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**TEST PLAN (TEST CYCLE 2)**

**MQXFAP1 PROTOTYPE QUADRUPOLE**

**BACKGROUND**

The MQXFAP1 magnet is the first full length quadrupole in the MQXF design, which is to be used in the Q1/Q3 triplets of the High Luminosity LHC. It consists of four double layer (inner and outer) coils wound with Nb3Sn 40-strand cable with stainless steel core. The predicted short sample quench current for MQXFAP1 is 21.6 kA at 1.9 K [1]. This prototype will be followed by another prototype, and then a “pre-series” model magnet, after which there will be 20 production, or series, magnets which will be tested and sent to Fermilab for assembly into cold masses for the LHC triplets. MQXFAP1 stands apart from subsequent magnets in that it is still funded by LARP and contains coils whose magnetic length is 4.0 m rather than the 4.2 m length of the present specification. Also, the coils are not matched in conductor properties and the magnet is not considered a magnetic field quality model. In addition, coil 03 has a number of discrepancies that have been noted elsewhere and these include coil shorts to pole island and quench protection heaters with no copper and only stainless steel.

The cryogenic test is to be done at mostly at 1.9 K (with possibly some tests at 4.5 K) in the newly refurbished and designed Vertical Test Dewar #2 at the BNL Magnet Division Vertical Test Facility (VTF). This facility was commissioned in 2017 with the successful test of the single coil mirror magnet MQXFPM1, containing the first MQXF long coil. Cooling to 4.5 K will be by liquid helium bath provided by the Magnet Division CTI 4000 Refrigerator/Liquefier. Liquid helium is introduced near the magnet nonlead end (bottom end) by the bottom fill line. Magnet nonlead end is at bottom and lead end is at top. Liquid helium is also introduced by a top fill above a lambda plate. Cooling to 1.9 K is accomplished by pumping on the liquid helium in a heat exchanger below the lambda plate until the vapor pressure in the heat exchanger is down to about 16 mbar. The heat exchanger is immersed in the liquid helium below the lambda plate and runs the length of the magnet.

The first test cycle was performed in August 2017. The original plan for this cycle was to train the magnet up to ultimate current. However, after the first training quench, the test had to be interrupted because of high pressure following the quench and causing a ruptured burst disk. This required a complete thermal cycle in order to perform the necessary repairs and cryogenic system modifications. In addition, analysis of the quench data showed that the detection delay was significantly longer than expected, requiring further analysis and modifications of the detection system to understand the cause and correct the issue.

With this in mind, the main goals for the second test cycle are the following:

1) demonstrate that the cryogenic and quench detection issues have been corrected, and that all

 systems required to perform the test are ready;

2) perform training up to ultimate current (18 kA nom), without exceeding the safe thresholds for

 maximum voltage and temperature, and acquiring data to characterize the magnet mechanical

 behavior;

3) the quench locations and the mechanisms originating the quenches;

4) verify stable operation through an extended hold at 18 kA or 95%Imax (whichever is less);

**MQXFAP1 NOMINAL PARAMETERS**

Coil inner aperture : D = 150 mm

Coil magnetic length: L = 4.0 m **(MQXFAP1 only; otherwise 4.2 m)**

Coil actual length: L = 4.310 m **(MQXFAP1 only; otherwise 4.523 m)**

Yoke length L = 4.5629 m

Total length with end plates L = 5 m (nom)

Operational temperature T = 1.9 K

LHC nominal operating current (1.9 K) Inom = 16.470 kA

LHC ultimate operating current (1.9 K) Iult = 17.890 kA

Maximum current (300 K) I300 = 10 A

Conductor limit at 1.9 K: Iss = 21.600 kA

Conductor limit at 4.5 K: Iss = 19.550 kA

Peak field in the coil at Inom (1.9 K): Bnom = 11.4 T

Peak field in the coil at Iult (1.9 K): Bult = 12.3 T

Peak field in the coil at Iss (1.9 K): Bss = 14.5 T

Field Gradient at Inom (1.9 K): Gnom = 132.6 T/m

Field Gradient at Iult (1.9 K): Gult = 143.2 T/m

Field Gradient at Iss (1.9 K): Gss = 168.1 T/m

Magnet resistance at room temperature: R = 2.37 Ω

Magnet inductance (20Hz at room temperature): L = 38.1 mH

Magnet inductance (at 1.9 and 1 kA) : L = 40.9 mH (see note below)

Magnet inductance (at 1.9 and Inom=16.5 kA) : L = 32.8 mH (see note below)

Operating stored energy (at Bnom, Inom): Emax = 4.5 MJ assuming L=32.8 mH

Maximum allowed temperature at quench: Tmax = 350 K

Maximum allowed voltage across magnet Vmax = 1000 V (500 V to ground) with 50 mΩ EE

Dump resistor (energy extraction) options RD = 30, 37.5, 50, 75, 150 mΩ

**NOTE ON THE INDUCTANCE**

The magnet inductance will decrease as it is ramped to higher currents. Dynamic inductance measurements have shown this to be the case for the short quadrupole MQXFS1 (coil length 1.5 m).

The inductance vs current measured on MQXFS1 corresponded well to ROXIE calculations.

