October 6th, 2017

MQXFAP1 Test Readiness Review Report

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September 26 and 28, 2017

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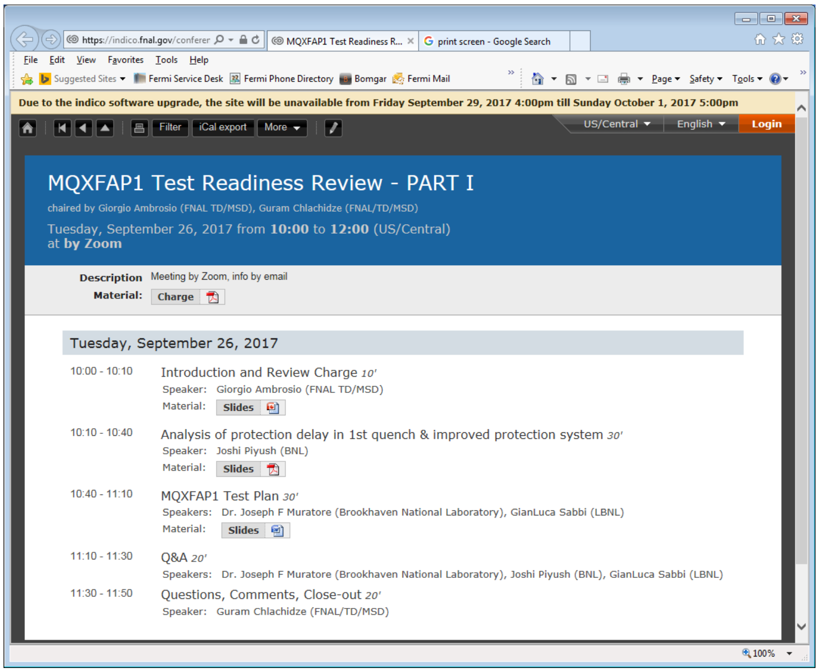
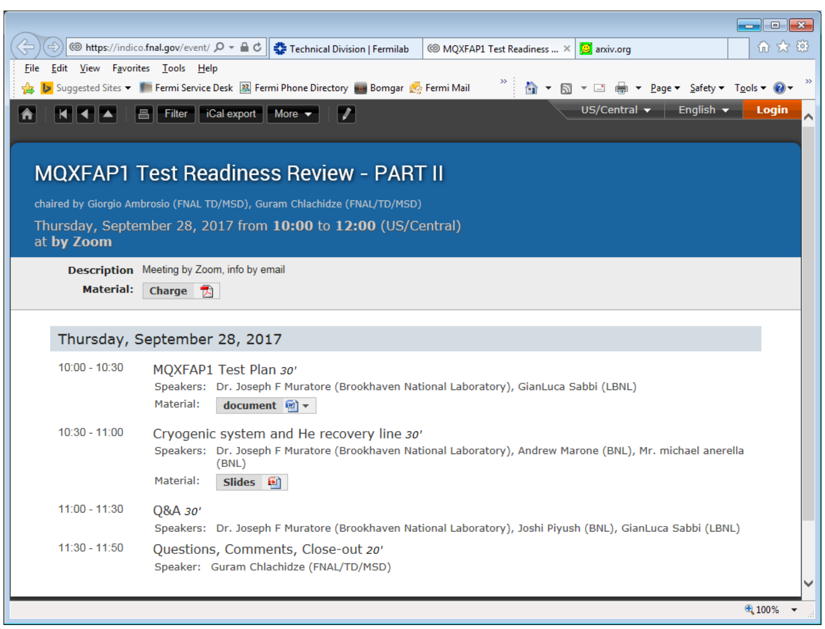
Introduction

The review process was split in two sessions. Quench detection system was discussed on Sep. 26, while the test plan and cryogenic system modifications - on Sep. 28, 2017.

The review committee would like to thank the presenters for the work putting together presentations and answering numerous questions during and after the discussions.

The review charge can be found in the Appendix.





2.0 Findings

2.1 *Quench Detection and Protection Systems*

- New FPGA based quench detection system was recently developed for the 2nd test cycle of MQXFAP1. This system is not commissioned yet. The new FPGA and old PXI based systems will run in parallel.

- FPGA system detects quenches in Half-coil and Whole-coil signals, while Ground fault and Lead signals are not included in the FPGA quench detection system.

