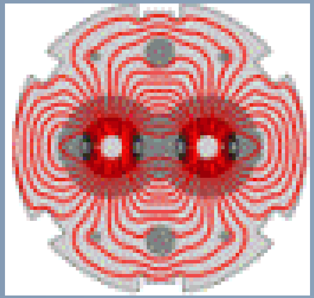
Do the splices limit us to 5TeV – plans for the 2010 run



Preconditions for operating at 5 TeV in 2010

Session 1 - 25th January 2010

M. Koratzinos TE/MPE

Outline of the talk

- The landscape
  - Types of splices
  - Methods of measurement and results of splice resistances
- The constraints
  - How safe is it to operate at a higher current?
- The options
  - Three strategies for measuring / verifying splice resistances
  - Pros and cons of each option
- Conclusions

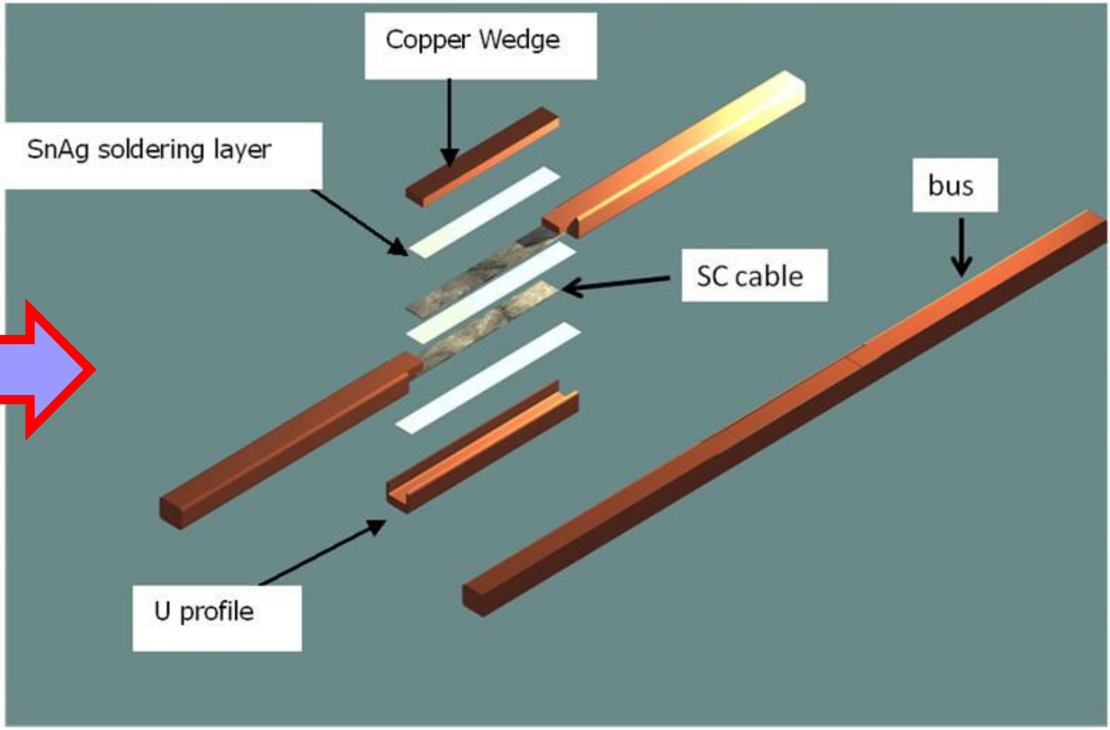
I am indebted to the following for a number of stimulating discussions and suggestions: B. Flora, H. Pfeffer, A. Verweij, A. Siemko, F. Bertinelli, J. Strait, R. Schmidt, ...

The landscape I: splices

The main circuits of the LHC (RB, RQD, RQF) have about 24000 splices.

Out of these there are:
- 10170 interconnect splices and
- 13796 magnet splices

Interconnect splices are not protected by diodes and in the case of a problem all the current of the circuit passes through them



Nominal interconnect splice resistance:
- At cold: **300pΩ**
- At warm (300K): **10μΩ**

