Measurement and Simulation of Thermal Runaway Conditions in the LHC Interconnects

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Based on work and many contributions from:

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C. Urpin, G. Willering,

MAC, 26.10.2009

Outline

- The issue of thermal runaways
- A model experiment
  - Sample and characterization
  - Results
- Simulations
  - Model validation
  - Predictions for LHC operation
- Conclusions and plan for the future

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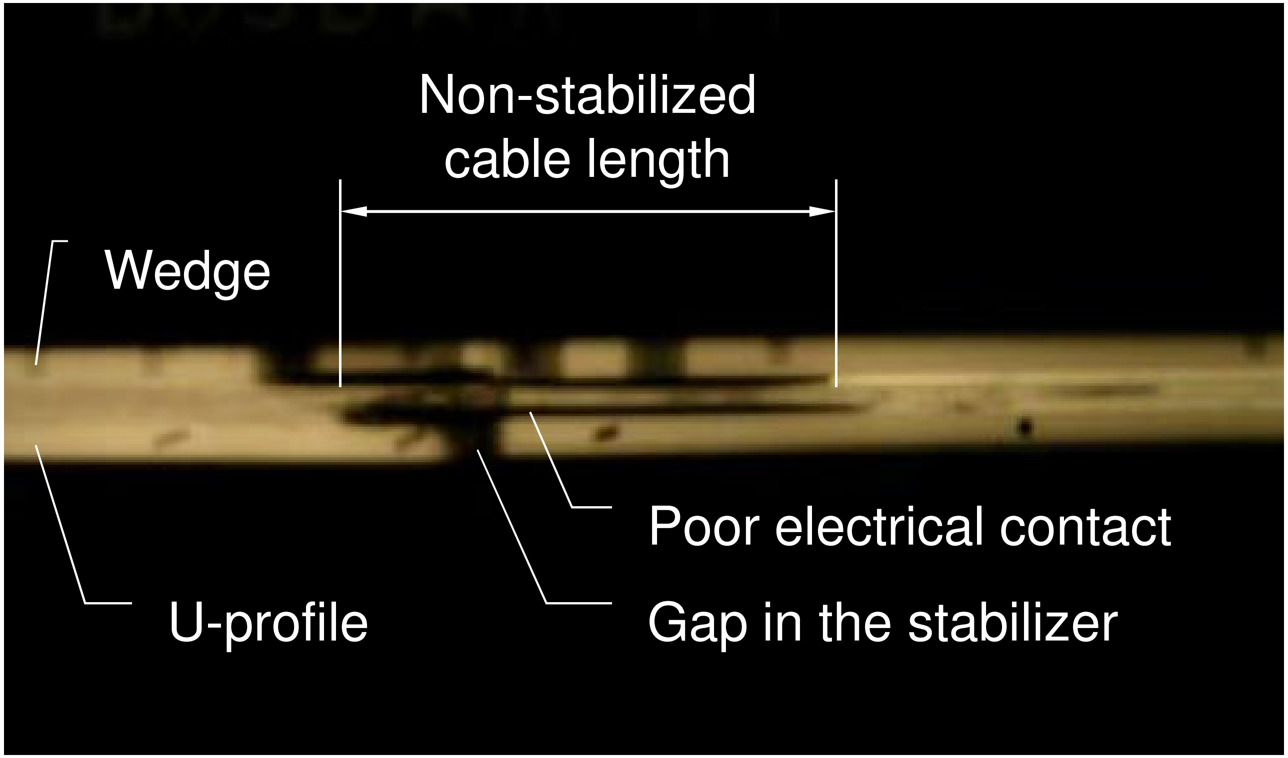
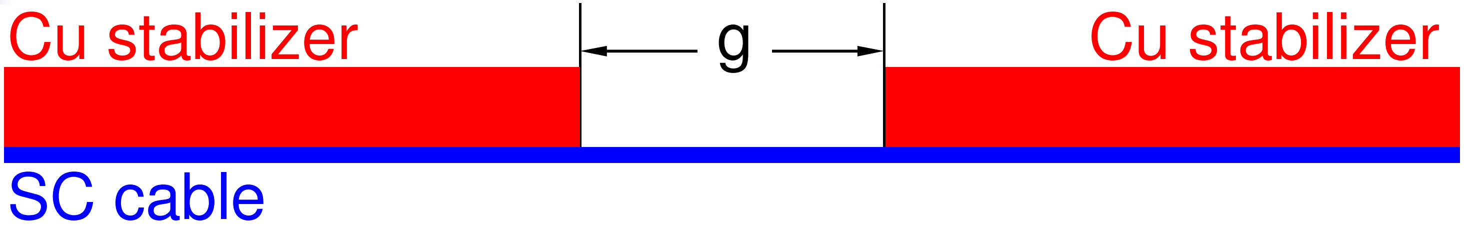
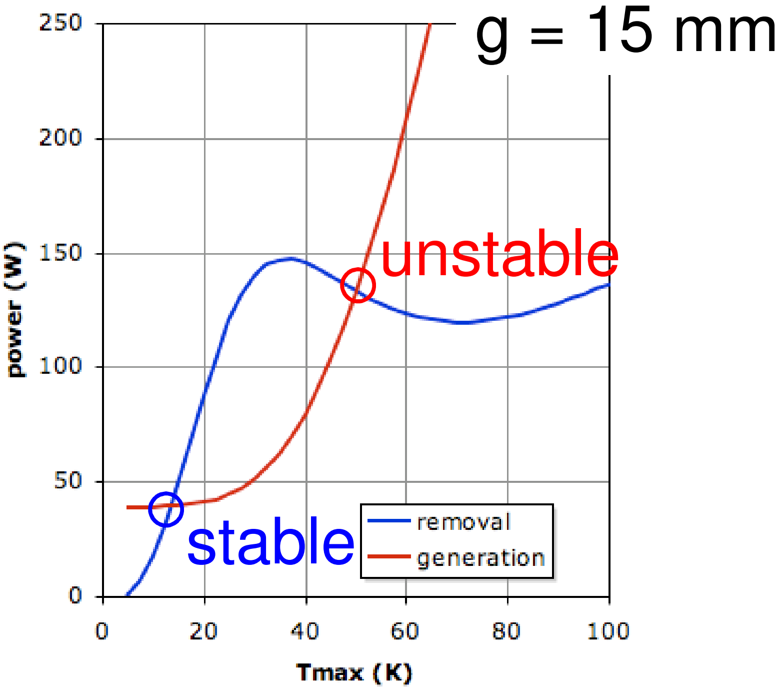
An *ideal defect* in a quadrupole interconnect

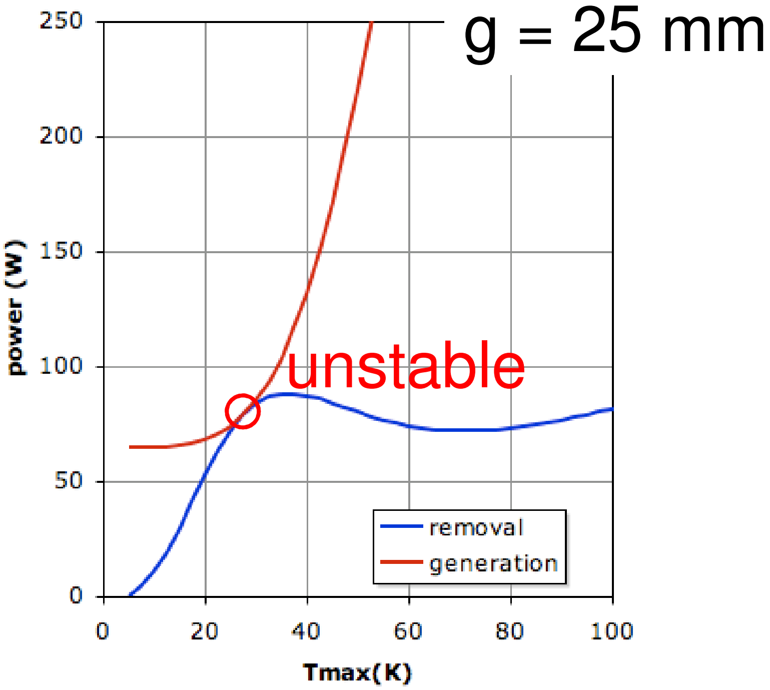


Sample of interconnect with a ≈ 45 mm soldering defect introduced **for testing purposes** (see later results)

Thermal runaway in a faulty interconnect







The maximum stable temperature is in the range of 30…40 K

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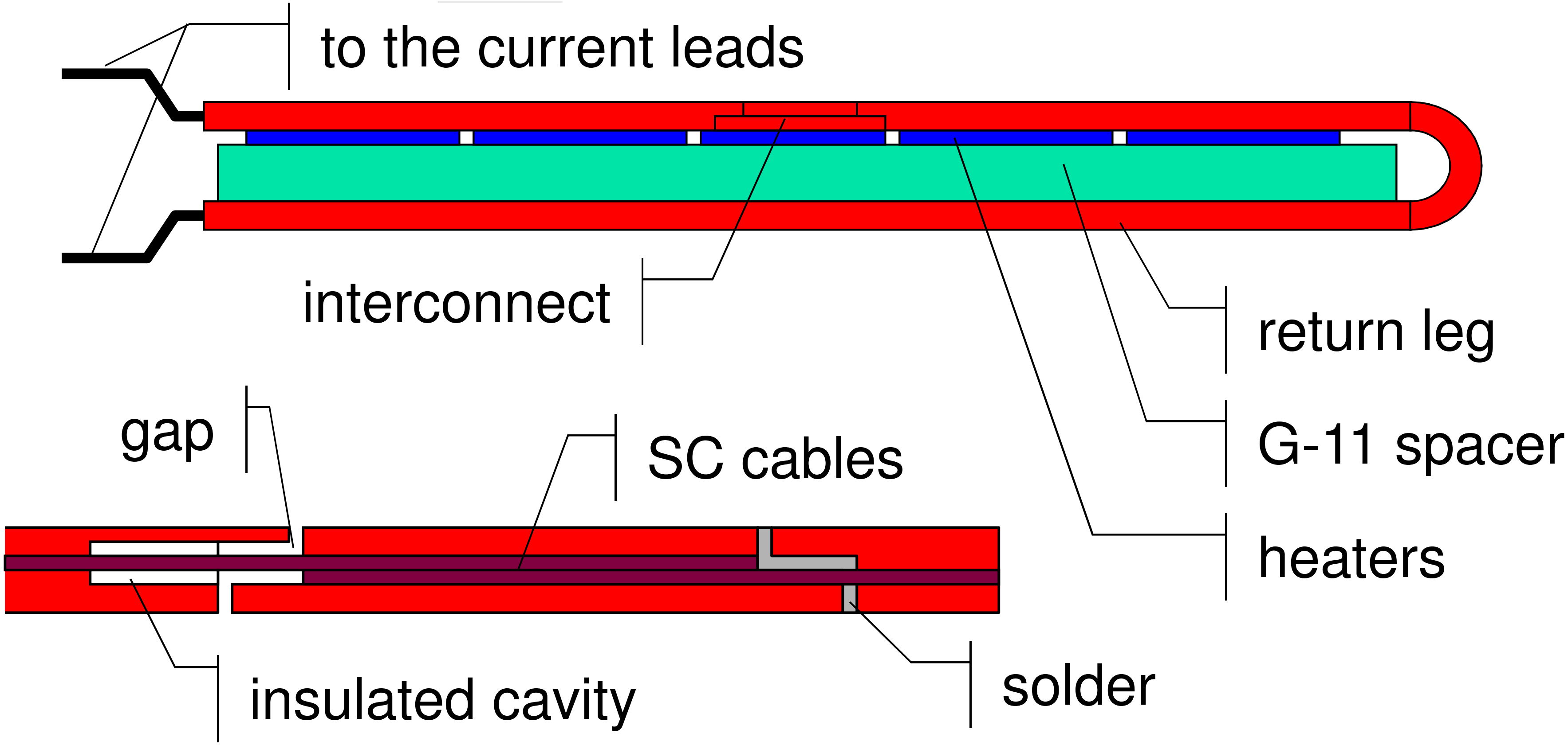
Sample design

