NSTX-U Startup Arc Fault Technical Explanation

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OH Arc Fault External Review
May 28, 2014

r4

Direct Causes of Arc: Summary

- The OH ground plane braid had a continuous toroidal loop.
  - Currents induced by OH coil flux swing during the shot.
  - Experienced a JxB force that pushed it up into the exposed coil cooling water fittings *during the shot*.

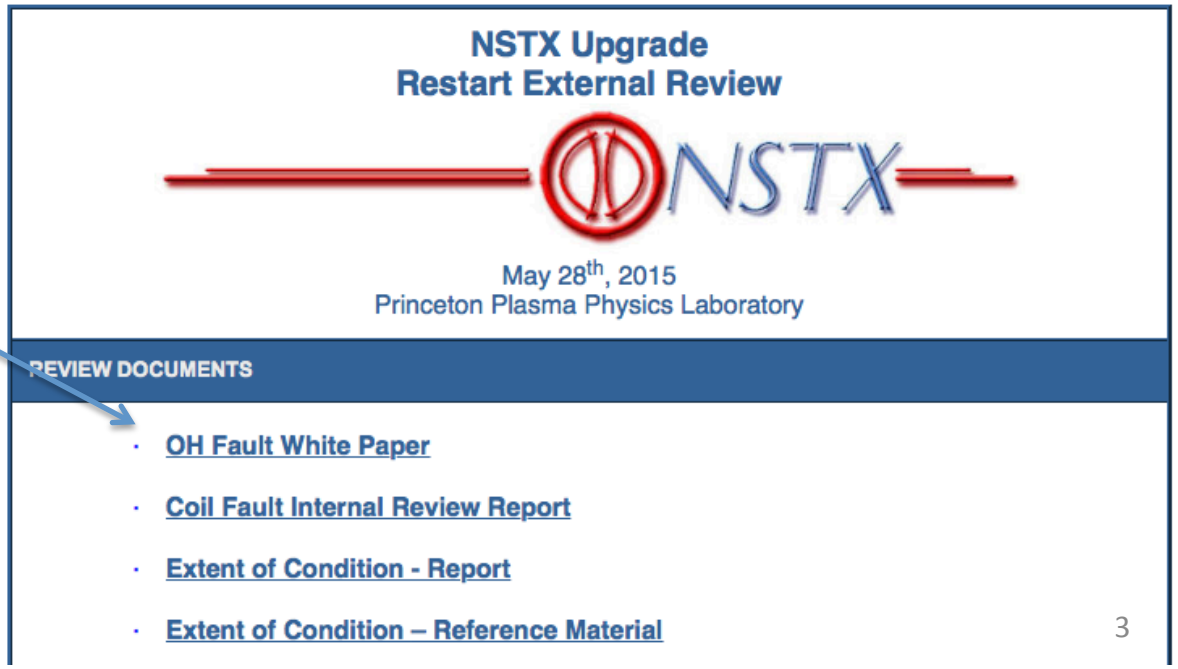
- The Belleville washer stack assembly was not grounded.
  - Communication between OH coil and assembly could not be detected by high-pots or ground fault interlocks.

Remainder of the talk is dedicated to explaining these assertions.

Outline

- Technical background
- Some context on the day of the fault
- Technical analysis of the fault

White paper has more details on all of these topics



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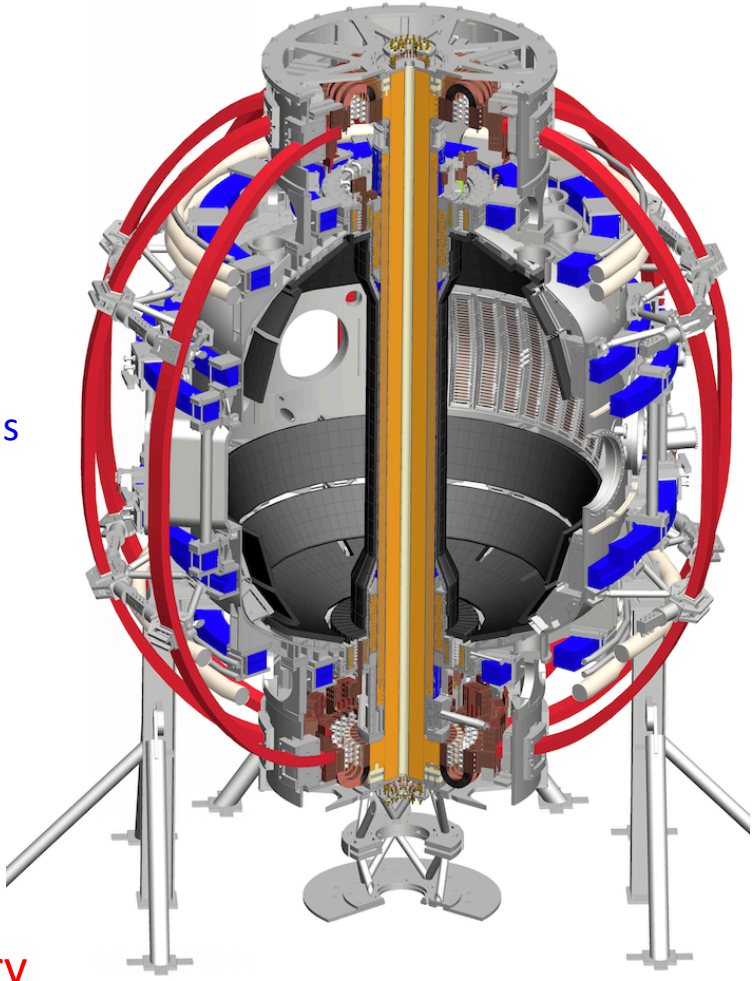
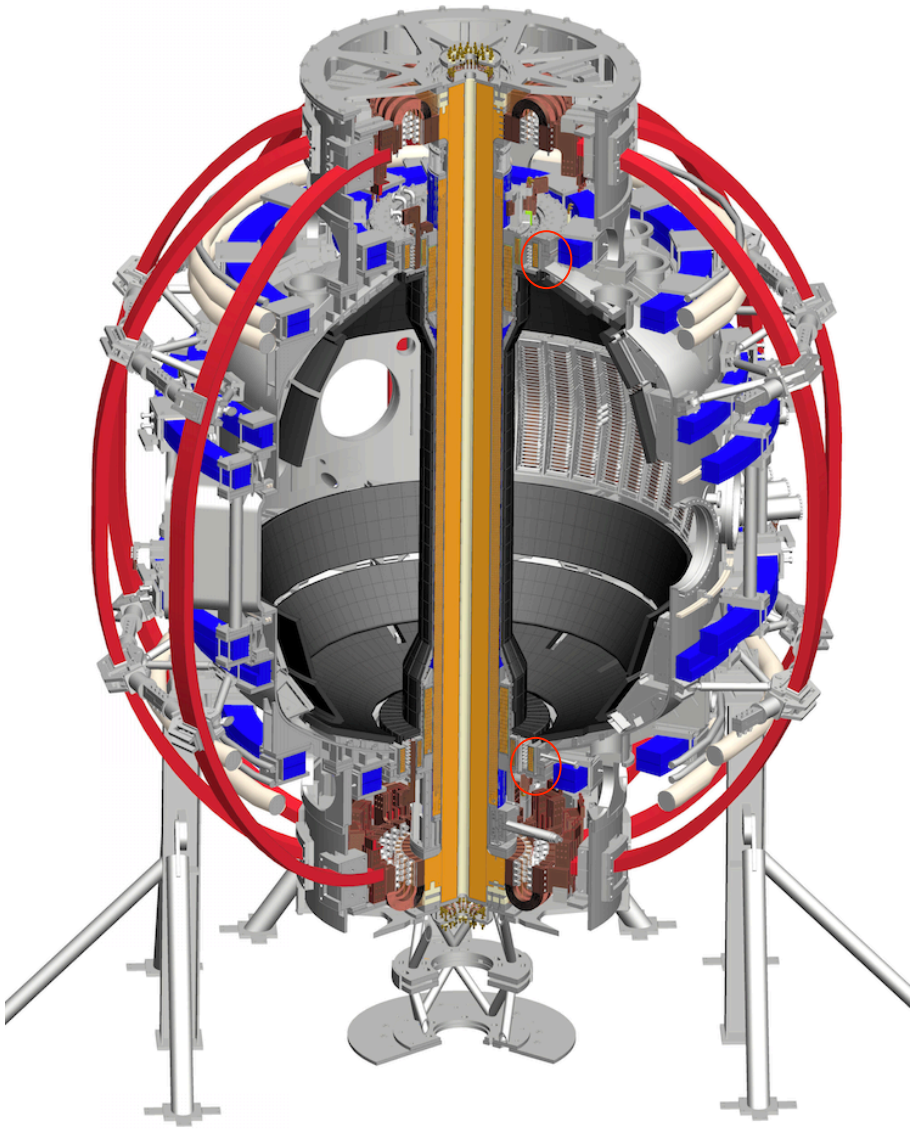
NSTX-U Operations Scheme…what is a "shot"?

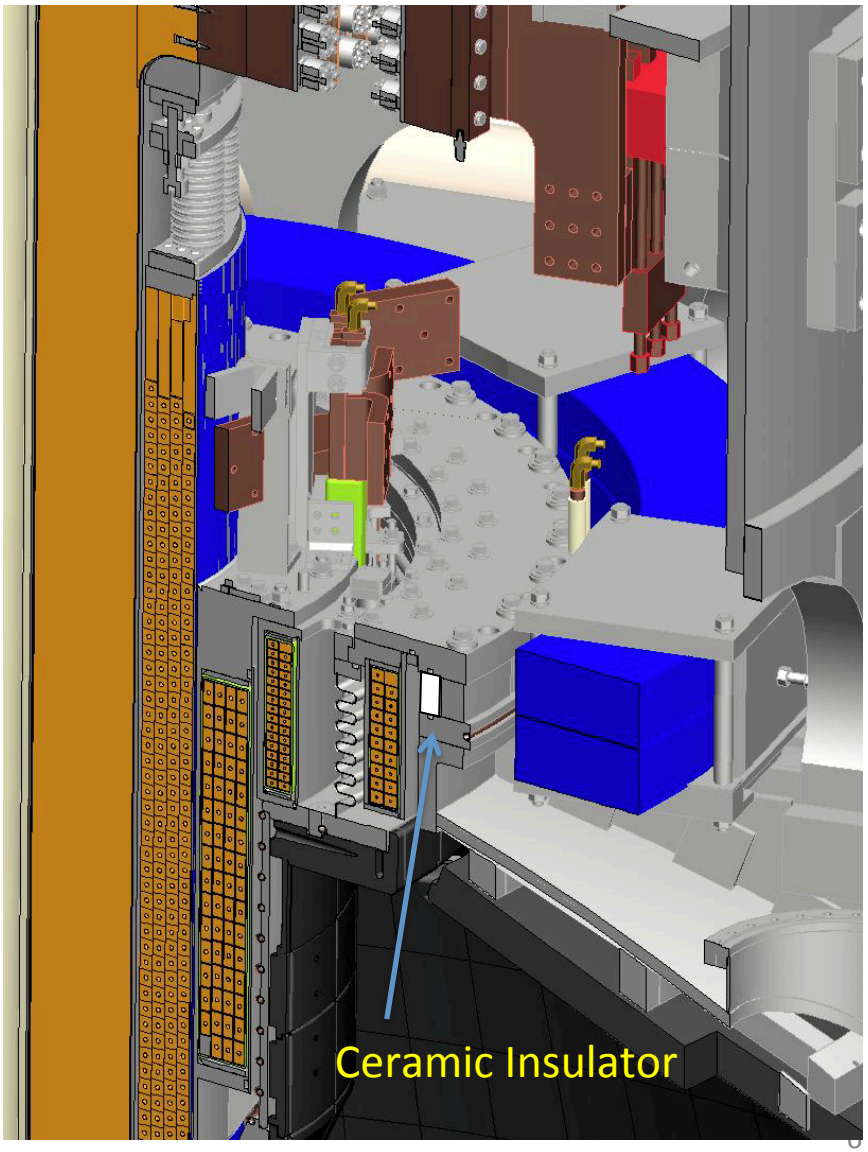
- Pulse the magnets once every 10-30 minutes, for durations ~5 seconds.
  - Each pulse is assigned a unique shot number.
- Two kinds of pulses…or "shots".
  - Test shots:
    - Single coil at a time, or combined field shots.
  - Plasma shots:
    - Specific combinations of multiple coils, along with gas injection, results in a plasma discharge.
- Arc occurred on the "Ohmic Heating" coil.
  - This is a tightly wound solenoid…makes vertically directed flux.
  - When current is ramped in this coil, the flux changes, and this applies a voltage.
    - High voltage required to drive fast current swings.
  - The plasma current is essentially the secondary of a transformer…is Ohmically heated.



