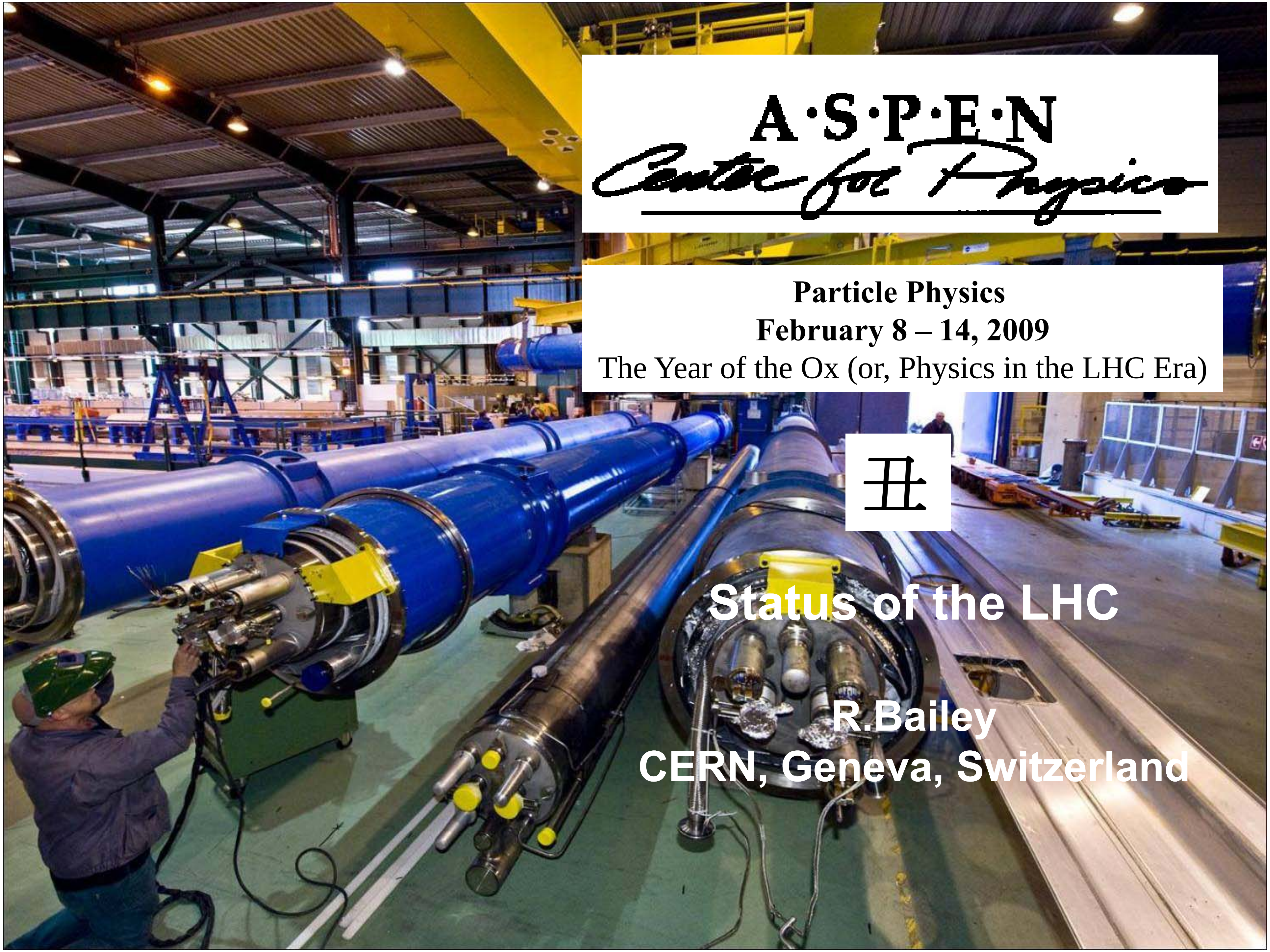


A·S·P·E·N Center for Physics

Particle Physics
February 8 – 14, 2009
The Year of the Ox (or, Physics in the LHC Era)

丑

Status of the LHC

R.Bailey
CERN, Geneva, Switzerland

Construction and commissioning 2002-2008

Tunnel activity determined by

LEP | Helium Distribution Line | Triplet | Cryo

2002	2003	2004	2005	2006	2007	2008

Magnet tests

PC SC tests

Magnet installation

Magnet interconnects

Required magnet storage ☹

Allowed magnet sorting ☺

Definitive cooldown and commissioning for 5TeV

Problem

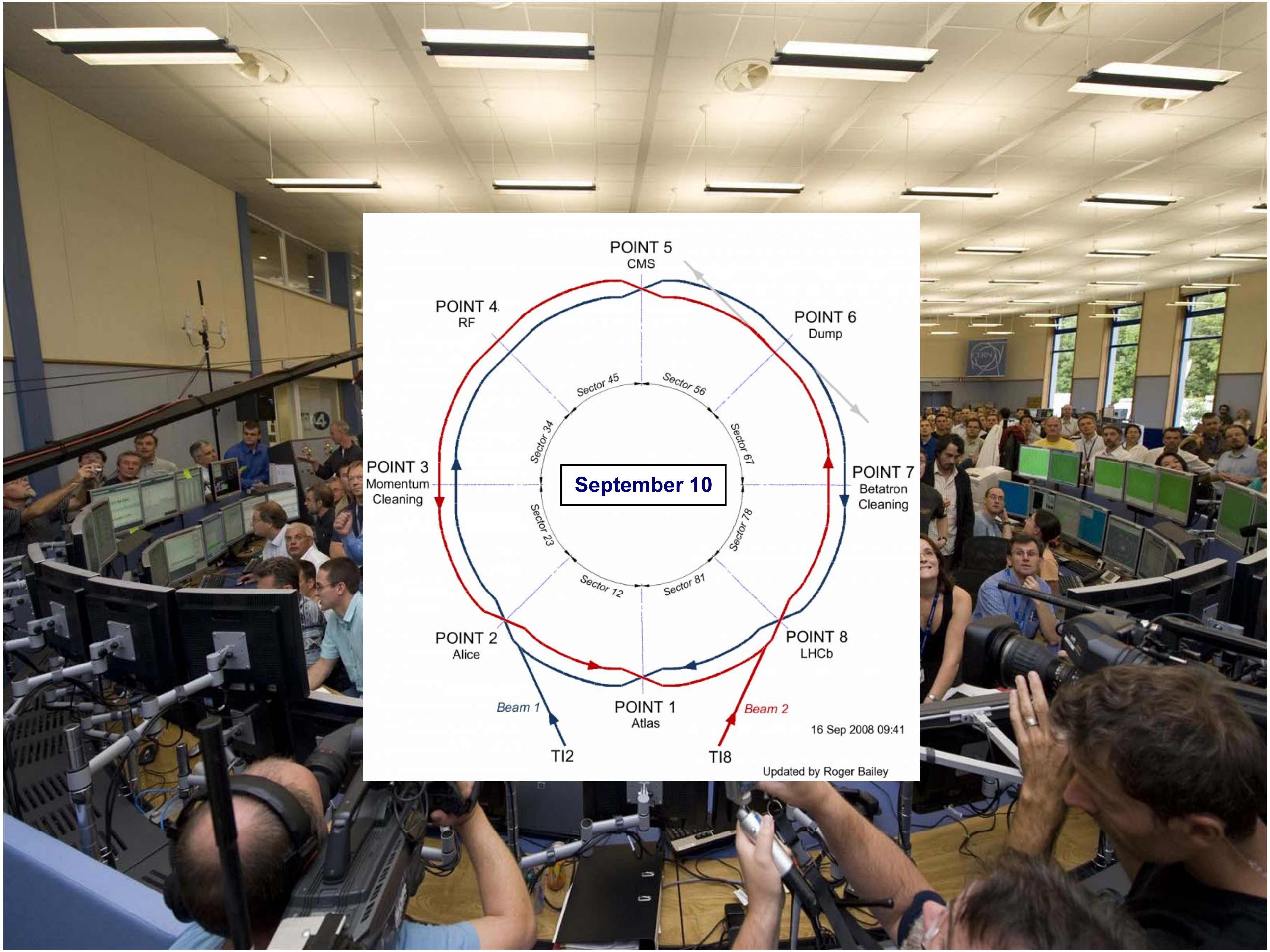
Sector 78 commissioning

Sector 45 commissioning

Beam

While not forgetting several major accelerator systems

- Injection systems
- Extraction systems
- RF systems
- Collimation systems
- Vacuum systems
- Beam instrumentation systems
- Machine protection systems
- Controls
- Experiments

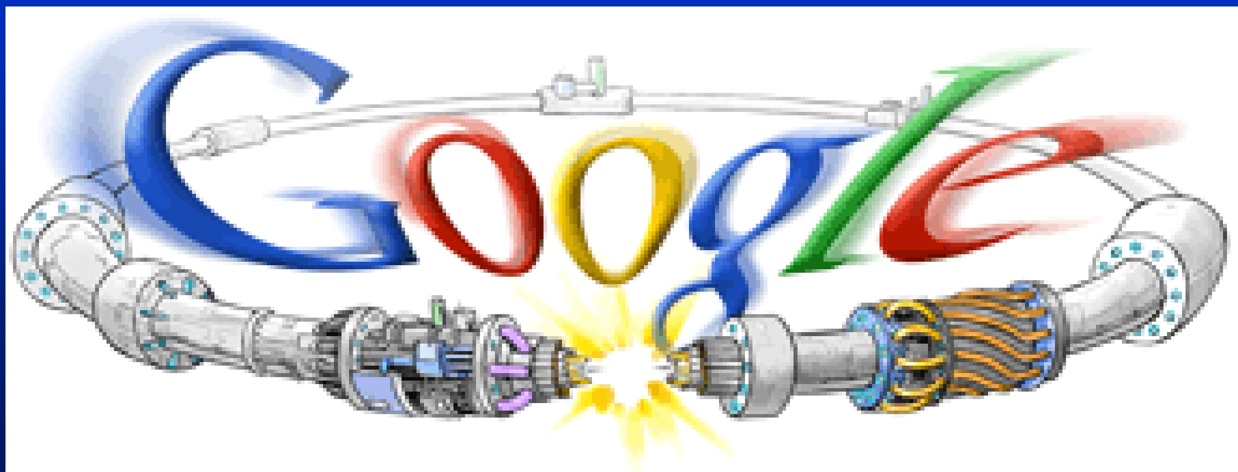

POINT 5
CMS
POINT 4
RF
POINT 6
Dump
Sector 45
Sector 56
Sector 34
Sector 67
POINT 3
Momentum
Cleaning
September 10
POINT 7
Betatron
Cleaning
Sector 23
Sector 78
Sector 12
Sector 81
POINT 2
Alice
POINT 8
LHCb
Beam 1
POINT 1
Atlas
Beam 2
16 Sep 2008 09:41
TI2
TI8
Updated by Roger Bailey

September 10^{th}

- Single bunch of protons 3 10^9
- Achieved
  - Beam 1 injected IP2
  - Threaded around the machine in 1h
  - Trajectory steering gave 2 or 3 turns
  - Beam 2 injected IP8
  - Threaded around the machine in 1h30
  - Trajectory steering gave 2 or 3 turns
  - Q and Q' trims gave a few hundred turns

