US HL-LHC Accelerator Upgrade Project

TEST PLAN
MQXFA04 PRE-SERIES QUADRUPOLE

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Revision History

Revision	Date	Section No.	Revision Description
V1	10/23/2019	All	Initial Release
V2	10/30/2019	1, 2.2.8	Magnetic Measurement up to 10 kA were added before the quench test

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1 OVERVIEW

In this chapter the abbreviated version of the run plan is outlined, focused on the high level steps that need to be performed while only detailing out some of those parameters that usually need discussions. For executing the tests, Chapter 2 (Run Plan) needs to be followed during testing since it refers to the procedures and general documents (found in the Appendix and References) that guide and add further detailed information for correctly executing the tests. MQXFA04 magnet Background, Magnet and System parameters, Instrumentation, and Procedural Notes can be found in the Appendix. Test Cycle start time is when the magnet is connected to the top plate and placed into the dewar. There are magnet inspection tests after the magnet is received from LBNL and prior to connecting it to the top plate.

Magnet inspection after receiving from LBNL

1. Mechanical condition inspection including accelerometer readings
2. Electrical checkout of the instrumentation – magnet is on its shipping fixture on horizontal electrical checkout test stand
    a. Continuity and resistance measurements of the instrumentation (voltage taps, strain gauges, acoustic sensor, and quench protection heaters).
    b. High voltage withstand tests (warm air values can be applied – coils have not seen He yet)
        i. Coil to ground **3680 V**
        ii. Quench heaters to coil **3680 V**
        iii. Quench heaters to ground **3680 V.**
    c. Set up HBM strain gauge system
        i. Input HBM gauge information into Catman program.
        ii. Connect mobile strain gauge harness to HBM DAQ units.
        iii. Take strain reads while magnet is horizontal and before up-righting.

Test Cycle I

1. Preliminary Room Temperature Electrical Checkout and Initial Setup – Magnet attached to test fixture
    a. Resistance measurements of coils, heaters, strain gauges, acoustic sensor, and temperature sensors.
    b. Voltage tap continuity and voltage drop tests.
    c. High voltage withstand tests (warm He gas can be present)
        i. Coil to ground **368 V**
        ii. Quench heaters to coil **460 V**
        iii. Quench heaters to ground **460 V.**
    d. Quench Protection Heater (strip heater) HFU initial setup.
    e. Strain gauge reading initial setup – HBM strain gauges at 1 kHz.
    f. Verification tests of fast and slow data loggers.
    g. Verification of insulating vacuum and N_2 gas flow.
    h. Perform magnetic measurements z-scan at room temperature
    i. Perform gravity sensor z-scan at room temperature
2. Cooldown and Magnetic Field Measurements
    a. During cool down maintain gradient of 50 K or less between the magnet ends.

   b. From the start of fill the initial 70 K drop needs to be a slow process; it should take at least 3 hours.
   c. Perform z-scan during cool down
3. Preliminary Electrical Checkout at 4.5 K (or less)
   a. Perform resistance measurements of coils, heaters, strain gauges, acoustic sensor, temperature sensors, and voltage taps.
   b. AC measurements of voltage segments.
   c. High voltage withstand tests
      i. Coil to ground **1840 V**
      ii. Quench heaters to coil **2300 V**
      iii. Quench heaters to ground **2300 V**
   d. Verify all instrumentation signals.
4. Setup for Testing at 4.5 K (or less)
   a. Make all the electrical connections (main leads, CLIQ, HFU) and verify them
   b. Balance the I-dot quench detection circuit and configure quench detection system
   c. Set HFU and CLIQ capacitance and voltage values
   d. Verify that acoustic detection system is properly configured.
   e. Set power supply parameters
   f. Set proper gas flow rates for the leads (main and CLIQ)
   g. Install Quench Antenna
5. Quench Protection System tests at 4.5 K (or less)
   a. Power supply shutoffs at 1000 A and 2000 A.
   b. Quench Protection Heater validation tests at 2000 A and 6000 A.
   c. Preliminary test of the CLIQ system.
6. Spontaneous Quench Test Program at 1.9 K
   a. Setup:
      i. Fast (100 kHz) and slow (1 Hz) data loggers.
      ii. HFU voltages (600 V max) and capacitance values, 0 delay.
      iii. CLIQ 40 mF, 500 V, 0 delay.
      iv. Energy extraction R=37.5 mΩ and 10 ms delay.
      v. HBM strain gauge at 50 Hz.
      vi. Acoustic system set up to run during ramps.
   b. Magnetic measurements up to 10 kA.
   c. Gravity sensor measurements to 10 kA.
   d. Ramp to I_{nom} + 200 A = 16670 A with 20 A/s ramp rate and with 0.9 A/s^2 acceleration and deceleration rate
      i. If quench occurred, repeat the current ramp.
      ii. If no quench occurred, hold the current for 30 min then ramp down with 20 A/s and with 0.9 A/s^2 acceleration and deceleration rate.
   e. Ramp to I_{nom} = 16470 A with 30 A/s, 0.9 A/s^2 , then ramp down to 0 A with 100 A/s, 0.9 A/s^2
7. Holding Current test at 1.9 K
   a. Ramp to I_{nom} + 100 A = 16570 A with 20 A/s, 0.9 A/s^2
   b. Hold the current for 300 min.
8. Magnetic field measurements.
9. Gravity sensor measurements.
10. Splice resistance measurements at 1.9 K.
11. Quench Current Temperature Dependence Study
   a. Perform current ramp to I = 16470 A, at 4.5 K, 20 A/s, 0.9 A/s^2
   b. Hold the current for 30 min then ramp down, 20 A/s, 0.9 A/s^2

12. Warmup to room temperature
    a. Before warmup starts, set up RRR measurements to record all available voltage segments' signals.
    b. During warmup, maintain gradient of 50 K or less between the magnet ends.

Room Temperature magnetic field z-scan should be executed between 250 K – 300 K.

Test Cycle II

1. Cooldown
    a. During cool down maintain gradient of 50 K or less between the magnet ends.
    b. From the start of fill the initial 70 K drop need to be a slow process it should take at least 3 hours.
2. Preliminary Electrical Checkout at 4.5 K (or less)
    a. Perform resistance measurements of coils, heaters, strain gauges, temp sensors, acoustic sensor, and voltage taps.
    b. AC measurements of voltage segments.
    c. High voltage withstand tests
        i. Coil to ground **1840 V**
        ii. Quench heaters to coil **2300 V**
        iii. Quench heaters to ground **2300 V.**
    d. Verify all instrumentation signals.
3. Setup for Testing at 4.5 K (or less)
    a. Verify all electrical connections (main leads, CLIQ, HFU).
    b. Balance the I-dot quench detection circuit and configure quench detection system.
    c. Set HFU and CLIQ capacitance and voltage values.
    d. Verify that acoustic detection system is properly configured.
    e. Set power supply parameters.
    f. Set proper gas flow rates for the leads (main and CLIQ).
    g. Install Quench Antenna.
4. Quench Protection System verification at 4.5 K (or less)
    a. Power supply shutoff at 2000 A.
    b. Quench Protection Heater validation tests at 6000 A.
    c. Preliminary test of the CLIQ system.
5. Spontaneous Quench Test Program at 1.9 K
    a. Setup:
        i. Fast (100 kHz) and slow (1 Hz) data loggers.
        ii. HFU voltages (600 V max) and capacitance values, 0 delay.
        iii. CLIQ 40 mF, 500 V, 0 delay.
        iv. Energy extraction R=37.5 mΩ and 10 ms delay.
        v. HBM strain gauge at 50 Hz.
        vi. Acoustic system set up to run during ramps.
    b. Ramp to I_{nom} + 200 A = 16670 A with 20 A/sec ramp rate and with 0.9 A/s^2 acceleration and deceleration rate
        i. If quench occurred, repeat the current ramp.
        ii. If no quench occurred, hold the current for 30 min then ramp down with 20 A/s and with 0.9 A/s^2 acceleration and deceleration rate.
    c. Ramp to I_{nom} = 16470 A with 30 A/s, 0.9 A/s^2 , then ramp down to 0 A with 100 A/s, 0.9 A/s^2
6. Holding Current Test at 1.9 K
    a. Ramp to I_{nom} + 100 A = 16570 A with 20 A/s, 0.9 A/s^2 .

    b. Hold the current for 300 min.
7. Final warmup to room temperature
    a. Before warmup starts, set up RRR measurements to record all available voltage segments' signals.
    b. During warm up, maintain gradient of 50 K or less between the magnet ends.
    c. At 100 K, perform HV withstand measurements
        i. Quench protection heaters to coil **425 V.**

Room Temperature magnetic field and gravity sensor z-scans should be executed between 250 K – 300 K.

2 Run plan

2.1 Magnet Inspection after Receiving from LBNL

Magnet incoming inspection after receiving from LBNL:

1. Mechanical condition inspection including accelerometer readings.
2. Move the magnet in its shipping fixture to the horizontal stand before start of electrical checkout.
3. Electrical checkout of the instrumentation:
    a. Continuity and resistance measurements of the instrumentation (strain gauges, acoustic sensor, and quench protection heaters).
    b. Voltage tap voltage drop tests (series resistances).
    c. Voltage tap voltage drop tests (point-to-point resistances).
    d. High voltage withstand tests (warm air values can be applied – coils have not seen He yet). See Section 3.2.4 High Voltage Withstand Testing (Hipot) for required equipment and settings.
        i. Coil to shell, which is grounded **3680 V**
        ii. Quench heaters to coil **3680 V**
        iii. Quench heaters to shell, which is grounded **3680 V**
    e. Set up HBM strain gauge system
        i. Input HBM gauge information into Catman program.
        ii. Connect mobile strain gauge harness to HBM DAQ units.
        iii. Take strain reads while magnet is horizontal and before up-righting.

For more details, see the traveler documents *AUP-300 MQXFA Testing – Preparation for Cold Test* and *SMD-AUP-4001 Procedure, Room Temperature Electrical Checks of AUP MQXFA Quadrupole Magnets*.

2.2 Test Cycle I

2.2.1 Preliminary Room Temperature Electrical Checkout with Magnet Attached to Test Fixture - in Wiring Stand or in Test Dewar #2

Steps 1-6 should be done with the magnet attached to the test fixture while still in the wiring stand.

1. Record the appropriate hanging distances below the top plate in order to determine the correct location for the LHe levels and the quench antenna. Verify that the level probes are 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, acoustic sensor leads, and the strip gauge leads.
3. Check resistances to ground for the power leads and the strip heaters and to each other.
4. Hipot tests at room temperature (with Test Dewar #2 opened to air). See Hipot Parameter table in the Appendix: Section 3.2.4 High Voltage Withstand Testing (Hipot).

   Perform HV withstand test using the procedure described in the Appendix: Section 3.2.4 High Voltage Withstand Testing (Hipot) for required equipment and settings.

   368 V hipot of coil to test structure, which is grounded.

   460 V hipot of each strip heater circuit to test structure, which is grounded, and to coil with all other systems grounded.

   Maximum target leakage current is 10 μA over 30 s.
5. 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.
6. Point-to-point (voltage tap pairs) resistance measurement at 1 A of all taps in order from positive lead to negative lead. Do a four-wire measurement with 1 A.

Steps 7-15 should be done after placing the magnet with test fixture into Test Dewar #2

7. Attach all cable connectors from DAQ wiring racks to top hat connector trees. Verify that all top hat connectors are properly hooked up: all rack cable connector labels should match with all top hat connector labels.
8. Strip heater HFU's should be connected to the strip heaters but set at 20 V.
   8 strip heater circuits will each have an independent HFU and should be configured as follows:
   a. Outer heaters of Coils 203 and 113 (adjacent): follow the alternative configuration, connecting together strips from adjacent coils (HF with HF, LF with LF).
   b. Outer heaters of Coil 206 and Coil 112 (adjacent): follow the alternative configuration, connecting together strips from adjacent coils (HF with HF, LF with LF).

   See the quench heater connection diagram in the Appendix. This shows how the strips are connected to each other and to the Hypertronics connector at the lead end of the magnet structure. See also the HFU – heater circuit connection table in the Appendix.
9. Perform 1 A and 10 A level shift tests 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 all HFUs set at 20-30 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 that the HBM strain gauge system is in excitation mode and reading properly at room temperature. Set the HBM strain gauge sampling rate to 1 Hz (24 HR INTERVAL program). **NOTE: THESE STRAIN GAUGE SETTINGS SHOULD ALWAYS BE USED FOR STRAIN**

GAUGE READS RUNNING IN THE BACKGROUND WHEN NOT RAMPING THE MAGNET. The proper settings for current ramps are different and are given in the procedures below for PS shutoffs, strip heater quenches, spontaneous quenches, and ramps to target currents.

12. Verify proper values of insulating vacuums for both Cryostats 2 and 3 and the warm bore tube.
13. Verify proper operation of the N_2 gas flow and fans for the main and CLIQ copper leads.
14. Introduce N_2 gas into warm bore tube to prevent freezing.
15. Install the transporter assembly and measuring coil.

