PROBABILITY OF BURN-THROUGH OF DEFECTIVE 13 KA SPLICES AT INCREASED ENERGIE LEVELS

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Abstract

In many 13 kA splices in the machine there is a lack of bonding between the superconducting cable and the stabilising copper along with a bad contact between the bus stabiliser and the splice stabiliser. In case of a quench of such a defective splice, the current cannot bypass the cable through the copper, hence leading to excessive local heating of the cable. This may result in a thermal runaway and burn-through of the cable in a time smaller than the time constant of the circuit. Since it is not possible to protect against this fast thermal run-away, one has to limit the current to a level that is small enough so that a burn-through cannot occur. Prompt quenching of the joint, and quenching due to heat propagation through the bus and through the helium are considered. Probabilities for joint burn-through are given for the RB circuit for beam energies of 3.5, 4 and 4.5 TeV, and a decay time constant of the RB circuit of 50 and 68 s.

INTRODUCTION

At the Chamonix 2009 workshop [1] a quench scenario of the 13 kA joints was presented that could not be protected and that could lead to burn-through and arcing between the two cables of the splice, similar to the incident on 19 Sept. 2008 [2]. Such an unprotectable burn-through could occur in case of a quench in a joint having a lack of bonding between the superconducting cable and the copper stabiliser, coinciding with a longitudinal interruption of the bus stabiliser. Fig. 1 shows various ways causing a quench of a joint and the probabilities of a burn-out. Note that steady-state resistive losses in the splices are detected with the new QPS bus protection ***before*** they could lead to a quench of the joint.

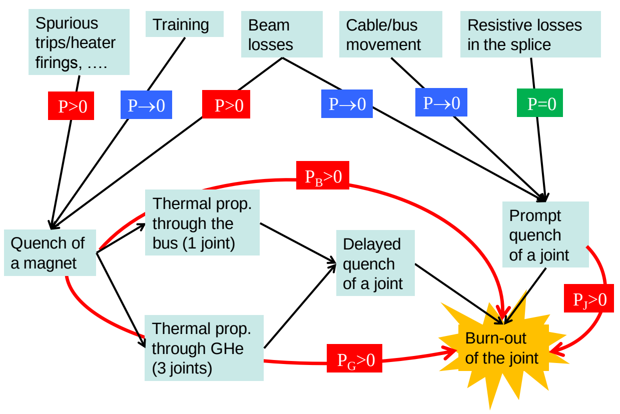

Figure 1: Probability flow chart for currents up to 9 kA.

Up to 9 kA the most likely scenario for quenching a joint is by means of thermal propagation from an adjacent quenching magnet.

In this paper the probabilities P_B, P_G and P_J will be discussed and estimated, for beam energies of 3.5, 4 and 4.5 TeV.

P_G: The probability that a joint burns through due to the propagation of gaseous helium if an adjacent magnet quenches.

P_B: The probability that a joint burns through due to the heat propagation from an adjacent quenching magnet, including the diode and its lead, through the bus towards the interconnect.

P_J: The probability that a joint burns through when it promptly quenches, e.g. due to beam losses.

The probability per year (P_Y) that a joint burns through can then be written as:

$$P_Y=N_M(3P_G+P_B)+N_JP_J$$

With N_M the number of magnet quenches per year and N_J the number of prompt joint quenches per year. Note that each dipole magnet quench affects 4 joints: 1 joint quenches through thermal propagation through the bus, while 3 joints quench through warm gaseous helium. The probability P_G is therefore multiplied by a factor 3.

All calculations have been performed using the computer code QP3 [3].

ASSUMPTIONS

The calculation of possible quench scenario's and hence the probabilities P_G, P_B, and P_J depend not only on the operating current and the decay time constant τ, but also on several other parameters, such as:

- Defect size (represented by R_{addit}).
- RRR of the bus, the diode lead, and the cable.
- “Dipole-Bus-Diode” geometry.
- Heating up of the magnet coil.
- Heating up of the diode.
- Heat transfer to helium (for the bus, diode lead, and joint area).
- Resistance of the ‘half moons’.
- GHe propagation time.

Assuming a worst case value for all these parameters would result in an unrealistically low safe current. Therefore, most parameters will be fixed to best-known (but somewhat conservative) values, as given below:

Defect size:
The distribution of defects around the machine is taken from an analysis based on a few hundred so called R16 measurements [4]. The number of defects larger than a certain limiting value R_{lim} is shown in Fig. 2. The percentage is calculated based on the total number of about 10000 joints in the machine.

