# Minimum requirements for the 13 kA splices for 7 TeV operation

- type of defects
- FRESCA tests and validation of the code QP3
- a few words on the RRR
- $I_{\mathrm{safe}}$ vs $R_{\mathrm{addit}}$ plots
- conclusion

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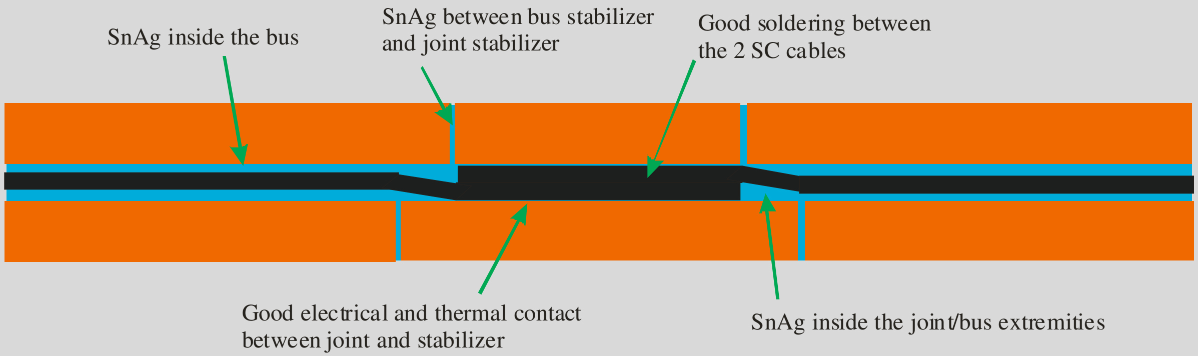
Good splice
(R=0.3 nΩ)



SnAg inside the bus

SnAg between bus stabilizer and joint stabilizer

Good soldering between the 2 SC cables

Good electrical and thermal contact between joint and stabilizer

SnAg inside the joint/bus extremities

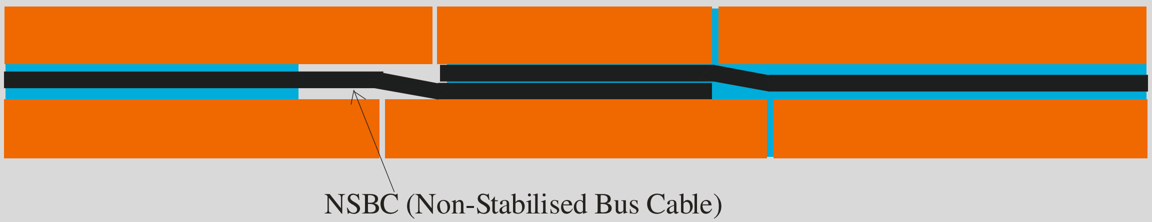
**Defect A**:
Unsoldered splice
(R>>0.3 nΩ)

Defect **A** is very likely to be found using the monitoring feature of the nQDS system, which should reveal all bad splices with a resistance larger than a few nΩ.

Additionally, the sub mV detection threshold on the bus segments will trigger before the resistive dissipation will cause the SC-to-normal transition followed by a thermal runaway.

Defect **A** is mechanically weak (even if it has a resistance of a few nΩ), and running the machine with such a defect presents a serious risk!!!

**Defect B**:
Soldered splice with *outside* void and/or lack of bonding



**Defect C**:
Badly soldered splice ($R>0.3$ nΩ) with *inside* void and/or lack of bonding

**Defect D**:
Splice with void and/or lack of bonding and small amount of SnAg in vertical gap

- Defects B, C, and D can be present on 1 or 2 sides of the joint.
- Single sided defects **B** and **C** are the worst case scenarios, assuming that the defect size is estimated from a $R_{16}$ measurement or from a $R_{segment}$ measurement (30-100 m long). These defects have been used in the FRESCA tests.
- Defect **D** is the predominant defect in the machine. The stabiliser-stabiliser contact in the vertical gaps may degrade in time (see lateron).
- Maximum safe operating currents are given for single-sided defect **B** (or **C**) as a function of the additional resistance $R_{addit}$ (at 300 K), with $R_{addit}=R_{16,defect}-R_{16,good}$.

# FRESCA tests and validation of the code QP3

Thanks to:

**G. Willering, G. Peiro, D. Richter, H. Prin, C. Urpin, P. Fessia,**
**Th. Renaglia, Ch. Scheuerlein, L. Gaborit, L. Bottura, K. Chaouki,**
**L. Gaborit, L. Fiscarelli, V. Inglese, G. Montenero, C. Petrone,**
**R. Principe, S. Triquet**

for sample preparation, instrumentation, data acquisition, and running of the test station and cryogenics.

Thanks to:

**R. Berkelaar and M. Casali**

for comparison of QP3 with two other models for a specific case study.

Experiments in FRESCA (B-163) are performed, mainly **to validate the calculation code.**

Up to now 3 samples with 'on-purposely-built-in' defects are measured. Two more samples will be measured in Feb. 2010.

**Step 1: Sample definition**

Determine values for $R_{addit}$, $RRR_{cable}$, $RRR_{bus}$, $RRR_{joint}$, and geometry (type of insulation, positioning of heaters, spiders, spacers etc.)

**Step 2: Measurements**

Measure the thermal runaway time $t_{TR}$ for various currents, temperatures, and fields. During each test the voltage and temperatures are recorded. The power converter is switched off before the defective joint reaches 300 K.

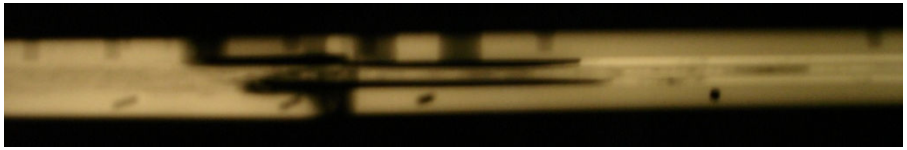
**Step 3: Analysis**

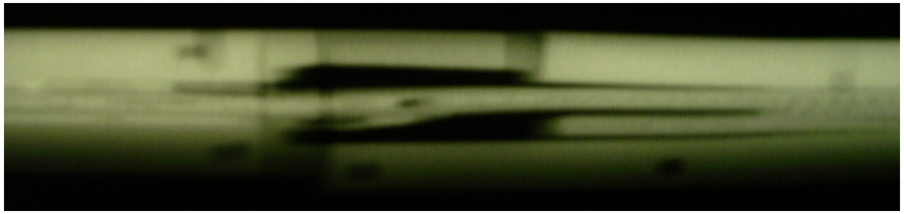
Fine-tune the effective cooling through the bus insulation and the joint insulation, so that the calculated $t_{TR}(I, B=0, T=1.9\text{ K})$ curve and calculated $V(t)$ curves are in good agreement with the measurements.

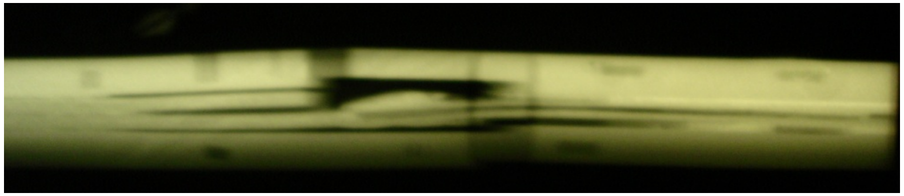
The **validated code** is then used to calculate $I_{safe}(R_{addit})$ for the machine, assuming the worst heat transfer observed on the samples, and the worst RRR values that can occur in the machine.

