NSTX-U

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Update on Analysis of the OH Coil Fault on 4/24/2015

Stefan Gerhardt

NSTX-U Team Meeting
MBG Auditorium, PPPL
5/1/2015

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Large Team Has Been Investigating This Fault List Includes, But is Not Limited to:

- Electrical Engineers
  - Raki Ramakrishnan, Tim Stevenson, Andy Gao, Mike Williams, John Lacenere, Hans Schneider,…
- Mechanical Engineers
  - Steve Raftopoulos, Larry Dudek, Erik Perry, Neway Atnafu,…
- Research Staff
  - Stefan Gerhardt, Dennis Mueller, Clayton Myers, Masa Ono, Jon Menard, Devon Battaglia,…
- NSTX-U Machine Techs
  - Joe Winston and his entire crew

The material in this talk attempts to synthesize & summarize all of their contributions.

This Talk

- Some vocabulary
- Observations on the run day
- Our present scenario for what happened
- Good news and next steps

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Critical Vocabulary
Belleville Washer Stack

- Many stacks of springs
- Wedged in between the top of the OH and the bottom of the TF.
- Pushes the OH coil down, providing a pre-load mechanism to prevent the coil from lifting out of the lead block.

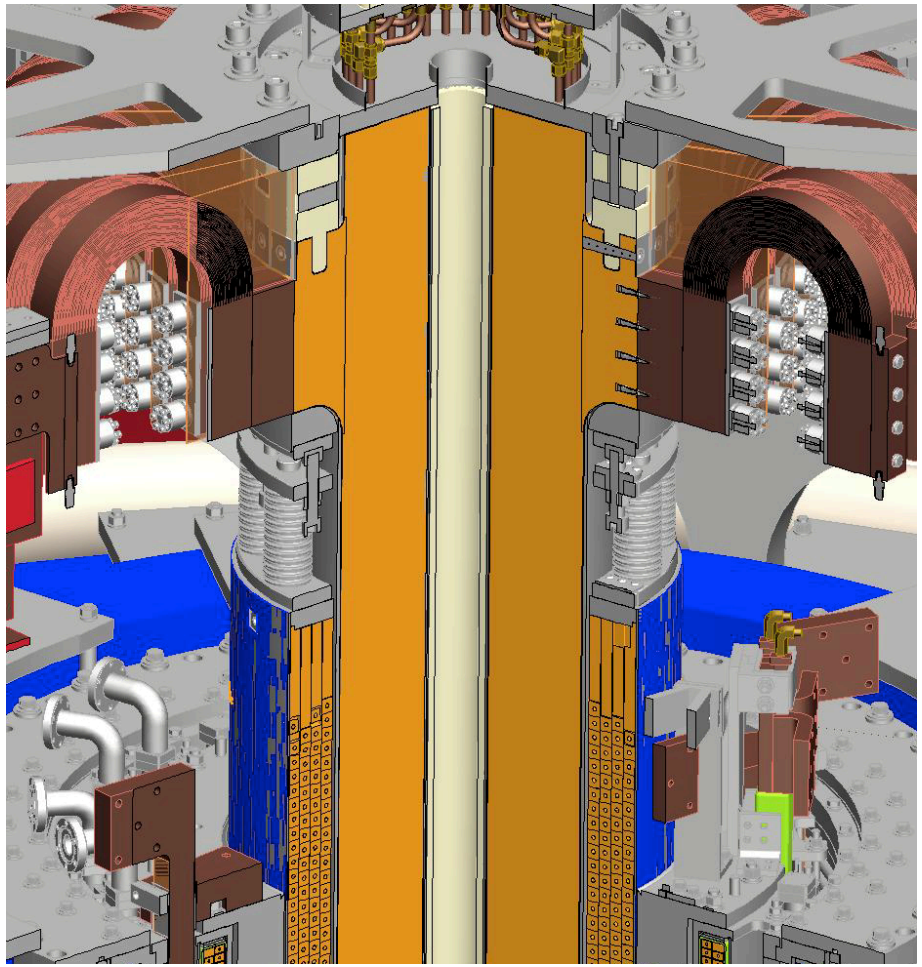
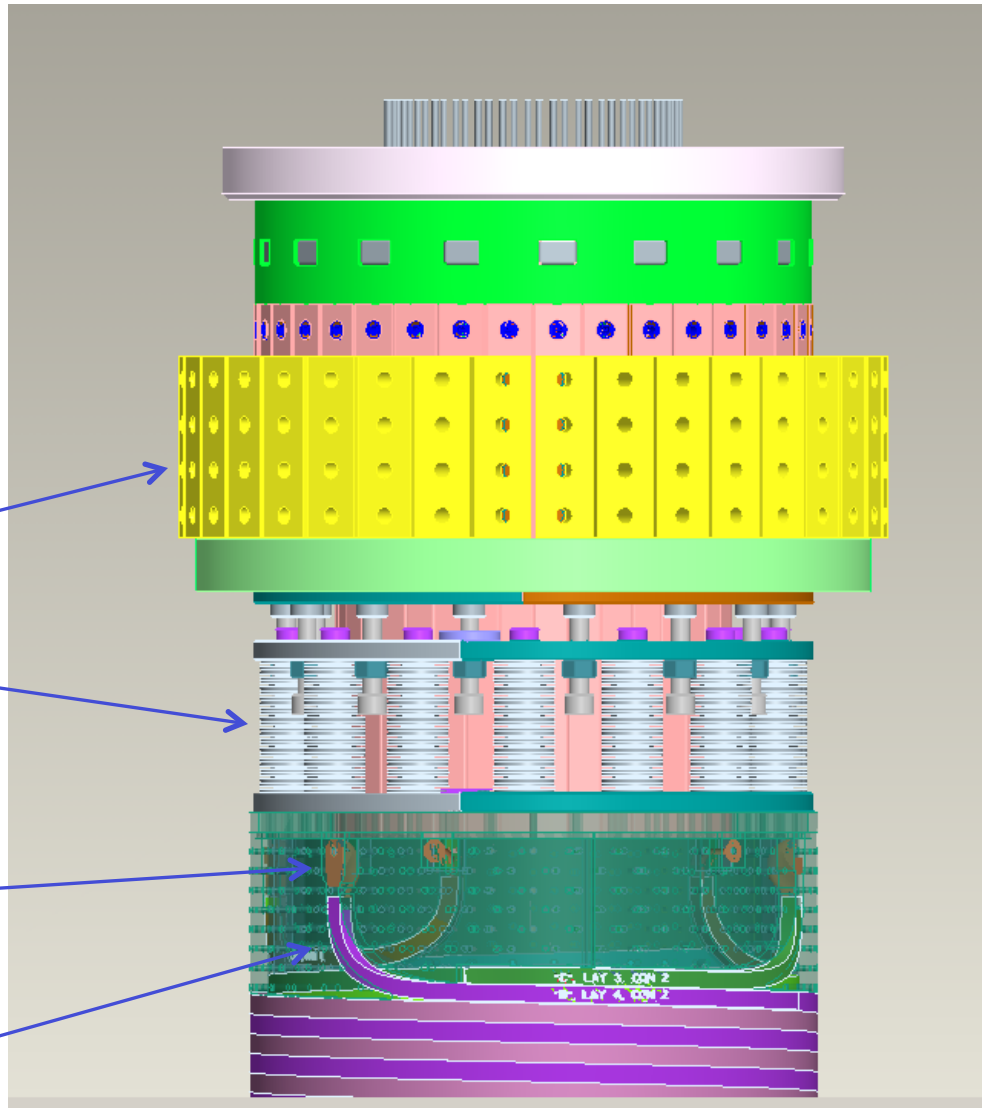


Photo of the Belleville Washer Stack During Removal

Critical Vocabulary
OH Coil and OH Water Feeds

- OH coil made from hollow conductor, to allow water cooling.
- OH coil has four layers, with each layer providing two “circuits”
  - So eight total sections.
- Consecutive sections are “TIG Brazed”, with the remaining conductor run out of the coil as water feeds.
- Each section has water feeds at the top and bottom



