LHC

HardWare Commissioning

Who knew what when?

Bob Flora
&
Howie Pfeffer

LHC HWC OVERVIEW

- Early Commissioning
- 2008 September 10... Utopia
- 2008 September 19... Disaster
  - What actually happened? First hand account
  - Collateral damage
  - Who knew what when?
- QPS Reborn: “nQPS”
  - Bus Monitoring redone 500,000 better!
  - Symmetric Quench Detector
- Bad News... The Silent Thrillers
- Good News... Great Joints (Superconducting)
- Why 3.5 TeV ? The Chamonix Decision ==> Howie

Early Commissioning

(before 2008 September... a time of innocence)

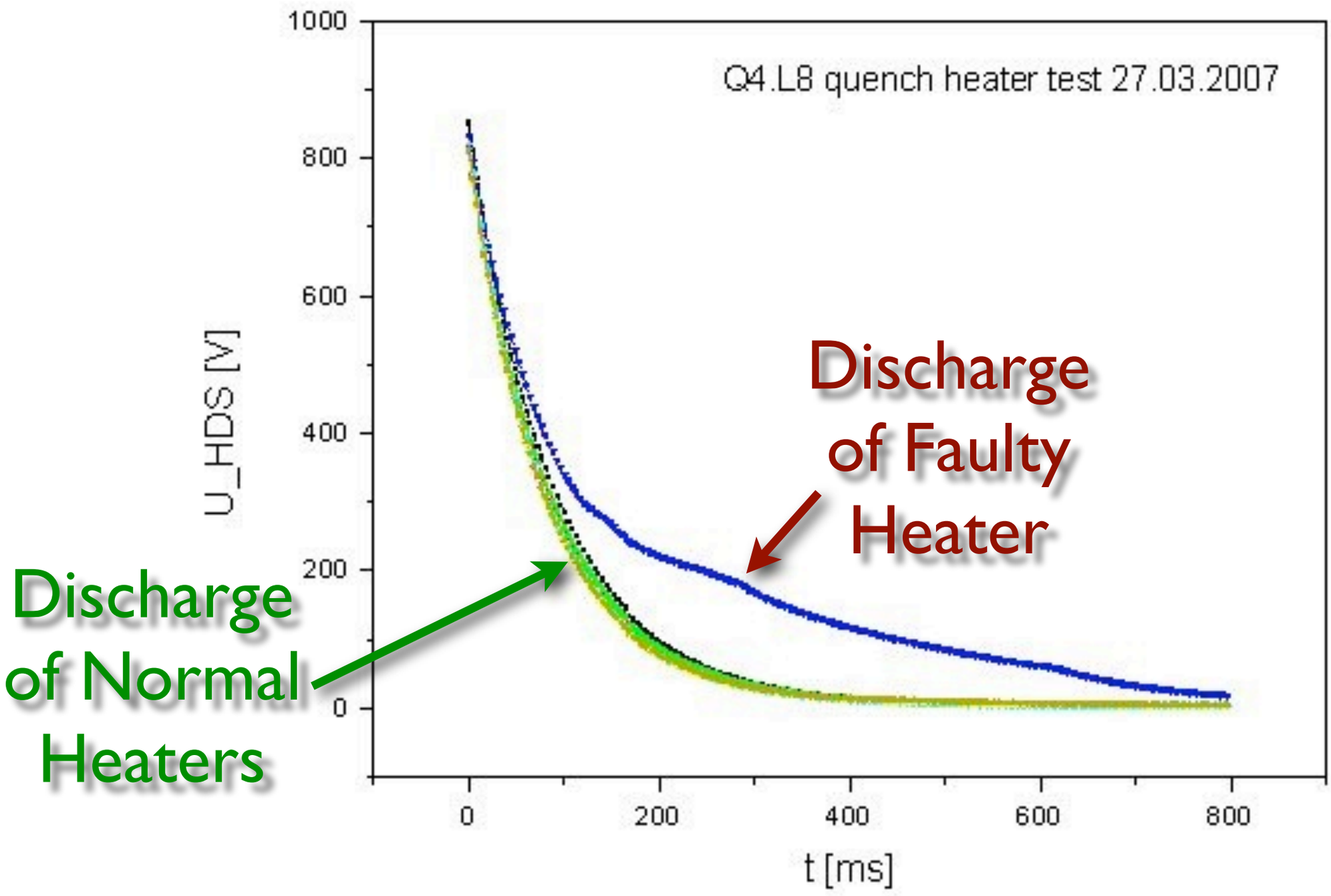
Who know what was lurking?

VARIOUS ISSUES SURFACED

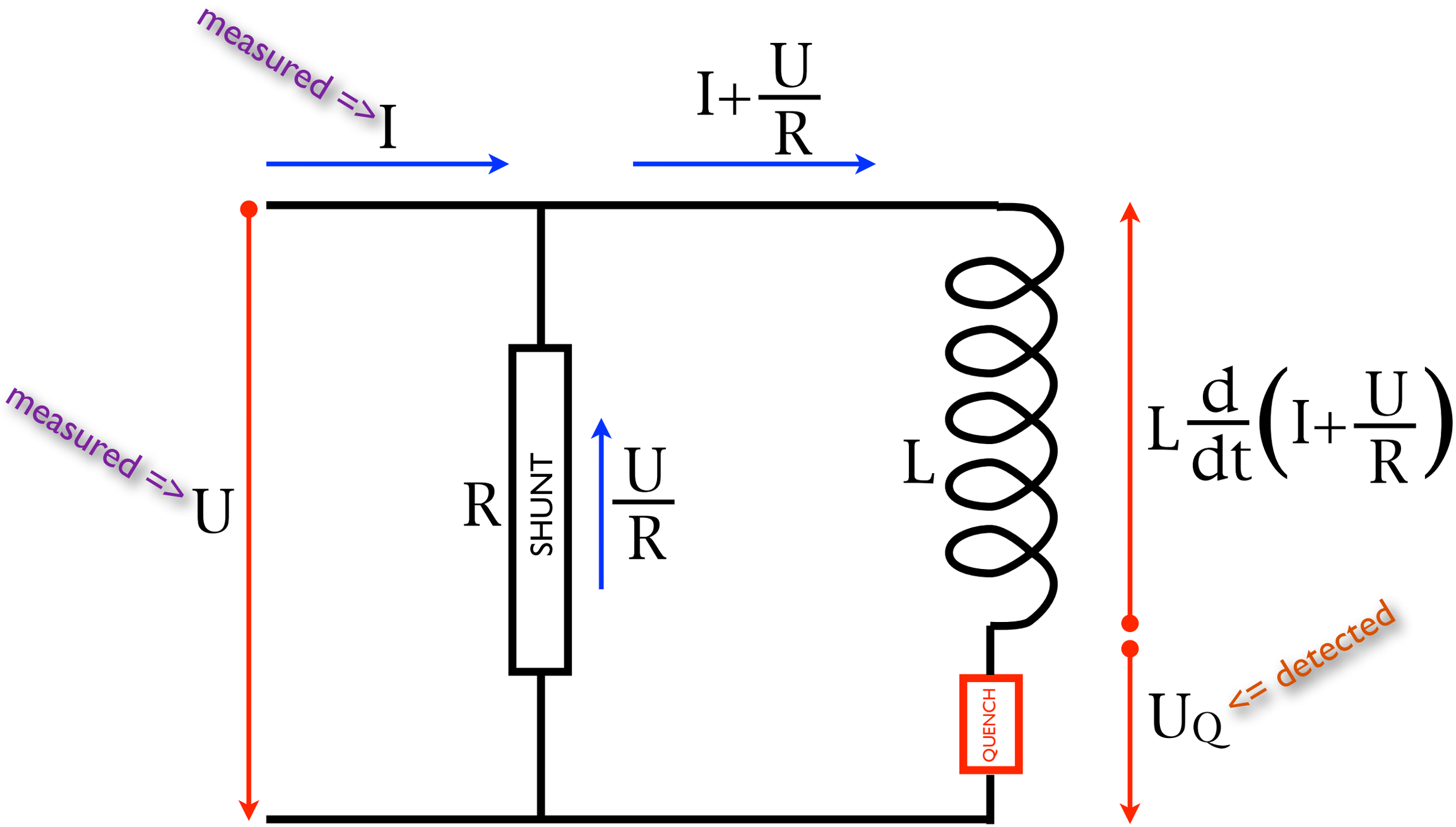
- faulty heaters
- differential interstrand eddie current time constants
- transmission line gas bubbles
- second order effects in absolute detectors
- symmetric quenches

All Quench Heaters in 7/8 performed Admirably except One

This heater was subsequently retired, however the remaining heaters provided more than adequate protection, thanks to built in redundancy.



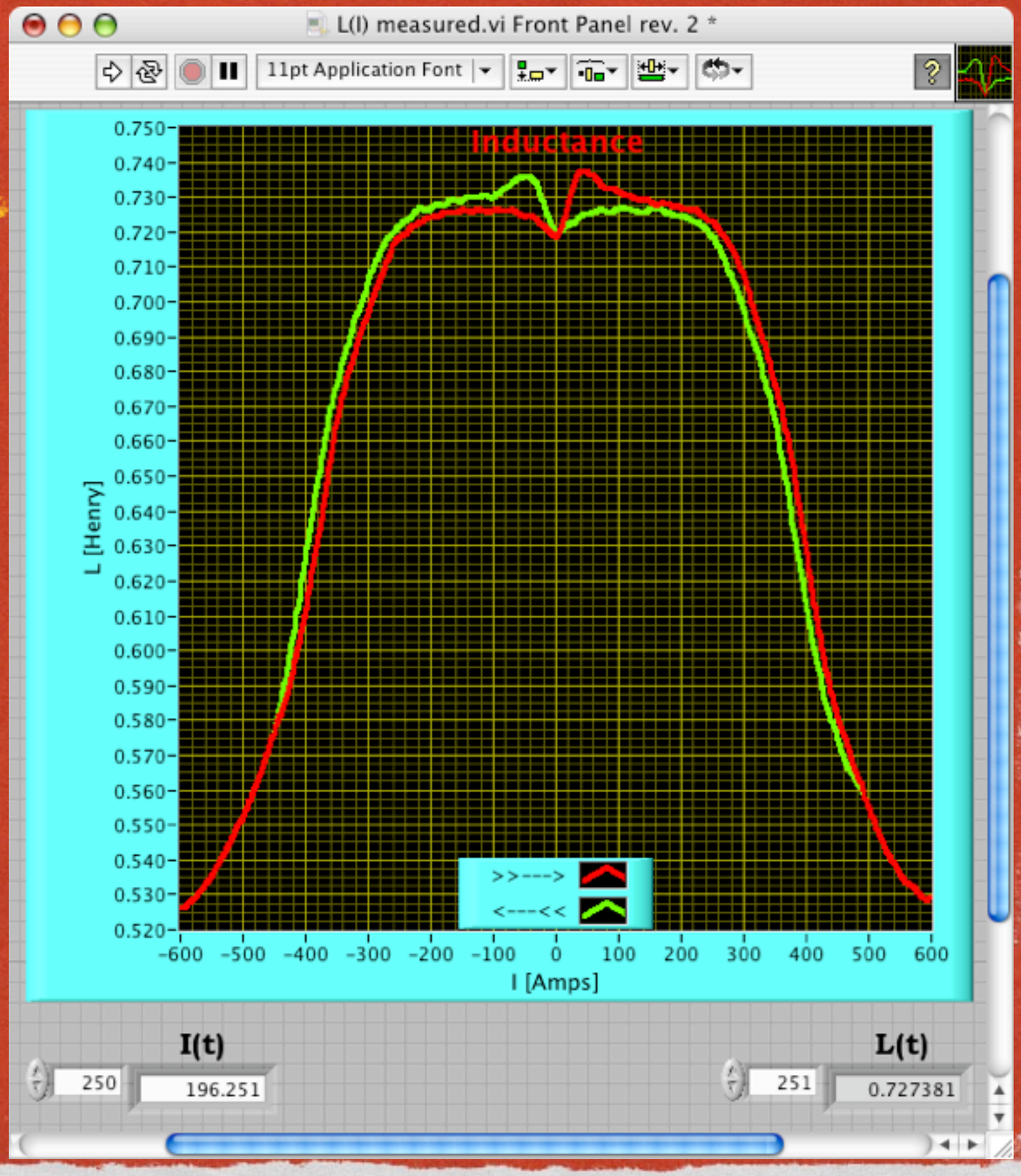
Direct Quench Detection with Shunt

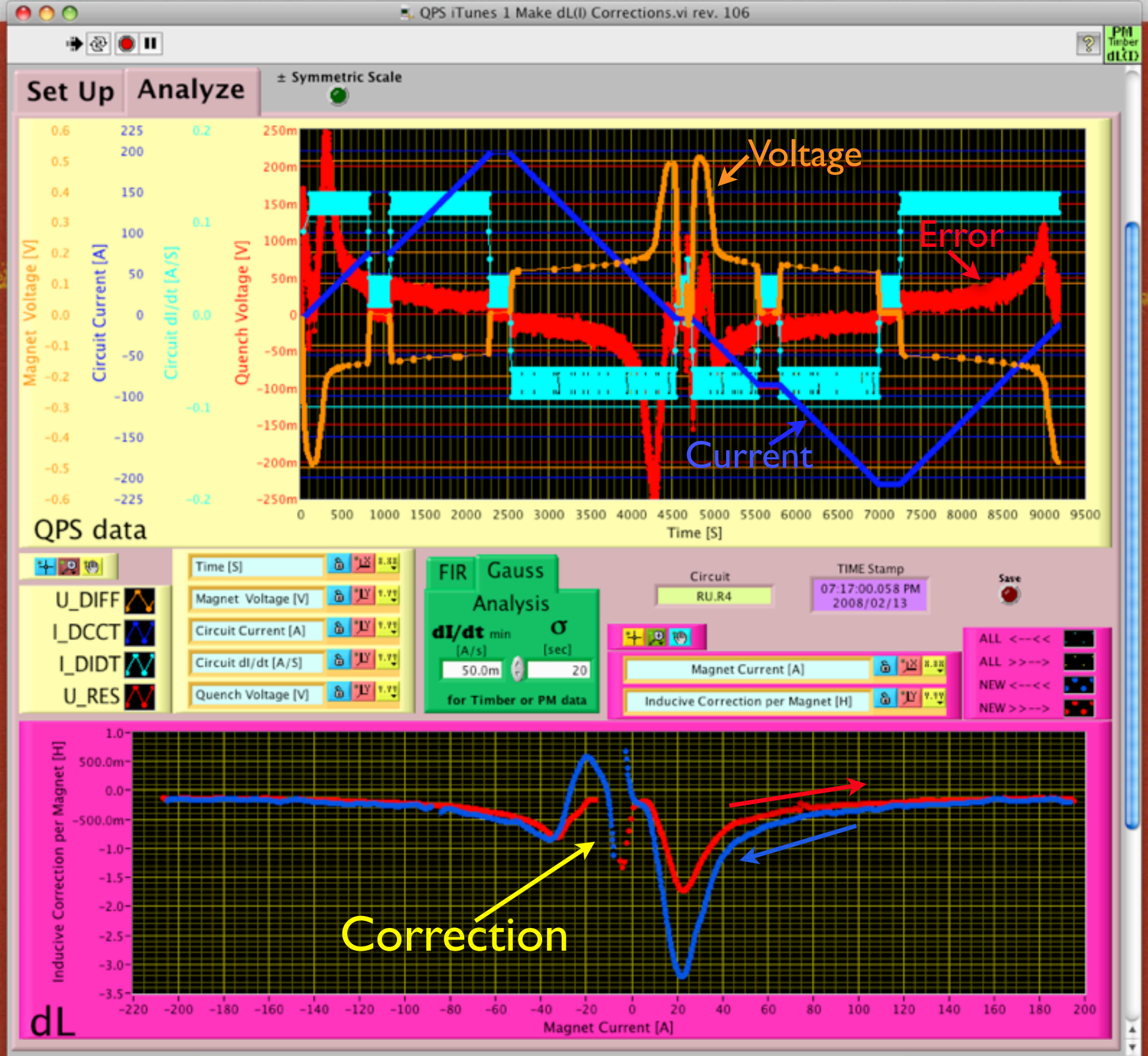


$$U_Q = U + L\frac{d}{dt}\left(I+\frac{U}{R}\right) = U + L\left(\dot{I}+\frac{\dot{U}}{R}\right)$$

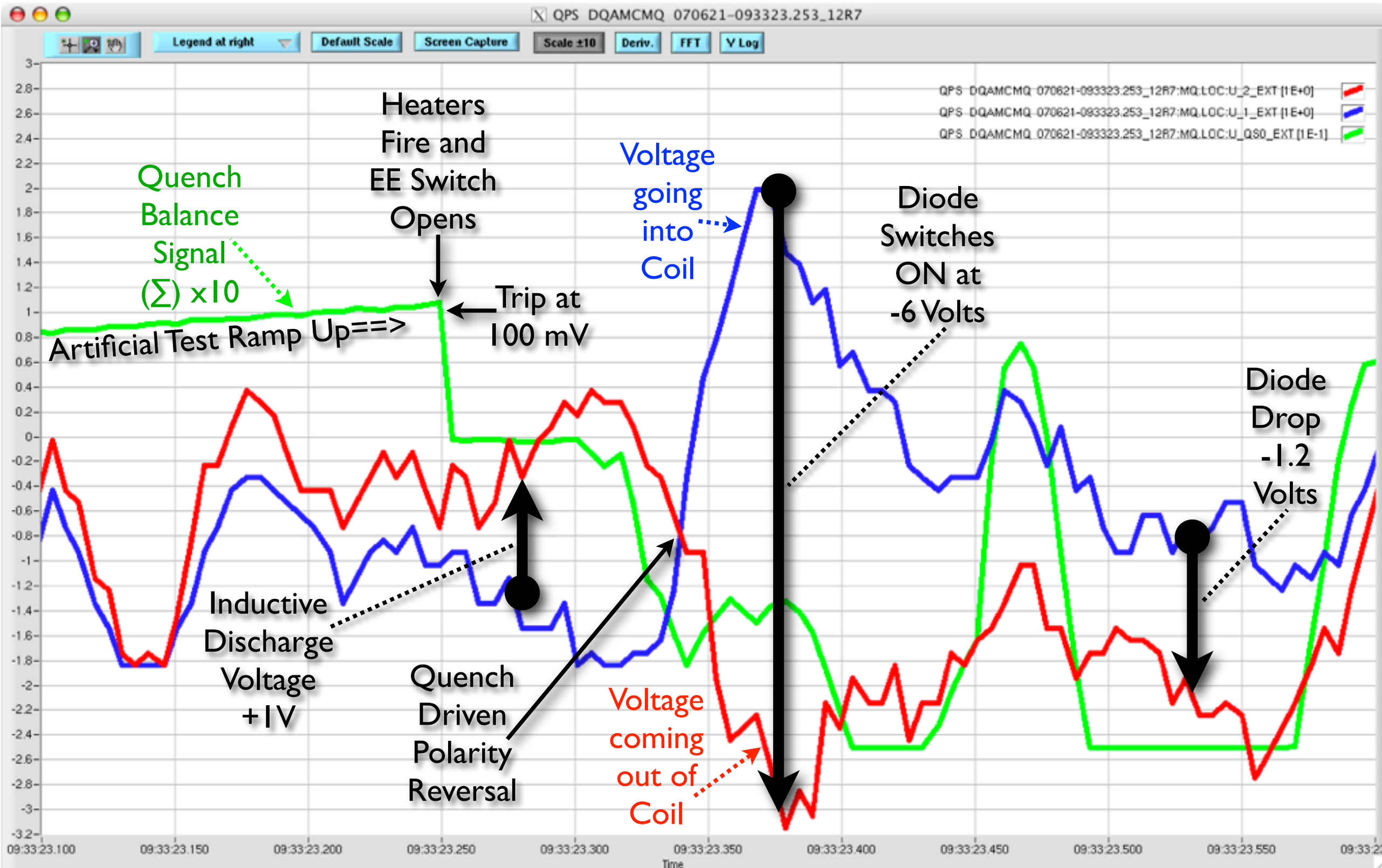
CORRECTOR STRING INDUCTANCE

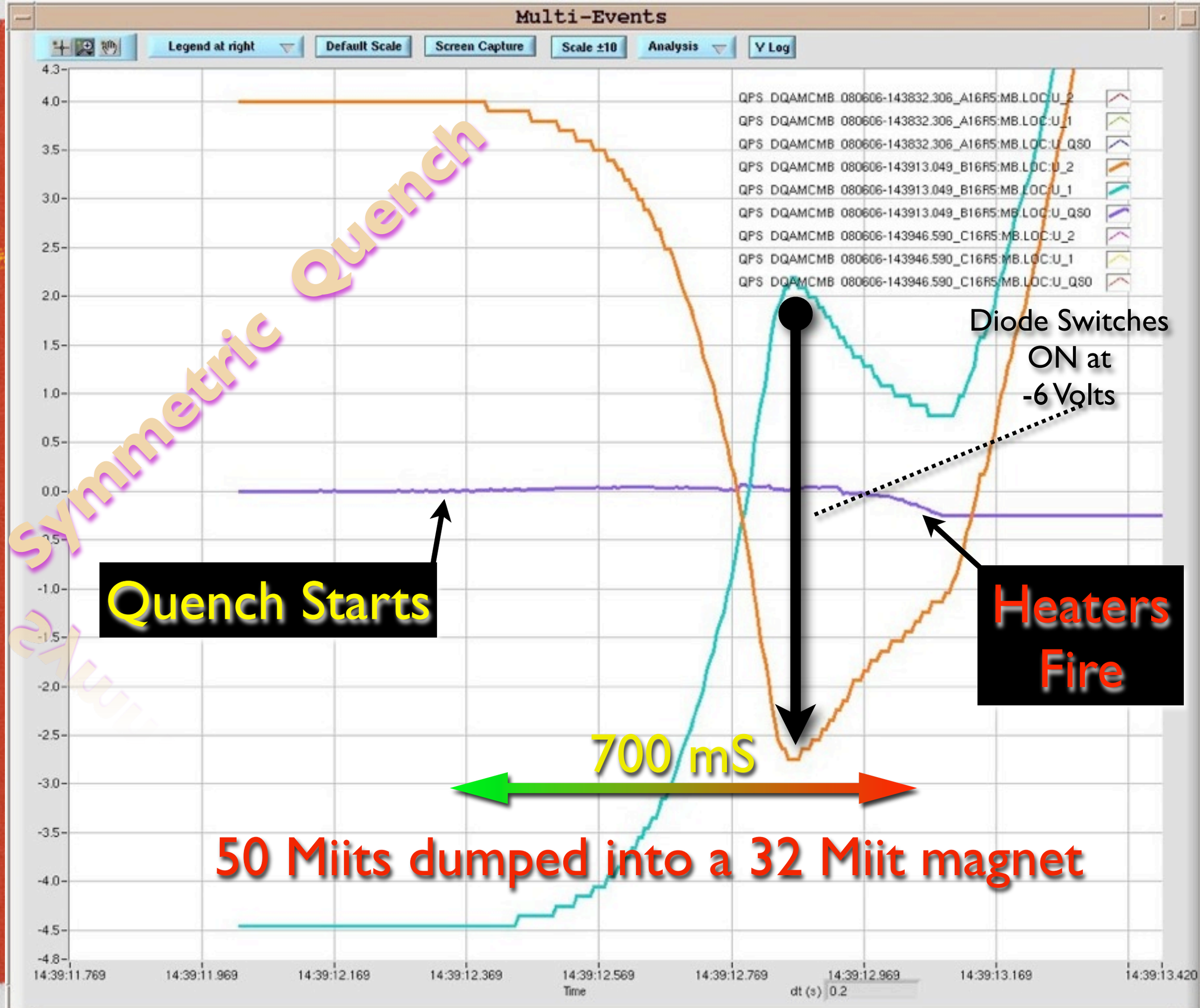
- saturation
- hysteresis
- in situ measured corrections




QPS iTunes 1 Make dL(I) Corrections.vi rev. 106
Set Up
Analyze
± Symmetric Scale
Voltage
Error
Current
Magnet Voltage [V]
Circuit Current [A]
Circuit dI/dt [A/S]
Quench Voltage [V]
Time [S]
QPS data
U_DIFF
I_DCCT
I_DIDT
U_RES
Time [S]
Magnet Voltage [V]
Circuit Current [A]
Circuit dI/dt [A/S]
Quench Voltage [V]
FIR
Gauss
Analysis
dI/dt min [A/s]
σ [sec]
50.0m
20
for Timber or PM data
Circuit
RU.R4
TIME Stamp
07:17:00.058 PM
2008/02/13
Save
Magnet Current [A]
Inducive Correction per Magnet [H]
ALL <--<<
ALL >>-->
NEW <--<<
NEW >>-->
Correction
Inducive Correction per Magnet [H]
Magnet Current [A]
dL

Diode Performance during 6.5 kA Quench of Main Quad QD.12R7




Multi-Events
Legend at right
Default Scale
Screen Capture
Scale ±10
Analysis
Y Log
QPS DQAMCMB 080606-143832.306_A16R5:MB.LOC:U_2
QPS DQAMCMB 080606-143832.306_A16R5:MB.LOC:U_1
QPS DQAMCMB 080606-143832.306_A16R5:MB.LOC:U_QS0
QPS DQAMCMB 080606-143913.049_B16R5:MB.LOC:U_2
QPS DQAMCMB 080606-143913.049_B16R5:MB.LOC:U_1
QPS DQAMCMB 080606-143913.049_B16R5:MB.LOC:U_QS0
QPS DQAMCMB 080606-143946.590_C16R5:MB.LOC:U_2
QPS DQAMCMB 080606-143946.590_C16R5:MB.LOC:U_1
QPS DQAMCMB 080606-143946.590_C16R5:MB.LOC:U_QS0
Symmetric Quench
Diode Switches ON at -6 Volts
Quench Starts
Heaters Fire
700 mS
50 Miits dumped into a 32 Miit magnet
4.3
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-1.0
-1.5
-2.0
-2.5
-3.0
-3.5
-4.0
-4.5
-4.8
14:39:11.769
14:39:11.969
14:39:12.169
14:39:12.369
14:39:12.569
14:39:12.769
14:39:12.969
14:39:13.169
14:39:13.420
Time
dt (s) 0.2

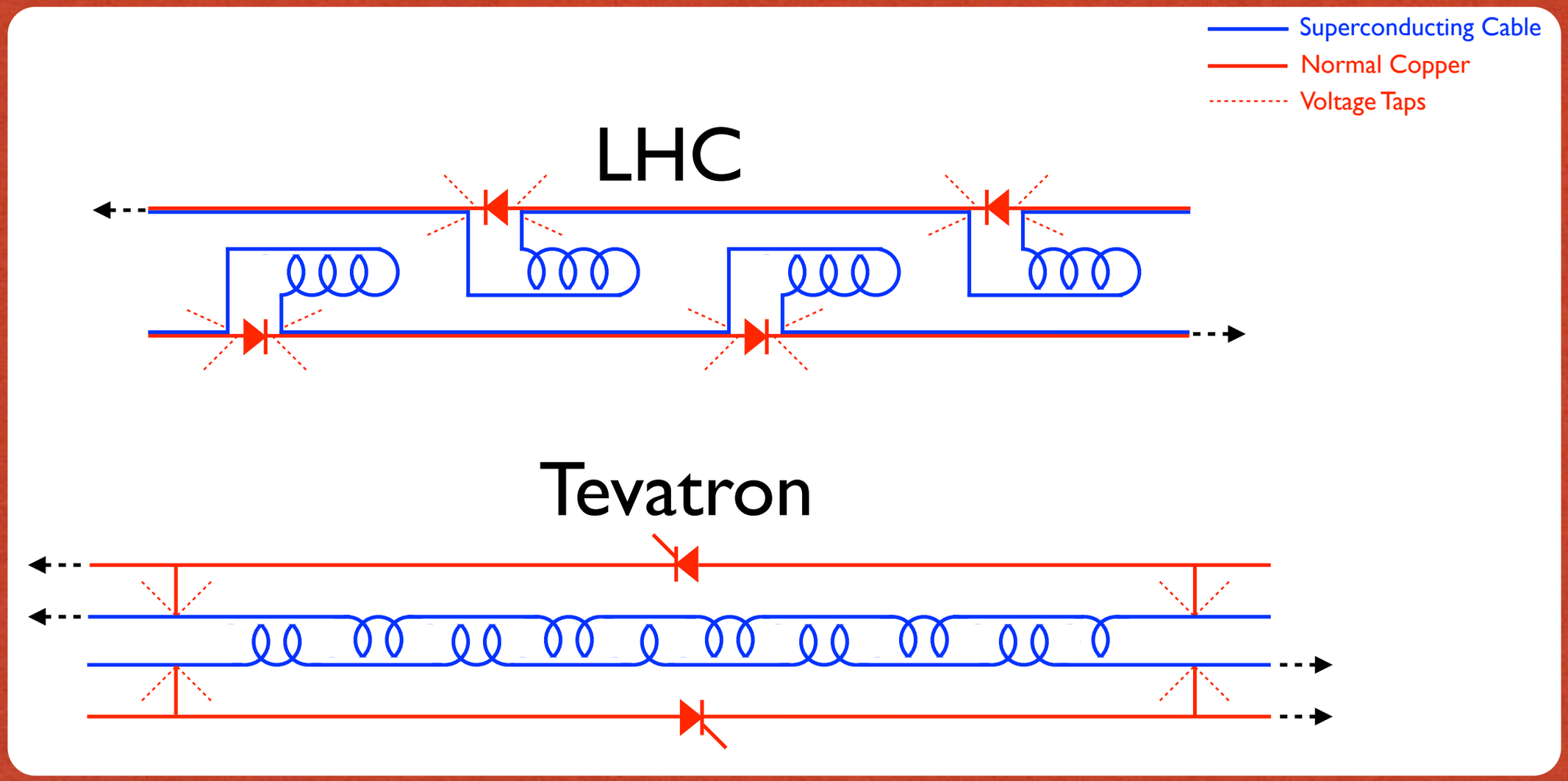
- Mission Accomplished!
  - (except for one small sector... 34)

2008 September 10 ... Utopia!

2008 SEPTEMBER 19 11:18:36 AM

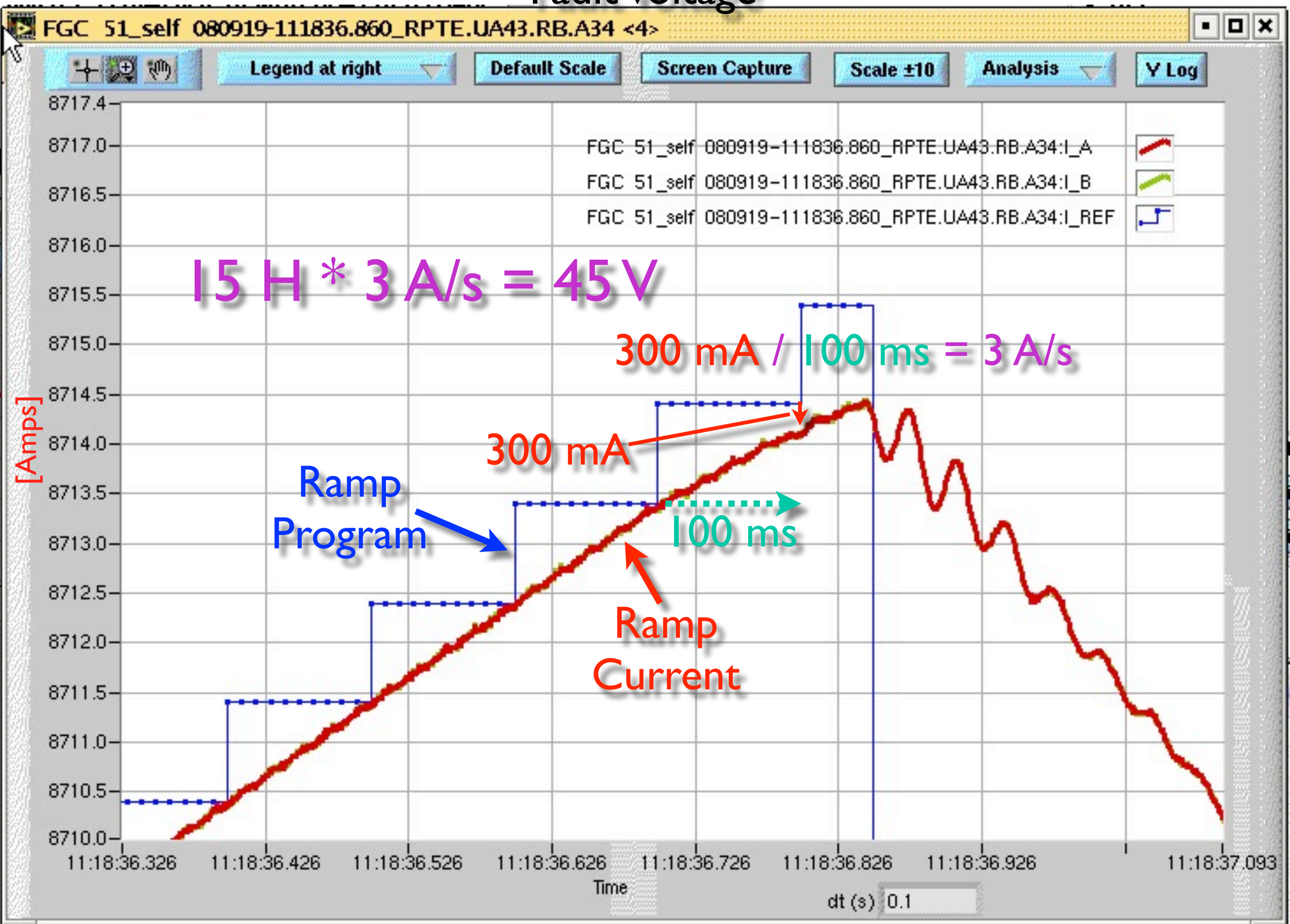
~~DISASTER~~ "bad solder joint and helium leak"

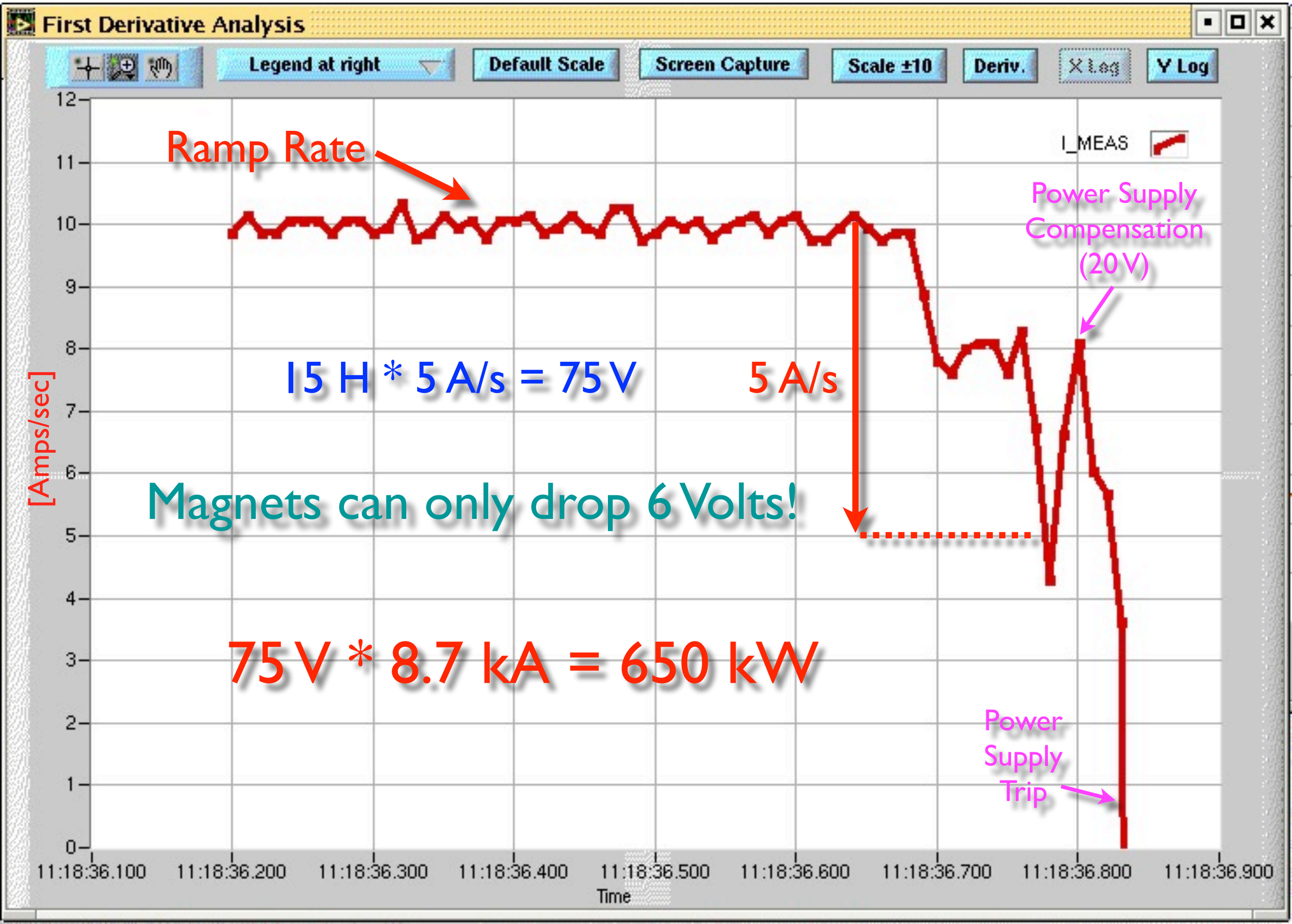
Bypass Topology Comparison



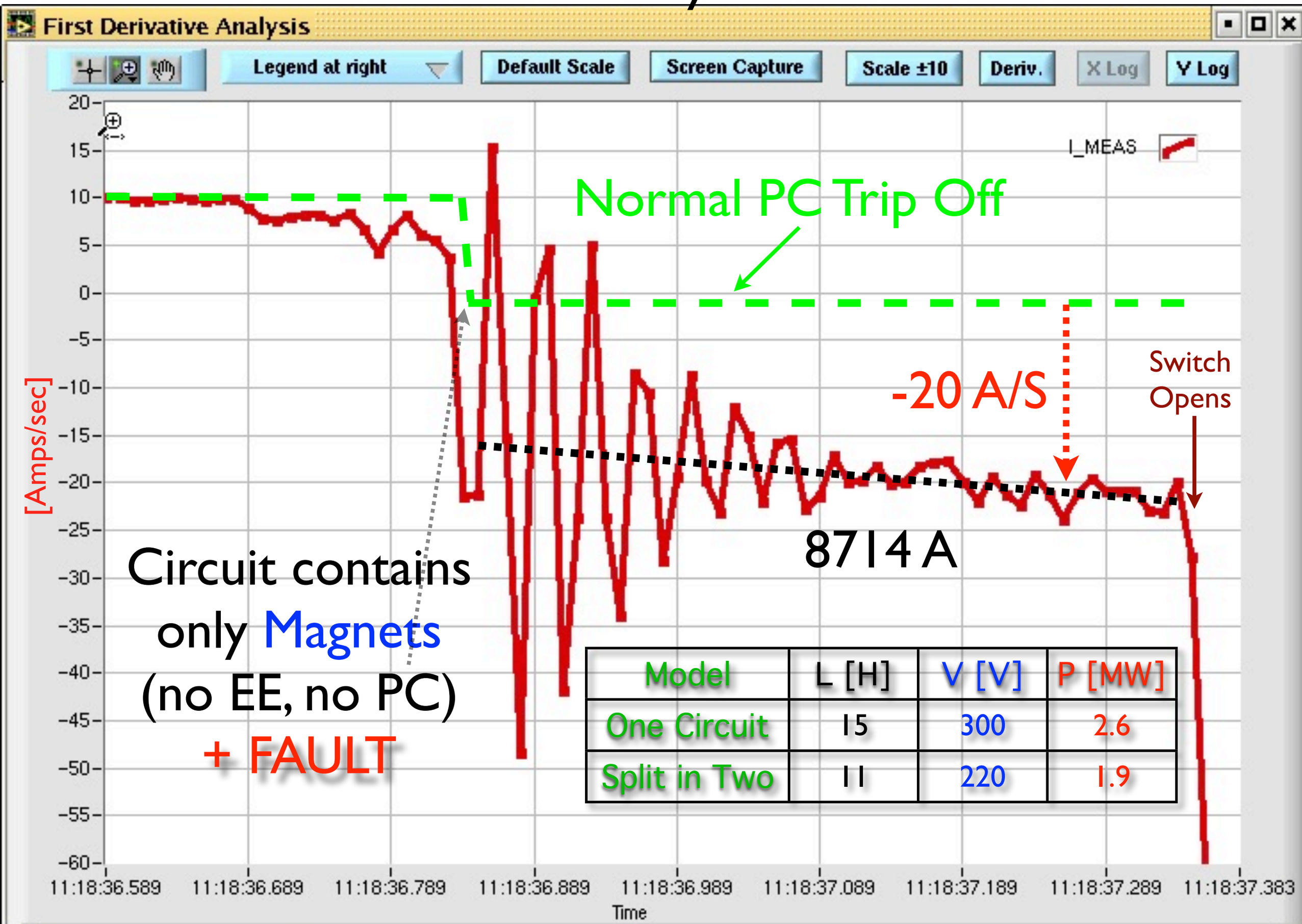
- At ~11 AM Friday morning, Boris (later to be known as the "The Destroyer") with the click of a mouse, initiated the fateful ramp.

