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Quench Protection of the Fermilab-Built LHC Inner Triplet Quadrupole MQXB

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***Abstract*—High-gradient quadrupoles (MQXB) are being developed at Fermilab within the framework of the US-LHC Accelerator project for the LHC interaction regions. These 5.5-m-long magnets have a single 70-mm aperture and operate in superfluid helium at a peak gradient of 215 T/m. Magnet quench protection is provided by quench heaters installed on the outer surface of the coil. This paper reports the results of quench protection studies on the first full length MQXB prototype (MQXP01). The measurements from these tests as well as results from the 1.9-m-long model magnet program are combined with computer generated quench simulations to predict the MQXB performance under LHC operating conditions.**

***Index Terms*—Accelerator, quench protection, superconducting magnet.**

I. Introduction

QUENCH protection strip heaters have been shown to be effective at protecting 1.9-m–long model MQXB quadrupole magnets from excessively high temperatures and high coil to ground voltages, due to spontaneous quenches in superfluid helium [1]. Heater parameters such as heater location, coil to heater insulation and geometries were studied as part of the overall model magnet test program. Results from the final two model magnets HGQ08 and HGQ09 led to the choice of a heater design which was adopted for the full scale 5.5 m long MQXB magnets [2].

A full scale prototype (MQXP01) of the MQXB using the production style heaters has been successfully built and tested at Fermilab. The quench and mechanical performance as well as field quality are presented elsewhere at this conference [3], [4]. The results of the quench protection studies reported here are used along with model magnet data to predict the quench protection performance of the full scale MQXB in the LHC inner triplet. In the LHC, two 5.5 m long MQXB magnets (Q2a,Q2b) are combined into a single cryostat powered in series to form the central optical element Q2 in the final focus inner triplet.

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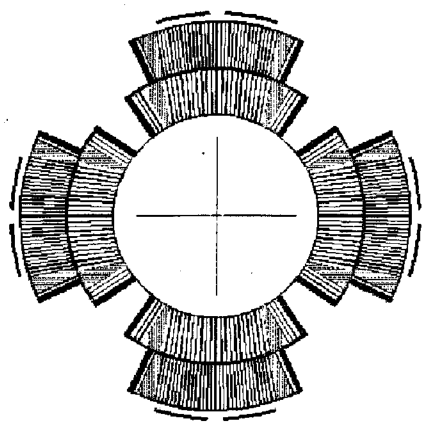

Fig. 1. Coil cross section. Coil aperture is 70 mm. Azimuthal location of quench protection heaters (H1–H4) are shown.

TABLE I
MQXP01 Heater Parameters

Location	Outer coil 2 mm from midplane
Material	Copper plated stainless steel
Copper thickness	4 μm
SS thickness	25 μm
Copper Plating	102 mm etched areas at 306 mm intervals
Width	15 mm
Insulation to Coil	225 μm

II. Magnet Description

Details of the baseline magnet design have been described elsewhere [5]. The cross section of the 70 mm aperture coil is shown in Fig. 1. These cold iron superconducting quadrupoles consist of eight coils positioned in a two-layer geometry. The coils are electrically connected in series through inner coil pole turn to outer coil pole turn splices in each quadrant and through midplane turn quadrant to quadrant splices.

The coils are made of NbTi Rutherford cable wrapped with Kapton tape with polyimide adhesive. The coil is insulated from the stainless steel collars with four layers of Kapton forming the ground plane.

The prototype magnet has been equipped with four protection heaters whose properties are shown in Table I, and their azimuthal positions are shown in Fig. 1. The heaters have a "racetrack" geometry covering approximately 10 turns of one side of two azimuthally adjacent coils. Two "opposite heaters" (H1 and H3 or H2 and H4) are connected in series to form a heater circuit. Each circuit provides protection to all four magnet quadrants.

Unfortunately, one of the MQXP01 heaters developed a short to ground during construction, therefore only one heater circuit was operational. A spot heater used for inducing quenches was placed adjacent to one of the outer coil pole turns. A 6 cm length of coil was segmented with voltage taps in order to measure the voltage growth from the spot heater induced quench.