Arjan Verweij, TE/MPE-PE, 15/4/2009, updated 5/8/2009

FRESCA experiment on a NSBC (Non-Stabilised Bus Cable):
Sample lay-out, instrumentation, data acquisition, measurements


to the current leads

interconnect

return leg

G-11 spacer

heaters

gap

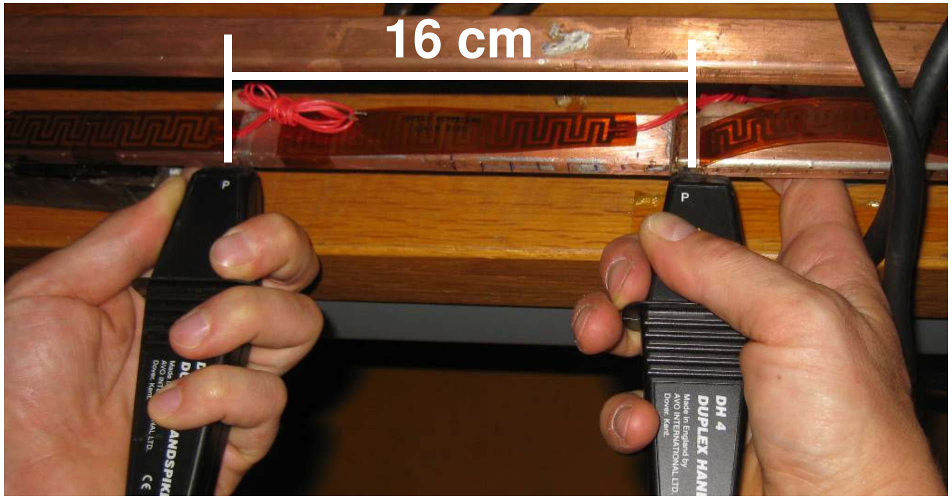
SC cables

insulated cavity

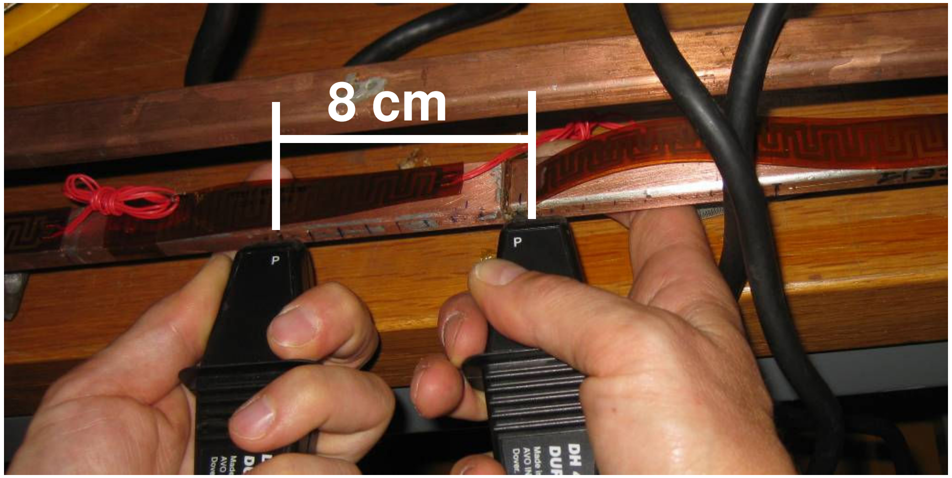
solder

Courtesy of Ch. Scheuerlein, TE-MSC

R-16 and R-8 measurement



R-16 = 79.0±0.9 μΩ
(additional R-16 = 61.2 μΩ)

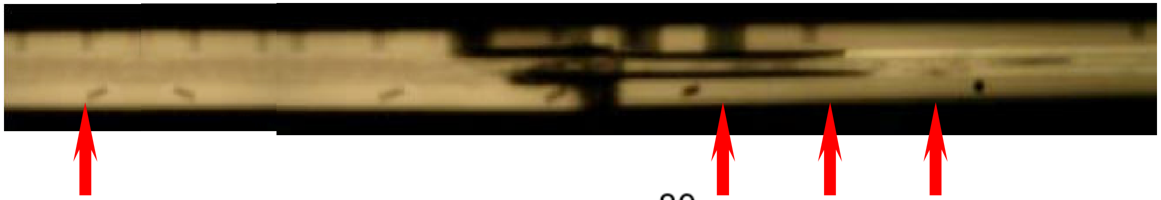


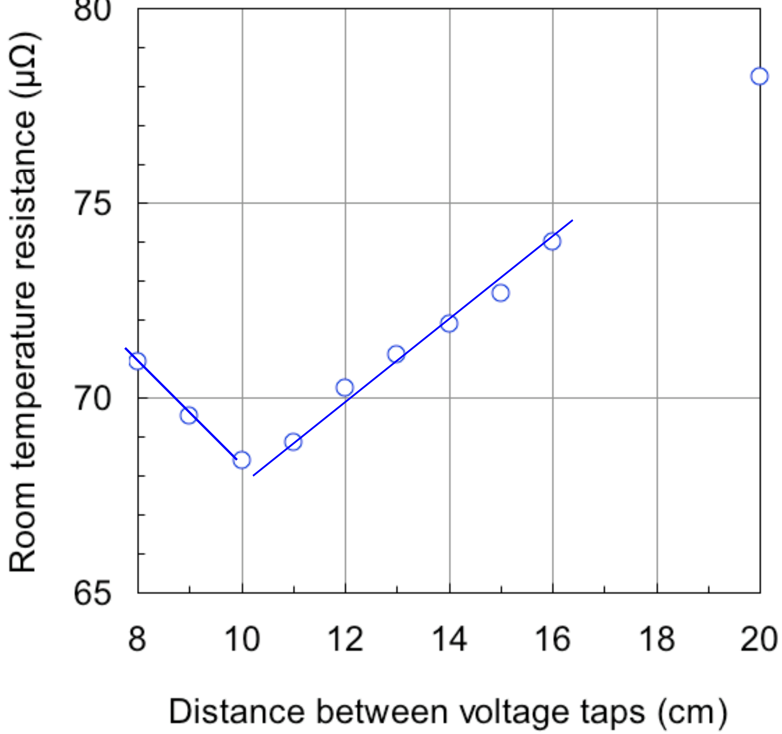
R-8 = 69.7±0.5 μΩ
(additional R-8 = 60.2 μΩ)

(opposite R-8 = 10.0±0.3 μΩ)

Courtesy of Ch. Scheuerlein, TE-MSC

RT resistance vs. length



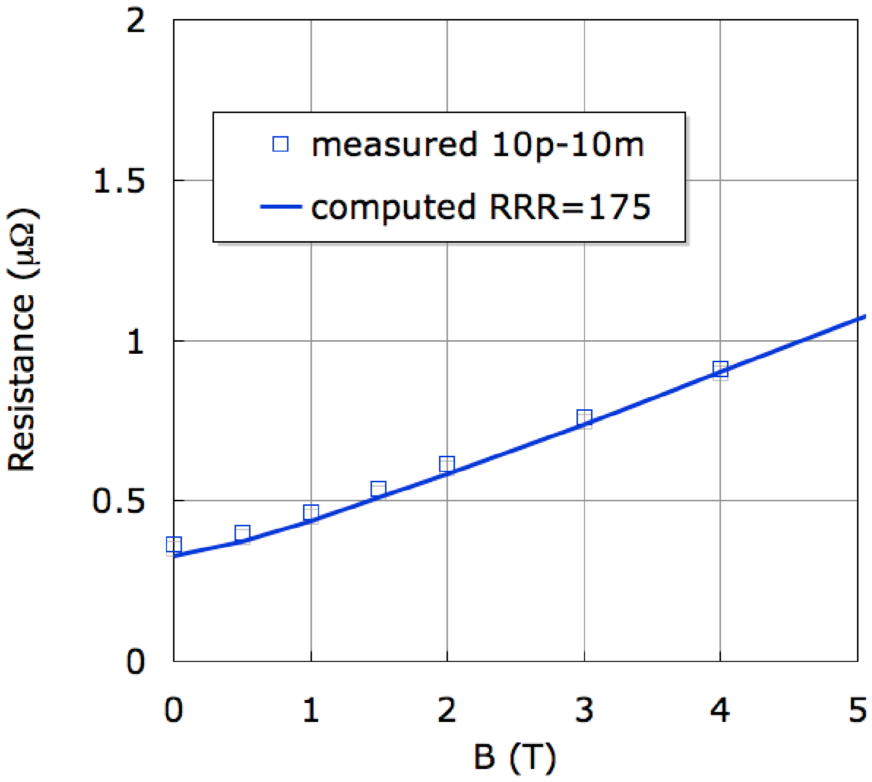


- The measured RT resistance decreases moving the probe by 2 cm, which confirms *poor electrical contact* between the cable and the stabilizer (as desired)
- The excess resistance is approximately 20 μΩ higher than the worst defect found so far in MQ bus-bars, but still 30 μΩ short of the recommended *worst case of* **90 μΩ** (LMC August 5th, 2009)
- Local RT resistance measurements **resolve very accurately** this type of defect

RRR of the cable

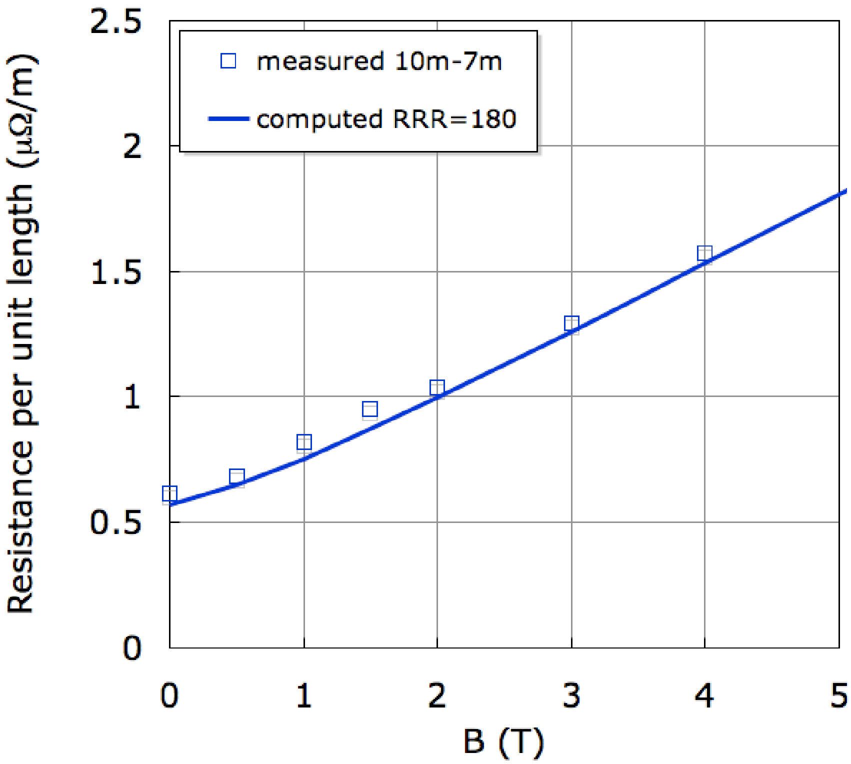
- Data from cool-down and quench suggest relatively high cable RRR: ≈ **175** vs. an expected minimum of **80** (LMC August 5th, 2009)
- This is consistent with magneto-resistance, and with a study on the effect of low-T heat treatments on LHC strands (see later)

Voltage across the soldering defect in normal state (10…20 K) and applied background magnetic field of FRESCA



RRR of the bus-bar profile

Example of voltage on bus-bar in normal state (10…20 K) and applied background magnetic field of FRESCA

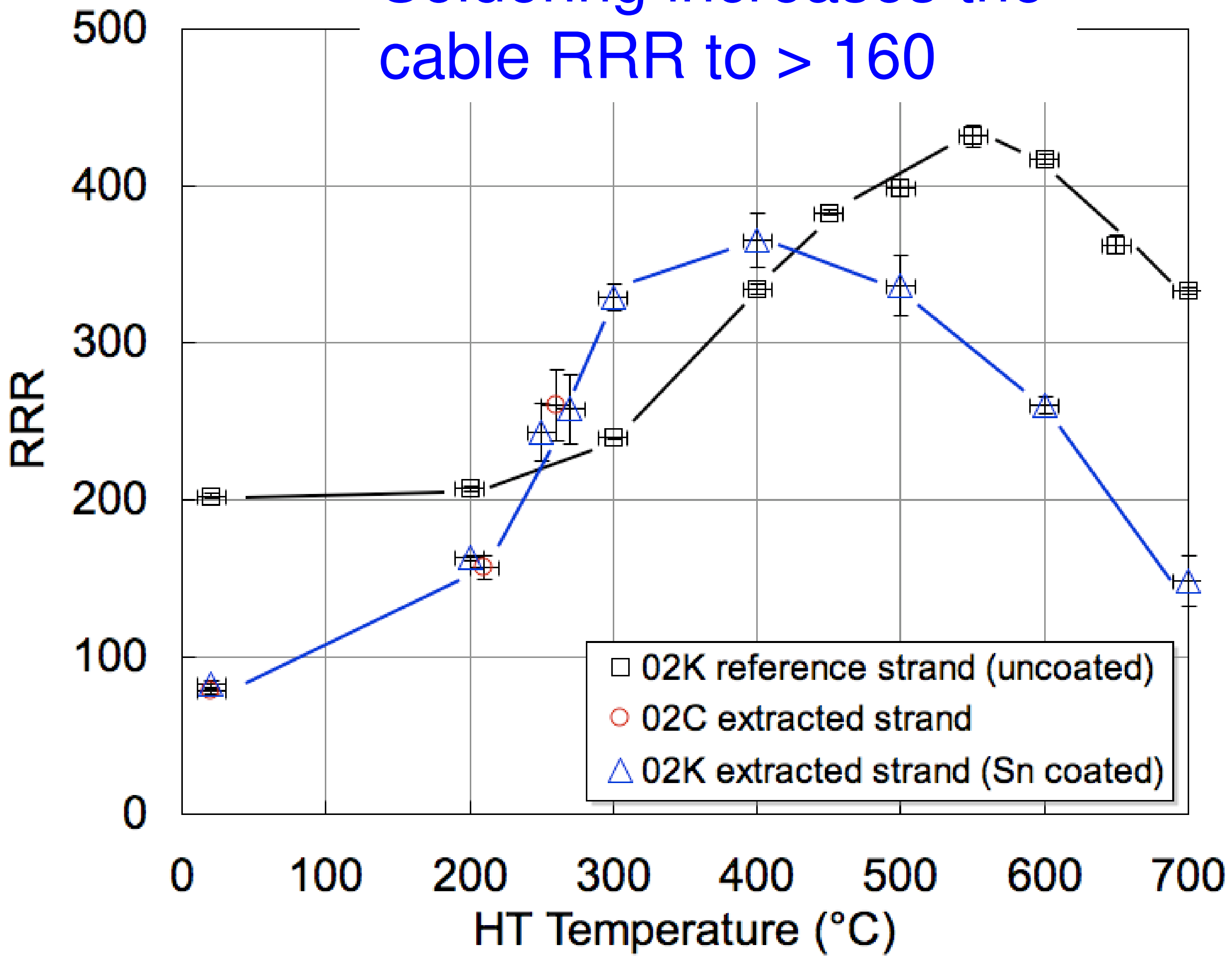


- For the bus-bar profile the RRR appears to be very high, in the range of 200
- Because of the small signal level the data has relatively large scatter
- The best RRR estimate is **240 ± 70** vs. an expected minimum of **100** (LMC August 5th, 2009)