- PXI system delays observed during the mirror test campaign appeared appropriate and the system was tested and responded well. Adding more input and output signals into this system for MQXFAP1 made it clear that the updated PXI system does not provide adequate protection of the magnet.

- PXI system is a combination of the quench detection and characterization systems. Along with the signals important for quench detection, there are also numerous signals useful for quench characterization (heater voltages etc.). As a consequence, digital response (decision) time reached about 25 ms.

- Details on quench detection and protection elements, in particular which voltage taps were used to form the leads, splices or coil segments, and what actions will follow after a quench is detected, were provided after the review meetings.

- Splice and SC lead quenches, as well as ground fault, trigger fast power discharge with energy extraction but without firing protection heaters.

- Quench detection voltage thresholds and validation time can be changed during magnet operation, for example when ramping to quench.

- Quench detection software allows disabling the quench detection at currents below 600 A (the magnet is self-protected up to 1500 A)

- Capability of inducing quenches by protection heaters is now implemented.

- Same validation procedure is applied for different quenching signals

2.2 *Test plan*

- MQXFAP1 test plan does not have an outline showing sequence of tests.

- The test plan does not specify when the quench training should end.

- The test plan still refers to the mirror magnet test

- The CLIQ and magnetic measurement systems will be available before the end of test, but probably after the quench training.

- The Hipot test description is not clear. Nominal thresholds based on CERN requirements are shown in the test plan, while these thresholds were not reached in the 1st test cycle.

- Not clear why copper and SC lead signals in quench detection are labeled as Interlocks.

- Hot-spot temperature as a function of MIITs is shown in the test plan, but not clearly specified for each test step.

- Strain gauge systems are not introduced. The test plan does not specify that the CERN SG system settings have to be changed before the excitation tests

- The holding test is suggested at 17890 A or 0.95*Imax whichever is less

- 50 mΩ dump resistor can be used during the quench training for currents up to 18000 A.

- All training ramps will be stopped at 2000 A for about 60 s to check various magnet and cryogenic parameters

- Training quench at 4.5 K is not in the test plan.

2.3 *Cryogenic System*

- The quench recovery line and the relief valve at the test facility were not optimized for maximum gas flow and pressure observed in MQXFAP1. As a consequence, the very first quench caused the rupture disk burst.

- The quench recovery path is changed so that about 15 ft section of 2” piping with two restrictive globe valves is replaced with a longer section of 4” piping, utilizing 4” and 6” butterfly valves.

- Quench detection system will trigger one of the 4” butterfly valves in the recovery line to open automatically after each quench or trip

- Larger (1.5”) helium relief valve with the lower set pressure (~30 PSIG) is installed. Rupture disc limit is about 40 PSIG.

- Two quench tanks are included in the quench recovery system

- Liquid level above and under the lambda plate are monitored through the main and redundant sensors

3.0 Comments

3.1 *Quench Detection and Protection Systems*

- Two quench detection systems are not really redundant since the FPGA-based is the only system actually managing to protect the magnet adequately.

- Using newly developed protection system poses certain risk. Therefore, commissioning of FPGA system is very important. Various trigger tests based on flux jumps and/or heater provoked quenches could be used during this commissioning.

- Potential interference between FPGA and PXI-based systems should be considered and tested. For example, separate isolation channels could be used for input signals in FPGA and PXI systems to provide redundancy of these systems (comment: separate isolation amplifiers were implemented during the review process). A systematic testing of the quench detection systems should be planned, performed and documented.

- The capability of changing the quench detection voltage thresholds and validation time during magnet operation appears risky. It should be carefully considered whether such a feature is needed at all.

- If a ground fault is detected, the magnet should be ramped down slowly, not with an energy extraction, to avoid the risk of developing high voltages in the magnet in the presence of a short circuit to ground. If a quench is detected during the slow ramp down, the quench protection system should be activated.

- Gas cooled (copper) leads and SC leads (splices) are protected in PXI based system with a reaction time up to ~25 ms. In low field area we expect very slow quench propagation, therefore 25 ms delay may not cause any problem. Nevertheless, we prefer to see some calculations supporting this assumption.