Fault Voltage




First Derivative Analysis
Legend at right
Default Scale
Screen Capture
Scale ±10
Deriv.
X Log
Y Log
I_MEAS
Ramp Rate
Power Supply Compensation (20 V)
15 H * 5 A/s = 75 V
5 A/s
Magnets can only drop 6 Volts!
75 V * 8.7 kA = 650 kW
Power Supply Trip
[Amps/sec]
0
1
2
3
4
5
6
7
8
9
10
11
12
11:18:36.100
11:18:36.200
11:18:36.300
11:18:36.400
11:18:36.500
11:18:36.600
11:18:36.700
11:18:36.800
11:18:36.900
Time

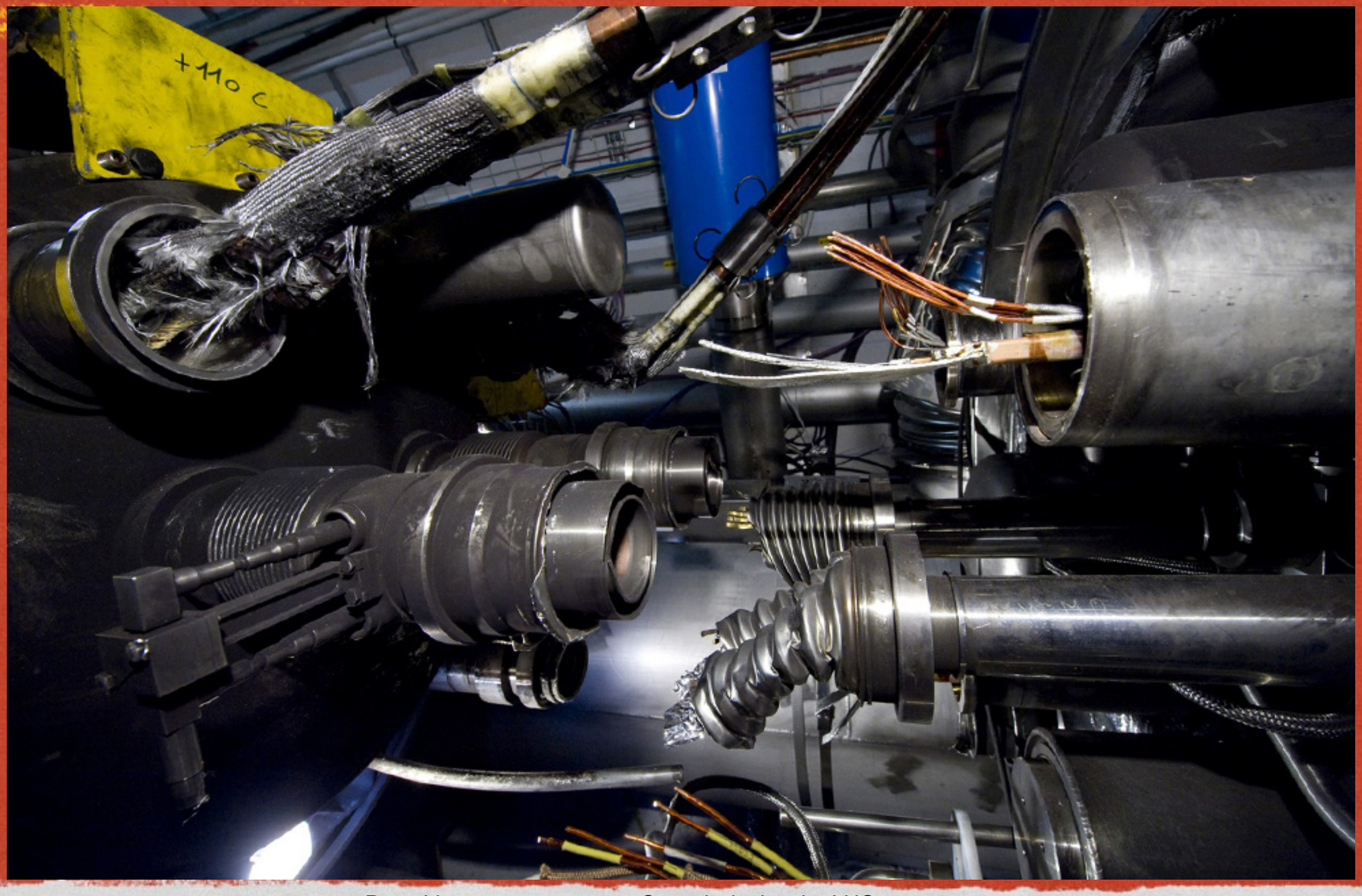
dI/dt analysis

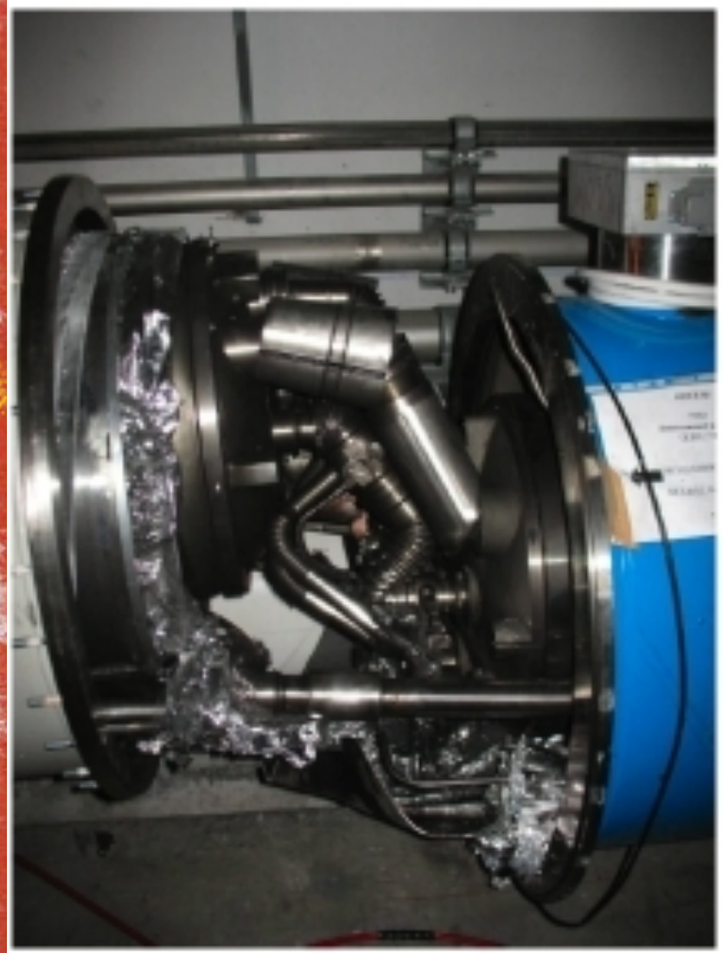


Model	L [H]	V [V]	P [MW]
One Circuit	15	300	2.6
Split in Two	11	220	1.9

Primary Damage

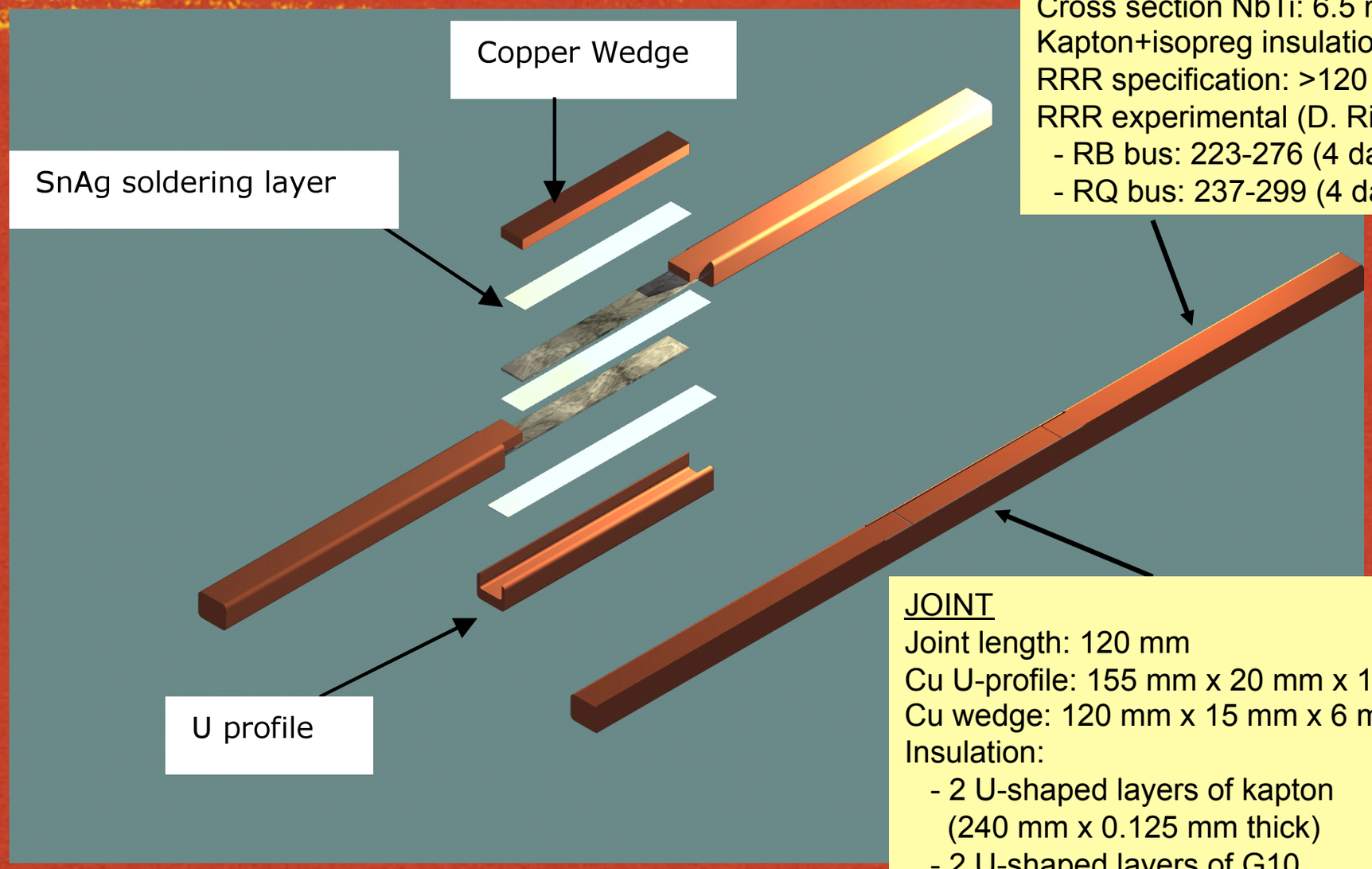
- "bad solder joint and helium leak"





- Examples of Collateral Damage

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)

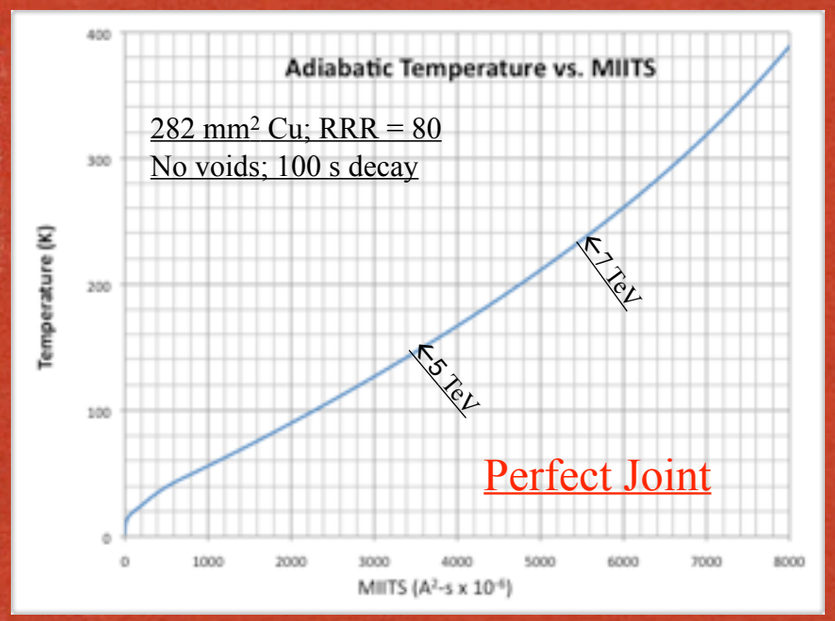
LHC Temperature vs. MIITS

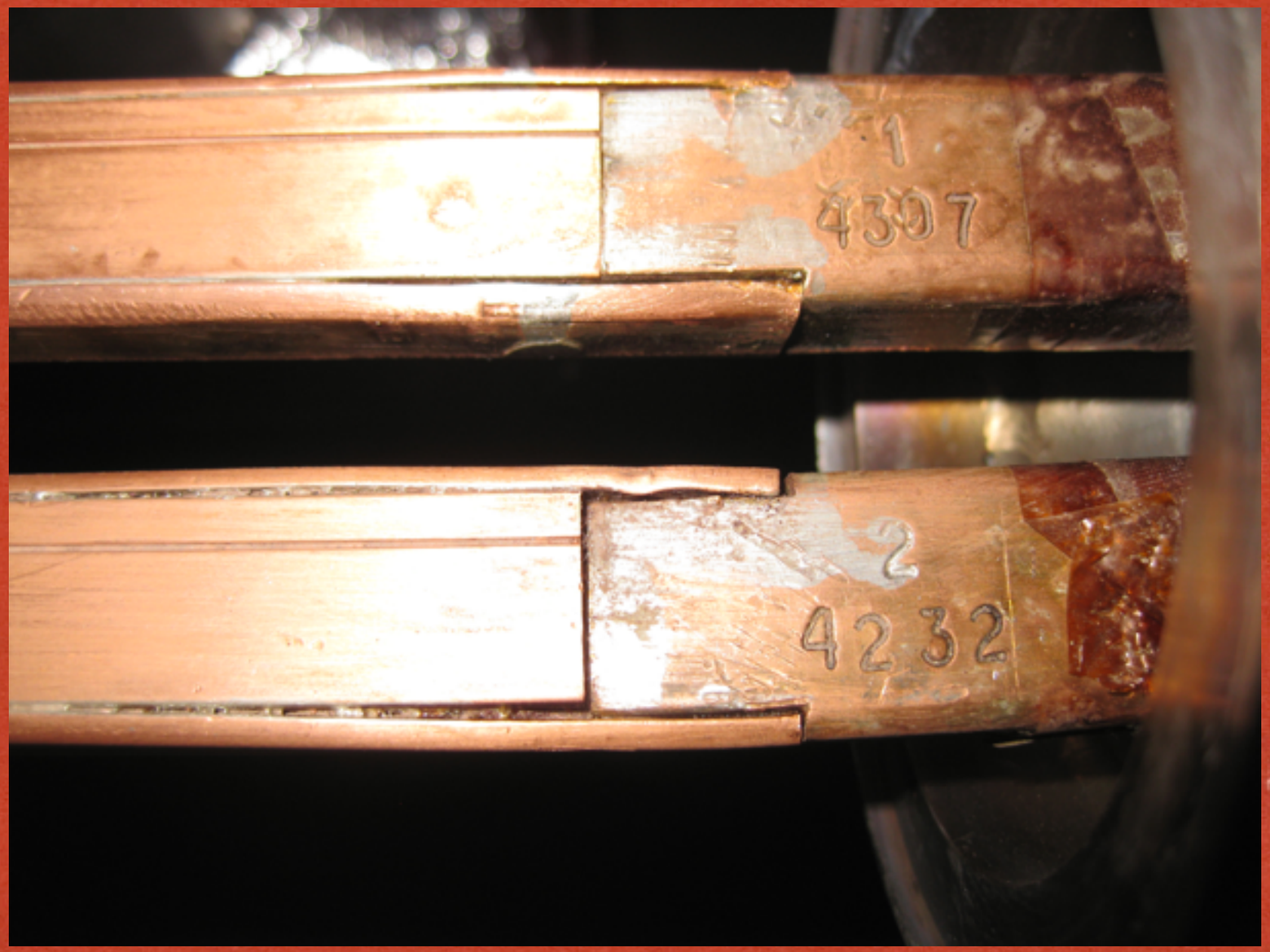
$$\int_{t_0}^{t_1} I(t')^2 dt' = A \cdot A_{cu} \cdot \int_{T_0}^{T} \frac{c(T')}{\rho(T')} dT' \equiv F(T)$$

- Good joint = No problem
- So, what happened on 9/19?

I^2t in units of 10^6 A^2-s (MIITS)

- Not all joints are perfect



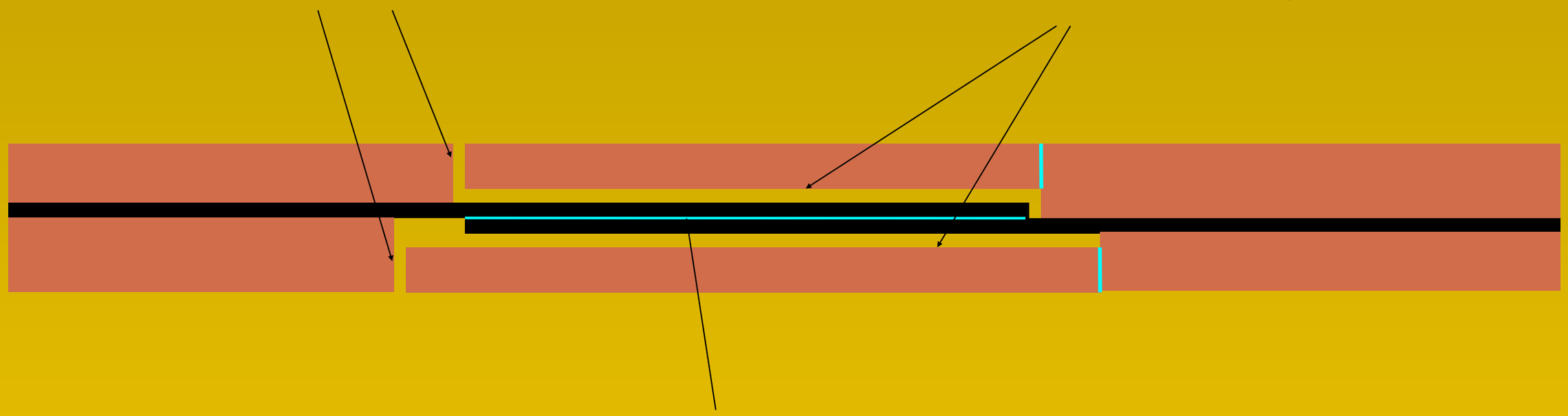


Peter Limon

The incident: most likely scenario

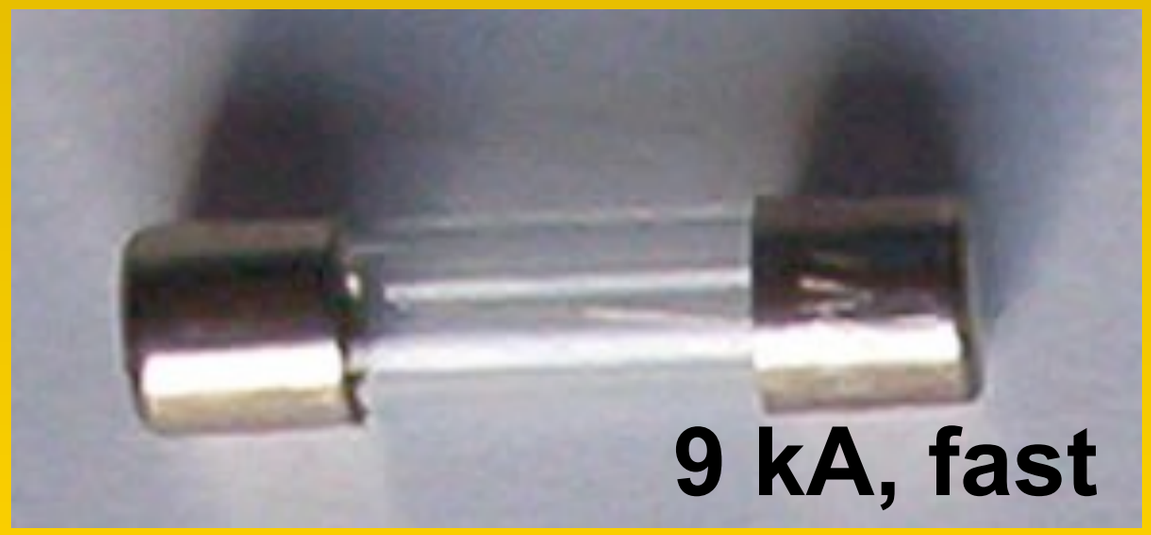
Bad electrical contact between wedge and U-profile with the bus on at least 1 side of the joint

Bad contact at joint with the U-profile and the wedge



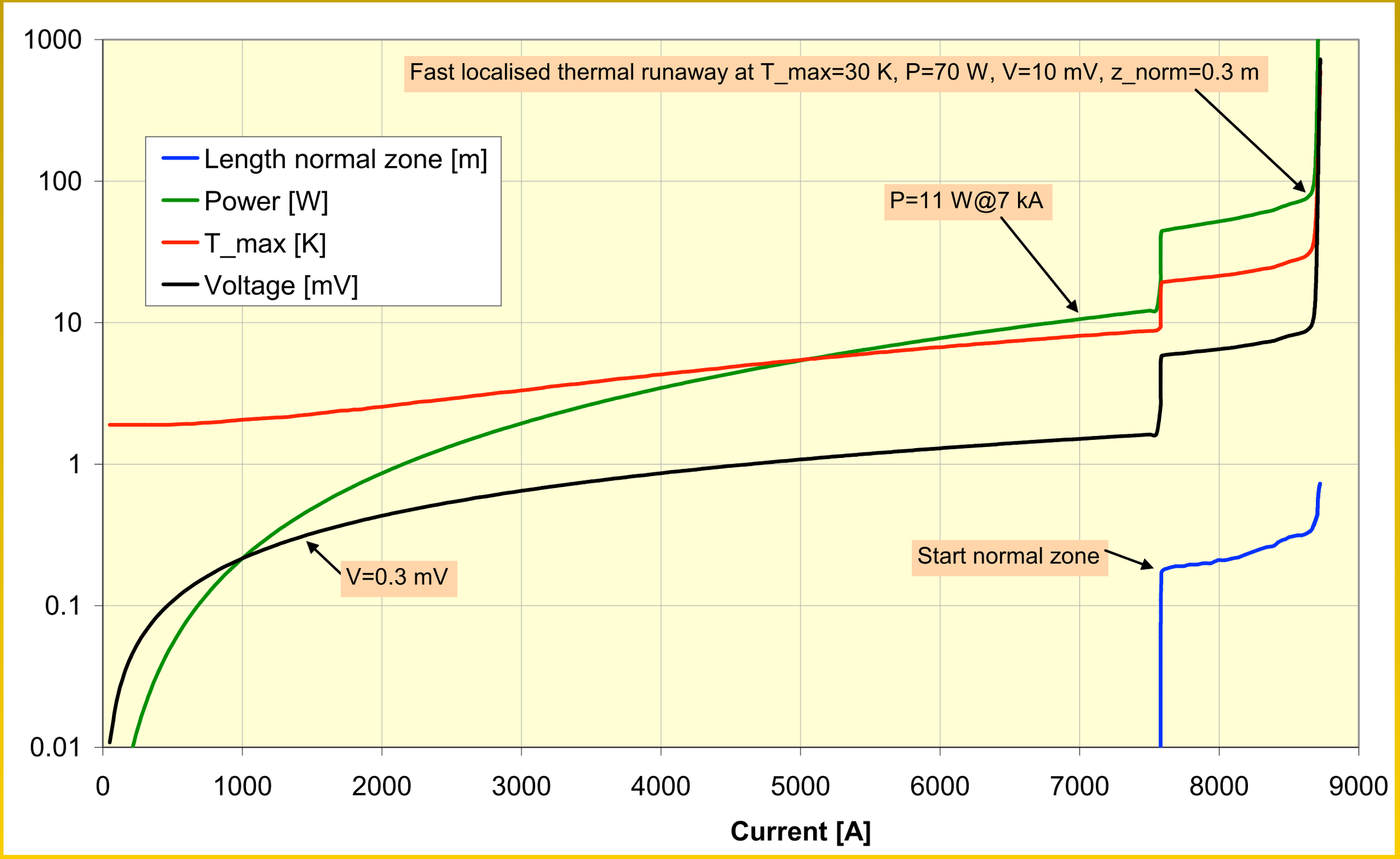
Resistive joint of about 200 nΩ

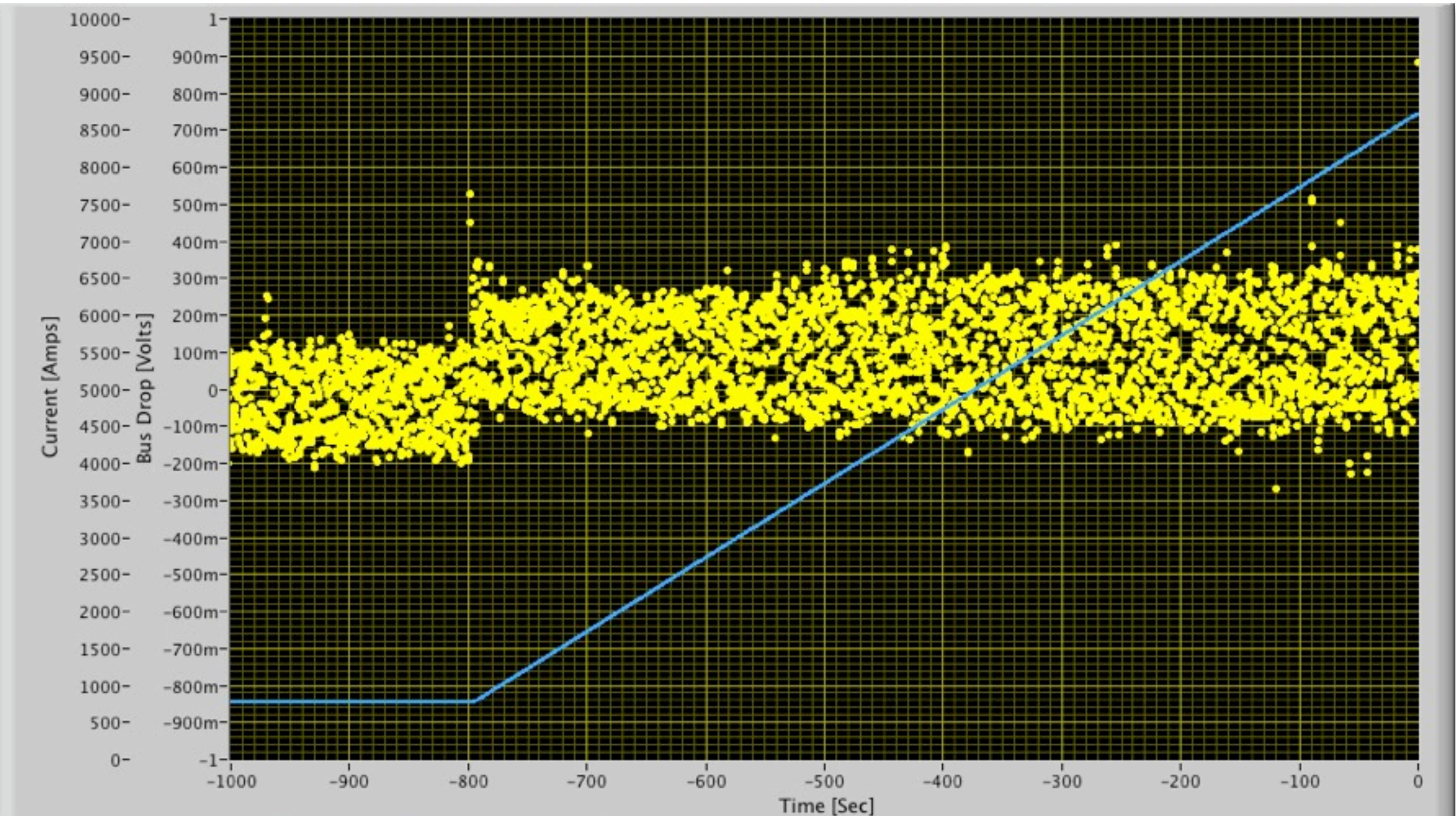
=

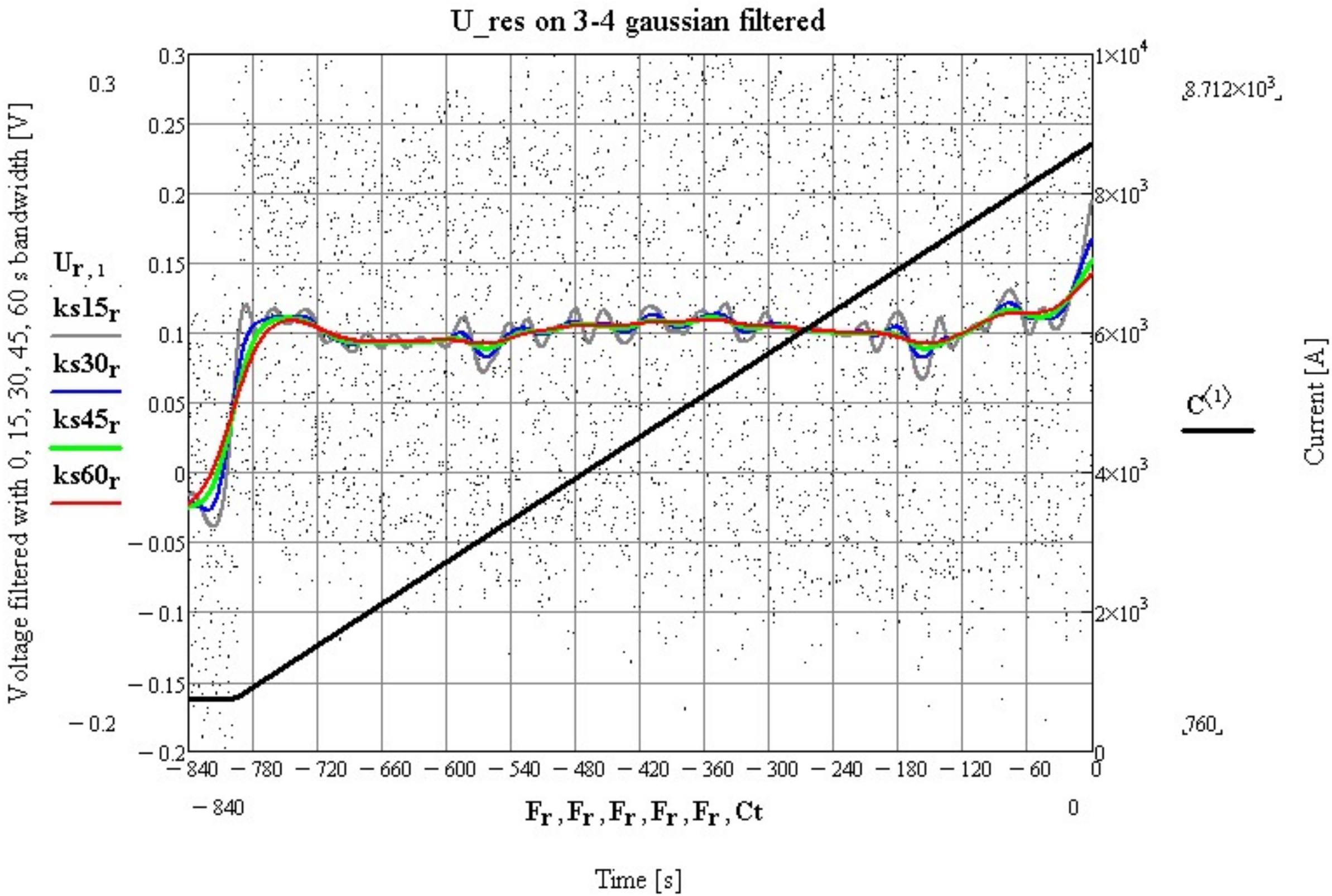


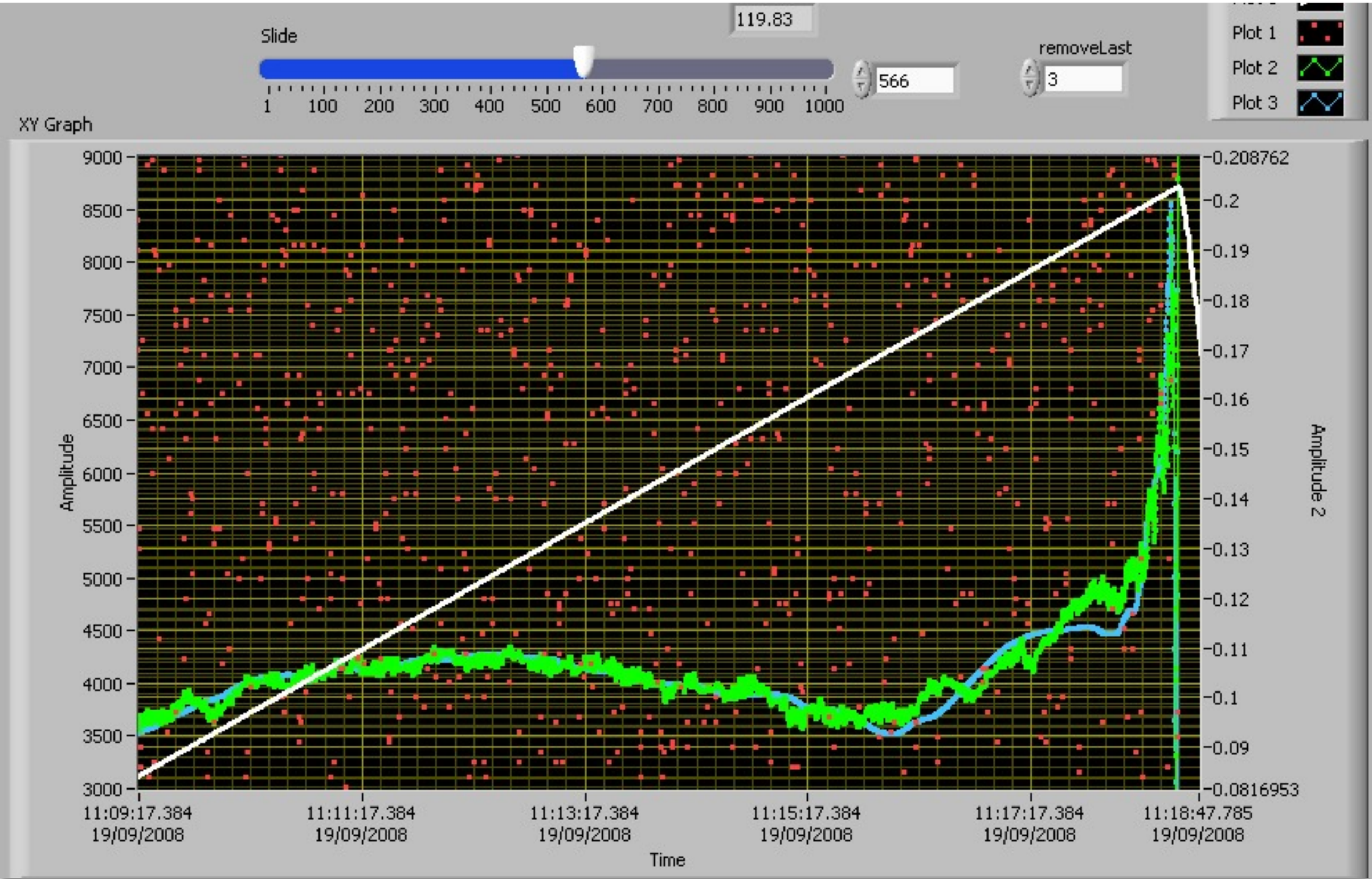
An electrical fuse is a current interrupting device which protects an electrical circuit in which it is installed by creating an open circuit condition in response to excessive current. The current is interrupted when the element which carries the current is melted by heat generated by the current. Most types of fuses are designed to minimize damage to conductors and insulation from excessive current.

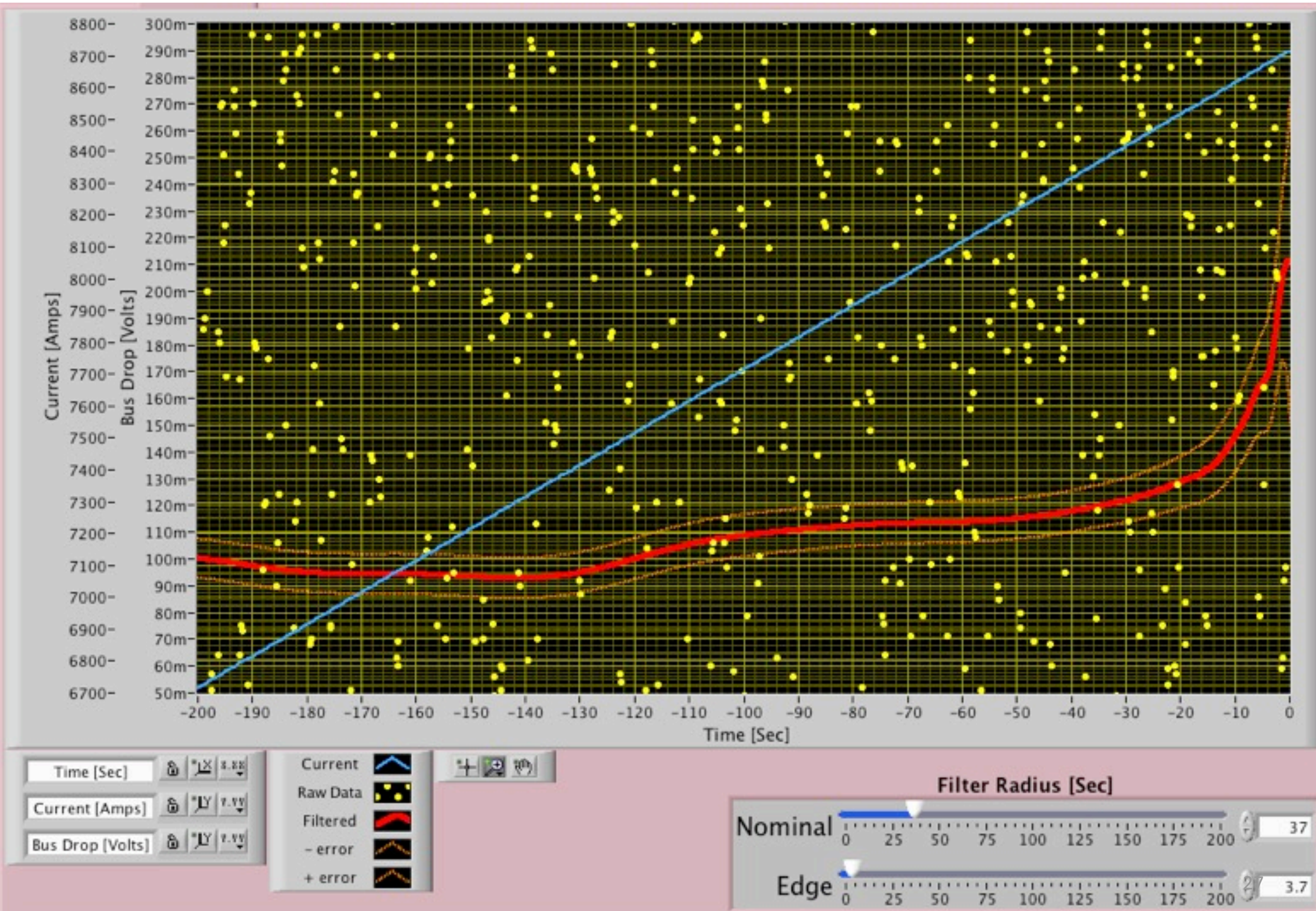
Simulation of the incident




Current [Amps]
Bus Drop [Volts]
Time [Sec]
10000
9500
9000
8500
8000
7500
7000
6500
6000
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
1
900m
800m
700m
600m
500m
400m
300m
200m
100m
0
-100m
-200m
-300m
-400m
-500m
-600m
-700m
-800m
-900m
-1
-1000
-900
-800
-700
-600
-500
-400
-300
-200
-100
0
Time [Sec]
Current
Raw Data
Filter Radius [Sec]

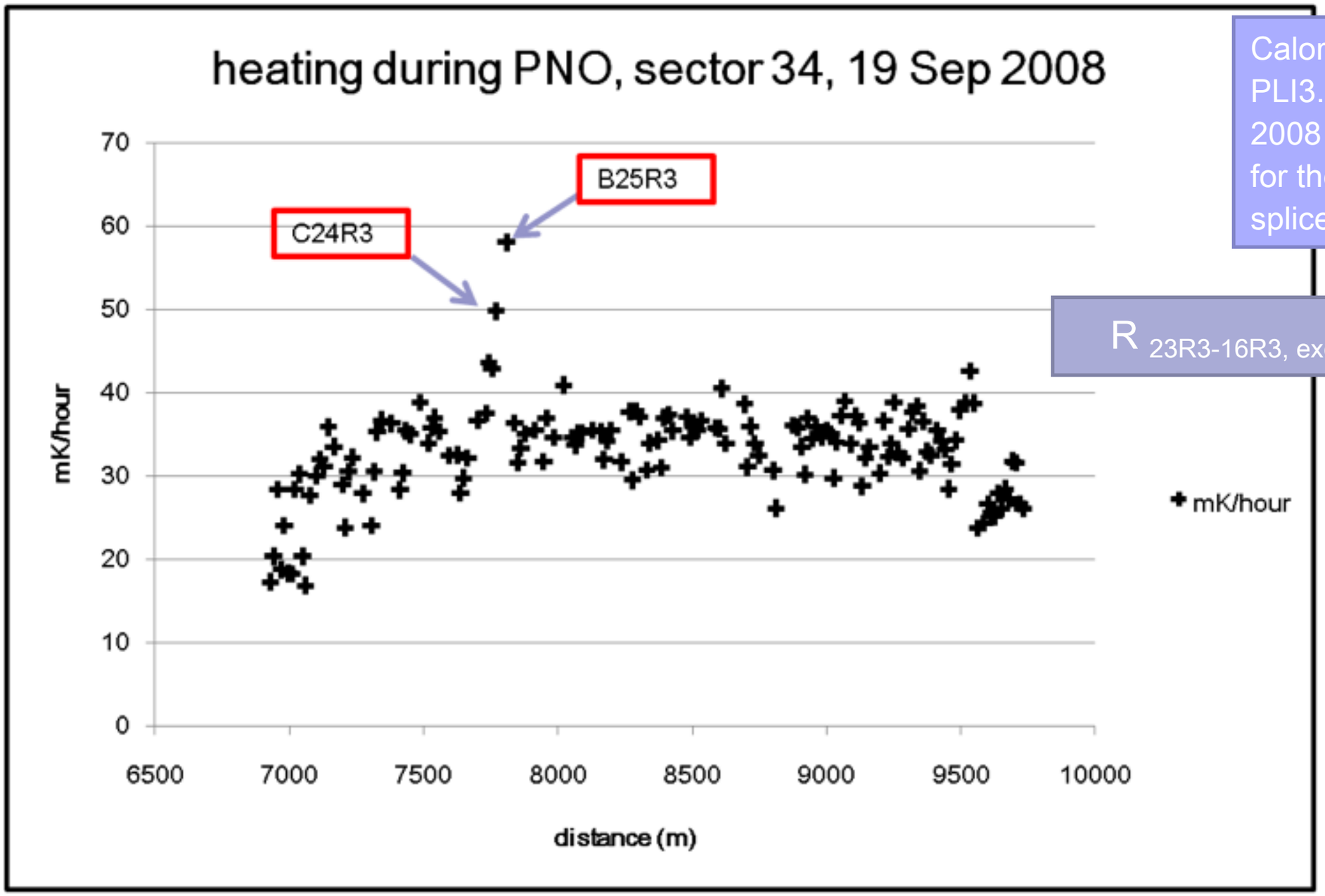

U_res on 3-4 gaussian filtered
Voltage filtered with 0, 15, 30, 45, 60 s bandwidth [V]
Current [A]
Time [s]
$U_{r,1}$
$ks15_r$
$ks30_r$
$ks45_r$
$ks60_r$
$C^{\langle 1 \rangle}$
0.3
0.25
0.2
0.15
0.1
0.05
0
−0.05
−0.1
−0.15
−0.2
1×10^4
8×10^3
6×10^3
4×10^3
2×10^3
0
8.712×10^3
760
−840 −780 −720 −660 −600 −540 −480 −420 −360 −300 −240 −180 −120 −60 0
$F_r, F_r, F_r, F_r, F_r, Ct$


119.83
Slide
1
100
200
300
400
500
600
700
800
900
1000
566
removeLast
3
Plot 1
Plot 2
Plot 3
XY Graph
9000
8500
8000
7500
7000
6500
6000
5500
5000
4500
4000
3500
3000
Amplitude
-0.208762
-0.2
-0.19
-0.18
-0.17
-0.16
-0.15
-0.14
-0.13
-0.12
-0.11
-0.1
-0.09
-0.0816953
Amplitude 2
11:09:17.384
19/09/2008
11:11:17.384
19/09/2008
11:13:17.384
19/09/2008
11:15:17.384
19/09/2008
11:17:17.384
19/09/2008
11:18:47.785
19/09/2008
Time


Current [Amps]
Bus Drop [Volts]
Time [Sec]
Time [Sec]
Current [Amps]
Bus Drop [Volts]
Current
Raw Data
Filtered
- error
+ error
Filter Radius [Sec]
Nominal
Edge
37
3.7

The landscape II: motivation

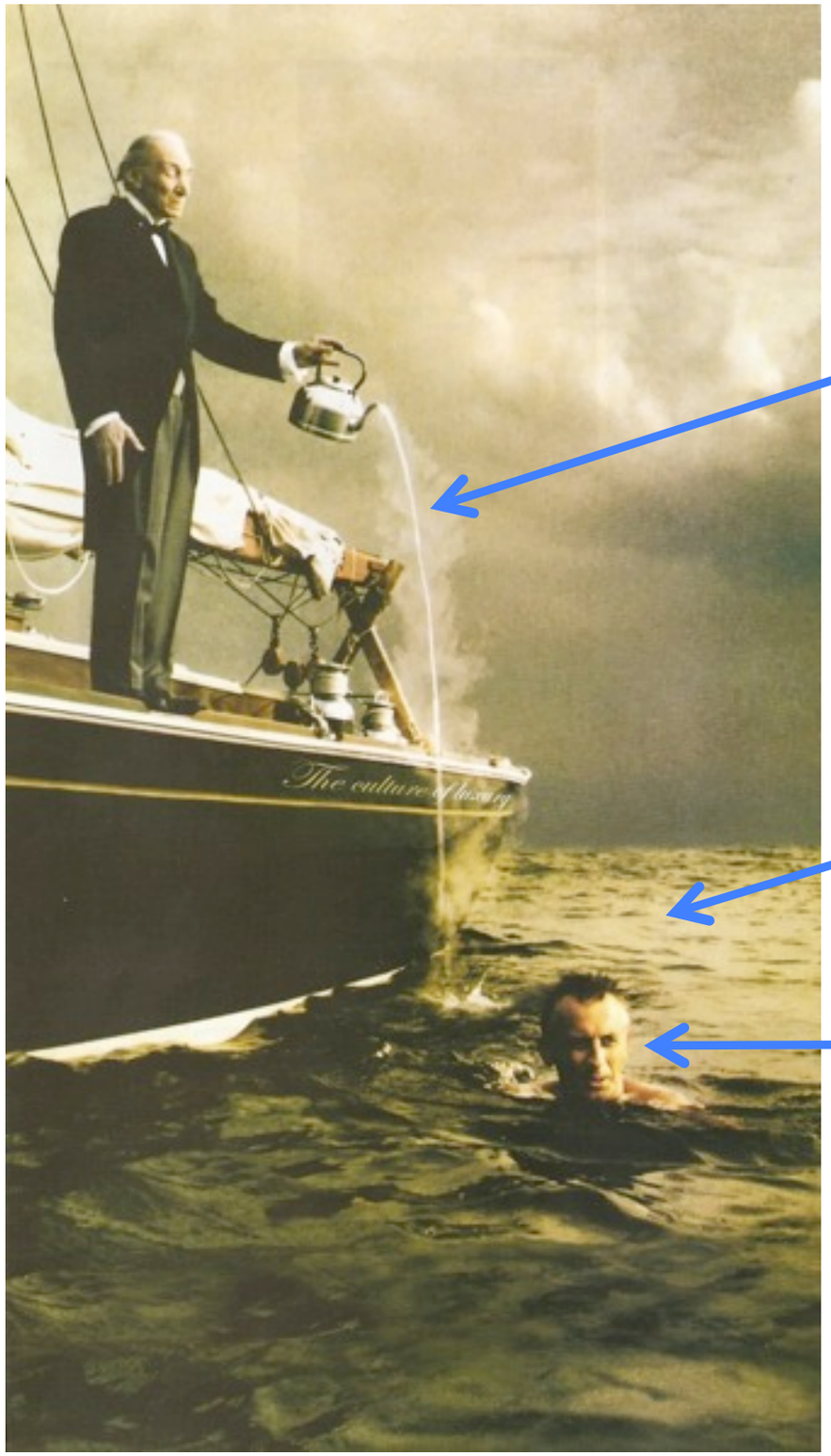
- We know what is an unsafe resistance (19 September 2008):



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

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

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

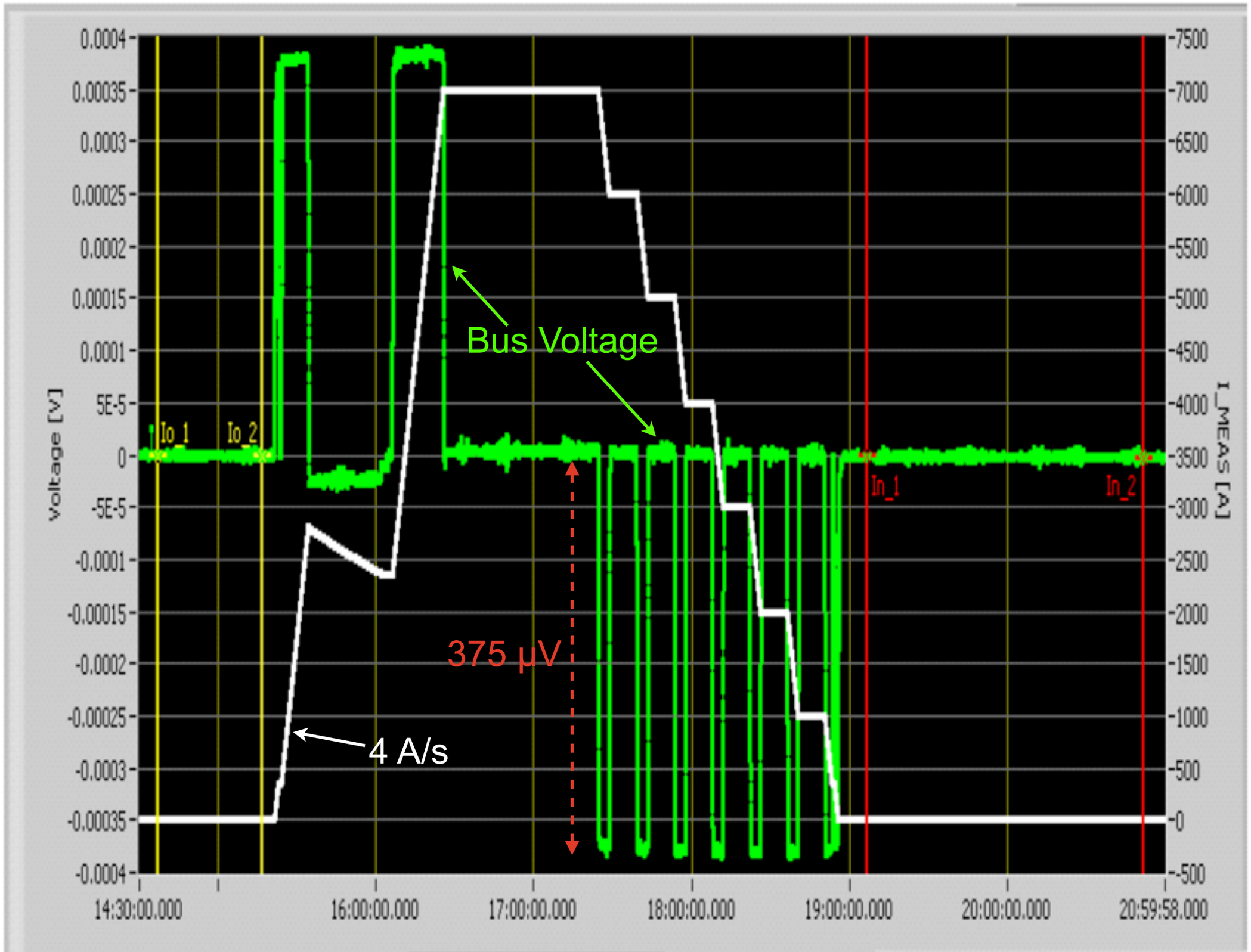
QPS REBORN: “NQPS”

Bus Monitoring redone 500,000 better!

