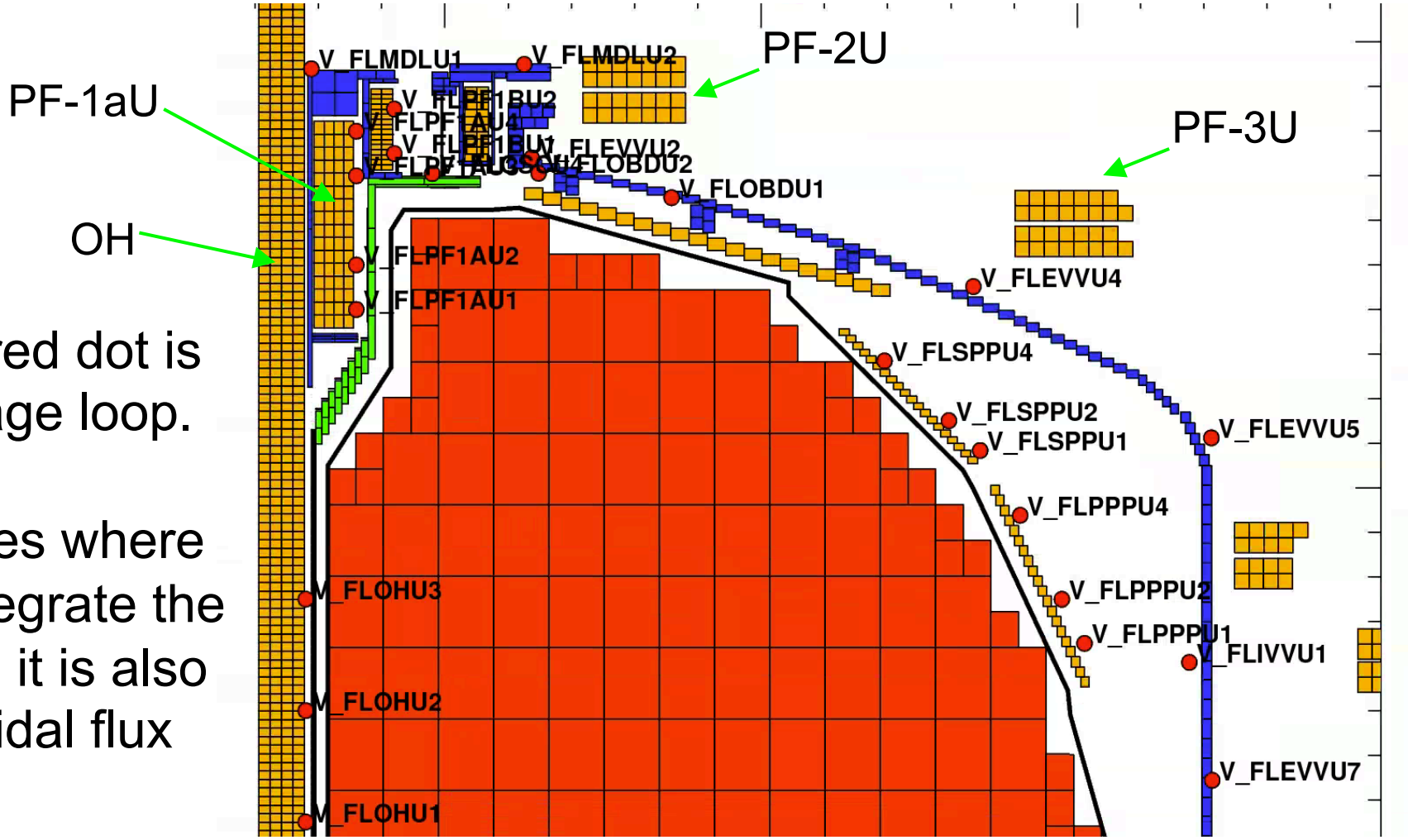
Overview

- Observations from Our Testing Last Week
- Model of Circulating Currents in the PF-1a Coils
- Analysis of Some Historical Data

Overview

- Observations from Our Testing Last Week
- Model of Circulating Currents in the PF-1a Coils
- Analysis of Some Historical Data

Reminder of Geometry



Each red dot is a voltage loop.

In cases where we integrate the signal, it is also a poloidal flux loop

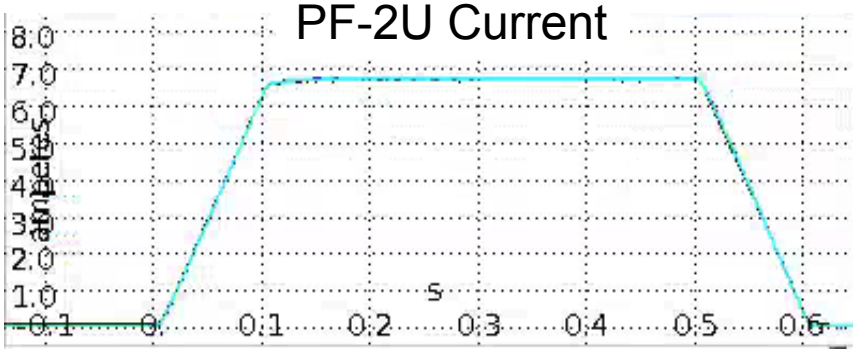
Reminder: Status @ Last Team Meeting Friday, 7/15/2016

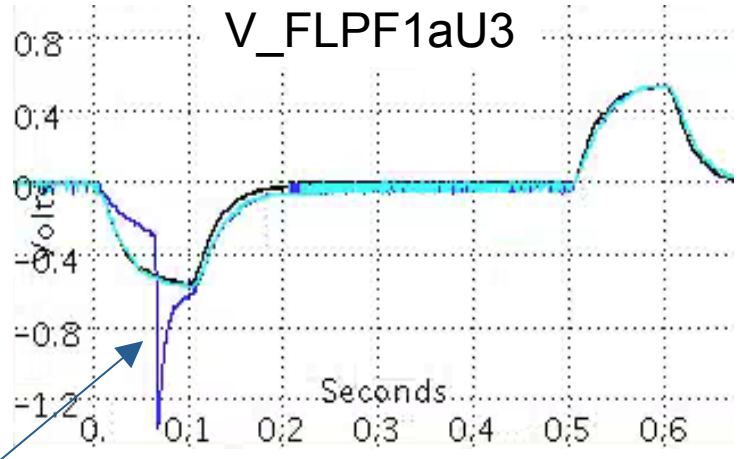
- PF-1aU flow blockage on Tuesday 6/28/2016
- Copper slug, presumably from the coil, found in the water on Tuesday 7/5/2016.
- Water leak develop on PF-1aU on Tuesday 7/5/2016
  - PF-1aU coil was taken out of service.
- Wednesday 7/6 – Friday 7/15 spend drying the CS
- Were still waiting for the TF insulation resistance to recover before restarting operations.

---------- Team Meeting ----------

- Met Tuesday 7/19/16 to make a plan for restoration of operations.
  - Start with PF-2U shots to "tickle" the PF-1aU, then move to OH, then OH +TF
- Insulation resistance recovered sufficiently by Wednesday 7/20/16.
  - Thanks to clever drying techniques by the machine techs.

