Bus bar joints stability and protection

- joint stability
- what was wrong with the ‘old’ bus-bar protection?
- the incident
- required threshold for QPS upgrade

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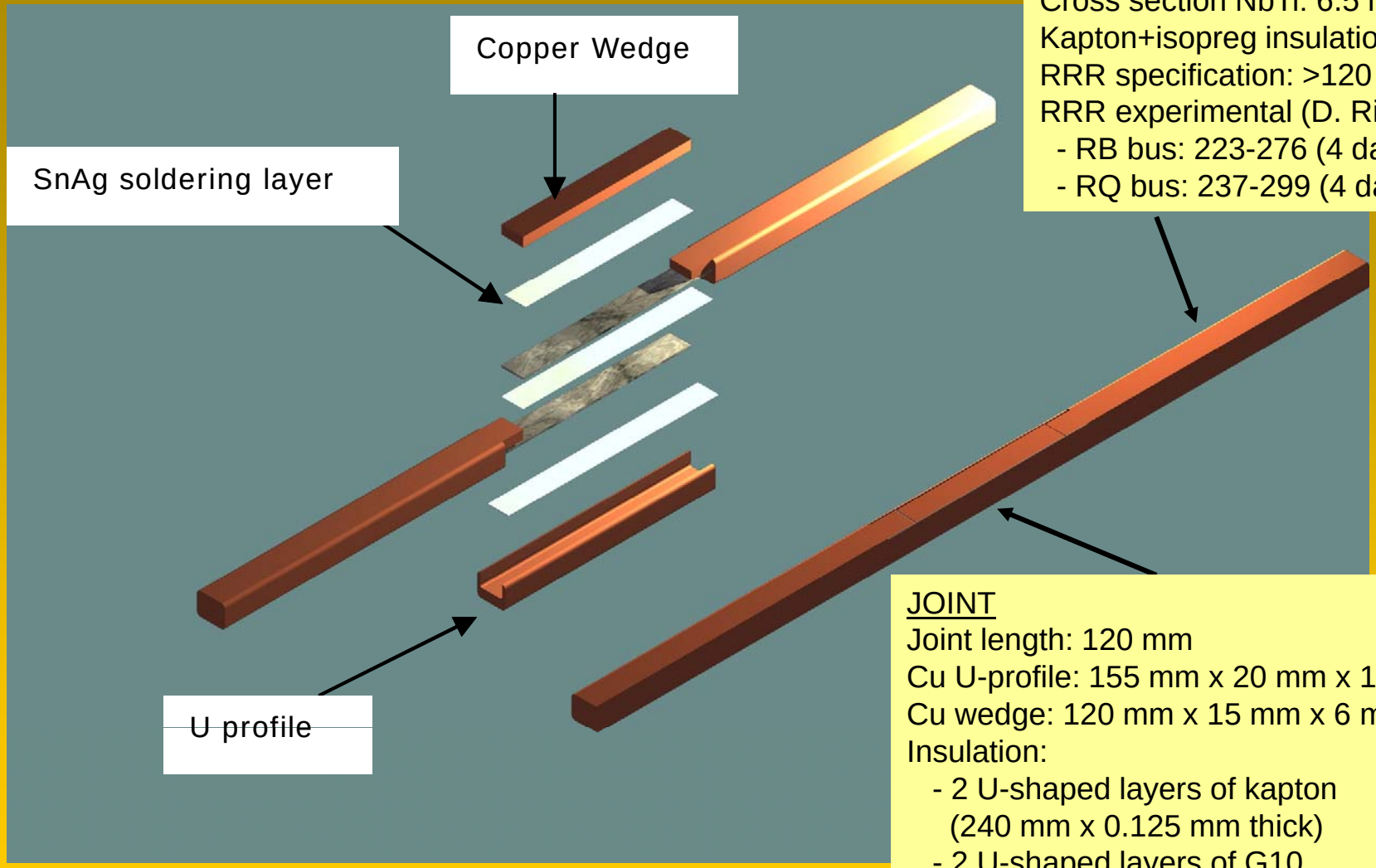
RB bus and joint



BUS
Cross-section Cu: 282 mm^2
Cross section NbTi: 6.5 mm^2
Kapton+isopreg insulation
RRR specification: >120
RRR experimental (D. Richter)
- RB bus: 223-276 (4 data)
- RQ bus: 237-299 (4 data)

JOINT
Joint length: 120 mm
Cu U-profile: 155 mm x 20 mm x 16 mm
Cu wedge: 120 mm x 15 mm x 6 mm
Insulation:
- 2 U-shaped layers of kapton (240 mm x 0.125 mm thick)
- 2 U-shaped layers of G10 (190 mm x 1 mm)