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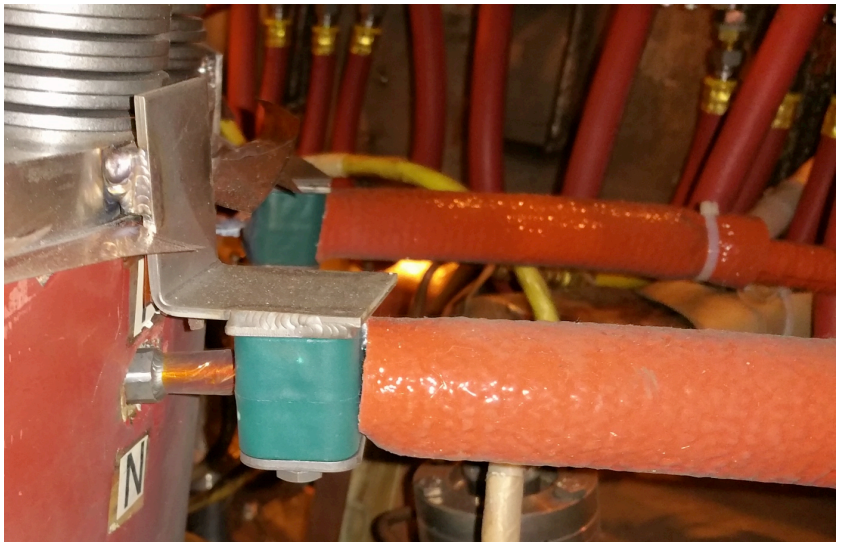
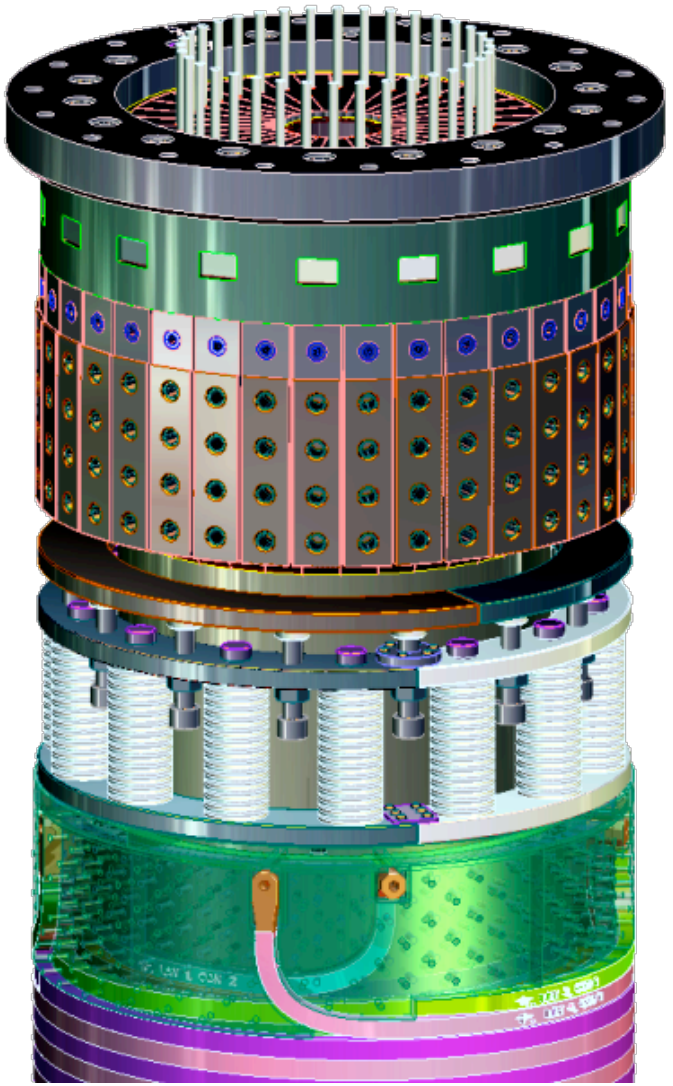
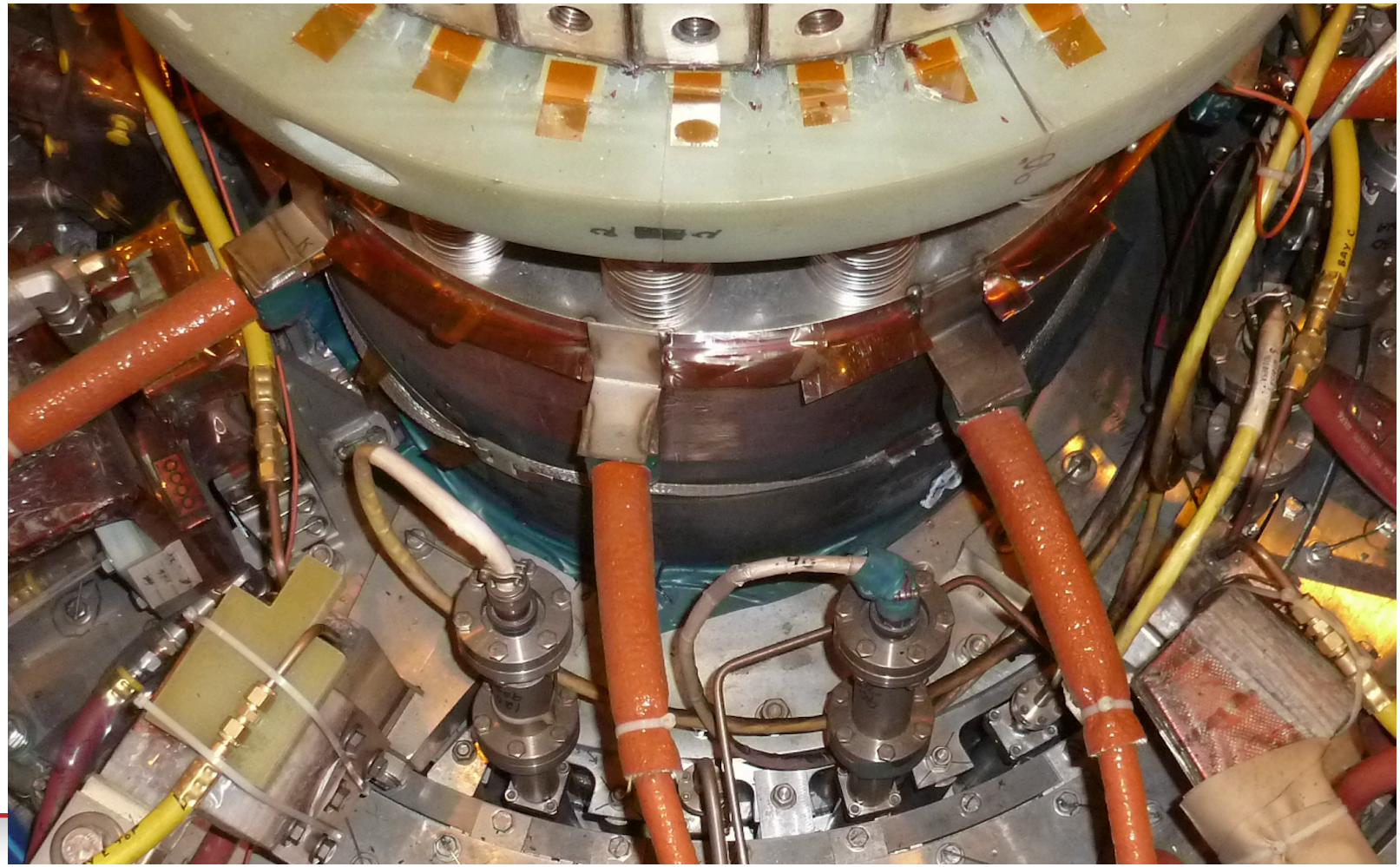




Critical Vocabulary
OH Ground Plane and Ground Plane Braid

- Outside of the OH coil has glass/epoxy wrap, and then a conducting paint.
  - Conducting paint provides a ground plane, so that the electric field is contained within the insulation.
- Tinned copper braid wrapped around the ground plane.
- Braid is then attached to the appropriate ground, providing the reference for the ground plane.

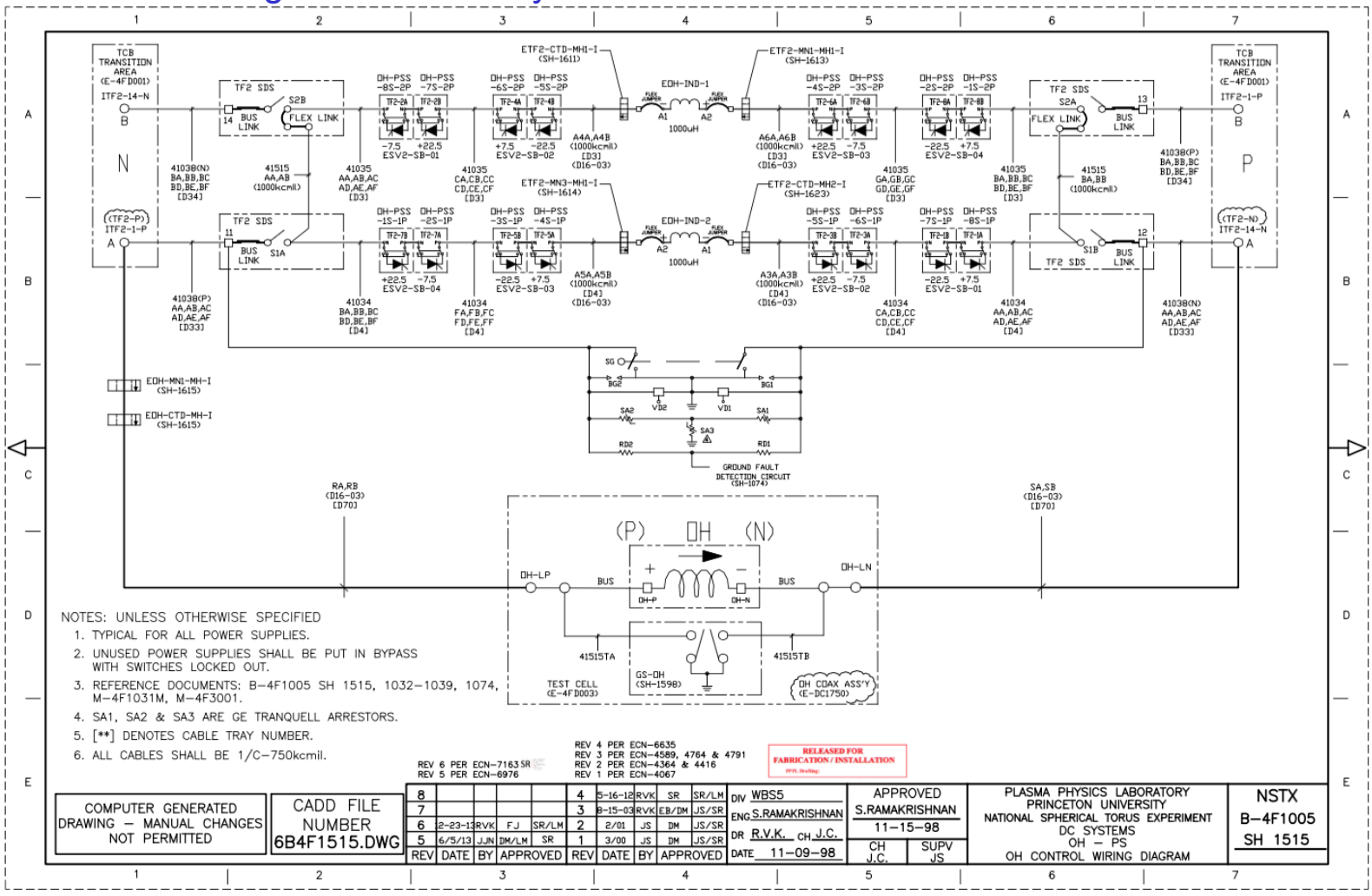
Post-Fault Photo, on Undamaged Side of the CS



Critical Vocabulary
OH Supply and Ground Fault Circuits

- OH Supply is has a central ground in FCPC with two ground fault detectors:
  - "Instantaneous" ground fault relays.
    - Build for when those supplies were the TFTR TF supplies.
  - "Inverse time" ground fault relays.

