TEST PLAN (FIRST TEST CYCLE)
MQXFAP2 PROTOTYPE QUADRUPOLE
DRAFT 7/24/2018
Authors

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1 BACKGROUND

The MQXFAP2 magnet is the second 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 Nb_3Sn 40-strand cable with stainless steel core. The predicted short sample quench current for MQXFAP2 is 21.0 kA at 1.9 K [1]. This prototype will be followed by a retest of the first prototype MQXFAP1, and then a "pre-series" model magnet MQXFA3, after which there will be 19 production, or series, magnets which will be tested and sent to Fermilab for assembly into cold masses for the LHC triplets. MQXFAP2 is the first full length MQXFA quadrupole that contains coils whose magnetic length is 4.2 m, which is the baseline.

The cryogenic test is to be done mostly at 1.9 K (with possibly some tests at 4.5 K) in the newly refurbished and designed Vertical Test Cryostat #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. Subsequently starting in Aug 2017, the first full length quadrupole MQXFAP1 was tested. 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 non-lead end (bottom end) by the bottom fill line. Magnet non-lead 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 in one of the cooling channels.

It is to be noted that the MQXFAP2 test will consist of two main parts.
1) Test cycle 1: Cooldown to 1.9 K and training to 18 kA (110 A above the ultimate current of 17.89 kA), magnetic field measurements,. The magnet will be warmed up to room temperature but kept in the test cryostat.

2) Test cycle 2: After thermal cycle, verification of training memory and continued training if necessary, quench protection studies with quench protection heaters and CLIQ, and completion of tests that were not finished in first test cycle.

The main priorities for this first test cycle are to address, to the extent possible, the functional requirements and acceptance criteria for MQXFA magnets, as described in [2]-[3]. Additional tests directed at gaining additional feedback on the design and fabrication in view of series production will be performed in the second thermal cycle.

2 MAGNET AND SYSTEM PARAMETERS

2.1 MQXFAP2 NOMINAL PARAMETERS

Coil inner aperture :	D = 150 mm
Coil magnetic length:	L = 4.2 m
Coil actual length:	L = 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)	I_{nom} = 16.470 kA
LHC ultimate operating current (1.9 K)	I_{ult} = 17.890 kA
Maximum current (300 K)	I_{300} = 15 A
Conductor limit at 1.9 K:	I_{ss} = 21.000 kA
Peak field in the coil at I_{nom} (1.9 K):	B_{nom} = 11.4 T
Peak field in the coil at I_{ult} (1.9 K):	B_{ult} = 12.3 T
Field Gradient at I_{nom} (1.9 K):	G_{nom} = 132.6 T/m
Field Gradient at I_{ult} (1.9 K):	G_{ult} = 143.2 T/m
Magnet resistance at room temperature:	R = 2.37 Ω
Magnet inductance (at 1.9 and 1 kA):	L = 43.0 mH (see note below)
Magnet inductance (at 1.9 and I_{nom}=16.5 kA) :	L = 34.4 mH (see note below)
Operating stored energy (at B_{nom}, I_{nom}):	E_{max} = 4.67 MJ assuming L=34.4 mH
Ultimate stored energy (at B_{ult}, I_{ult})	E_{max2} = 5.57 MJ (L=34.4 mH and I_{ult}=18 kA)
Maximum allowed temperature at quench:	T_{max} = 250K (training); 350K (protection studies)
Maximum allowed voltage across magnet	V_{max} = 1000 V (500 V to ground) with 50 mΩ EE
Dump resistor (energy extraction) options	R_D = 30, 37.5, 50, 75, 150 mΩ

2.2 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 inductances 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 4.2/1.192 (for MQXFA/MQXFS).