NSTX-U Vacuum Vessel Has Two Electrically Isolated Sections

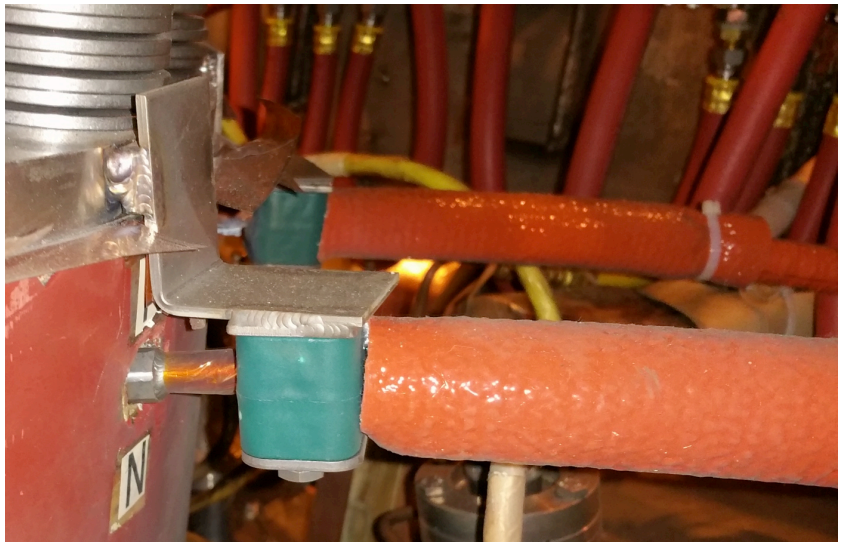
Ceramic Break Assemblies at Top and Bottom



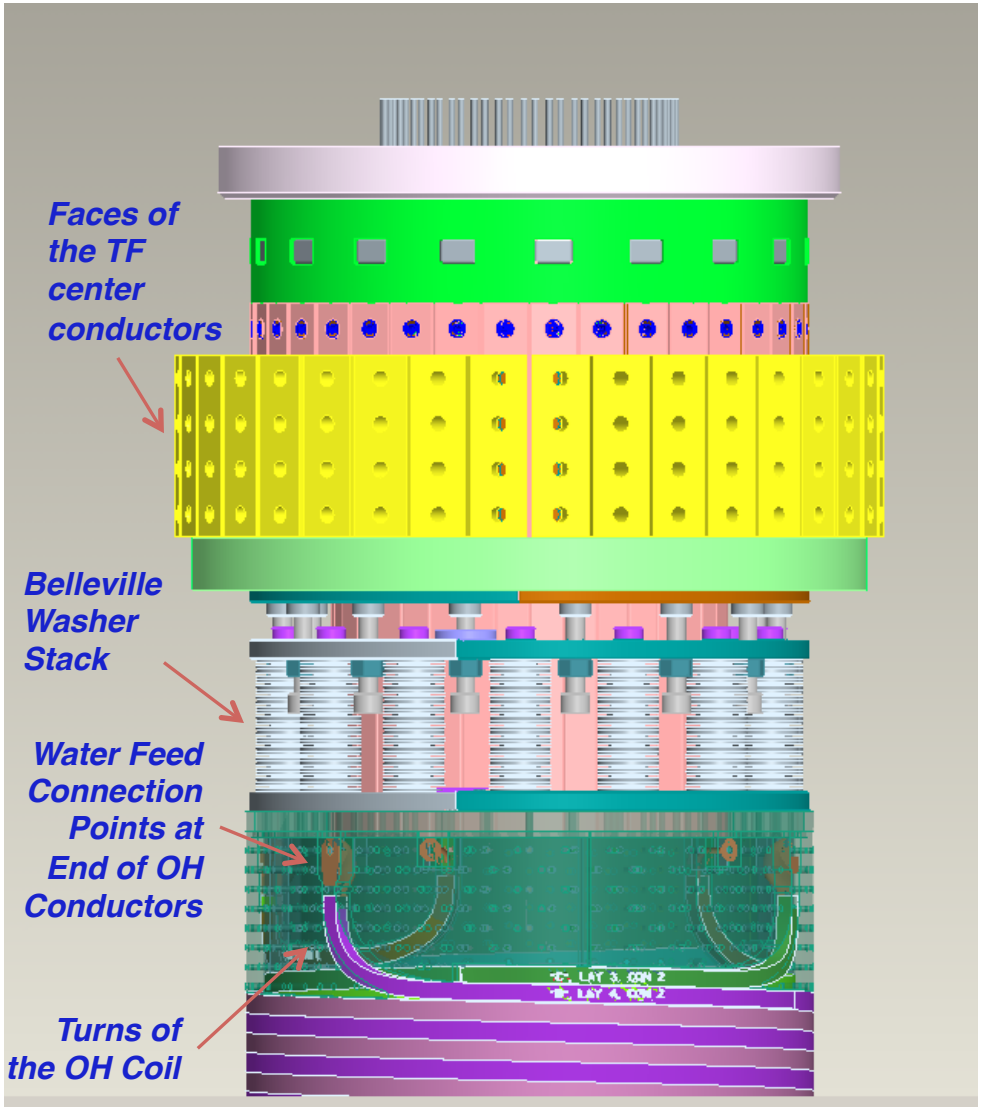


OH Coil and Water Feeds

- OH coil made from hollow conductor
- 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



Polypropylene clamp as used on NSTX



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.

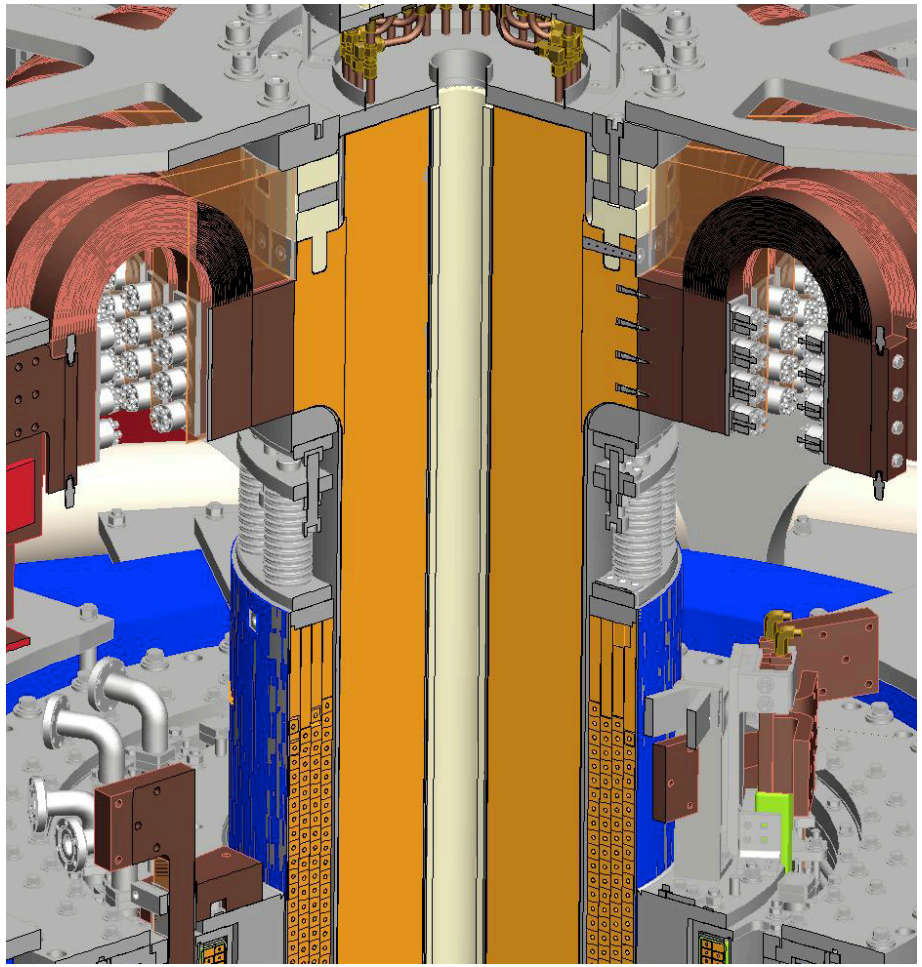
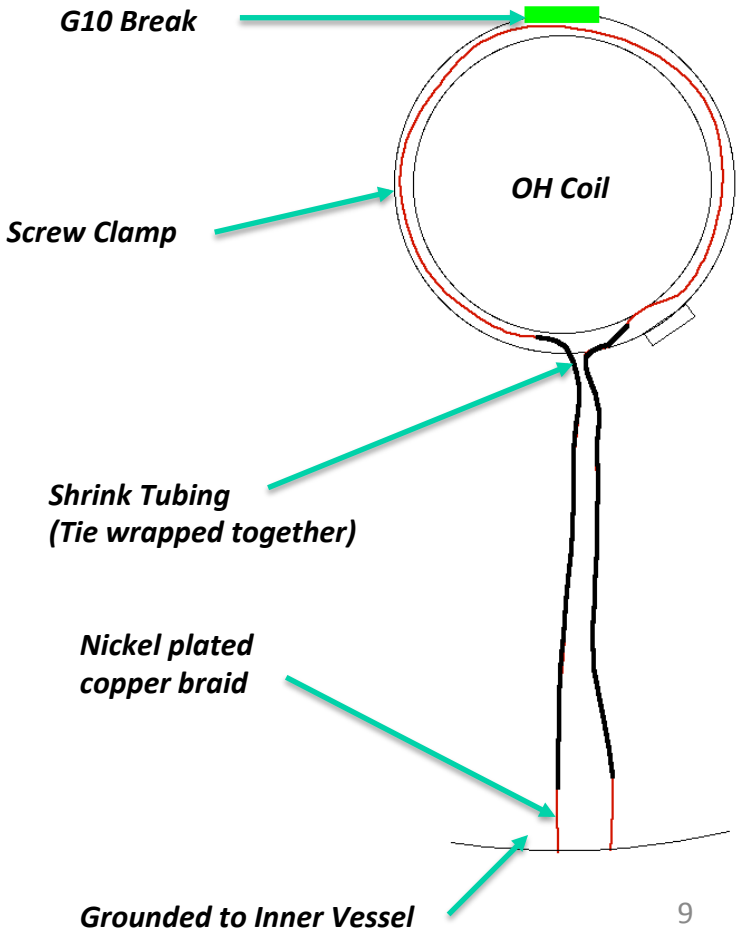


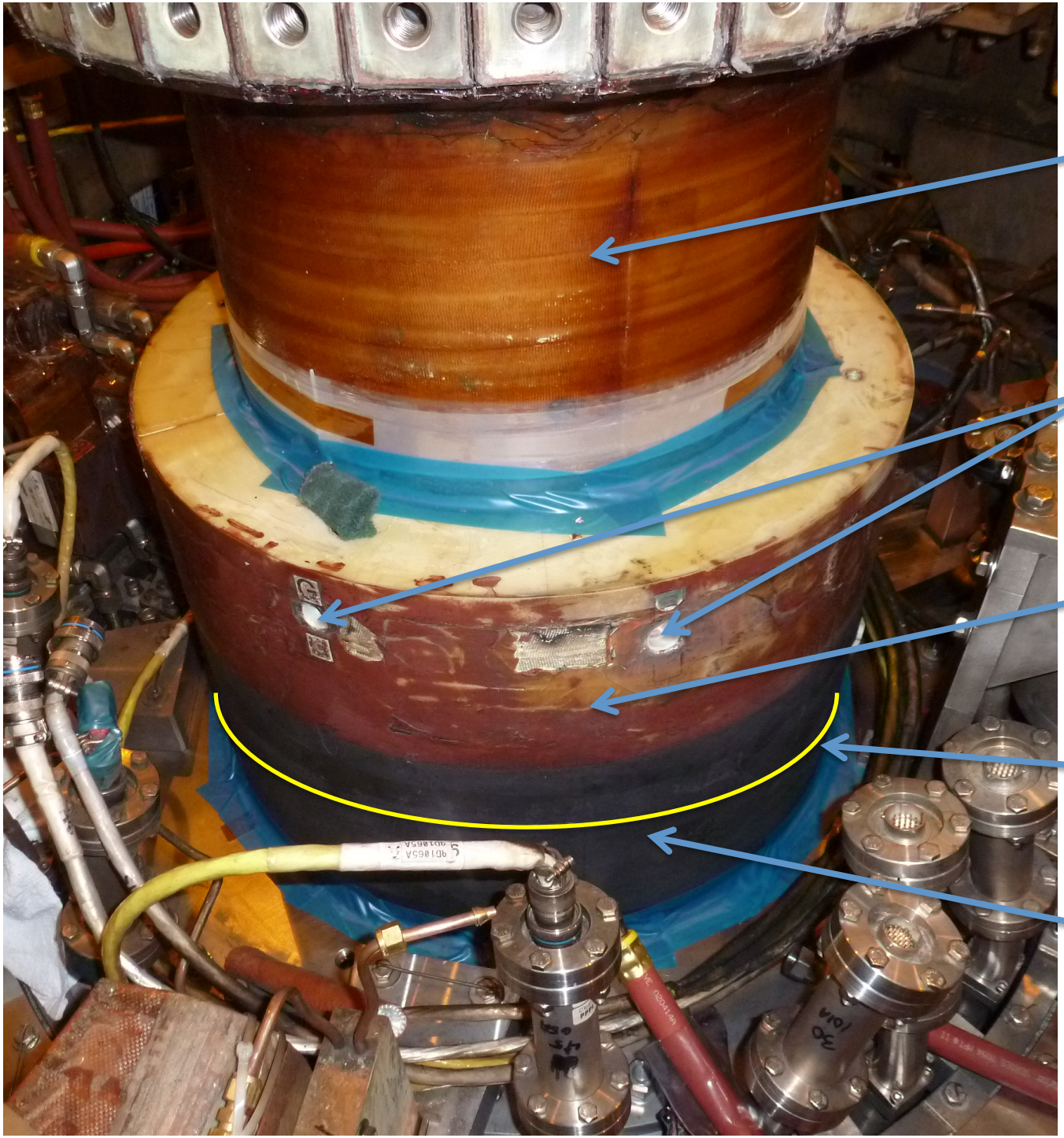
Photo of the Belleville Washer Stack During Removal

OH 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.
- Nickel plated copper braid wrapped around the ground plane.
- Braid is then attached to the appropriate ground, providing the reference for the ground plane.

Schematic of Installation on 4/24/2015




TF bundle (OH Preload Assembly removed)
OH cooling water channels
OH coil
Path of Ground Braid (Schematically)
OH ground plane (black conductive paint)

Outline

- Technical background
- Some context on the day of the fault
- Technical analysis of the fault

Context: Activities on April 24th

- We had successfully completed the NSTX-U machine Integrated System Test Procedure (ISTP) on Tuesday, April 21, 2015.
  - Had successfully run all coils individually to 100% of their CD-4 current requirements.
  - Had executed full-field combined coil test shots.
  - Thus, established magnet operating envelope for CD-4 KPP attempt
- On Friday, April 24, 2015, we were performing test shots in preparation for the CD-4 KPP attempt when an arc occurred.

