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Quench Protection Test Results and Comparative Simulations on the First 10 metre Prototype Dipoles for the Large Hadron Collider

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Abstract—The first 10 metre long dipole prototypes made by European Industry within the framework of the R&D programme for the Large Hadron Collider (LHC) have been tested at CERN. As a part of the test programme, a series of quench protection tests have been carried out in order to qualify the basic protection scheme foreseen for the LHC dipoles (quench heaters and cold diodes). Results are presented on the quench heater performance, and on the maximum temperatures and voltages observed during quenches under the so-called “machine conditions”. Moreover, an update of the quench simulation package specially developed at CERN (QUABER 2) has been recently made. Details on this new version of QUABER are given. Simulation runs have been made specifically to validate the model with the results from the measurements on quench protection mentioned above.

I. INTRODUCTION

Three of the first 10 metre long dipole prototypes tested so far at CERN [1], [2] have been subjected to quench protection tests at superfluid helium temperatures in order to qualify their performance in terms of temperatures and voltages when dissipating their full stored energy in their windings. These are the conditions under which they have to work in the LHC String environment [3], where they are bypassed by cold diodes and therefore no energy extraction is possible from the magnets. These are also the conditions for the quench protection of such magnets in the future LHC machine.

The conditions in the LHC Test Bench (see Fig. 1) can easily approach the machine ones (where the quenching magnet commutates the current through its parallel diode in a situation similar to a shortcircuit).

Fig. 1. Simplified electrical circuit for the 10 metre prototype quench tests.

In order to obtain that, one needs to switch off the power supply once the quench is detected, and leave the switches closed. In this way the magnet will discharge itself through the freewheeling thyristors of the power supply, dissipating almost all its energy in the windings, since the total external resistance seen from the magnet terminals is only 0.4 mΩ.

In the absence of spot heaters, the magnets are brought to the resistive transition by different means, either by fast ramping or by firing simultaneously all the quench heaters. During the quenches, current and voltages are recorded and post-processed in order to have the information on the quench load (in MIITS, integral with respect to time of the current squared in mega-amperes-squared-seconds) and on the voltages across the different sections of the magnet (layers, poles and apertures). A pre-event recording of data allows us to measure the thermal diffusion times for the quench heaters and the times required for detecting the quench once the transition has started. The results are then compared to the results obtained with the new version of QUABER [4], the quench simulation package used at CERN.

II. QUENCHES WITHOUT ENERGY EXTRACTION: TEST RESULTS

A. MIITS and adiabatic temperatures

In order to achieve the conditions in which the magnets dissipate their own energy, the opening of the switches has been delayed stepwise up to 1 second. At this time, the current is already zero, and hence the opening does not modify the quench behaviour of the magnet.

For the tests of the first magnet, the resistive transitions were produced by the two methods mentioned before. When provoking the quench by fast ramping (150 A/s), the quenching current was 12640 A (8.55 T) and the number of MIITS absorbed was 33, which for the outer layer cable of that magnet would correspond to a maximum adiabatic temperature of 220 K (based on a Residual Resistivity Ratio, or RRR, of 75). When provoking the quenches by firing all the quench heaters at the same time at a slightly higher current (12820 A), 32 MIITS were measured. This lower value is, as expected, due to the fact that in the second case one does not need to detect the quench to fire the heaters and create the large volume resistive transition.

For the second magnet, quenches were only provoked by firing the heaters. In this case the number of MIITS was 32

as well. And for the third magnet, where quenches were provoked by ramping to the training level (around 14000 A, 9.4 T), the number obtained was 34, corresponding to the maximum adiabatic temperature of 225 K. This result indicates the displacement of the curve "MIITS-current" for the different magnets.

B. Maximum voltages to ground

The measured maximum voltages against ground developed by the magnets are in the range from 170 V to 270 V. This large range is due to the scatter in RRR from coil to coil and in heater delays between the different magnet apertures.