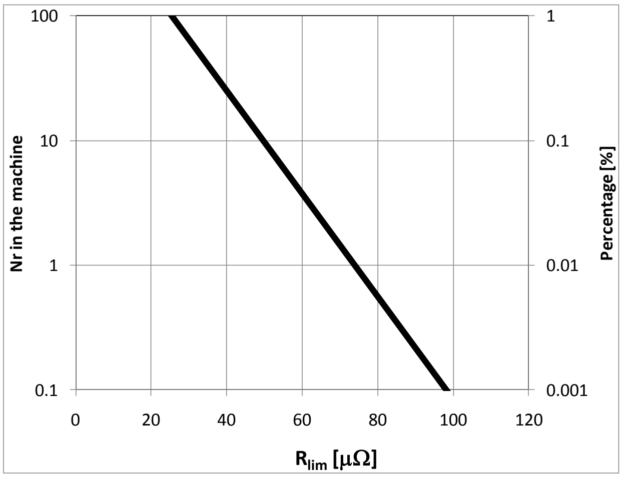

Figure 2: The cumulative distribution of all available measured R16 resistance data.

RRR:
Recent measurements [5] show that the bus bars have a RRR of 250±50. A value of 200 is therefore used for the RRR of the bus, the wedge, the U-profile and the diode leads. The RRR of the cable is assumed to be 80, similar to the value after cable production [6]. The magneto-resistivity of copper is also taken into account.

Geometry magnet - bus – diode:
Four slightly different geometries are studied (see Fig. 3), which have different lengths of the diode lead and the bus between magnet and joint. The most critical geometry (namely type B connected to the upper heat sink) is used as default case.

The calculations performed with QP3 are done in such a way that only the bus bars are simulated (including the half moon and the joint), and not the diode heat sink and the magnet itself. This approach requires a time-dependent boundary temperature at the interface between bus bar and magnet and at the interface between bus bar and diode. These temperature profiles are discussed in the next two sub-sections. In the model, the main bus bar with standard bus insulation (i.e. on the left of the joint in Fig. 3) is taken long enough so that the temperature gradient equals 0 at the end of the bus.

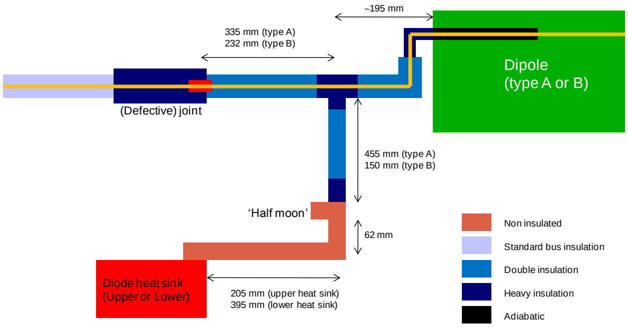

Figure 3: Schematic view of the dipole, bus, diode, diode lead and joint. Only one connection is shown. Lengths vary among the 4 possible geometries.

Heating up of the magnet coil:
Immediately after quench detection, the heaters in the magnet are fired, the magnet resistance and voltage increase, and the current deviates into the by-pass diode as soon as the magnet voltage reaches the diode opening voltage of 6 V. The exact shape of the current decay in the magnet is not very important for the simulation, and for simplicity an exponential function (with decay time τ_{mag}) is assumed, although in reality it is not. During this process the magnet coil heats up, especially in those parts of the coils where the field is high. The bus is connected to the cable entering the mid-plane of the outer coil. This part of the coil is in low field and not in direct contact with the heaters, and warming up is therefore limited [7,8]. For all calculations I have used the following maximum temperatures and times τ_{mag}:

- 20 K and 1.3 s (for 3.5 TeV)
- 22 K and 1.1 s (for 4 TeV)
- 26 K and 1.0 s (for 4.5 TeV)

Heating up of the diode:
As soon as the current bypasses the quenching magnet, the diode starts to warm up. Of course the rate of warm-up depends on the current and on the decay time constant of the circuit. Experimental data are shown in Fig. 4 [9],[10].
All calculations are performed with an approximate temperature increase equal to: $T=T_0+At^B$ with the constants A and B equal to:

- 18.55 and 0.384 (for 3.5 TeV)
- 18.62 and 0.396 (for 4 TeV)
- 18.69 and 0.408 (for 4.5 TeV)

Heat transfer to liquid helium:
The heat transfer (in W/m^2) from the non-insulated bus (between the diode heat sink and the half moon) to the helium is given by Kapitza cooling equal $180(T_{\mathrm{bus}}^4\text{-}T_{\mathrm{He}}^4)$ up to a maximum of 35000 W/m^2. Above this value film boiling is assumed equal to $1250(T_{\mathrm{bus}}\text{-}T_{\mathrm{He}})$.

