BUSBAR AND JOINTS STABILITY AND PROTECTION

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Abstract

A defective bus connection between two dipole magnets was the primary cause of the incident in sector 3-4 on September 19th. I will show how this could have happened, i.e. how a highly resistive joint has caused a thermal runaway and burned (or opened) before the QPS threshold was reached. Furthermore I will present the new detection limits for the QPS upgrade of the RB circuits, required to avoid similar thermal runaways in the future.

INTRODUCTION

Triggered by the incident in sector 3-4, the stability of the RB bus including the soldered joints has been re-assessed. In the first section the geometry of the bus will be described, with special attention to the joint. Then the protection of the bus will be briefly explained, and three types of thermal runaway will be differentiated, namely *localised slow*, *non-localised slow*, and *fast* thermal runaways. Differences between these three types will be illustrated by means of a simplified bus in adiabatic conditions. In the next section the 'old' QPS threshold is presented, and it is shown in which situations the protection would be effective or non-effective.

In the following section three scenarios of faulty joints are introduced that could all have lead to the incident. The electro-dynamic and thermal behaviour of the bus during the current ramp leading to the incident are then simulated for the most plausible scenario. Based on further calculations the 'new' threshold for the QPS upgrade is introduced, and the improvement with respect to the 'old' protection is discussed. Finally, it is stressed that the 'new' QPS threshold cannot protect the bus under all conditions, due to reasons intrinsic to the design of the bus.

BUS AND JOINT LAYOUT

A schematic view of the RB bus is shown in Figure 1. The bus-bar has dimensions of 20 mm x 16 mm, and contains a single Nb-Ti Rutherford type 02 cable. The cross-section of the copper 'bus stabilizer' (A_{Cu}) is about 282 mm^2 with RRR>120 according to the specification. Actual measurements show a RRR of about 210-220 [1] and 230-300 [2].

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 'joint stabilizer'. The joint 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 joint can be found in [3].

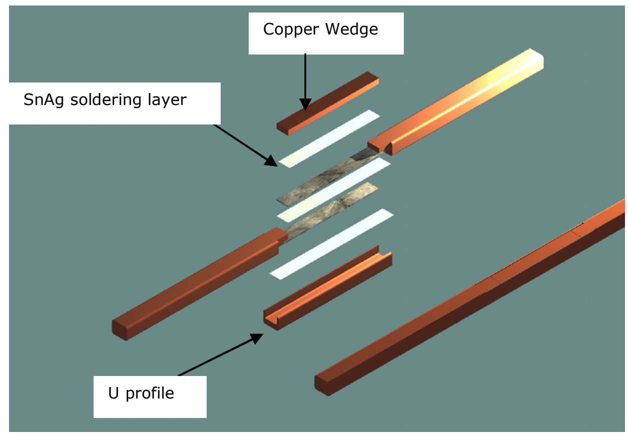

Figure 1: Layout of a RB bus and joint.

In a good joint 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 joint stabilizer and the bus stabilizer (on either side of the joint) should work as a continuous electrical shunt to the cables. This is achieved when the solder fills all the voids in and around the joint (see Figure 2), as well as the thin slots between the bus stabilizer and the joint stabilizer. Finally, a good joint should be mechanically strong enough so that it does not open due to the mechanical and electromagnetic forces acting on it.

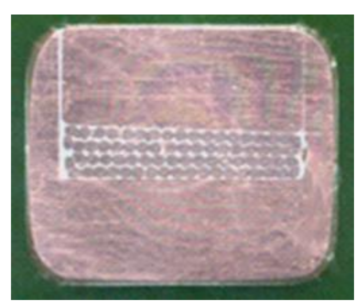

Figure 2: Cross-section of a properly solder-filled RB joint.

BUS PROTECTION

During operation several disturbances can release heat in the bus. Disturbances are either transient, such as mechanical movement, or beam losses, possibly leading to a local quench, or non-transient, such as resistive heating due to a joint resistance or due to a locally non-SC cable (see also Figure 3).