- A splice or SC lead quench will trigger only energy extraction without firing protection heaters (and CLIQ). Since quench may propagate to Nb3Sn segment, especially if developed near VTA01 or VTB01, it will be safer to protect the magnet with heaters (and CLIQ) too.

- When differential signals are used for half-coils, it would be better to exclude the SC lead segments, including the splice segments, and protect them separately.

3.2 *Test Plan*

- We understand that the HL-LHC requirements for High Voltage Withstand Thresholds cannot be met due to insulation weakness in the instrumentation tree. Additional attempts to reach high voltage thresholds and more failures can lead to further insulation degradation. It will be safer to perform the Hipot test up to 1000V at cold and warm, which will be sufficient for operation with 50 mOhm dump resistor and symmetric magnet grounding system.

- It would be useful to have a plot of the noise in quench detection signals as a function of current to justify the choice for the protection thresholds.

- The holding test is suggested at 17890 A or 0.95*Imax whichever is less. Since the maximum current we can reach during the first portion of quench training is only 18000 A, better to demonstrate stable magnet operation first at the nominal current of 16480 A. Later on we could try another holding test at the ultimate current.

3.3 *Cryogenic System*

- Pressure drop calculations along with quench boil-off rate calculations are available at BNL. According to Andy Marone, the new (1.5”) relief valve will handle a 18kA quench even in a worst case scenario when no other helium path is available, if 50% of stored energy is extracted. After MQXFAP1 test, this relief valve will be replaced with a larger one, which will handle a full quench without energy extraction.

- Longer section of 4” piping significantly improves pressure drop in the helium transfer line compared to the old ~15 ft. section of 2” piping

4.0 Recommendations

- We recommend developing comprehensive commissioning plan for the recently developed FPGA quench detection system.

- Quench logic and delays in FPGA and PXI systems should be verified before each magnet test. Ad-hoc tests should be performed for every critical feature of the quench logic.

- We recommend changing the quench logic when a ground fault is detected. The magnet should be ramped down slowly, without an external energy extraction. If a quench is triggered during the slow ramp down, the quench protection system should be activated, and quench data should be saved.

- We recommend changing the quench logic for SC lead (which may contain splices) quenches and make it identical with the logic for coil quenches. Thresholds for a splice and SC lead detected quench will be lower.

- It is recommended to disable capability of changing the quench detection voltage thresholds and validation time if magnet is powered. A maximum possible threshold values should be identified and recorded in a look-up table. FPGA and PXI systems should use different look-up tables for the voltage threshold limits.

- (**Recommendation not for this test**) FPGA and PXI systems should be further upgraded to provide a required redundancy in quench detection. Quench characterization and quench detection functions should be separated as much as possible in PXI system. Leads, Splices and Ground Fault protection should be included in FPGA system.

- It is recommended to include at least SC leads in FPGA for MQXFAP1 test. If not possible, it should be demonstrated that PXI decision time of ~ 25 ms is safe for a SC lead quench.

- (**Recommendation not for this test**) Separate isolation amplifiers should be considered for FPGA and PXI systems to improve the quench detection redundancy (comment: separate isolation amplifiers were implemented during the review process).

- We recommend to carefully check prior to energizing the magnet circuit whether the voltage segment based quench protection system was done correctly. The following magnet circuit signals must be detected and protected with different threshold values:

- Power (copper) lead protection: V-taps at the upper section and bottom section of the power leads must make up the Power Lead Voltage segments. The threshold value depends on the Power Lead manufacturer specifications (usually within 50-100 mV).
- Superconducting lead/bus protection: Every superconducting lead (or bus) segments (that potentially have less field value than the conductor has in the coil) must have V-taps at the beginning and at the end of the segment. A lead segment starts right at the end of the coil. Splices can be part of the lead segment (**recommendation not for this test**). The threshold value should be as low as possible.
- Coil protection: Coil V-taps at both end of the coil (as close as possible to the coil still in the high field region) make up the coil voltages. Threshold value should be as low as possible (usually within 100-500 mV).

- We recommend performing all (warm and cold) Hipot tests in MQXFAP1 up to 1000 V only.

- Holding test is recommended at the nominal current of 16480 A. If successful, then repeat this test at 17890 A.

- We recommend a thermal cycle after the quench training and the holding tests are done. Quench protection study, and probably magnetic measurements too, will follow after the thermal cycle.

- We recommend having a reference inner layer heater tests performed after the quench training is finished, but before the thermal cycle.