2.2.2 Magnetic Field and Gravity Sensor Measurements at Room Temperature

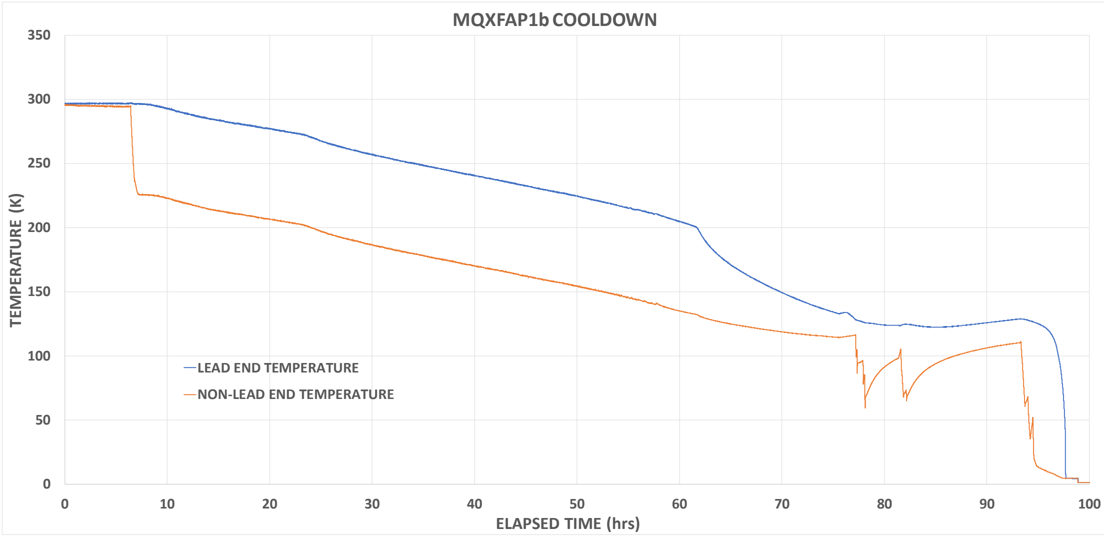
Purpose: To measure geometric harmonics at room temperature. And to measure deflection from vertical with gravity sensors at room temperature.

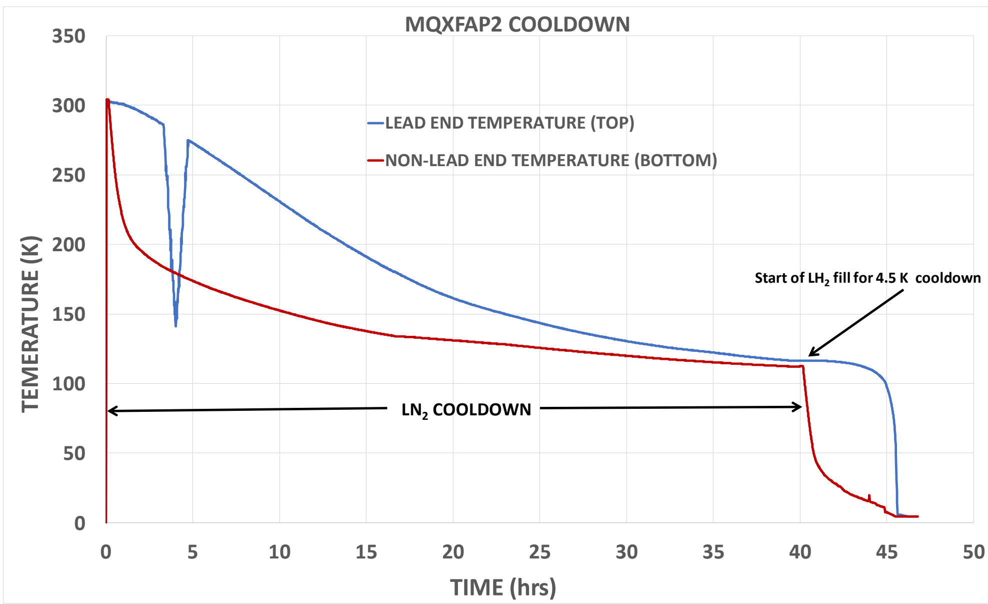
NOTE: Two windings are included on the PCB in the field measuring probe, one with nominal 110 mm length, and the second with nominal 220 mm length. Considering the detailed design of the PCB, the actual magnetic length is 108.74 mm for the 110 mm circuit, and 217.88 mm for the 220 mm circuit. Therefore, assuming the probe is moved by half of the relevant magnetic length at each step of the z-scan, the required step is 54.37 mm for the circuit #1 (110 mm) scan; and 108.94 mm for the circuit #2 (220 mm) scan. For more details there is a separate document for magnetic field measurement procedures [6].

1. Install the transporter assembly and measuring coil after the magnet has been inserted into Test Dewar #2.
2. Perform z-scan at ±15 A. Use the required step and locations for the 220 mm winding.
3. Raise probe and connect gravity sensor instrumentation and perform gravity sensor z-scan.
4. When the cryogenics system is ready for magnet cooldown, stop operation of the magnetic field measuring system.

2.2.3 Cooldown and Magnetic Field Measurements

1. Inform the cryogenics operator to start a pre-cooldown to 100 K with liquid N_2 heat exchanger.
   Maintain a gradient of 50 K or less between the magnet ends during cooldown.
2. When the temperature is about 100 K, start the LHe bottom fill for cooldown to 4.5 K. Cooldown to 1.9 K can be performed as well if the schedule benefits.
   Note: The plots below show the cooldown of the previous magnets MQXFAP2 and MQXFAP1b. From start of LHe fill the bottom temperature initially dropped 70 K in first hour, total time to 4.5 K being about 5 hours. For the cooldown of MQXFA04, we will also slow down the initial 70 K drop from 1 hour to 3 or more hours in order to maintain a gradient of 50 K or less during LHe fill .





3. During cooldown, slow logger sampling interval should be 10 min. HBM strain gauge sampling rate should be 1 Hz (24 HR INTERVAL program).
4. Perform z-scans during cooldown as a function of temperature using the following maximum current values depending on the temperature range:

Maximum Allowed Current for Different Temperature Ranges During Cooldown or Warmup.

Temp. (K)	Current (A)
200 – 295	± 15
100 – 200	± 20
< 100	± 30

2.2.4 Preliminary Electrical Checkout at 4.5K (or less) in Test Dewar #2

NOTE: The initial cold electrical checkout (except for hipots) can actually be done when the magnet temperature is less than 20K (at both ends) if this benefits the test schedule. Main and CLIQ leads should initially not be connected to their power supplies. Strip heaters also 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 strip heater quench tests can be done only when the magnet has cooled to least 4.5 K or less and the magnet is in LHe near bottom of copper leads (at least 9" on LHe level probes below the lambda plate).**

1. Check resistances to ground for the main and CLIQ 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 60 Hz AC series measurements of coils 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 (or less) and in liquid He**).
   Perform hipot tests using the procedure described in the Appendix:
   Section 3.2.4 High Voltage Withstand Testing (Hipot) for required equipment, target high voltage values, and settings. The target high voltage values at cold are as follows:
      1840 V hipot of coil to test structure, which is grounded.
      2300 V hipot of each strip heater circuit to test structure, which is grounded, and to coil with all other systems grounded.
   Maximum target leakage current is 10 μA over 30 s.
7. 5A level shift test (to be done only if there was an unusual result in the room temperature checkout in Part 2.2.1.9). Set the fast data loggers to 1 kHz. Strip heater HFU's should be connected to the strip heaters but set at minimum voltage (20-30 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.

2.2.5 Setup for Testing at 4.5 K (or less) in Test Dewar #2

NOTE: The magnet must be at 4.5 K (or less) in liquid He, NOT gas. Power supply shutoffs and strip heater quench tests can be done only when the magnet has cooled to 4.5 K or less and the magnet is in LHe near bottom of copper leads (at least 9" on LHe level probes below the lambda plate).

1. Connect main leads to the power supply.

. 2. Connect CLIQ magnet leads to the CLIQ power supply.

3. Strip heater HFU's should be connected to the strip heater circuits but set only at 20-30 V.

3. Balance the I-dot quench detector for a ramp rate of 20 A/s and known magnet inductance.

4. Configure quench detection system.

Nominal voltage thresholds and validation times for the quench detectors:

Detector	Threshold	Validation Time
Delta QDC	Variable (I < 8 kA)	Variable (I < 8 kA)
	150 mV (I ≥ 8 kA)	4 ms (I ≥ 8 kA)
I-dot QDC	Variable (I < 8 kA)	Variable (I < 8 kA)
	1.9 V (I ≥ 8 kA)	4 ms (I ≥ 8 kA)
Superconducting leads	50 mV	4 ms
Gas-cooled leads	80 – 100 mV	4 ms

NOTE: The above are nominal values based on the previous testing of MQXFAP1, P2, and P1b. The values of threshold voltages and/or validation times for currents below 8 kA will depend on the observed spike activity due to flux jumps and/or mechanical motion. Validation times may be varied up to 20 ms if necessary and will depend on the current. As a worst case, at 8 kA, each 1 ms of added delay will add 0.064 MIIts to the quench integral, so this will be taken into account in order to adhere to the maximum allowed quench integral/hot spot temperature, which is estimated to be 27 MIIts/250 K. (See Section 3.2.3 in Appendix.)

Minimum time delay settings for quench detectors and quench protection:

Detector	Delay
Delta QDC	0 ms
I-dot QDC	0 ms
Strip Heaters	0 ms
Dump resistor switch	10 ms
CLIQ	0 ms
Power supply shutoff	0 ms

5. Verify that each HFU capacitance is at nominal default values (12.4 mF units 1 – 8 and 13.05 mF units 9 - 12.) Note that units 9 – 12 have 900 V capacity, but no unit may be charged to more than 600 V for any test. Nominal voltages for all strips has been 465 V.
6. HFU's should be connected to the strip heaters but set at 20 V.
7. Verify that the 8 strip heater circuits are configured as follows:
   Each strip heater circuit will have an independent HFU's and should be configured as follows:
   a. Outer heaters of Coils 203 and 113 (adjacent): follow the alternative configuration, connecting together strips from adjacent coils (HF with HF, LF with LF).
   b. Outer heaters of Coil 206 and Coil 112 (adjacent): follow the alternative configuration, connecting together strips from adjacent coils (HF with HF, LF with LF).
8. Verify that CLIQ leads and parallel diode string have been properly connected.
9. Set the power supply input impedances over the current range to inductance values measured during previous test of MQXFAP2. The starting (1 kA) and ending (≥ 16.480 kA) inductances are L = 43.0 mH and L = 34.4 mH, respectively.
10. Set the roll-off parameter for start and end of all ramps to correspond to the requested acceleration and deceleration of 0.9 A/s^2 to **α = 0.3076**.
11. Set proper flow rates for the main and CLIQ 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 2.2.1.1, corrected for magnet contracted length when at 1.9 K, to properly position the antenna. Center of antenna should be at center of magnet coil. Verify correct vertical height and correct orientation with respect to magnet top.
    NOTE: Never leave the quench antenna in the warm bore tube overnight. At the end of the day's testing, remove the quench antenna and store it in the quench antenna storage stand.
13. Verify that the acoustic system is properly connected to its scope and computer which runs

the DAQ and control program.

2.2.6 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 **37.5 mΩ** for this test. **CLIQ turned off.**
2. Initially, set quench detection thresholds and validation times to follow the current-dependent scheme given in the following table:

CURRENT RANGE [A]	**VOLTAGE THRESHOLD (mV)**	**VALIDATION TIME (ms)**
0 – 400	**600**	**4**
400 – 1500	**1500**	**4**
1500 – 3000	**1800**	**8**
3000 – 4000	**1500**	**4**
4000 – 5000	**1500**	**4**
5000 – 6000	**800**	**4**
6000 – 8000	**500**	**4**
8000 - 22000	**150**	**4**

3. Set fast logger sampling rate to 10 kHz.
4. Set strip heater delay to 0 ms and energy extraction delay to 10 ms.
5. Set HFUs to minimum voltage (about 20 V) 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. Set the HBM strain gauge system to run at the 50 Hz sampling rate (TRIGGER program).
9. Ramp magnet at 20 A/s to 500 A. Measure inductance at 20 A/s. Check lead voltages for stability.
10. Ramp magnet at 20 A/s to 1000 A. Measure inductance at 20 A/s. Check lead voltages for stability.
11. Manually trip the delta (voltage difference) quench detector circuit.
12. Verify fast data logger acquisition of all voltage tap pair voltages and other signals. Check all signals for anomalies and proper behavior before proceeding.
13. Verify that the voltage signals are consistent with the 37.5 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 **37.5 mΩ** for this test. **CLIQ turned off.**

1. Set fast logger sampling rate to 10 kHz.
2. Set strip heater delay to 0 ms and energy extraction delay to 10 ms.
3. Set HFUs to 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. Set the HBM strain gauge system to run at the 50 Hz sampling rate (TRIGGER program).
7. Ramp magnet at 20 A/s to 1500 A. Measure inductance at 20 A/s. Check lead voltages for stability.
8. Ramp magnet at 20 A/s to 2000 A. Measure inductance at 20 A/s. Check lead voltages for stability.
9. Manually trip the delta (voltage difference) quench detector circuit.
10. Verify fast data logger acquisition of all voltage tap pair voltages and other signals. Check all signals for anomalies and proper behavior before proceeding. and check for any indications of degradation of the electrical insulation.
11. Verify that the voltage signals are consistent with the 37.5 mΩ dump resistance.