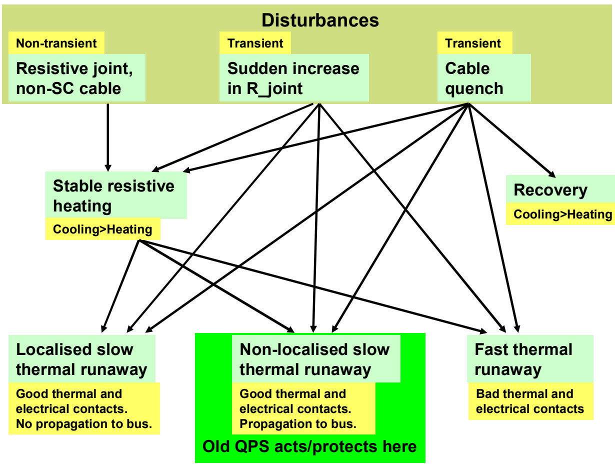

Figure 3: Schematic view of bus/joint protection and different types of thermal runaway.

Below a certain current, the resistive losses (that are the consequence of the initial disturbance) will be equal or smaller than the cooling, leading to a stable state, or possibly to recovery of the SC state. However, above a certain current, the resistive losses exceed the cooling, causing a temperature rise of the bus, hence increasing the resistivity, which in turn increases the resistive losses and so on. A so-called thermal runaway occurs that can only be stopped by reducing the current in the circuit. This is accomplished by putting a dump resistance in series as soon as the QPS system detects a voltage over the bus (V_{bus}) larger than a certain threshold V_{thr}. The external dump causes an almost exponential current decay with a time constant τ_{RB}=104 s. A properly functioning protection should limit the maximum bus temperature T_{max} to below 500 K, i.e. the temperature at which the kapton insulation and solder inside the bus/joint could start to melt.

As a first approximation the voltage over the bus can be written as:

$$V_{bus} = I\left(R_{joint} + \int \frac{\rho(T(z))}{A_{Cu}} dz\right) \qquad (1)$$

with R_{joint} the effective resistance of one or more joints and ρ(T(z)) the temperature dependent resistivity of the copper stabilizer. The integral has to be taken over the length of the normal zone.

As shown in Figure 3, three types of thermal runaway can be distinguished, namely 'slow non-localised', 'slow localised', and 'fast localised'. The entire electro-dynamic and thermal process of a thermal runaway is very complex due to the strong dependency of various parameters on temperature, field, and current, and is therefore solved numerically with the computer code QP3 [4]. However, a qualitative feeling of the three types of runaway can be obtained by assuming a certain length of bus in the normal state with uniform temperature and no cooling to the helium. The results of such a simplified approach are given in the following three sub-sections.

Non-localised slow thermal runaway

The typical characteristic time t_{TR} of the thermal runaway can be defined as the time it takes to warm up the bus from the current sharing temperature (equal to about 9 K) to 500 K at constant current. τ_{TR} depends basically on the amount of stabilising copper (which is in good contact with the superconductor), the cooling conditions, and the operating current. Figure 4 shows t_{TR} vs. I for a properly soldered RB bus with A_{Cu}=282 mm^2, assuming RRR=200, and adiabatic conditions. τ_{TR} is typically 90 s at 13 kA and 105 s at 11.85 kA.

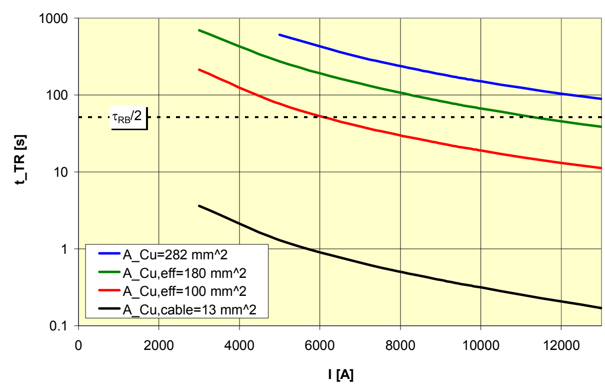

Figure 4: Typical characteristic time of a thermal runaway for a standard bus (A_{Cu}=282 mm^2), a single SC cable (A_{Cu}=13 mm^2), and two cases with reduced Cu stabilizer (A_{Cu}=100 and 180 mm^2).

