Design and Fabrication of the 1.9 K Magnet Test Facility at BNL, and Test of the First 4m Long MQXF Coil

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US HL-LHC AUP

The future high luminosity upgrade of the Large Hadron Collider (LHC) at CERN will include twenty 4.2 m long Nb_3Sn high gradient quadrupole magnets which will be components of the triplets for two LHC insertion regions. In order to test these and four pre-production models, the vertical superconducting magnet test facility of the Superconducting Magnet Division (SMD) at Brookhaven National Laboratory (BNL) has been upgraded to perform testing in superfluid He at 1.9 K and 1 bar, which is the operational condition at the LHC. This has involved extensive modifications of the 40-year old, 4.5 K cryogenics plant at SMD. These upgrades include new piping, compressors, and other critical components, a new vertical test cryostat with top plate and hanging fixture which can accept larger diameter and longer magnets, up to actual length 5 m long, a 1.9 K heat exchanger, newly designed warm bore tube, and a lambda plate designed with a novel seal configuration for both strength and minimum heat loss. In addition, the former short sample cable test facility 30 kA power supply has been upgraded with an energy extraction system using IGBT switches and fast shutoff capability, and a new high energy dump resistor, and reconfigured to supply 24 kA to test high field Nb_3Sn magnets.

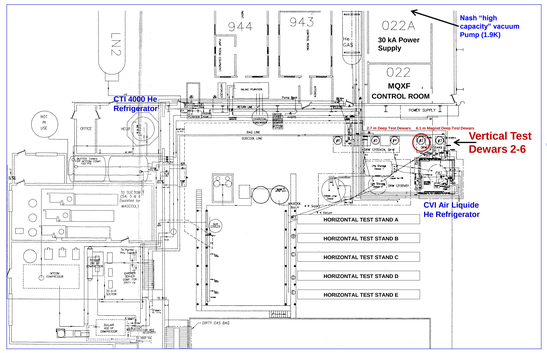
We have also assembled completely new data acquisition, signal analysis, and control software and hardware, allowing for high precision and large volume data collection.

This paper describes the design, assembly, and commissioning of the upgraded test facility and the first magnet test performed, on a mirror model, which consists of a single coil quadrant and an iron yoke filling the other three quadrants and is designed to have peak fields close to that of the production quadrupoles. The mirror coil was the first long coil of the MQXF design to be tested.

MQXFA TEST PARAMETERS

Coil inner aperture	D = 150 mm
Coil magnetic length	ℓ = 4.2 m
Coil actual length	ℓ = 4.523 m
Yoke length	ℓ = 4.5629 m
Total length with end plates	ℓ = 5 m (nom)
Operational temperature	T = 1.9 K
LHC nominal operating current (1.9 K)	I_{nom} = 16.470 kA
LHC ultimate operating current (1.9 K)	I_{ult} = 17.890 kA
Maximum current (300 K)	I_{300} = 10 A
Conductor limit at 1.9 K	I_{ss} = 21.600 kA
Conductor limit at 4.5 K	I_{ss} = 19.550 kA
Peak field in the coil at I_{nom} (1.9 K)	B_{nom} = 11.4 T
Peak field in the coil at I_{ult} (1.9 K)	B_{ult} = 12.3 T
Peak field in the coil at I_{ss} (1.9 K)	B_{ss} = 14.5 T
Field Gradient at I_{nom} (1.9 K)	G_{nom} = 132.6 T/m
Field Gradient at I_{ult} (1.9 K)	G_{ult} = 143.2 T/m
Field Gradient at I_{ss} (1.9 K)	G_{ss} = 168.1 T/m
Magnet resistance at room temperature	R = 2.37 Ω
Magnet inductance (20Hz at room temperature)	L_{RT} = 38.1 mH
Magnet inductance (at 1.9 and 1 kA)	L_1 = 40.9 mH
Magnet inductance (at 1.9 and I_{nom}=16.5 kA)	$L_{16.5}$ = 32.8 mH
Operating stored energy (at B_{nom}, I_{nom})	E_{max} = 4.5 MJ assuming L=32.8 mH
Maximum allowed temperature at quench	T_{max} = 350 K
Maximum allowed voltage across magnet	V_{max} = 1000 V (600 V to ground) with 50 mΩ EE
Dump resistor (energy extraction) options	R_D = 30, 37.5, 50, 75, 150 mΩ