III. Prototype Test Program

Tests were performed between May–August 2001 at the Fermilab Technical Division Magnet Test Facility. Magnet current is supplied by a 18 kA dc power system. The protection strip heaters are powered by a 900V (±450 V) power supply with 7.2 mF capacitance. The cold resistance of the strip heater circuit was 11 Ω giving an RC time constant of proximately 80 ms. The capacitance and power supply voltage were set to match the expected values in LHC operation.

During the course of the magnet quench training, three quench protection studies were performed. First, a study was performed at 670 A excitation current, the lowest expected injection current for the LHC operation, to see if the quench heaters could initiate a quench. The power supplies were turned off and the strip heaters were fired simultaneously. Except for room temperature bus resistance, the magnet absorbed all of the stored magnetic energy. The second data set was taken at 3000 A, which roughly corresponds to 20% of the measured short sample. Finally, at 12 000 A, a current corresponding to slightly above the peak operating LHC gradient of 215 T/m, a quench was induced using the spot heater in the outer coil pole turn.

IV. Protection Results

Fig. 2 shows t_{fn}, the time between quench heater firing and resistive voltage initiation, for the prototype in comparison to data taken in the model program. Note that the model heaters differed only slightly from the one used in the prototype MQXP01. All heaters have the same width and thickness. The prototype heater was placed approximately 2 mm (two turns) closer to the pole in order to place the heaters in a slightly higher field region. In HGQ09, the copper plating geometry had a 1 : 1 stainless steel : copper coverage. HGQ08 and the prototype had the same 1 : 2 stainless steel : copper coverage. However all tests were performed with the same heater peak power density (~45 W/cm^2) and circuit RC time constant (~80 ms).

The curves show the expected trend of decreasing t_{fn} with increasing excitation current. As shown previously in the model program [2], the t_{fn} performance is not sensitive to slight variations in heater geometry and this is still the case with the prototype magnet. The heater performance at 670 A (0.04 I/Ic) also demonstrates that the heaters are quite effective at initiating a quench over the entire range of operating currents.

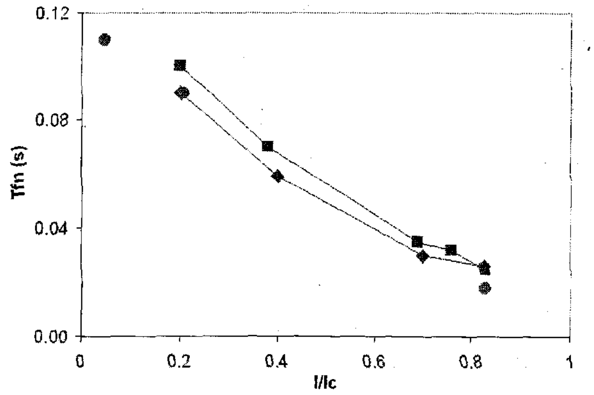

Fig. 2. The time difference from heater firing to resistive growth initiation, for production magnet(circles) and the last two MQXB model magnets HGQ08 (squares) and HGQ09 (diamonds).

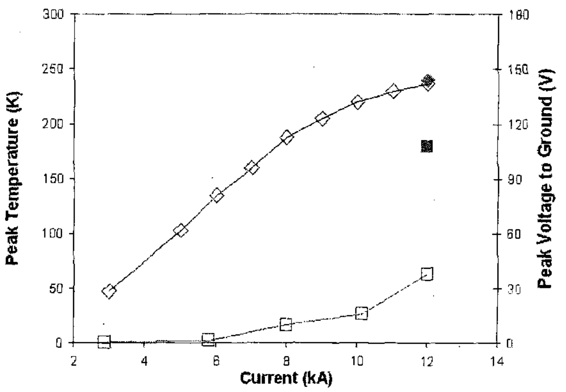

Fig. 3. Peak temperature (diamonds) and peak voltage to ground (squares). Closed symbols represent MQXP01 magnet, open symbols are model magnet results.