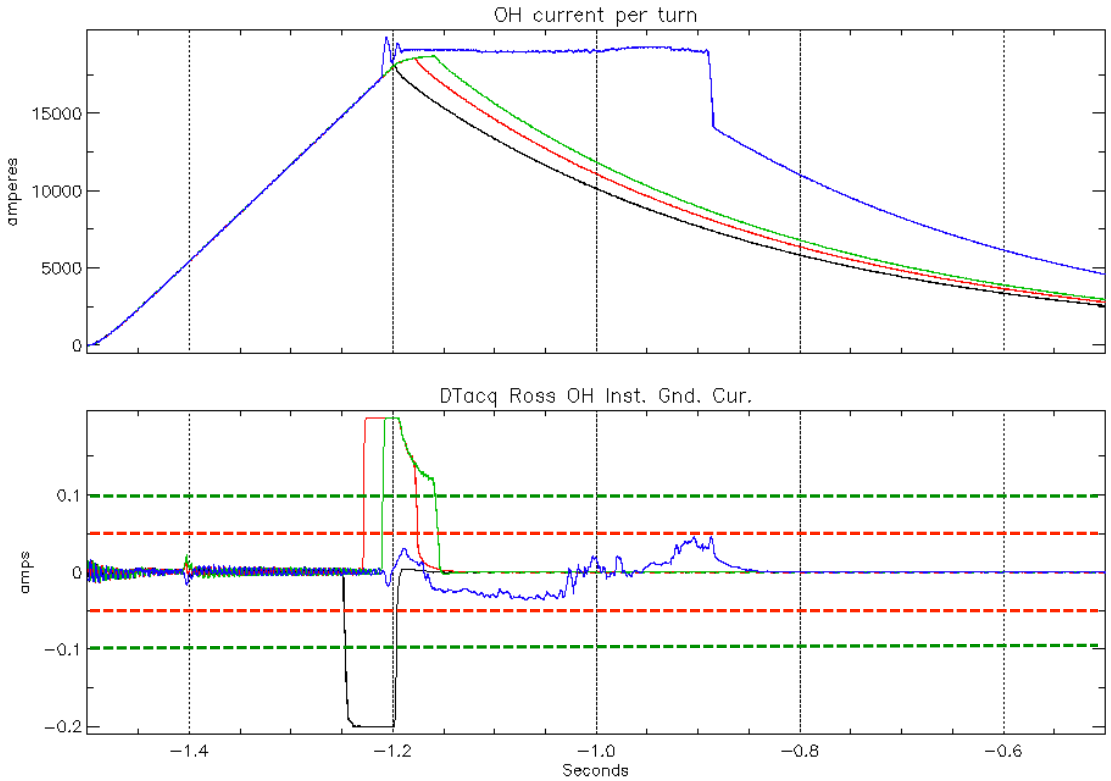
Context: Shots Leading Up to the Arc

- 200183, 200184: Successful 8% and 50% test shots
- 200185 (100% test shot): First OH Ground Current Trip
  - Machine inspections found no water leaks.
  - Did a low-pot of the OH coil from rectifier room.
    - Found leakage resistance was identical to earlier in the day.
  - Repeat the shot.
- 200187: Second Trip
  - Discussion, increased the threshold on the instantaneous ground fault relay from 50 mA to 100 mA
  - Repeat the shot
- 200189: Trip again
  - Discussion, noted the previous good low-pot and lack of water leaks.
    - Operations team erred in not checking the ground currents
    - Didn't consider the possibility of a part moving under OH induction
  - OH Instantaneous ground fault relays were taken out of circuit.
    - *But the inverse time relays were NOT removed.*
- 200190: Shot with the damaging arc

Sequence of Shots Leading Up to Fault

Ground Currents Were Much Different on 200190

Shots:
200185
200187
200189
200190



- Ground currents noticed during forensic analysis following the arc
- 200190 had different characteristics than the previous ground fault trips.
  - Less ground current, but much more damage.
- Instantaneous ground fault detector would not have detected any problem or terminated the shot.
  - Hence, removal of that instantaneous GF detector cannot be blamed for the damaging arc.
  - Again, the inverse-time GF relays were always present.

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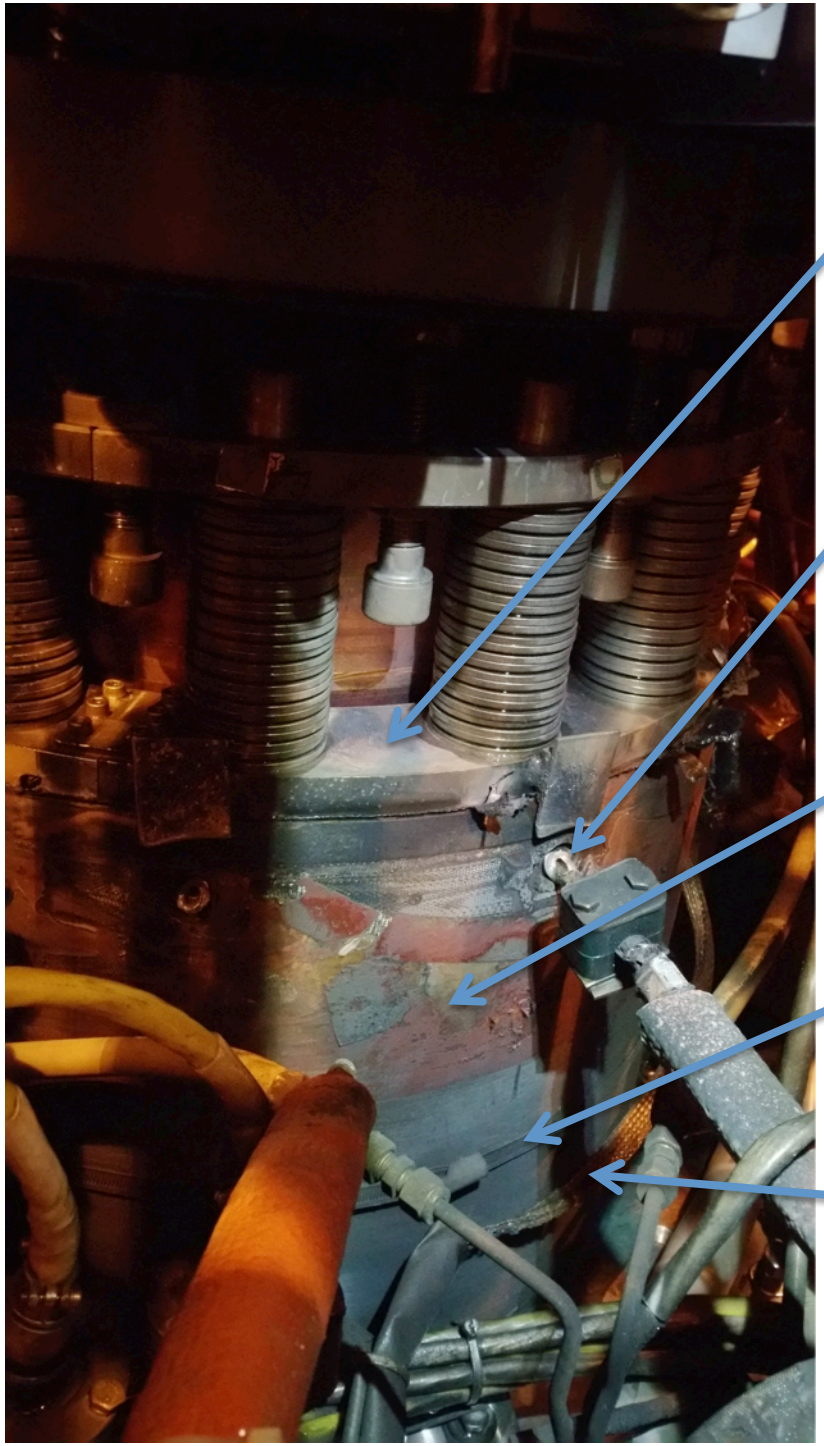


Electrically floating OH Preload Assembly

Damaged water fitting and strain relief bracket (4 places)

OH coil

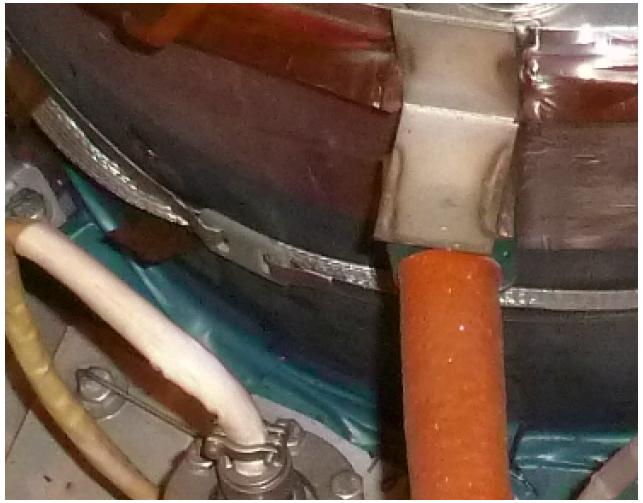
OH ground plane reference conductor clamp

OH ground plane reference conductor (loose, and note rest position)

Direct Causes of Arc: Ground Braid

- The braid pulled away from its clamp and touched ohmic heating coil water coolant tubes initiating an arc.
  - The braid was improperly installed and formed a continuous current loop.
  - Loop reacted to ohmic heating coil flux swing & magnetic field.
    - This creates a vertical JxB "launching" force.
  - The conducting braid had worked loose of its clamp, and was free to move vertically over part of its toroidal extent.
  - Differences in the vertical motion of the braid resulted in different current/fault characteristics on consecutive shots.
  - Between-shot electrical tests didn't identify this issue.

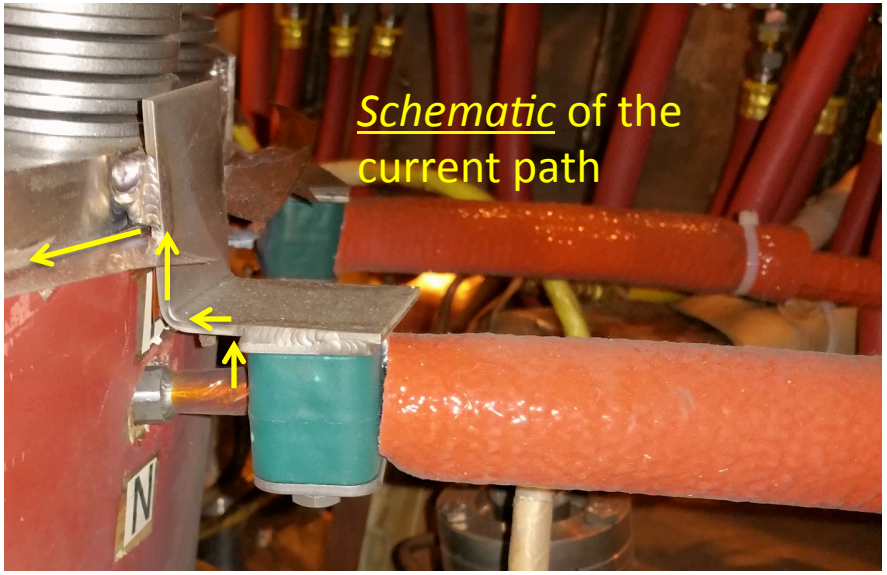
Rest position is well below the location of the largest arc damage, but braid damage was observed.



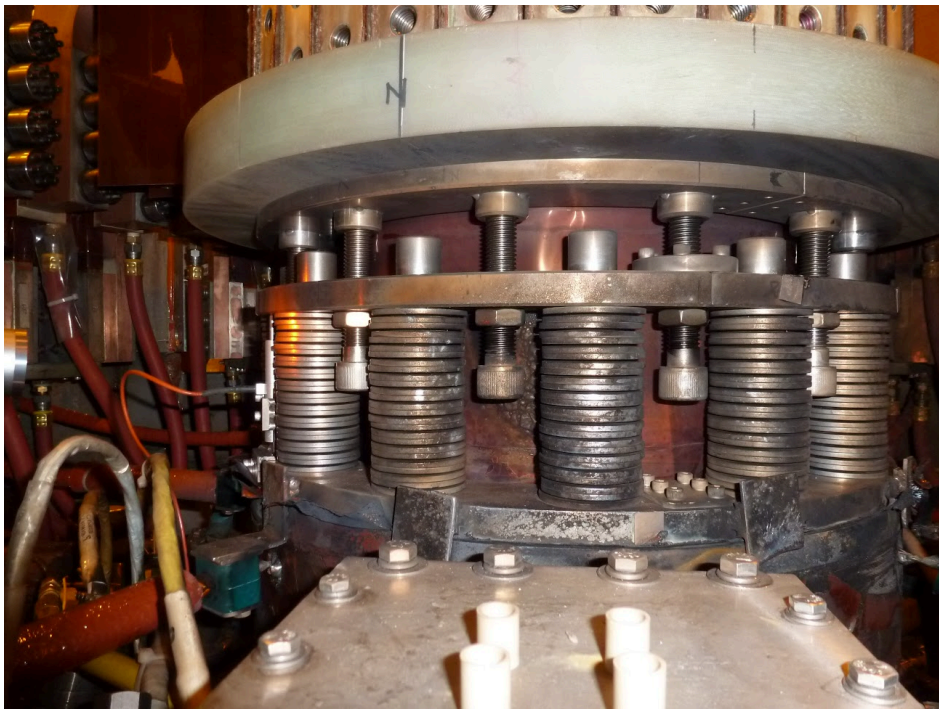
Braid bridged the insulating break in the clamp, but was restrained at that location, ~180 degrees from the fault area

