NSTX-U OH Coil Fault Internal Review

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Team Members

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The committee appreciates the all of the efforts by the project to collect and provide the documentation requested as well as the open, forthright communications by the team regarding the issues leading up to this event.

Root technical cause: **Is the cause for the arc correctly identified and understood? Are there any other likely causes that should be more carefully considered? Are there contributing causes that also need to be addressed prior to implementing any repair or re-design work?**

Findings:

- The NSTX-U Team developed a plausible explanation of the fault based on a thorough examination of data and inspection of the affected areas.
- The root technical cause appears to have been a "double ground fault" arising from contact between an uninsulated, inadequately restrained, braided ground strap and two of the water cooling fittings at the top of the OH solenoid.
- This contact initiated an arc which then involved the ungrounded stainless-steel OH preload assembly, effectively short-circuiting three fourths of the coil turns.
- The arc persisted for several tenths of a second until a ground fault trip in the TF power circuit shut the systems down.
- Considerable energy was dissipated in the water fittings and supports which melted. As a result of the damage, cooling water then flooded the area and leaked to the bottom of the machine.

Findings Continued:

- Prior to the shot with the damaging fault, there had been 3 shots that resulted in ground fault trips on the OH circuit. These trips apparently resulted from the contact between the ground strap and a water fitting. However, these "single ground faults" were current limited by the high impedance grounding network in the power supply system.
- The ground strap which contacted the high voltage components had become detached from its clamp to the OH solenoid. The strap was intended to provide a connection between the conductive paint on the solenoid and the appropriate ground.
- Because of an installation error the low-resistance braid encircled the solenoid completely without a toroidal break. As a result, large toroidal currents were induced in the loop when the OH solenoid was pulsed resulting in large vertical forces on the conductor which worked loose from its clamp.
- The OH ground plane connection including the did not conform to the original NSTX design because it lacked a toroidal break in the braid and a spring washer in the clamp to allow for thermal expansion, only provided a connection at the top of the solenoid, and it was not grounded through a resistor.

Root technical cause - continued

Observations:

- The OH fault appears to have occurred due to the inadequate design and installation of the ground plane connection. As installed, the low-resistance braid encircled the solenoid completely. As a result, large toroidal currents were induced in the loop when the OH solenoid was pulsed resulting in large axial forces on the conductor which worked loose from its clamp.
- Although the OH coil experienced unusual internal distributions of current and voltage during the fault, there is no evidence that any immediate damage resulted in the main body of the coil.

Conclusion:

- The committee concurs with the root technical cause explanation.

Root technical cause - continued

Recommendations:

- Determine the root cause of the ground plane connector design/installation errors [Separate committee using procedure QA-019].
- Continue to perform diagnostic electrical tests including repeat of coil resistance measurement, inductance measurement and impulse test to confirm that the turn-to-turn insulation is intact.
- The design of the OH ground plane and its connections needs to undergo the standard PPPL design review, installation and inspection process, rather than relying on a “field fit-up.”

***Root procedural and process causes*: Are there any procedural or process lapses that contributed to the fault – either in design/installation or in machine operations/ interlocks? Are there any procedural or process improvements that should be implemented?**

Findings:

- Repeated difficulties in passing the inner-to-outer vacuum vessel hipot led to the practice of disconnecting the OH ground plane connection from the Cat. 4 ground during hipot, indicating that the operations team did not understand the purpose OH ground plane and that it should be connected to the Cat. 3 ground.
- It appears that the OH ground strap was not adequately specified before installation or inspected after installation.
- ISTP-001 was successfully completed. No ground faults occurred during this testing.
- The project went into operations using NSTX-02 to prepare for and complete the CD-4 test shots.
- On April 24, the planned 8% and 50% test shots were successful.
- Subsequently three shots at 100% were not successful – all due to ground fault trips.
- After 1st trip – entered test cell to inspect and moved the OH ground from Cat. 4 to Cat. 3.
- After 2nd trip – revised the instantaneous ground threshold from 50mA to 100mA
- After 3rd trip OH instantaneous ground fault relays were disabled.