Courtesy of A. Bonasia, S. Heck, Ch. Scheuerlein, TE-MSC

Study of cable RRR vs. HT

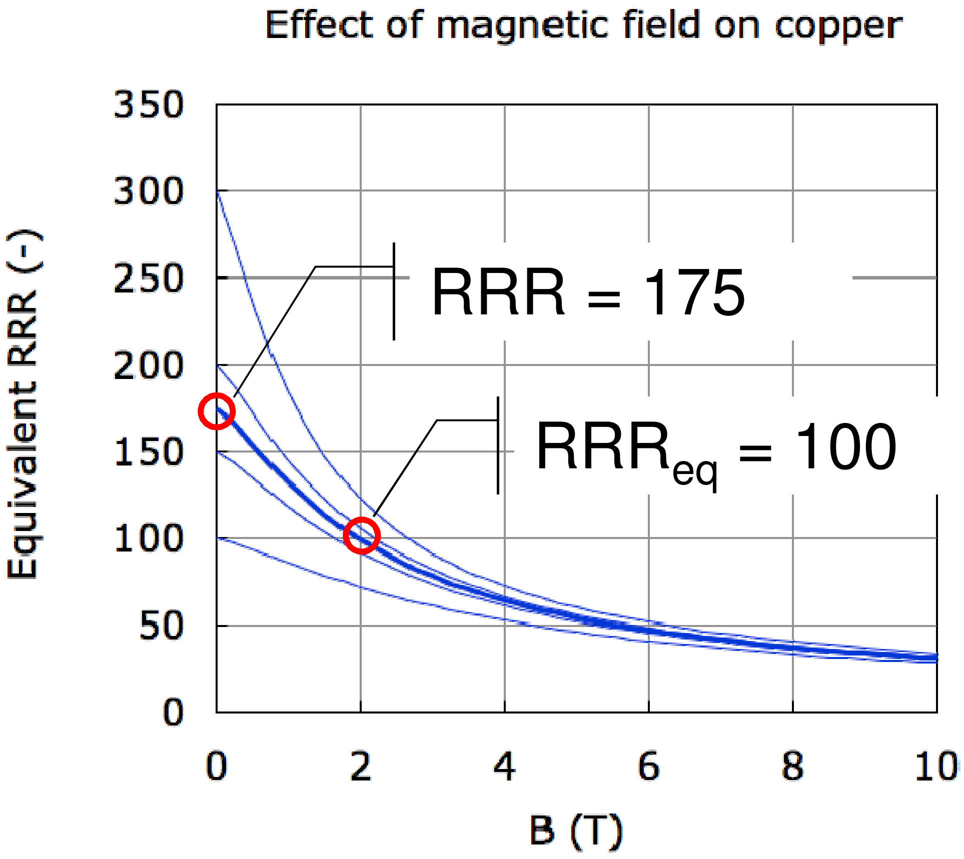
Soldering increases the cable RRR to > 160



Magneto-resistance

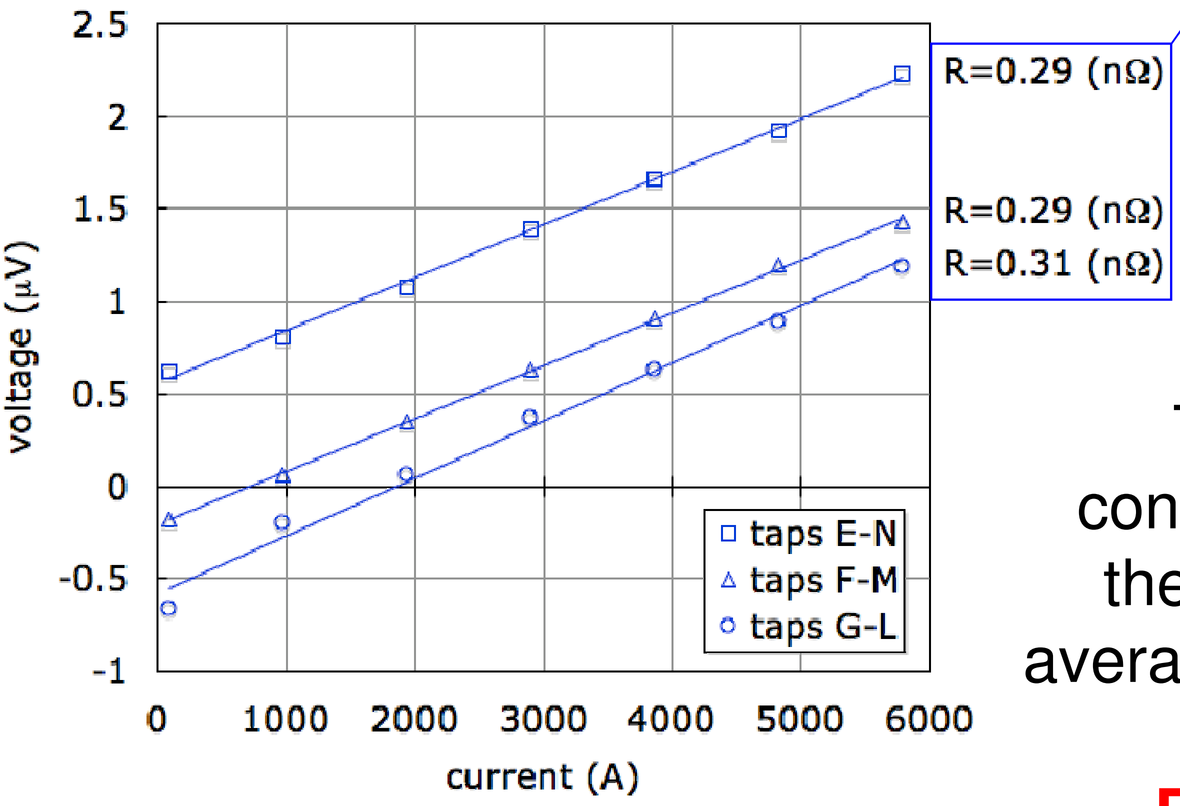
- A background field has been used in FRESCA to
  - Increase the electrical resistivity, and
  - Decrease the thermal conductivity

  thus simulating the effect of a lower RRR in the cable and the bus-bar.
- An applied field of 2 T produces an effect equivalent to RRR ≈ 100 for both cable and bus-bar



Data and analysis by courtesy of W. de Rapper, TE-MSC

Joint resistance



Computed values using 3 voltage taps of different length across the joint

The joint resistance is constant (as expected) in the range of 0-6 kA. The average measured value is

$R_{joint} = 0.29 \pm 0.02\ \mathrm{n}\Omega$

Re-cap on the experience collected building the sample

- Continuity defects in the range of few μΩ **can be clearly identified** by local RT resistance measurements
- A non-stabilized cable **does not** (necessarily) **appear as a bad joint** in operating conditions
- The assumption of a minimum cable RRR of 80 is **pessimistic**, so far we have RRR > 160
- The assumption of a minimum bus-bar profile RRR of 100 is **possibly on the conservative side**, but more work is required to establish a realistic lower bound

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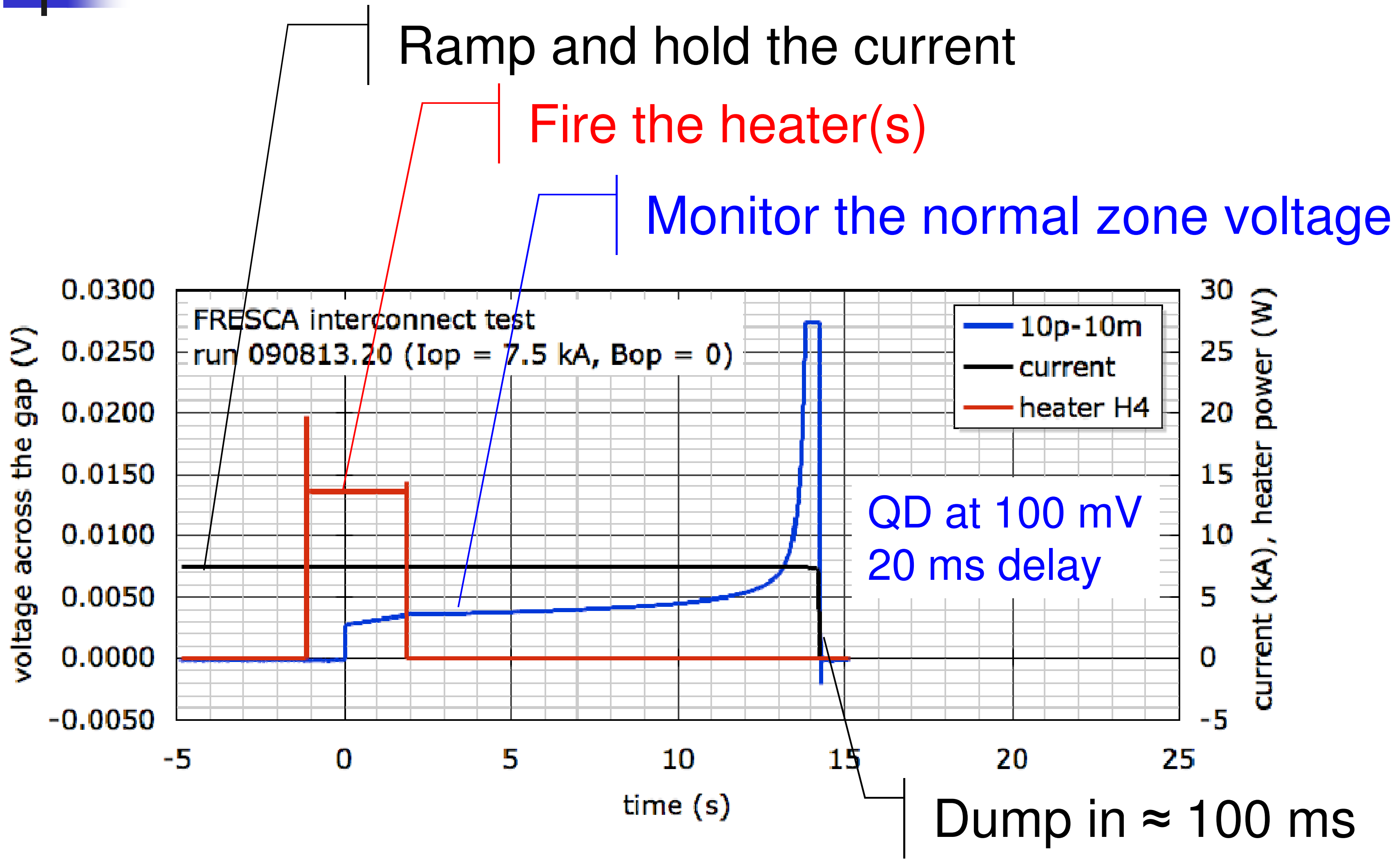
Typical quench test



Ramp and hold the current

Fire the heater(s)

