BEAM LOSS INDUCED QUENCH LEVELS

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Abstract

The quench process is briefly review and the methodology for the estimation of the minimum quench energy required for quenching a magnet is presented. Existing parametrization of the NbTi critical surface are presented which provide the temperature margin and examples of their application in two dimensional magnet cross section are shown. The calculation of the cable enthalpy is presented and the importance of a fair estimation of the fraction of helium in direct contact with the conductor is clarified. Finally numerical simulation of the minimum quench energy as a function of the length of the perturbation and of its duration are reported.

INTRODUCTION

The experience gained during the operation of the existing superconducting accelerator magnets (Tevatron, HERA and RHIC) demonstrated that the beam induced quenching happens. The integrated luminosity is by definition compromised by any type of quenches because of the downtime required for reestablishing the operating condition. The high luminosity operation can even be limited by beam induced quenching, for instance Tevatron is not far from such limitation: the luminosity increase requires continues amelioration of the collimation system and its efficiency in order to limit the beam loss to the magnets.

A fair estimation of the quench energy margin of different magnet families along the accelerator ring, is an essential specification for a compatible design of the collimation scheme. Moreover a correct setting of the so called beam loss monitor system can minimize the downtime of the machine if the quench can be predicted before its happen. The beam loss can be classified in three regimes, namely very fast beam loss (single turn loss), fast loss (between several to several hundred turns) and steady state beam loss. LHC main magnets operated at high overall current densities are by necessity working in the quasi-adiabatic regime. Under this condition, the heat produced by the transient beam loss must be absorbed by the enthalpy of the conductor and/or helium. In practice, due to the time constant of typical very fast beam loss ($100\,\mu$s) energy must entirely be absorbed by the enthalpy of the conductor whereas for typical fast loss (¿1 ms) the energy is absorbed by the enthalpy of the conductor and surrounding helium. In the following the fast beam loss is considered and the methodology for estimating the amount of deposited energy required to quench a superconducting magnet is presented. The very fast beam loss are also considered in the approximation of dry superconducting cables.

THE TEMPERATURE MARGIN

The temperature margin is a property of the superconducting material and of its operating conditions [6, 7, 8]. It is defined as following

$$\Delta T_q = T_c(J, B) - T_b, \quad (1)$$

where T_c is the critical temperature for a given current density, J, and a given magnetic field, B, usually referred as the temperature of current sharing, T_{cs}. In Table 1 the calculation of the temperature margin for the pick-field region of several LHC superconducting magnets at nominal operating conditions are given. Knowing the magnetic field map in the magnet coil cross section, the temperature margin map, $\Delta T_q(x, y)$ can be calculated. Two examples of such maps are presented in Fig. 1 and in Fig. 2 for the MB and the MQY at nominal operating conditions.

Table 1: Temperature Margin

Magnet Type	**Cable Type**	**Op-T (K)**	**ΔT_q (K)**
MB	1	1.9	1.58
MB	2	1.9	1.60
MQ	2	1.9	1.93
MQMC	4	1.9	1.59
MQM	7	1.9	1.59
MQM	7	4.5	0.84
MQML	4	1.9	1.59
MQML	4	4.5	0.84
MQY	5	4.5	1.01
MQY	6	4.5	1.18
MQT	c3	4.5	1.47

Table 2: Cable Characteristics

Cable Type	**NbTi (mm^2)**	**Cu (mm^2)**
1	9.412	15.530
2	7.547	11.697
4	2.369	4.145
5	2.237	3.915
6	4.205	5.256
7	2.369	4.145
c3	0.265	0.424

THE CABLE ENTHALPY

The temperature margin can be translated into an actual energy density estimating the enthalpy of the material in