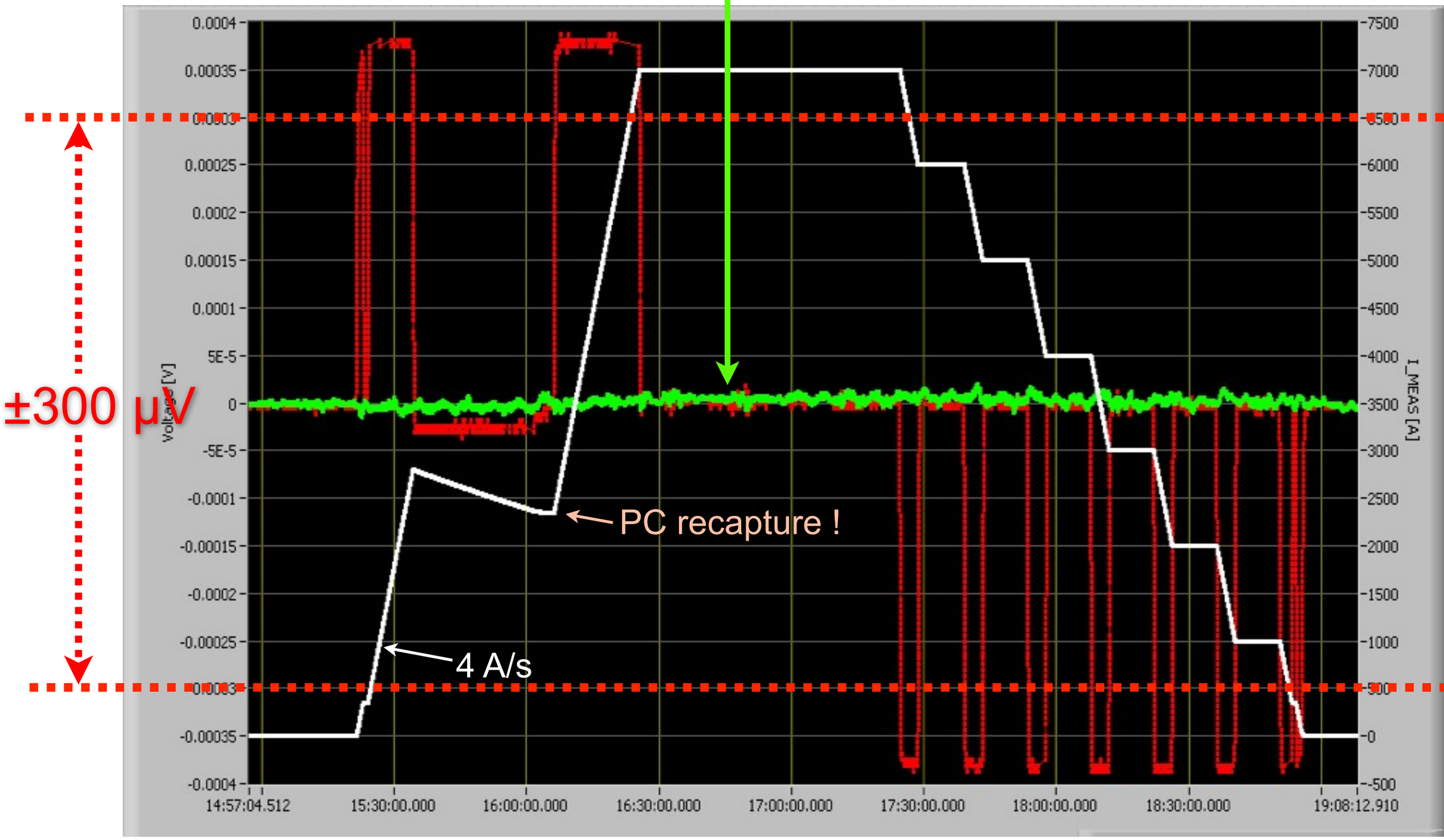
- Monitors: One circuit ==> 150 individual segments
- Noise Floor: 300 mV ==> 10 μV
- Detection Threshold: 1 Volt ==> 300 μV
- Integration Time: 1 sec ==> 10 sec
- Response: Too Late ==> Preemptive Early Warning

Serious Attempt at Compensation

Uncompensated Bus Signal



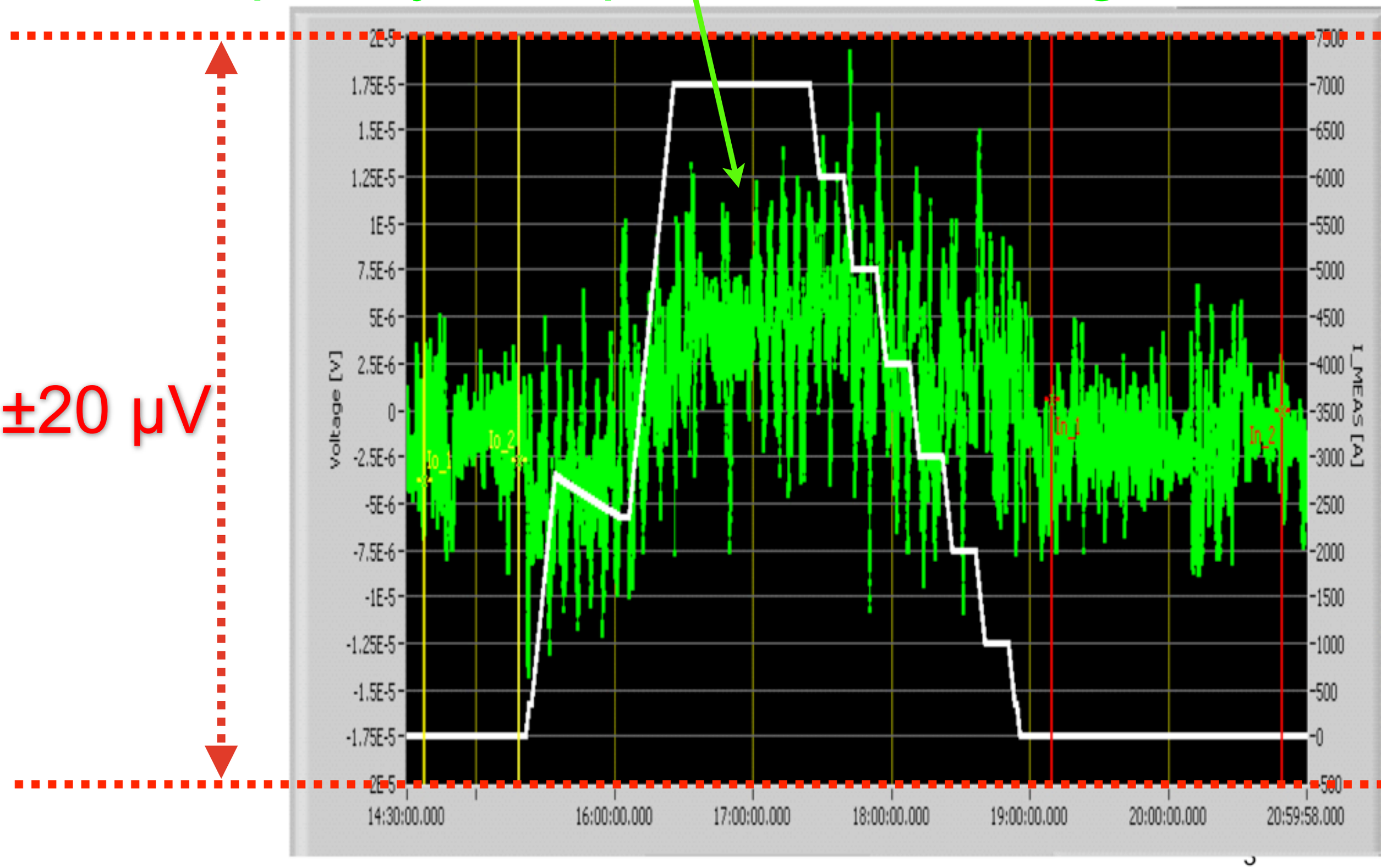
Completely Compensated Bus Signal



Can we have a detection threshold better than 300 µV ?

YES WE CAN !

Completely Compensated Bus Signal

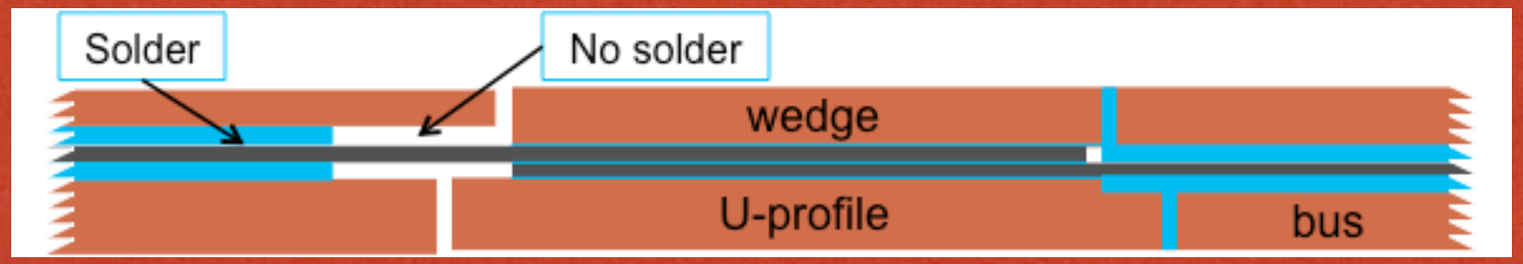


Can we have a detection threshold better than 300 µV ?

YES WE CAN !

Bad News… The Silent Thrillers

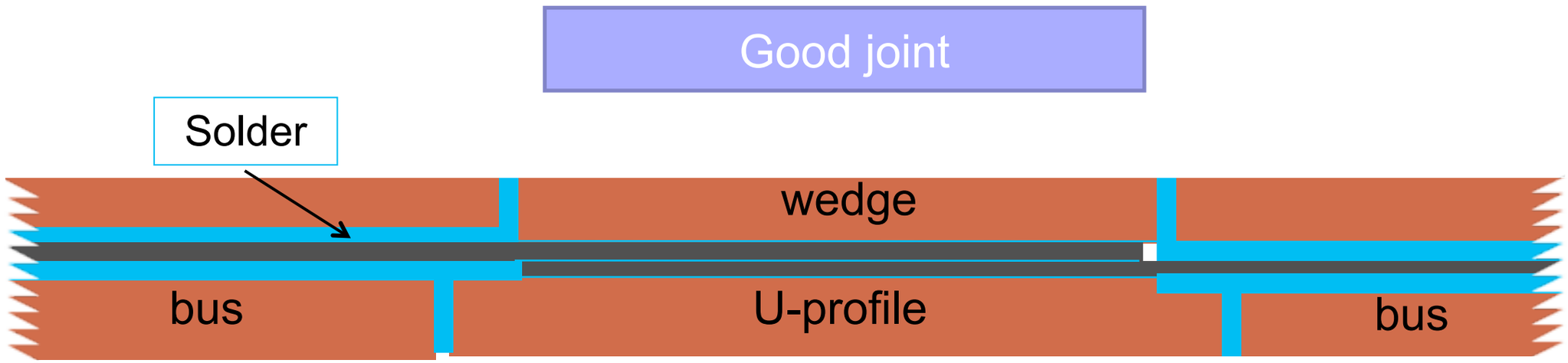
- **But wait; there's more!**
- **The Verweij / Pfeffer conjecture**
  - Not actually a conjecture, because it's a fact
  - Voids & poor electrical contact that forced current through SC

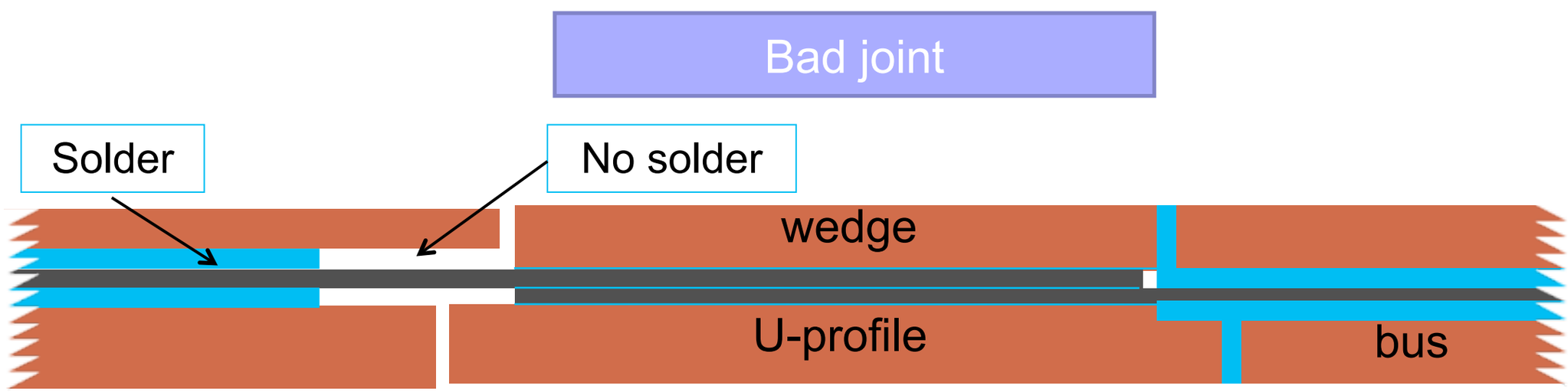


  - The final temperature depends on the length of the void
    - Cable blows up during dump, even at 300 μV detection if void is > Some critical length
  - **What is the safe energy to run at?**
    - It depends on the length of voids, which are characterized by their 300 K resistance
    - There are hundreds of voids in the LHC interconnects

Resistances at warm

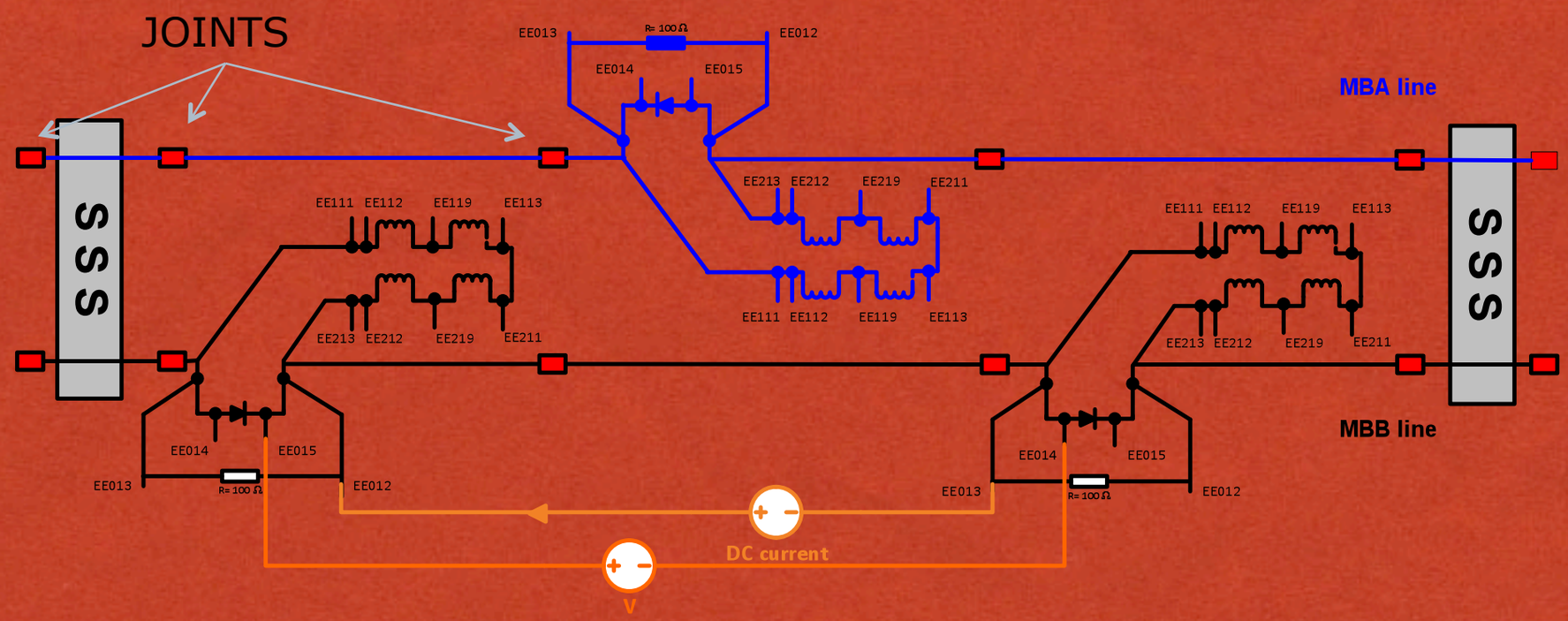
- A copper stabilizer with no continuity coupled to a superconducting cable badly soldered to the stabilizer poses a real problem (A. Verweij)





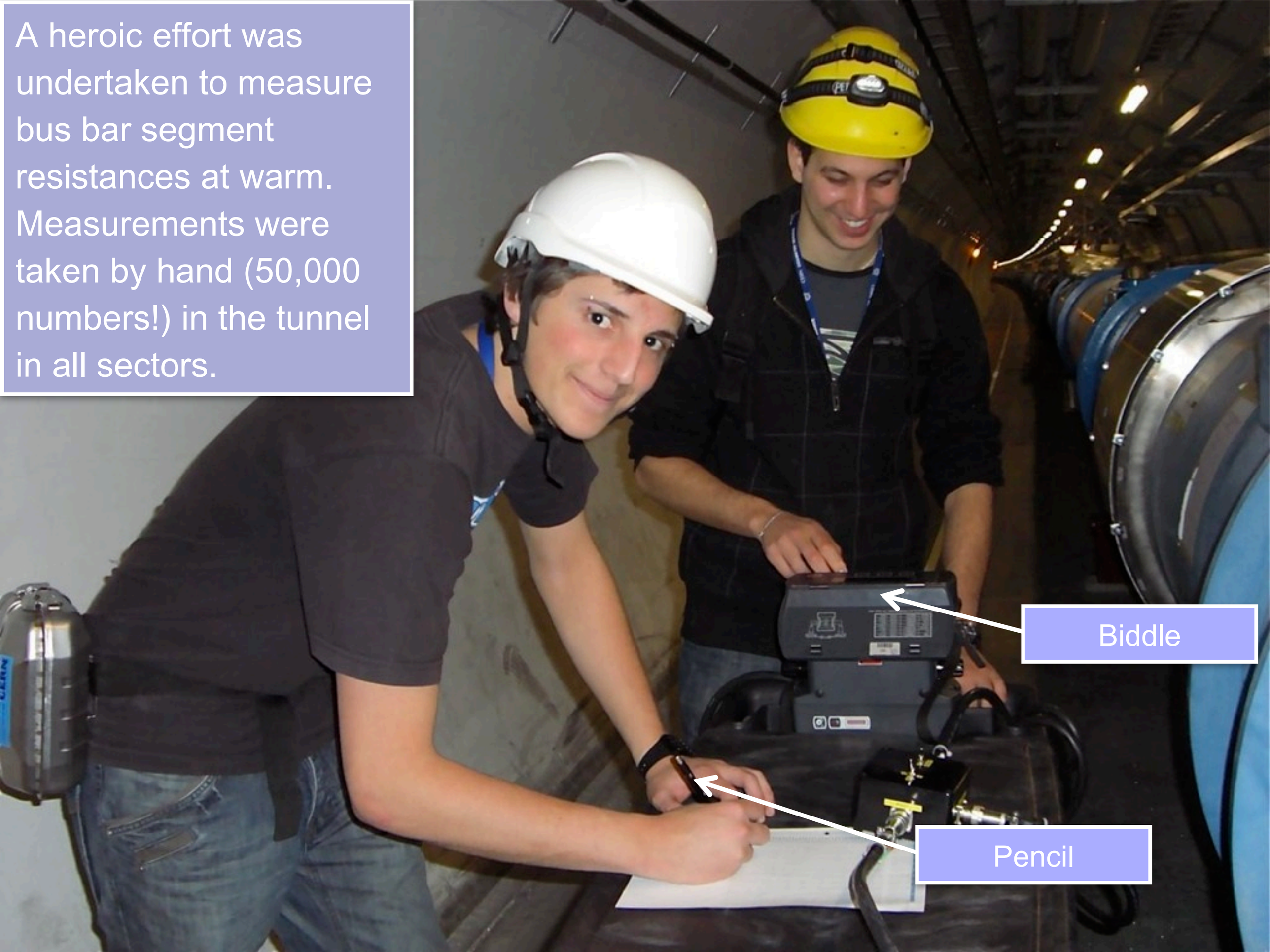
Non invasive splice resistance measurements

- DC method of measuring bus segment resistances

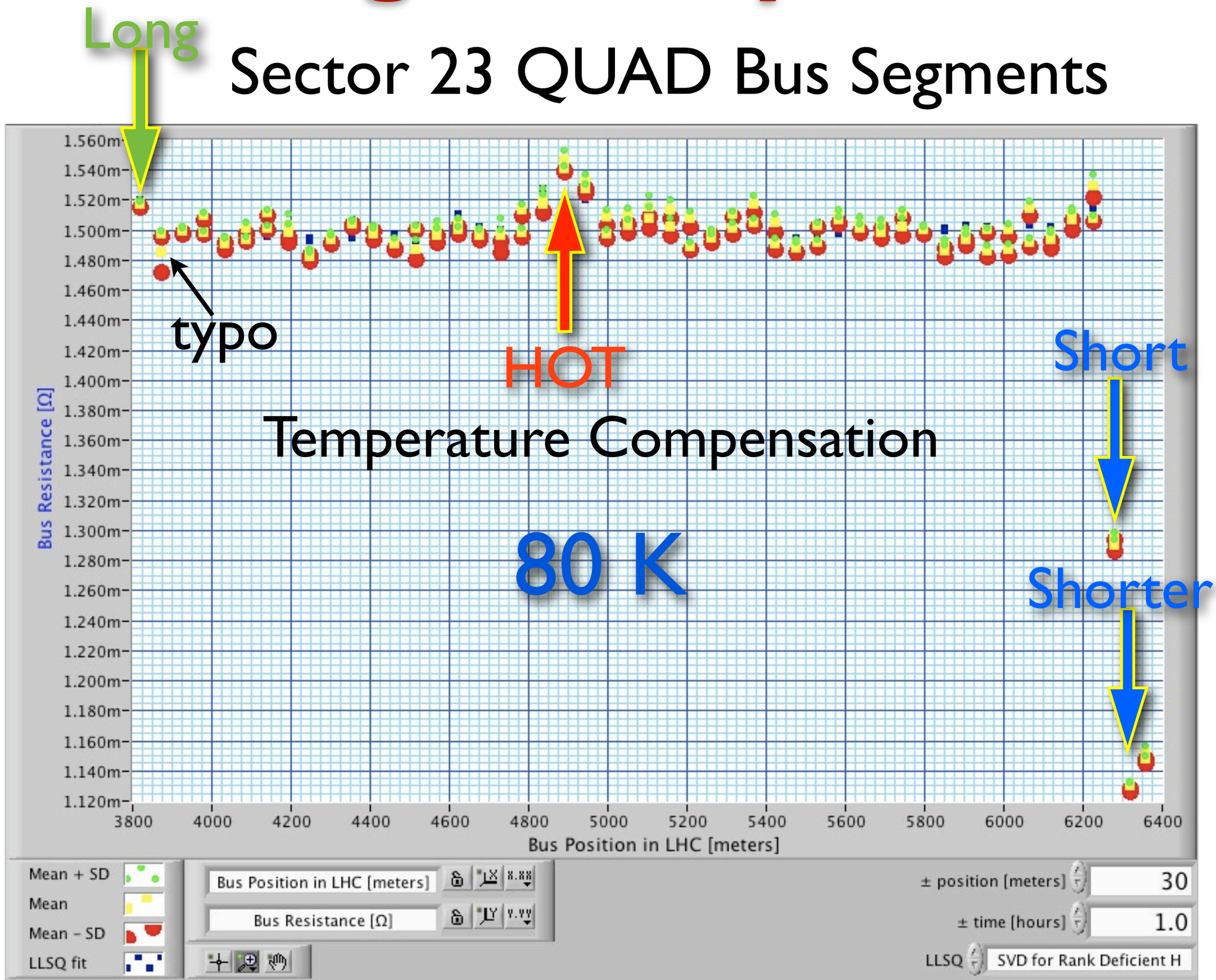


- Simplified schematics for two adjacent dipoles

A heroic effort was undertaken to measure bus bar segment resistances at warm. Measurements were taken by hand (50,000 numbers!) in the tunnel in all sectors.



Bus Length Compensation



1248 Bend Bus Segments

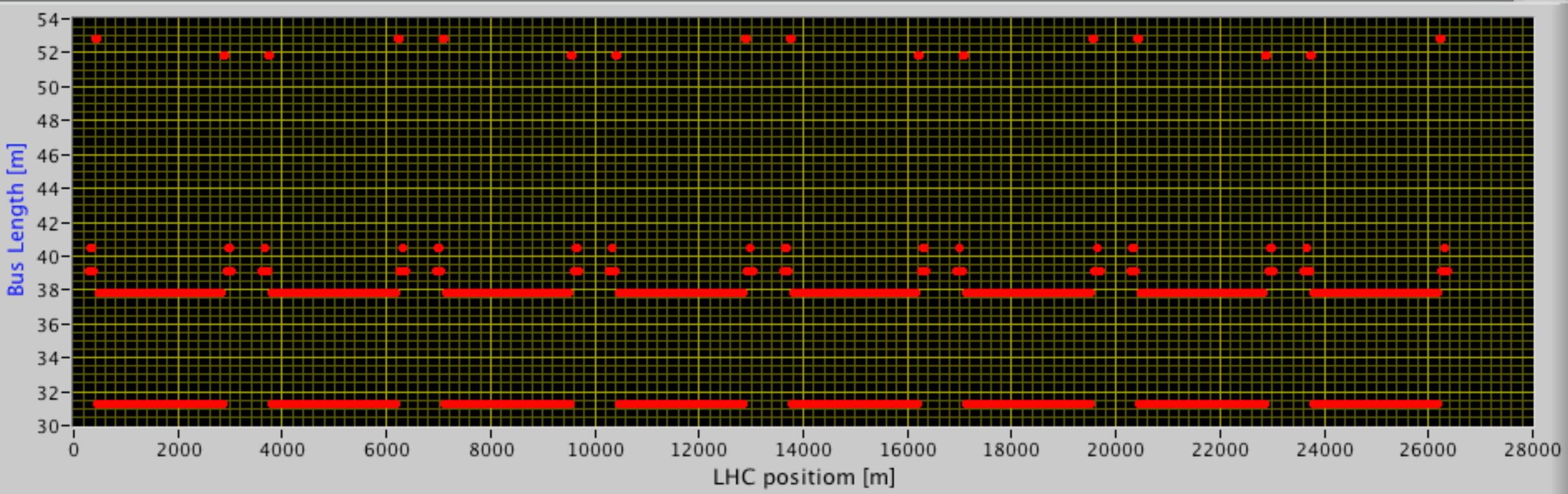
get Bus Length Data.vi Front Panel rev. 23

11pt Application Font

Position Data Folder

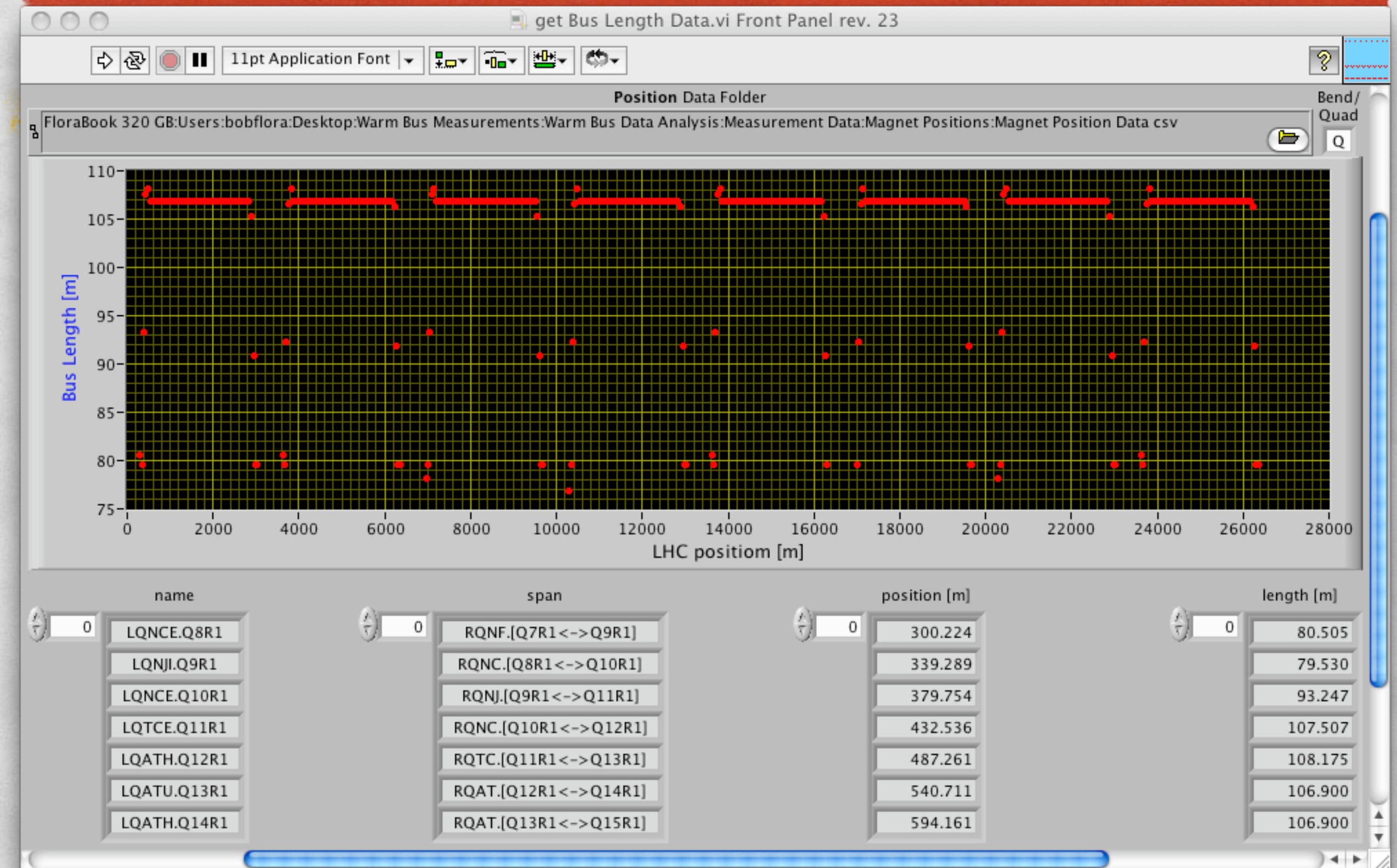
FloraBook 320 GB:Users:bobflora:Desktop:Warm Bus Measurements:Warm Bus Data Analysis:Measurement Data:Magnet Positions:Magnet Position Data csv

Bend/ Quad B



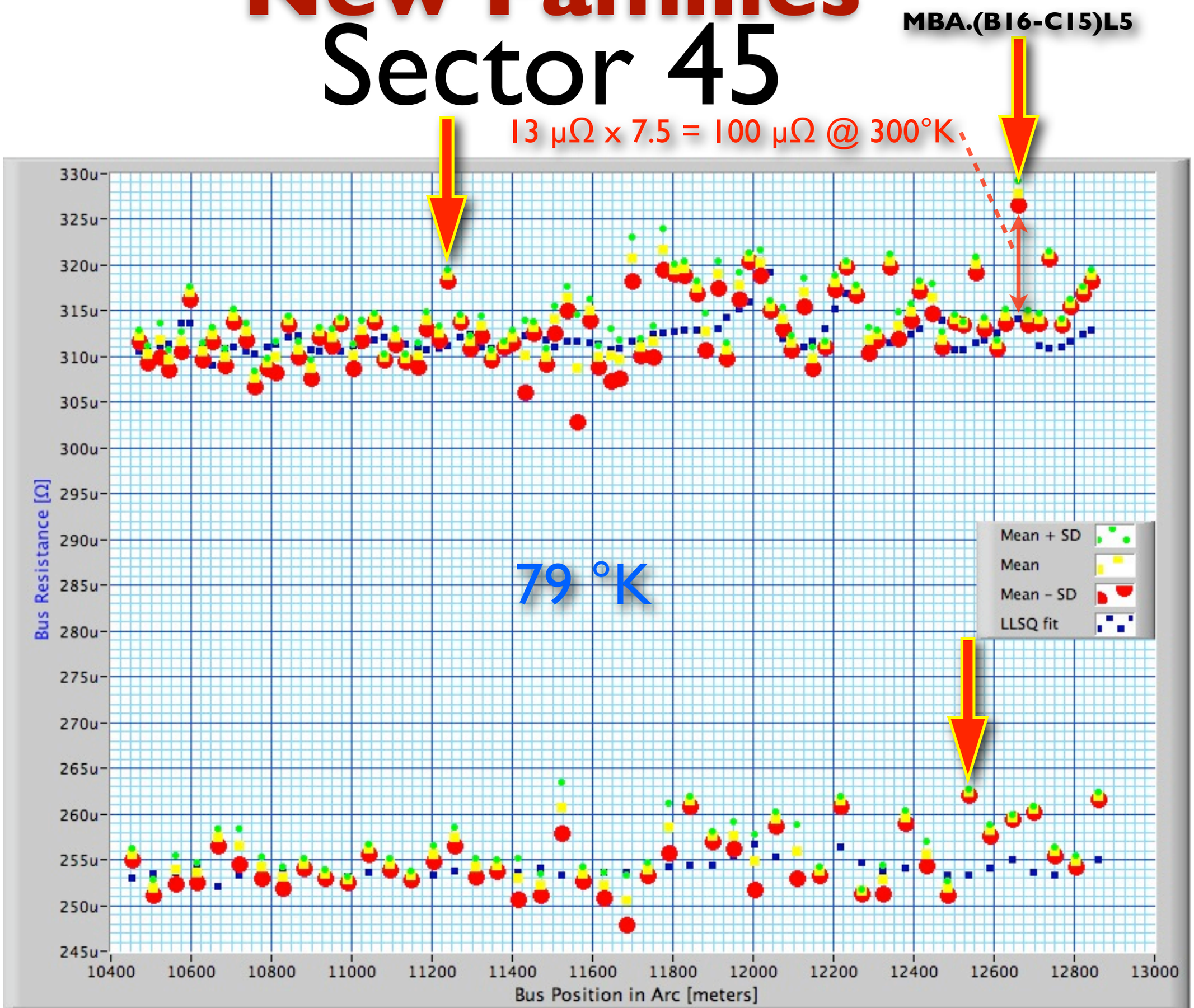
	name	span	position [m]	length [m]
0	LBBRF.B8R1	RBAR.[A8R1<->A9R1]	284.564	39.065
	LBARE.A9R1	RBBR.[B8R1<->B9R1]	307.969	39.065
	LBBRG.B9R1	RBAR.[A9R1<->A10R1]	323.629	40.465
	LBARE.A10R1	RBBR.[B9R1<->B10R1]	348.434	40.465
	LBBRF.B10R1	RBAR.[A10R1<->A11R1]	364.094	39.065
	LBARA.A11R1	RBBR.[B10R1<->B11R1]	387.499	39.065
	LBBRA.B11R1	RBAR.[A11R1<->A12R1]	403.159	52.782

