Bad splice detection

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The first page

☞ In this talk I will deal only with the splices of the main circuits (RB, RQD, RQF) since they are the most important as far as stored energy is concerned (other circuits: same principles apply)

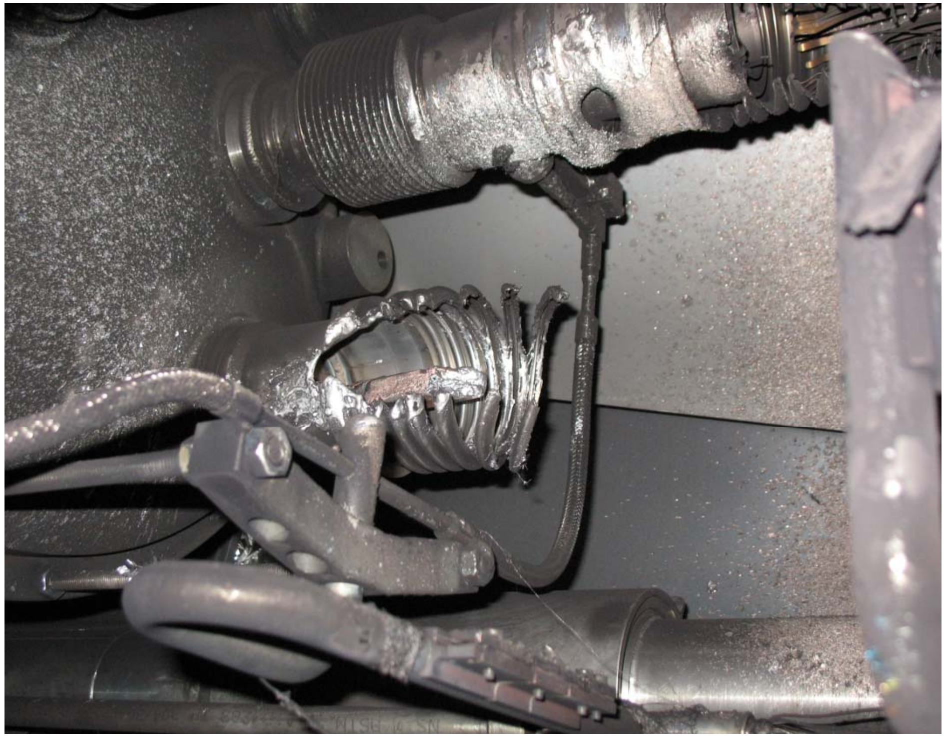
Many thanks for the hard work and stimulating discussions with many people: Jim Strait, Rob Wolf, Bob Flora, Zinur Charifoulline, Piotr Jurkiewicz, Knud Dahlerup-Petersen, Reiner Denz, Ruediger Schmidt, Andrzej Siemko, Jean-Philippe Tock, Karl Schirm, Nuria Catalan Lasheras, Serge Claudet, Laurent Tavian ...

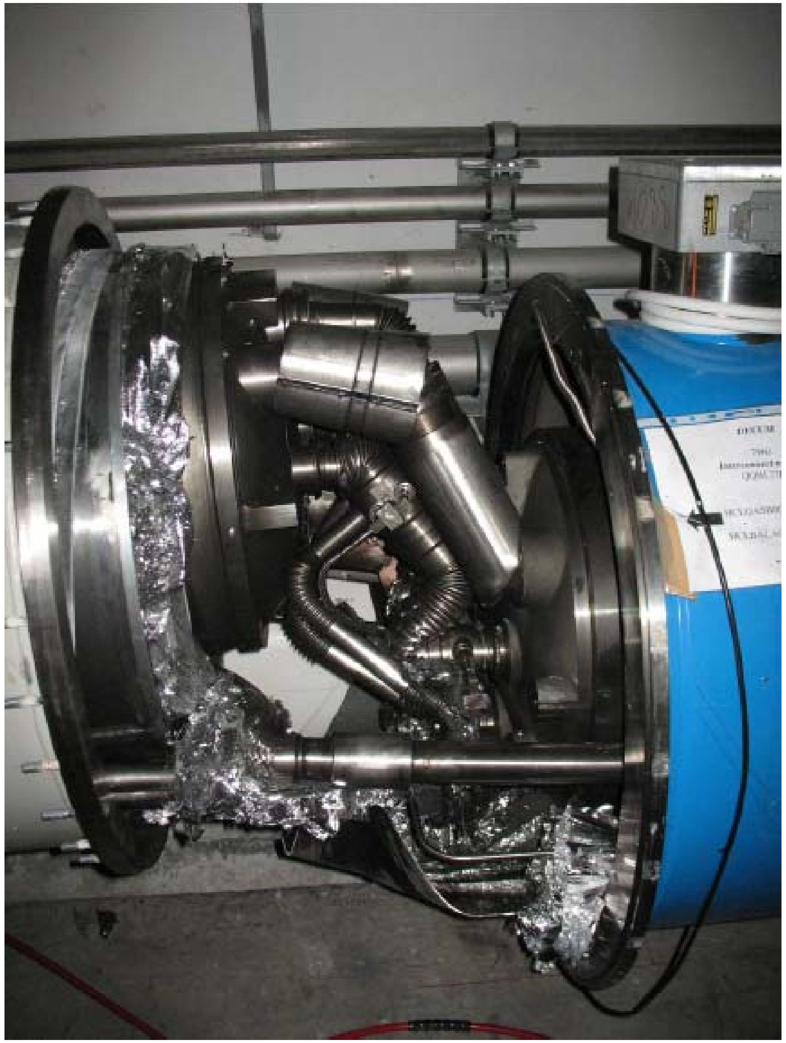
Why?

- Why do we need to measure splice resistances?

A bad splice can make quite a bit of damage...