The ROXIE calculated differential inductance per unit length at 1 kA and 16.5 kA is 10.232 and 8.193 mH/m, respectively. The magnetic length of MQXFS1 is 1.192 m; so if we want to scale the inductance we can use the factor 4.0/1.192 (for MQXFA/MQXFS).

In conclusion, the expected MQXFAP1 inductance is **40.9 and 32.8 mH** at 1 and 16.5 kA, respectively.

As part of the test procedures outlined in this document, inductance measurements at 1.9 K will be done to get the actual values for MQXFAP1.

**NOTE ON MIITs VS TEMPERATURE**

The strand Cu/non-Cu ratio for coil 03 is 1.08 (less than the specifications). Below is a plot showing the calculated adiabatic hot-spot temperature versus quench load, for constant field B = 13 T, RRR = 100, Cu/non-Cu = 1.08.

In consideration of the particular situation of coil 3 we will set an initial target to limit the quench load to 27 MIIts in order to keep the hot-spot temperature below the empirical limit of 250 K (for HQ02b we started seeing detraining above this value). It might not be possible to achieve this target, in this case we will review the target and protection settings accordingly. It is recommended to start the training with a conservative setting of the quench protection thresholds and validation delays even if it might result in false triggers.



**Note: In the first quench, 34 MIITs were recorded; however, due to lower field than the 13 T assumed above and location in Coil 2, the adiabatic calculation gives a lower temperature of 295K. A more refined calculation taking into account the measured decay gives an even lower temperature estimate of 253K. We maintain the goal to keep the temperature below 250K but the 27 MIITs limit may be re-evaluated. We also reconfirm the plan to use conservative settings for protection thresholds and validation delays, even if this might result in false triggers.**



**HIGH VOLTAGE TEST PARAMETERS**



**POWER SUPPLY**

The magnet will be powered by the former Magnet Division Short Sample Cable Test Facility dual 15 kA power supplies (30 kA), which are now reconfigured and upgraded to power magnets up to 24 kA, and each of which includes a ceramic non-inductive energy extraction circuit with six 3.6 kA IGBT switches in parallel. During testing, critical IGBT-related parameters, such as the individual IGBT collector currents, collector-emitter voltages, and temperatures, will be continuously monitored for all switches. Also the individual and total power supply currents and voltages and the ground fault current signals will be monitored. All critical parameters involving the power supply and switches are subject to interlock thresholds, the violation of which will result in a slow power supply discharge.

**INSTRUMENTATION**

**Voltage Taps**

Each coil is instrumented with 16 auxiliary voltage taps, 8 in each of the layers, and at least 4 taps on each lead, and a warm tap at the top of each gas-cooled lead, for a total of up to 80 taps. With these, we monitor the inner and outer layers, selected sections of the windings, the superconducting leads, the lead splice joints, and the gas-cooled leads. There are also three sets of 2 redundant taps for quench detection; these are located between the two layers and on each NbTi lead below the splice box. These will allow the monitoring of the total coil voltage, the half coil voltages, and the quarter coil voltages, and the use of these signals will provide inputs to the quench detector. In addition, the power supply current, voltage, and ground current, the voltages, currents, and ground currents of the strip heater discharge circuits, and the voltage across and current through the CLIQ unit will also be monitored. The voltage tap configuration for each of the four coils is shown in the following schematic:



Layer 1 (A taps) is the inner layer and Layer 2 (B taps) is the outer layer.

It should be noted that for MQXFAP1, the following taps are open and not useable:

Coil 3 - A01, A08

Coil 5 - A06

These will be jumped to create the required voltage tap pairs and will be so noted in the database for the fast data logger.

Also, for Coil 3, four extra taps have been installed on the pole segments to monitor for shorts during electrical checkouts.

During the first test cycle, two more taps were lost: tap B3 on both Coil 2 and Coil 5.This means that, since B3 is the tap between the two outer layer multi-turns, for each of Coils 2 and 5, there will be one large multi-turn, which will cover all the turns except the pole turn.

**Temperature Sensors**

Liquid helium temperature will be monitored by two redundant pairs of Lakeshore Cernox resistive temperature sensors at the top and bottom of the magnet. Four wire measurements of these resistors will be monitored during testing as part of the slow logger data acquisition system. There are also Cernox sensors on the gas-cooled leads and attached to the middle level probe to get temperature reads halfway along the magnet’s length.

**LHe Level Probes**

The test fixture is equipped with three 7” (17.78 cm), four 30” (76.2 cm), and one 12” (30.48 cm) LHe level probes installed at various locations in Test Dewar #2. (See diagram below showing locations and lengths of the level probes.)

Liquid helium level on the top probe should be at least **9” (22.86 cm)** to cover the copper flags between the magnet leads and the gas cooled leads. There are also level probes in the heat exchanger.



**Quench Protection**

**Active quench protection** for this test will be provided by an energy extraction system and heaters installed on the coils. A coupling-loss induced quench (CLIQ) unit will be added for improved performance and redundancy in future tests.

Quench Protection Heaters

Quench Protection heaters QPH (also known as strip heaters), 4 strips on the outer layer outer surface and 2 strips on the inner layer inner surface of each coil. PH delay times at nominal parameters are about 15 ms. The heaters are configured into eleven independent circuits, with two strips connected in series composing each circuit, and each of which is fired by pulse discharge from a heater firing unit (HFU) with a tunable capacitor bank. Capacitance can be adjusted by changing the number of capacitors connected or by connecting them in indifferent configurations.

