PROTECTION OF LHC SUPERCONDUCTING CORRECTOR MAGNETS

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Abstract

The protection of superconducting magnets in case of a quench has to be considered already in the design phase for the proton-proton collider LHC. The protection of main dipole and quadrupole magnets, based on cold diodes and quench heaters, is reported elsewhere [1]. In this paper the protection of other magnets is discussed. In the arcs some of the magnets are connected in series : sextupole magnets to correct the lattice chromaticity, small sextupole and decapole magnets to correct systematic field errors of the dipoles, and octupole magnets. The magnets in the arcs to correct horizontal and vertical closed orbit excursions are powered individually. In the insertions other superconducting magnets will be used : quadrupole magnets for the low-beta insertions, orbit corrector magnets etc. Some magnets will be constructed with sufficient copper stabilization to safely absorb the energy. For other magnets different methods of protection after the detection of a quench in the circuit are envisaged.

1 PROTECTION OF SUPERCONDUCTING MAGNETS

For the protection of LHC main dipole and quadrupole magnets quench heaters and diodes will be used [1]. After the detection of a quench, the heaters are fired and the power converter is switched off. During the slow discharge after a quench the current passes through the bypass diode of the magnet which quenched. To reduce the time constant for the discharge of the other magnets a resistor is switched in series.

Corrector magnets can be protected without heaters and diodes. By sufficient copper content in the superconducting cable the heating of the hot spot (the origin of the quench) is limited. For corrector magnets this is of great interest, because the cost for the total amount of copper is small compared to the cost of the magnets, and the performance is hardly affected. For the main dipole and quadrupole magnets operating close to the short sample limit such protection compromises the margin and is therefore not desirable.

A resistor can also be switched into the corrector circuit after quench detection. For magnets without diodes the current decays with a time constant which depends on the sum of the resistance of the quenched magnets and the resistor in series. Another protection method used in certain circumstances is with a resistor installed parallel to the magnet. When the magnet quenches, the resistance of the magnet increases, and the current is shared by both magnet and resistor in parallel.

2 ESTIMATION OF MAGNET TEMPERATURE AFTER A QUENCH

A simple calculation yields a lower limit for the magnet temperature after a quench :

- The total energy stored in all magnets connected in series is calculated : $E_{\mathtt{total}} = 0.5 \times n \times L \times I^2$ (with I the initial current, L the inductance of one magnet, n the number of magnets connected in series)
- It is assumed that only one magnet quenches, either only one pole or all poles. During the tests of prototype magnets it has been frequently observed that the quench remains in one pole [2], therefore such an assumption is not too pessimistic. It is further assumed that the energy is absorbed uniformly in the winding volume of one pole.
- The specific energy (the energy absorbed by a unit volume of cable), is given by : $E_{\mathtt{spec}} = E_{\mathtt{tot}}/l \times A$, with l the length of the cable in the magnet, and A the metal cross-section. From the specific energy and the enthalpy of the NbTi - Cu cable the average temperature is calculated. If, assuming uniform energy distribution, already this temperature exceeds the maximum allowed temperature, the magnet needs to be protected.

If a resistor is switched into the circuit after the detection of a quench, an upper limit for the hot spot temperature can be estimated as follows : For a given cable, the temperature as a function of $\int I^2 dt$ is calculated [3]. It is assumed, that the time between the start of the quench and the time the resistor is switched into the circuit, is given by δt. Then the integral can be calculated : $\int (I^2 \times dt) = I_0^2 \times (\delta t + \tau/2)$, with $\tau = L/R_{ext}$. The resistance of the magnet after the quench is neglected, therefore this approximation gives a hot spot temperature higher than the real value.

If a more precise calculation of temperature and voltage is required, the QUABER program is used [4]. In particular in the study of magnets without heaters and external resisitors to extract the energy QUABER is the only available tool.

3 LHC CORRECTOR MAGNETS

The corrector magnets discussed in this report are a combined dipole sextupole magnet (MSCB), sextupole and de-

	unit	MCS proto	MCBS sex/dip	MCD	MCBX
Turns/pole		26	112/2240	12	406
Aperture	mm	56	56	56	123.7
Current	A	625	500/50	600	600
Mag.length	m	0.104	1.25	0.08	0.38
Tot.length	m	0.15	1.3	0.10	0.60
Max.Field	T	2.1	1.1/1.8	1.6	4.75
Metal area	mm^2	0.61	0.69/0.075	0.523	1.48
Ratio Cu/SC		1.6	1.6/4.2	1.6	1.6
RRR		120	120	120	120
N-Series		154	23/1	154	1
L/magnet	mH	0.7	72/14600	0.11	166

Table 1: Magnet characteristics

capole magnets (MCS and MCD), and a dipole magnet (MCBX)[5].

3.1 Combined Dipole Sextupole Magnet (MCBS)

This magnet will be installed in the arcs, one per cell. The sextupole magnets to correct the chromaticity are powered in series, the dipole magnets for closed-orbit correction are powered individually.