| | **Machine** | **Sample 1** | **Sample 2A** | **Sample 2B** | **Sample 3A** | **Sample 3B** |
|---|---|---|---|---|---|---|
| (to be) Measured | | Oct 2009 | Nov 2009 | Nov 2009 | Feb 2010 | Feb 2010 |
| Interconnect type | RB and RQ | RQ | RQ | RQ | RQ | RQ |
| Defect type | (A, B, C,) D | Single-sided B | Double sided C | Single-sided C | Double sided C | Single sided C |
| Length NSBC | 0-50 mm ?? | 47 mm | 27 + 35 mm | 35 mm | 33 + 20 mm | 16 mm |
| $R_{addit}$ | → talk Koratzinos | 61 μΩ | 32 + 43 μΩ | 42 μΩ | 43 + 26 μΩ | 21 μΩ |
| RRR bus | >100 ? | ≈300 | ≈270 | ≈290 | 150 ? | 150 ? |
| RRR cable | > 80 ? | ≈180 | ≈130 + 100 | ≈160 | 100-150 ? | 100-150? |
| Splice insulation | Machine-type | 2 mm G10 + glue | Machine-type | | | |
| Eff. cooled surface | ≈90% | 25-60% | ≈60-70% | | | |
| Field | Self-field | Self-field (+ applied field) | | | | |
| Current profile | Expon. decay (τ=10-100 s) | Constant current | | | | |
| Helium environment | LHe and GHe | LHe | | | | |
| Enclosure | Horizontal tube with diam. 90 / 103 mm | Vertical tube with diameter 72 mm | | | | |
| Length sample | | ≈1.5 m | | | | |