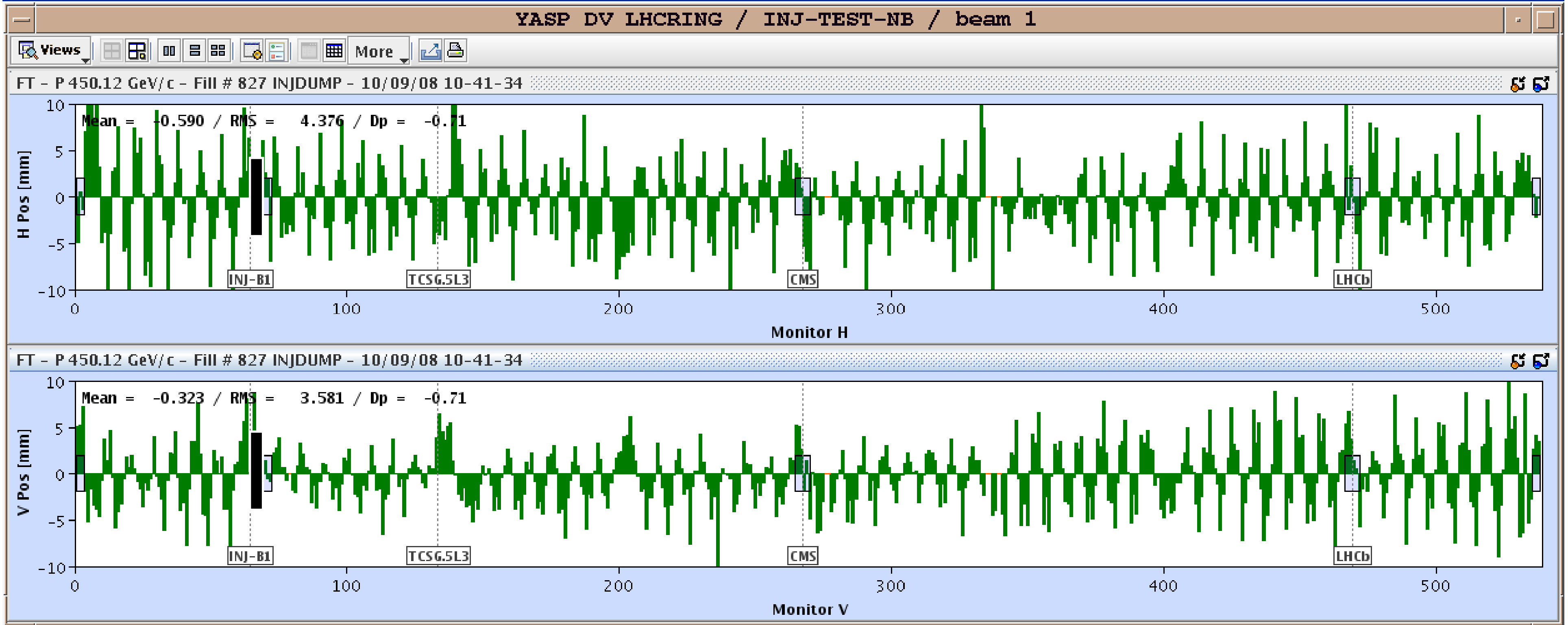
No Major Obstacle

No Major Magnetic Problem

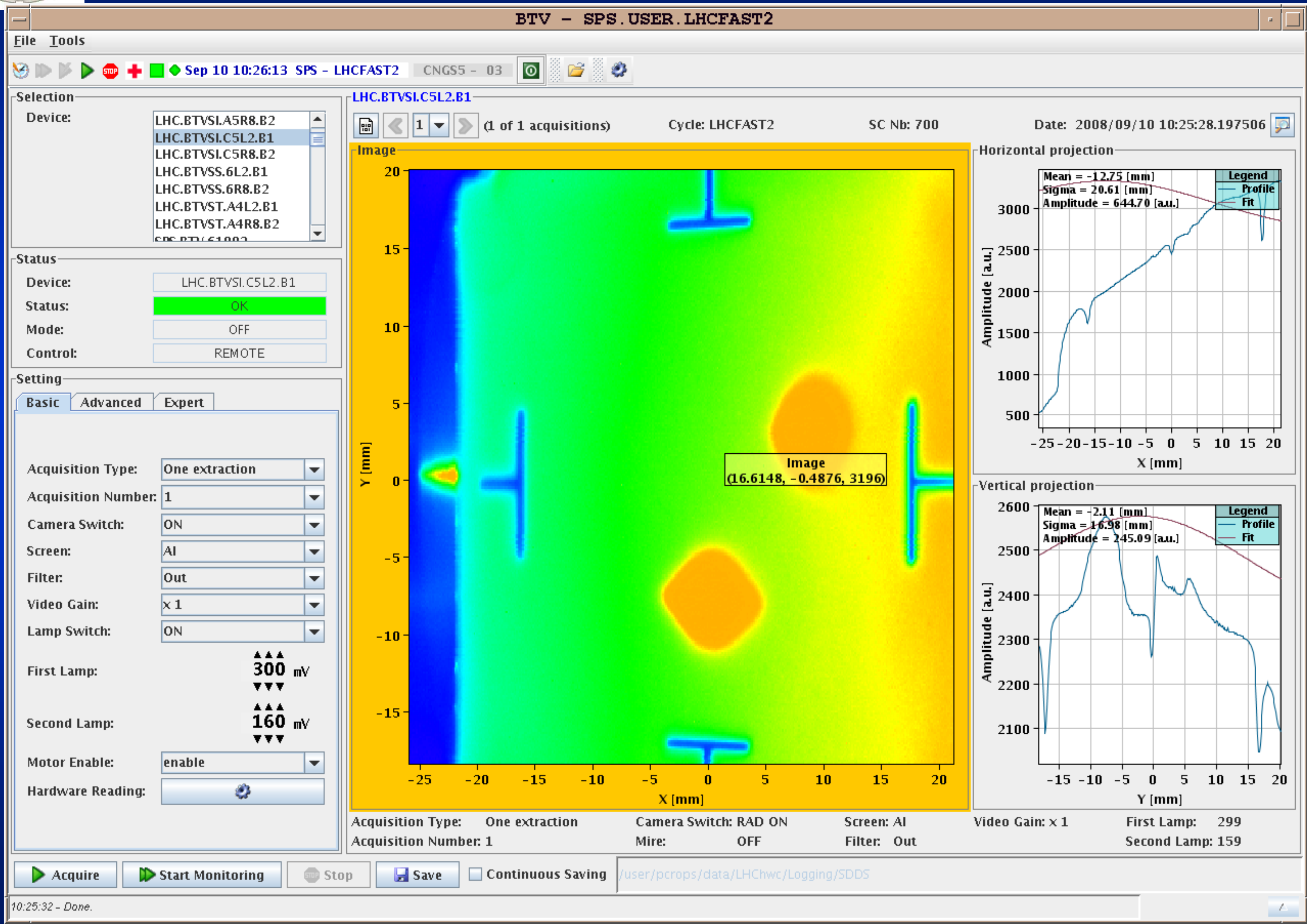


Day	Beam 1 progress	Beam 2 progress	Images	Significant events
Mon 08				Electrical problem point 8 in evening Q8.L8 short circuit investigations
Tue 09				Few accesses in the morning Q8.L8 fixed in the afternoon Cryogenics point 8 OK in evening
Wed 10	First turn 09.30 to 10.30 Makes 2 to 3 turns	First turn 13.30 to 15.00 Few hundred turns BPM on multiple turns Measure Q working Fast BC working Systematic polarity checks	screen shows beam on turns 1& 2 few 100 turns tune measurements fast BCT	Turbine stop in 78 at 04h Search dropped in point 2 All OK by 08h !!
Thu 11		Inject and dump Circulate and dump 50ms Circulate - dump request RF capture working Integer tunes OK Mountain range working Systematic polarity checks	dump dilution sweep integer tunes mountain range	RB34 trip in early hours Other problems follow in 56, R8, R2 QPS experts need to go in Access until 18h
Fri 12		Circulating beam Beta-beat measurement Wire scan H and V works	H beta-beat H wire scan	No beam from SPS 16h to 20h Transformer fault point 8 at 23.30 - serious
Sat 13	**3 days of beam**			Cryogenics reconfigure to stabilise Supply 400V for cryogenics Transformer exchange Sector 45 cryogenics in evening
Sun 14				Transformer work continues Sector 56 cryogenics

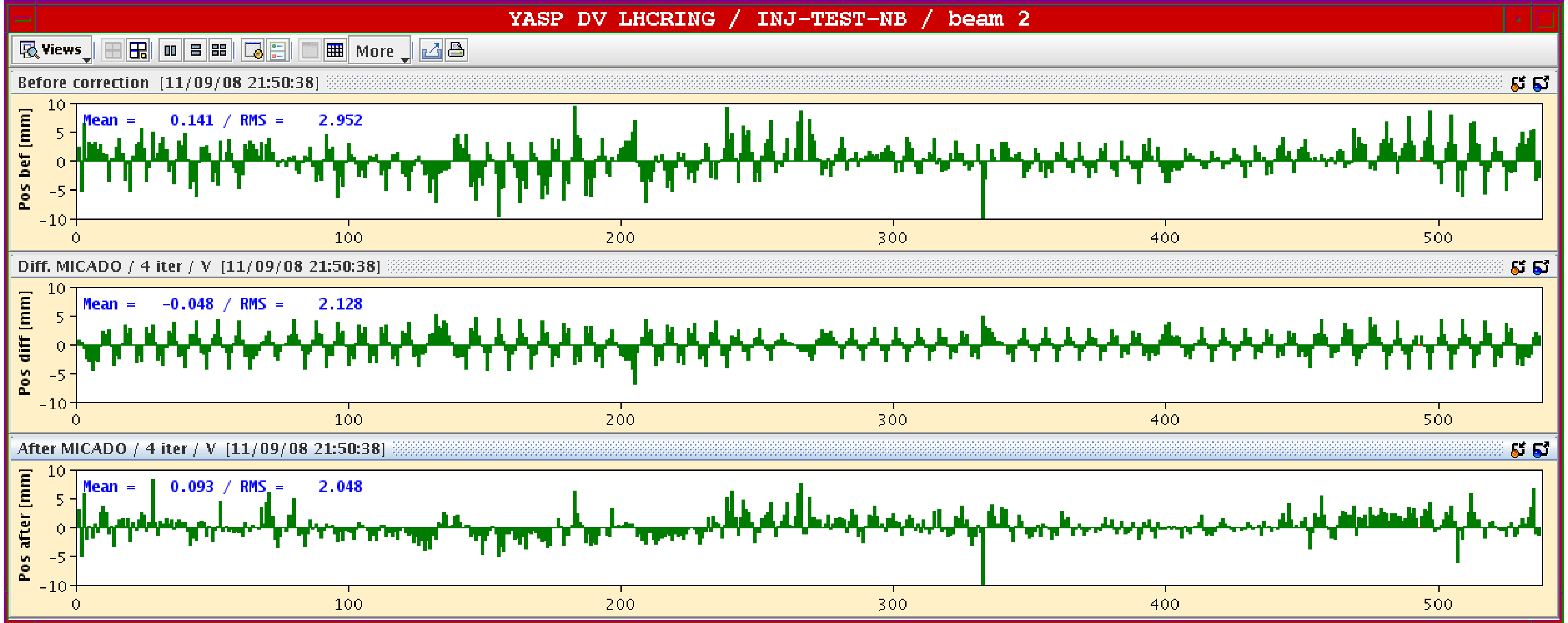
Beam 1 – First turn trajectory



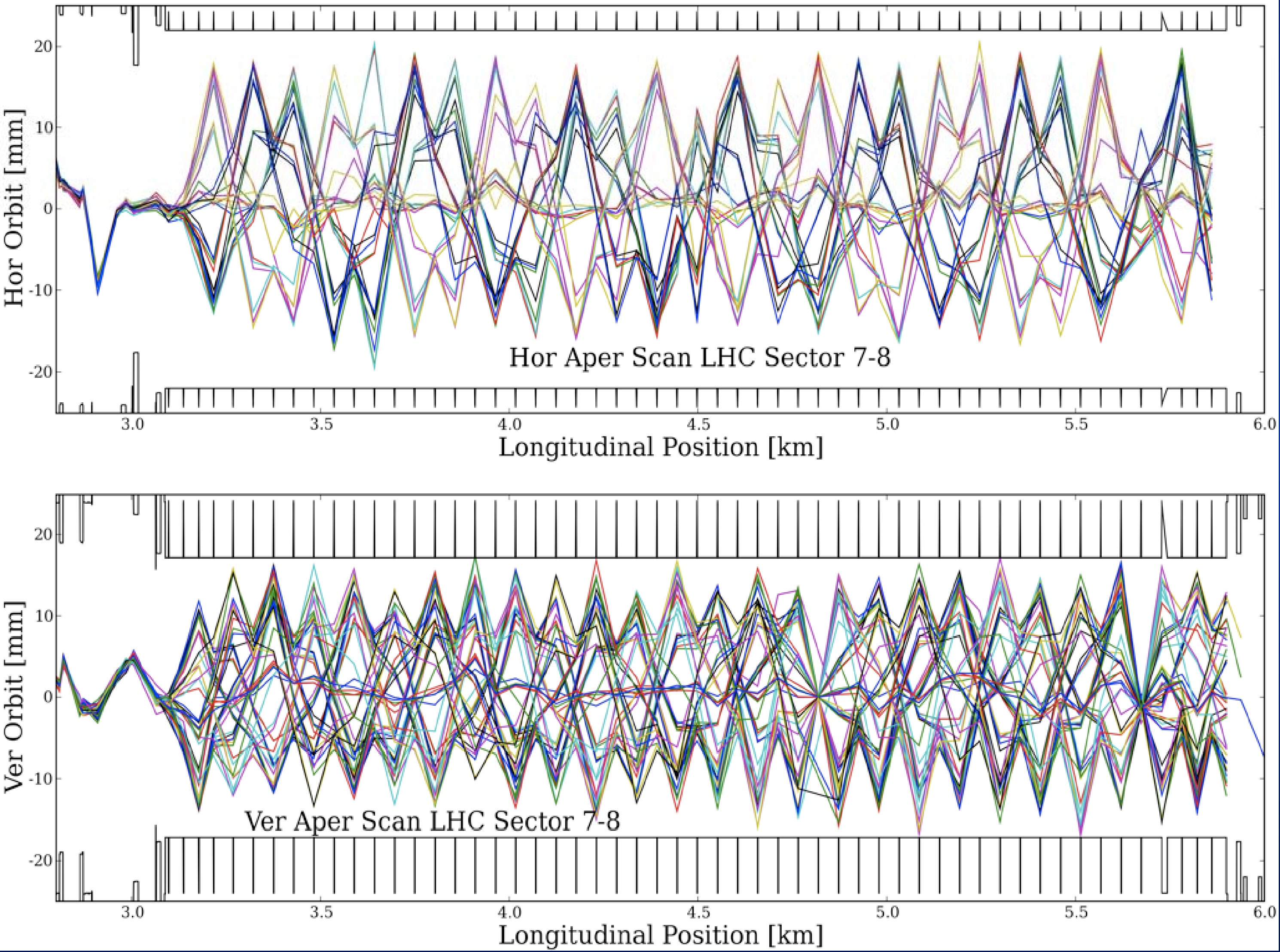
Beam 1 on injection screen – 1st and 2nd turns