A prototype was tested in 1995 and the results of the test were analyzed and presented in [2]. Some of the experimental results were used in the study of the protection for other magnets, which are not yet constructed : the time for a quench to travel from turn to turn is in the order of 3 ms. For many quenches it was observed that the quench remains in one pole or in one block. Therefore in the worst case scenario it is assumed that only one pole of the magnet quenches.

The operation of the dipole magnet is safe, because the magnet is not connected in series with other magnets. For the sextupole, which is powered in series with 23 magnets, it is proposed to switch an external resistor of 1 Ω into the circuit after the detection of the quench, which would extract enough energy to protect the magnet without exceeding about 600 V across the resistor.

3.2 Sextupole magnet (MCS)

One magnet will be installed at the end of each dipole. The magnets will be connected in series to form two families, one for each ring.

The parameters of a prototype of this magnet are given in Table 1 [6]. If the energy is distributed in all poles, the temperature increases to above 300 K, in case only one pole quenches, the maximum temperature exceeds 1000 K (for a current of 600 A). For magnets with impregnated coils even a value of 300 K is considered to be too high. Assuming constant current the temperature of a hot spot is about 350 K after 100 ms (see Fig. 1). The temperature can be reduced by switching a resistor into the circuit. To be efficient, the time constant must be much smaller than 100 ms, which requires a resistor of at least 2 Ω. The voltage across the resistor then exceeds 1000 V which is too high.

Modified conductor: By increasing the ratio of copper to superconductor to 2.25, the conductor cross section increases from 0.61 mm^2 to 0.76 mm^2. This reduces the temperature of the hot spot to about 105 K (100 ms after a quench assuming constant current, see Fig.1). With a resistor of 1 Ω switched into the circuit 60 ms after the start of the quench, the time constant L/R is 110 ms and the hot spot temperature after the current has decayed to zero is reduced to about 130 K. The voltage drop of 600 V across the resistor is acceptable. Advancing the delay for the switch to 20 ms reduces the hot spot temperature to about 70 K, an increase to 100 ms leads to 260 K.

Resistor in parallel: With 50-100 mΩ in parallel, the magnet can operate with the conductor of smaller dimension. In Fig. 2 current and hot spot temperature are compared for the magnet quenching with/without a 0.1 Ω resistor in parallel to the magnet. It is assumed for both cases, that an external resistor of 1 Ω is switched into the circuit 60 ms after the quench. Whether such a protection is a suitable option for LHC corrector magnets, requires further investigations.

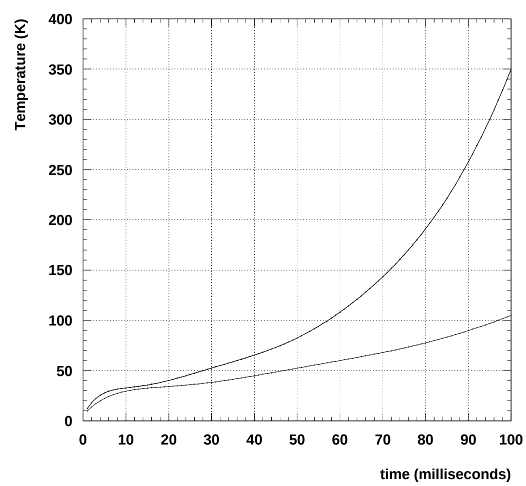

Figure 1: MCS: Hot spot temperature versus time for 100 ms after the magnet quenches. It is assumed that the current of 600 A remains constant during this time. The upper curve represents a wire with 0.61 mm^2, the lower with 0.76 mm^2 metal cross-section.

3.3 Decapole magnet (MCD)

One magnet will be installed at the end of each dipole, and connected in series to form two families, as for the sextupole magnets. The parameters for the magnet are given in Table 1. Due to the low inductance the current decreases quickly when a resistor of 0.4 Ω is switched into the circuit, and the magnet hot spot temperature remains below 70 K. A delay of 60 ms between start of the quench and the resistor switched into the circuit was assumed.

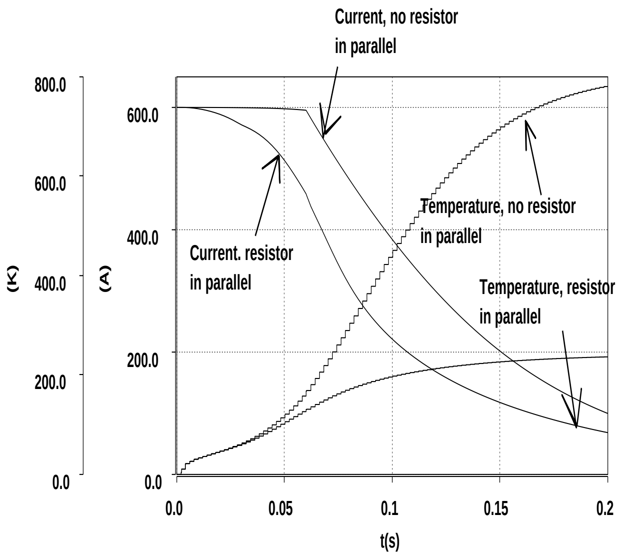

Figure 2: MCS: Current and hot spot temperature versus time with and without a resistor of 0.1 Ω in parallel to the magnet.