Root procedural and process causes - continued

Findings - continued:

- There were no drawings of the grounding system including the specifics of the clamp holding the ground strap or the electrical schematic of the grounding connections.
- No real-time measurement of the current in the OH ground strap itself was available (note: electrical testing alone without the OH coil energized would not detect this fault cause – needed physical observation of ground strap in the field).
- Staff in control room did not inspect the measured power supply ground currents and line voltages during any of the shots. These signals showed anomalies on the shots that suffered trips prior to the major fault.
- Attempts to obtain the OH Coil CDR and PDR files from the Ops Center was not successful (committee did obtain a copy of the files from the cognizant engineer).

Observations:

- Unclear why OH ground was initially connected to Cat. 4 ground system. The "hipot" test routinely performed between the inner (Cat. 3) and outer (Cat. 4) parts of the vacuum vessel repeatedly failed unless the OH ground braid was disconnected.
- The grounding system should have been defined in a drawing with a specific review of the system (drawing for NSTX was only document available).

Observations - continued:

- Some field assembly is always required. However, it is not clear whether sufficient, appropriate reviews of this critical hardware were conducted.
- Even though there were three consecutive trips, and some actions taken to determine the cause, it appears that staff did not believe the "indicators", did not examine the ground current signals that were causing the trips, and proceeded to the fourth attempt without fully determining the cause of the trips.
- Assumptions about the cause of the OH ground fault trips appear to have been made based on past history – generally a ground fault indicated a water leak. The absence of any obvious leak when the machine was inspected and a successful "lopot" (500V) test may have contributed to the decision to proceed.
- Displacement of the ground strap apparently did not come to mind.
- A T-mod was not used to implement and document changed interlocks.
- Despite an abundance of experienced staff in the control room, the "stop work" rule was not invoked, even after three successive ground faults.

Root procedural and process causes - continued

Recommendations

- Revise operational procedures to require a full stop of operations upon a ground fault trip – need to understand what went wrong – require inspections to determine reason.
- COEs should have a collection of MDS Scope pages set up to monitor critical operations and diagnose faults under operations procedure. The pages used should be optimized for the type of operation underway (test shot, ISTP, plasma ops, etc.).
- Determine NSTX-U project line of authority - who must approve proceeding with operations if causes of ground fault (or other problem causing a trip) have not been determined and resolved.
- Engineering needs to establish a policy for field installations – when does a review have to be completed of field design.
- The Laboratory should determine whether the operators (e.g. COEs) report up to and through the NSTX-U organization rather than engineering.
- The Laboratory needs to determine whether sufficient high voltage electrical expertise is available for current and future projects.

Recommendations - continued

- Project needs to demonstrate how it will prevent this type of management control failure from recurring in the future.
- Project needs to verify design documentation packages (CDR, PDR, FDR) are available in the operations center for the NSTX-U centerstack and beamline 2.
- OH coil hipot level should be 2E+1=2(6+2)+1=17kV per approved design point documentation, which was also checked and signed off by coil designer. If operation requirements are to be revised (e.g. OH <=4kV with CHI, and/or Vchi = 3kV) then relevant documentation should be revised accordingly.
- Incorporate electrical analysis and design into development of upgraded components.
- Engineering needs to establish rules for grounding each experimental machine as part of the formal design review process.

Extent of condition: **Are there any other areas of NSTX-U, not yet identified, that might have been compromised by the fault, or be subject to similar defects? Are there any other similar weaknesses in the NSTX-U design, procedures, or processes that could lead to future difficulties?**

Findings:

- The project has been consumed by the investigation and disassembly of the machine.
- The project did not present a plan on how they were going to address this charge.

Observation:

- The review team noted that the OH Coil hipot level was not per the approved design documentation.
- The review team noted the suggestion by J. Menard for a task force to conduct a walkdown of critical components of the machine
- The team has been made aware of a root cause analysis being conducted also, but results are not yet available.
- Disassembly of the lower hub for inspection of the OH base is an appropriate first step for assessing the “extent of condition”.