+/- 24 kA, +/- 6 kV



This Talk

- Some vocabulary
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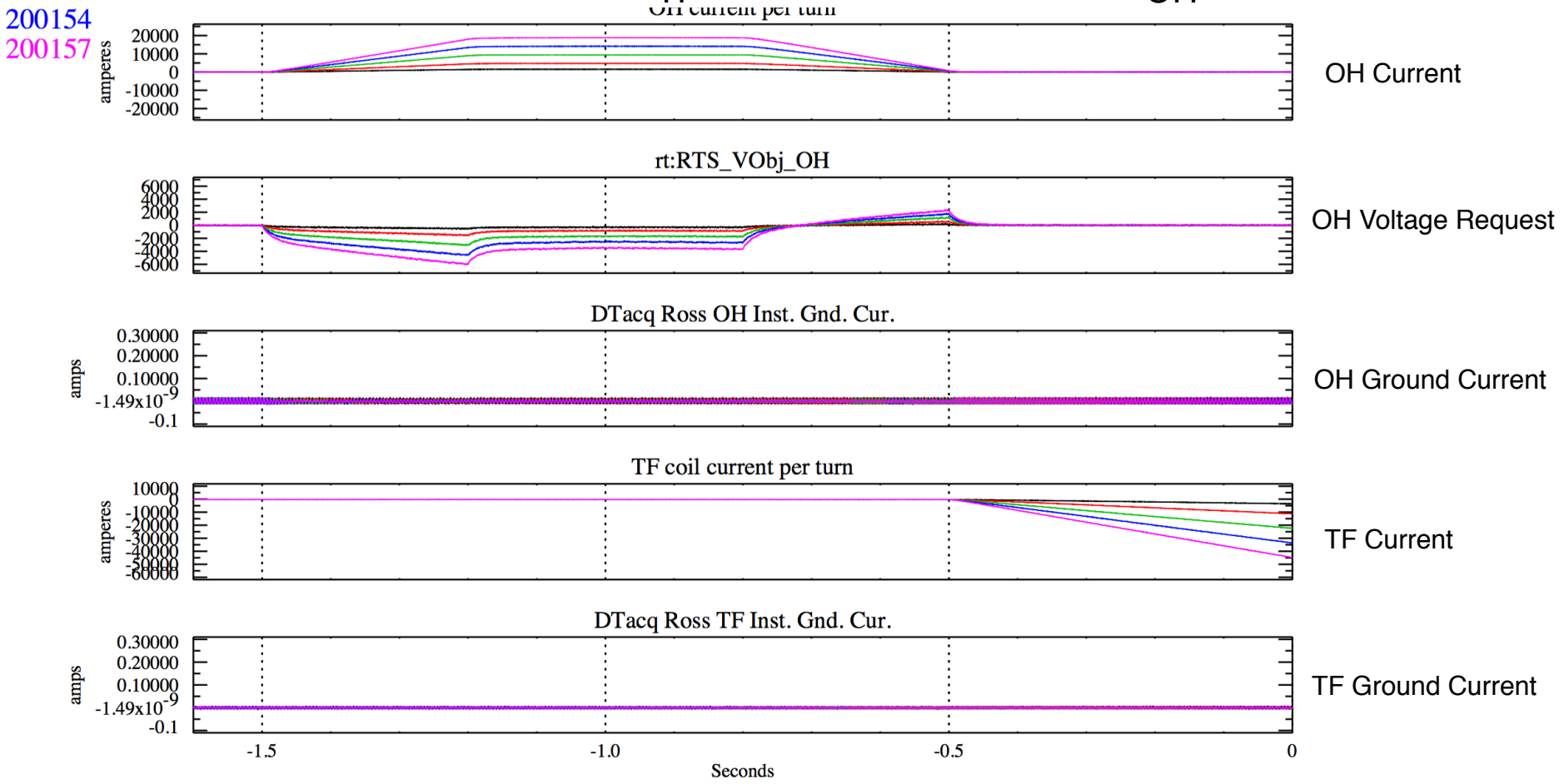
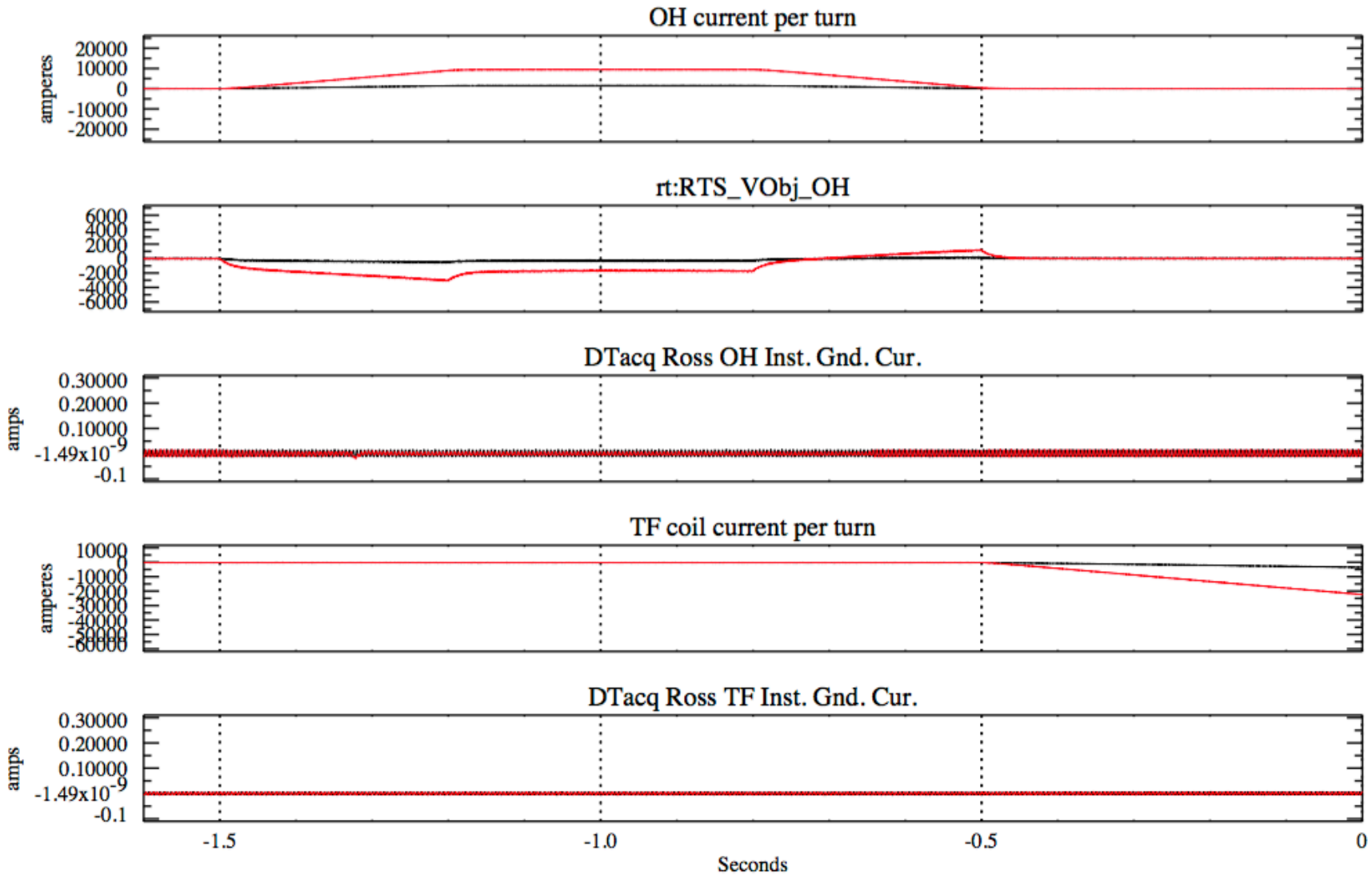
Sequence of Events Leading Up to Fault
ISTP Was Completed Without Issue