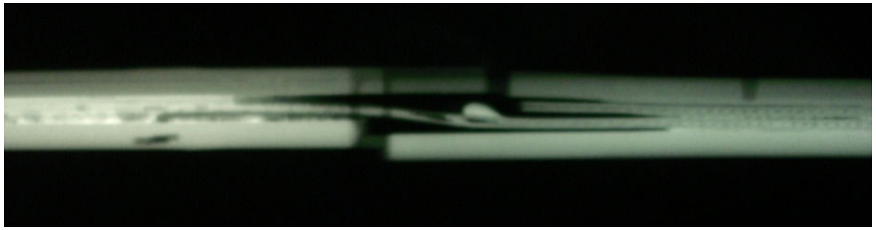
# Sample pictures

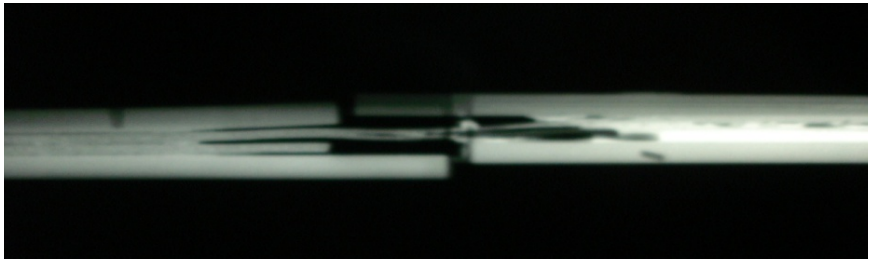

**Sample 1 (61 $\mu\Omega$)**

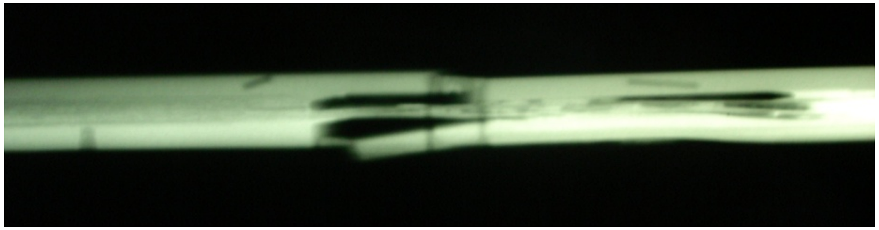

**Sample 2A left (32 $\mu\Omega$)**


**Sample 2A right (43 $\mu\Omega$)**


**Sample 2B (42 $\mu\Omega$)**


**Sample 3A left (26 $\mu\Omega$)**

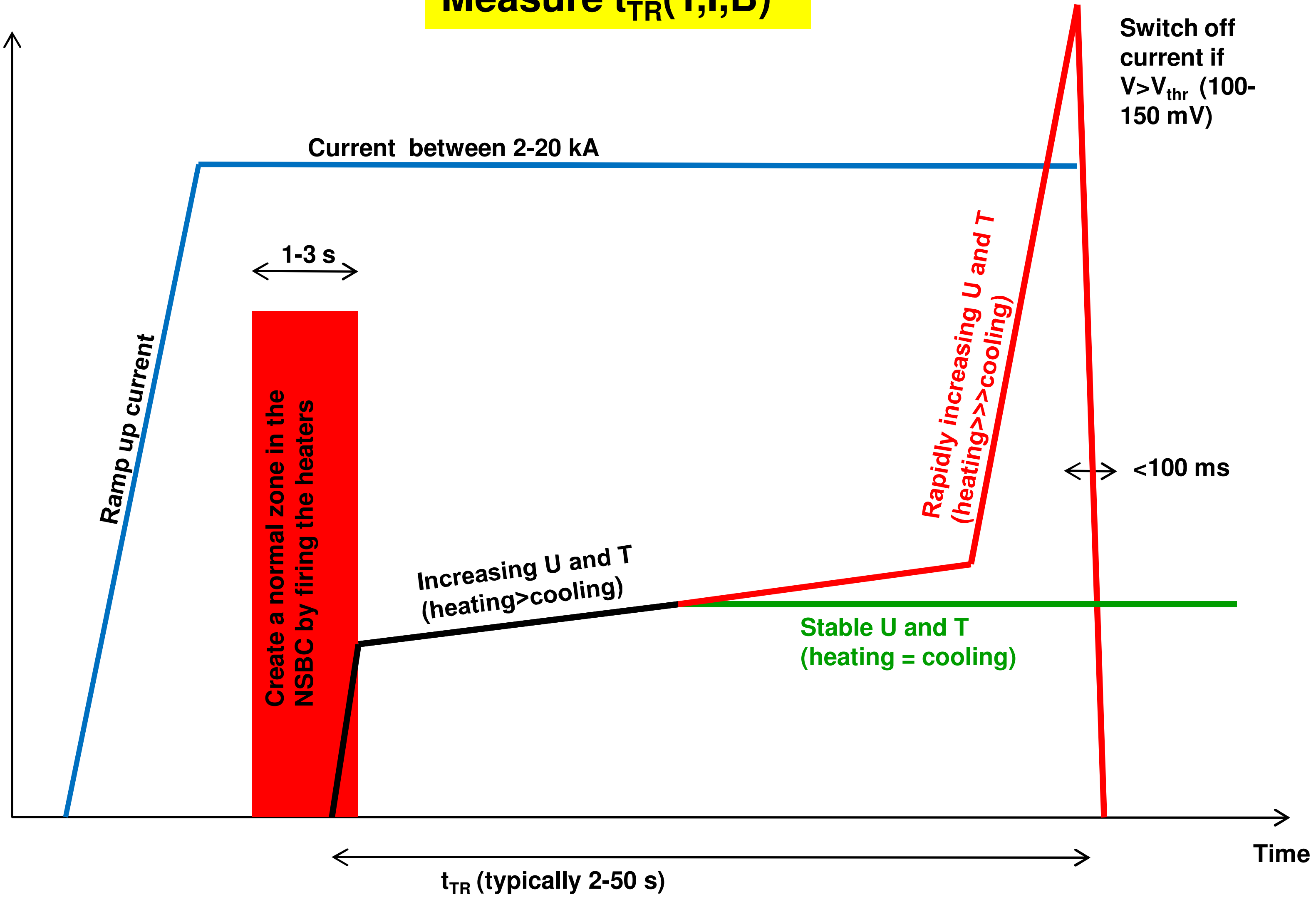

**Sample 3A right (43 $\mu\Omega$)**

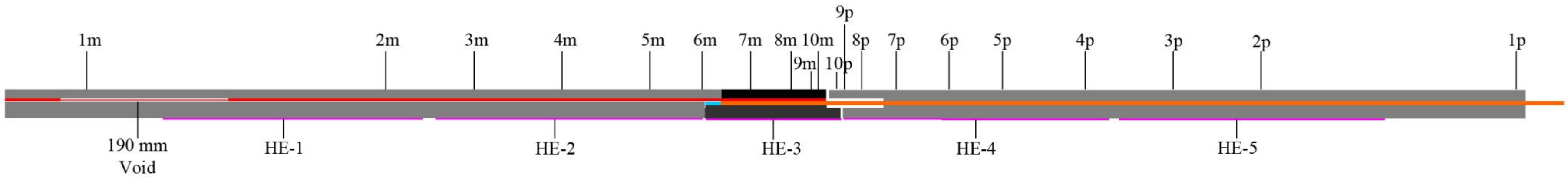

**Sample 3B (21 $\mu\Omega$)**

**Pictures by J.-M. Dalin**

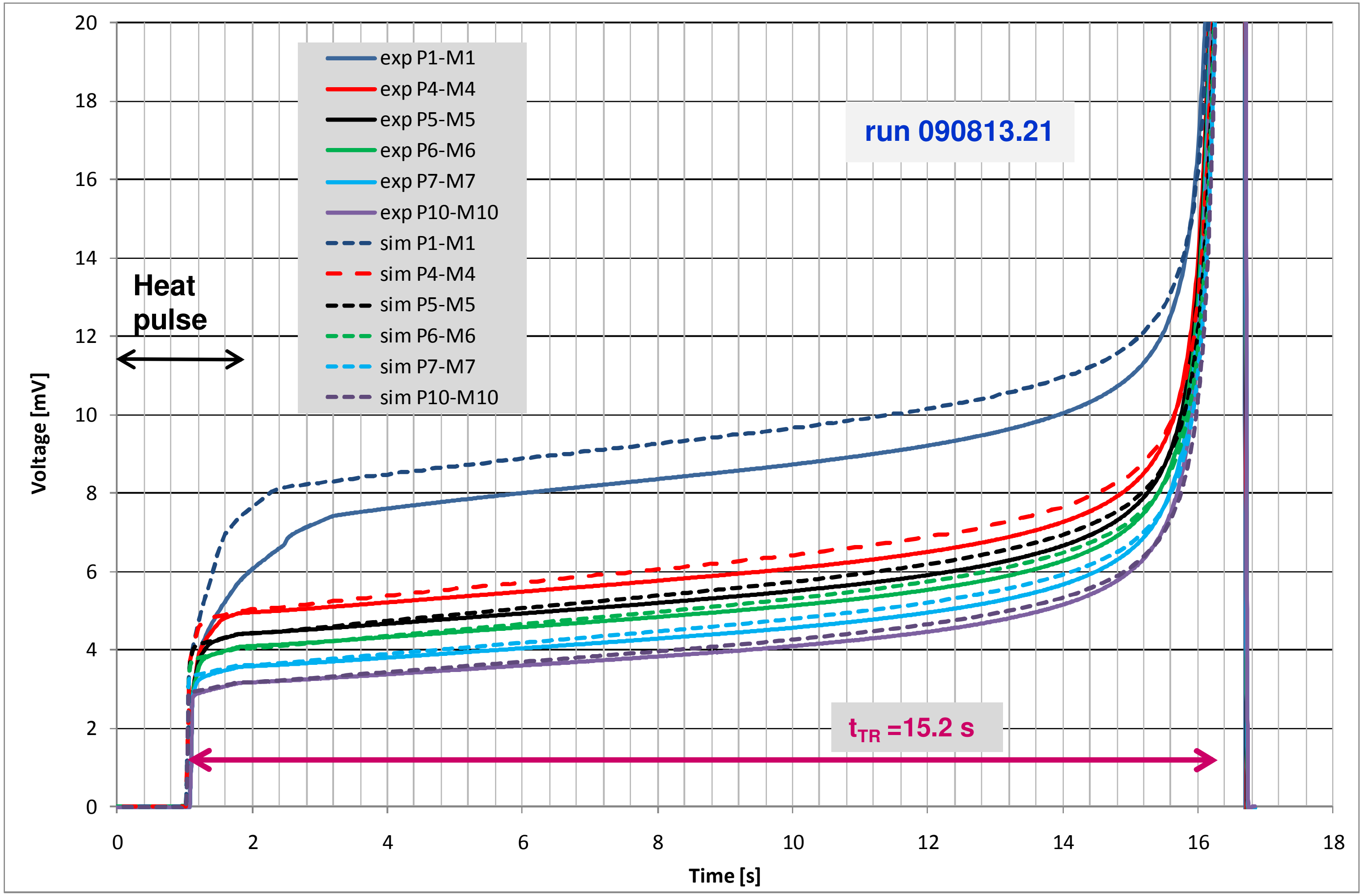
# Typical test run with and without thermal runaway

**Measure $t_{TR}$(T,I,B)**



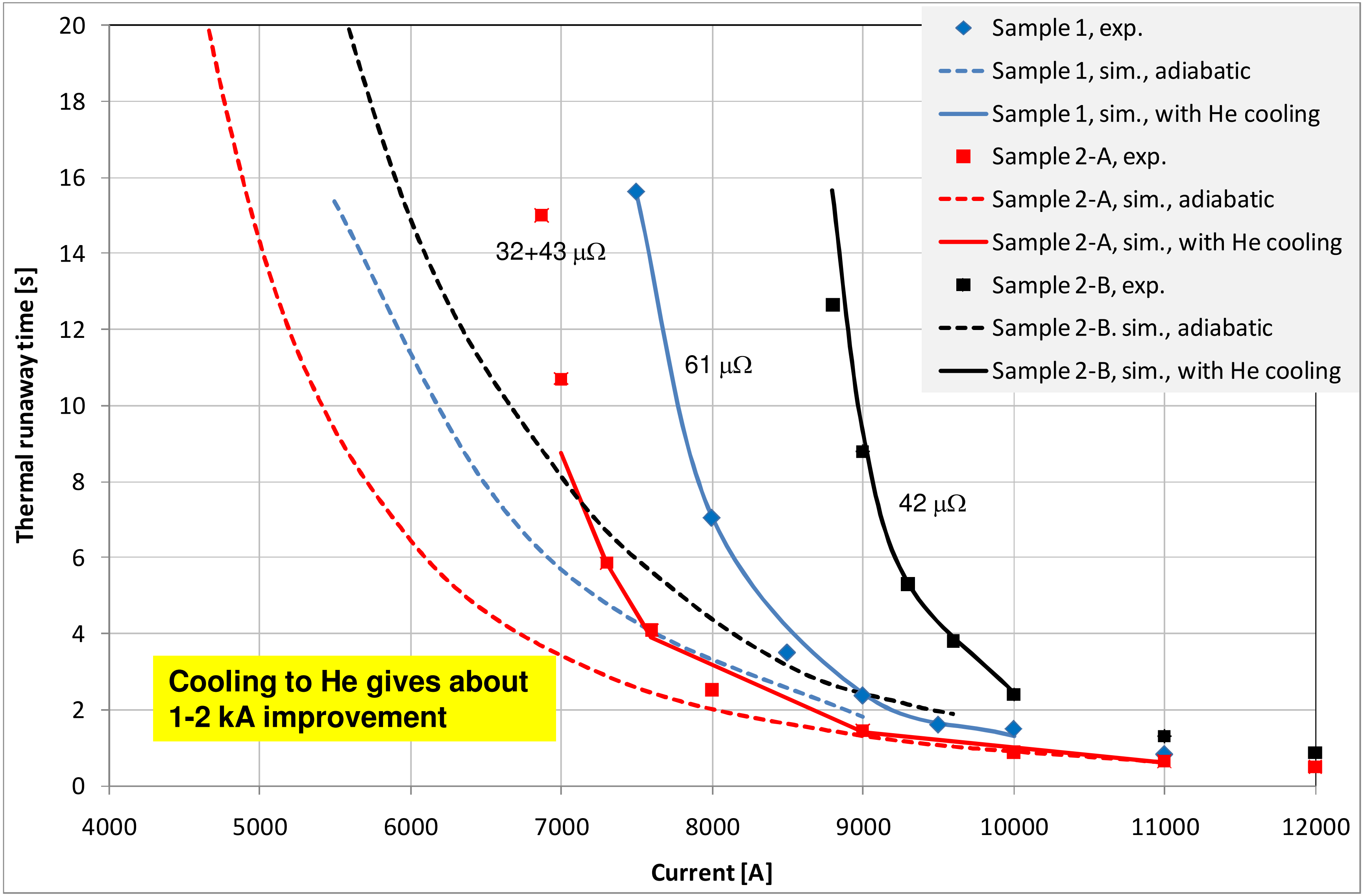


# Typical correlation experimental and calculated V(t) curves



# Correlation experimental and calculated $t_{TR}(I)$ curves.

## For each sample the effective heat transfer to the helium is individually fitted



**Cooling to He gives about 1-2 kA improvement**

# Applying the ‘best fit’ heat transfer values for a large and a small defect under ‘machine conditions’

| | FRESCA Sample 1 | FRESCA Sample 2A | FRESCA Sample 2B |
|---|---|---|---|
| Defect type | Calculated for a single-sided defect B | | |
| RRR bus | Scaled to 160 | | |
| RRR cable | Scaled to 80 | | |
| Interconnect insulation | Calculated for machine type | | |
| Effective cooled bus surface | Scaled to 90% | | |
| Field | Self field | | |
| Helium environment | LHe at 1.9 K | | |
| Effective heat transfer factor (resulting from fit to experimental data) | 1.8 | 1.6 | 0.89 |
| $I_{\text{safe}}$ for $R_{\text{addit}}=67\ \mu\Omega$ with $\tau=10$ s (RQ) | 7.13 kA | 7.03 kA | 6.95 kA |
| $I_{\text{safe}}$ for $R_{\text{addit}}=26\ \mu\Omega$ with $\tau=20$ s (RQ) | 11.95 kA | 11.48 kA | 11.06 kA |