C. Dependency on the quench detection threshold

During the tests on the third magnet, the level of detection threshold was shifted to 150 mV (usually the value used for the bridges between apertures and poles is 50 mV), and to 300 mV. The number of MIITS then increased only to 34.6 and 35.1, respectively. The two quenches were provoked by ramping at 10 A/s to the training level (around 14000 A) and both occurred in the outer layers. The high initial resistance rise rate developed in the outer layers is responsible for this small difference in MIITS. Along the training tests of the prototypes, natural quenches occurring in the inner layers typically gave around 0.5 MIITS more, due to the longer detection times required.

III. QUENCH HEATER TESTS

Each magnet has four quench heaters mounted on top of each side of the outer layer shells. A quench heater consists of two 20 metre long, U-shaped stainless steel strips mounted on a 125 microns Kapton base. These strips are 15 mm wide and 25 microns thick, covering 13 turns over the whole length of each pole.

In order to optimize the energy deposition required to protect the magnet without using high voltages, the strips are partially clad with copper on one side, alternating cycles of 25 cm with cladding and 25 cm without cladding. The copper layer has a thickness between 1 and 1.5 microns, enough to reduce the resistance of the strips at low temperature by almost a factor of two.

Each strip is powered by two capacitors of 6.6 mF each connected in series, with a central ground connection (1 M Ω), and charged up to ± 400 V.

The efficiency of the strips is typically calibrated at 7000 A (4.8 T), powering the strips with ± 340 V. The measured thermal diffusion times vary from 54 milliseconds to 74 milliseconds for the different magnets.

At fields from 8.6 T to 9.6 T, the transition of all of the conductors underneath the heaters is observed after a delay of 50 and 30 milliseconds respectively.

Heater studies were performed on one of the prototypes. Table I contains the results on the thermal diffusion time, measured from heater firing up to the appearance of the first resistive signal at different current levels. The heater power supplies were charged to ± 400 V for these tests. These values confirm that the magnet is well protected over the whole range of currents.

IV. QUABER 2

The first version of this package, already based on the use of the system analysis program SABER^{TM} [5], was presented in [4]. While keeping the maximum of flexibility and open possibilities for defining both the magnet geometry and the electrical circuits in the program, in QUABER 2 [6], [7] we have tried to unify the language used in the quench tracking process so as not to have external parts of the code in other languages such as Fortran or C (as was the case for the first version). We have added a more universal way of defining the coil structure and a more user-friendly interface in view of a more extended use of the application for the simulations on the superconducting magnet system for the LHC.

The evolution of MAST (SABER's modelling language) has allowed us to implement the new features mentioned above. In particular, we succeeded in programming an iteration loop. A loop, which is very useful, was not possible until release SABER 3.2.

One of the main differences between the two versions of QUABER is the way a superconducting magnet is defined. In the first version the basic modelling unit was the layer or the block of conductors, newly defined for each magnet. In QUABER 2 instead, each block of the n-pole magnet corresponds to a general type in which the number of layers in the azimuthal position and in the radial position are just parameters. A natural quench propagation or a quench heater effect are modelled by different templates in each case (a template is nothing but a MAST subprogram defining the behaviour of a real element).

The application package consists of:

- 1) the simulator itself,
- 2) a collection of templates which define the quench propagation,
- 3) four MAST functions used in the templates like foreign routines,
- 4) the electric netlist file,
- 5) data files containing the MIIT curves and the resistivity of the stabilizer material.

TABLE I
THERMAL DIFFUSION TIMES (THDT) AT DIFFERENT CURRENT LEVELS

I [kA]	1.5	2.5	3	6	9	12
B [T]	1.0	1.7	2.0	4.1	6.1	8.1
THDT [ms]	144	59	57	42	36	15

As far as the calculation method is concerned, the basic equation which links the temperature of the conductor with the current is given by the usual heat balance per unit of volume under adiabatic conditions [4]:

$$\int_{t_0}^t i^2(t) \cdot dt = A_{Cu} \cdot A_T \cdot \int_{T_0}^T \frac{C(T)}{\rho_{Cu}(B, T, RRR)} \cdot dT \quad (1)$$

where A_{Cu} is the section of copper of a conductor, A_T the whole section of the conductor, $C(T)$ the average specific heat of the conductor, and $\rho_{Cu}(B, T, RRR)$ is the resistivity of the copper as a function of magnetic field, temperature and the residual resistivity ratio.