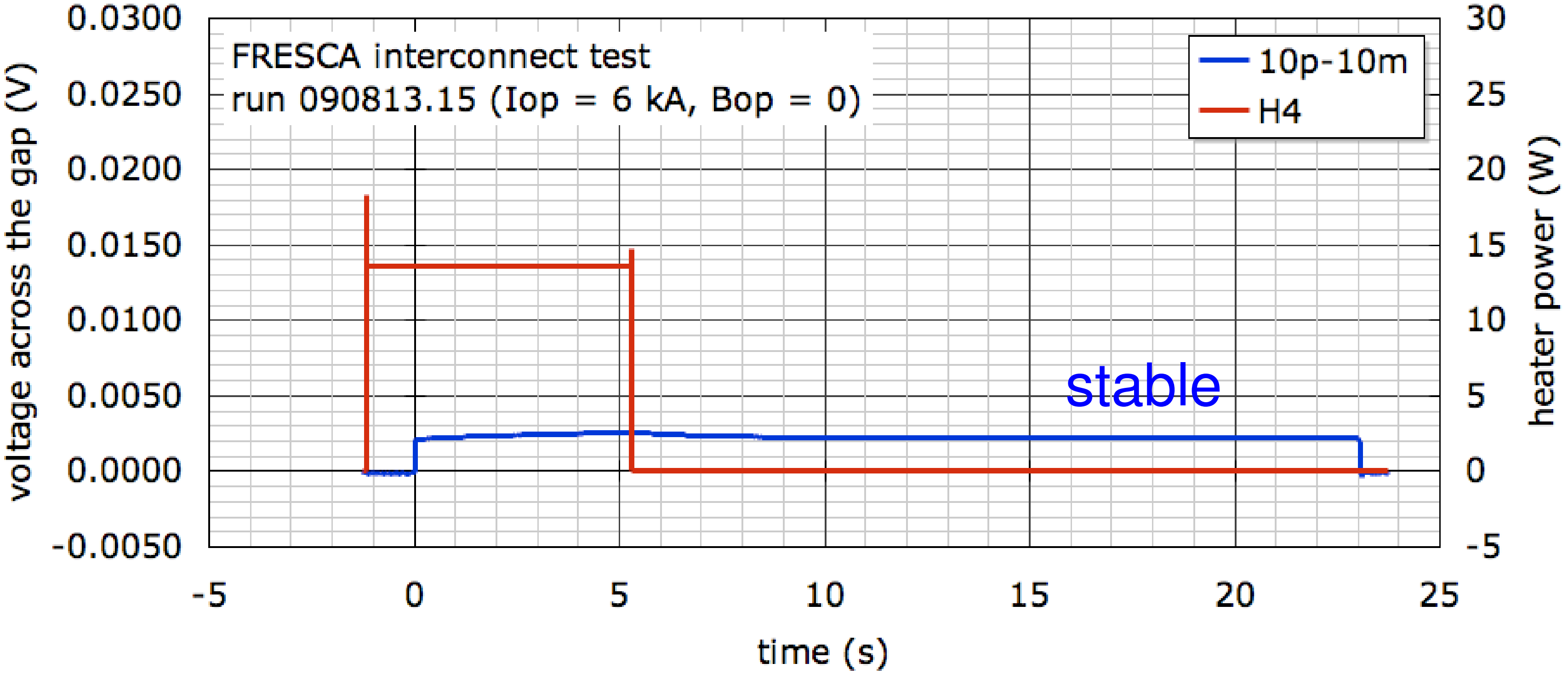
Monitor the normal zone voltage

QD at 100 mV
20 ms delay

Dump in ≈ 100 ms

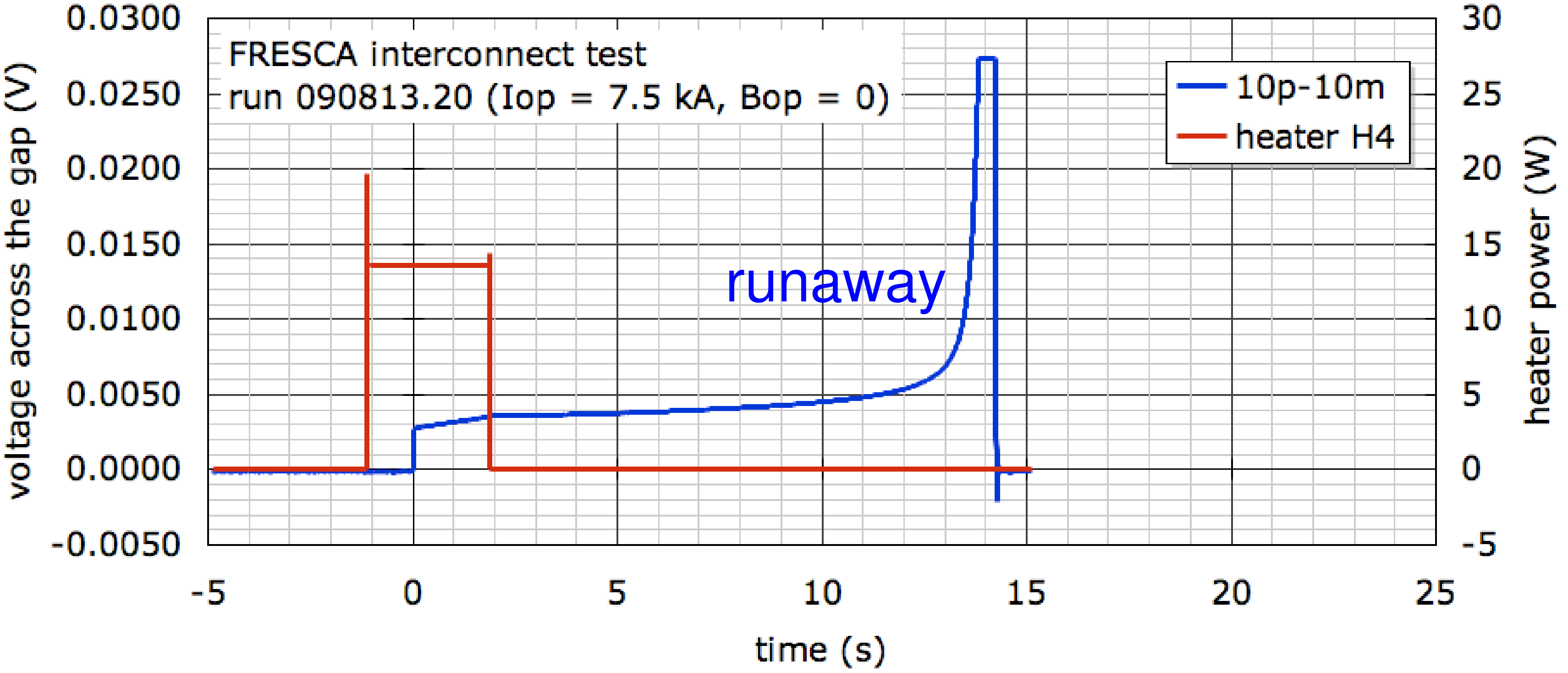
Run 090813.15

Stable quench: a normal zone is established and reaches steady-state conditions at a temperature such that the Joule heat generation is removed by conduction/convection cooling



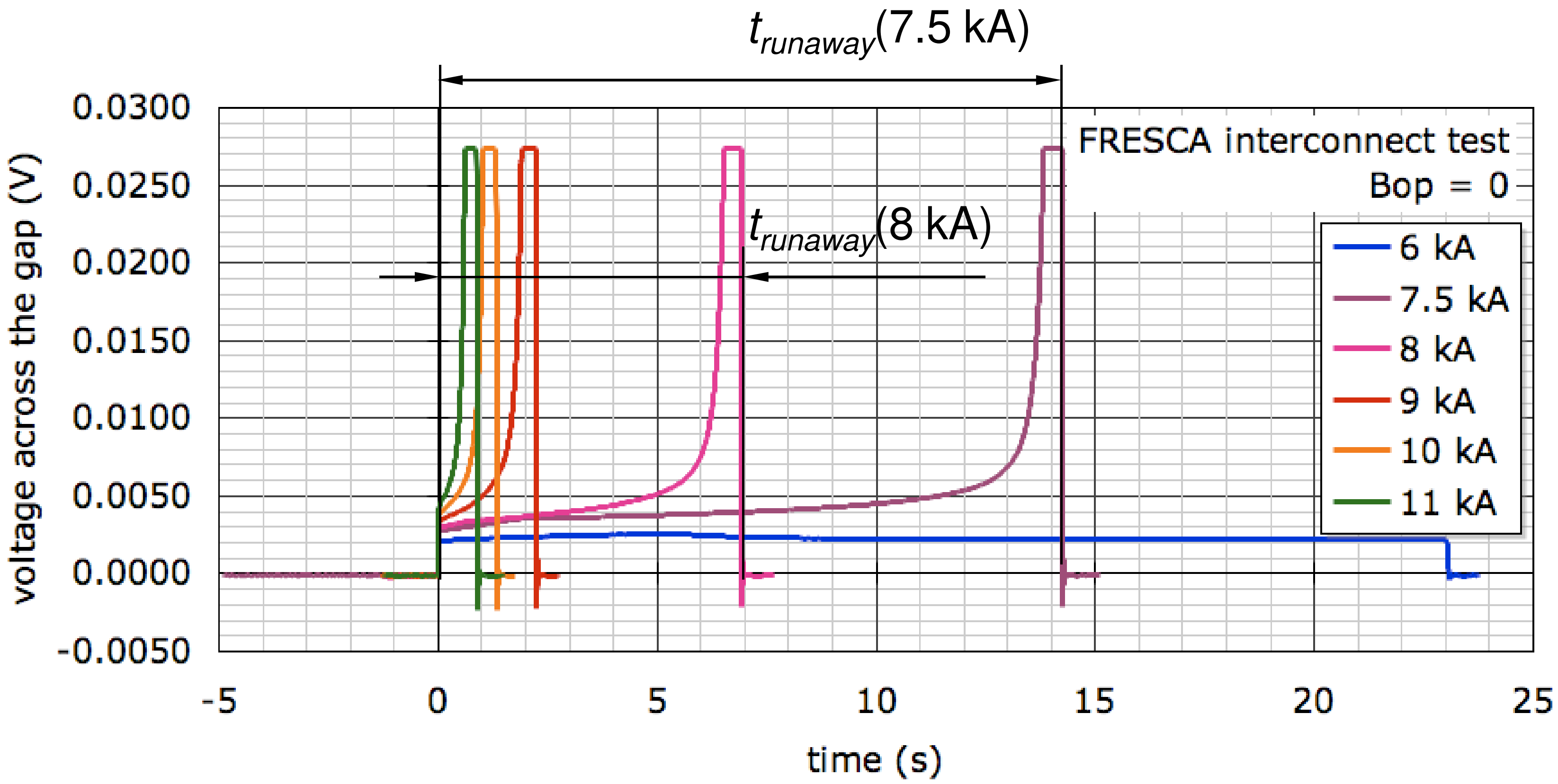
Run 090813.20

Runaway quench: the normal zone reaches a temperature at which the Joule heat generation in the normal zone exceeds the maximum cooling capability leading to a thermal runaway



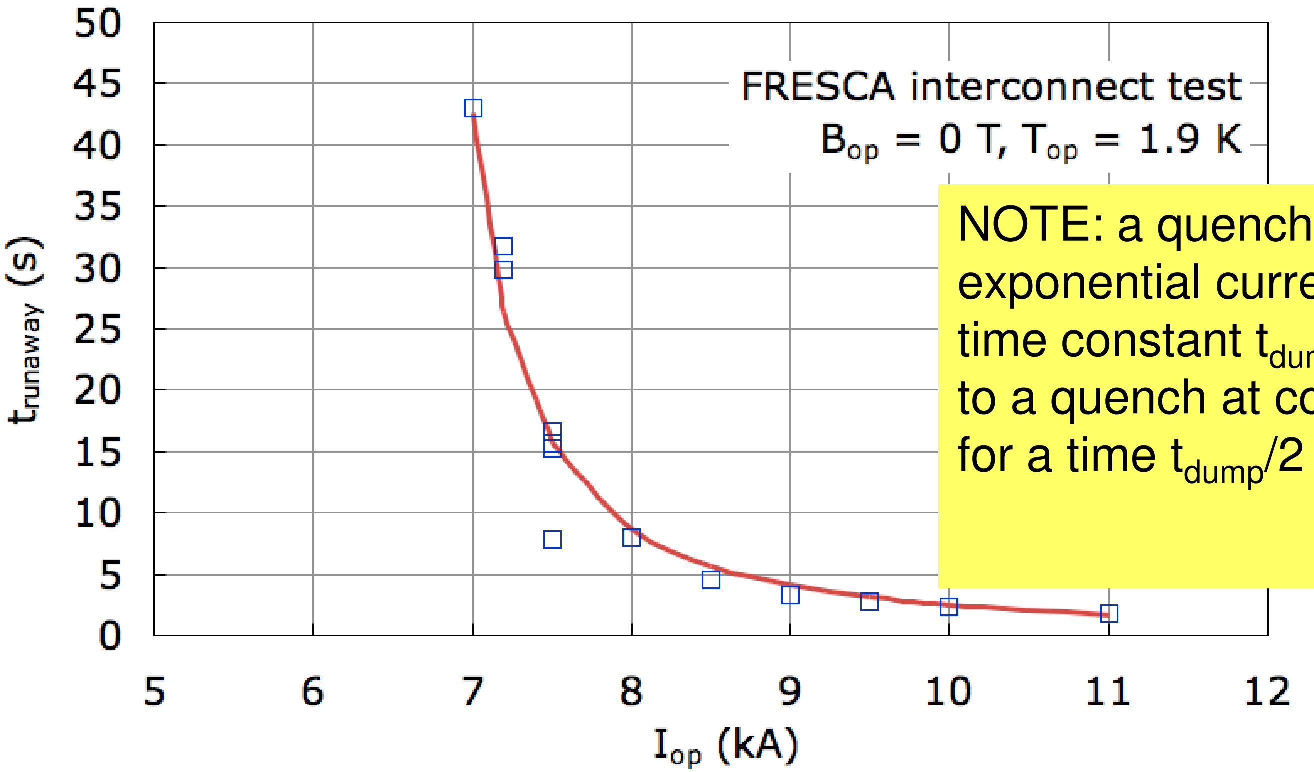
Runs at “0” background field

For identical test conditions, the time necessary to reach the thermal runaway ($t_{runaway}$) depends on the operating current



