Status of the Large Hadron Collider

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CERN, Geneva, Switzerland

All-Russian Particle Physics Community Meeting
IHEP Protvino, 22 December 2008

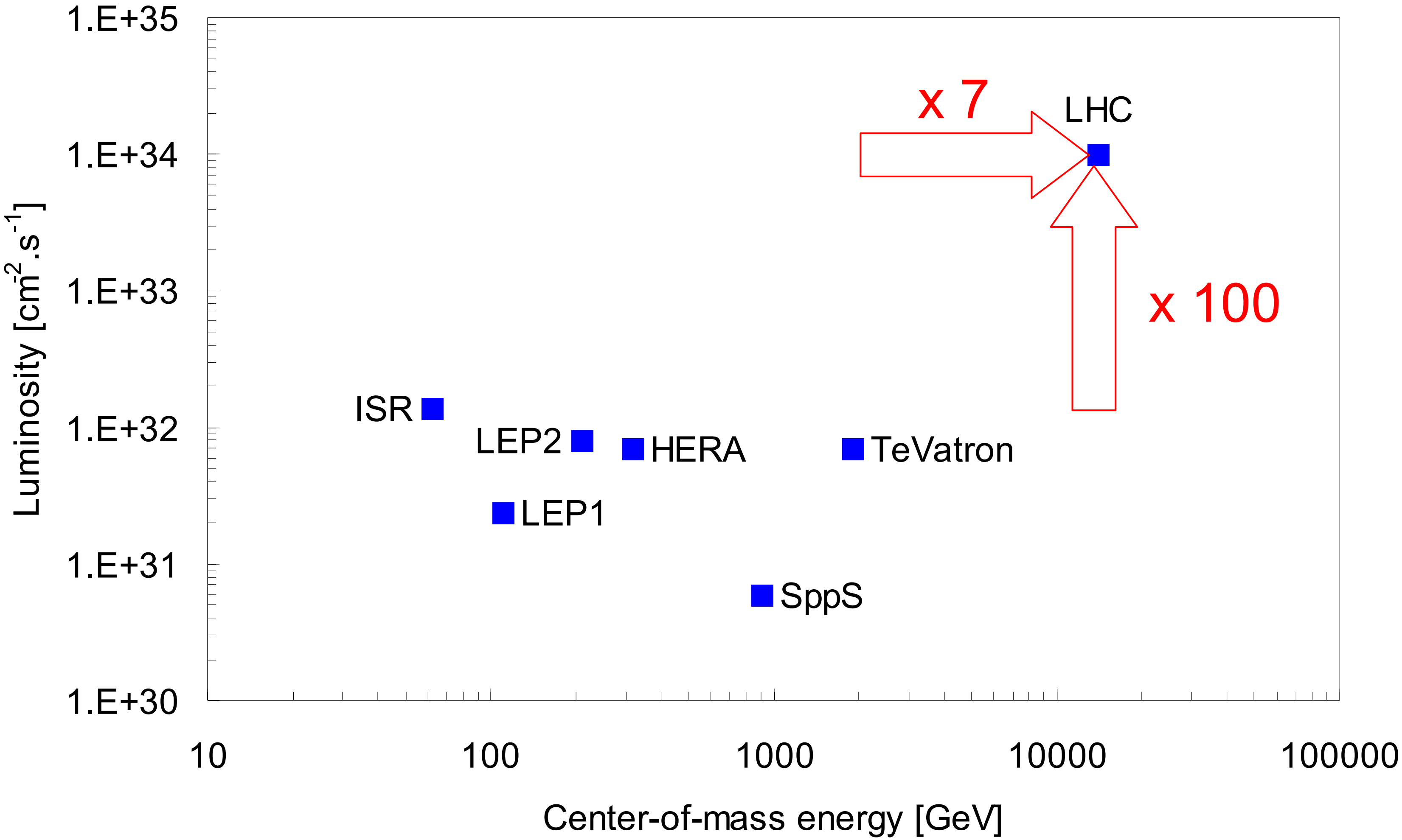
The largest scientific instrument in the world

LHC 2008

Advanced technology at work

23 km of superconducting magnets cooled in superfluid helium at 1.9 K

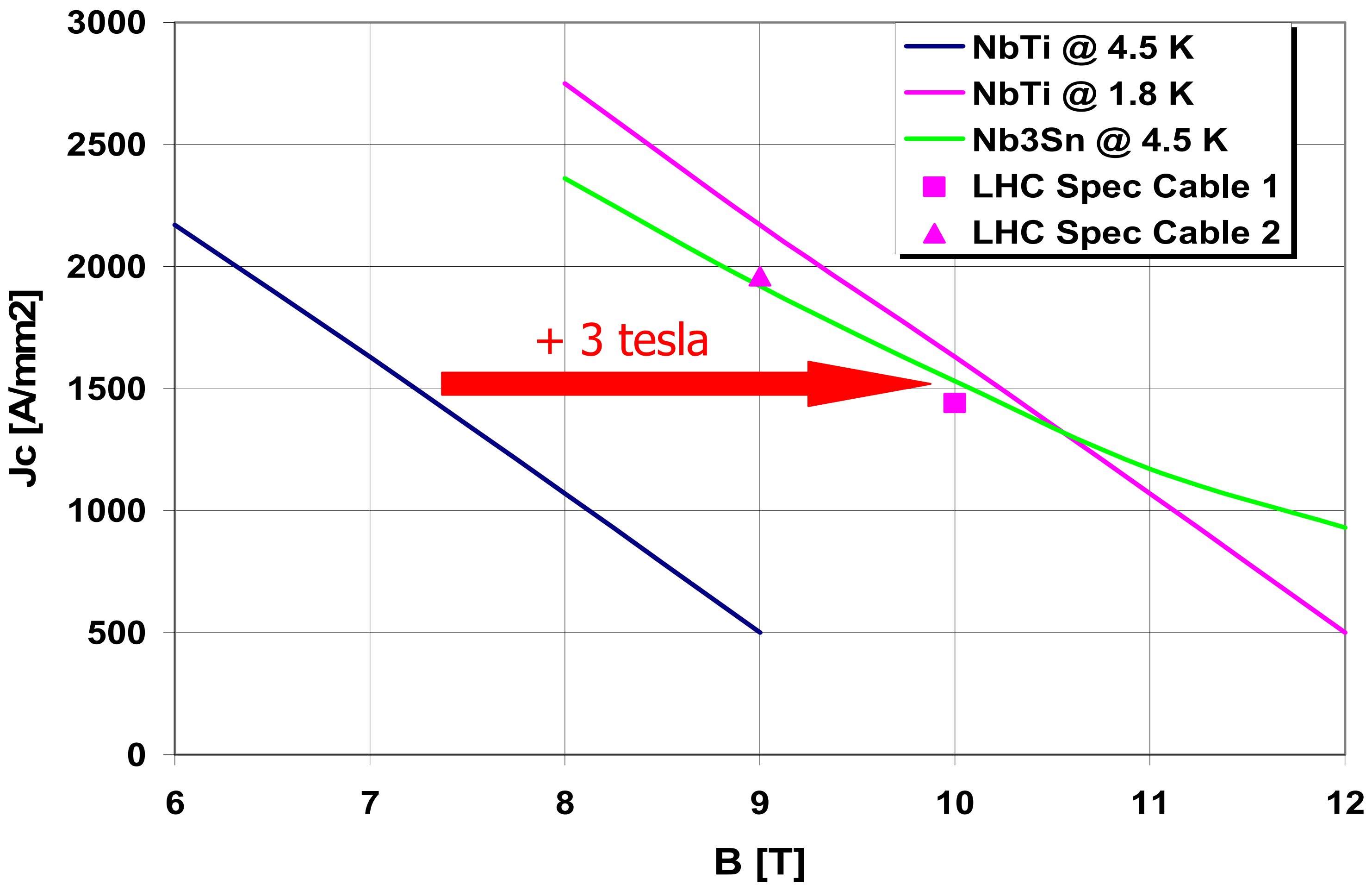
A new territory in energy and luminosity



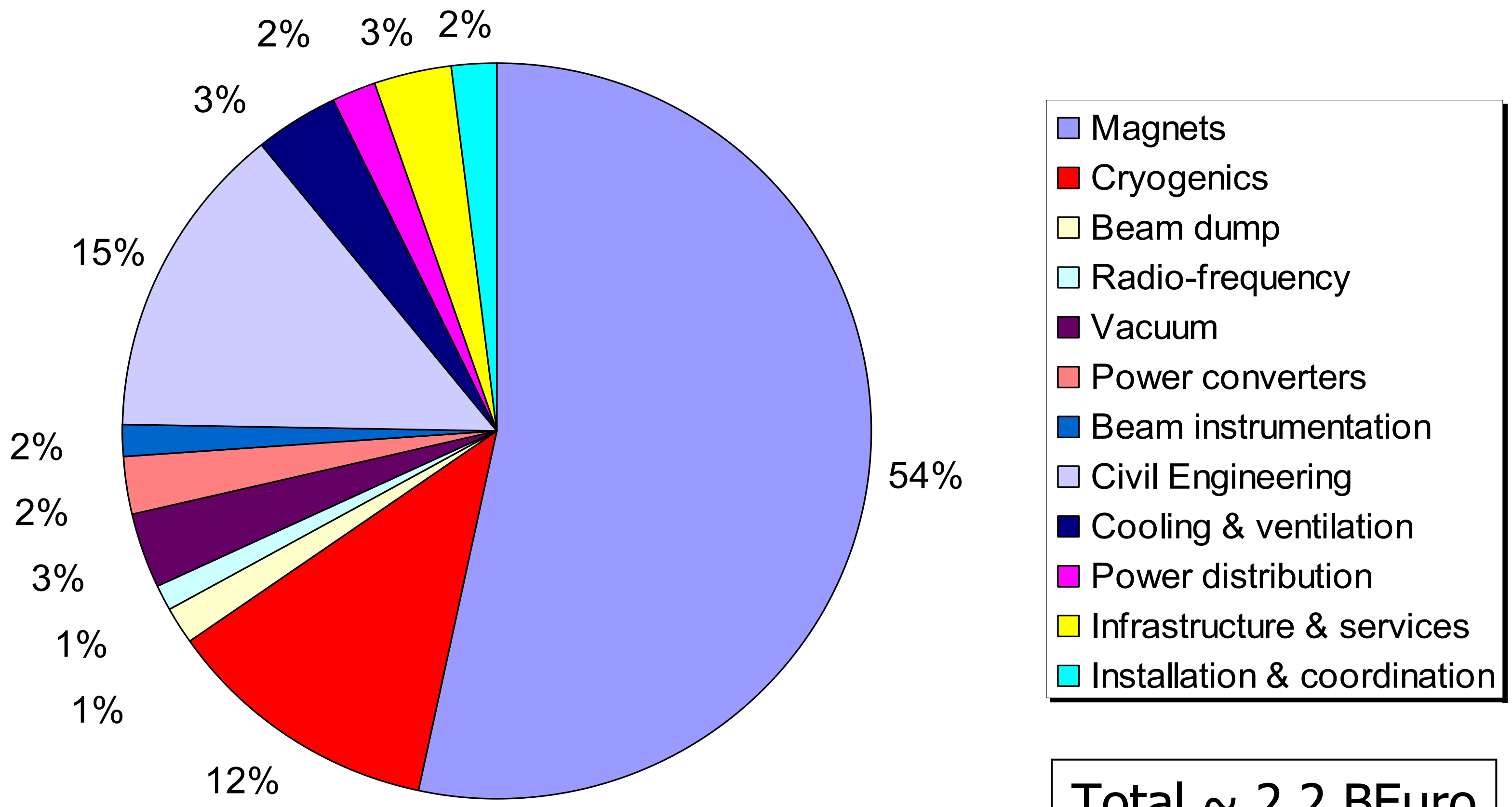
Main parameters of LHC (p-p)

• Circumference	26.7	km
• Beam energy at collision	7	TeV
• Beam energy at injection	0.45	TeV
• Dipole field at 7 TeV	8.33	T
• Luminosity	10^{34}	$cm^{-2}.s^{-1}$
• Beam current	0.56	A
• Protons per bunch	1.1×10^{11}	
• Number of bunches	2808	
• Nominal bunch spacing	24.95	ns
• Normalized emittance	3.75	μm
• Total crossing angle	300	μrad
• Energy loss per turn	6.7	keV
• Critical synchrotron energy	44.1	eV
• Radiated power per beam	3.8	kW
• Stored energy per beam	350	MJ
• Stored energy in magnets	11	GJ
• Operating temperature	1.9	K

Critical current density of technical superconductors



Cost structure of the LHC accelerator



Total ~ 2.2 BEuro

90 main industrial contracts in the world

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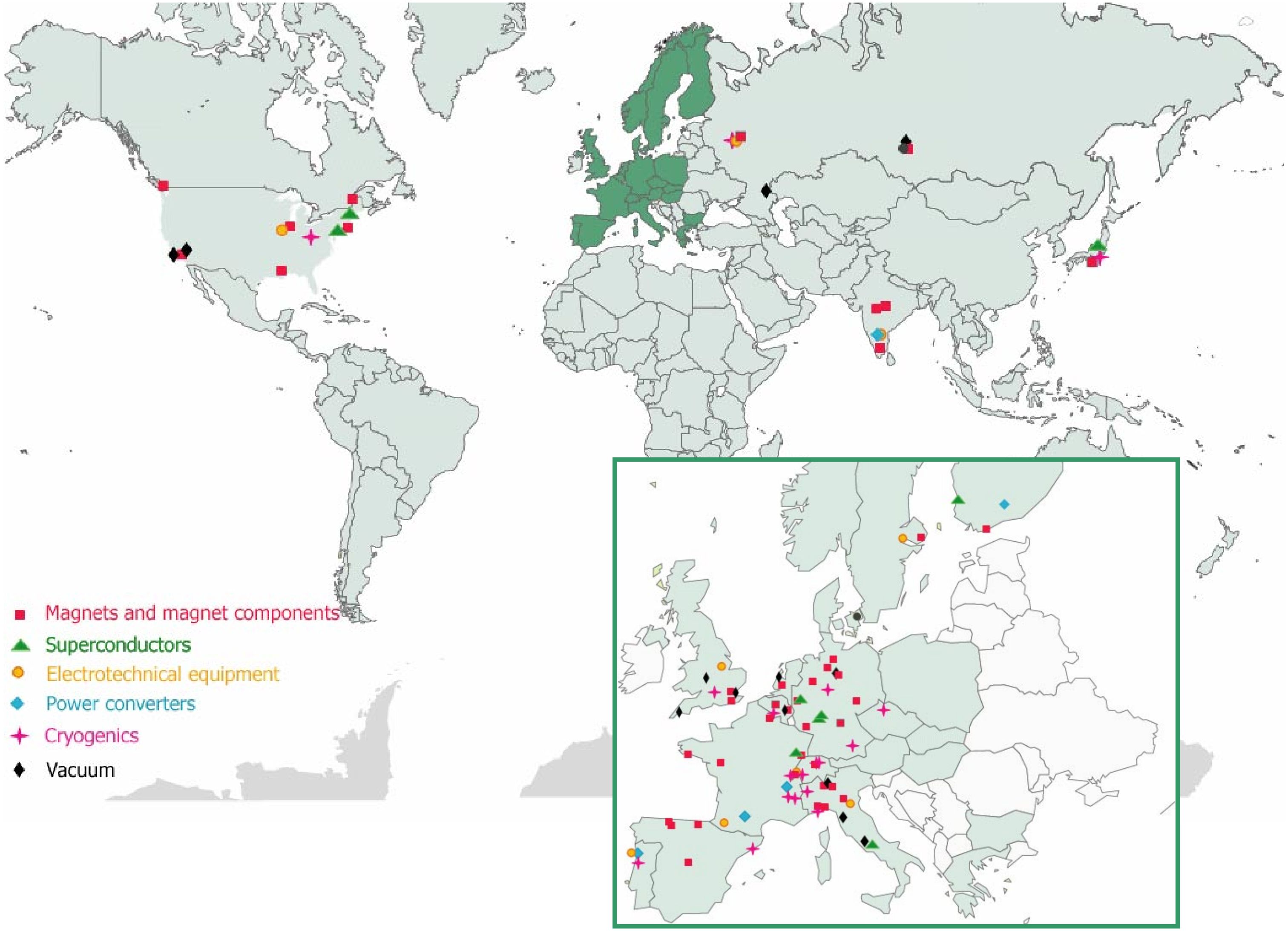