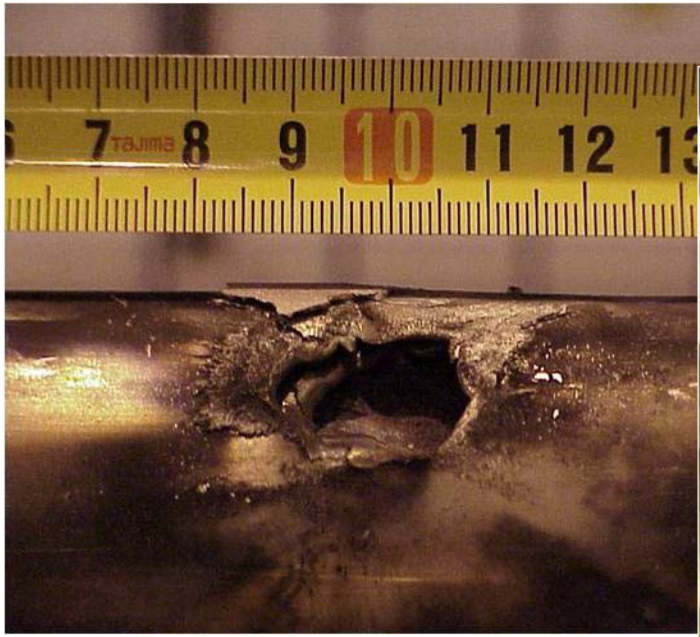
...when the splice is on a high power circuit and not protected by a diode...





Also, a single MB magnet carries a significant amount of energy...

...as witnessed by the “Noell 4 (3004) incident” on 15.10.2002



Energy enough to puncture a hole to the beam pipe and inflict collateral damage

QPS review

- The recent "LHC Enhanced Quench Protection System Review" held 24 -26 February 2009 (chair: Jay Theilacker, FNAL) made a series of recommendations including the following (under "operational issues"):
  - *Prior to physics operation, measure all splice resistances (bus and magnet) using developed techniques*
  - *Define a dedicated operational procedure for taking, analyzing and responding to joint resistance measurement data.*

...This is what we are set to do.

Splices, splices:

- *How many* are there in the machine?
- *What kind*?
- *How* have they been tested?
- *To what level* have they been tested?
- *How many* have they been tested?

Types of splices

- There are two broad categories of splices (categorised according to their position and hence to the damage they can potentially inflict)
- Splices between magnets (interconnect spices): these are not 'protected' by a diode and in case of rupture they are faced with the power of the complete circuit.

Main dipole bus:
•2 interconnect splices

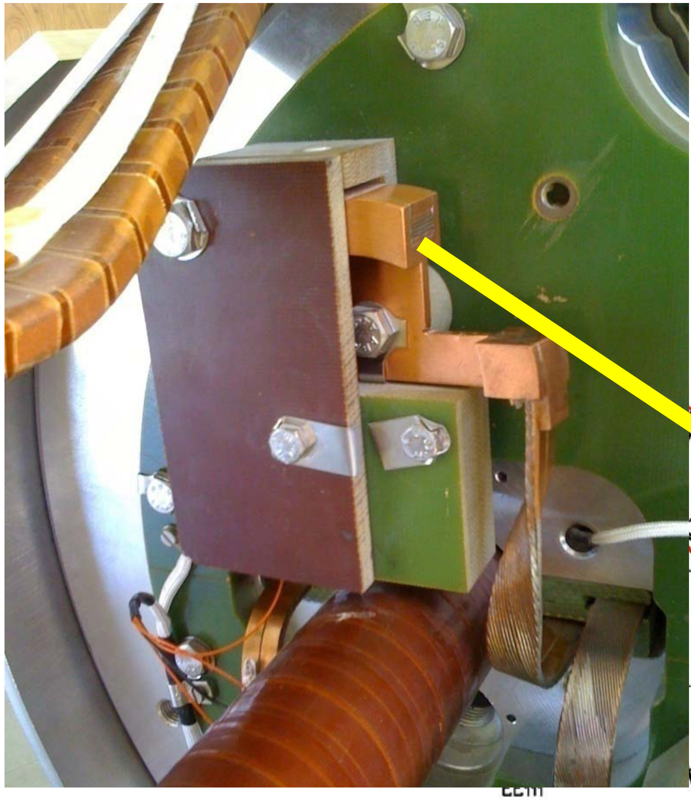
Main quadrupole bus:
•4 interconnect splices