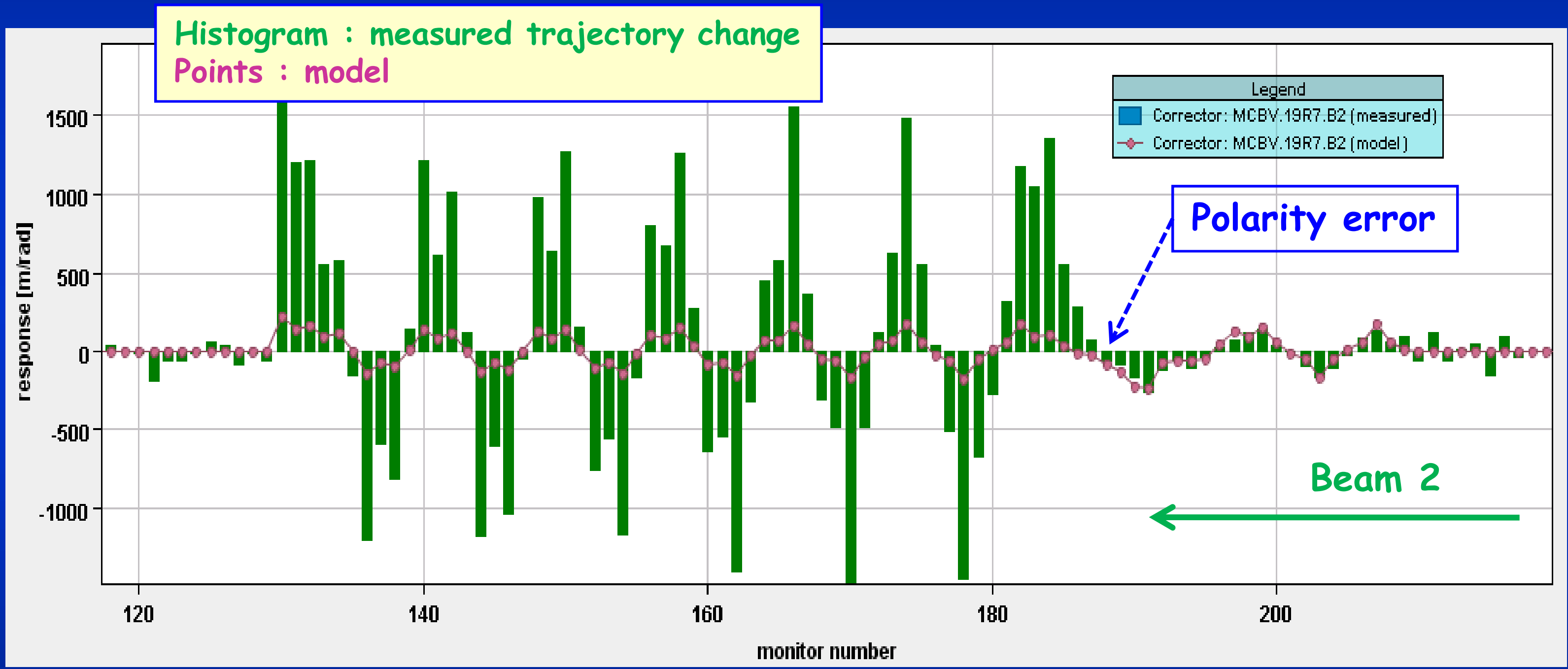
Beam 2 – Closed orbit system working



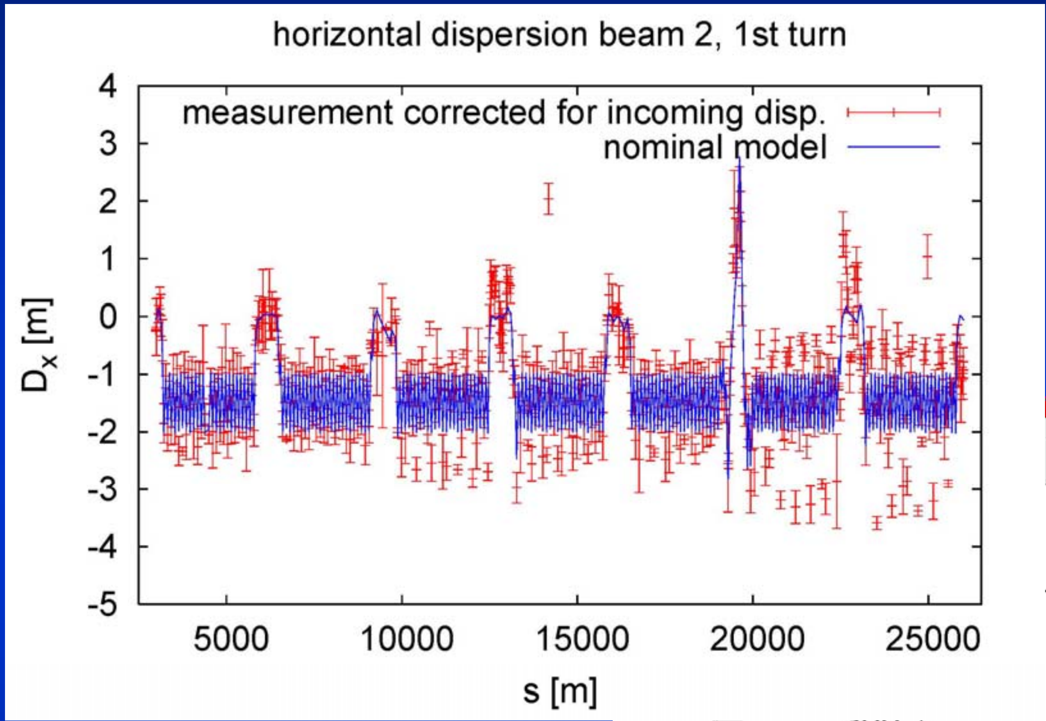
Beam 2 – Aperture checks

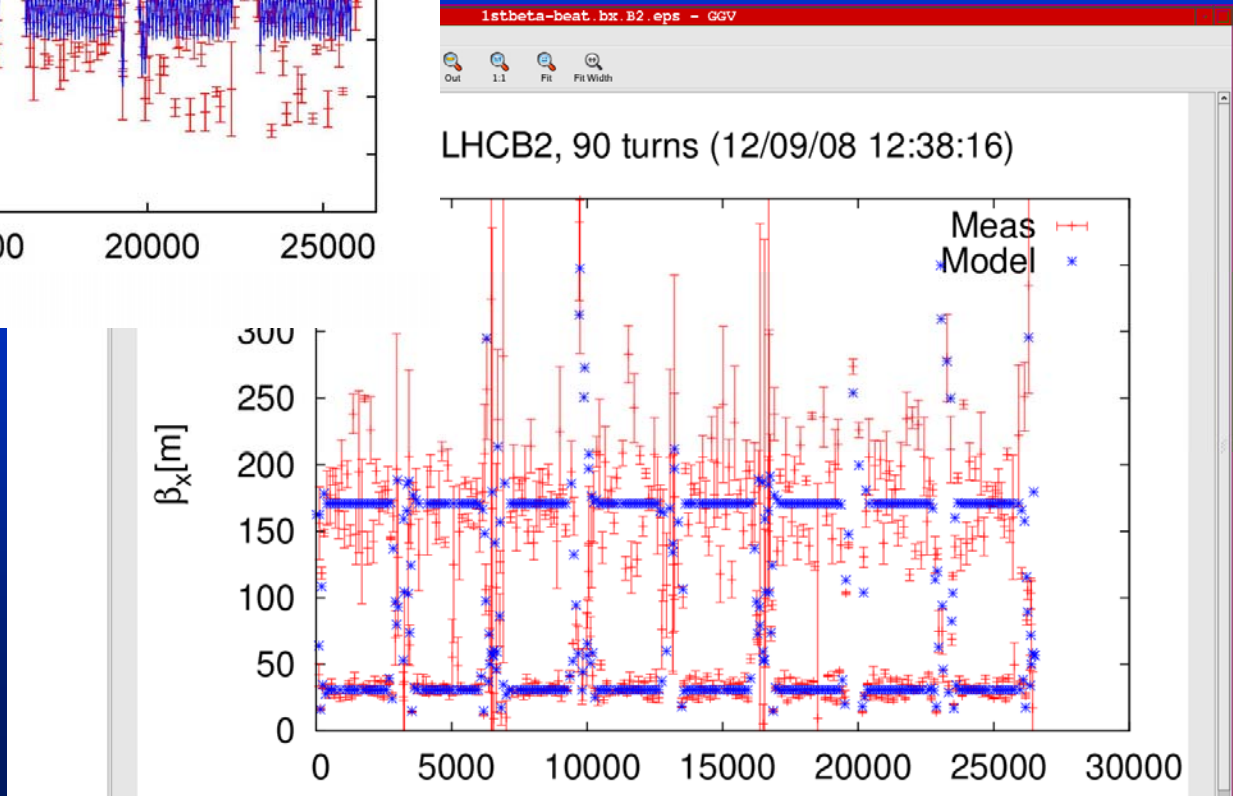


Beam 2 – Polarity checks

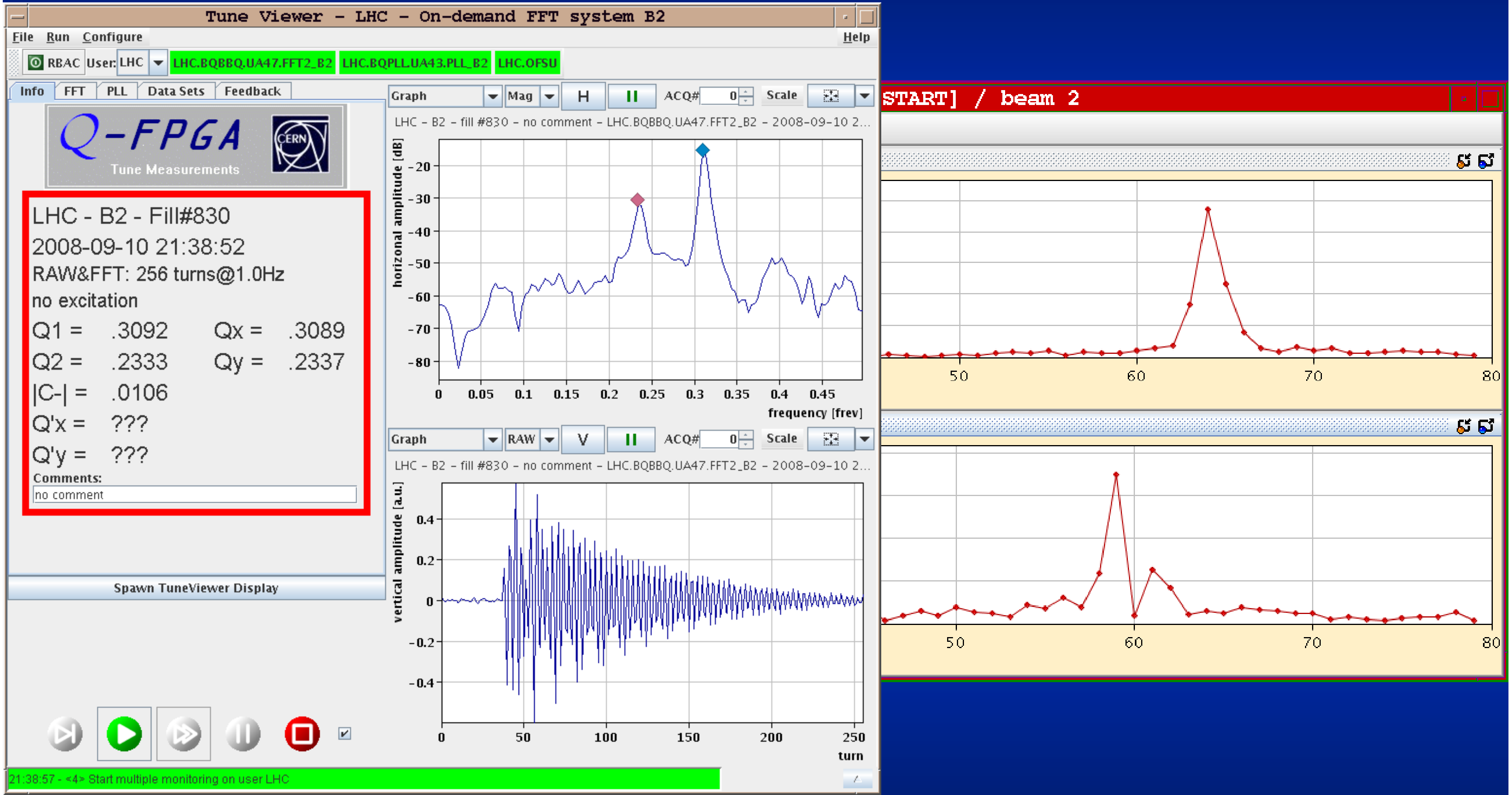


Beam 2 – Optics measurements

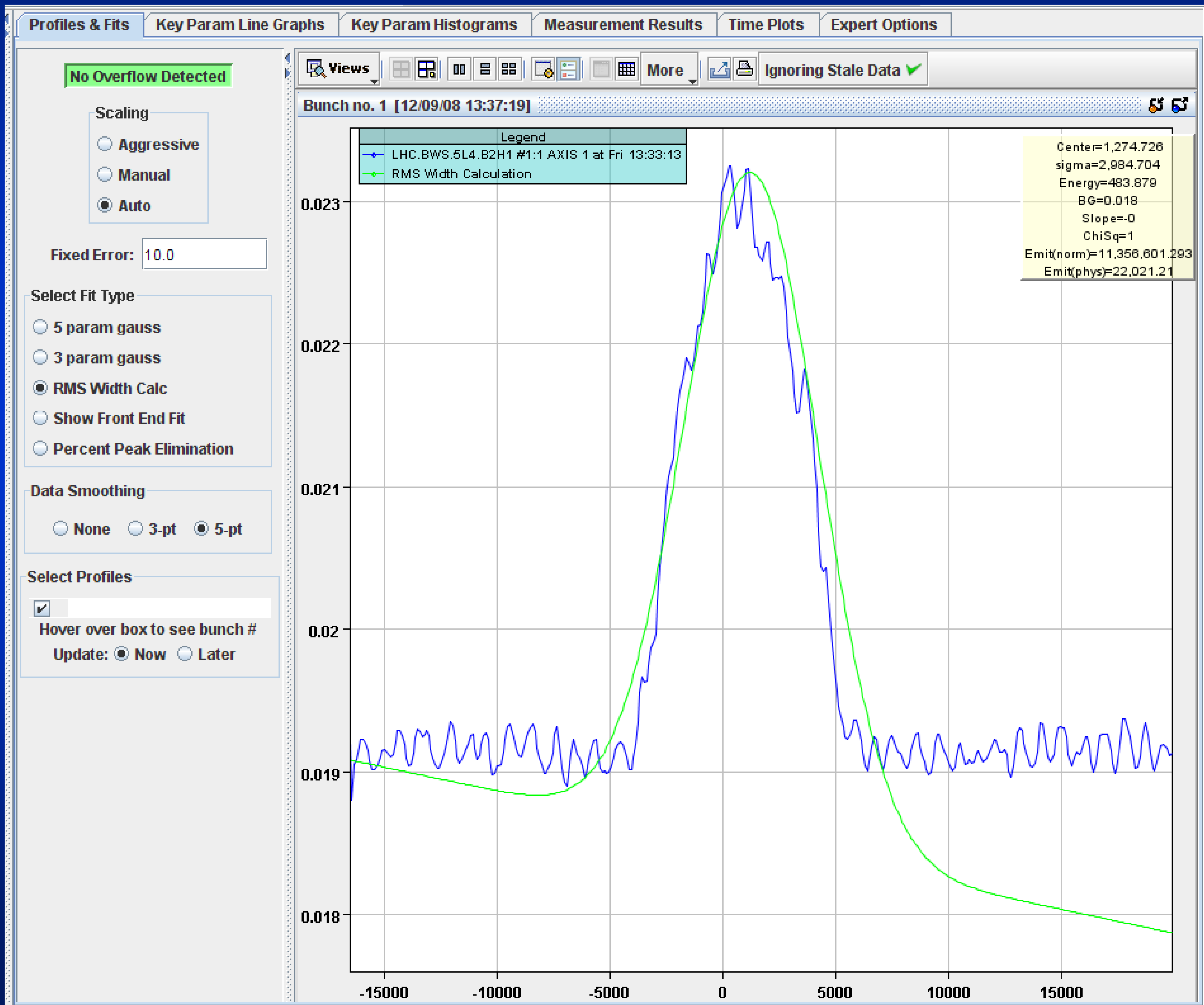




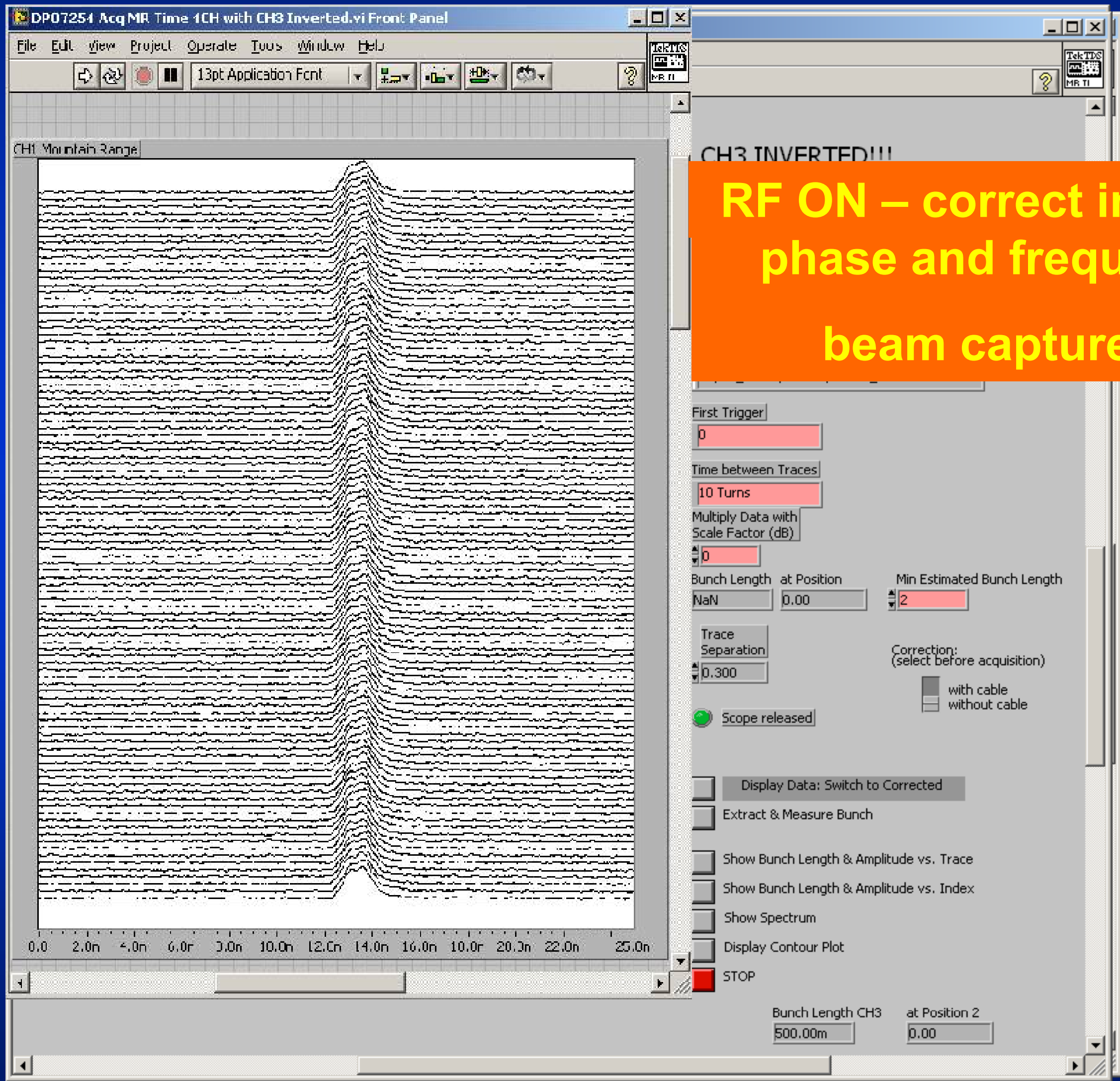
Beam 2 – Tune measurement working



Beam 2 – Transverse profile with wire scanner



Beam 2 – RF capture



RF ON – correct injection phase and frequency:

beam captured !

Fast start (September 10 11 12)

- A lot done in 3 days
  - Made possible by
    - Meticulous preparation
    - Magnetic model data
    - Sophisticated settings generation
    - Dry runs
    - Injection tests
    - Powerful control system (LSA)
    - Powerful beam instrumentation working very quickly
    - Logging a multitude of parameters
  - Allowed
    - Early look at several machine parameters
    - Systematic check of orbit system
- Recovery from transformer failure through the following week
  - Cryogenics
  - Completion of hardware commissioning
- Serious problem during power tests on September 19th

Incident of September 19th 2008

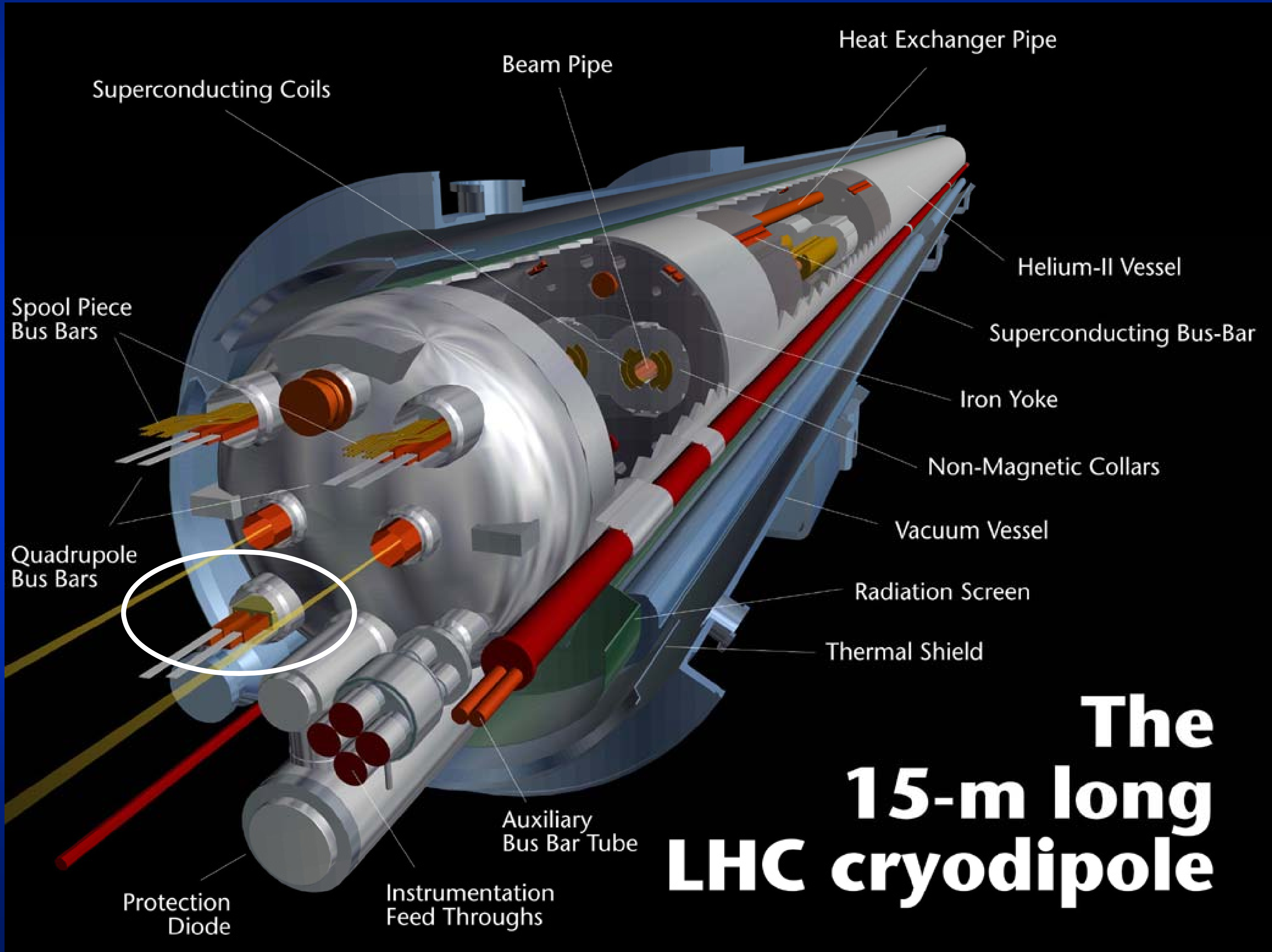
- During a few days period without beam

- Making the last step of dipole circuit in sector 34, to 9.3kA
- At 8.7kA, development of resistive zone in the dipole bus bar splice between Q24 R3 and the neighbouring dipole