Procurement & installation logistics

Quality & quantity at the right time in the right place

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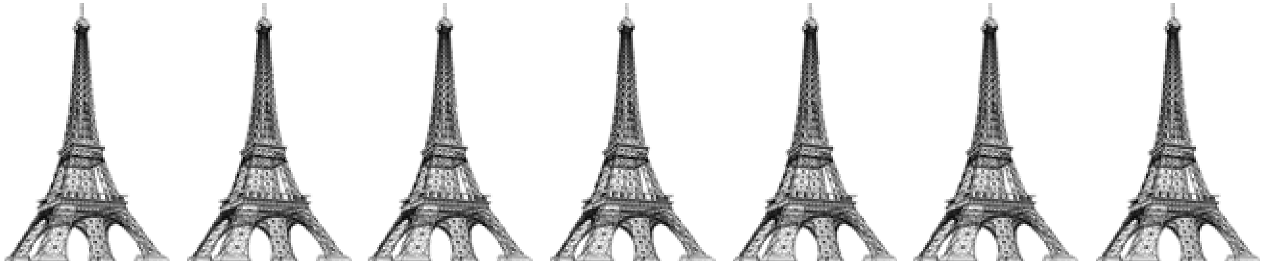
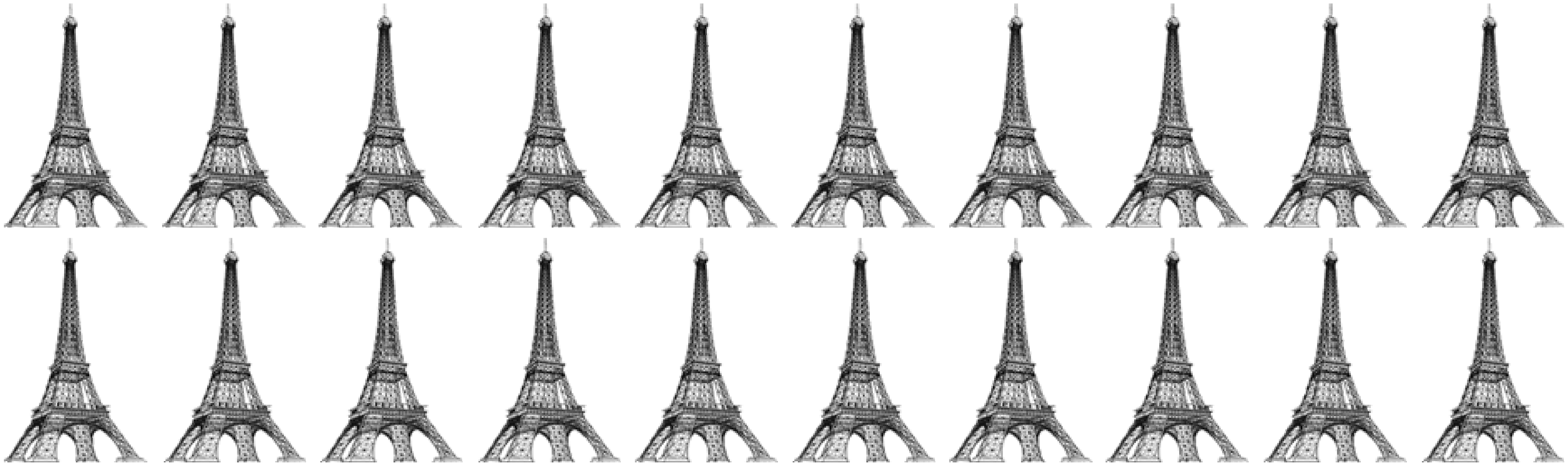
Installed in LHC tunnel: 50 000 t



Transported throughout Europe: ~150 000 t



A global project spanning space…

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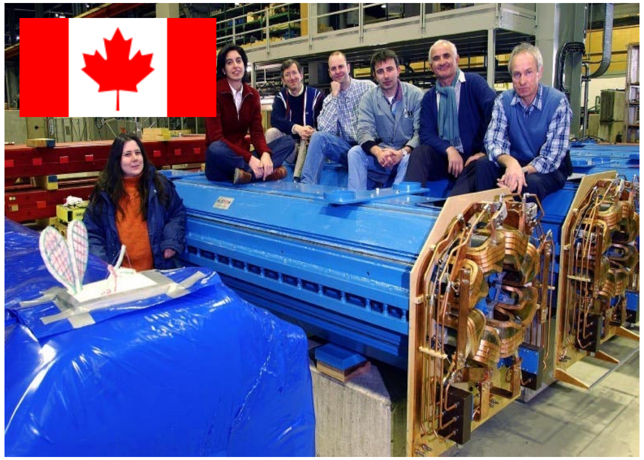
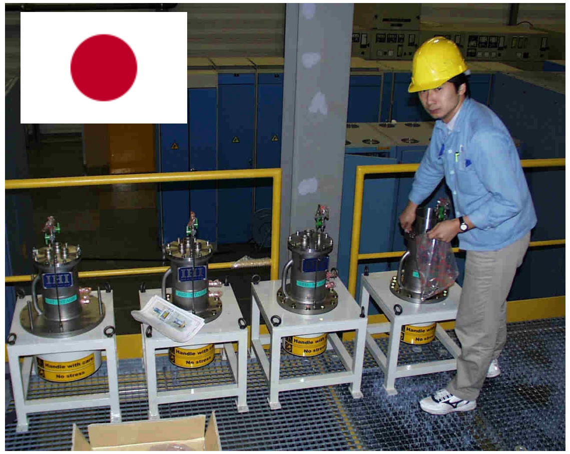
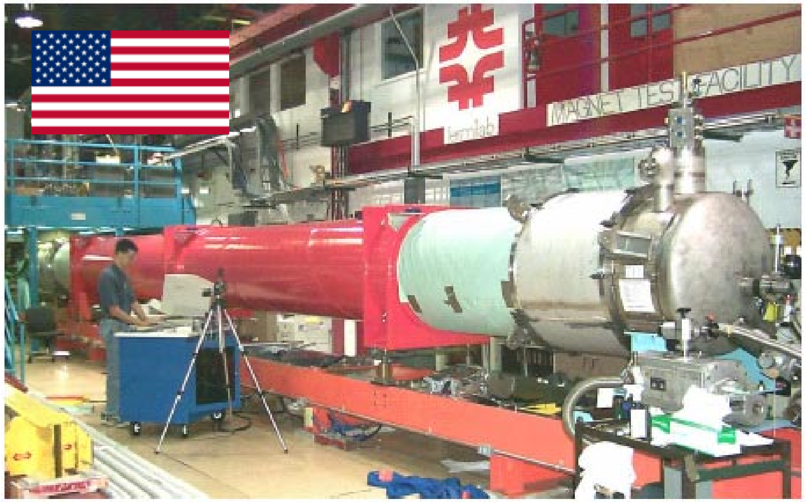
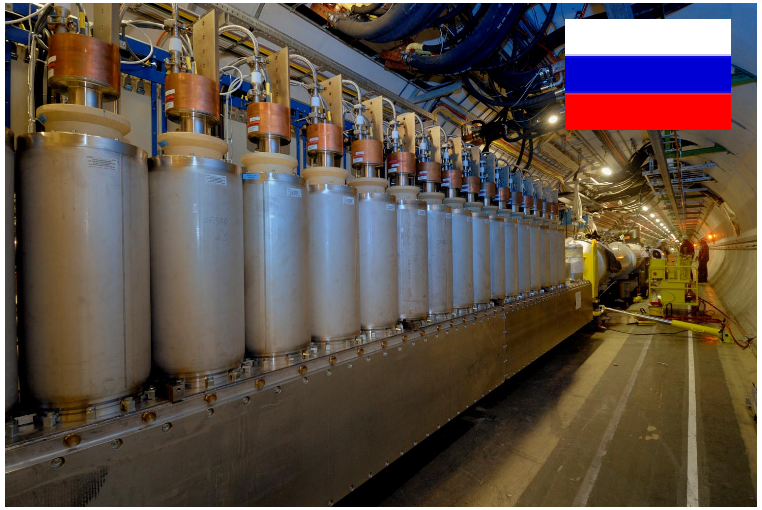


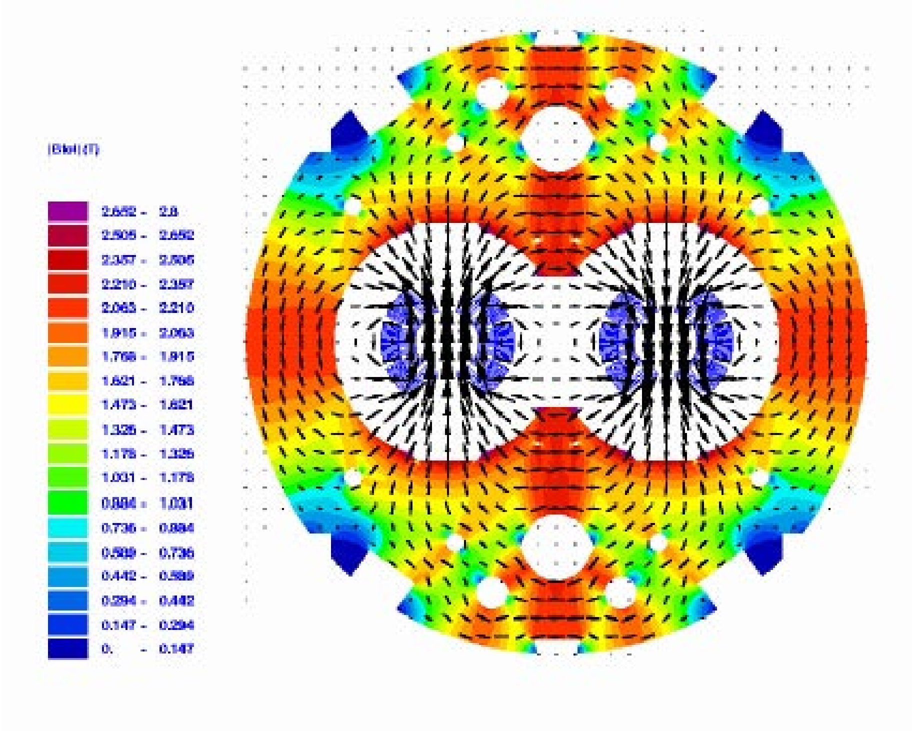



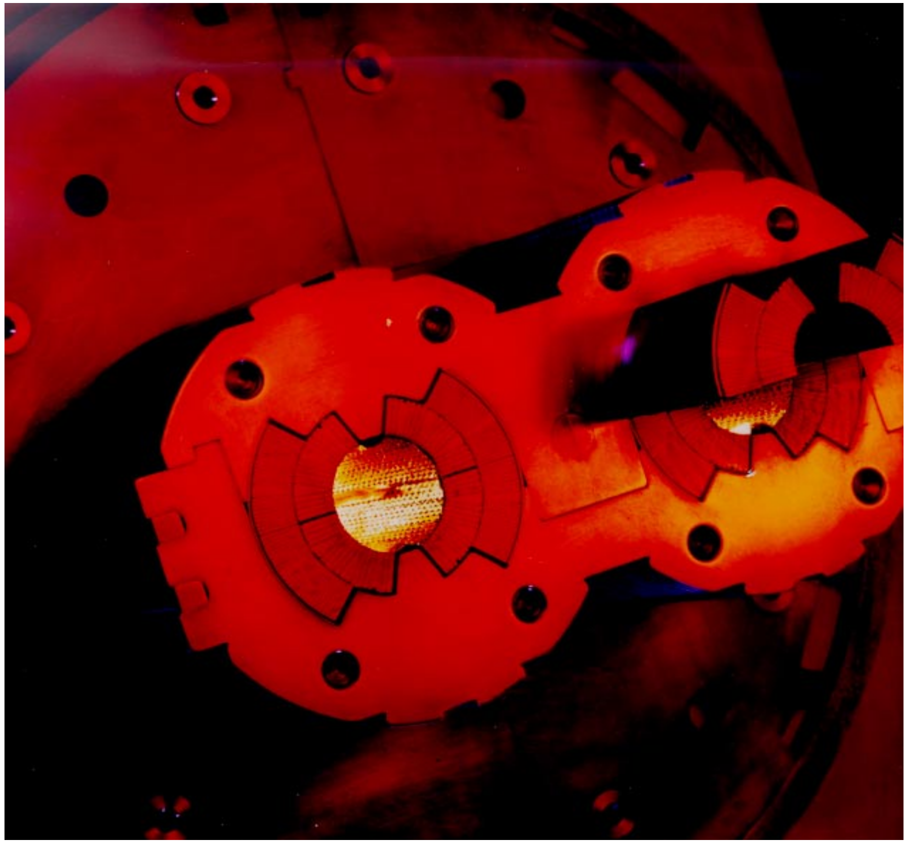


…and time

• Preliminary conceptual studies	1984
• First magnet models	1988
• Start structured R&D program	1990
• Approval by CERN Council	1994
• Industrialization of series production	1996-1999
• DUP & start civil works	1998
• Adjudication of main procurement contracts	1998-2001
• Start installation in tunnel	2003
• Cryomagnet installation in tunnel	2005-2007
• Functional test of first sector	2007
• Commissioning with beam	2008
• Operation for physics	2009-2030

Twin-aperture dipole magnet





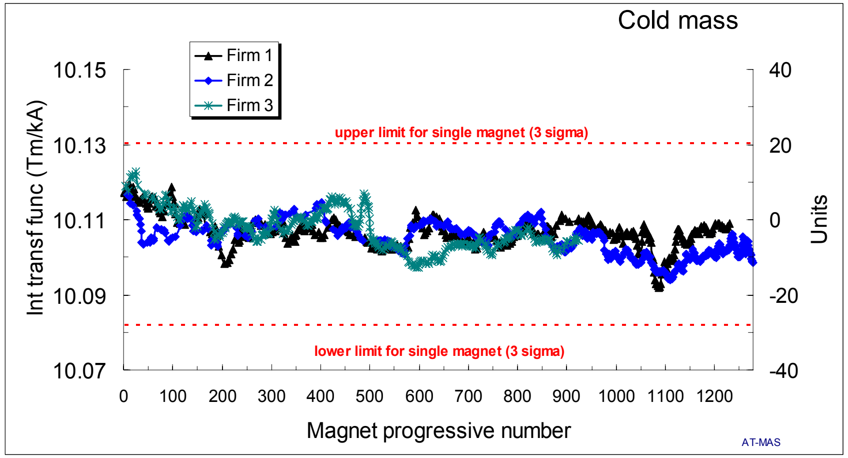
Field reproducibility/precision ~ 10^{-3}