There are 12 HFU capacitive discharge assemblies, which include eight 600 V, 12.4 mF units and four 900 V, 13.05 mF units.

Nominal strip heater parameters:

1. HFU capacitances are initially set to 12.4 mF and 13.05 mF for the 600 V and 900 V HFUs, respectively.

2. Strip heater current decay time depends on HFU capacitance and strip heater resistances. Time constants will be in the range of 25 to 45 ms.

3. An HFU needs to generate enough initial power density from the heaters on the surfaces of both layers in order to induce a quench. The nominal values for outer and inner heaters are 213 and 98 W/cm2, respectively.

4. Capacitors are rated to 450 V for the 8 600 V HFUs and to 1000 V for the 900 V HFUs.

5. 15 ms or greater detect / diffusion time for heat to reach the cable and initiate a quench.

Strip resistances at 10K have been calculated (E. Ravaioli) to be

Inner strip: Calculated 1.72 Ω

Outer strip: Calculated 1.10-1.14 Ω

These will be measured when cold.

Energy Extraction

Energy extraction (dump) resistors are installed, for each of the two 15 kA power supplies in parallel. Dump resistance values can be varied as 30, 37.5, 50, 75, and 150 mΩ. Each dump resistor is center-tapped to ground. Each energy extraction circuit is enabled by six IGBT switches for each power supply. This will limit the voltage across the magnet to 671 V (335 V to ground) with 37.5 Ω and 895 V (447 V to ground) with 50 mΩ.

**Quench detection** will be achieved by both a delta (outer – inner layer voltage difference) and an I‑dot (current derivative) quench detector circuit. Voltage thresholds and time delays for quench detection are tunable and will depend on ramp rate and power supply current level. In addition there are also a number of other signals input into the quench detector such as whole coil and quadrant voltage differences.

**Magnetic Field Measurements**

The magnetic field measuring system is expected to be operational before the end of the test (after training and protection studies).

**Strain Gauges**

For each coil there are 4 full bridge type strain gauges on the pole, on the inner surface, two at each of two axial locations 1/3 of the way from each end; one of each pair measures axial strain and the other azimuthal strain. There are also 32 azimuthal strain gauges located on the shell, along with two temperature compensating gauges. The strain is to be measured throughout cooldown, testing, and warmup by taking reads continuously in the background during the course of the testing with control software, at intervals of 1-10 minutes, and also at more frequent intervals of 5 s during magnet excitation ramps and specific strain gauge measurement runs. Each gauge is read in a 4-wire Wheatstone bridge configuration. Readout uses 1.5 V excitation and 1 μV resolution. Initial strain measurements before cooldown will be compared to the reading taken at FNAL before shipping.

**Quench Antenna**

A quench antenna will be installed prior to the beginning of training. It consists of 16 dual-winding configuration printed circuit boards. There are 4 boards 5.08 cm apart on each end, and 8 boards along the magnet straight section 42.7 cm apart. Expected quench antenna winding voltages during quench are 100 – 500 mV.

**SOME PROCEDURAL NOTES**

Cryogenic tests will be nominally be at 1.9 K and 4.5K. All training quenches will be at 1.9 K Initial checkouts may be performed at 1.9 K or 4.5 K, depending on what is most efficient in terms of schedule and operation. One or few quenches at 4.5K are planned after training at 1.9K to help assess the magnet performance limits and temperature margins.

Fast data logger nominal sampling rate is 10 KHz (sampling interval of 100μs) on all channels during a quench, with pre-trigger data capture of 1 s before quench event and 4 s of data capture after quench event. Before and after time intervals and sampling rate can be varied when necessary.

Due the generation of flux jump spikes, false trips of the delta and current derivative (I-dot) detectors are probable and to be expected during ramping in the lower current range, to about 6 kA. For this reason, the I-dot detector threshold will be varied (0.8 to 1.0 V typically) according to current level and ramp rate. The threshold of the delta detector can be set initially to 0.250 V. The variation will be set and controlled programmatically, and will not be changed during a ramp.

Nominal voltage thresholds for the quench detectors:

Detector Threshold Validation Time

Delta QDC 50-250 mV (variable); **125 mV to start** 2-5 ms; **2 ms to start**

Idot QDC 0.8 to 1.0 V (variable) 2-5 ms

Gas-cooled leads interlock 80 – 100 mV 2-5 ms

Superconducting leads interlock 25 mV 2-5 ms

Minimum time delay settings for quench detectors and quench protection:

Detector Delay

Delta QDC 0 ms

Idot QDC 0 ms

Strip Heaters 0 ms

Dump resistor switch 0 ms

Power supply shutoff 0 ms

Time delays can be adjusted to suit the testing focus.

NOTE: A fuse in the power supply circuitry protects the power supply from ground faults, and ground fault currents are indicated by a warning light. Also, the ground fault current, along with strip heater ground currents, are instrumented to be written to both fast and slow data loggers. IGBT fault lights are located on the power supply IGBT buckets.

Proper flow rates should be determined and set for the pair of liquid-cooled leads being used.

