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LHC Project Report 419

PROTECTION OF THE SUPERCONDUCTING CORRECTOR MAGNETS FOR THE LHC

R.Schmidt[1], C.Giloux[1], A. Hilaire[1], A Ijspeert[1], F. Rodriguez-Mateos[1] and F. Sonnemann[1],[2]

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Presented at the Seventh European Particle Accelerator Conference (EPAC 2000)
26-30 June 2000, Vienna, Austria

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Geneva, 23 September 2000

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In the LHC about 6500 superconducting corrector magnets will be powered either in stand-alone mode or in electrical circuits of up to 154 magnets. Single corrector magnets are designed to be self-protected in case of a quench. The protection scheme of magnets powered in series depends on the energy stored in the magnet and on the number of magnets in the circuit. A quench is detected by measuring the resistive voltage of the circuit. The power converter is switched off, and for most circuits part of the energy is extracted with a resistor. Some magnets may require a resistor or possibly a diode parallel to the magnet in order to avoid overheating of the superconducting wire or an unacceptable voltage level. Experiments have been performed to understand quenching of prototype corrector magnets. In order to determine the adequate protection schemes for the magnet circuits the results have been used as input for simulations to extrapolate to the LHC conditions.

1 INTRODUCTION

The superconducting corrector magnets of 15 different types will be powered in about 1500 electrical circuits. The parameters for the magnets considered in this report are given in Table 1. Inside the cold mass of the dipoles, sextupole, octupole and decapole magnets ("spool pieces" - MCS, MCO and MCD) will compensate imperfections of the dipole magnetic field. To correct the chromaticity, sextupole magnets (MS) are installed close to the main quadrupole magnets. Each orbit corrector magnet (MCB) at the arc quadrupole is connected to its power converter via a local current feedthrough. Other orbit corrector magnets are for the insertions (MCBY and MCBC). For correction of the betatron tunes and matching of betatron functions, small quadrupole magnets are installed close to the main quadrupoles in arcs and dispersion suppressors (MQT and MQTL). For magnets powered in series, a large number of superconducting bus bars run through the cryostats connecting the corrector magnets in various circuits fed from feed boxes at the end of the arcs.

Each of the eight LHC sectors will be powered independently to limit the amount of energy stored in the circuits for main dipole and quadrupole magnets [1]. The powering scheme is similar for corrector magnets with the consequence of a large number of circuits.

The corrector magnets are designed to operate at a current substantially below the critical current of the superconductor, typically at 60 %. A quench of a corrector magnet cannot be excluded and protection is required, although, in case of beam loss, it is unlikely that a corrector magnet quenches without a quench in an adjacent main dipole or quadrupole magnet. After a quench in a main magnet, it is foreseen to discharge all electrical circuits in the sector.

For reasons of standardisation only four types of superconducting wires are being used to wind the coils for corrector magnets.

TABLE 1: Parameters of corrector magnets, electrical circuits and protection schemes

Name		MCS	MCD	MCO	MS	MQT	MQTL	MO	MCB	MCBY	MCBC
Description		Spool piece 6-pole	Spool piece 10-pole	Spool piece 8-pole	Chrom. 6-pole	Tune trim quadrupole	Matching quadrupole	Arc 8-pole	Orbit dipole arc	Orbit dipole insertion	Orbit dipole insertion
Wire section	[mm^2]	0.689	0.689	0.214	0.689	0.689	0.689	0.689	0.110	0.214	0.214
Cu/SC		1.6	1.6	4	1.6	1.6	1.6	1.6	4	4	4
Mag.L	[m]	0.11	0.066	0.066	0.369	0.32	1.3	0.32	0.65	0.90	0.90
Induct.	[mH]	0.8	0.4	0.4	36	31	120	1.5	7000	5260	2840
Nom.I	[A]	550	550	100	550	550	550	550	55	72	100
dI/dt	[A/s]	10	10	10	0.5	0.5	0.5	10	1	1	1
Max. Family size		154	77	77	12	8	5	12	1	1	1
Energy/circuit [kJ]		18.6	4.66	0.154	64.8	37.6	91	2.7	9.2	13.6	14.2
Energy extraction		Yes	Yes	No	Yes	Yes	Yes	Yes	No	No	No
R_{par}	[Ω]	0.08	No	No	0.15	0.25	0.2	No	No	No	No
I_{leak}	[A]	0.1	0	0	0.12	0.08	0.3	0	0	0	0
Heatload	[mW]	0.8	0	0	2	1	18	0	0	0	0