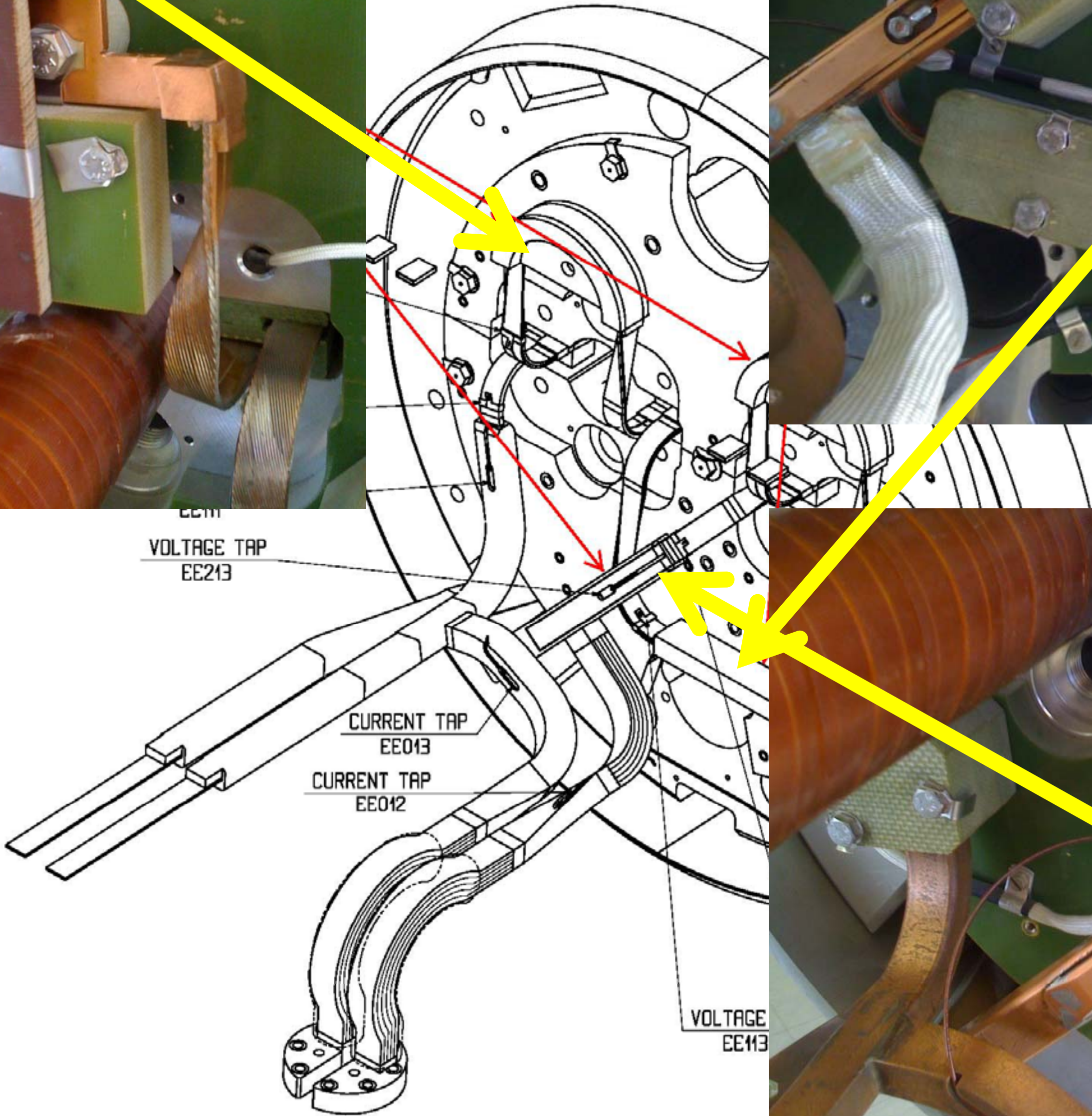
- Splices inside a cold mass cryostat (magnet splices): these are 'protected' by a diode, however they still have to deal with the power stored in one magnet, which is sufficient to potentially rupture the beam vacuum

Main dipole magnets:
• 4 interlayer splices per magnet
• 2 inter-pole splices per magnet
• 1 inter-aperture splice per magnet
• 1 internal bus splice per magnet

Main quadrupole magnets
•6 inter-pole splices per magnet
•4 internal bus splices per magnet

