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CALCULATION OF THE THERMO-STRUCTURAL TRANSIENT IN
LHC DIPOLE AT QUENCH

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Calculation of the thermo-structural transient in LHC dipole at quench

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Abstract—Computations have been made of the transient mechanical behaviour of the magnet if a sudden loss of superconductivity (quench) occurs.

The time-dependent map of temperature in the cross-section where the quench starts is computed using a new quench analysis program called QUABER. After having defined the geometrical configuration of the magnet, conditions close to the real situation in the Large Hadron Collider (LHC) machine have been simulated.

The temperature distribution is used as input for the following steps of our investigation. The thermo-mechanical transient in the structure is analysed by means of a finite element model approach.

The results presented here give predictions about the cycle of loads and stresses in the dipole during normal operation and in case of quench.

I INTRODUCTION

In the framework of the R&D programme for the proposed LHC machine, several 10 meter long dipole magnets [1] are under construction in different European companies. The cross section of one of these magnets is shown in Fig. 1. It is the thermo-structural transient, once the propagation process of a resistive zone in the coils has started, which is analysed here.

Fig. 1. The LHC dipole cross-section.

During quench, the magnet's internal resistance increases; as soon as the resistive voltage drop across the magnet reaches the threshold value for the detection system, this drives the shut down of the power supply and fires the protection heater circuit. In the meantime, once the voltage seen by the diode in parallel with the windings (Fig. 2) exceeds the turn-on voltage, the current is by-passed from the magnet. All this occurs in the decrease of the magnet current and in the subsequent variation of Lorentz body forces in the cables. All the stored magnetic energy of the magnet is dissipated in the cable volume which turned to the resistive state. The temperature increase in the coils therefore gives rise to further stresses due to the expansion inside the collars.

The scope of this work is to assess the stress distribution in the structure during the quenching process and to check whether these thermo-mechanical loads are dangerous or not for the magnet. The analysis is a two-dimensional one. It is therefore clear that such a model cannot assess the stress distribution in the direction of the magnet axis and that the quench is assumed to start in the middle magnet cross-section.

II THE QUENCH SIMULATION

The time-dependent temperature map in the cross section of the dipole has been obtained by means of a simulation performed with the quench analysis program QUABER [2].

Fig. 2. Simplified electrical scheme of a LHC dipole powering sector where one of the magnets has quenched. L : magnet's inductance; N : number of dipoles in one powering sector of the LHC; R_q : quench resistance; R_d : diode resistance in conduction; R_D : dump resistance.

As soon as the quench is detected, several actions must be taken in order to avoid any danger. The graph in Fig. 3 shows the temporal process, as it has been modelled in the simulation. The quench starts developing at time equal zero and is detected after a certain delay (qdt); at this point, a signal is sent to the power supply in order to shut it down, this becoming effective after a time delay $cssdt$. After that, the process of discharge of the powered sector through a dump resistor is started. The values for both qdt and $cssdt$ are given in Table I.

The heater circuit receives the activation signal; the delay $hidel$ includes all the elapsed time from the quench detection till the moment the turns, which are underneath the stainless steel strips, exceed their critical temperature and become resistive.

Coming back to Fig. 2, when the bypass diode reaches its turn-on voltage, the current commutates from the quenching magnet to the diode. The rest of the diodes for the other ($N-1$) magnets are not in the conducting state, as the other magnets are still superconducting.

It has been assumed that the quench starts at the middle cross-section of the magnet, in the high field turn of the outer layer.

The natural quench begins at time zero, and propagates both longitudinally and transversely. The initial value of the longitudinal velocity is given as input to the simulator; the transverse propagation is mainly defined by the turn-to-turn delay (the time for the quench to propagate from one turn to the next one through the insulation).

In order to simulate a rather pessimistic situation, it has been assumed that the quench propagates longitudinally only in one direction and no propagation from the outer layers towards the inner layers has been considered. The inner layers become resistive only by a quench-back process when the magnetic field variation dB/dt exceeds the critical value.

Fig. 3. Quench process sequence.

TABLE I
SOME PARAMETERS FOR THE QUENCH SIMULATION

Initial current	15000 A
Quench detection time (qdt)	10 msec
Heater delay ($hidel$)	40 msec
Current source shut down time	20 msec
Initial quench velocity	100 m/sec (only one direction)
Critical dI/dt	6000 A/sec
Turn-to-turn delay	30 msec
Peak field in windings	10.2 T

Concerning the turn-to-turn delay, a large value of 30 milliseconds has been used.