A non-localised slow thermal runaway can be defined as a runaway without overheating of the bus, which means (in first approximation):

$$\left(t_{TR} - t_{thr}\right) > \frac{\tau_{RB}}{2} \qquad (2)$$

with t_{thr} the duration between the start of the thermal runaway and the detection of the quench (i.e. V_{bus}>V_{thr})

As an example, consider a normal zone of 2 m length with I=10 kA, RRR=200, V_{thr}=200 mV, and adiabatic conditions, so t_{TR}=150 s. Figure 5 shows the start of the thermal runaway (at t≈0 s) resulting in a slowly increasing voltage that reaches the threshold after about 70 s, when the bus has a temperature T_{thr}=95 K. The small resistive heating, combined with the high enthalpy of the bus, limits the maximum temperature (T_{max}) to about 260 K at the end of the exponential current decay. Condition (2) confirms that no overheating occurs because (150-70)>104/2.

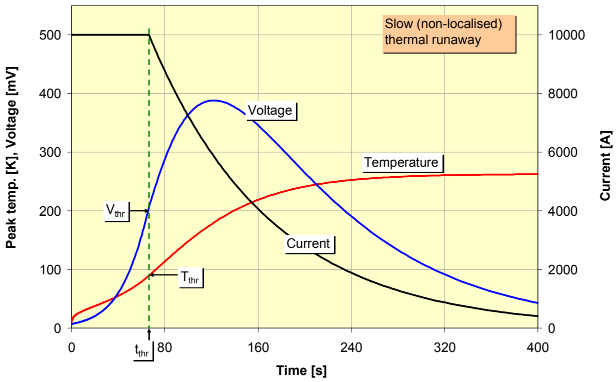

Figure 5: Non-localised slow thermal runaway, with limited maximum temperature because the threshold is reached in an early stage of the runaway.

Localised slow thermal runaway

Figure 4 shows that for a properly soldered bus (so A_{Cu}=282 mm^2) condition (2) is met for any current assuming that t_{thr} is small. In order to reach the threshold as fast as possible it is important to have a fast growing (or propagating) normal zone. The propagation speed of a normal zone depends on the current, the bus characteristics, and the cooling conditions, as shown in Figure 6. The current I* denotes the current below which the propagation speed becomes negative, in other words, the normal zone recovers. The typical I* for the RB bus-bar inside a HeII bath is 16 kA, which means that those parts of the bus are cryostable under all LHC operating conditions. However, due to the thicker insulation, the typical I* for the RB joint is 8 kA. Other parts of the bus, such as the lyre, and the bus-bar inside the key of the cold mass will again have different I*.

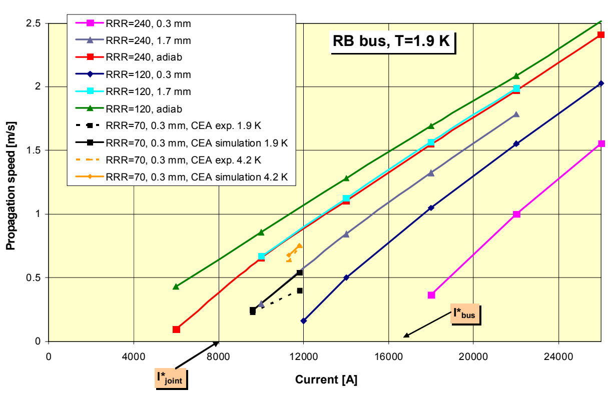

Figure 6: Normal zone propagation speed vs. current for various RRR and insulation thicknesses (calculations using QP3).

As long as a normal zone is propagating, the thermal runaway is often non-localised, and the bus voltage will usually reach the threshold fast enough to limit T_{thr} and T_{max}. However, when an initially propagating normal zone stops growing (for example because it enters a part of the bus with better cooling) the thermal runaway remains localised. In this case, the local resistivity of the normal zone, and therefore its temperature, will be much higher by the time the threshold is reached (see eq. 1). An example is shown in Figure 7, with the same conditions as before (see Figure 5), except that the normal zone is now only 0.4 m long in stead of 2 m.

