TD-04-057
12/3/2004

Status of LQXB06 Quench Protection Heaters

Michael J. Lamm
December 3, 2004

Abstract

LQXB06 is a “Q2” element in the LHC IR inner triplet. It consists of two Fermilab-built MQXB magnets (Q2a,Q2b) internally bussed in series. Each MQXB has two heater circuits, each circuit providing full protection against excessive coil temperature and voltage to ground as a result of a spontaneous quench. During the cold test of LQXB06, one of the four heater circuits lost its electrical continuity. As this lost heater cause no danger to the LQXB06 operation, the test program was completed. Later, a determination of the continuity break was performed at room temperature, off the test stand. This report summarizes the test results, outlines the program to determine the location of the heater failure and discusses the consequences of this heater loss.
.

Test Particulars

LQXB06 was tested on the TD Magnet Test Facility in August September 2004. The "standard" test program was performed[1], a program which is designed to validate the agreed upon US LHC acceptance plan[2]. The program consists of training of the individual MQXB cost masses; electrical checks of the instrumentation and heaters; tests of the quench protection heater effectiveness; magnetic field harmonics and field strength measurements; and room temperature and cold alignment of the two MQXB magnetic axes. As part of the LQXB test program, a test report is being generated [3].

Prior to magnet quenching, each heater was successfully powered with 0 A and 3000 A magnet excitation current. After the second training quench of Q2a, the operators were unable to recharge the quench heater firing circuits. The firing circuit fault logic detected a loss of a "resistive load". At this point, we were only able to determine that the loss of continuity was in the liquid helium part of the test stand, the LQXB06 magnet or magnet/test stand interconnect.

The test program continued with three working heater circuits. All parts of the program were completed. As shown in the test report, both MQXB magnets in LQXB06 performed well. Quench training, magnetic field harmonics, field gradient strength, and alignment are all acceptable and consistent with other production magnets. There is no evidence that this heater failure has a negative impact on the other magnet acceptance parameters.

Heater Geometry

In order to discuss the heater location break, the geomerty of the heater circuit needs to be explained. The heaters consist of stainless steel strips ~15 mm wide and 25 microns in depth (the heater strips are plated with copper along the length to distribute the energy deposition, a detail that is not important for this discussion). The heaters are sandwiched between layers of Kapton, as shown in figure 1

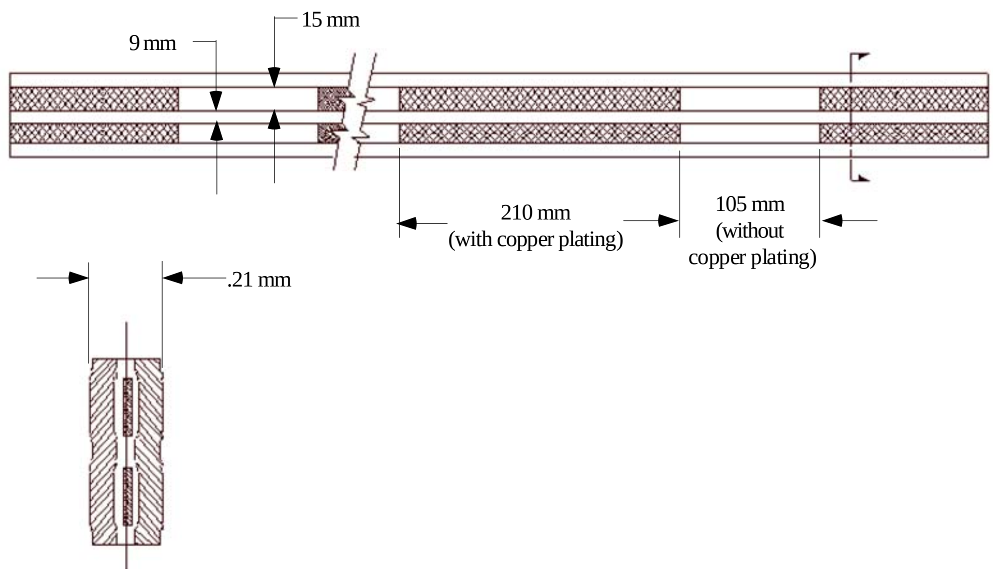

Figure 1 MQXB heater element. As shown consists of two heater strips sandwiched in between Kapton.

There are two heater elements/circuit, two strips/element and therefore four strips/circuit, each strip runs along the length of a quadrupole outer coil. The elements are placed between the coil and collar with additional kapton to reduce the possibilities of shorts. The heaters in elements H1&H3 series'ed together to make one circuit, H2&H4 makes the redundant circuit. See figure 2. The four strips/circuit are series'ed together through soldered jumper wire connections. The heater circuit leads are brought out to the instrumentation connector.