magnet s

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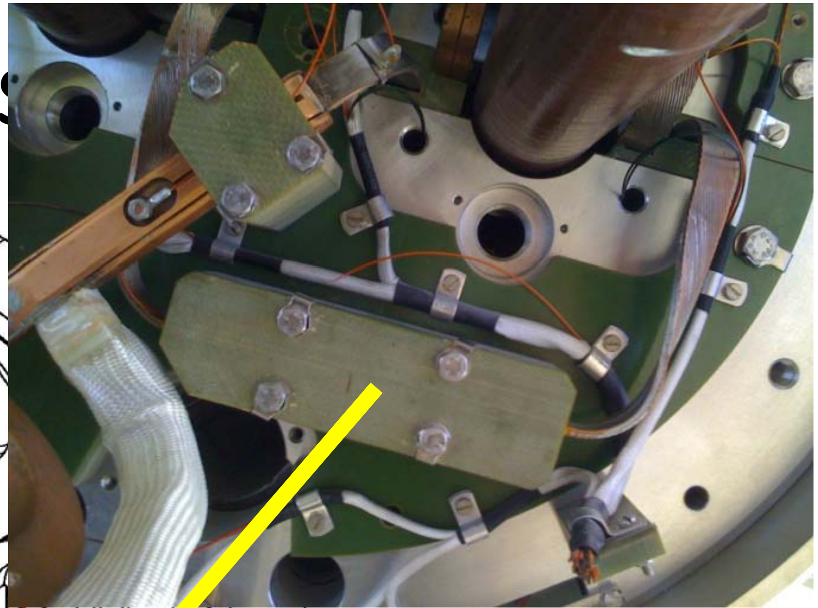
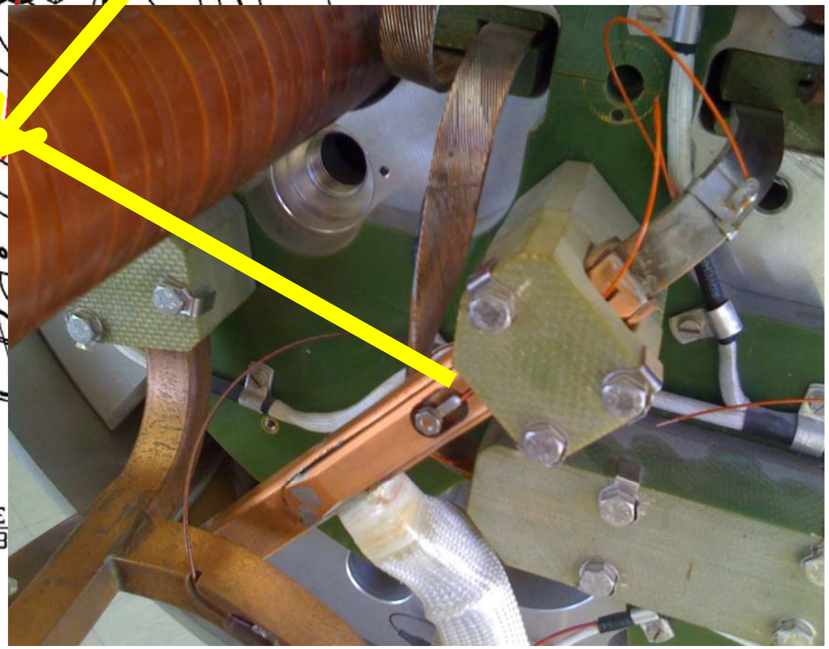
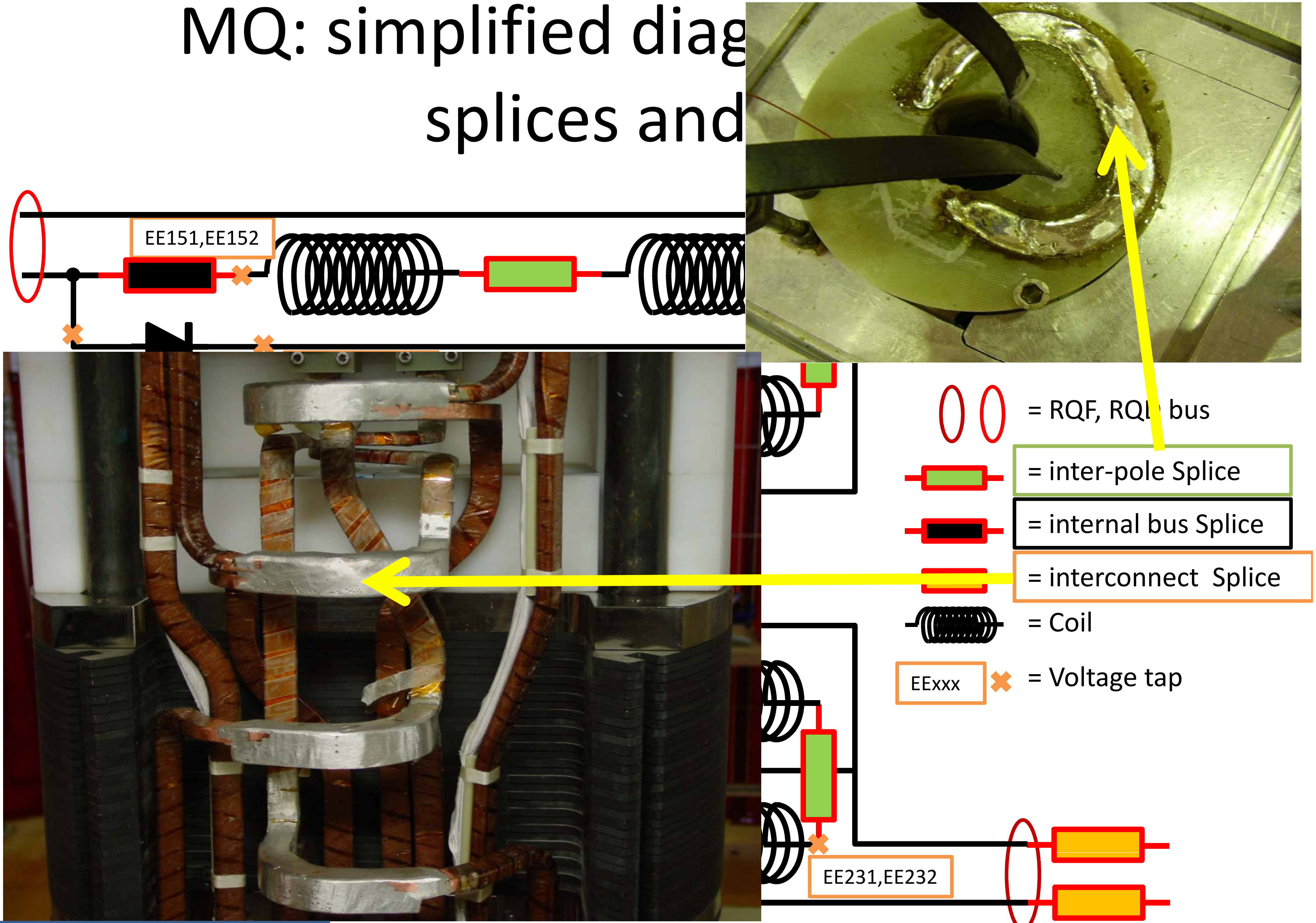




MQ: simplified diag
splices and



Courtesy K. Schirm

Number of splices in RB, RQ circuits

circuit	splice type	splices per magnet	number of units	total splices
RB	inter pole	2	1232	2464
RB	inter aperture	1	1232	1232
RB	interlayer	4	1232	4928
RB	internal bus	1	1232	1232
RB	interconnect	2	1686	3372
RQ	Inter pole	6	394	2364
RQ	internal bus	4	394	1576
RQ	interconnect	4	1686	6744
total				23912