**Data Handling**

Measurement data must be electronically recorded and should be backed up regularly. All data must be saved on a separate computer or a network disk at the end of each test run. This data will be backed up to the Discovery server in a directory with permissions for all personnel involved in the testing and analysis. Data to be recorded include all voltage tap signals, power supply current and voltage signals, strain gauge data, capacitive transducer data, magnetic field Hall probe signal, temperature signals, and level probe signals.

**Test Communications and Data Sharing**

The following are methods of sharing previously discussed:

1) Daily email to the list.

2) Quench log in Excel by attachment or by download from fixed link.

**Documents (Traveler Packet)**

Work Planning (Green) Sheet is to be generated by the SMD Work Control Coordinator. This run plan is to be attached to the Green Sheet, which, along with this Run Plan, is to be placed in a clear packet and hung at the side of Test Dewar 2 and be clearly visible to all.

**Safety Precautions**

Only authorized personnel are allowed to operate the system. All personnel who are taking part in the testing must be up to date on the appropriate BNL training in order to be authorized.

Since this magnet has an iron yoke which acts as a flux return, the leakage field should be insignificant and the red fence should provide an adequate safety limit of approach. However, there will be measurement of stray field at the maximum test current and this will be recorded for the Magnet Traveler.

Make sure that the current leads are being cooled properly throughout the test. Leads must be monitored throughout the test using the voltage taps.

NOTE: In case of any problems or issues with the performance of the following test plan, or in case of an emergency relating to the testing procedures, contact the following personnel:

Joe Muratore x2215

Piyush Joshi x3847

 **RUN PLAN**

**A. Preliminary Room Temperature Electrical Checkout in Test Dewar #2**

 1. Record the appropriate hanging distances below the top plate in order to determine the correct

 location for the LHe levels. The probes must be placed at proper locations before installation in

 Test Dewar #2.

 2. Measure resistance across each coil and compare with previous resistance measurements done

 before installation in the test dewar. Measure the total resistance of the magnet coils and record

 for use at warmup. Measure the resistance across each strip heater circuit, each temperature

 sensor, and each strain gauge.

 3. Check resistances to ground for the power leads and the strip heaters and to each other.

 4. Hipot tests (with Test Dewar #2 opened to air). See Hipot Parameter table in Introduction.

 3.7 kV hipot of coil and each strip heater circuit off ground with all other systems grounded.

 3.0 kV hipot of coil to each strip heater circuit off ground with all other systems grounded.

 Maximum target leakage current is 10 μA over 30 s.

 5. Check all main taps and auxiliary voltage taps for continuity (each tap has a 200 Ω resistor)

 at the patch panel.

 6. Series resistance measurement at 1 A of all taps in order from positive lead to negative lead. Do

 a four-wire measurement with 1 A.

 7. Verify that all top hat connectors are properly hooked up.

 8. Perform 5A level shift test and check all data channels for proper operation. Set the fast data

 loggers to 1 kHz. Verify fast data logger acquisition of all voltage tap pair voltages and other

 signals.

 9. Strip heater HFU’s should be connected to the strip heaters but set at 20 V.

 Strip heater circuits should be configured as follows:

 a. Outer heaters of Coils 02 and 04 (not adjacent): follow the final design configuration,

 connecting together strips from non-adjacent coils (HF with HF, LF with LF).

 b. Outer heaters of Coil 05 (facing 03): connect together strips from the same coil (HF with HF,

 LF with LF).

 c. Outer HF heaters of Coil 03 (non-plated): these two strips are powered individually.

 d. Outer LF heaters of Coil 03 (non-plated): these two strips are not powered at all.

 e. Inner heaters of Coils 02 and 04 (not adjacent): follow the final design configuration,

 connecting together strips from non-adjacent coils.

 f. Inner heaters of Coil 05 (facing 03): connect together strips from the same coil.

 g. Inner heaters of Coil 03 (non-plated): these two strips are powered individually.

 10. Verify slow logger data acquisition of all signals for 10 min intervals before and during

 cooldown: voltage tap pairs, power supply current, LHe level probes, strain gauges,

 Compare strain gauge readouts with strain gauge calibrations.

 11. Insert quench antenna into warm bore tube. Verify proper insulating vacuum and flow of warm

 N2 gas. Use measurements made in Part A.1, corrected for magnet contracted length when at

 1.9 K to properly position the antenna.

 12. Verify cryostat insulating vacuum and proper operation of copper lead heaters and fans.

 13. Inform the cryogenics operator to start cool down to 4.5K. Maintain a gradient of 100 K or less

 between the magnet ends during cooldown

 14. During cooldown, monitor magnet resistance using 4-wire measurement with 10 A. As

 temperature approaches 20 K, increase slow logger sampling rate to get 5 s sampling interval.

 Stable and uniform measurements at room temperature, 77 K, and 20 K are most important.

 Resistances at room temperature and 20 K are necessary to calculate RRR.

**B. Preliminary Electrical Checkout at 4.5K (or less) in Test Dewar #2**

 NOTE: The initial cold checkout at 4.5 K can actually be done when the magnet temperature is 20K

 or less if this benefits the test schedule. Strip heaters should initially be disconnected from HFU’s.