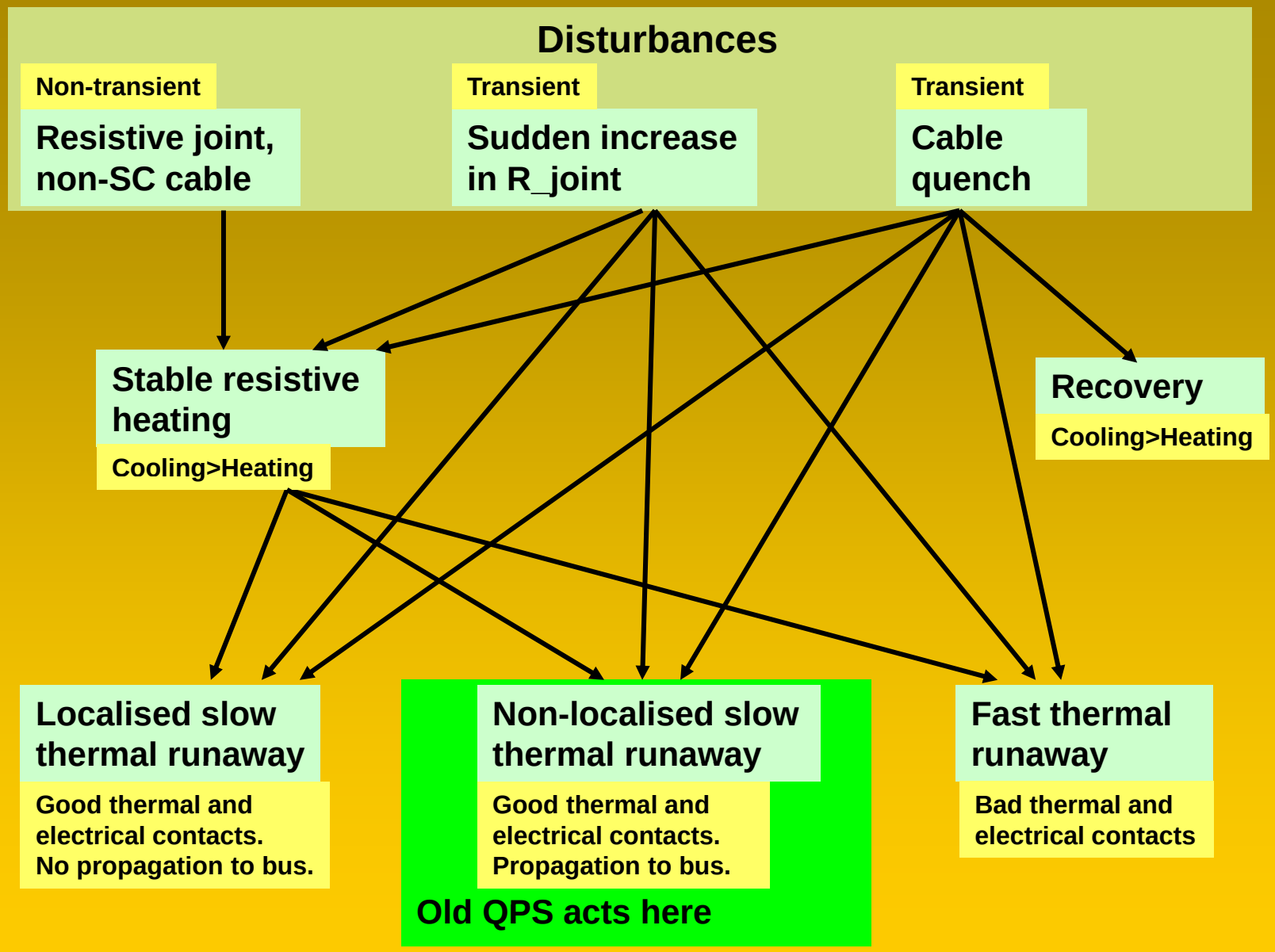
A good joint

Characteristics of a good joint

- Both cables are superconducting
- Good electrical contact between both cables
- Good transverse thermal (and electrical) contact between cables and stabilising copper (U-profile and wedge)
- Good longitudinal electrical (and thermal) contact between bus and stabilising copper
- Good mechanical properties