2 PROTECTION PRINCIPLES

The protection of main dipoles and quadrupoles requires a quench detector for each magnet, heater strips on the coils pulsed by power supplies after quench detection, cold bypass diodes and extraction of energy with a dump resistor switched into series with the magnet chain [2]. Such a protection cannot be considered for corrector magnets, since this would be an over-design and the number of magnets would make such a scheme too expensive and complex, possibly compromising reliable operation of the LHC.

If no other precautions were taken, all the energy in one electrical circuit would be deposited in the quenching magnet. One could increase the copper stabilisation taking into account the energy stored in the electrical circuit but the copper cross section is not a free parameter. Other ideas for the protection had to be developed and validated, such as installing resistors in parallel to the magnet to absorb part of the energy [3], and extracting the energy using a switch as for the main magnets. Protection with diodes parallel to corrector magnets mounted inside the cold mass has also been considered.

For all electrical circuits with corrector magnets the resistance in the circuits is monitored by measuring the voltage with taps at the bottom of the current leads. The inductive voltage during current ramp is subtracted. When a threshold of between 0.1 V and 0.5 V (to be determined) is exceeded, the power converter is switched off. If the energy in the circuit is small relative to the magnet parameters, the magnet can absorb it without overheating and no further protection is required.

The maximum temperature in a magnet after a quench is a function of the quench load $\int I^2 dt$ [4], and depends on the excitation current, the wire and magnet parameters, the quench detection time and voltage threshold for detection, and on the parameters of the magnets and the electrical circuit. The time to detect a quench is determined by the quench propagation along the superconducting wire and by the time for the quench to propagate from one turn to the next. The first contribution to the quench load comes from the time between start and detection of the quench, including a short time (~10 ms) to validate the signal. During this period the current remains constant. The second contribution comes from the decay of the current after detection.

In order to reduce the quench load, as a first defence, a resistor $R_{\_ext}$ can be switched in series after quench detection. The time constant for the discharge is approximately given by $\tau = L/R_{\_ext}$. The value of the resistor is limited by the voltage that commercially available switches can tolerate (about 440 V). For redundancy, the opening of the switches is performed with different modes, and takes 10-25 ms.

In some of the circuits the stored energy is too large and the time for the current decay is not acceptable. Therefore it can also be considered to install a resistor $R_{\_par}$ parallel to the magnet at cold to bypass the current during a quench. For protection, the value of the resistor should be small, however, the value of $R_{\_par}$ should not be too low due to the leakage current ($I_{\_leak}$) during a current ramp caused by the inductive voltage across the magnet: $I_{\_leak}(t) = dI(t)/dt * L / R_{\_par}$

The leakage current could have an impact on beam operation, and possibly needs to be taken into account in programming the current ramps. During the ramp, an additional heat load for the 1.9 K cryogenic system has to be considered: $P(t) = (dI(t)/dt)^2 * L^2 / R_{\_par}$

3 HOW TO DETERMINE PARAMETERS OF THE PROTECTION SCHEMES

The maximum temperature after a quench in a magnet and the voltage distributions in the electrical circuit is calculated with QUABER [5]. The coils of corrector magnets are impregnated, and a conservative limit for the hot spot temperature is 200 K. Inputs to the program are magnet and circuit parameters, as well as longitudinal and transverse quench propagation velocities. The quench propagation velocity is a critical parameter for the protection since it determines the resistive growth. It has been measured on a number of corrector magnets and predicted by simulation programs [6]. For the MQT magnet the quench velocity has been measured to about 10 m/s at 300 A, to 40 m/s at 600 A [7]. Earlier measurements of the time for a quench to propagate to an adjacent turn in prototype magnets yielded values of about 2-3 ms [8].

As an example of a simulation result, current decay and temperature variation during a quench are shown in Fig. 1 for the MCO magnet in a circuit with 77 magnets.