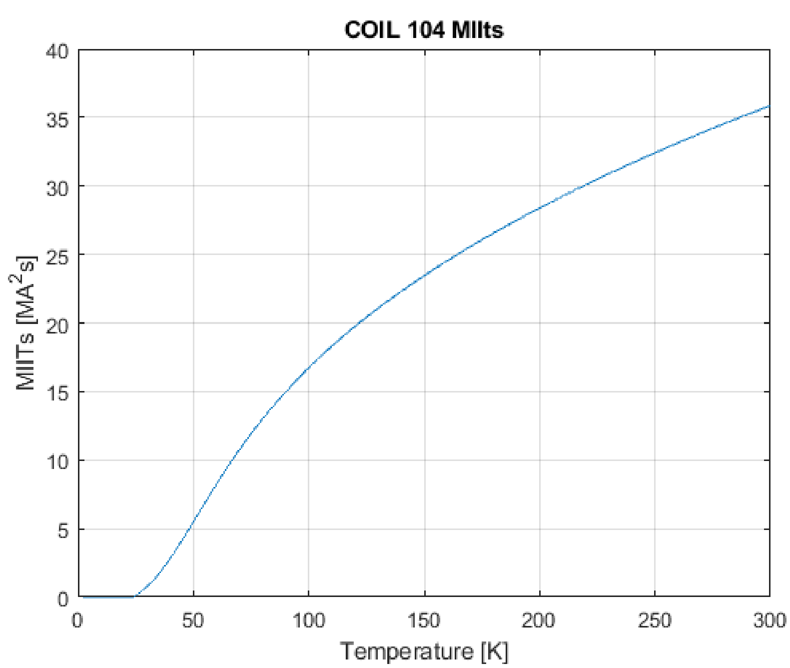
In conclusion, the expected MQXFAP2 inductance is **43.0 mH and 34.4 mH** at 1 and 16.5 kA, respectively.

As part of the test procedures outlined in this document, inductance measurements at 1.9 K will be performed to get the actual values for MQXFAP2.

Note that for the first prototype MQXFAP1 (4.0 m magnetic length), the inductance at 16.470 kA was measured to be 33 mH, as predicted by calculation.

2.3 NOTE ON MIITs VS TEMPERATURE

The target for the first thermal cycle is to maintain the hot spot temperature below 250K. The larger hot spot temperature is expected for quenches originating in coil 104, which has the lowest RRR (253). The following plot reports the coil 104 MIITs at 13 T. It show that a maximum quench integral of ~32 MIITs is compatible with the hot spot temperature limit. The protection setting will be chosen accordingly. The MIITs limits and protection settings may be revised based on data from the first quenches.



2.4 HIGH VOLTAGE TEST PARAMETERS

From MQXFA Final Design Report (US-HiLumi-doc-948, 5/16/18)

Maximum expected coil voltage at quench (V) [2]	To ground	670
	To quench heater	900
Minimum design withstand coil voltage at nominal operating conditions (V)	To ground	1840
	To quench heater	2300
Minimum design withstand coil voltage at warm* (V)	To ground	3680
	To quench heater	4600
Test voltage to ground for installed systems at nominal operating conditions (V)		804
Test voltage to ground for installed systems at warm (V)		368
Test voltage to heater for installed systems at nominal operating conditions (V)		1080
Test voltage to heater for installed systems at warm (V)		460
Maximum leakage current (µA) – not including leakage of the test station		10
Test voltage duration (s)		30

* T = 20±3 °C and humidity lower than 60%

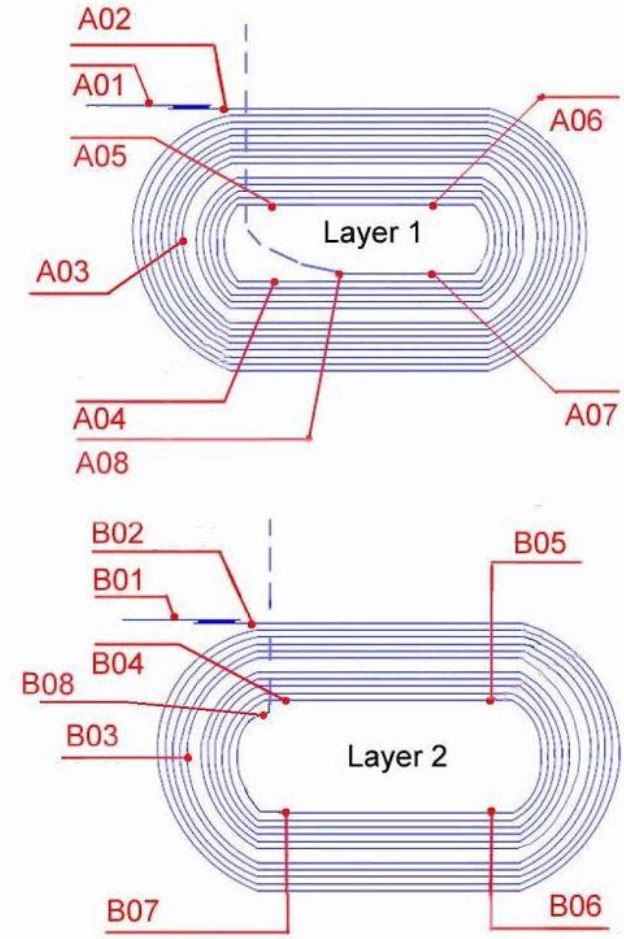
2.5 POWER SUPPLY

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 an energy extraction circuit with six 3.6 kA IGBT switches in parallel. The dump resistors are ceramic non-inductive resistors which can be changed over the values R_D = 30, 37.5, 50, 75, 150 mΩ 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.