**Used for $I_{\text{safe}}(R_{\text{addit}})$ plots for the machine**

**Conclusion:** Although the difference in effective heat transfer is a factor 2, the resulting error in $I_{\text{safe}}$ is about ±0.5 kA (at high currents). The error might be a bit larger for the RB circuit due to the longer decay time constant.

# A few words on:

- $RRR_{cable}$
- $RRR_{bus}$
- $RRR_{U\text{-}profile}$ and $RRR_{wedge}$

Data coming from:

**F. Bertinelli, A. Bonasia, Z. Charifoulline, P. Fessia, B. Flora, S. Heck, M. Koratzinos, D. Richter, C. Scheuerlein, G. Willering**

# $\mathrm{RRR}_{\mathrm{cable}}$

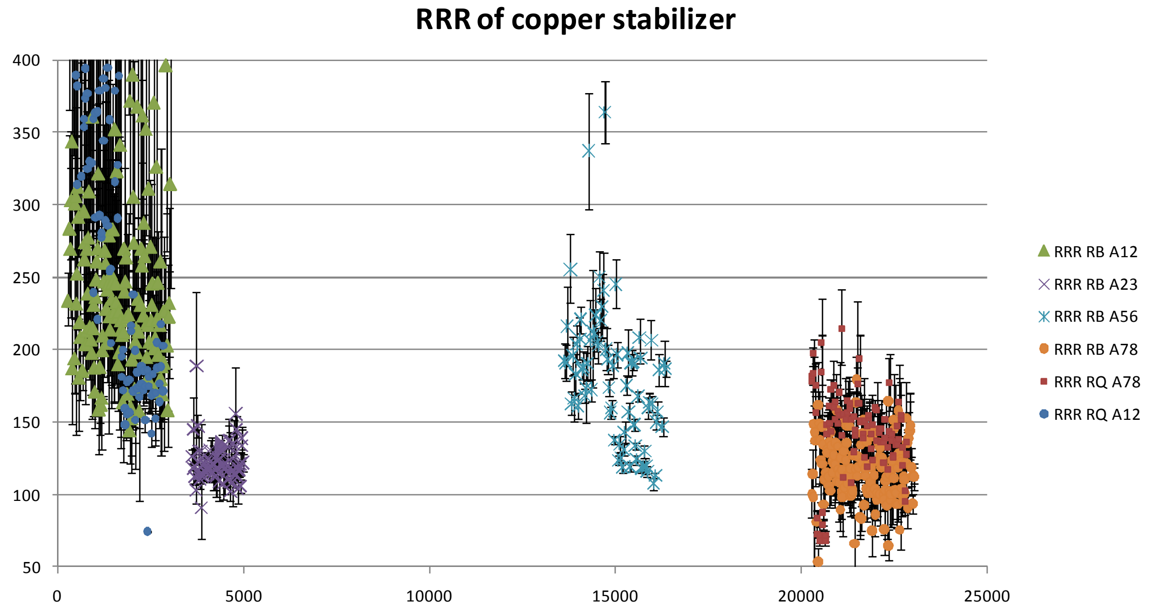
- RRR of the virgin cable (i.e. after production) is 70-100.
- Data from FRESCA tests show RRR of 100, 130, 160 and 180.
- RRR increases to about 130 and 200 when the cable is heated during 4 minutes to 222 °C (SnAg melting temperature) and 270 °C (nominal soldering peak temperature) respectively (using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

**Conclusion:**

The RRR of the 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 enhancement due to the soldering process is small.

For simulations I will assume $\mathrm{RRR}_{\mathrm{cable}}=80$.

# $RRR_{bus}$



←

- Biddle data in many segments of the machine show large spread in RRR from 50-400 (measurements: MPE-CP, analysis: M. Koratzinos).

- Biddle data are unreliable in the measured range (10-20 μV)
- (Task Force LHC splices consolidation, 17/12/2009).
- Few Keithley data from sector L2 show RRR of 200-300.
- There is no evidence that different sectors contain copper from different production batches.
- Data from FRESCA tests show RRR>250.
- Data from on 4 RB and 4 RQ bus samples show RRR of 220-300.

**Conclusion:** I will use RRR of 100 and 160. Better measurements in the machine using the nQPS boards in stead of the Biddle may give a more realistic RRR value.

# $\text{RRR}_{\text{U-piece}}$ and $\text{RRR}_{\text{wedge}}$

- 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.

For simulations I will use $\text{RRR}_{\text{U\_piece}}=\text{RRR}_{\text{wedge}}=\text{RRR}_{\text{bus}}$ (so also 100 and 160).

# $I_{safe}$ vs $R_{addit}$ plots

**The currents in the following plots are calculated for:**

- $RRR_{cable}$=80,
- $RRR_{bus}$=$RRR_{wedge}$=$RRR_{U\text{-}profile}$=100 and 160,
- $T_{prop}$=10 and 20 s
- Worst heat transfer coefficient as deduced from the 3 FRESCA samples

**No additional safety margin is added!!**

# Quench scenarios

**Quenches in LHe:**

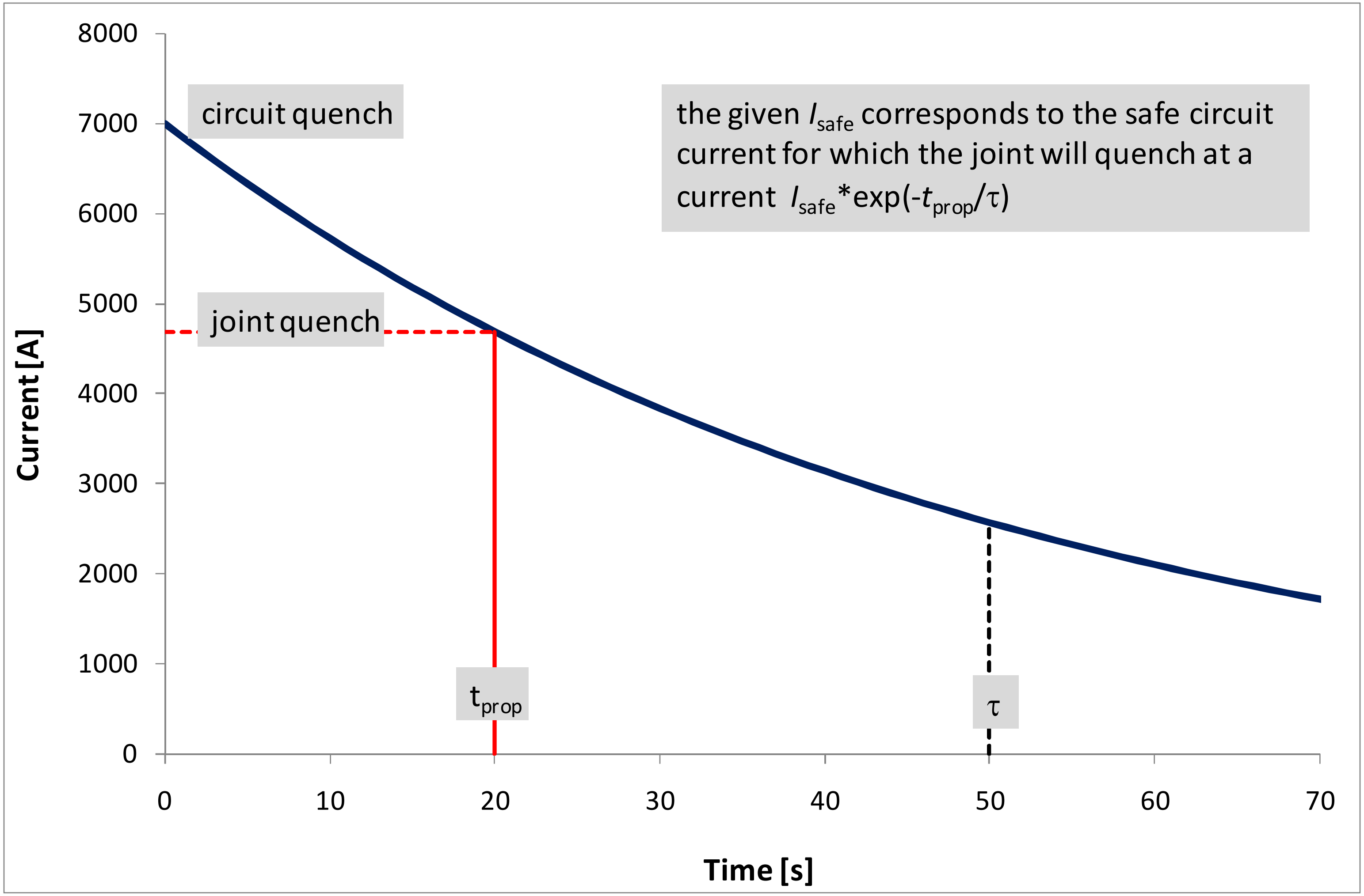
- Quench due to mechanical movement of the Non-Stabilised Bus Cable. Not very likely below 7 kA (because all sectors already powered up to 7 kA).
- Quench due to global beam losses.
- Quench due to normal zone propagation through the bus from an adjacent quenching magnet. Not possible below 6 kA (RQ) and 8 kA (RB) respectively.

