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MEASUREMENT OF SUPERCONDUCTING BUSBARS MODELS FOR THE LHC MAIN DIPOLE

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J.-L. Perinet-Marquet[1] and J.Vlogaert[1]

Abstract

The LHC main dipoles will be connected in series by superconducting busbars, consisting of a superconducting cable brazed onto a stabilizing copper profile. In case of a quench detection, protection heaters will be activated to drive the magnet to theresistive state. In addition, the magnet will be protected by a bypass diode. In order to limit quench propagation, the excitation current is ramped down at an initial rate of 113 A/s and with a time constant equal to 104 s. When a busbar quenches, its temperature must stay below safe values. Comparative measurements of a hollow and a solid busbar were performed in 1.9 K superfluid helium, 4.2 K liquid helium and 4.2 K gaseous helium during the current ramp down. We describe the experimental set-up and report the results. The development of temperatures, the quench propagation velocities as well as the residual resistance ratio (RRR) were measured. The busbar stabilized by a solid copper profile was found to be the most appropriate choice.

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Measurement of Superconducting Busbars Models for the LHC Main Dipole

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***Abstract* -The LHC main dipoles will be connected in series by superconducting busbars, consisting of a superconducting cable brazed onto a stabilizing copper profile. In case of a quench detection, protection heaters will be activated to drive the magnet to theresistive state. In addition, the magnet will be protected by a bypass diode. In order to limit quench propagation, the excitation current is ramped down at an initial rate of 113 A/s and with a time constant equal to 104 s. When a busbar quenches, its temperature must stay below safe values. Comparative measurements of a hollow and a solid busbar were performed in 1.9 K superfluid helium, 4.2 K liquid helium and 4.2 K gaseous helium during the current ramp down. We describe the experimental set-up and report the results. The development of temperatures, the quench propagation velocities as well as the residual resistance ratio (RRR) were measured. The busbar stabilized by a solid copper profile was found to be the most appropriate choice.**

I. INTRODUCTION

The LHC main dipoles [1] will be connected in series by superconducting (SC) busbars, made up from a SC cable brazed on to a stabilizing copper profile. This cable will be the same as used for the outer coil layer of the dipoles. The main cable parameters are listed in Table I.

In case of a quench in an LHC dipole, the energy stored in the magnet chain is extracted by switching a resistor in series with the magnets. To limit the voltage in the dipole excitation circuit, the time constant for the exponential discharge of the current from 12 kA is about 100 s. During the discharge, the magnets are protected by bypass diodes but the busbars must carry the current. Should a busbar quench because of warm helium gas flow or quench propagation, its temperature must not exceed 400 K. The maximum temperature depends on the copper cross- section, copper RRR and on heat transfer conditions. Since the latter cannot be reliably predicted (helium may be in the superfluid, liquid above the lambda point or gaseous state) it is assumed that the busbar temperature increases adiabatically. To verify busbar behaviour, an experiment was carried out at Saclay in collaboration with CERN. Busbar models were quenched with a heater, and the current ramped down linearly at an initial rate close to that of the initial current decay in LHC. The experiment had two aims. The first was to compare the solid and hollow busbars during current ramp down after resistive transition in different cooling conditions and at different ramp rates. The second was to measure the maximum temperatures and compare them with the values expected from calculations based on adiabatic assumptions. The busbars profiles have the same external dimensions 20 x 16 mm^2 but differ in their cross-sections. The first one is solid while the second one presents a 5 mm diameter central cooling hole, with the purpose of enhancing thermal transfer to the liquid helium. Measurements were performed in 1.9 K superfluid helium, 4.2 K liquid helium and 4.2 K gaseous helium during the current ramp down. The quench propagation was measured and maximum temperatures were observed. The velocity of longitudinal temperature propagation as well as the transverse propagation to an adjacent unpowered busbar were measured. Finally a measurement of the residual resistance ratio (RRR) was performed.

TABLE I.
CABLE CHARACERISTICS

Width	15.10 + 0, -0.02 mm
Mid-thickness at 50 MPa	1.480 ± 0.006 mm
Keystone angle	0.90 ± 0.05 deg
Transposition pitch	100 ± 5mm
Number of SC strands	36
Inter-strand resistance	40 μΩ
Min. Icr at 1.9 K	12960 A at 9 T
RRR	≥70
Transposition direction	Left-hand screw

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II. DESCRIPTION OF THE EXPERIMENT

A. The measurement facility

The CEA-Saclay test facility used for this experiment is described in details in [2]. It was already used for the successful measurements of several magnet models and prototypes. This test station is further described in [3] where the measurements of the very first Twin Aperture Prototype for the CERN LHC are reported.