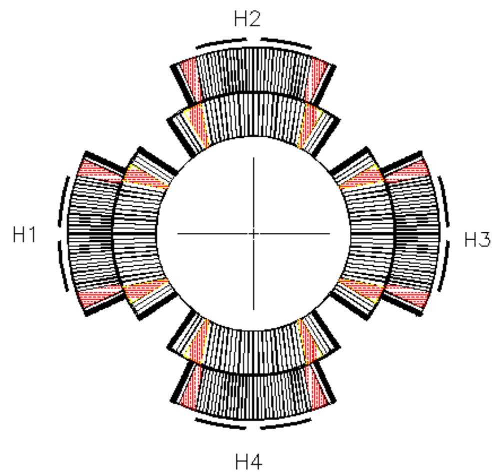

Figure 2. Heater placement in MQXB magnet The 4 heater strips in H1&H3 form one heater circuit, the 4 heater strips in H2&H4 form another.

Determination of Heater Break

After the magnet was warmed to room temperature, tests were performed on the test stand and LQXB06. The electrical continuity break was determined to be inside the LQXB06 (and not in the test stand.) There are no voltage taps in the heater circuit so resistance measurements do not provide any additional information on the break. The geometry heaters and electrical insulation make it possible to study the break exploiting the capacitance between the heaters and the quadrupole coils and collars. Tests were performed by the Technical Division Dev & Test Instrumentation and Controls Group. (Table1 and Figure 3 provided to me by Yuriy Pischalnikov of the I&C Group)

Figure 3 shows a schematic of the strip heater elements. Using the heater circuit lead wires, the capacitance of the heater circuit to the coils and collars is measured. The results are shown in Table 1. For a working heater circuit (resistance ~20 ohms) the capacitance is about 60 nF. for both the coil and the collar. The readings from + or - leads are the same, since they are connected symmetrically to the given heater circuit. The situation is different for Heater Q2a #2, which has the open circuit. Here the capacitance readings depend on the lead, with the + lead giving a value that is ~ 3 times the value of the - lead to coil or collar capacitance. The sum of the "+" and "-" lead capacitance roughly equals the capacitance of a "normal" heater circuit, as expected.

This leads to the conclusion that the break is 3/4 of the way from the + to the - heater circuit lead, as illustrated in figure 3. Unfortunately, it is difficult to make a more precise determination, since we don't have an independent determination of the heater-coil or heater-collar capacitance. There is also likely stray capacitance, capacitance between lead wires etc. We plan to explore this further, during the construction of the next MQXB cold mass, after yoking and skinning but prior to making the heater series connection.

.

	Q2A		Q2B	
	Heater#1	Heater#2	Heater#1	Heater#2
Resistance	20 Ohm	More than 20MOhm	17.9 Ohm	18.1 Ohm
Capacitance (+lead to Collar)	59.542 nF	45.750 nF	58.818 nF	61.708 nF
Capacitance (-lead to Collar)	59.540 nF	16.510 nF	58.821 nF	61.713 nF
Capacitance (+lead to SCCoil)	62.611 nF	47.523 nF	58.954 nF	61.845 nF
Capacitance (-lead to SCCoil)	62.606 nF	16.725 nF	58.952 nF	61.841 nF

Table 1 Room temperature resistance and capacitance measurements to determine location of heater failure.

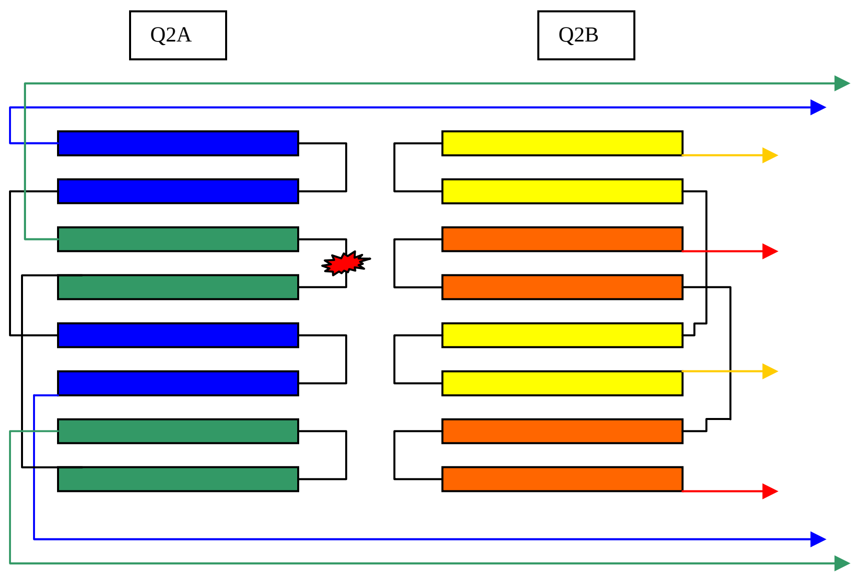

Figure 3. Schematic of Heater for LQXB. Each MQXB (Q2a,Q2b) has two heater circuits, identified with a color code. The approximate location of the circuit break is shown.