Methods for testing splices

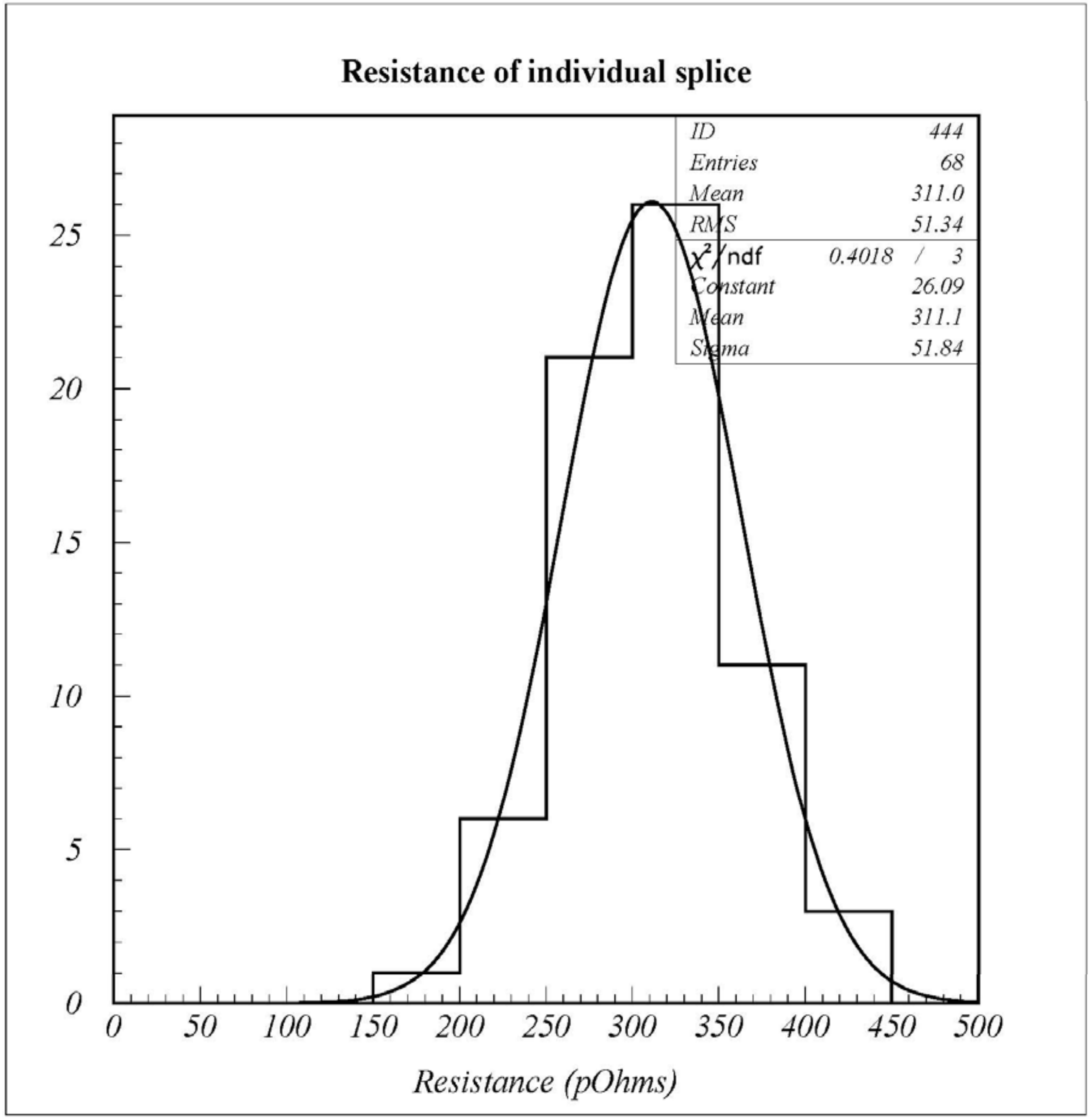
- The methods we have at our disposal to measure spice resistances (either directly or indirectly) are four:
  - The ‘Keithley’ method
  - The ‘QPS snapshot’ method
  - The calorimetric method
  - The ultrasound method

Testing methods: Keithley

- An ad-hoc method developed to look for interconnection splice resistances by using sensitive voltmeters.
- Labour intensive to set up. Only a limited number of splices were checked using this method (76).
- Will be superseded by the new QPS system.
- Out most accurate method to date → has yielded an accurate measurement of the average splice resistance

Accuracy: Keithley

- Accuracy is about 50pOhms
- Has been applied to 2.2% of all RB interconnects. Has not been applied to any RQ interconnects.
- Zero bad splices have been found