B. The electrical circuit

Fig.1 shows the powering circuit of the busbar experiment. A short dipole model was used as an inductive load in order to facilitate the regulation of the excitation current. The busbars connected the power supply to the inductive load and were mounted in separate tubes.

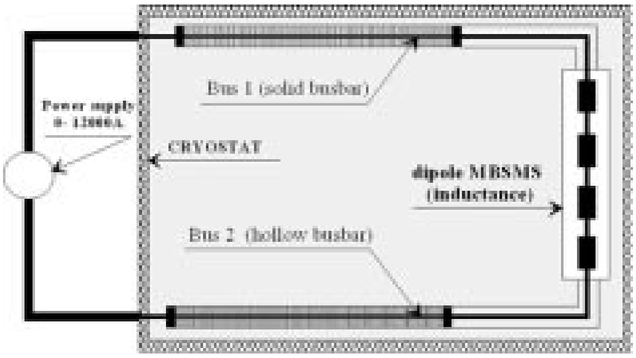


Fig. 1: Powering circuit

C. The busbars

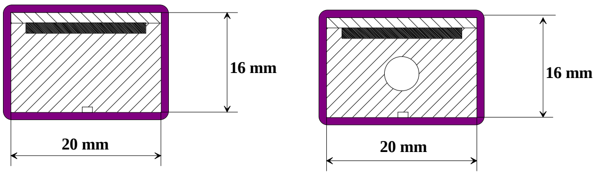
The cross sections of the busbars are shown in Fig.2. The superconducting cable is embedded in a copper profile.

The busbars were made long enough for the temperatures and transition propagation rate in the central part of the busbar to be unaffected by end effects. Fig.3 shows the layout of the busbars. Each eight meter long busbar was bent and inserted into a tube in order to make it fit into the cryostat. Flexible connections, made from a much thinner stabilized profile (15 x 2 mm^2) and a stack of 65 copper laminations, each with a thickness of 0.2 mm, were used for the bend bewteen the two busbar straight lengths.

The tubes were separated from the other helium volumes by plugs fitted with radiators for the extraction of the heat passing through the plugs. In addition they were provided with dedicated helium valves and external and internal heaters for temperature control.

D. Instrumentation

As shown in Fig.3, the busbars were fitted with quench heaters for triggering the resistive transition and with induction coils for the detection of transition and eventual recovery [4]. A number of voltage taps provided precise information about transition propagation during de-excitation of the circuit. Logarithmic signal converters [5] were used with carbon resistor thermometers to monitor temperatures below 30 K. This improved both sensitivity and measurement range. Platinum thermometers covered the upper temperature range during the current ramp-down.



Bus 1
(solid busbar)

Bus 2
(hollow busbar)

Fig. 2: Cross-section of busbars

E. Data acquisition system

In the busbar experiment we used a new data acquisition system based on the real time operating system QNX. Its three nodes architecture has a first PC for the data acquisition system, a second one to drive the 20 kA power supply whereas the third is interfaced to control the entire system and to visualize the data.

These double networked architecture on QNX, with an acquistion card working at 21kHz (per channel), was sufficient to make the fast acquisition on 48 data channels and to trigger the power supply current ramp down when the transition was detected. For this case the transition was detected by a channel of the data acquisition system looking at the transition detecting coil. The measurement results were stored for subsequent analysis using Gnuplot on QNX or Microsoft Excel on Windows NT

III. MEASUREMENT RESULTS

A. Transition propagation velocities

The transition propagation velocities were measured by means of voltage taps. The calculations were based on measurements on three straight sections of the busbar defined by the positions of the sensors, including the voltage tap near the heater. The measurements were made under different