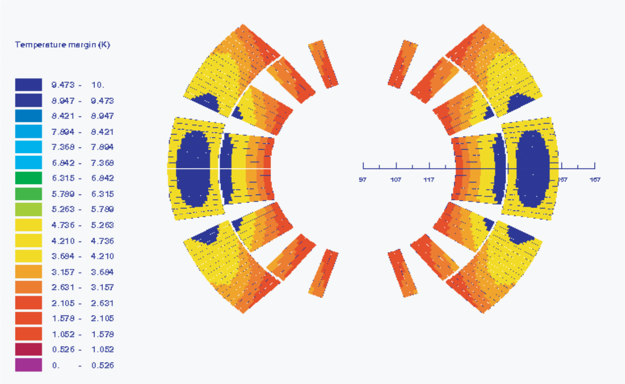

Figure 1: The temperature margin map of the LHC dipole magnet cross section (ROXIE) for nominal operating conditions. (Courtesy C.Vollinger and N.Schwerg)

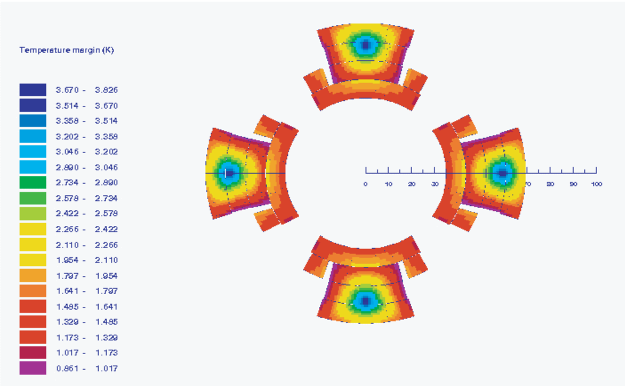

Figure 2: The temperature margin map of the LHC MQY magnet cross section (ROXIE) for nominal operating conditions. (Courtesy G.Kirby)

the cable cross section with the following formula,

$$\Delta E_q = \int_{T_b}^{T_c(J,B)} c_{eff}(T)dT, \qquad (2)$$

where ΔE_q is the energy density required to drive the superconducting cable into normal resistive state under the assumption of no external cooling and no heat conduction. c_{eff} is the effective heat capacity per unit volume of the materials which compose the cable cross section defined as the weighted average among the components,

$$c_{eff} = \frac{A_{NbTi} \cdot c_{NbTi} + A_{Cu} \cdot c_{Cu} + A_{He} \cdot c_{He}}{A_{NbTi} + A_{Cu} + A_{He}}, \qquad (3)$$

where the "c" are the heat capacity per unit volume of the NbTi, copper and helium and the "A" are the relative cross sections. The most problematic parameter is the helium cross section which is not uniformly distribution and it does play an important role. Moreover during a beam loss the metallic part are warm-up more than the helium, consequently there will be a thermalization time between the two components which has to be estimated. Using the (3) the thermalization time is considered simply equal to zero. The enthalpy calculation gives a correct value of the minimum quench energy if the perturbation involved a long enough piece of cable and if its duration in enough short, as it is quantitatively demonstrated in the following section.

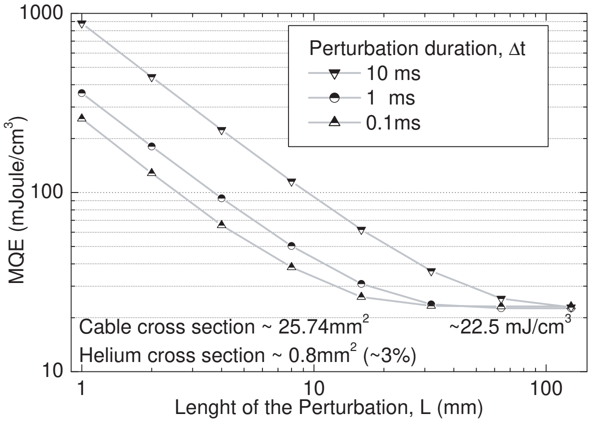

Figure 3: The minimum quench energy for the dipole inner cable (type-1) as a function of a given extension in space (L) and time (Δt).