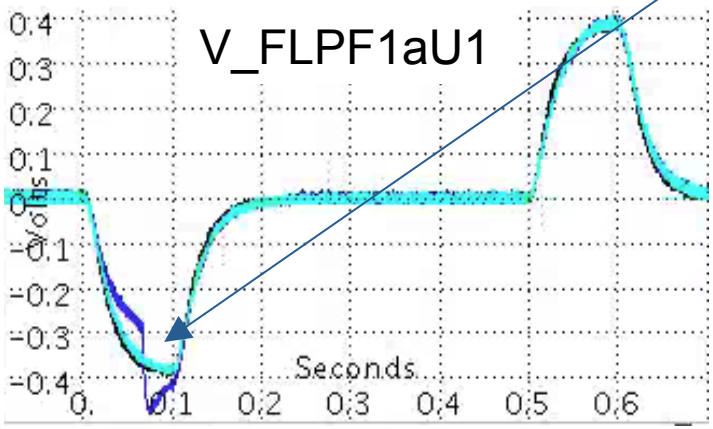
First Shot of 7/20/2016 Was a PF-2U Shot; Showed a Large Voltage "Glitch"

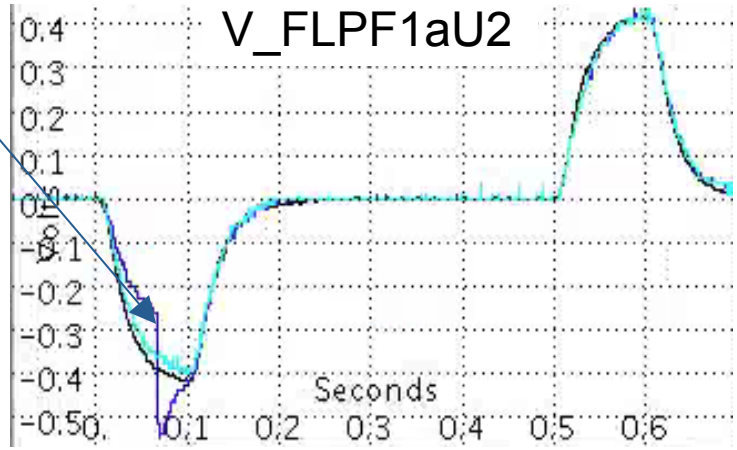




202124 – reference from December
205321 – 1st 50% PF2U
205323 – next 50% PF2U

Glitch on 203521

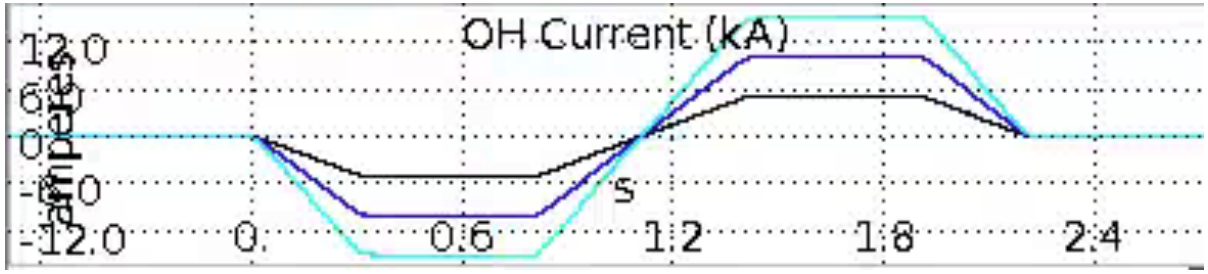




7/20/16

Similar Glitch Observed on an OH Shot

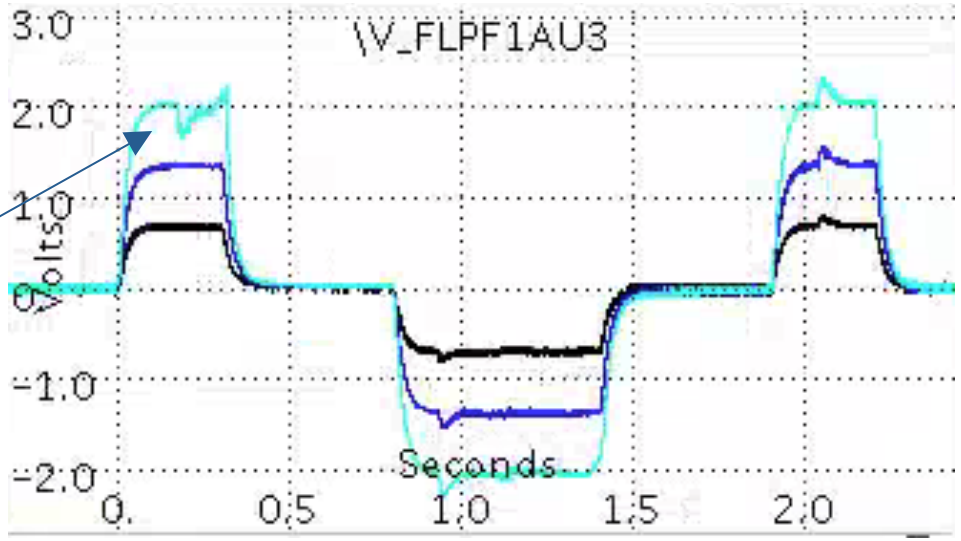
- [25%, 50%, 75%] test shots taken (fractions with respect to 21 kA allowable).



205326: 25% OH
205327: 50% OH
205328: 75% OH

Voltage on a loop wrapped around the 1aU coil

Glitch on 203528

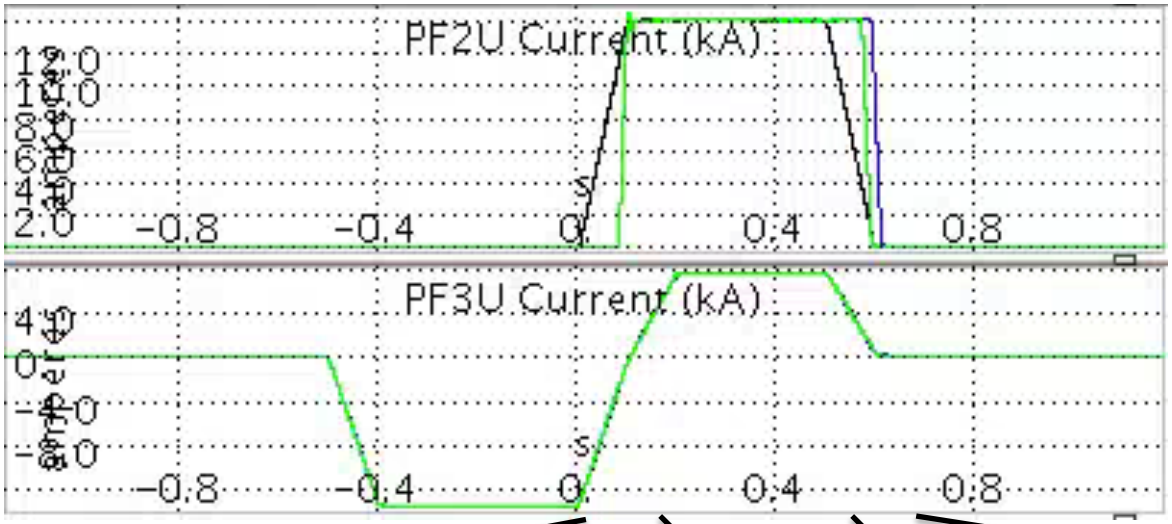


We stopped on 7/20/16 at this point and formulated a new test plan on 7/21/16

7/20/16

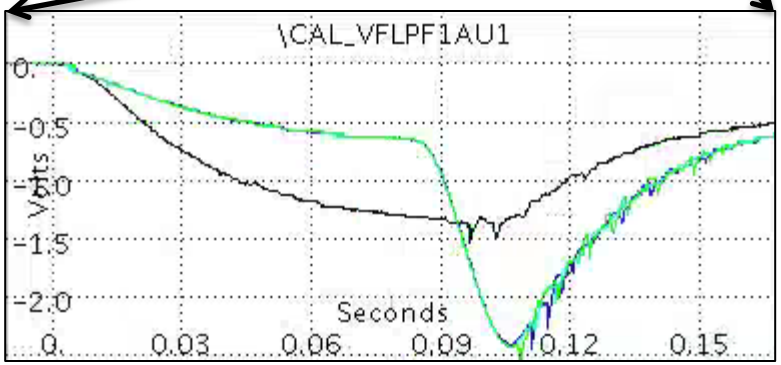
Operations on Subsequent Days Found Smaller Voltage Transients

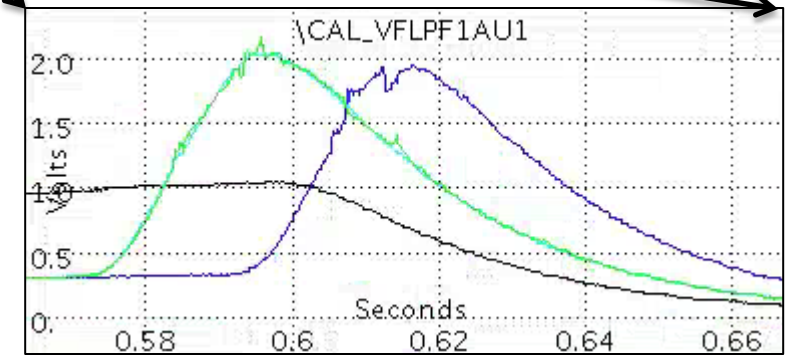
XMP-156: Use PF-2U and PF-3U only



205350
205355
205357
205359

These were the last shots before stopping operations.