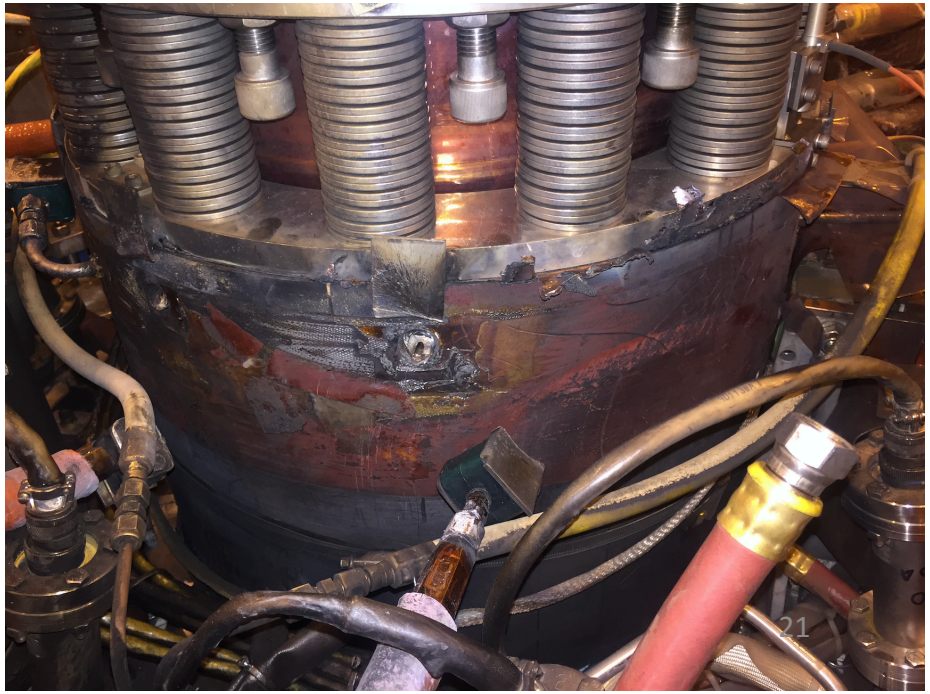
Direct Causes of Arc: Belleville Stack

- The arc engaged the *ungrounded* preload-assembly and was sustained for about 300 milliseconds.
  - the OH Preload Assembly was not electrically referenced to the NSTX-U inner vacuum vessel, and therefore:
    - did not produce a OH circuit ground current trip, and
    - High-pots of the OH coil system could not detect communication between the coil and the washer stack.
  - the OH coil water cooling tube strain relief assemblies were compromised due to the initiated arc

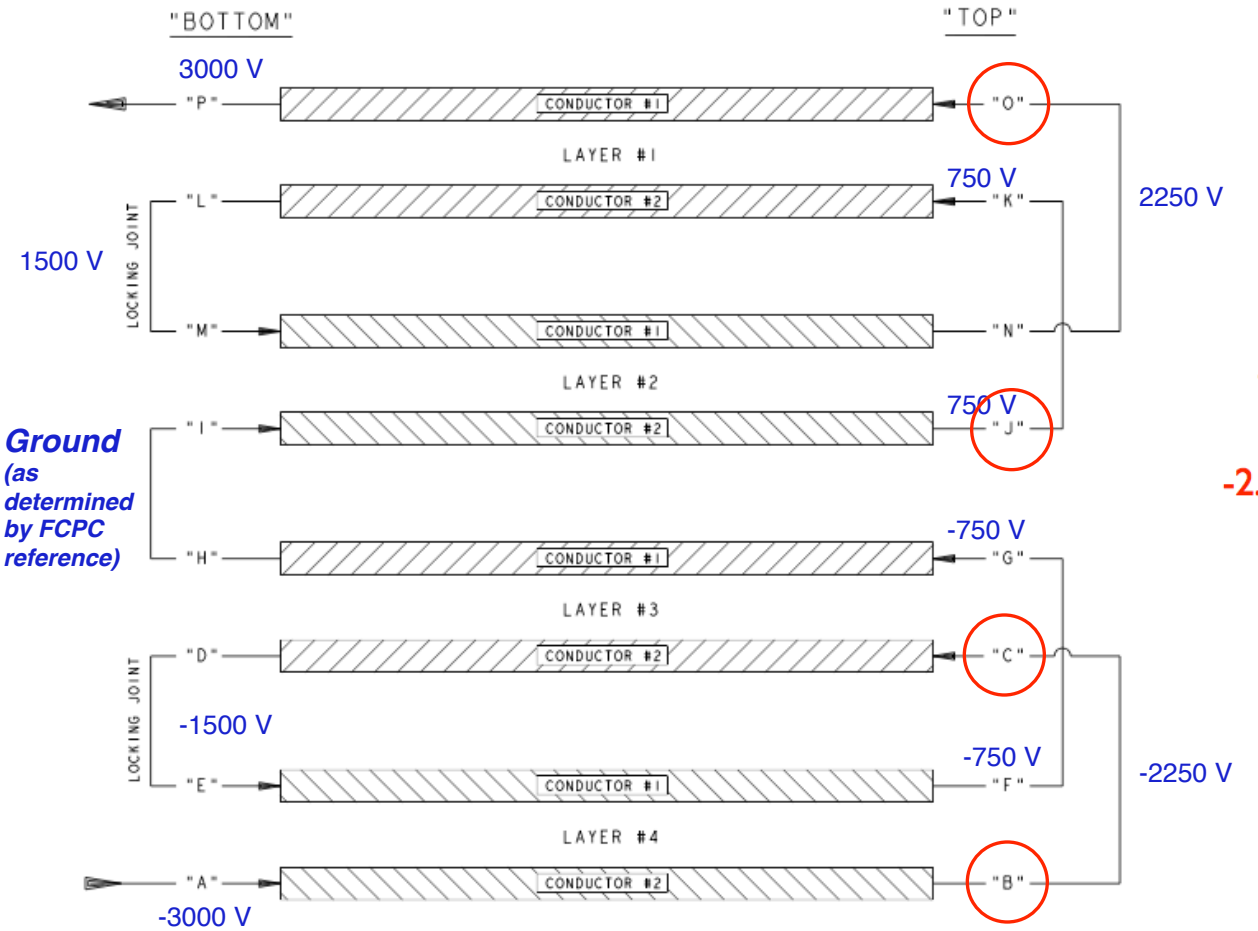



U.S.A

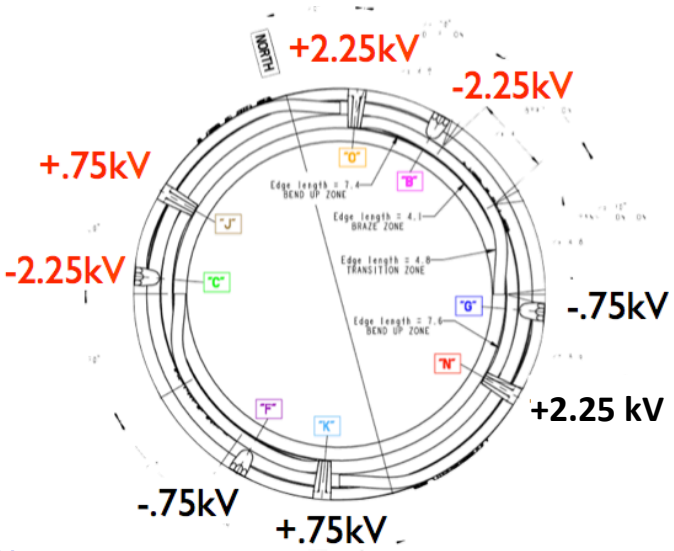




The Arc Included the Two Highest Voltage Water Feeds



Red indicates where there was damage



Message

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

Corroborating Information

(Details in Backup)

- The line-to-ground voltages were observed to drop symmetrically during the arc.
  - The arc did not pull the OH circuit off of its references.
  - Consistent with both highest and lowest voltage water feeds involved.
  - Also consistent with observed small OH ground current during the arc.
- The arc can be roughly modeled as a transient "shorting" of ¾ of the coil…this model can recover most features in the load current.

Technical Contributing Causes (Incomplete)

- NSTX-U lacked a detailed engineering design for the OH ground plane referencing conductor and clamp.
- NSTX-U lacked a formal policy regarding the referencing (grounding) and insulating of machine structures.
- NSTX-U lacked a design drawing depicting machine structure referencing and insulation requirements.
- Testing proceeded without a complete understanding of the cause of OH ground fault trips on shots preceding the final arc.

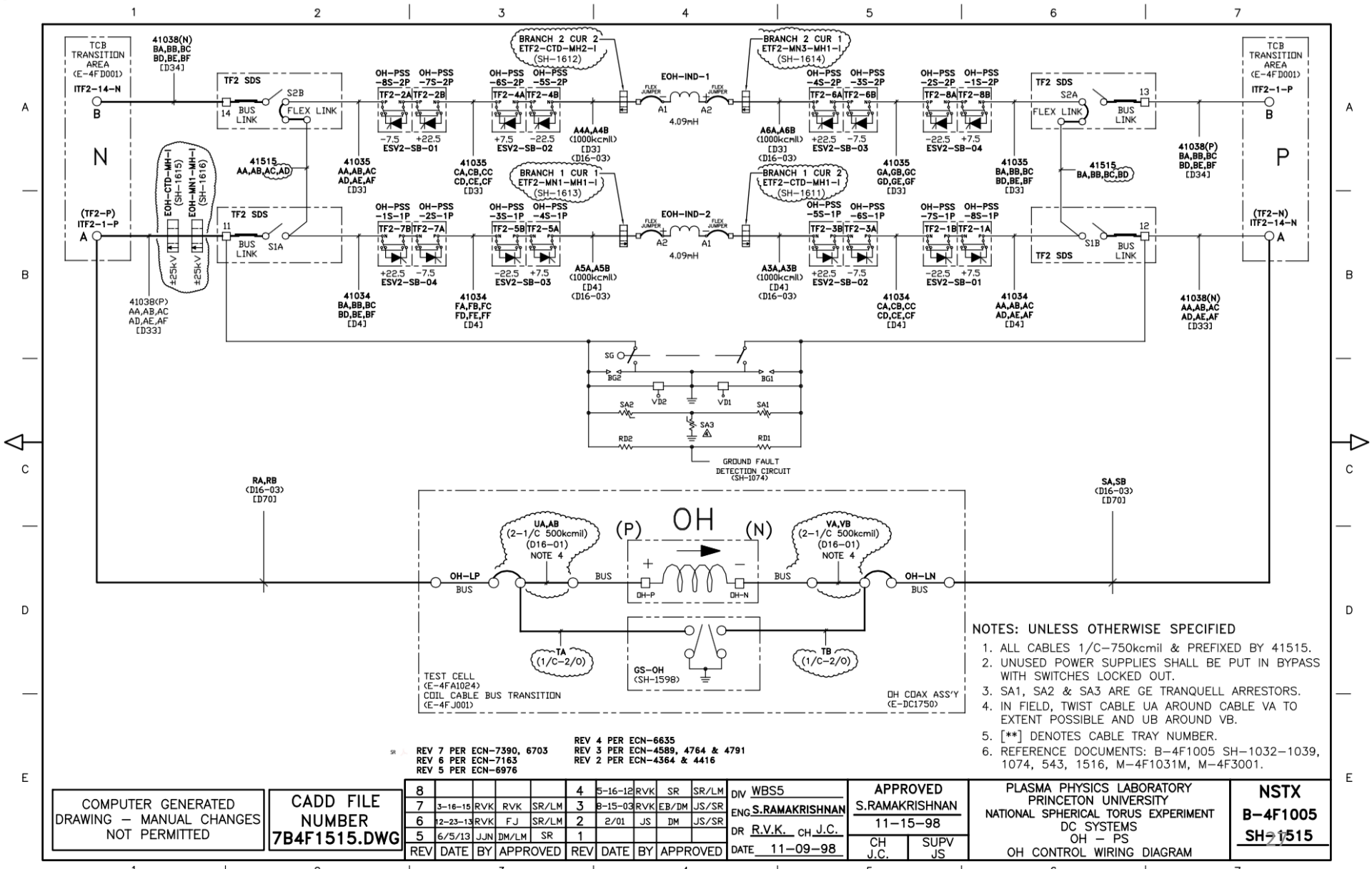
See talks by Ellis & Zatz for more analysis of causes.

Present Status Summary

- The overall health of the NSTX-U machine appears good.
  - The damage was contained to
    - four OH water coolant tubes that are readily replaced.
    - Some other water hoses were not penetrated, but showed some damage and will be replaced.
    - Ground braid itself…and gets a design upgrade.
    - Soot covering cables, pre-load assembly, OH coil, other items inside the umbrella.
    - Water flowing within and out of the upper umbrella.
  - Electrical continuity/insulation and hydrostatic testing of the ohmic heating coil (and other coils nearby) indicate the coils are fine.
  - Magnetic diagnostics check out OK.
  - Cleanup of the area is nearly complete.
- A number of "Extent of Condition" issues have been identified.
  - Talks by Raftopoulos, Hosea for more information

Backup

OH Supply: +/- 6 kV, +/- 24 kA



NOTES: UNLESS OTHERWISE SPECIFIED

1. ALL CABLES 1/C–750kcmil & PREFIXED BY 41515.
2. UNUSED POWER SUPPLIES SHALL BE PUT IN BYPASS WITH SWITCHES LOCKED OUT.
3. SA1, SA2 & SA3 ARE GE TRANQUELL ARRESTORS.
4. IN FIELD, TWIST CABLE UA AROUND CABLE VA TO EXTENT POSSIBLE AND UB AROUND VB.
5. [**] DENOTES CABLE TRAY NUMBER.
6. REFERENCE DOCUMENTS: B–4F1005 SH–1032–1039, 1074, 543, 1516, M–4F1031M, M–4F3001.