- Up to 100% shot -> I_{TF}=-65 kA, -21 kA<=$I_{OH<}$=21 kA

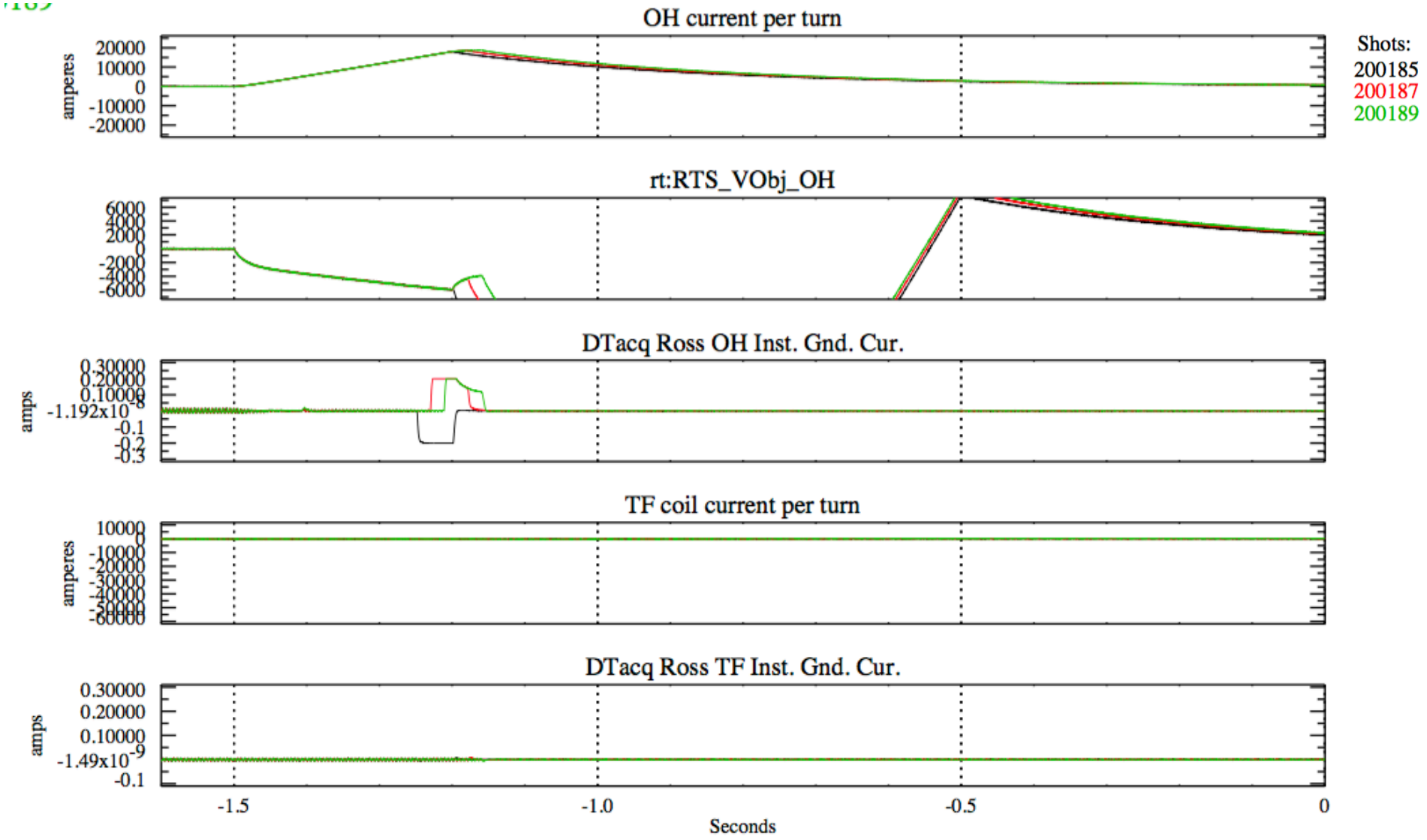


Note: Operations team was not routinely inspecting the ground current during any of the shots; critical trends in the ground currents were discovered after forensic analysis.

Sequence of Events Leading Up to Fault
8% and 50 % shots on 4/24/2015 Were Fine



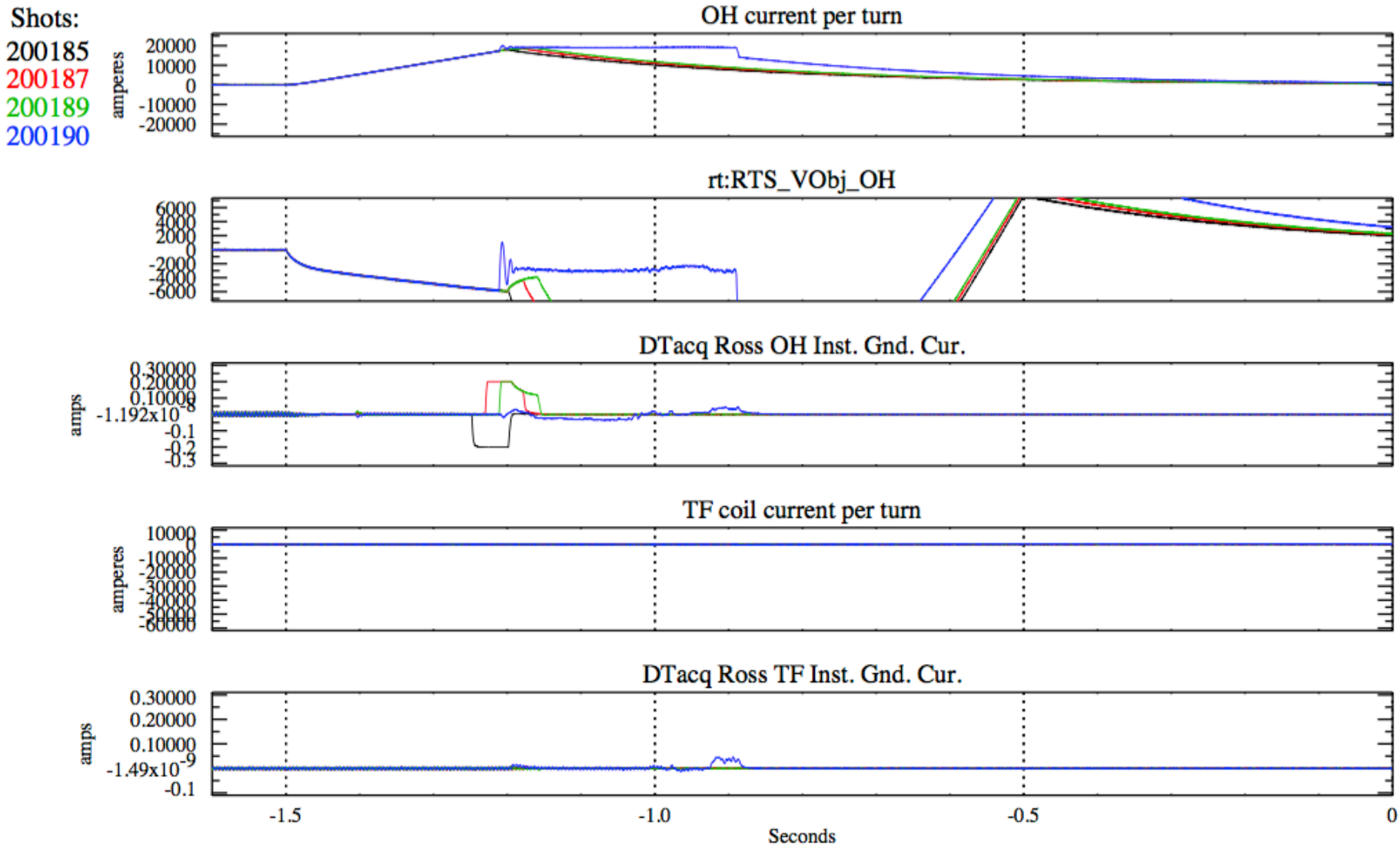
Sequence of Events Leading Up to Fault
Struggled in Attempts to Recreated Previous 100% Test Shot