Extent of condition - continued

Recommendations:

- The project needs to develop a comprehensive plan to address this charge question and be ready to present to the external review committee.
- Form a small "task force" (with appropriate expertise) to walk down all the high-voltage parts of NSTX-U to determine anything out of the ordinary, or potentially questionable from an “high voltage hygiene” stand-point.
- Evaluate other gaps, creepage paths, and insulation on other coils and appendages to see if problems exist similar to OH.
- Analyze and document electrical effect of Aquapour and dental floss wires in gap between OH and TF.
- Consider conducting a “blind spot” review, similar to the laboratory process.
- Complete root cause analysis and be prepared to present to external committee.

Repair and design solution: **Are the conceptual designs, repairs, and corrections identified by the NSTX-U team highly likely to avoid a recurrence of a similar fault? Are there other approaches that would be superior?**

Findings:

- Initial designs were presented to the committee.
- Design involves three major areas: OH ground plane connection; grounding of OH compression system and improved OH cooling tube support brackets.

Observations:

- It appears that many of the changes are being "field designed" without the benefit of an engineer with expertise in high voltage design practices to assure the most efficient and effective approach.
- None of the designs have gone through the PPPL design review process (CDR, PDR, FDR) yet.

Repair and design solution - continued

Recommendations:

- Ensure that ground plane connection does not form toroidal loop. If hose clamp approach is used to attach ground plane connector, ensure that type with thermal expansion spring is used. Demonstrate through measurement that the desired resistance is in the loop.
- Consider conducting elastomer solution to ground plane electrical attachment to avoid use of flex copper braid (ref. 13_010220_CLN_01.pdf, 13_010222_CLN_01.pdf, 13_010301_CLN_01.pdf). Provide documentation and drawings to justify and describe solution.
- Consider scheme to monitor load impedance in PSRTC (and/or DCPS) to sense situations where coil has become degraded.
- Review design of OH lead assembly: confirm cross sectional area of (+) and (-) conductors is equal; confirm that assumptions in design analysis are reflected in as-built configuration; confirm that insulation strength is good for at least 1.5 x Voh_hipot.

Recommendations - continued:

- Measure resistance of ground plane paint to confirm proper application and resistivity (200 ohms/square). Determine if OH groundwall thickness and composition is different than given in design point (as was mentioned during presentation) and provide explanation.
- For new design of clamps that support OH water lines: ensure adequate gaps, creepage, and insulation to pass hipot at 1.5 x Voh_hipot; use insulating boot over water line as it emerges from coil; do not use metallic screws; avoid splits in G10 blocks that provide line of sight creepage path.
- Consider placing water sensor(s) on floor of NSTX-U Test Cell under machine and interlock with water system to turn off pumps.
- Connect all metallic structures of inner vacuum vessel to Cat. 3 ground with 10 ohm resistors in each connection that can be opened up for troubleshooting. Provide an approved drawing of the electrical schematic.

Recommendations - continued:

- Evaluate whether or not method for clamping of OH water fittings allows for radial expansion of coil copper while support structure remains fixed, without placing undue stress on the water fittings. Consider placing a bend in the water fitting to avoid this issue.
- OH ground plane should be connected to Cat. 3 ground reference on both top and bottom ends through 10 ohm resistors. Analysis of ground plane behavior using PSCAD (W. Que "OHCoilGroundPlaneV3.ppt") should be updated accordingly and properly documented.
- Ensure that OH preload assembly fixture is connected to Cat. 3 ground via 10 ohm resistor.
- Consider installing real-time camera(s) and arc flash detectors inside hub assemblies.

Conclusions

- The project has determined the technical cause of this event.
- The project needs to re-design, fabricate and install a number of components to address the failure – full compliance with the Laboratory procedures is necessary.
- The project needs to improve its conduct of operations to preclude another similar event.
- The project needs to have an effective approach to the extent of condition question.