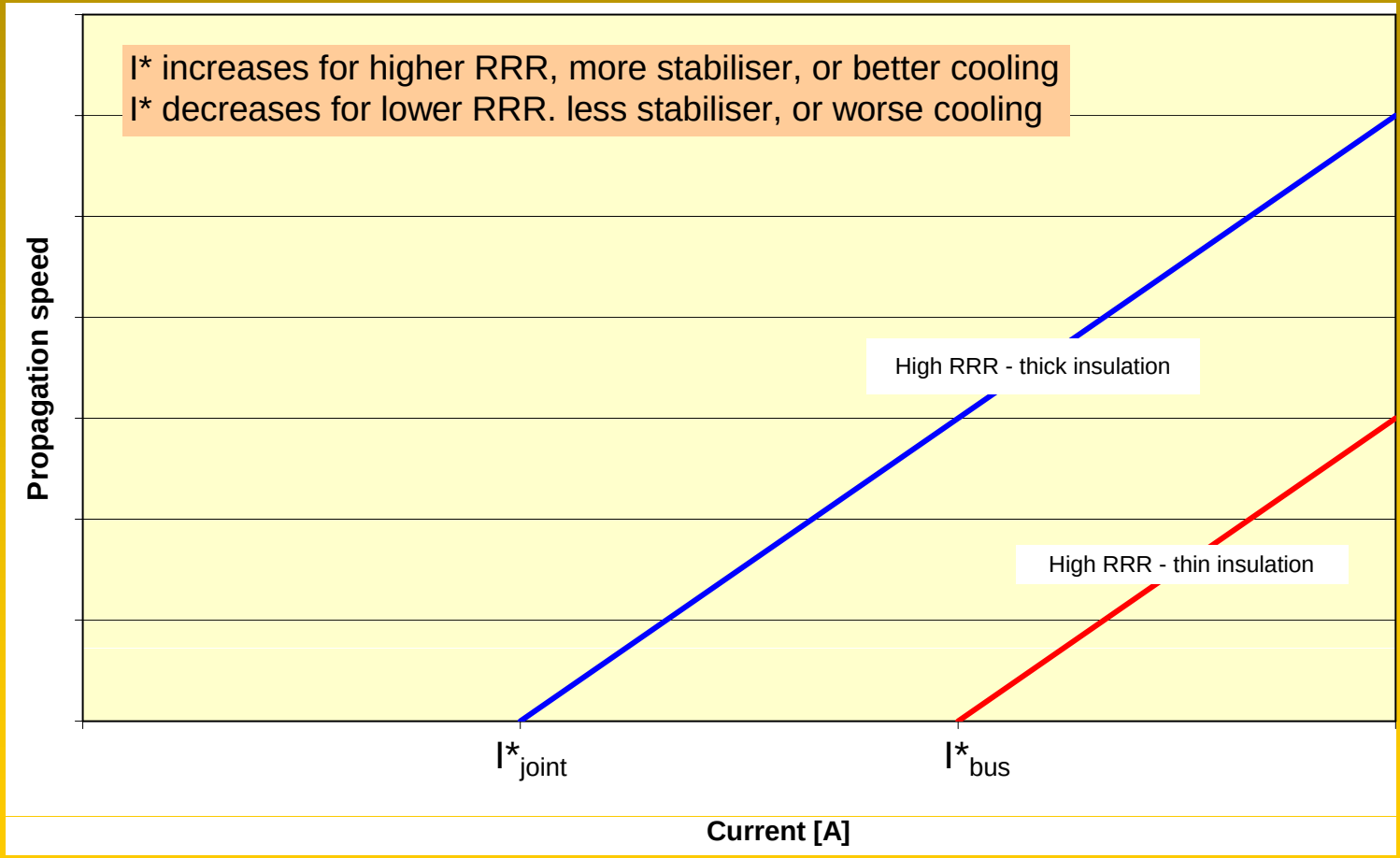
As long as the cables remain superconducting, the role of the stabilising copper is purely mechanic.

However, as soon as a SC-to-normal transition occurs, bad electrical and/or thermal contacts between cable and stabilising copper can (under certain conditions) lead to stability problems and possibly thermal runaway.

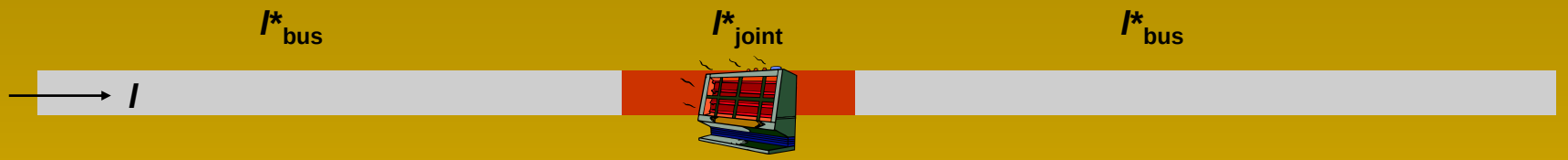

Disturbances
Non-transient
Resistive joint, non-SC cable
Transient
Sudden increase in R_joint
Transient
Cable quench
Stable resistive heating
Cooling>Heating
Recovery
Cooling>Heating
Localised slow thermal runaway
Good thermal and electrical contacts. No propagation to bus.
Non-localised slow thermal runaway
Good thermal and electrical contacts. Propagation to bus.
Old QPS acts here
Fast thermal runaway
Bad thermal and electrical contacts