Voltage Loop on -1aU Coil…Small Transients Observed

7/22/16

Overview

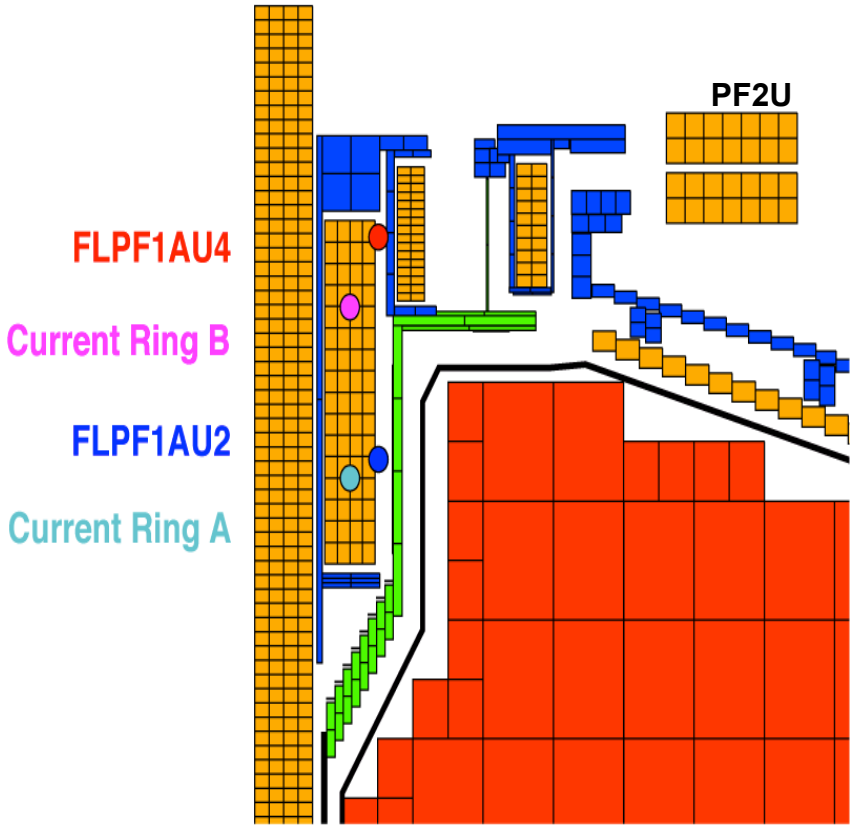
- Observations from Our Testing Last Week
- Model of Circulating Currents in the PF-1a Coils
- Analysis of Some Historical Data

Use Two Model 'Current Rings' in PF1aU to Estimate Current Transients

- The fluxes are measured at FLPF1AU4 and FLPF1AU2
- The difference between the fluxes measured during recommissioning in July and during reference shots in December can be used to infer circulating currents in the compromised PF1aU coil
- Model the circulating currents in PF1aU with two current rings (A & B)
- Compute the mutual inductance matrix and invert to find the currents that produce the measured flux differences
- Identical analysis on the bottom coil and loops

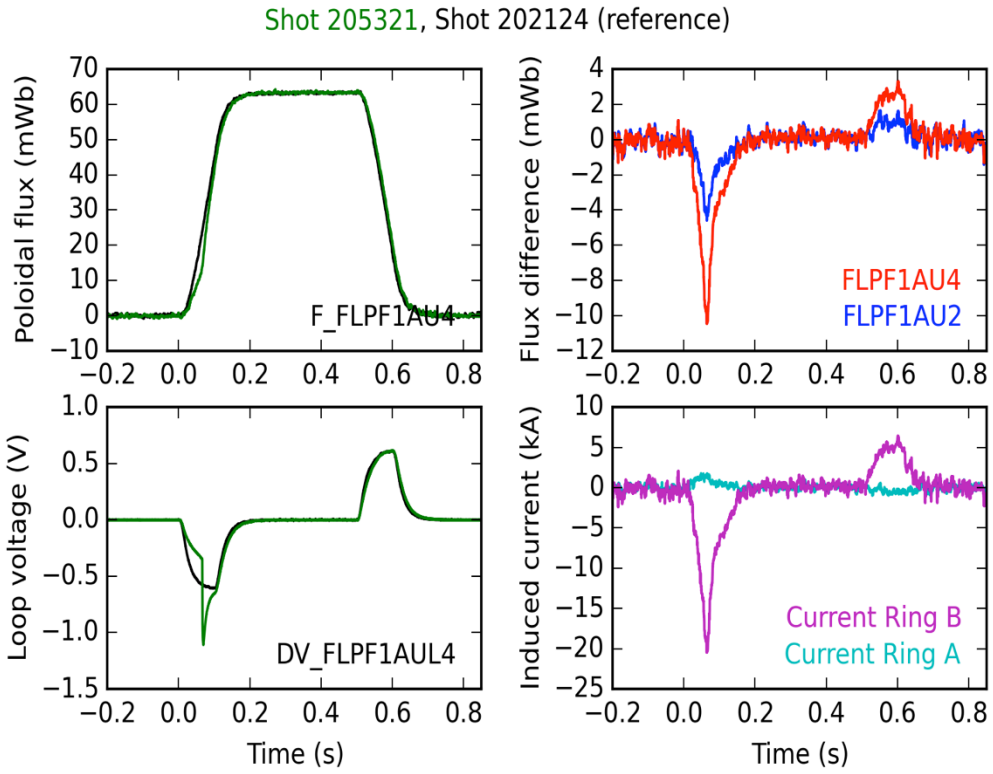
$$\begin{bmatrix}\psi_{1aU2}\\ \psi_{1aU4}\end{bmatrix}_{shot} - \begin{bmatrix}\psi_{1aU2}\\ \psi_{1aU4}\end{bmatrix}_{ref} = M\begin{bmatrix}I_A\\ I_B\end{bmatrix}$$

$$M = \begin{bmatrix}M_{1aU2,A} & M_{1aU2,B}\\ M_{1aU4,A} & M_{1aU4,B}\end{bmatrix}$$