REV 7 PER ECN–7390, 6703
REV 6 PER ECN–7163
REV 5 PER ECN–6976

REV 4 PER ECN–6635
REV 3 PER ECN–4589, 4764 & 4791
REV 2 PER ECN–4364 & 4416

COMPUTER GENERATED DRAWING – MANUAL CHANGES NOT PERMITTED

CADD FILE NUMBER 7B4F1515.DWG

REV	DATE	BY	APPROVED
8			
7	3–16–15	RVK	RVK
6	12–23–13	RVK	FJ
5	6/5/13	JJN	DM/LM
4	5–16–12	RVK	SR
3	8–15–03	RVK	EB/DM
2	2/01	JS	DM
1			

SR/LM SR/LM SR/LM SR SR/LM JS/SR JS/SR

DIV WBS5
ENG S.RAMAKRISHNAN
DR R.V.K. CH J.C.
DATE 11–09–98

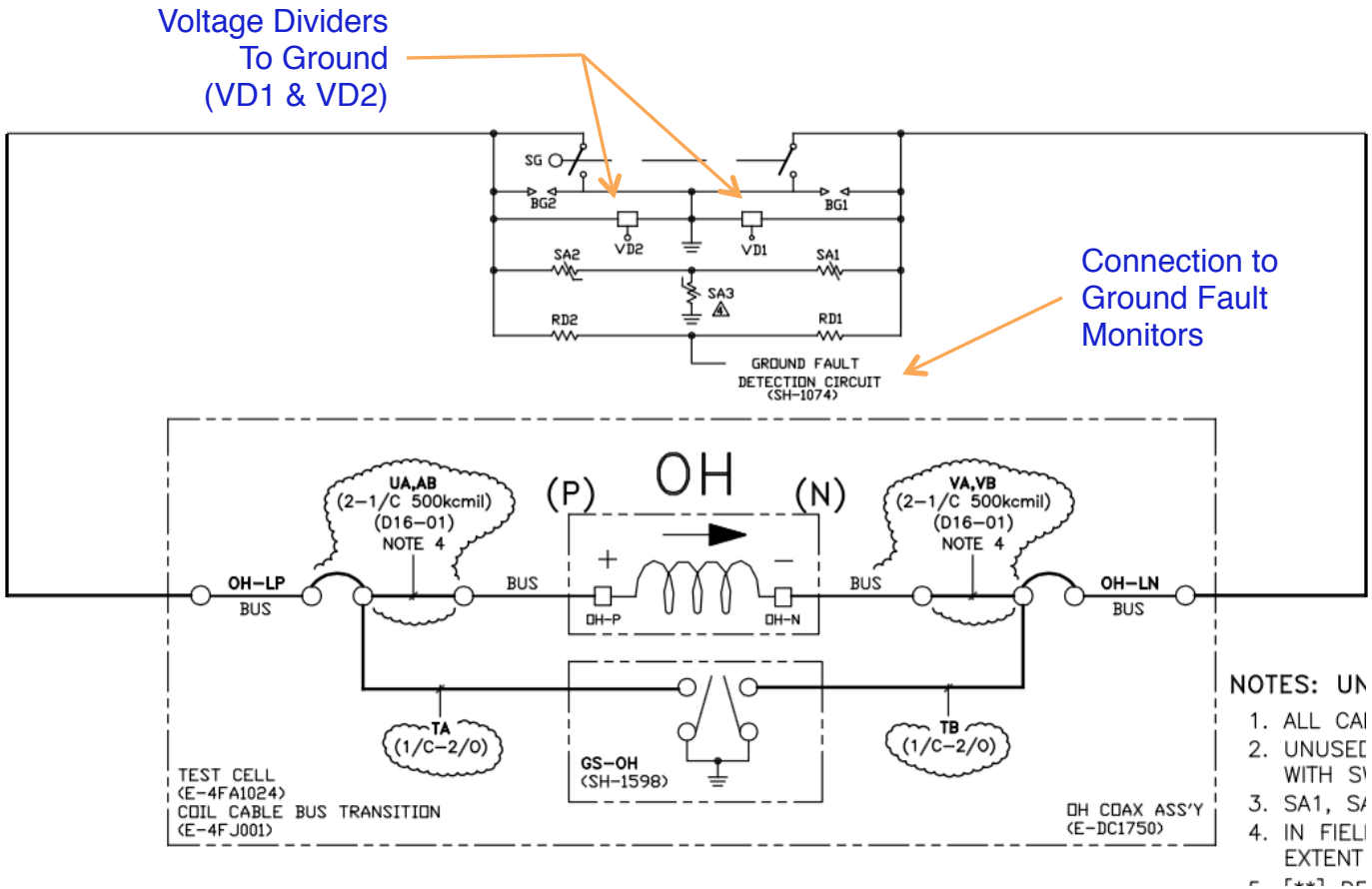
APPROVED S.RAMAKRISHNAN 11–15–98
CH J.C. | SUPV JS

PLASMA PHYSICS LABORATORY
PRINCETON UNIVERSITY
NATIONAL SPHERICAL TORUS EXPERIMENT
DC SYSTEMS
OH – PS
OH CONTROL WIRING DIAGRAM

NSTX
B–4F1005
SH–1515

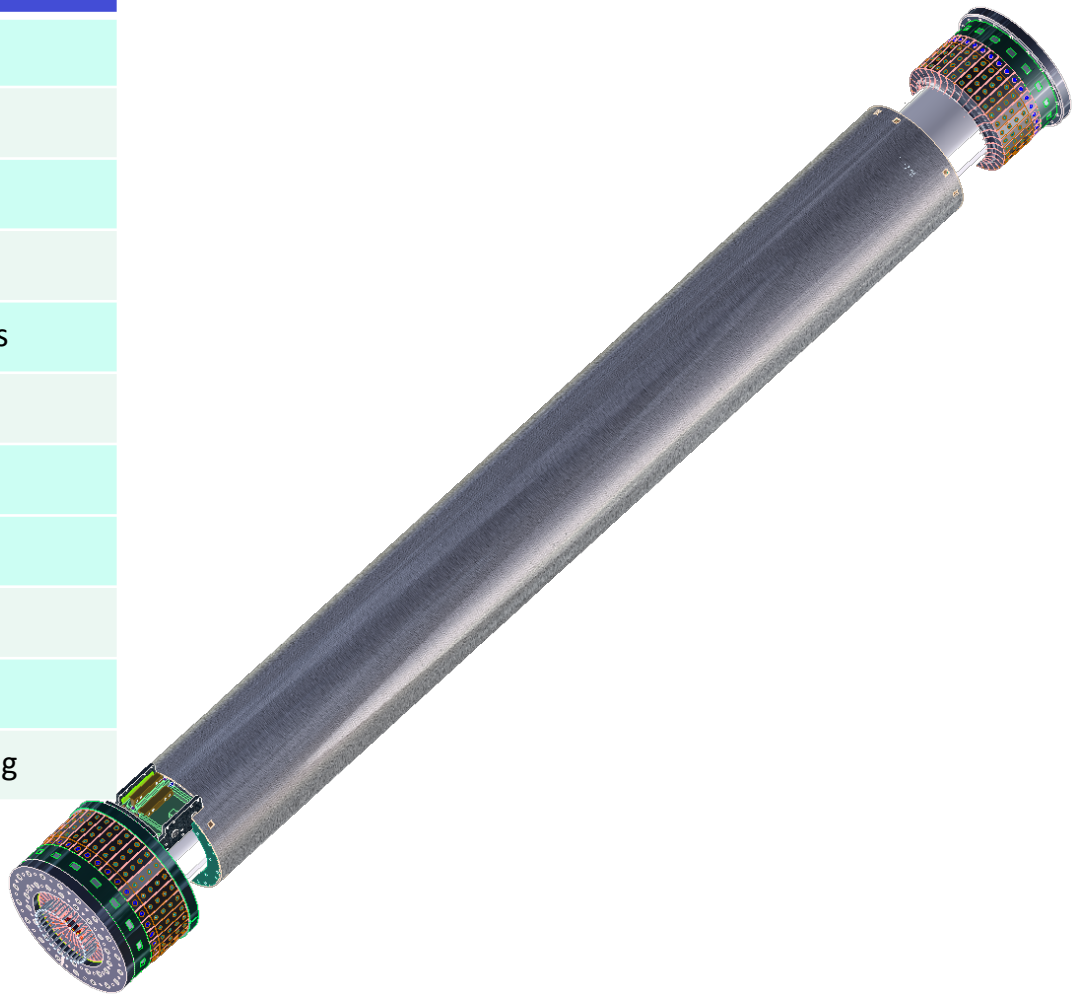
OH Supply: +/- 6 kV, +/- 24 kA

- 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.
    - Highly reliable industry standard system



OH Solenoid Parameters

Description	OH Parameters
Operating Voltage	6077 volts
Number of turns	884
Number of layers	4
Cooling hole diameter	0.2250 in
Operating current	24,000 amps
Groundwall insulation	0.1080 in.
Turn insulation	0.0480 in
Outside diameter	22.10 in
Copper mass	6184 lbs
Cooling paths	8
Coolant	DI Water @ 430 psig



OH Solenoid Materials

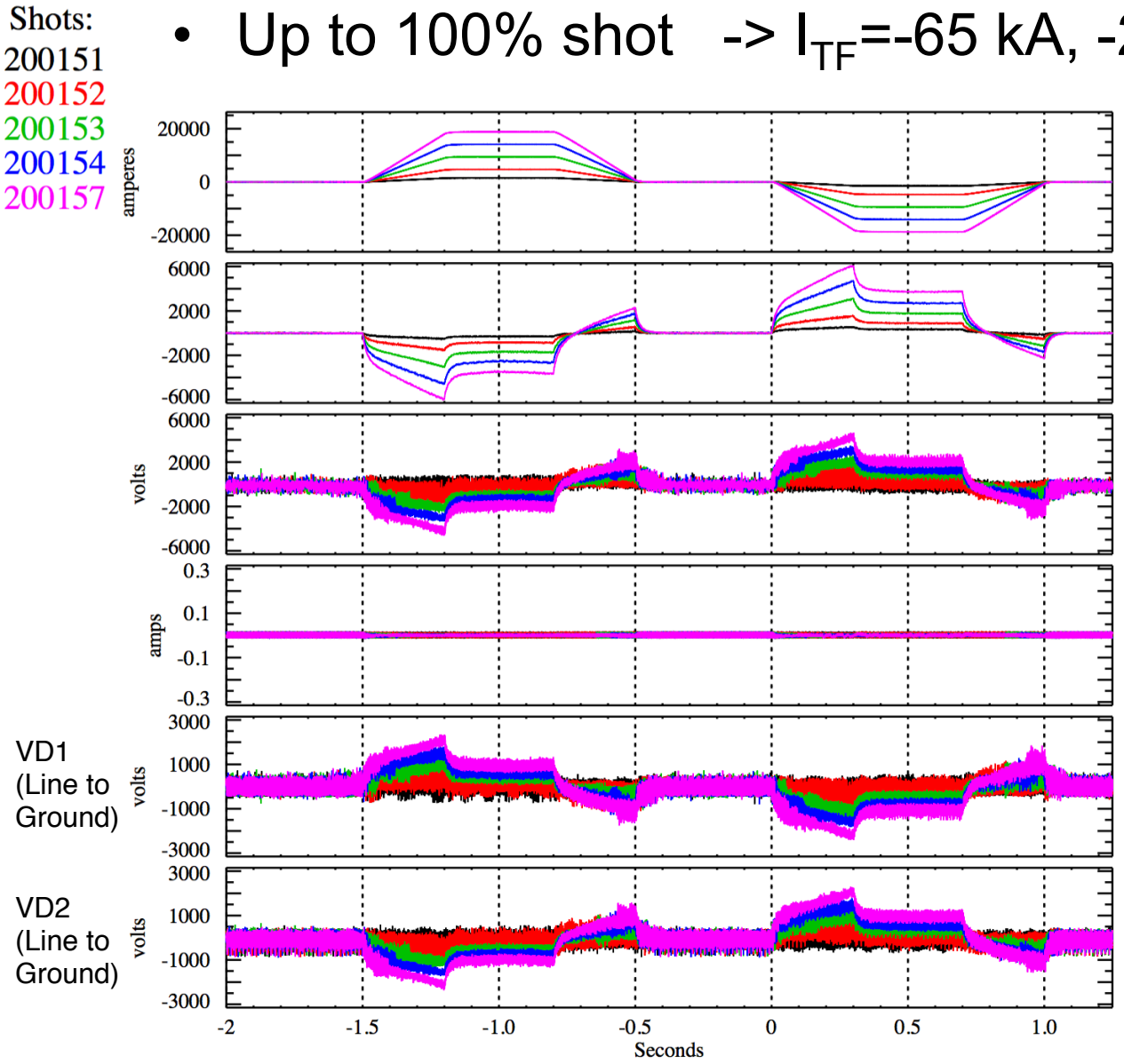
- Conductor : C10700 –Oxygen free-silver bearing copper conductor Insulation:
  - Turn Insulation: Co-wound Kapton/S2 glass tape
  - Ground wrap Insulation: Half-lapped layers- 0.006 inch thick S-2 (satin weave) standard silane finish glass tape- (Temperature class- 180 degrees C)
- Fillers: All G-11 laminate material
- Cooling Fittings: Custom cast copper components C10200
- VPI System- CTD-425 Cyanate-Ester Hybrid system
  - Cure cycle: 22 hours @ 100 degrees C
  - Post Cure Cycle: 24 hours @ 170 degrees C

Table of Relevant Shots

Shot #	When	Intent	Result
200151	4/21/2015	8% Test Shot, ISTP	Success
200152	4/21/2015	25% Test Shot, ISTP	Success
200153	4/21/2015	50% Test Shot, ISTP	Success
200154	4/21/2015	75% Test Shot, ISTP	Success
200157	4/21/2015	100% Test Shot, ISTP	Success
200183	4/24/2015	8% Test Shot, Morning	Success
200184	4/24/2015	50% Test Shot, Morning	Success
200185	4/24/2015	100% Test Shot, Morning	GF Trip
200187	4/24/2015	100% Test Shot, Morning	GF Trip
200189	4/24/2015	100% Test Shot, Morning	GF Trip
200190	4/24/2015	100% Test Shot, Morning	Electrical Arc

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



OH Current

OH Voltage Request
(Before slew rate and alpha limits applied)

VD2-VD1 (Line to Line Voltage)

