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Quench Protection Study of a Prototype for the LHC Low-Beta Quadrupole Magnets

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¹Abstract—LHC low-beta quadrupole magnets are being developed at KEK as part of the collaboration between CERN and KEK. Based on R&D progress of five 1-m long model magnets, a full-scale 6.7-m long prototype was developed and excitation tests were performed at KEK. A magnet protection scheme for the full-scale magnet is very important in case of the quench because a large stored energy has to be fully dissipated into the coils. The quench protection system which consists of heaters and power supplies was examined in a series of heater tests for the prototype. It was concluded that the quench protection system will protect the production magnet even in the worst quench situation.

Index Terms—LHC, quench protection heater, spot heater, superconducting quadrupole

I INTRODUCTION

Superconducting low-beta quadrupole magnets are being developed at KEK as part of the collaboration between CERN and KEK for the LHC [1]–[3]. KEK is responsible for providing eighteen 6.7-m long production magnets (MQXAs) including two backups. Four quadrupole magnets, two MQXAs of KEK and two MQXBs of FNAL, will be assembled into a common cryostat and installed in an insertion region of the LHC [4]. These four magnets will be energized in series at the LHC operation [5]. Each magnet must be individually protected by using diodes and quench protection heaters (QPHs) in case of a quench. A magnet protection scheme is very important because external dump resistors will not be used. A large stored energy will have to be safely dissipated into individual magnet. The QPHs are fired to induce a large amount of resistive region so that the energy deposition into a local spot is avoided.

Based on the R&D program of five 1-m long model magnets [6]–[9], the first full-scale prototype, MQXA-P1, was constructed and excitation tests were performed at KEK. MQXA-P1 was designed identically to the production magnets and was protected by the QPHs installed between coils and non-magnetic steel collars. Local spot heaters were set in MQXA-P1 to demonstrate the worst quench situation. Several heater tests were performed to evaluate the QPHs performance, maximum temperature and voltage of the full-

scale magnet were measured at the quenches. In this paper, the quench protection study of MQXA-P1 is described.

II HEATER SPECIFICATIONS AND QUENCH PROTECTION SCHEME

Based on the quench protection study for the 1-m model magnets [10], [11], the QPH design for MQXA was finalized by KEK and CERN. CERN provides QPHs including the heater leads. The QPH consists of stainless steel foils 50 % copper-plated, Kapton insulation films and copper electrodes. Two heater strips are sealed in Kapton films and heater cables of AWG-20 are soldered with Ω shaped electrodes at both heater ends. A simplified drawing of the QPH is shown in Fig. 1. Summary of the QPH specifications is listed in Table I. There are four QPHs covering outer surface of the coil. Each of eight heater strips is set on the octant. Every QPH with two heater strips simply covers the corresponding quadrant coil such as Q1A and Q1B in Fig. 1.

A power supply with a capacitance of 7.05 mF and a maximum voltage of 900 V is used to fire the QPHs. When the magnet quench is detected, a quench detector triggers the power supply to discharge a maximum energy of 2.9 kJ. One power supply is connected to four heater strips in series and all quadrant coils can be quenched. The heater connection is given in Table I. The quench protection system consists of two heater circuits and either of them was designed to protect the magnet. One circuit can protect the magnet with initiating the quench even if another power supply fails to fire.

TABLE I
SUMMARY OF QUENCH PROTECTION HEATER SPECIFICATIONS

QPH	
Strip	Stainless steel (SUS) with Cu plating
Strip Size (L*W*T)	6517 mm*15 mm*25 μ m
Cu Plate Thickness	4 μ m
Interval of Cu and SUS	120 mm / 120 mm
Resistance at 1.9 K	4.9 Ω / 9.8 Ω
Strip / QPH	
Insulation	Kapton Film
Insulation Size (L*W*T)	6517mm*111mm*200–225 μ m
Power Supply	
Capacitance (mF)	7.05 mF
Maximum Current	46 A
Maximum Voltage	900 V
Time Constant	138 msec
Stored Energy	2.9 kJ
Connection	
Power Supply-1	HT1A - HT2A - HT3A - HT4A
Power Supply-2	HT4B - HT1B - HT2B - HT3B