3 INSTRUMENTATION

3.1 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 five sets of 2 redundant taps for quench detection; these are located between the two magnet halves, between the quadrants (coils) and on each NbTi lead below the splice box. These will allow the monitoring of the magnet total voltage, half voltages, and the quarter 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 in the event of lost taps during testing, those taps will be jumped across to create the required voltage tap pairs and will be so noted in the databases for the data loggers.

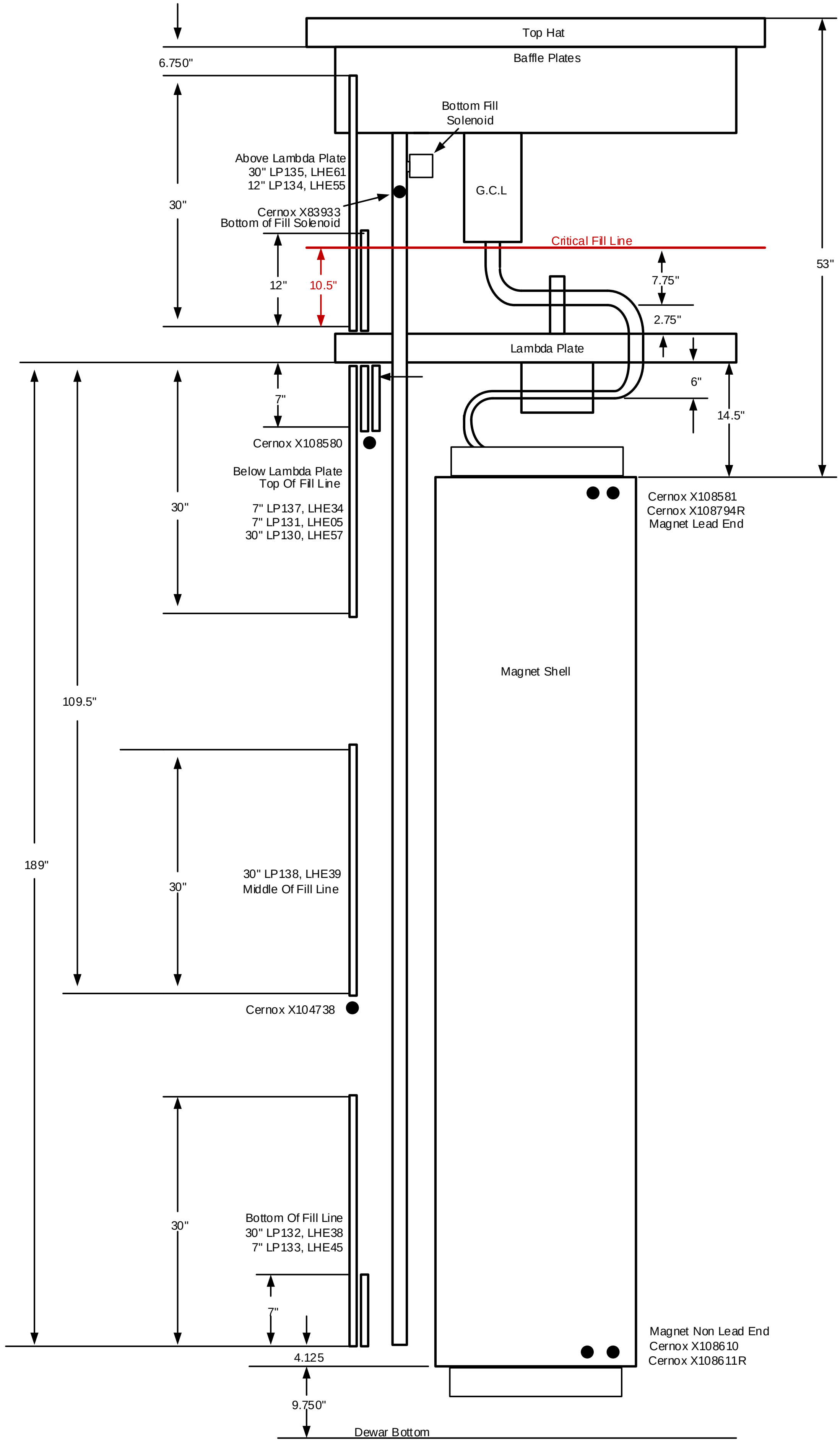
3.2 Temperature Sensors

Test temperatures will be monitored by a total of 12 Cernox temperature sensors, including liquid helium temperatures 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.