OH Ground Current

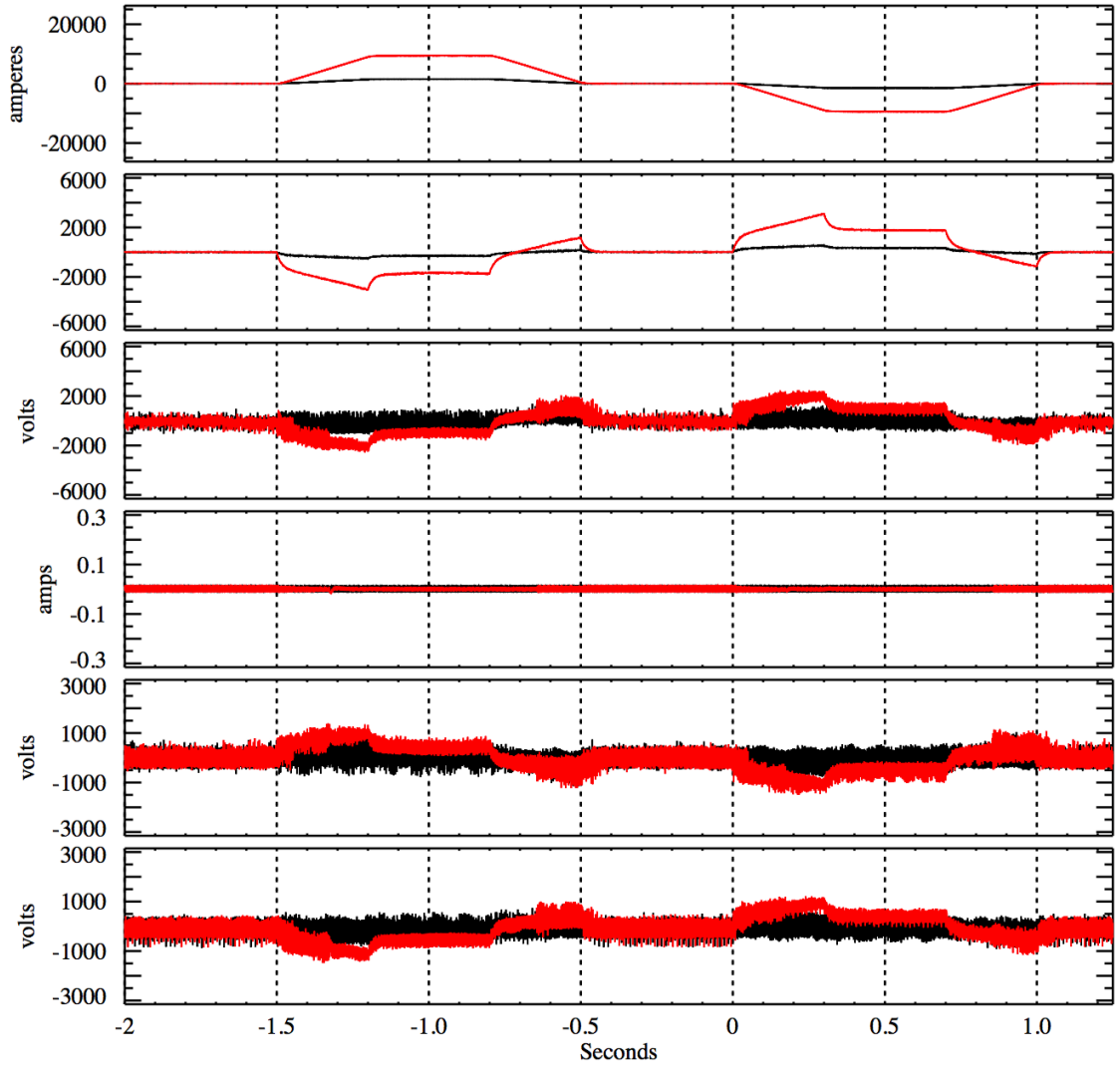
VD1 (Line to Ground)

VD2 (Line to Ground)

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

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

Shots:
200183
200184



OH Current

OH Voltage Request

VD2-VD1 (Line to Line Voltage)

OH Ground Current

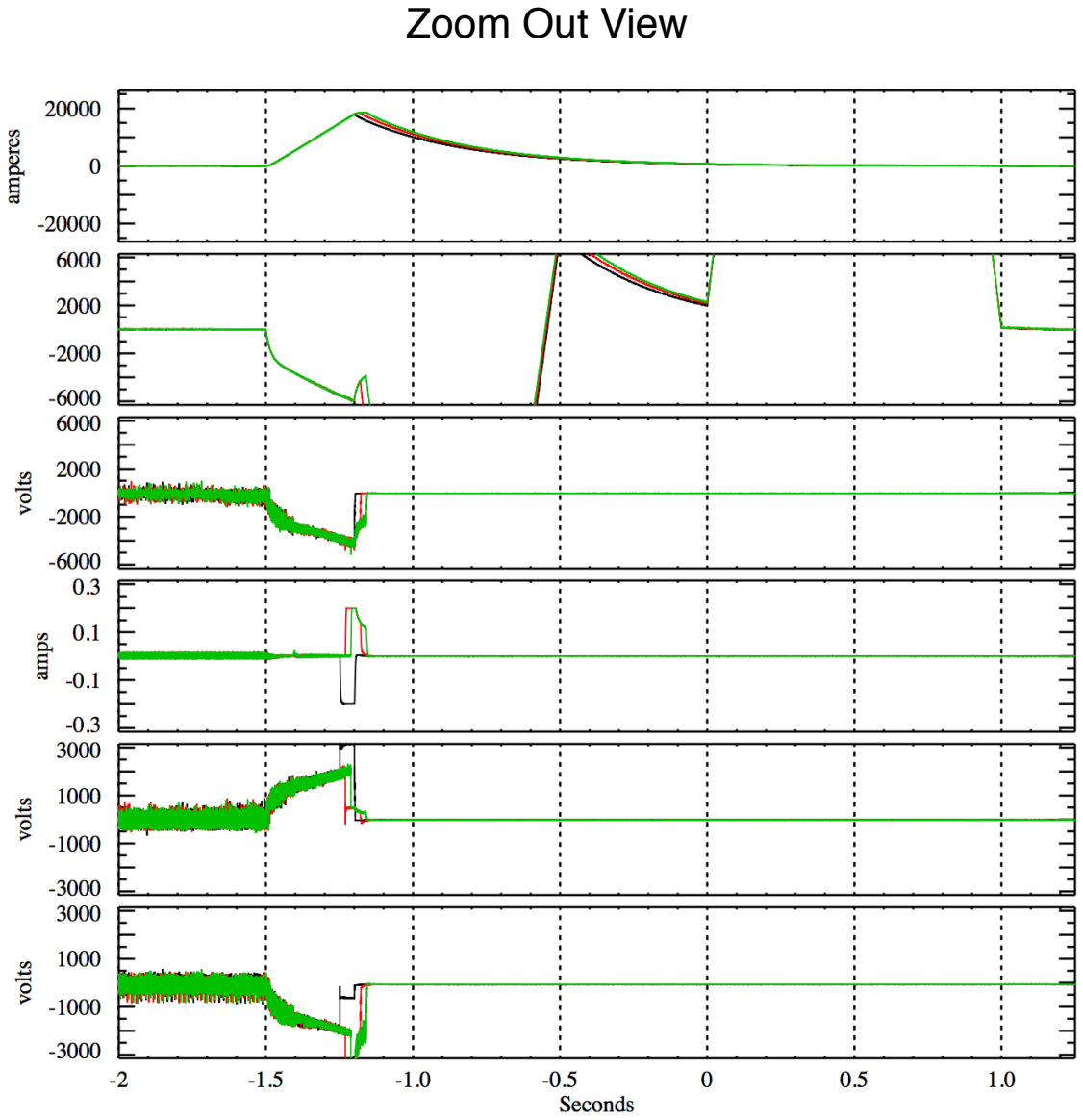
VD1 (Line to Ground)

VD2 (Line to Ground)

Sequence of Events Leading Up to Fault

Struggled in Attempts to Recreated Previous 100% Test Shot (II)

Shots:
200185
200187
200189



OH Current

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Sequence of Events Leading Up to Fault

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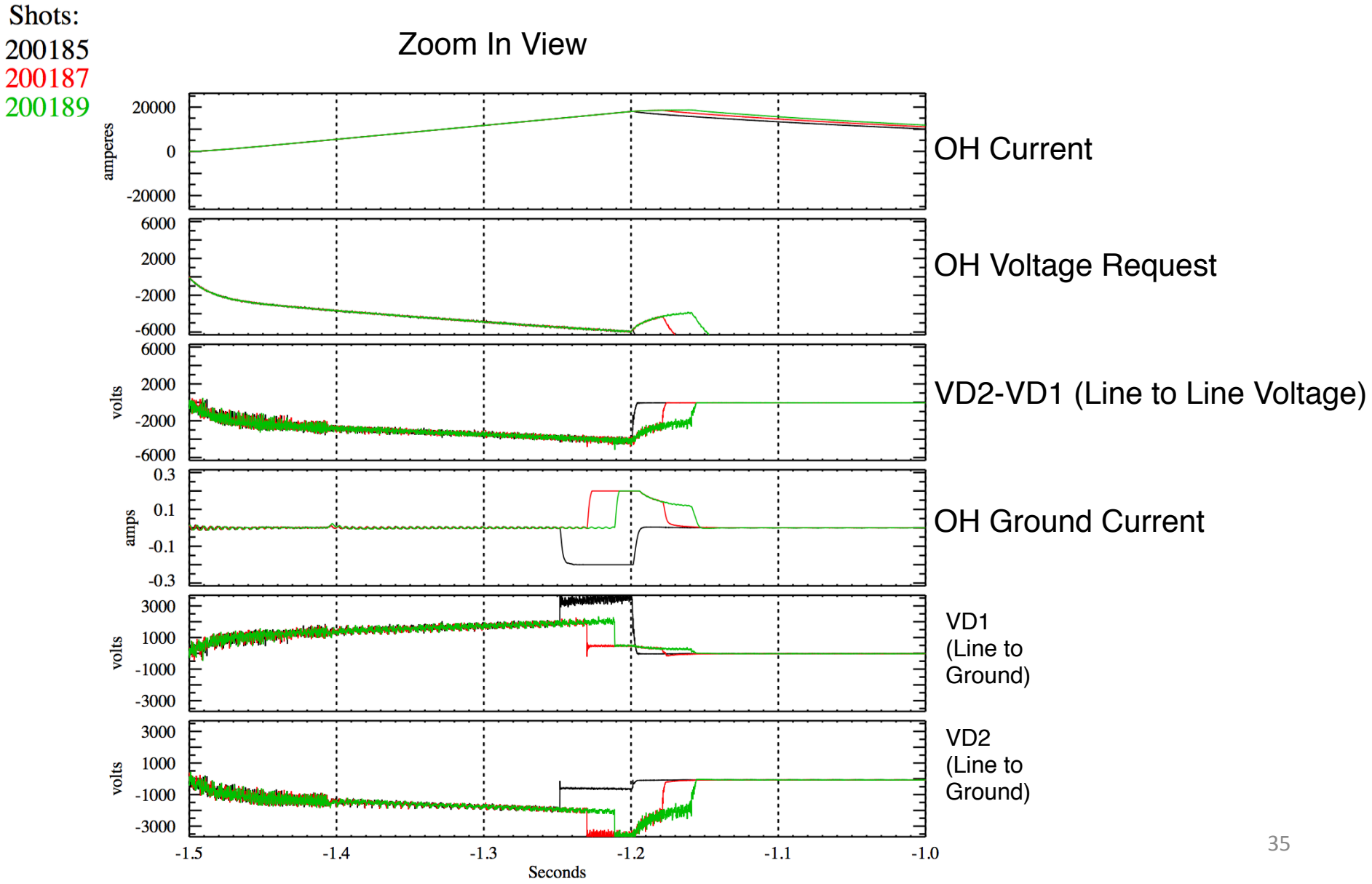
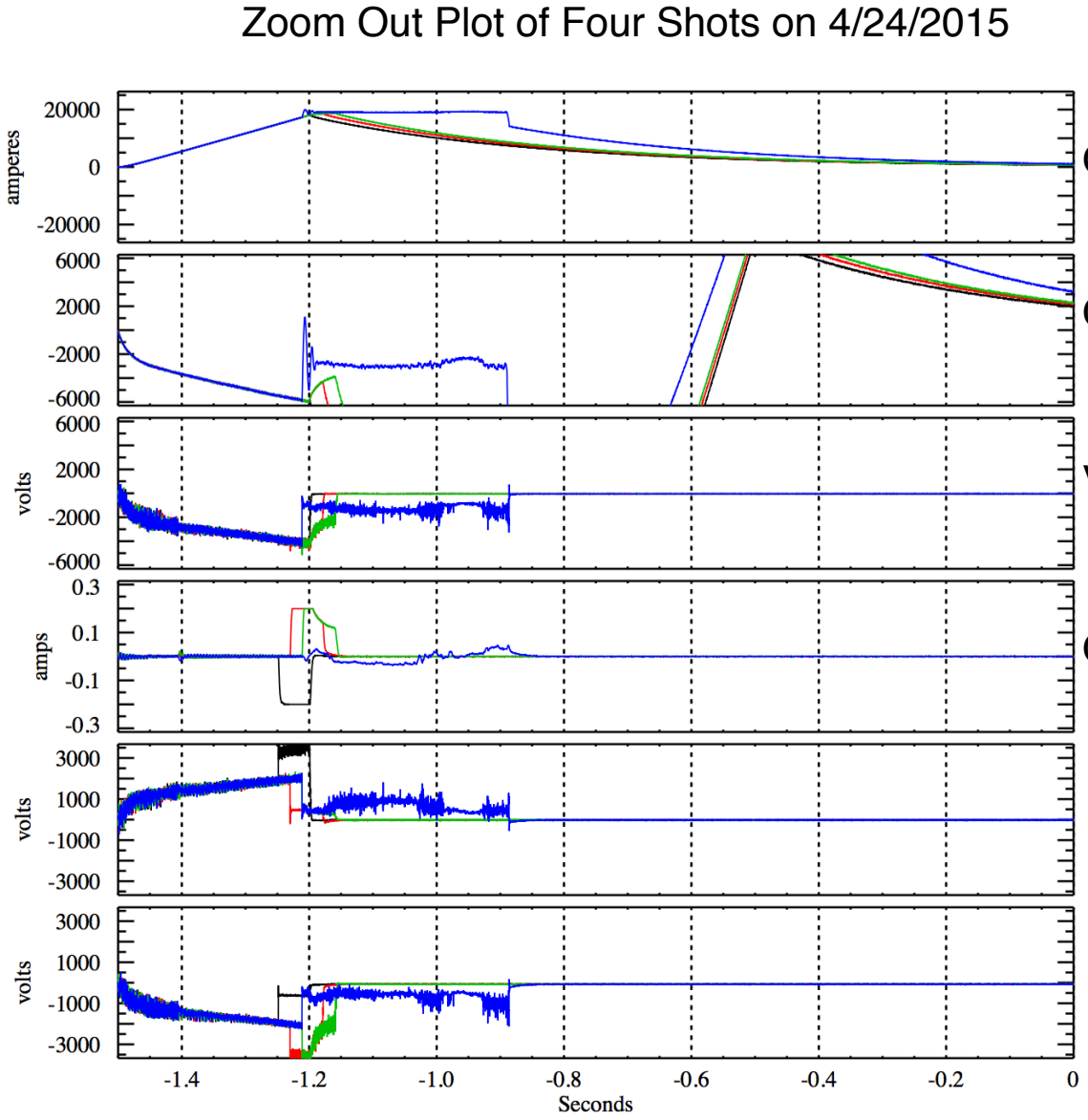