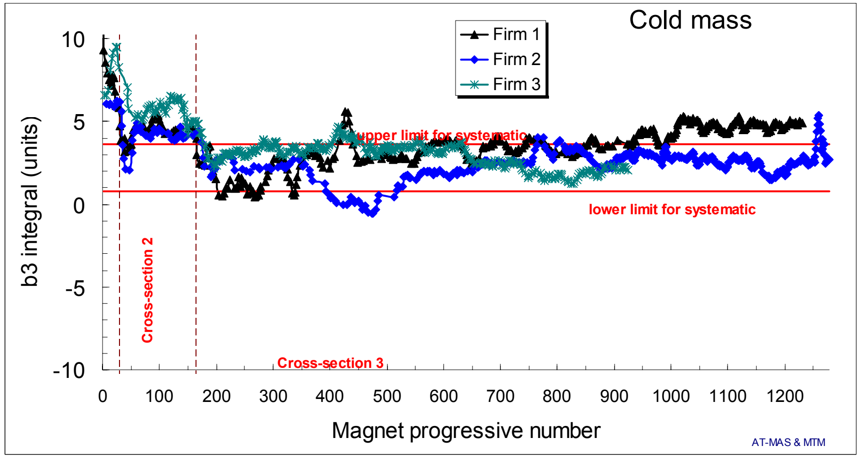
Field homogeneity ~ 10^{-4}

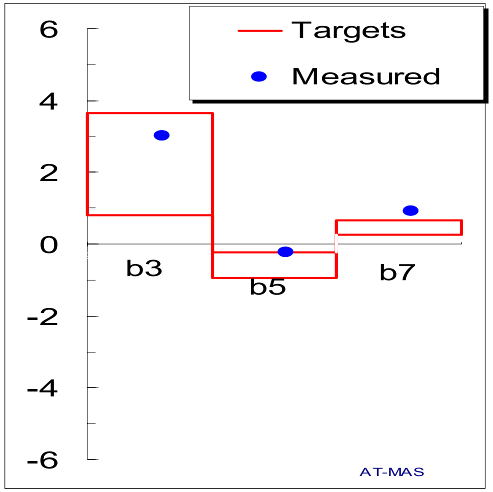
⇒ Winding precision < 0.05 mm

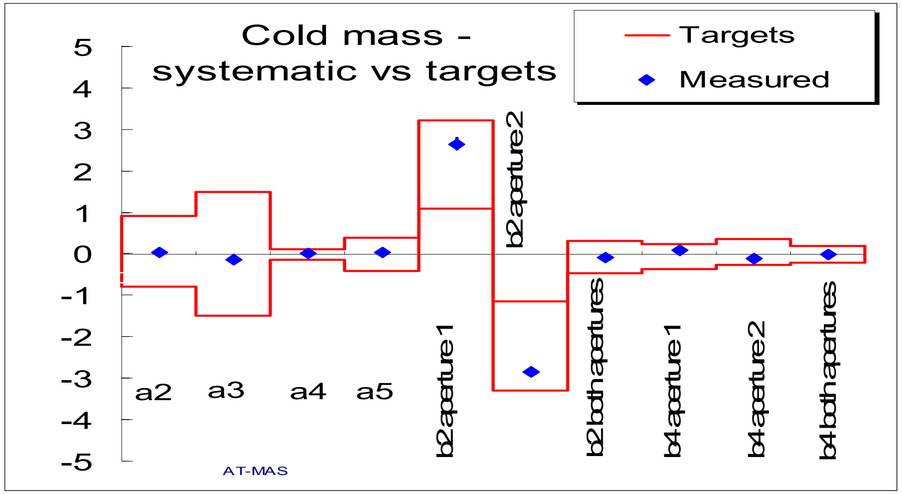
Cryogenic tests of magnets

Dipole field quality in series production

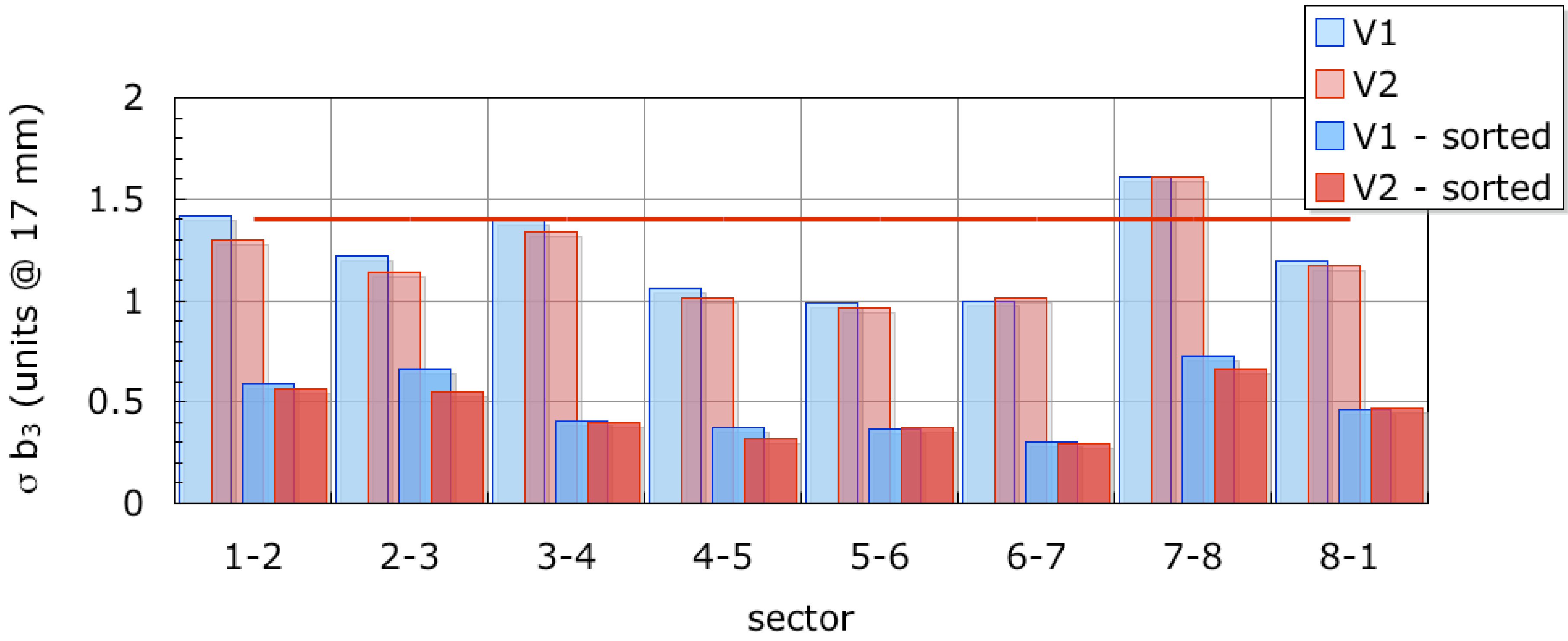




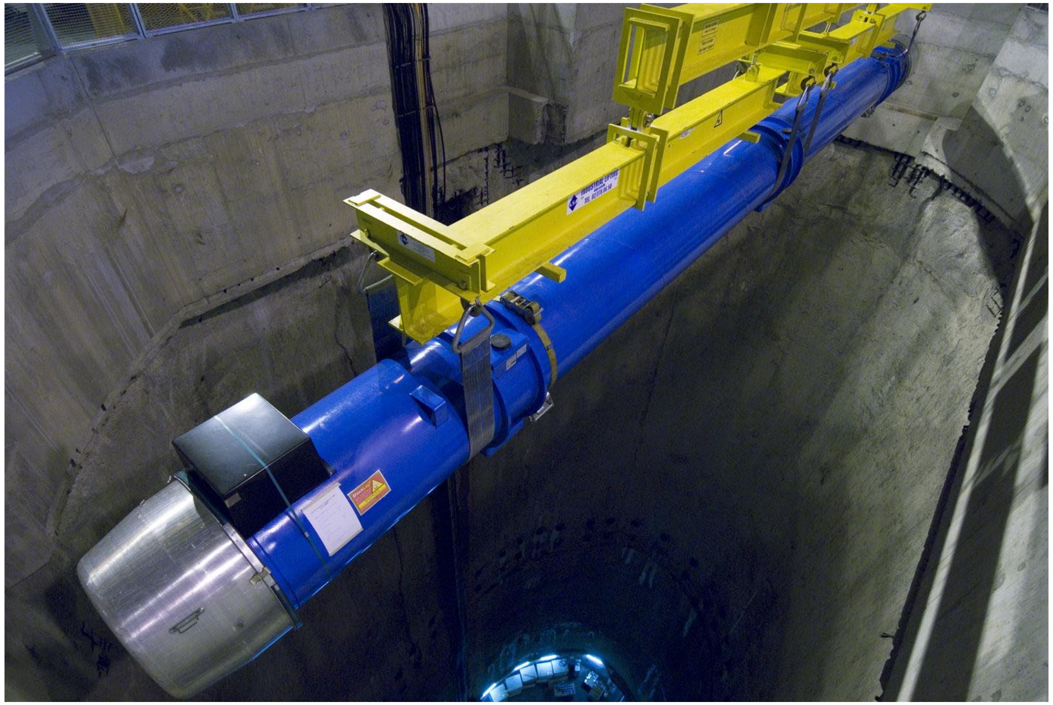




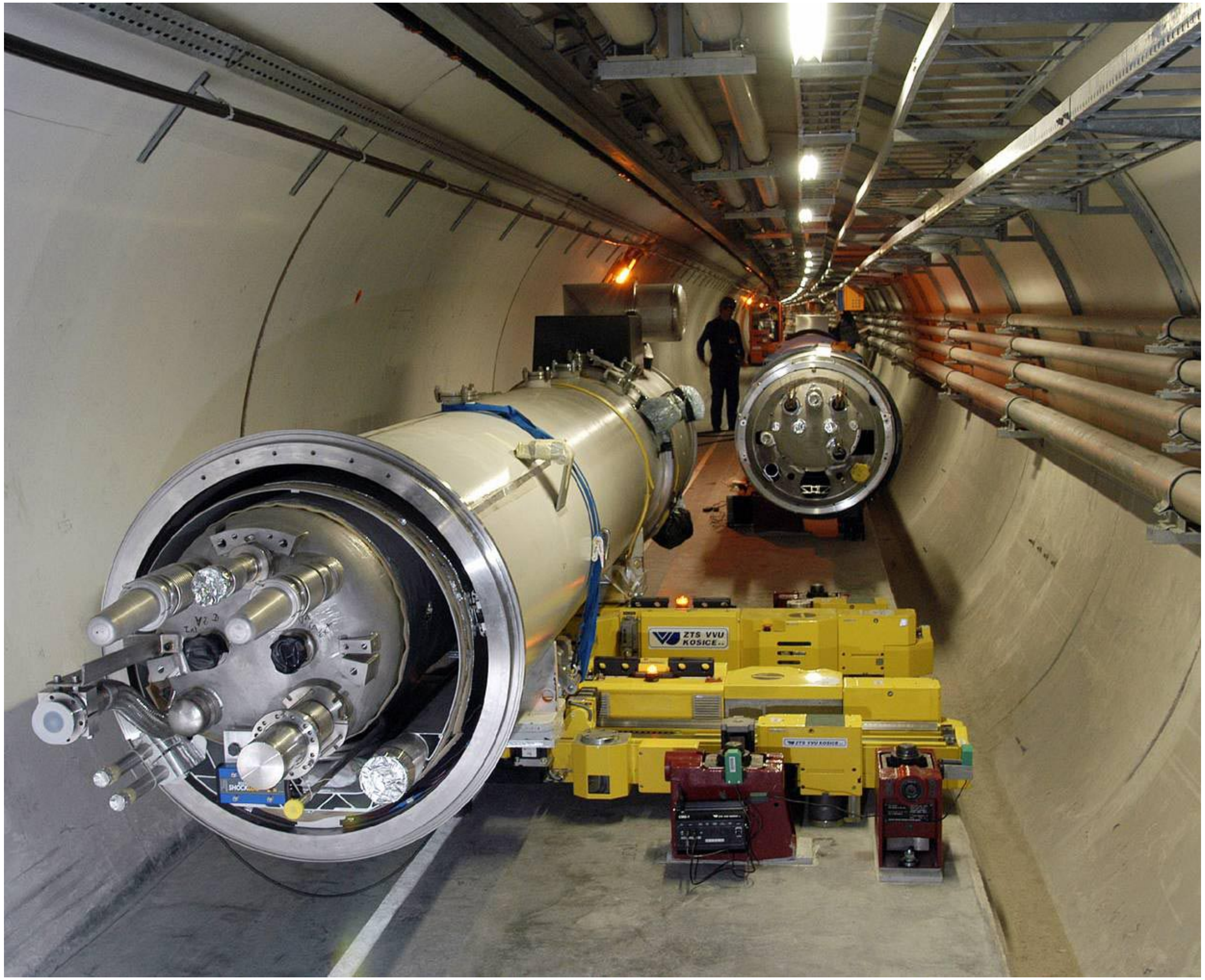
Sorting reduces dispersion



Lowering of magnets in tunnel



Cryomagnet installation in tunnel



Interconnections in tunnel

65'000 electrical joints

Induction-heated soldering

Ultrasonic welding

Very low residual resistance

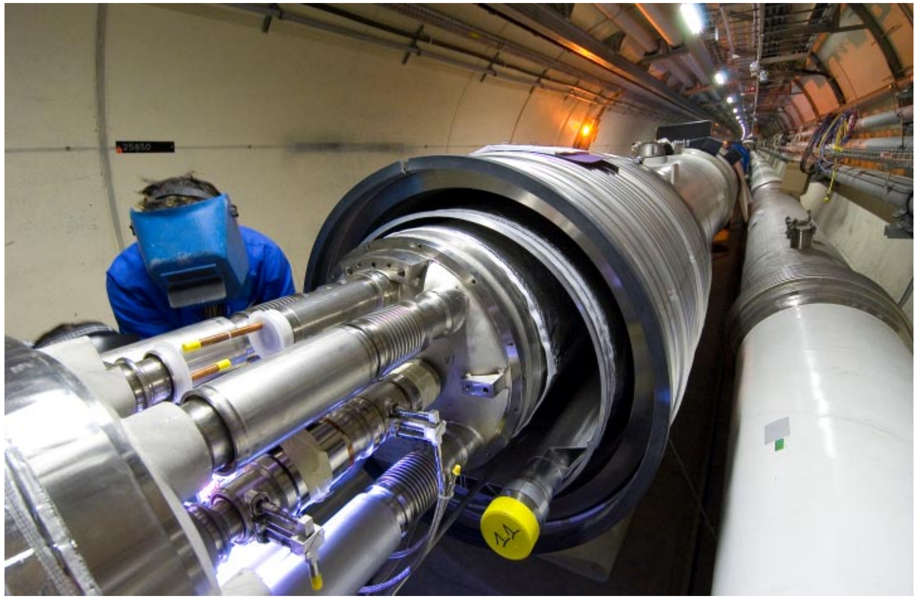
HV electrical insulation

40'000 cryogenic junctions

Orbital TIG welding

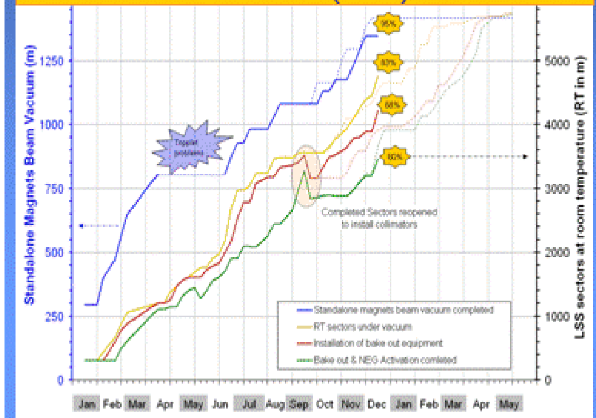
Weld quality

Helium leaktightness



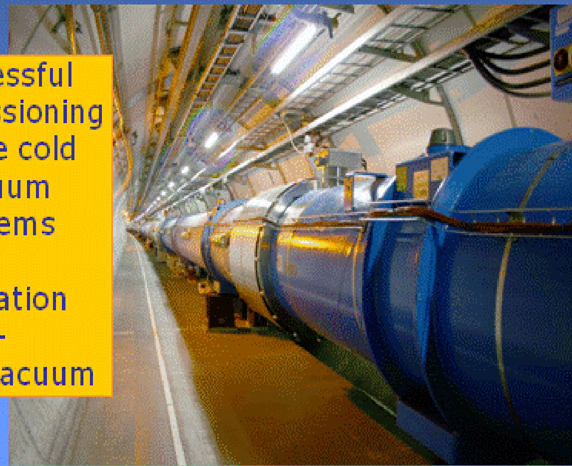
Installation and commissioning of LHC Vacuum systems