3.3 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.

MQXFA01 LARP QUAD LEVEL PROBES AND TEMP SENSORS AUG.2017



3.4 Quench Protection

Active quench protection for this test will be provided by an energy extraction system, protection heaters (strip heaters) installed on the coils, and a coupling-loss-induced quench (CLIQ) unit. All three systems will be used during quench training.

<u>Quench Protection Heaters</u>

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 twelve 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/cm^2, 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.

<u>Energy Extraction</u>

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.

<u>CLIQ (Coupling-Loss-Induced Quench) System</u>

The CLIQ system will be connected during quench training and for quench protection studies. The CLIQ settings will be 500 V and 40 mF.

<u>Quench Detectors</u>

Quench detection will be achieved by both a delta (half magnet voltage difference) and an I-dot (current derivative) quench detector circuit. Voltage thresholds, validation times, 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 total (whole) coil and individual coils (quadrant) voltage differences. The main QD signals are input into an FPGA-based quench detector, and as a backup, a PXIe QD, which also includes detection of thresholds in signals, such as gas-cooled leads, which result in a slow discharge that does not switch in the EE circuit and dump resistor.

3.5 Magnetic Field Measurements

Magnetic field measurements will be performed for the first time with a new rotating coil probe system. Magnetic measurement run plan is available separately.

3.6 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 24 full bridge strain gauges located on the shell and 24 full bridge strain gauges mounted on the coil inner surfaces. At each of the shell and coil locations, there are 2 bridges, one for each of the azimuthal and axial locations. Also there are 4 rod gauges. Each bridge circuit consists of two strain gauge grids bonded to the surface being measured and two passive grids not bonded and used for temperature compensation. 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.

3.7 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.

4 PROCEDURAL NOTES

Cryogenic tests will be nominally be at 1.9 K and 4.5 K. 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 a few quenches at 4.5 K are planned after training at 1.9 K to help assess the magnet performance limits and temperature margins.

Fast data logger nominal sampling rate is 10 kHz (sampling interval of 100 μs) 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 to the generation of flux jump spikes, false trips of the delta and current derivative (Idot) detectors are probable and to be expected during ramping in the lower current range, to about 6 kA. For this reason, the Idot detector threshold will be varied (0.8 to 1.0 V typically) according to current level and ramp rate. The final threshold of the delta detector (for **I** ≥ 8000 A can be set initially to 0.125 V. The variation will be set and controlled programmatically, and will not be changed during a ramp.

<u>Nominal voltage thresholds for the quench detectors:</u>

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
Superconducting leads	25 mV	2-5 ms
Gas-cooled leads	80 – 100 mV	2-5 ms

<u>Minimum time delay settings for quench detectors and quench protection:</u>

Detector	Delay
Delta QDC	0 ms
Idot QDC	0 ms
Strip Heaters	0 ms
Dump resistor switch	0 ms
CLIQ	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 gas-cooled lead pair.

4.1 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, magnetic field probe signal, temperature signals, and level probe signals.

4.2 Test Communications and Data Sharing

Regular updates on the status of the test are provided through emails to the MQXF_UPDATES list, including a quench summary file. Detailed test data is shared according to the guidelines provided in [4]

4.3 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 Cryostat 2 and be clearly visible to all.

4.4 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 by the SMD Safety Officer at the maximum test current and this will be recorded for the Magnet Traveler.

Make sure that the magnet gas-cooled leads and the long water-cooled bus-work are being cooled properly throughout the test. Leads must be monitored throughout the test using the voltage taps and temperature sensors.

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

5 RUN PLAN

5.1 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. 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 102 and 104 (adjacent): follow the alternative configuration, connecting together strips from adjacent coils (HF with HF, LF with LF).
   b. Outer heaters of Coil 105 and Coil 106 (adjacent): follow the alternative configuration, connecting together strips from adjacent coils (HF with HF, LF with LF).
   c. Inner heaters of all coils will not be used and the leads from these strips will not be brought out.
9. Perform 10 A 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. Strip heater discharges can be verified with HFUs set at 20 V.
10. Verify slow logger data acquisition of all signals for 10 min intervals before and during cooldown: main voltage tap pairs, power supply current and voltage, temperatures, LHe level probes. **Do not operate level probes in a vacuum.**
11. Verify strain gauge systems are reading properly at room temperature. Set LARP strain gauge current source to 5 mA and scanning rate to 1 scan/min. Verify that the CERN strain gauge system is in excitation mode and reading properly at room temperature. Compare strain gauge readouts with initial data from LBL to determine discrepancies, if any.
12. Verify cryostat insulating vacuum and proper operation of gas-cooled copper lead heaters and fans.
13. Apply 10 A across magnet leads.
14. Introduce N_2 gas into warm bore tube to prevent freezing.

