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PROPOSED METHOD FOR THE VERIFICATION OF THE LHC BUS BAR SPLICES DURING COMMISSIONING AT CRYOGENIC CONDITIONS

M. Calvi, L. Bottura and F. Rodríguez Mateos

Résumé

The commissioning of the Large Hadron Collider at CERN includes the powering of about 1600 superconducting electrical circuits to currents ranging from 55 A to 11.8 kA. A large number of splices (over 70'000) are present at the magnet interconnects, which can only be validated with current at cryogenic conditions. This paper discusses the thermal effects related to possible faulty splices during the powering of the circuits. The calculations of the quench and detection currents, as well as the hot spot temperatures, are described. The heat transfer model with the surrounding coolant and the current profiles inside the splices are presented. This study is completed with a sensitivity analysis on the hot spot temperature with respect to the model parameters. Finally, the implications with respect to the powering ramps and parameters to be applied during the first powering are discussed.

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Proposed method for the verification of the LHC bus bar splices during commissioning at cryogenic conditions

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Abstract—**The commissioning of the Large Hadron Collider at CERN includes the powering of about 1600 superconducting electrical circuits to currents ranging from 55A to 11.8kA. A large number of splices (over 70'000) are present at the magnet interconnects, which can only be validated with current at cryogenic conditions. This paper discusses the thermal effects related to possible faulty splices during the powering of the circuits. The calculations of the quench and detection currents, as well as the hot spot temperatures, are described. The heat transfer model with the surrounding coolant and the current profiles inside the splices are presented. This study is completed with a sensitivity analysis on the hot spot temperature with respect to the model parameters. Finally, the implications with respect to the powering ramps and parameters to be applied during the first powering are discussed.**

Index Terms— **LHC, commissioning, superconducting bus bars, splices.**

I. INTRODUCTION

The Large Hadron Collider, now under construction at CERN in a 27 km, long tunnel, will provide proton-proton collisions with a centre-of-mass energy of 14 TeV and an unprecedented luminosity of $10^{34}\,\mathrm{cm}^{-1}\mathrm{s}^{-2}$ [1]. In order to achieve this it must operate with more than 2800 bunches per beam and a very high intensity. The machine will also operate for heavy (Pb) ion physics at a luminosity of $10^{27}\,\mathrm{cm}^{-1}\,\mathrm{s}^{-2}$.

The LHC will require more than 8000 superconducting magnets of different types. The most challenging are the 1232 superconducting dipoles which must operate reliably at the nominal field of 8.34 T, corresponding to the centre-of-mass energy of 14 TeV, with the possibility of being pushed to an ultimate field of 9 T. As a part of the quality assurance program, all the LHC magnets are tested before the installation in the tunnel at nominal cryogenic conditions.

The LHC magnets are grouped into about 1600 circuits and are electrically fed at specific positions of the about 2.5 km long cryostats, through the current leads located in the Distribution Feed Boxes (DFB). Most of the current lead active elements include a high critical temperature superconductor [2]. They are connected at room temperature to the DC cables supplying the current from the power converters, and at 4.5 K to the superconducting bus bars connecting to the magnets.

The bus bars can be classified in the three following groups, depending on the current rating of the circuits and the respective time constants in case of resistive transitions: 13 kA, 6 kA and 600 A. The main parameters of these superconducting bus bars are shown in Table I.

TABLE I BUS BAR PARAMETERS

Parameter	units	13kAMB	13kAMQ	6kA	600A
A_{Cu}	mm^2	300.4	174.5	17.4	3.6
A_{NbTi}	mm^2	19.2	13.5	5.2	0.4
V_{th}	V	1	1	0.1	0.1
I_0	kA	4.0	4.0	1.0	0.27
I_n	kA	12.85	12.85	6.0	0.6
β	m/s/kA	0.05	0.05	1.6	20
l_{ins}	mm	1.0	1.0	1.0	1.0
RRR	-	200	200	200	200
L_s	cm	12.0	12.0	7.0	1.0
α	A/s	10.0	10.0	5.0	0.5

There are about 70.000 splice joints in the magnet circuits realized during the work of interconnection of the cryo-magnets in the LHC tunnel. These resistive joints are made using different techniques (inductive brazing for 13 kA and 6 kA superconducting bus and ultrasonic welding for the 600 A superconducting bus) [3]. The joints can also be classified according to the topology of the connection (see Figure 1). 13 kA splices are made according to Type A. Type B corresponds to the rest of the cases (6 kA and 600 A splices). In case of heating of the contact zone, the implications in terms of current redistribution are different for the two types.

