MINIMUM REQUIREMENTS FOR THE 13 kA SPLICES FOR 7 TeV OPERATION

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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 safe value below which such a burn-through cannot occur, taking into account the size of the defect, the characteristics of the splice, and the cooling. In this paper this safe current is presented based on simulations which are validated by means of experiments on three defective splice samples. Conclusions are given for running at 3.5 TeV and 5 TeV. Safe operation at 7 TeV is only possible by repair of the all the 13 kA splices, preferably by adding copper shunt to them.

INTRODUCTION

At the Chamonix 2009 workshop [1] a quench scenario of the 13 kA splices was presented that could not be protected and that could lead to burn-through and arcing 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 splice with a lack of bonding between the superconducting cable, the bus stabiliser, and the splice stabiliser. During the repair of sector 3-4 several defective splices were found by means of gamma-ray pictures, see for example Fig. 1, and by means of so-called R_8 or R_{16} measurements [3]. In the next section several types of defects are presented.

Figure 1: Gamma-ray picture of a defective splice [courtesy J.-M. Dalin].

Following these findings, a large measurement campaign was conducted in 5 sectors in order to map the defective splices [4]. However, since there are no voltage taps directly around the splices, the resolution of the measurements was limited. Some of the larger defects have been detected and repaired, but many defective splices are still in the machine. The effect of the presence of these defects on the maximum safe operating current I_{safe} is simulated using the code QP3 [5], and presented at the end of this paper. These calculations are validated through an experimental program in FRESCA, where three quadrupole bus splices with built-in defects have been tested. The calculations are performed for worst case RRR values, but otherwise no safety margin is added. Furthermore, the code is validated by comparing it for a benchmark case with a 1D model [6] and a 2D/3D model [7].

In the next section a brief overview of the different RRR values in the bus and splice is given. Then the calculations of the safe current versus additional stabiliser resistance (R_{addit}) are presented for liquid and gaseous helium conditions. Conclusions are given for operation at 3.5, 5, and 7 TeV.

The maximum allowed defect size to run at 7 TeV is so small that opening of all the M1, M2, and M3 lines in the machine is required to inspect all the 10,000 splices. Considering as well possible degradation of the splices, due to thermal and electromagnetic cycling, it is shown in the last part of the paper that an additional shunt is required on all splices. Requirements for these shunts from a thermo-electrical point of view are given.

TYPES OF DEFECTIVE SPLICES

The joint between the two superconducting (SC) cables is 120 mm long, and soldered while being compressed between a 120 mm long copper wedge and a 155 mm long copper U-profile. In the following the wedge and U-profile together are referred to as ‘splice stabilizer’. The splice is insulated by means of two U-shaped kapton pieces with a length of 240 mm and a thickness of 0.125 mm, and two U-shaped G10 pieces with a length of 190 mm and a thickness of 1 mm. More details on the splice can be found in [8].

In a good splice the resistance between the two SC cables should be less than 0.6 nΩ, so that, even at ultimate current of 13 kA, the heating is less than 0.1 W. Furthermore, the splice stabilizer and the bus stabilizer (on either side of the splice) should work as a continuous electrical shunt to the cables. This is achieved when the solder fills all the voids in and around the splice (see Figure 2), as well as the thin slots between the bus stabilizer and the splice stabilizer. Finally, a good splice should be mechanically strong enough to cope with the mechanical and electromagnetic forces acting on it.

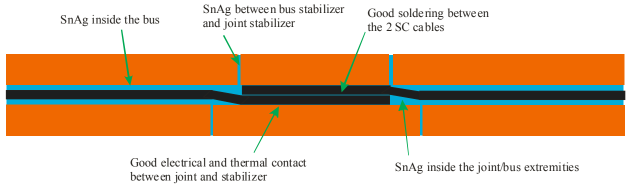

Figure 2: Schematic view of a 13 kA splice with good solder filling.

Several types of defects are schematically shown in Fig. 3. Defect type A represents an unsoldered splice with bad bonding between cable and U-profile and wedge, and probably a high resistance between the two SC cables. This defect is most likely the one that has caused the incident in 2008. Similar defects will now be detected with the nQPS, having a resolution of a few nΩ. Furthermore the 300 μV (or 500 μV below 6 kA) threshold on the nQPS will trigger before the resistive heating will cause the SC-to-normal transition.