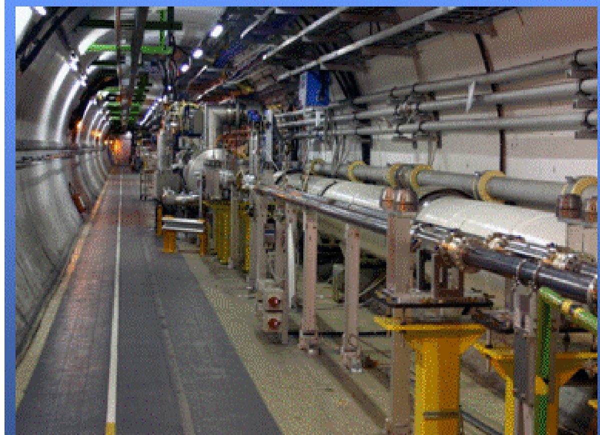
Installation of the Long Straight Sections (LSS)



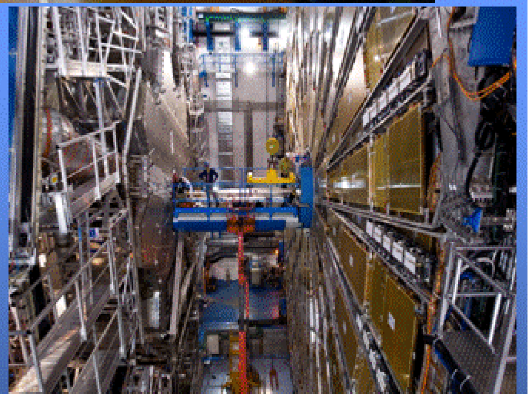
Successful commissioning of the cold vacuum systems

Insulation + beam vacuum





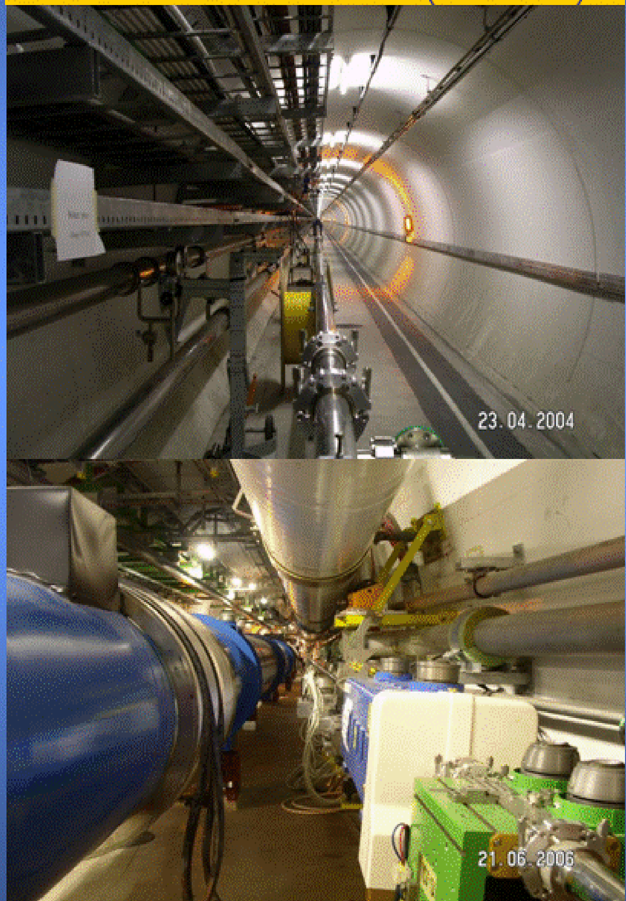
Bake out of the last sector in ALICE May '08



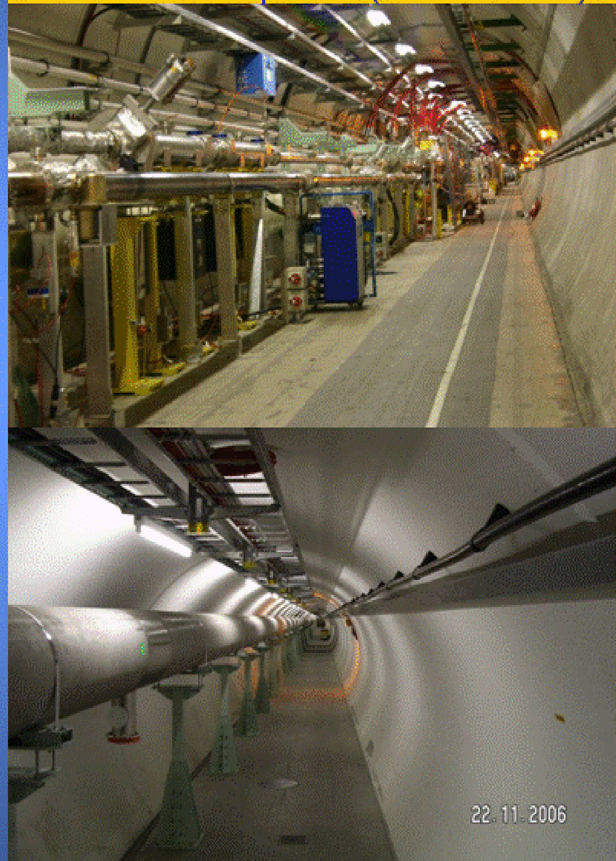
Installation of the last LHC beam pipe in ATLAS Detector

Vacuum of the LHC transfer lines has been successfully commissioned

SPS to LHC Transfer Lines (TI2 & TI8)



LHC Beam dump Lines (TD62 & TD68)

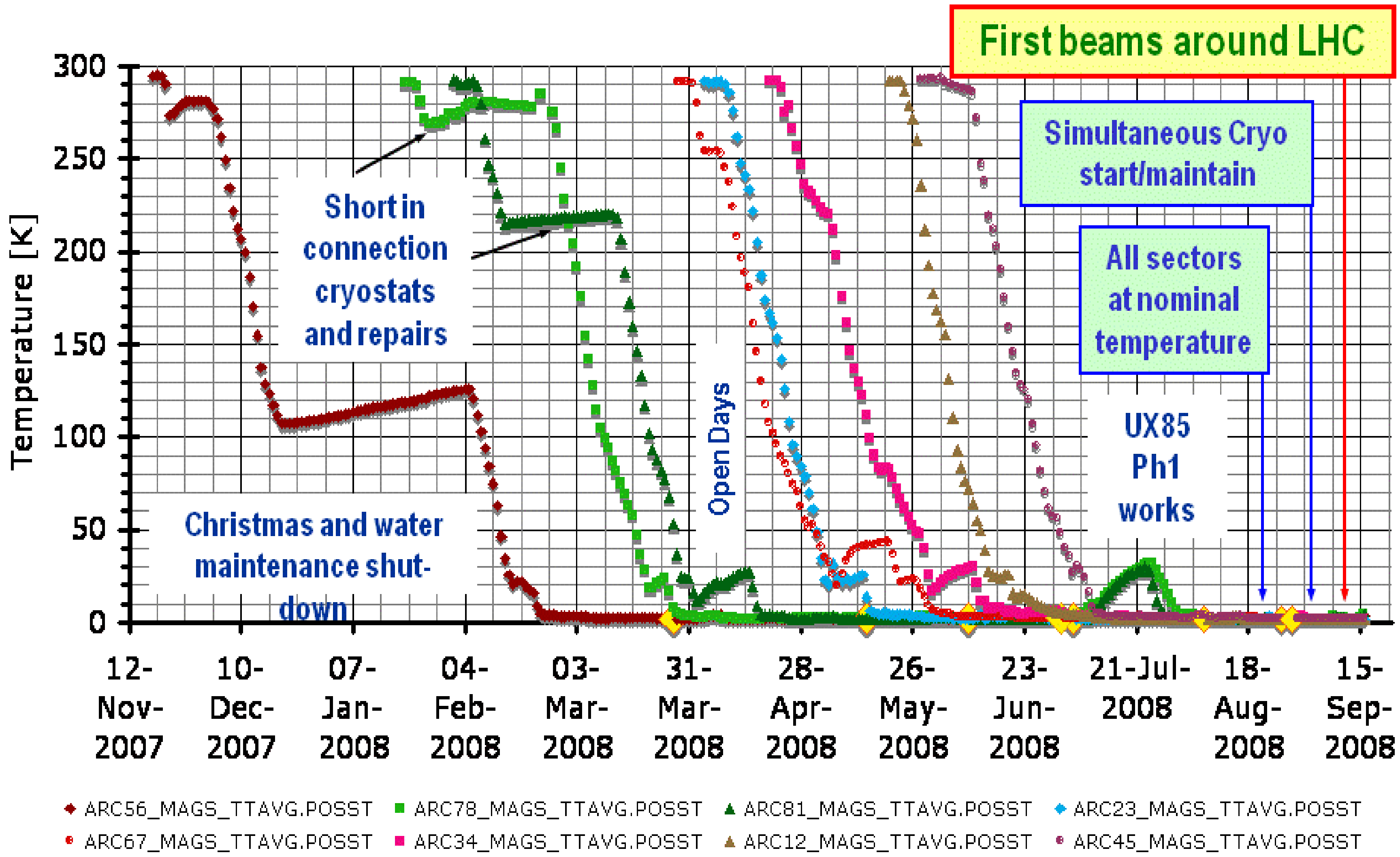


Eight 18 kW @ 4.5 K cryogenic plants

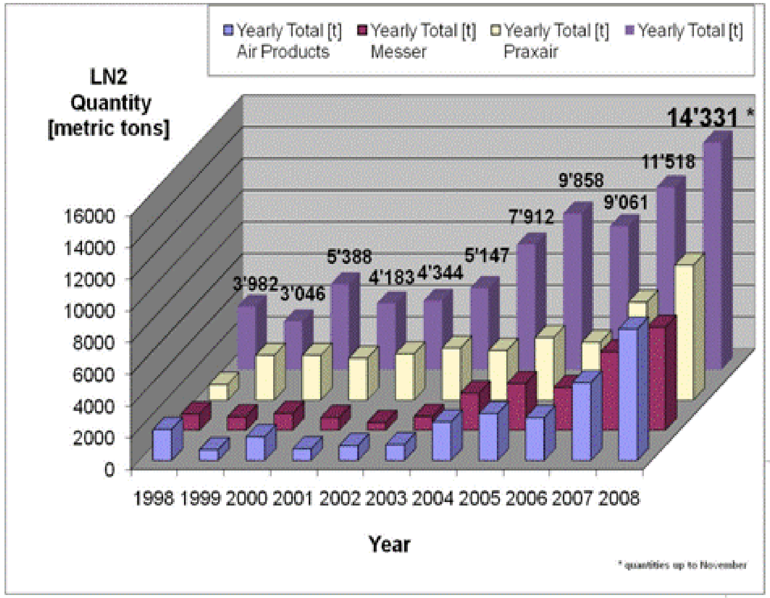
33 kW @ 50 K to 75 K
23 kW @ 4.6 K to 20 K
41 g/s liquefaction

600 kW precooling to 80 K with
LN2 (up to ~5 tons/h)