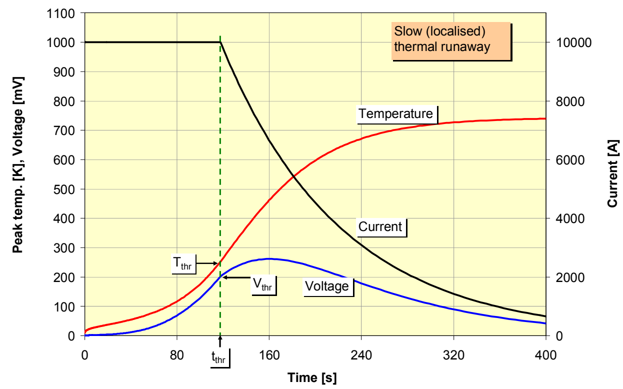

Figure 7: Localised slow thermal runaway, with T_{max}>500 K because the threshold is reached in a late stage of the runaway.

The figure shows that the temperature of the bus is already 250 K by the time the quench is detected (t_{thr}=120 s) and the current discharge starts. The final temperature is about 740 K which is well above 500 K, in line with condition (2) since (150-120)<104/2.

The only solution to avoid overheating is to set the threshold at a lower voltage. For this specific case t_{thr} should be smaller than (150-104/2)=98 s, which would have required a threshold smaller than about 120 mV. At higher currents, t_{TR} is smaller and therefore also t_{thr} and hence V_{thr} have to be smaller.

It is important to note that shorter localised normal zones will require even smaller V_{thr}. Potentially dangerous areas in the circuit are therefore badly cooled short parts of the bus such as the joints and plugs. Very short insulated parts are however safe again, due to the longitudinal cooling through the stabilizer.

Localised fast thermal runaway

Rewriting eq. (2) shows that thermal runaway to above 500 K is unavoidable for $t_{TR}<0.5\tau_{RB}+t_{thr}$. This can occur when the stabilising copper is in bad thermal contact with the cable, and at the same time has a high longitudinal resistivity (or even electrical discontinuity). This means that the effective amount of stabilizer cross-section $A_{Cu,eff}$ is reduced, hence increasing the resistive losses, and reducing the thermal enthalpy. Two examples are shown in Figure 4 for $A_{Cu,eff}$=100 and 180 mm^2, demonstrating clearly the safe current becomes smaller for reduced $A_{Cu,eff}$. An example is shown in Figure 8, with the same conditions as before (see Figure 7), except that $A_{Cu,eff}$=100 mm^2 in stead of 282 mm^2, and V_{thr}=10 mV.

Note that the maximum bus temperature will exceed 500 K during the discharge even if the detection voltage (and hence t_{thr}) are very small. No protection scheme is possible as soon as a fast thermal runaway starts.

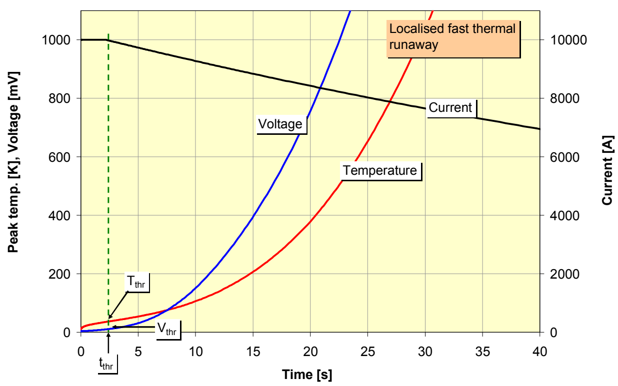

Figure 8: Localised fast thermal runaway, with T_{max}>500 K because local resistivity is too high and local enthalpy too low.