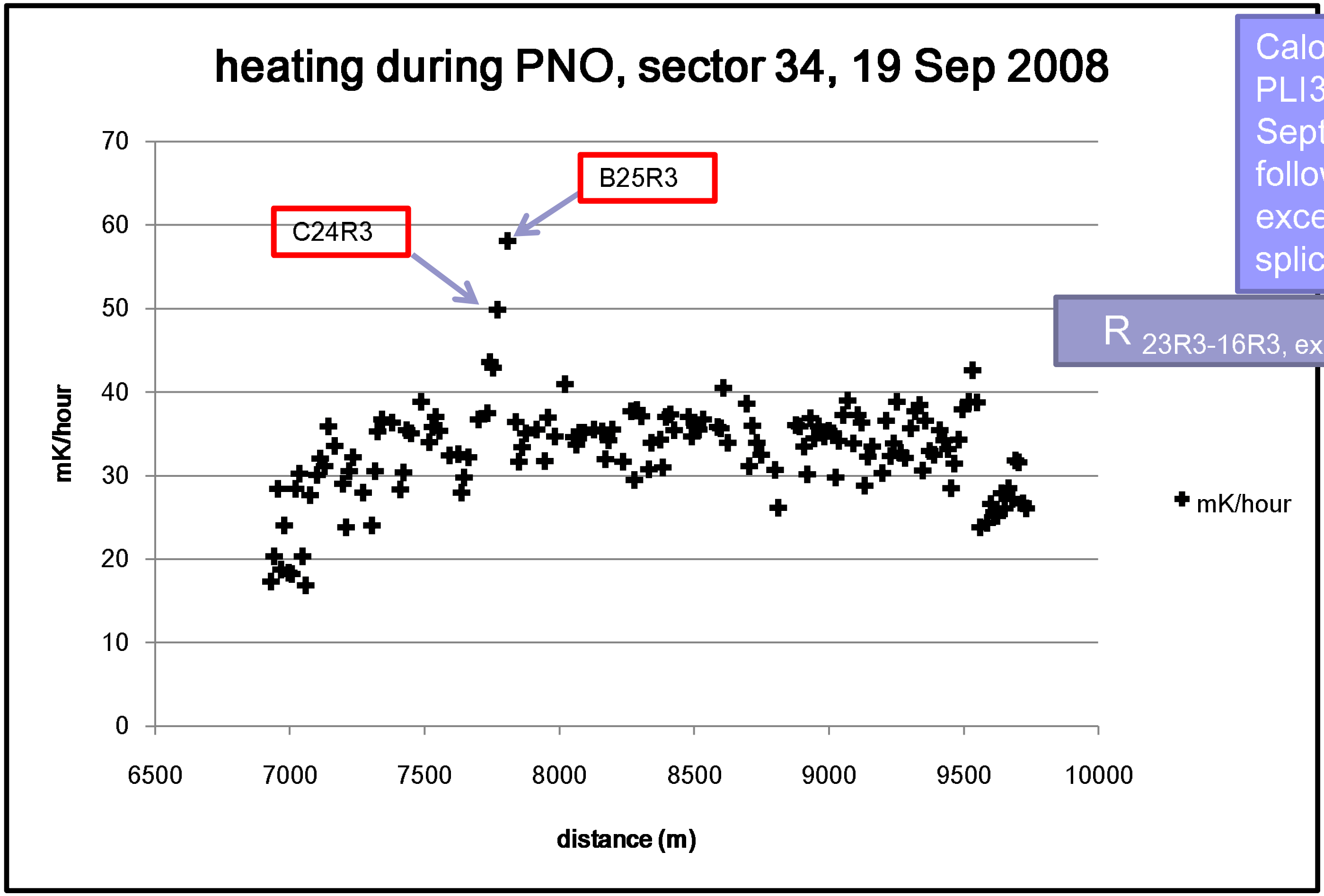
For the LHC to operate safely at a certain energy, there is a limit to how big a splice resistance can be

Splices - nomenclature

- Individual splices are measurable only with **invasive** methods
- Under non-invasive conditions, we are limited by the amount of voltage taps available. What we can measure between successive voltage taps is a **busbar segment**
- **A typical bus bar segment for the RB bus contains 2 or 3 splices.**
- **A typical bus bar segment for the RQ bus contains 8 splices**
- Non-invasive methods at non-superconducting temperatures measure the resistance of the splices but also the resistance of the bus bar segment.
- Busbar **excess resistance** is the resistance of a busbar minus its nominal resistance.

The landscape II: motivation

- We know what is an unsafe resistance (19 September 2008):



Calorimetric analysis of test PLI3.a2 done on 15 September 2008 yields the following value for the excess resistance of the splice:

$R_{23R3\text{-}16R3,\,\text{excessive}} = 234 \pm 15\ \text{n}\Omega$

Measurements at cold

- A nominal splice resistance at cold is about 300pOhms.The faulty one in Sector 34 was 1000 times that value
- We have measured the resistance of splices at cold in a variety of ways:
  - Calorimetry
  - Ad Hoc electrical measurements
  - nQPS measurements in 2009

Calorimetry

1 watt

250 m of magnets – 350t of cold mass

Cryo in strict regulation

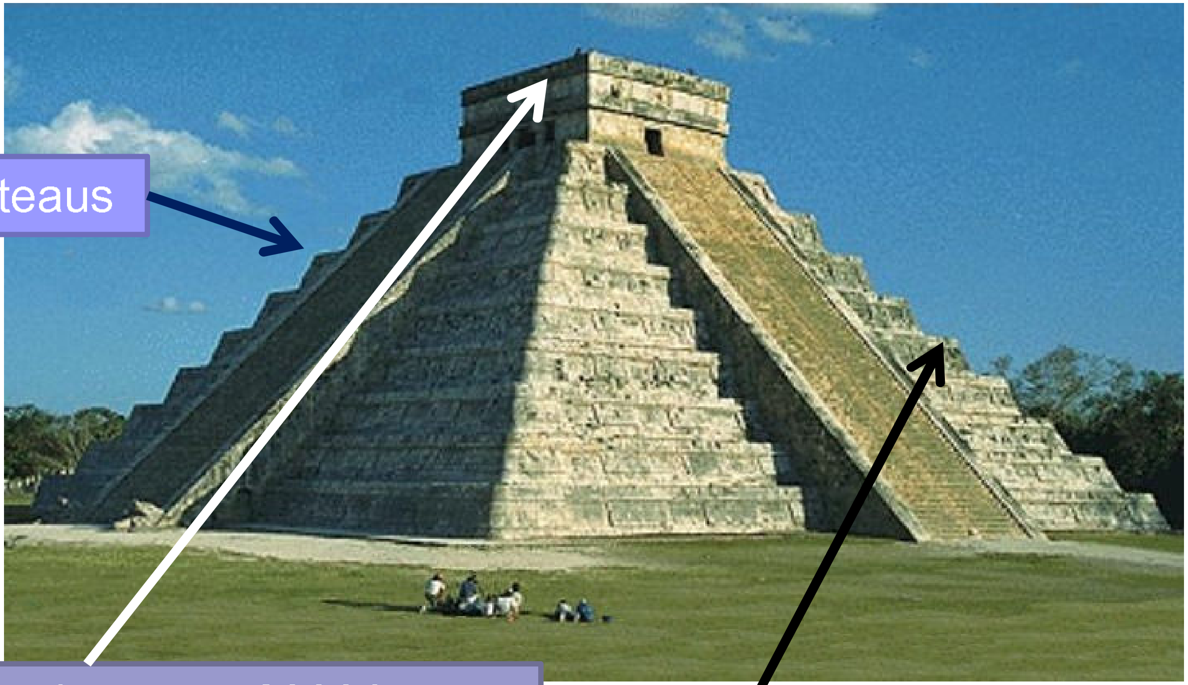
Very impressive, and is sensitive to all bad splices, but good for finding excess resistances of 40nΩ or more

Magnet splice resistances

- We have performed (ad hoc) measurements using the old QPS system which covered 6 out of 7 magnet splices (RB) and 6 out of 10 splices (RQ).
- Two significant excess resistances found:
  - B16R1 (MB2334) (100nOhms)
  - B32R6 (MB2303) (50nOhms)
- Any rupture of a splice here might result in the destruction of a magnet but will not lead to a 19-September-type event.
- Much more accurate results are expected from the nQPS campaign of 2009/2010.