15. 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
16. During cooldown, monitor magnet resistance using 4-wire measurement with 1 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.

5.2 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. **<u>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.</u>**

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 taps for continuity at patch panel by measuring the resistances of all taps (each tap has a 200 Ω resistor).
6. Hipot tests (**magnet at 4.5 K and in liquid He**). See Hipot Parameter table in Introduction.
   1.0 kV hipot of coil to test structure, which is grounded.
   1.0 kV hipot of each strip heater circuit to test structure and to coil 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 5.1). Set the fast data loggers to 1 kHz. Strip heater HFU's should be connected to the strip heaters but set at minimum voltage (20 V). 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.

5.3 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. Connect CLIQ leads to the magnet.
3. Balance the Idot quench detection circuit for a ramp rate of 20A/s.
4. Configure quench detection system.

<u>Nominal voltage thresholds for the quench detectors:</u>

<u>Detector</u>	<u>Threshold</u>
Delta QDC	50 mV – 250 mV (variable); **start with 125 mV**
Idot QDC	0.8 to 1.0 V (variable)
Superconducting leads	25 mV (set alarms on monitor to 80 mV)
Gas-cooled leads	80 – 100 mV (set alarms on monitor to 80 mV)

<u>Minimum time delay settings for quench detectors and quench protection systems:</u>

<u>Detector</u> <u>Delay</u>

Delta QDC	0 ms
Idot QDC	0 ms
Strip Heaters	0 ms
Dump resistor switch	0 ms
CLIQ	0 ms
Power supply shutoff	0 ms

Power supply shutoff 0 ms

5. Verify each HFU capacitance at nominal default values (600 V-12.4 mF units and 900 V-13.05 mF units.
6. HFU's should be connected to the strip heaters but set at 20 V.
7. Verify that strip heater circuits are configured as follows:
   a. Outer heaters of Coils 102 and 104 (adjacent): follow the alternative configuration, connecting together strips from adjacent coils (HF with HF, LF with LF).
   b. Outer heaters of Coil 105 and Coil 106 (adjacent): follow the alternative configuration, connecting together strips from adjacent coils (HF with HF, LF with LF).
   c. Inner heaters of all coils will not be used and the leads from these strips will not be brought out.
8. Verify that CLIQ leads and parallel diode have been properly connected
9. Set the power supply input impedance for the starting magnet inductance of L = 43.0 mH.
10. Set the power supply overcurrent to 5.5 kA.
11. Set proper flow rates for the two gas-cooled copper leads.
12. Insert quench antenna into warm bore tube. Verify proper insulating vacuum and flow of warm N_2 gas. Use measurements made in Part 5.1.1, corrected for magnet contracted length when at 1.9 K to properly position the antenna.
13. Set CLIQ capacitance to 40 mF and voltage to 500 V.

5.4 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.

5.5 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

However, these values of voltage thresholds as a function of current will be lowered if variable validation time as a function of current has been implemented in the power supply control program (LabVIEW).

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
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.
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 delay, validation times, and threshold settings.
12. Verify that both layers quench <500 ms after heater firing. Check heater current and voltage waveforms.
13. Calculate the MIITs value for this quench and verify that it does not exceed the maximum safe value corresponding to 250 K for this magnet's conductor.
14. If the criteria in (12) is not satisfied, increase HFU voltages and repeat steps (5) - (13).
15. Repeat above with OL LF strip circuits set to quench and the rest for protection.

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.
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 delay, validation times, and threshold settings.
12. Verify that both layers quench <100 ms after heater firing. Check heater current and voltage waveforms.
13. Calculate the MIITs value for this quench and verify that it does not exceed the maximum safe value corresponding to 250 K for this magnet's conductor.
14. If the criteria in (12) is not satisfied, increase HFU voltages and repeat steps (5) - (13). Ramp to 6000 A without stopping.
15. Repeat above with OL LF strip circuits set to quench and the rest for protection.

5.6 Power Supply Shutoffs with 50 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

However, these values of voltage thresholds as a function of current will be lowered if variable validation time as a function of current has been implemented in the power supply control program (LabVIEW).

1. 2000 A power supply shutoff after changing EE resistance to 50 mΩ.

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 5.4.2, 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.

5.7 Preliminary Test of CLIQ system

Purpose: To verify settings of CLIQ parameters and proper CLIQ output signal before use during quench training.