As already mentioned before, Figure 4 and equation (2) are based on a simplified model without taking into account heat transfer along the cable and towards the helium. Including both types of heat transfer will make the thermal runaway slower (and hence T_{max} smaller), especially if the length of bus with reduced $A_{Cu,eff}$ is small. Note also that in the worst case, all current passes through the cable ($A_{Cu,cable}$=13 mm^2), and the bus will behave like a fuse with t_{TR}<1 s at high currents, see Figure 4.

THE 'OLD' QPS THRESHOLD

The 'old' QPS threshold on the bus was set at 1 V as recommended in 2000 [5], [6]. Additional calculations in 2006 confirmed that this threshold was sufficiently low even in the case of local resistive heating due to faulty splices [7]. The latter however assumed that the bus around the faulty splice is continuous, implying perfect electrical contact between the joint stabilizer and the bus stabilizer. New calculations with QP3 clearly show that the threshold of 1 V was far too high because possible coincidence of different longitudinal variations in the bus was not properly taken into account in the past. As shown before, these longitudinal variations could lead to localised slow or fast thermal runaways resulting in temperatures above 500 K. Localised slow runaways would result from variations in the propagation speed, eventually becoming very low or even 0, which could then result in a very localised normal zone reaching already a high temperature by the time the threshold was reached. Localised fast runaways could occur in parts of the bus were the copper stabilizer was (partially) interrupted coinciding with a bad thermal contact between cables and stabilizer.

Summarised, the old QPS was mainly designed to protect the bus in case of a non-localised thermal runaway (see also Figure 3), a situation that can only occur in large parts of the bus with non-zero propagation speed, i.e. with poor heat transfer to the helium (see Figure 6). Calculations with QP3 show that only the 15 m long part of the bus located in the key of the main dipoles was effectively protected, and probably only for currents below about 10-12 kA.

SIMULATION OF THE 19/9/08 INCIDENT

Analysis of the incident in sector 3-4 occurring on 19/9/2008 resulted in the following findings:

- The QPS triggered at the maximum current of 8715 A.
- The bus threshold of 1 V was reached before a voltage increase was observed in any of the dipoles.
- The voltage increase on the bus was extremely fast: from about 10 mV to 1 V in about 1 s.
- The resistive voltage on the bus increased very likely with about 10 mV during the last minute before the incident.

Post analysis of calorimetric data, performed during a current plateau at 7 kA, revealed an additional local power of 10.7±2.1 W at 7 kA [8], corresponding to an additional resistance of 220±40 nΩ.

These findings clearly indicate that a phase of initially stable resistive heating moved into a fast thermal runaway, eventually leading to local melting of the bus and arcing, see also Figure 9. In order to have a very fast thermal runaway, the heating should occur in the superconducting cable, and the bus should be electrically interrupted and in bad thermal contact with the cable.

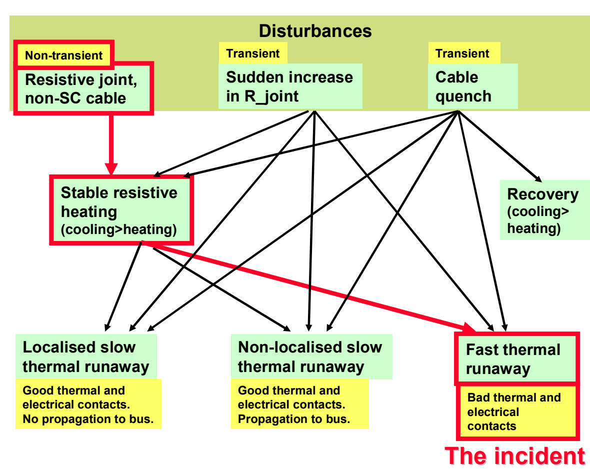

Figure 9: Schematic view of sequence of phases leading to the incident in sector 3-4.