Estimate ~20 kA-Turns Induced During the First PF2U Recommissioning Shot

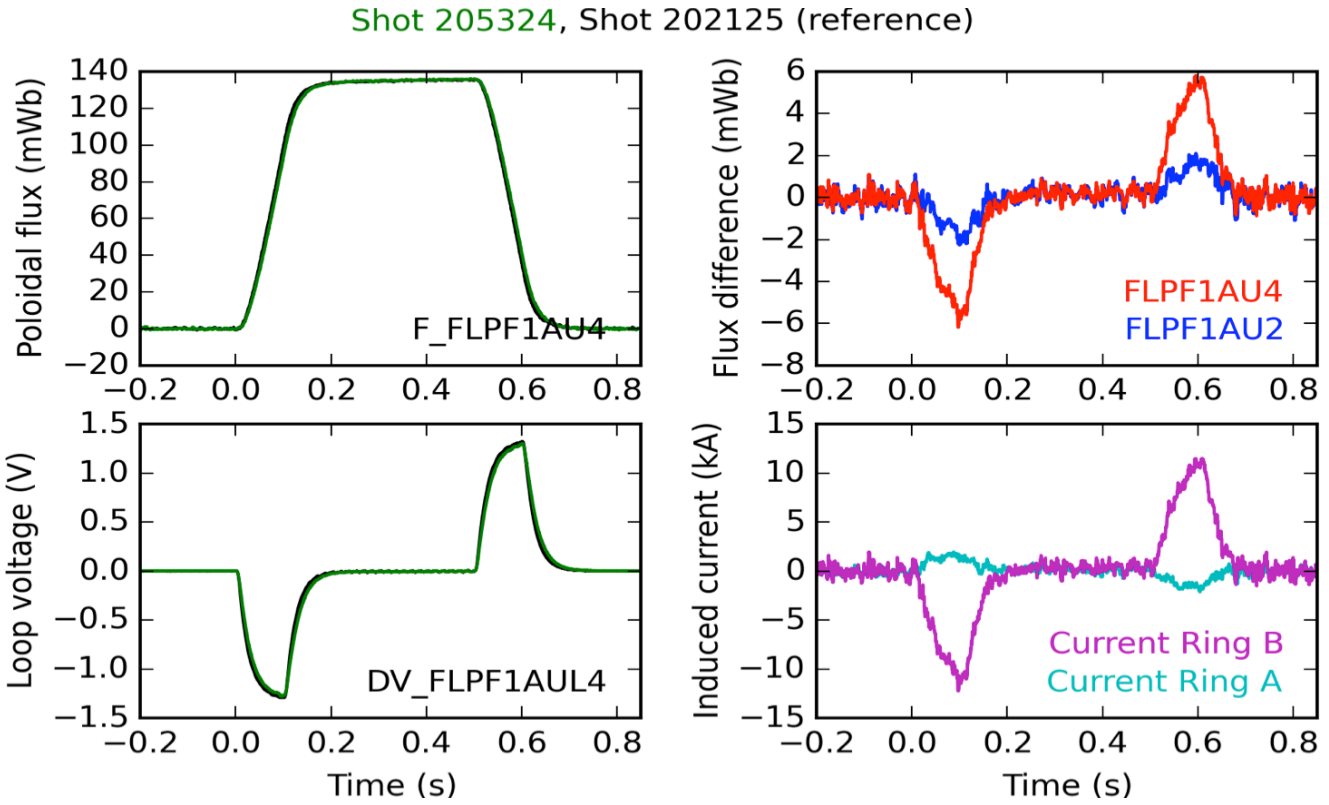
- Large voltage transient suggests initially shorted turn(s) open up
- Total induced current in transient is ~20 kA-turns (at the top of the coil)
- In second hump of induced voltage, a steady difference is still visible
- The second hump has ~5 kA-turns of induced current



7/20/16

Subsequent Shots Showed Circulating Induced Currents in PF-1aU

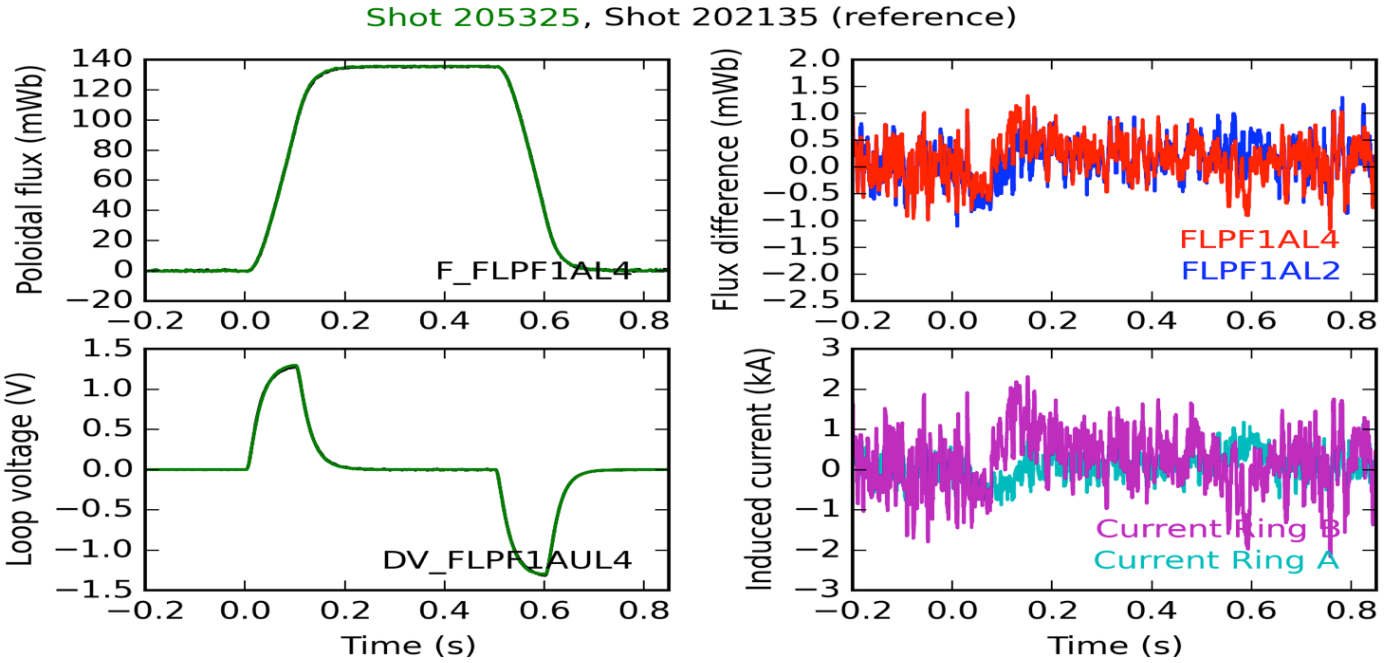
- Shot 205324 is a 100% PF2U shot
- The previous 5 kA-turn behavior is a consistent 10 kA-turn signature…at 1 volt loop voltage
- The melting potential implied by these currents during plasma scenarios drove us to halt operations on 7/25/16 in consultation with FES.



7/20/16

Similar Analysis on the PF-1aL Shows No Errant Circulating Currents

- Shot 205325 is a 100% PF2L shot
- Negligible circulating current is measured
- The error bars are +/-2 kA at this larger PF2L current