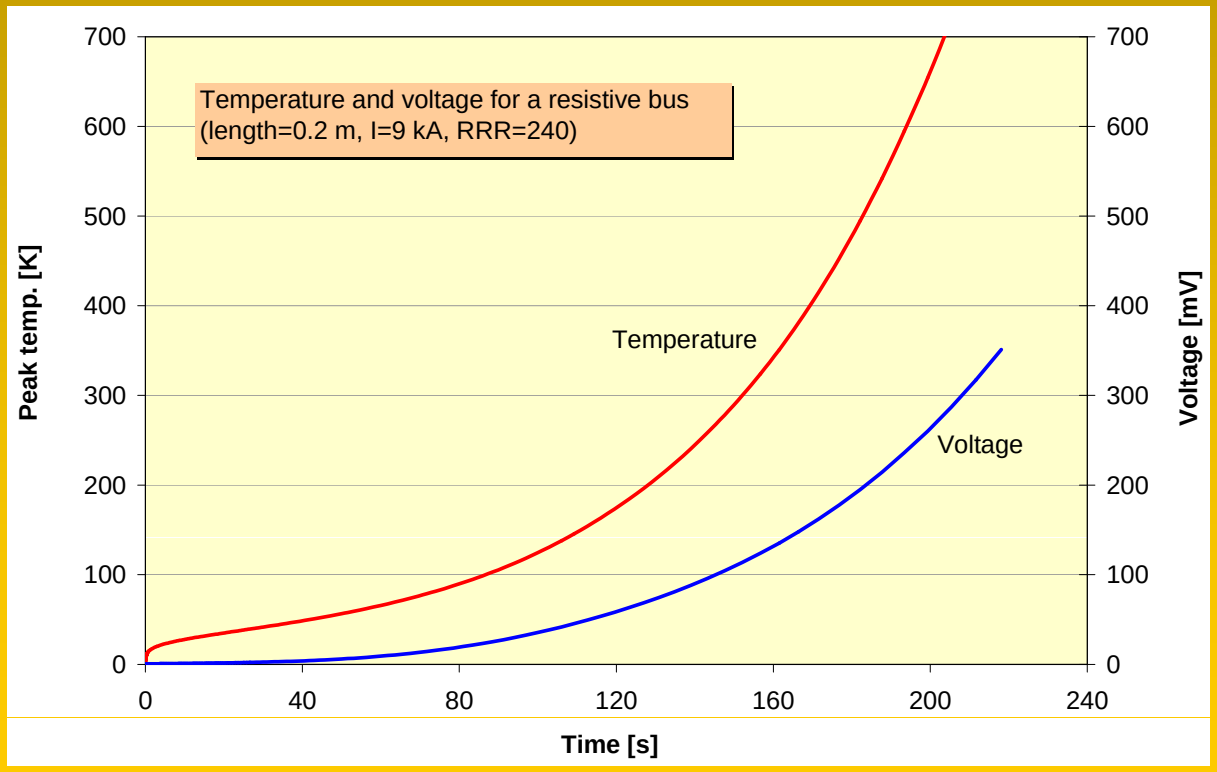
The ‘old’ bus protection

The old bus protection (threshold at 1 V) could only handle **non-localised slow thermal run-aways**. However, **localised run-aways** are very likely to occur, due to variations in quench propagation speed!



Assume a highly insulated resistive joint, so $I^*_{joint} < I^*_{bus}$.
Thermal run-away will occur when the Joule heating exceeds the cooling ($I > I^*_{joint}$).
The run-away will be **localised** (and hence the voltage relatively small) when the adjacent bus acts as a "quench stopper", i.e. when $I < I^*_{bus}$.





Conclusion:

The solder of the joint is already melting even before the voltage reaches the 1 V threshold!!

The incident

Facts:

1.
Estimated power of 10.7±2.1 W at 7 kA (so 175-260 nΩ).

2.
Maximum current of 8715 A.

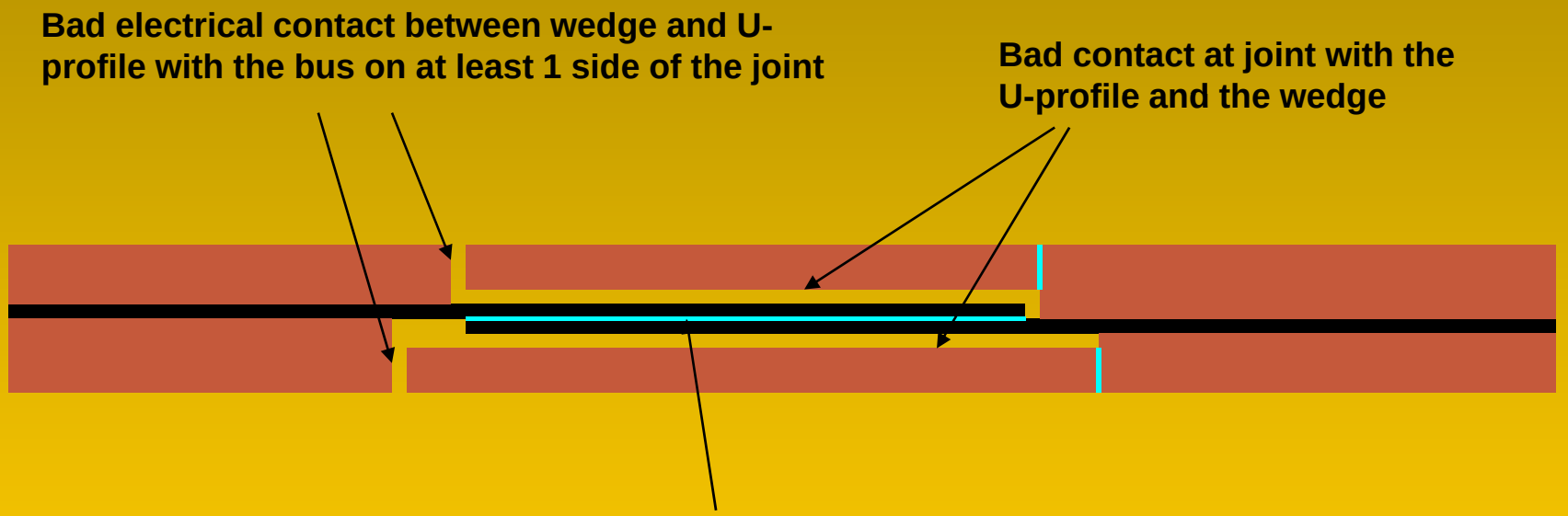
3.
Fast voltage increase during incident: ~0 to 1 V in about 1 sec.

4.
Possible small voltage increase (about 10 mV) during 30 sec before incident.

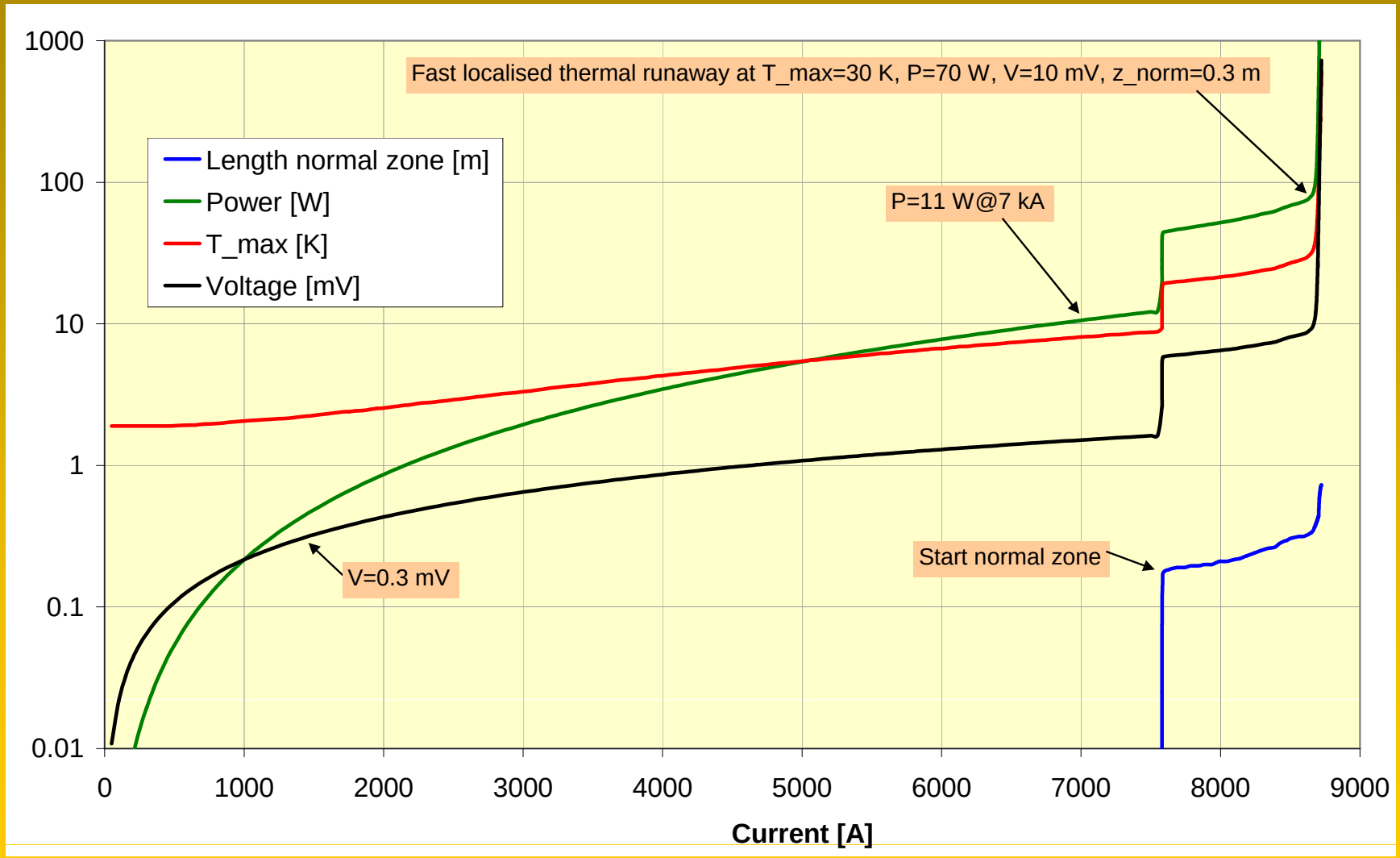
5.
Busbar QPS threshold reached before any voltage increase on the magnets.