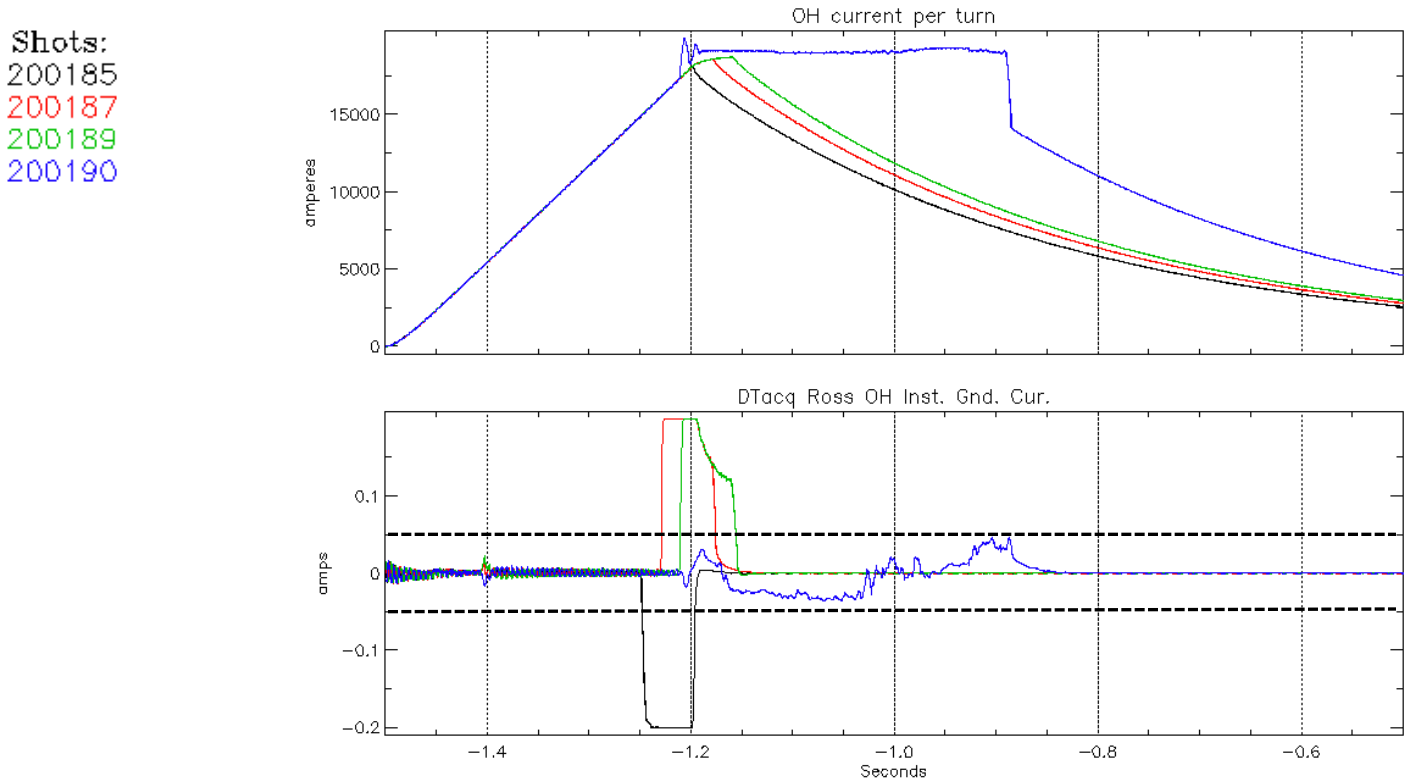
Sequence of Events Leading Up to Fault
Reactions to Those Trips

- 200185: First Trip + Cat.3 – Cat. 4 loop fault
  - This fault shows up clearly on the ground NTC ground/loop fault monitors
  - Moved ground connection braid from Cat. 4 to Cat. 3 during a controlled access.
    - That cleared the loop fault (likely due to intermittent contact between the ground plane paint and the PF1aU mandrel).
  - Did a low-pot of the OH coil from FCPC (the SDS cabinet).
    - Found leakage resistance was identical to earlier in the day.
  - Repeat the shot.
- 200187: Second Trip
  - Increased the threshold on the instantaneous ground fault relay from 50 mA to 100 mA
  - Repeat the shot
- 200189: Trip again
  - Noted the good low-pot and the known issue of nuisance trips on the instantaneous ground fault system.
  - OH Instantaneous ground fault relays were taken out of circuit.
    - But the inverse time relays were NOT removed.

Sequence of Events Leading Up to Fault
Next Shot Had The Damaging Fault



Sequence of Events Leading Up to Fault
Ground Currents Were Much Different on 200190



- Instantaneous ground fault detector would not have detected any problem or terminated the shot
- This was a different beast than the previous ground fault trips.
  - Less ground current, but much more damage.
  - So what changed?...will come back to that in a few slides.

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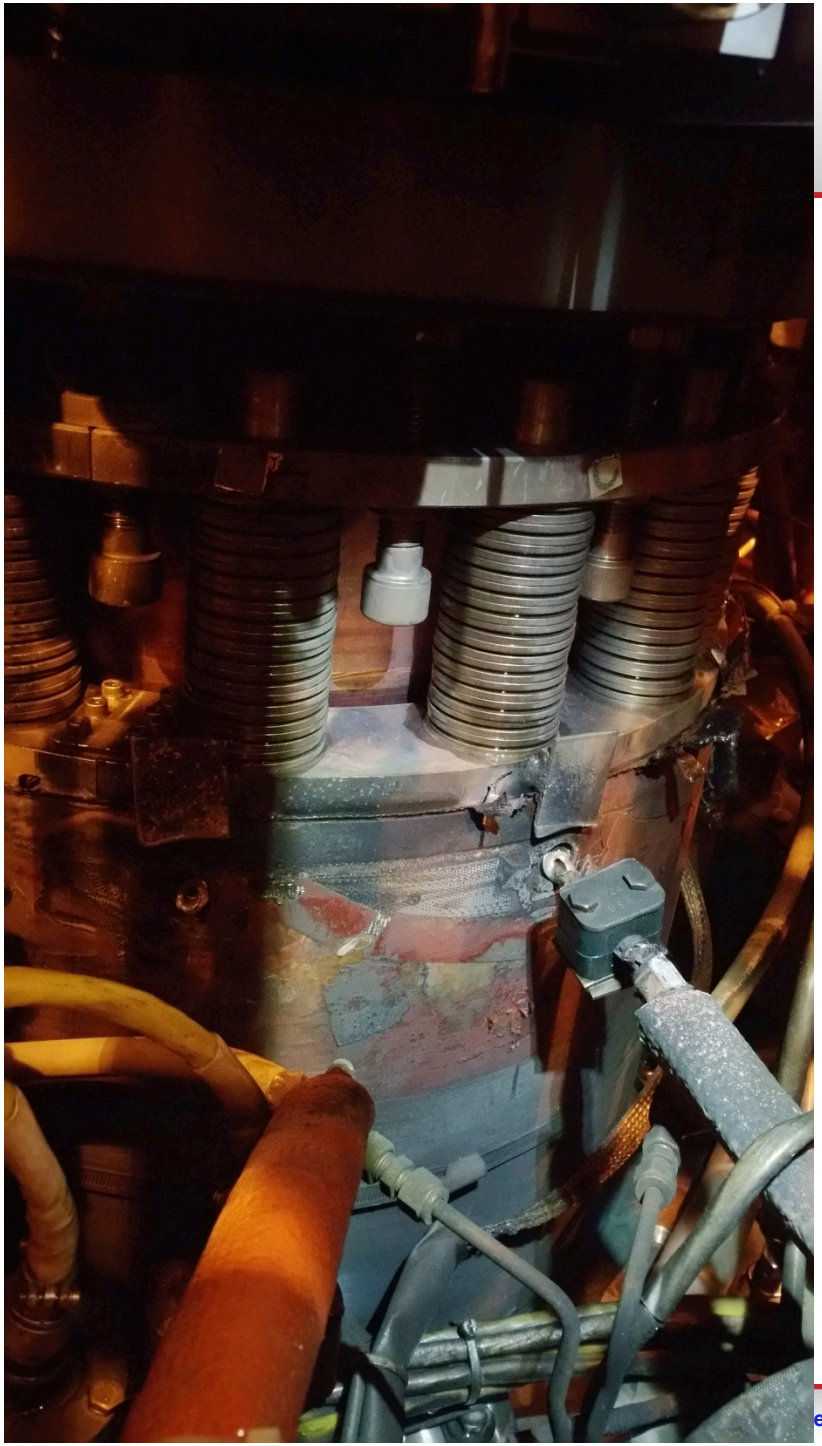
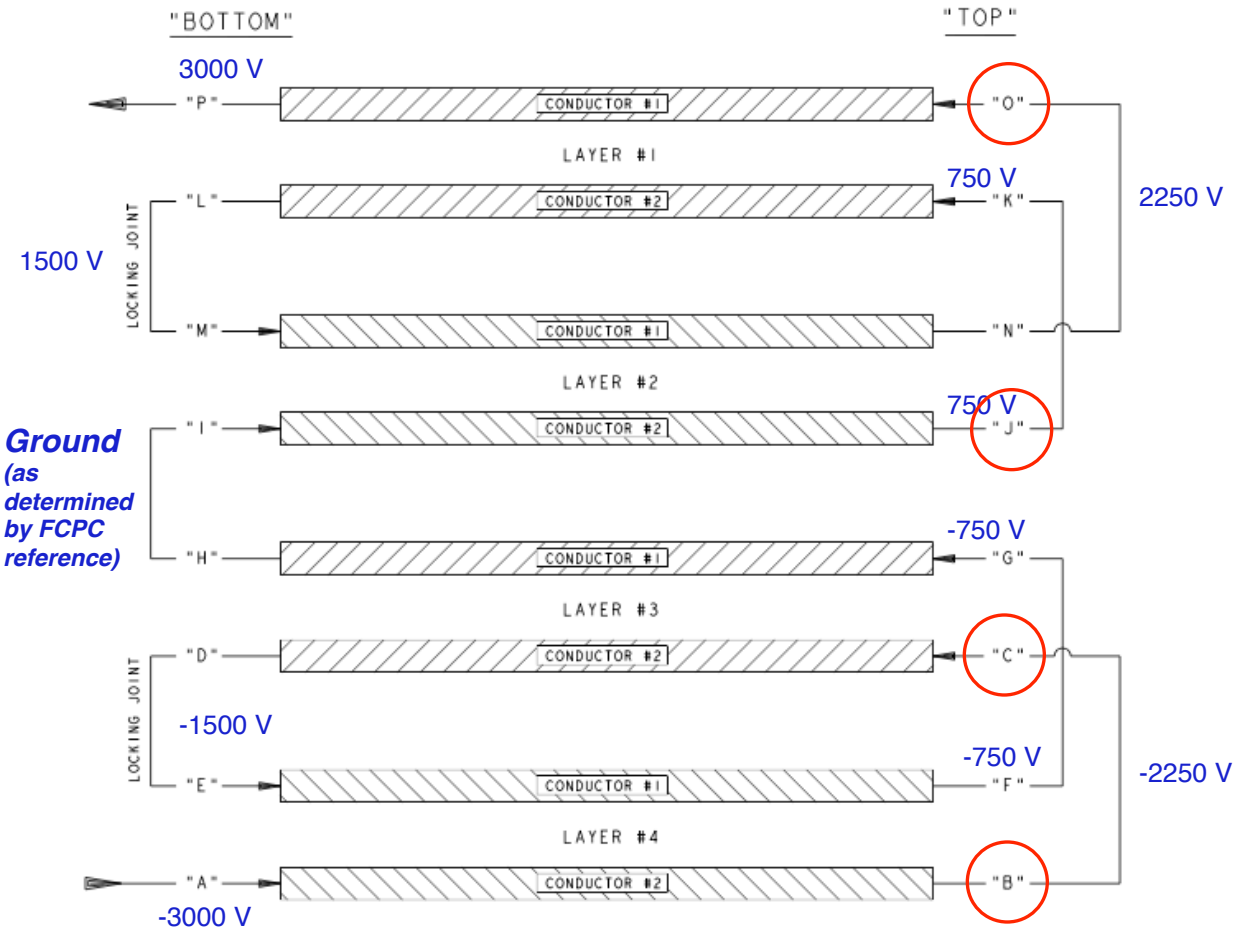