$t_{runaway}$ vs. I_{op}

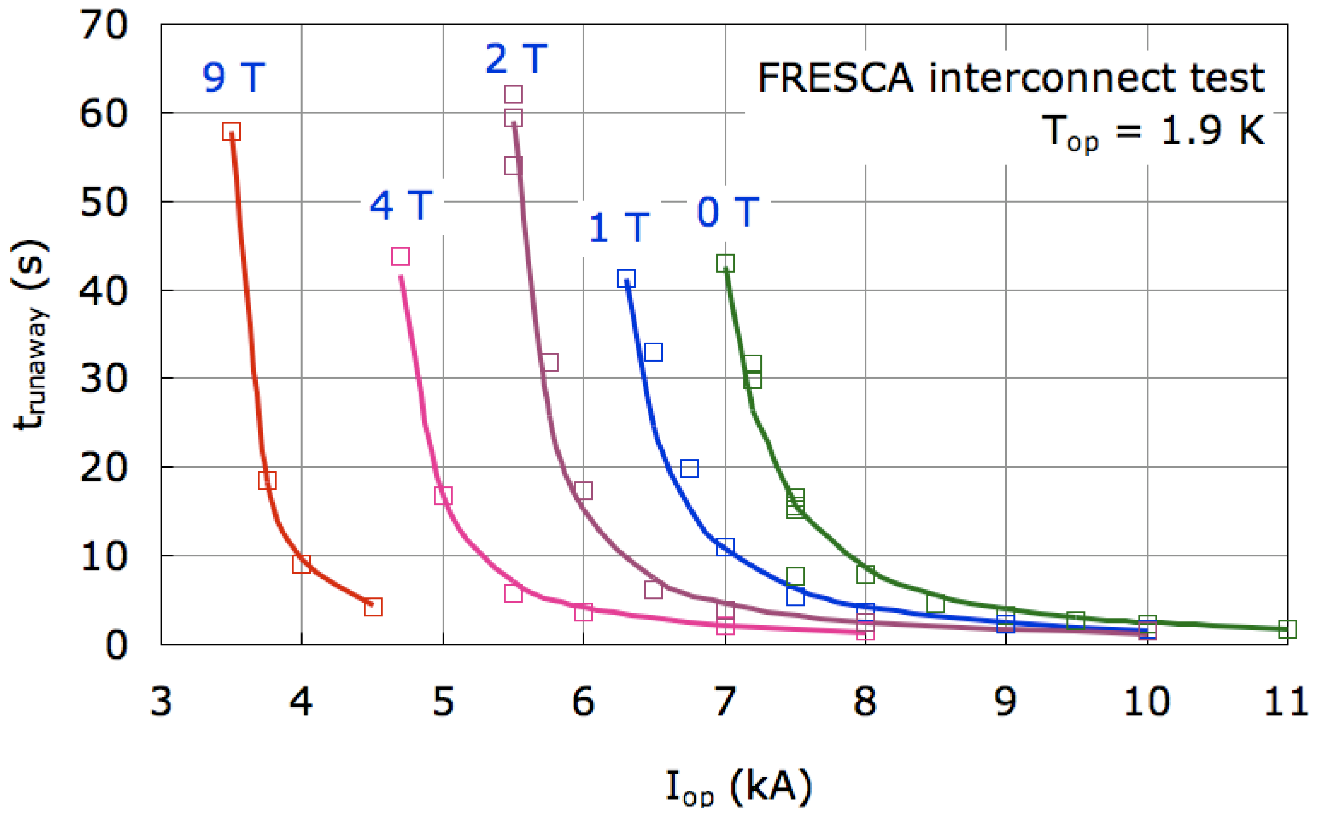
For any given test condition of temperature and background field it is possible to summarise the above results in a plot of runaway time $t_{runaway}$ vs. operating current I_{op}



NOTE: a quench followed by an exponential current dump with time constant t_{dump} is equivalent to a quench at constant current for a time $t_{dump}/2$

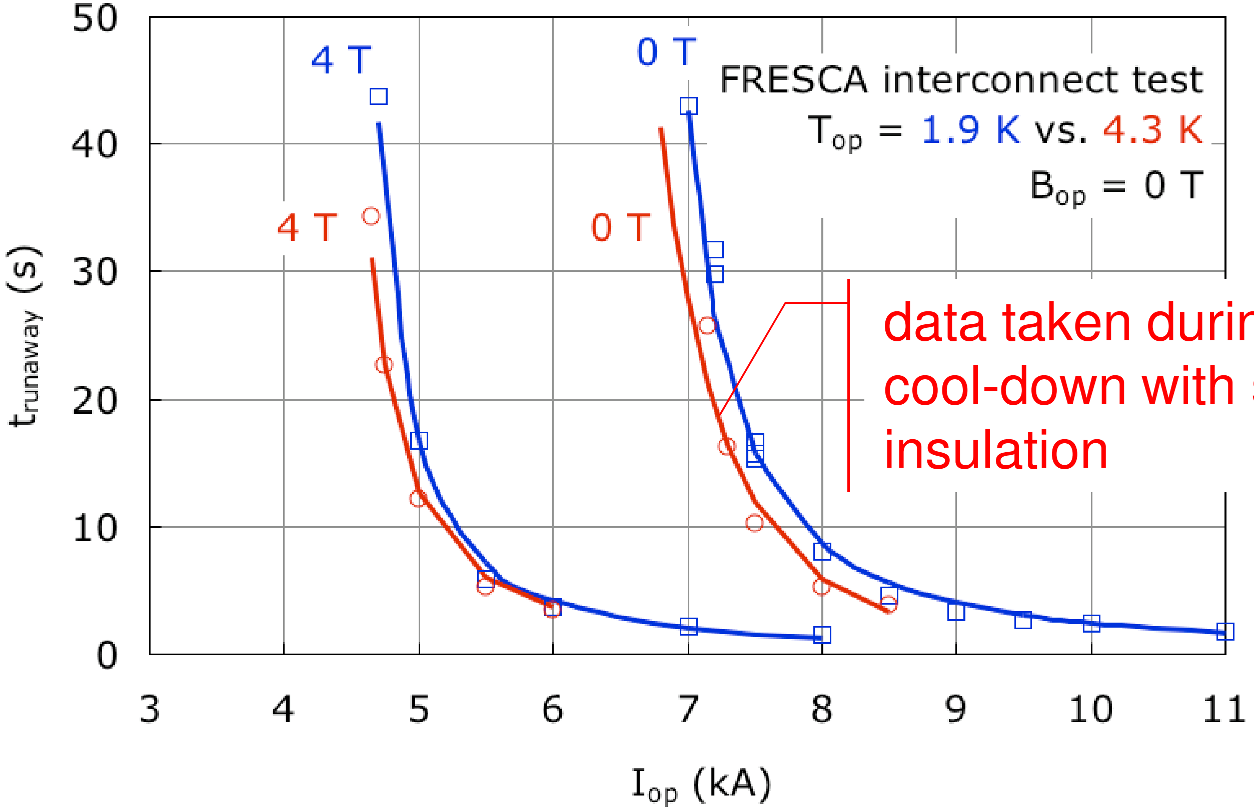
Effect of B_{op} (RRR)

An applied magnetic field induces magnetoresistance and reduces thermal conduction ⇒ the effect is an increased tendency to thermal runaway



Effect of T_{op}

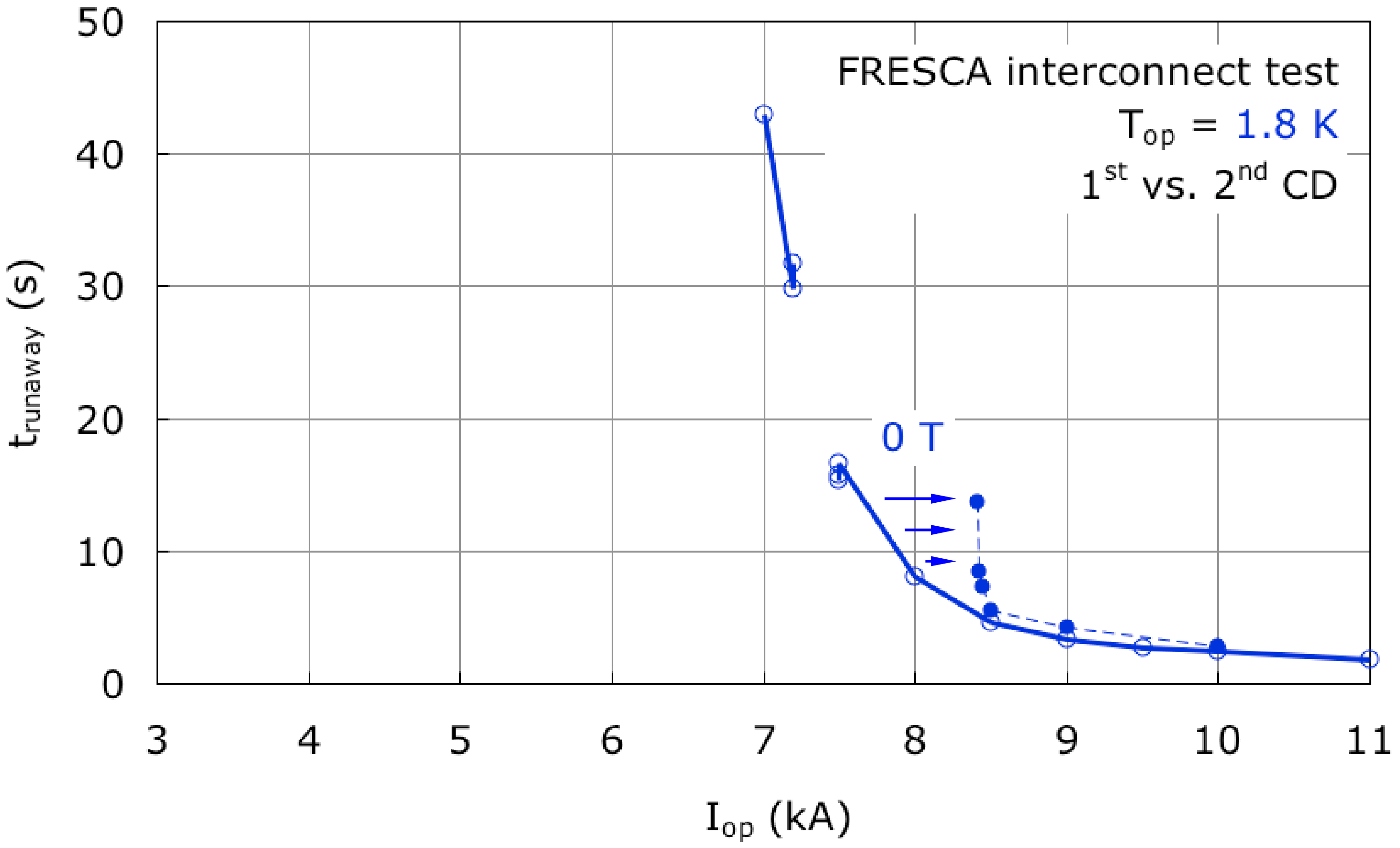
Changing bath conditions (1.9 K vs. 4.3 K) changes the heat transfer, but has no apparent effect on $t_{runaway}$. The behavior of the sample is nearly **adiabatic** for this run