Fig. 3 shows the peak temperature and peak voltage to ground for the prototype magnet spot heater event, in comparison to data taken during the model magnet program. The peak temperature is inferred from the room temperature resistance of the 6 cm segment near the spot heater and the known temperature dependence of copper resistivity. The measured peak temperature is comparable to that found in with the model magnets. This is expected because the heater coverage and magnet inductance roughly scale with length, thus the power dissipation/length should be similar. There should be a small difference in the peak temperature since the resistive voltage from the spot heater quench does not scale with length, however this difference is likely within the estimated temperature measurement uncertainty of 25 K.

The peak voltage to ground is a consequence of an asymmetry between the resistive and inductive voltages in the magnet. Regardless of the location of the quench, the outer coils develops more resistance than the inner coils because of the location of the strip heaters. The peak voltage should scale approximately with magnet length since the strip heater resistance and magnet inductance scale with length. The peak voltage ratio between prototype and model magnets at 12 kA is 3.1 which is consistent with the expected value of 2.8.

V. Quench Model

A model was developed to predict the expected quench development for the MQXB and the full scale Q2 element in the LHC inner triplet. The quench model is explained in detail elsewhere [6].

The model simulates the quench development of the MQBX or Q2a/Q2b element from a spontaneous quench in the high field region of one of the outer coils. The Q2 system is modeled as a series connection of resistive and inductive elements. The segmentation is based on field distribution in the MQXB as well as the expected quench growth from the model magnet program studies.

The simulated quench is propagated longitudinally and radially from segment to segment using empirically measured quench propagation velocities from the model magnet as well as simple scales factors to account for variations in magnetic field [7].

The resistance growth in the model was first assumed to follow an adiabatic growth. In other words, the joule heating from the quenched portion of the magnet is absorbed by the coil material and causes the temperature to rise. However, in the model magnet program, the resistance growths from finely segmented coil segments near the spot heater were measured for several magnets and from several coil locations. It was observed that the adiabatic approximation predicts temperatures that are 20–30 percent higher than measured. Thus the adiabatic model does not adequately account for heat carried away from the joule heating. We therefore modeled the magnets with a quench integral vs. temperature curve scaled to match the measured values.

We also observed in the model magnet program as well as in the prototype that all coil segments become resistive after approximately 50 ms after the quench heaters become effective. This was observed even in coil segments that were not adjacent to a quench segment. In this time interval the current is changing rapidly due to the increase in energy dissipation from the heater-quenched coil segments. This effect is attributed to eddy current heating "quench back" and its resistive contribution is empirically included in the quench model.

The voltage from the spontaneous quench reached the quench detection threshold of 200–400 mV typically in 10 ms. The heater unit elements are assumed to fire at the quench detection time. The time of onset of resistive voltage from heater firing time, again measured from the model program is approximately 20 ms. The magnet circuit leads are shorted together creating a decaying L/R circuit, with magnet inductance matrix constant in time and current, but the resistance changing in time as the quench develops. The quench evolution is performed in small time increments, typically 1 ms. In this time window, the resistance is first allowed to evolve due to propagation and temperature increase. For the purpose of calculating decay, the resistance is then assumed to be constant. This process is iterated until the current in the magnet goes to zero.

VI. Model Results

The model was first applied to the MQXB prototype magnet, using the same quench threshold detection times as in the Fermilab magnet test facility. The predicted peak temperature is 240 K and the predicted peak voltage is 100 V, in good agreement with the measured values of 240 K and 118 V.

In the LHC, two 5.5 m long magnets are combined into a single cryostat powered in series to form the central optical element (Q2) in the final focus inner triplet. While the powering of the Q2 is coupled to the Q1 and Q3 MQXA the quench protection is largely decoupled through the use of current bypass diodes [8]. Thus the quench protection problem can be simplified to consider a singly powered Q2a/Q2b system consisting of two MQXB magnets. When a quench is detected the power supplies is turned off, the heaters fired and the leads are shorted together. We use a 250 mV detection threshold and a 10 ms detection integration time delay. We consider the case where a quench occurs at the operating gradient 215 T/m, in the outer coil pole turn, which is the high field region in the outer coil.