SMD TEST FACILITY FLOOR PLAN



SMD MAIN CRYOGENICS FACILITY

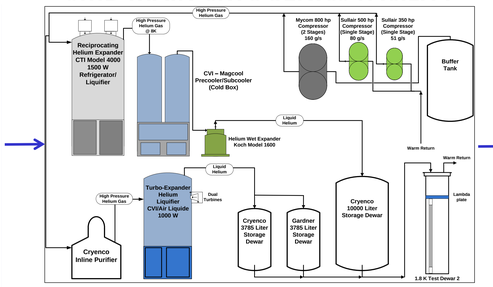


Diagram courtesy of W. McKeon, Cryogenics Facility

1.9 K PROCESS FLOW DIAGRAM

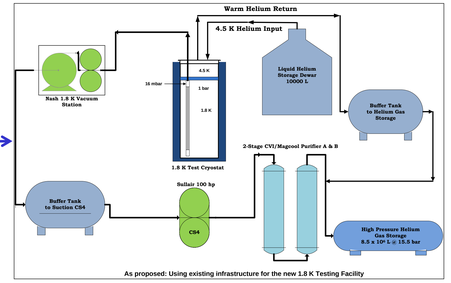
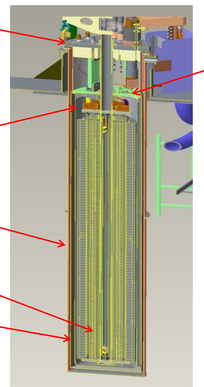


Diagram courtesy of W. McKeon, Cryogenics Facility

NEW RE-DESIGNED TEST CRYOSTAT FOR 1.9 K AND 24 kA



New Top Plate

New top plate to accommodate lambda plate and fixturing for MQXF 4.2 m quads and 24 kA vapor-cooled leads and heat exchanger for 1.9 K, 1 bar operation.

Redesigned Inner He Vessel
Rated at 5.86 bar

Existing Outer Dewar

MQXF Magnet

4.5 K Heat Shield

Lambda Plate

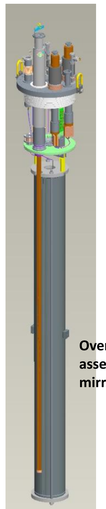
Top is 38.1 mm thick G10 (lower heat load)

Bottom is 19.05 mm thick 304 stainless steel (for added strength and sealing to He vessel interior flange)

Bonded together with Stycast 2850FT

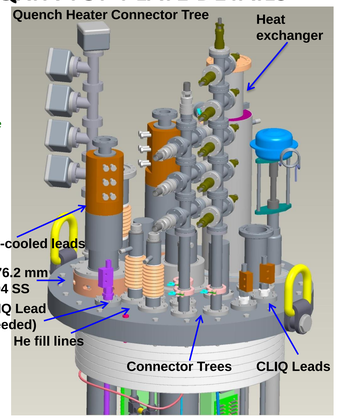
Total heat load < 1.4 W

Components below lambda plate and internal to heat exchanger are designed for 5.86 bar, above lambda plate for 3.45 bar.



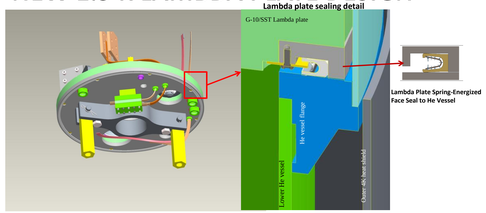
Overall test fixture and hanging assembly (insert), shown with mirror magnet MQXFPM1.

1.9 K MQXFA TOP PLATE DETAILS

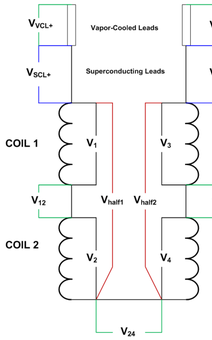


- (2) 24 kA main coil vapor-cooled leads
- (2) 1 kA CLIQ vapor-cooled leads
- (3) instrumentation wiring trees
- (2) helium fill lines
- Heat exchanger port, 3rd CLIQ lead port
- Manifolds and solenoid valves under plate
- Warm bore tube port
- Helium vent port

NEW 1.9 K LAMBDA PLATE DESIGN



QUENCH DETECTION



The MQXFA quench detection system is based on a redundant scheme which relies on a number of voltage signals. When any one of the following signals reaches its specified *threshold voltage* after a specified *validation time*, a fast discharge is instigated (current decays through dump resistor). Typical threshold voltages and validation times are listed here.

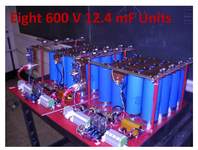
1)	Half coil voltage V_{half1} - V_{half2}	50-250 mV	2-5 ms
2)	Quarter coil voltage $V_1 - V_2$	50-250 mV	2-5 ms
3)	Quarter coil voltage $V_3 - V_4$	50-250 mV	2-5 ms
4)	Total coil voltage V_{total}	50-250 mV	2-5 ms
5)	SC lead voltages V_{SCL+} and V_{SCL-}	10-50 mV	2-5 ms
6)	Splice voltages V_{12}, V_{34}, V_{24}	8-10 mV	2-5 ms
7)	Current Derivative $V_{total} - L\ dI/dt$	0.1-1.0 V	5-10 ms

Note: The above thresholds are for currents higher than 6 kA. In Nb_3Sn magnets, current-dependent thresholds as high as several volts at low currents are necessary and are set in the software. This is to avoid false QD trips due to flux jump spikes.