Despite the lack of resolution from the present measurement, it should be pointed out that a heater failure at the jumper connections is clearly the most likely place for a failure. The connection requires two solder splices. Furthermore, the portion of the heater element used for the soldered splice, (extending out of the magnet) is somewhat vulnerable to damage if not handled according to procedure.

Consequence of the Heater Failure

Proper heater performance is essential for the safe operation of the LQXB, to minimize the peak temperature and voltage to ground. Redundancy is built into the protection system, to reduce the risk. The MQXB magnets are designed to operate safely with one heater circuit. The series connection of two MQXB magnets into a LQXB adds some complexity to the protection. To understand these issues, several quench heater studies were performed on the 1.8 M models, the full length prototype MQXP01, and the first production LQXB01. A Laurea thesis was devoted to the study of the LQXB peak temperature and voltage to ground during various magnet and LHC operating parameters, including the loss of one or more heaters[4]. These results were published in a conference proceedings[5] and summarized in an internal memo[6].

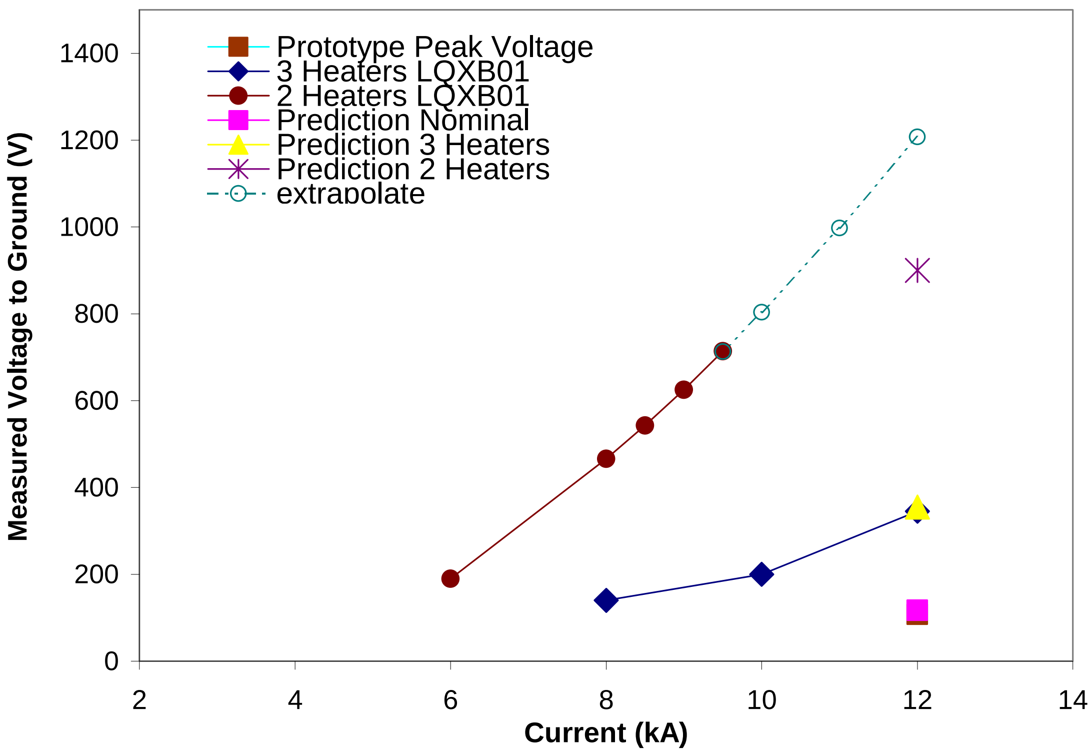

Figure 4 Heater Studies on LQXB01 and Prototype MQXP01

Luisa Chiesa's thesis predicts that a single powered MQXB with one heater will have a peak voltage to ground of about 120 volts; a LQXB (2 MQXB in series) with one heater missing will have a peak voltage of about 350 volts; a LQXB with one heater in each MQXB will have a voltage comparable to a single MQXB (135 V); a LQXB with a MQXB with two working heaters and a MQXB with working heaters will have a peak voltage of 900 volts. The "2 heater" prediction is based on Eddy current generated "quench back" in the unprotected MQXB. This quench back phenomena was observed in the model magnet program, during special heater tests with one unprotected quadrant. Note the voltage in the LQXB could be higher, up to 1100 V, depending on the effectiveness of the non-heater MQXB to generate this quench back resistive voltage.