2.2.7 Quench Protection Heater (Strip Heater) Tests at 4.5 K (or less) and 37.5 mΩ

Quench detector threshold at 150 mV and validation time at 4 ms at high current (above 8000 A). Voltage thresholds and validation times for the entire regime of currents during the ramp are given in the table below:

CURRENT RANGE [A]	**VOLTAGE THRESHOLD (mV)**	**VALIDATION TIME (ms)**
0 – 400	**600**	**4**
400 – 1500	**1500**	**4**
1500 – 3000	**1800**	**8**
3000 – 4000	**1500**	**4**
4000 – 5000	**1500**	**4**
5000 – 6000	**800**	**4**
6000 – 8000	**500**	**4**
8000 - 22000	**150**	**4**

1. Quench protection heater quenches at 2000 A:

Purpose: to check strip heater performance at 2000 A.

NOTE: **EE dump resistance should be set to 37.5 mΩ for this test. CLIQ turned off.**

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 strip heater HFU capacitance is set at nominal value of 12.4 mF for all HFUs.
4. Set strip heater HFU's to 465 V for the outer layer high field HFU and 465 V for outer layer low field HFU.
5. Set strip heater delay to 0 ms and energy extraction delay to 10 ms.
6. Verify proper lead flow operation.
7. Set the HBM strain gauge system to run at the 50 Hz sampling rate (TRIGGER program).
8. Ramp magnet to 2000 A at 20A/s. Check lead voltages for stability.
9. Set OL-HF strip circuits to quench the magnet. Set the remaining heater circuits for protection (i.e., to fire only when quench detected).
10. Manually fire the OL-HF HFUs to induce a quench.
11. Examine all quench signals for proper behavior. Check for any indications of degradation of the electrical insulation.
12. Verify delay, validation times, and threshold settings.
13. Verify that the pole multiturn blocks quench <500 ms after heater firing. Check heater current and voltage waveforms.
14. Calculate the MIIts value for this quench and verify that it is consistent at this low quench

current with the maximum safe value corresponding to 250 K (32 MIIts) for this magnet's conductor.
15. If the criteria in (13) is not satisfied, increase HFU voltages and repeat steps (5) - (14).
16. Repeat above with OL-LF strip circuits set to quench and the rest for protection.
Note the following change for OL-LF heater quenches:
Verify that the midplane multiturn blocks quench <500 ms after heaters fire.

2. Quench protection heater quenches at 6000 A:

Purpose: to check strip heater performance at 6000 A.

NOTE: **EE dump resistance should be set to 37.5 mΩ for this test. CLIQ turned off.**
Total voltage threshold should be lowered to 1100 mV for the 6000 A heater quenches.

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 strip heater HFU capacitance is set at nominal value of 12.4 mF for all HFUs.
4. Set strip heater HFU voltages to the value determined in the 2000 A strip heater quench.
5. Set strip heater delay to 0 ms and energy extraction delay to 10 ms.
6. Set the HBM strain gauge system to run at the 50 Hz sampling rate (TRIGGER program).
7. Verify proper lead flow operation.
8. Ramp magnet to 6000 A at 20 A/s. Check lead voltages for stability.
9. Set OL-HF strip circuits to quench the magnet. Set the remaining heater circuits for protection (i.e., to fire only when quench detected).
10. Manually fire the OL-HF HFU's to induce a quench.
11. Examine all quench signals for proper behavior. Check for any indications of degradation of the electrical insulation.
12. Verify delay, validation times, and threshold settings.
13. Verify that the pole multiturn blocks quench <100 ms after heater firing. Check heater current and voltage waveforms.
14. Calculate the MIIts value for this quench and verify that it is consistent at this low quench current with the maximum safe value corresponding to 250 K (32 MIIts) for this magnet's conductor.
15. If the criteria in (13) is not satisfied, increase HFU voltages and repeat steps (5) - (14). Ramp to 6000 A without stopping.
16. Repeat above with OL-LF strip circuits set to quench and the rest for protection.
Note the following changes for OL-LF heater quenches:
For the OL-LF 6000 V quench, validation time should be increased to 8 ms.
Verify that the midplane multiturn blocks quench <100 ms after heaters fire.

2.2.8 Preliminary Test of CLIQ system

Purpose: To verify settings of CLIQ parameters and proper CLIQ output signals before use of CLIQ during the 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, fire CLIQ unit by using QD manual trip.
5. Analyze magnet current and voltage, and current through CLIQ diodes, and CLIQ voltage signals and verify that these are nominal.
6. With 1000 A in magnet, fire CLIQ unit by using QD manual trip.

7. Analyze magnet current and voltage, and 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.

2.2.9 Spontaneous Quench Test Program at 1.9 K

Purpose: To train the magnet up to the **nominal operating current plus 200 A (16670 A)**. 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 have been 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 quench training. Quench detector threshold and validation time should be set according to value of current during ramp. Voltage thresholds and validation times for the entire regime of currents during the ramp are varied as a function of current (See table above in Section 2.2.6 for starting values). Using those values, at high current (above 8000 A), QD threshold and validation time will be 150 mV and 4 ms, respectively.

1. Set fast data logger sampling rate to 100 kHz (0.01 ms sampling interval).
2. Set slow data logger sampling rate to 1 Hz (1 s interval) during the test.
3. Verify that strip heater HFU capacitance is set at nominal value of 12.4 mF for all HFU's
4. Verify that the strip heater HFU voltages are set to the value determined previously 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 delay to 10 ms.
8. Set the HBM strain gauge system to run at the 50 Hz sampling rate (TRIGGER program).
9. Verify proper lead flow operation.
10. Ramp magnet to 600 A and hold for about 60 s to check critical parameters, including the following:
    a) power supply parameters – input and output cooling water temperatures, 15 kA and 24 kA water-cooled bus temperatures, IGBT temperatures, IGBT collector-emitter voltages, IGBT collector currents (all IGBT currents must be within 15% of the mean for all 12), SCR temperature, copper bus temperature, flows through IGBTs, diodes, and chokes; power supply AC and DC currents, and power supply ground currents;
    b) magnet and cryogenics parameters – top and bottom magnet temperatures, gas-cooled lead voltages, LHe level, superconducting leads.

    As the ramp is progressing, these parameters should continue to be closely monitored on the monitor screens.

    Main status alarms have been set for the following six parameters: power supply ground current fault, gas-cooled voltage fault, LHe level fault, IGBT fault, CLIQ fault, CLIQ uncharged fault.
11. Start acoustic system program. Stop program when quench occurs or ramp is done.
12. Ramp magnet to 10000 A at 20 A/s and use 0.9 A/s^2 acceleration/deceleration parameter (**α = 0.3076**) for roll-off at start and end of ramp.
    a. If a quench occurs follow steps 14 – 17 below. Note that ramp is to 10000 A in step 15. Then repeat this step (12).
    b. If no quench occurs ramp down at 20 A/s with 0.9 A/s acceleration and deceleration.
    c. Remove the quench antenna and install the tower and magnetic measurement system.

NOTE: The order of performing GS and MM tests can be varied depending on convenience and schedule. It is OK to be flexible with these to make sure there are no inconsistencies or conflicts.

d. Perform the following magnetic field measurements:
   1. Current ramp at center position to 10 kA ('stair-step' style)
   2. Z-scans at 2 different currents 1, 10 kA
      220mm probe, 440mm z increment (~9 positions: 0, +/- 440, 880, 1320, 1760mm)

e. Turn off power supply, raise MM probe and connect the gravity sensor to DAQ cable. Lower probe back into warm bore tube.
   Turn back on the power supply.

f. Perform the following gravity sensor measurements:
   1. Current ramp at center position to 10 kA ('stair-step' style)
   2. Z-scans at 2 different currents 1, 10 kA

g. After gravity sensor measurements are finished, remove the measuring system and tower.

h. Insert the quench antenna into the warm bore tube and continue with Step 13.

13. Ramp magnet to I_{nom} + 200 A = 16.670 A at 20 A/s and use 0.9 A/s^2 acceleration/deceleration parameter (**α = 0.3076)** for roll-off at start and end of ramp.
    a. If a quench occurs follow steps 13 – 16 following.
    b. If no quench occurs, then hold at 16.670 A for 30 min and ramp down at 20 A/s with 0.9 A/s acceleration and deceleration. Then skip down to Step 17.
14. Perform full analysis of quench signals, in particular to ensure the proper operation of the protection system, and check for any indications of degradation of the electrical insulation. Check carefully the ground current signal for any deviation from nominal and for any unexpected anomalies.
    Calculate quench integral in MIIts to verify that the safe temperature limit of 250 K (32 MIIts) is satisfied.
    Discuss and confirm any changes required before the next quench.
15. Repeat quench tests at 20 A/s until quench current reaches at least 16670 A or training has become slow, erratic, or stalled (e.g. more than 5 quenches without an increase in the maximum current). All training ramps will be stopped at 600 A for about 60 s to check power supply, magnet, and cryogenics parameters, as in (10).
16. For each quench, analyze quench data to determine the nature and causes of the training behavior. Determine quench location. Calculate the quench integral in MIIts to verify that the safe temperature limit of 250 K (32 MIIts) is satisfied. Check quench heater signals (current, voltage, and ground current) to verify that there was no degradation.
17. Between quenches the HBM strain gauge sampling rate can be set back to 1 Hz (INTERVAL program).
    NOTE: The HBM strain gauge system should always be set back to 50 Hz sampling rate (TRIGGER program prior to each current ramp.
18. When training to 16.670 A is finished, perform the following ramp:
    Set total voltage threshold to 2100 mV.
    Ramp the magnet to I_{nom} = 16.470 A at 30 A/s with 0.9 A/s acceleration and deceleration (**α = 0.3076**).
    Hold for 5 min.
    Set total voltage threshold to 4500 mV.
    Ramp the magnet down to 0 A at 100 A/s with 0.9 A/s acceleration and deceleration. (**α = 0.3076**).

2.2.10 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 2.2.8.
2. Ramp magnet at 20 A/s to nominal current + 100 A (**16.570** kA) and hold for 300 minutes.
3. Monitor the status of all slow logger signals to verify nominal values.

2.2.11 Magnetic Field Measurements with Rotating Coil Probe at 1.9 K

Purpose: To measure magnetic field harmonics, field angle, and integral field as a function of magnet axial location (z-scans), magnet current (I-scan, or DC Loop), and ramp rate.
NOTE: The order of performing GS and MM tests can be varied depending on convenience and schedule. It is OK to be flexible with these to make sure there are no inconsistencies or conflicts.

The magnetic measurement plan includes accelerator cycles, z-scans, DC loops (stair-step), and ramp rate dependence cycles. Magnetic measurements have different requirements from other tests; for example, they are not expected to generate quenches, and they require allocation of a continuous time window of several hours. Therefore, the magnetic field measurement schedule may be adjusted depending on system and resource availability to optimize the overall test schedule. The measurement goals, conditions, and detailed procedures are described in a separate document [6].

1. Remove the quench antenna.
2. Install the magnetic field measurement system tower, transporter, and rotating coil probe.
3. Verify all test parameters are the same as for the quench tests in Part 2.2.9.
4. Perform combined z-scan, accelerator cycle, and ramp rate dependence measurements at I_{nom} (16470 A). See detailed procedure in [6].
5. Perform DC Loop (stair-step measurements) to I_{max} (16670 A) with measurements to I_{nom} (16470 A). See detailed procedure in [6].
6. Perform special z-scan at I_{nom} (16470 A). See detailed procedure in [6].

2.2.12 Gravity Sensor Measurements at 1.9 K

Purpose: To measure changes in angle from vertical of the magnetic field probe (not rotating) as a function of magnet axial position and magnet current to determine evidence of bending or bowing of warm bore tube and/or magnet or magnet motion.
NOTE: The order of performing GS and MM tests can be varied depending on convenience and schedule. It is OK to be flexible with these to make sure there are no inconsistencies or conflicts.

1. Verify all test parameters are the same as for the quench tests in Part 2.2.9.
2. Raise probe, connect gravity sensor instrumentation, and lower probe back.
3. Perform gravity sensor z-scan at 16.470 kA.

4. Perform gravity sensor DC Loop (I-scan) to 16.470 kA.

2.2.13 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. Remove magnetic measurement transporter system and probe.
2. Install quench antenna and verify it is a proper vertical height and orientation.
3. Verify all test parameters are the same as for the quench tests in Part 2.2.9.
4. A precision of 0.1 nΩ is needed for this test, such as with an Agilent 3854 digital multimeter.
5. For splice measurements, dedicated stair step measurements (during up and down ramps) will be taken with a dedicated DVM, such as Agilent 3854 digital multimeter, that uses at least 20-line cycles to take data points. At each stair step, multiple data points should be taken. Signals should be taken directly from the connector tree to minimize noise picked up by the cables.