6.
Origin probably in or near busbar joint

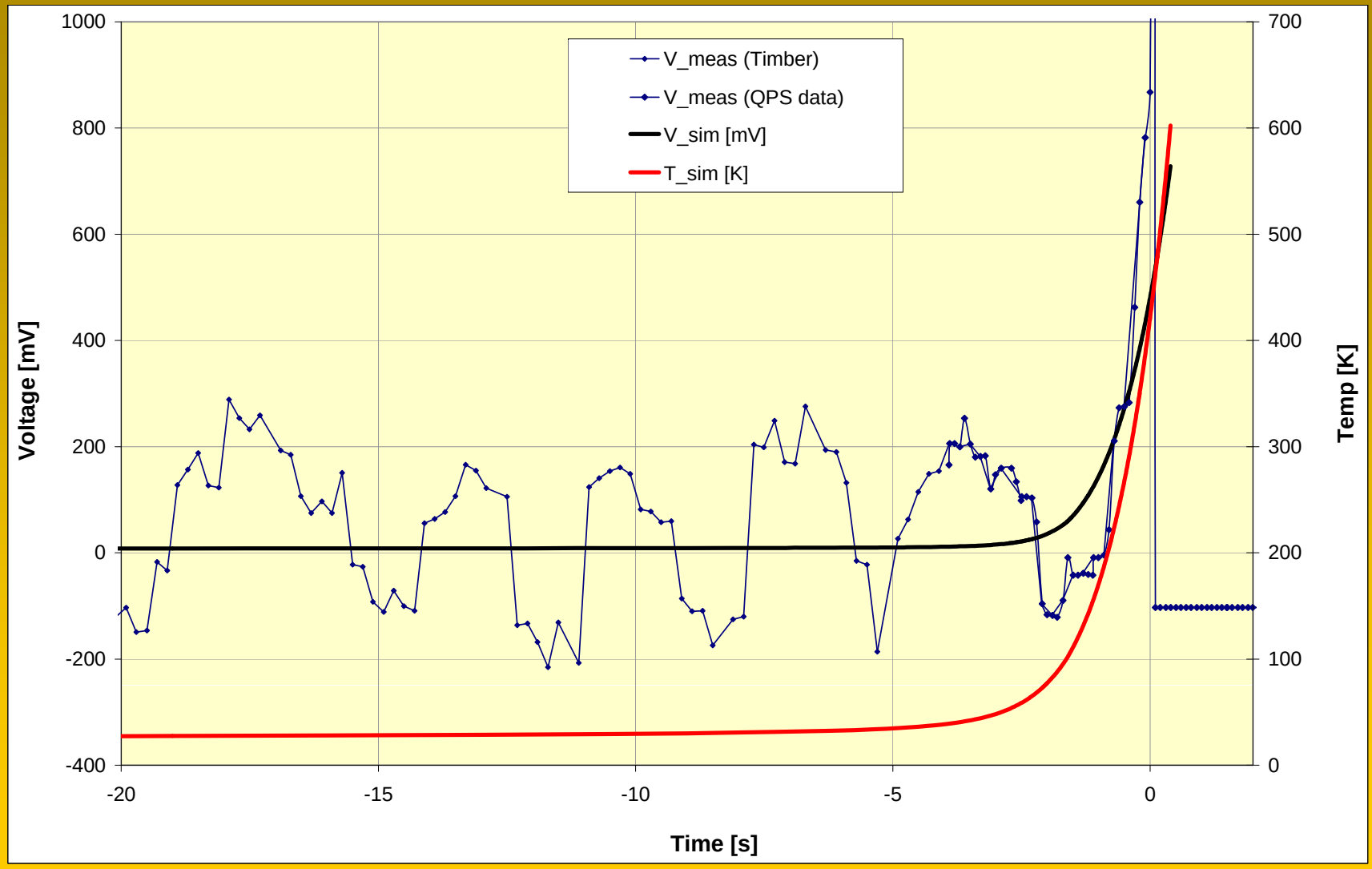
The incident: most likely scenario



Simulation of the incident



Simulation compared to (noisy) measurement



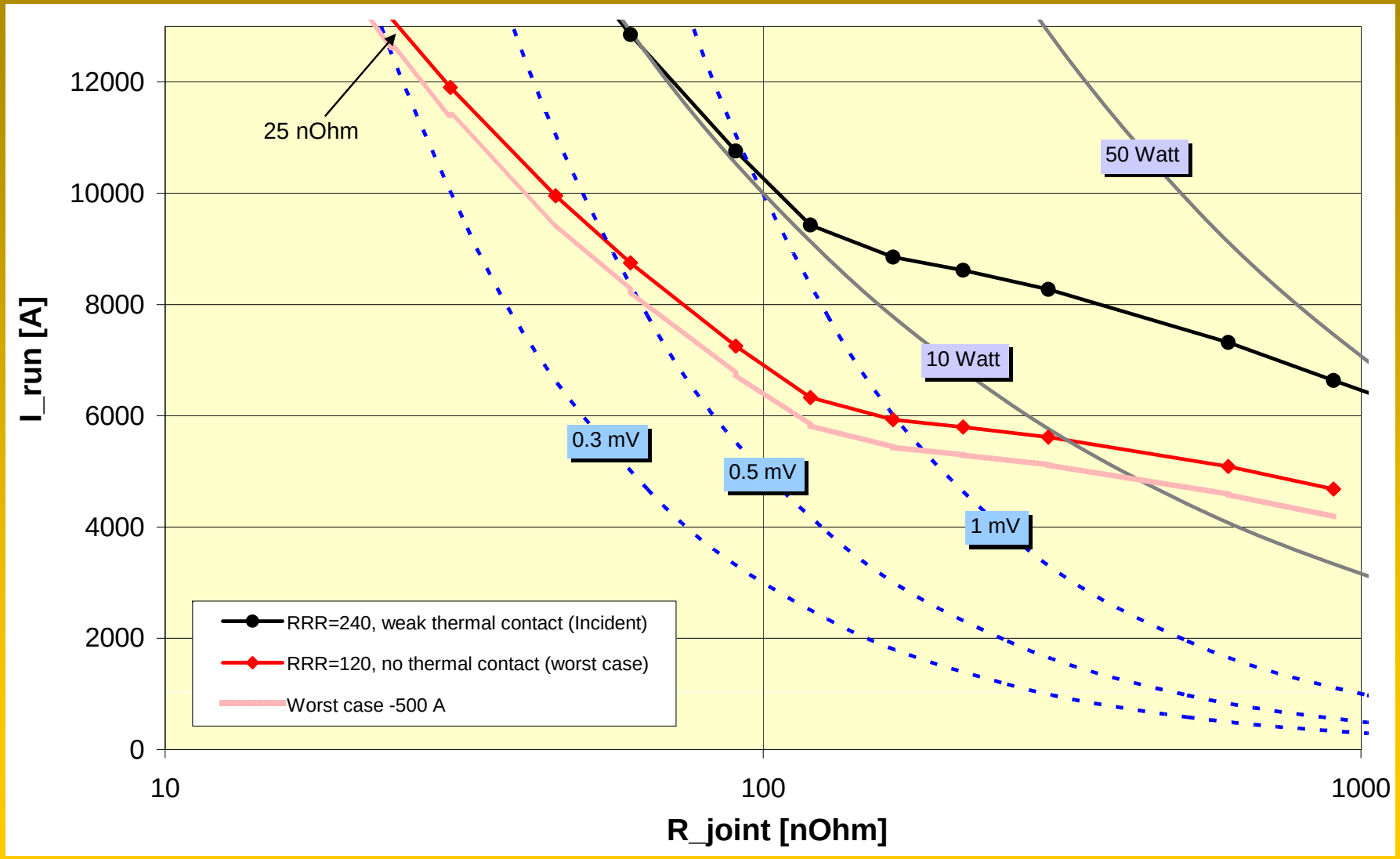
The incident: another scenario

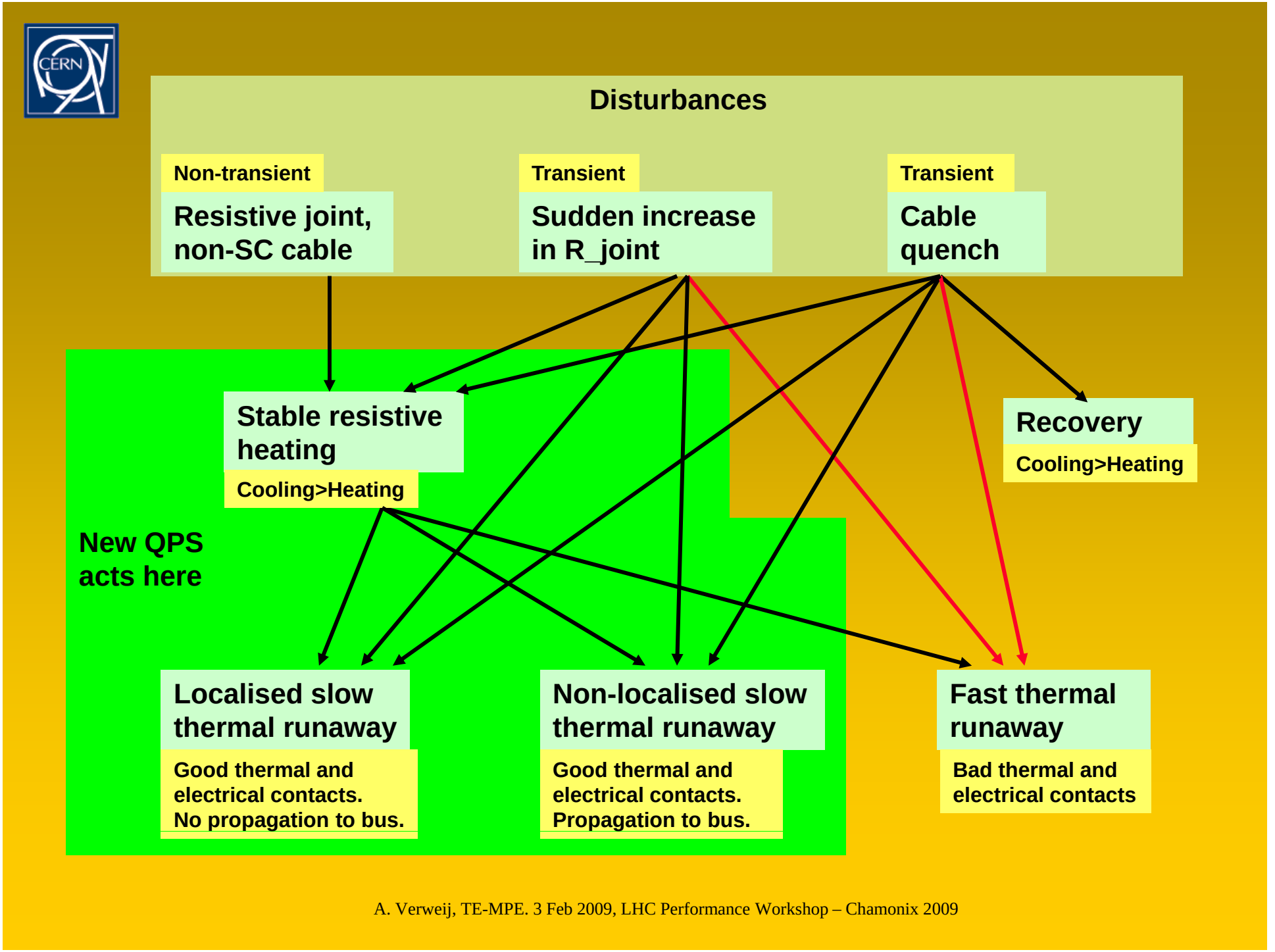
Resistive cable
(typically 90 nΩ/cm for RRR=150)

No electrical contact between wedge and U-profile with the bus

No bonding at joint with the U-profile and the wedge

Setting for the new QPS upgrade

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Conclusion

The original design 1 V QPS threshold was **much** too high to safely protect the dipole busbars. The possibility of combined production errors (e.g. longitudinal discontinuity and high joint resistance) and the effect of "quench stoppers" were at the time not properly taken into account.