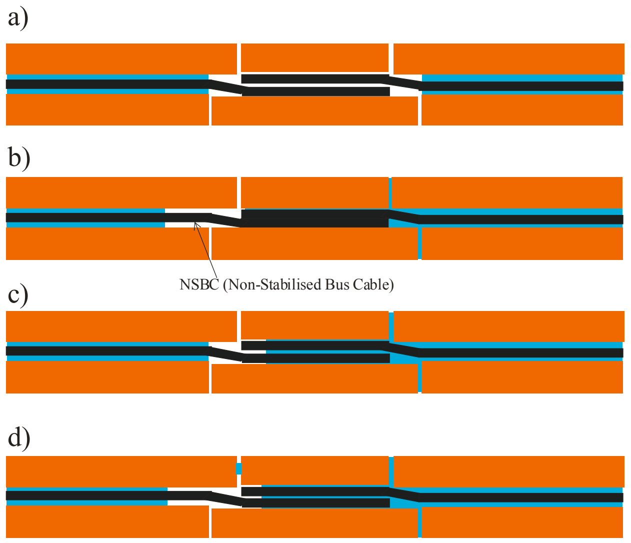

Figure 3: Schematic view of four different types of defective splices: a) Non-soldered, b) Soldered with outside void, c) Partially soldered with inside void, d) Badly soldered with void and some SnAg solder in between the bus stabiliser and the splice stabiliser.

Defect types B, C, and D can be single-sided or double-sided. The length l_{NSBC} of the Non-Stabilised Bus Cable (NSBC) is often 15 mm or more, due to the intrinsic design of the splice. Defect type B represents a defect for which part of the SnAg has flowed out of the bus. Defect type C represents a badly soldered splice, for which not all the SnAg reached the melting temperature. For defects B and C the additional stabiliser resistance at about 300 K is linear to the length of the NSBC, so: $R_{\text{addit}}= R_{\text{NSBC}}= 1.3 l_{\text{NSBC}}$ (with R in μΩ and l in mm).

Defect type D is the predominant defect in the machine, since in most cases at least some contact exists in the vertical gap between the bus stabiliser and the splice stabiliser. The resistance of this contact is denoted by $R_{\text{Cu-Cu}}$, and therefore $R_{\text{addit}}=R_{\text{Cu-Cu}}R_{\text{NSBC}}/(R_{\text{Cu-Cu}}R_{\text{NSBC}})$. In case of a quench the current will flow partially through the copper of the cable, and partially through the Cu-Cu contact. Two important comments have to be made:

1) The Cu-Cu contact can degrade in time, due to electromagnetic and thermal cycling, and possibly due to thermal and pressure shocks during a quench. So: R_{addit} can increase during the lifetime of the LHC, implying a reduction of the safe operating current.
2) If $R_{\text{Cu-Cu}}$ is small as compared to R_{NSBC} and if $\text{RRR}_{\text{Cu-Cu}}<<\text{RRR}_{\text{NSBC}}$ then the room temperature measurement of R_{addit} could give a somewhat underestimated R_{addit} at cold and hence an overestimated value of I_{safe}.

SAMPLES FOR VALIDATION OF THE CODE QP3

Several RQ bus splices with on-purposely built-in defects have been made and measured at the cable test facility FRESCA in B-163. The main purpose of these tests is to validate the calculation code QP3, and obtain an empirical value of the heat transfer from the bus to the helium through the kapton insulation.

The characteristics of the three samples are given in Table 1, and gamma-ray pictures are shown in Fig. 4.

Table 1. Characteristics of the three FRESCA samples.

Sample ID	1	2A	2B
Measured in:	Oct 2009	Nov 2009	Nov 2009
Interconnect type	RQ	RQ	RQ
Defect type	Single-sided B	Double sided C	Single-sided C
Length NSBC	47 mm	27 + 35 mm	35 mm
R_{addit}	61 μΩ	32 + 43 μΩ	42 μΩ
RRR bus	≈300	≈270	≈290
RRR cable	≈180	≈130 + 100	≈160
Splice insulation	2 mm G10 + glue	Machine-type	
Eff. cooled surface	25-60%	≈60-70%	
Field	Self-field (+ applied field)		
Current profile	Constant current		
Helium environment	Liquid helium		
Enclosure	Vertical tube with diameter 72 mm		
Length sample	≈1.5 m (with the splice in the centre)		