3.4 *Dipole magnet for insertion triplet (MCBX)*

For the orbit correction in the inner triplets of the LHC insertions short powerful dipole correctors are foreseen, combining an inner coil yielding a vertical dipole field, and an outer coil yielding a horizontal dipole field [7]. The calculations were performed for the outer coil (horizontal dipole field), with the parameters from Table 1.

Current, voltage and hot spot temperature versus time were calculated using QUABER [4]. The temperature versus time is shown in Fig. 3. Two different values for the quench propagation time from turn to turn were assumed, 3 ms and 12 ms. The temperature increases slowly to a maximum value below 250 K. The voltage to ground does not exceed 150 V. The energy can be efficiently extracted with a resistor, switched into the circuit 60 ms after the quench. With 0.5 Ω, the voltage across the resistor is limited to 300 V. Current and temperature versus time are shown in Fig. 4, with RRR = 120. Whether an extraction resistor is required depends on the quench propagation velocity and will be determined after the test of a prototype magnet.

4 CONCLUSIONS

Already in the design phase of the corrector magnets the protection in case of a quench needs to be considered. The copper content in the conductor must be sufficient to limit the hot spot temperature. A clue is the hot spot temperature 100 ms after the quench : if it is limited to less than about 100 K, an external resistor switched into the circuit to extract the energy can limit both temperature and voltage to acceptable values.

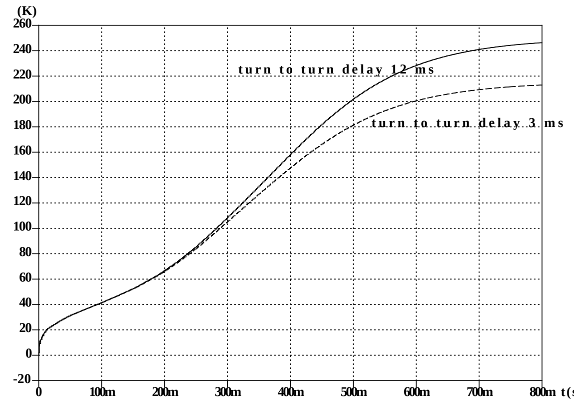

Figure 3: MCBX : Hot spot temperature versus time for turn-to-turn delays of 3 ms and 12 ms

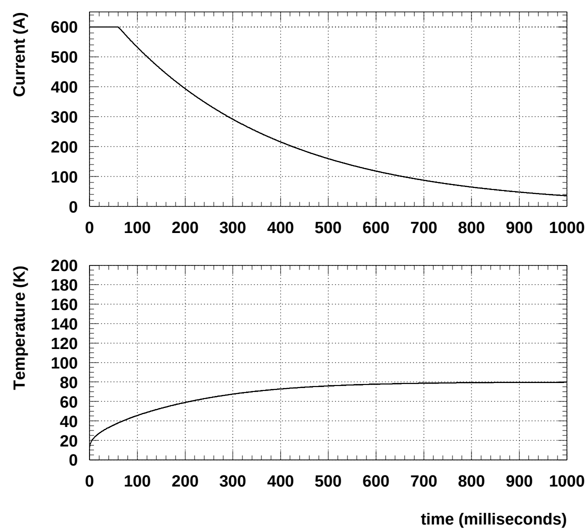

Figure 4: MCBX : Current and temperature versus time for magnet with external resistor of 0.5 Ω, RRR = 120

5 ACKNOWLEDGEMENTS

The authors would like to thank L.Coull and T.Taylor for helpful comments.

6 REFERENCES

[1] L.Coull et al., LHC Magnet Quench Protection System, 13th Int.Conf.Magnet.Tech. (MT13), Victoria, Canada, 1993

[2] R.Schmidt et al., LHC Project Note 28 (1995)

[3] D.Hagedorn, F.Rodriguez-Mateos, Modelling the quenching process in complex superconducting magnets, 12th Int.Conf.Magnet.Tech. (MT12), Leningrad, 1991

[4] F. Rodriguez-Mateos et al., Quench Protection Test Results..., 14th Int.Conf.Magnet.Tech. (MT14), Tampere, Finland, 1995

[5] The LHC study group, LHC Conceptual design, CERN/AC/95-05 (LHC)

[6] A.Ijspeert, J.Salminen, these proceedings

[7] A.Ijspeert, M.Karpinnen, J.Salminen, these proceedings