Maya Pyramids

- Using the nQPS system as a series of very accurate voltmeters, we can measure the resistance of a bus bar segment to <1nΩ



Series of current plateaus

Top current plateau at 2000A, 30+minutes

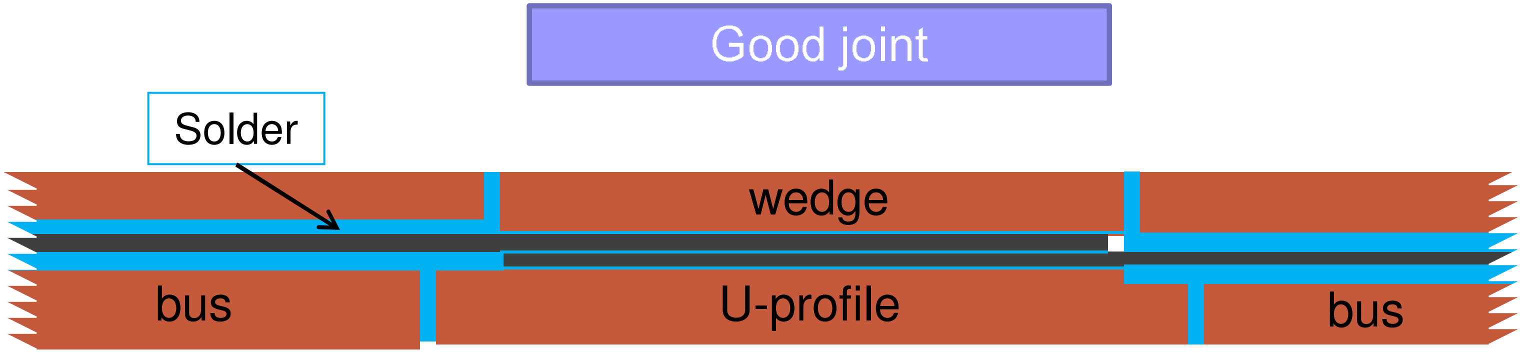
Back to zero to reduce systematic errors

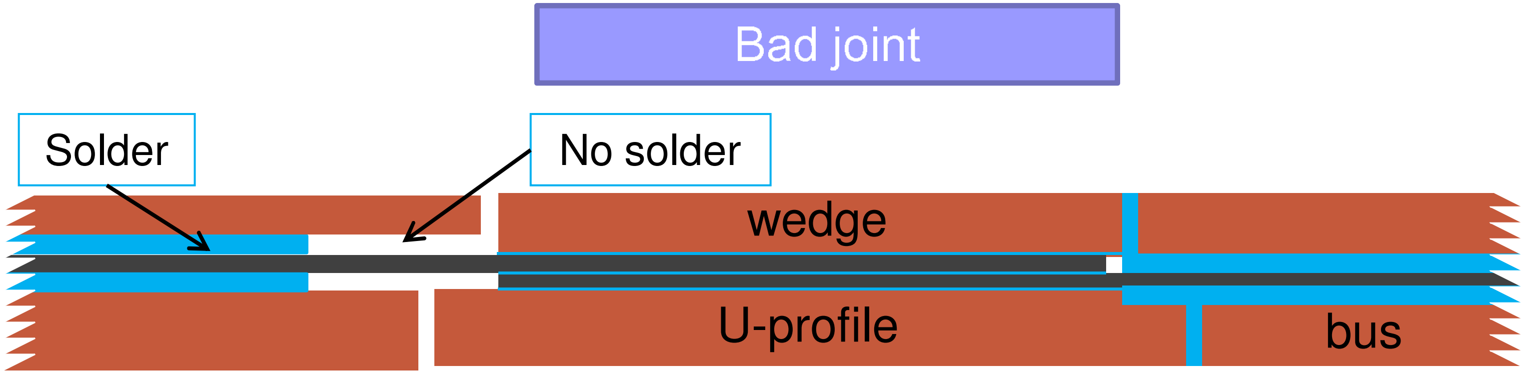
Interconnect splice resistances

- A rupture of one of the interconnect splices will have serious consequences
- The nQPS campaign of 2009 gave excellent results:
  - There is no excess resistance **above 4nΩ** anywhere in the machine
  - The splice resistances found above 2nΩ are:
    1. 2.87±0.14 (RQ circuit, sector 23)
    2. 2.32±0.14 (RB circuit, sector 34)
    3. 2.05±0.52 (RQ circuit, sector 34)
- An excess resistance at cold of 2nΩ:
  - Poses no problems under normal operation.
  - However it might suggest a structural problem or a problem with the soldering procedure which might be more serious
  - See P. Fessia’s talk
  - **Time evolution** would need to be followed closely
- The excess resistances found are natural candidates to be checked by the new X-ray tomograph.

Resistances at warm

- A copper stabilizer with no continuity coupled to a superconducting cable badly soldered to the stabilizer poses a real problem (A. Verweij)





Factors affecting resistance at warm

Bus segment (μΩ)	Typical resistance (μΩ)	Typical defect (μΩ)	Temperature change +1K	Cross-section nominal → nominal+50um	RRR 100→ 150
RB@300K	2000	50 (2.5%)	7 (0.4%)	12(0.6%)	7 (0.3%)
RQ@300K	11000	50(0.5%)	40(0.4%)	85 (0.8%)	40(0.3%)
RB@80K	270	7(2.5%)	8(2.9%)	2(0.6%)	7 (2.6%)
RQ@80K	1500	7(0.5%)	44(2.9%)	11(0.8%)	40(2.6%)

- Only the measurement at 300K for the RB bus is relatively easy.
- For measuring the RB at 80K we need to control the temperature and the RRR
- Measuring the RQ at 300K is on the limit of accuracy
- Measuring the RQ at 80K is very difficult

Resistances at warm II: the Biddle

Biddle

Pencil

A heroic effort (led by B. Flora) was undertaken to measure bus bar segment resistances at warm. Measurements were taken **by hand** (100,000 numbers!) in the tunnel in all sectors.