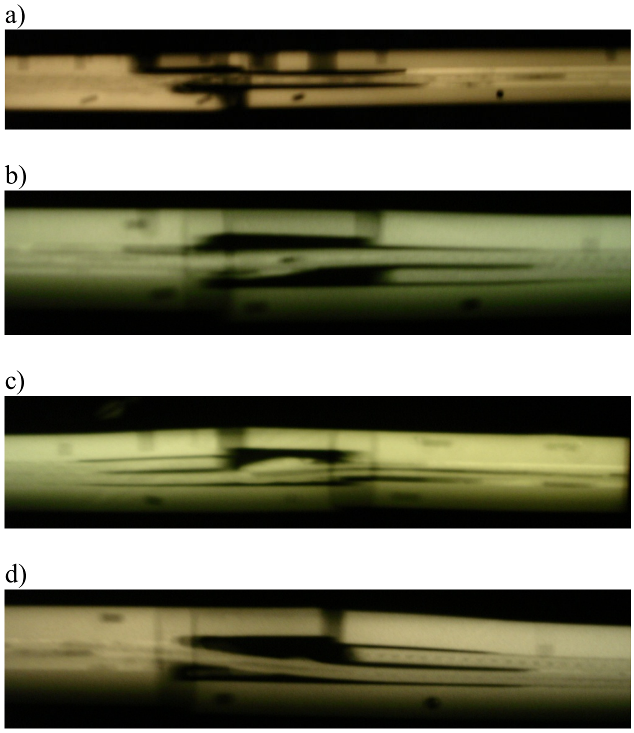

Figure 4: Gamma-ray pictures of: a) sample 1 (R_{addit}=61 µΩ), b) sample 2A left side (R_{addit}=32 µΩ), c) sample 2A right side (R_{addit}=43 µΩ), d) sample 2B (R_{addit}=42 µΩ).

These samples are made as similar as possible to the splices in the machine but there are still some important differences, especially:

- The samples have high RRR of the bus ($\mathrm{RRR}_{\mathrm{bus}}$), while there can be locally lower values in the machine (see also lateron).
- The cooling surface in the machine is higher than for the samples, mainly because one large face of the samples is covered by heaters.
- The length of the samples is limited to 1.5 m, requiring boundary conditions of T<T_C at both ends, resulting in a larger longitudinal heat drain than in the machine.

Furthermore, the samples are RQ type, are tested in liquid helium, are tested at constant current, and have a limited range of R_{addit} between 30 and 60 µΩ. The main purpose of the tests is therefore to validate the calculation code QP3. Once validated, the code can be used to simulate real scenarios that occur in the machine, namely RB and RQ, liquid and gaseous helium, exponential decaying current, and any value of R_{addit}, $\mathrm{RRR}_{\mathrm{bus}}$, $\mathrm{RRR}_{\mathrm{cable}}$, and heat transfer to helium.

VALIDATION OF THE CODE

The tests in FRESCA are carried out at constant current, see Fig. 5. A quench is created over a length of about 30 cm (about 15 cm on both sides of the defect), using two heaters glued to the copper stabiliser. The typical power required to quench the cable is 0.5-1 W per cm of bus. Once a normal zone is created, the heaters are switched off. Depending on the current level, cooling and sample characteristics, three scenarios can occur:

- The normal zone reduces to zero, and the superconducting properties of the cable recover. This scenario usually happens at smaller currents.
- The normal zone and the temperature distribution along the length become stable. In this case the generated resistive heating is equal to the heat transfer to the helium. In order to avoid warming up of the helum bath, the current is ramped down to 0 A after about 30 s.
- The local heating in the defect is much larger than the cooling and the NSBC enters a thermal runaway. As soon as the voltage over the defective splice reaches the threshold (typically 100-200 mV) the power converter is switched off, and the current is down to 0 A in about 100 ms, in order to avoid a burn-through of the splice. The time between the start of the normal zone and the switch-off of the converter is denoted by t_{TR}.

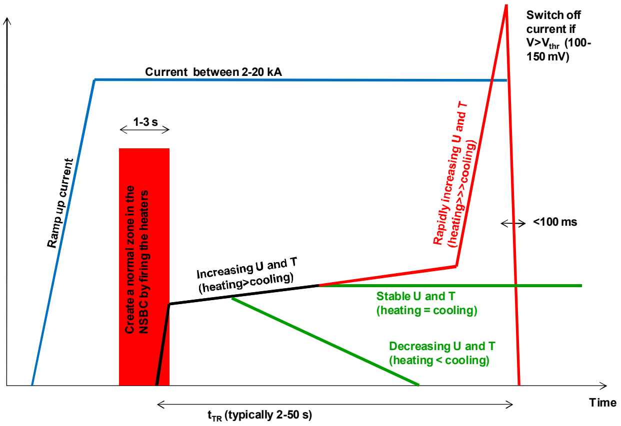

Figure 5: Schematic test sequence in FRESCA with three possible scenarios (recovery, stable normal zone, and thermal runaway).

The QP3 code is validated by comparing the measured and calculated voltage signals, and by comparing the measured and calculated t_{TR} as a function of the current. An example of the good agreement in voltage signals is shown in Fig. 6. Comparison of t_{TR} for the three samples is shown in Fig. 7. For comparison the adiabatic calculation is also depicted, indicating that helium cooling considerably increases the thermal runaway time for a given current.