2.2.14 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 2.2.9.
2. Set the test dewar temperature to 4.5 K.
3. At 4.5 K, perform current ramp to I = 16470 A at 20 A/s, 0.9 A/s^2 (**α = 0.3076**).
4. Hold the current for 30 min then ramp down at 20 A/s, 0.9 A/s^2 (**α = 0.3076**).

2.2.15 Magnet Warmup to Room Temperature and RRR Measurement

1. Set the slow data logger sampling interval to 1 s until the temperature is above 30 K. Then increase the sampling interval to 10 min.
2. Set the HBM strain gauge system to run at the 1 Hz sampling rate (INTERVAL program).
3. Start warmup of the magnet to room temperature. Warmup should be slow to minimize the temperature gradient between the magnet ends. Stable resistance measurement at 20 K is most important, since this is needed to calculate RRR. Up to that temperature, the warmup should be as uniform as possible to achieve a stable temperature of slightly above 20 K. After RRR measurements are done, a gradient of ≤ 50 K should be maintained.
4. The current source for RRR measurements should be a bipolar power supply that changes polarity ±10 A with a period of 30 s in order minimize thermal emf effects. Apply this current across the main leads prior to the magnet reaching 20 K.
5. When temperature reaches about 20 K and resistances become non-zero, trigger fast data logger to capture resistance values for all tap segments.
6. During the warmup, hold the magnet temperature at slightly above 20 K for at least 30 min with the bipolar supply on while making RRR resistance measurements.
7. Slow data logger and strain gauge data acquisition should be running until the magnet reaches a stable room temperature.
8. When magnet reaches stable room temperature, repeat step 4 to measure room temperature

resistances with the same procedure as was done to measure resistances at slightly above 20 K.

9. **Except for special circumstances where inspection of the magnet or additional work in the wiring stand is necessary, the magnet should remain sealed in He gas in Test Dewar #2.**

2.3 Test Cycle II

2.3.1 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 and the quench antenna. Verify that the level probes are at proper locations before installation in Test Dewar #2. NOTE: This step is only necessary if the magnet was removed from the Test Dewar after warmup and work was done on the wiring stand.

NOTE: In general, it is expected that the magnet will remain sealed in Test Dewar #2 in He gas during the thermal cycle.

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, acoustic sensor leads, and the strain gauge leads.
3. Check resistances to ground for the power leads and the strip heaters and to each other.
4. Hipot tests at room temperature (only if magnet is out of Test Dewar and opened to air). **Do not perform hipots if the magnet is sealed in the Test Dewar in He gas.**

   If performing hipot tests, use the procedure described in the Appendix: *Section 3.2.4 High Voltage Withstand Testing (Hipot)* for required equipment, voltage target values, and settings. The target high voltage values are as follows:

   368 V hipot of coil to test structure, which is grounded.

   460 V hipot of each strip heater circuit to test structure, which is grounded, and to coil with all other systems grounded.

   Maximum target leakage current is 10 μA over 30 s.

5. 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.
6. Point-to-point (voltage tap pairs) 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. Attach all cable connectors from DAQ wiring racks to top hat connector trees. Verify that all top hat connectors are properly hooked up: all rack cable connector labels should match with all top hat connector labels.
8. Strip heater HFU's should be connected to the strip heaters but set at 20 V.

   8 strip heater circuits will each have an independent HFU and should be configured as follows:

   b. Outer heaters of Coils 203 and 113 (adjacent): follow the alternative configuration, connecting together strips from adjacent coils (HF with HF, LF with LF).

   b. Outer heaters of Coil 206 and Coil 112 (adjacent): follow the alternative configuration, connecting together strips from adjacent coils (HF with HF, LF with LF).

   See the quench heater connection diagram in the Appendix. This shows how the strips are connected to each other and to the Hypertronics connector at the lead end of the magnet structure. See also the HFU – heater circuit connection table in the Appendix.

9. Perform 1 A and 10 A level shift tests 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 all HFUs set at 20-30 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 that the HBM strain gauge system is in excitation mode and reading properly at room temperature. Set the HBM strain gauge sampling rate to 1 Hz (24 HR INTERVAL program). **NOTE: THESE STRAIN GAUGE SETTINGS SHOULD ALWAYS BE USED FOR STRAIN GAUGE READS RUNNING IN THE BACKGROUND WHEN NOT RAMPING THE MAGNET.** The proper settings for current ramps are different and are given in the procedures below for PS shutoffs, strip heater quenches, spontaneous quenches, and ramps to target currents.
12. Verify proper values of insulating vacuums for both Cryostats 2 and 3 and the warm bore tube.
13. Verify proper operation of the N_2 gas flow and fans for the main and CLIQ copper leads.
14. Introduce N_2 gas into warm bore tube to prevent freezing.
15. Install the transporter assembly and measuring coil.

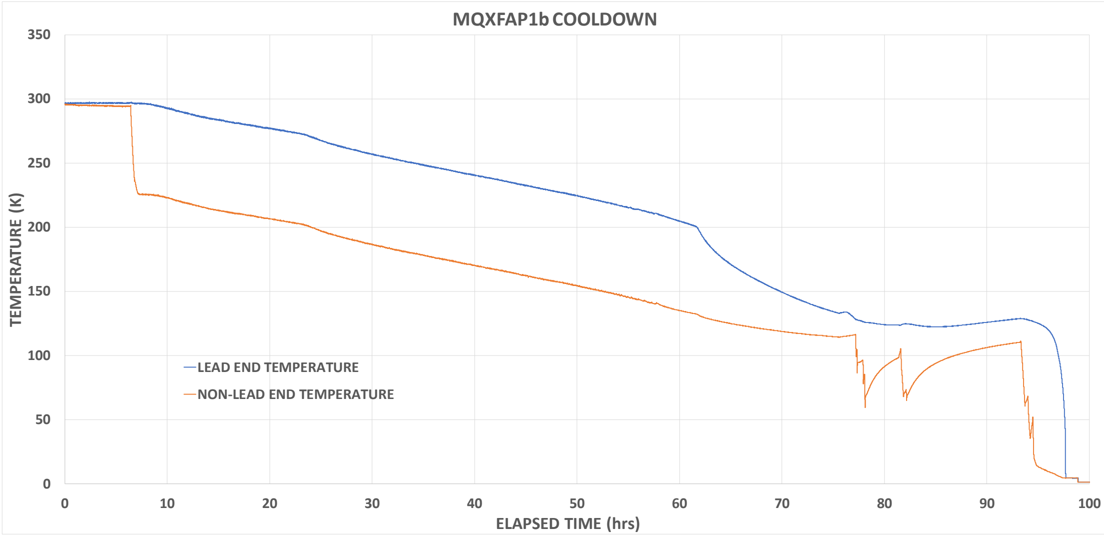
2.3.2 Magnetic Field and Gravity Sensor Measurements at Room Temperature

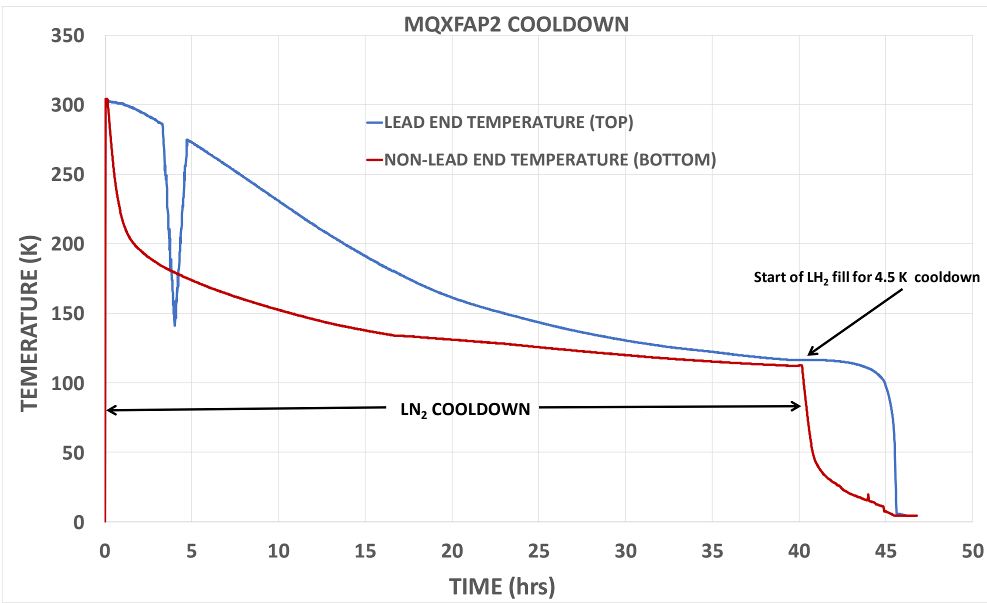
Purpose: To measure geometric harmonics at room temperature. And to measure deflection from vertical with gravity sensors at room temperature.
NOTE: Two windings are included on the PCB in the field measuring probe, one with nominal 110 mm length, and the second with nominal 220 mm length. Considering the detailed design of the PCB, the actual magnetic length is 108.74 mm for the 110 mm circuit, and 217.88 mm for the 220 mm circuit. Therefore, assuming the probe is moved by half of the relevant magnetic length at each step of the z-scan, the required step is 54.37 mm for the circuit #1 (110 mm) scan; and 108.94 mm for the circuit #2 (220 mm) scan. For more details there is a separate document for magnetic field measurement procedures [6].

1. If not already done, install the transporter assembly and measuring coil sometime during the warmup.
2. Perform z-scan at ±15 A. Use the required step and locations for the 220 mm winding.
3. Raise probe and connect gravity sensor instrumentation and perform gravity sensor z-scan.
4. When the cryogenics system is ready for magnet cooldown, stop operation of the magnetic field measuring system.

2.3.3 Cooldown and Magnetic Field Measurements

1. Inform the cryogenics operator to start a pre-cooldown to 100 K with liquid N_2 heat exchanger.
   Maintain a gradient of 50 K or less between the magnet ends during cooldown.
2. When the temperature is about 100 K, start the LHe bottom fill for cooldown to 4.5 K. Cooldown to 1.9 K can be performed as well if the schedule benefits.
   Note: The plot below shows the cooldown of the previous magnets MQXFAP2 and MQXFAP1b. From start of LHe fill the bottom temperature initially dropped 70 K in first hour, total time to 4.5 K being about 5 hours. For the cooldown of MQXFA04, we will also slow down the initial 70 K drop from 1 hour to 3 or more hours in order to maintain a gradient of 50 K or less during LHe fill.





3. During cooldown, slow logger sampling interval should be 10 min. HBM strain gauge sampling rate should be 1 Hz (24 HR INTERVAL program).
4. Perform z-scans during cooldown as a function of temperature using the following maximum current values depending on the temperature range:

Maximum Allowed Current for Different Temperature Ranges During Cooldown or Warmup.

Temp. (K)	Current (A)
200 – 295	± 15
100 – 200	± 20
< 100	± 30

2.3.4 Preliminary Electrical Checkout at 4.5K (or less) in Test Dewar #2

NOTE: The initial cold electrical checkout (except for hipots) can actually be done when the magnet temperature is less than 20K (at both ends) if this benefits the test schedule. Main and CLIQ leads should initially not be connected to their power supplies. Strip heaters also 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 strip heater quench tests can be done only when the magnet has cooled to least 4.5K or less and the magnet is in LHe near bottom of copper leads (at least 9" on LHe level probes below the lambda plate).**

1. Check resistances to ground for the main and CLIQ 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 60 Hz AC series measurements of coils 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 (or less) and in liquid He**).
   Perform hipot tests using the procedure described in the Appendix:
   Section 3.2.4 High Voltage Withstand Testing (Hipot) for required equipment, target high voltage values, and settings. The target high voltage values at cold are as follows:
      1840 V hipot of coil to test structure, which is grounded.
      2300 V hipot of each strip heater circuit to test structure, which is grounded, and to coil with all other systems grounded.
   Maximum target leakage current is 10 μA over 30 s.
7. 5A level shift test (to be done only if there was an unusual result in the room temperature checkout in Part 2.3.1.9). Set the fast data loggers to 1 kHz. Strip heater HFU's should be connected to the strip heaters but set at minimum voltage (20-30 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.

2.3.5 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. Power supply shutoffs and strip heater quench tests can be done only when the magnet has cooled to 4.5K or less and the magnet is in LHe near bottom of copper leads (at least 9" on LHe level probes below the lambda plate).

1. Connect main leads to the power supply.
2. Connect CLIQ magnet leads to the CLIQ power supply.
3. Strip heater HFU's should be connected to the strip heater circuits but set only at 20-30 V.
3. Balance the I-dot quench detector for a ramp rate of 20A/s and known magnet inductance.
4. Configure quench detection system.

Nominal voltage thresholds and validation times for the quench detectors:

Detector	Threshold	Validation Time
Delta QDC	Variable (I < 8 kA)	Variable (I < 8 kA)
	150 mV (I ≥ 8 kA)	4 ms (I ≥ 8 kA)
I-dot QDC	Variable (I < 8 kA)	Variable (I < 8 kA)
	1.9 V (I ≥ 8 kA)	4 ms (I ≥ 8 kA)
Superconducting leads	50 mV	4 ms
Gas-cooled leads	80 – 100 mV	4 ms

NOTE: The above are nominal values based on the previous testing of MQXFAP1, P2, and P1b. The values of threshold voltages and/or validation times for currents below 8 kA will depend on the observed spike activity due to flux jumps and/or mechanical motion. Validation times may be varied up to 20 ms if necessary and will depend on the current. As a worst case, at 8 kA, each 1 ms of added delay will add 0.064 MIIts to the quench integral, so this will be taken into account in order to adhere to the maximum allowed quench integral/hot spot temperature, which is estimated to be 27 MIIts/250 K. (See Section 3.2.3 in Appendix.)