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Fig 1 Simplified drawing of the quench protection heater (QPH) Left hand is the cross sectional view from the lead end which shows the arrangement of the QPHs on the coil surface Right hand shows the top view of the QPH

III EXPERIMENT

A Circumstances of KEK Cold Test Stand and LHC Operation

Prior to a shipment of MQXA to FNAL, performance tests at 1.9 K will be carried out at KEK. It is planned that a magnet will be trained up to a field gradient of 230 T/m which is a criteria required for the quench performance of MQXA. After an achievement of 230 T/m, a full energy dump test will be carried out. The QPHs will be fired to induce the quench without the dump resistor. The magnet performance will be confirmed by the ramp to 220 T/m right after the full dump. The quench protection system for the 6.7-m long magnets must function not only for the LHC operation but also for the quench test at KEK test stand.

To evaluate the quench performance and the protection system for the 6.7-m long magnet, series of quench tests were made for MQXA-P1 under the same condition as MQXA testing. The training was performed with a ramp rate of 10 A/sec. The stored energy was partially extracted by the dump resistor of 100 mΩ and temperature increase in the He-II bath was reduced, a recovery time was intended to be minimized. Voltage between both current leads, however, was expected to be around 800 V for the training quench around 230 T/m. For this reason, a middle point of the dump resistor was grounded and the voltage between leads was reduced to be half. Once the magnet was confirmed to reach 230 T/m, the full energy dump tests were carried out. The QPHs and the spot heater were fired to induce the quench without the dump resistor. In these cases, the total voltage was clipped around 20 V by diodes in a magnet power supply. It means that the full energy dump test at KEK can simulate the situation of the LHC operation.

B Quench Protection Tests During Training Quench

After the QPHs in MQXA-P1 were fired several times at the beginning of the quench tests, one heater circuit signal showed unusual behavior. We bypassed suspicious heater strips from the circuit. Instead, we connected the dummy resistor outside of the cryostat. The circuit specifications such as time constant, peak voltage and maximum current were not changed after the replacement. The following quench tests,

therefore, were carried out with firing two or three QPHs. In any case of the QPHs firing, the power supply was fully charged up to 900 V. An integration time and a threshold level of the quench detector were set to be 10 msec and 0.2 or 0.5 V, respectively.

Fig 2 Current dependence of Δt , time between QPHs firing and the normal zone initiation

Fig 3 Overview of the instrumentation signals at the typical training quench

1) QPH Performance

Fig 2 shows current dependence of Δt , time between QPHs firing and the normal zone initiation. This value could

be an index of the heater effectiveness lower Δt can decrease MIITs, time integral of a square of the current normalized to 10^6 , and the maximum coil temperature can be lowered

We attempted to induce the quench at 450 A corresponding to the LHC injection current by using the QPHs, but the quench did not occur. The minimum quench current was measured to be 500 A with Δt around 150 msec. Δt decreased with the current and was saturated to be around 20 msec at the nominal operation current of MQXA. It was confirmed that the prototype result was consistent with 1-m long Model #3.

Fig. 3 displays an overview of instrumentation signals at a typical training quench. The QPHs were simultaneously fired as the magnet power supply was shut down at $t = 0$. The resistive region in the outer coil, which is not obviously seen in this figure, was produced by the QPHs around $t = 20$ msec. Increment of the resistance by QPHs in the main circuit resulted in large derivative of the current respect to time. AC loss was enhanced. Quench back in the inner coil caused by the AC loss can be observed around $t = 50$ msec.

2) MIITs and Maximum Voltage

As mentioned above, the dump resistor of 100 m Ω was used during training quench tests. The MIITs and the extracted energy ratio, the extracted energy by the dump resistor normalized to the stored energy, during the training are plotted in Fig. 4 as a function of the quench current. Four lower quench currents below 6200 A were induced by a turn to turn short in a coil. Detailed report on the turn to turn short of MQXA-P1 can be found in [3]. The MIITs widely ranged from 8.6 to 11.3 and the maximum coil temperature was estimated to be 150 K to 200 K. The maximum temperature during the training was much lower than the critical temperature of 350 K.