**Quenches in GHe:**

- Quench due to warm helium from adjacent quenching magnet. Very unlikely below about 5 kA, almost certain above 9 kA. Time between quench of magnet and quench of interconnect depends mainly on:
  - current,
  - number of magnets that are quenching,
  - position in the cryogenic cell.

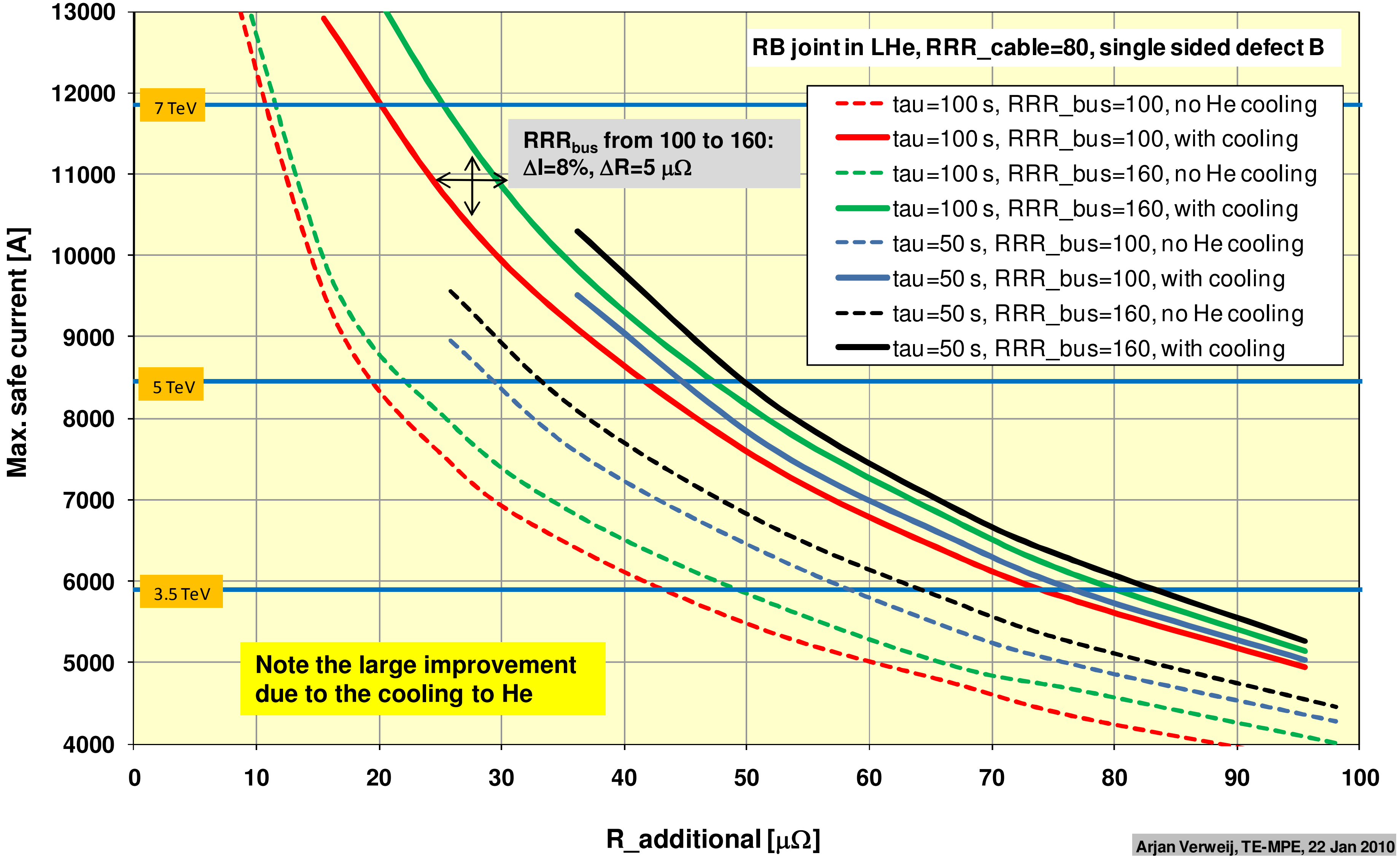
For the calculations I will assume no cooling to helium and a propagation time of:
10 s for high current quenches ($I$>11 kA),
20 s for intermediate currents (7-9 kA).

# Quenches in GHe



the given $I_{safe}$ corresponds to the safe circuit current for which the joint will quench at a current $I_{safe}*\exp(-t_{prop}/\tau)$