An RB average splice resistance has been measured to be: 310±50pOhms

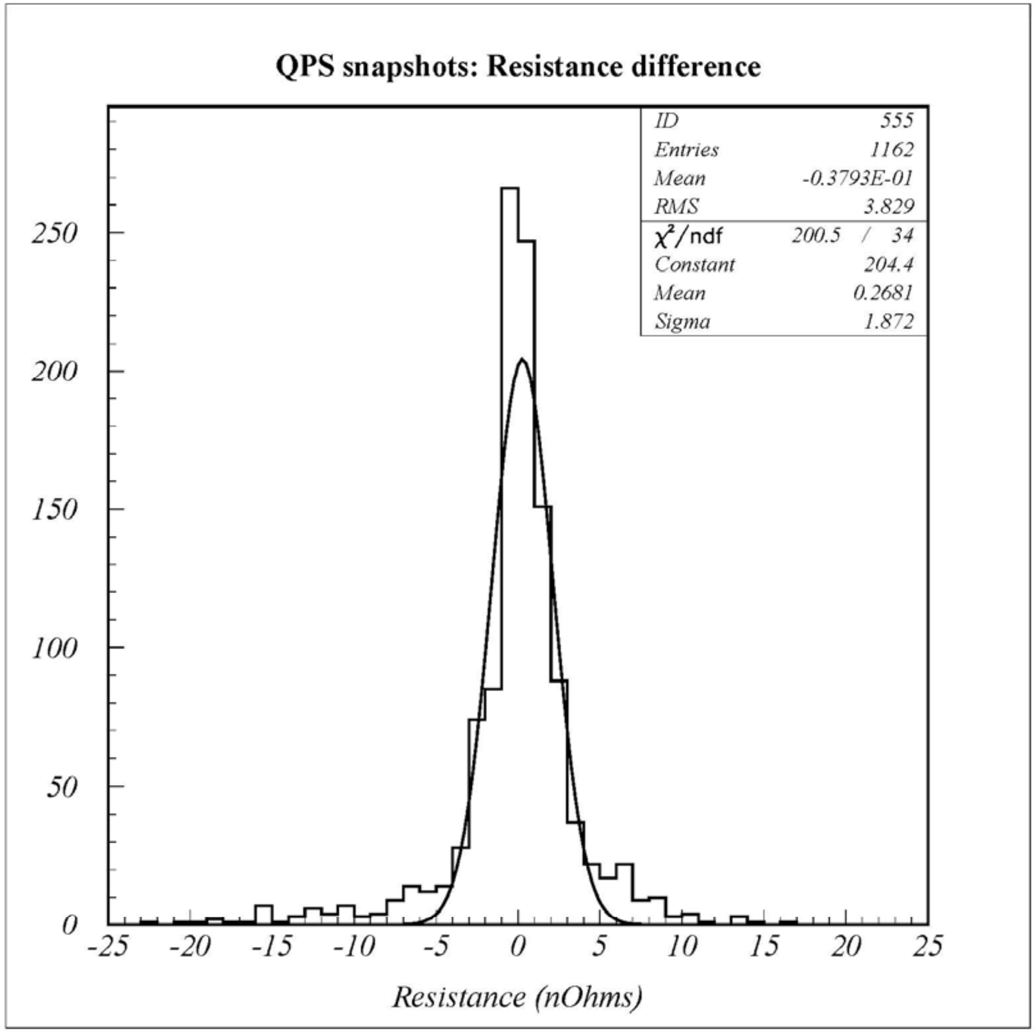
The QPS snapshot method

- Using the QPS system in a non-standard (and not envisaged) way, we can measure the splice resistance difference between:
  - 3 versus 4 internal splices in dipole magnets (1 not measured)
  - 1 versus 2 internal splices per aperture in quadrupole magnets (2 not measured)
- We need at least 3 and preferably more current plateaus, staying at each plateau for a few minutes (plus the zero-level before and after the test)

QPS snapshots: accuracy

- Intrinsic accuracy seems to be better than 2nOhms, but there are systematic effects (still to be understood) that give resistances as big as 20nOhms
- → overall accuracy of the method today is 20nOhm

•About 6600 splices have been tested using this method and 2 bad splices have been found



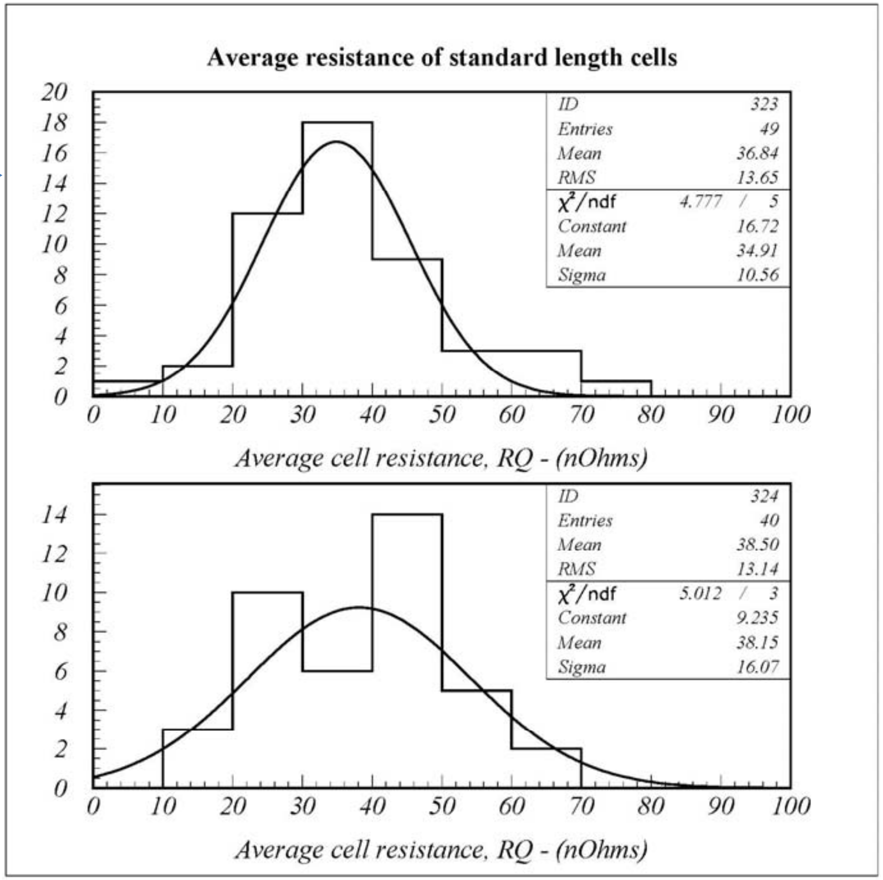
The calorimetric method

- Principle is to measure the ohmic heating of a high resistance splice
- The method becomes accurate only if a high current plateau is reached (7000A in 2008)
- Measures all splices (interconnect and magnet) with the granularity of one cryogenic cell (13 cryo cells per sector, mainly consisting of 16 magnets)
- Needs at least three current plateaus of one hour each, plus one hour before and one hour after the test
- Needs specific cryogenic regulation (takes time)
- Difficult method; need at least one shift per measurement (per circuit)

Calorimetry: accuracy achieved in 2008

- Accuracy is about 40nOhms (One sigma spread is 11-16nOhms)
- Has been applied to 57% of all splices

RB splices: average splice resistance comes out to be: 270+-80pOhms



Using this method:

- Two bad splices have been found and confirmed.