At the lower current, the resistive region induced by the QPHs was hardly developed in the coil because the superconducting cable had sufficient margin to critical surface. The resistance of the dump resistor was dominant in the main circuit at the lower quench current and majority of the stored energy was extracted by the dump resistor. The resistive region in the coil became dominant with an increase of the quench current; the extracted energy ratio linearly decreased. However, the ratio was accordingly saturated to be around 0.3 to 0.35 at the quench current above 7500 A.

Fig. 5 shows a voltage map in the magnet at the highest quench current of 7716 A ($G = 232$ T/m). During quench tests, the voltage of each eight coil was separately measured. Then the voltages at lead splices where the leads from different coils were connected were normalized from the negative lead end, not from the ground. For example, the voltage at "B" in Fig. 5 was the summation voltage of Q3 inner- and outer- coils, not the voltage between "A" and "B". The voltage at "H" corresponding to the voltage between both current leads showed the maximum voltage around 800 V in comparison with "A" to "G" and the unbalanced maximum voltage in the coils was not observed. Similar voltage maps were reproduced in another training quenches; the maximum voltage always appeared at "H" and never exceeded the expectation of 450 V from the ground.

Fig. 4 MIITs and extracted energy normalized to the stored energy during the training quench tests

Fig. 5 Voltage map in MQXA-P1 at the highest quench current of 7716 A ($G = 232$ T/m). The voltages at the splices were normalized from the negative lead end, not from the ground.

C Quench Protection Tests At Full Energy Dump by Spot Heater Quench

To simulate the worst quench at the LHC operation, the local spot heater was installed in the lead end of the median plane of the 3rd layer coil; it was expected that the normal propagation velocity was lowest and that the normal zone mostly propagated into the magnet center, not to the lead splice. Fig. 6 shows the MIITs by the spot heater quench as a function of the threshold voltages of the quench detector. The integration time of the quench detector was 10 msec. At first, the spot heater quenches with the dump resistor of 100 m Ω , closed diamonds, were performed to study the threshold dependence of the time between the normal zone appearance and the shut down of the main power supply. The MIITs before the shut down were determined. Next, the full energy dump tests by the spot heater quench were carried out at the minimum threshold of 0.05 V to avoid the serious problem and the MIITs after the shut down was obtained. When we assume that the normal zone induced by the spot heater was negligible and that the whole resistive region in the magnet was produced by the QPHs firing, the MIITs after the shut down was independent of the threshold of the quench detector.

By the summation of both MIITs, the total MIITs at different threshold levels can be predicted and are indicated as open squares and circles. The maximum MIITs was evaluated to be 18.3 with two QPHs firing at the threshold of 0.2 V which will be set at the LHC operation. The maximum coil temperature was around 320 K. It did not exceed the critical temperature of 350 K. It was confirmed that even the one heater circuit consisting of one power supply and two QPHs can protect the magnet from the worst quench situation. The calculation results by QUABER were also displayed in Fig. 6, but there is a large discrepancy between the experiment and the calculation. This may result from a wrong setting of the adjustable parameters such as normal propagation velocity. For improvement, appropriate parameters based on the experiments should be adopted to the calculation model.

Fig. 6 MIITs at the full energy dump by the spot heater quench as a function of the threshold voltages of the quench detector

Fig. 7 Voltage map in MQXA-P1 at the full energy dump by the spot heater quench. The voltages at the splices were normalized from the negative lead end, not from the ground.

Fig. 7 shows the voltage map in the magnet at the full energy dump by the spot heater quench. As explained in Fig. 5, the voltages from the negative lead end were displayed in this figure. The total magnet voltage, the voltage "H", was

clipped around 20 V by the diodes. The voltages, however, were distributed inside of the magnet and the maximum voltage was observed around 100V at "E". This value corresponded to the maximum voltage around several 10 V from the ground and it still had much sufficient margin to the expectation of 450 V.

IV SUMMARY

The quench protection tests were performed for the 6.7-m prototype of MQXA at KEK. The maximum temperature and voltage in case of the quench were estimated for the LHC operation and for the KEK test stand. It was confirmed that the quench protection system for MQXA functioned well and the magnet will be protected even in the worst quench situation.

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