After a time $hidel$ all the turns underneath the heaters become resistive and hence a transversal propagation starts towards the rest of the windings as well. The value chosen for $hidel$ is somewhat pessimistic (see Table I).

The result of all these processes is a current decrease in the magnet as shown in Fig. 4. Consequently the temperature in the magnet increases and the maximum value -the so-called hot spot temperature- is observed in the original quench area. Fig. 5 shows the time evolution of the following temperatures in the cross section considered: the maximum temperature (a), the temperature at the next turn (b), the temperature of the turns underneath the heaters (c) and the temperature in the inner layers where a quench-back process occurred once the critical dI/dt value (6000 ampere per second, which is again a pessimistic value) was exceeded during the quenching magnet discharge (d).

These values were used in the thermo-structural assessment of the cross-section. Stresses along the cables due to the difference of temperature between them could not be computed because we used only a two-dimensional model. In any case, because of the uncertainties concerning the temperature gradient across the insulation separating two cables, and the lack of data about sliding and the influence of friction if relative displacement should occur, further analysis in this sense would not be meaningful at the present time.

Fig. 4. Simulated current decay through the magnet after the quench.

Fig. 5. Temperature at different areas in the magnet coils. (a) hot spot temperature; (b) next turn to the quench origin (same cross section); (c) temperature in the volume underneath the heaters; (d) inner layers temperature.

General parameters used for the simulation are shown in Table I. More details concerning the simulation are given in [2].

III. THERMO-STRUCTURAL COMPUTATIONS

The next step has been to study the heat propagation in the collars during the period in which the current decreases from $I=15000$ A to $I=0$ A.

A non-linear transient thermal analysis in a two-dimensional model has been carried out. The way of approaching such a problem by a finite element model and the type of elements used are described elsewhere [3,4]. As can be seen in Fig. 6, after 0.7 second from the beginning of the quench the temperature of the collars has risen by a few degrees. The electrical insulation also behaves as a thermal barrier causing a huge difference of temperature between coils and collars. In view of the fact that below a few tens of kelvin the linear thermal shrinkage coefficient of all the materials is close to zero, the contribution to the general stress distribution due to the collars warming up can be neglected.

In order to follow the thermo-structural transient of the structure, two loads have been considered: the Lorentz body forces decreasing from their maximum value at $I=15000$ A, $B=10$ T to the zero when $I=0$ A, and the rising temperature in the quenched cables. The model adopted for this dynamic analysis is described elsewhere [5,6].

Fig. 6. Temperature distribution (K) in the aluminium collars after 0.7 seconds from the quench origin.

In Fig. 7 and Fig. 8 the trend of the compressive azimuthal stress in the middle points of the coils' poles and midplanes during the normal operational cycle and during quench is reported. Point A gives the room temperature situation, between A and B the cool-down between 293 and 2 kelvins takes place and the coil prestress increases its value. At point C, once the magnet is energized to 15000 amperes the compression reaches its minimum value at the coil pole and maximum at the midplane. From the point in which time is equal to zero onwards, stress versus time during the quench is plotted.

Fig. 7. Compressive azimuthal stresses in the coil inner layer (middle points).

Fig. 8. Compressive azimuthal stresses in the coil outer layer (middle points).

In general, the increase of temperature and the simultaneous reduction of the electromagnetic forces result in no increment of the compression in each coil. At any moment azimuthal stresses are inside the range given by the minimum and maximum compression under normal working conditions at $T=2$ K, $I=15000$ A.

Some problems could be caused by the stress concentration in the collars around the central pin and at the radii of curvature connecting the central post to the rest of the structure. For a three millimeter thick collar the reaction force coming from the central pin is 16067 N at room temperature, it increases to 21984 N at two kelvins, it decreases to 7704 N when in the cables there is a current $I=15000$ A and can exceptionally reach 24915 N at the end of the quench phase considered here. Moreover, since the constraints have a cyclic trend, it is important to investigate the low temperature fatigue behaviour of the collars.

It is foreseen to carry out experimental tests over the next few months in order to check the strength of the collars.

IV. CONCLUSIONS

The electrical insulation behaves as a thermal barrier limiting the short time heating of the collars to a few degrees.

Stresses in the coils during the quench stay within the range of the normal working conditions.

For the collars it is important to verify the design of some critical areas to ensure a good fatigue behaviour.

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