The ultrasound method

- Measures the reflectivity of a splice and hence if enough solder has been applied
- 4 measurements are taken transversely – if 3 or 4 are bad, this constitutes a non-conformity
- Can be used mainly on interconnect splices
- Can only be used on exposed splices (at room temperature) – i.e. of limited use on a closed machine
- 1388 interconnect splices (+77 in sector 34 after the incident) were checked using ultrasound (both in the RB and RQ circuits).
- 1 bad splice was found (3 put of 4 measurements bad, NCR 836841). The splice was re-soldered

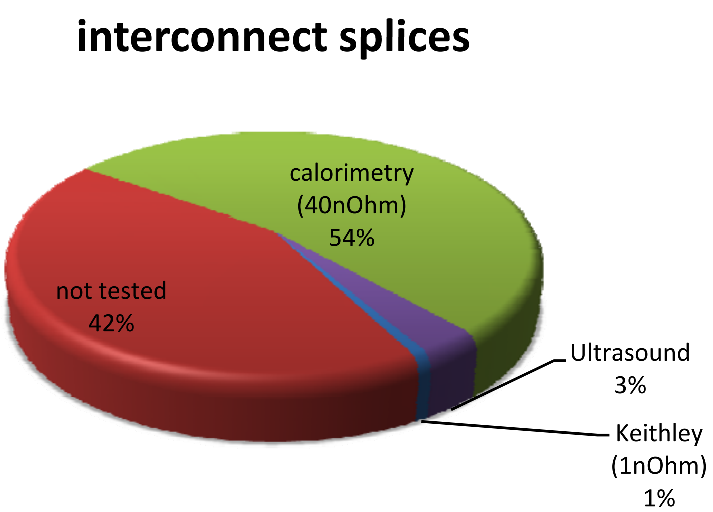
Number of splices tested

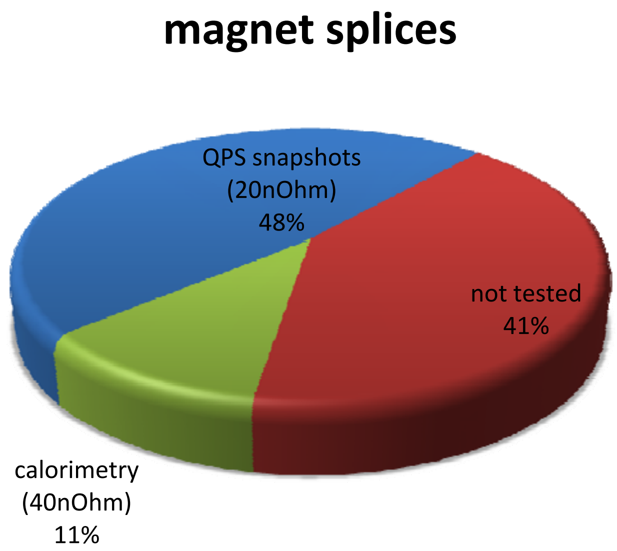
			splices tested			
circuit	**splice type**	**total splices**	**QPS snapshots**	**calorimetry**	**Keithley**	**ultrasound**
RB	inter pole	2464	1540	1540	0	0
RB	inter aperture	1232	770	770	0	0
RB	interlayer	4928	3080	3080	0	0
RB	internal bus	1232	0	770	0	0
RB	interconnect	3360	0	2107	76	486
RQ	Inter pole	2364	1182	1182	0	0
RQ	internal bus	1576	0	788	0	0
RQ	interconnect	6720	0	3372	0	979
total		23876	6572	13609	76	1465
% of total			27.5	56.9	0.3	6.1

Level of splice testing: recap

- 76/10080 (0.7%) interconnect splices have been tested to an accuracy of 1nOhm
- A further 5403/10080 (54%) interconnect splices have been tested to an accuracy of 40nOhm.

- 6572/13796 (48%) inter-magnet splices have been tested to an accuracy of 20nOhm.
- A further 1558/13796 (11%) inter-magnet splices have been tested to an accuracy of 40nOhm





Splice resistance non-conformities to date

- Interconnect splice C24-Q24R3: 200nOhms
- Inter-pole splice B16R1 (MB2334): 100nOhms
- Inter-pole(?) splice B32R6 (MB2303): 50nOhms
- Inter-aperture splice MB2420 (SM18): 30nOhms
- Interconnect splice RB Q20R1-A21R1: ?nOhms (ultrasound)

- About half the machine was checked to 40nOhms and 1/3 to 20nOhms
- What are the chances that in the other half of the machine (and in the first half with better accuracy) we will not find any more non-conformities in the splice resistances? – **very slim**

What level of splice resistance can be tolerated

- The nominal resistance of a splice is of the order of 0.3nOhms.
- Anything above 1nOhm is a non-conformity.
- This does not mean that the machine cannot run with a few such non-conformities
- The maximum tolerable level is a function of energy
- Interconnect splices have a higher damage potential but will be protected with a lower QPS threshold.
- Interconnect and magnet splices should have a different tolerance level than magnet splices