Minimum time delay settings for quench detectors and quench protection:

Detector	Delay
Delta QDC	0 ms
I-dot QDC	0 ms
Strip Heaters	0 ms
Dump resistor switch	10 ms
CLIQ	0 ms
Power supply shutoff	0 ms

5. Verify that each HFU capacitance is at nominal default values (12.4 mF units 1 – 8 and 13.05 mF units 9 - 12.) Note that units 9 – 12 have 900 V capacity, but no unit may be charged to more than 600 V for any test. Nominal voltages for all strips has been 465 V.
6. HFU's should be connected to the strip heaters but set at 20 V.
7. Verify that the 8 strip heater circuits are configured as follows:
   Each strip heater circuit will have an independent HFU's and should be configured as follows:
   c. Outer heaters of Coils 203 and 113 (adjacent): follow the alternative configuration, connecting together strips from adjacent coils (HF with HF, LF with LF).
   b. Outer heaters of Coil 206 and Coil 112 (adjacent): follow the alternative configuration, connecting together strips from adjacent coils (HF with HF, LF with LF).
8. Verify that CLIQ leads and parallel diode string have been properly connected.
9. Set the power supply input impedances over current ranges to inductance values measured during previous test of MQXFAP2. The starting (1 kA) and ending (≥ 16.480 kA) inductances are L = 43.0 mH and L = 34.4 mH, respectively.
10. Set the roll-off parameter for start and end of all ramps to correspond to the requested acceleration and deceleration of 0.9 A/s^2 to **α = 0.3076**.
11. Set proper flow rates for the main and CLIQ 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 2.2.1.1, corrected for magnet contracted length when at 1.9 K, to properly position the antenna. Center of antenna should be at center of magnet coil. Verify correct vertical height and correct orientation with respect to magnet top.
    NOTE: Never leave the quench antenna in the warm bore tube overnight. At the end of the day's testing, remove the quench antenna and store it in the quench antenna storage stand.
13. Verify that the acoustic system is properly connected to its scope and computer which runs

the DAQ and control program.

2.3.6 Power Supply Shutoffs

1. 2000 A power supply shutoff:

Purpose: To check quench detection, power supply, and data acquisition systems before actually initiating a quench.

NOTE: EE dump resistance should be set to **37.5 mΩ** for this test. **CLIQ turned off.**

1. Set EE dump resistance to **37.5 mΩ** for this test. **CLIQ turned off.**
2. Initially, set quench detection thresholds and validation times to follow the current-dependent scheme given in the following table:

CURRENT RANGE [A]	VOLTAGE THRESHOLD (mV)	VALIDATION TIME (ms)
0 – 400	600	4
400 – 1500	1500	4
1500 – 3000	1800	8
3000 – 4000	1500	4
4000 – 5000	1500	4
5000 – 6000	800	4
6000 – 8000	500	4
8000 - 22000	150	4

3. Set fast logger sampling rate to 10 kHz.
4. Set strip heater delay to 0 ms and energy extraction delay to 10 ms.
5. Set HFUs to minimum voltage (about 20 V) 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. Set the HBM strain gauge system to run at the 50 Hz sampling rate (TRIGGER program).
9. Ramp magnet at 20 A/s to 500 A. Check lead voltages for stability.
10. Ramp magnet at 20 A/s to 1000 A. Check lead voltages for stability.
11. Manually trip the delta (voltage difference) quench detector circuit.
12. Verify fast data logger acquisition of all voltage tap pair voltages and other signals. Check all signals for anomalies and proper behavior before proceeding and check for any indications of degradation of the electrical insulation.
13. Verify that the voltage signals are consistent with the 37.5 mΩ dump resistance.

2.3.7 Quench Protection Heater (Strip Heater) Tests at 4.5 K (or less) and 37.5 mΩ

Quench detector threshold at 150 mV and validation time at 4 ms at high current (above 8000 A). Voltage thresholds and validation times for the entire regime of currents during the ramp are given in the table below:

CURRENT RANGE [A]	VOLTAGE THRESHOLD (mV)	VALIDATION TIME (ms)
0 – 400	600	4
400 – 1500	1500	4
1500 – 3000	1800	8

3000 – 4000	**1500**	**4**
4000 – 5000	**1500**	**4**
5000 – 6000	**800**	**4**
6000 – 8000	**500**	**4**
8000 - 22000	**150**	**4**

1. Quench protection heater quenches at 6000 A:

Purpose: to check strip heater performance at 6000 A.

NOTE: **EE dump resistance should be set to 37.5 mΩ for this test. CLIQ turned off. Total voltage threshold should be lowered to 1100 mV for the 6000 A heater quenches.**

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 strip heater HFU capacitance is set at nominal value of 12.4 mF for all HFUs.
4. Set strip heater HFU voltages to the value used in the Thermal Cycle I testing.
5. Set strip heater delay to 0 ms and energy extraction delay to 10 ms.
6. Set the HBM strain gauge system to run at the 50 Hz sampling rate (TRIGGER program).
7. Verify proper lead flow operation.
8. Ramp magnet to 6000 A at 20 A/s. Check lead voltages for stability.
9. Set OL-HF strip circuits to quench the magnet. Set the remaining heater circuits for protection (i.e., to fire only when quench detected).
10. Manually fire the OL-HF HFU's to induce a quench.
11. Examine all quench signals for proper behavior. Check for any indications of degradation of the electrical insulation.
12. Verify delay, validation times, and threshold settings.
13. Verify that the pole multiturn blocks quench <100 ms after heater firing. Check heater current and voltage waveforms.
14. Calculate the MIIts value for this quench and verify that it is consistent at this low quench current with the maximum safe value corresponding to 250 K (32 MIIts) for this magnet's conductor.
15. If the criteria in (13) is not satisfied, increase HFU voltages and repeat steps (5) - (14). Ramp to 6000 A without stopping.
16. Repeat above with OL-LF strip circuits set to quench and the rest for protection.
Note the following changes for OL-LF heater quenches:
For the OL-LF 6000 V quench, validation time should be increased to 8 ms.
Verify that the midplane multiturn blocks quench <100 ms after heaters fire.

2.3.8 Preliminary Test of CLIQ system

Purpose: To verify settings of CLIQ parameters and proper CLIQ output signals before use of CLIQ during the 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, fire CLIQ unit by using QD manual trip.
5. Analyze magnet current and voltage, and current through CLIQ diodes, and CLIQ voltage signals and verify that these are nominal.
6. With 1000 A in magnet, fire CLIQ unit by using QD manual trip.

7. Analyze magnet current and voltage, and 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.

2.3.9 Spontaneous Quench Test Program at 1.9 K

Purpose: To train the magnet up to the **nominal operating current plus 200 A (16670 A)**. 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 have been 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 quench training. Quench detector threshold and validation time should be set according to value of current during ramp. Voltage thresholds and validation times for the entire regime of currents during the ramp are varied as a function of current (See table above in Section 2.2.6 for starting values). Using those values, at high current (above 8000 A), QD threshold and validation time will be 150 mV and 4 ms, respectively.

1. Set fast data logger sampling rate to 100 kHz (0.01 ms sampling interval).
2. Set slow data logger sampling rate to 1 Hz (1 s interval) during the test.
3. Verify that strip heater HFU capacitance is set at nominal value of 12.4 mF for all HFU's
4. Verify that the strip heater HFU voltages are set to the value determined previously 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 delay to 10 ms.
8. Set the HBM strain gauge system to run at the 50 Hz sampling rate (TRIGGER program).
9. Verify proper lead flow operation.
10. Ramp magnet to 600 A and hold for about 60 s to check critical parameters, including the following:
    a) power supply parameters – input and output cooling water temperatures, 15 kA and 24 kA water-cooled bus temperatures, IGBT temperatures, IGBT collector-emitter voltages, IGBT collector currents (all IGBT currents must be within 15% of the mean for all 12), SCR temperature, copper bus temperature, flows through IGBTs, diodes, and chokes; power supply AC and DC currents, and power supply ground currents;
    b) magnet and cryogenics parameters – top and bottom magnet temperatures, gas-cooled lead voltages, LHe level, superconducting leads.

    As the ramp is continuing, these parameters should continue to be closely monitored on the monitor screens.

    Main status alarms have been set for the following six parameters: power supply ground current fault, gas-cooled voltage fault, LHe level fault, IGBT fault, CLIQ fault, CLIQ uncharged fault.
11. Start acoustic system program. Stop program when quench occurs or ramp is done.
12. Ramp magnet to I_{nom} + 200 A = 16.670 A at 20 A/s and use 0.9 A/s^2 acceleration/deceleration parameter (**α = 0.3076**) for roll-off at start and end of ramp.
    a. If a quench occurs follow steps 13 – 16 following.
    b. If no quench occurs, then hold at 16.670 A for 30 min and ramp down at 20 A/s with 0.9 A/s acceleration and deceleration (**α = 0.3076**). Then skip down to Step 17.
13. Perform full analysis of quench signals, in particular to ensure the proper operation of the

protection system, and check for any indications of degradation of the electrical insulation. Check carefully the ground current signal for any deviation from nominal and for any unexpected anomalies.
Calculate quench integral in MIIts to verify that the safe temperature limit of 250 K (32 MIIts) is satisfied.
Discuss and confirm any changes required before the next quench.

14. Repeat quench tests at 20 A/s until quench current reaches at least 16670 A or training has become slow, erratic, or stalled (e.g. more than 5 quenches without an increase in the maximum current). All training ramps will be stopped at 600 A for about 60 s to check power supply, magnet, and cryogenics parameters, as in (10).
15. For each quench, analyze quench data to determine the nature and causes of the training behavior. Determine quench location. Calculate quench integral in MIIts to verify that the safe temperature limit of 250 K (32 MIIts) is satisfied. Check quench heater signals (current, voltage, and ground current) to verify that there was no degradation.
16. Between quenches the HBM strain gauge sampling rate can be set back to 1 Hz (INTERVAL program).
NOTE: The HBM strain gauge system should always be set back to 50 Hz sampling rate (TRIGGER program prior to each current ramp.
17. When training to 16.670 A is finished, perform the following ramp:
Set total voltage threshold to 2100 mV.
Ramp the magnet to I_{nom} = 16.470 A at 30 A/s with 0.9 A/s acceleration and deceleration (**α = 0.3076**).
Hold for 5 min.
Set total voltage threshold to 4500 mV.
Ramp the magnet down to 0 A at 100 A/s with 0.9 A/s acceleration and deceleration. (**α = 0.3076**).

2.3.10 Holding test at 1.9 K

Purpose: To verify stability of magnet operation at a flattop current.
Verify all test parameters are the same as for the quench tests in Part 2.2.8.

1. Ramp magnet at 20 A/s to nominal current + 100 A (**16.570** kA) and hold for 300 minutes.
2. Monitor the status of all slow logger signals to verify nominal values.

2.3.11 Final Magnet Warmup to Room Temperature and RRR Measurement

1. Set the slow data logger sampling interval to 1 s until the temperature is above 30 K. Then increase the sampling interval to 10 min.
2. Set the HBM strain gauge system to run at the 1 Hz sampling rate (INTERVAL program).
3. Start warmup of the magnet to room temperature. Warmup should be slow to minimize the temperature gradient between the magnet ends. Stable resistance measurement at 20 K is most important, since this is needed to calculate RRR. Up to that temperature, the warmup should be as uniform as possible to achieve a stable temperature of slightly above 20 K. After RRR measurements are done, a gradient of ≤ 50 K should be maintained.
4. The current source for RRR measurements should be a bipolar power supply that changes polarity ±10 A with a period of 30 s in order minimize thermal emf effects. Apply this current across the main leads prior to the magnet reaching 20 K.

5. When temperature reaches about 20 K and resistances become non-zero, trigger fast data logger to capture resistance values for all tap segments.
6. During the warmup, hold the magnet temperature at slightly above 20 K for at least 30 min with the bipolar supply on while making RRR resistance measurements.
7. Slow data logger and strain gauge data acquisition systems should be running until the magnet reaches a stable room temperature. Make sure cognizant physicist has determined that these systems can be stopped before doing so.
8. When the test temperature reaches 100 K, perform a hipot of quench protection heaters to coil with target high voltage value of **425 V**. Use the procedures and settings as
9. When magnet reaches stable room temperature, repeat step 4 to measure room temperature resistances with the same procedure as was done to measure resistances at slightly above 20 K.
10. For final inspection, electrical testing, and preparation for shipping, see the traveler documents *AUP-320 MQXFA Testing – Preparation for Shipping* and *SMD-AUP-4001 Procedure, Room Temperature Electrical Checks of AUP MQXFA Quadrupole Magnets*.