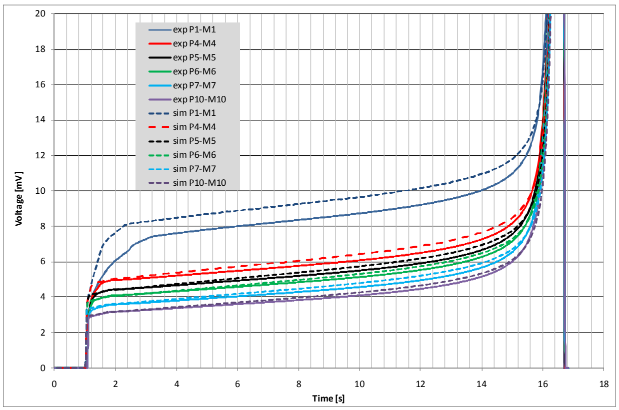

Figure 6: Example of the typical measured voltage signals (solid lines) and simulated voltage signals (dashed lines) for 6 different voltage tap pairs.

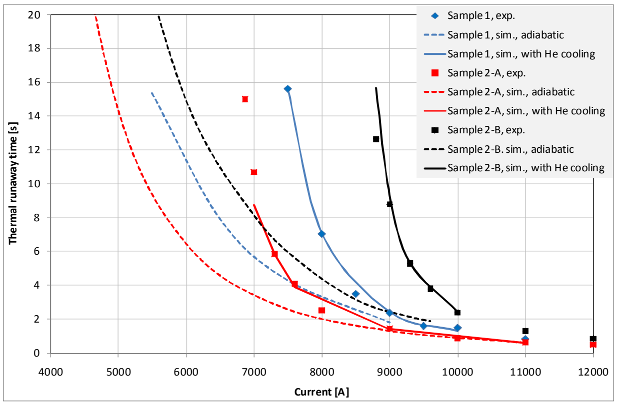

Figure 7: Comparison between measured (markers) and calculated (solid lines) t_{TR} curves. The calculated curves for adiabatic conditions (dashed lines) are shown as well.

A scaling factor F_{HT}, associated with the effective heat transfer to helium through the kapton bus insulation and the kapton/G10 splice insulation, is used as a fitting parameter in order to get good agreement between experimental data and calculations. This resulted in F_{HT}=1.8 (sample 1), F_{HT}=1.6 (sample 2A), and F_{HT}=0.89 (sample 2B). These variations can be due to variations in the winding tightness of the insulation, or due to simplification of the cooling model in the calculation code, or can be indirectly due to small variations in other parameters (RRR, wetted surface, heat flow from the heaters into the bus). These three different coefficients of F_{HT} have been used to calculate the safe current I_{safe} for the following two 'machine-type' cases:

- Case 1: RQ circuit, single-sided defect type B with R_{addit}=67 μΩ, exponential decay with τ=10 s.
- Case 2: RQ circuit, single-sided defect type B with R_{addit}=26 μΩ, exponential decay with τ=20 s.

Both cases are calculated for RRR_{cable}=80, RRR_{bus}=160, and a wetted bus surface of 90%. The results (see Table 2) show that the variation in I_{safe} is less than ±0.5 kA. One can therefore conclude that the results of the calculation code QP3 are in good agreement with experimental results, and that the incertainty in F_{HT} causes a relatively small error in I_{safe}. For all calculations of I_{safe} versus R_{addit} in the following sections the worst heat transfer coefficient is assumed, i.e. the lowest value for F_{HT}.

Table 2. Calculation of the safe current for two 'machine-type' cases, and for three different scaling factors that were deduced from the FRESCA experiments.

F_{HT}	**1.8**	**1.6**	**0.89**
I_{safe} for case 1	7.13 kA	7.03 kA	6.95 kA
I_{safe} for case 2	11.95 kA	11.48 kA	11.06 kA

RRR VALUES USED FOR THE CALCULATION OF THE SAFE CURRENT

The RRR of the cable, the copper bus stabiliser, and the copper wedge and U-profile play an important role in the stability of a defective splice and will be discussed in the following three subsections.

RRR of the cable.

Facts:

- RRR of the virgin cable (i.e. after production) is 70-100 [9].
- Data from the FRESCA tests give RRR_{cable} of 100, 130, 160 and 180 (see Table 1).
- RRR_{cable} increases to about 130 and 200 when the cable is heated during 4 minutes to 222 °C (SnAg melting temperature) and 270 °C (nominal soldering peak temperature) respectively (using 100 °C/min) [10].