Sequence of Events Leading Up to Fault
Next Shot Had The Damaging Fault

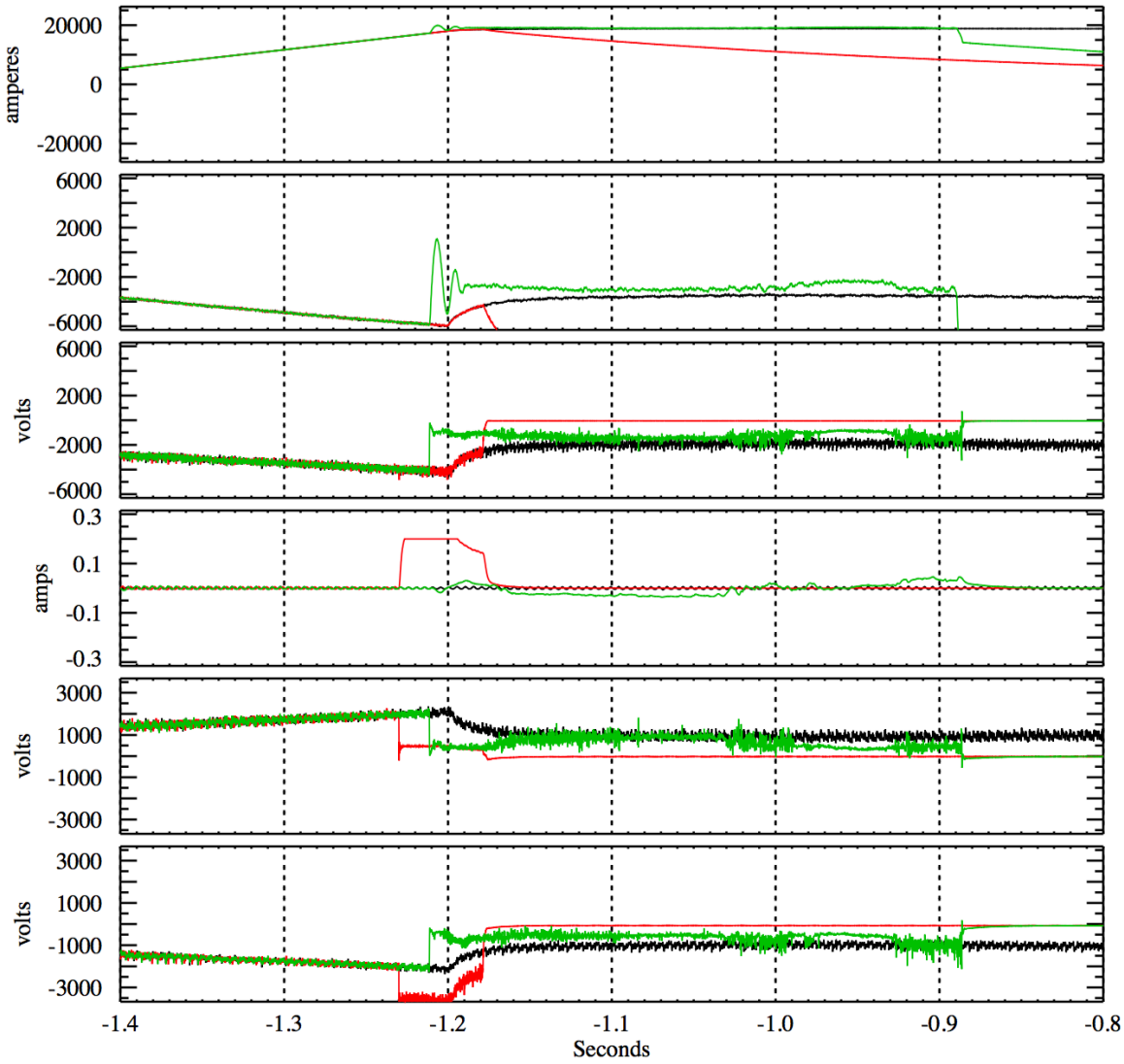
Shots:
200185
200187
200189
200190



Sequence of Events Leading Up to Fault
Next Shot Had The Damaging Fault (Zoom In)

Shots:
200157
200187
200190

Zoom in on good 100% from 4/21, trip shot from 4/24, and fault from 4/24



OH Current

OH Voltage Request

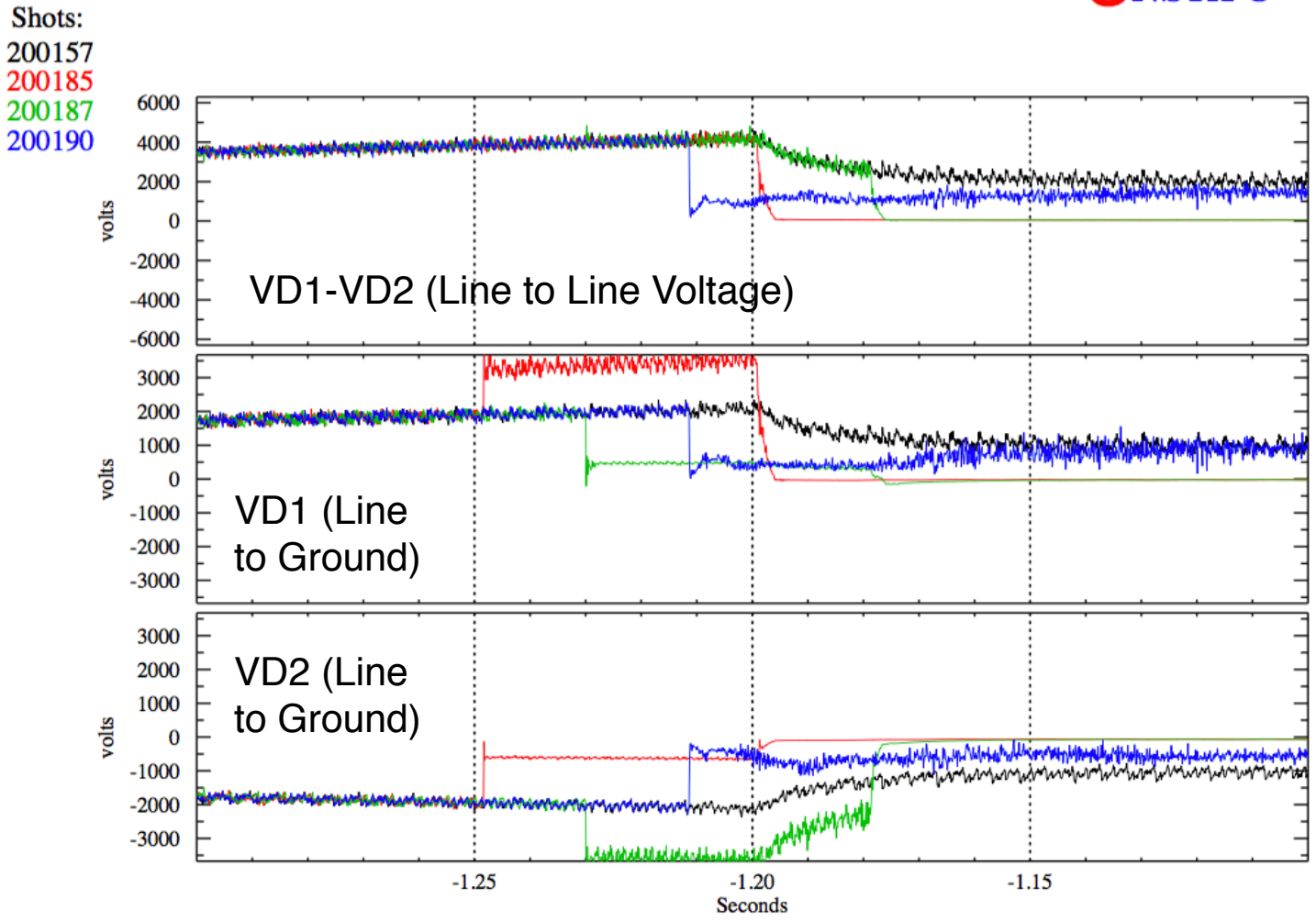
VD1-VD2 (Line to Line Voltage)

OH Ground Current

VD1 (Line to Ground)

VD2 (Line to Ground)

Changes in the Line-Ground Voltage Go With Changes in the Ground Current



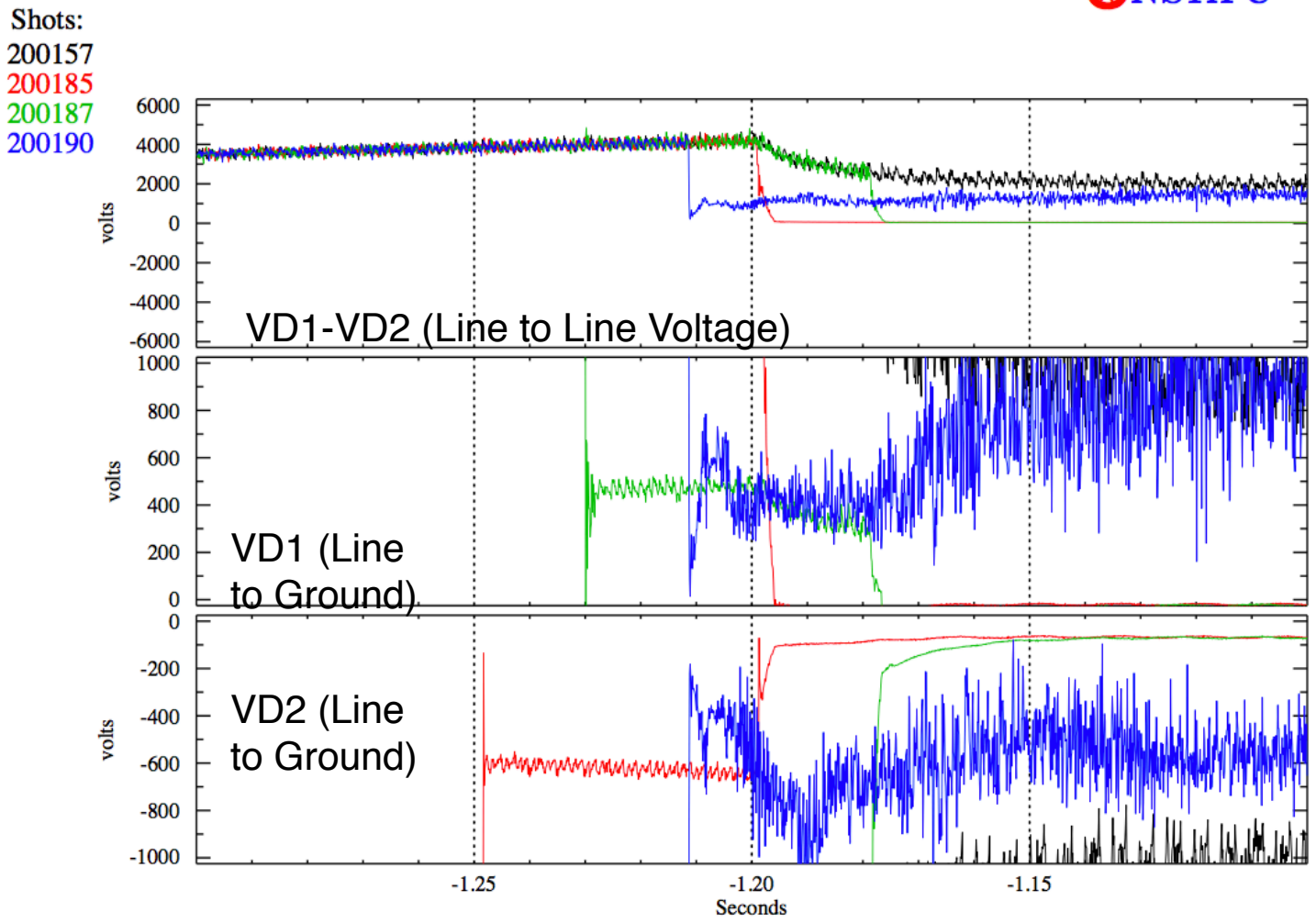
200157: Good 100% shot from ISTP, Symmetric

200185: Ground Fault VD1 goes to 3200V, VD2 goes to ~600 V. 600 V / 3800 ~ 1/8 of total coil voltage.

200187: Ground Fault VD1 goes to ~500 V. VD2 goes to -3400. 500 V / 3900 V ~ 1/8 of coil

200190: Large Arc (Next Slide)

Line-To-Ground Voltages Drop On Both Sides During Final Arc



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VD1 goes to 3200V, VD2 goes to ~600 V.
600 V / 3800 ~ 1/8 of total coil voltage.