2.3.12 Final Magnetic Field and Gravity Sensor Measurements at Room Temperature

Purpose: To measure geometric harmonics at room temperature. And to measure deflection from vertical with gravity sensors at room temperature.

NOTE: Two windings are included on the PCB in the field measuring probe, one with nominal 110 mm length, and the second with nominal 220 mm length. Considering the detailed design of the PCB, the actual magnetic length is 108.74 mm for the 110 mm circuit, and 217.88 mm for the 220 mm circuit. Therefore, assuming the probe is moved by half of the relevant magnetic length at each step of the z-scan, the required step is 54.37 mm for the circuit #1 (110 mm) scan; and 108.94 mm for the circuit #2 (220 mm) scan. For more details there is a separate document for magnetic field measurement procedures [6].

1. If not already done, install the transporter assembly and measuring coil sometime during the warmup.
2. Perform z-scan at ±15 A. Use the required step and locations for the 220 mm winding.
3. Raise probe and connect gravity sensor instrumentation and perform gravity sensor z-scan.

3 Appendix

3.1 Background

The MQXFA04 magnet is the second pre-series 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 MQXFA04 is 22.1 kA at 1.9 K [1]. This will be followed by 3 more pre-series magnets and 15 series magnets, which will be tested and sent to Fermilab for assembly into cold masses for the LHC triplets. MQXFA04 is the third full length MQXFA quadrupole (after MQXFAP2 and MQXFA03) 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 return end (bottom end) by the bottom fill line. Magnet return 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 MQXFA04 test will consist of two main parts.
1) Test cycle 1: Cooldown to 1.9 K and training to 16.670 A kA (200 A above the nominal current of 16.470 kA), and 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, and completion of tests that were not finished in first test cycle.

The main priorities for the 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.

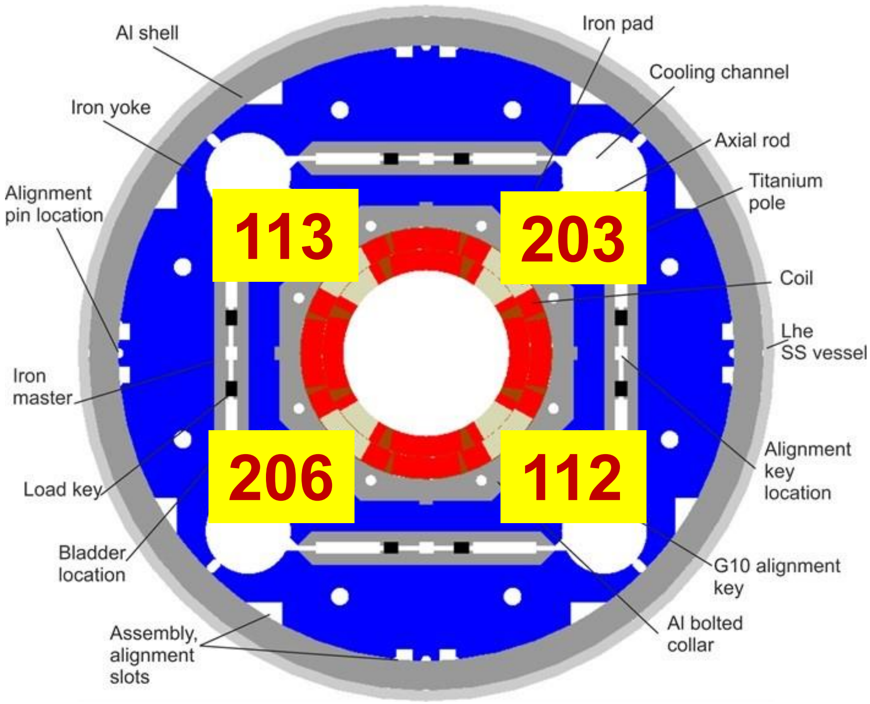
3.2 Magnet and System Parameters

3.2.1 MQXFA04 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 test current (1.9 K)	I_{max} = 16.670 kA
Maximum current (300 K)	I_{300} = 15 A
Conductor limit at 1.9 K:	I_{ss} = 22.100 kA (Coil 112)
Conductor limit at 4.5 K:	I_{ss} = ~20 kA
Peak field in the coil at I_{nom} (1.9 K):	B_{nom} = 11.4 T
Field Gradient at I_{nom} (1.9 K):	G_{nom} = 132.6 T/m
Magnet resistance at room temperature:	R = 2.37 Ω
Magnet inductance (20 Hz at room temperature):	L = 39.6 mH
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)
Maximum test stored energy (at $I_{nom+200}$):	E_{max} = 4.78 MJ assuming L=34.4 mH
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

The four coils are connected in the following order from the positive lead (Tap WC+) to the negative lead (Tap WC-): Coil 203 (Q1) → Coil 112 (Q4) → Coil 113 (Q2) → Coil 206 (Q3).

The cross-section diagram below shows the quadrant location of the four coils used in MQXFA04.



MQXFA04 cross-section (as seen from the lead end) showing the quadrant locations of the specific coils used.

3.2.2 Magnet 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 MQXFA04 inductance is **43.0 mH and 34.4 mH** at 1 and 16.5 kA, respectively. Note that for the prototype MQXFAP2 (the first magnet with 4.2 m magnetic length), the inductance at 16.470 kA was measured to be 34 mH, as predicted by calculation.

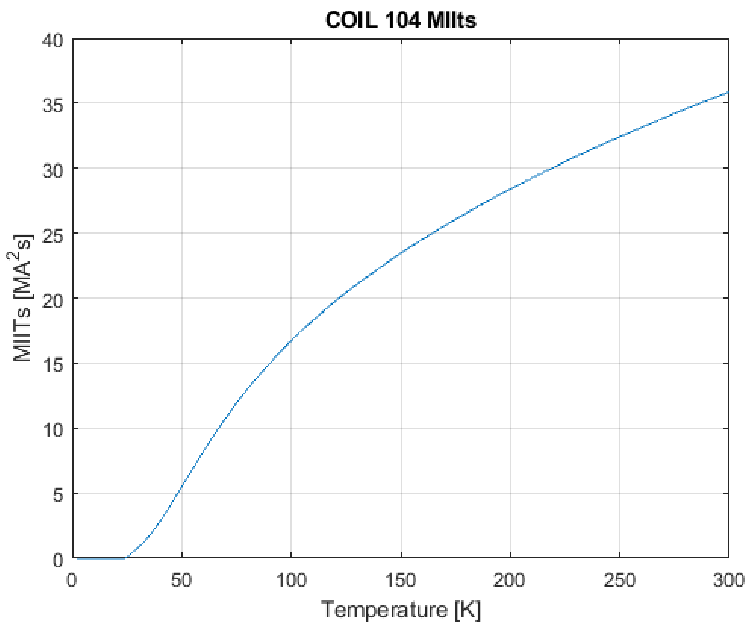
Since the slow data logger is always running at 1 Hz sampling rate during every ramp, actual inductance values can conveniently be calculated by dividing the measured coil voltage data during any ramp by the ramp rate, which is also measured. This is always available when required.

3.2.3 Hot spot Temperature and Quench Integral limits

The target for the first thermal cycle is to maintain the hot spot temperature below 250K. The hot spot temperature depends strongly on the detailed quench conditions and the protection system response.

In the same conditions, a larger hot spot temperature is expected for quenches originating in Coil 112 or Coil 113, which have the lowest RRR (225-230).

The following plot reports quench integral in MIIts vs Temperature at 13 T for Coil 104 in a previous MQXFA magnet. This result can be used here since Coil 104 RRR (253) approximates that of Coils 112 and 113. The plot shows that a maximum quench integral of ~32 MIIts is compatible with the hot spot temperature limit of 250K. The protection setting will be chosen accordingly. The MIIts limits and protection settings may be revised based on data from the first quenches.



3.2.4 High Voltage Withstand Testing (Hipot)

The MQXFA electrical requirements and verification procedures are described in detail in [4]. After the magnet has been exposed to helium, the maximum hipot values to be used are shown in the lower half of the table, in the lines labelled "Test voltage to ground/heaters for installed systems…"

Maximum expected coil voltage at quench (V) [2]	To ground	670
	To quench heater	900
Test voltage at Nominal Operating Conditions(1) at 'Manufacturing Facilities and Test Stations' stage (V)	To ground	1840
	To quench heater	2300
Test voltage at gaseous helium conditions(2) (V)	To ground, and to quench heater	425
Test voltage at warm(3) before first helium bath (V)	To ground	3680
	To quench heater	3680(4)
Test voltage at warm(3) after helium bath (V)	To ground	368
	To quench heater	460
Maximum leakage current (μA) – not including leakage of the test station		10
Test voltage duration (s)		30

(1) Nominal Operating Conditions are equivalent to 1.9 K superfluid helium in the cold mass
(2) T = 100±20 K and p = 1.2±0.2 bar
(3) T = 20±3 °C and humidity lower than 60%
(4) Value agreed in order not to exceed the test voltage coil to ground

Note the following requirements for hipot tests:

1. Required Equipment:
   a) DC Hipot Equipment: Associated Research HYPOTULTRA Model 7850 Dielectric Analyzer.
   b) Probe capable of reading temperature (T) and relative humidity (RH) to 0.1 C and 0.1 % RH @ room temperature). e.g., Omega HX93BD Series Relative Humidity /Temperature Transmitter/Indicator, or Dwyer RHP-2W11.
2. Set the following test parameters (nominal) for hipot tests:
   Set the arc sensitivity to 1.
   Set the duration (hold) at target voltage to 30 s.
   Set the ramp time to target voltage so that the voltage ramp rate is ≤ 3 - 4 V/s.
   Set the voltage to the target test value (as in table above).
   Set the threshold leakage current (in μA) to a value ≥ 10 μA.

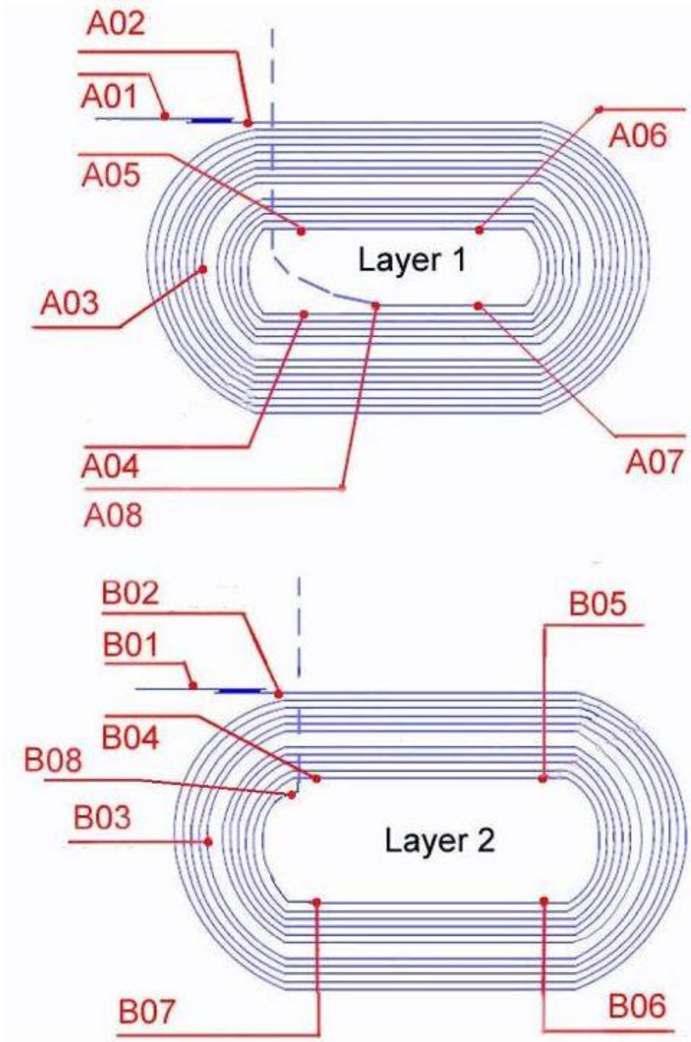
3.2.5 Power Supply

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/1700 V IGBT switches in parallel. The dump resistors are ceramic non-inductive resistors which can be varied with the discrete 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.