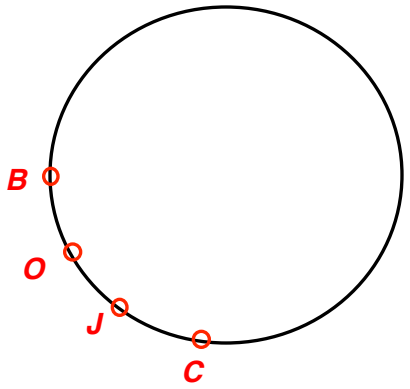
Disassembly and Recovery Efforts Started Immediately, Revealed Damage.

- Damage to water fittings & hoses was most obvious.
  - 4 of 8 upper water feeds severely damaged.
- Considerable soot covering many components on the north-west side of the CS.
- Quickly formed a working hypothesis:
  - The arc was formed between the water fitting on the coil, the bottom of the spring stack, and then another water fitting.
  - The arc + washer stack essentially shorted out the part of the coil.
- Hypothesis gained further traction when it was found that the Belleville stack had not been grounded.
  - No ground means no FCPC ground fault trip on final fault.

Inspection Revealed That the Arc Included the Two Highest Voltage Water Feeds

Red indicates where there was damage



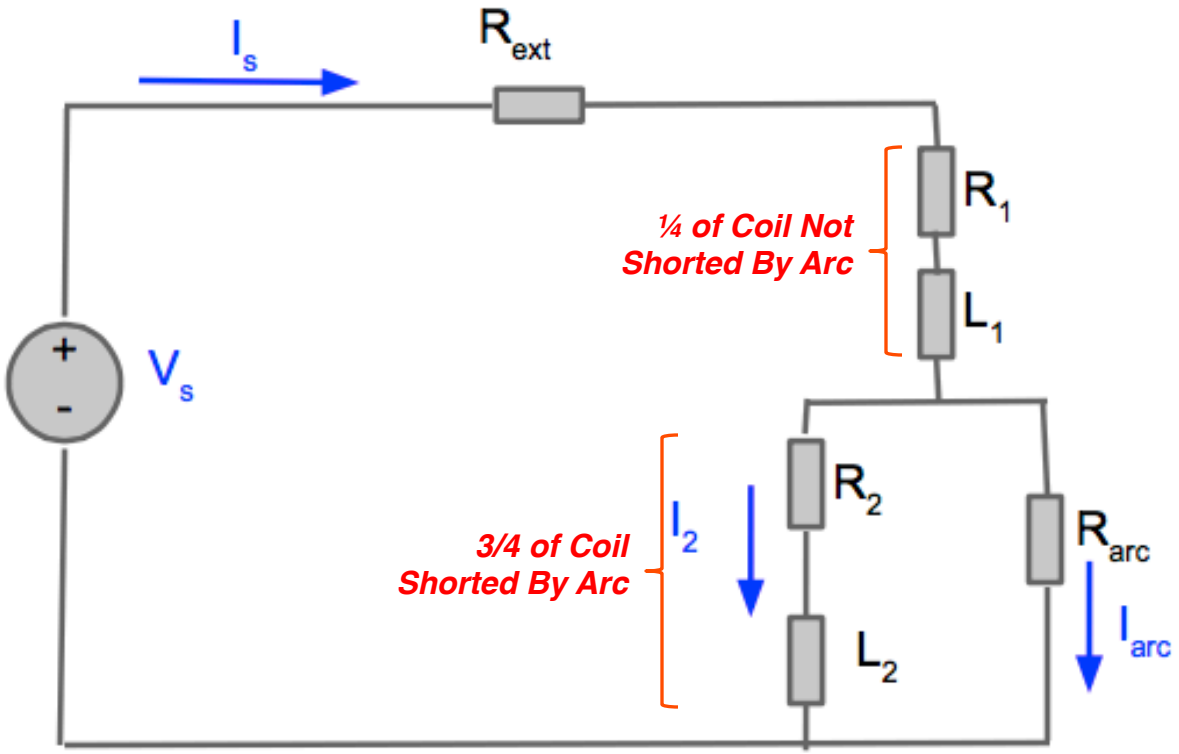


Message

Conceptualize the arc as shorting out ¾ of the length of the coil.

E-DC1554

This Hypothesis For the Arc Is Corroborated by Simple Modeling.



Assumptions of the Model

$R_1+R_2=R_{coil}$
$R_1 = R_{coil}/4$

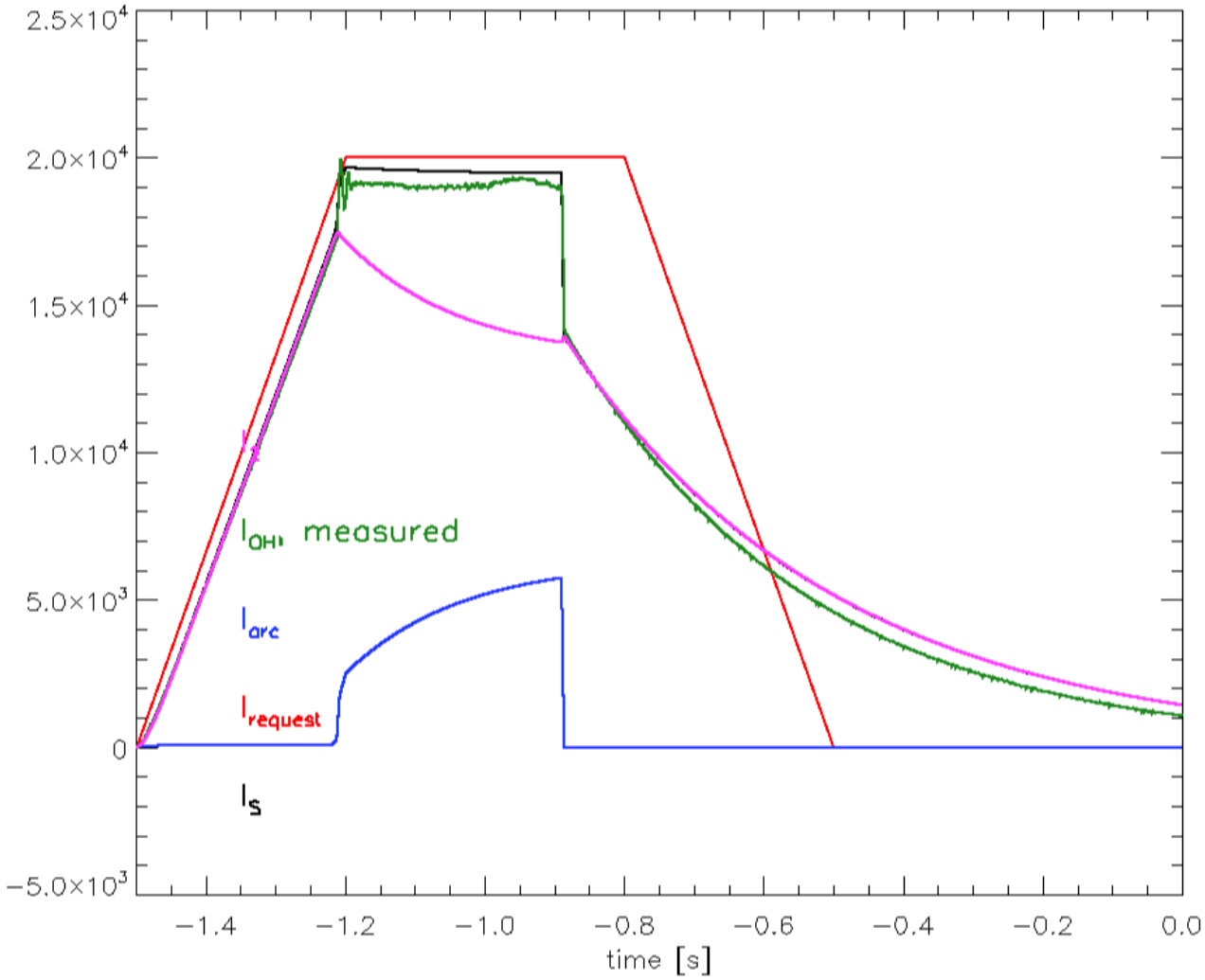
$L_1+L_2=L_{coil}$
$L_1 = L_{coil}/16$

Neglect mutual coupling between L_1 and L_2

$V_s=P(I_{coil}-I_s)$

Allow a time dependent R_{arc}.