 **Hipots must be done at 4.5 K (or less) and in liquid He, not gas. Power supply shutoffs and**

 **heater quench tests can be done only when the magnet has** **reached at least 4.5K.**

 1. Check resistances to ground for the power leads and the strip heater leads.

 2. Measure the resistances of magnet leads to strip heater leads.

 3. Measure the resistance across each strip heater circuit, each temperature sensor, and each

 strain gauge.

 4. 1A AC series measurements of coil and main taps.

 5. Check main taps for continuity at patch panel by measuring the resistances of

 all taps (each tap has a 200 ohm resistor).

 6. Hipot tests (**magnet at 4.5 K and in liquid He**). See Hipot Parameter table in Introduction.

 1.8 kV hipot of coil and each strip heater circuit off ground with all other systems grounded.

 2.3 kV hipot of coil to each strip heater circuit off ground with all other systems grounded.

 7. 5A level shift test (to be done only if there was an unusual result in the room temperature

 checkout in Part A). Set the fast data loggers to 1 kHz. Strip heater HFU’s should be

 connected to the strip heaters but set at minimum voltage. Verify fast data logger acquisition of

 all voltage tap pair voltages and other signals.

 8. Verify that the correct signals (voltages and current) are input into the quench detectors.

**C. Setup for Testing at 4.5K (or less) in Test Dewar #2**

 **NOTE: The magnet must be at 4.5K (or less) in liquid He (NOT gas) for these tests.**

 1. Connect magnet leads to power supply. Strip heater HFU’s should be connected to the strip

 Heater circuits but set only at 20 V.

 2. Balance the Idot quench detection circuit for a ramp rate of 20A/s.

 3. Configure quench detection system.

 Nominal voltage thresholds for the quench detectors:

 Detector Threshold

 Delta QDC 50 mV – 250 mV (variable); **start with 125 mV**

 Idot QDC 0.8 to 1.0 V (variable)

 Gas-cooled leads interlock 80 – 100 mV (set alarms on monitor to 80 mV)

 Superconducting leads interlock 25 mV (set alarms on monitor to 80 mV)

 Minimum time delay settings for quench detectors:

 Detector Delay

 Delta QDC 0 ms

 Idot QDC 0 ms

 Strip Heaters 0 ms

 4. Verify each HFU capacitance at nominal default values (600 V-12.4 mF units and

 900 V-13.05 mF units

 5. HFU’s should be connected to the strip heaters but set at 20 V.

 6. Verify that strip heater circuits are configured as follows:

 a. Outer heaters of Coils 02 and 04 (not adjacent): follow the final design configuration,

 connecting together strips from non-adjacent coils (HF with HF, LF with LF).

 b. Outer heaters of Coil 05 (facing 03): connect together strips from the same coil (HF with HF,

 LF with LF).

 c. Outer HF heaters of Coil 03 (non-plated): these two strips are powered individually.

 d. Outer LF heaters of Coil 03 (non-plated): these two strips are not powered at all.

 e. Inner heaters of Coils 02 and 04 (not adjacent): follow the final design configuration,

 connecting together strips from non-adjacent coils.

 f. Inner heaters of Coil 05 (facing 03): connect together strips from the same coil.

 g. Inner heaters of Coil 03 (non-plated): these two strips are powered individually.

 7. Set the power supply input impedance for the starting magnet inductance of L = 40.9 mH.

 8. Set the power supply overcurrent to 5.5 kA.

 9. Set proper flow rates for the two gas-cooled copper leads.

**D. Power Supply Shutoffs**

 **1. 1000 A power supply shutoff**:

 Purpose: to check quench detection, power supply, and data acquisition systems before

 actually initiating a quench.

 1. Set EE dump resistance to **150 mΩ** for this test.

 2. Set quench detection threshold to **125 mV**, validation time to **5 ms**.

 3. Set fast logger sampling rate to 10 kHz.

 4. Set strip heater and energy extraction delays to 0 ms.

 5. Set HFU minimum voltage (about 20V) for all heater circuits and nominal capacitance of

 12.4 mF.

 6. Set slow data logger system to take reads at 1 s intervals during the test.

 7. Check for proper lead flow operation.

 8. Ramp magnet at 20 A/s to 500 A. Measure inductance at 20 A/s. Check lead voltages for

 stability.

 9. Ramp magnet at 20 A/s to 1000 A. Measure inductance at 20 A/s. Check lead voltages for

 stability.

 10. Manually trip the delta (voltage difference) quench detector circuit.

 11. Verify fast data logger acquisition of all voltage tap pair voltages and other signals. Check

 all signals for anomalies and proper behavior before proceeding.

 12. Verify that the voltage signals are consistent with the 150 mΩ dump resistance.

**2. 2000 A power supply shutoff**:

 Purpose: to provide a baseline for shutoff signals to compare with 2000 A QPH quench.

 NOTE: EE dump resistance should be set to **150 mΩ** for this test.

 1. Set fast logger sampling rate to 10 kHz.

 2. Set strip heater and energy extraction delays to 0 ms.

 3. Set HFU minimum voltage (about 20V) for all heater circuits and nominal capacitance of

 12.4 mF.

 4. Set slow data logger system to take reads at 1 s intervals during the test.

 5. Check for proper lead flow operation.

 6. Ramp magnet at 20 A/s to 1500 A. Measure inductance at 20 A/s. Check lead voltages for

 stability.