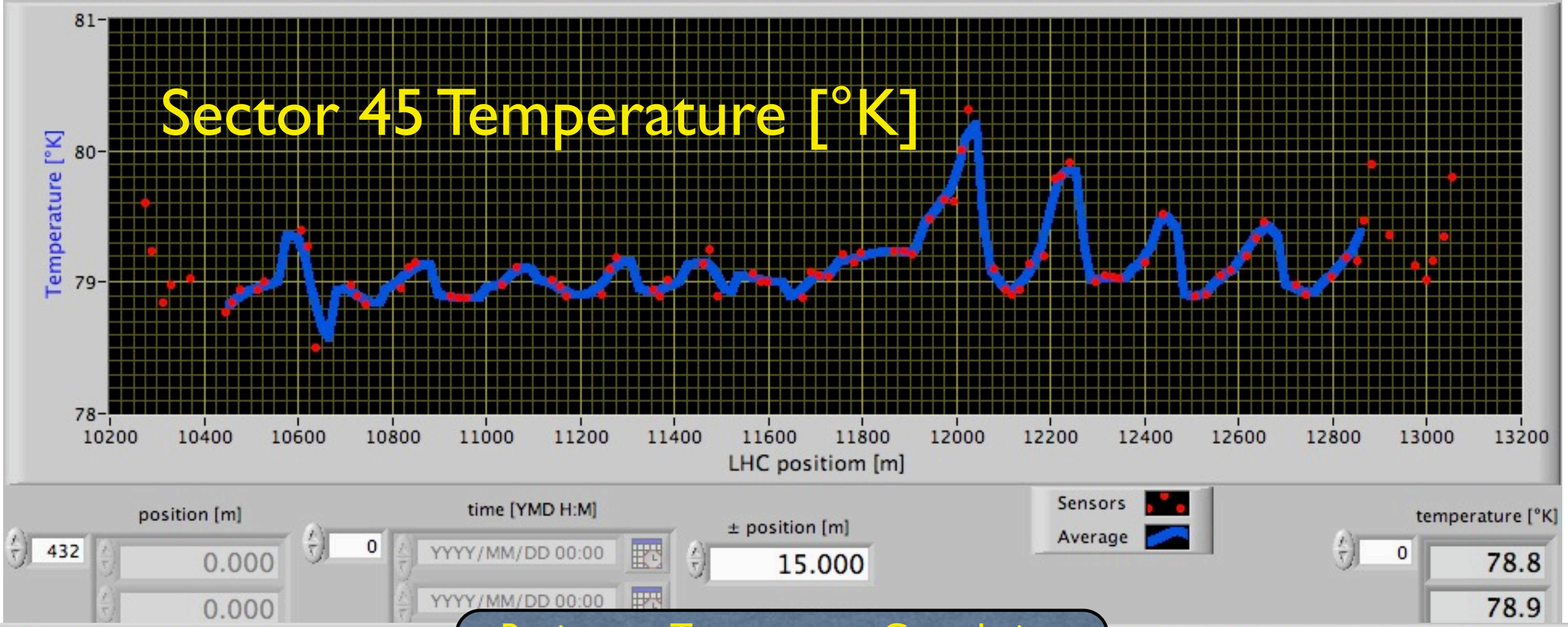
800 Quad Bus Segments



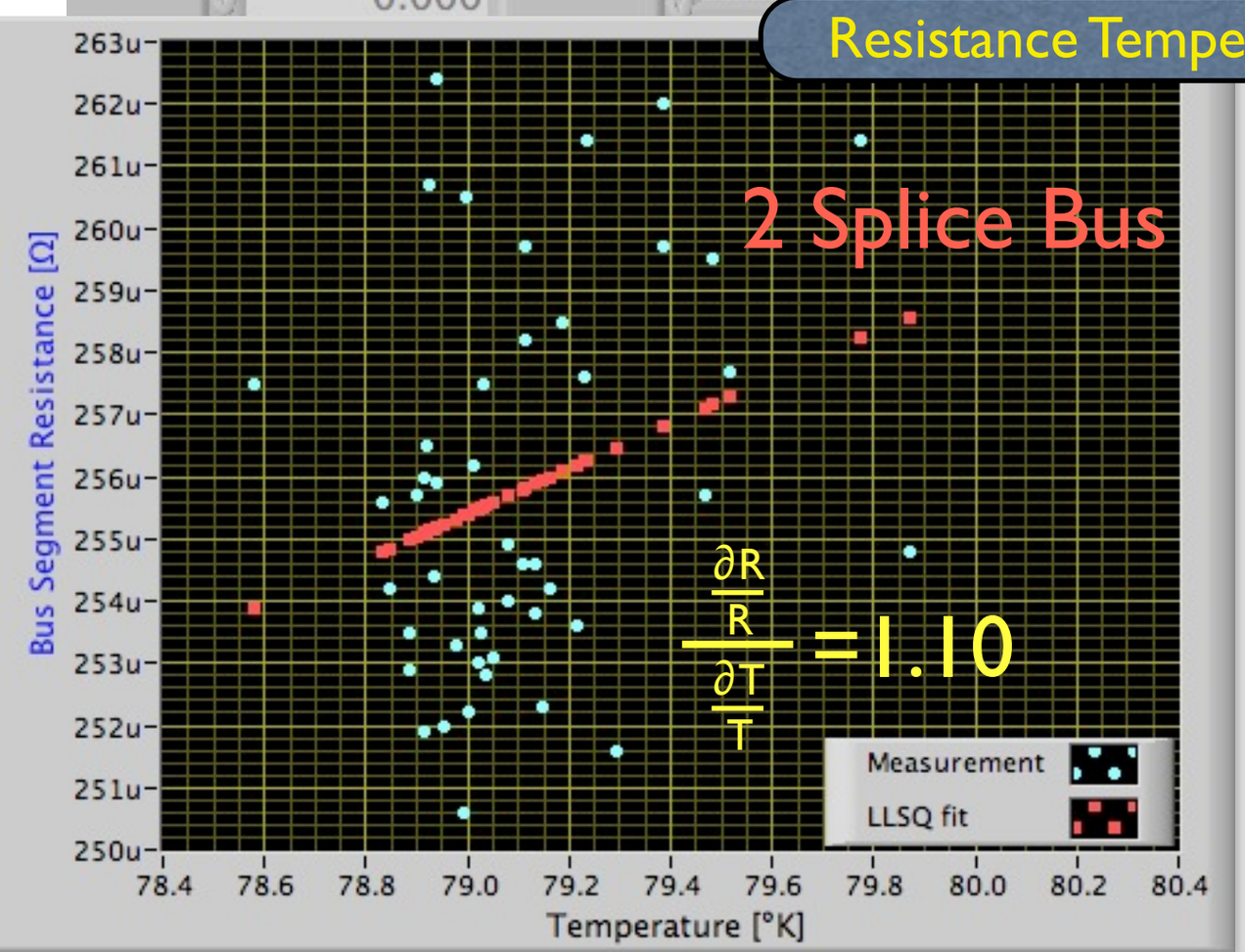
New Families

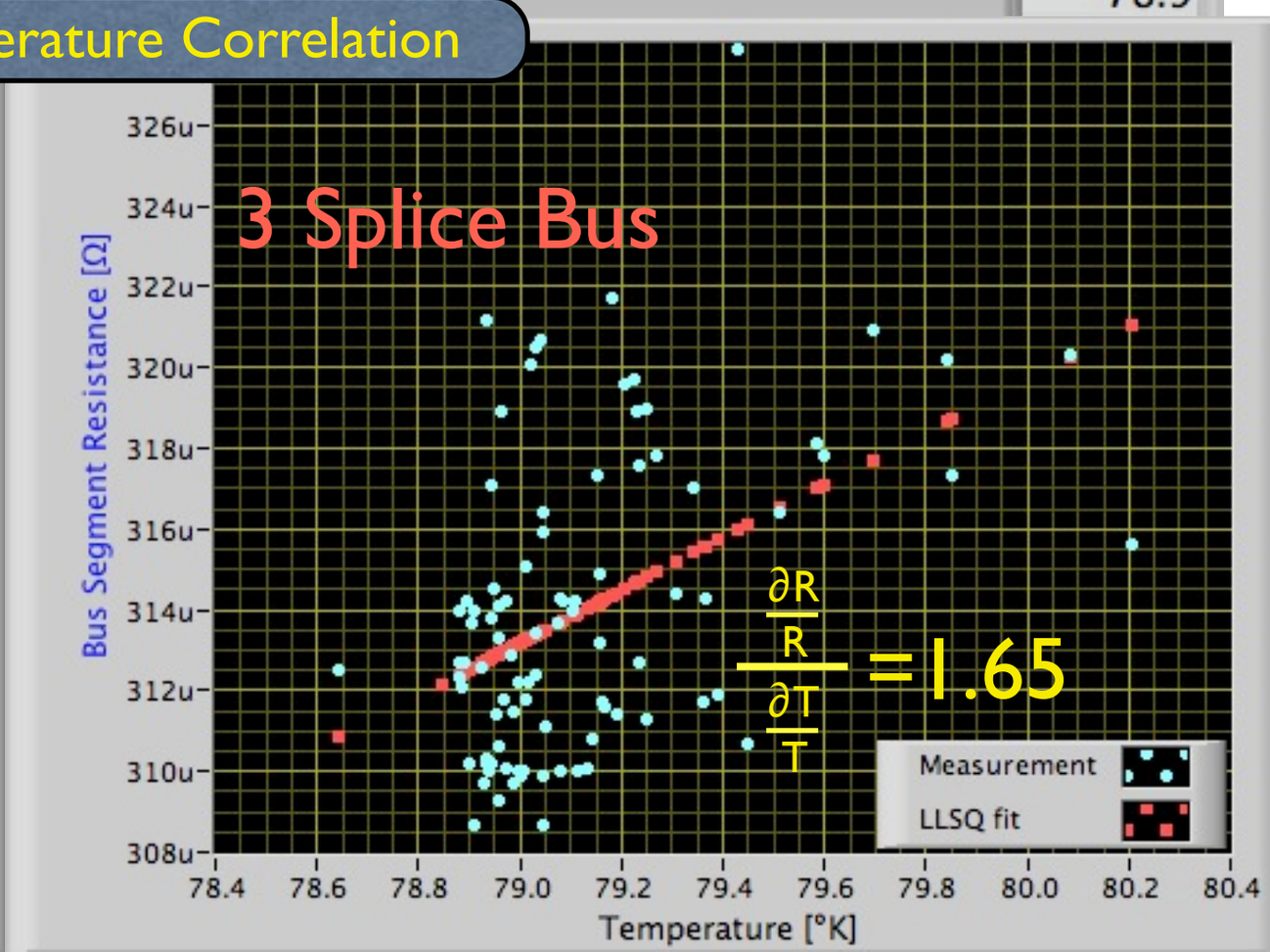
Sector 45



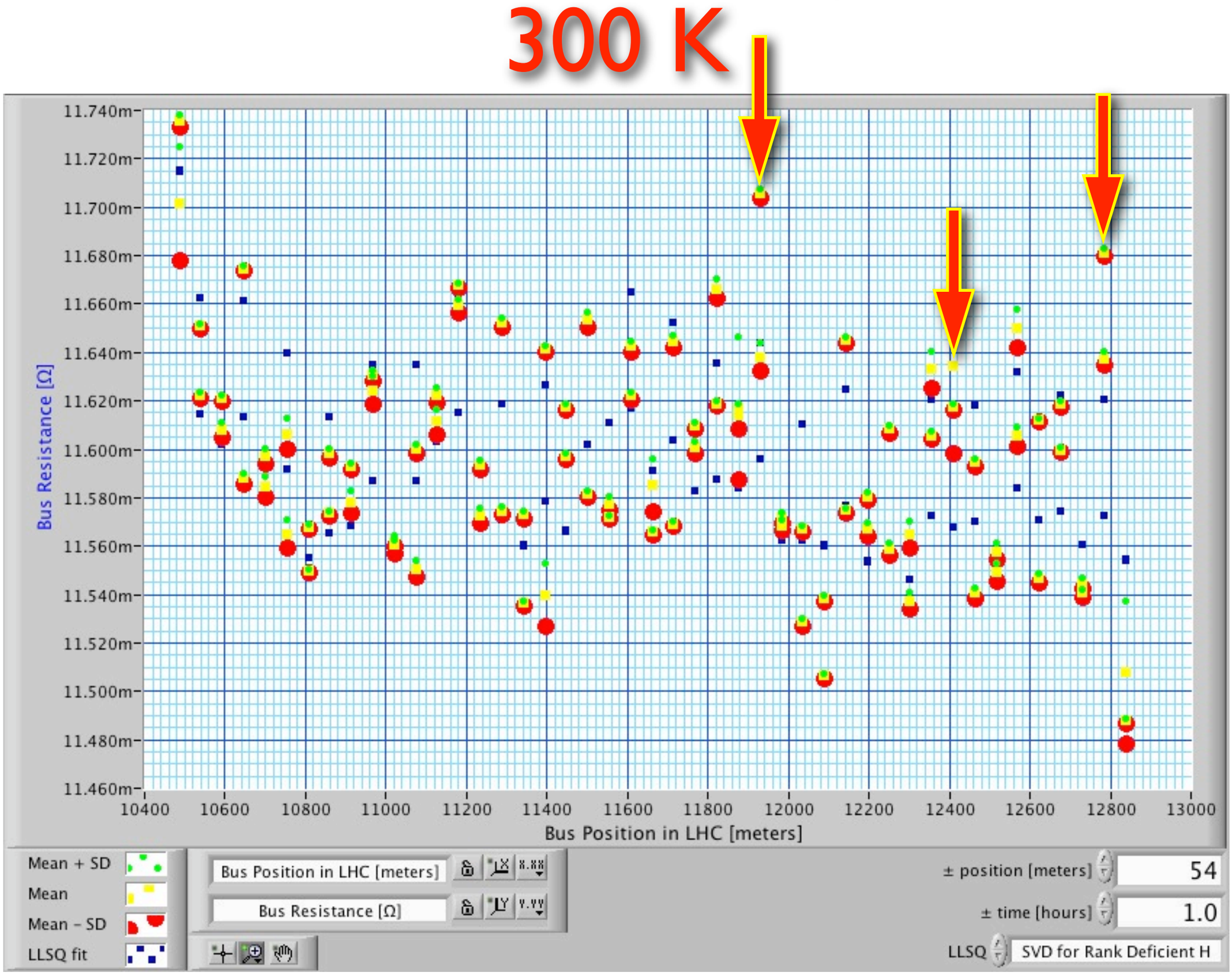


Resistance Temperature Correlation

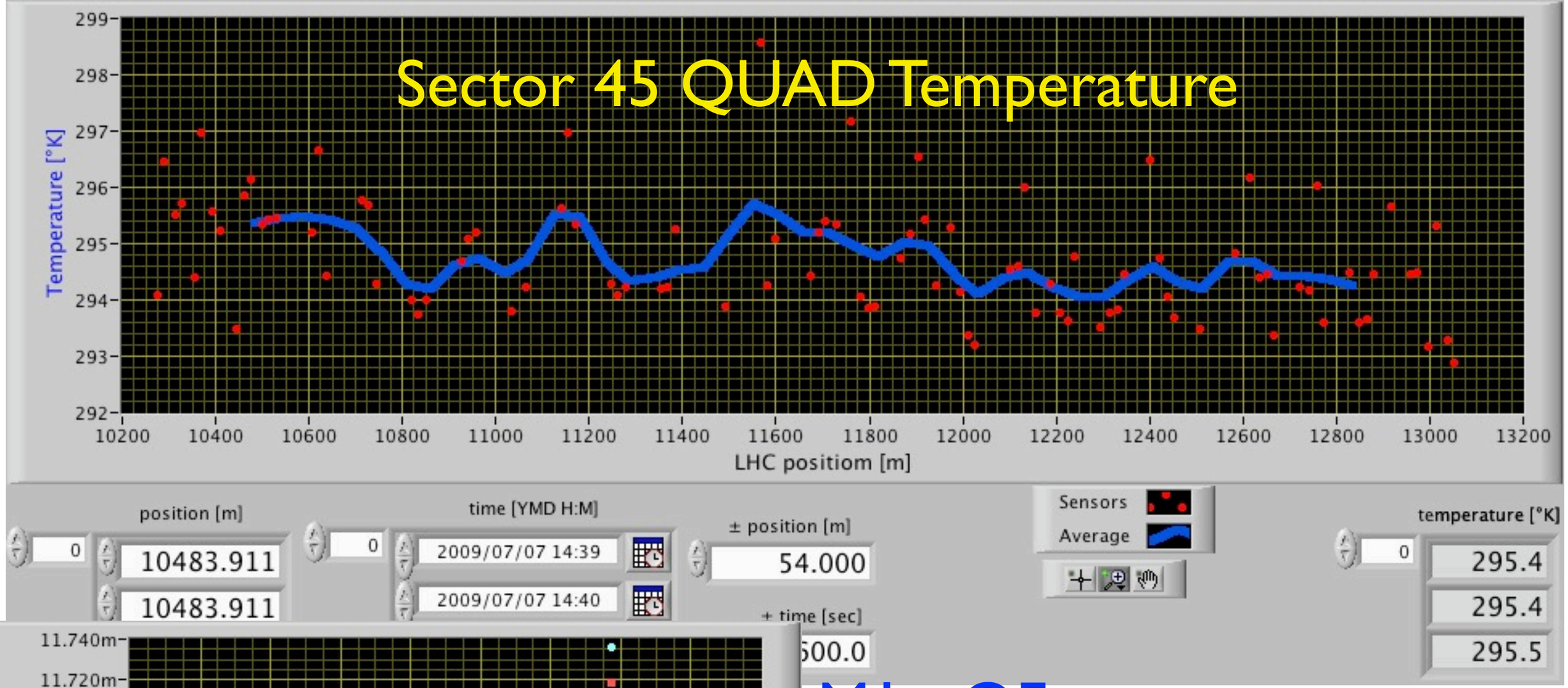


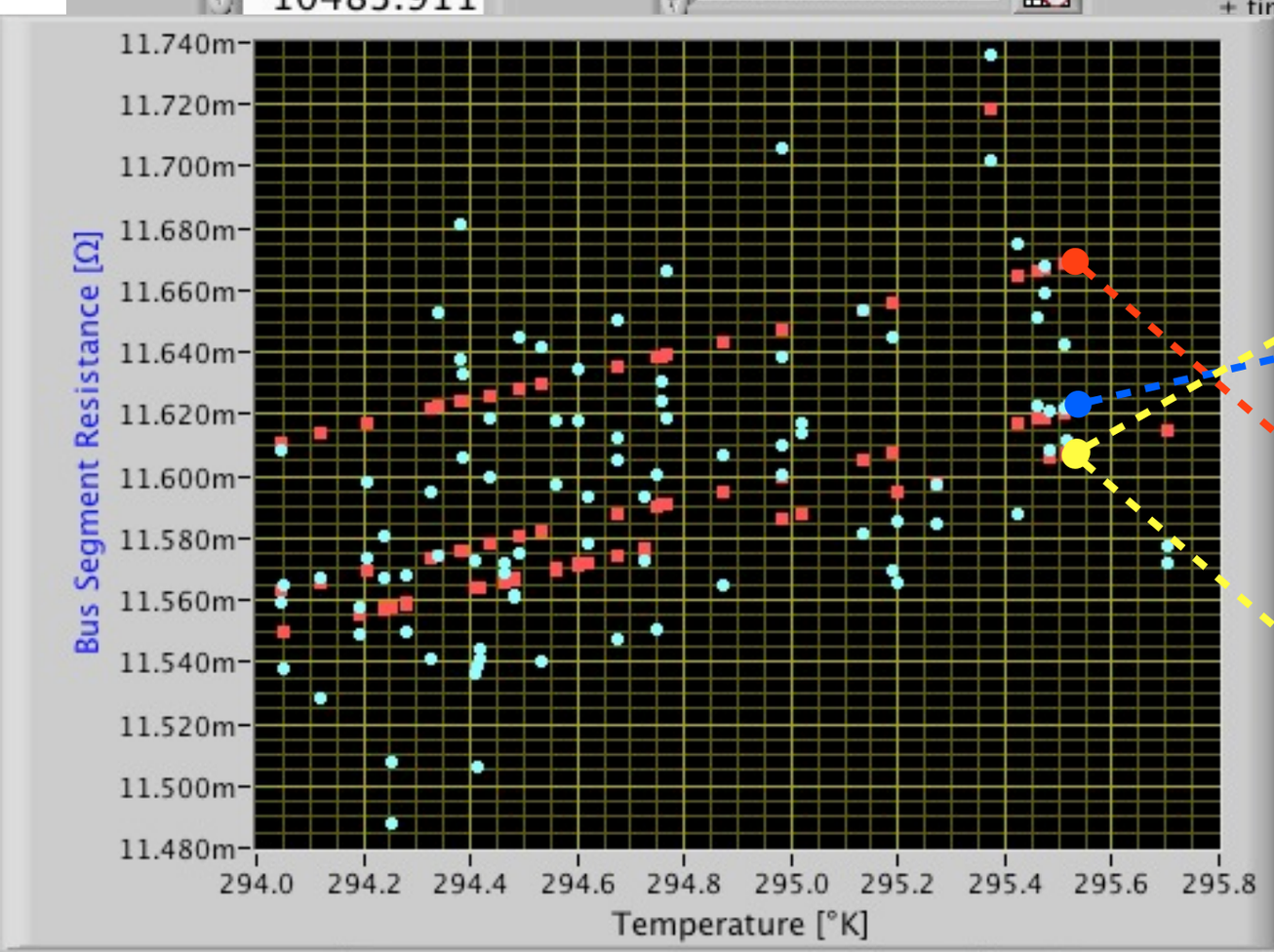


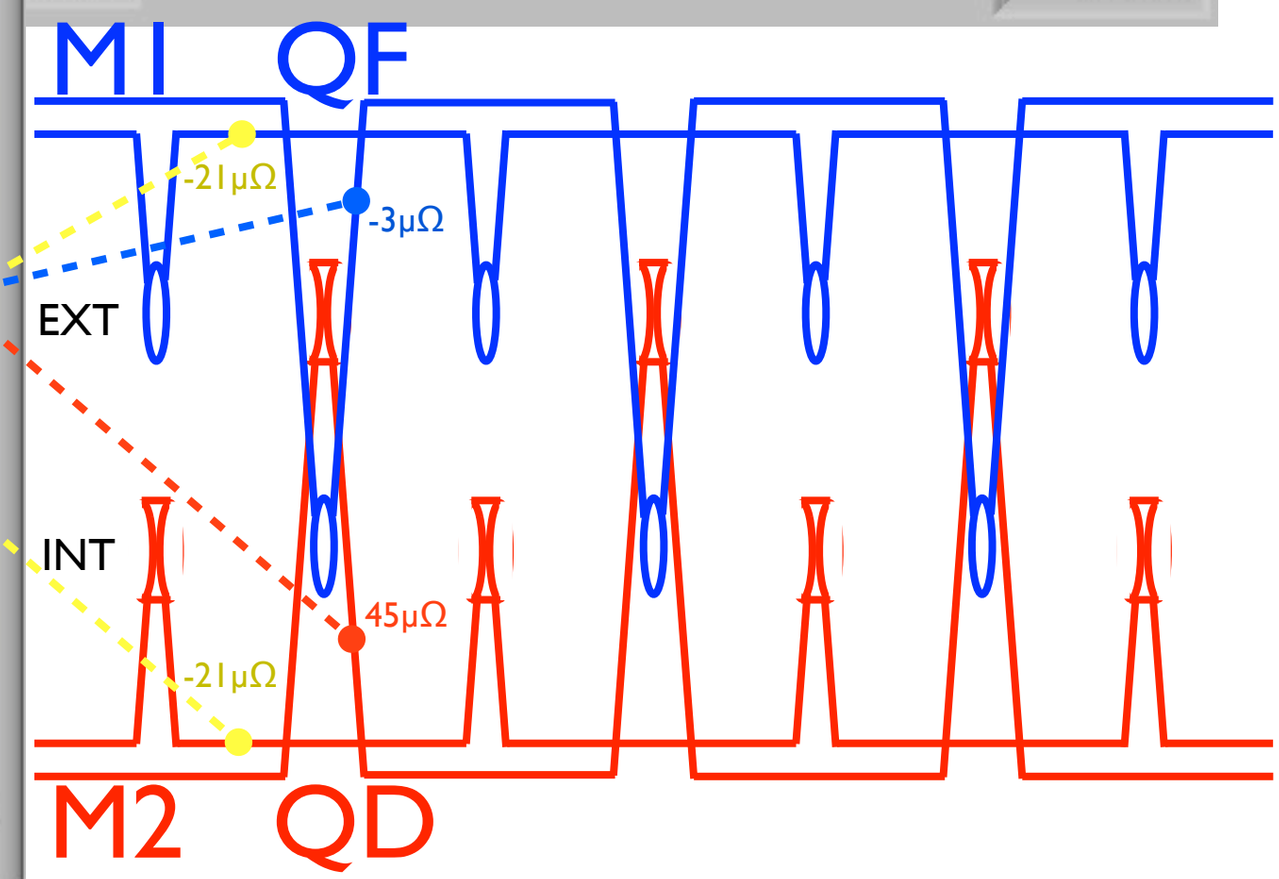
Sector 45 QUAD Bus Segments



Sector 45 QUAD Temperature

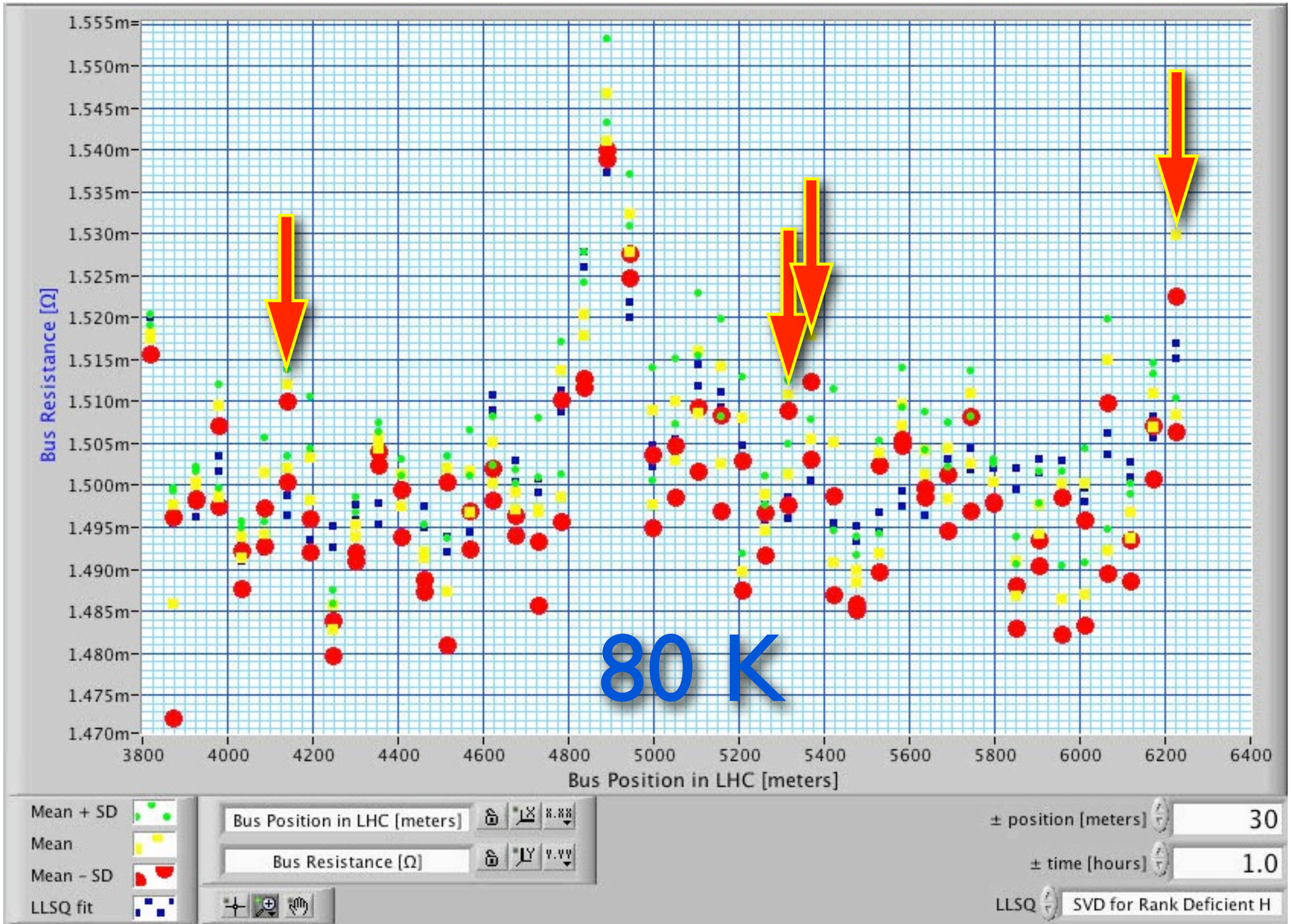


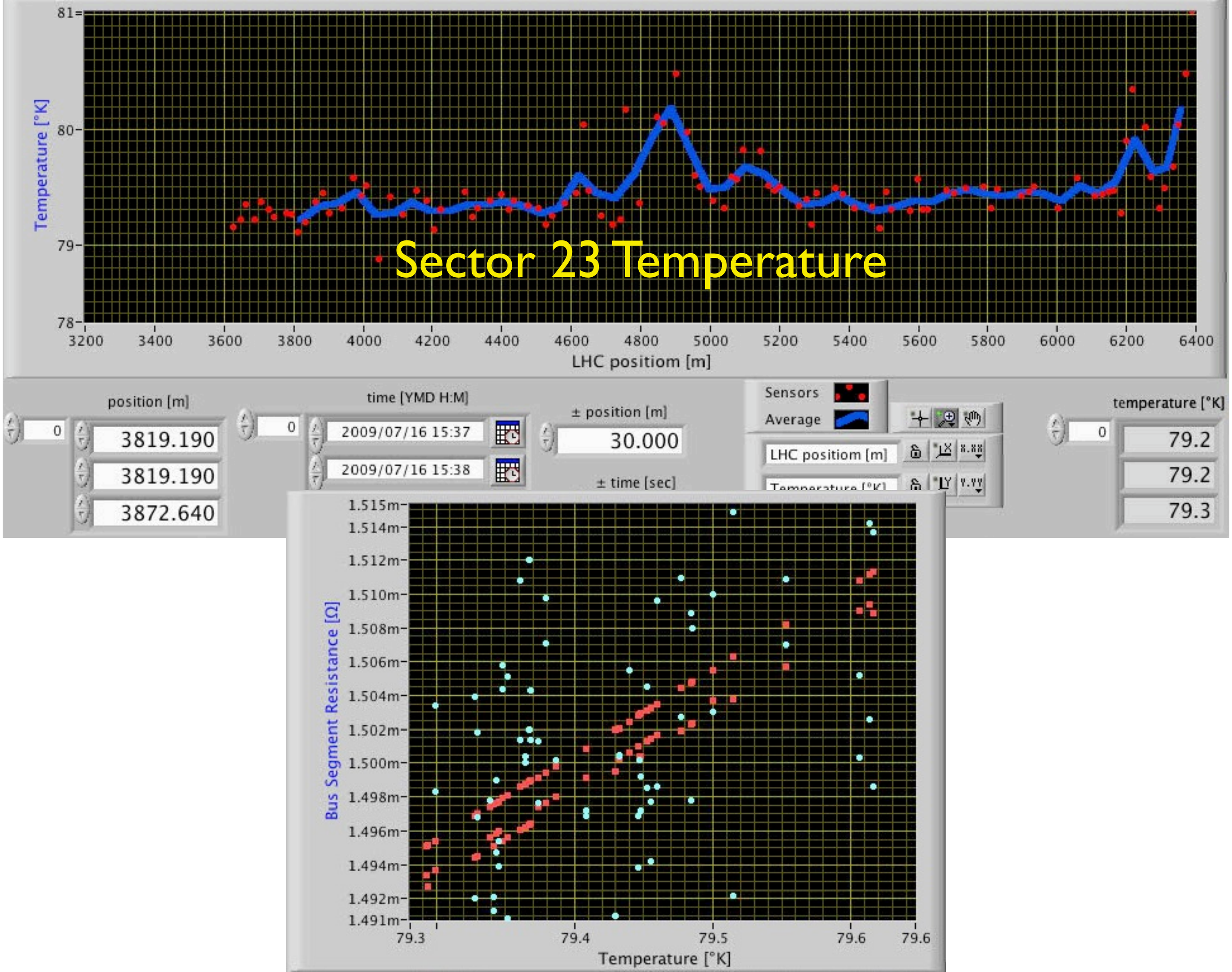




Temperature Compensation

Sector 23 QUAD Bus Segments

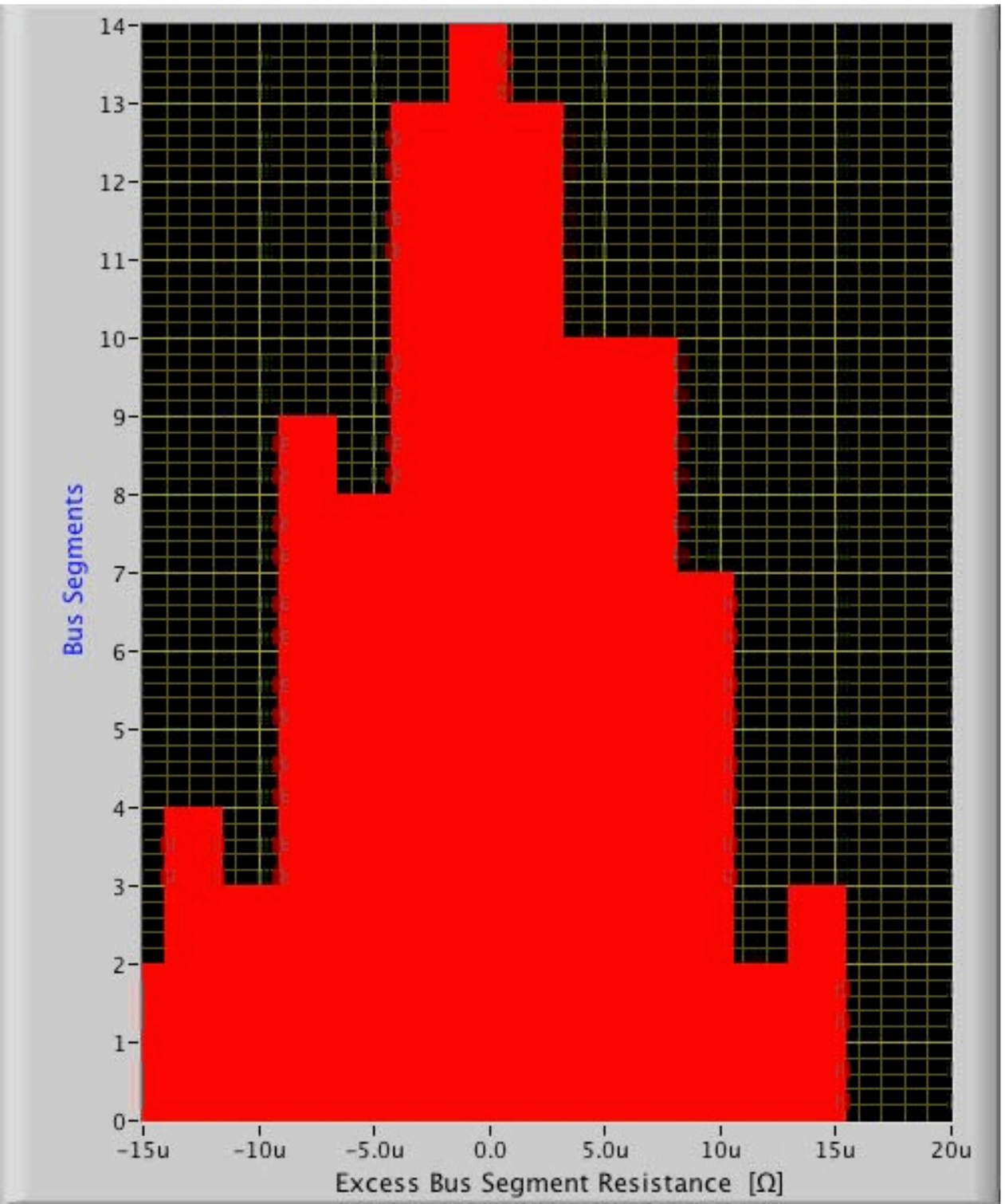



Sector 23 Temperature
Temperature [°K]
81
80
79
78
3200
3400
3600
3800
4000
4200
4400
4600
4800
5000
5200
5400
5600
5800
6000
6200
6400
LHC positiom [m]
position [m]
0
3819.190
3819.190
3872.640
time [YMD H:M]
0
2009/07/16 15:37
2009/07/16 15:38
± position [m]
30.000
± time [sec]
Sensors
Average
LHC positiom [m]
Temperature [°K]
temperature [°K]
0
79.2
79.2
79.3
Bus Segment Resistance [Ω]
1.515m
1.514m
1.512m
1.510m
1.508m
1.506m
1.504m
1.502m
1.500m
1.498m
1.496m
1.494m
1.492m
1.491m
79.3
79.4
79.5
79.6
79.6
Temperature [°K]

Sector 23 QUAD Bus Segments @ 80 K

15μΩ x 5 = 75μΩ @ 300K

Excess Resistance Distribution



Hit List

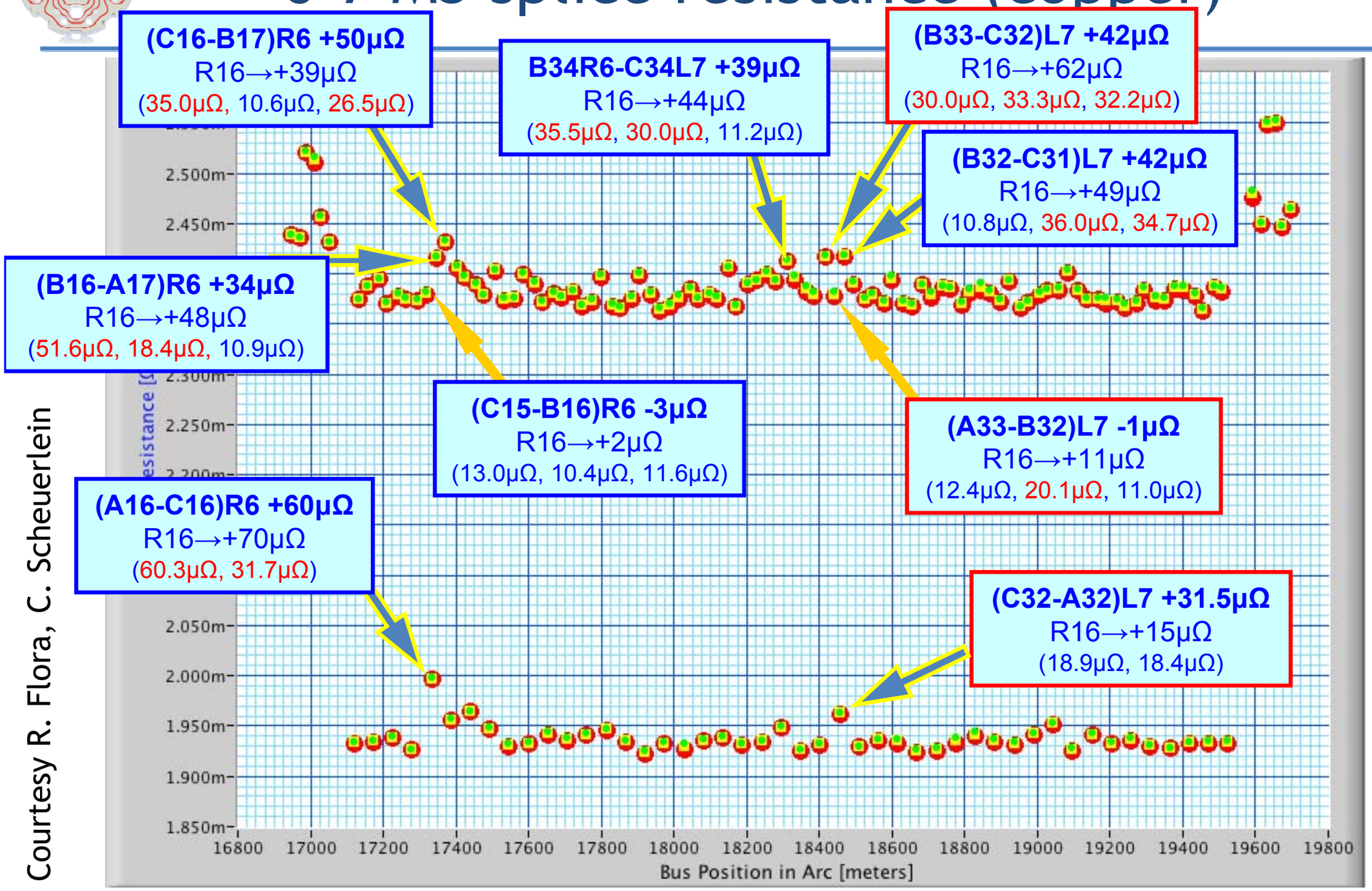
order

Hit List

∂R [Ω]	x [m]	Bus Segment Span
15.4u	5369	RQOA.[Q28L3<->Q26L3]i
14.7u	5316	RQOB.[Q29L3<->Q27L3]i
13.1u	4140	RQAT.[Q17R2<->Q19R2]e
12.8u	6224	RQAT.[Q12L3<->Q10L3]i
12.3u	4942	RQOA.[Q32R2<->Q34R2]e
10.4u	4354	RQAT.[Q21R2<->Q23R2]i
10.4u	5583	RQOA.[Q24L3<->Q22L3]i
9.8u	4193	RQAT.[Q18R2<->Q20R2]e
9.5u	5423	RQAS.[Q27L3<->Q25L3]i
9.5u	5583	RQOA.[Q24L3<->Q22L3]e
8.6u	6064	RQAT.[Q15L3<->Q13L3]e
8.2u	4514	RQOA.[Q24R2<->Q26R2]i
7.6u	4086	RQAT.[Q16R2<->Q18R2]i
7.3u	4567	RQOA.[Q25R2<->Q27R2]i
7.0u	5530	RQOA.[Q25L3<->Q23L3]e
6.9u	4888	RQOA.[Q31R2<->Q33R2]e
6.6u	5743	RQAT.[Q21L3<->Q19L3]e
6.5u	4354	RQAT.[Q21R2<->Q23R2]e
6.3u	5049	RQOA.[Q34R2<->Q32L3]e
6.1u	3980	RQAT.[Q14R2<->Q16R2]i

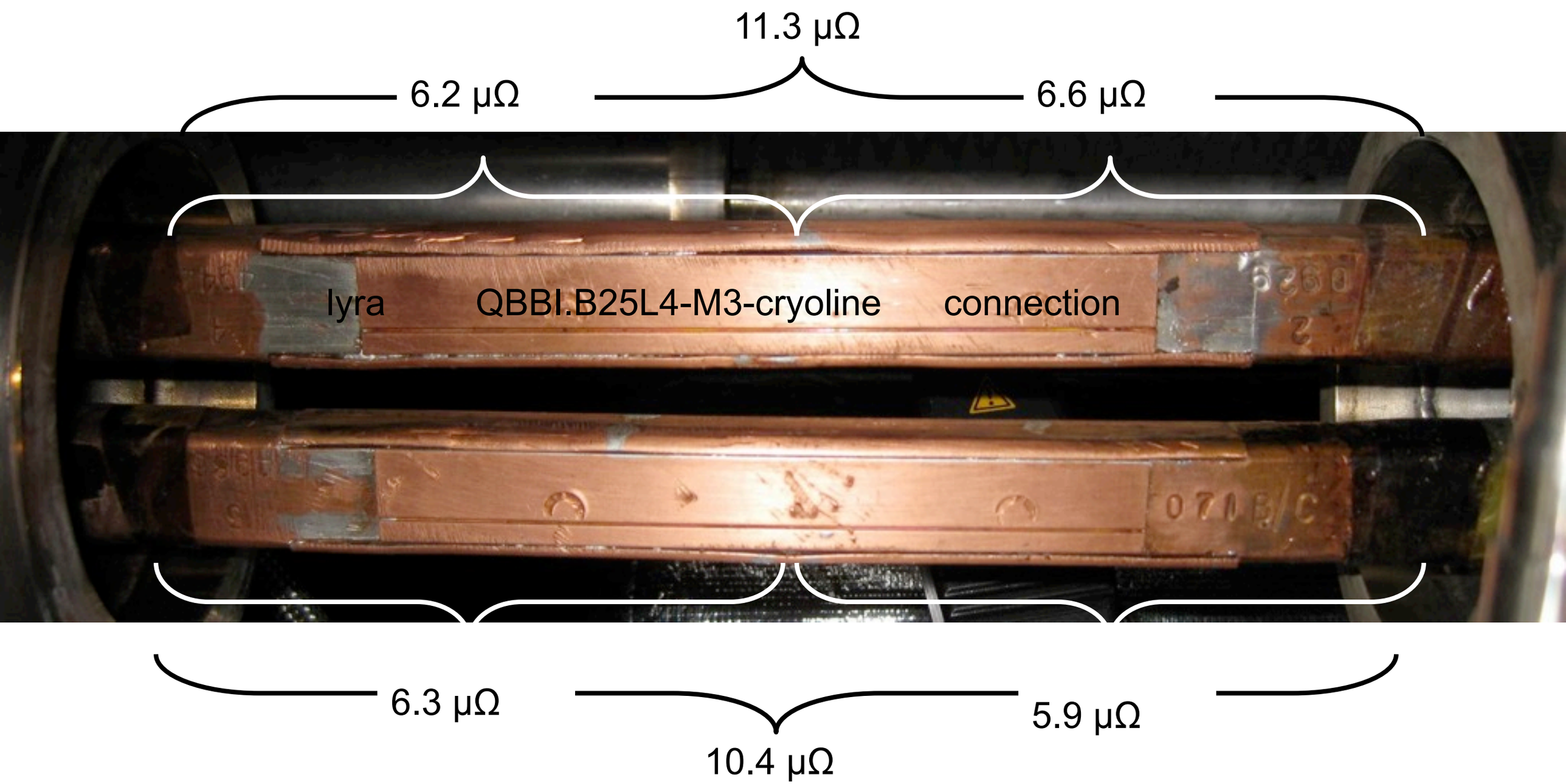
Open Up and Repair

6-7 M3 splice resistance (copper)