1. Set CLIQ voltage to 500 V.
2. Set CLIQ capacitance to 40 mF.
3. Set protection heater circuit HFUs to about 20 V.
4. With no current in magnet, manually trip CLIQ system.
5. Analyze magnet current, current through CLIQ diodes, and CLIQ voltage signals and verify that these are nominal.
6. With 1000 A in magnet, manually trip CLIQ system.
7. Analyze magnet current, current through CLIQ diodes, and CLIQ voltage signals and verify that these are nominal.
8. If above tests show nominal performance, continue to quench training program.

5.8 Spontaneous Quench Test Program at 1.9 K

Purpose: To train the magnet up to the ultimate operating current and higher. This goal will be re-evaluated in case of slow progress (e.g. more than 5 quenches without an increase in the maximum current)

NOTE:

EE dump resistance should now be set to and have been verified at 37.5 mΩ for the remaining tests. The dump resistor delay should be set to 10 ms for the training, in order to reduce the layer-to-layer peak voltages during the quench. Quench detector threshold should be 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 in Part 5.6). However, these values of voltage thresholds as a function of current will be lowered if variable validation time as a function of current has been implemented in the power supply control program (LabVIEW).

1. Set fast data logger sampling rate to 10 kHz (0.1 ms sampling interval).
2. Set slow data logger sampling rate to 1 Hz (1 s interval) during the test.
3. Verify that each strip heater HFU capacitance is set at nominal value of 12.4 mF for the outer layer HFU's.

4. Set outer layer strip heater HFU's to the values determined in the 2000 A strip heater quench.
5. Verify that CLIQ leads are connected and set CLIQ parameters to 40 mF and 500 V.
6. Set strip heater and CLIQ delays to 0 ms.
7. Set energy extraction dealy to 10 ms (this delay is useful to reduce layer-layer voltages)
8. Verify proper lead flow operation.
9. Ramp magnet to quench at 20 A/s with stop at 600 A for about 60 s to check various magnet, cryogenic, and power supply parameters. Monitor closely lead voltages and IGBT voltages and current sharing.
10. 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. Discuss and confirm any changes required before the next quench.
11. Repeat quenches at 20 A/s to quench. All training ramps will be stopped at 600 A for about 60 s to check various magnet and cryogenic parameters.
12. 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 the safe temperature limit of 250 K is satisfied. Check quench heater signals (current, voltage, and ground current) to verify that there was no degradation.
13. Optional test to check for heater degradation after training finished: repeat 6000 A OL-HF heater quench in Part 5.5.2.

5.9 Holding test at 1.9 K

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

1. Verify all test parameters are the same as for the quench tests in Part 5.7.
2. Ramp magnet at 20 A/s to nominal current (16.470 kA) at 1.9 K and hold for 300 minutes
3. Monitor the status of all slow logger signals to verify nominal values.

5.10 Quench Current Ramp Rate Dependence Study at 1.9 K

Purpose: To measure the variation of quench current with ramp rate.

1. Verify all test parameters are the same as for the quench tests in Part 5.7.
2. Ramp the magnet to quench at the following ramp rates: dI/dT = 10, 50, 100, 167 A/s.

NOTE: The maximum possible ramp rate with the 30 kA power supply system will be 167 A/s due to the maximum voltage achievable with this system.

5.11 Magnet Inductance Measurements at 1.9 K

Purpose: To measure the variation of magnet inductance with ramp rate.

1. Verify all test parameters are the same as for the quench tests in Part 5.7.
2. Verify that the slow data logger is set at 1 Hz sampling rate (1 s sampling interval).
3. Ramp the magnet at the following ramp rates to values below those determined in the ramp rate study in Part 5.9: dI/dT = 50, 100, 200, 300 A/s.

4. Analyze slow logger data channels containing total coil voltage, half coil voltages, quarter coil voltages, and layer voltages to determine inductance.

NOTE: Values of the coil and layer voltages generated by the slow logger at 1 Hz sampling rate during the different ramps in Part 5.9 ramp rate study may be used to determine the coil and layer inductances, and this test 5.10 can be omitted if those data are judged to be OK.

5.12 Splice Resistance Measurements at 1.9 K

Purpose: To measure resistance of the splices as a function of magnet current to determine the stability of the solder joints.

1. Verify all test parameters are the same as for the quench tests in Part 5.7.
2. Ramp the magnet in 1000 A steps to 0.95 I_{max} at 20 A/s and stop at each level to record the splice resistances using Agilent 3854 as data acquisition. A precision of 0.1 nΩ is needed for this test.