Two possible origins of the incident are identified, that fulfill the observed facts (about 11 W @ 7 kA, Imax=8.7 kA, $\Delta t\_runaway \cong 1$ s), namely:

1) Resistive joint with very bad bonding to wedge and U-profile, **and** longitudinal discontinuity of the copper (bus).
2) Resistive cable with bad contact to bus at the start of the joint, **and** longitudinal discontinuity of the copper (bus). The cable can be resistive due to strongly reduced critical current or due to mechanical movement below 7 kA.

Both origins would have been detected with a QPS threshold voltage <1 mV long before the start of the thermal runaway.

A QPS threshold of 0.3 mV is needed to protect the RB bus and the joints in all imaginable conditions. This value can possibly be slightly modified when more experimental data (RRR, cooling, propagation speed) become available.

Conclusion

A small gap (up to a few mm) between bus and joint is acceptable as long as there is a good thermal contact between joint and U-profile/wedge.

Fast thermal run-aways resulting from sudden transient disturbances (without intermediate stable heating) are unprotectable by any QPS system (whatever the threshold).

To avoid such fast thermal runaways one needs to assure a good thermal contact between joint and U-profile/wedge (by means of clamping) **or** to assure a good electrical and thermal contact between bus and joint (perfect soldering between bus and joint).

Of course, the QPS system cannot protect the circuit in case of a sudden mechanical opening of the joint (without precursor 100 sec before).

Very similar conclusions hold for the RQF/RQD circuits, but what about all the other joints, busbars, pigtails, ...