3.3 Instrumentation

3.3.1 Voltage Taps

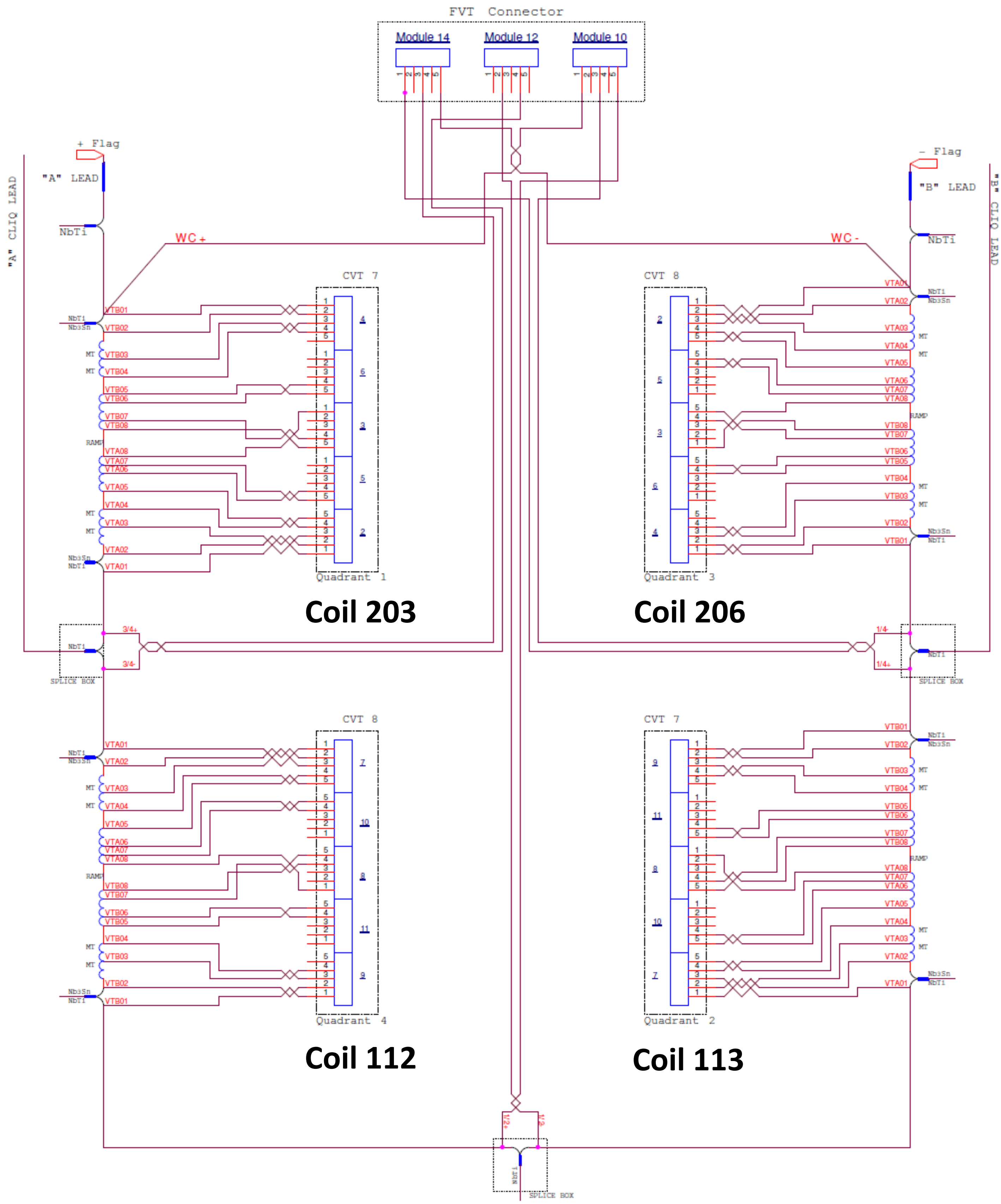
Each coil is instrumented with 16 auxiliary voltage taps, 8 in each of the layers, and at least 4 taps on each lead, and a warm tap at the top of each gas-cooled lead, for a total of up to 80 taps. With these, we monitor the inner and outer layers, selected sections of the windings, the superconducting leads, the magnet/test fixture splices, the Nb_3Sn/NbTi 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. All splices will also be monitored. 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 auxiliary (configurable) 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 has been common for voltage taps to become open and therefore lost during testing operations, such as cooldowns and warmups and especially during quench tests. In the event of open taps during testing, each such lost tap will be bypassed with a jumper to create a new voltage tap pair (and therefore section of coil) from the taps to either side of the lost tap, and which includes the original two sections that were separated by the lost tap before it opened. The jumper will be applied to the taps where they enter the iso-amplifier connection panel before input to the iso-amplifier. This will also be accounted for in the databases of the fast and slow databases as necessary, and also in the electrical checkout data sheets.

The following schematic is the wiring diagram which shows how the voltage taps are located in the coils and how they are connected to the Hypertronics connectors on the magnet structure lead end. The fixed (main) voltage taps are connected to Hypertronics Connector FVT, and these are the taps used for quench detection. The configurable (auxiliary) taps are connected to Hypertronics Connectors CVT7 and CVT8. These are used for quench start location.


FVT Connector
Module 14
Module 12
Module 10
+ Flag
"A" LEAD
"A" CLIQ LEAD
NbTi
WC +
WC -
- Flag
"B" LEAD
"B" CLIQ LEAD
CVT 7
CVT 8
Quadrant 1
Quadrant 3
Coil 203
Coil 206
SPLICE BOX
CVT 8
CVT 7
Quadrant 4
Quadrant 2
Coil 112
Coil 113
SPLICE BOX

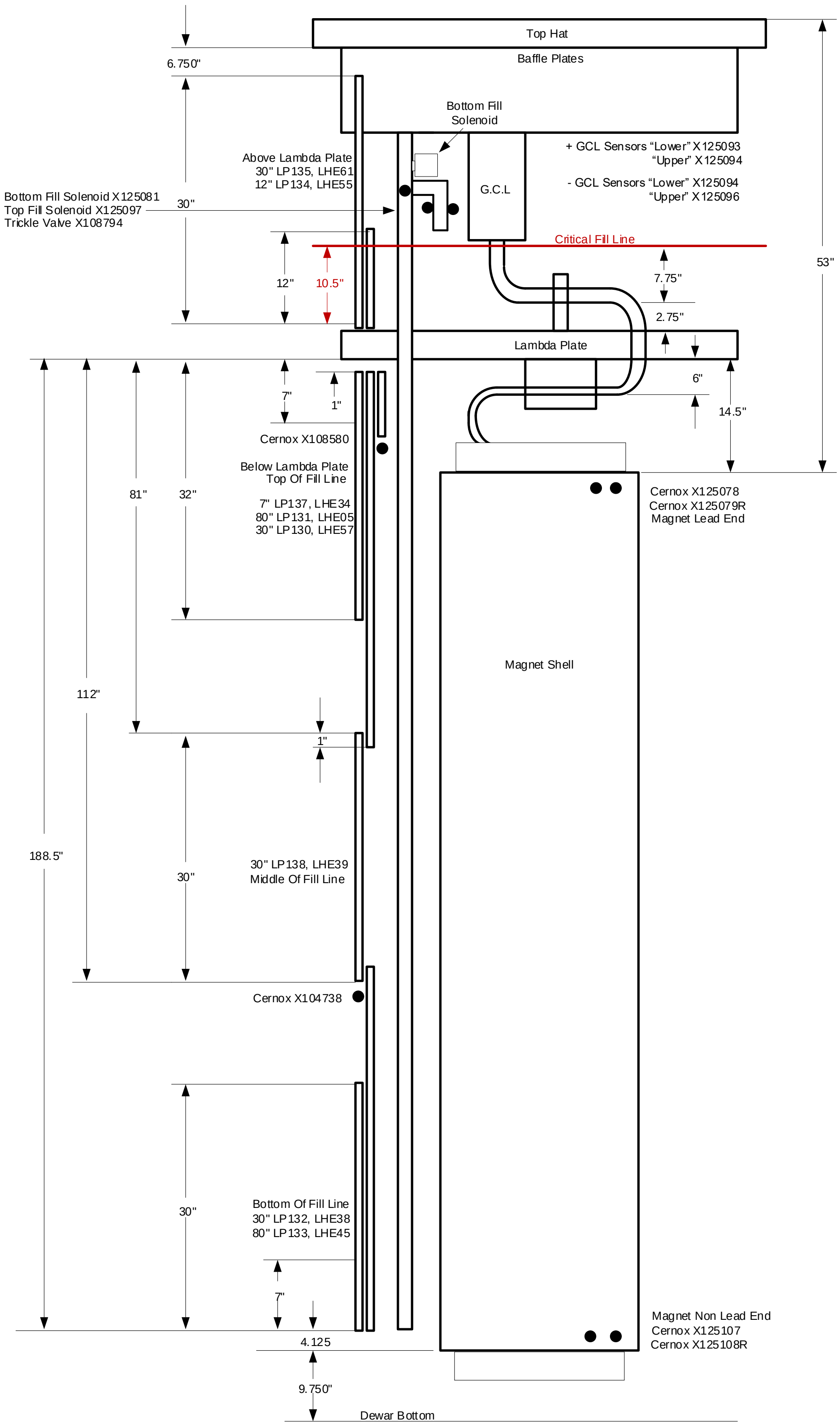
3.3.2 Temperature Sensors

Test temperatures will be monitored by a total of 14 Lakeshore Cernox resistive temperature sensors located at various positions inside the test cryostat, including temperatures monitored by two redundant pairs of Cernox sensors mounted to the stainless steel end blocks attached to the magnet structure at the lead end (top) and return end (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 bottom of the middle level probe to get temperature reads halfway along the magnet's length. A Cernox sensor is also located inside the 1.9 K heat exchanger at the top.

3.3.3 LHe Level Probes

The test fixture is equipped with numerous LHe level probes and Cernox temperature sensors installed at various locations in Test Cryostat #2. (See diagram below showing locations and lengths of the level probes and locations of the temperature sensors.) There are also level probes and temperature sensors in the 1.9 K heat exchanger. Liquid helium level on the top probe should be at least **9" (22.86 cm)** to cover the copper flags between the magnet SC leads and the gas-cooled copper leads.

TEST CRYOSTAT #2: LEVEL PROBES AND TEMPERATURE SENSORS MARCH 2019



3.3.4 Quench Protection

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

Quench Protection Heaters

Quench protection heaters (QPH), also known as strip heaters, consist of 4 strips on the outer layer outer surface of each coil. The heaters are configured into eight independent circuits, with two strips connected in series composing each circuit, and each of which is fired by capacitive 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 different configurations. Each circuit will consist of an outer layer high field (OL-HF) strip from one coil connected in series to an OL-HF strip on an adjacent coil. Outer layer low field (OL-LF) strips will also be connected in this way between adjacent coils. High field strips are near the pole and low field strips are near the midplane of each coil on each side of the pole. The schematic below shows how the strips from adjacent coils are connected to each other and to the Hypertronics Connector HTR2 on the magnet structure lead end. There are 12 HFU capacitive discharge assemblies, which include eight 600 V, 12.4 mF units and four 900 V, 13.05 mF units. Starting with MQXFA03 and all following MQXFA magnets, inner strip heaters will not be installed. Each of the eight heater circuits will be connected to its own HFU and can be fired independently. Only the eight 600 V HFUs will be used. The maximum allowed HFU voltage is 600 V.

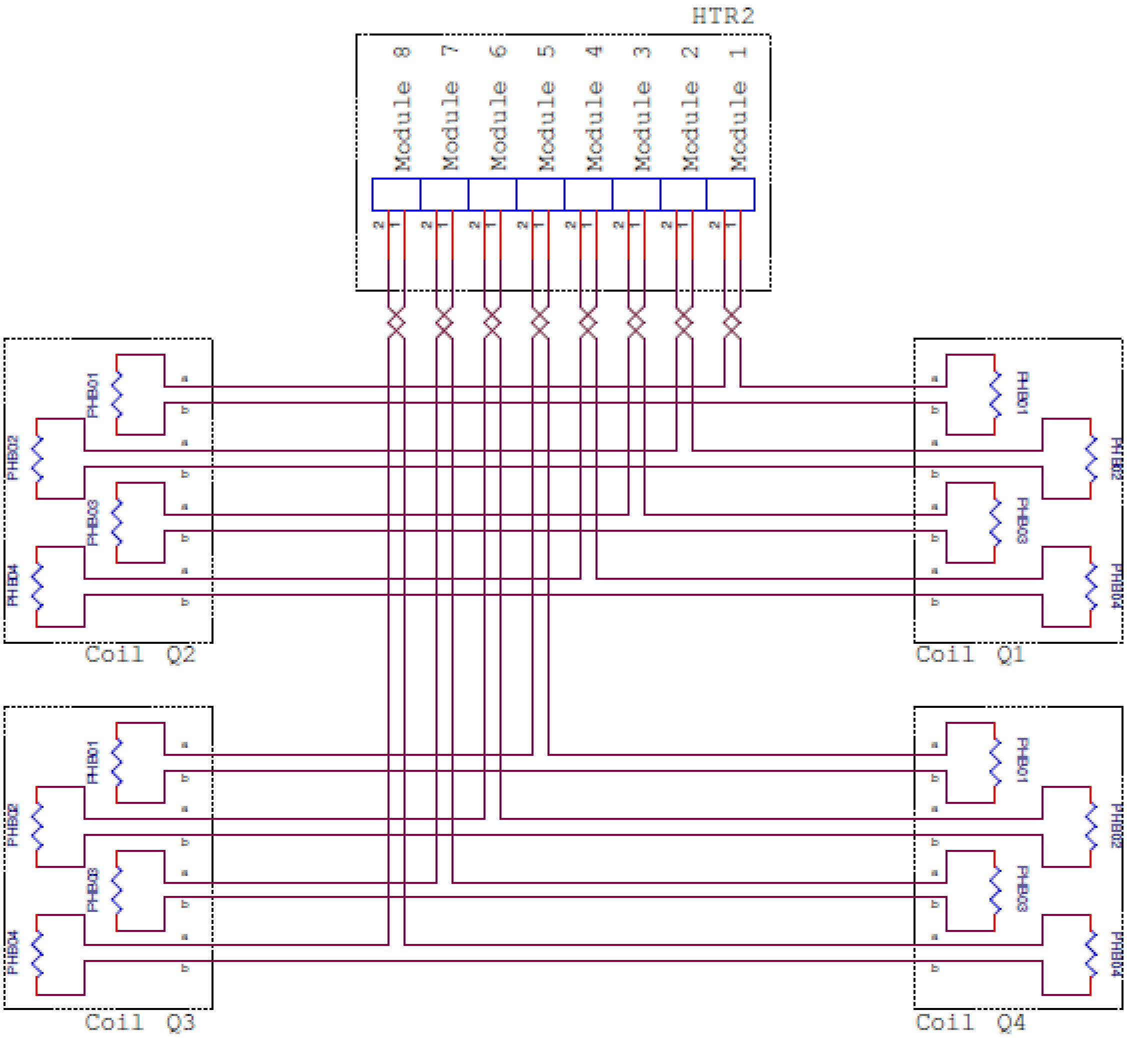
Nominal strip heater parameters:

1. HFU capacitances are initially set to 12.4 mF (and 14 mF for two of them) for the 600 V HFUs.
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. Each 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 heaters are 213 W/cm^2. NOTE: There is a 15 ms or greater detect / diffusion time for heat to reach the SC cable and initiate a quench.
4. For training quench tests with this magnet, QPHs will be triggered at QD trip with no time delay.
5. Strip resistances at 10 K have been calculated (E. Ravaioli) to be
   Outer strip: Calculated 1.10 – 1.14 Ω
   NOTE: These will be measured at room temperature and when cold.
6. Typical heater circuit resistances are about 4 Ω (room temperature) and about 2 Ω (1.9 K).