5.13 Quench Current Temperature Dependence Study

Purpose: To measure the variation of quench current with temperature.

1. Verify all test parameters are the same as for the quench tests in Part 5.7.
2. Use 20 A/s ramp rate for all quench tests.
3. Bring magnet temperature from 1.8 K to 4.5 K in steps (to be determined) by increasing the vapor pressure of He in heat exchanger.
4. If a stable temperature can be established, ramp magnet to quench at 20 A/s.
5. Finish test at temperature of 4.5 K.

5.14 Magnetic Field Measurements with Rotating Coil Probe at 1.9 K

The magnetic measurement plan is described in a separate document

5.15 Quench Protection in operational conditions

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Purpose: to demonstrate that the magnet can be protected in the operational conditions in the tunnel,

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

5.16 Magnet Warmup to Room Temperature and RRR Measurement

1. Apply 10 A to the magnet.
2. Set the slow data 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 data logger and strain gauge data acquisition 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.

6 SECOND THERMAL CYCLE

The main goal of the second thermal cycle is verifying the training memory. The second thermal cycle will also include studies directed at checking reproducibility of key parameters, and additional relevant but lower priority studies that could not be included in the first thermal cycle due to schedule constraints.

A specific test plan will be developed for the second thermal cycle, but the additional studies to be performed are listed here in order to provide a complete view of the scope of the test.

6.1 Protection studies

Purpose: To measure the minimum power density to quench and quench delay for the protection heaters with and without CLIQ and without EE, and with varying time delays.

1. For all tests involving CLIQ, CLIQ settings should be 500 V and 40 mF.
2. Inner quench protection heaters are not to be used.

A. Protection heater delay vs current.

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

1. Configure the protection so that the OL heaters are to fire and CLIQ is 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 rate may be used to save time during these tests.

B. 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 CLIQ is 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 test

C. O-QH + CLIQ quench integral tests (with reduced CLIQ charging voltage)

Purpose: to explore the possibility of lowering the CLIQ voltage in order to reduce the peak voltages on the magnet during a quench, and potential cost reduction on the CLIQ units.

1. --C=40 mF, U0=500 V
2. --nominal QH parameters
3. --EE delayed by 1000 ms
4. --current levels: 80, 100%, 108% nominal current
5. --C=40 mF, U0=400 V

6.2 Other studies

For discussion: option to move some of the lower priority tests from TC1 to TC2.

7 REFERENCES

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2. G. Ambrosio et al., “MQXFA Functional Requirements Specification”, US HiLumi Doc 36, July 2017
3. G. Ambrosio et al., Acceptance Criteria Part A: MQXFA Magnet”, US HiLumi Doc 1123, July 2018
4. G. Ambrosio et al., “Guidelines for MQXFA Data Organization”, US HiLumi Doc 1325, July 2018.
5. G. Ambrosio et al., “MQXFA Final Design Report”, US HiLumi Doc 948, July 2018
6. MQXFS1 and MQXFAP1 Test plans in HiLumi DocDB: http://us-hilumi-docdb.fnal.gov/cgi-bin/DocumentDatabase/ Search keyword: TESTPLAN

8 APPENDIX – TEST PLAN VS. MQXFA REQUIREMENTS

8.1 *Tests which directly address MQXFA requirements*

Requirement	Description	Relevant elements of the vertical test (MM are covered separately)
MQXFA-R-T-03	The MQXFA magnet must be capable of operate at steady state providing a central gradient of 143.2 T/m in superfluid helium at 1.9 K.	Training to ultimate and holding test
MQXFA-R-T-05	MQXFA magnets shall be capable of operation in pressurized static superfluid helium (HeII) bath at 1.3 bar and at a temperature of 1.9 K.	Training to ultimate and holding test
MQXFA-R-T-10	The MQXFA magnet shall be capable of surviving a maximum temperature gradient of 100 K, during a controlled warm-up or cool-down, and to experience the thermal dynamics following a quench without degradation in its performance	Magnet cool-down
MQXFA-R-T-11	The MQXFA magnets shall be capable of operating at a ramp rate smaller than ±30 A/s	Ramp to quench (partial)
MQXFA-R-T-12	The MQXFA magnet shall withstand a maximum operating voltage of 670 V to ground during quench.	Quench studies (quench without dump)
MQXFA-R-T-13	MQXFA magnets must be delivered with a (+) Nb-Ti superconducting lead and a (-) Nb-Ti superconducting lead, both rated for 18 kA and stabilized for connection to the cold mass LMQXFA electrical bus.	Training to ultimate and holding test
MQXFA-R-O-04	Splice resistance target is less than 1.0 nΩ at 1.9 K	Splice resistance measurement
MQXFA-R-T-15	Voltage Taps: the MQXFA magnet shall be delivered with three redundant (3x2) quench detection voltage taps located on each magnet lead and at the electrical midpoint of the magnet circuit; and two (2) voltage taps for each internal MQXFA Nb3Sn-NbTi splice. Each voltage tap used for critical quench detection shall have a redundant voltage tap	Quench training (partial)
MQXFA-R-T-16	The MQXFA magnet coils and quench protection heaters shall pass the hi-pot test specified in Table 3 [2] before cold test	Electrical QA (partial)
MQXFA-R-T-17	After a thermal cycle to room temperature, MQXFA magnets shall attain the nominal operating current with no more than 3 quenches	Thermal cycle
MQXFA-R-T-18	MQXFA magnets shall not quench while ramping down at 300 A/s from the nominal operating current.	300 A/s down ramp test
MQXFA-R-O-06	MQXFA magnets should survive at least 50 quenches.	Quench training (partial)