Conclusion:

RRR_{cable} is probably >150 in a well-soldered joint. However, in a defective joint, especially of types A and C, the cable has probably not been subject to a high temperature (>200 °C) and the RRR_{cable} enhancement due to the soldering process is small. The calculations of I_{safe} are based on the worst case scenario RRR_{cable}=80.

RRR of the bus.

Facts:

- 'Biddle' data in many segments of the machine show a large spread in RRR_{bus} from 50-400 [11], see Fig. 8. However it is very likely that the 'Biddle' data are unreliable in the measured range (10-20 μV).
- A few 'Keithley' data from sector L2 show RRR values of 200-300.
- There is no evidence that different sectors contain copper from different production batches.
- Data from FRESCA tests show RRR_{bus}>250 (see Table 1).
- Data on four RB and four RQ bus samples show RRR_{bus} of 220-300 [12].

Conclusion:

For the worst case scenario RRR_{bus}=100 is assumed. Additionaly, results will be given for RRR_{bus}=160 in order to see the increase in safe current. The latter can be useful if more accurate measurements in the machine become available using the nQPS boards in stead of the Biddle.

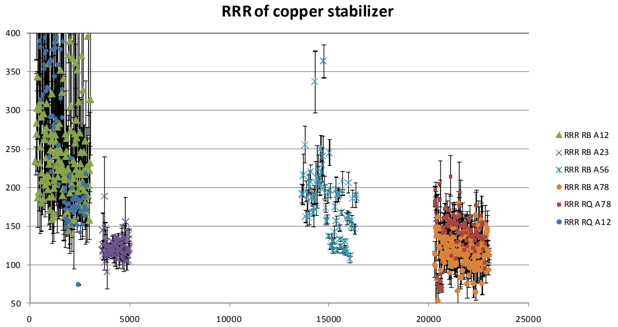

Figure 8: RRR measurements obtained using the 'Biddle' [11].

RRR of the U-piece and wedge.

Facts [13]:

- All U-pieces used before 2009 are produced by hot extrusion.
- RRR measurements on 8 U-profiles from several sectors in the machine show RRR of 250-300.
- The RRR of the U-pieces of the 2009 production (machined from OFE Cu sheet) and the RRR of all wedges have a lower RRR of about 130, as deduced from the correlation between the 'Vickers hardness' and the RRR.

Conclusion:

For all calculations of I_{safe} versus R_{addit} in the following sections it is assumed that RRR_{U_piece} and RRR_{wedge} are equal to RRR_{bus} (so also 100 and 160).

SAFE CURRENT

The safe current is calculated for two scenario's:

A) Quenches in liquid helium (LHe), that can occur:

- due to mechanical movement of the NSBC. This is not very likely below 7 kA, because all sectors have already been powered (several times) up to 7 kA.
- due to global beam losses.
- due to normal zone propagation through the bus from an adjacent quenching magnet. This is not possible below 6 kA (RQ) and 8 kA (RB).

The calculations are done assuming the worst heat transfer coefficient as deduced from the FRESCA tests (see before). For comparison, calculations under adiabatic conditions are given as.

B) Quenches in gaseous heloum (GHe), that can occur due to warm helium from an adjacent quenching magnet. This is very unlikely below about 5 kA, and almost certain above 9 kA. The time between the magnet quench and the interconnect quench is denoted by t_{prop} and depends mainly on:

- the current,
- the number of magnets that are quenching,
- the position in the cryogenic cell.
- the setting pressure of the quench relief valve.

At present there is quite some experimental data about magnet-to-magnet propagation times [14], but none about magnet-to-splice propagation times. For the calculations no cooling to helium is assumed and a propagation time of:

- t_{prop}=10 s for high current quenches (I>11 kA),
- t_{prop}=20 s for intermediate currents (7-9 kA).

The calculations of I_{safe} versus R_{addit} are given in Figs. 9-12, for the RB and RQ circuits for the LHe and GHe scenario's.

Note that operation at 13 kA requires decay time constants of 100 s (RB) and 20 s (RQ), whereas at 3.5 TeV they are half. It is assumed for all calculations that R_{addit}=R_{NSBC} and that RRR_{NSBC}=RRR_{cable}.

The maximum allowed R_{addit} for both types of circuits, can be obtained from these figures for both scenarios, namely LHe (with and without cooling) and GHe (with t_{prop}=10/20 s). In the following three subsections conclusions are given concerning these maximum values for the energy levels of 3.5, 5, and 7 TeV.