# RB in LHe

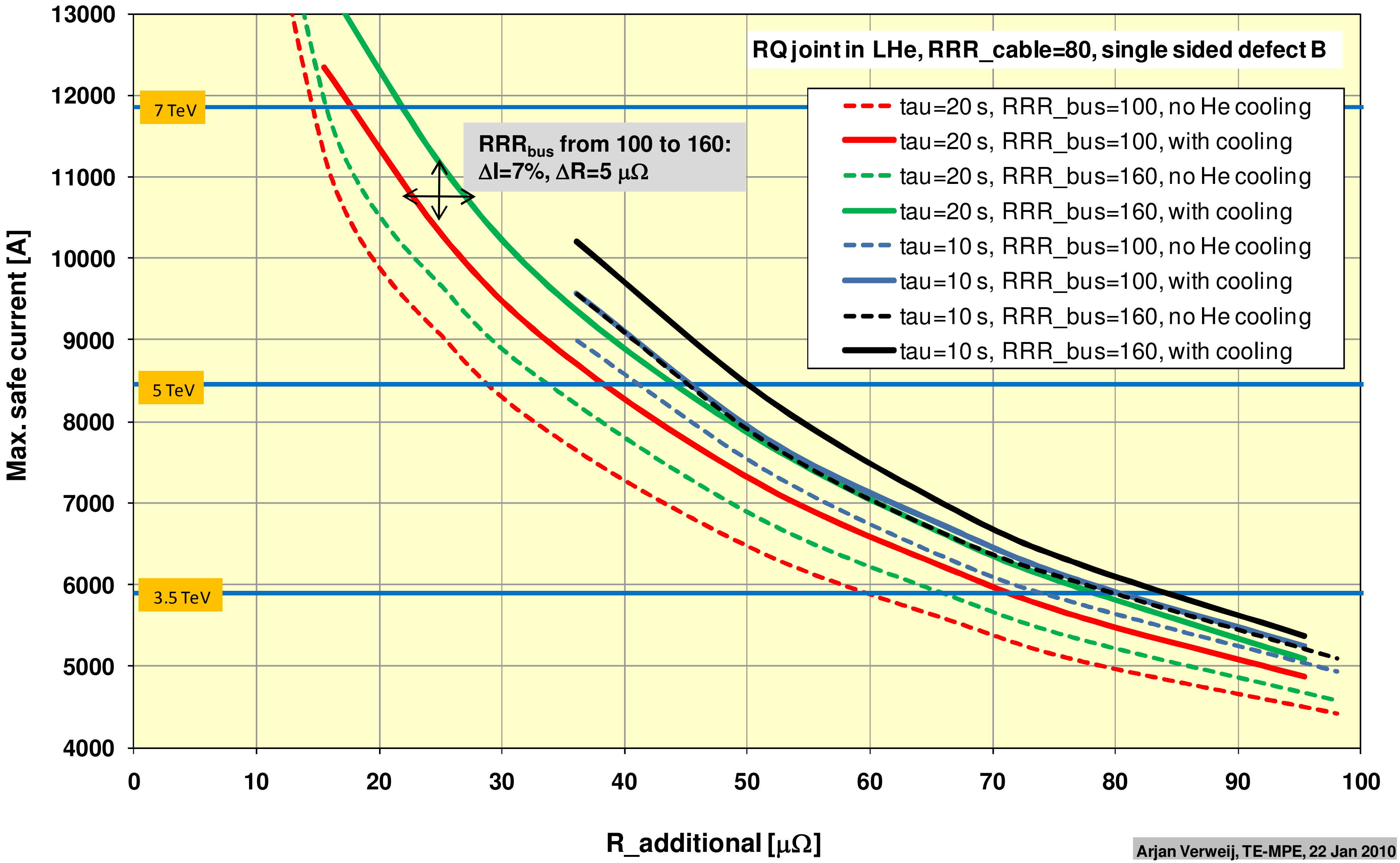


$RRR_{bus}$ from 100 to 160: ΔI=8%, ΔR=5 μΩ

Note the large improvement due to the cooling to He

Arjan Verweij, TE-MPE, 22 Jan 2010

# RQ in LHe

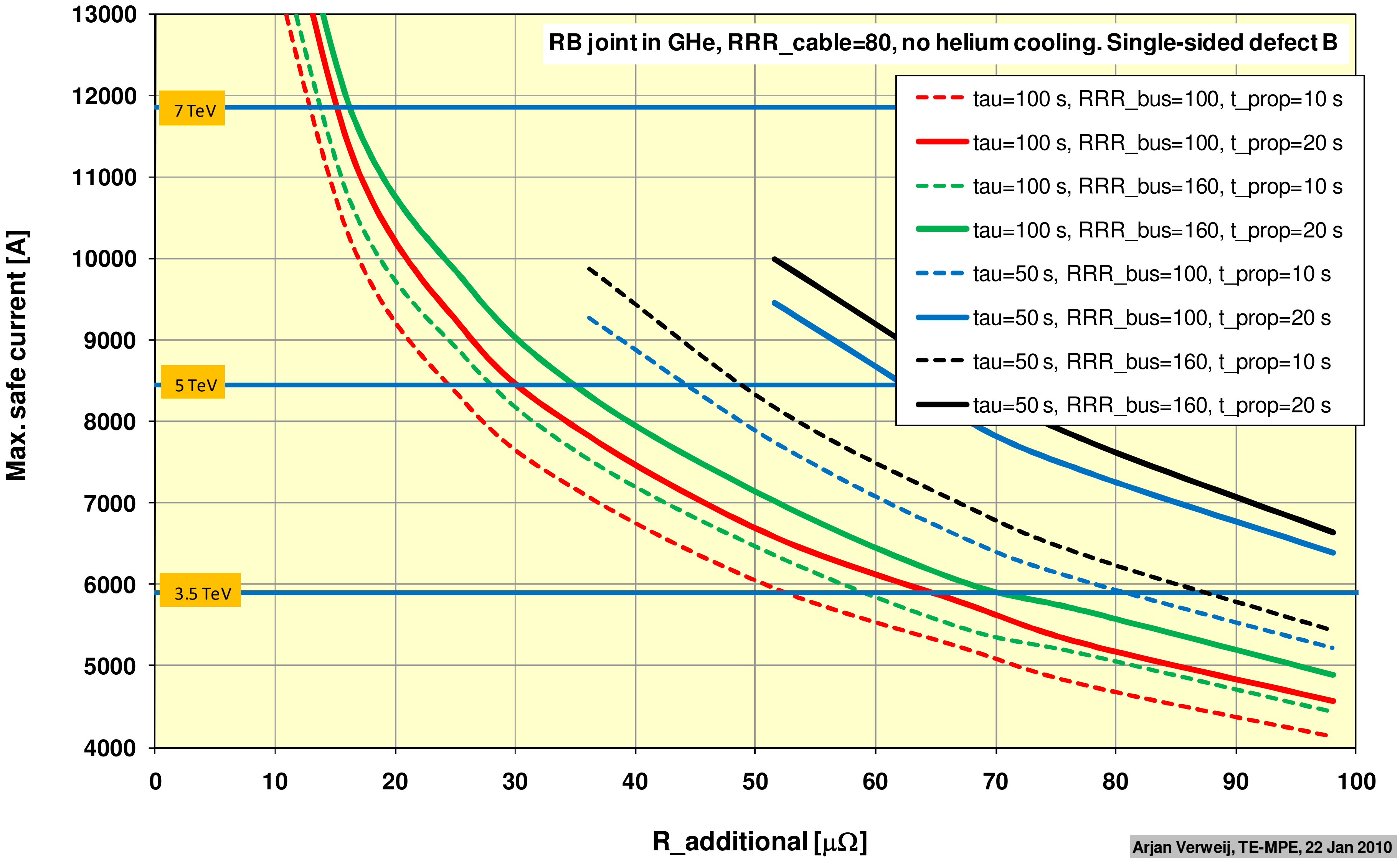


RQ joint in LHe, RRR_cable=80, single sided defect B

$RRR_{bus}$ from 100 to 160: $\Delta I=7\%$, $\Delta R=5\ \mu\Omega$

Arjan Verweij, TE-MPE, 22 Jan 2010

# RB in GHe



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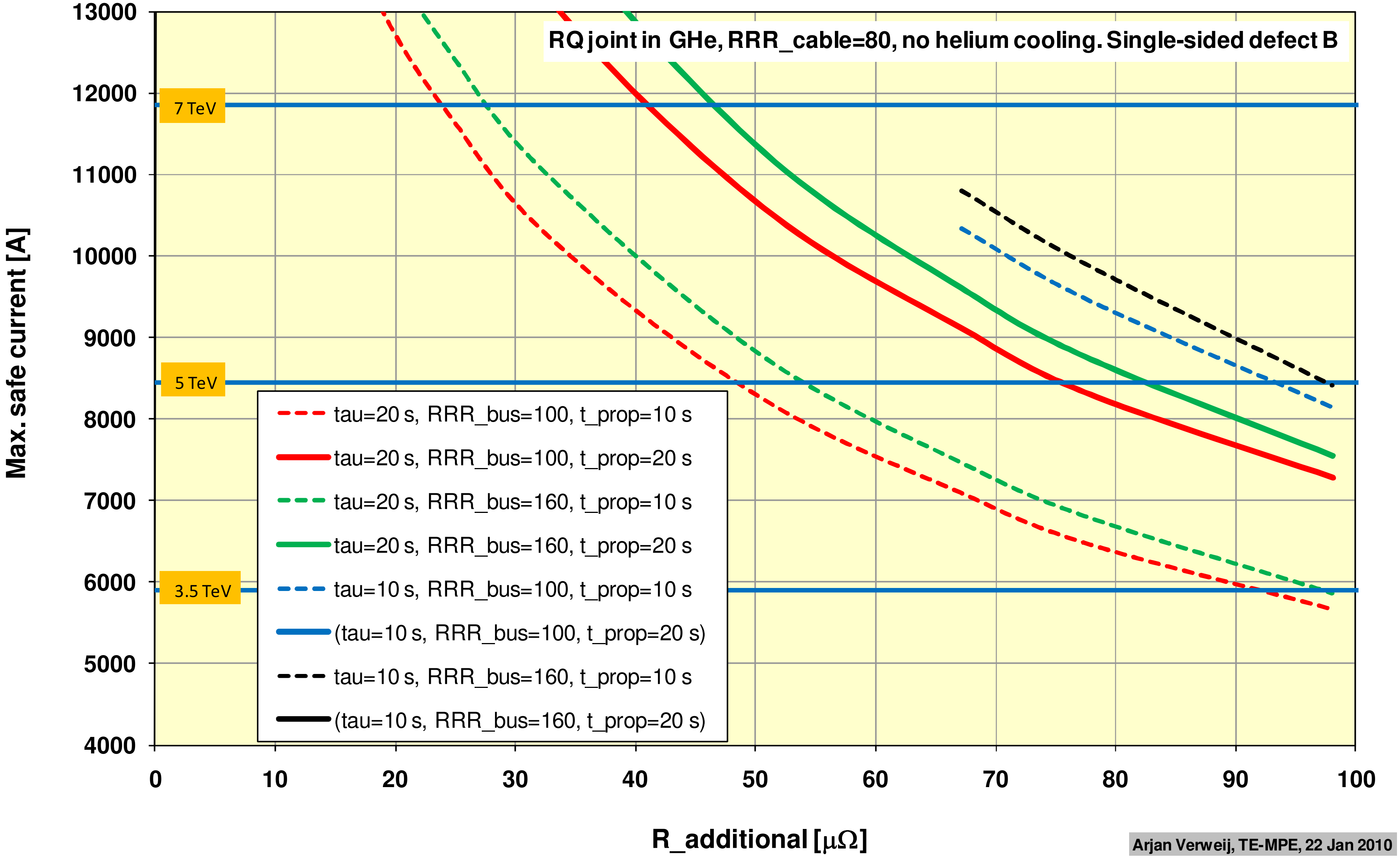
# RQ in GHe



**Arjan Verweij, TE-MPE, 22 Jan 2010**

# 13 kA requirements

| circuit | $\tau$ [s] | Condition | Max $R_{addit}$ for $RRR_{bus}$=100 | Max $R_{addit}$ for $RRR_{bus}$=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 |

**Conclusion:** $R_{addit,RB}<11\ \mu\Omega$ and $R_{addit,RQ}<15\ \mu\Omega$ are required for operation around 7 TeV.

Better knowledge of $RRR_{bus}$ will hardly increase these numbers

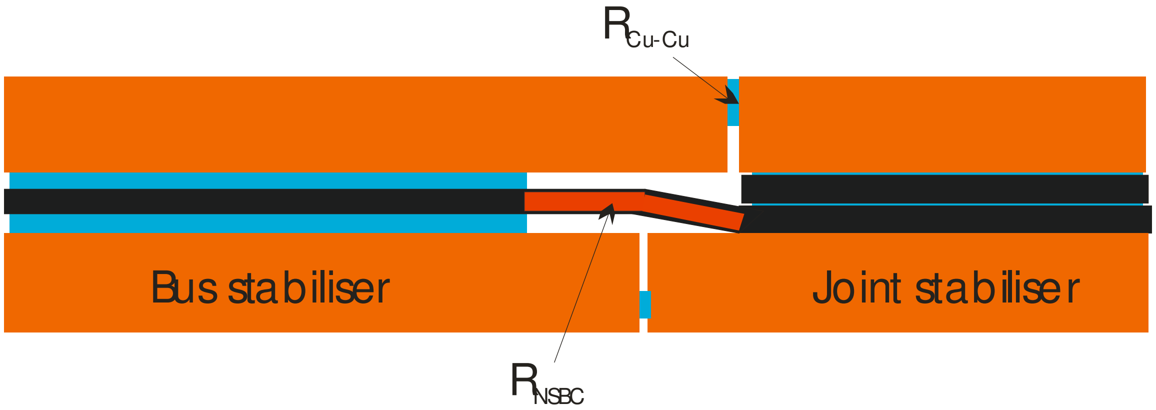
# 5 TeV requirements

| circuit | τ [s] | Condition | Max $R_{addit}$ for $RRR_{bus}$=100 | Max $R_{addit}$ for $RRR_{bus}$=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 |

Remark: better knowledge of $RRR_{bus}$ may give another 10 μΩ margin.

# 3.5 TeV requirements

| circuit | $\tau$ [s] | Condition | Max $R_{addit}$ for $RRR_{bus}$=100 | Max $R_{addit}$ for $RRR_{bus}$=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 |



$R_{\text{addit}} = R_{\text{NSBC}} \parallel R_{\text{Cu-Cu}}$

- In case of a quench the current will flow partially through the copper of the cable, and partially through the Cu-Cu contact between the bus stabiliser and the joint stabiliser.
- We know that many joints have a non-stabilised bus cable with a length of at least 15 mm (so $R_{\text{NSBC}}$>20 µΩ).