A prototype of the MCS magnet with a resistor of 0.075 Ω across the magnet has been tested [9]. The magnet that has an inductance of 0.8 mH was powered in series with two other superconducting magnets with a total inductance of 152 mH, to simulate the electrical circuit in the LHC. The MCS magnet was quenched at various current levels with a spot heater. Fig. 2 shows the currents in magnet and resistor as a function of time during the quench. As expected, most of the energy is deposited into the resistor. The maximum temperature of the magnet did not exceed 140 K.

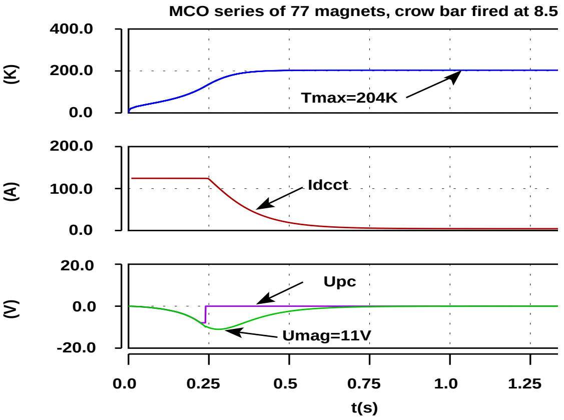

Fig. 1: QUABER results: current decay, temperature, and voltage for a MCO magnet during a quench.

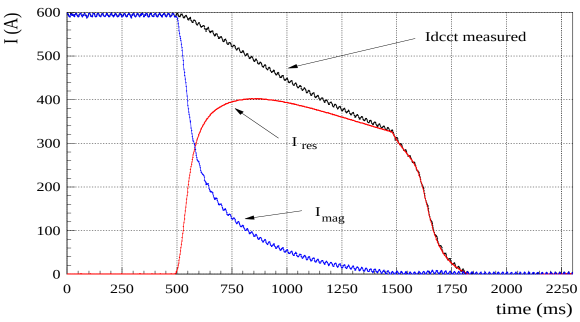

Fig. 2: Current sharing between magnet and resistor for a quench in a MCS magnet [9]

4 PROTECTION SCHEMES

Spool piece magnets: For the MCO with an energy in the circuit of only 0.15 kJ it is sufficient to switch off the power converter. For the MCD an energy extraction system is required. The protection of the MCS foresees energy extraction and resistors parallel to each magnet.

Closed orbit corrector magnets (MCB, MCBY): The magnets are powered individually. Since their number is substantial (about 1000), the protection should be simple. The maximum voltage that the power converter can deliver is about 8.5 V. After a quench at nominal current this voltage is exceeded after about 170 ms for the MCB (60 ms for MCBC and MCBY), and the power converter activates a crow-bar parallel to the magnet. The current decays, and the energy is deposited into the magnet. The hot-spot temperature expected from QUABER calculations is about 180 K.

Lattice corrector magnets: The energy stored in the electrical circuits with lattice corrector magnets could heat one coil of one magnet to a temperature as large as 500 K. A resistor of about 0.15 Ω parallel to each MS magnet limits the temperature to below 200 K. The 0.12 A leakage current during ramping could be taken into account in the programming of the current ramps. Experiments are under way to investigate if a higher value of the resistance could be acceptable for magnet protection, since this would simplify ramping. For the MQT and MQTL magnets, a value of the parallel resistor of 0.25 Ω / 0.2 Ω is acceptable for magnet protection and operation. The heat load for the cryogenic system is negligible. For the MO magnets no parallel resistors are required.

5 CONCLUSIONS

It has been shown that all corrector magnets for the LHC can be safely protected in case of a quench using 1) a global detection system, 2) energy extraction for some of the circuits and 3) resistors parallel to magnets for some circuits. Some questions are being studied, how to integrate the protection of current leads and superconducting bus bars into the general protection system, to establish the maximum temperature acceptable for safe operation of a magnet and to find an optimum value for the parallel resistors acceptable both for protection and beam operation.

6 ACKNOWLEDGEMENTS

The corrector team instrumented the prototypes and the MTA team performed the tests, their work is gratefully acknowledged. O.Brüning provided us with the ramp rates. We also like to thank F.Bordry, K.Dahlerup-Petersen, R.Denz, D.Hagedorn, L.Hall, P.Proudlock, N.Siegel, T.Taylor and L.Walckiers for their valuable contributions and discussions.

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