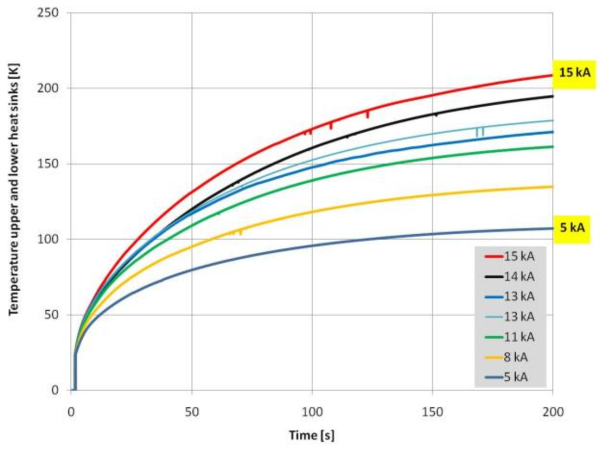

Figure 4: Experimental data of the temperature increase of the heat sink of a dipole by-pass diode for currents between 5 and 13 kA.

The heat transfer from a kapton insulated bus to the helium is given by a series transfer through solid kapton (using the NIST data for kapton) and film boiling, using 1250(T_{ins}-T_{He}) with T_{ins} the temperature of the outer surface of the kapton. This approach gives a good fit to heat transfer measurements performed on a bus bar sample [11], and is qualitatively and quantitatively similar to the analysis given in [12]. The thickness of the kapton layer used in the above given approach equals 0.29 mm (for a standard bus insulation), 0.6 mm (for a double insulation), 1 mm (for a heavily insulated bus), and 2 mm (for the joint area over a length of 24 cm), see also Fig. 3.

Resistance of the half moons:
The resistance of the so-called half moons (connecting the diode lead with the internal bus of the diode) is based on measurements performed in SM18 during a current discharge from 3 kA, see Fig. 5.
Calculations of the probability for joint burn-out are performed for a resistance of 2.5 μΩ.

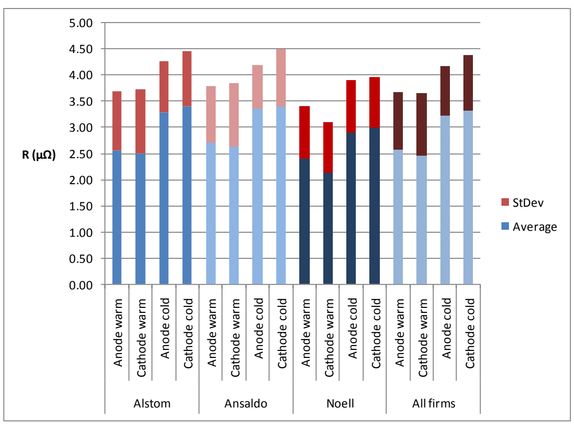

Figure 5: Overview of the ‘half moon’ resistance values, as deduced during the magnet reception tests in SM18.

Gaseous helium propagation time:
All calculations assume that warm gaseous helium reaches the joint 20 s after the quench in an adjacent magnet, independent of the current in the magnet. This somewhat conservative value is based on data from the HWC 2008 campaign [13], see Fig. 6.

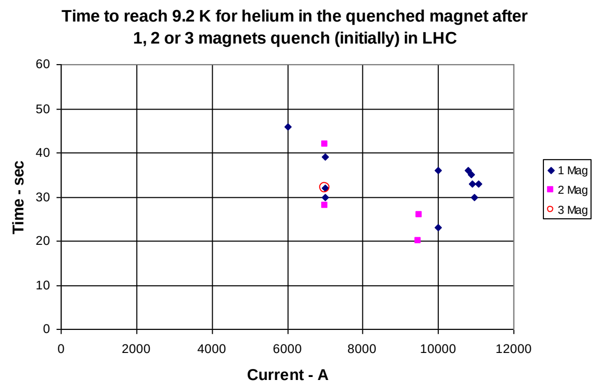

Figure 6: Calculated time to quench the joint in the M3 line after a quench in an adjacent dipole magnet for various currents between 6 and 11 kA.

