MODELLING OF THE QUENCH PROCESS FOR THE OPTIMISATION OF
THE DESIGN AND PROTECTION OF
SUPERCONDUCTING BUSBARS FOR THE LHC

R. Schmidt¹, F. Sonnemann¹,²

Abstract
The superconducting busbars powering the LHC magnets are highly stabilised with copper to reduce the probability of a quench starting in a busbar and to avoid excessive temperatures after a quench during current discharge. In order to determine the required copper stabilisation and the parameters of the protection system a finite difference program has been developed. The program numerically approximates the heat balance equation and evaluates the temperature profile after a quench as a function of time and space. The approach emphasises the modelling of heat transfer into helium. The evaluation of the temperature includes the entire quench process, i.e., the time for quench detection and the current decay.

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Modelling of the Quench Process for the Optimisation of the Design and Protection of Superconducting Busbars for the LHC

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The superconducting busbars powering the LHC magnets are highly stabilised with copper to reduce the probability of a quench starting in a busbar and to avoid excessive temperatures after a quench during current discharge. In order to determine the required copper stabilisation and the parameters of the protection system a finite difference program has been developed. The program numerically approximates the heat balance equation and evaluates the temperature profile after a quench as a function of time and space. The approach emphasises the modelling of heat transfer into helium. The evaluation of the temperature includes the entire quench process, i.e., the time for quench detection and the current decay.

1 INTRODUCTION

The solution of the heat balance equation determines the temperature profile after a quench along a superconducting busbar as a function of time and space in presence of various cooling conditions. As the heat balance equation is not analytically solvable, a finite difference program has been developed in order to evaluate the required design and the parameters of the protection system of the different superconducting busbars that will power the various types of magnets of the LHC. Simulation studies of busbar quenches are necessary to scale experimental results from quenching prototype busbars [1] to the situation of a busbar quench in the LHC when the quench load increases up to an order of magnitude. The simulations allow to estimate the hot spot temperature for different copper stabilisations. The theoretical approach described here was also used to better understand experimental results of the quench propagation of the busbar cable powering the auxiliary magnets of the LHC [2].

2 THEORETICAL MODEL

The busbar is represented by N equidistant elements of length $Dx$ with temperature $T_n$, cross-section $A_i$ and wetted perimeter $P_i$. The busbar is treated as a homogeneous structure, i.e. the copper cross-section is the sum of the copper stabiliser ($A_{Cu}^{St}$) and the copper fraction of the superconducting cable ($f_{Cu}A_{cable}$). The quench is initiated by a Gaussian temperature profile of temperature $T_{init}$ and width $\sigma_t$. In case of the busbar the temperature as a function of time $t$ and $x$ is the solution of the one dimensional heat balance equation

$$\frac{d}{dx} \left( k(T(x,t)) \frac{d}{dx} I(x,t) \right) A(x) - h(x)(T(x,t),t)P(x) + G(T(x,t),t) = c(T(x,t)) A(x) \frac{dT(x,t)}{dt};$$

with $c$ being the heat capacity, $k$ being the heat conductivity, $h$ determining the heat transfer into helium, and $G$ being the internal heat generation. $G(T(x,t))$ is given by

$$G(T(x,t),t) = \begin{cases} 0 & \text{if } T(x,t) \leq T_{coh}(t) \\ \rho_{coh}(T(x,t)) \frac{I(t)^2}{A(x)} \frac{T(x,t) - T_{r}(t)}{T_{r}(t)} & \text{if } T_{coh}(t) < T(x,t) \leq T_{crit}(t) \\ \rho_{coh}(T(x,t)) \frac{I(t)^2}{A(x)} & \text{if } T(x,t) > T_{crit}(t) \end{cases}$$
Heat is generated if the temperature exceeds the current sharing temperature $T_{cs}$. The current $I$ is constant until the resistive voltage that increases in case of a propagating quench exceeds the detection threshold. The current then decays exponentially with a decay time constant $\tau$. The cooling conditions are determined by the heat transfer from the busbar surface into the helium bath of temperature $T_{bath}$. The simple model (model 1) for the heat transfer coefficient $h$ is

$$h_{eq}(T(x,t), t) = \alpha \cdot (T(x,t) - T_{bath})$$

A complex model (model 2) for transient heat transfer including Kapitza regime and film boiling requires more parameters [3]

$$h_{eq}(T(x,t), t) = \begin{cases} 
0 & \text{if } T(x,t) \leq T_{bath} \\
\alpha_1 \cdot (T(x,t) - T_{bath}) & \text{if } T(x,t) \leq T_{n,boil} \\
\alpha_2 = h(T_{n,boil}) & \text{if } T_{f,boil} > T(x,t) > T_{n,boil} \\
\alpha_3 \cdot (T(x,t) - T_{bath}) & \text{if } T(x,t) > T_{f,boil} \wedge t - t(T > T_{n,boil}) < t_{boil} \\
\alpha_4 & \text{if } t - t(T > T_{f,boil}) > t_{boil}
\end{cases}$$

with $T_{n,boil}$ and $T_{f,boil}$ being the temperatures of starting nucleate and film boiling, and $t_{boil}$ being the time interval for burn-out.

The quench propagation velocity $v_q$ is determined from the simulation result as the increase of the resistive zone with time. The hot spot temperature $T_{max}$ and $v_q$ for the given quench load can be compared with experimental results for validation of the cooling model.

Since the heat transfer rate into helium is limited due to the heat conductivity of the insulation material, the temperature has to be evaluated separately for the cable surface $T$ and the insulation layer surface $T_{iso}$ to obtain a cooling model without fit parameters (model 3). Both heat balance equations are connected by heat conduction from the cable surface into the insulation layer.