Studies of magnets with missing heaters were performed with the full length prototype MQXP01 and the first production magnet LQXB01. The results are shown in Figure 4 and compared to prediction. The prototype, a single MQXB dipole, was tested with one heater circuit. The peak voltage to ground at 12000 amps was 120 volts. On LQXB01, tests were performed with three heaters active (one unused), as a function of current. The peak voltage to ground at 12000 amps was 350 volts. These results are in agreement with the model.

Finally, tests were performed on LQXB01 for the case with two heaters used on one MQXB, no heaters on the other MQXB. These tests were performed at a maximum current of 9500 amps, where the peak voltage to ground was measured to be 650 volts. (because of hipot problems with the test stand, the study was limited to this current). A simple quadratic extrapolation predicts a peak voltage at 12000 A to be 1200 Volts. This extrapolation is pessimistic, as it is an extension of data with no "quench back" It is expected that as with the model magnets, the "quench back" will be observed at the higher excitation currents, where the heaters will be more effective and the collapse of the magnetic field will occur more rapidly,

The results of these heaters studies show conclusively that LQXB can operate safely with three out of the four heaters operational. The voltage to ground under these circumstances will not exceed 350 volts. The case where there is only one heater circuit per MQXB is equally safe, with voltages on the order of 150 volts to ground, with slightly higher temperatures, but still below 300 K.

The case of two operational heaters in one MQXB and no operational heaters in the other MQXB has been modeled, but not verified experimentally. The model predictions are that the peak voltage will range from 900V to 1100 V, depending on the effectiveness of the non-heater MQXB to generate resistive voltage due to Eddy currents from the collapse of the LQXB magnet current during the quench process. Note that each LQXB is hipotted on the test stand in liquid helium to 1200 V. The inner triplet quadrupoles utilize "LHC standard" instrumentation and bus interconnects which are rated to operate without failure in this voltage regime.

Possibility of Future Heater Failures

An area of concern is the probability of an additional failure during operation. During the history of the LHC model, prototype and production program, this was the only heater to fail during testing. In the model programs, there were heaters which failed during cooldown, but this condition was attributed to improper strain relief of the heater leads. (The failure in LQXB06 occurred in the middle of the cold test program, and in a location with a very short wire jumper, separation of 9 mm, with good mechanical support). Admittedly the statistics are low (8 models, 1 prototype, 7 production tests) however the model magnet heaters were exercised 50 or more times during a test campaign, in multiple thermal cycles, with no failures during the cold test.

Summary

LQXB06 has a heater circuit which failed (open). The failure was detected after a spontaneous quench. The location of the heater element has been determined to be at or near the return end connection of one the Q2a heater elements. Further work is required to refine the location, although the magnet end is by far the most likely location.

This failure, while disappointing to occur in a production magnet is not in itself a serious problem for operation. With three operating heaters, LQXB06 performed well in every way, despite the missing heater. While there is a real concern about future heater failures, it should be noted that through hundreds of heater powerings in the model, prototype and production program, this is the only time a heater has failed during operation. The loss of an **additional** heater in LQXB06, could generate voltages to ground on the order of ~1000V, depending on which heater is lost. This voltage level, predicted from studies performed during the model program, is comparable to the expected peak voltage to ground for the arc dipoles [7], is lower than the cold hipot test level of 1200 V, and therefore would not be a problem for operation.

References:

[1] S. Feher, "LMQXB Production Test Plan", TD Internal Note TD-01-055
[2] M. Lamm "LQXB Acceptance Plan" LHC Document: LHC-LQX-ES-0013
[3] P. Schlabach "LQXB06 Test Report", TD Internal Note TD-04-056
[4] L. Chiesa, "Quench Protection Analysis for the Superconducting Quadrupoles Q2a/Q2b for the Inner Triplet of LHC", Laurea Thesis, Universita' Delgli Studi Di Milano, Academic Year 1999-2000.
[5] R. Bossert et. al., "Quench Protection of the Fermilab-built LHC Inner Triplet Quadrupole MQXB", IEEE Transactions on Applied Superconductivity, Vol 12, No. 1, p. 133, March 2002.
[6] L. Chiesa et al., "Measurement of Peak Voltage to Ground of LQXB Quadrupoles", TD Internal Note 03-023.
[7] F. Rodriguez-Mateos, "Voltage Withstand Levels for Electrical Insulation Tests on Components and Bus Bar Cross Sections for the Different LHC Machine Circuits", Engineering Specification LHC-PM-ES-0001 rev 2.0 Oct. 27, 2004.