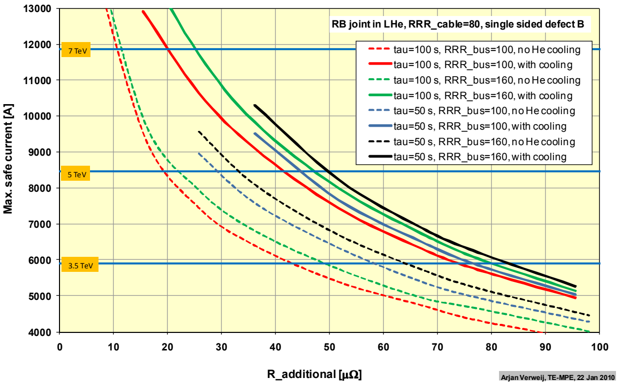

Figure 9: Maximum safe current as a function of R_{addit} for a defective RB splice in LHe conditions. RRR_{cable}=80, RRR_{bus}=100/160, τ_{RB}=50/100 s. The adiabatic case (dashed lines) is given for comparison only.

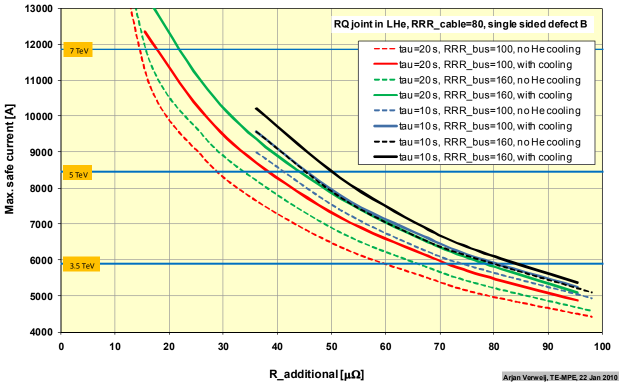

Figure 10: Maximum safe current as a function of R_{addit} for a defective RQ splice in LHe conditions. RRR_{cable}=80, RRR_{bus}=100/160, τ_{RQ}=10/20 s. The adiabatic case (dashed lines) is given for comparison only.

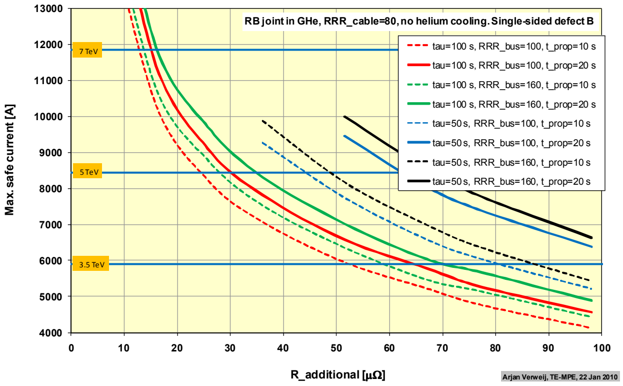

Figure 11: Maximum safe current as a function of R_{addit} for a defective RB splice in GHe conditions. RRR_{cable}=80, RRR_{bus}=100/160, τ_{RB}=50/100 s, t_{prop}=10/20 s.

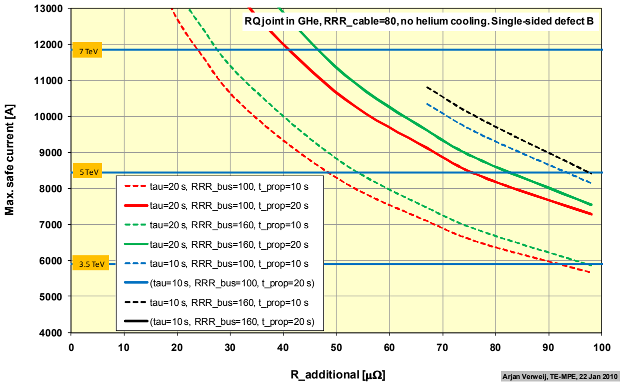

Figure 12: Maximum safe current as a function of R_{addit} for a defective RQ splice in GHe conditions. RRR_{cable}=80, RRR_{bus}=100/160, τ_{RQ}=10/20 s, t_{prop}=10/20 s. The curves for τ_{RQ}=10 s, t_{prop}=20 s are out of the plot range.