7/20/16

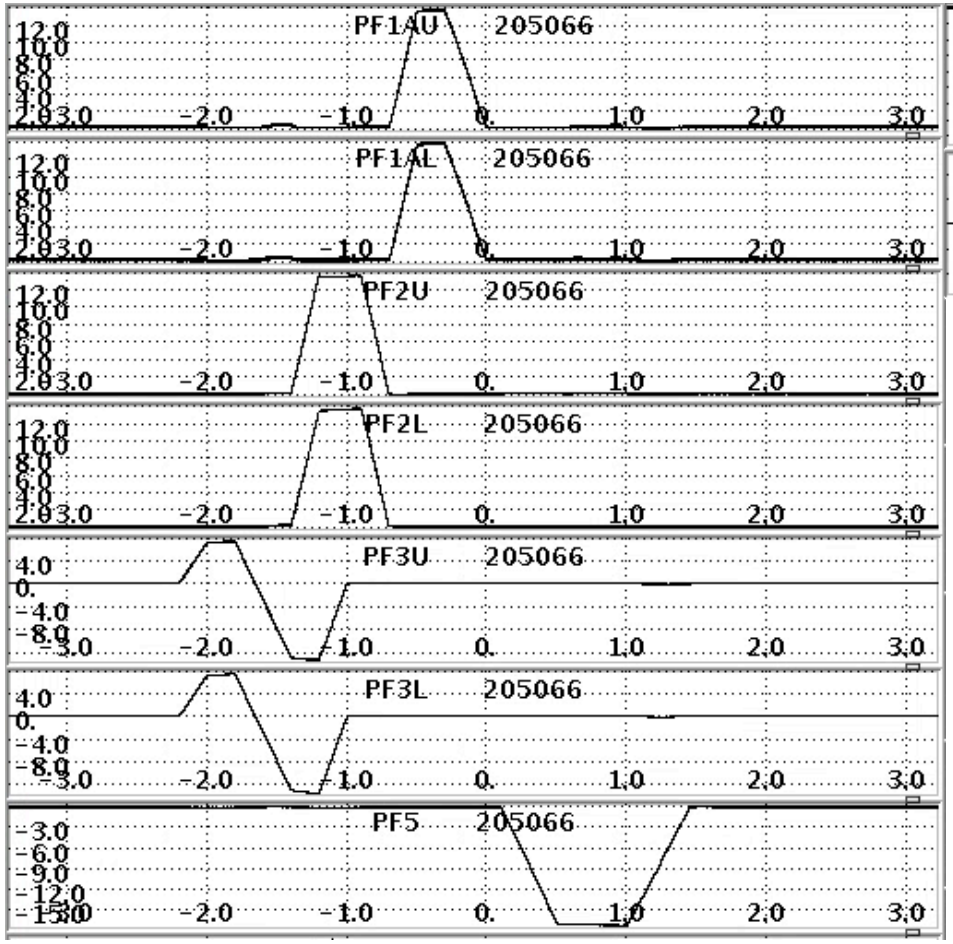
Overview

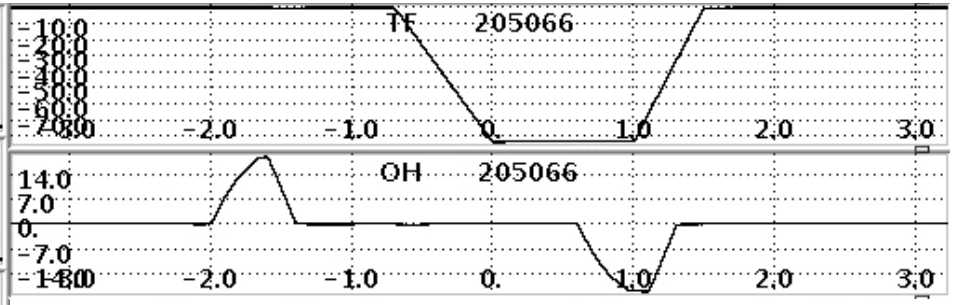
- Observations from Our Testing Last Week
- Model of Circulating Currents in the PF-1a Coils
- Analysis of Some Historical Data

Initial Analysis of Historical Data Yielded No Trends

- Firing angle request on the -1aU rectifier during test shots not visibly different on 6/28/2016 compared to previous days.
- PSRTC “dI/dt algorithm” didn’t register anything.
- EFIT chi-squares may have been creeping up, but not dramatically.
- The process of analyzing the issues on 6/20/16-6/22/16 taught us more sensitive means of looking at magnetics data.

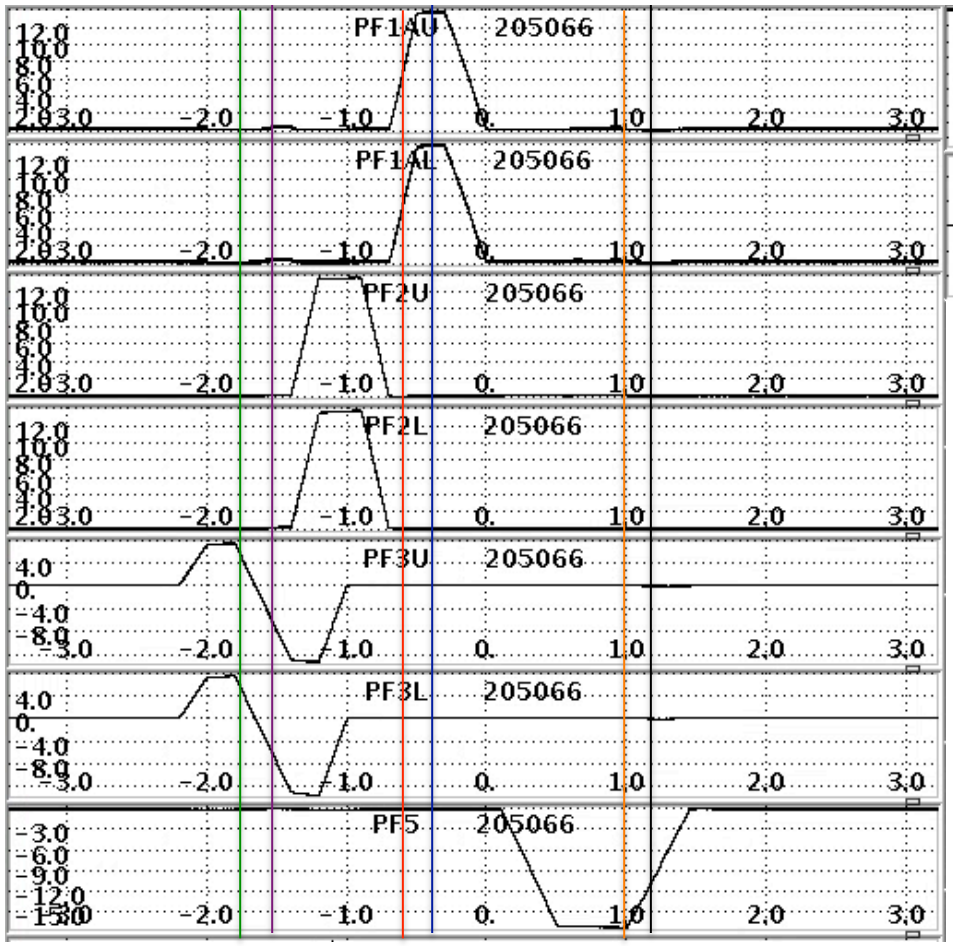
Test Shots Have Coils Coming and Going at Various Times

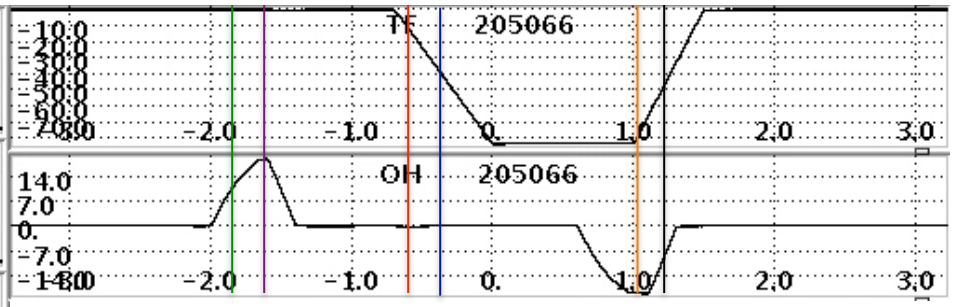




Test shot defined by requirement to run all coils in a single shot w/o violating any DCPS or FCPC allowables.

Test Shots Have Coils Coming and Going at Various Times





Test shot defined by requirement to run all coils in a single shot w/o violating any DCPS or FCPC allowables.

OH & PF-3 Ramps
OH Flat Top and PF-3 Ramp
PF1a Ramp
PF-1a Flat Top
OH Flat Top and PF-5 Ramp
OH & PF-5 Ramps