With "Reasonable" Models For the Arc Resistance, Can Match the Supply Waveform: Full View



Requested Current

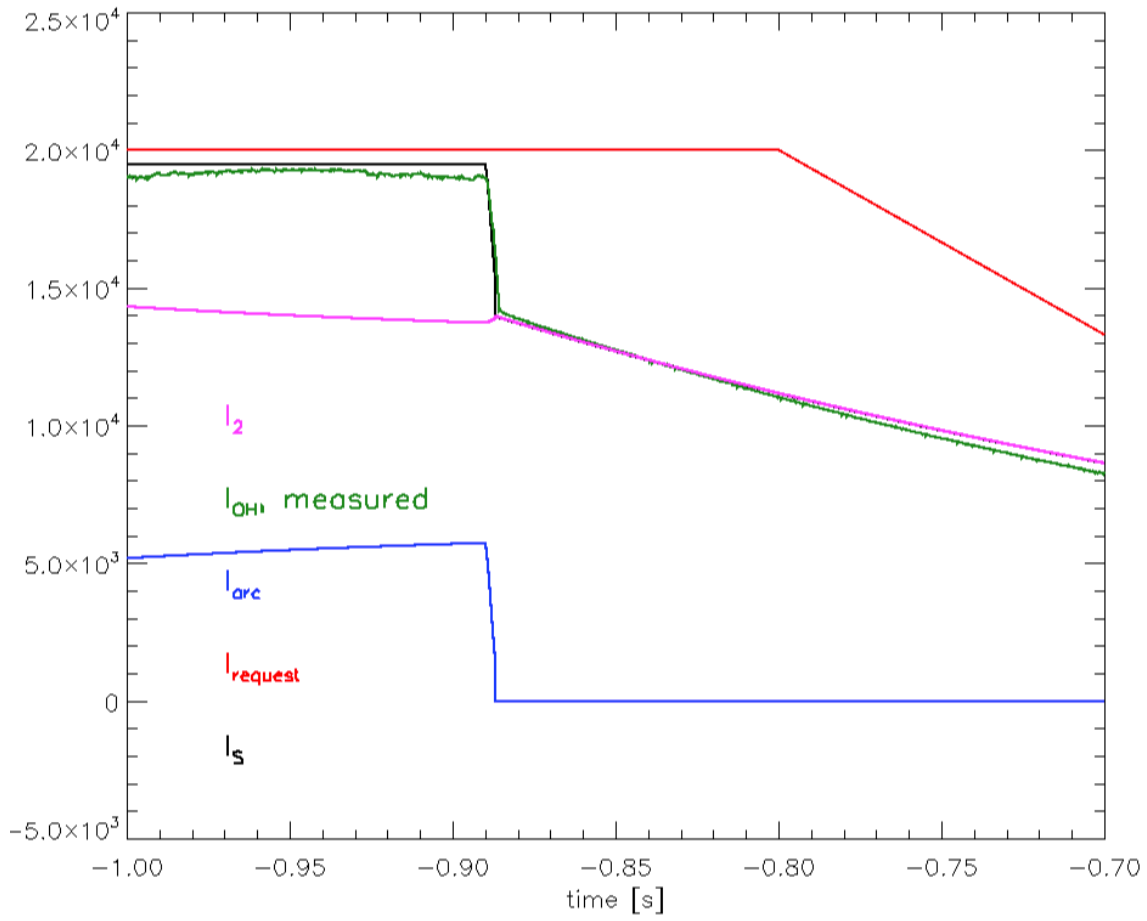
Measured Supply Current

Model of Supply Current

Model of Arc Current

Model of Current in Part of Coil Shorted by Arc

With "Reasonable" Models For the Arc Resistance, Can Match the Supply Waveform: Zoom In