data taken during the 2nd cool-down with sealed insulation

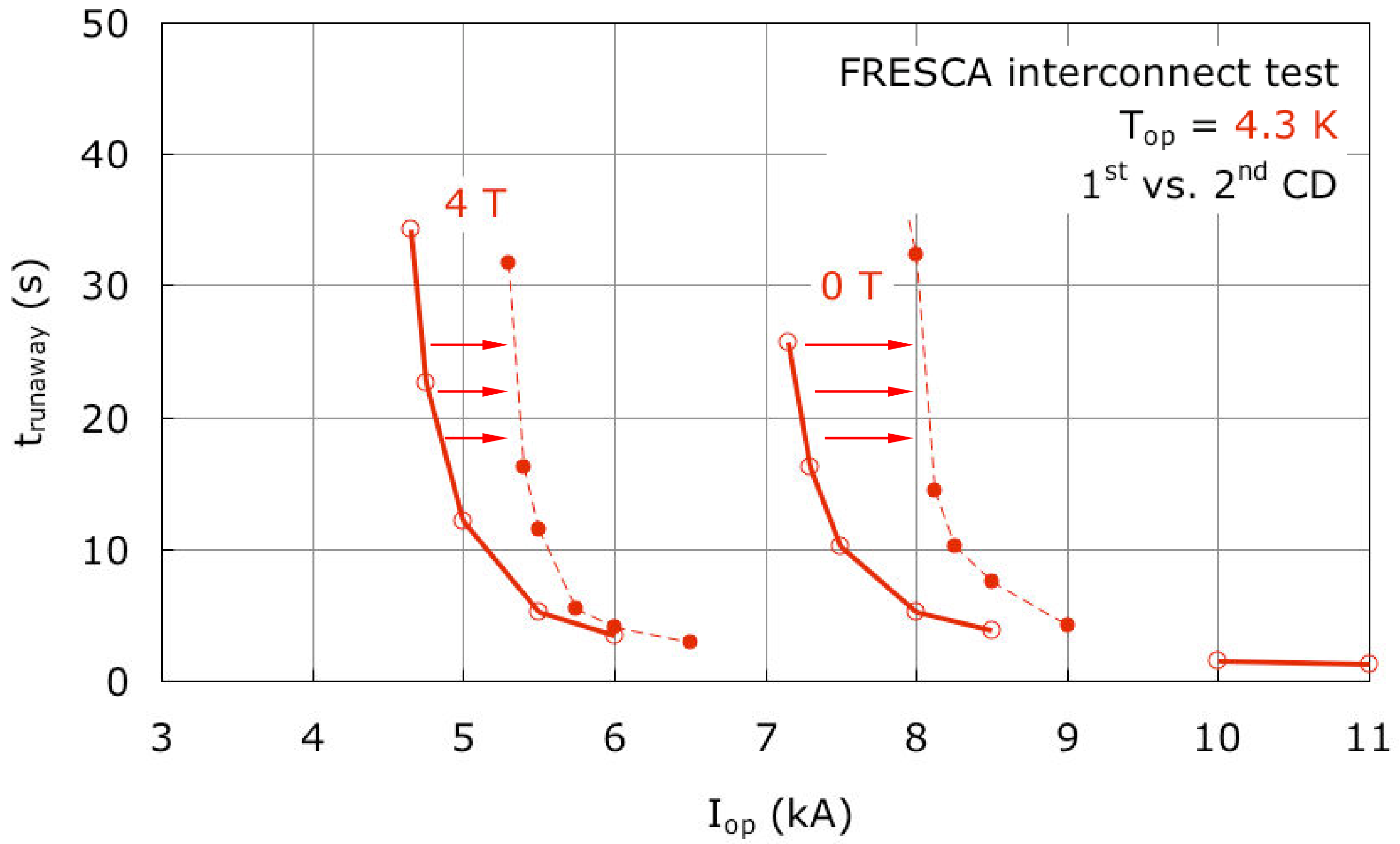
Effect of cooling at 1.8 K

Part of the sealing insulation was opened during the second test run. The behavior of the sample changed considerably



Effect of cooling at 4.3 K

The cooling induced by the partially opened insulation had a strong effect also at 4.3 K, resulting in steeper runaways



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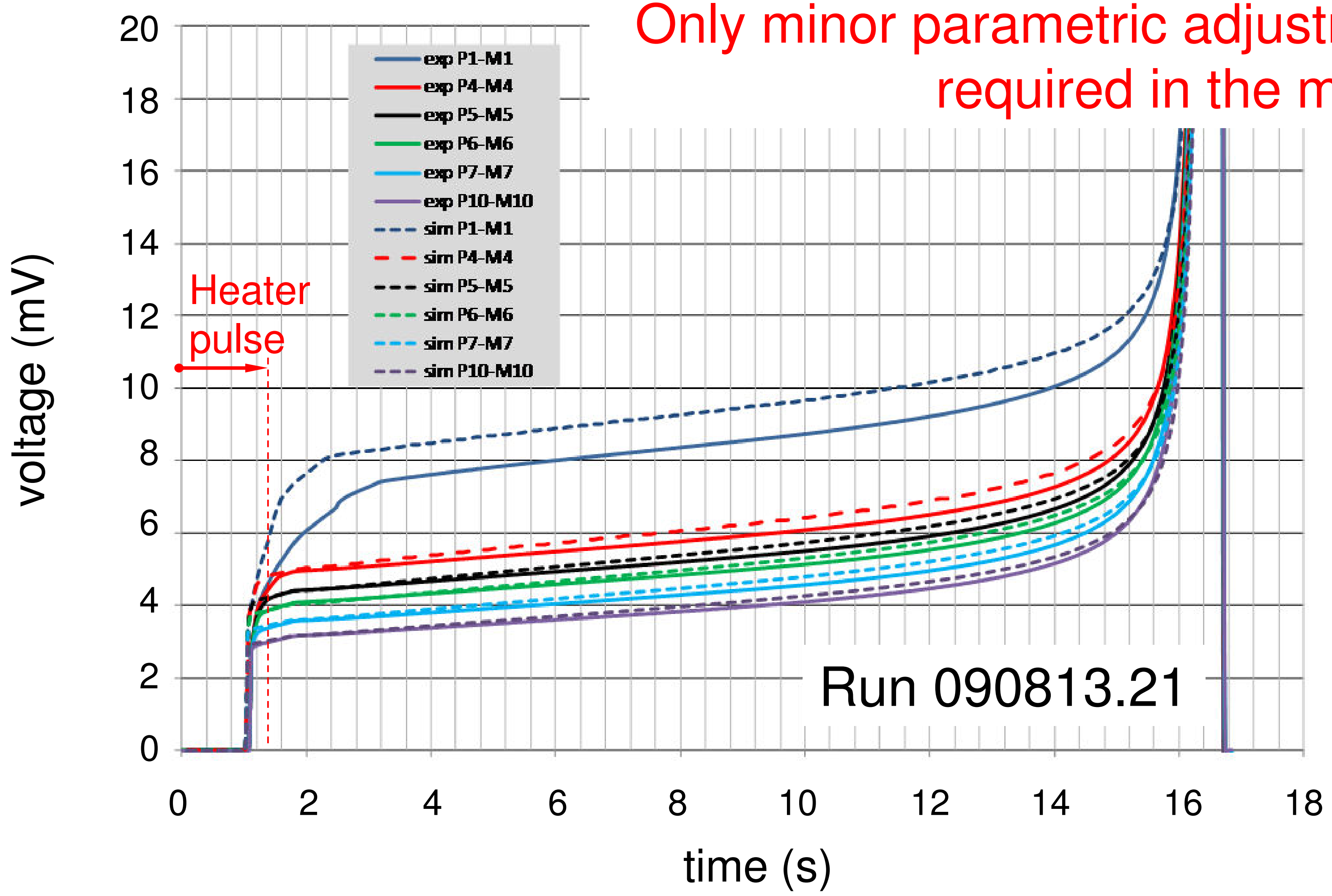
Model

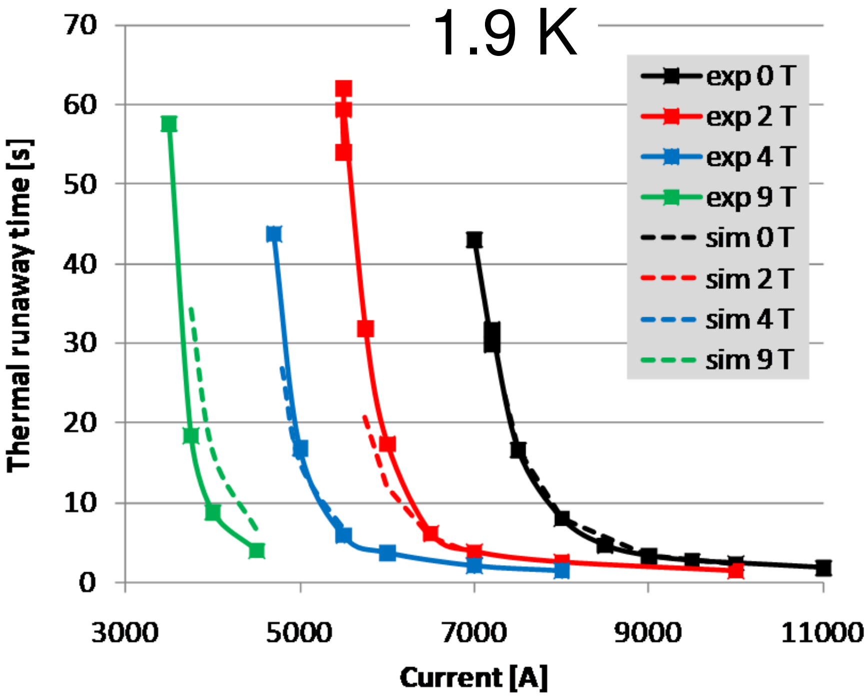
- Model developed by A. Verweij, first analyses presented at Chamonix-2009:
  - A. Verweij, *Busbar and Joints Stability and Protection*, Proceedings of Chamonix 2009 workshop on LHC Performance, 113-119, 2009
- 1-D heat conduction with:
  - Variable material cross section to model the local lack of stabilizer
  - Temperature dependent material properties
  - Heat transfer to a constant temperature He bath through temperature dependent heat transfer coefficient
- Various adjustments and cross-checks performed against other models (1-D and 3-D)

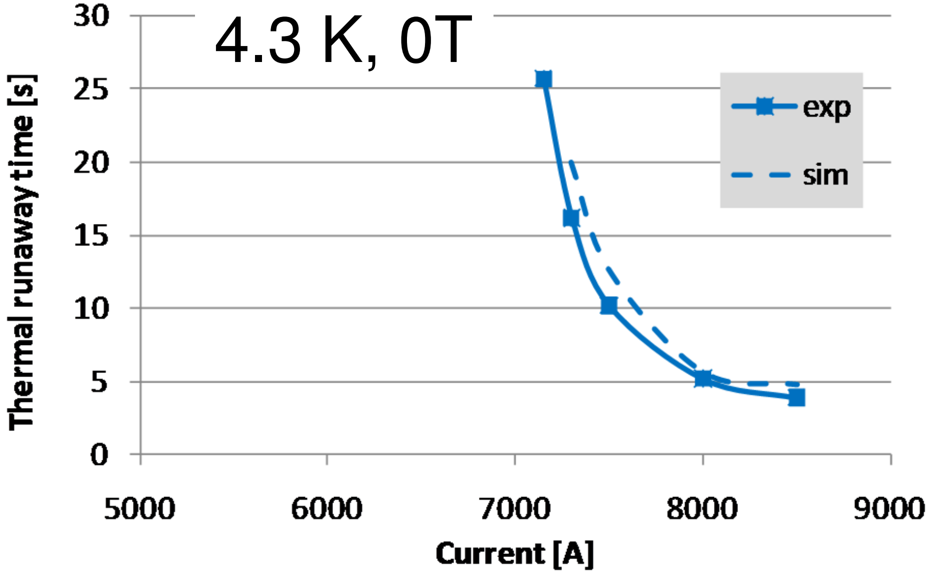
Simulation of voltage traces



Only minor parametric adjustments required in the model !

Simulation of $t_{runaway}$ vs. I_{op}





Good agreement over the complete data-set of experimental results, gives good confidence on the capability to predict *safe operating conditions* for a given defect size