There are also designed into the system a number of interlocks which also rely on various signals which, if they do not meet specified conditions such as *voltage threshold* or *on-off state*, will instigate a slow discharge, with the dump resistor out of the circuit. These include:

1) Vapor-cooled lead voltages 80-100 mV 500-1000 ms
2) Strip heater capacitor bank not charged
3) IGBT switch temperature or voltage too high
4) Others

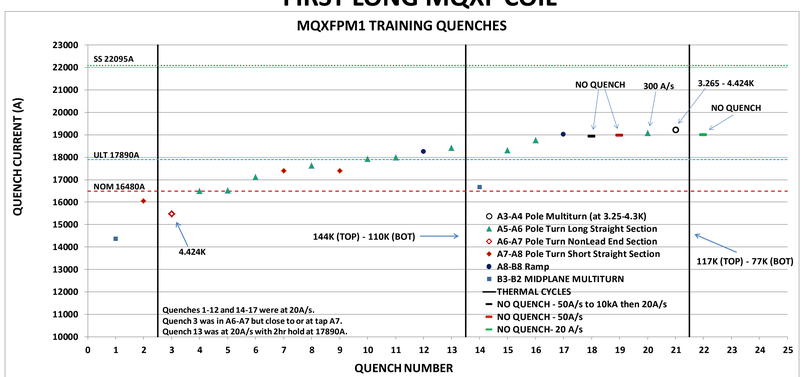
QUENCH PROTECTION HEATER FIRING UNITS FOR 12 INDEPENDENT CIRCUITS



TEST FACILITY COMMISSIONING

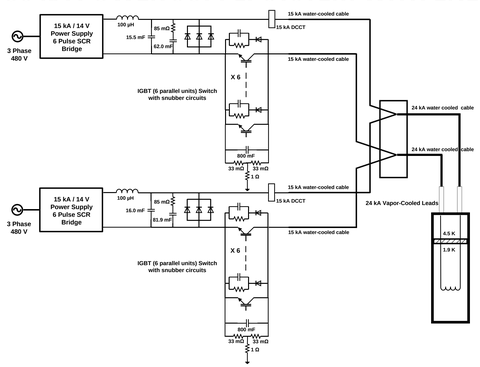
MQXFPM1 MIRROR MAGNET

FIRST LONG MQXF COIL

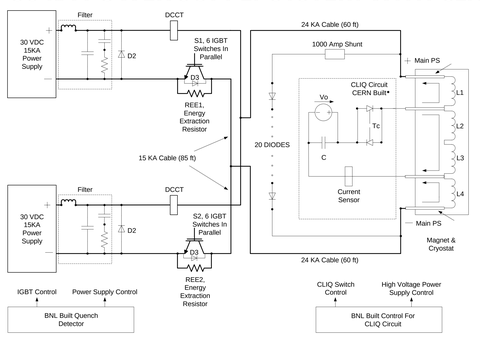


CONCLUSION As can be seen by the quench training results for the MQXFPM1 magnet, the upgraded facility as described here successfully fulfilled the acceptance test requirements for the MQXFA quadrupole magnets which are being built and supplied to the LHC for the insertion region Q1/Q3 of the high luminosity upgrade. These requirements include operation at 1.9 K at 1 bar, powering up to 19 kA, and proper protection of the magnet during quench testing. For the test of the MQXFPM1, quench protection included a newly designed and faster quench detection system, energy extraction with faster and state-of-the-art electronic switching using specially designed IGBT circuitry and infrastructure. Future magnets will be using the already upgraded energy extraction system with a higher power and more versatile dump resistors, and twelve new quench protection heater firing units, which meet the requirements for quench protection heater systems in the LHC.

30 kA POWER SUPPLY SYSTEM WITH ENERGY EXTRACTION



30 kA POWER SUPPLY SYSTEM WITH CLIQ



CLIQ (Coupling Loss-Induced Quench) is a system which provides quench protection, along with quench heaters and energy extraction.

FASTER HIGHER PRECISION DATA ACQUISITION SYSTEMS

FAST DATA LOGGER DAQ
National Instruments PXIe-4300 (16 Units)
Number of channels = 8 differential, simultaneous sampling
Analog input = ±10 V, ±5 V, ±2 V, ±1 V
ADC resolution = 16 bit
Sampling rate = 250 kHz max per channel
Time scale resolution = 10 ns
TOTAL CHANNELS = 128 differential, simultaneous sampling
Usage = fixed (main) voltage taps and configurable (auxiliary) voltage taps
Status: Assembled and Tested

SLOW DATA LOGGER DAQ
National Instruments PXI-6289 (4 Units)
Number of channels = 16 differential
Analog input = ±10 V, ±5 V, ±2 V, ±1 V, ±0.5 V, ±0.2 V, ±0.1 V
ADC resolution = 18 bit
Sampling rate = 500 kHz max multichannel (31.25 kHz max)
Time scale resolution = 50 ns
TOTAL CHANNELS = 64 differential
Usage = monitoring of vapor-cooled lead voltages, splice voltages, SC lead voltages, temperatures, LHe levels, and other instrumentation
Status: Assembled and Tested

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