Three possible and realistic scenarios fulfilling these criteria can be distinguished (see Figure 10), all of them requiring a lack of solder between the joint stabilizer and the bus stabilizer (i.e. electrical interruption):

1. A non-soldered joint causing a highly resistive joint, and at the same time a bad thermal (and electrical) contact between cable joint and joint stabilizer. This scenario could be caused by the absence of the heat treatment during the joint manufacture, or by a heat treatment at a temperature below the melting point of the solder.
2. A non-superconducting cable **and** a lack of solder inside the bus and/or inside the joint (over a few cm). Extremely large I_C-degradation is required so that the cable is non-superconducting at 7 kA, i.e. at a very low self-field <0.5 T. Following [9] this is possible if the cable has been subject to high temperatures, typically 550 °C for at least several minutes or 600 °C or more for several tens of seconds. Although such a temperature excursion cannot be excluded, this scenario is quite unlikely because it requires the coincidence of two non-conformities (non-uniform soldering and overheating).
3. A cable that is heavily damaged at the interface between joint and bus **and** a lack of solder inside the bus and/or inside the joint (over a few cm). A similar scenario as nr 2, but in this case the cause of the cable degradation is mechanical. In order to see a resistance at 7 kA most of the strands should be severely damaged.

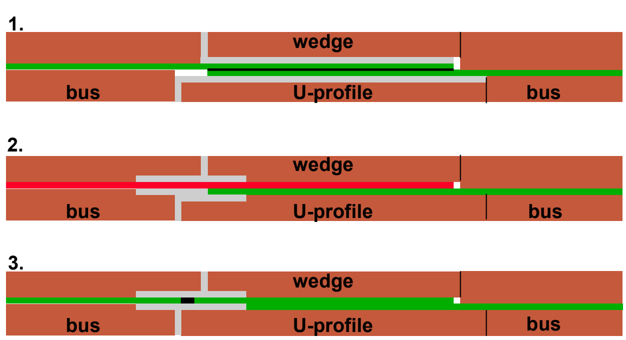

Figure 10: Three possible scenarios that could have been the origin of the fast thermal runaway during the incident. The light gray areas denote bad thermal and electrical contact. Green cables are superconducting; red cables are normal. The black spot denotes a mechanically damaged cable.

Several non-soldered (dry) joints inside cold masses were found in recent months (having joint resistance values in the order of 10-100 nΩ) but it should be noted that the inter-dipole joints in the machine have been made using different procedures, equipment, and people. There is also evidence that solder is frequently lacking in the gaps between the bus stabilizer and the joint stabilizer, and probably also between the SC cable and the bus stabiliser.

The exact defect causing the incident will never be known, since the joint has evaporated. In the following, the electromagnetic and thermal behaviour of a 'Scenario 1' joint has been calculated using the code QP3. Note however that the other scenario's would give very similar results. The following model parameters are taken:

- The joint resistance is 220 nΩ which is uniformly distributed over its length.
- The cable joint has no electrical and thermal contact to the joint stabilizer.
- The Nb-Ti cable in the bus is in perfect electrical and thermal contact to the copper of the bus.
- The RRR of the copper in the superconducting cable is 200 and the RRR of the copper stabilizer is 240.
- The insulation of the bus is 0.3 mm thick non-porous kapton with negligible heat capacity.

In order to have a good agreement with the findings (given at the beginning of this chapter) the transverse cooling (in Watt/m) of the joint is assumed as $6.5*(T-T_{He})$, and the heat flow from the insulation to the helium (in Watt/m) is assumed as $3.4(T_{ins}^4-T_{He}^4)$

The result of the calculation is presented in Figure 11, showing three distinct parts:

- 0-7.6 kA: the joint temperature is below the critical temperature of the SC, so that $V=R_{joint}I$ and $P=R_{joint}I^2$. At 7 kA the heating is 11 W and the voltage is 1.5 mV.
- 7.7 kA-8.7 kA: at 7.7 kA the temperature of the cable inside the joint reaches the critical temperature and almost instantaneously about 15 cm of cables (corresponding to the length with thick insulation) becomes normal. The normal zone is expanding slowly for higher currents, reaching a length of about 30 cm at 8.7 kA, with P=70 W. During the slow expansion of the normal zone the voltage is increasing from several mV to 10 mV, and the maximum temperature in the joint from 10 K to about 30 K.