- The Cu-Cu contacts might degrade in time, due to electromagnetic and thermal cycling, and possibly due to thermal and pressure shocks during a quench.

So: $R_{\text{addit}}$ may increase and hence $I_{\text{safe}}$ decrease.

- Furthermore, if $R_{\text{Cu-Cu}}$ is small as compared to $R_{\text{NSBC}}$ and if $\text{RRR}_{\text{Cu-Cu}} \ll \text{RRR}_{\text{NSBC}}$ then the room temperature measurement of $R_{\text{addit}}$ could give a somewhat underestimated $R_{\text{addit}}$ at cold and hence an overestimated value of $I_{\text{safe}}$.

# Safe running at 13 kA

- Safe 13 kA operation requires $R_{\text{addit,RB}}$<11 μΩ and $R_{\text{addit,RQ}}$<14 μΩ. Proper quench protection is usually based on an adiabatic approach which further decreases the maximum $R_{\text{addit}}$ to 8 and 13 μΩ. One can be sure that there are many hundreds of defects with larger $R_{\text{addit}}$ in the machine. Better know-how of the $\text{RRR}_{\text{bus}}$ might increase the maximum $R_{\text{addit}}$ a bit, but they will stay well below 20 μΩ.

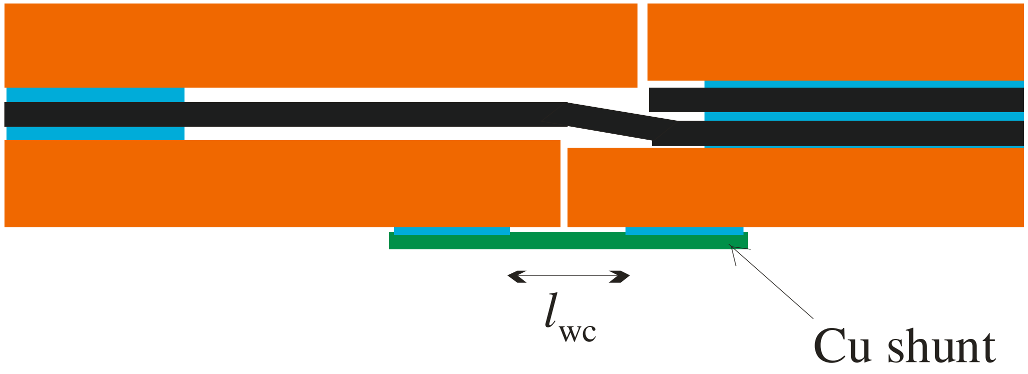
- 'Segment' measurements at warm (or any other temperature) are not accurate enough to detect these small values.

- "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.

- $R_{\text{addit}}$ may degrade during the lifetime of the LHC.

- Especially for small resistances, the measured $R_{\text{addit}}$(300 K) may not be representative for $R_{\text{addit}}$(10 K).

! **Conclusion:** For safe running around 7 TeV, a shunt has to be added on **all** 13 kA joints, **also on those with small $R_{\text{addit}}$**. Joints with high $R_{\text{addit}}$ or joints with large visual defects should be resoldered and shunted.