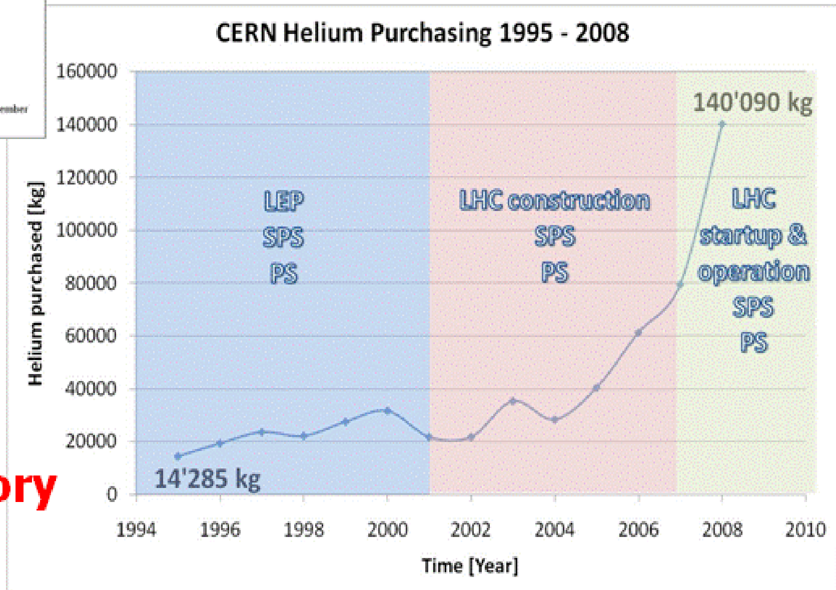
First cool-down of LHC sectors



Supply of cryogenic fluids

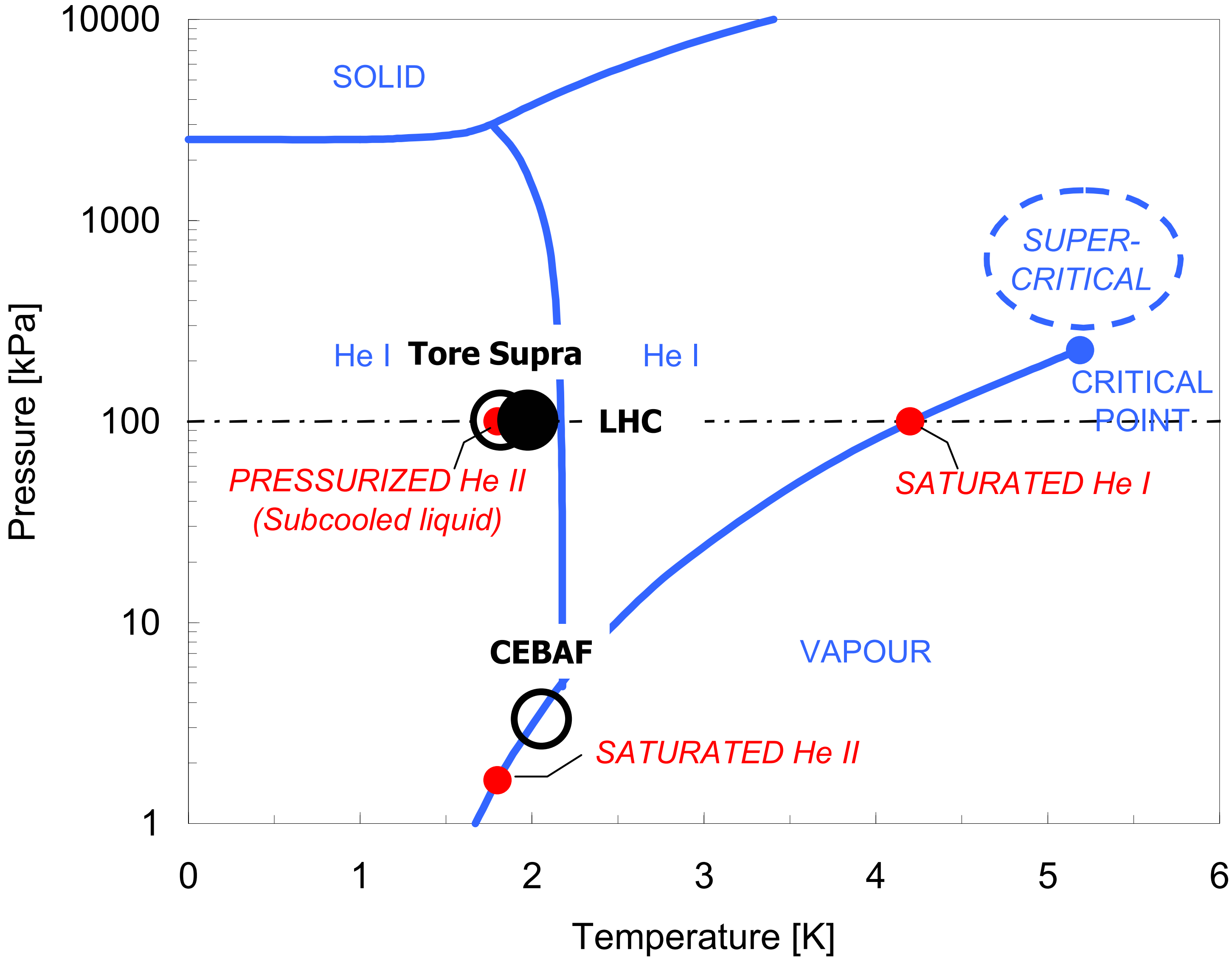


Liquid nitrogen procurement: 10000 tons for LHC cool-down

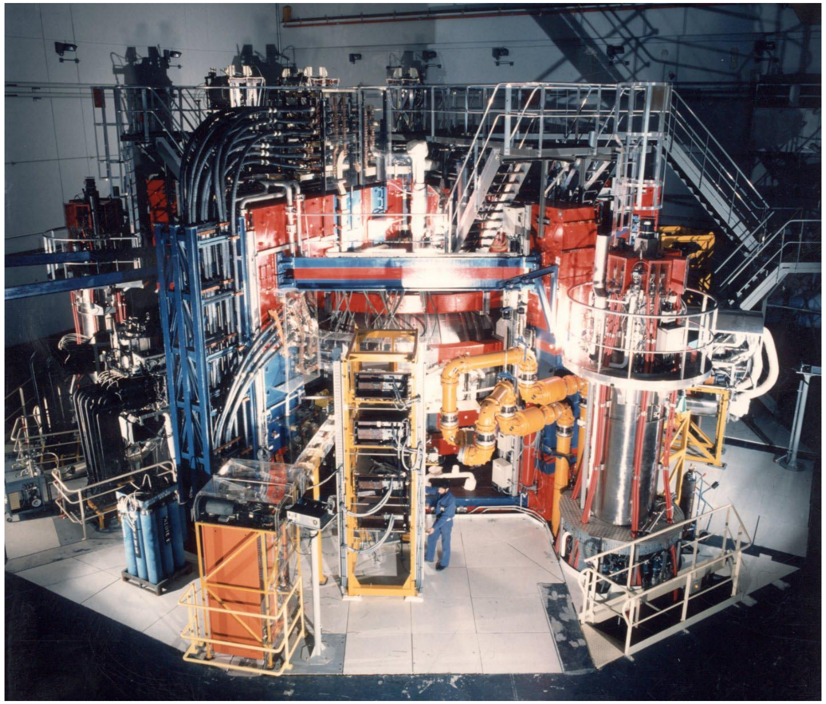


Helium procurement: Completion of LHC inventory

Superfluid helium cooling



Large projects cooled by superfluid helium

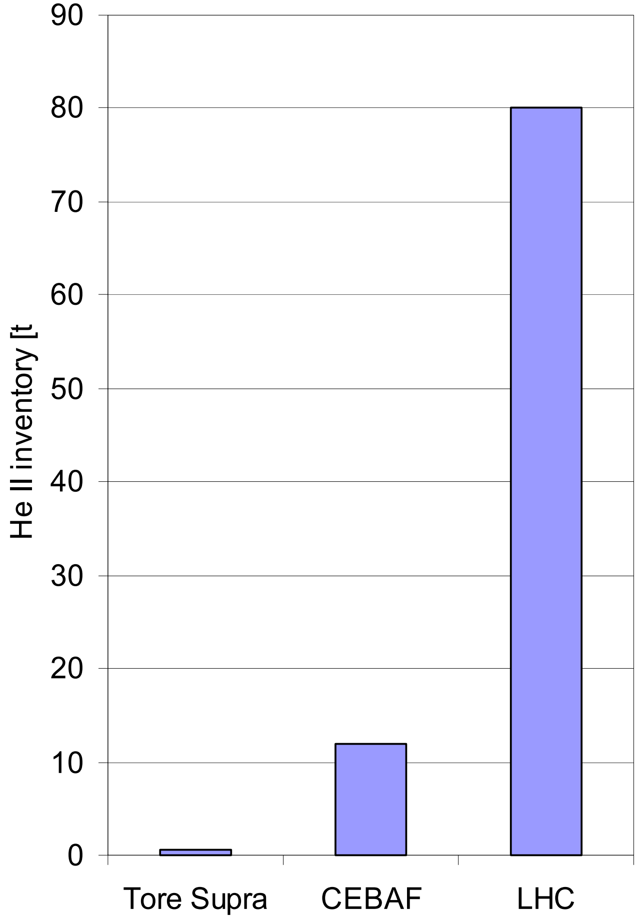


Tore Supra tokamak,
Cadarache (France)

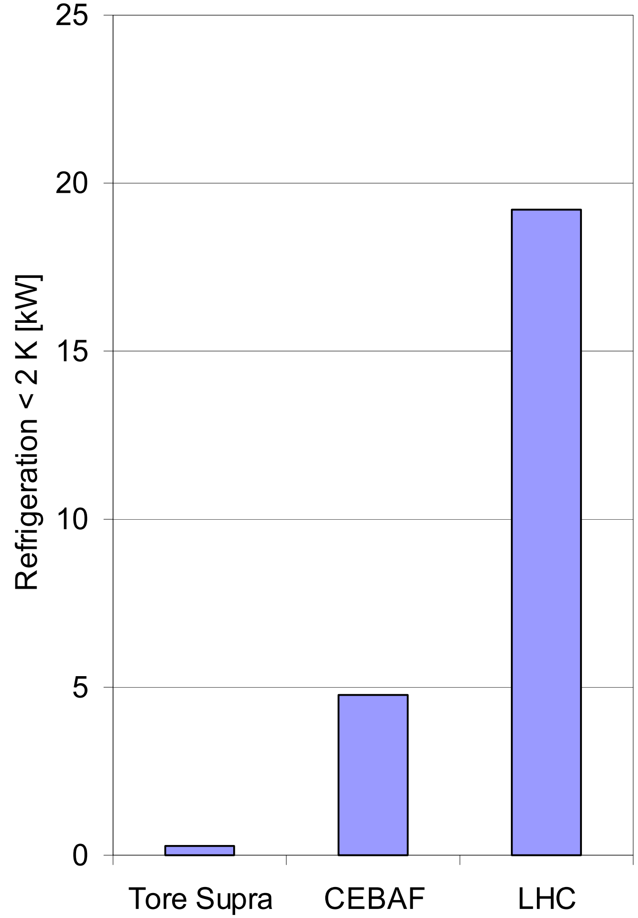
CEBAF accelerator,
Newport News (USA)