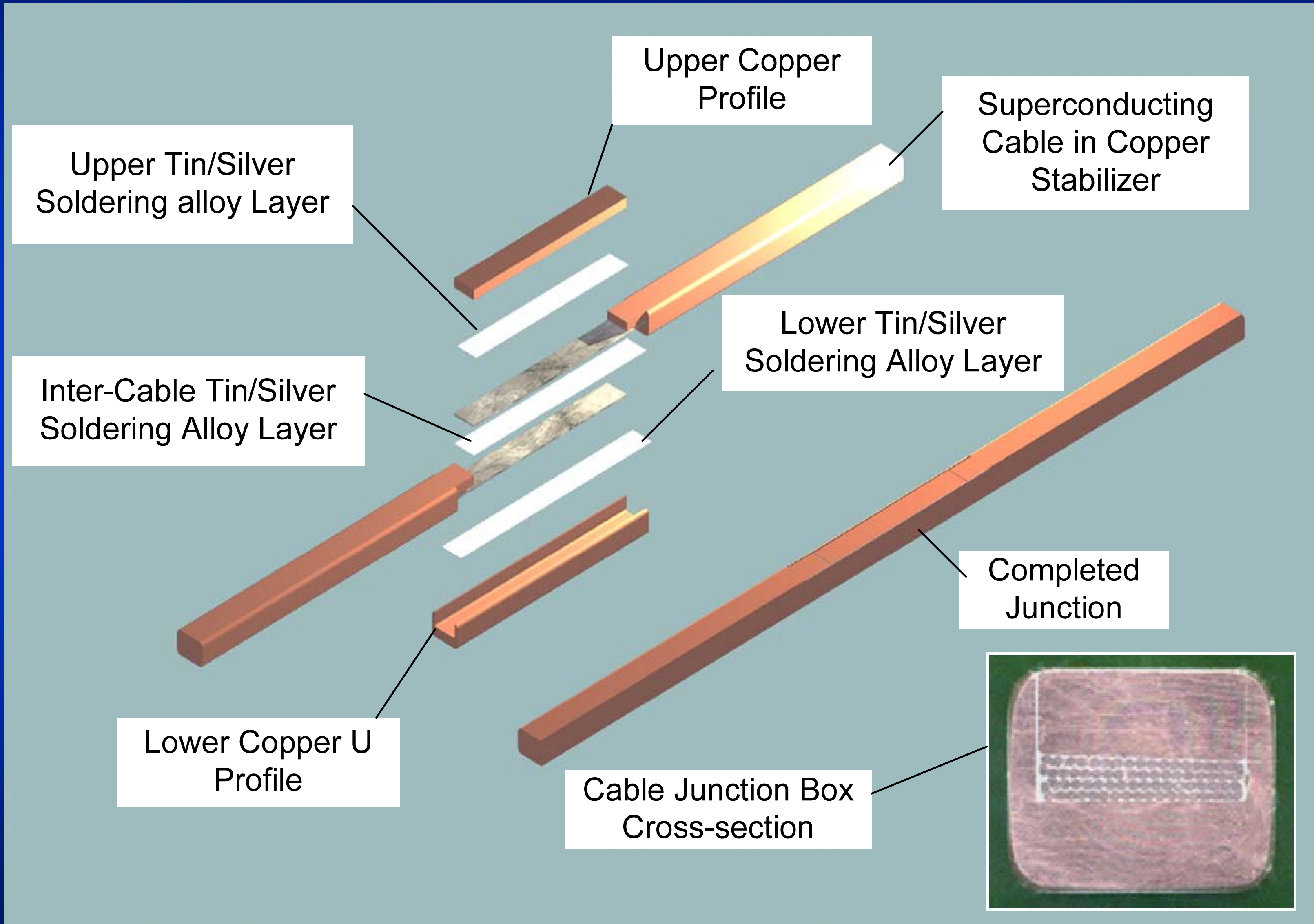
- Electrical arc developed which punctured the helium enclosure
- Helium released into the insulating vacuum

- Rapid pressure rise inside the LHC magnets
  - Large pressure wave travelled along the accelerator both ways
  - Self actuating relief valves opened but could not handle all
  - Large forces exerted on the vacuum barriers located every 2 cells
  - These forces displaced several quadrupoles and dipoles
  - Connections to the cryogenic line affected in some places
  - Beam vacuum also affected

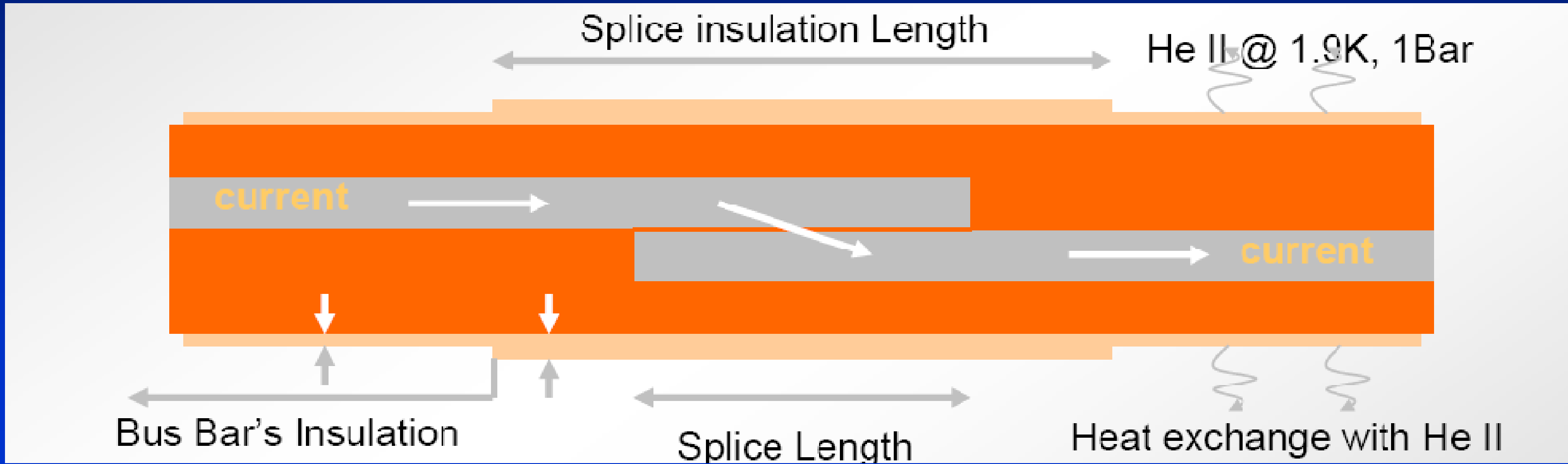
Development of resistive zone in dipole bus bar splice



Bus bar splice



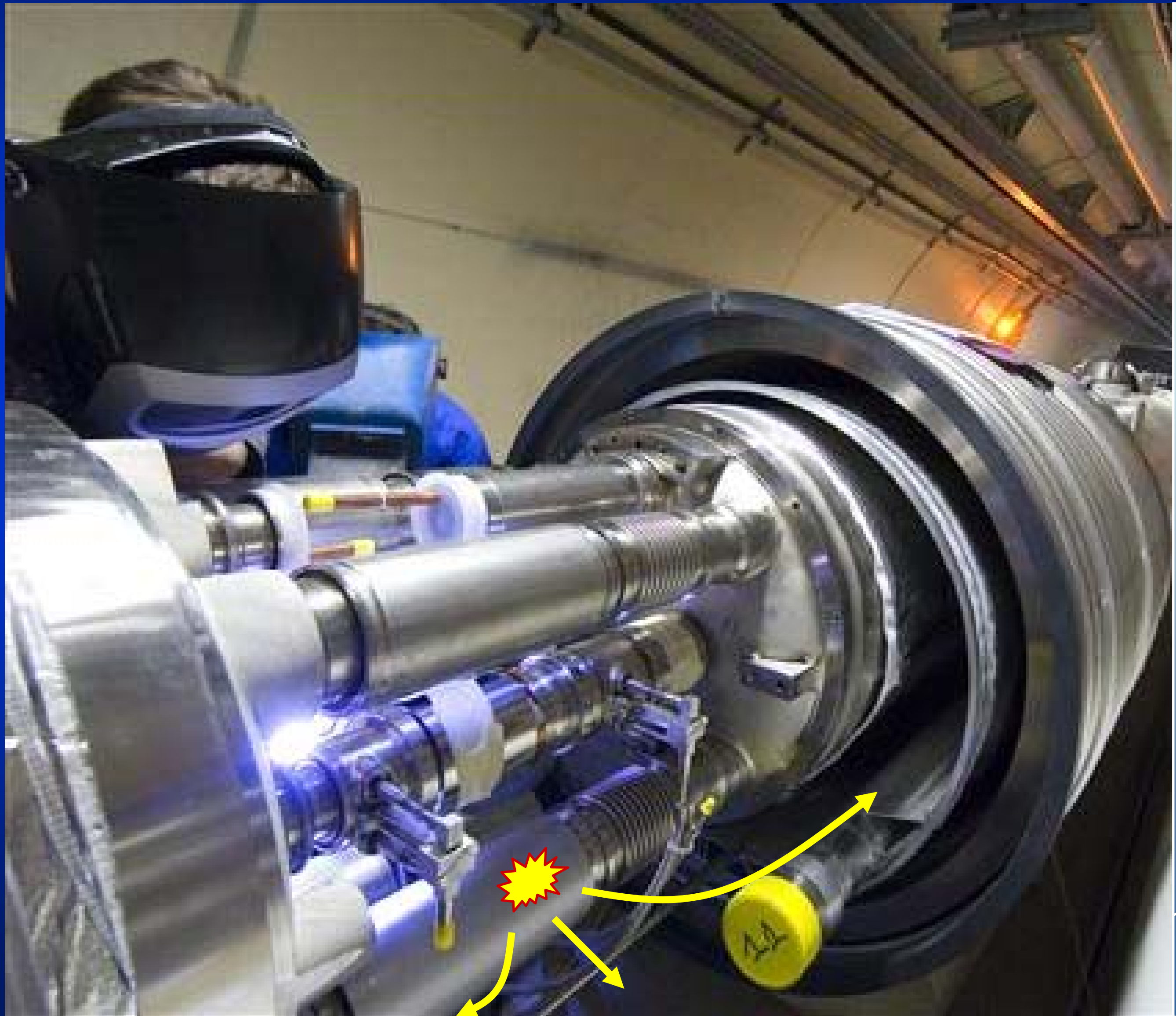
Working hypothesis



Favored *hypothesis* for the S34 incident cause :

- Temperature increase due to excessive resistance (estimate ~ 200nΩ)
- Superconductor quenches and becomes resistive at high current
- Up to a certain current, the copper can take it (cooled by the He II)
- Beyond a certain current, 'run-away' of the temperature, splice opens, electrical arc …