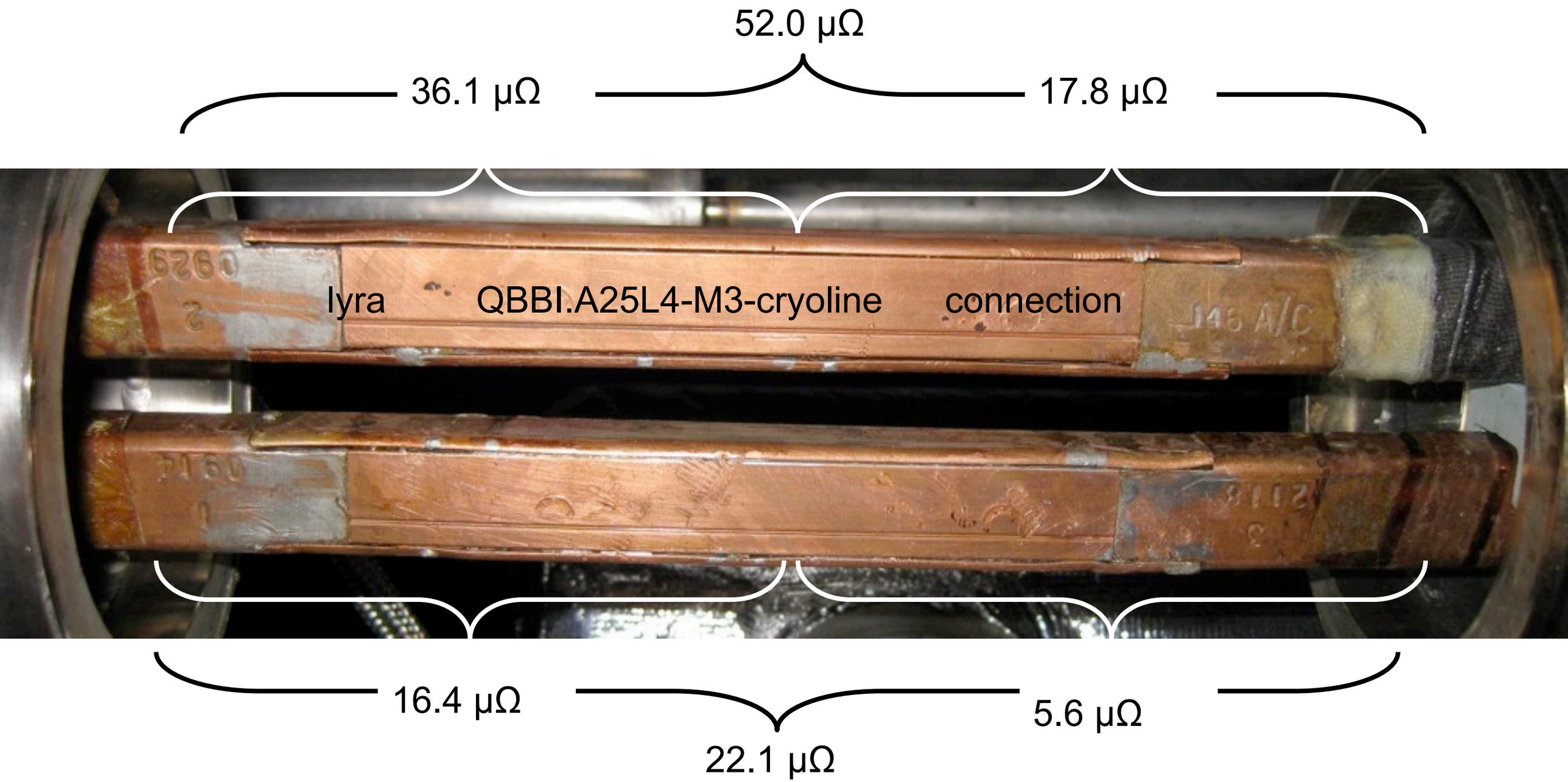


Courtesy R. Flora, C. Scheuerlein

QBBI.B25L4-M3



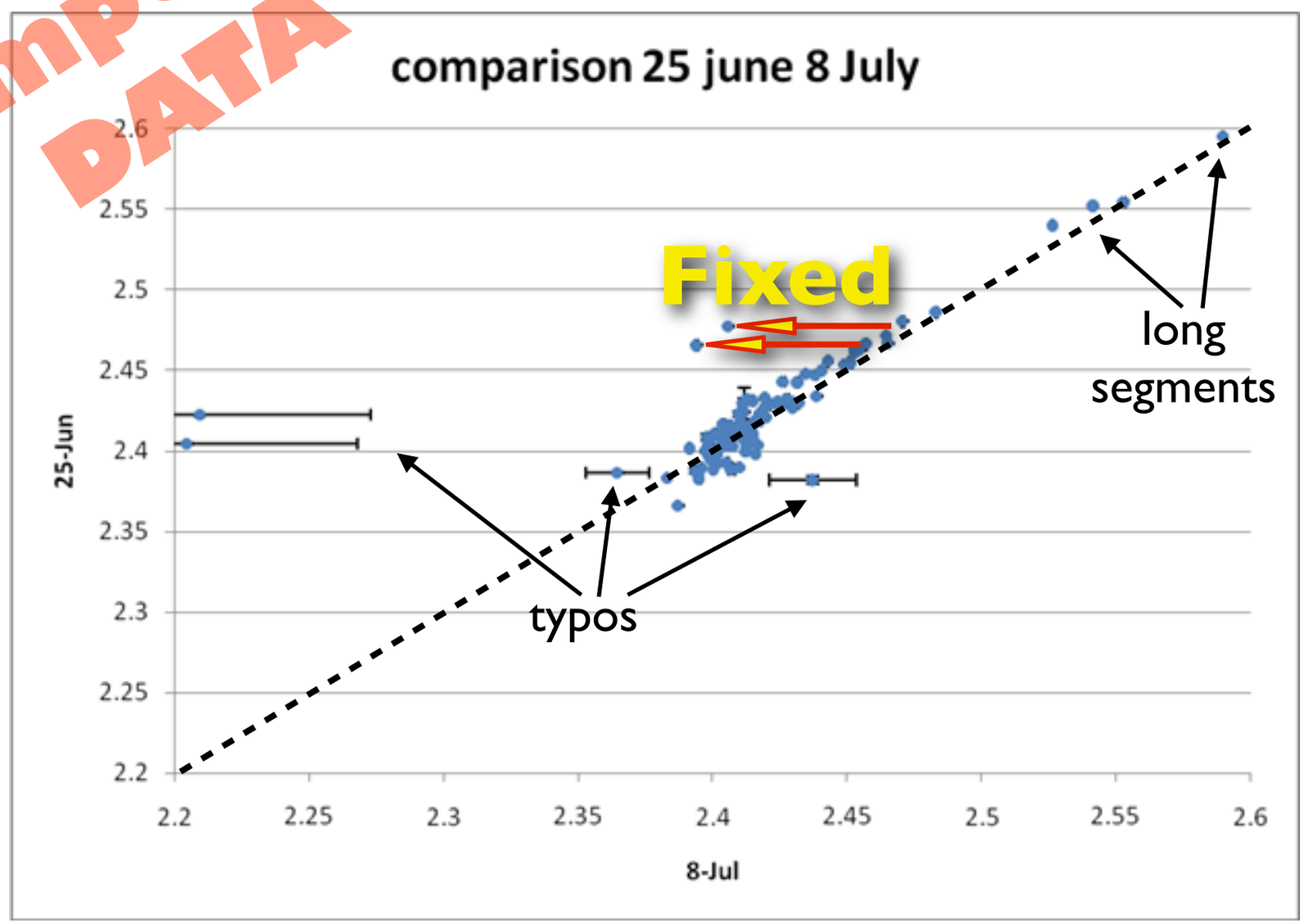
QBBI.A25L4-M3



Before & After Repair

Sector 45 BEND Bus Segments

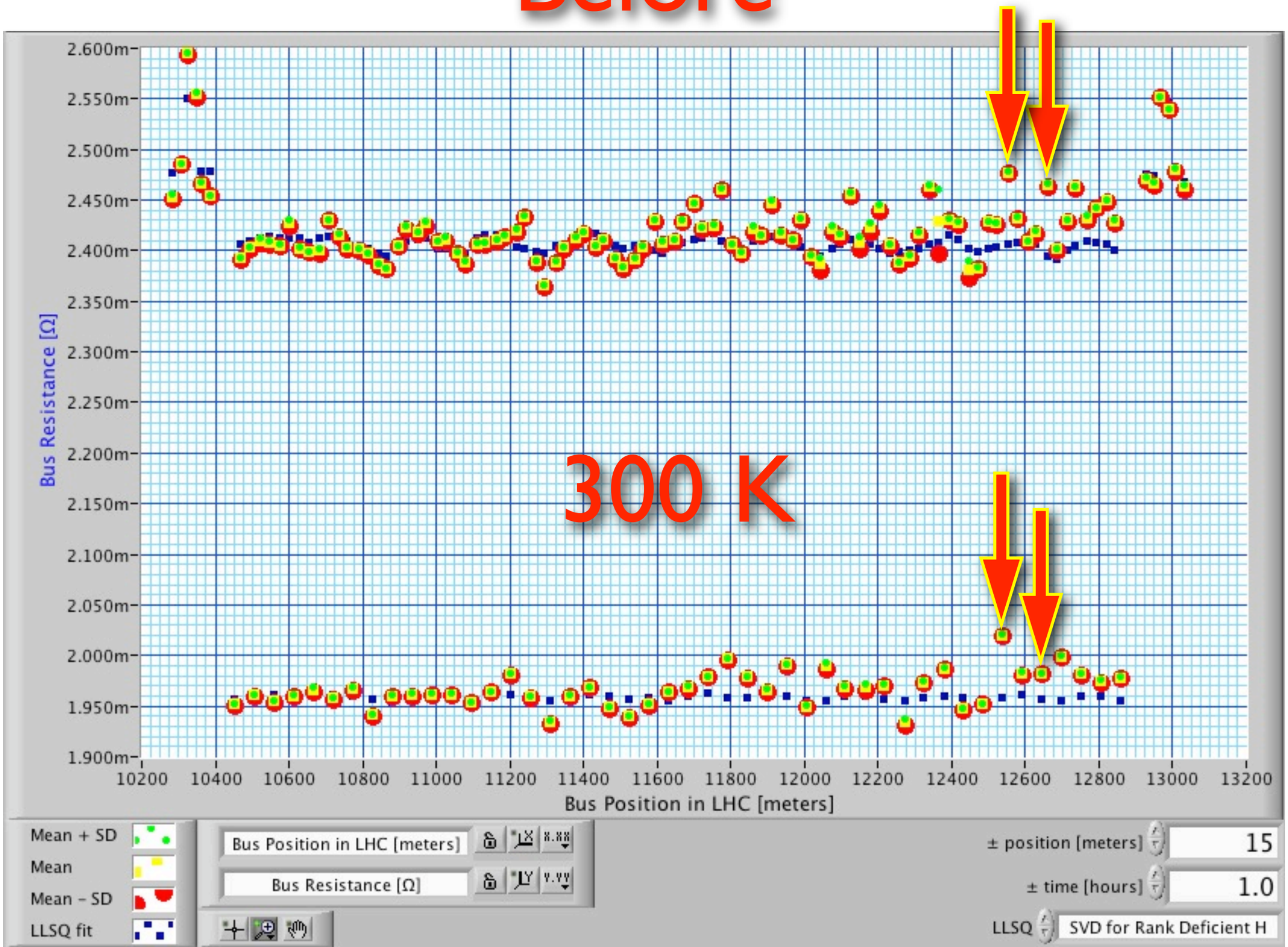
RAW Uncompensated DATA



Mike Koratzinos

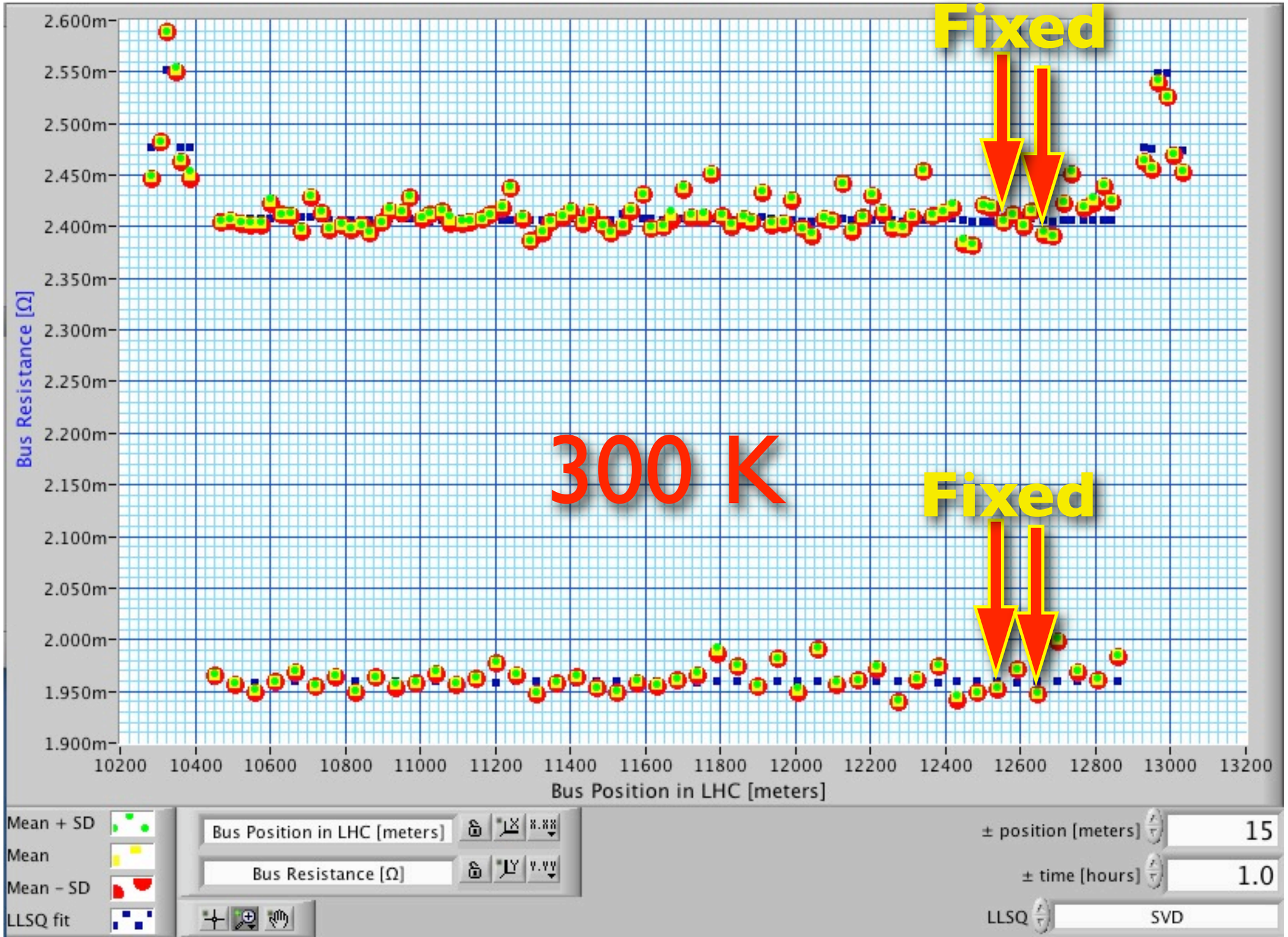
Sector 45 BEND Bus Segments

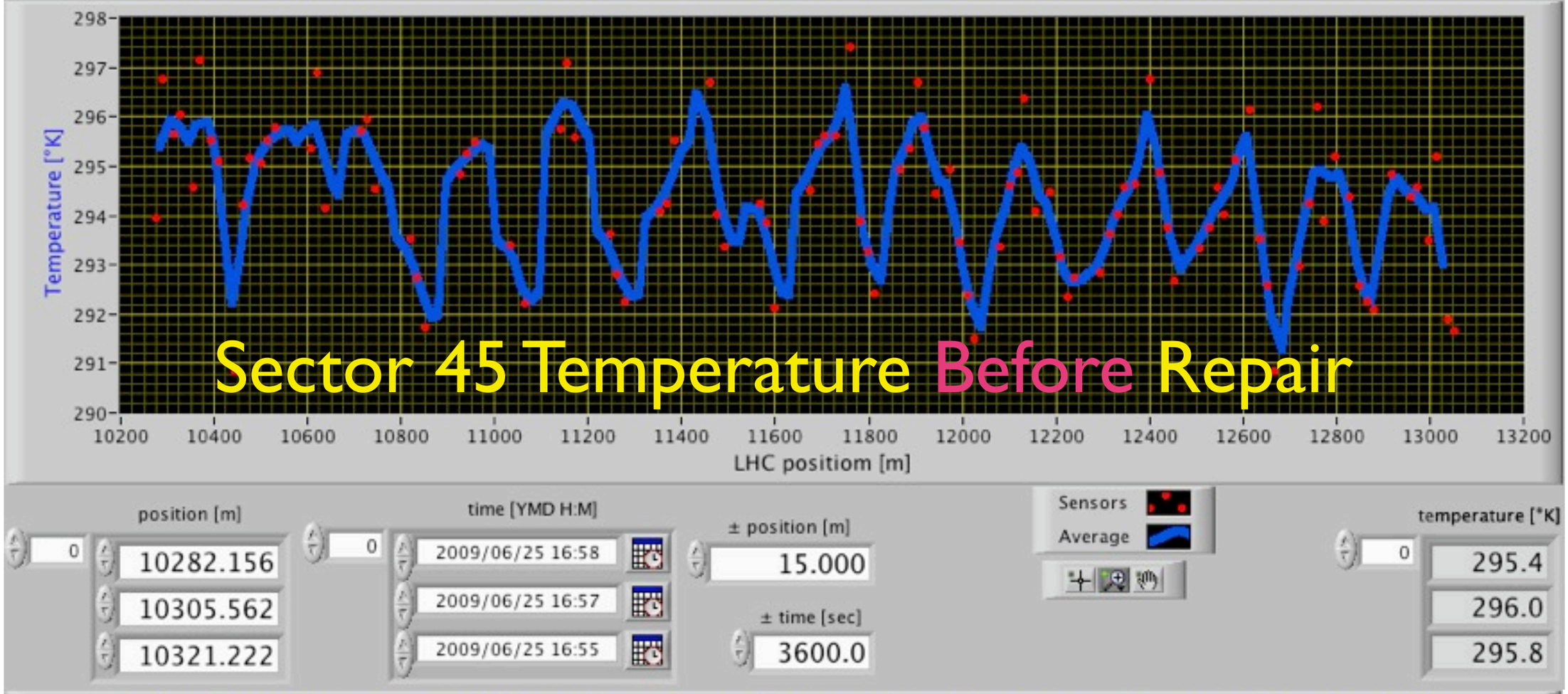
Before

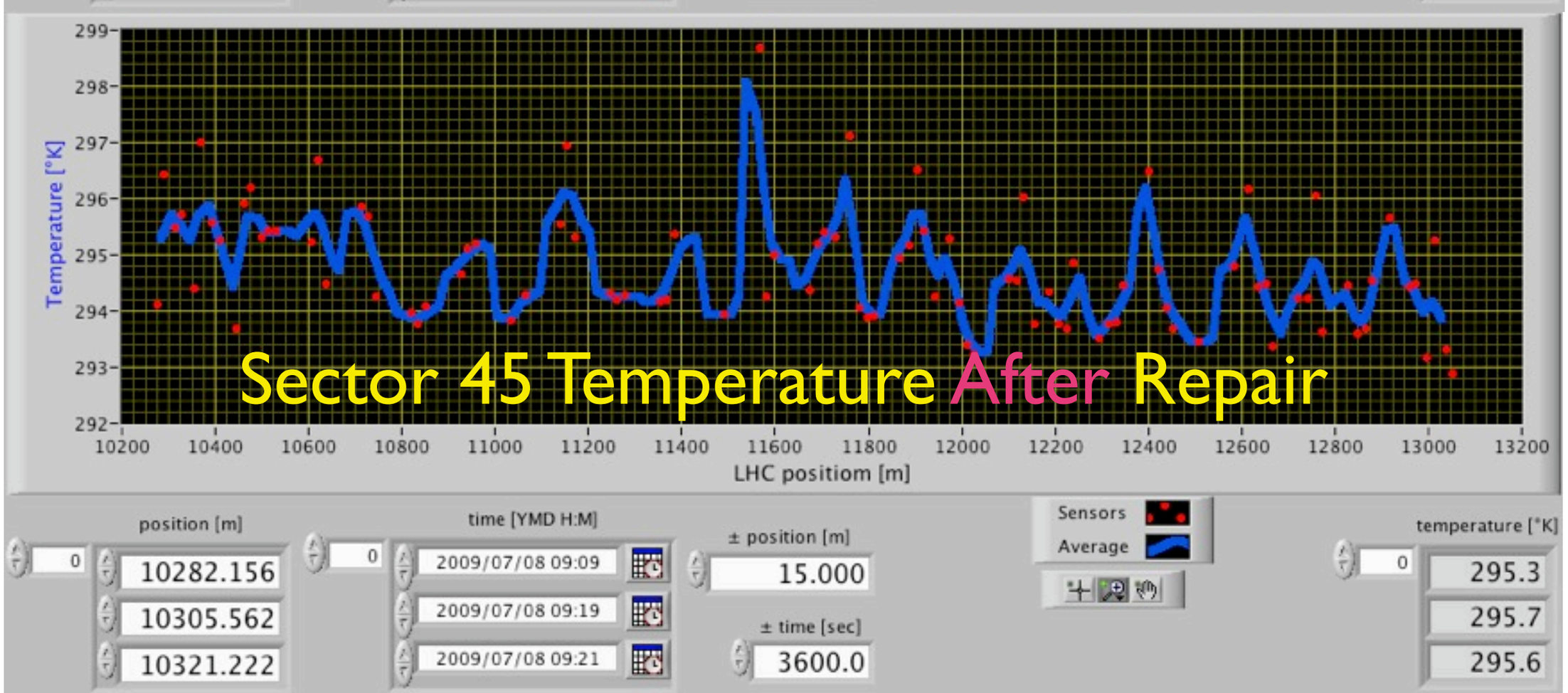


Sector 45 BEND Bus Segments

After



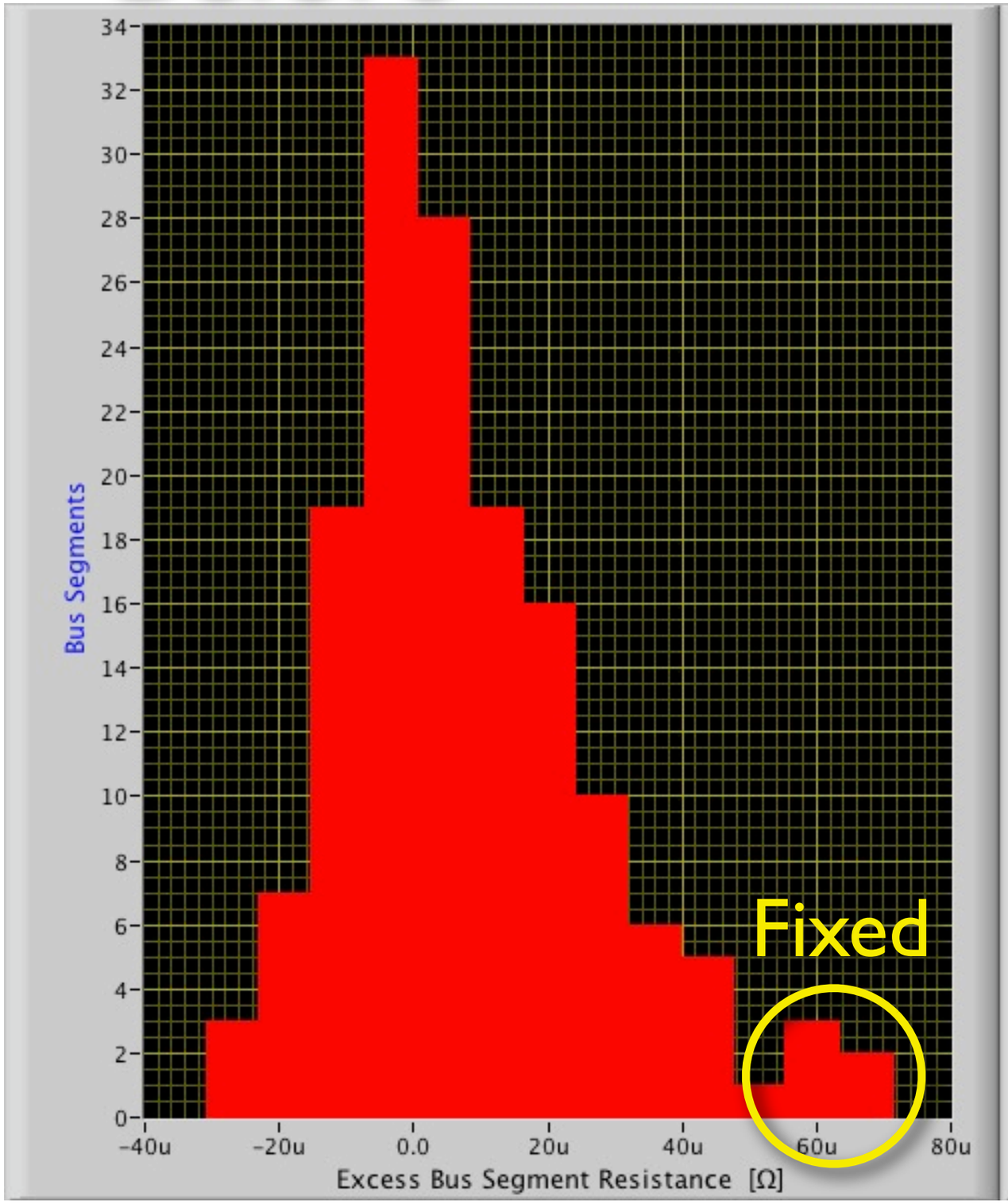

Sector 45 Temperature Before Repair
Temperature [°K]
LHC positiom [m]
position [m]
10282.156
10305.562
10321.222
time [YMD H:M]
2009/06/25 16:58
2009/06/25 16:57
2009/06/25 16:55
± position [m]
15.000
± time [sec]
3600.0
Sensors
Average
temperature [°K]
295.4
296.0
295.8


Sector 45 Temperature After Repair
Temperature [°K]
LHC positiom [m]
position [m]
10282.156
10305.562
10321.222
time [YMD H:M]
2009/07/08 09:09
2009/07/08 09:19
2009/07/08 09:21
± position [m]
15.000
± time [sec]
3600.0
Sensors
Average
temperature [°K]
295.3
295.7
295.6

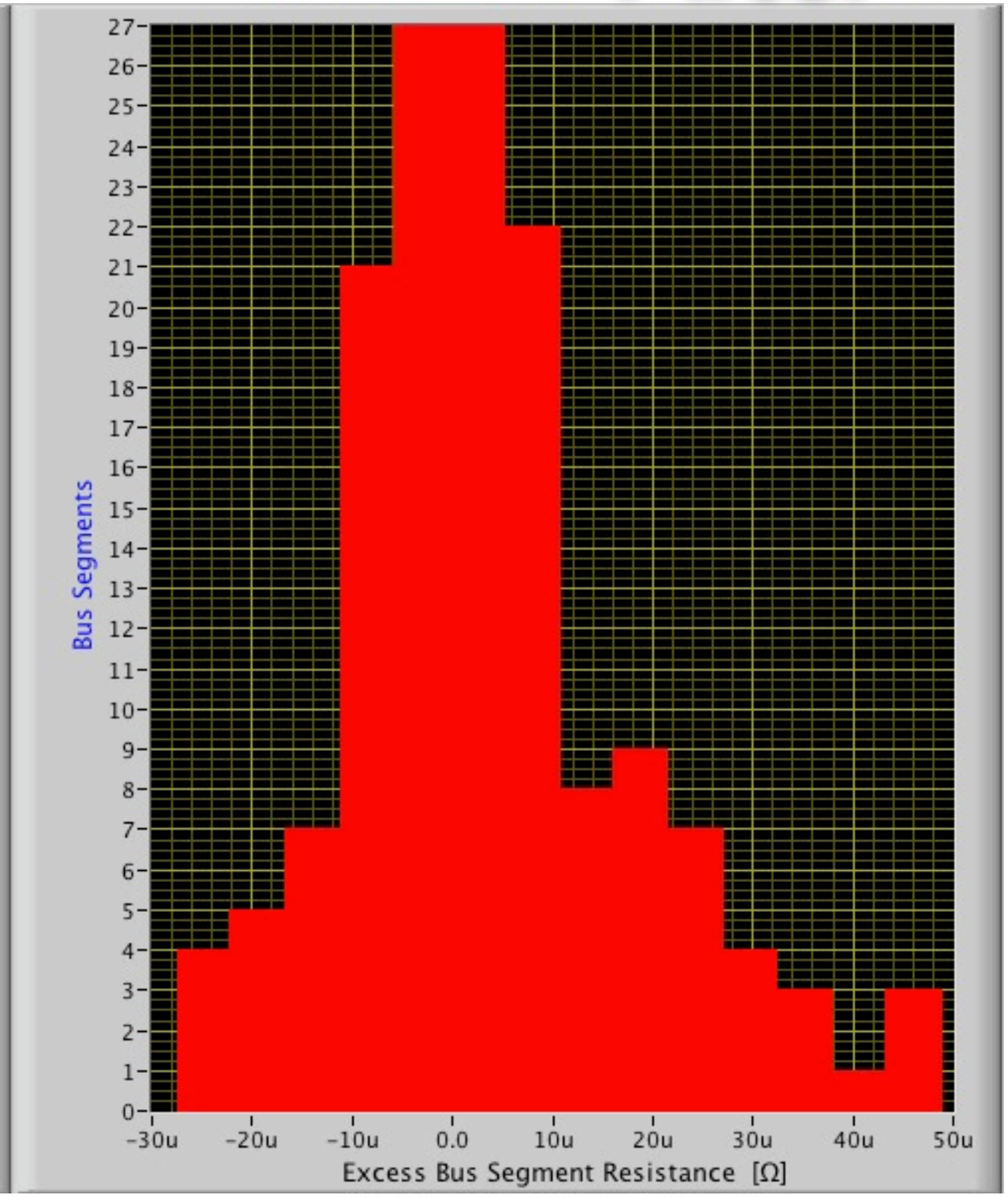
Sector 45 BEND Bus Segments @ 300 K

Excess Resistance Distribution

Before



After



Sector 45 BEND Bus Segments @ 300 K

Hit List Before

∂R [Ω]	x [m]	Bus Segment Span
70.9u	12553	RBAL.[B18L5<->C17L5]
69.6u	12660	RBAL.[B16L5<->C15L5]
61.9u	12537	RBBL.[C18L5<->A18L5]
57.3u	12339	RBAL.[B22L5<->C21L5]
57.1u	12735	RBAL.[A15L5<->B14L5]
52.0u	11773	RBAL.[A33L5<->B32L5]
46.0u	10321	RBAL.[A9R4<->A10R4]
44.6u	12125	RBAL.[B26L5<->C25L5]
44.3u	12697	RBAL.[C15L5<->A15L5]
43.8u	12820	RBBL.[B13L5<->C12L5]
40.4u	12201	RBAL.[A25L5<->B24L5]
39.0u	11789	RBBL.[C32L5<->A32L5]
35.1u	11698	RBAL.[B34L5<->C33L5]
34.0u	12056	RBAL.[C27L5<->A27L5]
33.7u	12789	RBBL.[A14L5<->B13L5]
33.2u	11911	RBAL.[B30L5<->C29L5]
32.9u	11239	RBAL.[C26R4<->B27R4]
30.7u	11949	RBAL.[C29L5<->A29L5]
28.9u	11987	RBAL.[A29L5<->B28L5]
28.8u	11591	RBAL.[B33R4<->A34R4]

✓ Fixed
✓ Fixed
✓ Fixed

Hit List After

∂R [Ω]	x [m]	Bus Segment Span
48.7u	12339	RBAL.[B22L5<->C21L5]
46.0u	12735	RBAL.[A15L5<->B14L5]
44.7u	11773	RBAL.[A33L5<->B32L5]
40.9u	12697	RBAL.[C15L5<->A15L5]
37.7u	10321	RBAL.[A9R4<->A10R4]
34.9u	12125	RBAL.[B26L5<->C25L5]
33.9u	12820	RBBL.[B13L5<->C12L5]
32.1u	11239	RBAL.[C26R4<->B27R4]
31.5u	12056	RBAL.[C27L5<->A27L5]
30.6u	11789	RBBL.[C32L5<->A32L5]
30.1u	11698	RBAL.[B34L5<->C33L5]
25.5u	11911	RBAL.[B30L5<->C29L5]
25.5u	12201	RBAL.[A25L5<->B24L5]
24.6u	12858	RBBL.[C12L5<->A12L5]
23.8u	11591	RBAL.[B33R4<->A34R4]
23.0u	12874	RBAL.[B12L5<->B11L5]
23.0u	11949	RBAL.[C29L5<->A29L5]

Warm Cold Correlation

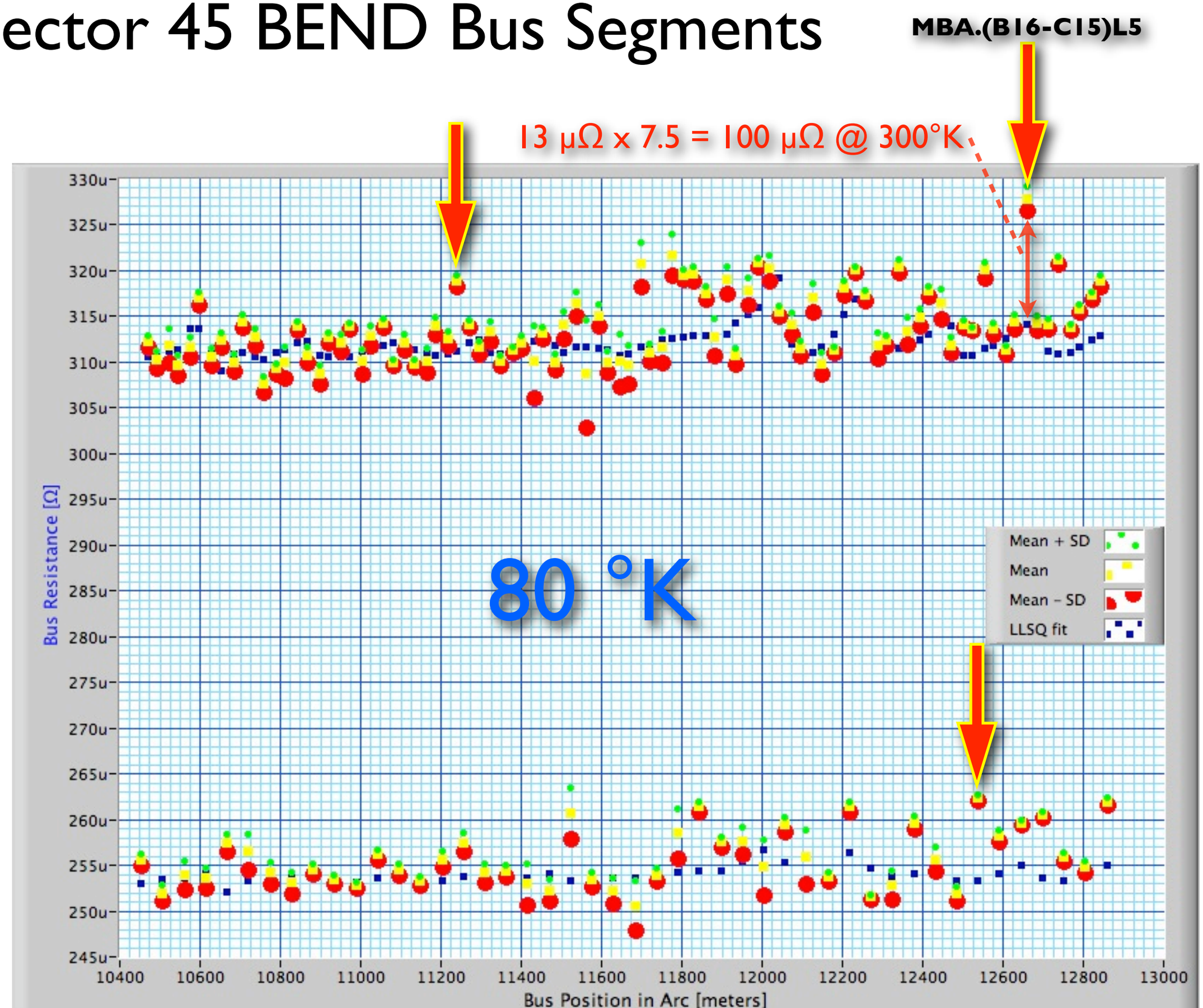
Bus Measurements in S45 @ 80K & 300K

(: Sadistical OHMS :)

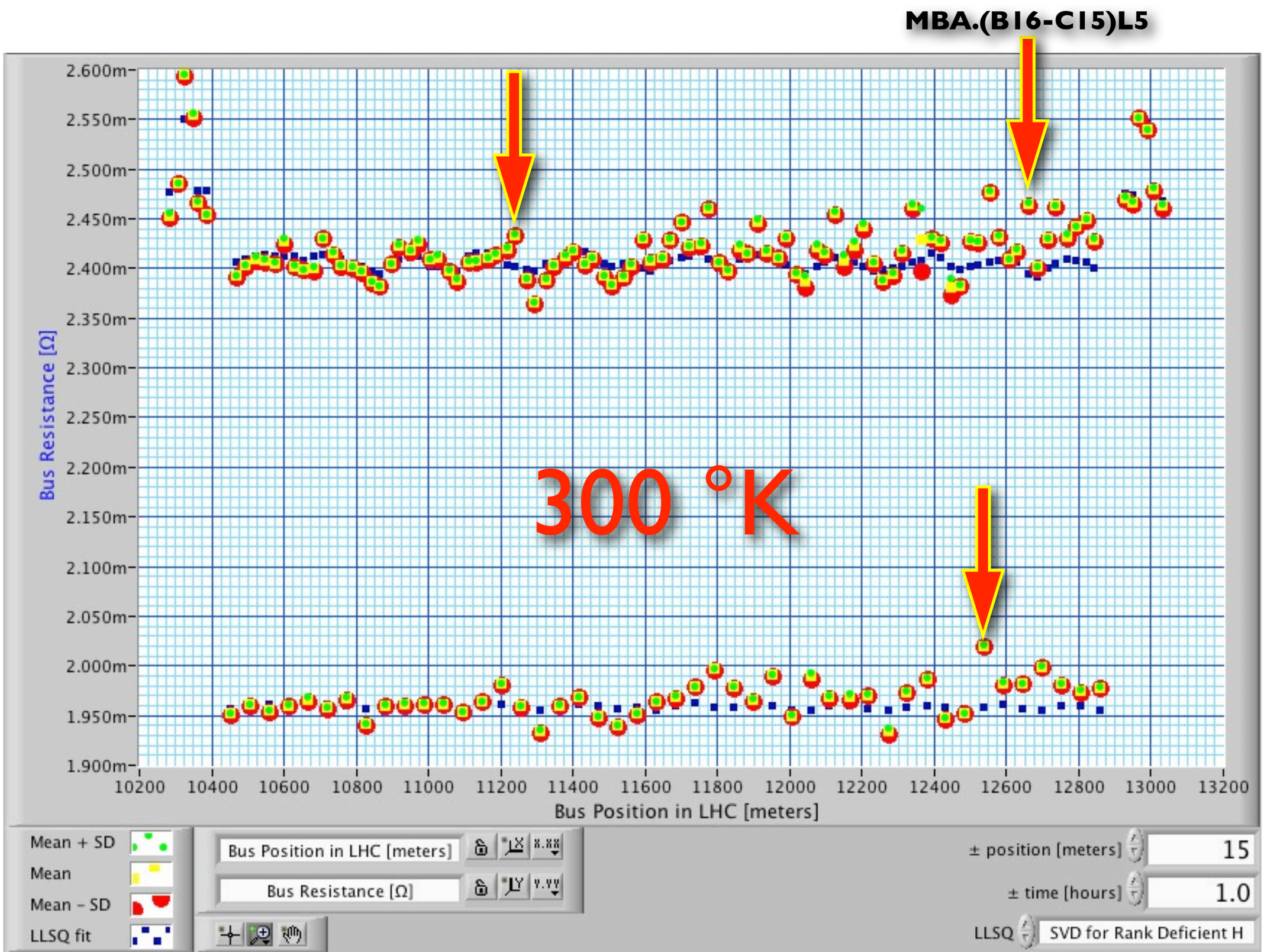
Analysis: Bob Flora, Mike Koratzinos, Howie Pfeffer, Zinur Charifoulline, Alex Tuna, Kent Wootton
Measurements: Grzegorz Seweryn, Edward Nowak, Arkadiusz Gorzawski, Adam Drozd, Andrzej Skoczen, Aleksander Skala, Romain Duse, Floran Zanarone, Jerome Ducret, Kent Wootton

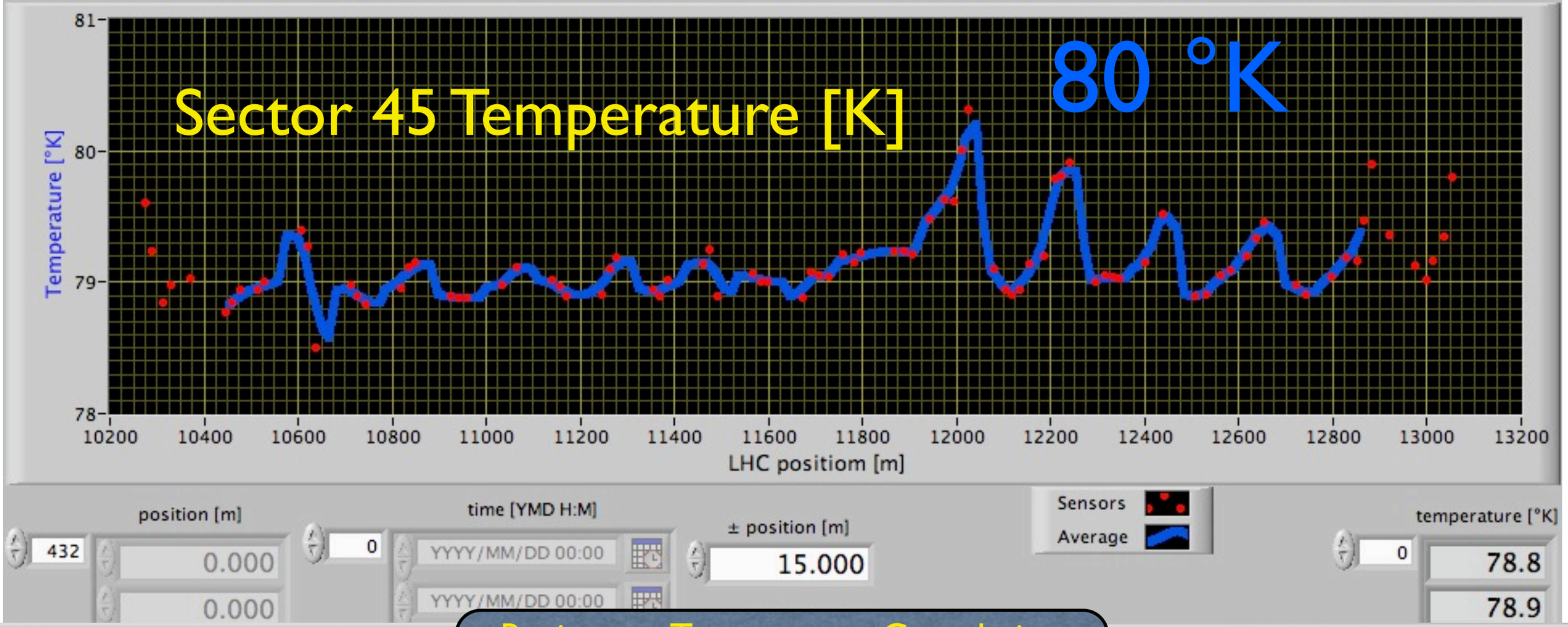
LMC 15.07.2009

Sector 45 BEND Bus Segments

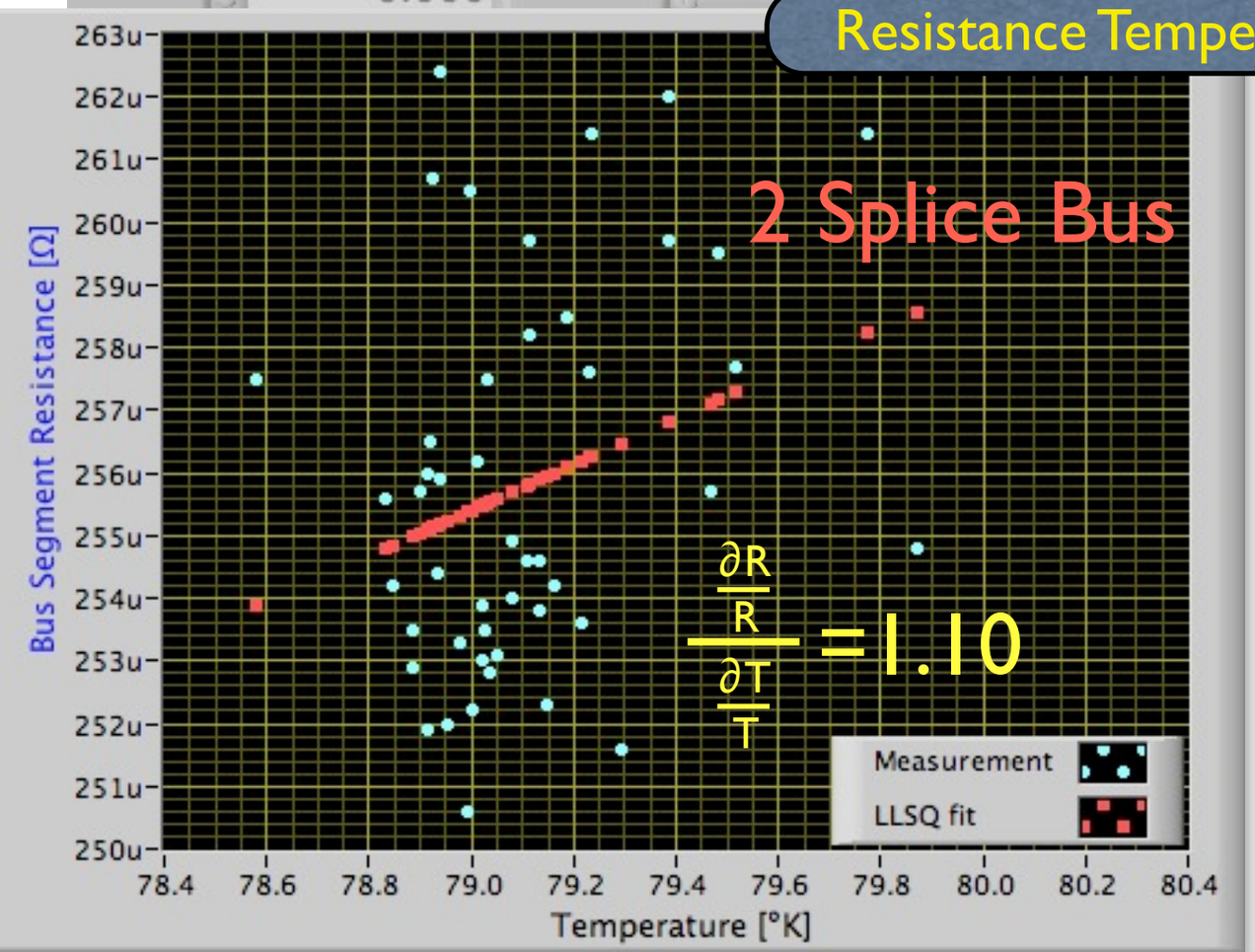


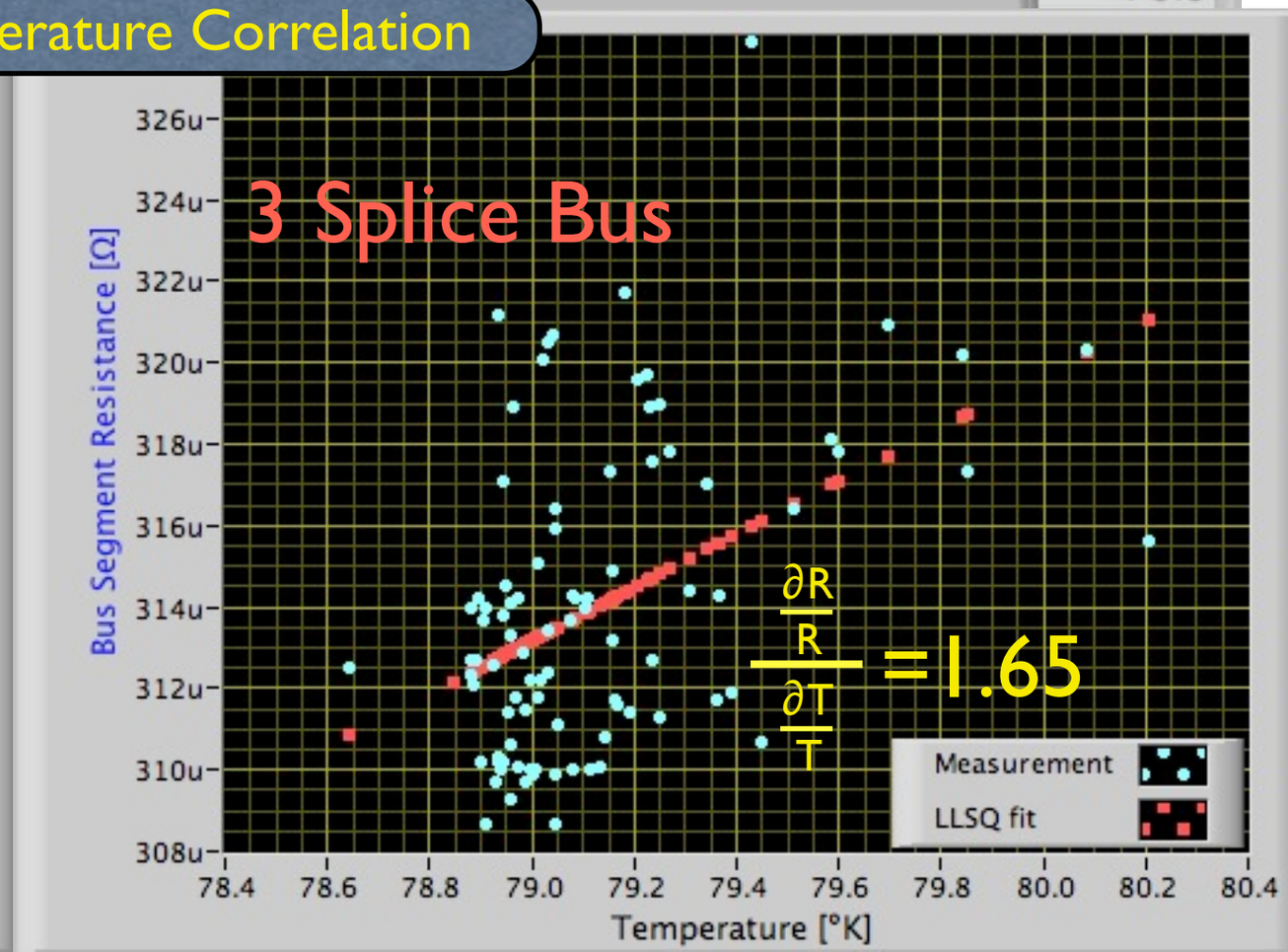
Sector 45 BEND Bus Segments

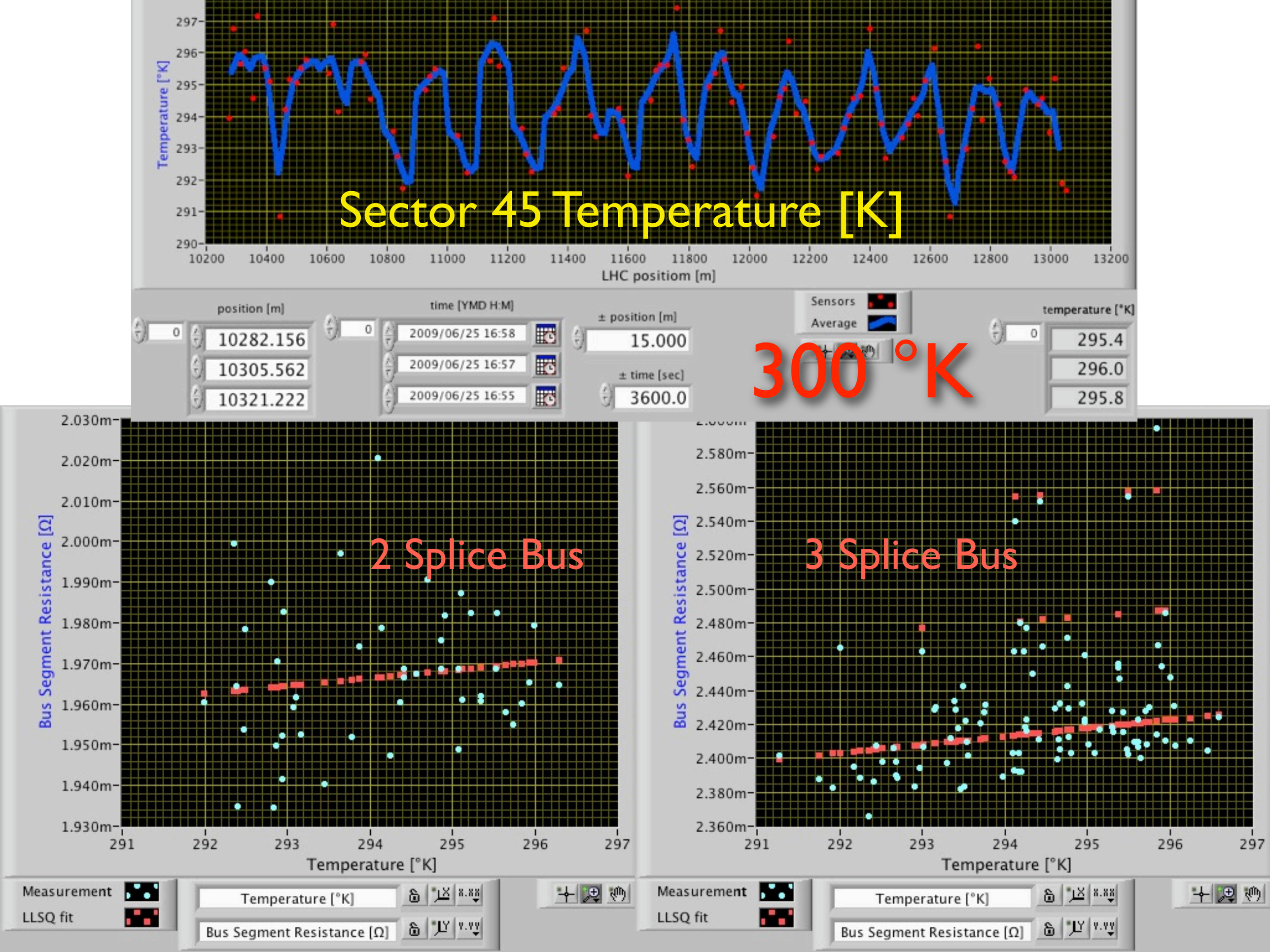




Resistance Temperature Correlation



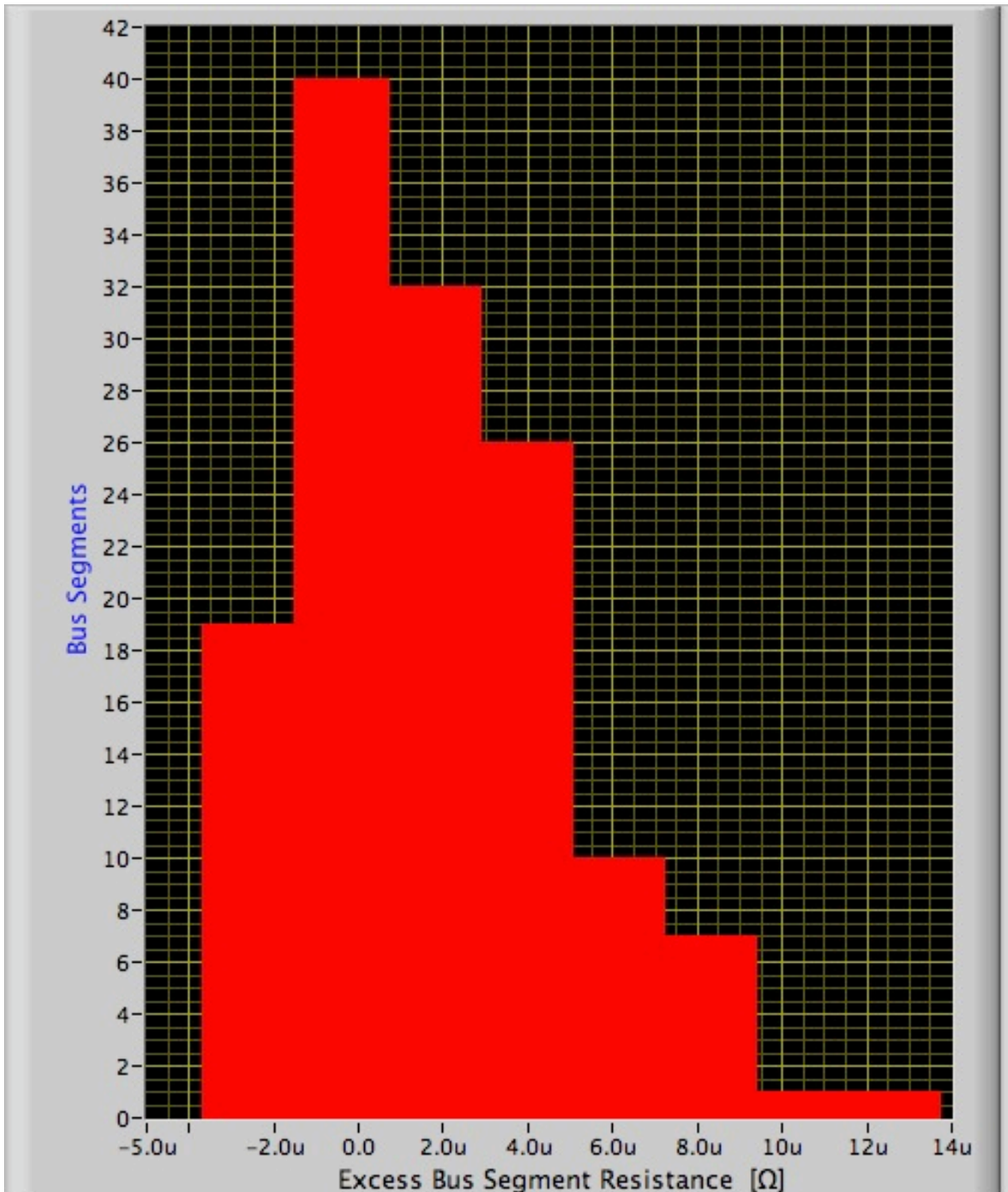



Sector 45 Temperature [K]
Temperature [°K]
LHC positiom [m]
position [m]
10282.156
10305.562
10321.222
time [YMD H:M]
2009/06/25 16:58
2009/06/25 16:57
2009/06/25 16:55
± position [m]
15.000
± time [sec]
3600.0
Sensors
Average
temperature [°K]
295.4
296.0
295.8
300 °K
2 Splice Bus
Bus Segment Resistance [Ω]
Temperature [°K]
Measurement
LLSQ fit
Temperature [°K]
Bus Segment Resistance [Ω]
3 Splice Bus
Bus Segment Resistance [Ω]
Temperature [°K]
Measurement
LLSQ fit
Temperature [°K]
Bus Segment Resistance [Ω]