Large-scale superfluid helium systems

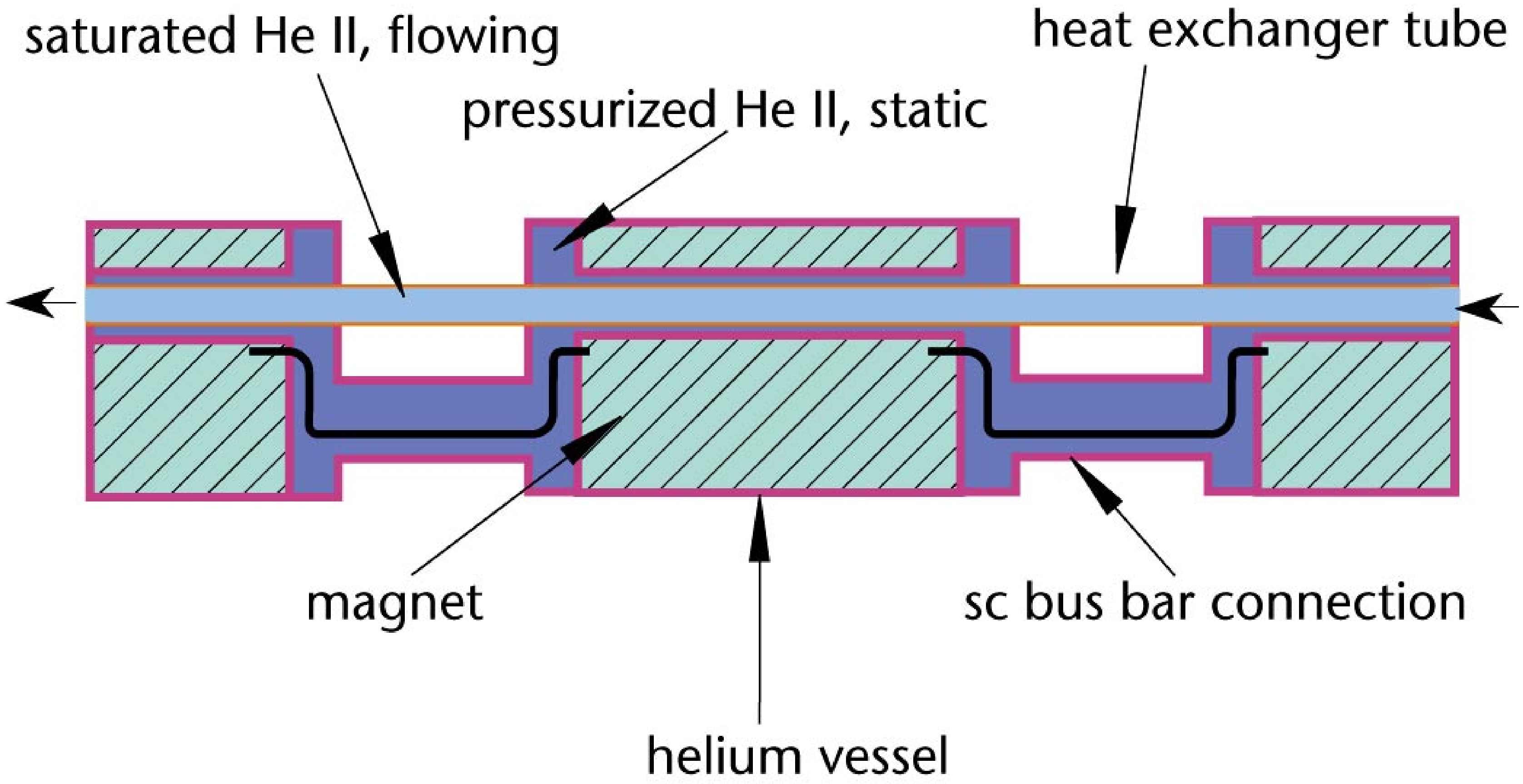
He II inventory



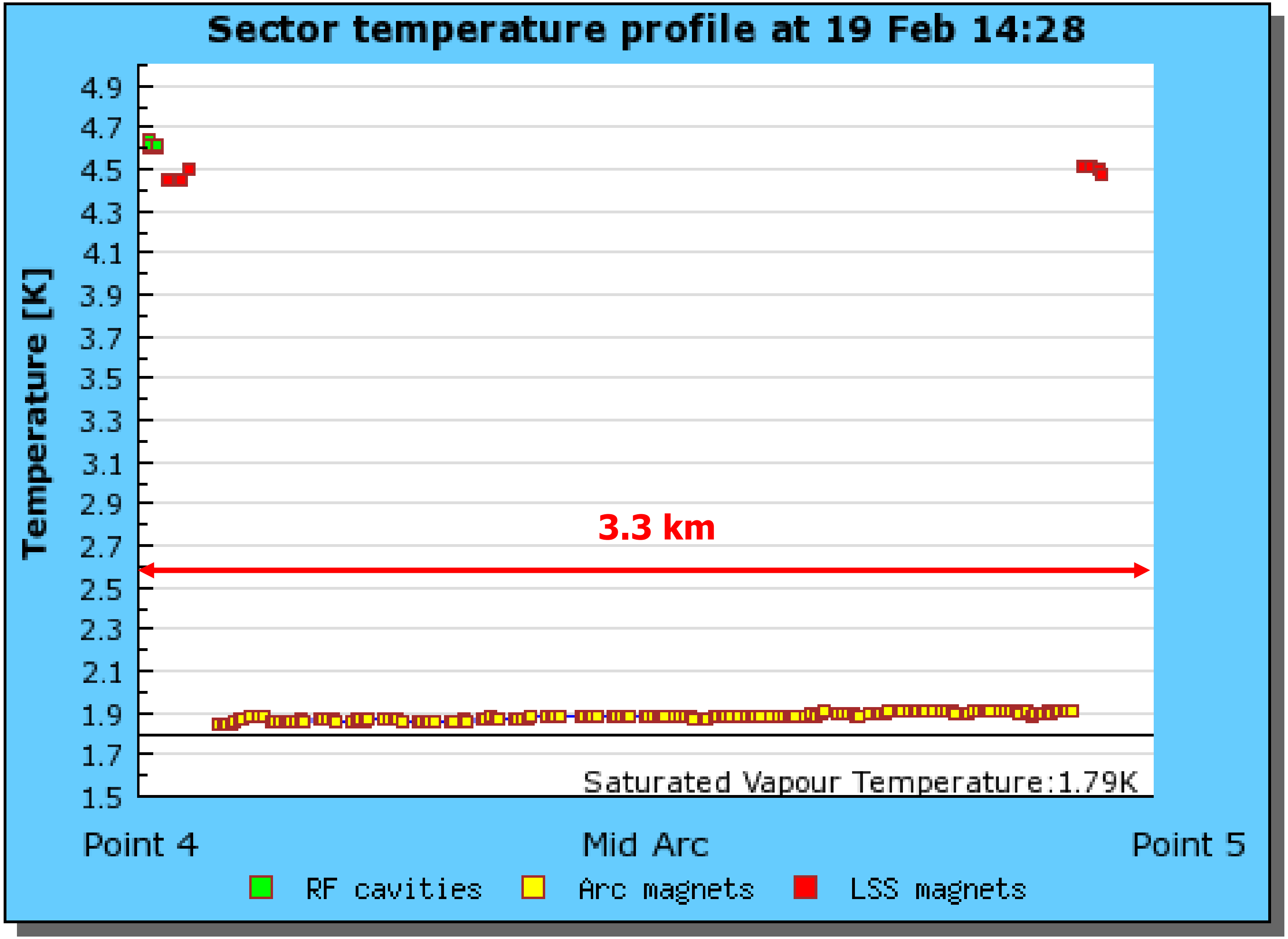
Refrigeration power < 2 K



LHC magnet string cooling scheme



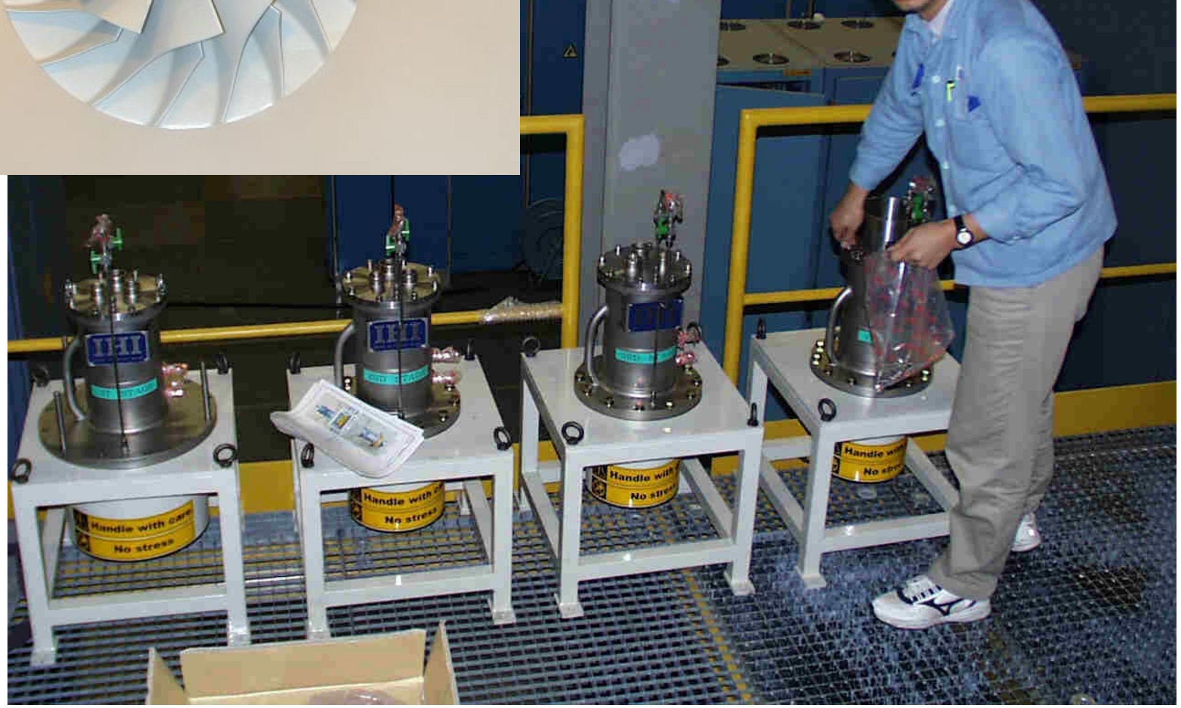
Cryogenic operation of LHC sector



Cold compressors for 1.8 K refrigeration

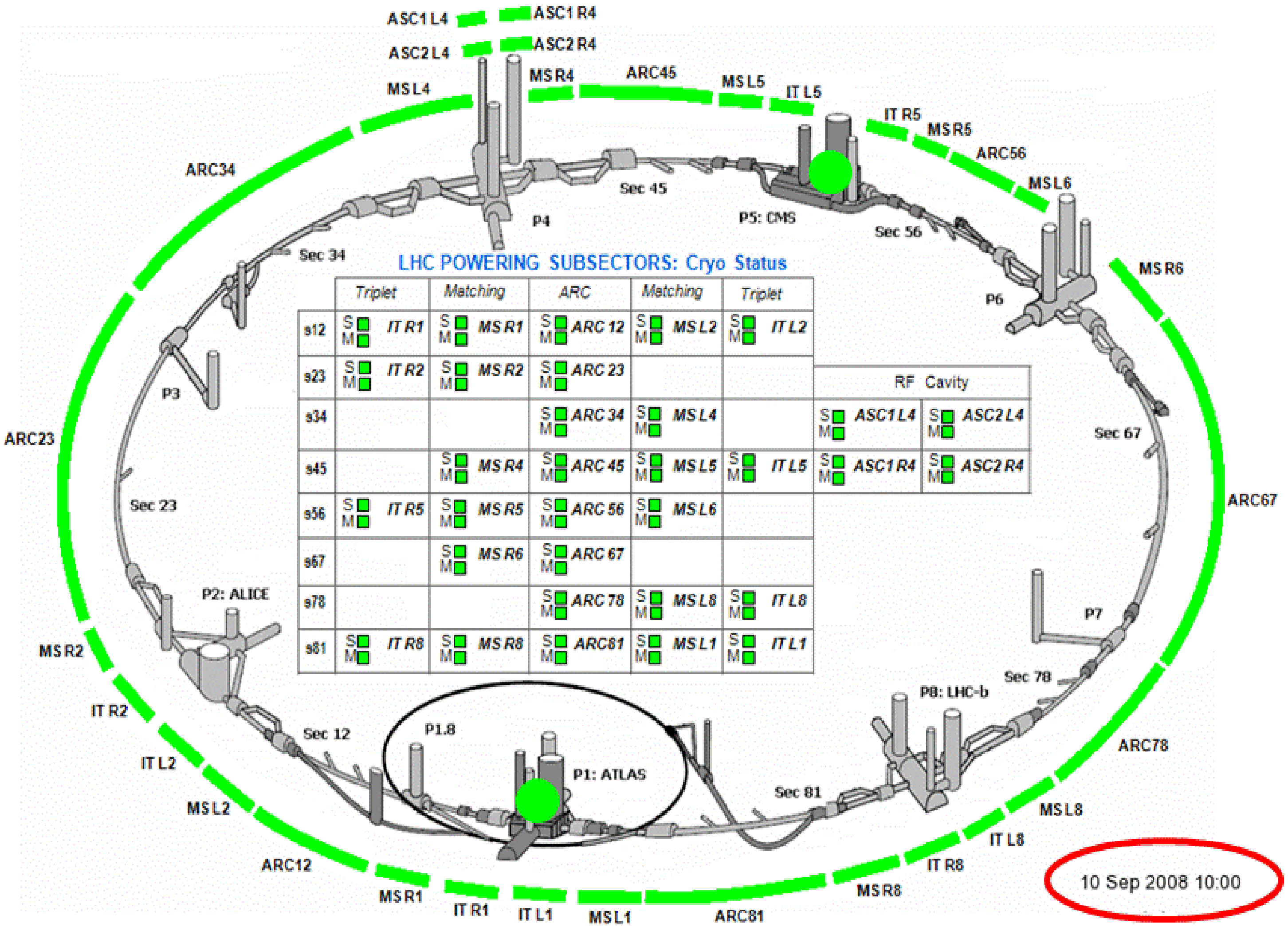
Axial-centrifugal impeller

Cartridge 1st stage



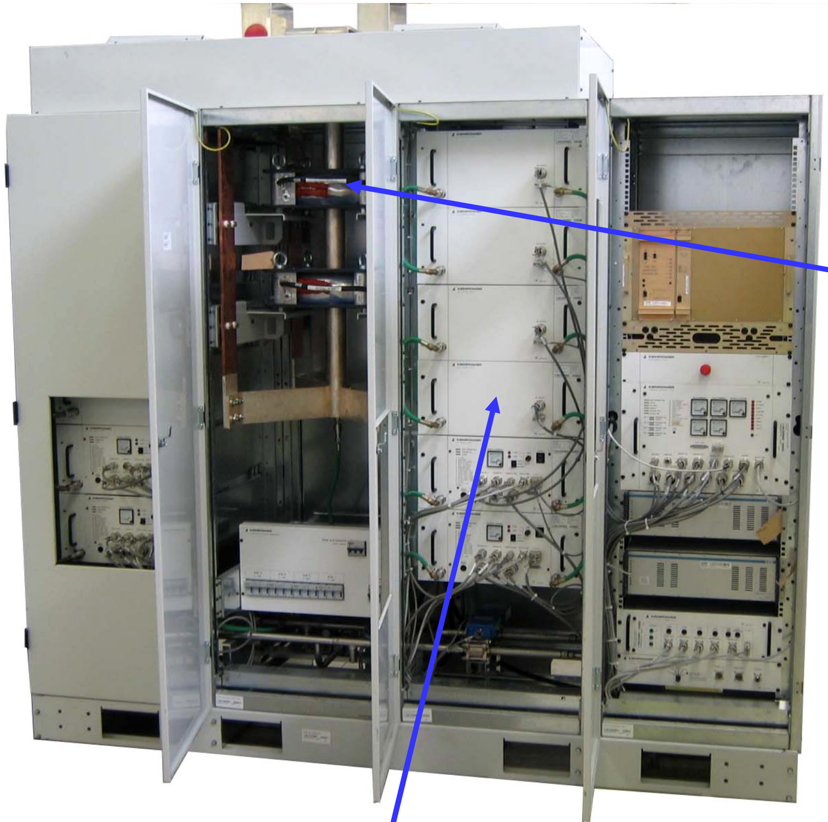
4 cold compressor stages

LHC cryogenics on 10 September 2008



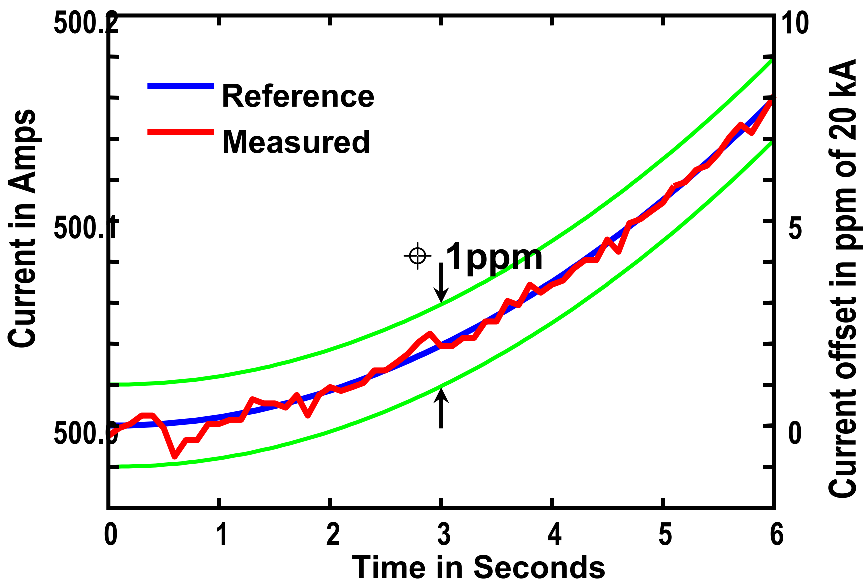
	Triplet	Matching	ARC	Matching	Triplet	RF Cavity	
s12	S M IT R1	S M MS R1	S M ARC 12	S M MS L2	S M IT L2		
s23	S M IT R2	S M MS R2	S M ARC 23				
s34			S M ARC 34	S M MS L4		S M ASC1 L4	S M ASC2 L4
s45		S M MS R4	S M ARC 45	S M MS L5	S M IT L5	S M ASC1 R4	S M ASC2 R4
s56	S M IT R5	S M MS R5	S M ARC 56	S M MS L6			
s67		S M MS R6	S M ARC 67				
s78			S M ARC 78	S M MS L8	S M IT L8		
s81	S M IT R8	S M MS R8	S M ARC81	S M MS L1	S M IT L1		