- We recommend performing comprehensive checkout of all strain gauges (CERN and LARP type) after the magnet is connected to the header assembly (**currently in progress at BNL**).

- We recommend a detailed discussion of quench protection tests after the thermal cycle. Plans for quench study should be scrutinized for safety both of the magnet and the test facility.

- We recommend preparing a technical note describing modifications in cryogenic system for MQXFAP1 test at BNL.

5.0 Response to Review Charge Questions

Question: Is the cryogenic system, and in particular the recovery line, adequate for the MQXFAP1 test?

Answer: Yes, the longer recovery path with the section of 4" piping and larger valves should address the pressure build-up problem observed in the very first training quench of MQXFAP1.

Question: Are the detection and protection systems adequate for the MQXFAP1 test up to ultimate current?

Answer: Yes, with the fully commissioned FPGA system and the PXI system running in parallel, the detection and protection systems are adequate for the MQXFAP1 test up to ultimate current.

Question: Is the DAQ system for strain gauges operational and adequate for the goals of this test?

Answer: At the moment of writing this report, the strain gauge checkout is still in progress and results are expected soon. The DAQ system for the CERN type sensors already demonstrated adequate performance for a short model test.

Question: The original test plan had two phases: the 1st phase, without CLIQ, aimed at training up to ultimate current; the 2nd phase, with CLIQ, aimed at exploring higher than ultimate current, and demonstrating quench protection in operating conditions. Is this still a good plan, or do you recommend a different one?

Answer: Yes, we recommend to proceed with the quench training up to 18000 A and quench memory demonstration after thermal cycle. Additional training (if possible), all protection studies, including CLIQ tests, will be done after the thermal cycle.

Question: Is the test plan reasonable for achieving test goals? Is it sufficiently detailed and clear to avoid un-necessary risks?

Answer: Yes, the test plan is reasonable and sufficiently detailed for the first part of the test: quench training. Quench protection plans still should be discussed, probably during the thermal cycle.

Question: Is there any other comment or recommendation to assure a successful MQXFAP1 test?

Answer: See our recommendations at pp. 7-8.

6.0 Appendix: Review Goal and Charge

MQXFAP1 Test Readiness Review

Goal & Charge

MQXFAP1 is the first prototype of the MQXFA magnets to be used in Q1 and Q3 for the High Luminosity LHC. MQXFAP1 has slightly shorter coils than nominal (4 m instead of 4.2 m magnetic length), whereas the supporting structure has nominal length. One coil has 1st generation cable and x-section design. All other coils have the final cable and x-section design.

The main goal of MQXFAP1 test is to demonstrate that MQXFA magnets can meet "quench performance" requirements (i.e. reach ultimate current, and show good training memory), and that they can be protected in HL-LHC operating conditions. Field quality requirements will be target of subsequent prototypes and/or re-assemblies.

Before this review MQXFAP1 was cooled down to 2 K, and energized up to the first quench at 15.5 kA. The test was interrupted because of a ruptured burst disk leading to a complete thermal cycle in order to perform the necessary repairs.

The goal of this review is to assess test facility readiness to re-start MQXFAP1 test, and to confirm the test goals and plan for the next cycle.

The committee is requested to answer the following questions:

1. Is the cryogenic system, and in particular the recovery line, adequate for the MQXFAP1 test?
2. Are the detection and protection systems adequate for the MQXFAP1 test up to ultimate current?
3. Is the DAQ system for strain gauges operational and adequate for the goals of this test?
4. The original test plan had two phases: the 1st phase, without CLIQ, aimed at training up to ultimate current; the 2nd phase, with CLIQ, aimed at exploring higher than ultimate current, and demonstrating quench protection in operating conditions. Is this still a good plan, or do you recommend a different one?
5. Is the test plan reasonable for achieving test goals? Is it sufficiently detailed and clear to avoid un-necessary risks?
6. Is there any other comment or recommendation to assure a successful MQXFAP1 test?

Committee: G. Chlachidze (chairperson), H. Bajas, S. Feher, E. Ravaioli.

Date and Time: Part I - September 26, 2017; Part II – September 28, 2017

Location/Connection: Video-link by Zoom, info by email.

Link to talks: https://indico.fnal.gov/conferenceDisplay.py?confId=15372