200187: Ground Fault
VD1 goes to ~500 V. VD2 goes to -3400.
500 V / 3900 V ~ 1/8 of coil

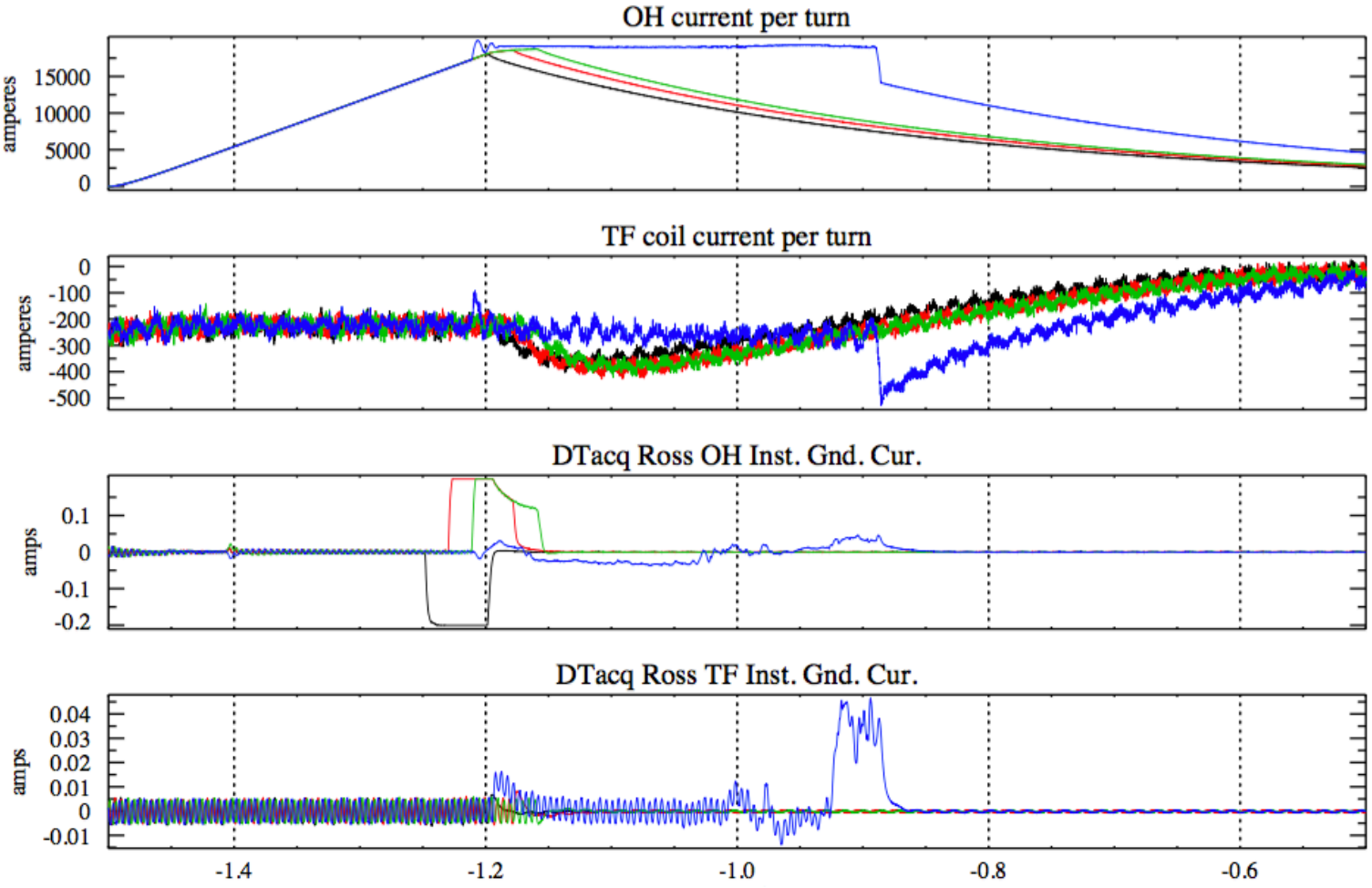
200190: Large Arc at t = -1.21 s
Both sides dropped to similar level.

(and thus no ground current)

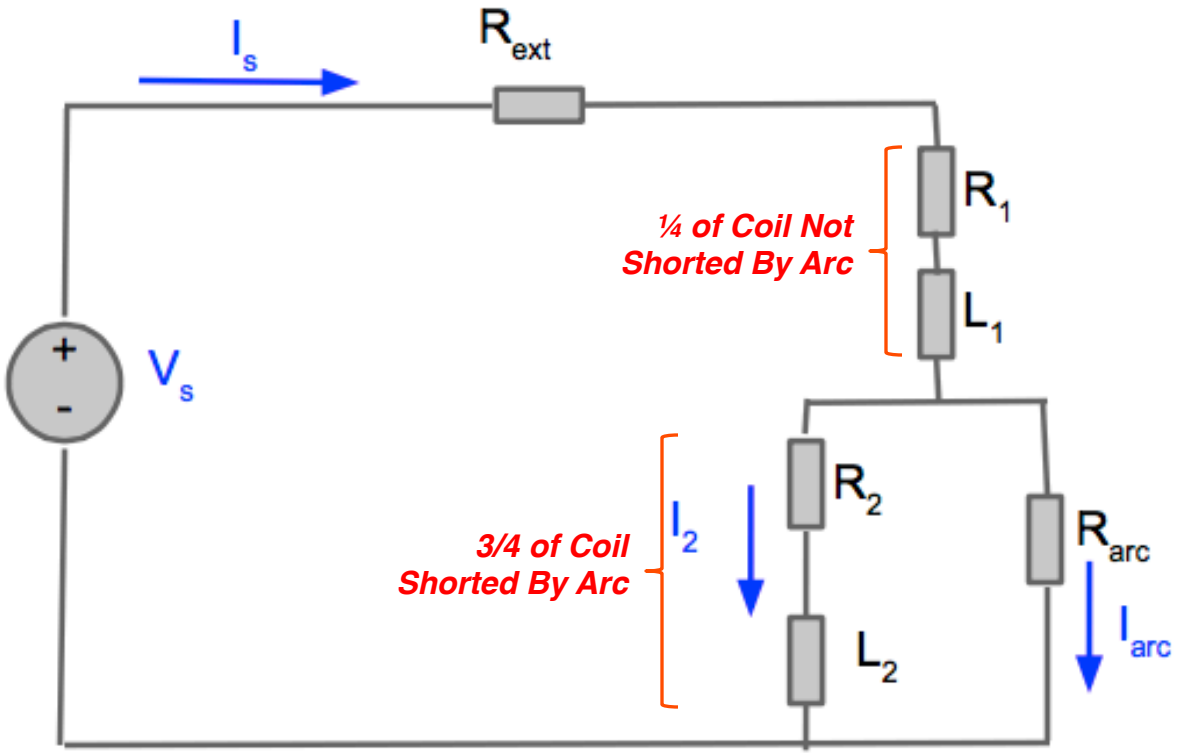
The Final Shot Tripped Off on TF Ground Fault Warning

Shots:
200185
200187
200189
200190

Note: No TF Ground Currents Observed on Any Previous Shots



This Hypothesis For the Arc Is Corroborated by Simple Modeling



Assumptions of the Model

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

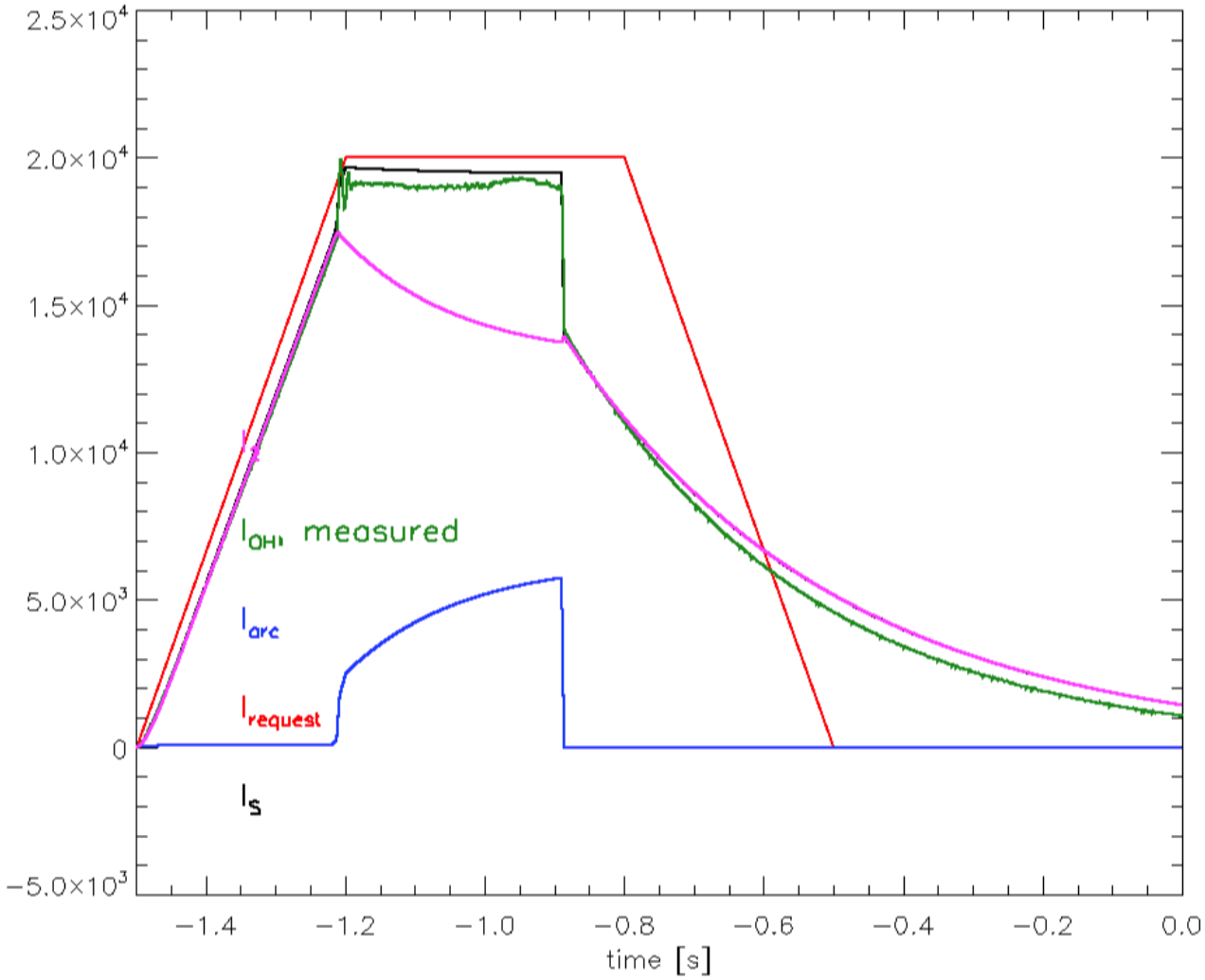
$L_1+L_2=L_{coil}$
$L_1 = L_{coil}/16$

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

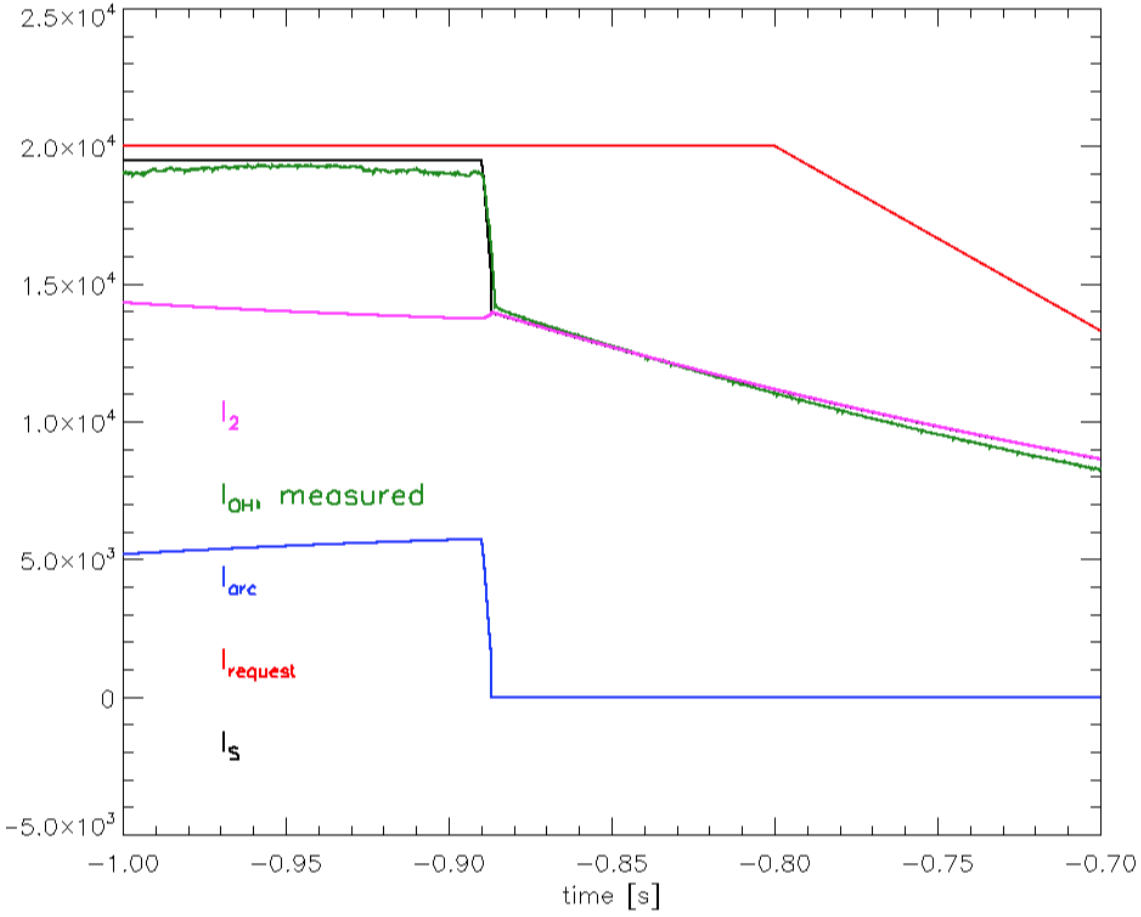
Measured Supply Current

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