High-precision, modular switched-mode power converters

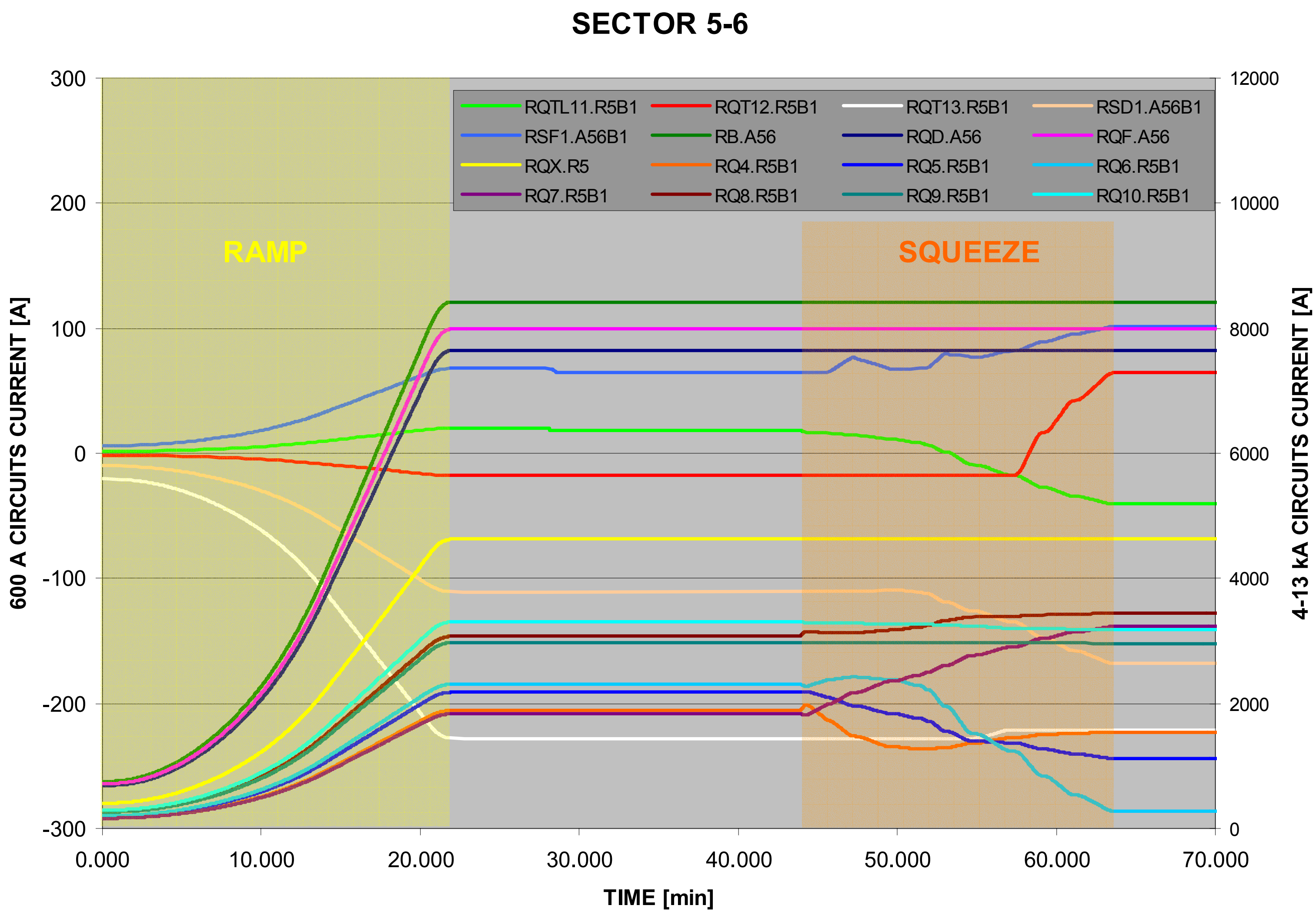


[2kA,8V] converters

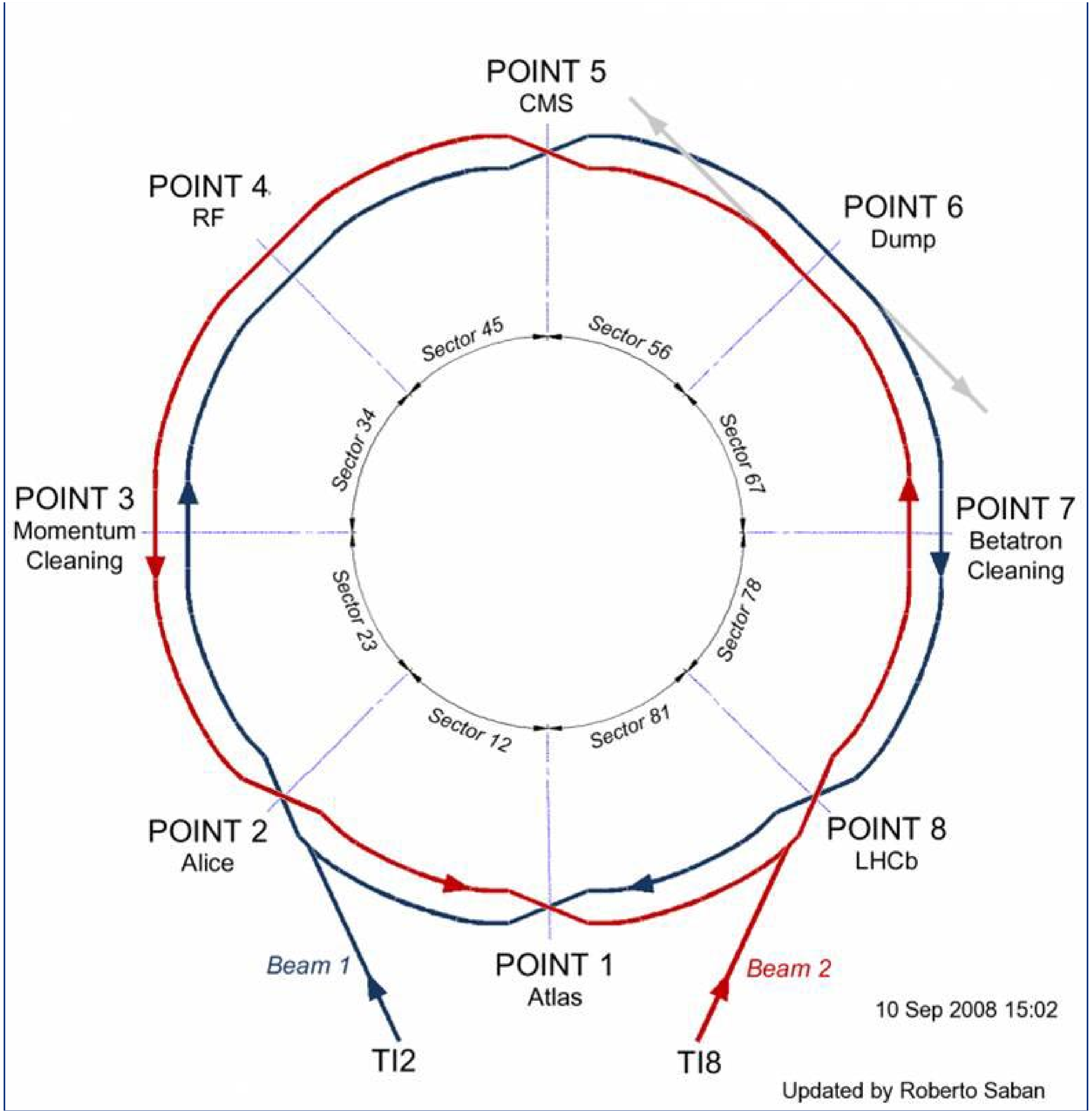
High-precision DCCT



Ramp and squeeze of the main circuits



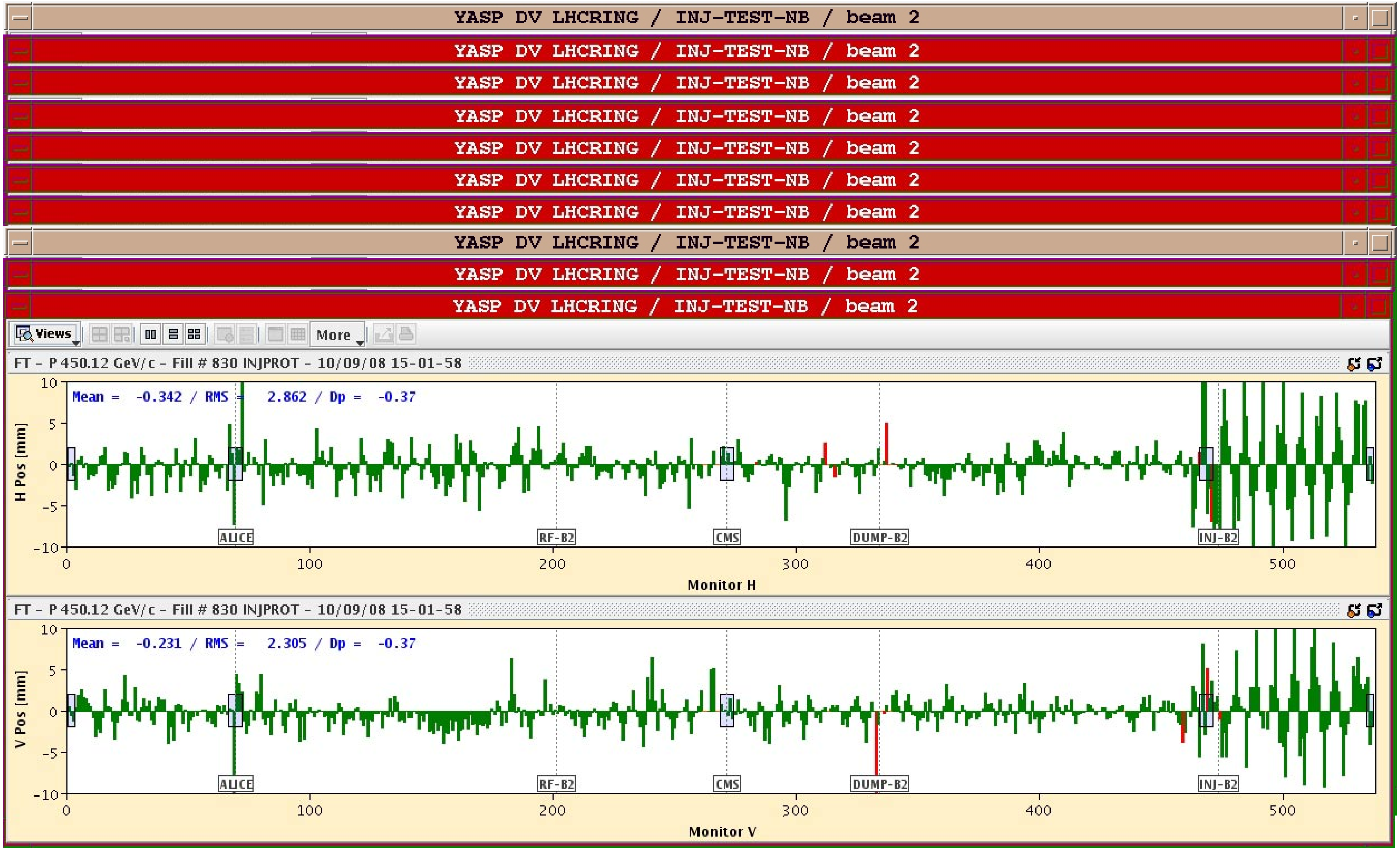
10 September 2008- first beam in LHC



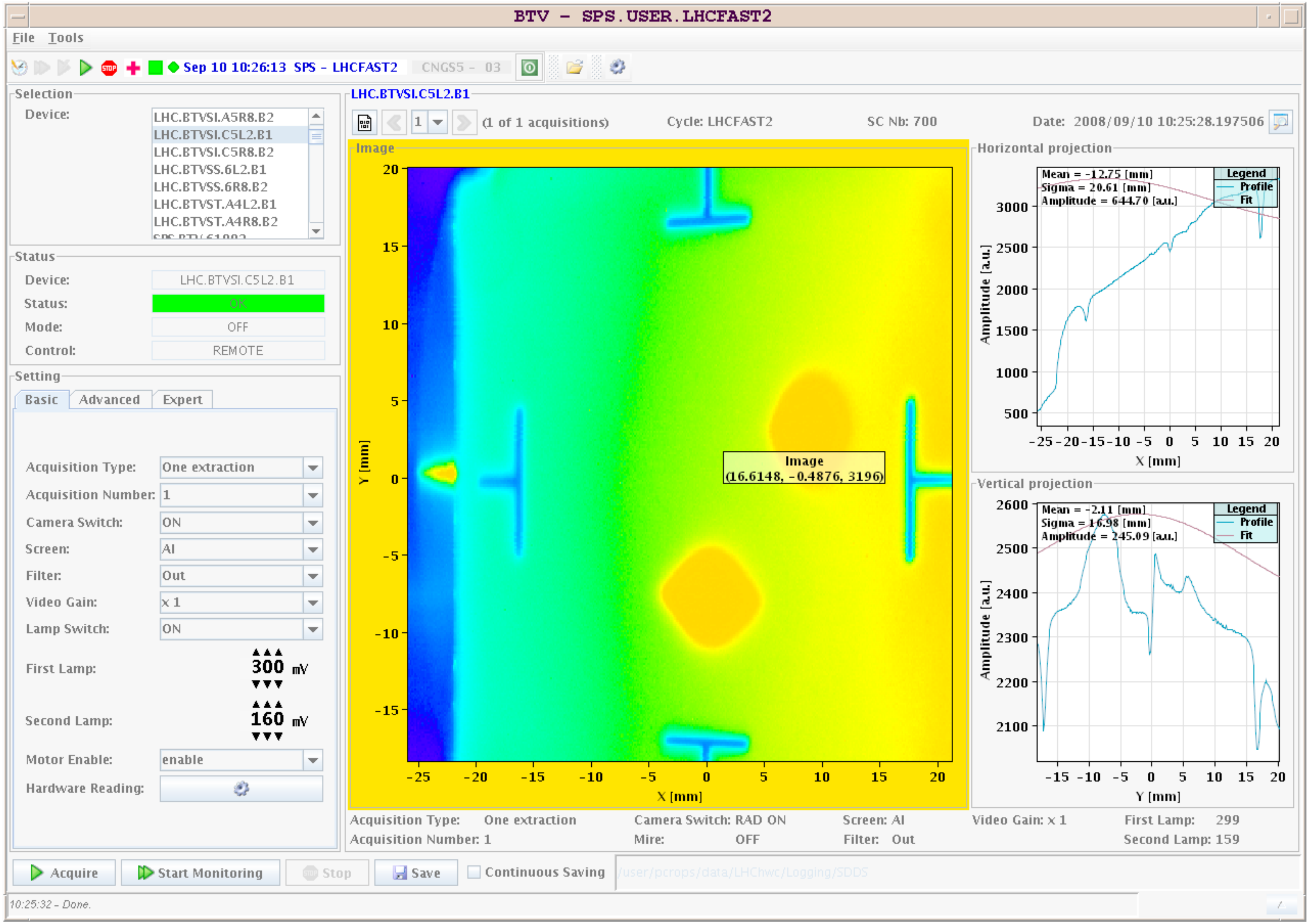
POINT 5
CMS
POINT 4
RF
POINT 6
Dump
Sector 45
Sector 56
Sector 34
Sector 67
POINT 3
Momentum
Cleaning
POINT 7
Betatron
Cleaning
Sector 23
Sector 78
Sector 12
Sector 81
POINT 2
Alice
POINT 8
LHCb
Beam 1
POINT 1
Atlas
Beam 2
10 Sep 2008 15:02
TI2
TI8
Updated by Roberto Saban

LHC 2008

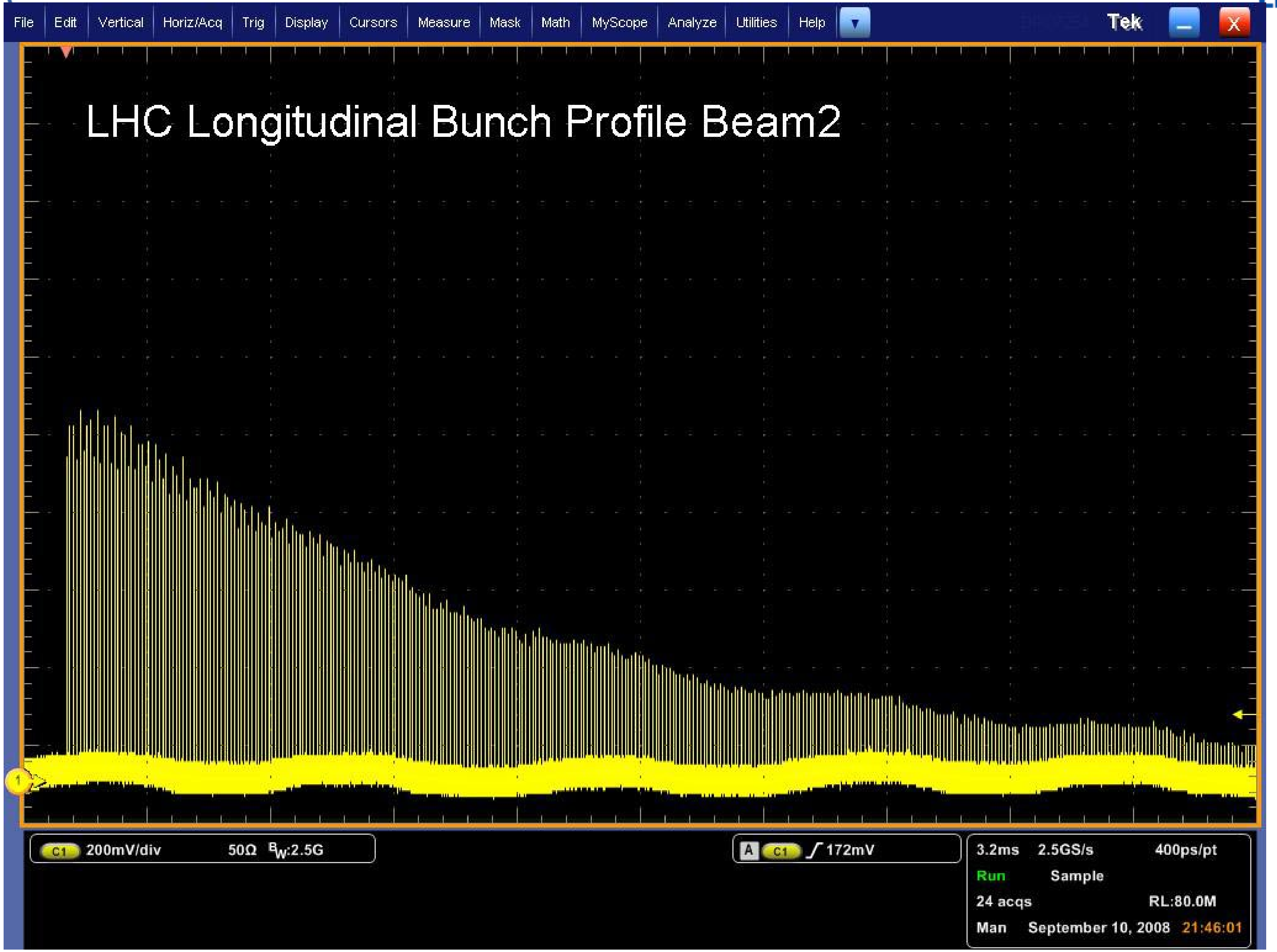
First beam – 10 September 2008



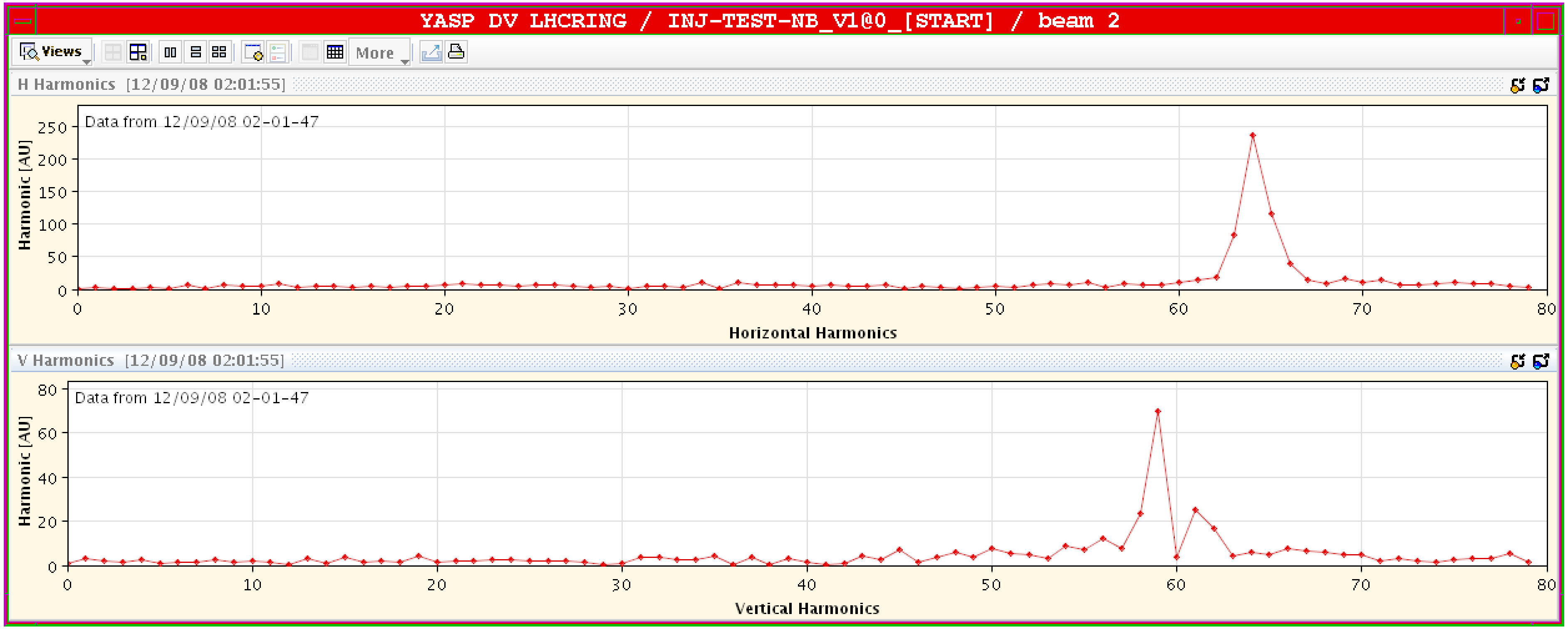
Beam on turns 1 and 2 – 10 September 2008