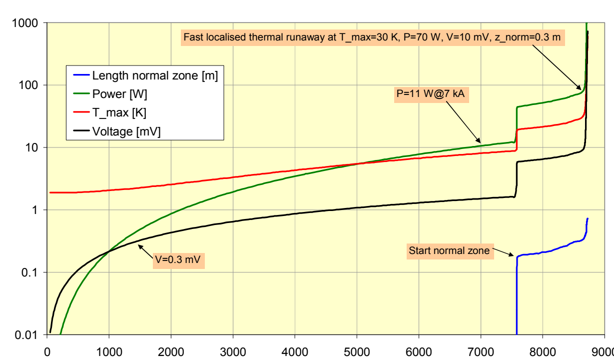

Figure 11: Simulation of temperature, voltage, power and length of the normal zone for the ramp with 10 A/s leading to the incident in sector 3-4.

- Fast thermal runaway, with an increase in temperature from 30 K to 500 K in a few seconds, see also Figure 12 showing a zoom of the last 20 s before the incident. Note that the large noise in the bus voltage makes it impossible to re-establish the exact voltage shape.

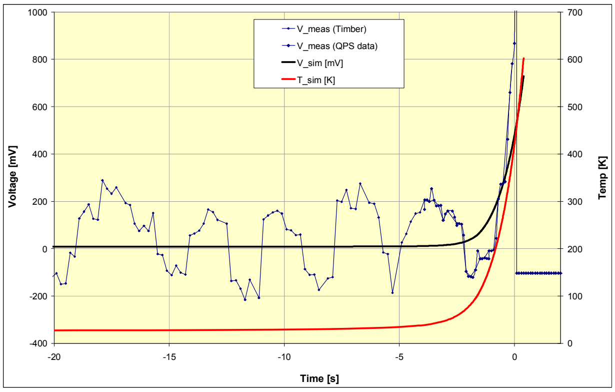

Figure 12: Measured and simulated voltage during the last 20 s before the incident. The simulated temperature is shown as well.

REQUIRED THRESHOLD FOR THE QPS UPGRADE

Many simulations of thermal runaways are performed varying the RRR and cooling conditions, in order to find the 'worst case scenario', i.e. the case that gives the lowest thermal runaway current I_{run} for a given joint resistance. Figure 13 shows this worst case scenario along with the scenario leading to the incident, but now calculated for various joint resistances. An additional current equal to $\tau_{RB}/2*(dI/dt)=500$ A is subtracted from the worst case in order to assure a safe exponential discharge of the RB circuit before the fast thermal runaway starts. The figure shows as well the current at which the voltage over the bus reaches 0.3 mV, 0.5 mV and 1 mV, assuming that the bus and joint are still below T_{cs} so that there is no normal zone. Combining the worst case scenario with the bus voltage it becomes clear that a threshold of 0.3 mV is needed to assure that the QPS triggers the discharge before the bus enters into a fast thermal runaway.

Note that the fast thermal runaway leading to the sector 3-4 incident would have been avoided having V_{thr}=0.3 mV. If the disturbance was non-transient (i.e. the resistance of 220 nΩ was already present at low currents), the new QPS would have triggered at about 2 kA. If the disturbance was transient (i.e. the resistance of 220 nΩ occurred suddenly during the ramp), it would have happened before 7 kA (because additional heating was observed at 7 kA), so the new QPS would have triggered somewhere during the ramp between 2 and 7 kA.

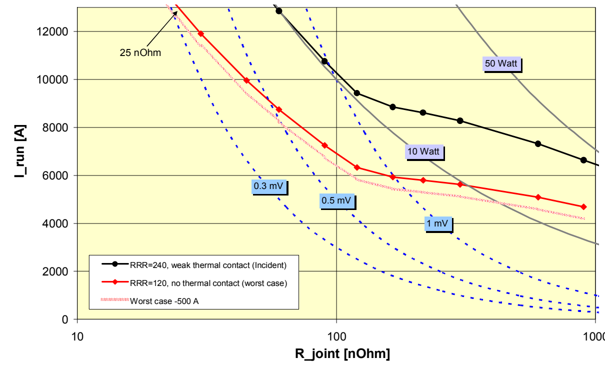

Figure 13: Thermal runaway current versus joint resistance for 'incident-type' joint and worst case scenario.