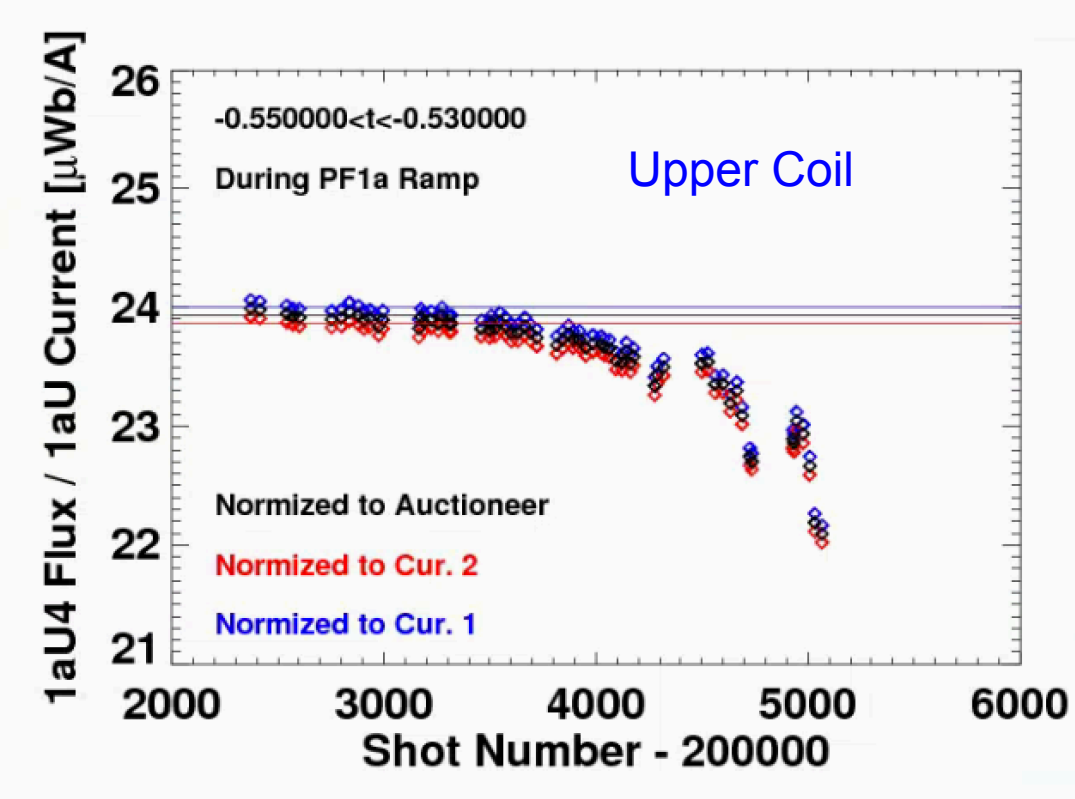
Analysis of 100% Test Shots Found a Slow Degradation of the -1aU Coil

Method: Normalize the flux on the -1aU coil to the -1aU power supply current
Flux Measurement: Flux loops on the coil OD
Current Measurement: Cur1, Cur2, and (Cur1+Cur2)/2

Less poloidal flux for the same power supply current

-> Inductance of the coil slowly changing in time

Rapid degradation leading into the final set of shots



After Some Confusion, Lower 1a Coil Was Found to NOT have the Same Bad Inductance Trend

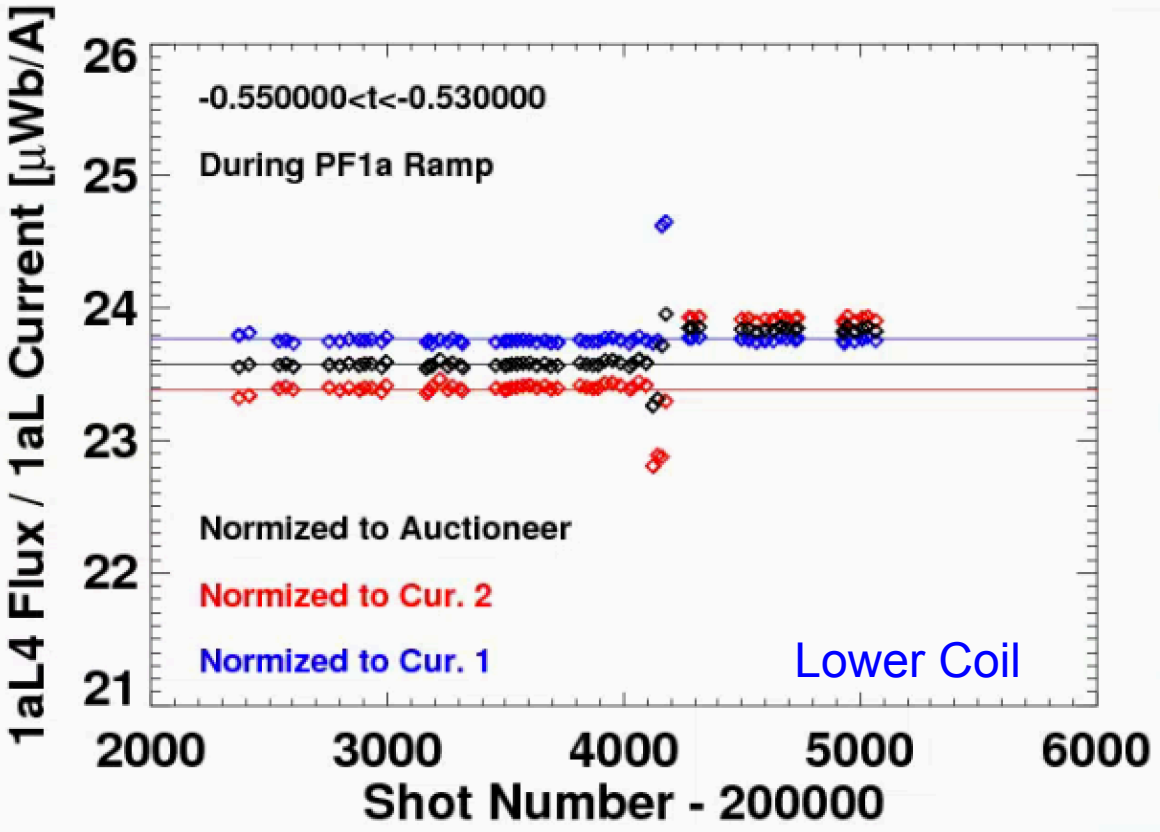
Method: Normalize the flux on the -1aL coil to the -1aL power supply current
Flux Measurement: Flux loops on the coil OD
Current Measurement: Cur1, Cur2, and (Cur1+Cur2)/2

Change in the Cur2 calibration on April 5th

Coil current is controlled against the average of Cur1 and Cur2.

The actual current in the coil during the test shot changed by a few %

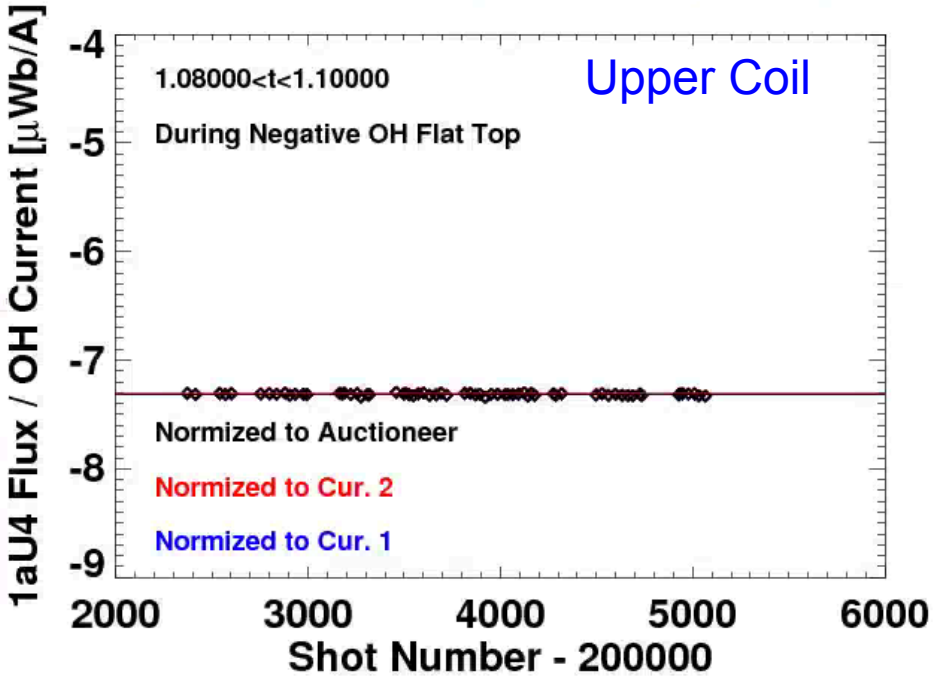
<u>Flux normalized to Cur1 has a flat trend</u>