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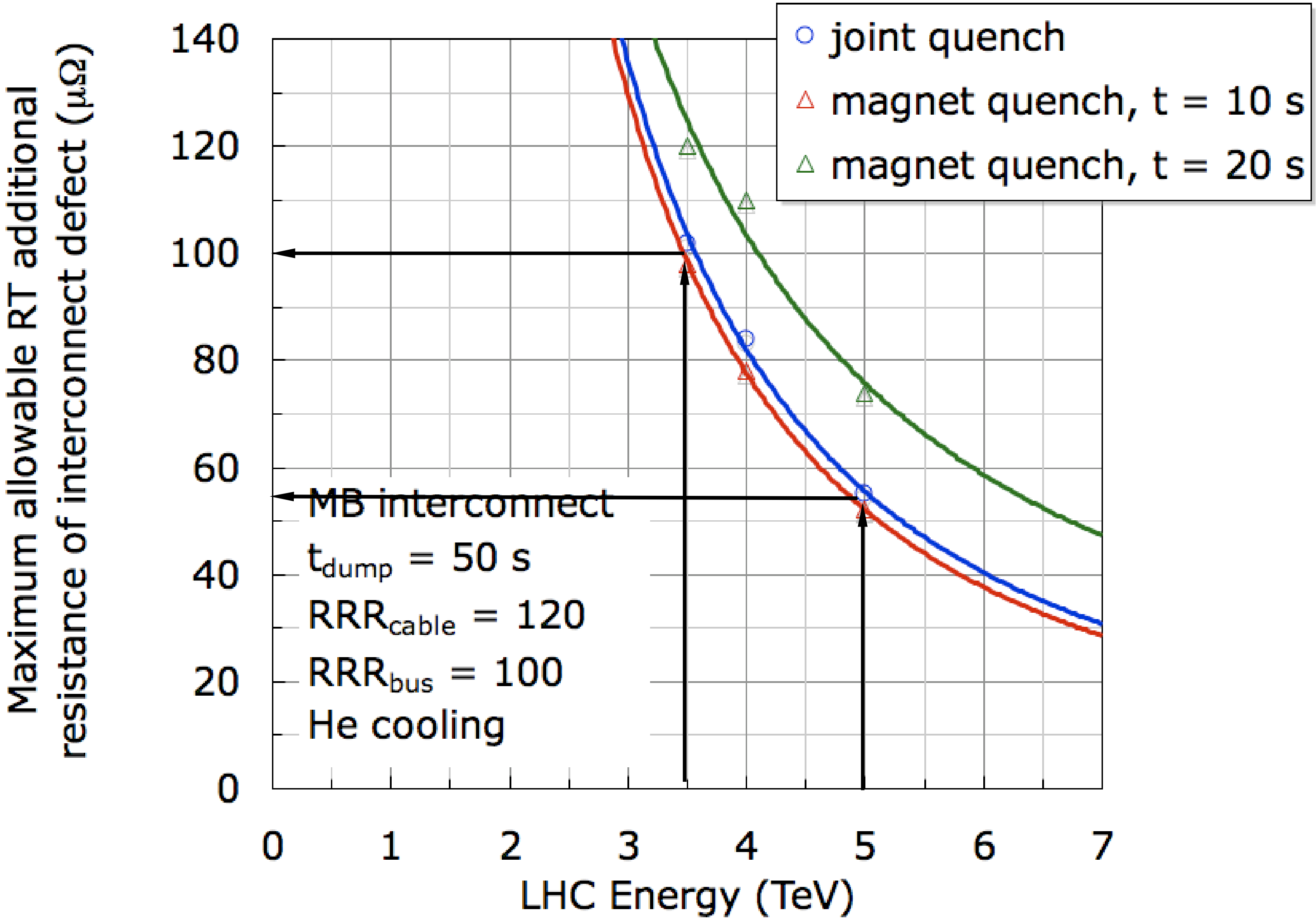
Cases analyzed

- Joint quench from normal operating conditions, at an initial temperature of 1.9 K, followed by (fast) quench detection and dump with the time constant of the relative circuit
- Induced quench, at a time 10…20 s after quench initiation in a neighboring magnet, during current dump with the time constant of the relative circuit, at an initial temperature above 10 K

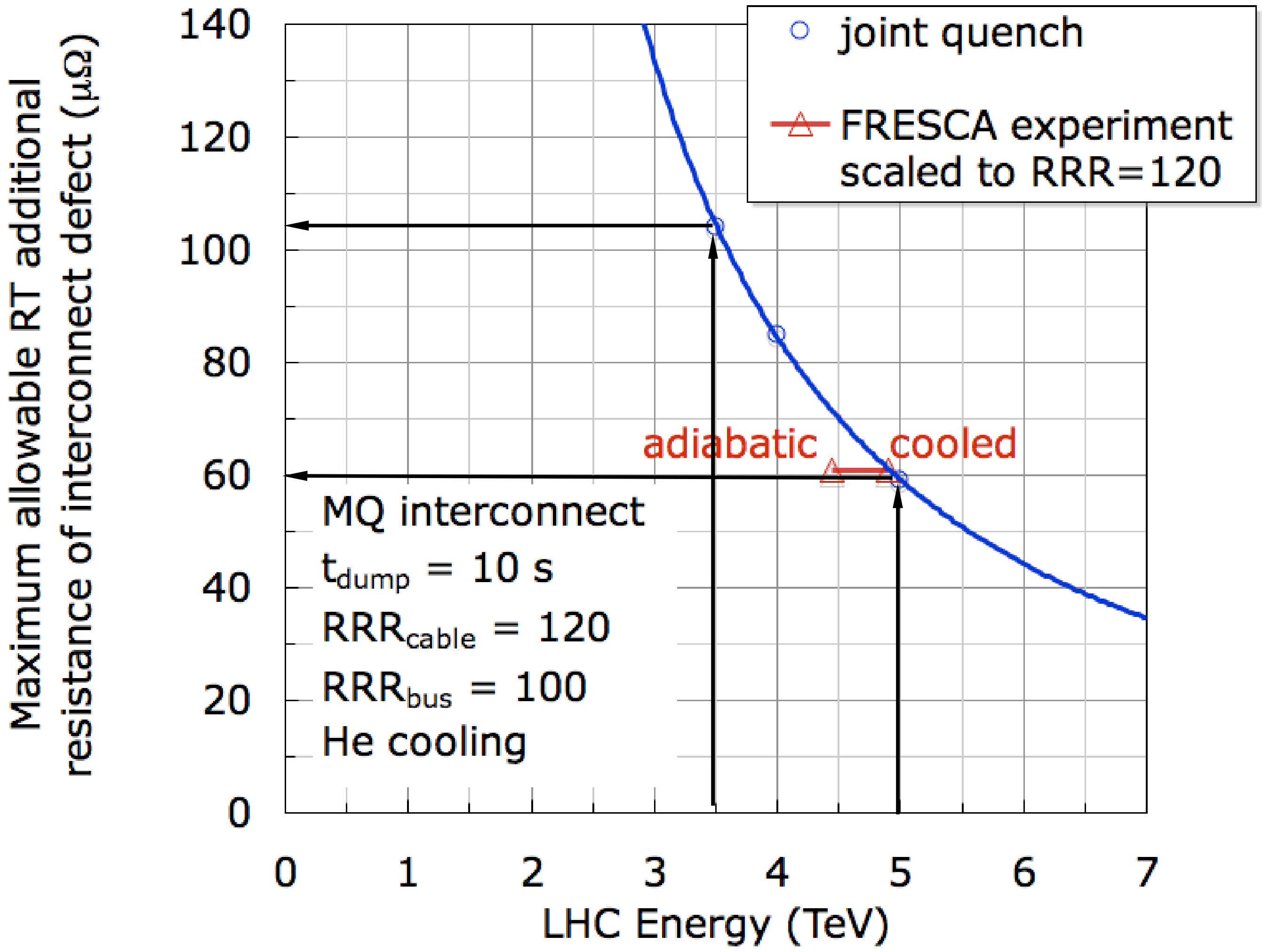
Caveats

- The RRR plays a very important role in the balance of heat generation vs. heat removal. Predictions are made on the *conservative side* (RRR_{cable} = 120, RRR_{bus} = 100)
- Local heat transfer conditions in the interconnect are difficult to measure/model
- The defect tested is *clean* and located *on one side* of the joint, which may not be the most common situation in the machine (see later)
- The energy deposition for a quench initiated in a magnet and propagating to an interconnect depends on the propagation time, during which the current is being dumped

Predictions - MB interconnect



Predictions - MQ interconnect



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Conclusions - 1/3

- We have a good grip on the mechanism of non-protected quenches in MB and MQ interconnect defects
  - Dependence of thermal runaway conditions on the defect characteristics and size
  - Experimental validation in controlled conditions
  - Relation of RT resistance to defect size
- Main parameters affecting the runaway conditions have been identified (cable/bus RRR, He cooling, quench propagation time). Work is in progress to reduce uncertainties, but defect detection in the LHC remains an issue

Conclusions - 2/3

- The experimental activity devoted at modeling an interconnect defect has been very useful, and we plan further tests (3 samples by end 2009)
  - Geometric configuration modified to mock-up tunnel interconnect conditions, including heat transfer
  - Samples for:
    - Maximum measured defect in MQ interconnect ($R_{excess} \approx 45\ \mu\Omega$)
    - Maximum expected defect in the LHC ($R_{excess} \approx 2 \times 45\ \mu\Omega$)
    - Most relevant interconnect for operation 5…7 TeV, e.g. largest leftover after an acceptable repair campaign ($R_{excess} \approx 15\ \mu\Omega$)
    - Tunnel scrap material ($RRR_{bus} \approx 100$) and special Cu profiles for $RRR_{bus} \approx 100$

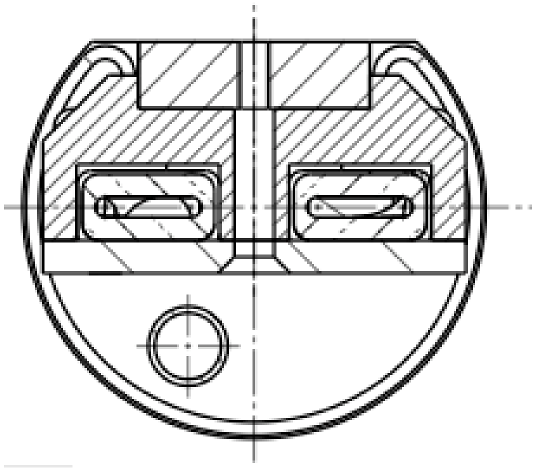
Conclusions - 3/3

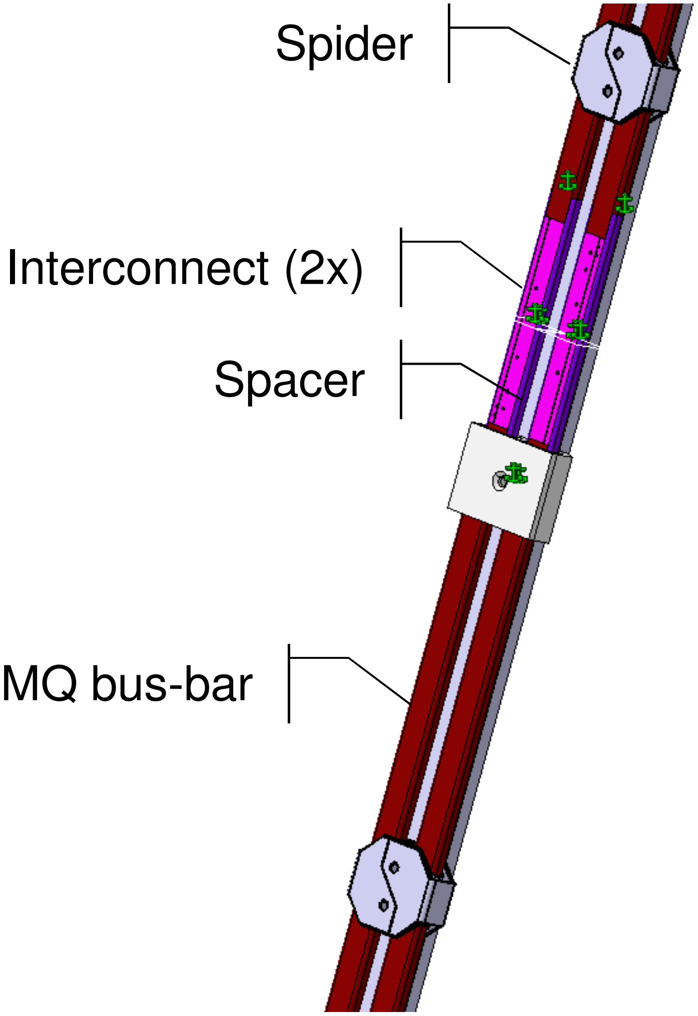
- Both simulations and experiment indicate that operation at 3.5 TeV should be safe, even with the present (rather pessimistic) assumptions of:
  - Maximum expected defect in a faulty interconnect (double defect of 45+45 μΩ localized in one joint)
  - Minimum expected cable and bus RRR, in the range of 100
- We may be able to relax this constraint, once:
  - The diagnostic/statistics of defects is improved
  - We advance with the review of the material RRR
  - We collect more data from short samples in heat transfer configuration close to tunnel conditions