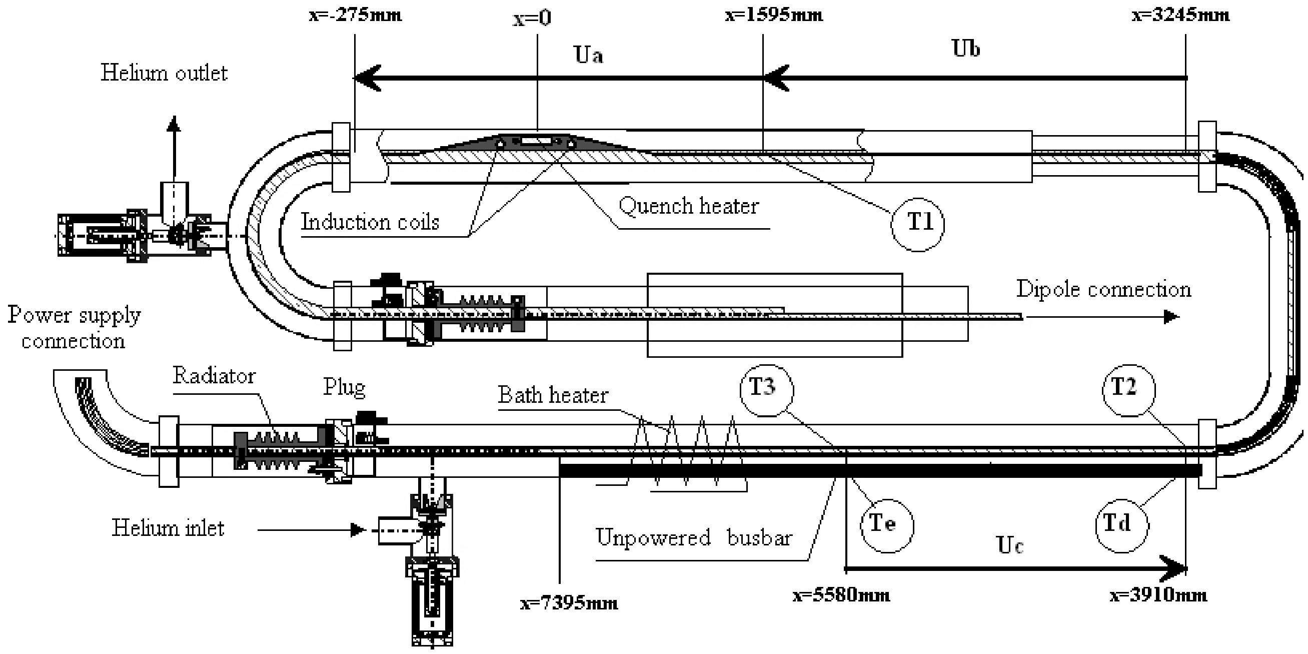


Fig. 3: Layout of busbars

linear current ramping conditions (90-113 A/s). The value of excitation current used to plot the propagation velocity versus current is the mean value during the transition of the considered section. We may note that the eddy currents due to magnetic field variation during the discharge leads to a joule heating of several order of magnitude lower than the heat deposited by the transition. So we do not expect any effect of the current decreasing rate on the measured velocities. The results are summarized in Fig. 4.

For reasons of readability, we did not plot the point in 4.2 K gaseous helium cooling mode: 4.7 m/s at 12000 amperes for busbar no. 1. We can make the following remarks:

- The transition propagation velocity strongly depends on the cooling conditrions. The values measured in liquid helium (0.2-0.7 m/s) are significantly lower than those measured in 4.2 K gaseous helium, this indicates that the transition propagation is not adiabatic. As a consequence, the transition propagation velocities are lower in the hollow busbar no.2 in which the lower copper section area is widely compensated by a larger heat exchange surface. In the same way, lower velocity values were found in the superfluid helium cooling mode.
- In the hollow busbar no.2, there is a conflict between two phenomena: the transition propagation in the copper section and the fluid movement in the hollow conductor. This may change the heat exchange conditions in the vicinity of the propagation front and therefore leads to some spread in the computed velocities due to the onset conditions of the transition.
- As expected, the quench propagation velocity decreases with decreasing current. As the current diminishes, the heat deposited by the transition is lower. Because of the current sharing and the critical temperature increase, the required energy to induce transition of the conductor increases.

B. Maximum temperatures

Maximum temperatures are shown in Table II for each type of busbar, for the different initial cooling conditions and for a linear current ramping from 12000A at a rate of –113A/s. Temperature expected from calculation based on adiabatic assumptions are also shown in Table II (T ad). Measurements were not possible in the helium gas for the hollow conductor, because the heating through the separating plugs exceeded the chosen interlock criteria.