Requested Current

Measured Supply Current

Model of Supply Current

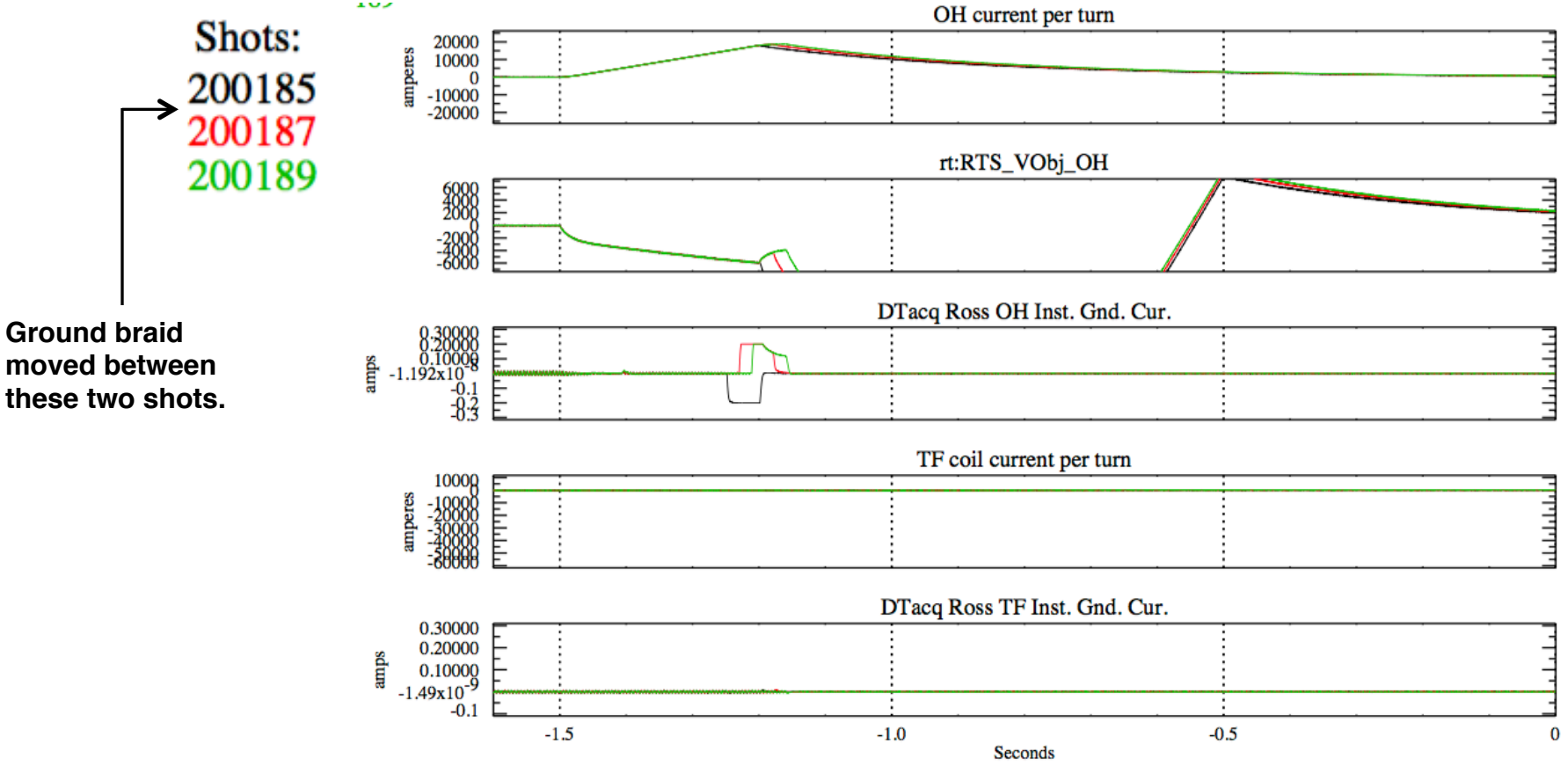
Model of Arc Current

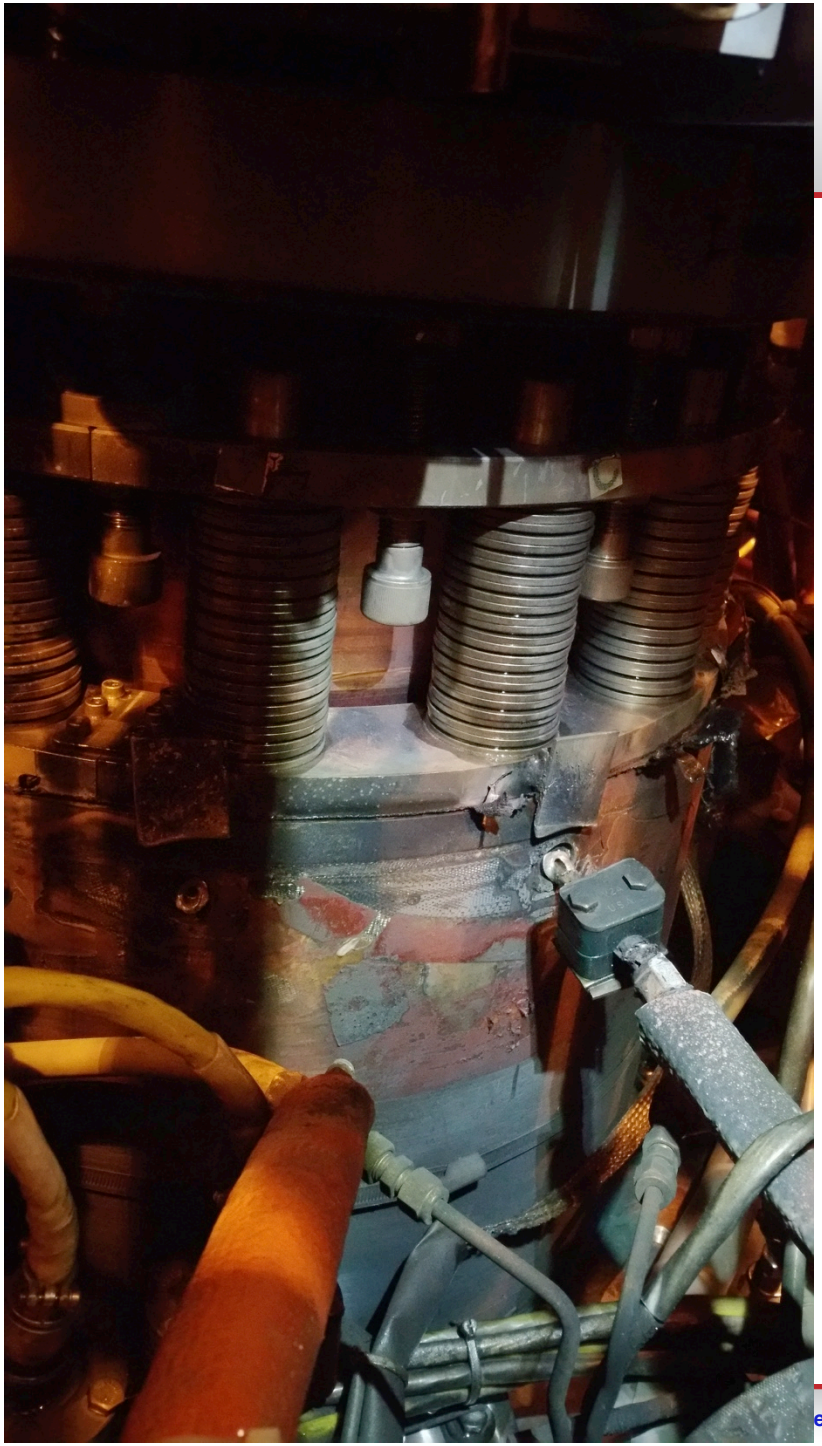
Model of Current in Part of Coil Shorted by Arc

- So the events of the final arc are grossly understood, but:
  - What about the ground currents?
  - What changed from the good ISTP and 50% shots to the large arc?

Major Clue Can Be Found in the Ground Currents

- Ground currents changed sign when the OH ground plane braid was moved from Cat. 4 to Cat. 3 reference.
  - So the ground braid was likely part of the issue.





Inspection Showed the Ground Braid Likely Played a Key Role

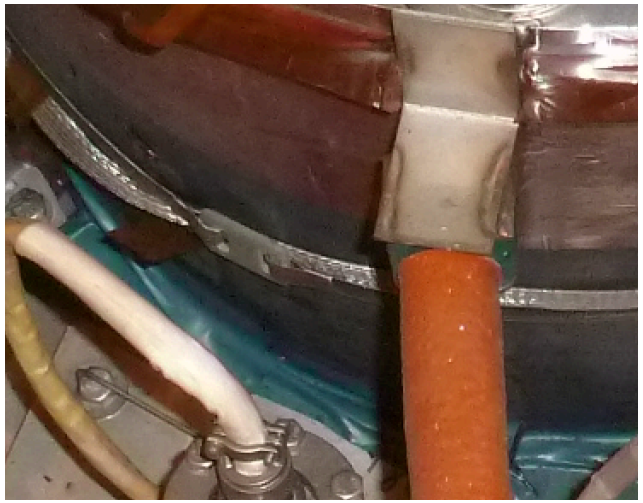
- Ground braid was observed to:
  - be toroidally continuous, and thus subject to eddy currents and launching loads.
  - have come loose from its clamps, and able to slide up and down.
- We believe that:
  - the ground braid was moving up and down, working its way loose.
  - Came in contact with the water fittings, resulting in ground faults on the shots before the fault.
  - Localized damage, consistent with this theory, can be found on the braid.
- The ground braid may have sparked or even bridged the water feed / clamp gap on the final discharge.
  - This likely accounts for the change in fault characteristics.

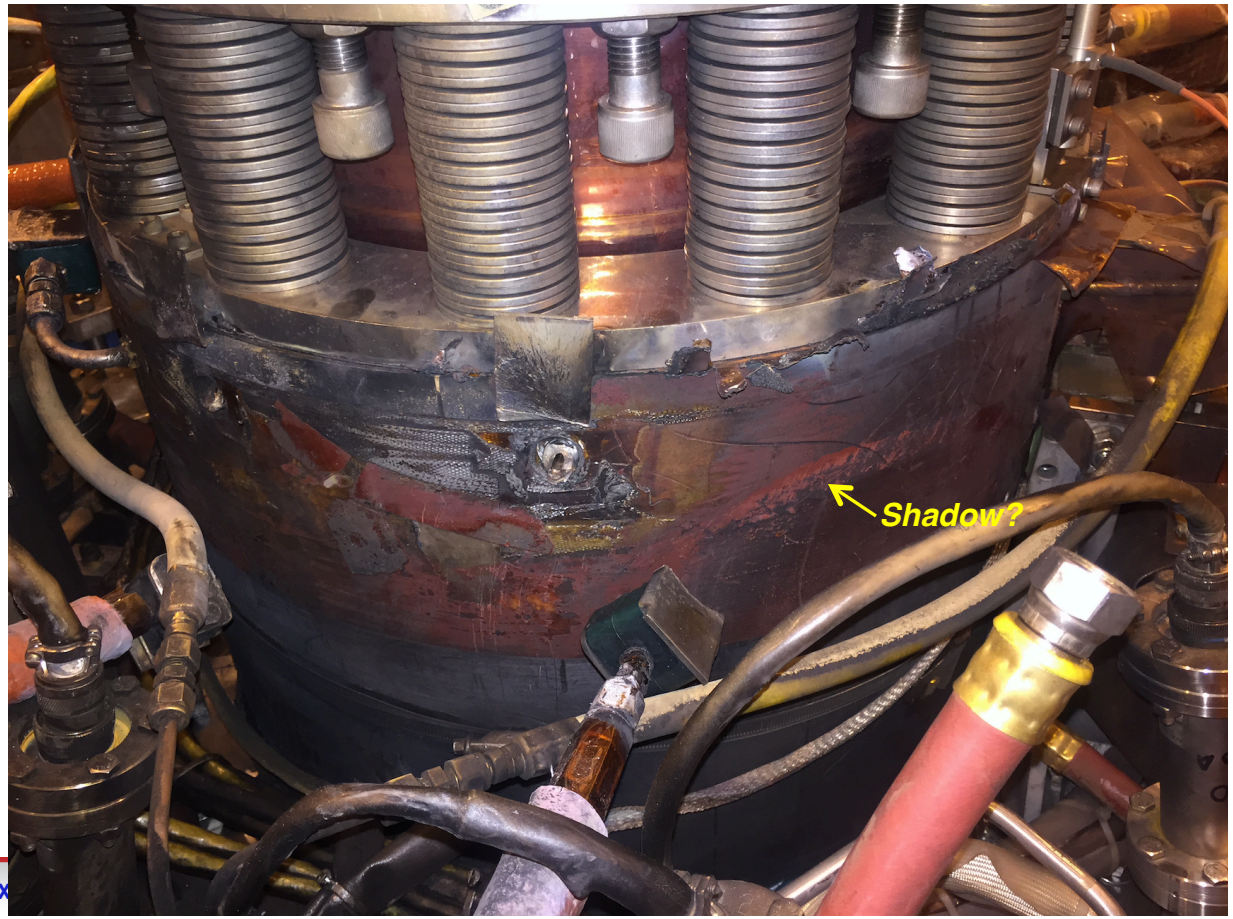
More on the Ground Braid

Damage observed at multiple points along the braid

Resting point of the braid is well below the fault area
JxB lifted it up, into the are of the fault

Braid bridged the gap in the clamp
But was pinned at that location,
~180 degrees from the fault area





Summary of Technical Causes

This is our present understanding, subject to further evolution

- Ground Braid
  - Was toroidally continuous and felt a launching load
  - It worked free, and was pinned on the side opposite where the damage was observed
  - Caused ground faults to the water feeds and likely the final trigger
- Belleville stack
  - Formed a part of the current path during the final arc
  - Lack of a ground meant:
    - Could not detect any issues with a high-pot
    - FCPC ground fault detectors did not protect against that particular flavor of arc.
- Water fitting isolation
  - Could be better, though this is the third-in-line cause.
  - We are assessing the present design, potential upgrades.

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Recent News Has Been Encouraging With Regard to Recovery

- The charred water fittings have been removed from the coil without issue.
  - The cooling paths are appear to be intact, and no excavation is required.
- 6 of 8 cooling paths have passed hydrostatic test
  - didn't have fittings to test the other two…should be done tonight.
- The TF insulation behind the belleville spring stack looks great.
- All magnetic sensors on the top of the machine survived just fine.
  - Just need to clean the soot off the cables.
- The MGI valve at the top was protected by its massive support structure.

Shiny insulation on the TF coil

Water Fitting: Melted on one side, just "used" on the other.

Next Steps
See talk by Steve R. for More Details

- Engineering Tests & Design Improvements
  - See Steve's talk.
- Consider a control code upgrade to detect transient load changes.
  - Is under design.
- Review of the fault, root causes, and technical solutions by internal PPPL committee.
  - Next week.
- External review called by PU.
- Once reviews are settled and fixes are in, try CD-4 again
  - See Masa's slides for more details on that.

Backup

Summary of NSTX-U Coil and Rectifier Protection Systems