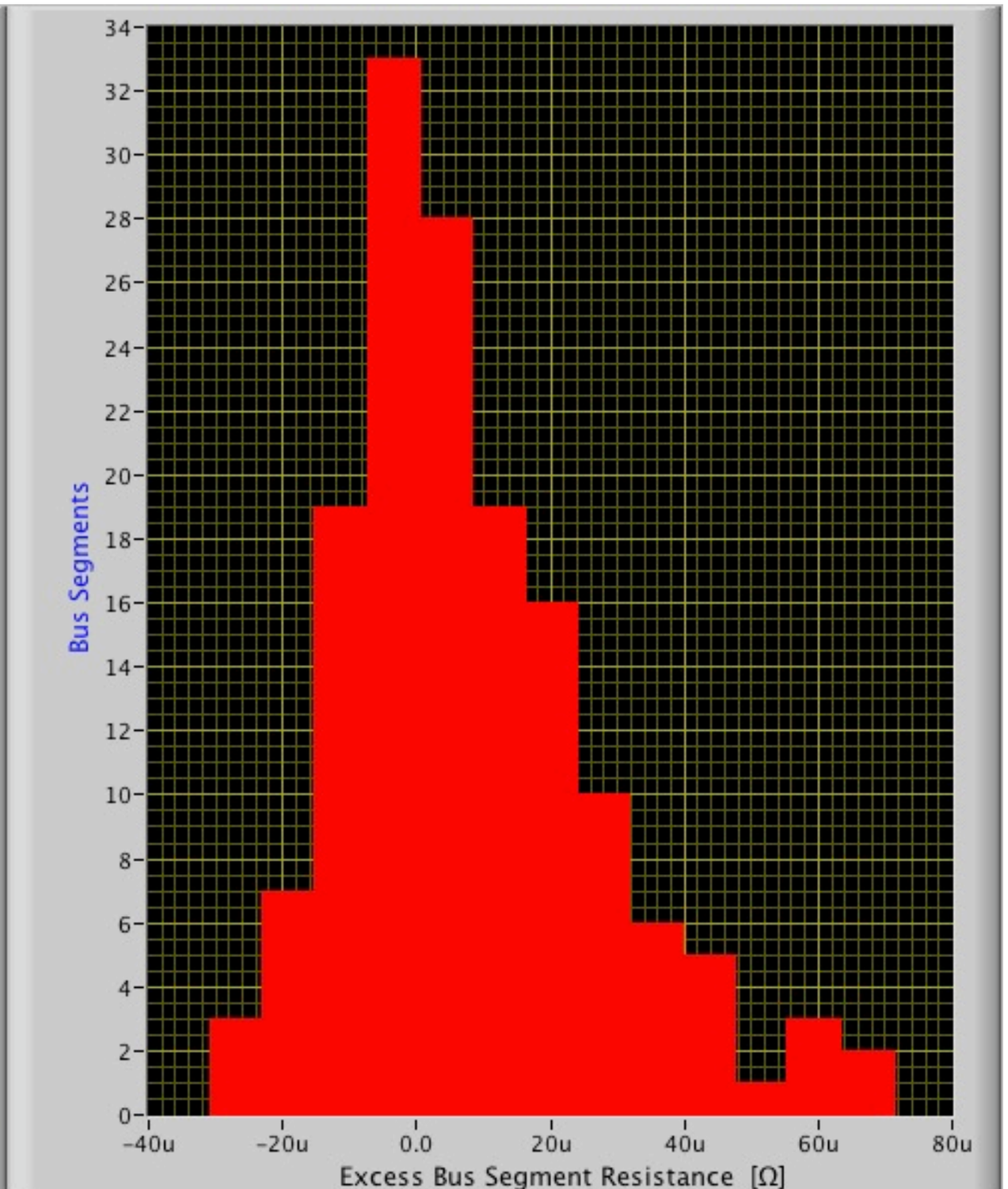
Sector 45 BEND Bus Segments

Excess Resistance Distribution

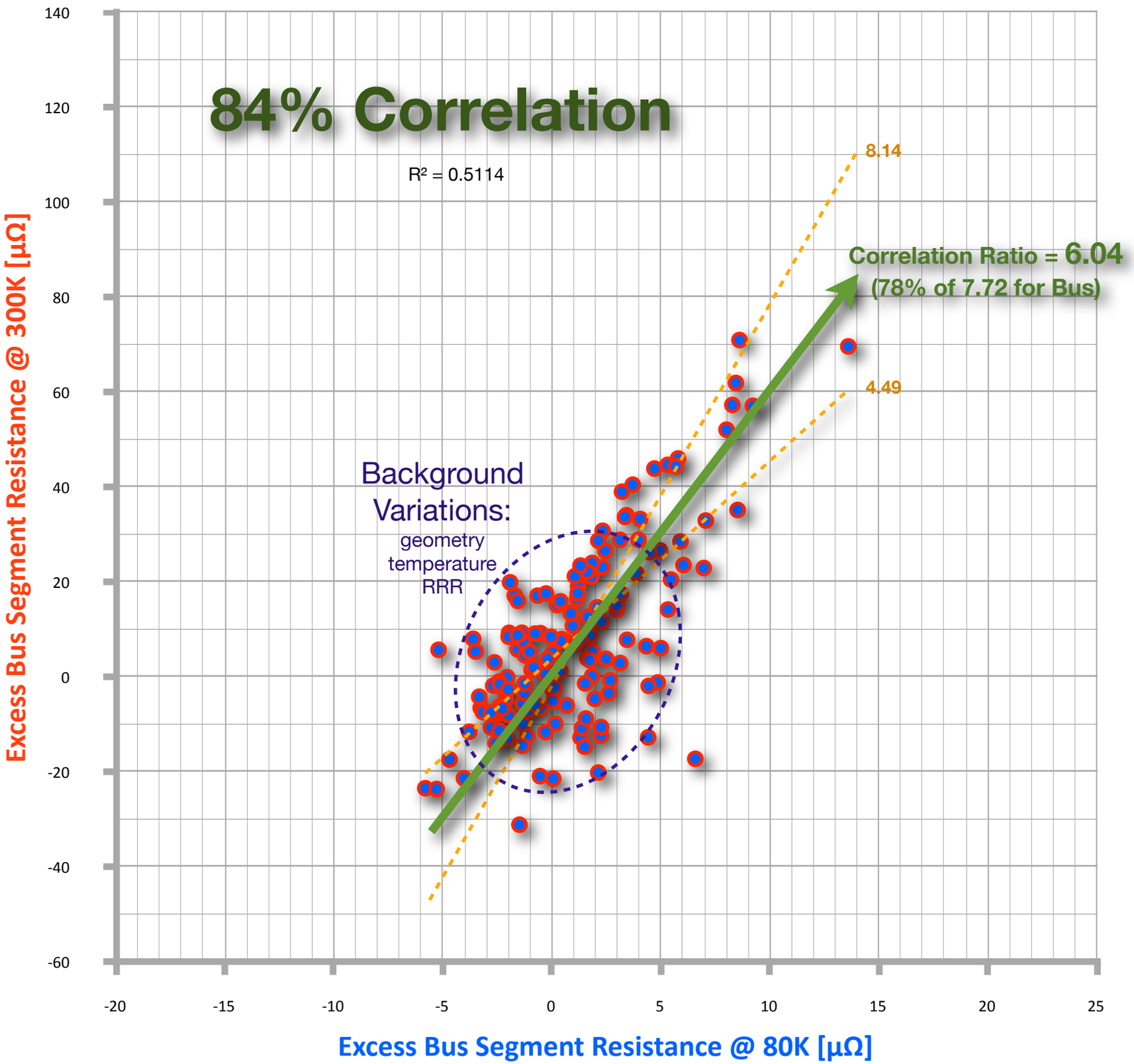
80 K



300 K



BEND Bus 80K => 300K Correlation



Sector 45 BEND Bus Segments

Hit List Shuffle (hash table)

80 K

Hit List

∂R [Ω]	x [m]	Bus Segment Span
13.7u	12660	RBAL.[B16L5<->C15L5]
10.3u	12735	RBAL.[A15L5<->B14L5]
9.2u	11773	RBAL.[A33L5<->B32L5]
9.1u	11698	RBAL.[B34L5<->C33L5]
9.0u	12537	RBBL.[C18L5<->A18L5]
8.9u	12339	RBAL.[B22L5<->C21L5]
8.6u	12553	RBAL.[B18L5<->C17L5]
7.8u	11239	RBAL.[C26R4<->B27R4]
7.4u	11522	RBAL.[A32R4<->C32R4]
7.0u	12858	RBBL.[C12L5<->A12L5]
6.9u	11842	RBAL.[C31L5<->A31L5]
6.9u	12697	RBAL.[C15L5<->A15L5]
6.9u	11805	RBAL.[B32L5<->C31L5]
6.9u	11827	RBBL.[A32L5<->B31L5]
6.1u	12125	RBAL.[B26L5<->C25L5]
6.0u	12842	RBAL.[A13L5<->B12L5]

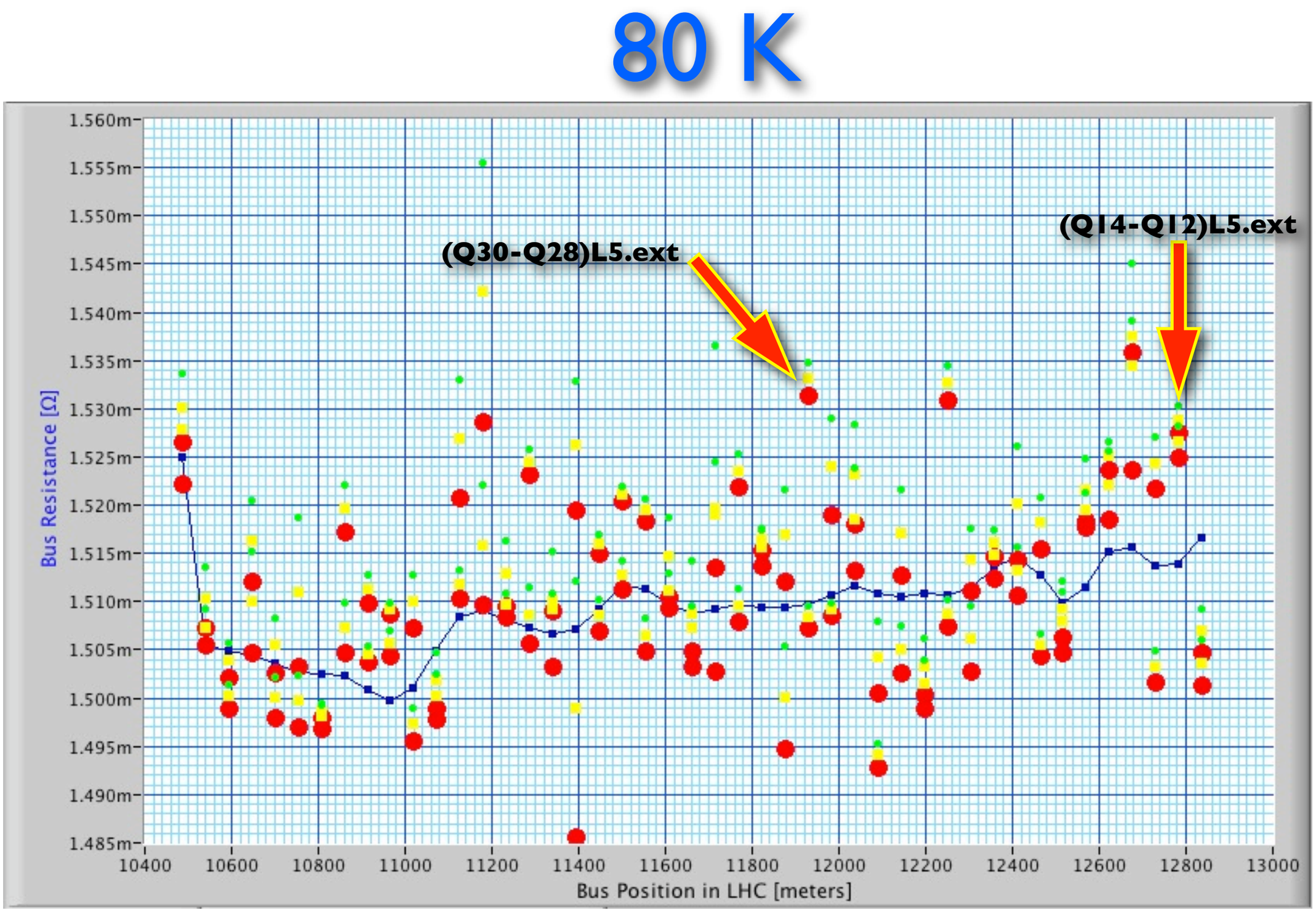
300 K

order

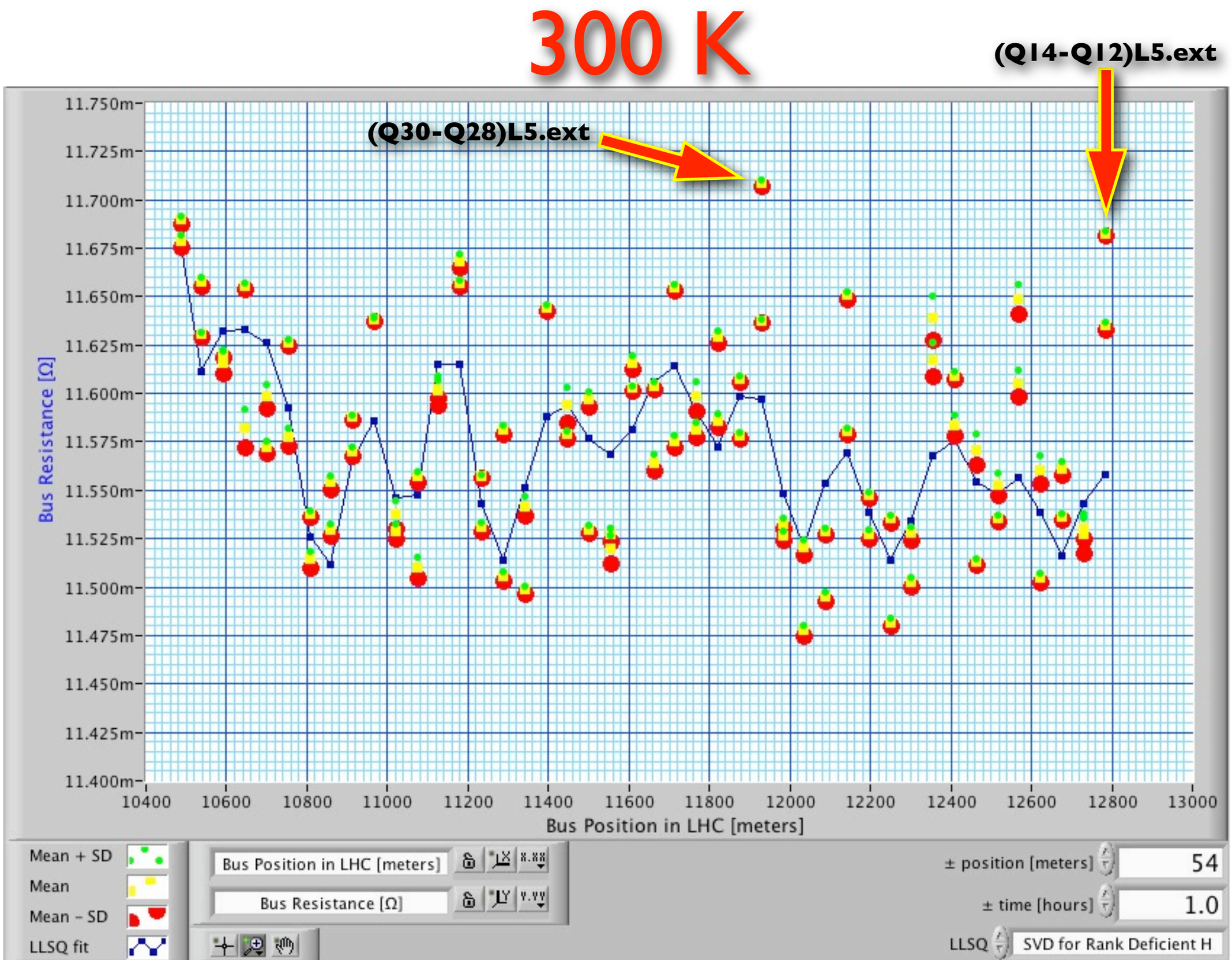
Hit List

∂R [Ω]	x [m]	Bus Segment Span
70.9u	12553	RBAL.[B18L5<->C17L5]
69.6u	12660	RBAL.[B16L5<->C15L5]
61.9u	12537	RBBL.[C18L5<->A18L5]
57.3u	12339	RBAL.[B22L5<->C21L5]
57.1u	12735	RBAL.[A15L5<->B14L5]
52.0u	11773	RBAL.[A33L5<->B32L5]
46.0u	10321	RBAL.[A9R4<->A10R4]
44.6u	12125	RBAL.[B26L5<->C25L5]
44.3u	12697	RBAL.[C15L5<->A15L5]
43.8u	12820	RBBL.[B13L5<->C12L5]
40.4u	12201	RBAL.[A25L5<->B24L5]
39.0u	11789	RBBL.[C32L5<->A32L5]
35.1u	11698	RBAL.[B34L5<->C33L5]
34.0u	12056	RBAL.[C27L5<->A27L5]
33.7u	12789	RBBL.[A14L5<->B13L5]
33.2u	11911	RBAL.[B30L5<->C29L5]

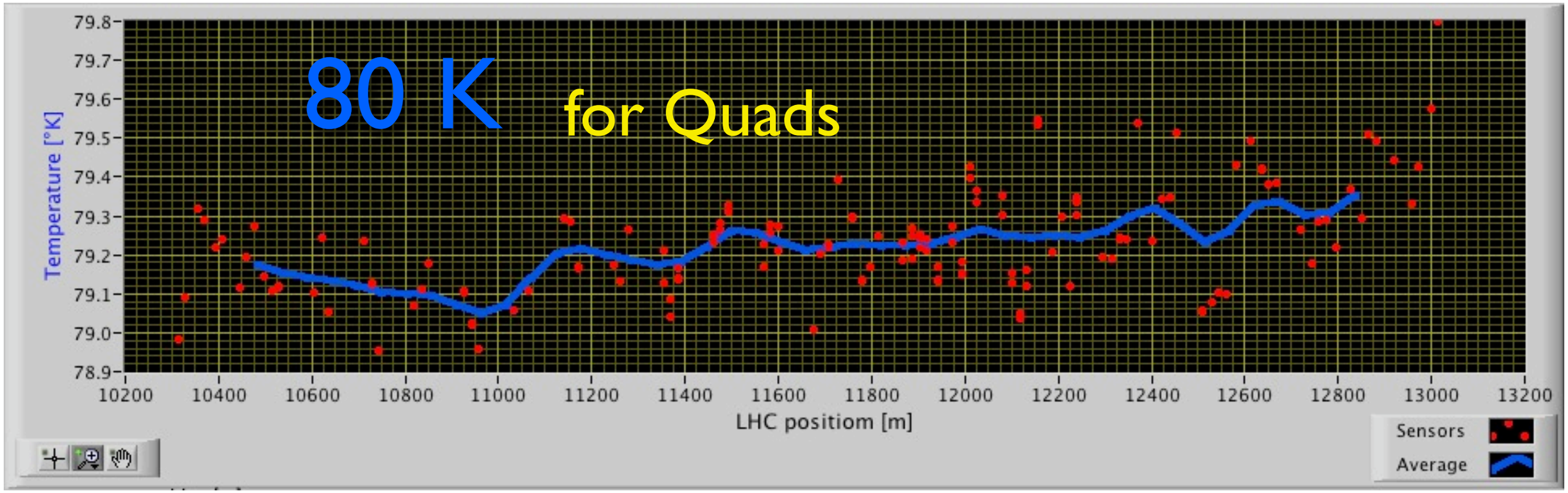
Sector 45 QUAD Bus Segments Measurements

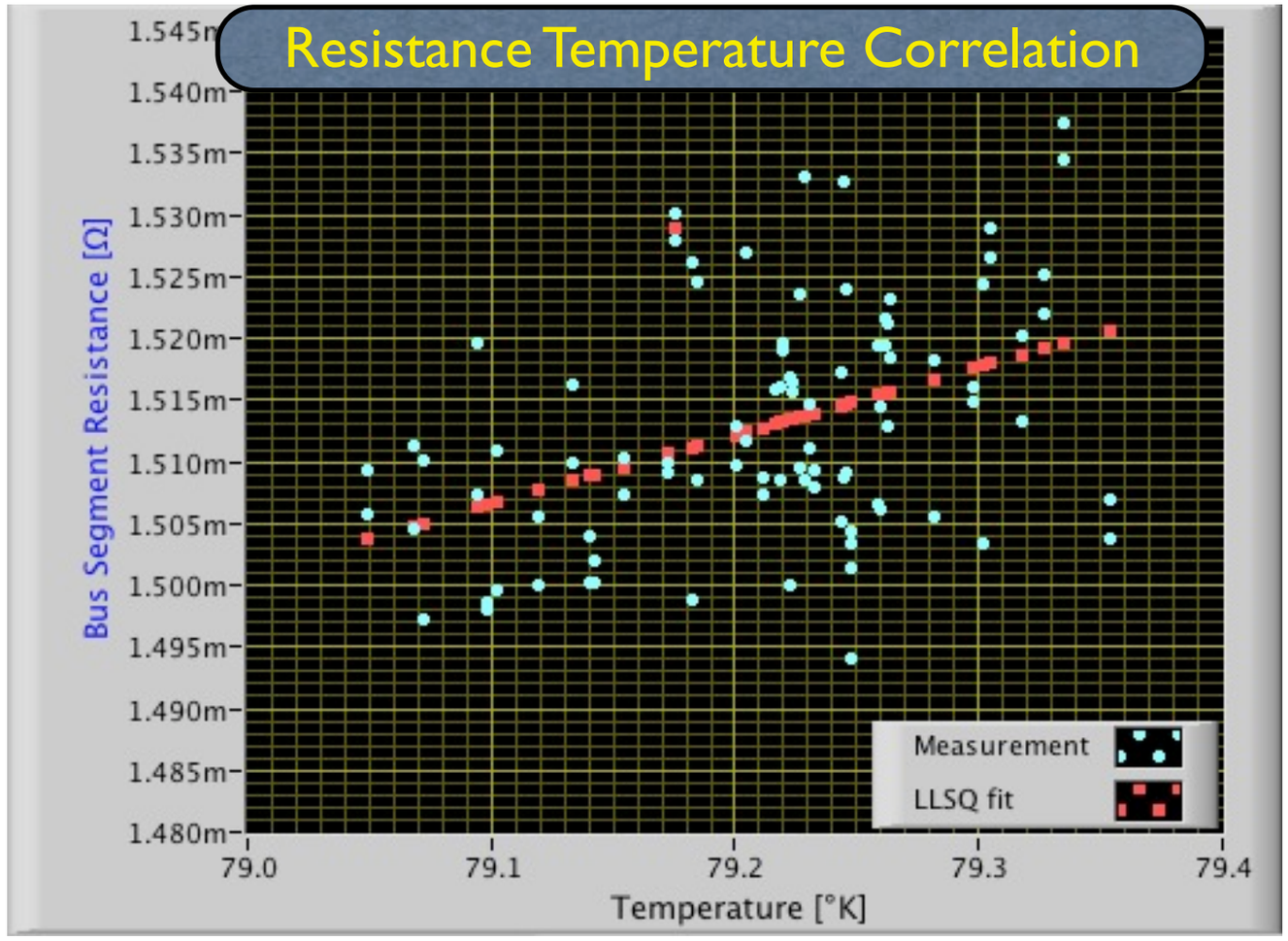


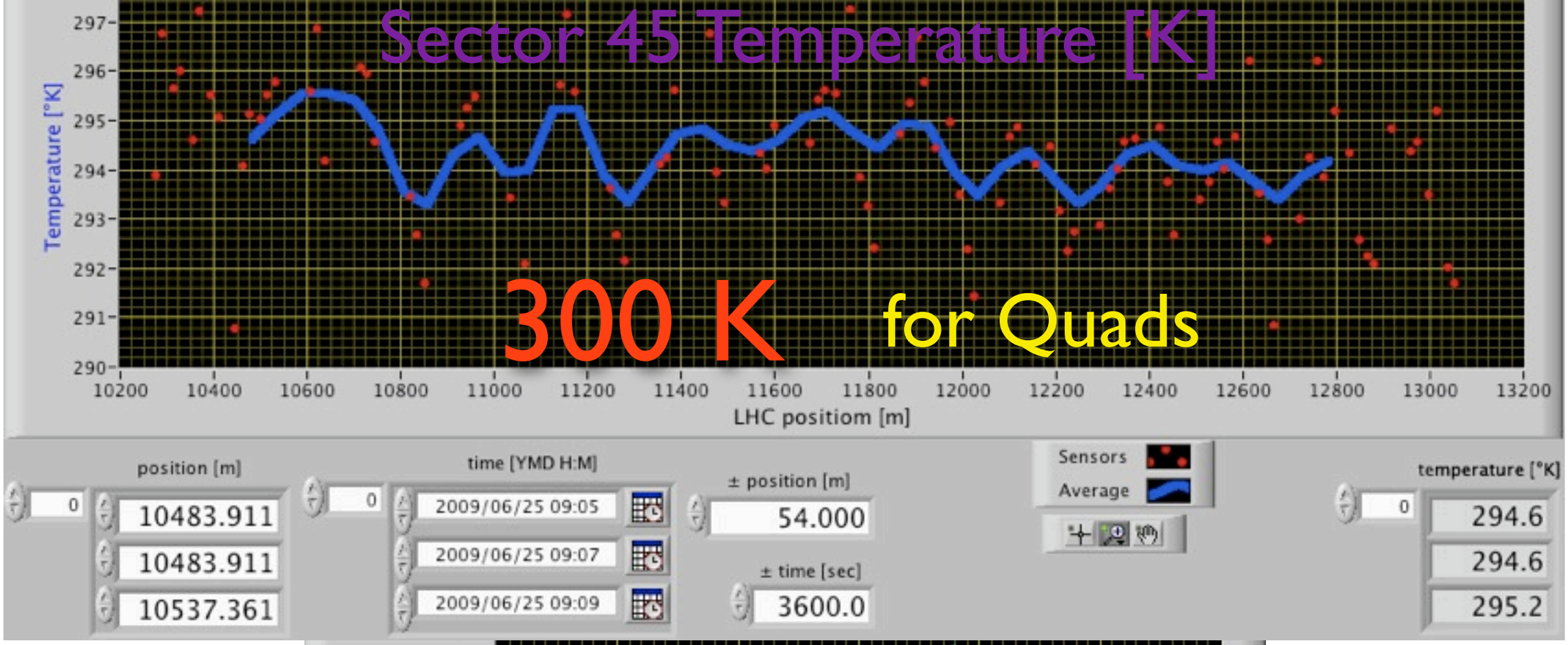
Sector 45 QUAD Bus Segments Measurements

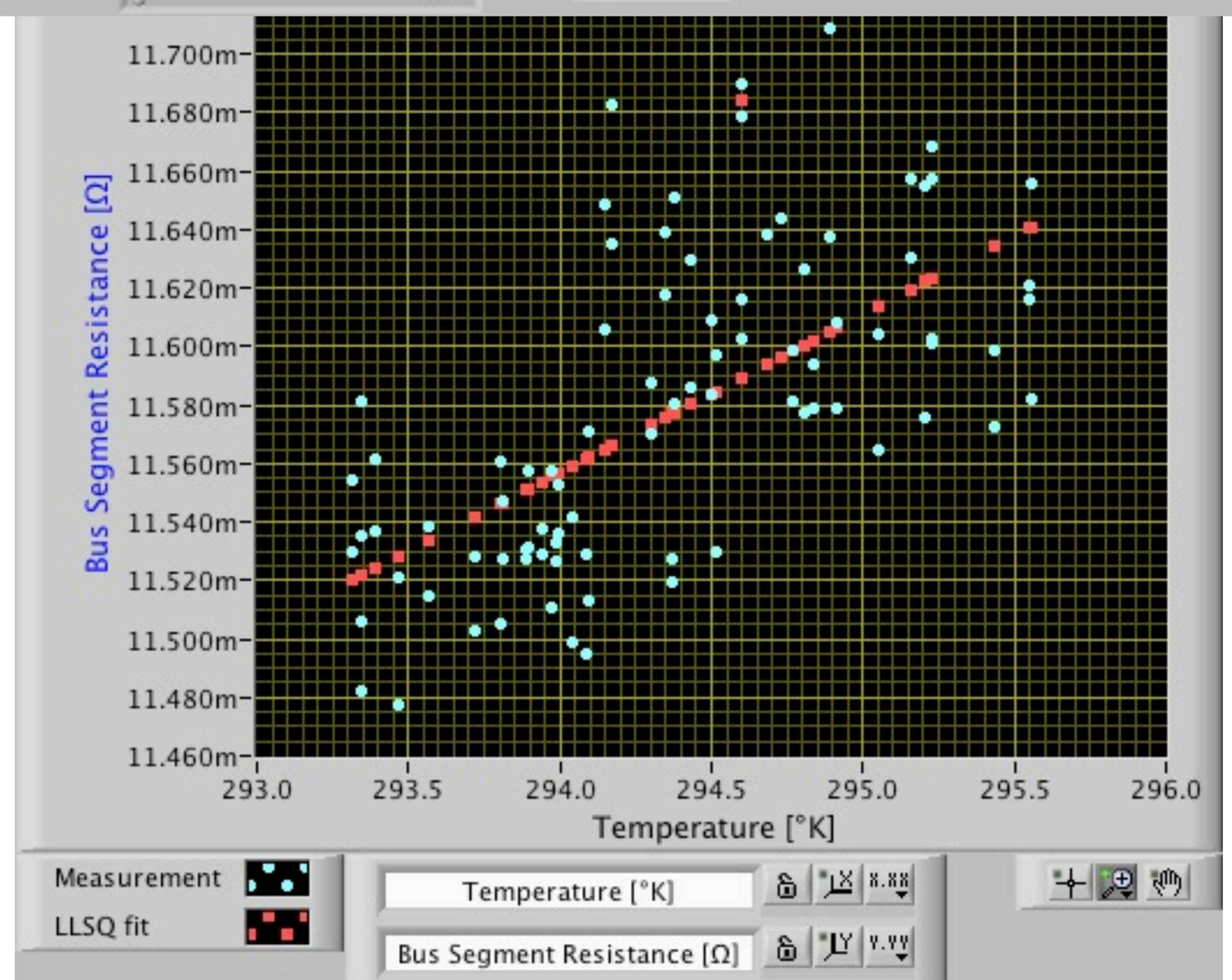


Sector 45 Temperature [K]





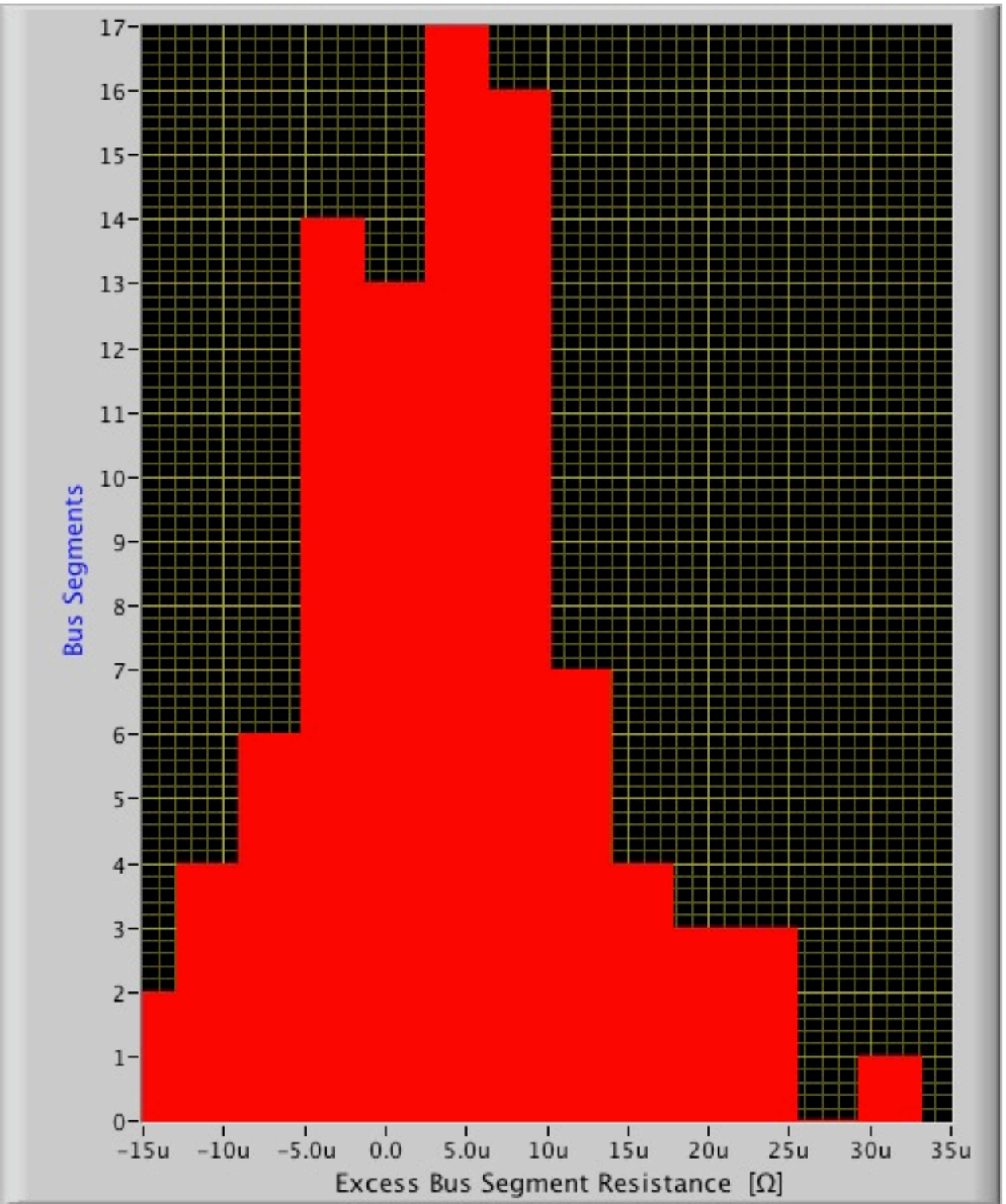

Sector 45 Temperature [K]
300 K
for Quads
Temperature [°K]
297
296
295
294
293
292
291
290
10200
10400
10600
10800
11000
11200
11400
11600
11800
12000
12200
12400
12600
12800
13000
13200
LHC positiom [m]
position [m]
0
10483.911
10483.911
10537.361
time [YMD H:M]
0
2009/06/25 09:05
2009/06/25 09:07
2009/06/25 09:09
± position [m]
54.000
± time [sec]
3600.0
Sensors
Average
temperature [°K]
0
294.6
294.6
295.2


Bus Segment Resistance [Ω]
11.700m
11.680m
11.660m
11.640m
11.620m
11.600m
11.580m
11.560m
11.540m
11.520m
11.500m
11.480m
11.460m
293.0
293.5
294.0
294.5
295.0
295.5
296.0
Temperature [°K]
Measurement
LLSQ fit
Temperature [°K]
Bus Segment Resistance [Ω]

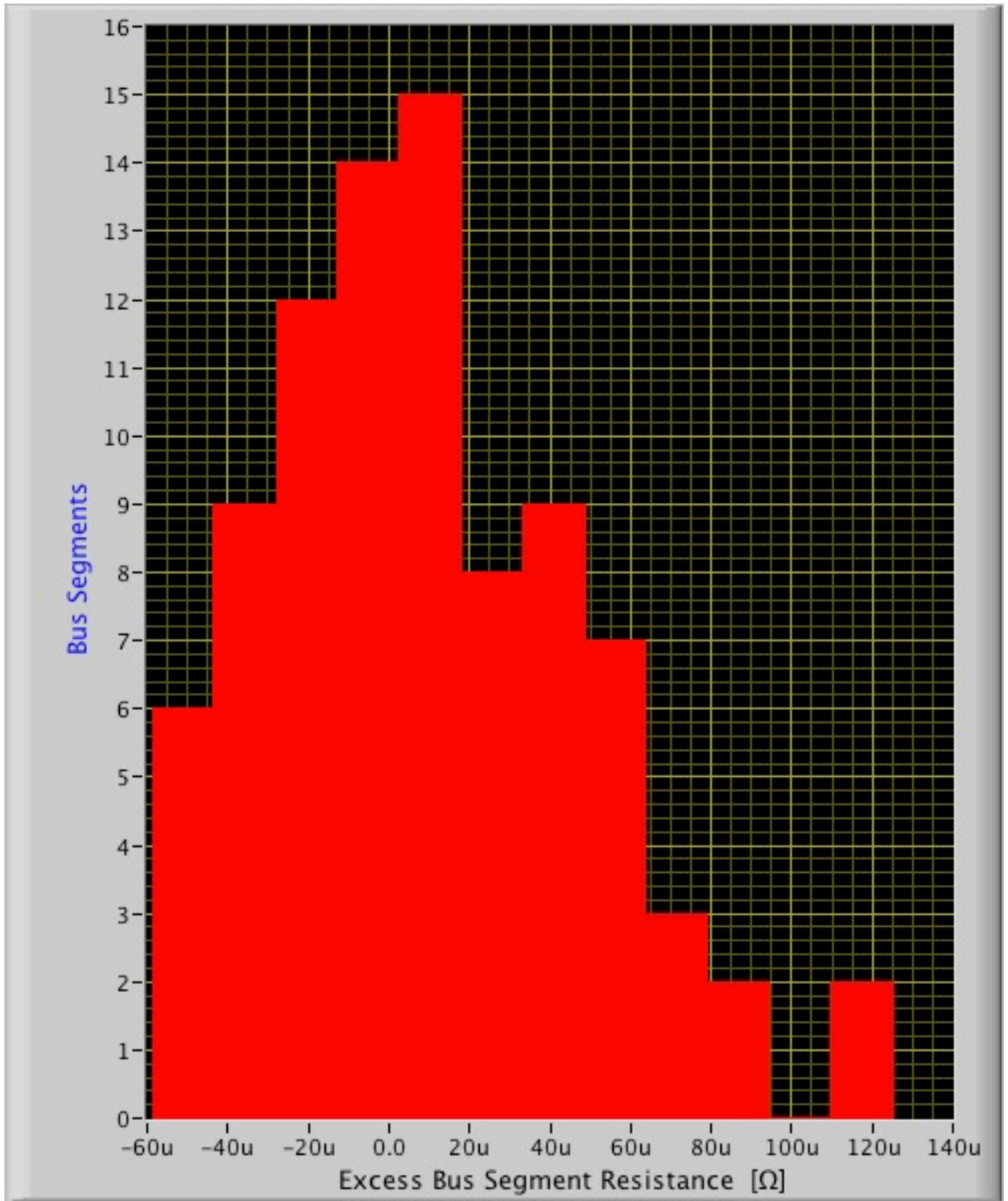
Sector 45 QUAD Bus Segments

Excess Resistance Distribution

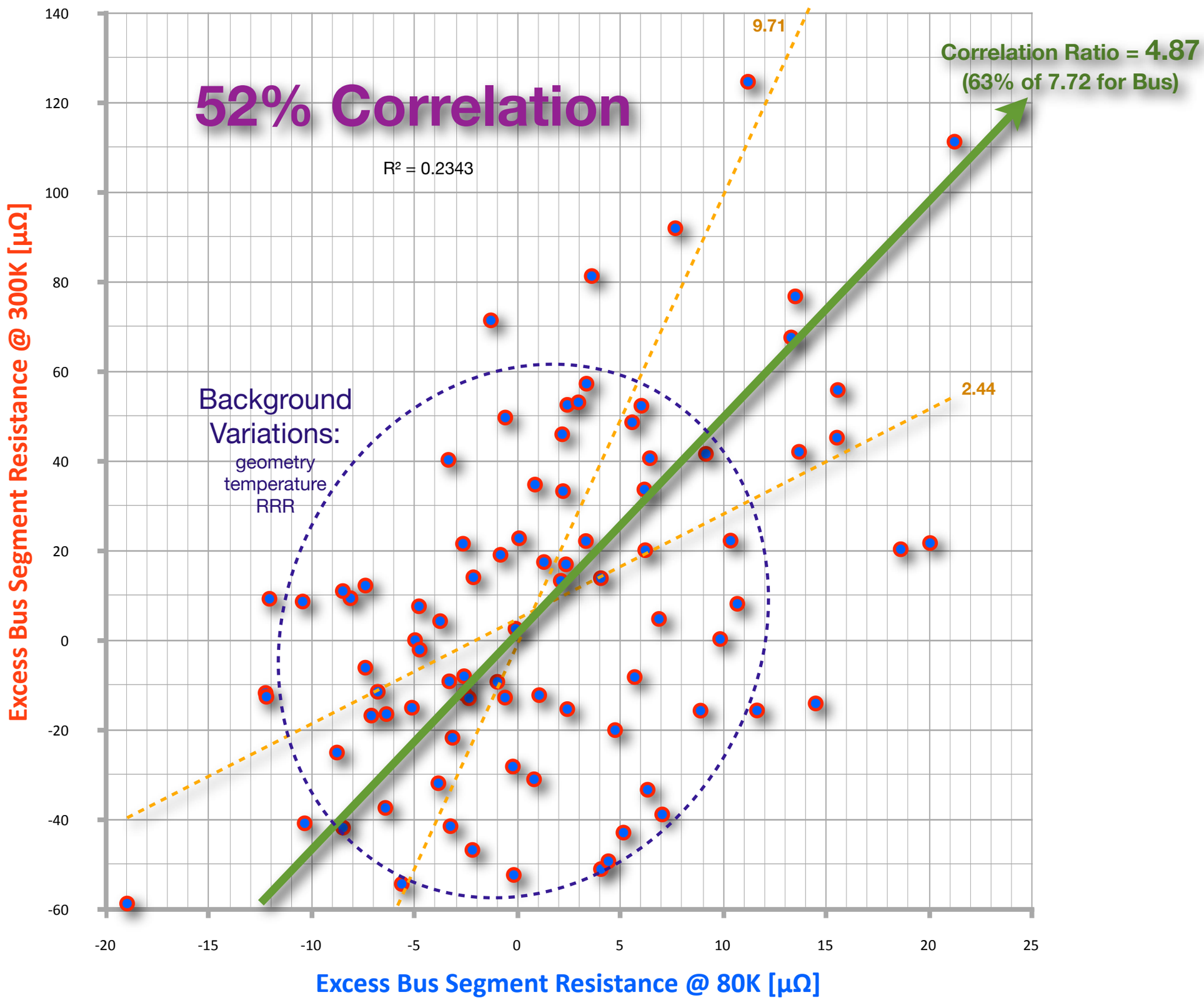
80 K



300 K



QUAD Bus 80K => 300K Correlation



Sector 45 QUAD Bus Segments
Hit List Shuffle
(hash table)