Arc and helium released into the insulating vacuum

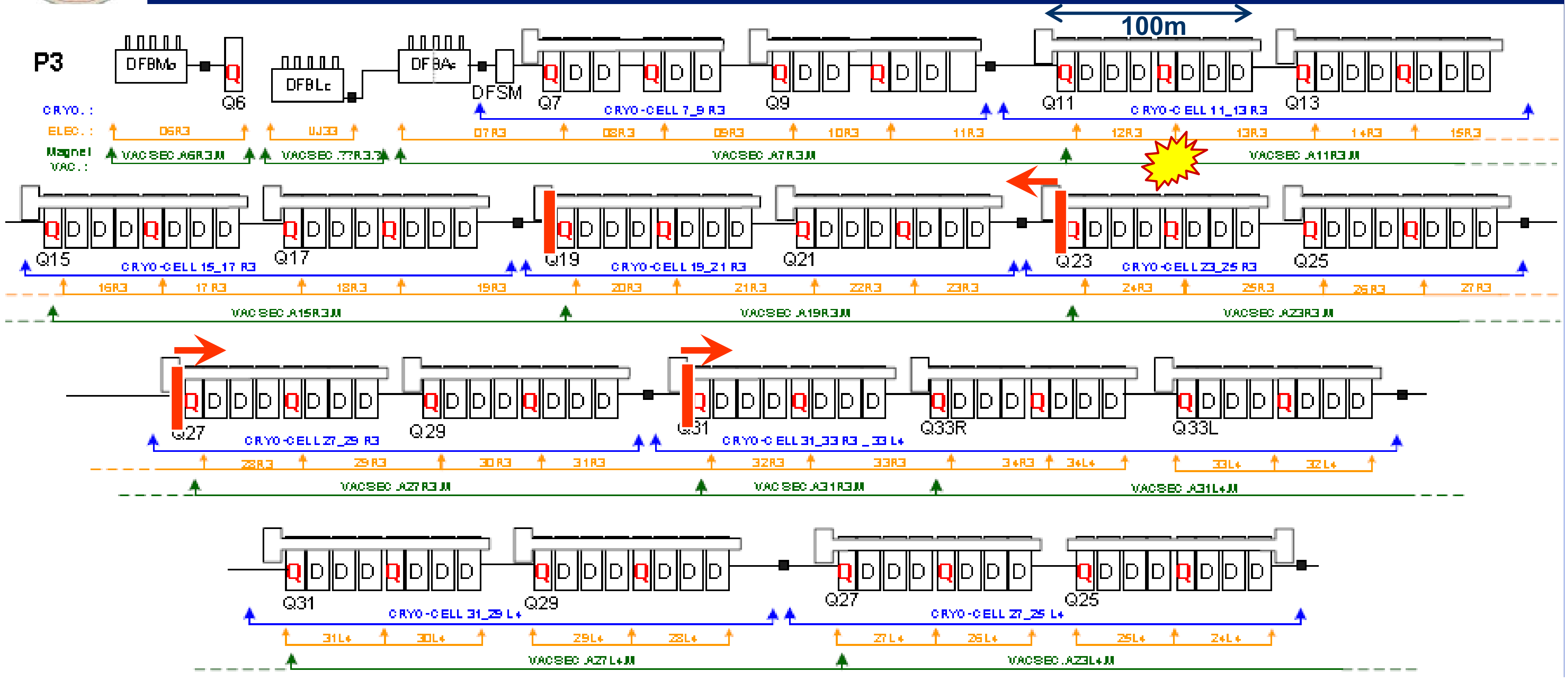


Liquid
to
Gas
Expansion
Factor

1000

Multi kA electrical arc

Consequences



Insulating vacuum barrier every 2 cells in the arc

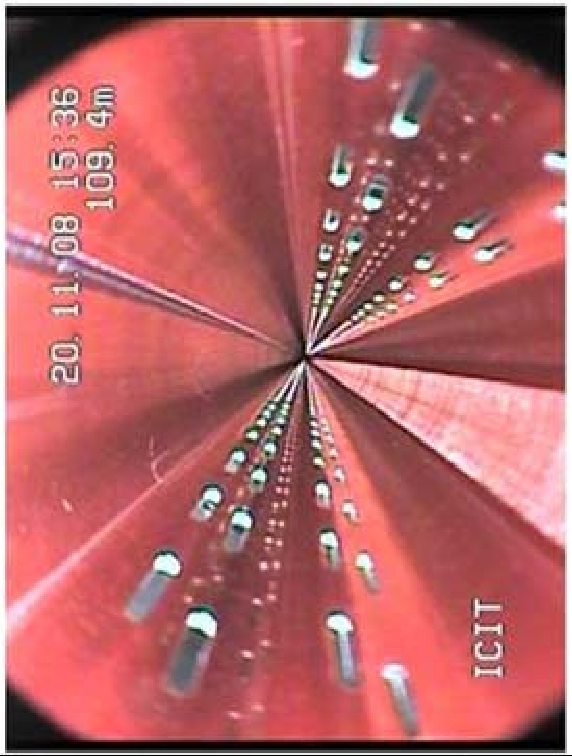
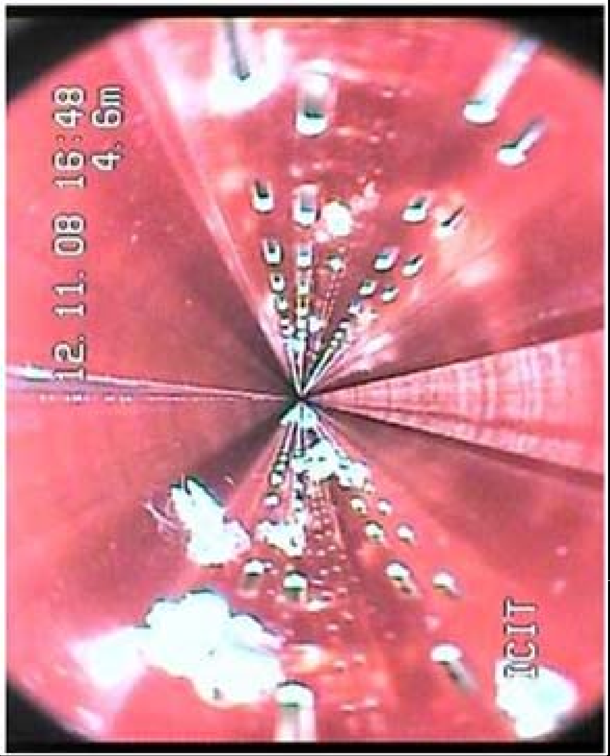
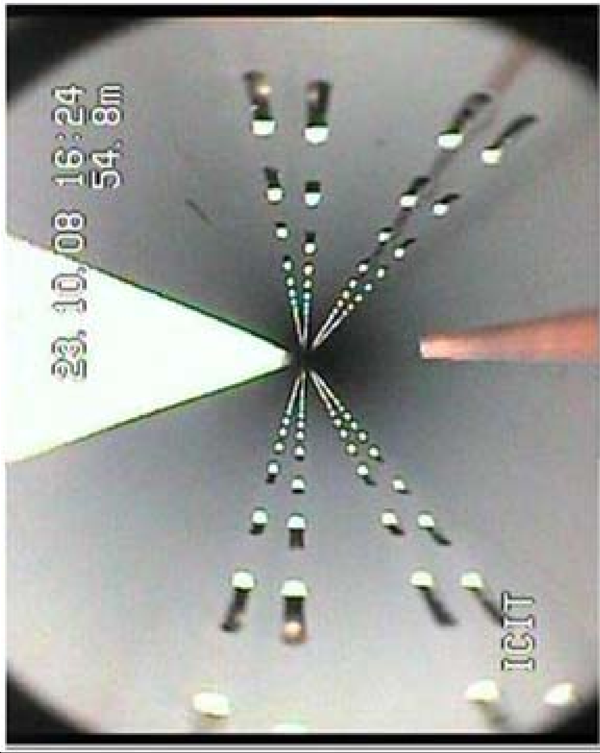
→ Some moved

- **Considerable collateral damage over few hundred metres**
- **Damage to superinsulation blankets**
- **Contamination (by soot and insulation blankets) of beam pipes**
- **Large release of helium into the tunnel (6 of 15 tonnes)**

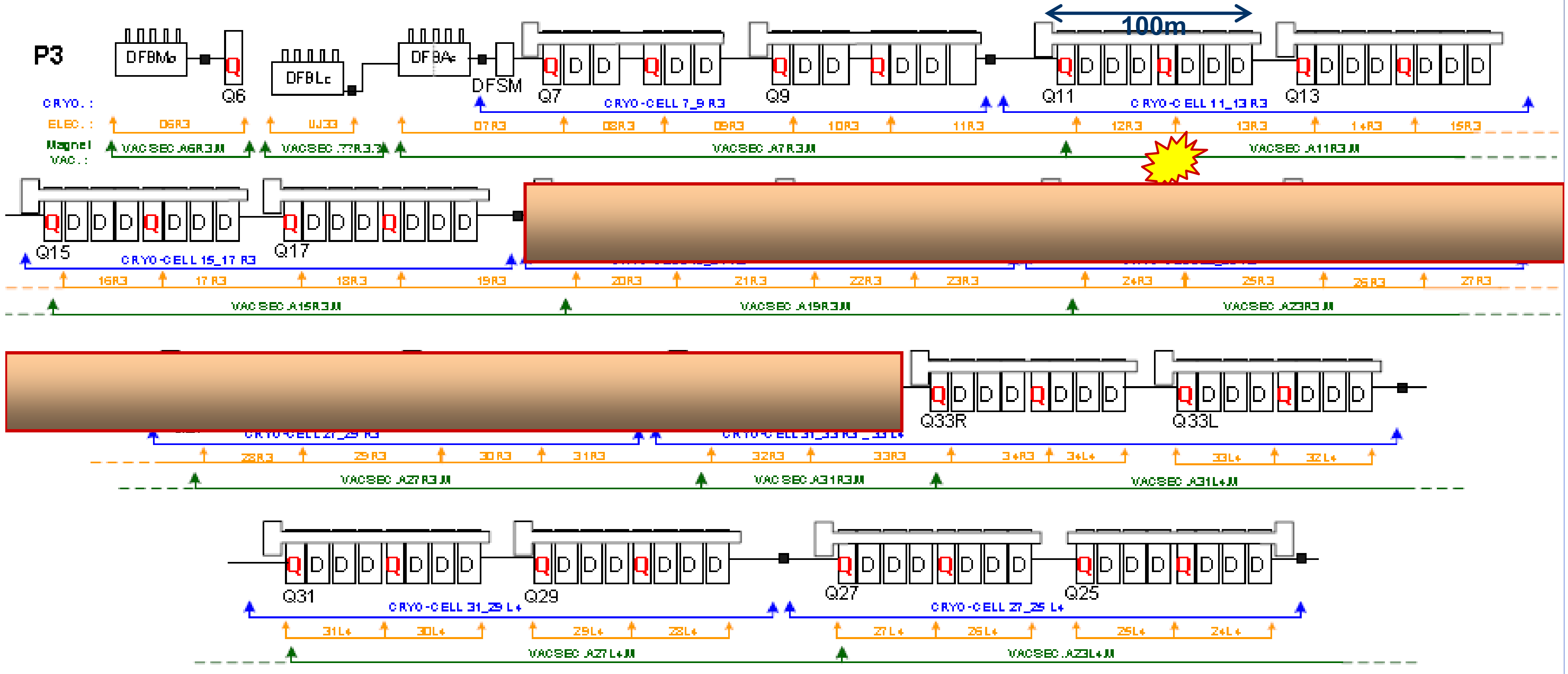
Consequences – Magnets displaced

Consequences – Magnets displaced

Consequences – Vacuum chamber contamination

Beam Screen (BS) : The red color is characteristic of a clean copper surface	BS with some contamination by super-isolation (MLI multi layer insulation)	BS with soot contamination. The grey color varies depending on the thickness of the soot, from grey to dark.
		

Repair

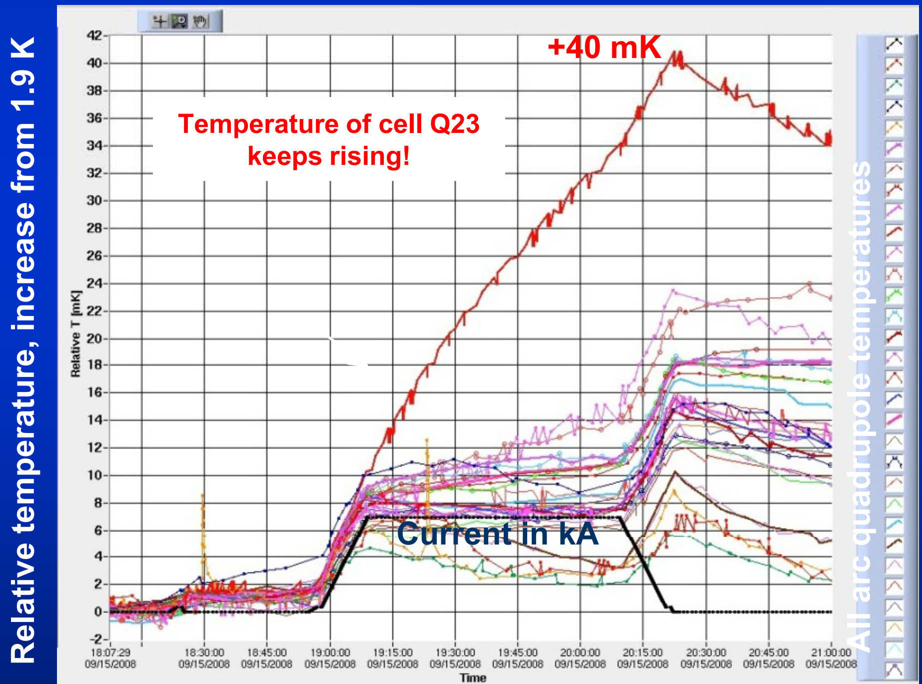


- Present strategy assumes treating all magnets Q19 to Q33
- 53 have to be brought to the surface (39 dipoles and 14 quads)
- Will be replaced with spare / refitted retested and reinstalled
- Estimate for magnets November 08 to April 09
- Not forgetting cleaning the beam pipes
- Then have to finish interconnection, cool down, power test

Needles and haystacks

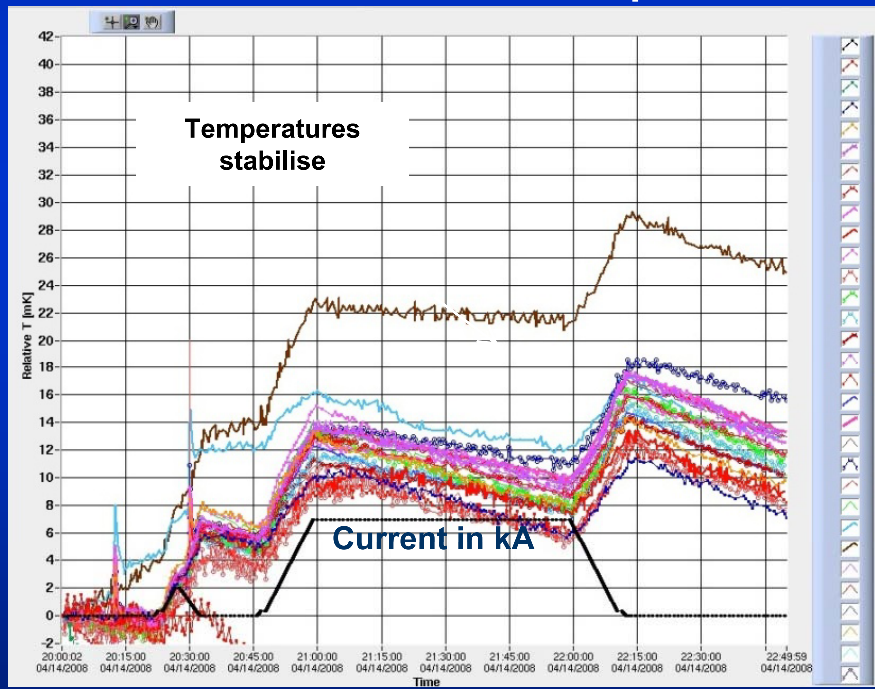
- **Following the incident, a close look at the logged cryogenic data (temperatures and valve states) clearly indicated abnormal behaviour in the cell that was at the origin of the S34 incident**

7 kA test on Sector 3-4, Sept 15



1h

7 kA test on Sector 2-3, April 14



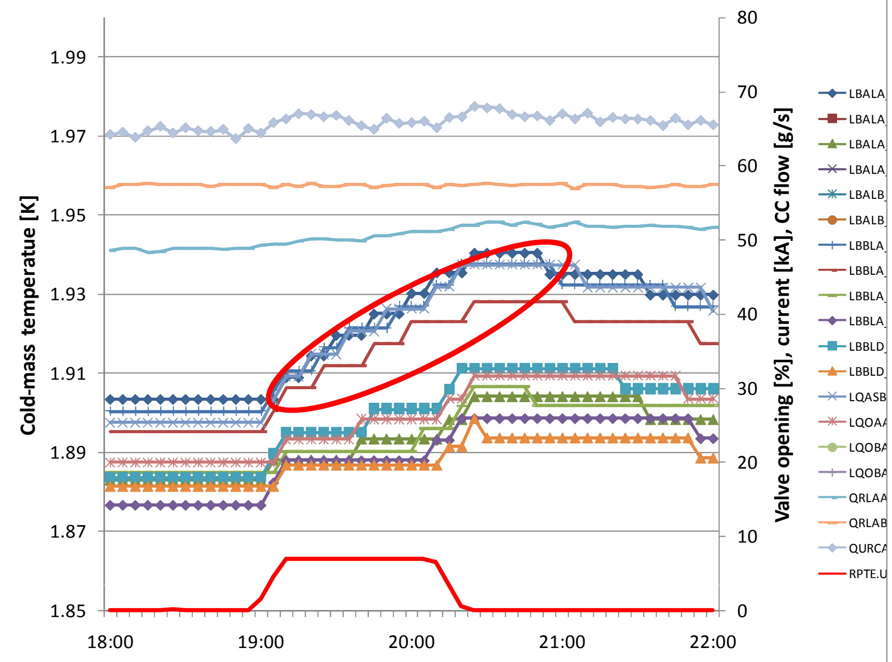
For comparison, another sector, identical scales

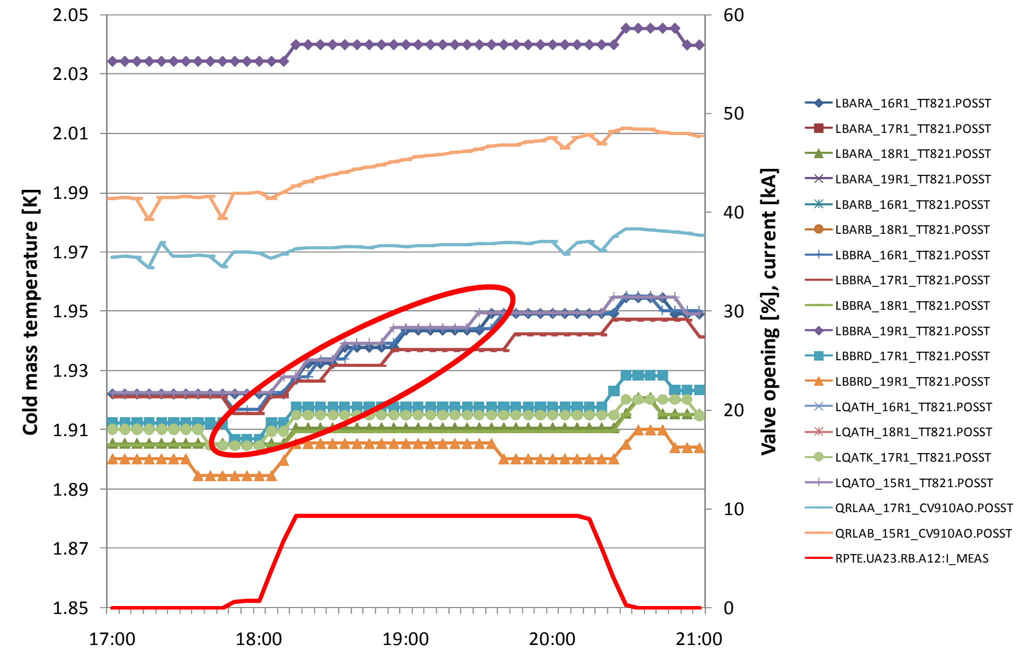
Warning signs

- This was followed by systematic scrutiny of all data logged during the weeks of power testing of all 8 sectors
- Anomalous cryogenic behaviour found in sector 12 at 7kA
  - Higher than nominal heat load in cryogenic sector 15 R1

Post-mortem analysis of the powering at 7 kA of the sub-sector 23R3 (15/09/2008)