PROBABILITY P_G

Fig. 7 shows the burn-out current versus the defect size for a joint quench initiated by gaseous helium from an adjacent magnet. Data are given for initial currents of 6, 6.8, and 7.6 kA, corresponding to about 3.5, 4, and 4.5 TeV (with an additional margin of about 100 A).

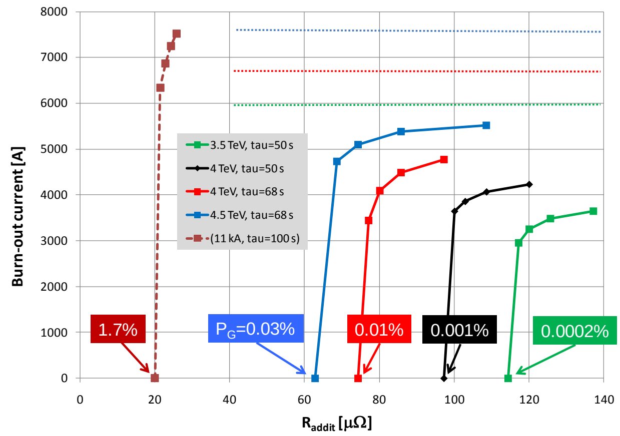

Figure 7: Burn-out current vs defect size for several operating currents, and the probability P_G (in % per magnet quench) using Fig. 2.

The 6.8 kA case is calculated for τ=50 and τ=68 s, since it was not yet completely sure which time constant has to be used (depending on possible limitations from QPS, power converters, and energy extraction). For comparison, also the 11 kA, τ=100 s case is plotted. Using the estimated defect distribution in the machine (see Fig. 2), the probability P_G is calculated that a defective joint burns through. P_G equals 0.0002% per magnet quench for 3.5 TeV, up to 0.03% per magnet quench for 4.5 TeV.

PROBABILITY P_B

Fig. 8 shows the burn-out current versus the defect size for a joint quench initiated by thermal propagation through the bus from the warm magnet, diode and diode lead (including the half moon). Data are given for the same currents as previously. Using the estimated defect distribution in the machine (see Fig. 2), the probability P_B is calculated that a defective joint burns through. P_B equals 0.002% per magnet quench for 3.5 TeV, up to 0.1% per magnet quench for 4.5 TeV.

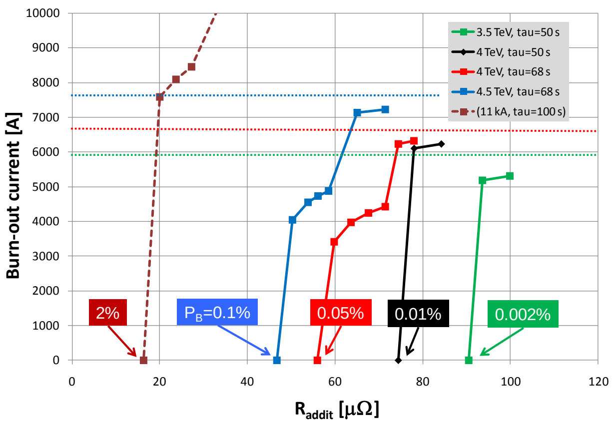

Figure 8: Burn-out current vs defect size for several operating currents, and the probability P_B (in % per magnet quench) using Fig. 2.

PROBABILITY P_J

Fig. 9 shows the burn-out current versus the defect size assuming that the joint quenches promptly, e.g. due to excessive beam losses. Data are given for the same currents as previously. Using the estimated defect distribution in the machine (see Fig. 2), the probability P_J is calculated that a defective joint burns through. P_J equals 0.003% per prompt joint quench for 3.5 TeV, up to 0.12% per magnet quench for 4.5 TeV.

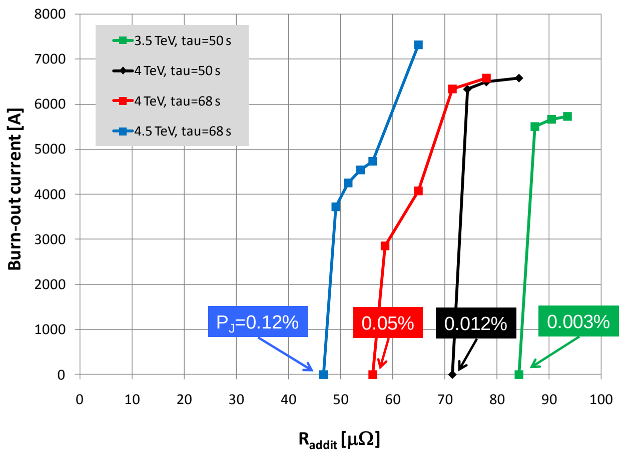

Figure 9: Burn-out current vs defect size for several operating currents, and the probability P_J (in % per prompt joint quench) using Fig. 2.