The joints between magnets will be tested with current at cryogenic conditions for the first time during the commissioning of the accelerator without beam. At this moment of first powering, precautions have to be taken in order to make sure that the overheating of possible faulty splices is detected on time by the quench protection system. This overheating occurs at low currents because the bus bars are cryogenically stable and therefore no resistive propagation occurs. The voltage threshold at the quench detectors may be too high to detect this local overheating.

What follows in this paper is the systematic study conducted on quench protection, thermal stability and current distribution of all types of splices present in the LHC circuits. Answers are given to the following questions:

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- What are the allowed and the forbidden current ramps and current plateau during first powering?
- How efficient is the quench protection system in limiting the hot spot temperature in case of overheating of the splice regions?
- Can the parameters of the protection systems, like detection thresholds, be modified to avoid overheating?

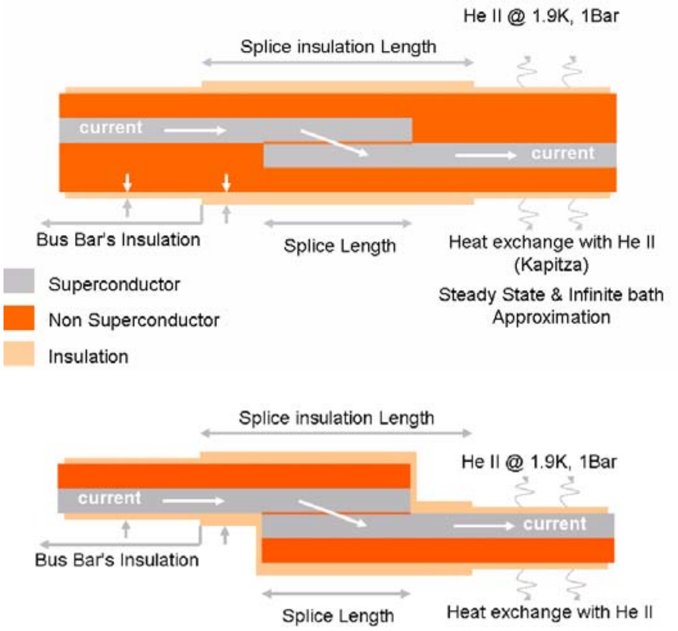

Figure 1 The type A splice (upper picture) and the type B splice (lower).

II. QUENCH PROTECTION IN CASE OF EXTRA HEATING IN THE SPLICE

Computer simulations and experimental tests have validated [4] that the LHC circuits are protected against resistive transitions (i.e. quenches). A quench induced by overheating in the splices must not happen since it may compromise the operation of the LHC accelerator. Strict requirements on the contact resistance have been specified to avoid such situations. Nevertheless it can happen that a few faulty splices will have a resistance higher than expected and the consequent overheating will be observed only during the commissioning of the circuits. These faulty splices will have to be repaired but must be discovered without compromising the integrity of the circuits. Since this should not occur during normal operation, the protection system has neither been designed nor configured to detect this type of event. This type is however similar but not equivalent to the ones caused by the external perturbation (e.g. beam loss, degradation of cryogenic conditions) because the heat source responsible for the instability is inside the conductor and proportional to the square of the current.

The first parameter to start investigating the response of the protection system against these instabilities is the value of the splice resistance R_s. For a given circuit and current ramp the quench current I_q and the detection current I_d are defined for a given R_s. In Fig. 2 this process is described in the plot of resistance versus current. While the operating current increases, the resistance of the splice stays constant until the curve of the quench resistance R_q is intercepted, where the balance between heat produced in the splice and heat absorbed by the cooling breaks. Afterwards a resistive transition occurs and the current starts leaving the superconductor to fill the surrounding copper stabilizer. As the resistance increases the temperature increases too, giving rise to a thermal runaway. Below the current I_0 the voltage may increase only due to the increasing temperature, since the normal conducting zone cannot expand. Above I_0 the expansion of the normal conducting zone starts and gives an important contribution to the quench detection. This is the main reason, as it will be demonstrated below, why the operation at low current regime may be more delicate than in nominal conditions. The value of I_0 and β has been measured for the 600 A and 6 kA bus bars [5][6], for the other bus bars these values have been calculated with computer code [4], tuned on available measurements. In the following, the mathematical model of this process is presented in detail.