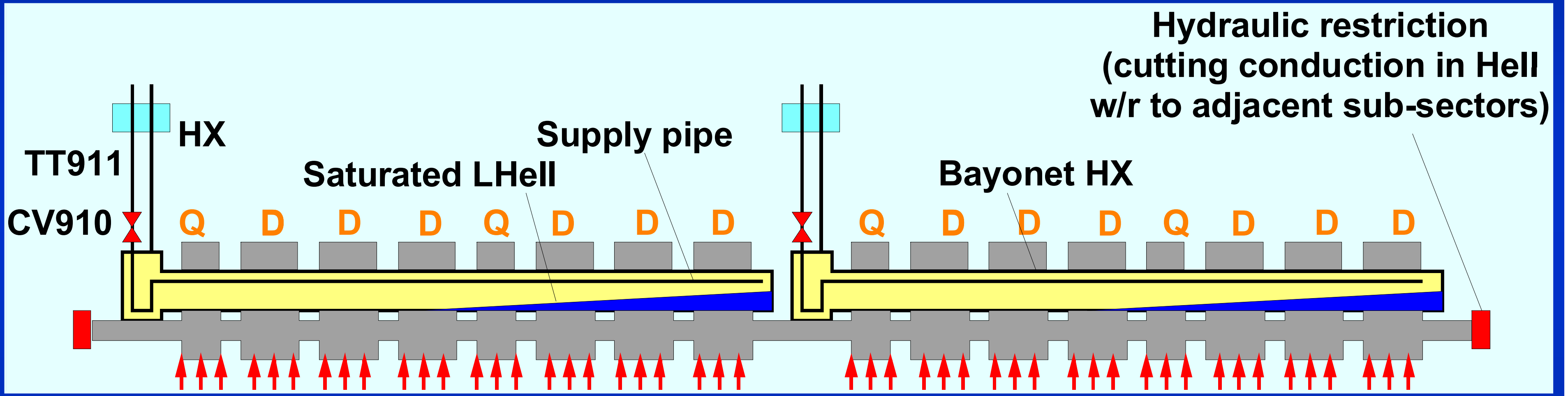
Analysis of the powering at 9.3 kA of the sub-sector 15R1 (01/09/2008)





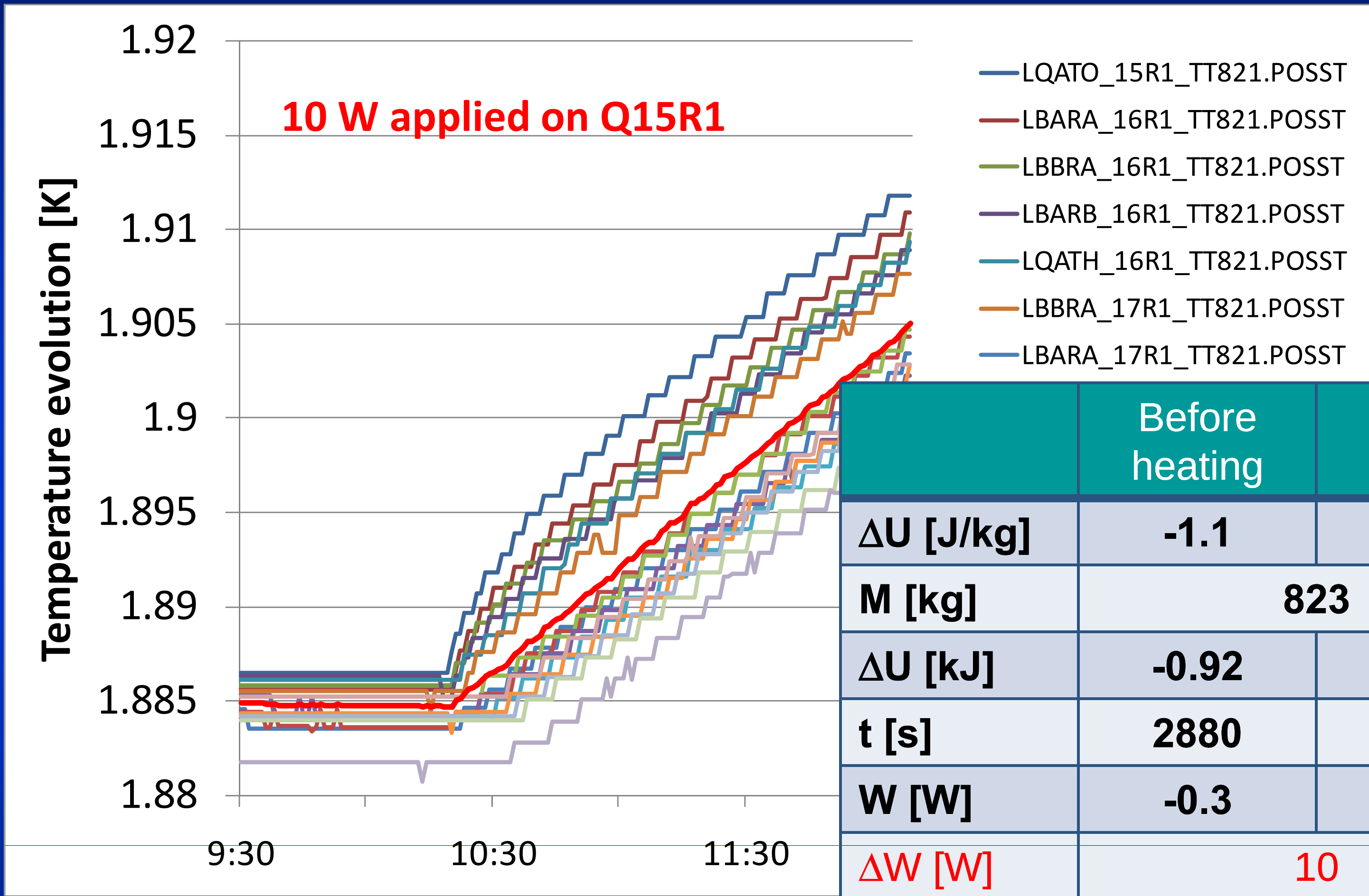
Calorimetry

- How can we use this information ?
- Can we develop a measurement system along these lines ?



- Block the JT valve (CV910) at a value to extract the static heat in-leaks before the powering
- Then, the temperature drift is mainly due to electrical resistive heating dissipated during the powering

Calorimetry – validation of method

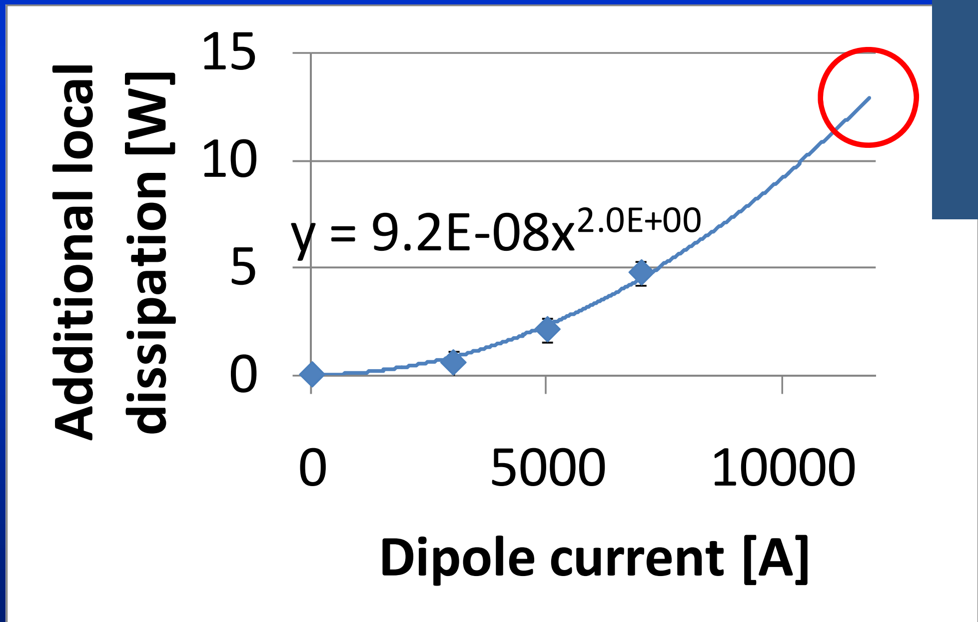


	Before heating	With heating
ΔU [J/kg]	**-1.1**	**78**
M [kg]	**823**	
ΔU [kJ]	**-0.92**	**64.2**
t [s]	**2880**	**6600**
W [W]	**-0.3**	**9.7**
ΔW [W]	10	

- **The power variation calculated by calorimetry came out at 10 W corresponding to the applied electrical power**

Calorimetry – application to sector 15 R1

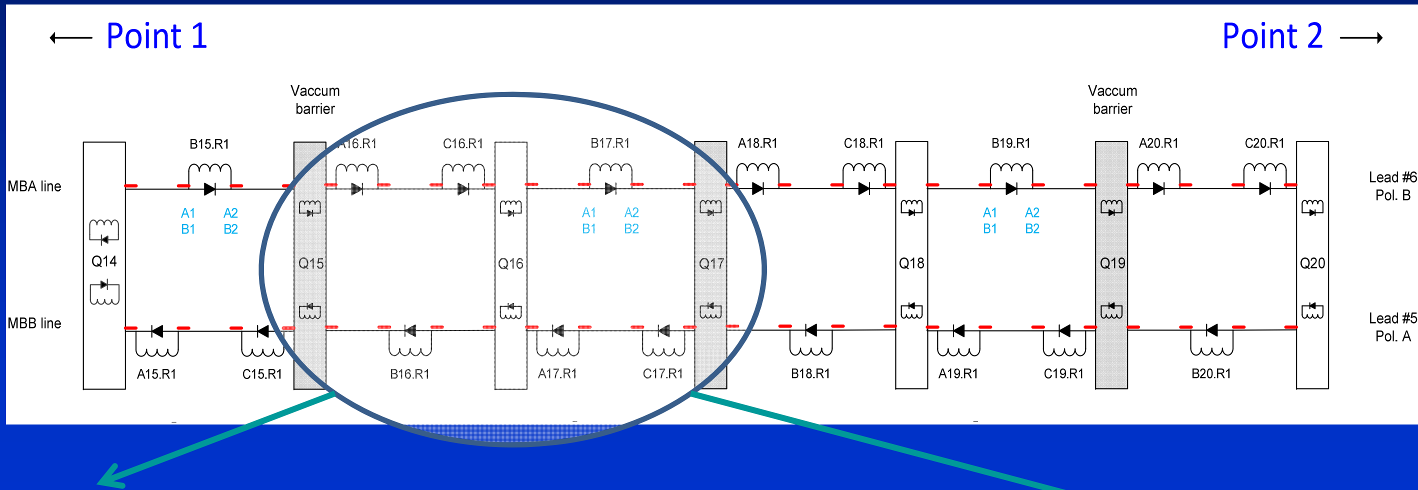
- Controlled tests made late October at different currents
  - Measure temperature increase at XkA — mK/h
  - Derive rate of energy deposition — J/s = W
  - Fit Energy deposition vs current
  - Deduce equivalent resistance — nΩ

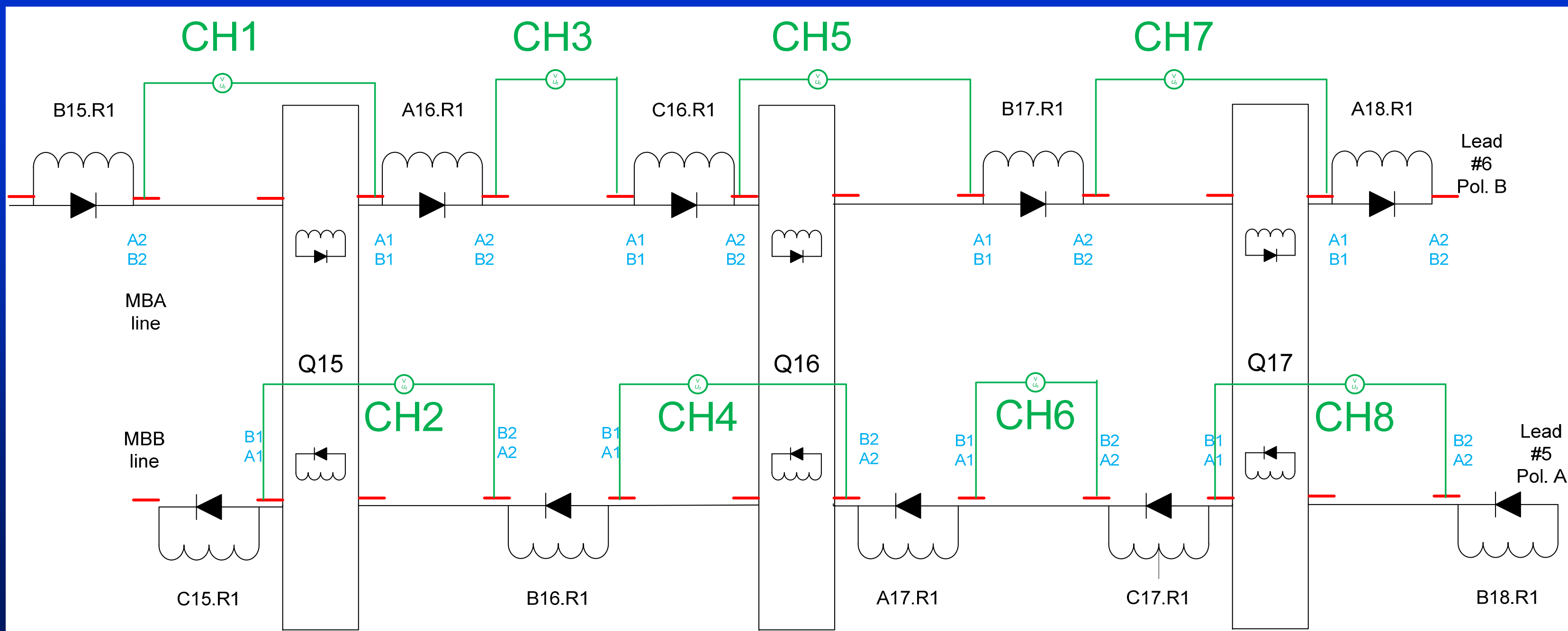


Nominal dissipation
13W
OK for cryogenic system

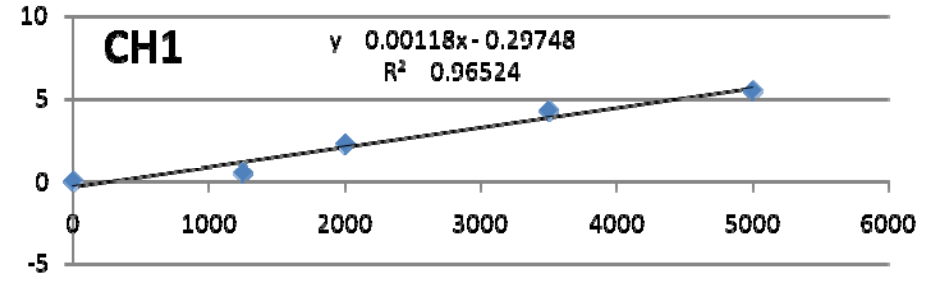
Corresponding electrical resistance
90 nΩ