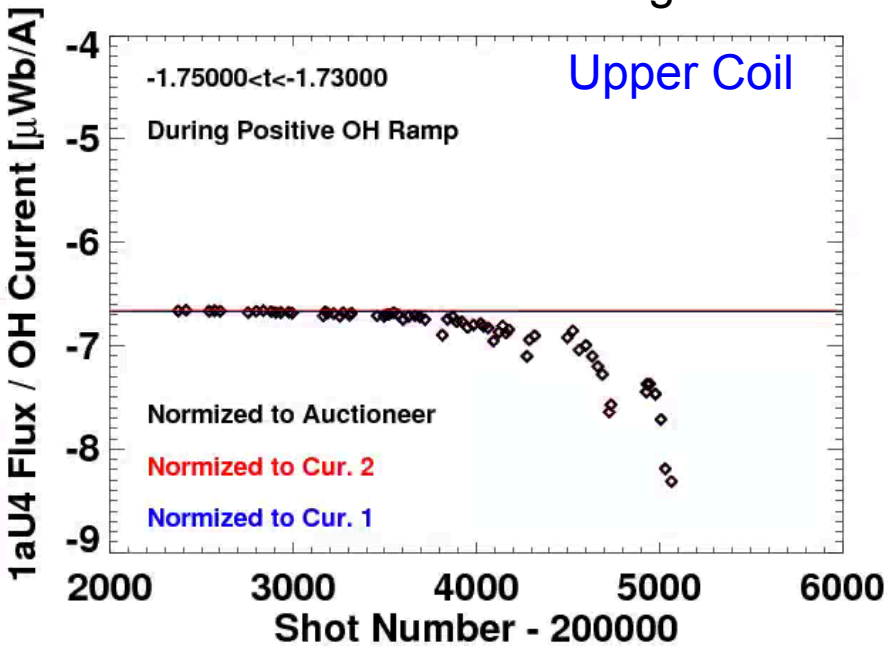
Similar Trends Observed on PF-1aU from OH-Dominant Part of Test Shots

Method: Normalize the flux on the -1a*U* coil to the OH supply current
Flux Measurement: Flux loops on the coil OD…difference fluxes!!
Current Measurement: Cur1, Cur2, and (Cur1+Cur2)/2

No trend when the OH is flat-topped



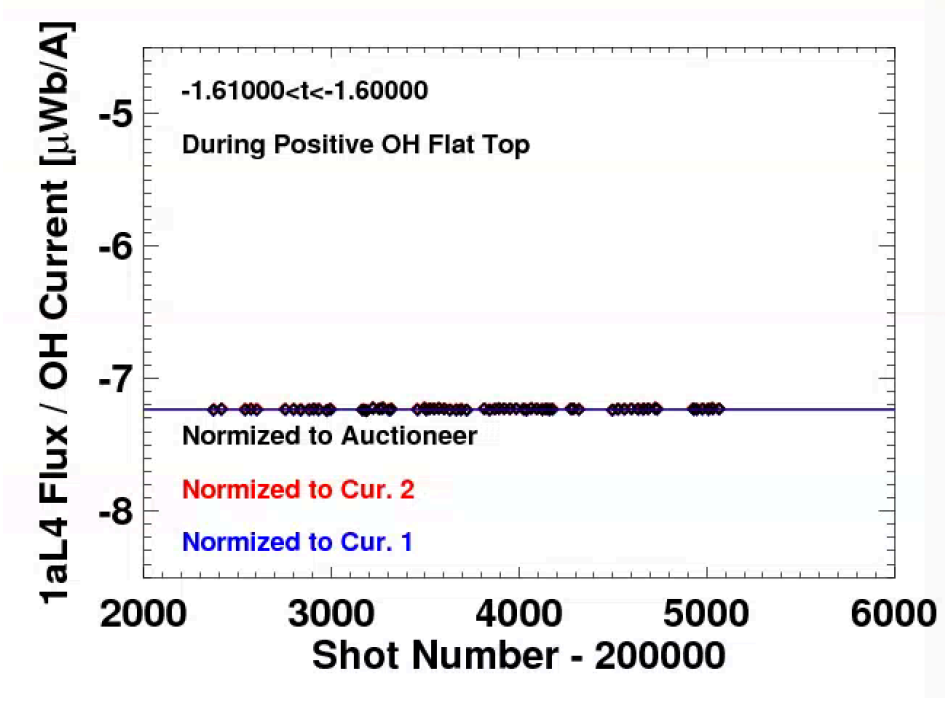
Large trend when the OH is swinging
Flux relative to the midplane is reduced later in the run
Consistent with induced currents trying to buck the OH flux change



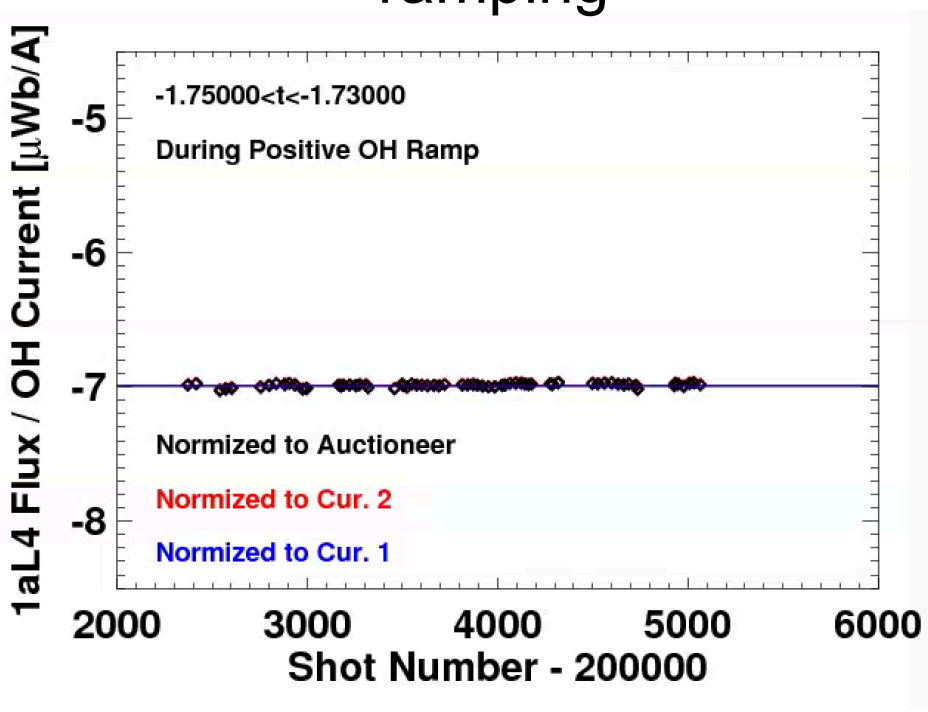
PF-1aL Shows No Concerning Trends When Considering OH Coupling

Method: Normalize the flux on the -1a*L* coil to the OH supply current
Flux Measurement: Flux loops on the coil OD…difference fluxes!!
Current Measurement: Cur1, Cur2, and (Cur1+Cur2)/2