80 K

Hit List

∂R [Ω]	x [m]	Bus Segment Span
33.0u	11179	RQOA.[Q24R4<->Q26R4]i
23.4u	11927	RQOA.[Q30L5<->Q28L5]e
22.1u	12248	RQOA.[Q24L5<->Q22L5]e
21.8u	12675	RQAT.[Q16L5<->Q14L5]i
19.0u	11393	RQOA.[Q28R4<->Q30R4]e
18.7u	12675	RQAT.[Q16L5<->Q14L5]e
18.5u	11125	RQAS.[Q23R4<->Q25R4]e
17.4u	10858	RQAT.[Q18R4<->Q20R4]e
17.2u	11286	RQOA.[Q26R4<->Q28R4]e
14.9u	12782	RQAT.[Q14L5<->Q12L5]i
13.9u	11767	RQOB.[Q33L5<->Q31L5]i
13.3u	11981	RQOB.[Q29L5<->Q27L5]i
12.6u	12782	RQAT.[Q14L5<->Q12L5]e
11.8u	10644	RQAT.[Q14R4<->Q16R4]e
11.5u	12034	RQOA.[Q28L5<->Q26L5]e
10.6u	12729	RQAT.[Q15L5<->Q13L5]i
10.6u	10912	RQAT.[Q19R4<->Q21R4]i
10.4u	11713	RQOA.[Q34R4<->Q32L5]i
10.0u	12568	RQAT.[Q18L5<->Q16L5]e

300 K

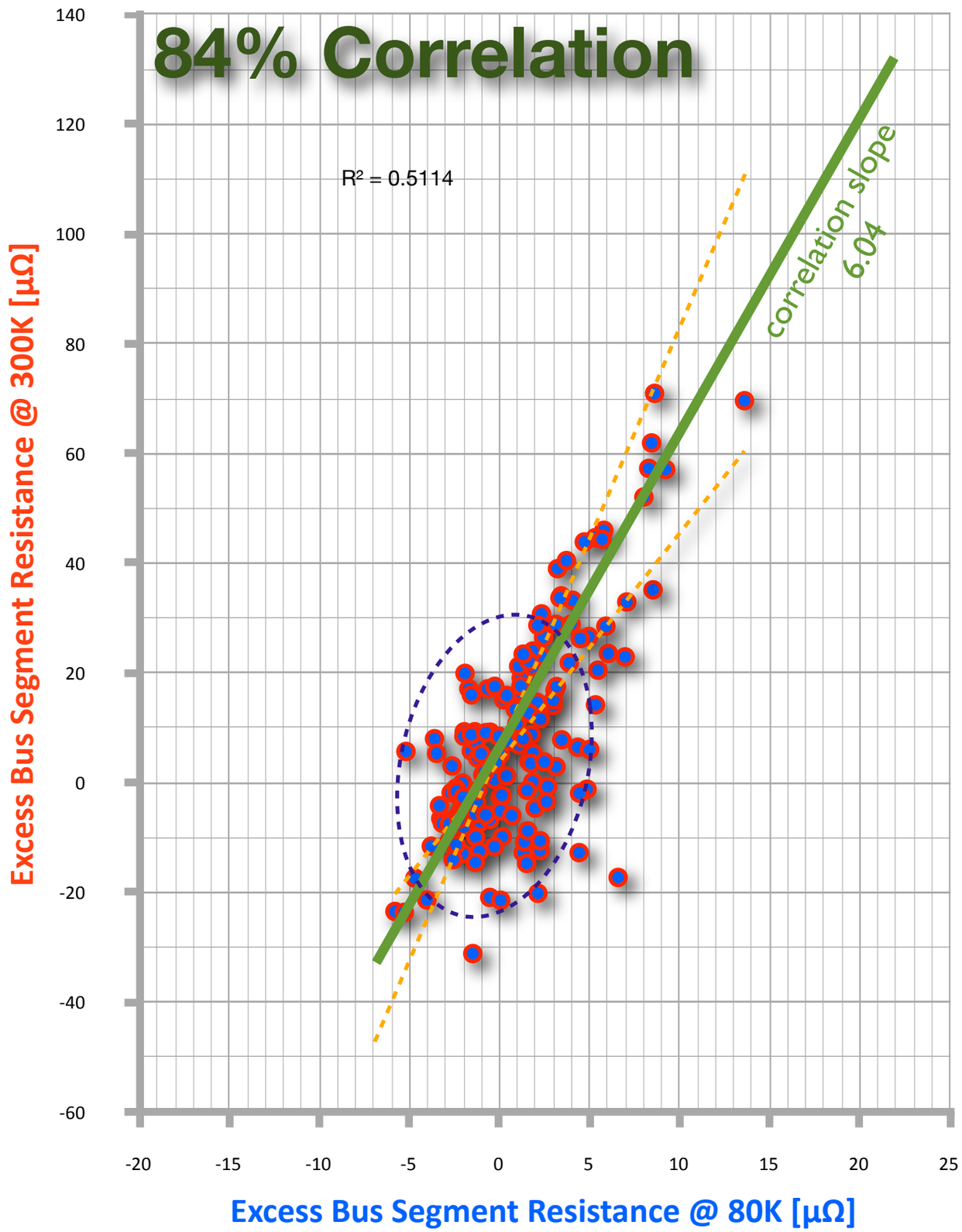
Hit List

∂R [Ω]	x [m]	Bus Segment Span
124.7u	12782	RQAT.[Q14L5<->Q12L5]e
111.3u	11927	RQOA.[Q30L5<->Q28L5]e
92.0u	12568	RQAT.[Q18L5<->Q16L5]e
81.4u	12141	RQOA.[Q26L5<->Q24L5]e
76.8u	12782	RQAT.[Q14L5<->Q12L5]i
71.5u	12355	RQOA.[Q22L5<->Q20L5]i
67.6u	11286	RQOA.[Q26R4<->Q28R4]e
57.3u	11820	RQOA.[Q32L5<->Q30L5]e
55.9u	11393	RQOA.[Q28R4<->Q30R4]e
53.2u	11179	RQOA.[Q24R4<->Q26R4]e
52.6u	10965	RQAT.[Q20R4<->Q22R4]e
52.4u	10965	RQAT.[Q20R4<->Q22R4]i
49.8u	12355	RQOA.[Q22L5<->Q20L5]e
48.7u	12568	RQAT.[Q18L5<->Q16L5]i
46.0u	10537	RQAT.[Q12R4<->Q14R4]e
45.3u	12675	RQAT.[Q16L5<->Q14L5]e
42.1u	10858	RQAT.[Q18R4<->Q20R4]e

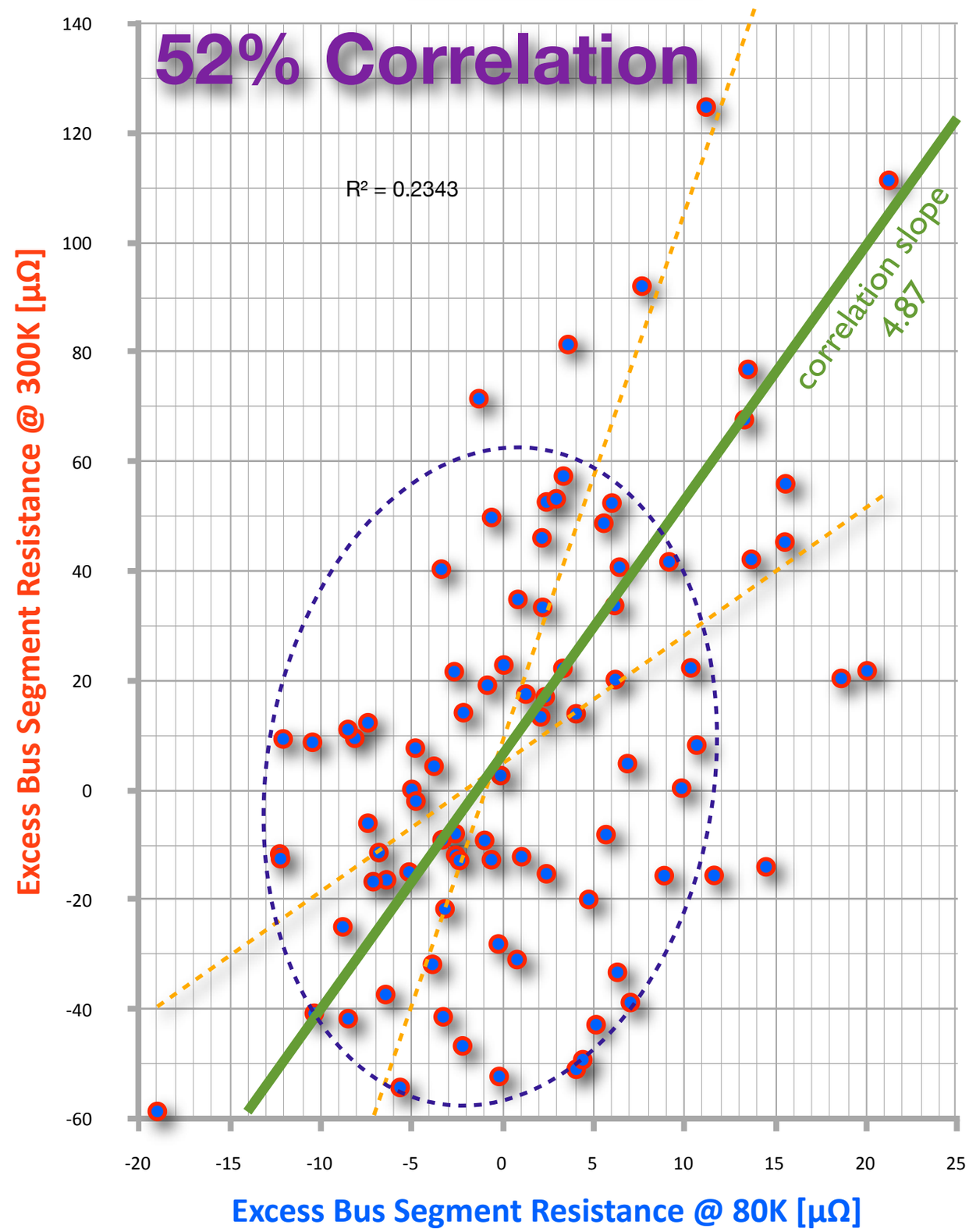
The Challenge of Warm Bus measurements made at 80K

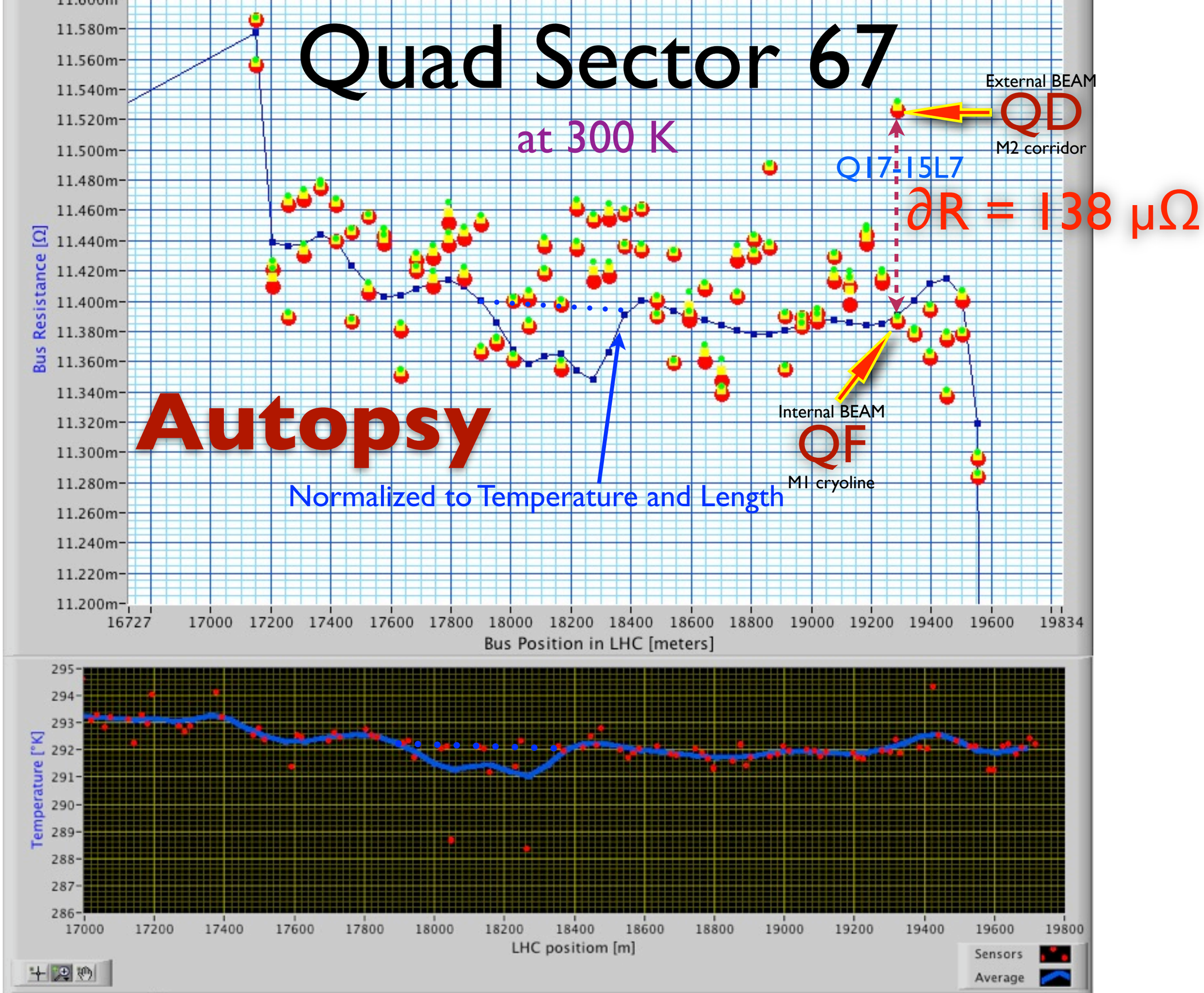
300K <=> 80K Correlation

BEND Bus

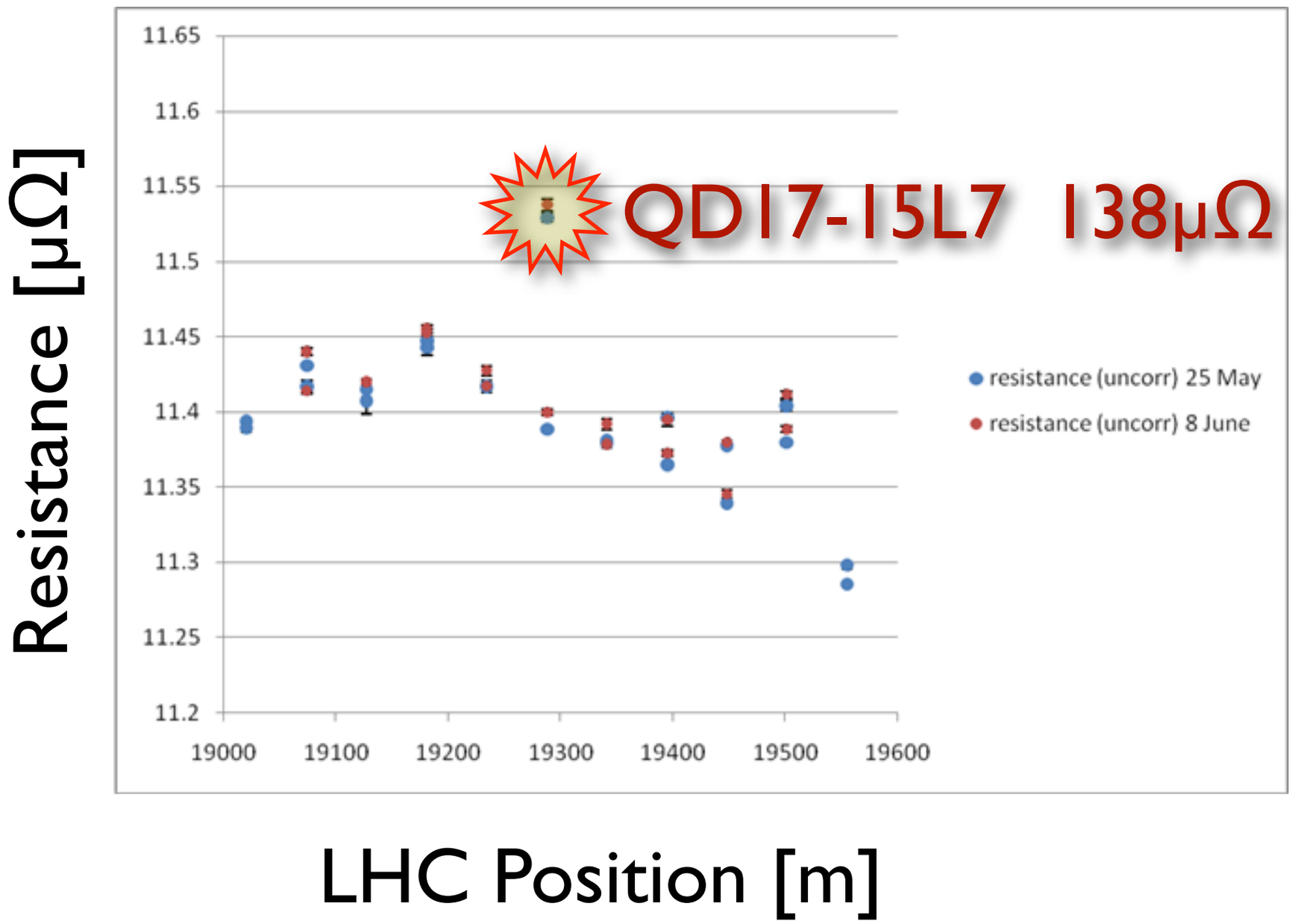


QUAD Bus

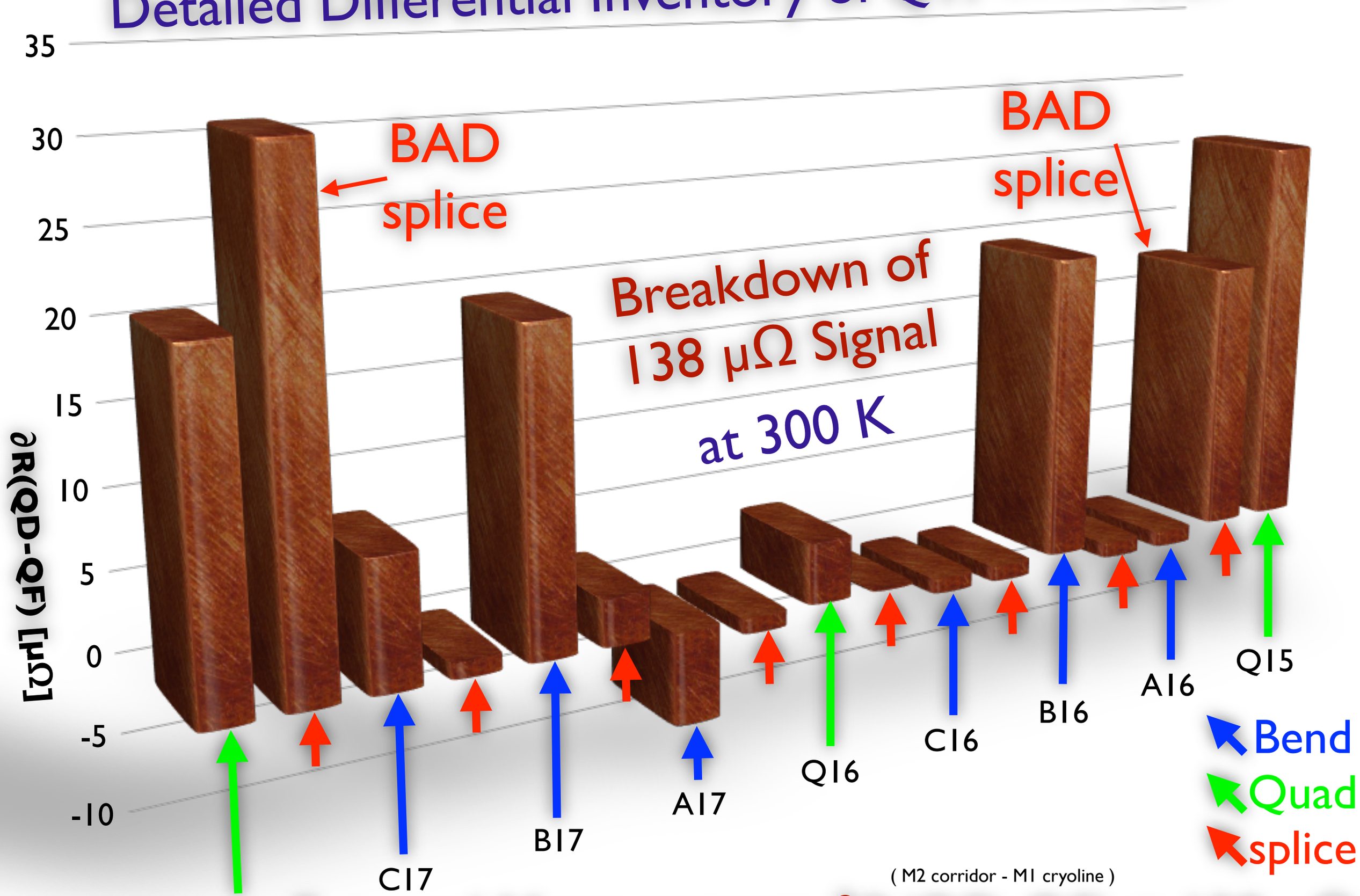



Quad Sector 67
at 300 K
External BEAM
QD
M2 corridor
Q17-15L7
∂R = 138 μΩ
Internal BEAM
QF
M1 cryoline
Autopsy
Normalized to Temperature and Length
Bus Resistance [Ω]
Bus Position in LHC [meters]
Temperature [°K]
LHC positiom [m]
Sensors
Average

External Quad Bus Resistance in 67 at 300 K



Detailed Differential Inventory of Q17<==>15L7



(M2 corridor - M1 cryoline)

External Measurement ∂R(QD-QF) = 138 μΩ

Non invasive splice resistance measurements

- Summary of measurements performed on RB and RQ circuits

Circuit	Sector 12	Sector 23	Sector 34	Sector 45	Sector 56	Sector 67	Sector 78	Sector 81
RB	300		300, 300	300, 300	300	300, 300		
RB		80		80			80	80
RQ	300		300	300	300	300, 300		
RQ		80		80			80	80, 80

- Huge effort of dedicated measurement teams
  - About 35000 manual measurements
  - Over 400 kilometers walked in the tunnel

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

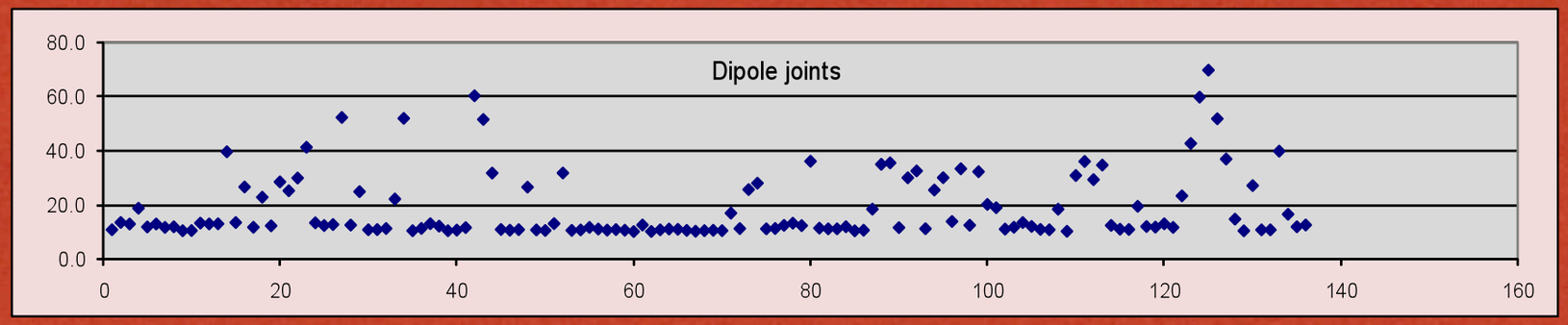
Biddle measurements recap

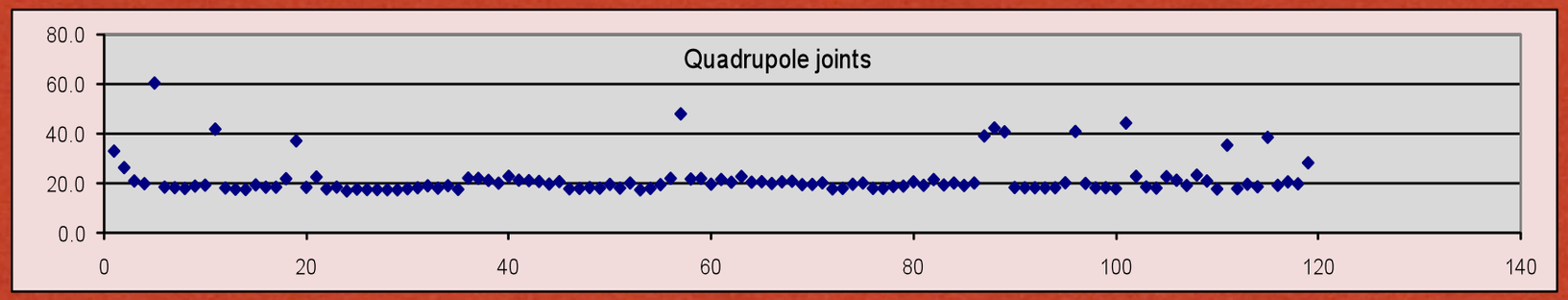
- The most reliable Biddle measurements (RB at room temperature only) are shown in the table below
- Five sectors were measured at warm and the worst splices were opened up and repaired
- The table below shows the situation after the repairs

Circuit/ Sector	Temperature spread (K)	Excess resistance	Highest remaining excess	Excess resistance limit
A12 RQ	1.1	13	37	51
A34 RQ	1.87	10	35	47
A45 RQ	0.9	17	53	78
A56 RQ	0.4	9	20	34
A67 RQ	0.6	14	31	48

Local Joint Resistance Measurements

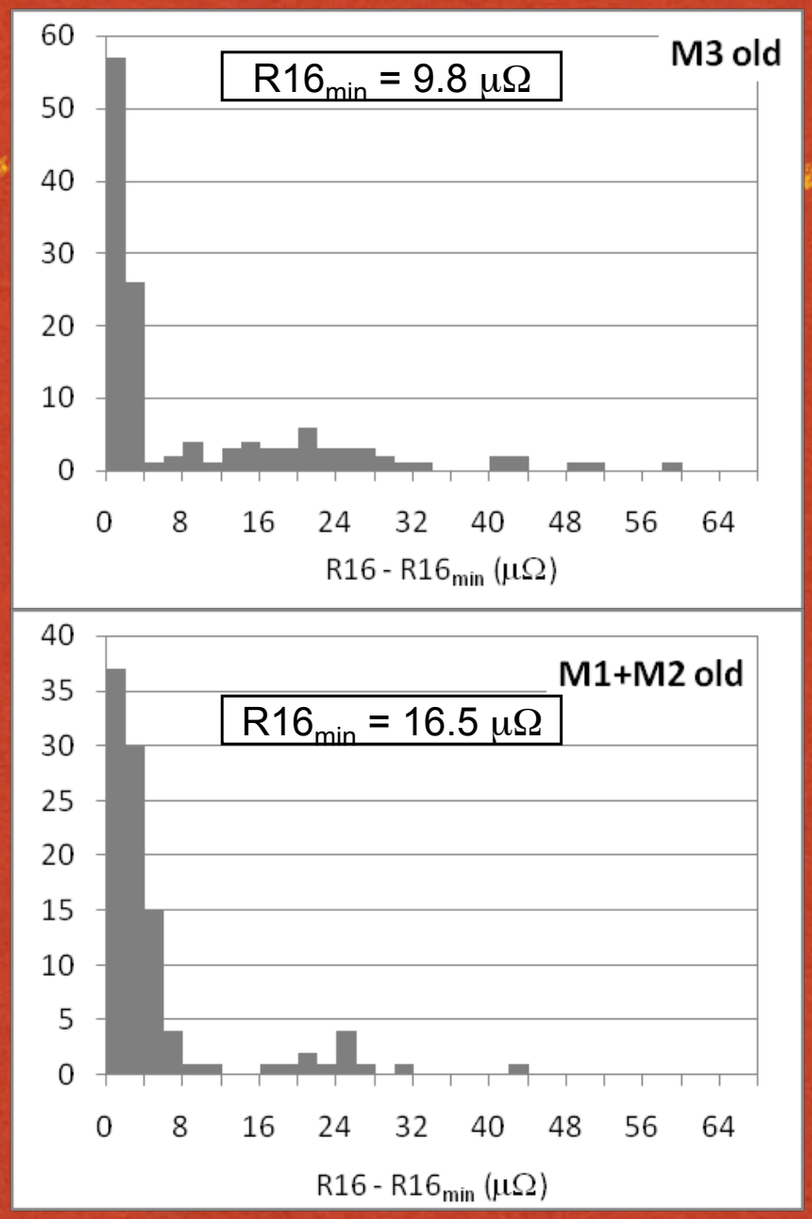
- After screening by non-invasive, room temperature measurements and/or visual inspection, invasive local splice resistance measurement were performed in 5 sectors for:
  - Dipole circuits – 136 joints, 43 joints were found excessive
  - Quadrupole circuits – 120 joints, 14 joints were found excessive





Local Joint Resistance Measurements

- **Observations:**
  - $\Delta R16_{max}$ = 60 μΩ
  - Narrow peak near ΔR16 = 0
  - Separated broad distributions
    - **For dipoles:**
      <R> ~ 23.9 μΩ, rms ~ 1.8 μΩ
    - **For quadrupoles:**
      <R> ~ 23.2 μΩ, rms ~ 2.2 μΩ
  - 2nd "peak" around 40~60 μΩ unsoldered, moving joints were observed in this range



Jim Strait

FIRE ALL HEATERS!

LAST RESORT BUS PROTECTION

- **Pros**

  - Protects against bus arc damage that develops suddenly without any warning between one and 50 seconds.
  - Mitigates bus arc damage that develops suddenly without any warning in less than one second.

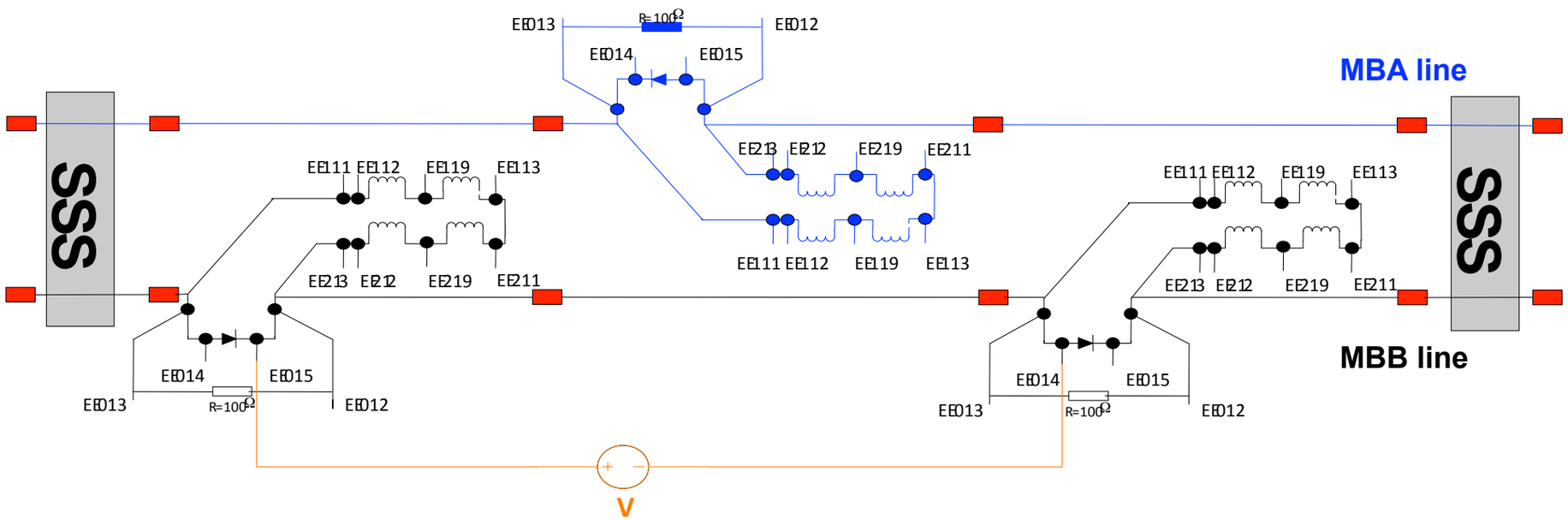
- **Cons**

  - Can only mitigate damage that develops suddenly in less than one second.
  - Threatens the hydraulic integrity of the entire cryo system which is never the less designed to take the pressure.
  - Threatens the electrical integrity of the cold diodes which are never the less designed to take the voltage.
  - Will dump a large amount of He to atmosphere.
  - Misfires will occur.
  - Requires design, cost, and development of significant new QPS infrastructure which currently doesn't exist.
  - Requires significant veto rejection to discriminate against false triggers.
  - Can not be implemented before beam next year.
  - The medicine may be worse than the sickness.

Good News... Great Joints (Superconducting)

- Preemptive Quality Characterization
- Measured all 10,000 Superconducting Bus Joints
- Measurement Accuracy ±50 pΩ
- All below 3 nΩ (<< 200 nΩ on September 19)

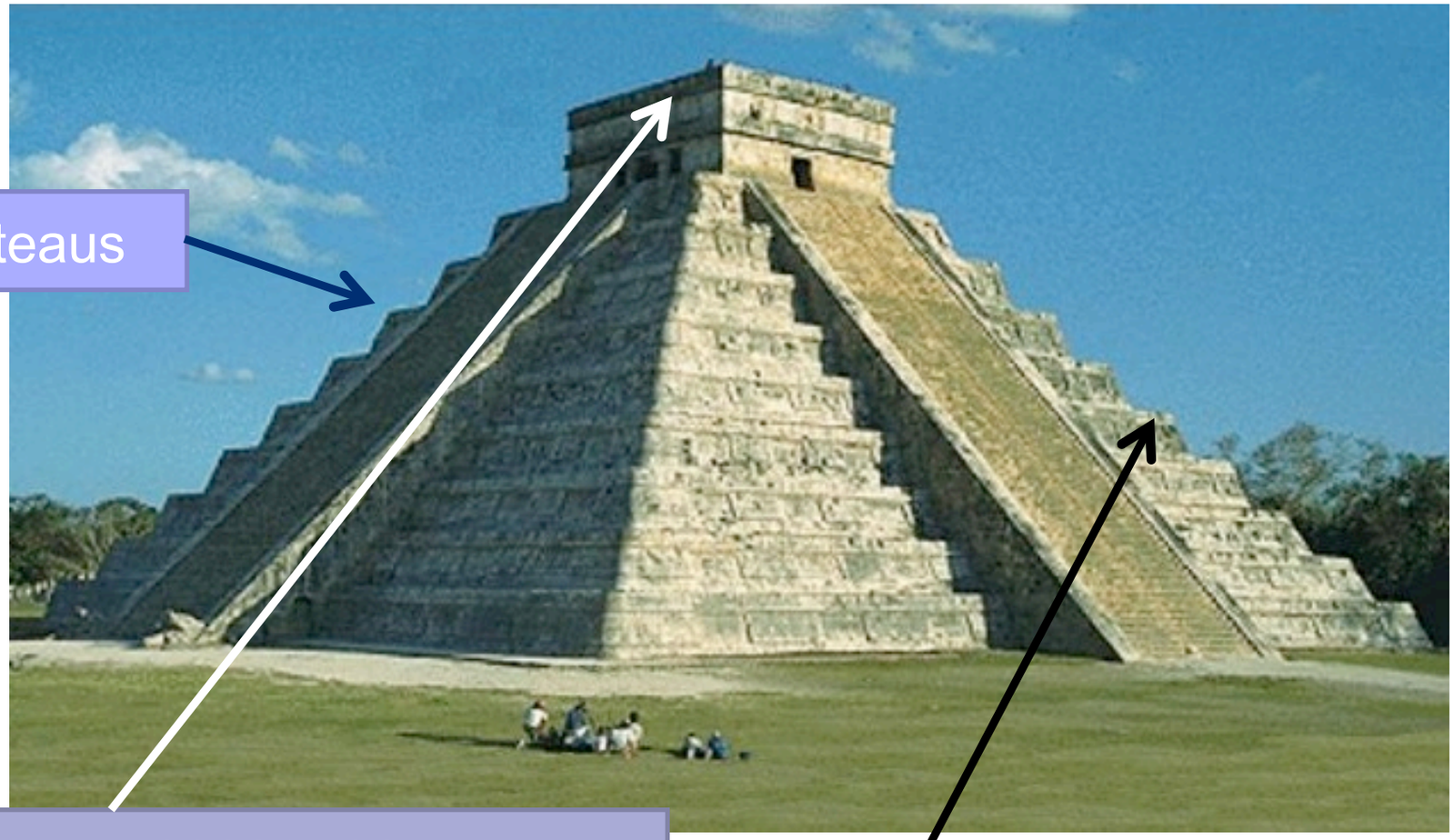
nQPS measurements of bus bar segment resistances



- For the RB circuit there are mostly 2 or 3-splice bus bar segments
- For the RQ circuit there are mostly 8-splice bus bar segments
- Resistance is measured during dedicated tests PLI2.s1 (otherwise known as Maya Pyramid tests)
- Progress is posted daily on the HCC pages: http://hcc.web.cern.ch/HCC/meetings_schedules/?version=2009. The file is called StatusBusbarResistances

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

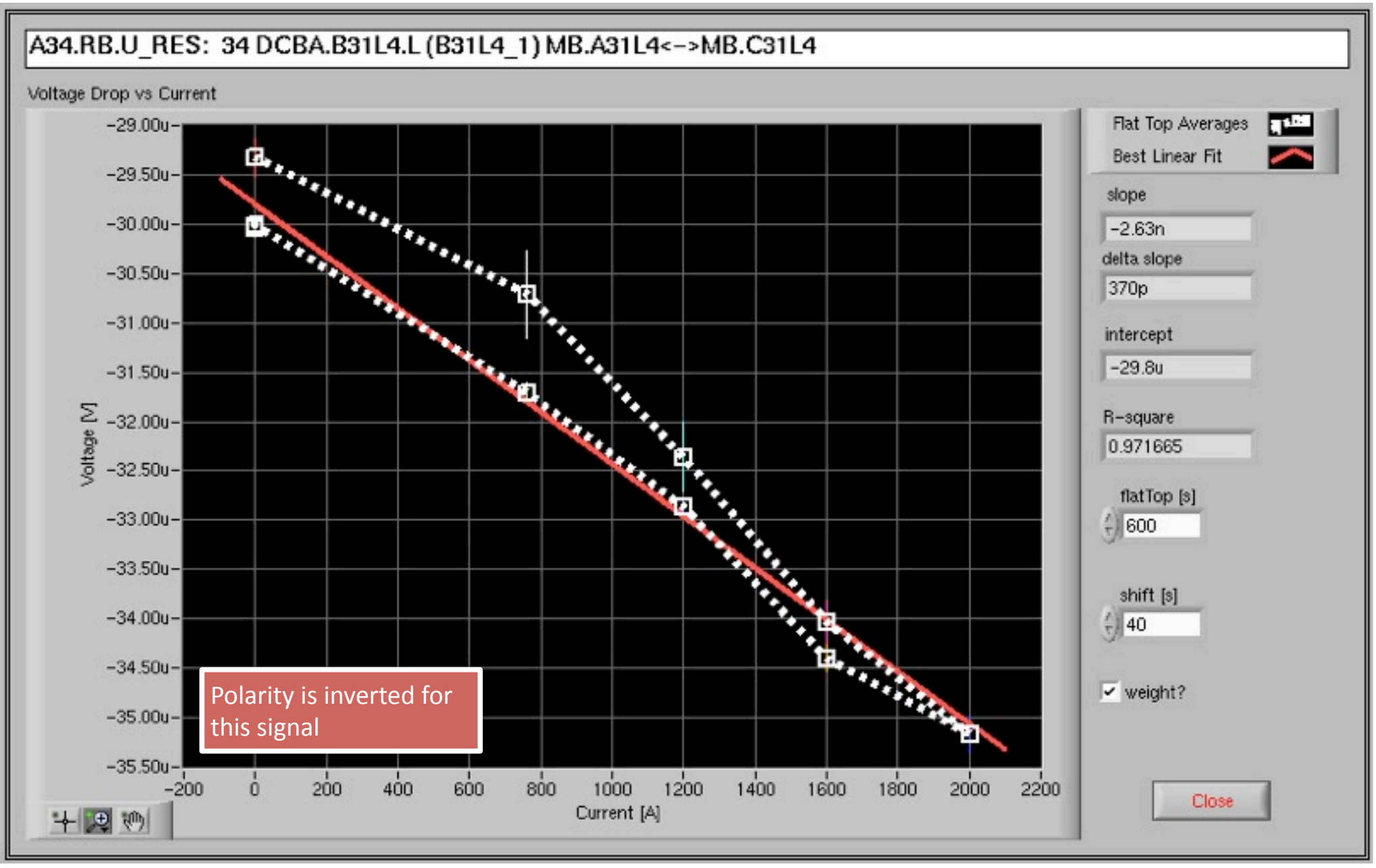
Top current plateau at 2000A, 30+minutes

Back to zero to reduce systematic errors

What is a Maya Pyramid?