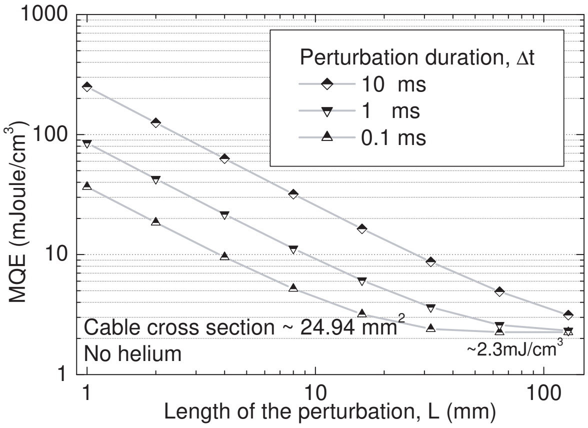

Figure 4: The minimum quench energy as a function of the perturbation length for different heat power load.

THE MINIMUM QUENCH ENERGY

The problem of the minimum quench energy (MQE) refers to the calculation of the transient response of an initially superconducting cable to an arbitrary energy input. The main result of the analysis is the stability margin, the maximum energy that can be deposited in the cable over a given extension in space and time and with a given waveform for which the transient response ends with the cable back to the superconducting state. A one-dimensional heat balance equation has been adopted to follow this approach,

$$Ac(T)\dot{T} = A\frac{d}{dz}\left(k(T)\frac{dT}{dz}\right) + \frac{\rho(T,B)I^2}{A} + \dot{q}(x,t) \quad (4)$$

where A is the overall cable cross section and c, k and ρ are the effective heat capacity, heat conductivity and resistivity [5] of the cable and $\dot{q}$ is the wave form which describe how the heat is deposit in the cable as a function of space and time. For sake of simplicity this last therm is chosen as an uniform distribution

$$\dot{q}(x,t) = P_h \cdot W_{\delta t}(t - t_0) \cdot W_L(z - z_0) \tag{5}$$

where W is defined as following

$$W_{\delta x}(x - x_0) = \begin{cases} 1, & x_0 < x < x_0 + \delta x; \\ 0, & \text{otherwise} \end{cases} \tag{6}$$

For a given length L and for a given duration δt two values of the P_h are chosen, P_h^{min} (for which there is no quench) and P_h^{max} (for which there is a quench). Afterwards the average between this two extremes is used as an input for the next simulation, if it is enough for quenching the cable it becomes the new P_h^{max}, if it is not enough for quenching it becomes the new P_h^{min}. Iterating this procedure, the gap between the two extremes gets lower. Defining a given required accuracy ε, the procedure can be stopped when

$$|P_h^{max} - P_h^{min}| < \varepsilon. \tag{7}$$

Finally the minimum quench energy density is

$$MQED = \frac{P_h^{min} \cdot \delta t}{A \cdot L}. \tag{8}$$

An example of such calculation has been performed for the inner layer cable in the pick-field of the LHC superconducting dipole at nominal operating condition (Fig. 3). The simulations shown that for time lower than tens of milliseconds and length longer that tens of centimeters the value of the enthalpy are correct. In Fig. 4 the same calculation is performed assuming that there is no helium. The time and space scale are very close to the previous one but the absolute value of the MQED is one order of magnitude lower.

CONCLUSIONS

An accurate prediction of the quench levels of the main ring superconducting magnets will allow only necessary, preventive dumps of the beam, based on beam loss measurements with beam loss monitors before the magnet quench, thus limiting the downtime of the machine. The particle energy deposition in the coils is calculated by using simulation programs like GEANT or FLUKA. The magnet quench levels as a function of proton loss distribution and magnet specific parameters can be estimated using codes like SPQR and ROXIE. Until now only simplified analytical calculations have been done for the main magnet families. An outlook on further simulations for the quench levels and envisaged experiments to validate the simulations was sketched.

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