The following table shows how the eight heater circuits should be configured and which HFU to connect to each circuit. The system connector names and connector pin numbers refer to the connectors on the tree above the top plate.

HFU – Heater Circuit Connection Table

Heater Firing Unit	Sys Conn	Conn Pins	Module	Quadrant	Heater
5	HTR 2	3 to 4	1	Q1+Q2	PHB01 (LF)
1	HTR 2	5 to 6	2	Q1+Q2	PHB02 (HF)
2	HTR 2	7 to 8	3	Q1+Q2	PHB03 (HF)
6	HTR 2	9 to 10	4	Q1+Q2	PHB04 (LF)
7	HTR 3	11 to 12	5	Q3+Q4	PHB01 (LF)
3	HTR 3	1 to 2	6	Q3+Q4	PHB02 (HF)
4	HTR 3	3 to 4	7	Q3+Q4	PHB03 (HF)
8	HTR 3	5 to 6	8	Q3+Q4	PHB04 (LF)



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 (symmetric grounding). Each energy extraction circuit is enabled by six IGBT switches in parallel for each power supply. At the ultimate current 17.890 K, 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. For the training quench tests of this magnet MQXFA04, dump resistance will be limited to 37.5 mΩ with 10 ms delay.

CLIQ (Coupling-Loss-Induced Quench) System

The CLIQ system will be connected during quench training and for quench protection studies. The CLIQ settings will be 500 V and 40 mF. For training quench tests with this magnet, CLIQ will be initiated at QD trip with no time delay.

Quench Detectors

Quench detection will be achieved by a delta (half magnet voltage difference) signal and an I-dot (total magnet voltage – L dI/dt) signal. 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 SC lead voltages. These main QD signals are input into an FPGA-based quench detector, and as a backup, into another identical FPGA-based quench detector, which also includes detection of thresholds in signals such as gas-cooled lead voltages and power supply ground fault signals, which result in a slow discharge that does not switch in the EE circuit and dump resistor, or trigger the protection heaters or CLIQ.

3.3.5 Magnetic Field Measurements

Magnetic field measurements will be performed with a rotating coil probe and transport system. There will be initial room temperature field measurements, measurements during cooldown, measurements at 1.9 K, and final room temperature measurements. The magnetic measurement run plan is available separately. See [6].

3.3.6 Strain Gauges

CERN-style (HBM) strain gauges will be taking measurements continuously in the background during the testing of the magnet, and this includes initial room temperature, cooldown, cold testing, warmup, and before removal from test fixture and shipping to FNAL. Initial room temperature measurements will be compared to reads taken at LBNL before shipping to BNL.

There are in total 36 HBM strain gauges. There are 8 coil gauges, 2 of which are mounted on each of the 4 poles at Station 3, close to lead end, measuring axial and azimuthal strain. There are 21 shell gauges mounted at top, bottom, right, and left for each of three axial locations, Shells 2, 4, and 7. Axial and azimuthal strain is measured at all coil and shell locations. All coil and shell gauges are 5 wire devices in half bridge configurations with temperature compensation. 4 RE rod axial gauges are 6-wire devices in full bridge configuration. The HBM DAQ units allow for simultaneous reading of all 36 gauges with fast sampling rates suitable for magnet excitation ramps; for this test the sampling rates will be: 50 Hz for ramps and 1 Hz for the rest of the time during testing. Measurement reads are controlled with the HBM Catman program, which writes voltages and strains into binary files which can be converted to text or Excel.

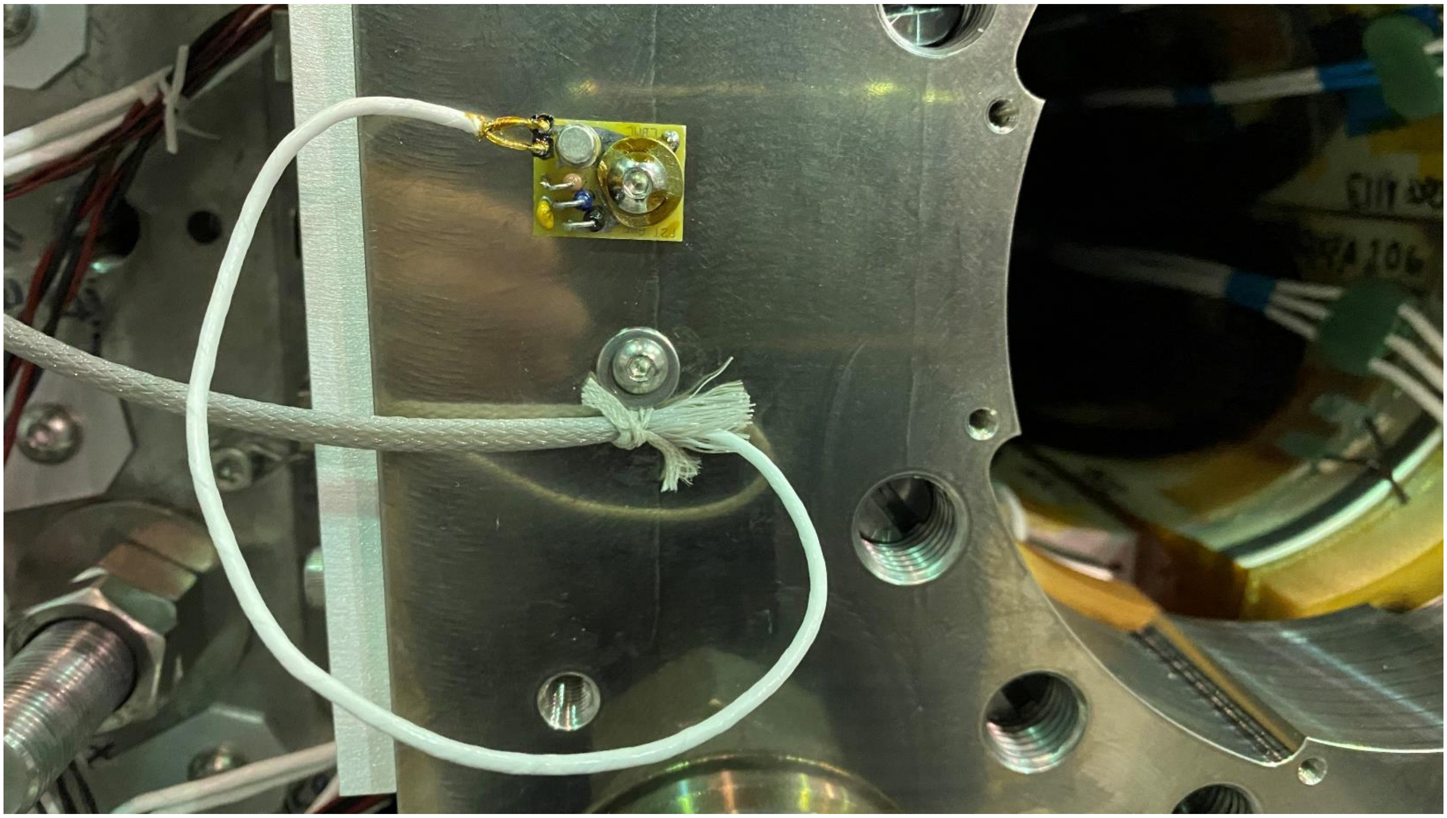
3.3.7 Quench Antenna

A newly re-built quench antenna is available to be installed prior to the beginning of training. It consists of 27 axially-distributed printed circuit boards each with dual-winding configurations, for a total of 54 fast data logger channels. The circuitry has been newly designed to increase the signal-to-noise ratio problems of the previous 16-element antenna version when used in the long magnets. Expected quench antenna winding voltages during quench are 100 – 500 mV.

There is also a new quench antenna with a different design that may be ready in time for the test of MQXFA04. If so this one will be installed instead of the one described above. More information will be added if necessary and when available.

3.3.8 Acoustic Sensor for Quench Detection

An acoustic sensor (piezoelectric transducer) is mounted on the return end plate of the magnet. (See photo below). It will be used to provide added data during quenches. During testing, the acoustic system will be operated independently. The control and DAQ systems are independent of the other more standard instrumentation, such as voltage taps and quench antenna, but will be provided with a trigger signal from the QD for reference. The acoustic system will be controlled by a provided program, which is to be running for each ramp to quench.



3.4 Procedural Notes

Cryogenic tests will be nominally 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.

Fast data logger sampling rate is 10 kHz (sampling interval of 100 μs) on all channels during a strip heater quench, with pre-trigger data capture of 1 s before quench event and 5 s of post-trigger data capture after quench event. Fast data logger sampling rate is 100 kHz (sampling interval of 10 μs) on all channels during a training quench, with pre-trigger data capture of 0.1 s before quench event and 0.5 s of post-trigger data capture after quench event. Before and after time intervals and sampling rate can be varied when necessary. File size is 60000 data points.

Due to the generation of flux jump spikes in Nb_3Sn conductors, 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 in particular. For this reason, detector thresholds will be varied (0.15 to 3.0 V typically) according to current level (< 8 kA) during a ramp. The final threshold and validation time settings of the delta detector (for I ≥ 8000 A) can be set initially to 0.150 V and 4 ms, respectively. The variation will be set and controlled programmatically, and these values will not be changed during a ramp. Also, the validation time will be varied as a function of current during a ramp (I < 8 kA) in order to lower the voltage thresholds. The most effective validation time values will be determined during the initial ramps, where we will start with the values used for the last test (MQXFAP1b).

Nominal voltage thresholds and validation times for the quench detectors:

Detector	Threshold	Validation Time
Delta QDC	Variable (I < 8 kA)	Variable (I < 8 kA)
	150 mV (I ≥ 8 kA)	4 ms (I ≥ 8 kA)
I-dot QDC	Variable (I < 8 kA)	Variable (I < 8 kA)
	0.8 – 1.0 V (I ≥ 8 kA)	4 ms (I ≥ 8 kA)
Superconducting leads	50 mV	4 ms
Gas-cooled leads	80 – 100 mV	4 ms

NOTE: The above are nominal values based on the previous testing of MQXFAP1b. The values of threshold voltages and/or validation times for currents below 8 kA will depend on the observed spike activity due to flux jumps and/or mechanical motion. Times may be varied up to 20 ms if necessary and will depend on the current. As a worst case, at 8 kA, each 1 ms of added delay will add 0.064 MIIts to the quench integral, so this will be taken into account in order to adhere to the maximum target quench integral/hot spot temperature, which is estimated to be 27 MIIts/250 K. (See Section 3.2.3 above.)

Minimum time delay settings for quench detectors and quench protection:

Detector	Delay
Delta QDC	0 ms
I-dot QDC	0 ms
Strip Heaters	0 ms
Dump resistor switch	10 ms
CLIQ	0 ms
Power supply shutoff	0 ms

NOTE: Time delays can be adjusted to suit the testing focus (for example, during quench protection studies).

3.4.1 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 Flashpoint 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, voltage, and ground current signals, QPH voltages, currents, and ground currents, quench antenna voltages, CLIQ voltage and current, strain gauge data, magnetic field probe signals, temperature signals, and level probe signals.

3.4.2 Test Communication 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 and plot. Detailed test data is shared according to the guidelines provided in [5]

3.4.3 Document (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 (Traveler) and hung at the side of Test Cryostat 2 and be clearly visible to all.

3.4.4 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 main and CLIQ 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

4 References

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