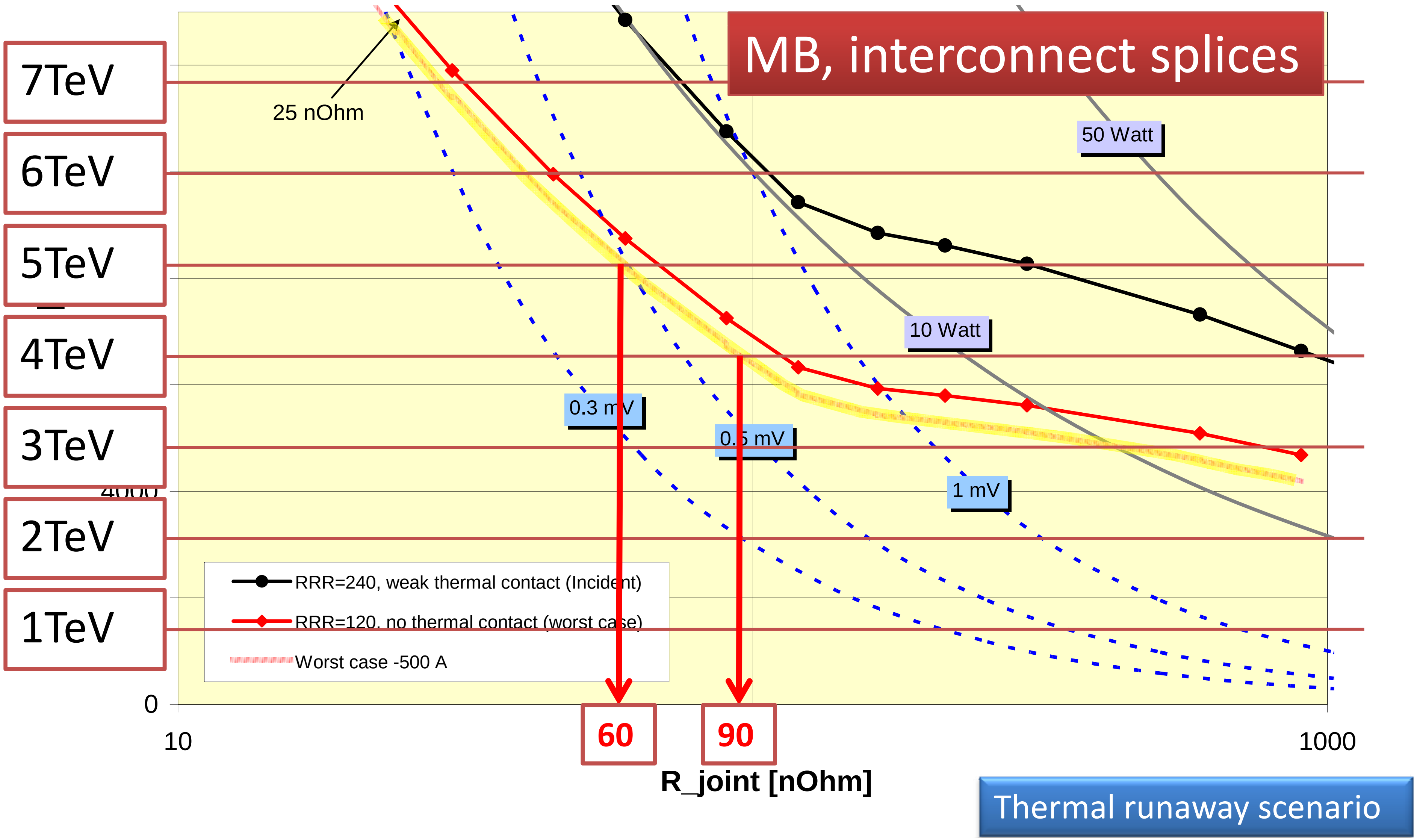
Facts – from operation in 2008

- An interconnect splice resistance of 200nOhms suffered a breakdown
- An inter-pole resistance of 100nOhms did not degrade for a small number [O(10)] of cycles
- A 100nOhm splice and a 30nOhm splice, when opened, were found to contain very little solder (and therefore with compromised mechanical integrity).

Limits from electrical simulations

- Considering only electrical effects, simulations give us the safe limit to avoid a thermal runaway
- Currently only RB interconnect splice simulations exist (A. Verweij, Chamonix 09) but work is in progress for other circuits and types of splices.
- The electrical simulation does not consider mechanical effects (metal fatigue for instance) associated with a non-conforming splice. Such effects should be taken into account.

“Busbar and Joints Stability and Protection”, A.Verweij (Chamonix 09)



Tools for 2009

- Calorimetry and (new) QPS snapshots will be the tools at our disposal for comprehensive splice resistance measurements.
- The two methods are nicely complementary. The accuracy of the calorimetric method in 2008 was 40nOhms and of the QPS method 20nOhms. There is room for improvement for both methods.
- It is hoped that the QPS system will also give a method for day-to-day monitoring of splice resistances during operation. This is not practical for the calorimetric method, so it will probably always remain a specialist tool, performed always during dedicated periods.

Strategy for 2009 - basics

- Need to define a level of maximum tolerated splice resistance. This level should probably be a function of the energy we intent to run. This level will be different for interconnect and inter-magnet splices (stricter for interconnect splices?)
- This should be defined before we start measuring.
- We should then proceed with a comprehensive measuring campaign.
- Invariably, an executive decision might need to be taken

Strategy to measure splices

- Problem of thermal runaway becomes important only above a certain current I_r (5000A in Arjan's simulation). Tests below that current can proceed without splice resistance measurements. (mechanical stability is not taken into account in the above. A bad splice can break with no warning – there is a degree of risk even below 5000A!)
- Use calorimetry and QPS snapshots starting at I_r to verify before we can go to the next step ($I_{runaway}$***1.22** for instance, etc.)
- Do a complete census of all splices on the high-power circuits of the machine
- Stop and repair all splices with resistance above our maximum tolerable limit (according to the top energy we intend to run on)
- All splices with resistance above normal but below the maximum tolerable limit should be monitored daily for degradation.
- If such a degradation is seen, stop and repair

Your input is needed to define all those parameters!

End

Work still to be done

- Finalise simulation work on other circuits, splices and scenarios
- Get a better understanding of mechanical risks – ramp the MB2303 magnet for 1000 times in SM18?
- Work on understanding and improving the measuring methods for 2009