Safe operation at 3.5 TeV (6 kA)

The maximum allowed values for R_{addit} are given in Table 3. Since the LHe case without cooling is not realistic, one can see that safe operation at 3.5 TeV requires that all R_{addit} are smaller than 76 μΩ (RB) and 80 μΩ (RQ) respectively. A statistical approach based on measurements of R_{addit} in 5 sectors has given a maximum expected value of 90 μΩ [4]. One can therefore not declare that 3.5 TeV is 100% safe. However, burn through of a splice will only occur in the very unlikely event that a splice quenches that has a high R_{addit}, and at the same time a low RRR_{cable}, a low RRR_{bus}, and a small heat transfer to helium. Furthermore, the defect should be single sided, which is unlikely for high values of R_{addit} (PS: a double sided defect of 45+45 μΩ is much more stable than a single-sided defect of 90 μΩ). Knowing also that normal zone propagation in LHe is not possible below 6 kA, one can conclude that the possibility of a burn-through of a defective splice at 3.5 TeV is extremely small, even when operating LHC for several years.

Table 3. Max. allowed R_{addit} for safe operation at 3.5 TeV. The worst case realistic scenario is given in bold.

	τ [s]	**Condition**	**Maximum R_{addit}**	
			RRR=100	**RRR=160**
RB	50	GHe with t_{prop}=10 s	80	87
		GHe with t_{prop}=20 s	>100	>100
		LHe without He cooling	58	65
		LHe with He cooling	**76**	83
RQ	10	GHe with t_{prop}=10 s	>150	>150
		GHe with t_{prop}=20 s	>150	>150
		LHe without He cooling	74	80
		LHe with He cooling	**80**	84

Safe operation at 5 TeV (8.5 kA)

For operation at 5 TeV decay times of 75 s (RB) and 15 s (RQ) are assumed. The maximum allowed values for R_{addit} are given in Table 4. The LHe case without cooling is not realistic, as well as thermal propagation at 9 kA with t_{prop}=10 s. Safe operation at 5 TeV therefore requires that all R_{addit} are smaller than 43 μΩ (RB) and 41 μΩ (RQ) respectively.

Table 4. Max. allowed R_{addit} for safe operation at 5 TeV. The worst case realistic scenario is given in bold.

	τ [s]	**Condition**	**Maximum R_{addit}**	
			RRR=100	**RRR=160**
RB	75	GHe with t_{prop}=10 s	34	37
		GHe with t_{prop}=20 s	46	51
		LHe without He cooling	23	28
		LHe with He cooling	**43**	48
RQ	15	GHe with t_{prop}=10 s	71	75
		GHe with t_{prop}=20 s	>120	>120
		LHe without He cooling	35	40
		LHe with He cooling	**41**	47

Splices with R_{addit} up to 60 μΩ have been observed in the machine; it is known that there is still one splice with R_{addit}=51±15 μΩ, and R_{addit} has not been measured at warm in 3 sectors.

One can therefore conclude that operation at 5 TeV implies a non-negligable risk that a splice will burn through if it quenches.

For confident operation at 5 TeV, the remaining three sectors should be measured at warm, and all "outlier" splices should be repaired. Unfortunately, the resolution limit of warm R_{addit} segment measurements is about 20-50 μΩ. Operation at 5 TeV remains therefore risky, unless it can be proven that RRR_{bus} and $\text{RRR}_{\text{cable}}$ are everywhere much larger than assumed, and that R_{addit} does not degrade in time. Additional information concerning operation at 5 TeV can be found in [15].

Safe operation at 7-7.5 TeV (12-13 kA)

The maximum allowed values for R_{addit} are given in Table 5. The LHe case without cooling is not realistic. Safe operation at 13 kA therefore requires that all R_{addit} are smaller than 11 μΩ (RB) and 15 μΩ (RQ) respectively. Note that an increase of t_{prop} from 10 s to 20 s, or an increase of RRR_{bus} from 100 to 160 has only a small effect on this maximum allowable value, which in any case will stay below 20 μΩ.

Table 5. Max. allowed R_{addit} for safe operation at 13 kA. The worst case realistic scenario is given in bold.

	τ [s]	Condition	Maximum R_{addit}	
			RRR=100	RRR=160
RB	100	**GHe with t_{prop}=10 s**	**11**	12
		GHe with t_{prop}=20 s	13	14
		LHe without He cooling	8	9
		LHe with He cooling	15	21
RQ	20	GHe with t_{prop}=10 s	18	22
		GHe with t_{prop}=20 s	34	39
		LHe without He cooling	13	14
		LHe with He cooling	**15**	17

It is important to note that:

- Proper quench protection is usually based on an adiabatic approach which further decreases the maximum R_{addit} to 8 and 13 μΩ. One can be sure that there are many hundreds of defects with larger R_{addit} in the machine.
- Due to the intrinsic design of the splice an internal void of 15 mm is often present, resulting in R_{NSBC}=20 μΩ. This means that one has to rely on the $R_{\text{Cu-Cu}}$ contact to keep R_{addit} below 11 μΩ. However, due to thermal and mechanical cycling $R_{\text{Cu-Cu}}$ and hence R_{addit} may degrade during the lifetime of the LHC.
- Especially for small values, the measured R_{addit} at 300 K may not be representative for R_{addit} at 10 K, because the RRR of the Cu-Cu contact can be low.
- 'Segment' measurements at warm (or any other temperature) are not accurate enough to detect above given small values.
- "High current pulsing" seems no option given the large number of defects, but might eventually be useful for a final in-situ qualification test of the circuits.