No trend when the OH is flat-topped

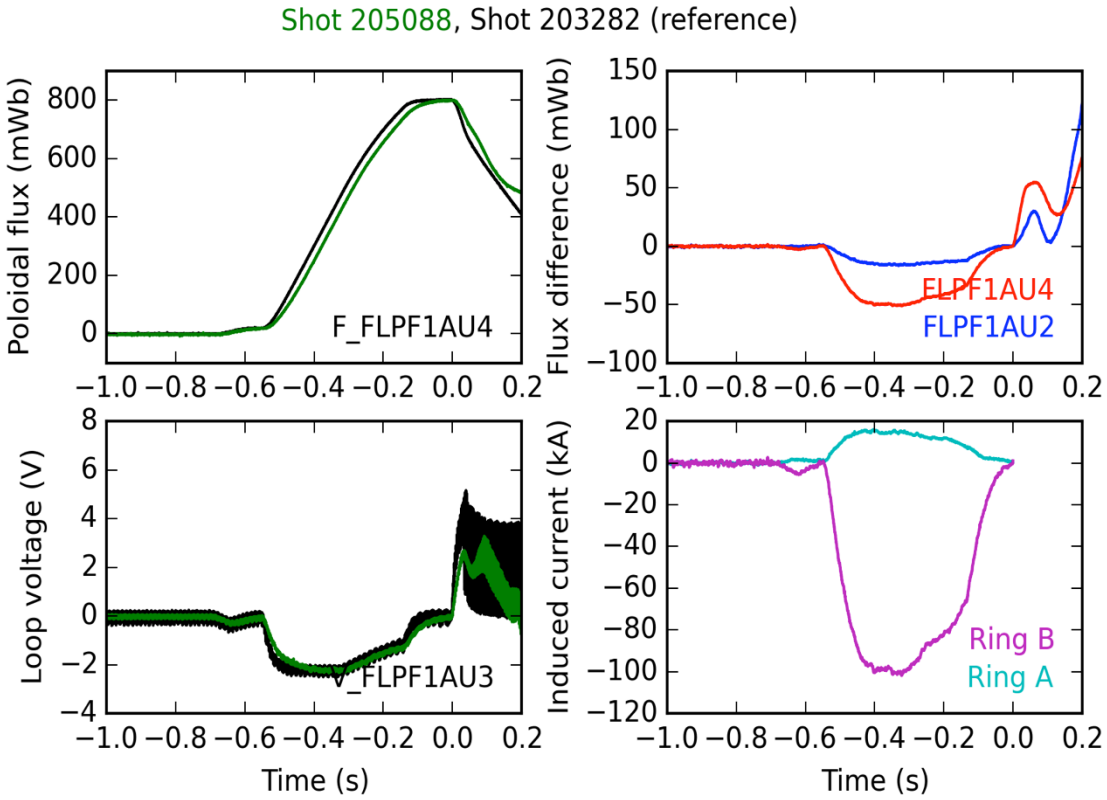


No trend when the OH is ramping



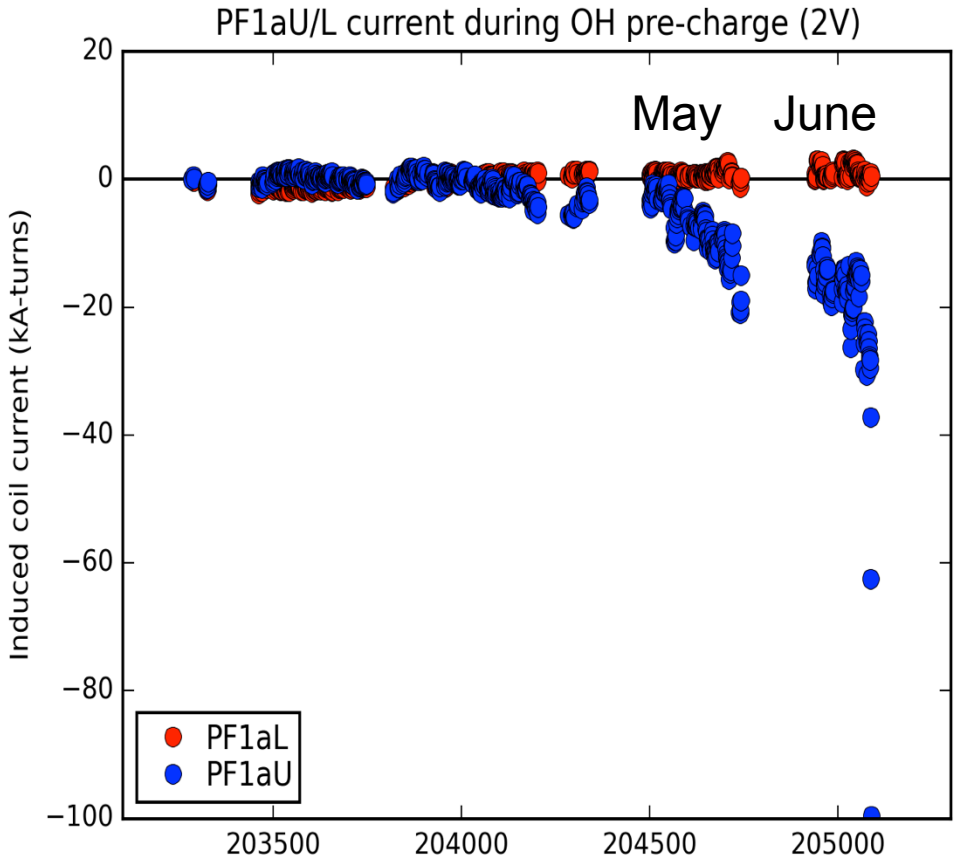
OH Pre-Charge Used on Every Shot Provides Another Opportunity for Trending

- Shot 205088 is the last plasma shot of the run
- Approximately 100 kA-turns of current induced in PF1aU
- Minimal induced current in PF1aL



Database Analysis During OH Ramp Confirms Degradation of -1aU, Consistency of -1aL

- PF1aL trend is flat zero through to the end of the run
- PF1aU first starts to conduct current at the end of the March/April run period
- Consistent degradation during the May run period
- Coil *does not* continue to degrade during May/June maintenance period
- Very fast degradation on the final run day in June



Summary w/ Regard to PF-1a Coils

- PF-1aU coil suffered a failure on 6/28/2016
  - Initially manifest as a flow blockage, but now understood to have involved some conductor melting.
  - Process of attempting to unblock the flow resulted in a water leak that required cleanup and recovery
- After attempting to resume operations 7/20-7/22, it was determined in consultation with FES that plasma operations was unwise.
  - Voltage transients and circulating currents indicate potential for further damage to the coil and nearby elements, including possible/ likely Cu melting under plasma scenarios.
- Analysis of historical data shows that the PF-1aU has been deteriorating for some period
  - The PF-1aL does not show similar trends.
- A forensics team has been identified to define and execute a plan to determine the failure mode of the coil.

Remaining Tasks

- Completed some RWM coil shots on Tuesday 6/26/2016
- Ran XMP-157 on 6/27/16 (Wednesday)
  - Study the beam species mix using the FIDA system, NB into D_2 gas operations.
- MAPP samples installed 6/28/16 (yesterday)
- Boronization on 6/29/16 for surface science studies
- XMP-158 (MSE-LIF Beam into Gas w/ Fields) and XMP-106 (Magnetics Calibration Shots) will be performed next week
  - Loop voltage levels & duration will be beneath any threshold for melting or arcing.
  - No TF or OH operations.
- Will likely repeat some coil hydrostatic tests and low-frequency inductance tests.
- Rayleigh-Raman scattering during the week of 8/15

Overview

- Observations from Our Testing Last Week
- Model of Circulating Currents in the PF-1a Coils
- Analysis of Some Historical Data

Want to Thank the Team for All the Work During the Run

- Physics Operations Group
- COEs, Shift Supervisors, Construction Managers
- Diagnostic Operations…techs, engineers, physicists
- NB Engineering & Operations
- RF Engineering & Operations
- FCPC and MG Engineering and Operations
- Electronics Design and Fabrication
- ME Design, Analysis, and Fabrication
- IT, CODAC
- Machine Techs, Vacuum Techs, Water System Techs.
- AC Power
- Tech Shop
- Facilities
- QA and Best Practices
- Business Operations
- Industrial hygiene, health physics, and other ES&H functions.
- Special teams…BN removal, PF-1a flex bus repairs

Overview

- Observations from Our Testing Last Week
- Model of Circulating Currents in the PF-1a Coils
- Analysis of Some Historical Data

We Accomplished an Enormous Amount in the Last Year

- Made enormous improvements to PCS with minimal downtime, while operating the new DCPS and MDS+ systems
- Commissioned many many many diagnostics
- Commissioned MGI and APS, got LITER probes to the very edge of deployment
- Got 12 MW of NB power running
- Recommissioned the HHFW system
- Recovered full FCPC/MG operations
- Got routine breakdown, current ramp, long-pulse L-mode scenarios
- Studied plasma control, error fields, fast ion physics, diagnostic techniques, surface science & H-mode scenario development