In QUABER 2, the MIIT curves for the different conductors and the resistivity of copper for the different RRR values are contained in a data file which is included in the netlist and directly passed as a parameter to the templates that need them. This allows the possibility of having different types of conductors used in the same magnet (e.g. graded coils) or to have several different magnets in the same netlist (e.g. the present LHC String configuration with one superconducting twin quadrupole and two superconducting twin dipoles).

The calculations of these curves are still performed outside the simulator by a C program running under an UNIX environment. It generates data files which are used directly in the netlist without any modification.

At time equal zero, the quench starts propagating in a certain block of conductors with a velocity for which the components in both longitudinal and transversal directions can either be given as input or calculated as described in [4]. In the case of the transverse propagation, the parameter used is the turn-to-turn delay, typically deduced from experimental measurements.

A very important parameter for magnets protected by quench heaters is the total heater delay, defined as the sum of the detection time and the thermal diffusion time from heaters to coil through the insulation (without any doubt the two largest contributions to the time elapsed from the quench take-off to the moment when the effect of the heaters provokes the fast increase of resistance in the coils). The values for this parameter are also deduced from measurements and given as inputs.

V. QUENCH SIMULATIONS COMPARISON WITH MEASUREMENTS

One of the runs from the second magnet tested at CERN has been used as reference in order to study the accuracy of QUABER 2 with respect to the experimental results. The conditions for the simulation are as follows:

1) Initial current (12.8 kA) and protection sequence as in the real test (power supply off time as measured and no opening of the switches). The magnet dissipates its own

energy. The quench is provoked by firing all the heaters, and the resistances of the external circuit are taken into account.

2) No quench back, i.e. no resistive contribution from the inner layers.

3) No layer to layer quench propagation.

4) All the turns underneath the heaters are considered to become resistive along their full length and at the same time.

5) Equal heater delays for all the strips.

6) Turn-to-turn delay for the transversal propagation (across the turns in the outer layers not triggered by the heaters) equal to 30 milliseconds, value deduced from the resistive voltage rise rate during a natural quench.

The calculated number of MIITS by the simulation programme is 34, and the value measured was 32 (6% lower). This difference comes from the fact that the simulation program did not match each strip to its own thermal diffusion time (due to the lack of the relevant information). Moreover, it is not possible to know what volumes underneath the heaters become resistive in the first instant, nor the sequence of quenching for the rest of those volumes. Certainly, not all of the turns are triggered at the same time.

The effect of the copper cladding on the heater surface was not taken into account (half of the volume under the heaters is triggered by longitudinal propagation). In any case, the influence of this is not estimated to be very important.

The voltages (simulated and measured) developed by an outer layer are shown in Fig. 2.

Fig. 2. Measured and simulated voltages (V) across one outer layer of the 10 metre prototype dipole during a quench without energy extraction. Time in milliseconds.

The simulation is able to trace back the voltage evolution, giving in general a good estimation for the peak values. In the beginning of the quench process, the onset of quench resistances in the magnet and the switch-off of the power converter make the relative difference larger.

VI. CONCLUSIONS

The quench protection tests on the first 10 metre dipole prototypes for the LHC have shown that these magnets are able to dissipate their full energy in the windings with acceptable values for both peak temperatures and voltages. The first step towards the confirmation of the basic quench protection scheme foreseen for the dipole circuits in the LHC machine (cold diodes and quench heaters) has been taken.

The quench heaters acting on the outer layers of the dipole prototypes appear as the main element in the quench protection of the magnets. The contribution from the inner layers to the quench resistance is negligible. Nevertheless, the quenching of the inner layers is important in order to have a better balance in voltage distribution, as well as to avoid high temperature gradients.

The new version of QUABER has been tested and shows good accuracy with respect to the measurements in terms of MIITS (maximum temperatures) and voltages. The validity of the model is therefore proven.

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