 7. Ramp magnet at 20 A/s to 2000 A. Measure inductance at 20 A/s. Check lead voltages for

 stability.

 8. Manually trip the delta (voltage difference) quench detector circuit.

 9. Verify fast data logger acquisition of all voltage tap pair voltages and other signals. Check

 all signals for anomalies and proper behavior before proceeding.

 10. Verify that the voltage signals are consistent with the 150 mΩ dump resistance.

**E. Quench Protection Heater (Strip Heater) Tests at 4.5 K (or less) and 150 mΩ**

 **Quench detector threshold at 125 mV and validation time at 2 ms at high current**

 **(above 8000 A). Voltage thresholds for the entire regime of currents during the ramp**

 **are given in the table below:**

|  |  |
| --- | --- |
| **CURRENT RANGE [A]** | **VOLTAGE THRESHOLD (mV)** |
| **0 – 400** | **150** |
| **400 – 1500** | **1500** |
| **1500 – 3000** | **2000** |
| **3000 – 4000** | **3000** |
| **4000 – 5000** | **2500** |
| **5000 – 6000** | **2000** |
| **6000 – 8000** | **1000** |
| **8000 - 22000** | **125** |

 **1. Quench protection heater quench at 2000 A:**

 Purpose: to check strip heater performance at 2000 A.

 NOTE: **EE dump resistance should be set to 150 mΩ for this test.**

 1. Set fast logger sampling rate to 10 kHz.

 2. Set slow data logger system to take reads at 1 s intervals during the test.

 3. Verify that each strip heater HFU capacitance is set at nominal values of 12.4 mF for the outer

 layer HFU and 13.05 mF for inner layer HFU.

 4. Set strip heater HFU’s to 475 V for the outer layer high field HFU and 490 V for outer layer

 low field HFU, and 490 V for the inner layer HFU. For the Coil 3 stainless steel heaters, set

 the HFU to 900 V.

 5. Set strip heater and energy extraction delays to 0 ms.

 6. Verify proper lead flow operation.

 7. Ramp magnet to 2000 A at 20A/s. Check lead voltages for stability.

 8. Set OL HF strip circuits to quench the magnet. The rest for protection.

 9. Manually trip the OL HF strip circuit to induce a quench.

 10. Examine all quench signals for proper behavior.

 11. Verify that both layers quench <500 ms after heater firing. Check heater current and voltage

 waveforms.

 12. Calculate the MIITs value for this quench and verify that it does not exceed the maximum

 safe value for this magnet's conductor.

 13. If the criteria in (10) and (11) are not satisfied, increase HFU voltages and

 repeat steps (6) - (11).

 14. Repeat above with OL LF strip circuits set to quench and the rest for protection.

 15. Repeat above for the IL strip circuits.

 16. Repeat above for OL HF heaters of Coil 03 (non-plated).

 17. Repeat above for IL heaters of Coil 03 (non-plated).

 **2. Quench protection heater quench at 6000 A:**

 Purpose: to check strip heater performance at 6000 A.

 NOTE: **EE dump resistance should be set to 150 mΩ for this test.**

 1. Set fast logger sampling rate to 10 kHz.

 2. Set slow data logger system to take reads at 1 s intervals during the test.

 3. Verify that each strip heater HFU capacitance is set at nominal values of 12.4 mF for the outer

 layer HFU and 13.05 mF for inner layer HFU.

 4. Set strip heater HFU voltages to the value determined in the 2000 A strip heater quench.

 5. Set strip heater and energy extraction delays to 0 ms.

 6. Verify proper lead flow operation.

 7. Ramp magnet to 6000 A at 20 A/s. Check lead voltages for stability.

 8. Set OL HF strip circuits to quench the magnet. The rest for protection.

 9. Manually trip the OL HF strip circuit to induce a quench.

 10. Examine all quench signals for proper behavior.

 11. Verify that both layers quench <100 ms after heater firing. Check heater current and voltage

 waveforms.

 12. Calculate the MIITs value for this quench and verify that it does not exceed the maximum

 safe value for this magnet's conductor.

 13. If the criteria in (11) and (12) are not satisfied, increase HFU voltages and

 repeat steps (6) - (12). Ramp to 6000 A without stopping.

 14. Repeat above with OL LF strip circuits set to quench and the rest for protection.

 15. Repeat above for the IL strip circuits.

 16. Repeat above for OL HF heaters of Coil 03 (non-plated).

 17. Repeat above for IL heaters of Coil 03 (non-plated).

**F. Quench Protection Heater (Strip Heater) Tests at 4.5 K (or less) and 50 mΩ**

 Purpose: to determine if **50 mΩ** EE resistance is safe for IGBT operation at higher currents.

 **Quench detector threshold at 125 mV and validation time at 2 ms at high current**

 **(above 8000 A). Voltage thresholds for the entire regime of currents during the ramp**

 **are given in the table below:**

|  |  |
| --- | --- |
| **CURRENT RANGE [A]** | **VOLTAGE THRESHOLD (mV)** |
| **0 – 400** | **150** |
| **400 – 1500** | **1500** |
| **1500 – 3000** | **2000** |
| **3000 – 4000** | **3000** |
| **4000 – 5000** | **2500** |
| **5000 – 6000** | **2000** |
| **6000 – 8000** | **1000** |
| **8000 - 22000** | **125** |

 **1. 2000 A power supply shutoff after changing EE resistance**

 Purpose: To verify that the EE dump resistor has been properly changed before the first quench.