Studies were performed with this model to understand the effect of expected variations in cable RRR, heater t_{fn}, the onset of quench back and heater failure modes, on peak temperature and voltage to ground. RRR variations of 20% had little effect on the system parameters. The system was also insensitive to 20 ms variations in the onset of quench back. Systematic differences of 10 ms in heater t_{fn} between Q2a and Q2b can increase voltage to ground by ~100 V, while systematic delaying of the

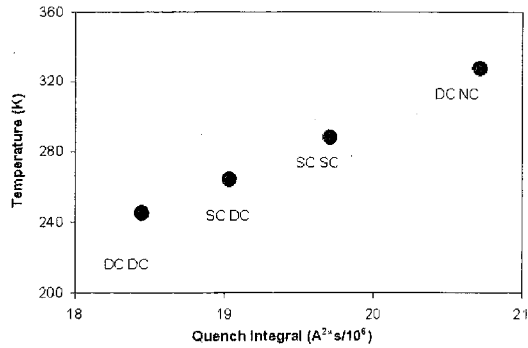

Fig. 4. Predicted peak temperature for Q2a/Q2b pair: DC DC both heater circuits fire on both MQXB (nominal), SC DC both fire on one MQXB, only one fires on the other, SC SC one heater/MCBX fires, DC NC both fires on one MQXB no heater circuit fires on the other.

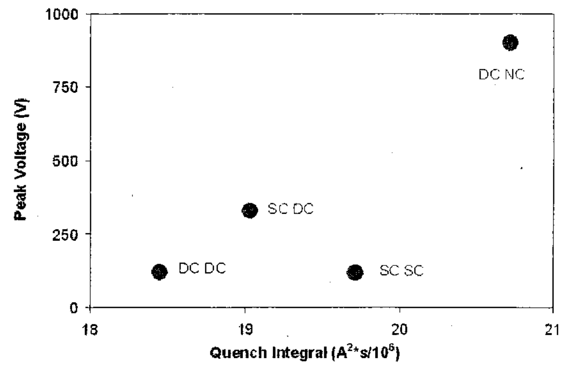

Fig. 5. Predicted peak voltage to ground for Q2a/Q2b pair: DC DC both heater circuits fire on both MQXB (nominal), SC DC both fire on one MQXB only one fires on the other, SC SC one heater per MCBX fires, DC NC both fire on one MQXB no heater circuit fires on the other.

heater firing for both Q2a and Q2b by 10 ms increases the peak temperature by ~30 K.

As previously stated, each MQXB has two heater circuits for quench protection redundancy. During normal operation each of the four heater circuits from each of the two MQXB in the Q2 will be fired. For the study of heater failures, we considered the following cases involving none, one or two heater failures: 1) nominal, both MQXB magnets have double heater coverage (DC DC), 2) one magnet has double coverage, the other has a single heater covered (DC SC), 3) both MQXB have a single coverage (SC SC) and 4) the case where one heater has double coverage while the second MQXB has no coverage (DC NC). The single coverage heaters was most widely used throughout the model and prototype program in order to establish the minimum quench protection required. Note that the final two scenarios would require a multiple failure in the quench protection logic.

Fig. 4 shows the expected peak temperature as a function of quench integral for these four scenarios. The peak temperature increases with increasing quench integral, which is expected from an adiabatic model and observed in the model magnet program. As expected, an increase in peak temperature is observed in the failure scenarios. Less heater coverage translates into larger quench integrals and peak coil temperatures.

The expected peak voltage to ground is shown in Fig. 5. These voltages are largest in the cases where there is an unequal coverage of heaters between the Q2a and Q2b magnets. In the case of one heater failure (SC DC) the voltage to ground is estimated to be less than 400 V.

VII. Conclusion

Quench protection results from MQXP01 demonstrate that the full scale magnets are protected against excessive peak temperature and voltage to ground. The peak temperature for a spot heater induced quench and peak voltages to ground are well below the design limits of 400 K and 1000 V, respectively, [9]. Results are consistent with data previously presented from the 1.9 m long magnet program.

Results from prototype and model program as well as our quench model show that the peak temperatures in the LHC inner triplet will be acceptable, even in the case of a heater failure.

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