The conclusion is therefore that a shunt has to be added on all 13 kA splices, also on those with small R_{addit}, in order to guarantee safe running up to 13 kA. Splices with high R_{addit} or splices with large visual defects should be resoldered and shunted.

Shunt requirements

For good electro-thermal functioning of the splice the shunt should fulfil the following requirements:

- Both sides of the splice should be shunted. Of course, for redundancy and an increase of margin it would be beneficial to have two shunts on each side.
- The shunt should preferably be made of high RRR copper.
- The shunt should have a good electrical and thermal contact with the bus stabiliser and the splice stabiliser

The cross-section of the shunt depends on the distance l_{wc} between the soldering points to the stabilisers (see Fig. 13).

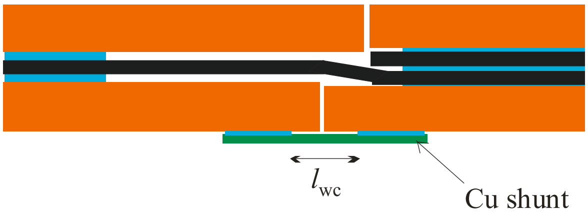

Figure 13: Schematic view of a shunted splice.

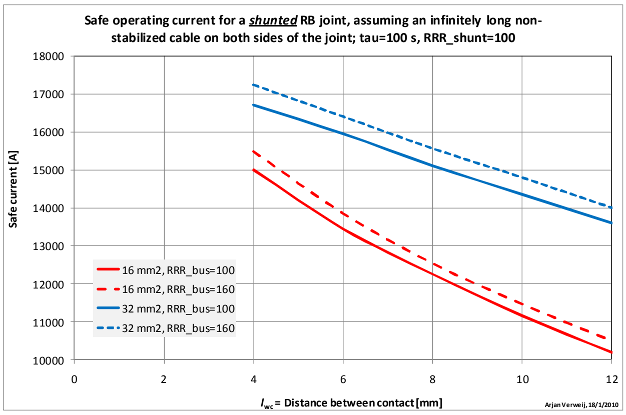

Figure 14: Safe operating current for a RB splice under adiabatic conditions for an exponential current decay with τ_{RB}=100 s.

Assuming $\mathrm{RRR}_{\mathrm{shunt}}=100$, $R_{\mathrm{NSBC}}=\infty$, $l_{\mathrm{wc}}=8$ mm, and adiabatic conditions, then a section of 20 mm^2 is sufficient (see Fig. 14). Of course a safety margin has to be added. The mechanical design, requirements, and restrictions are presented in [16].

CONCLUSIONS

The calculation code QP3 is validated by means of three FRESCA tests on 13 kA splices with built-in defects. A different effective heat transfer to helium is needed per sample in order to have very good quantitative agreement. This difference causes an uncertainty of about ±500 A in the calculated safe current.

The FRESCA tests have clearly demonstrated the susceptibility of a defective 13 kA splice to thermal runaway and eventually burn-through.

Actual calculations of the safe current as a function of R_{addit} are based on conservative values for $\mathrm{RRR}_{\mathrm{cable}}$ and $\mathrm{RRR}_{\mathrm{bus}}$. No other safety margin is added. An overview of the maximum allowable R_{addit} for 3.5, 5 and 7 TeV operation is given in Table 6.

The possibility of a burn-through of a defective splice at 3.5 TeV is extremely small, even when operating during several years.

Operation at 5 TeV implies a non-negligable risk that a splice will burn through if it quenches.

For safe running at 7 TeV, a shunt has to be added on **all** 13 kA splices, **also on those with small R_{addit}**. Splices with high R_{addit} or splices with large visual defects should be resoldered and shunted. Experimental confirmation by means of a test in FRESCA/Block-4/SM-18 should be foreseen.

Table 6: Summary of maximum allowable R_{addit} for operation at 3.5, 5, and 7 TeV.

Energy [TeV]	**τ_{RB} [s]**	**Max. $R_{\mathrm{addit,RB}}$ [μΩ]**	**τ_{RQ} [s]**	**Max $R_{\mathrm{addit,RQ}}$ [μΩ]**
3.5	50	76	10	80
5	75	43	15	41
7	100	11	20	15

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