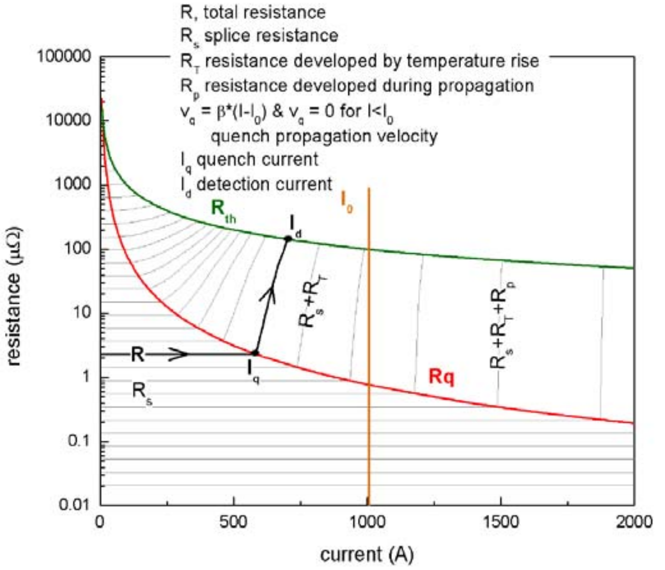

Figure 2 Schematic view of the calculation procedures used for the estimation of the quench process and consequently the hot spot temperature in the splice.

The following relation has been used to define the resistance which drives the system into normal conducting state at a given current I

$$R_s I^2 = H\left(T_{cs}(I)\right) \tag{1}$$

where the Joule heat generated by the resistance of the splice is equated to the cooling power H (for details see section III) and T_{cs} is the current sharing temperature. Inverting (1) gives I_q for a given splice resistance. After reaching I_q we assume that the temperature of the splice, θ, evolves adiabatically, following the following differential equation,

$$C(\theta)\dot{\theta} = R_{sw}(\theta) I^2(t), \tag{2}$$

where R_{sw} is the splice resistance in the normal conducting state as a function of the temperature (see section IV) and C is the equivalent heat capacity of the splice region. The hot spot evolution is given by the solution of (2),

$$\int_{T_{cs}}^{T(t)} \frac{C(\theta)}{R_{sw}(\theta)}\, d\theta = \int_{tq}^{t} I^2(t')\,dt'. \qquad (3)$$

Consider a current cycle of this shape:

$$I(t) = \begin{cases} \alpha \cdot (t - t_0) & t_0 \le t \le \min\{t_{\max}, t_d\} \\ I_{\max} & t_{\max} \le t \le t_d \\ I_d \cdot \exp[-(t - t_d)/\tau] & t \ge t_d \end{cases} \qquad (4)$$

where α is the ramp rate, I_{max} the maximum current and τ is the discharge time constant of the circuit. To calculate the detection time (or detection current, I_d) we numerically solve the following equation

$$V_{th} = \left[R_{sw}(\theta(t)) + R_p(t)\right] \cdot I(t) \qquad (5)$$

where all functions grow monotonically with time. R_p is the resistance developed by the quench propagation, defined with the following integral,

$$R_p(t) = \frac{\rho_0}{A_b} \int_{tq}^{t} v_q(I)\,dt \qquad (6)$$

where ρ_0 is the resistivity of copper below 20 K and A_b is the bus bar cross section. The current dependence of the quench propagation velocity, v_q, is approximated with a linear ramp, which fits well the experimental results as well as the numerical simulations, in the current range where the system is operated,

$$v_q = \begin{cases} \beta(I - I_0) & I > I_0 \\ 0 & I < I_0 \end{cases}. \qquad (7)$$

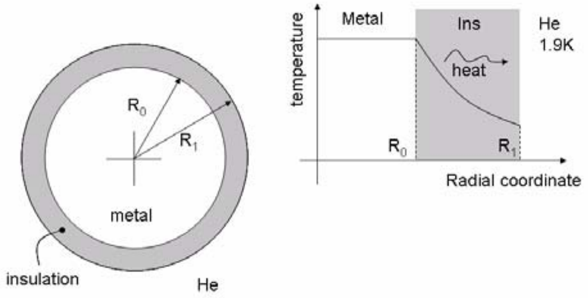

Figure 3 Heat transfer model of the splice. The heat produced inside the splice is transferred into the helium bath through a thick layer of insulation, which mainly limits the efficiency of the heat transfer. In this example the simplified cylindrical symmetry used in the actual calculation is represented.