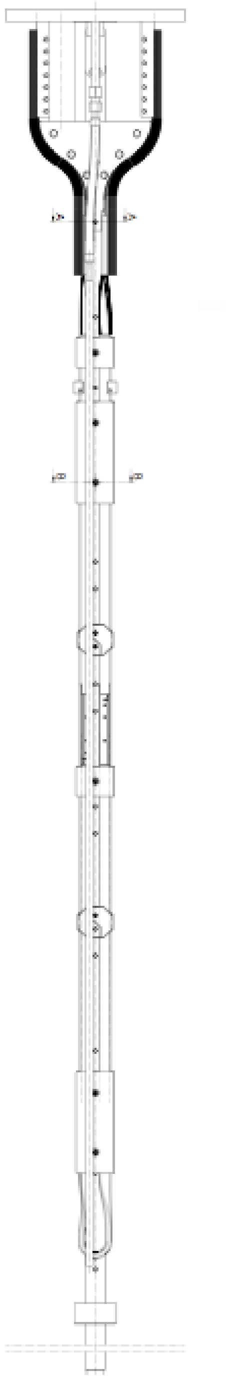
Additional material

Detailed design by Th. Renaglia, EN-MME

Updated sample design



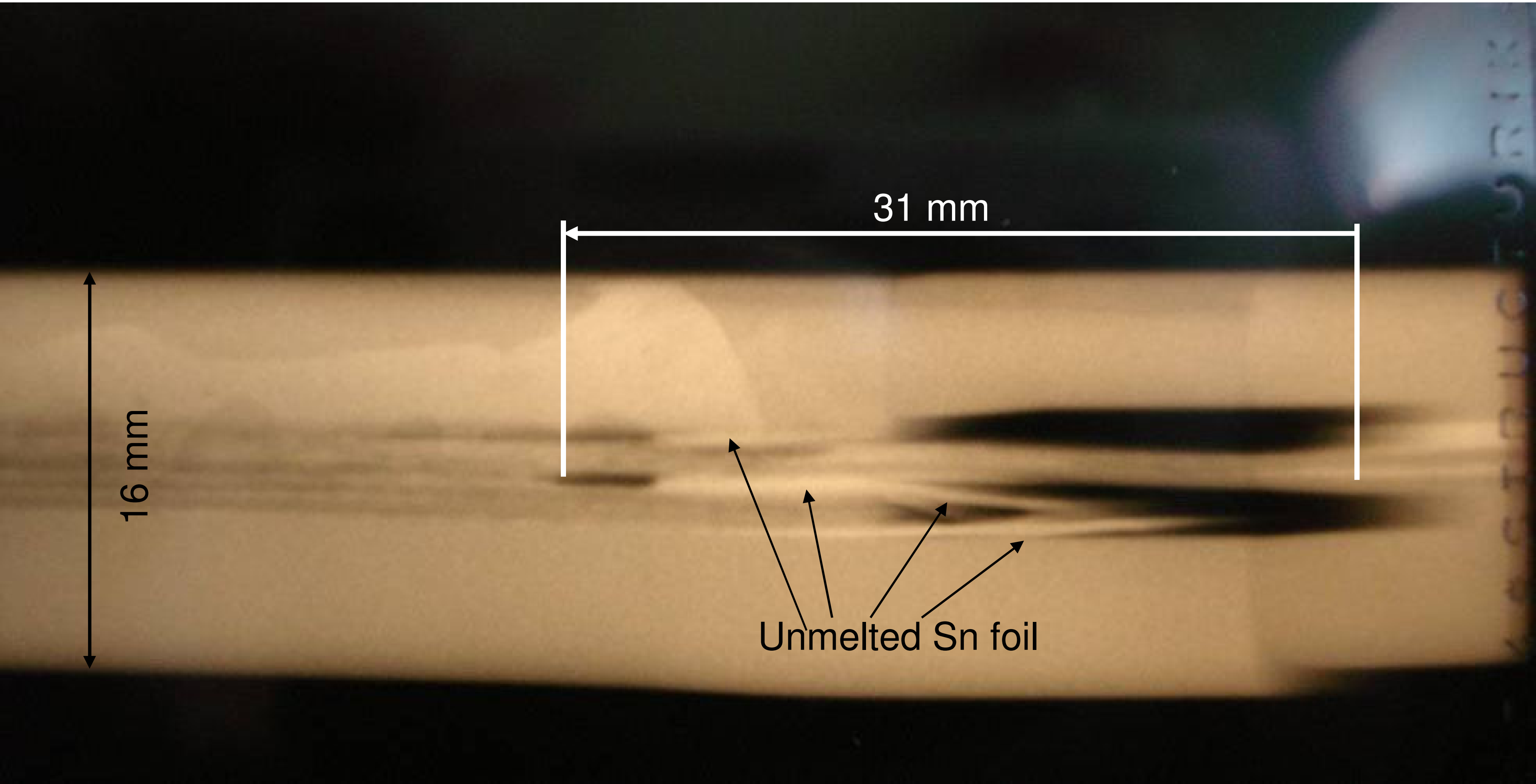




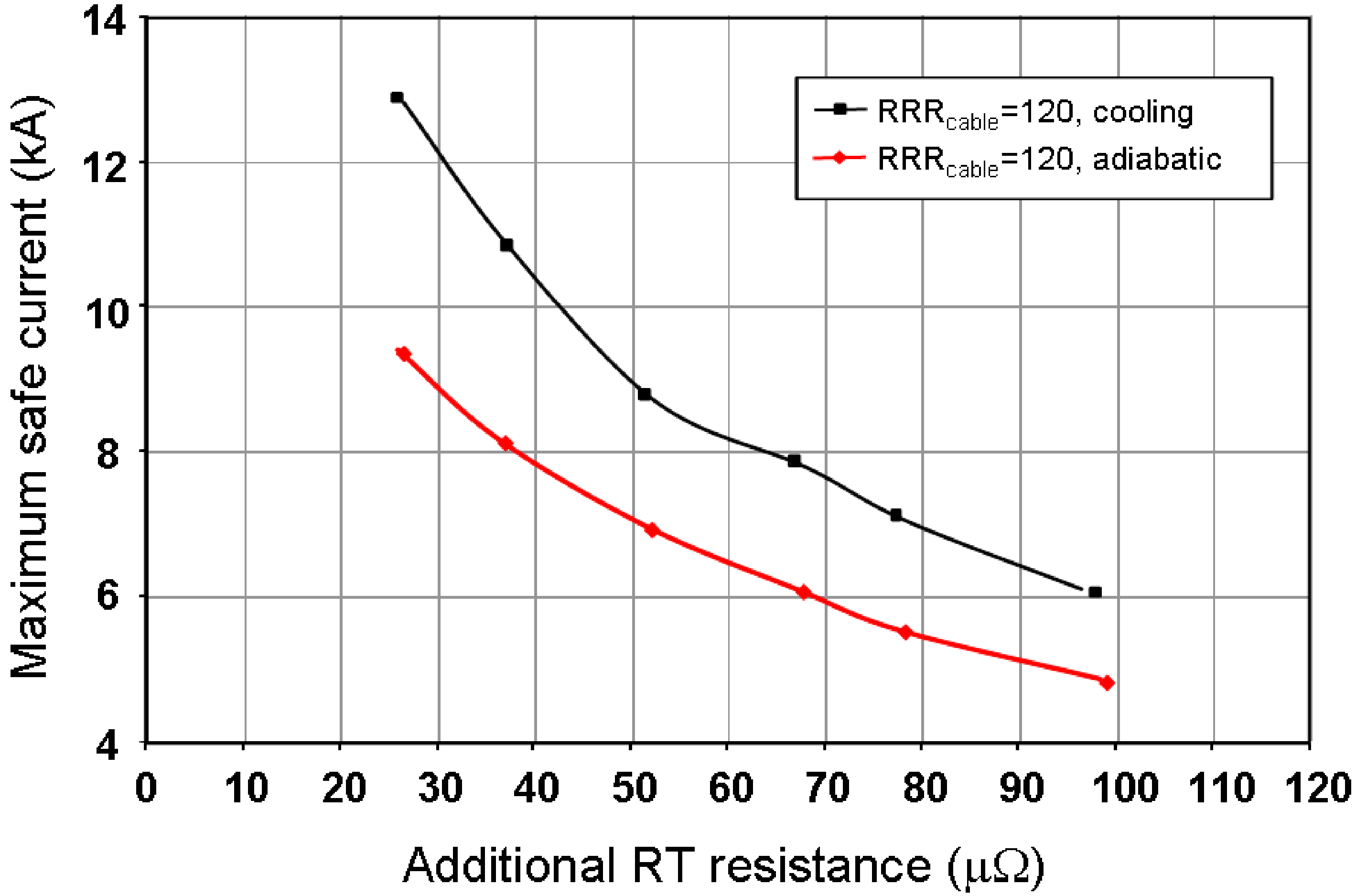
Courtesy of C. Scheuerlein, TE-MSC

Defect in the interconnect

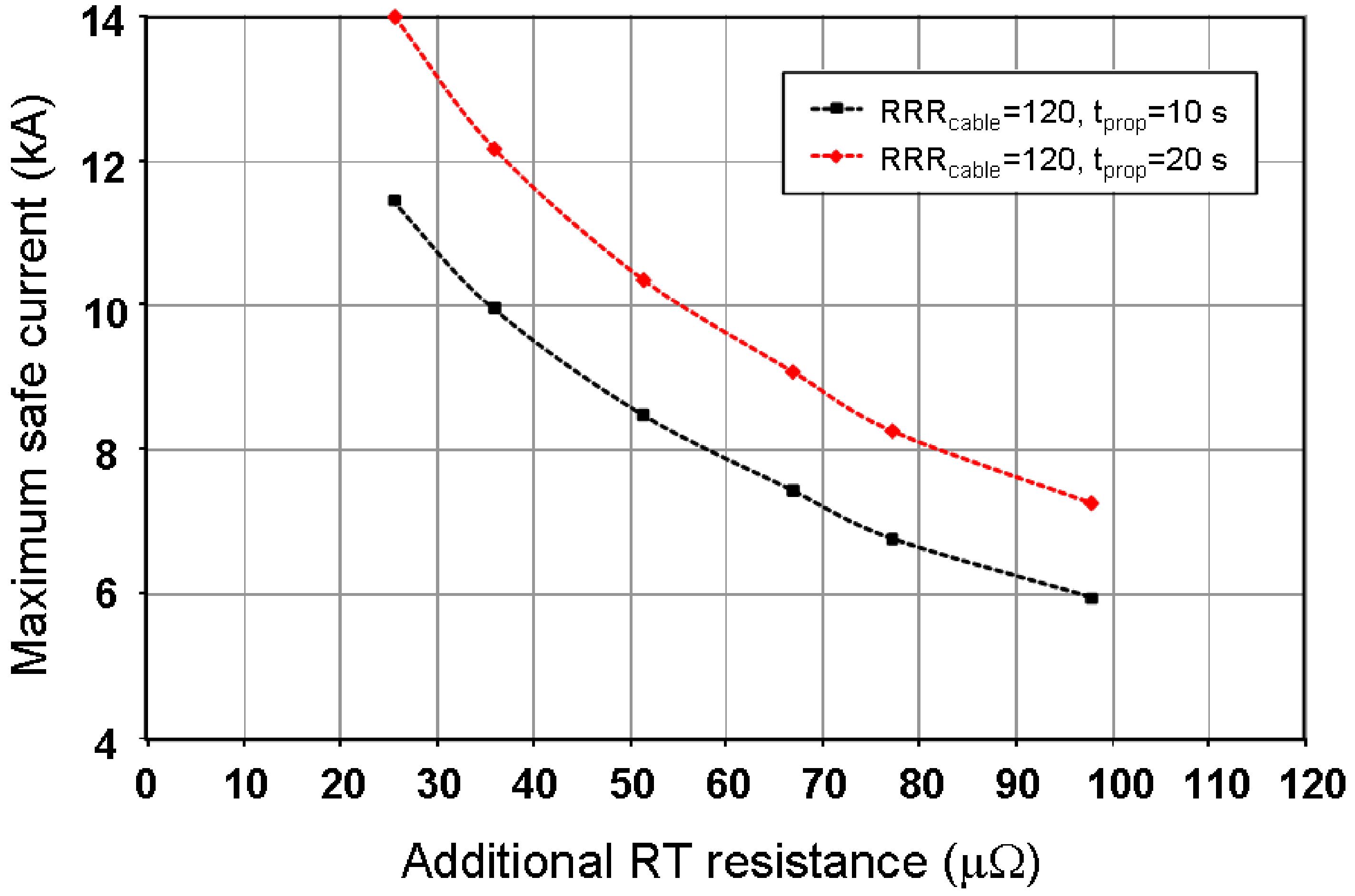
QBBI.A25L4-M3-cryoline-lyra side (+30 μΩ)



Predicted RB *safe current* for joint quench



Predicted RB *safe current* for induced quench



Maximum allowable additional resistance for RB circuit with $t_{dump} = 50$ s

Case	3.5 TeV	4 TeV	5 TeV
LHe (case 1), RRR_{cable}=80, no He cooling	55	42	27
LHe (case 1), RRR_{cable}=120, no He cooling	70	55	33
LHe (case 1), RRR_{cable}=80, with He cooling	78	65	45
LHe (case 1), RRR_{cable}=120, with He cooling	102	84	55
GHe (case 2), RRR_{cable}=80, t_{prop}=10 s	75	62	(40)
GHe (case 2), RRR_{cable}=80, t_{prop}=20 s	103	85	(60)
GHe (case 2), RRR_{cable}=120, t_{prop}=10 s	98	78	(52)
GHe (case 2), RRR_{cable}=120, t_{prop}=20 s	120	110	(74)

tau=100 s	7 TeV
LHe (case 1), RRR_{cable}=120, with He cooling	26

For info

Maximum allowable additional resistance for RQ circuit with t_{dump} = 10 s

Case	3.5 TeV	4 TeV	5 TeV
LHe (case 1), RRR_{cable}=80, no He cooling	68	54	36
LHe (case 1), RRR_{cable}=120, no He cooling	94	73	48
LHe (case 1), RRR_{cable}=80, with He cooling	80	65	46
LHe (case 1), RRR_{cable}=120, with He cooling	104	85	59
GHe (case 2), RRR_{cable}=80, t_{prop}=10 s	>200	(>200)	(>200)
GHe (case 2), RRR_{cable}=80, t_{prop}=20 s	>200	(>200)	(>200)
GHe (case 2), RRR_{cable}=120, t_{prop}=10 s	>200	(>200)	(>200)
GHe (case 2), RRR_{cable}=120, t_{prop}=20 s	>200	(>200)	(>200)