The measurements had a 1% accuracy and, predictably, worked o.k. for the RB at 300K (when looking for a 2.5% defect), but worked less well for the RQ and at 80K were not sufficiently precise to spot outliers

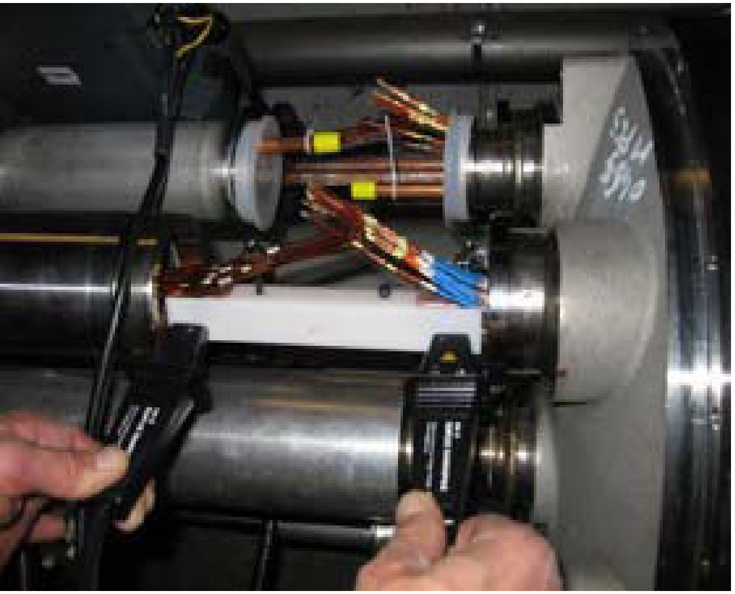
Biddle measurements recap

- The most reliable Biddle measurements (RB at room temperature only) are shown in the table below
- Five sectors were measured at warm and the worst splices were opened up and repaired
- The table below shows the situation **after** the repairs

Circuit/ Sector	Temperature spread (K)	Excess resistance spread	Highest remaining excess resistance	Excess resistance limit 90%CL
A12 RB	1.1	13	37	51
A34 RB	1.9	10	35	47
A45 RB	0.9	17	53	78
A56 RB	0.4	9	20	34
A67 RB	0.6	14	31	48

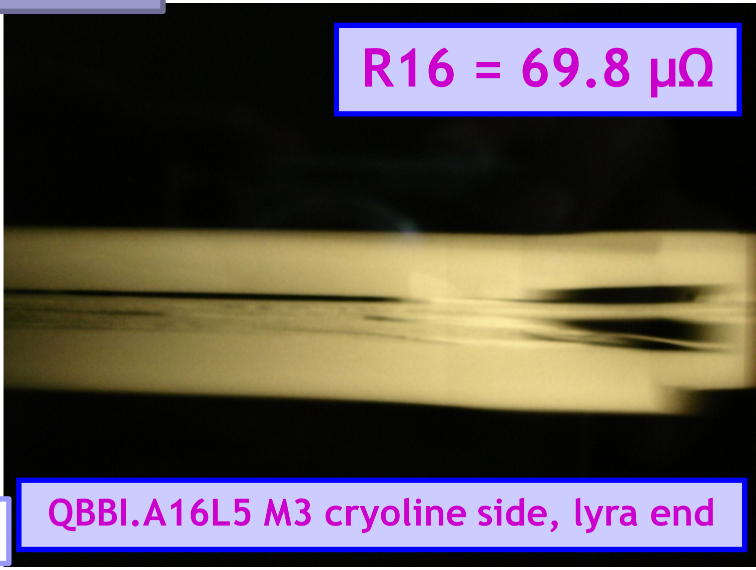
R16 measurements

- A number of interconnect splices were opened and measured (measurements called the R16 measurements). Some were measured after an indication by Biddle measurements.



The worse R16 resistance measured was 70uOhms. Therefore the highest excess resistance is: $R_{excess}=(R_{total}-R_{best})$ and $R_{best}=10\ \mu\Omega$

$\therefore R_{excess,worst}=60\ \mu\Omega$



R16 = 69.8 µΩ

QBBI.A16L5 M3 cryoline side, lyra end

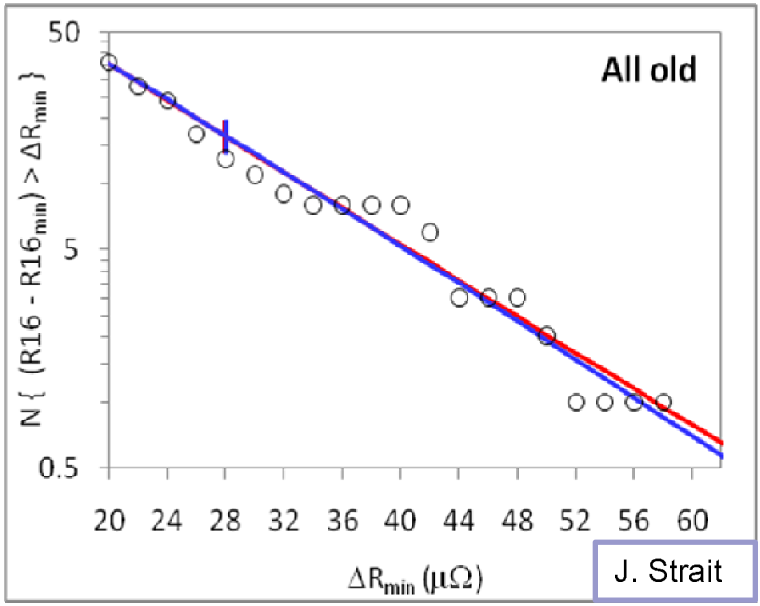
Courtesy Ch. Scheuerlein

The worst remaining splice

- The only reliable Biddle measurements are the RB measurements at 300K (5 sectors)
  - Worst **measured** excess resistance RB: 74±15μΩ(A45)
  - Worst **remaining** excess resistance RB: 53±15μΩ (A45)
- The worst measured R16 measurement is 60±1 μΩ
- To find out the worst remaining splice in the machine we need to rely on a **statistical extrapolation.**