Developing (6) the propagation resistance gets the following analytical expression,

$$R_p(t) = \begin{cases} 0 & I < I_p \\ \dfrac{\rho_0}{A_b}\dfrac{\beta}{2\alpha}\left[I^2 - I_p^2 - 2I_0 \cdot (I - I_p)\right] & I > I_p \end{cases}, \qquad (8)$$

where I_p is the current at which the propagation of the quench starts,

$$I_p = \begin{cases} I_0 & I_q < I_0 \\ I_q & I_q > I_0 \end{cases}. \qquad (9)$$

Finally the hot-spot temperature of the splice can be estimated introducing the following integral,

$$\int_{tq}^{+\infty} I^2(t)\,dt = \frac{I_d^3 - I_q^3}{3\alpha} + \tfrac{1}{2} I_d^2 \tau, \qquad (10)$$

in the right side of (3).

III. SPLICE THERMAL STABILITY

The beginning of a resistive transition has been defined in (1). To evaluate the cooling term (i.e. the transversal heat leaving the splice) we use the steady state heat transfer model from the conductor into an infinite bath of He II through a layer of insulation material, see Figure 3. During the whole heat transfer process we assume that the helium does not modify its properties.

The splice geometry is simplified as an equivalent cylinder where $R_1=P_w/2\pi$ and $R_0=R_1-l_{ins}$ where P_w is the wet perimeter and l_{ins} is the insulation thickness. The equation which describes the steady heat transfer in radial coordinate is the following:

$$k_{ins}(\theta)\frac{\partial\theta}{\partial r} 2\pi r + P_w h(T_1) = 0, \qquad (11)$$

where $R_0<r<R_1$, k_{ins} is the heat conductivity of the insulation material and h is the heat flux absorbed by helium when it is in contact with a material with a surface temperature T_1. This equation has the following integral solution

$$\int_{T_1}^{T_0} k_{ins}(\theta)\,d\theta = P_w h(T_1) \cdot \ln(R_1/R_0), \qquad (12)$$

which establishes the relation between the two boundary temperatures ($T_1=f(T_0)$). Finally the transversal heat is defined

$$H(\theta) = L_s \cdot P_w \cdot h(f(\theta)), \qquad (13)$$

where L_s is the splice length.

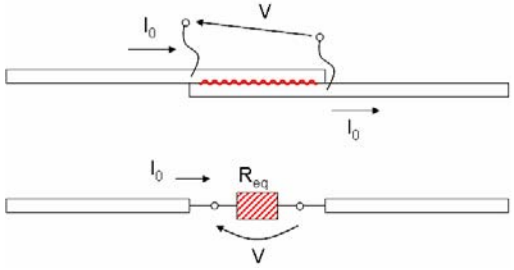

Figure 4 Schematic view of the equivalent electrical resistance of the splice region

IV. SPLICE RESISTANCE FOR TYPE B

The resistance of the splice region during normal operation at 1.9 K is only defined by the contact between extremities of the two bus bars. In the following we make the assumption that the contact resistance is uniformly distributed along the splice length, L_s. This simplifies the definition of the linear conductance as a function of the total splice resistance at cold to the following expression:

$$g = 1 / R_s L_s \,. \qquad (14)$$

This assumption implies that during normal operation the current is distributed uniformly from one cable to the next one (i.e. the current profile in the splice region is linear). The diffusion equation (15) describes the current profile in steady state [7] for the general situation where the bus bars may not be superconducting,

$$\frac{\partial^2 I}{\partial z^2} - 2grI + grI_0 = 0, \tag{15}$$

where r is the linear resistance of bus bar defined as

$$r = \rho(\theta) / A_b . \tag{16}$$

Solving (15) gives the current for an average temperature of the splice region. In Figure 4 a schematic view of the splice connection is given and the definition of the splice equivalent resistance is introduced. We solve (15) with the following boundary conditions,

$$I(0) = I_0 \quad , \quad I(L_s) = 0 \tag{17}$$

and defining for simplicity $k = \sqrt{2gr}$, the equivalent resistance gets the following expression

$$R_{eq} = \tfrac{1}{2} rL_s + \sqrt{\frac{r}{2g}} \cdot \left[\sinh^{-1}(kL_s) + \tanh^{-1}(kL_s)\right]. \tag{18}$$

Equation (19) gives the total splice resistance for a given temperature in steady state conditions. It can be approximated into

$$R_{eq} \approx rL_s + \frac{1}{gL_s} \qquad if \quad \sqrt{2rg}L_s << 1, \tag{19}$$

which corresponds to the resistance in case of a linear current profile and expression (14) is refound if the resistance of the stabilizer (r) is equated to zero.