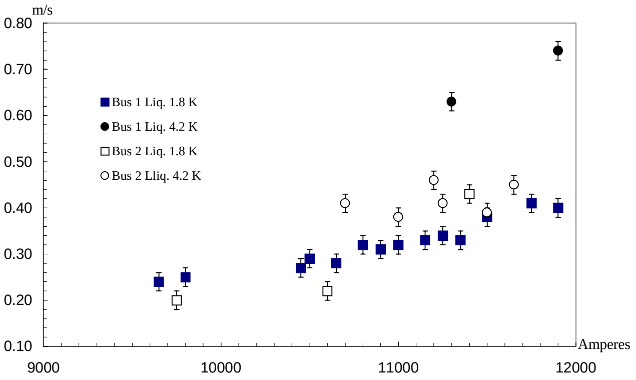


Fig. 4: Quench propagation velocities

C. Temperature propagation (longitudinal and transverse)

For both the longitudinal and transverse propagation, the measurements relating to the solid busbar no 1. are shown below. These measurements are made under a –113A/s linear current ramping from 12000A, with a 4.2 K liquid helium cooling mode.

The longitudinal propagation is illustrated in Fig.5 by the temperatures T1, T2 and T3 indicated on the right scale and voltages Ua, Ub and Uc on the left scale. The locations where the above values were taken are shown in Fig. 3.

The transverse temperature propagation was measured on a length of unpowered busbar, mounted adjacent to the solid busbar. Fig.6 shows the development in time of excitation current and temperatures.

The curves T2 and T3 show temperature measurements on the powered busbar and refer to the left scale. The curves Td and Te show measurements on the unpowered busbar and refer to the right temperature scale. The excitation current, I is also indicated. It is noticed that the adjacent busbar did not reach the critical temperature level during the current ramping.

TABLE II
MAXIMUM TEMPERTURES

Bus	Initial cooling conditions	T max (K)	T ad (K)
Solid	1.9 K superfluid helium	55	80
	4.2 K liquid helium	74	80
	4.2 K gaseous helium	100	80
Hollow	1.9 K superfluid helium	72	110
	4.2 K liquid helium	97	110

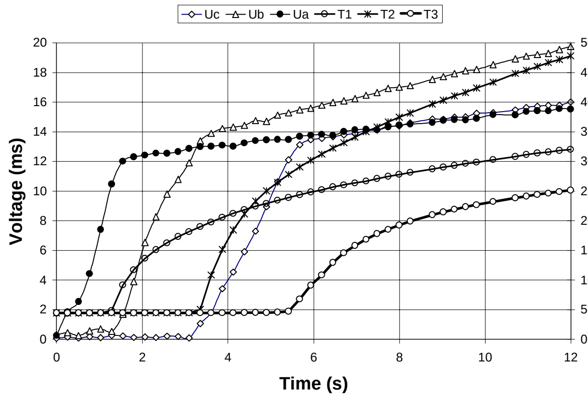


Fig. 5: Temperature and voltage during propagation quench

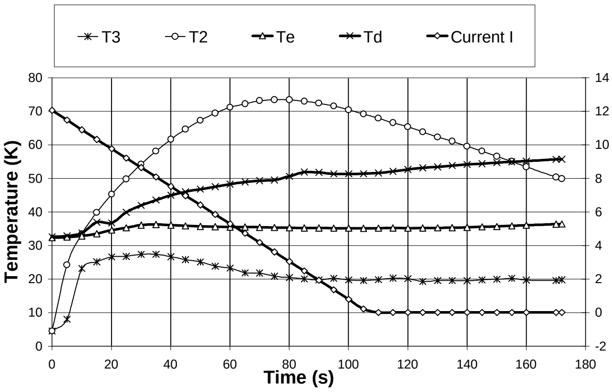


Fig.6: Transverse heat propagation from the quenched busbar to unpowered busbar

D. Residual resistance ratio

The RRR value of each busbar was measured as the resistivity ratio for temperatures of 294 K and approximately 12 K. It was not possible to eliminate the temperature gradients at cold. Temperatures between 9.8 K and 16.8 K were observed. The applied currents were 40 A at cold and 20 A in warm conditions. The resulting RRR values were RRR = 70 for the solid busbar and RRR = 77 for the hollow busbar. The value given by the supplier of the copper bar was RRR = 80. The small difference is explained by the mechanical deformations of the bars during fabrication.

IV. CONCLUDING REMARKS

The measurements showed very early that there would be no advantage in choosing the more expensive and complicated hollow conductor design. It was observed that for both busbars the quench propagation velocity in normal liquid helium is twice the speed of that in the superfluid. It was also observed that in the solid busbar the transition propagation rate in gaseous helium is several times the speed of that in the superfluid. Measurements in gaseous helium could not be performed in the hollow busbar. The data gathered during the experiment allowed to adjust the computer models used for the design of the magnet protection system. It was thus confirmed that the present busbar design is safe for the foreseen operating conditions [6], with an exponential decay of the magnet excitation current and an allowance of several seconds for the detection of quenches in the busbars system.

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