•The statistic of the 'worse splice seen' is not particularly robust
•We have performed a statistical analysis on the R16 measurements
•This gave a confidence bound at the 90%CL of R_{excess} = 98μΩ

Most realistic max. excess resistance (RB, RQ)
$R_{max} \approx 90\ \mu\Omega$ (LMC 5/8/2009)



J. Strait

The motivation

- By going up in energy we gain in two ways: interesting cross-sections increase with energy and we also gain in aperture and reduced emitance.
- In the region 3.5TeV to 5TeV per beam, even a modest increase in energy gives sizable increase in physics yield.
- The question is how much can we safely increase the energy of the LHC this year?

The constraints

- A. Verweij(*) has updated his calculations of what is the worst splice we can tolerate as a function of energy:
  - For **5.0TeV** (energy extraction time constant for the RB 75sec for the RQ 15sec, RRR=100):
    - **RB: 43 μΩ**
    - **RQ: 41 μΩ**
  - For **3.5TeV** (energy extraction time constant for the RB 50sec for the RQ 10sec, RRR=100):
    - **RB: 76 μΩ**
    - **RQ: 80 μΩ**
  - If RRR is 200, add 10 μΩ to the above numbers for both RB and RQ
  - If the RRR in increased from 100 to 160, we gain **0.3TeV** per beam

(*) see his talk this afternoon

The options

- I have tried to concentrate on options applicable this year, that is, relatively simple methods that would not need a huge infrastructure effort.
- I will assume that the time available for major repairs in the machine this year will be minimal. Therefore I will mostly concentrate on how we can increase our knowledge of the splices in the machine without actually a major repair campaign.
- There are three broad categories of options during 2010 that would increase our knowledge of the splices in the machine and allow us to run at a higher energy:
    1. Warm up and measure (with selective repairs) at 300K
    2. Measure splices using low currents (RRR measurements)
    3. Measure splices using high currents (Thermal amplifier)