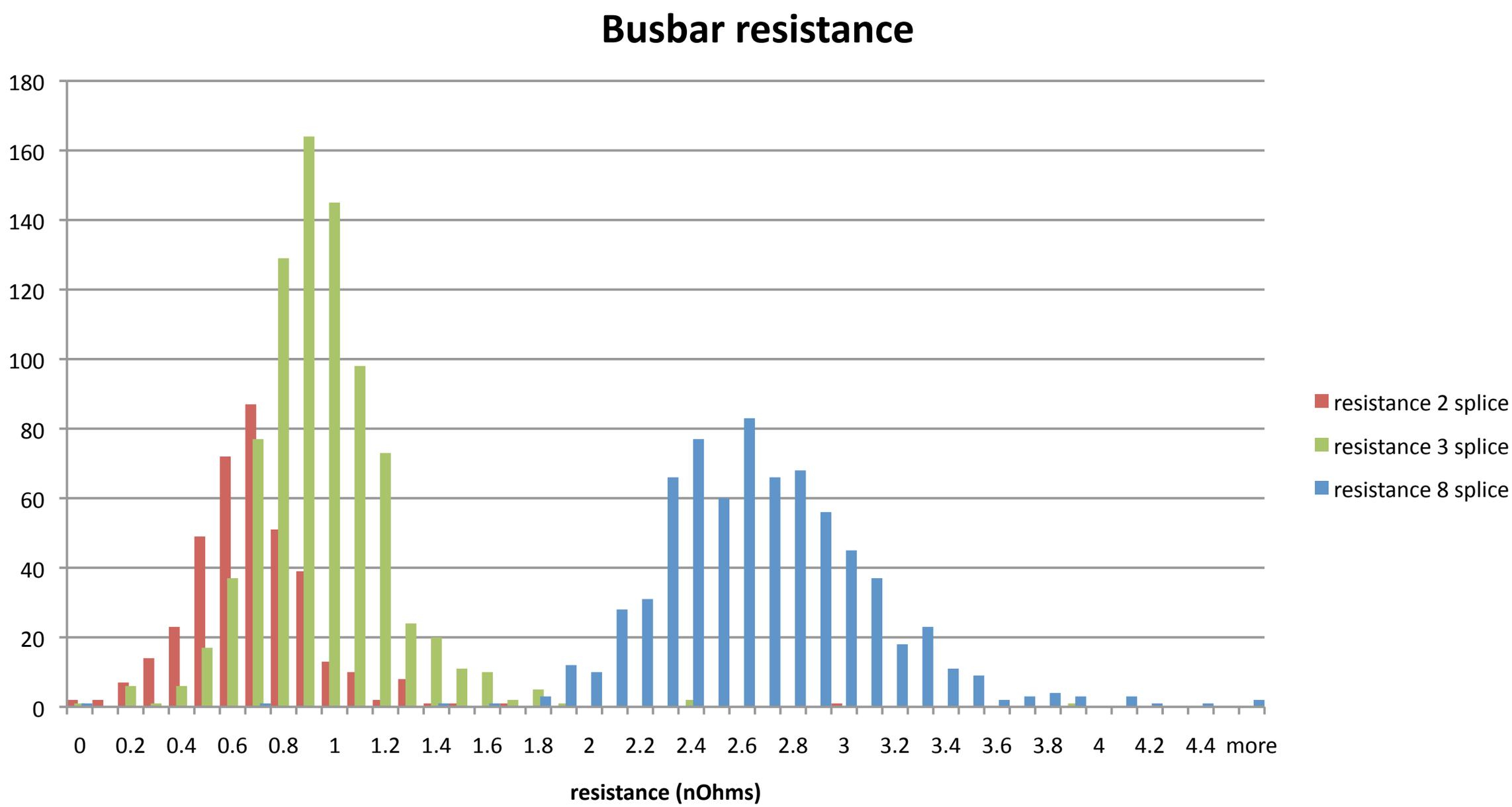
- Test name is PLI2.s1, part of the standard sequence of HC tests
- Current (white) goes through a series of plateaus: 0A, 760A, 1200A, 1600A, 2000A, 1600A, 1200A, 760A, 0A
- Coloured traces are the bus segment voltages

From voltage levels to resistance

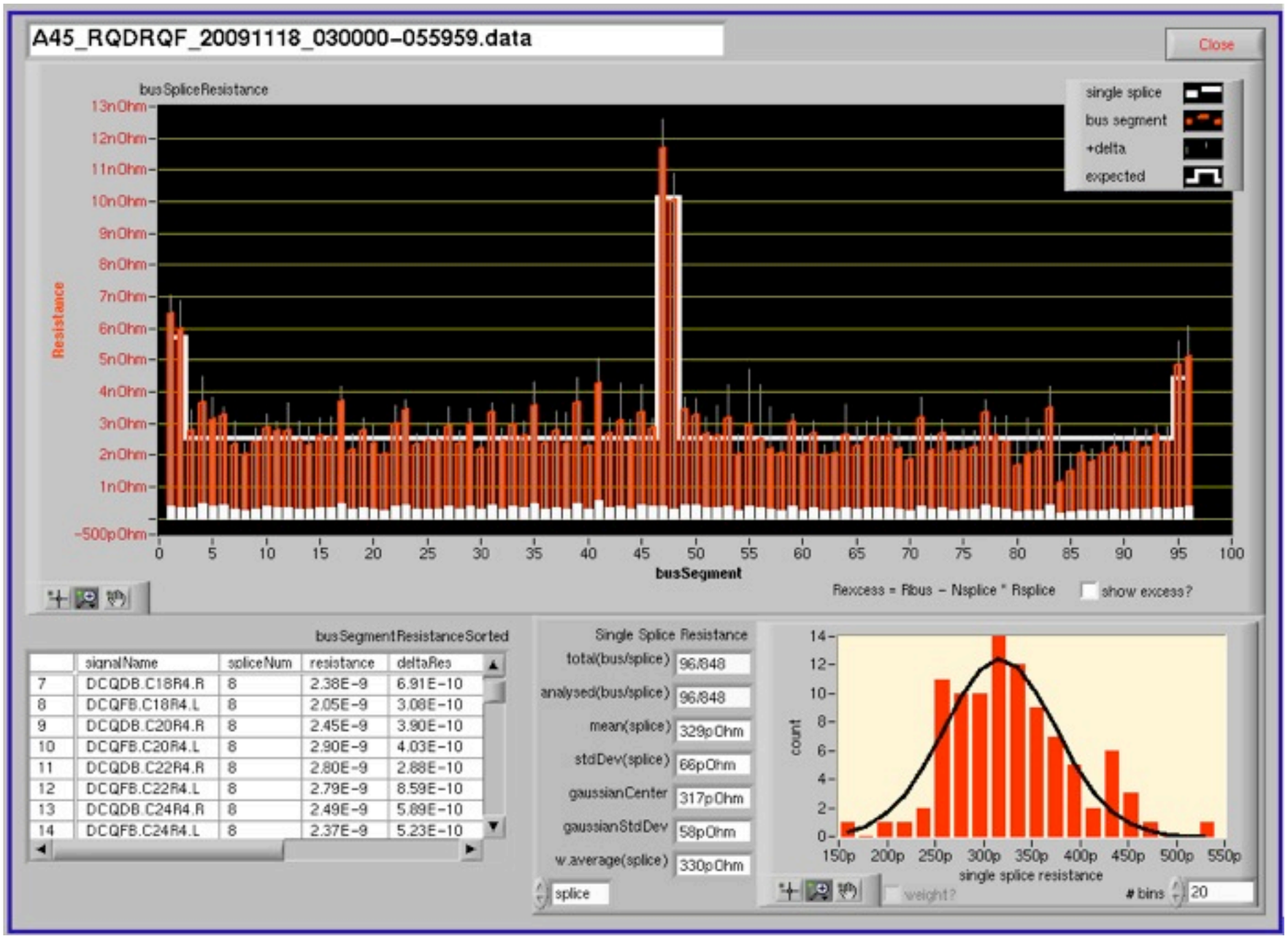


For each busbar segment, we take the voltages at every plateau and fit a straight line. The slope of this line gives the resistive part of the segment. Error is also estimated

2, 3 and 8-splice busbar resistances



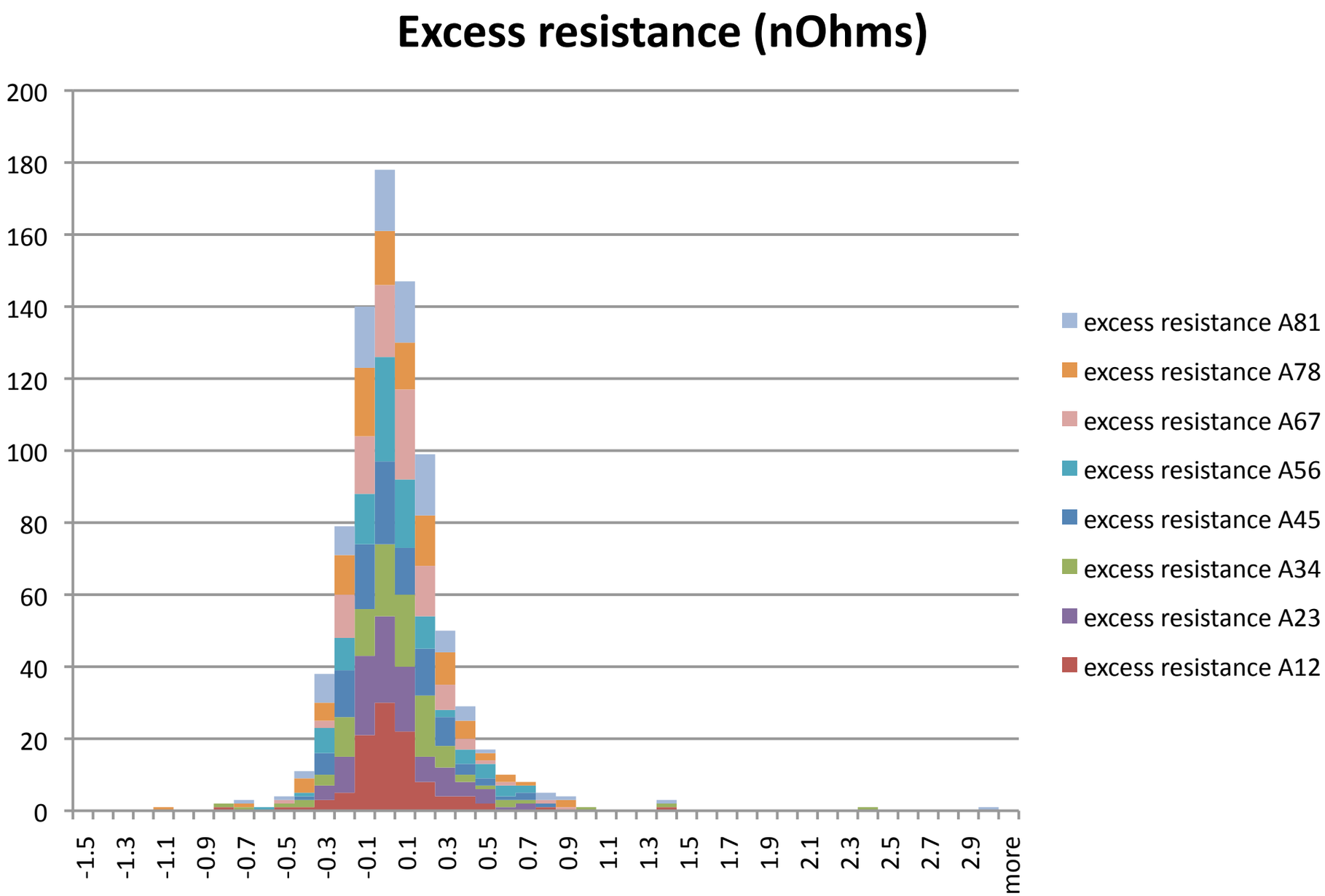
Pyramid analysis



- Each pyramid is analyzed with a semi-online tool (prepared by Zinur)
- At a glance we can see the fitted busbar resistances (red bars) and the resistance per splice (in white)
- If quality is adequate, data is saved so that it can be averaged with other pyramids in that circuit

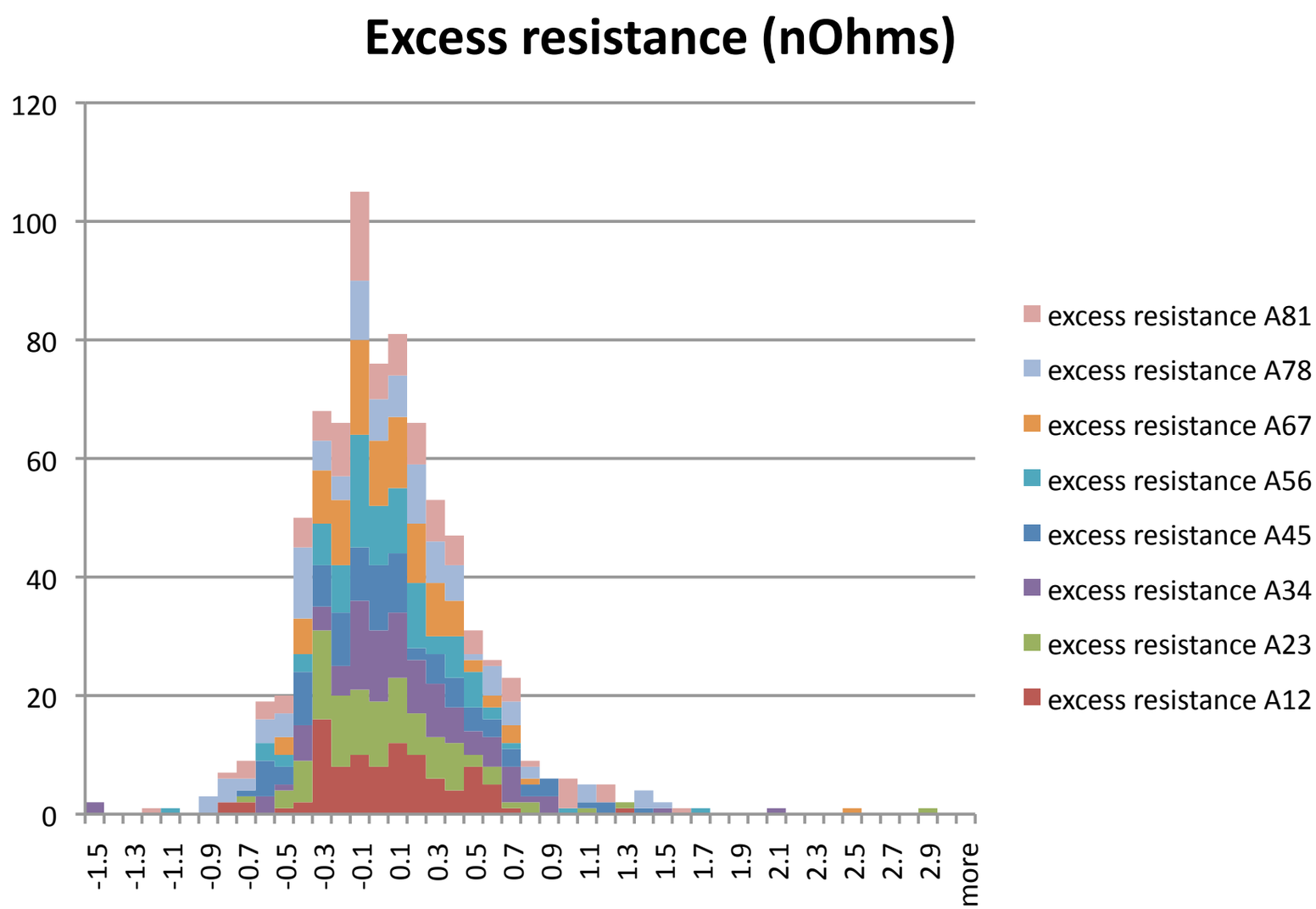
...Then all pyramids from a specific circuit are averaged

Excess resistance, RB, all sectors



- At this resolution, the asymmetry of the distribution is clearly seen
- There are clear outliers, albeit not larger than 3 nOhms

Excess resistance, RQ, all sectors

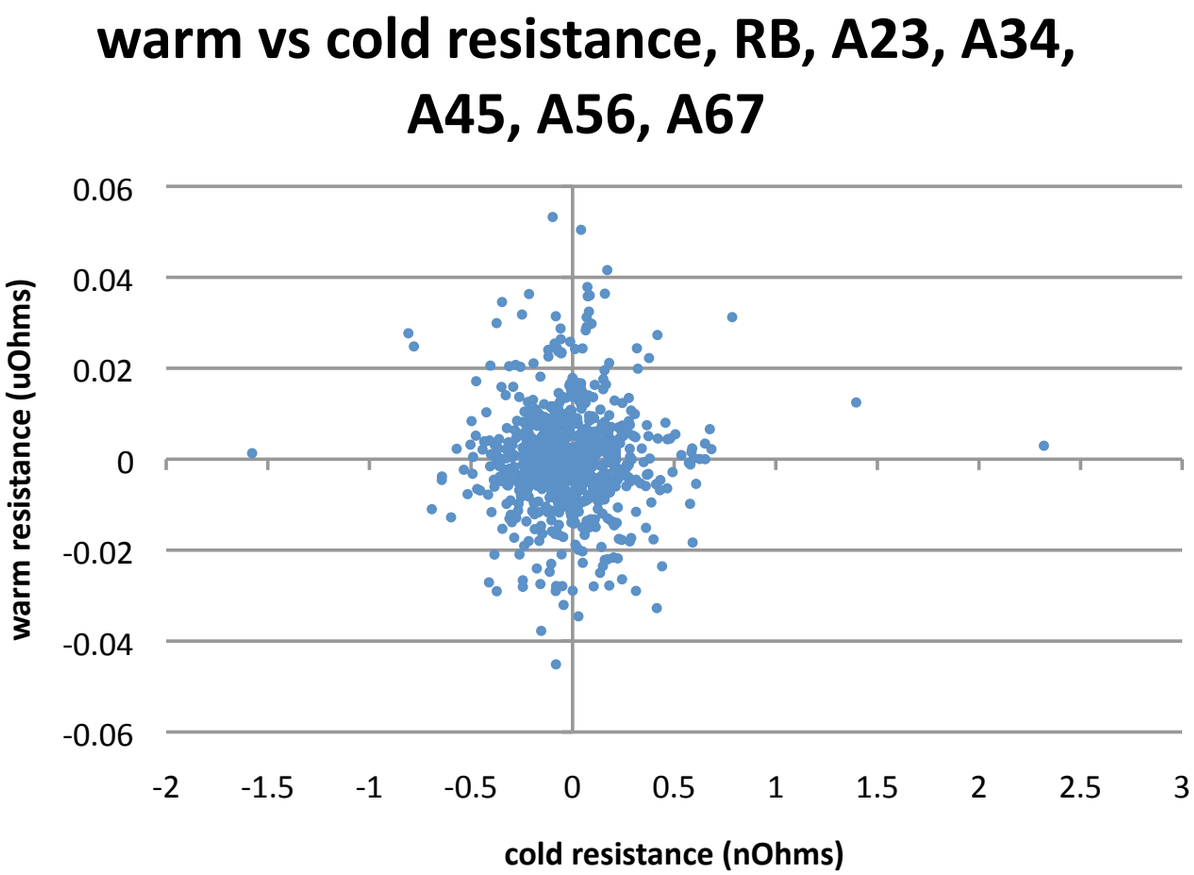


- Here distribution is wider as we have mostly 8 splices per bus bar segment (compared to less than 3 in the case of RB)
- Again, distribution is asymmetric and there are outliers

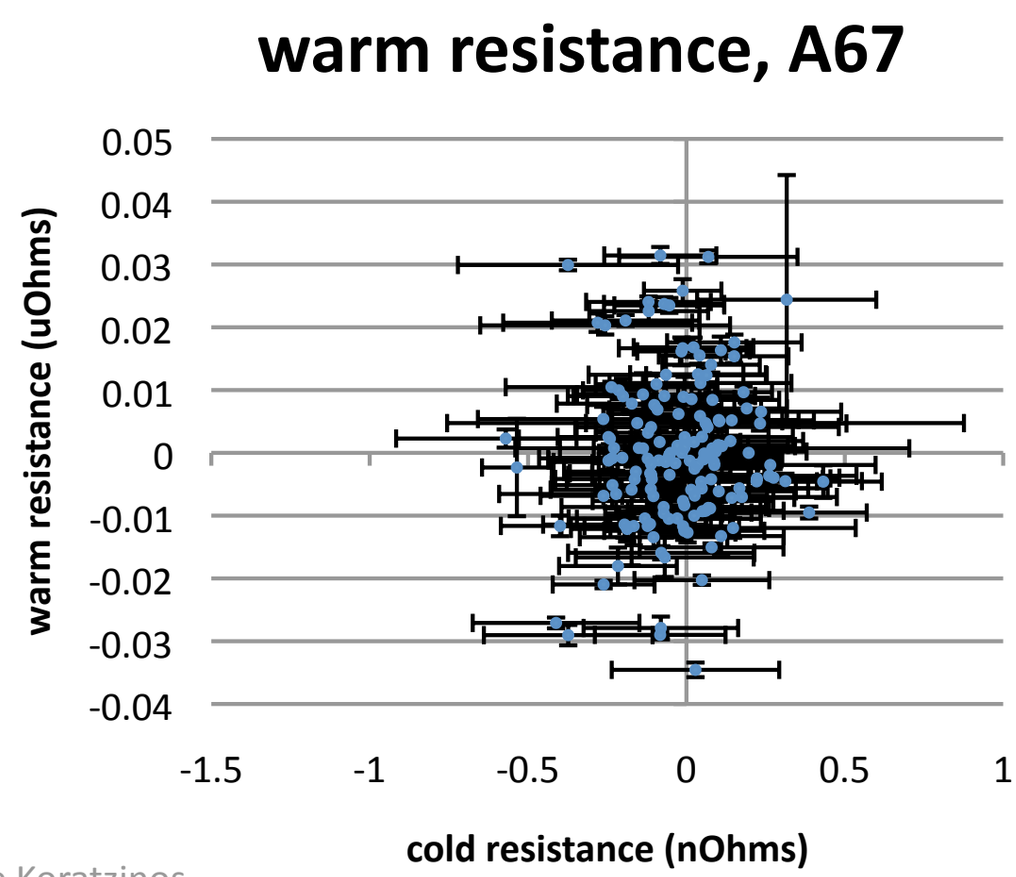
Interconnect splice resistances

- 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 is:
  - 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.

Correlation of splice and stabilizer resistances



This is **very preliminary**.
No clear correlation is seen between cold (at superconducting temperatures) and warm (at room temperature) bus bar resistance measurements



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.

What was done wrong?

- **Conceptual mistakes**
  - Superconductor and bus not protected everywhere
  - Assumed all installation work would be perfect
  - Assumed bypass bus could not spontaneously quench
  - Poor estimate of the maximum credible accident
- **Design errors**
  - Joints not overlapped enough (contact area)
  - Joints not clamped
  - Joints not easily inspected
  - Wrong installation solder; same melting temperature as bus solder
  - Not enough voltage taps
- **Execution errors**
  - Installation done by piecework, jeopardizing quality
  - Poor quality assurance plan and sleepy quality control
  - Poor equipment maintenance; some equipment malfunctions

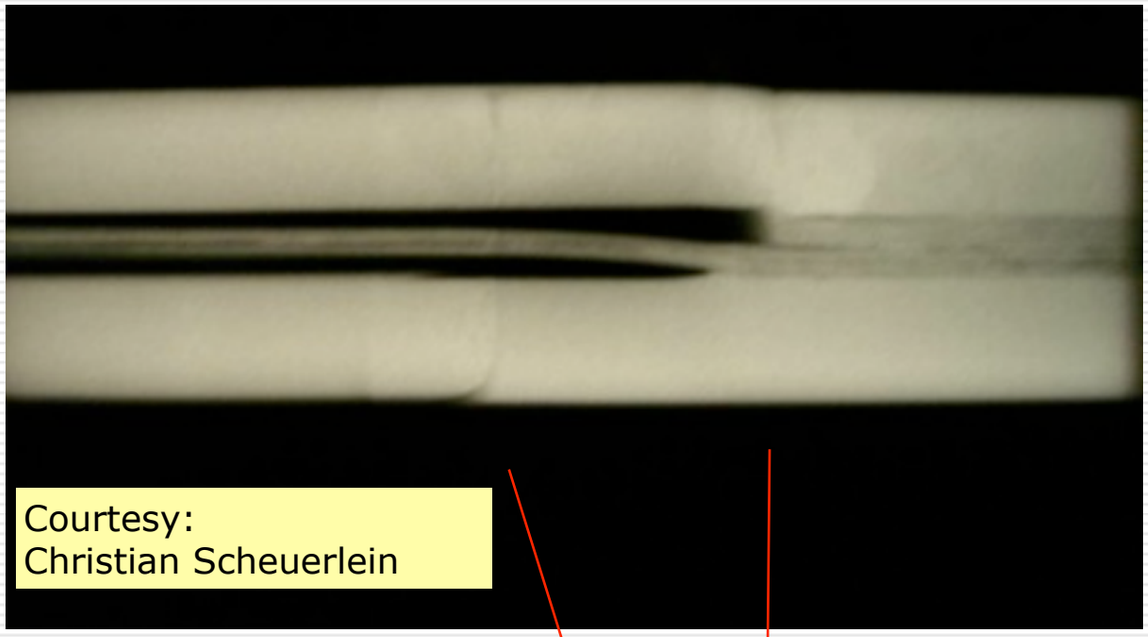
Why 3.5 TeV ? The Chamonix Decision

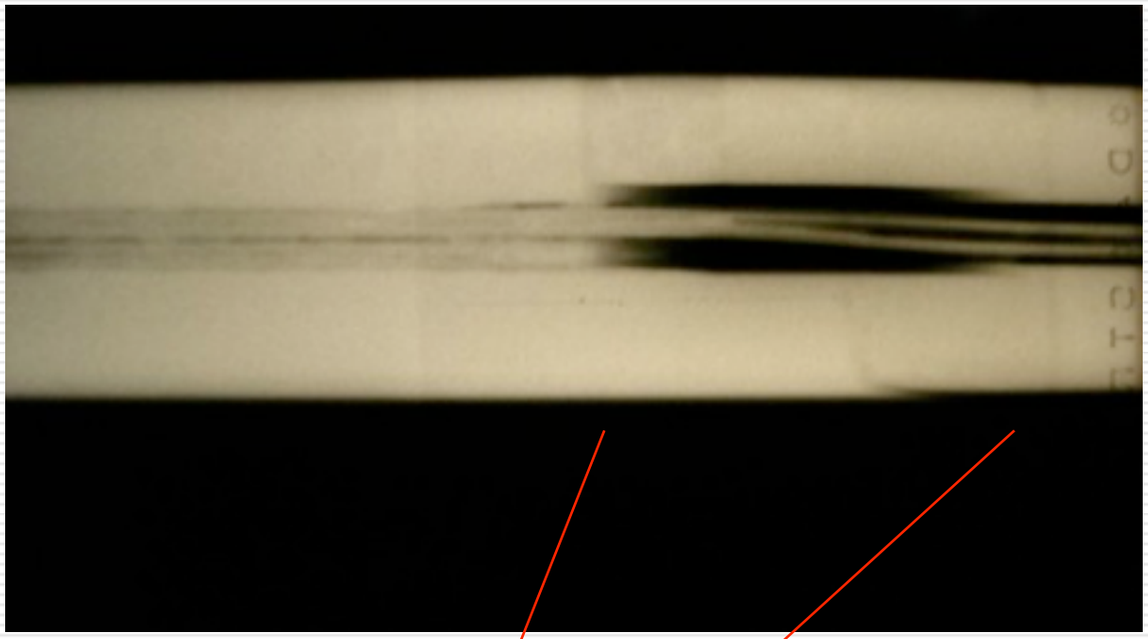
- The splice fault on 9/19/08
- Stabilizer splice concerns
- Thermal Runaway Potential
- Stabilizer splice survey results
- Calculation of Safe Operating Area

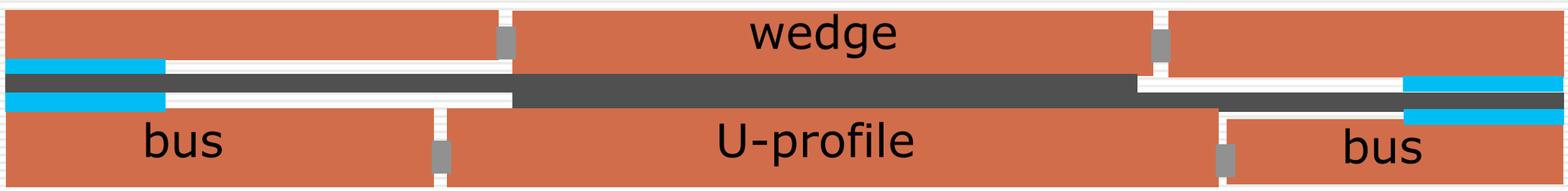
Howie Pfeffer ACE

- Superconducting Splice Precipitated Incident
- Stabilizer Splice Also Bad

Gamma rays QBBI.B25R3-M3 before disconnection (connection & lyra sides)

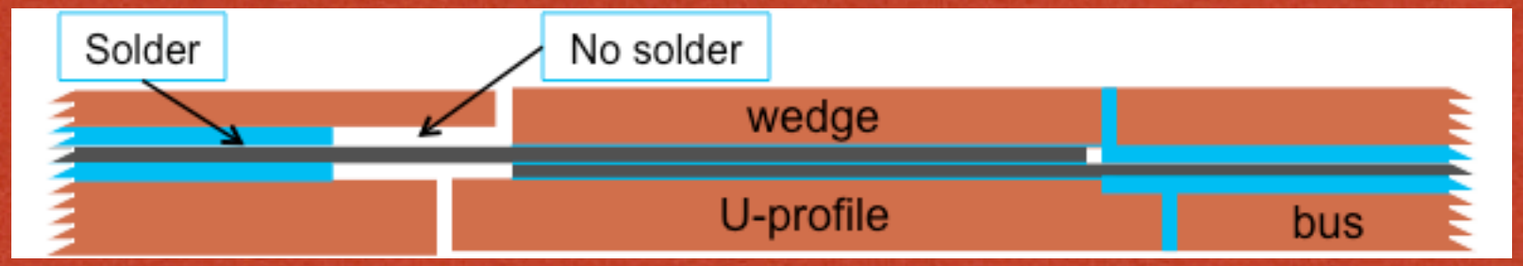






Stabilizer Splice Concerns

- Superconducting splice not protected by cold diode.
- Even a perfect Superconductor Splice can be quenched by beam or hot gas from nearby magnet quench.
- If stabilizer splice is open, then quenched superconductor must conduct during the 106 sec energy dump.
- At 32 MIIT™ limit, wire would last .5 seconds @ 8 kA
- Bonding to nearby stabilizer critical to survival



Thermal Runaway Potential

- Resistance of superconductor copper matrix grows with T.
- Longitudinal thermal conductivity decreases with T.
- Runaway triggers above 30K with 4 to 5 kA current.
- Trigger is dependent on length of superconductor and dump time constant.
- Bend dump time: 100 s to 50 s. Quad dump time: 30 s to 10 s. (@ lower I max)

Temperature [K]	Resistance [μΩ]	$(5kA)^2R$ [W]	Thermal Conductivity [W/m K]
273	40	1,000	400
80	5	125	557
20	0.2	5	10,800

Stabilizer splice survey results

- Normal splice = 10 uOhms @ 300K.
- 36 splices found with between 20 and 60 uohms extra.
- Extra R indicates 1.5 to 4.6 cm unprotected superconductor inside.
- Direct local measurements and statistical calculations give worst expected R.

Estimates from Local Joint Resistance Measurements

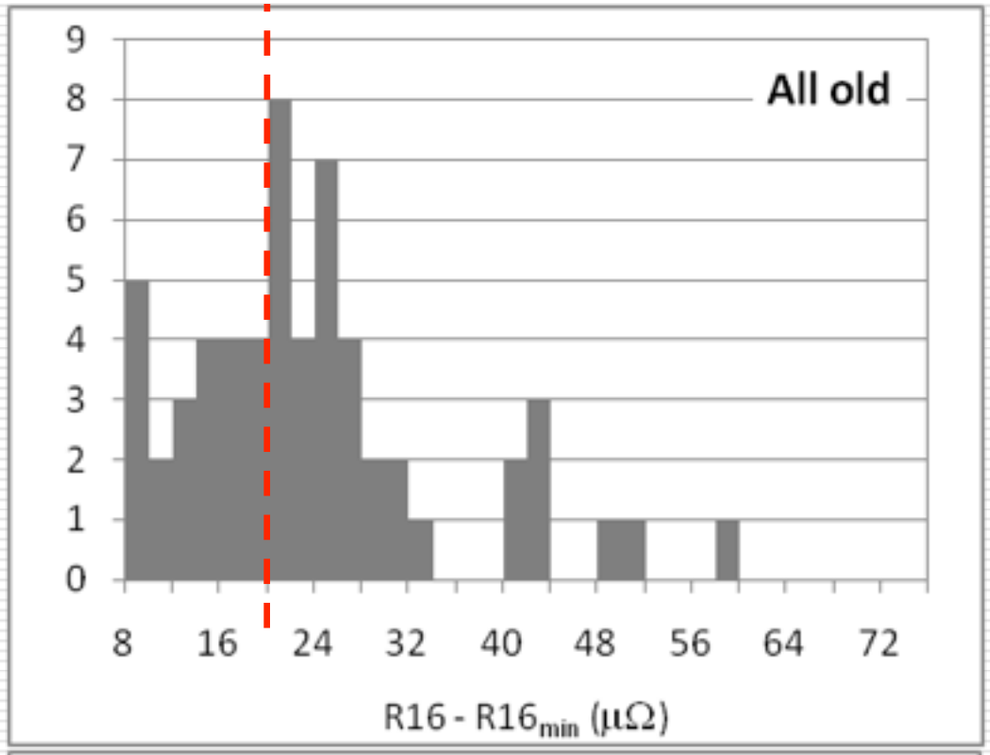
- the statistic of "the largest value we have seen so far" is does not have high enough significance
- since the distributions for the two bus samples are similar we combine all the data and fit to a cumulative distribution above the peak value
  - **<u>The 90% CL bad joint estimate is:</u>**

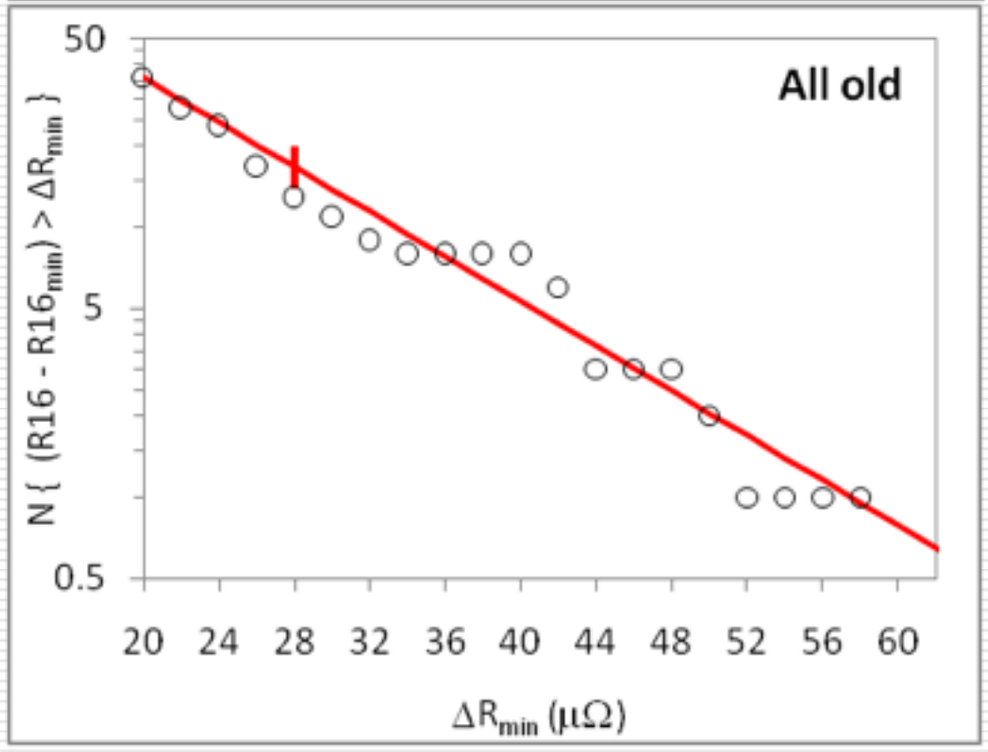
    $\Delta R16_{max} = 82\ \mu\Omega$

- Assuming this sample represents 5/8 of dipole circuts (20% of joints)
  - **<u>The limit for 90% CL bad joint is:</u>**

    $\Delta R16_{max} = 98\ \mu\Omega$

$\Delta R16_{max} = 88\ \mu\Omega$ assuming this sample represents 50% of the machine joints





Jim Strait

Conclusions (2/2)

- Combining the results of three types of analysis
  - Analysis of non-invasive warm dipole measurements
  - Statistical analysis of invasive warm R16 measurements
  - Analysis of failure modes and of the worst joints found

- Our most realistic estimates of the excessive joint resistances are of the order of:
  - **<u>For dipole circuits:</u>**

$$R_{max} \approx 90\ \mu\Omega$$

  - **<u>For quadrupole circuits:</u>**

$$R_{max} \approx 90\ \mu\Omega$$

- Modeling and vertical cryostat tests determine I max vs extra R.

Sample 1 (61 μΩ)

Sample 3A left (26 μΩ)

Sample 2A left (32 μΩ)

Sample 3A right (43 μΩ)

Sample 2A right (43 μΩ)

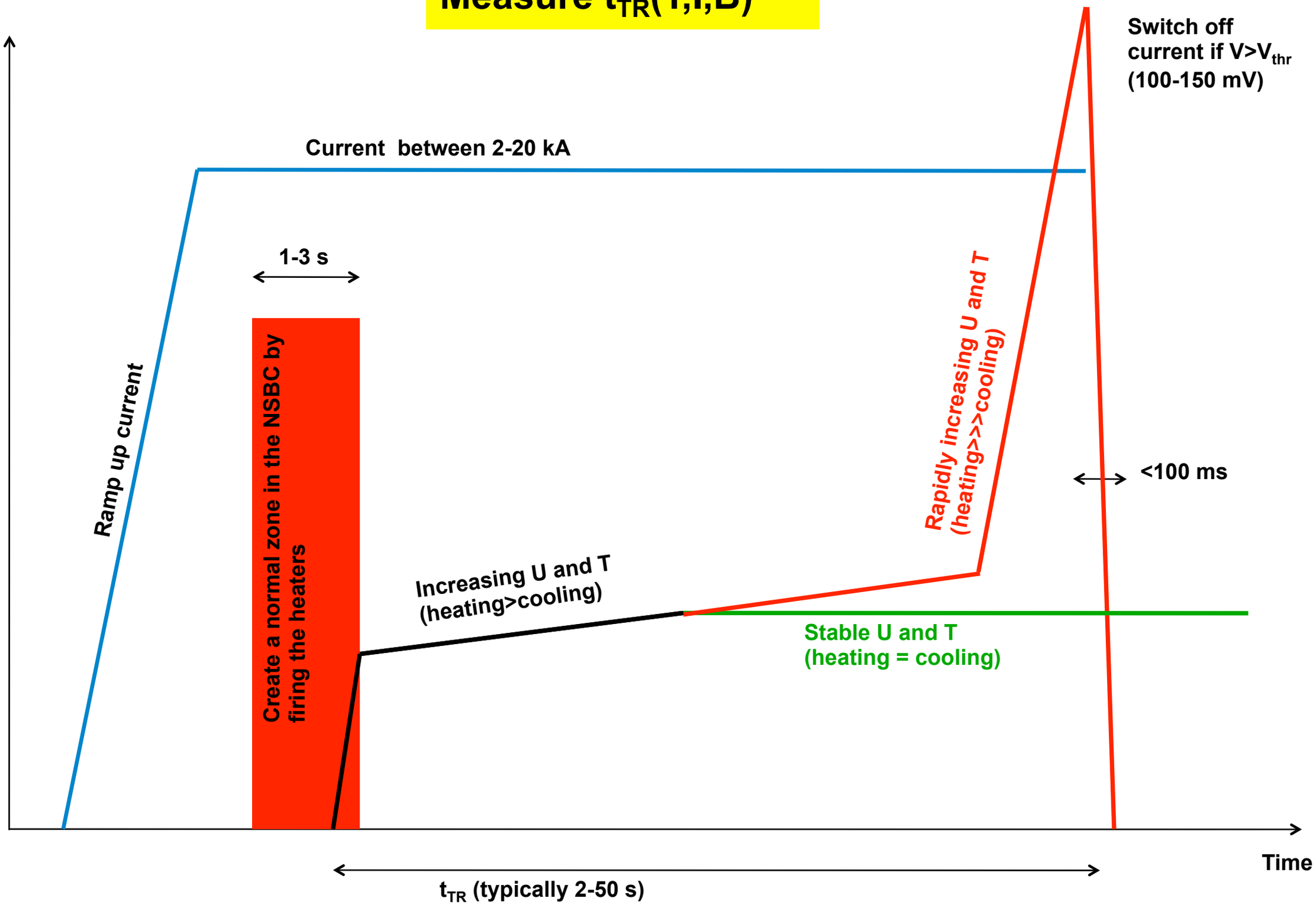
Sample 3B (21 μΩ)

Sample 2B (42 μΩ)

Pictures by J.-M. Dalin

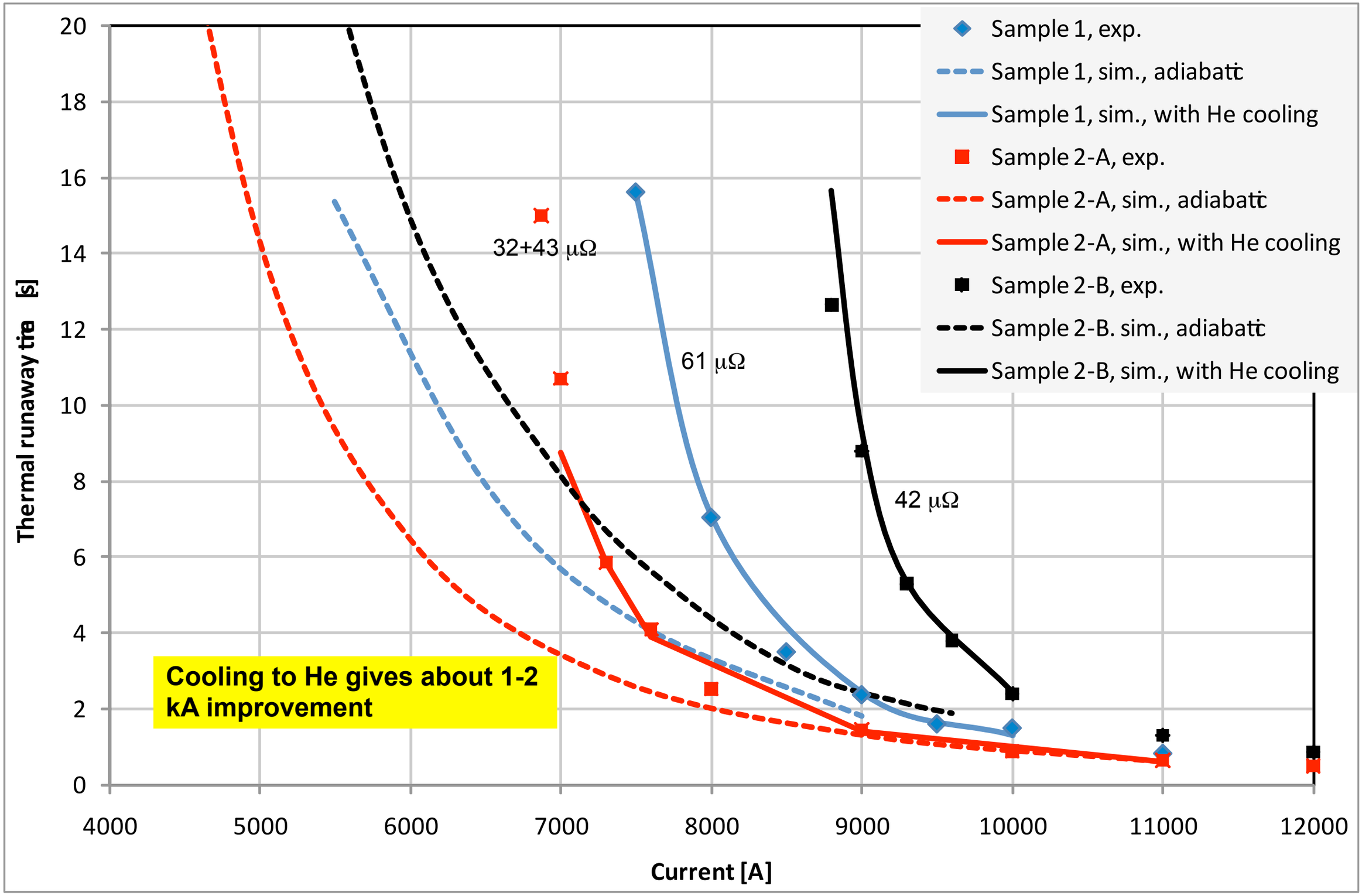
Typical test run with and without thermal runaway

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

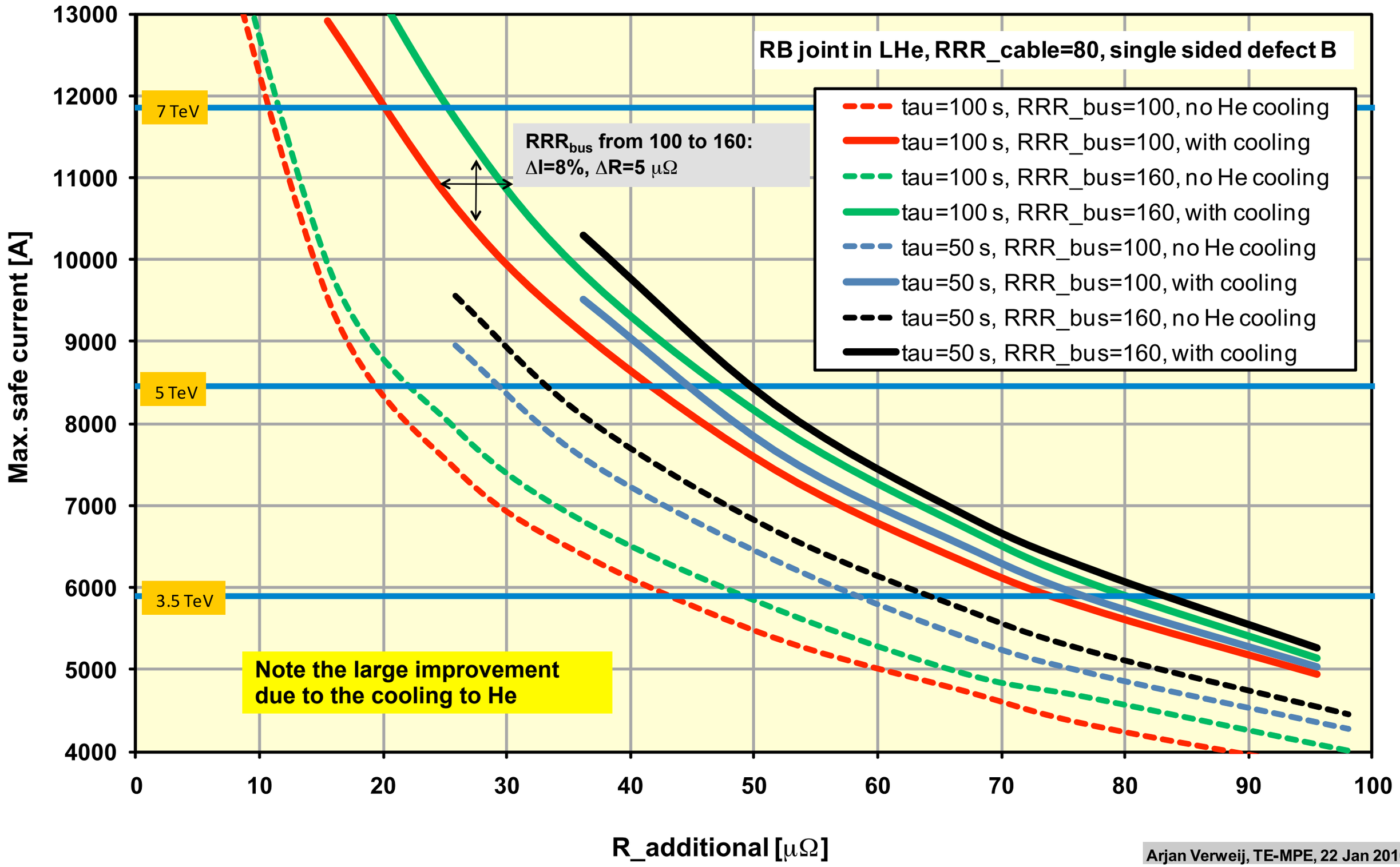


Correlation experimental and calculated $t_{TR}(I)$ curves.

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



RB in LHe



Arjan Verweij, TE-MPE, 22 Jan 2010

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	τ_{RB} [s]	Max. $R_{addit,RB}$ [μΩ]	τ_{RQ} [s]	Max. $R_{addit,RQ}$ [μΩ]
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 interest 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.