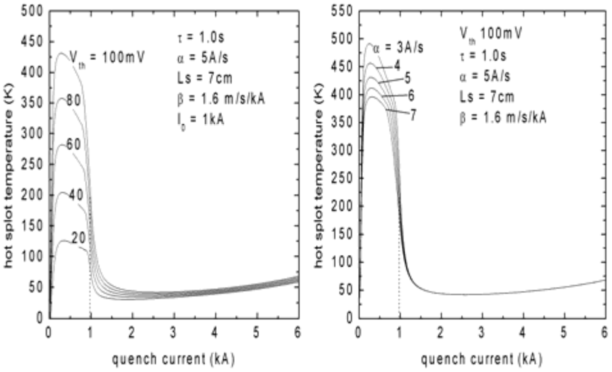

Figure 5 Example of hot spot calculation as a function of the quench current for the 6kA bus bars. In particular the sensitivity to the voltage threshold (left plot) and the ramp rate (right plot) has been studied.

V. RESULTS OF CALCULATIONS

To explain the results of the calculations, it is convenient to distinguish between the two types of bus bar. The type A bus bars are less critical because - if the stabilizer is correctly soldered to the cable - the resistance of the splice region is naturally limited to less than 100 nΩ, which is close to the resistance of copper in the splice region. At such low level of resistance, below I_0 the bus bars are cryo-stable while above I_0 and up to nominal current, the quench propagates with limited temperature (<30 K): this has been investigated numerically and validated experimentally. The type B bus bars on the contrary are more critical since there are no mechanisms, like for type A, which limits the resistance, since the current is forced to pass through the connections. Both the 600 A and the 6 kA bus bars configurations have been extensively investigated with the model described in this paper and the analysis of the parameters has been carried out. The system variables which can be tuned and which have a relevant impact on the detection and the protection are the voltage threshold (V_{th}) and the current ramp rate (α) as presented in Figure 5. At low current the hot spot temperature is higher because the time for detection is longer. When the quench occurs close to I_0 the detection time decreases significantly and consequently limits the hot spot temperature. This is the case for a ramp up to nominal current which is well above I_0, however, for ramps to lower currents (lower or close to I_0) the situation is more delicate.

TABLE II SUMMARY OF THE ANALYSIS

Bus Bars Circuit	Proposal	Comments
13kA MB	Baseline	-
13kA MQ	Baseline	-
6kA	Baseline	No plateau between 40-600A
6kA	V_{th} = 20 mV	-
600A	V_{th} = 20 mV	No plateau between 10-200A

VI. CONCLUSIONS

The protection of the superconducting circuits has been analyzed to investigate the effect of overheating caused by faulty splices. All circuits have been taken into account and in Table II the summary of the main results and actions to be taken are presented. Type A bus bars are not critical: nevertheless, the assembly of a type A splice is crucial; in fact poorly soldered stabilizers can damage the bus bars in case of quench and this defect cannot be preventively detected in cold conditions prior to the event. Additional attention should be paid for the circuits equipped with type B bus bars since the value of the resistance of a faulty splice is not intrinsically limited. However the 6 kA bus bars are well protected with both baseline voltage threshold (100 mV) and current ramp-rate but the current plateau between 40 A and 600 A should be avoided because they may lead, in case of high resistive splices, to very long detection time which will eventually cause over-heating above safe operating temperatures. On the contrary the voltage threshold for the 600 A bus bars should be decreased down to 20 mV while a regular ramp rate of 0.5 A/s is applied. The current plateau between 10 A and 200 A should be avoided for the same reasons already mentioned for the 6 kA. In both circuits the *forbidden* current plateau can be safely operated only decreasing further the voltage threshold. Obviously this level cannot be fixed as low as desired and any decision should take into account the actual parameters of the detection system.

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