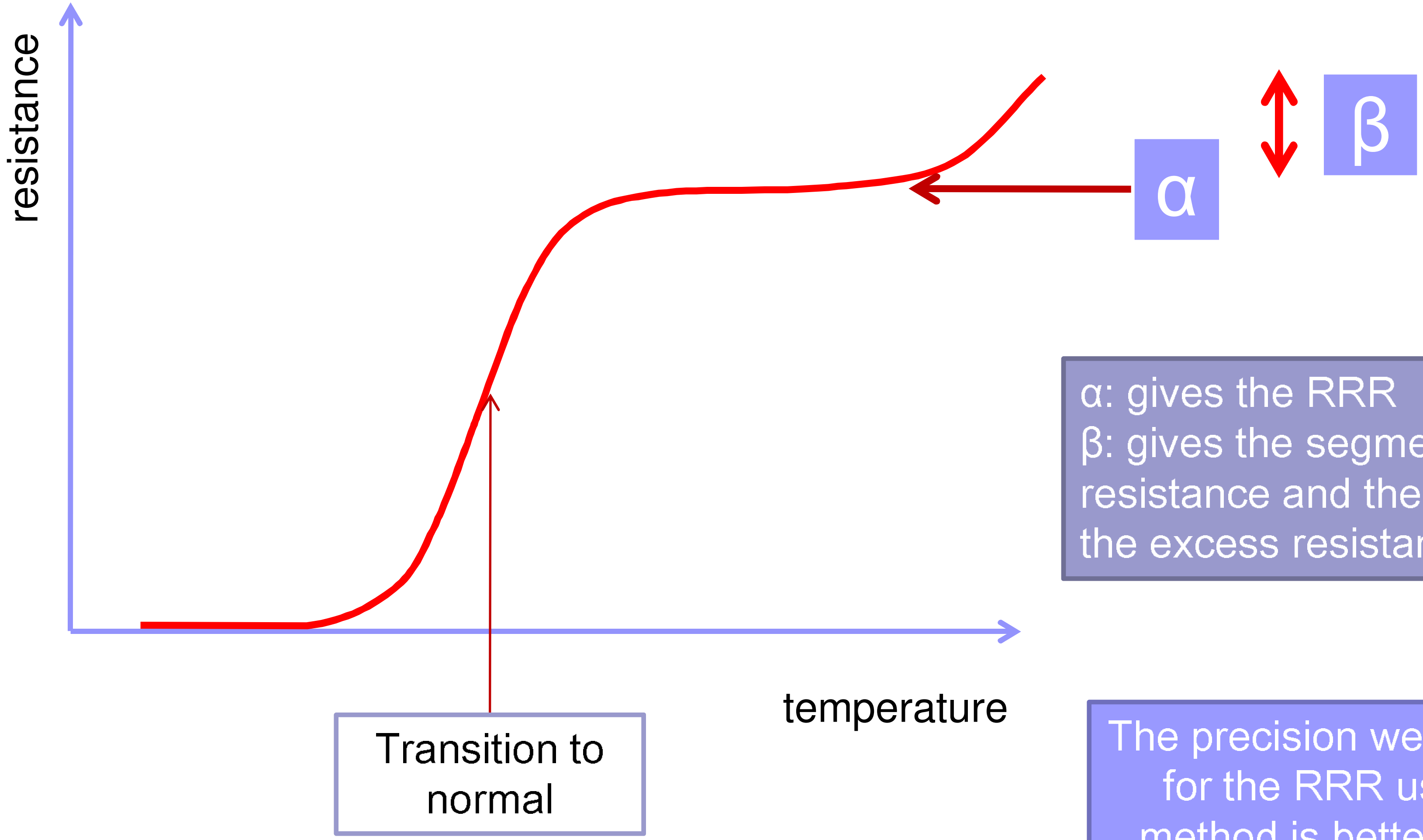
Option 1: warm up

- Idea is to warm up the 3 sectors we have not measured at warm, measure the busbar resistances, repair, and cool down again.
- (At the same time and in the shadow we can repair the 4-5 worse splices in the rest of the machine)
- Advantages:
  - We know how to do it
- Disadvantages:
  - The option with the longest intervention – heavy re-commissioning
  - Our knowledge of the **RQ bus** in the remaining sectors is not good enough
- Time needed:
  - 1 month for warm up; 1 month of repairs; 1 month of cool down; 2 weeks of re-commissioning
- Possible gain:
  - Highest excess resistance from 90uOhms→60uOhms **but only for the RB**

Option 2: RRR measurements

- Currently the RRR measurements of the copper stabilizer of the machine are not very accurate and plagued by systematic errors.
- This has led us to take the conservative approach to assume a RRR of 100 for the whole machine.
- A method has been proposed to measure the RRR with a precision of a few % using the nQPS system by injecting a **low** current (20-30A) to the three main circuits of a sector.
- A type test is being performed as we speak (21-28 January 2010)

Option 2: RRR measurements II

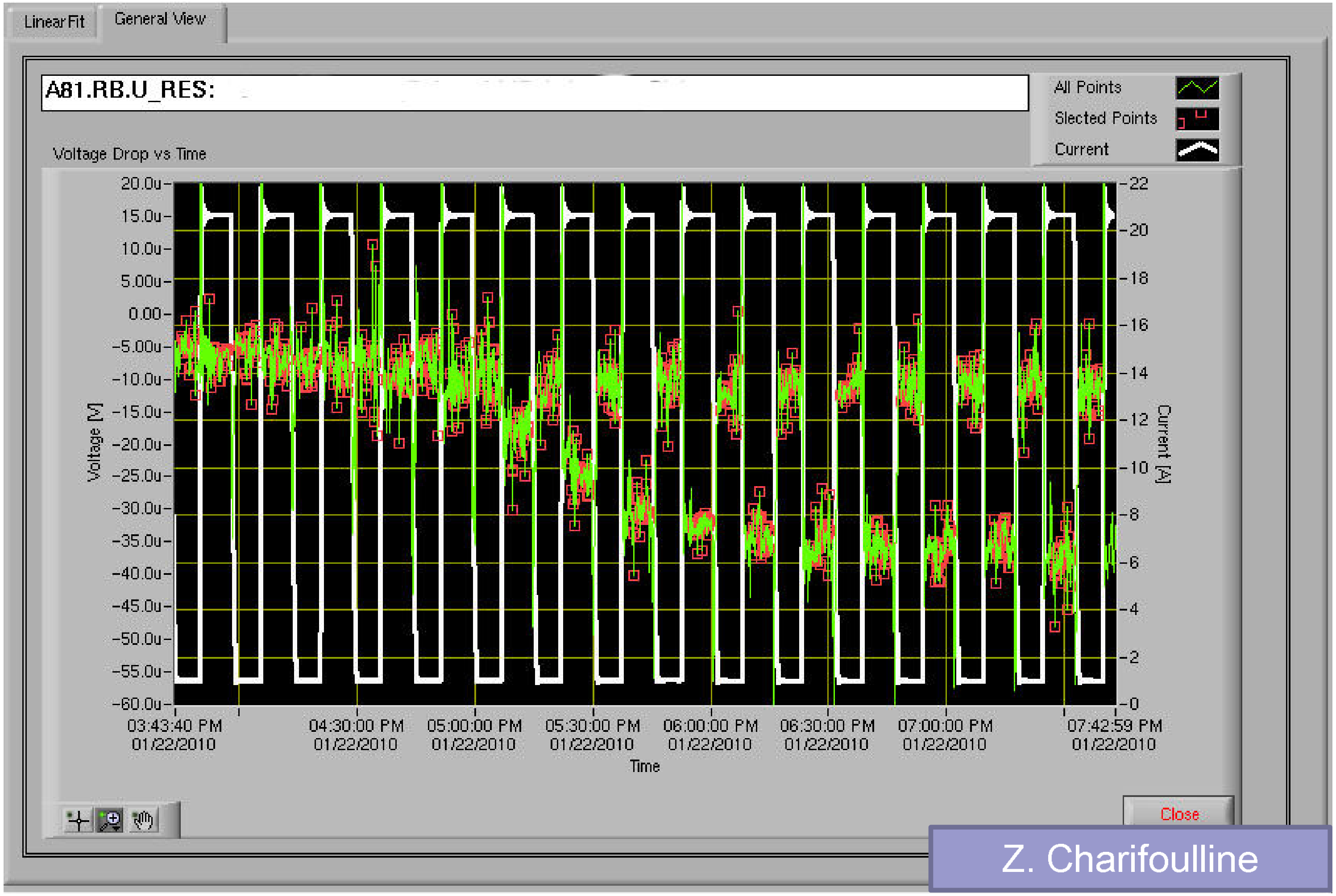


α: gives the RRR
β: gives the segment resistance and therefore the excess resistance

The precision we can obtain for the RRR using this method is better than we will ever need

RRR type test

- What we see in practice:



Z. Charifoulline

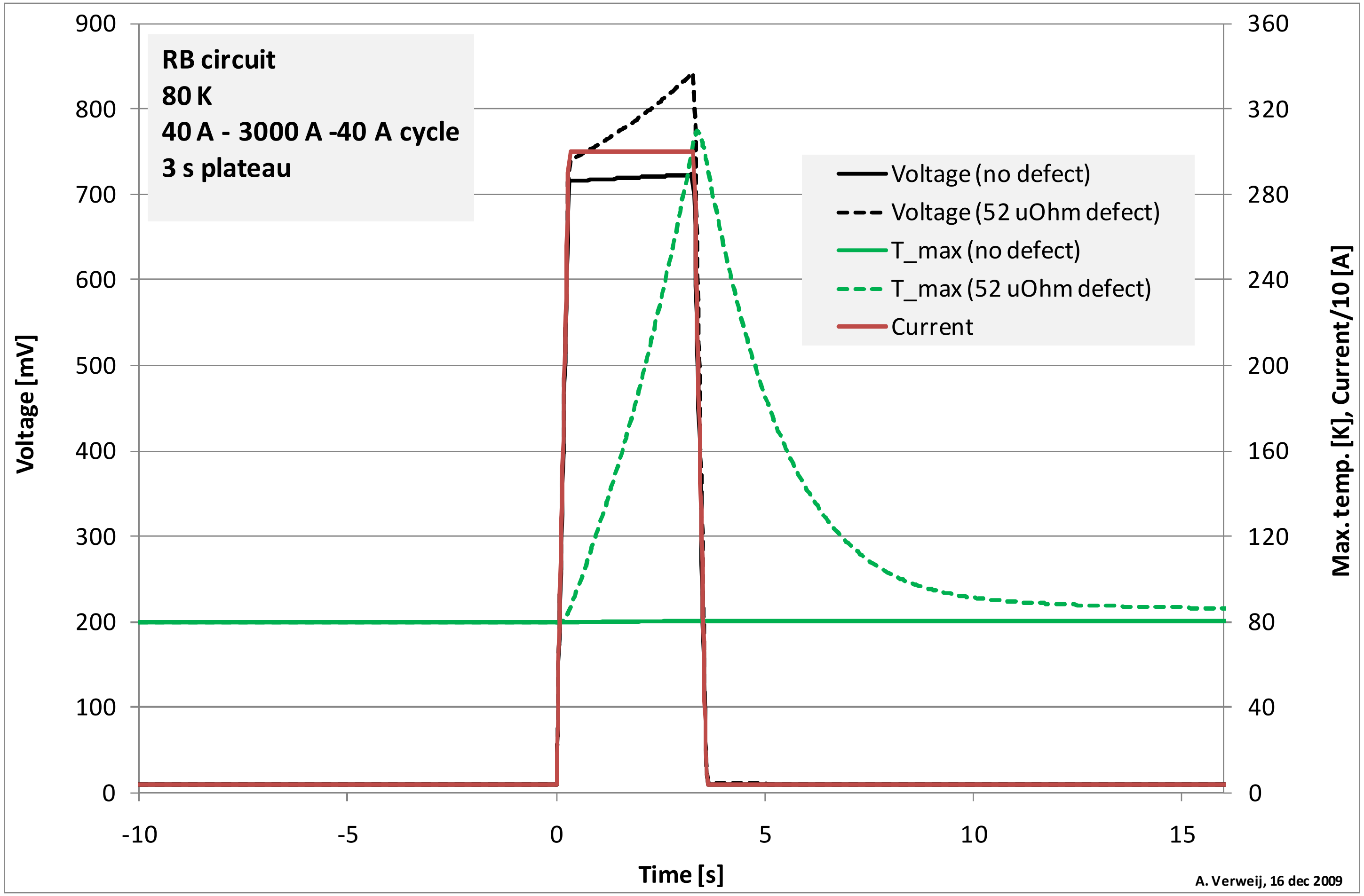
RRR measurements pros and cons

- Advantages:
  - uses low current so it is safe
  - only moderate increase of temperature makes test rather fast (to 15K for RRR measurements, to 35K if excess resistance also is to be measured)
  - type test under way
- Disadvantages:
  - difficult to measure excess resistances
- Time needed:
  - for RRR only: 3 days to warm up, 1 for measurement, 2 for cooldown
  - RRR plus excess resistance: 2 weeks
- Possible gain:
  - getting confidence that the lowest RRR of the machine is 160 and not 100 would allow to run 0.3TeV higher; alternatively, would give a higher margin at 3.5TeV

Option 3: Thermal amplifier

- The original idea comes from H. Pfeffer and has been refined by A. Verweij who also did the calculations
- A **high current** pulse **warms up** selectively the bad joints in a highly non-linear way
- **Low current** is used for **reading out** voltages using the nQPS system and hence identify areas where the temperature has increased the resistance of the copper
- The method is safe as the high current pulse will go in steps (to order 3000A and order 10 seconds maximum)
- The method is a **before-after** measurement, meaning that various parameters that affect the resistance (for example RRR, geometry, etc.) cancel out
- The method is sensitive to the **highest** resistance in a segment, not to the **sum** of all splices.