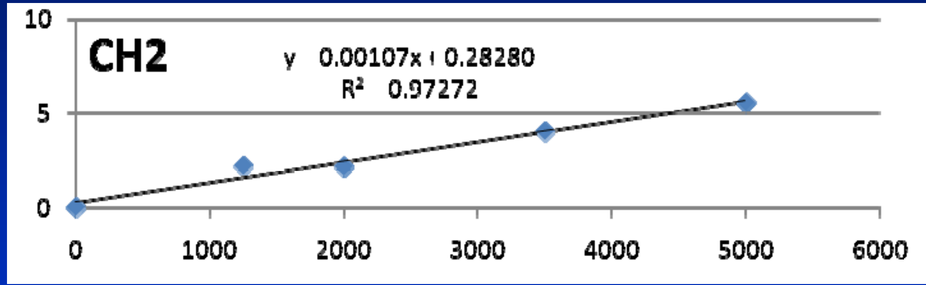
Electrical measurements – splices

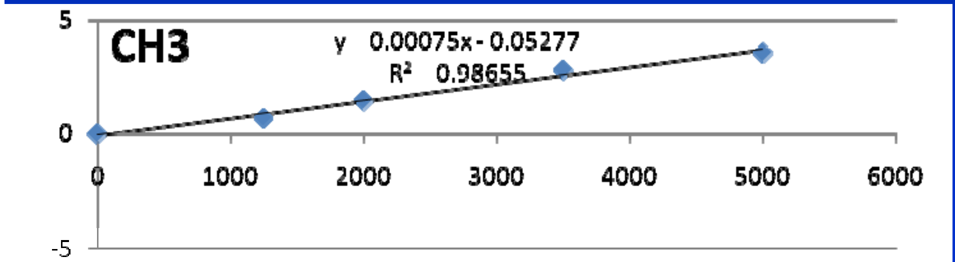


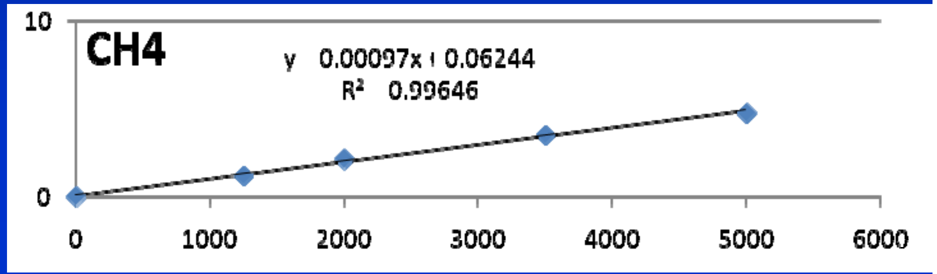


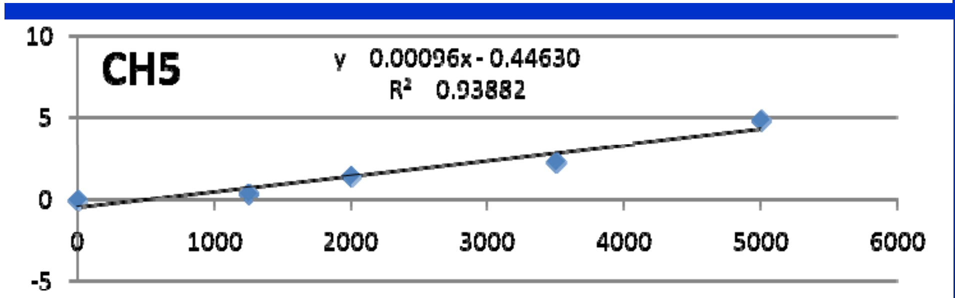
Electrical measurements – splices – data

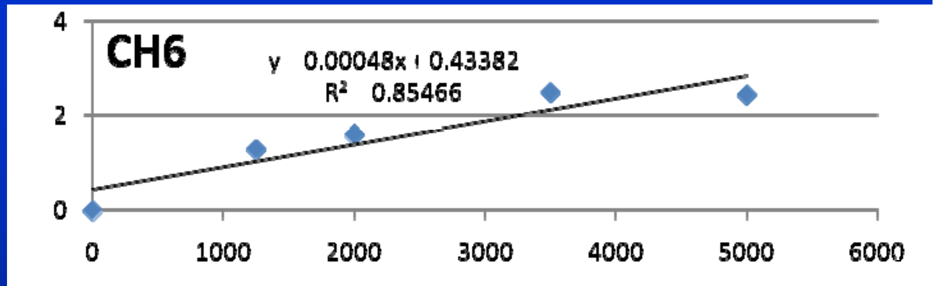


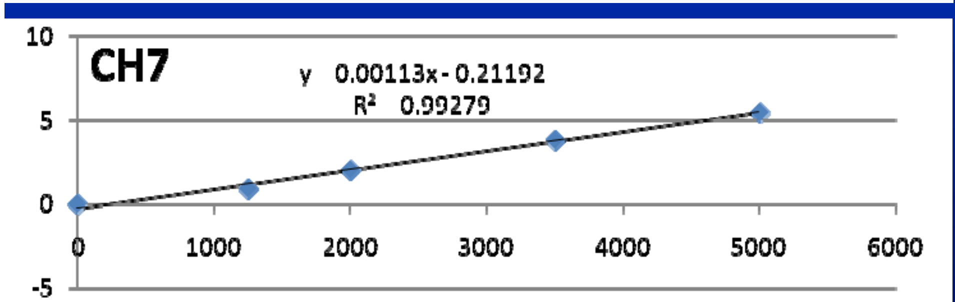


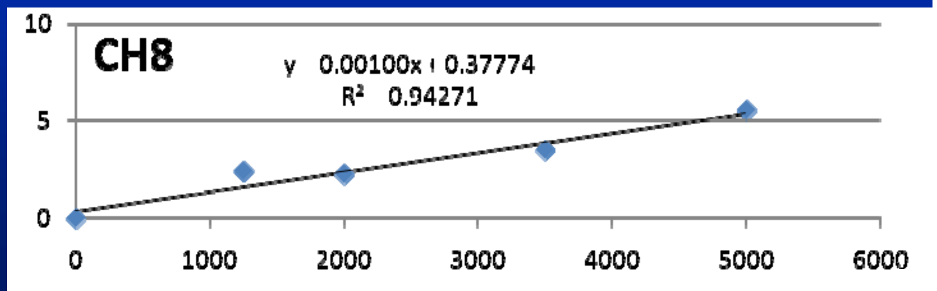












Electrical measurements – splices – all perfect!

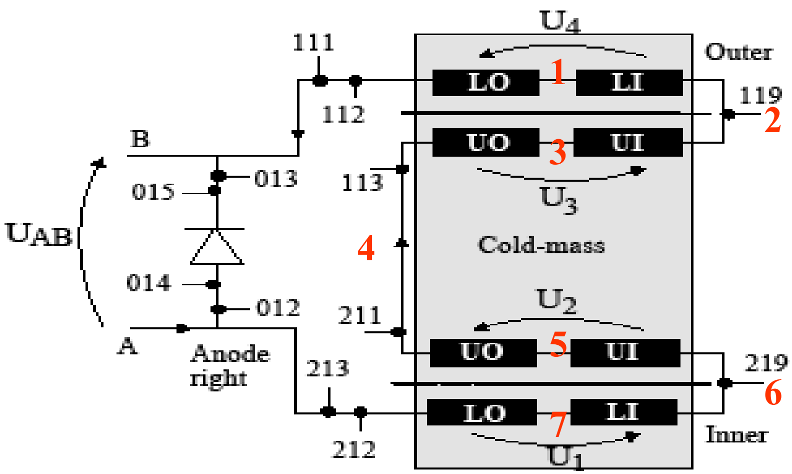
Electric half-cells 15&16

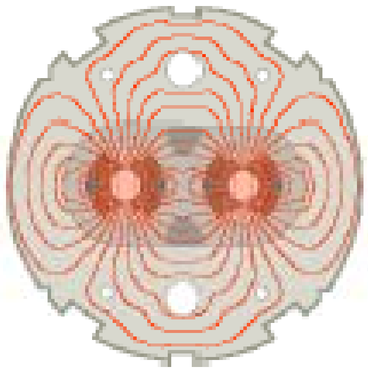
Channel	Resistance	No of splices	R/Splice
CH1	1.18	3	0.39
CH2	1.07	3	0.36
CH3	0.75	2	0.38
CH4	0.97	3	0.32
CH5	0.96	3	0.32
CH6	0.48	2	0.24
CH7	1.13	3	0.38
CH8	1	3	0.33
		Average	0.34 nΩ
		StDev	0.05

Electric half-cells 17&18 (including 7000A run)

Channel	Resistance	No of splices	R/Splice
CH11	1.069	3	0.36
CH12	1.14	3	0.38
CH13	0.694	2	0.35
CH14	0.81	3	0.27
CH15	0.99	3	0.33
CH16	0.75	2	0.38
CH17	1.175	3	0.39
CH18	0.98	3	0.33
		Average	0.35 nΩ
		StDev	0.04

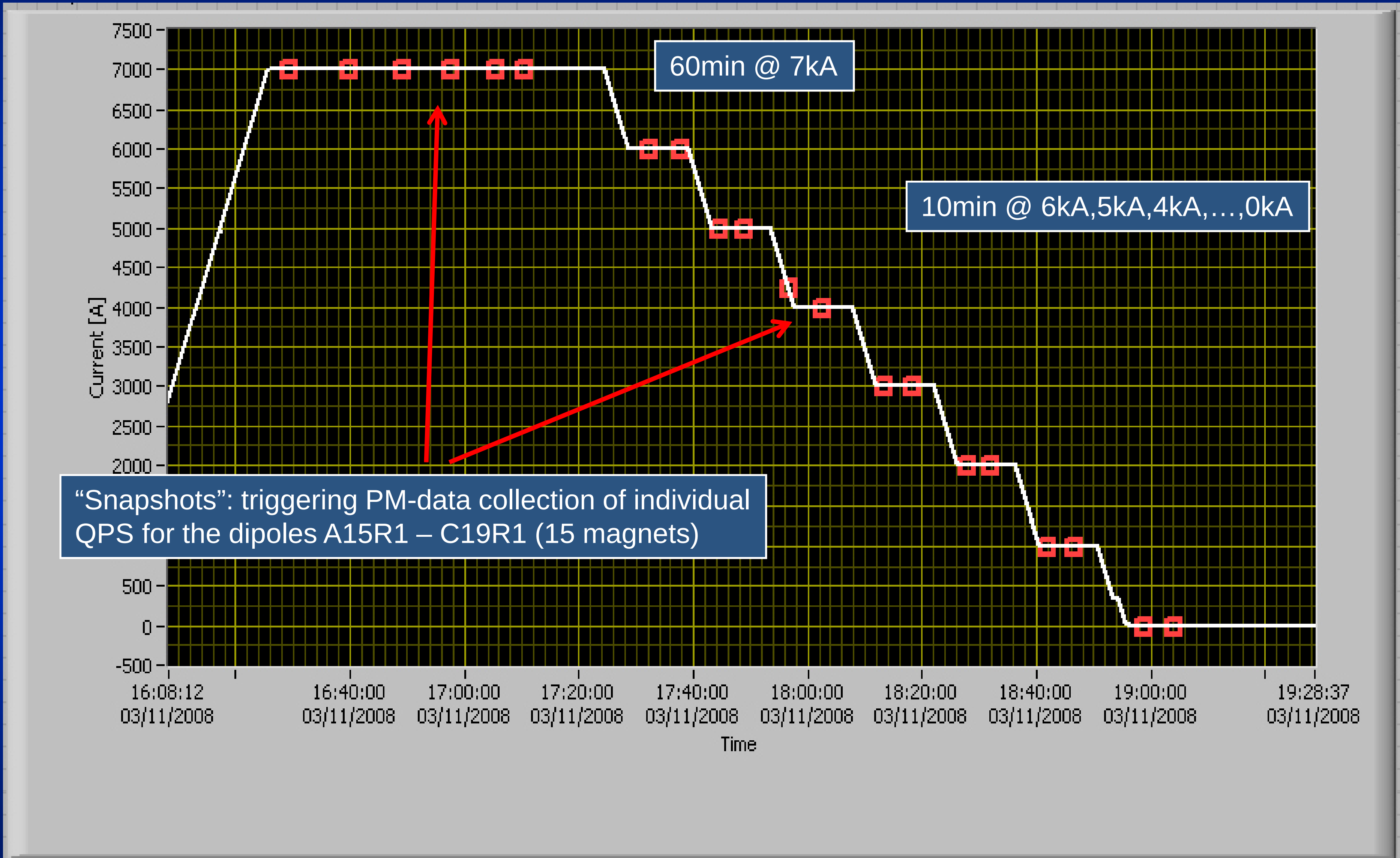
Electrical measurements – dipoles – voltage taps





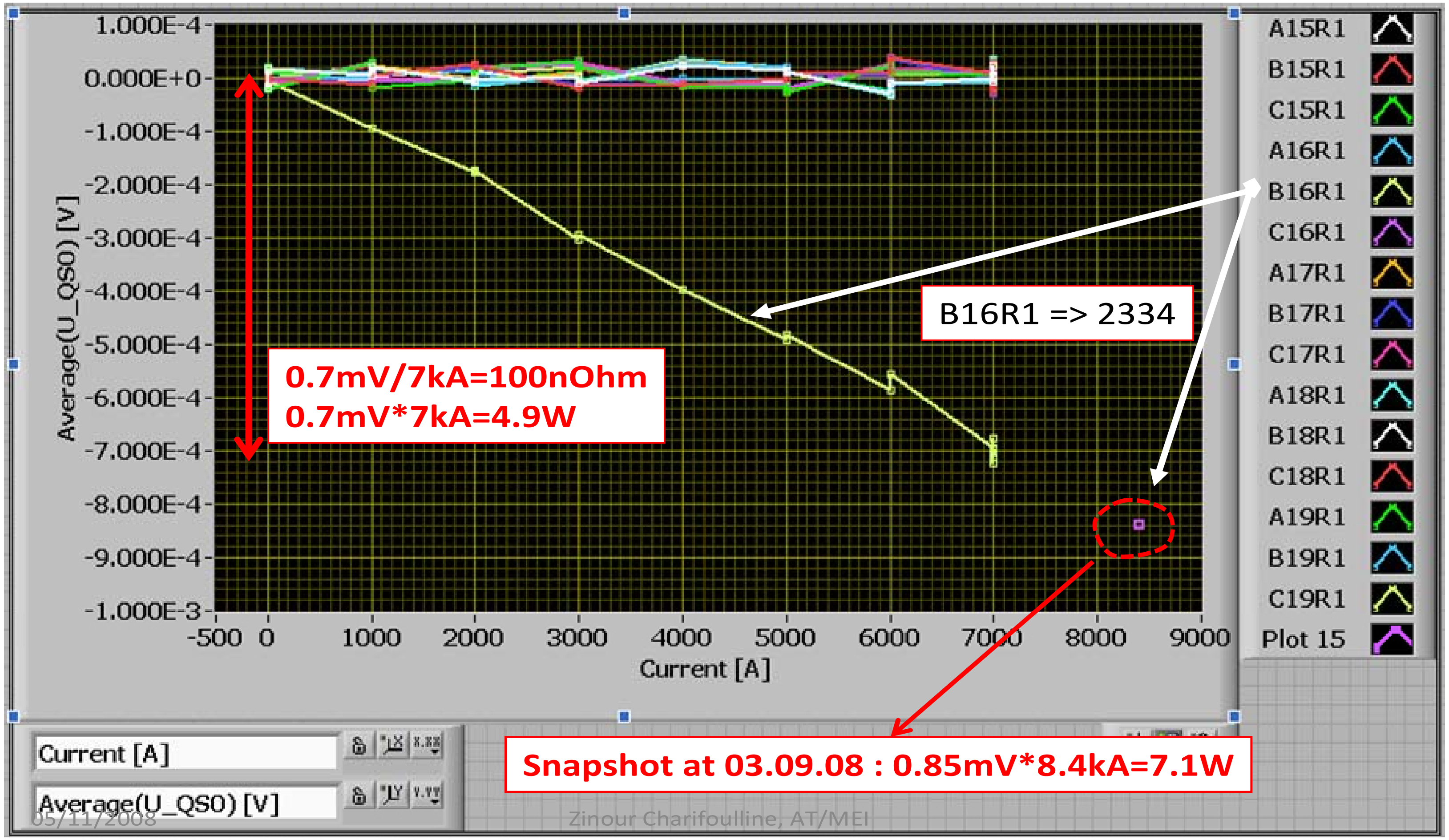
DQLPU Main Dipole Quench Detector
Board A: 112 – 211 and 211 – 213
Board B: 111 – 113 and 113 – 212
U_QS0 is the difference between the two aperture voltages
By the polarity of U_QS0 of the two boards we know
-if the higher resistance is located in outer or inner aperture
-if the higher resistance is located in the interconnect between the two apertures.