3 SIMULATION STUDIES

3.1 Quench propagation

An example of the quench propagation is shown in Fig.1. The simulation studies demonstrated that an

![Figure 1: Temperature profile as a function of space and time showing the expanding normal conducting zone. The parameters for this simulation study are $A_{surf}=258 \text{mm}^2$, $U_{diss} = 1V$, $I_0 = 12.5 \text{kA}$, cooling conditions according to model 3. The quench was initiated with $T_{init}=20 \text{K}$, $\sigma = 0.8 \text{m}$. The time interval between two curves in the figure is 25s.](image)
increasing temperature at the quench origin always leads to an expanding normal conducting zone for realistic cooling scenarios and \( A(x) \equiv A \). Otherwise the temperature decreases and recovery takes place. Due to the long time period of the quench process the hot spot temperature does not depend on the quench initialisation temperature. When the normal conducting zone is neither expanding nor shrinking the hot spot temperatures remains constant until the cooling conditions vary. This unlikely situation would increase the heat load on the cryogenic system. If the cooling power decreases the temperature will start to increase and the normal conducting zone will expand followed by quench detection and current decay. The limits for the copper cross-section of the busbars presented below ensure that no excessive temperatures will be obtained in such a case.

3.2 Calibration

The simulation model was calibrated using experimental results of prototype busbar tests [1]. The prototype busbar for the LHC main dipole magnets has a cross-section of \( A_{Cu}=296.5 \text{mm}^2 \) and \( A_{NbTi}=6.5 \text{mm}^2 \). The quenches were induced firing a spot heater immediately followed by a linear current discharge. The wetted perimeter was fitted for the cooling models 1 and 2 to obtain the measured quench propagation velocity. The simulated hot spot temperature was then compared with the experimental result for the measured quench load during the tests. When the complex cooling model is used and the insulation layer is taken into account (model 3) the wetted perimeter is not a fit parameter. If a small amount of helium is present in the busbar or in the insulation layer this helium fraction has to be included for adjustment of the model (model 3 adjusted).

<table>
<thead>
<tr>
<th>model</th>
<th>variable</th>
<th>measurement</th>
<th>simulation</th>
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</thead>
<tbody>
<tr>
<td>model 3</td>
<td>( v_q )</td>
<td>0.3-0.4 m/s</td>
<td>0.42 m/s</td>
</tr>
<tr>
<td>model 3 adjusted</td>
<td>( v_q )</td>
<td>0.3-0.4 m/s</td>
<td>0.36 m/s</td>
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<tr>
<td>( T_{max}, T_{bath}=1.9 \text{ K} )</td>
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<td>60 K</td>
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<tr>
<td>( T_{max}, T_{bath}=4.2 \text{ K} )</td>
<td>76 K</td>
<td>80 K</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Comparison of simulation and experimental results. The parameters of the cooling model are \( a_1=180 \text{ W/m}^4, a_2=100 \text{ W/m}, n=4, m=1, t_{boil}=0.02 \text{ s}. \) A helium fraction of 0.5 % of the total cross-section is used for the adjustment.

When the cross-section is dominated by the copper stabilisation the adjustment of model 3 is negligible which indicates the robustness of the theoretical approach (see Table 1).

3.3 Scaling and Detection

In order to evaluate the hot spot temperature after a bus bar quench in the LHC, the time required for quench detection and opening the extraction switches, and the time for the current decay (\( \tau_1=100 \text{ s} \) for the main dipole magnet circuit) have to be included. For that reason the experimental results of prototype busbars [1] have to be scaled. The detection time for various threshold levels was evaluated as a function of cooling conditions keeping the busbar cross-section constant. As the long term cooling conditions are not very well known, the hot spot temperature was estimated using the different cooling models. The maximal temperature differences are about 50 K at a 1 V detection level. Table 2 shows that a detection level of 1 V limits the hot spot temperature to tolerable values whereas a threshold of 5 V leads to excessive temperatures.

3.4 Required Copper Stabilisation

For a detection level of \( U_{det}=1 \text{ V} \) the hot spot temperature after a quench for various copper cross-sections and operating currents was simulated for the busbars of the main dipole and quadrupole magnets. The simulation study includes modelling the heat transfer through an insulation layer of 200\( \mu \text{m} \) thickness and the complex cooling model.
The minimum required copper cross-section to avoid temperatures higher than 400 K was found to be

\[ A_{MB_{Cu}} = 240 \text{ mm}^2 \] for the busbar powering the main dipole magnets and

\[ A_{MQ_{Cu}} = 160 \text{ mm}^2 \] for the busbar powering the main quadrupole magnets (\( \tau_{I_{MQ}} = 45\text{s} \)). Due to the shorter current decay time the copper cross-section of the busbar for the main quadrupole magnets is smaller. This reduction causes the quench detection time being only half as long with respect to the busbar for the main dipole magnets.

For a given quench load, the cooling reduces the hot spot temperature with respect to the adiabatically calculated temperature. For the LHC dipole busbars, the difference could be as large as 200 K. The hot spot temperature varies by less than 10 % for the different cooling models when the same detection time is assumed. When the various cooling models determine the quench detection time, the hot spot temperature varies by about 20 %.

### 4 CONCLUSIONS

The quench process of the busbars has been simulated using the finite difference method. The theoretical approach allows studying different cooling models including the heat transfer through the insulation layer. The adequate thresholds for the quench detection for the busbars powering the LHC main magnets and the required copper stabilisation to avoid overheating were determined. The developed program also allows the assessment of more complex geometries, for example the reduction of the busbar cross-section through lambda plates, etc.

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### References