Example of a segment with a 52uOhm defect

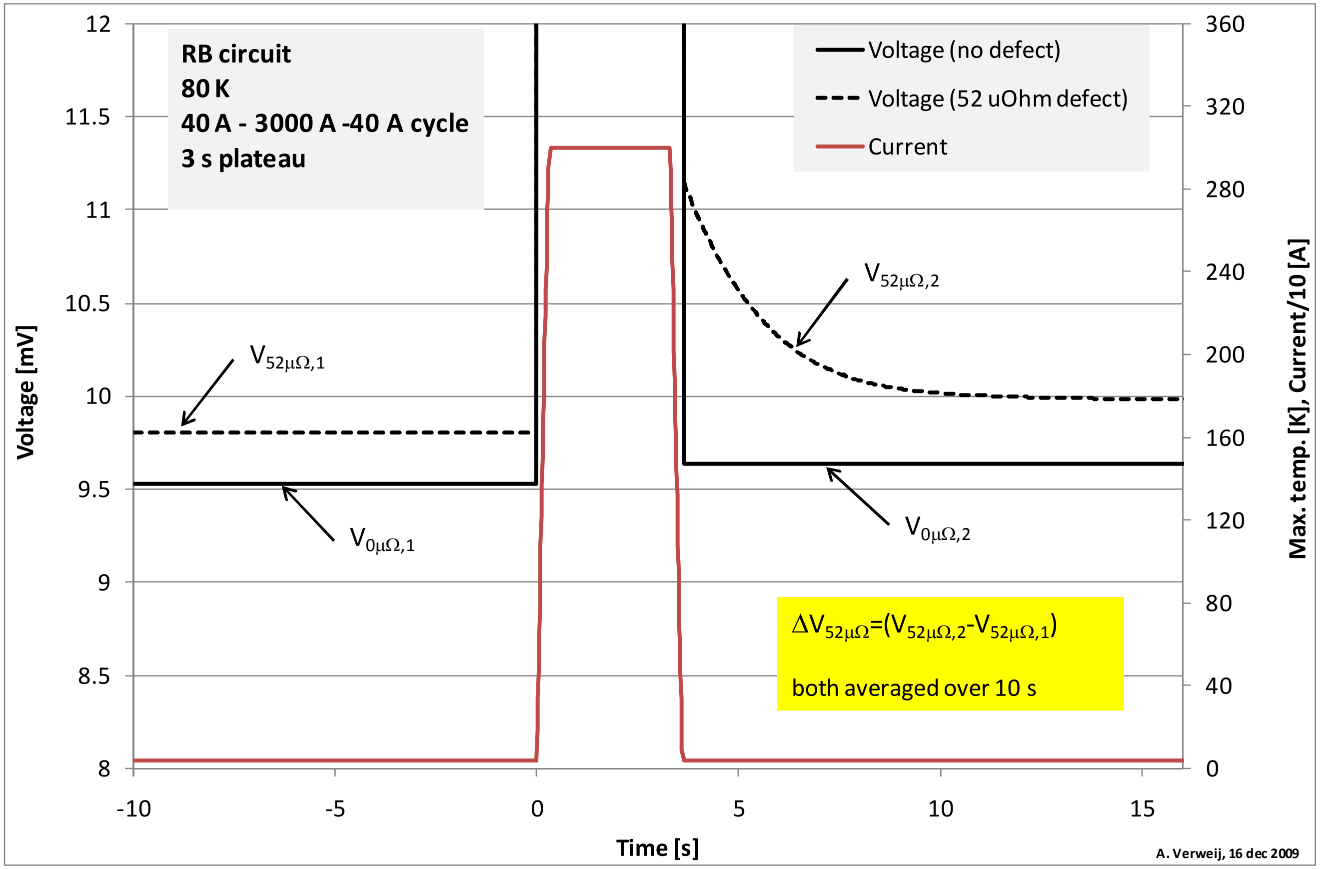


A. Verweij, 16 dec 2009

High Current pulse is 3000A for 3 seconds

- The temperature starts running away and reaches 320K.

Voltage (detail)



The voltage in case of a 52uOhm defect rises sharply and decays (with a time constant of 5 seconds) to a new level higher than before [this will eventually decay with a longer time constant].

- This (medium term) offset is what we will measure

How big an effect?

R_{addit} [$\mu\Omega$]	Temperature (K)	Circuit	$t_{plateau}$ [s]	T_{max} [K]	ΔV_{defect} [μV]	$\Delta V_{0\mu\Omega}$ [μV]	ΔV_{defect}-$\Delta V_{0\mu\Omega}$ [μV]	Ratio=B/A
52	80	RB	3	309	405	121	284	2.4
52	40	RB	10	49	70	61	9	.15
52	50	RB	10	394	553	120	433	3.6
52	60	RB	3	168	149	61	88	1.4
52	80	RQ	3	320	422	350	72	0.2

- A 52µΩ defect is not visible with this method at 40K but easily detectable at 50K (demonstrating the non-linearity of the method)
- We are not interested at defects of lower magnitude in 2010
- The nQPS system used to read out the voltages has a noise level of 5-10µV for 10 seconds

A. Verweij

The thermal amplifier II

- This method has a few engineering challenges
- An important ingredient is the power supplies needed for such a measurement
- the voltage requirements are as follows:
  - RB at 50K:
    - Diode: once diodes open will need 150V
    - Resistive: 10mOhms*3000A = 30V
    - Inductive 3mHenries*3000A/s=10V
    - **Total: 190Volts**. This just above the current RB power supply of 180V/13000A
  - RQ at 50K:
    - Diode: once diodes open voltage drop is 50V
    - Resistive: 1.6*RB bus = 50V
    - Inductive: 10V
    - **Total 110V**
- A small ‘igniter’ power supply will be needed to open the diodes in the RB case
- The requirements for the RB are just beyond the voltage available, and for the RQ circuit, the RB power supply will be sufficient. With a bit of fine tuning the existing RB power supplies might suffice.

Option 3: pros and cons

- Advantages:
  - Sensitive to the worst splice in the segment. This is **particularly interesting for the RQ bus** where all other methods find the sum of all excess resistances
  - Quick to perform once the infrastructure is there
- Disadvantages:
  - Interlocking issues due to the current level
  - engineering and integration issues
- Time needed (approx.):
  - 10 days to warm up, three days of measurements, 10 days to cool down
- Possible gain:
  - can find all splices larger than 50µΩ and if none are above, say , 60 µΩ would enable to run between 4-4.5TeV
- A type test will be needed.

Conclusions

- Splices at cold (in the superconducting state) have been measured with excellent accuracy and do not pose a problem.
- Splices at warm (copper stabilizer) have been measured in part of the machine and extrapolated to the whole machine using statistical methods.
  - worse splice measured: **60±1μΩ**
  - worse splice known to exist in the machine: **53±15μΩ**
  - worse splice extrapolated: **90μΩ**
- The current knowledge of the interconnect splices leaves no margin even for operation at 3.5TeV.
- 5TeV running is excluded without major repairs after a warm up.
- Two methods have been proposed to increase our knowledge of the interconnect splices
  - A low current method that can measure the RRR of the busbars
  - A high current method (the Thermal Amplifier) that is sensitive to the worst splices in all bus bar segments
- Using any of the above methods would allow us to either run at a higher energy around 4TeV and/or get a bigger margin at 3.5TeV.

End