 NOTE: **EE dump resistance should be set to 50 mΩ for this test.**

 1. Repeat procedure in Part D.2, but with **50 mΩ EE resistance.**

 2. Verify fast data logger acquisition of all voltage tap pair voltages and other signals. Check

 all signals for anomalies and proper behavior before proceeding.

 3. Verify that the voltage signals are consistent with the 50 mΩ dump resistance before

 proceeding.

 **2. Quench protection heater quench at 10000 A:**

 Purpose: to check quench and IGBT voltages at 10000 A.

 NOTE: **EE dump resistance should be set to 50 mΩ for this test.**

 1. Set fast logger sampling rate to 10 kHz.

 2. Set slow data logger system to take reads at 1 s intervals during the test.

 3. Verify that each strip heater HFU capacitance is set at nominal values of 12.4 mF for the outer

 layer HFU and 13.05 mF for inner layer HFU.

 4. Set strip heater HFU’s to 475 V for the outer layer high field HFU and 490 V for outer layer

 low field HFU, and 490 V for the inner layer HFU. For the Coil 3 stainless steel heaters, set

 the HFU to 900 V.

 5. Set strip heater and energy extraction delays to 0 ms.

 6. Verify proper lead flow operation.

 7. Ramp magnet to 10000 A at 20A/s. Check lead voltages for stability.

 8. Set OL HF strip circuit to quench the magnet. The rest for protection.

 9. Manually trip the OL HF strip circuit to induce a quench.

 10. Examine all quench signals for proper behavior.

 11. Verify that both layers quench <100 ms after heater firing. Check heater current and voltage

 waveforms.

 12. Calculate the MIITs value for this quench and verify that it does not exceed the maximum

 safe value for this magnet's conductor.

 **3. Quench protection heater quench at 12000 A:**

 Purpose: to check quench and IGBT voltages at 12000 A.

 NOTE: **EE dump resistance should be set to 50 mΩ for this test.**

 1. Set fast logger sampling rate to 10 kHz.

 2. Set slow data logger system to take reads at 1 s intervals during the test.

 3. Verify that each strip heater HFU capacitance is set at nominal values of 12.4 mF for the outer

 layer HFU and 13.05 mF for inner layer HFU.

 4. Set strip heater HFU’s to 475 V for the outer layer high field HFU and 490 V for outer layer

 low field HFU, and 490 V for the inner layer HFU. For the Coil 3 stainless steel heaters, set

 the HFU to 900 V.

 5. Set strip heater and energy extraction delays to 0 ms.

 6. Verify proper lead flow operation.

 7. Ramp magnet to 12000 A at 20A/s. Check lead voltages for stability.

 8. Set OL HF strip circuit to quench the magnet. The rest for protection.

 9. Manually trip the OL HF strip circuit to induce a quench.

 10. Examine all quench signals for proper behavior.

 11. Verify that both layers quench <100 ms after heater firing. Check heater current and voltage

 waveforms.

 12. Calculate the MIITs value for this quench and verify that it does not exceed the maximum

 safe value for this magnet's conductor.

 **4. Quench protection heater quench at 14000 A:**

 Purpose: to check quench and IGBT voltages at 14000 A.

 NOTE: **EE dump resistance should be set to 50 mΩ for this test.**

 1. Set fast logger sampling rate to 10 kHz.

 2. Set slow data logger system to take reads at 1 s intervals during the test.

 3. Verify that each strip heater HFU capacitance is set at nominal values of 12.4 mF for the outer

 layer HFU and 13.05 mF for inner layer HFU.

 4. Set strip heater HFU’s to 475 V for the outer layer high field HFU and 490 V for outer layer

 low field HFU, and 490 V for the inner layer HFU. For the Coil 3 stainless steel heaters, set

 the HFU to 900 V.

 5. Set strip heater and energy extraction delays to 0 ms.

 6. Verify proper lead flow operation.

 7. Ramp magnet to 14000 A at 20A/s. Check lead voltages for stability.

 8. Set OL HF strip circuit to quench the magnet. The rest for protection.

 9. Manually trip the OL HF strip circuit to induce a quench.

 10. Examine all quench signals for proper behavior.

 11. Verify that both layers quench <100 ms after heater firing. Check heater current and voltage

 waveforms.

 12. Calculate the MIITs value for this quench and verify that it does not exceed the maximum

 safe value for this magnet's conductor.

**G.** **Spontaneous Quench Test Program at 1.9 K**

 Purpose: To check the quench performance of the magnet up to the ultimate operating current.

 NOTE: **EE dump resistance should now be set to 50 mΩ for the remaining tests.**

 **Quench detector threshold at 125 mV and validation time at 2 ms at high current**

 **(above 8000 A). Voltage thresholds for the entire regime of currents during the ramp**

 **are varied as a function of current (See table of values above inn Part F).**

 1. Set fast logger sampling rate to 10 kHz.

 2. Set slow data logger system to take reads at 1 s intervals during the test.

 3. Verify that each strip heater HFU capacitance is set at nominal values of 12.4 mF for the outer

 layer HFU and 13.05 mF for inner layer HFU

 4. Set strip heater HFU’s to the value determined in the 2000 A strip heater quench.

 5. Set strip heater and energy extraction delays to 0 ms.

 6. Verify proper lead flow operation.

 7. Ramp magnet to quench at 20 A/s without stops. Monitor closely lead voltages.

 Perform full analysis of quench signals, in particular to ensure the proper operation of the

 protection system. Calculate the quench integral to verify that the quench temperature is

 within safe limits (nominally 250 K). Discuss and confirm any changes required before the

 next quench.