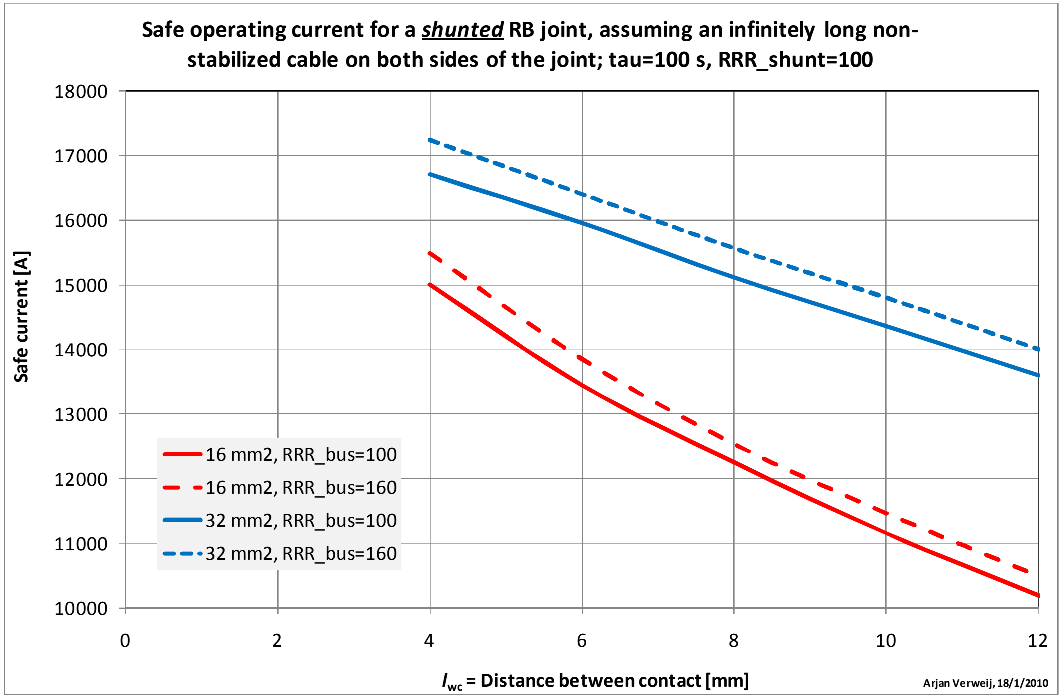
**For implementation see talk P. Fessia**

# Shunt requirements:

- One shunt on each side of the joint or one shunt covering both sides
- High RRR copper (>100).
- Sufficiently large cross-section.
- Short distance $l_{wc}$.
- Good electrical contact

  between shunt and stabilisers.
- Small forces acting on shunt

  (so somewhat flexible shunt).
- Large cooling surface.



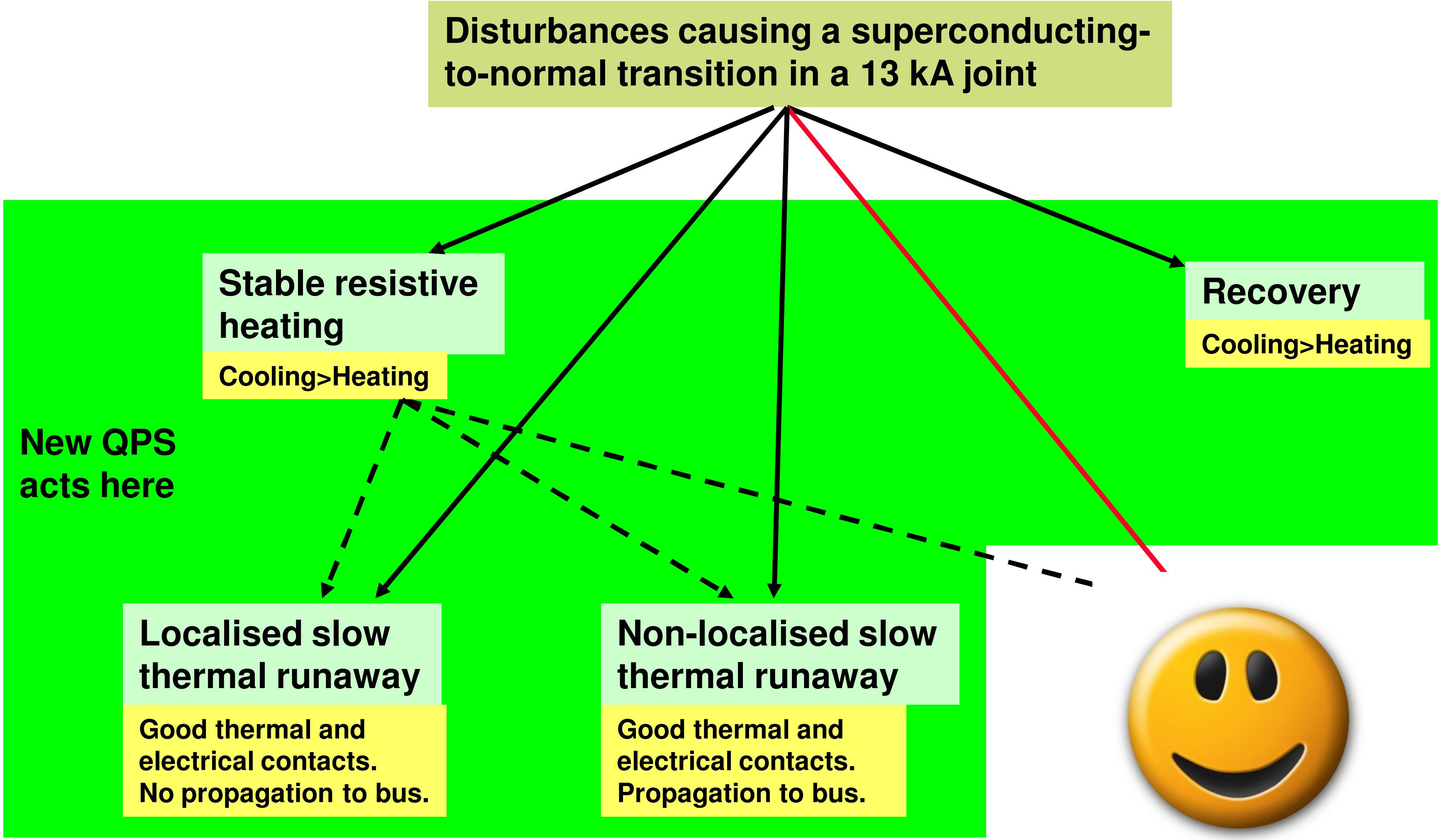
# Conclusion

- The calculation code QP3 is validated. Different effective heat transfer to helium is needed per sample in order to have very good quantitative agreement. This difference has an error of about ±500 A on the safe current.

| Energy | $\tau_{RB}$ [s] | Max. $R_{addit,RB}$ [$\mu\Omega$] | $\tau_{RQ}$ [s] | Max. $R_{addit,RQ}$ [$\mu\Omega$] |
|---|---|---|---|---|
| 3.5 TeV | 50 | 76 | 10 | 80 |
| 5 TeV | 75 | 43 | 15 | 41 |
| 7 TeV | 100 | 11 | 20 | 14 |

- Actual calculations of the safe current are based on conservative values for $RRR_{cable}$ and $RRR_{bus}$. Better knowledge of $RRR_{bus}$, by means of measurement in several sectors in the machine, is needed if one wants to push the energy from 3.5 TeV towards 5 TeV, but is of no real importance for operating at 7 TeV.

- For safe running around 7 TeV, a shunt has to be added on **all** 13 kA joints, **also on those with small $R_{addit}$**. Joints with high $R_{addit}$ or joints with large visual defects should be resoldered and shunted. A Cu-shunt with high RRR and a cross-section of 16x2 $mm^2$ is sufficient, if soldered at short distance from the gap. Experimental confirmation by means of a test in FRESCA should be foreseen.



Disturbances causing a superconducting-to-normal transition in a 13 kA joint

Stable resistive heating

Cooling>Heating

Recovery

Cooling>Heating

New QPS acts here

Localised slow thermal runaway

Good thermal and electrical contacts.
No propagation to bus.

Non-localised slow thermal runaway

Good thermal and electrical contacts.
Propagation to bus.