8.2 *MQXFA requirements not directly addressed by vertical test*

Requirement	Description	Relevant elements of the vertical test (MM are covered separately)
MQXFA-R-T-01	The MQXFA coil aperture at room temperature without preload is 149.5 mm. Coil bumpers (pions) shall be installed on coil poles. The minimum free coil aperture at room temperature after coil bumpers installation, magnet assembly and preload shall be 146.1 mm.	N/A
MQXFA-R-T-02	The MQXFA physical outer diameter shall not exceed 614 mm.	N/A
MQXFA-R-O-01	The target for the variation of the local position of magnetic center is ±0.5 mm; the target for the variation of the local position of magnetic axis is ±2 mrad. Local positions are measured with a probe of 500 mm maximum length, and measurements are performed at steps equal to probe length.	N/A
MQXFA-R-T-04	The MQXFA magnet must provide an integrated gradient between 554 T and 560 T when powered with current of 16.470 kA. The difference between the integrated gradient of all series magnets shall be smaller than 0.6%. The MQXFA magnetic length requirement is 4.2 m with a tolerance of ± 5 mm at 1.9 K.	N/A
MQXFA-R-O-02	The MQXFA field harmonics shall be optimized at nominal current. Table 2 provides expected values for field harmonics at a reference radius of 50 mm	N/A
MQXFA-R-O-03	The fringe field target, for the magnet installed in the cryostat, is lower than 50 mT at 10 mm from the outer surface of the cryostat	N/A (planned for horizontal test)
MQXFA-R-T-06	The MQXFA cooling channels shall be capable of accommodating two (2) heat exchanger tubes running along the length of the magnet in the yoke cooling channels. The minimum diameter of the MQXFA yoke cooling channels that will provide an adequate gap around the heat exchanger tubes is 77 mm.	N/A
MQXFA-R-T-07	At least 40% of the coil inner surface shall be free of polyimide	N/A
MQXFA-R-T-08	The MQXFA shall have provisions for the following cooling passages: (1) Free passage through the coil pole and subsequent G-11 alignment key equivalent of 8 mm diameter holes repeated every 50 mm; (2) free helium paths interconnecting the four yoke cooling channels holes; and (3) a free cross sectional area of at least 150 cm2	N/A
MQXFA-R-T-14	Splices are to be soldered with CERN approved materials	N/A
MQXFA-R-T-19	The MQXFA quench protection components shall be compatible with the CERN-supplied quench protection system and comply with the corresponding interface document specified by CERN.	N/A
MQXFA-R-T-20	All MQXFA components must withstand a radiation dose of 35 MGy, or shall be approved by CERN for use in a specific location as shown in MQXFA Materials List [EDMS# 1786261]	N/A
MQXFA-R-T-21	MQXFA magnets will operate in the HL-LHC era for an order of magnitude of 5000 cycles. The long-term reliability of the design will be proven having a short model magnet submitted to 2,000 powering cycles during individual test.	N/A
MQXFA-R-T-22	The MQXFA magnets shall meet the interface specifications with the following systems: (1) other LMQXFA Cold Mass components; (2) the CERN supplied Cryogenic System; (3) the CERN supplied power system; (4) the CERN supplied quench protection system, and (5) the CERN supplied instrumentation system. These interfaces are specified in Interface Control Document [US-HiLumi-doc-375].	N/A
MQXFA-R-T-23	The MQXFA magnets must comply with CERN's Launch Safety Agreement (LSA) for IR Magnets (WP3) [EDMS#1550065]	N/A