PROBABILITY OVERVIEW

Table 1 summarizes the probabilities P_G, P_B and P_J as given in Figs. 7-9. Note that each magnet quench affects 4 joints: 1 joint quenches through thermal propagation through the bus, while 3 joints quench through warm gaseous helium. The probability P_G is therefore multiplied by a factor 3.

As written in the introduction the probability of a burn-through of a joint during one year of operation can be summarised by $P_Y=N_M(3P_G+P_B)+N_JP_J$ with N_M the number of magnet quenches per year and N_J the number of prompt joint quenches per year.

Table 1: Overview of the probabilities for 4 operation scenario's. Note that P_G and P_B are given in % per MB quench, and that P_J is given in % per prompt joint quench.

Beam energy [TeV]	τ [s]	$I^2\tau$ [10^6A^2s]	P_G	P_B	$3P_G+P_B$	P_J
3.5	50	1800	0.0002	0.002	0.0026	0.003
4	50	2300	0.001	0.01	0.013	0.012
4	68	3150	0.01	0.05	0.08	0.05
4.5	68	3900	0.03	0.1	0.19	0.12

Considering that N_M>>N_J, and that P_J and ($3P_G+P_B$) are similar, the previous formula can be reduced to: $P_Y=N_M(3P_G+P_B)$. This relation is visualized in Fig. 10. Note that a possible asynchronous beam dump may cause prompt quenching in many interconnects, so that in this case also the probability P_J should be taken into account. Experience of operation in 2010 showed almost no dipole quenches, so for the risk evaluation, a number of about 10 quenches per year seems reasonable.

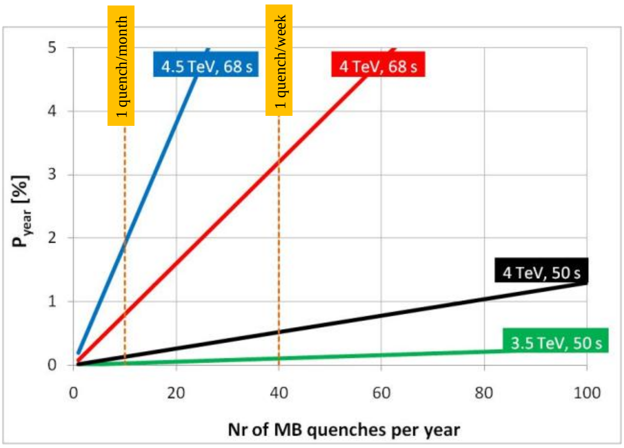

Figure 10: The probability per year of a joint burn-out as a function of the number of MB quenches, for 4 operating scenario's.

Note that the probability figures hold under the assumptions that:

- the R_{addit} measurements are representative for the entire machine, and hence the R_{addit} distribution in Fig. 2 is correct.
- the joints did not deteriorate over the last 2 years.

Up to now, only the RB circuit is analysed. The RQD/F circuits are safer, due to:

- the small decay time constant (9-15 s), also implying that P_G=0,
- the slightly smaller current,
- the longer distances between the magnet and the joint, and between the diode and the joint,

Sensitivity studies show that especially the GHe propagation and the thermal propagation from the diode & half moons to the joint have a large impact. Also the resistance of the 'half moon' plays an important role.

Bus signals can be measured with the nQPS after quenching one or a few dipoles in the machine. This will give accurate values of a few 'half moon' resistances, and might give some insight in the thermal propagation through the bus as well as the GHe propagation. However, a good understanding will be difficult due to limitations in current, external noise, limited number of voltage taps, and lack of useful temperature sensors.

Alternatively, a test in SM18 can improve our understanding of the thermal propagation through the bus. The advantages of such a test are that it can be performed up to high current, and that several temperature sensors and voltage taps can be connected to the diode and the bus. However, the test will not give relevant information on the GHe propagation, because the cryogenic system in SM18 is completely different from the tunnel.

A 'thermal amplifier test' in all sectors could qualify the safe operating current in situ (see [5]).

ACKNOWLEDGMENT

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