With the reduced threshold the 'new' QPS will protect the circuit for both localised and non-localised slow thermal runaways. At the same time it will trigger a discharge in case it detects the phase of stable resistive heating that could eventually cause a slow or fast thermal runaway (see Figure 14).

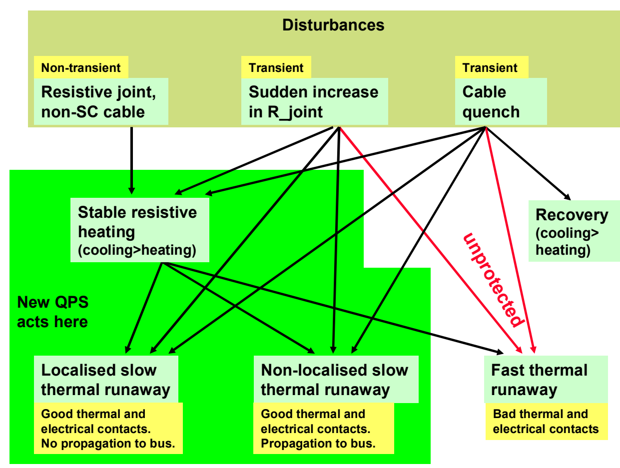

Figure 14: Schematic view of radius of action of the QPS upgrade with the 'new' threshold.

It is very important to note that the new QPS threshold will not protect the circuit in the following two cases:

1. Fast thermal run-away resulting from a sudden transient disturbance (without intermediate stable heating). To avoid such fast thermal runaways one needs to assure a good thermal/electrical contact between the SC cables and the joint stabilizer **or** between the bus stabilizer and joint stabilizer. Both are achieved by having a perfect solder filling of the joints.
2. Sudden mechanical opening of the joint. The best way to avoid this, is by clamping the joint.

Also note that:

- All joints will probably see (sooner or later) a transient disturbance due to the SC-to-normal transition of the joint due to a quench in an adjacent magnet.
- Having a relatively low electrical joint resistance does not automatically mean that the joint is perfectly soldered.
- Thermal cycling and powering can deteriorate the thermal contact between SC cables and joint stabilizer, and/ the electrical contact between bus stabilizer and joint stabilizer.

For a 100% fail-safe protection all joints should be clamped and the SC cable should be everywhere in good thermal and electrical contact with the stabilizer. In those areas where a good contact cannot be guaranteed one has to assure the electrical continuity of the stabilizer.

In other words: any part of the bus for which a good contact cannot be guaranteed and for which (at the same place) also the electrical continuity cannot be guaranteed is susceptible to burn through, resulting in an arc causing serious additional damage.

CONCLUSIONS

Calculations clearly indicate that the origin of the incident in sector 3-4 is linked to the occurrence of:

- a highly resistive joint between two SC cables being in bad contact with the copper stabilizer,

  or:
- a non-superconducting cable, thermally insulated from the stabiliser coinciding with a longitudinal electrical interruption of the stabiliser (at the end of the joint),

  or:
- a heavily damaged superconducting cable, thermally insulated from the stabiliser coinciding with a longitudinal electrical interruption of the stabiliser (at the end of the joint),

The current could therefore not (or only for a small fraction) bypass the resistive joint or non-superconducting cable and due to the small local effective enthalpy, a fuse-type thermal runaway occurred, very quickly resulting in a burn-through of the bus.

Reducing the QPS threshold to 0.3 mV will limit thermal run-aways caused by resistive joint heating to well below 500 K. The same threshold can be used for the RQ circuits if powered to 9.5 kA maximum. For higher currents the threshold has to be slightly reduced due to the smaller amount of copper stabiliser in the bus.

The new QPS threshold will however not protect the 13 kA circuits in case of a 'fast' thermal run-away resulting from a sudden transient disturbance (without intermediate stable heating), and in case of a sudden mechanical opening of the joint. Here 'fast' means a thermal runaway with a characteristic time smaller than half the discharge time constant of the circuit.

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