Electrical measurements – dipoles – data

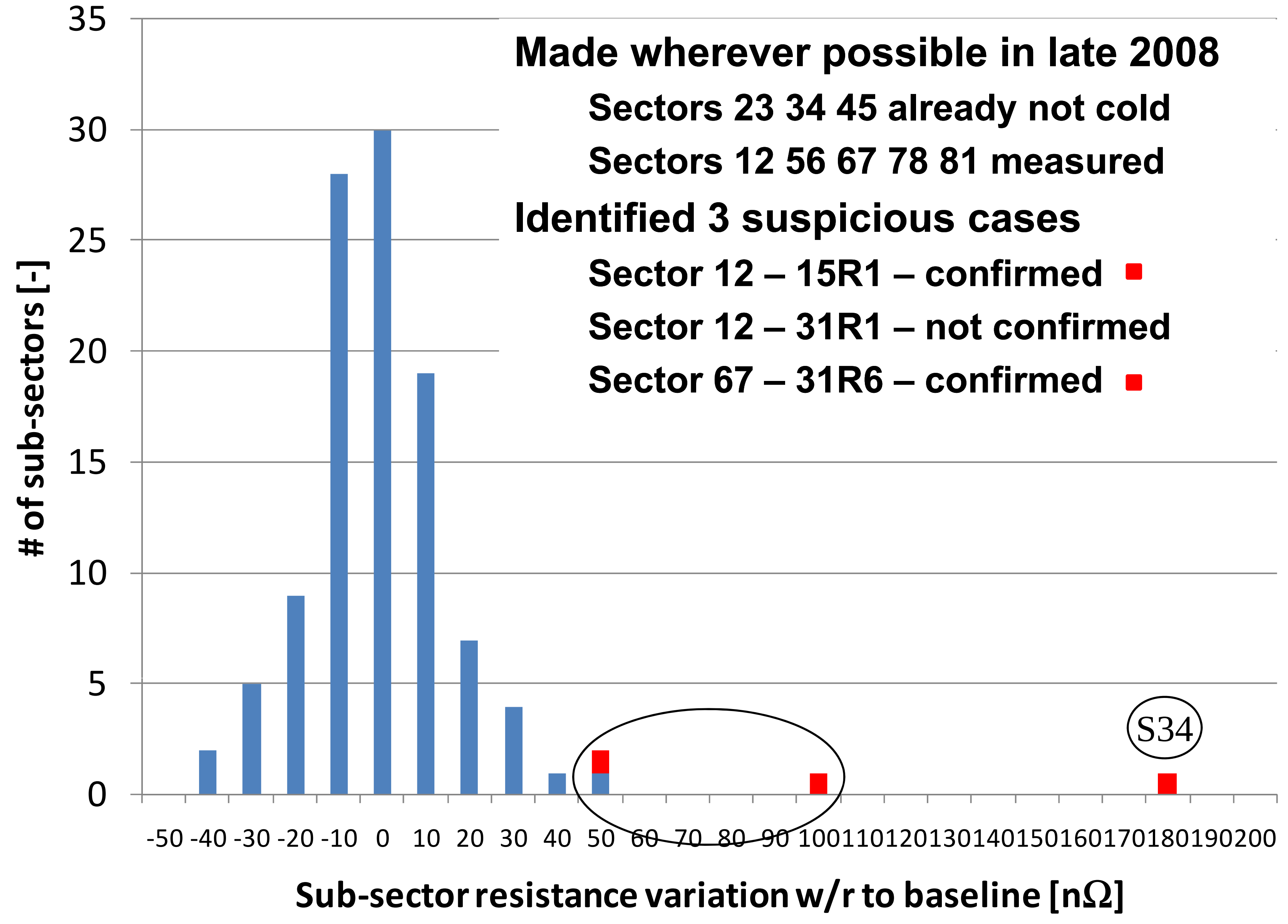


Electrical measurements – dipoles – found it!

Sector A12: A15R1 – C19R1: Dipole Measurements made on 03.11.08

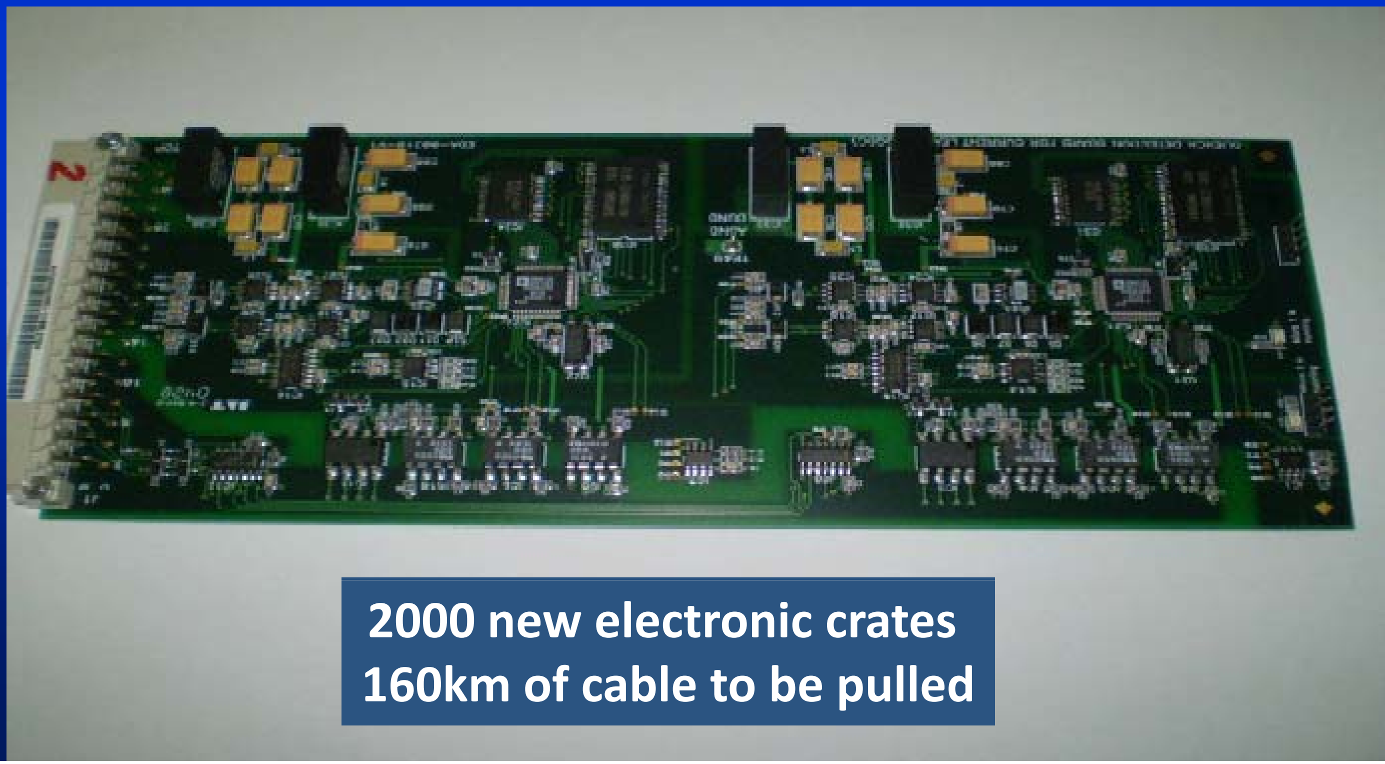


Calorimetric and electrical measurements



Protection against future incidents

- **These electrical methods have been prototyped and will be further improved before being installed machine-wide and applied as <u>dedicated procedures</u> during the machine commissioning**



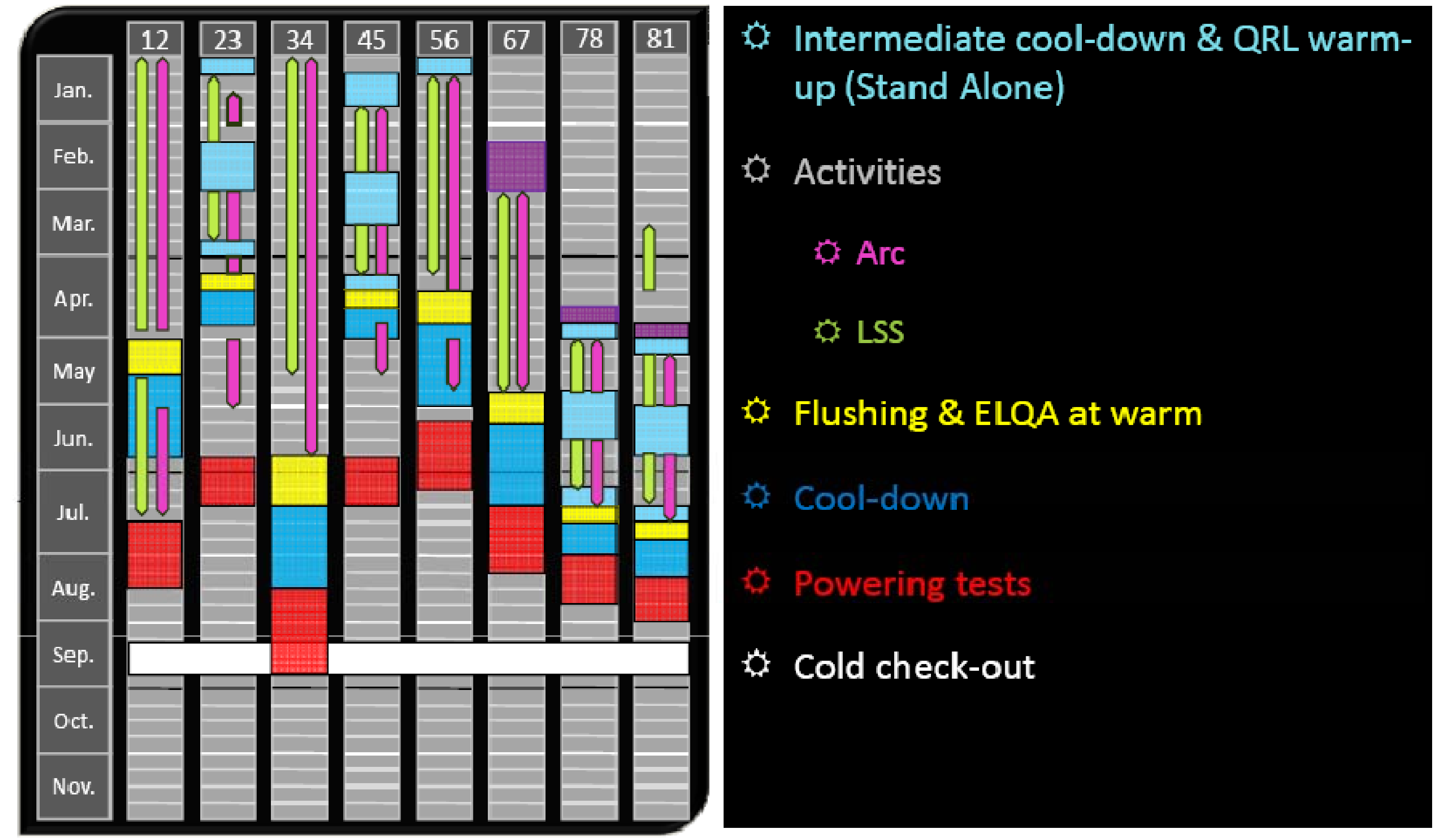
2000 new electronic crates
160km of cable to be pulled

Further measures

- Mitigate the consequences of any event similar to that in sector 34 by increasing the helium gas release capability
- Studies have been made to protect against Maximum Credible Incident
- Needs to increase helium release capability by Factor 20
- All quadrupole cryostats have spare flanges
  - Equip them with new full-flow release valves
  - Gives Factor 8 in discharge cross section
  - Can and will be done *in situ* at cold
- Addition of full-flow release valves on EVERY dipole cryostat
  - Brings overall discharge cross section increase to Factor 40
  - Necessitates cutting 20cm diameter holes in the cryostat
  - Can only be done at warm

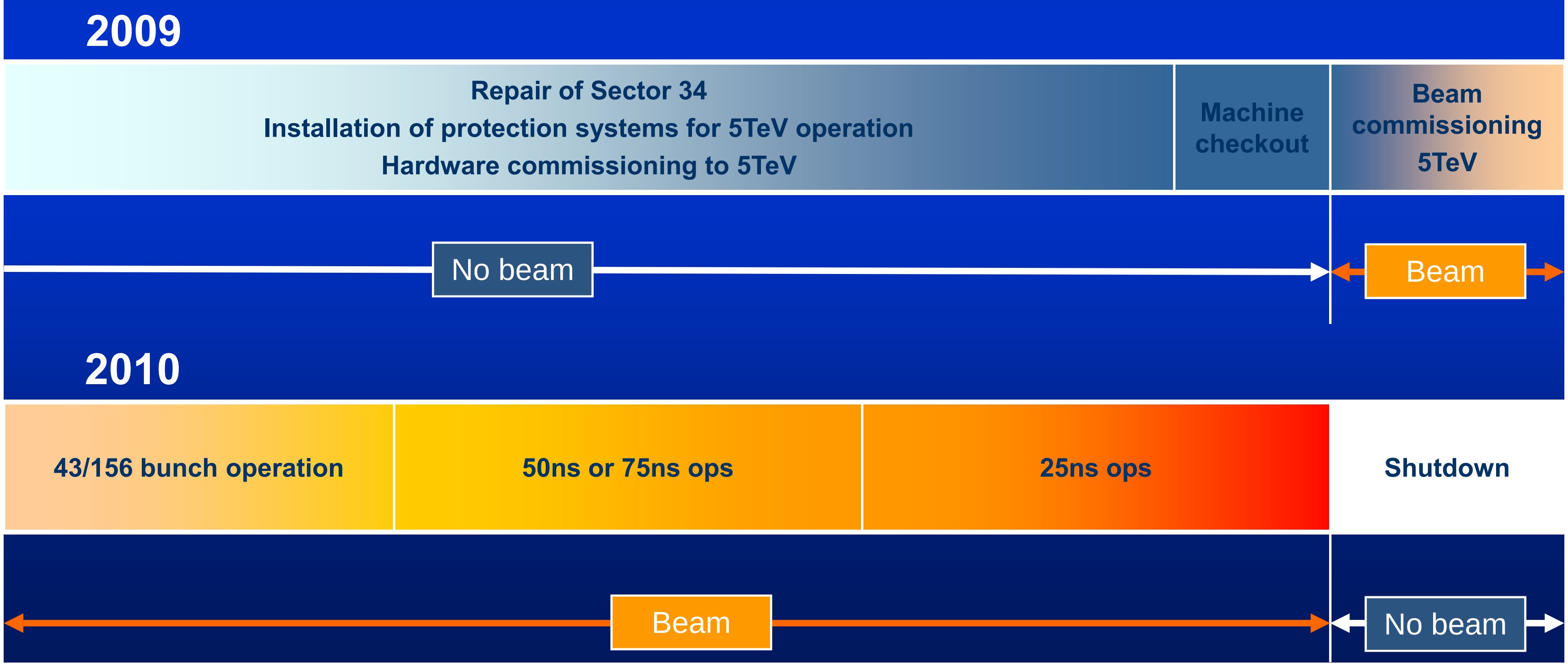
Restart

- Repair of Sector 34 and commissioning to 5TeV
- Installation of protection systems necessary for this
- Beam commissioning starts in late summer 2009



Geneva, 6 February 2009

At the conclusion of a workshop held in Chamonix this week, recommendations have been made to the CERN management for the restart schedule of the Large Hadron Collider (LHC). If accepted in a management meeting on Monday, these recommendations will ensure that the LHC starts to produce physics data in late 2009, running through the winter and on to autumn 2010 at an energy of 5 TeV per beam and ensuring sufficient data for the experiments to produce their first new physics results.



43/156 bunch operation

$$L = \frac{N^2 k_b f \gamma}{4\pi\varepsilon_n \beta^*} F$$

$$Eventrate / Cross = \frac{L\sigma_{TOT}}{k_b f}$$

Optimum parameters studied for early running (aperture)

4 10^{11} per bunch at nominal emittance

Rates in 1 and 5 shown

Rates in 2 and 8 can be optimised to meet ALICE and LHCb requirements

Energy (TeV)	β^* (m)	$\mathcal{L}_{43}$ ($cm^{-2}s^{-1}$)	$\mathcal{L}_{156}$ ($cm^{-2}s^{-1}$)
0.45	6	$0.13 \cdot 10^{30}$	$0.47 \cdot 10^{30}$
2.75	1	$4.30 \cdot 10^{30}$	$15.6 \cdot 10^{30}$
5.00	0.6	$13.0 \cdot 10^{30}$	$47.0 \cdot 10^{30}$

Multibunch operation

$$L = \frac{N^2 k_b f \gamma}{4\pi \varepsilon_n \beta^*} F$$

$$Eventrate / Cross = \frac{L \sigma_{TOT}}{k_b f}$$

Crossing angle the new parameter that comes into the game

5 10^{11} per bunch at nominal emittance

Rates in 1 and 5 shown (x 10^{32})

Rates in 2 and 8 can be optimised to meet ALICE and LHCb requirements

Energy (TeV)	β^* (m)	$\mathcal{L}_{936}$ ($cm^{-2}s^{-1}$)	$\mathcal{L}_{1404}$ ($cm^{-2}s^{-1}$)	$\mathcal{L}_{2808}$ ($cm^{-2}s^{-1}$)
5.0	3.0	0.9	1.4	2.8
5.0	2.0	1.4	2.1	4.2
5.0	1.0	2.6	4.0	8.0
7.0	3.0	1.3	2.00	4.0
7.0	2.0	2.0	3.00	6.0
7.0	1.0	4.0	6.00	12.0

(10^6 seconds @ <L> of 10^{33} cm^{-2} s^{-1} → 1 fb^{-1})