 8. Repeat quenches at 20 A/s to quench without stops.

 9. For each quench, analyze quench data to determine the nature and causes of the

 training behavior. Determine quench location. Calculate quench integral to verify that a safe

 temperature limit is satisfied.

**H. Holding test at 1.9 K**

 Purpose: To verify stability of the magnet operation at a flattop current.

 1. Verify all test parameters are the same as for the quench tests in Part F.

 2. Ramp magnet at 20 A/s to **Iult = 17.890 A or 0.95 Imax, whichever is**

 **less.**

 3. Hold for 8 hours. But as little as 2 hrs may also be acceptable depending on system

 performance, schedule, and budget considerations.

 4. Monitor the status of all slow logger signals to verify nominal values.

**I. Quench Protection Heater Studies at 1.9 K.**

 Purpose: To determine optimal parameters for the quench protection heaters.

 **1. Quench delay vs current.**

 Purpose: To determine PH time delay (from PH ignition) to quench as a function of current.

 1. Configure the protection heaters so that the OL heaters are to fire and the IL heaters are to

 protect the coil. Increase the delay of the energy extraction to 3 ms.

 2. Set OL HFU voltage to minimum value determined in Part I.1 for the current 0.2Iss.

 3. Ramp current to 0.2Iss at 20 A/s.

 4. Fire the OL protection heater to provoke a quench.

 5. Analyze fast data logger signals to determine the following: quench origin location, time delay

 of quench with respect to heater firing, total energy, and energy density deposited by heaters.

 6. Repeat Steps 3 – 5 for the following currents: 0.4Iss, 0.6Iss, and 0.8Iss. Higher ramp rates may

 be used to save time during these tests.

 7. Repeat Steps 1 – 6 for IL heater to quench the coil and OL heater to protect the coil.

 **2. Minimum required power/energy density to quench**

 Purpose: To determine minimum PH power and energy density needed to quench the coil as a

 function of current.

 1. Configure the protection heaters so that the OL heaters are to fire and the IL heaters are to

 protect the coil.

 2. Set OL HFU voltage to a minimum value to be determined.

 3. Ramp current to 0.2Iss at 20 A/s.

 4. Fire the OL protection heater.

 5. Increase HFU voltage in 10 V steps until a quench is provoked.

 6. Analyze fast data logger signals to determine the following: quench origin location, time delay

 of quench with respect to heater firing, total energy, and energy density deposited by heaters.

 7. Repeat Steps 3 – 6 for the following currents: 0.4Iss, 0.6Iss, and 0.8Iss. Higher ramp rates may

 be used to save time during these tests.

 8. Repeat Steps 1 – 7 for IL heater to quench the coil and OL heater to protect the coil.

**J. CLIQ Tests**

-CLIQ unit check out at 0 A
--manually triggering quench detection.
--EE delayed by 1000 ms
--QH not powered
--C=40 mF, gradually increase CLIQ charging voltage: 50, 100, 250, 500 V
--check proper functioning of CLIQ system (triggering time, peak current, oscillation frequency)
--note: Diode string must be installed across the magnet before this tests

-CLIQ performance tests at 2kA and 5 kA
--C=40 mF, U0=500 V
--manually triggering quench detection.
--EE delayed by 500 ms
--QH not powered
--check proper functioning of CLIQ system and that a normal zone is introduced in the magnet

-O-QH + CLIQ quench integral tests
--C=40 mF, U0=500 V
--nominal QH parameters
--EE delayed by 1000 ms
--manually triggering quench detection. QH and CLIQ triggered simultaneously
--increase current level 10, 20, 30, 50, 80, 100, 108% nominal current

-O-QH + CLIQ quench integral tests (with reduced CLIQ charging voltage)
--same as before with lower CLIQ charging voltage
--current levels: 80, 100%, 108% nominal current
--C=40 mF, U0=400 V

**K. Magnetic Field Measurements**

 See document MQXFAP1-2-MMPlan-v0.docx

**L. Magnet Warmup to Room Temperature and RRR Measurement**

 1. Apply 10 A to the magnet.

 2. Set the slow logger sampling interval to 5 s until the temperature is above 25 K. Then increase

 the sampling interval to 10 min.

 3. Start warmup of the magnet to room temperature. Warmup should be slow to minimize the

 temperature gradient between the magnet ends.

 4. Slow logger should be running until the magnet reaches a stable room temperature.

 Stable measurements at room temperature, 77 K, and 20 K are most important. Resistances at

 room temperature and 20 K are necessary to calculate RRR.

References:

[1] L. Cooley, MQXFAP1 Conductor and Coil Readiness Review, <https://indico.fnal.gov/getFile.py/access?contribId=0&resId=1&materialId=slides&confId=14087>