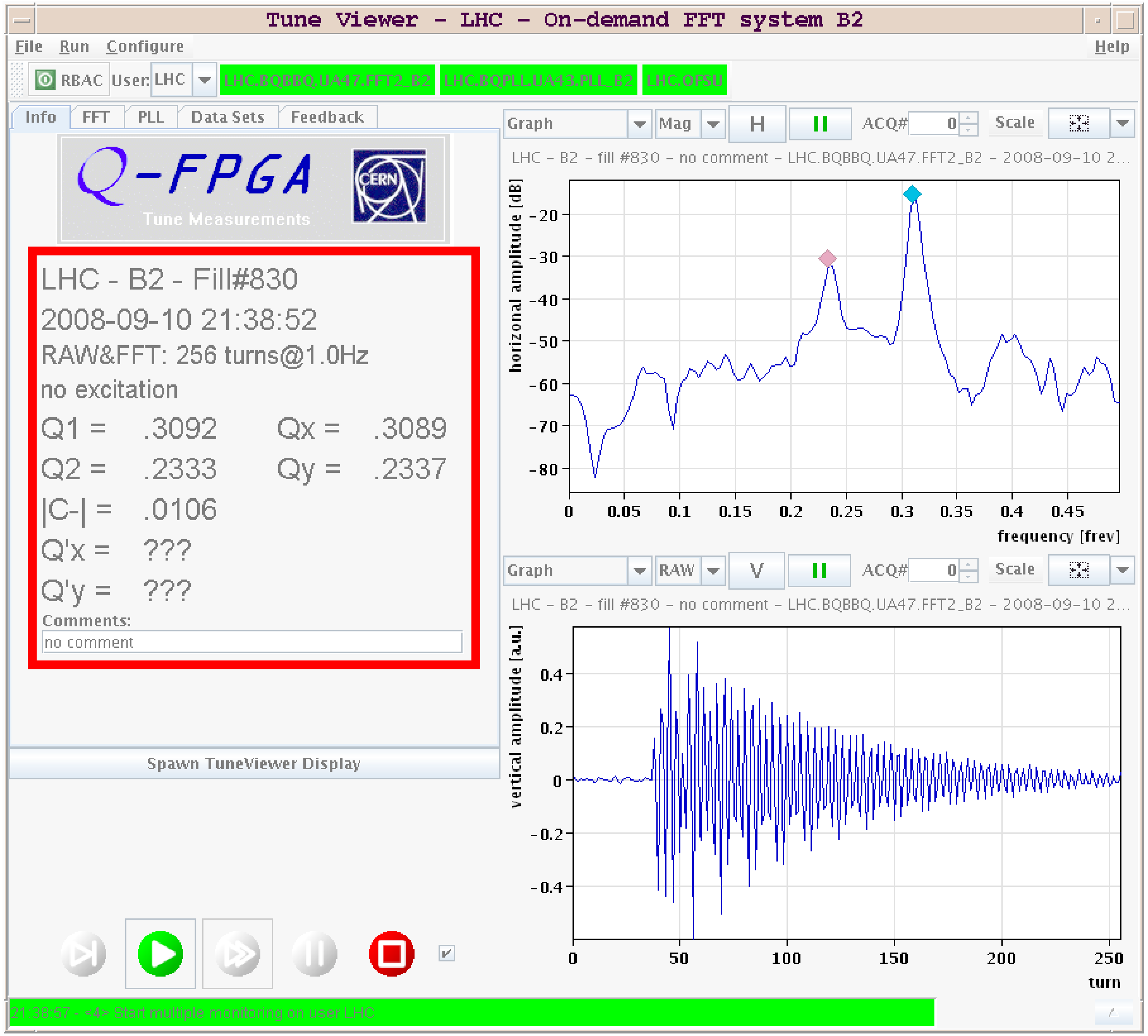
Few hundred turns



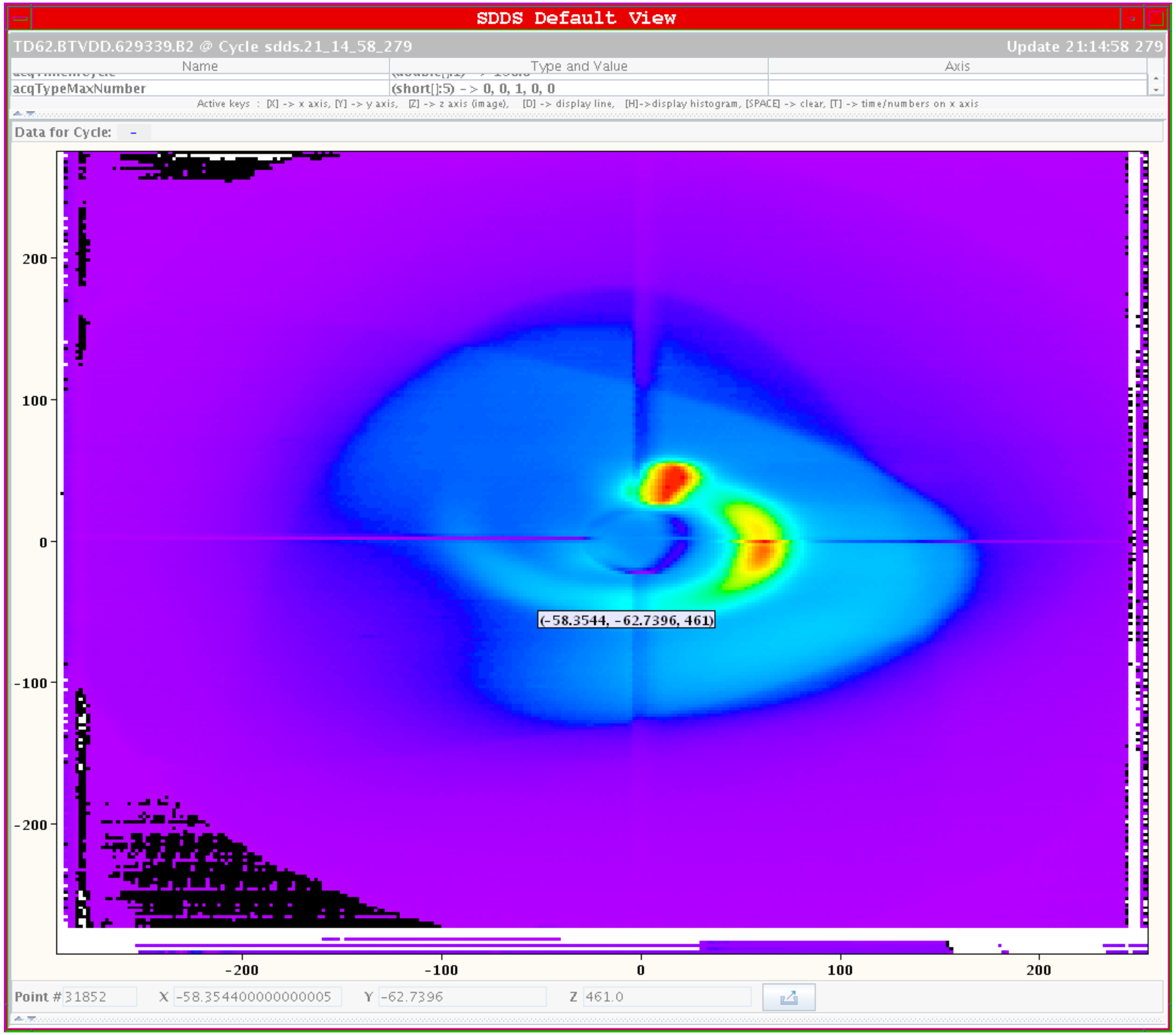
Integer tune measurements



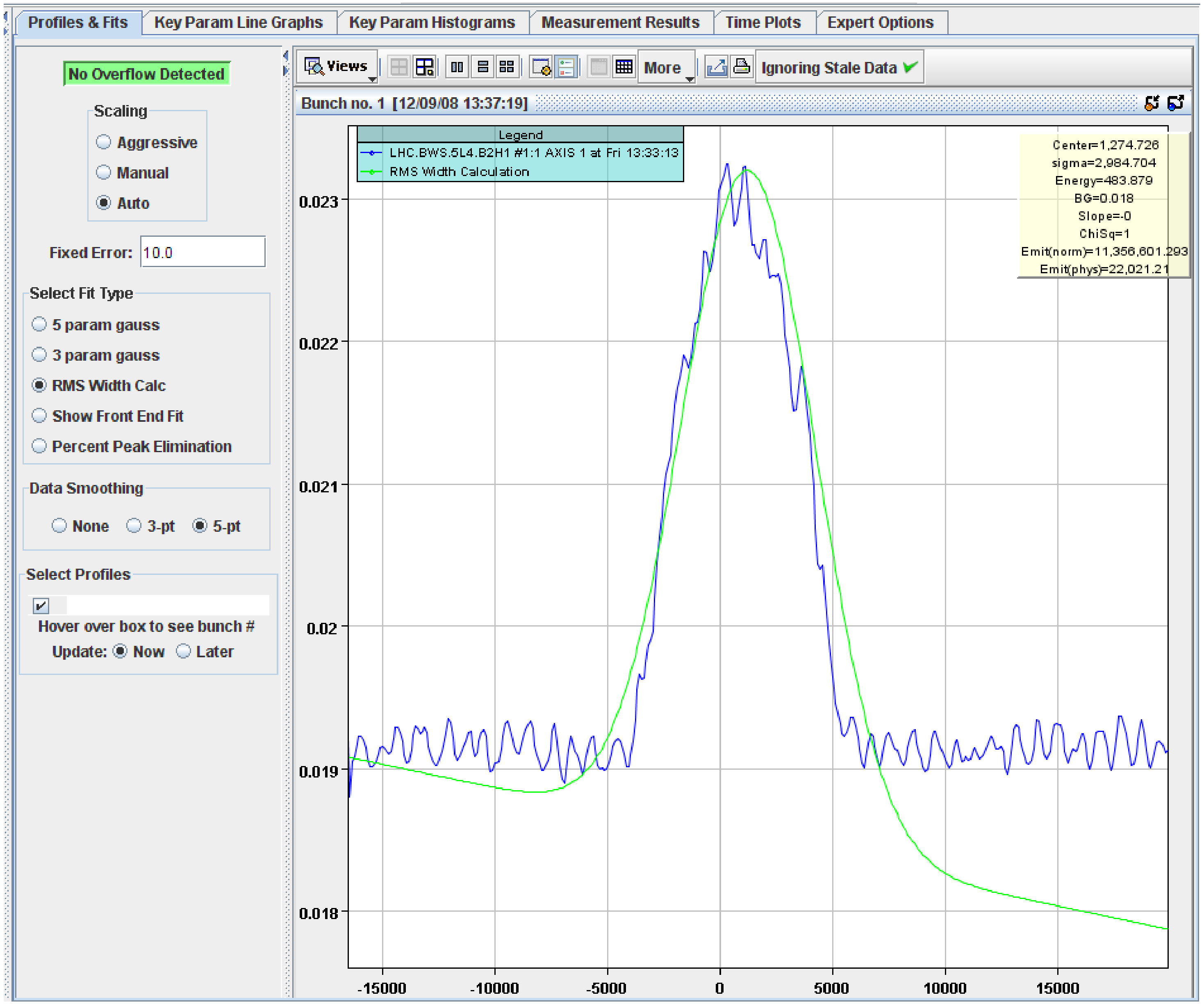
Fractional tune measurements



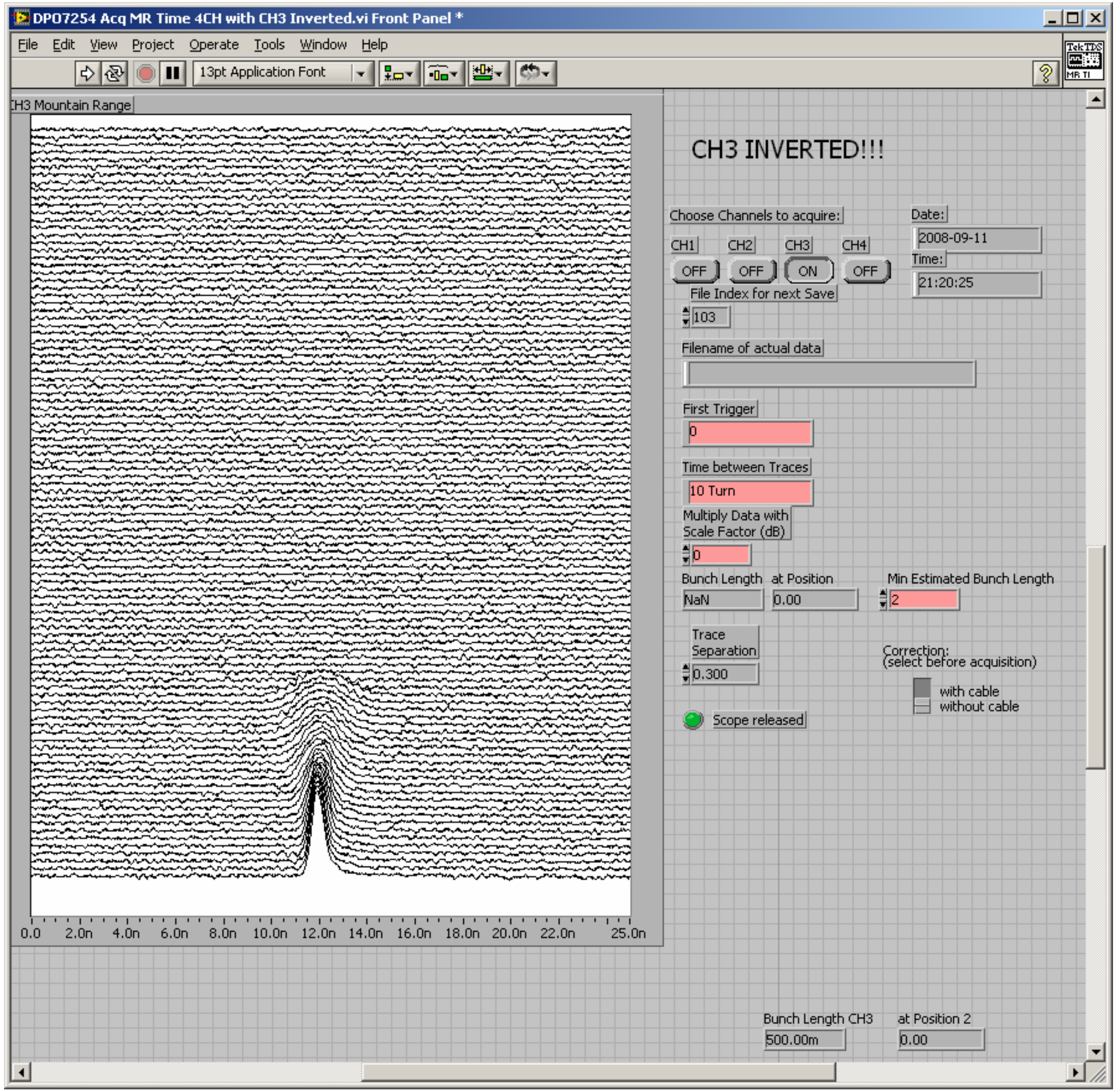
Dump dilution sweep



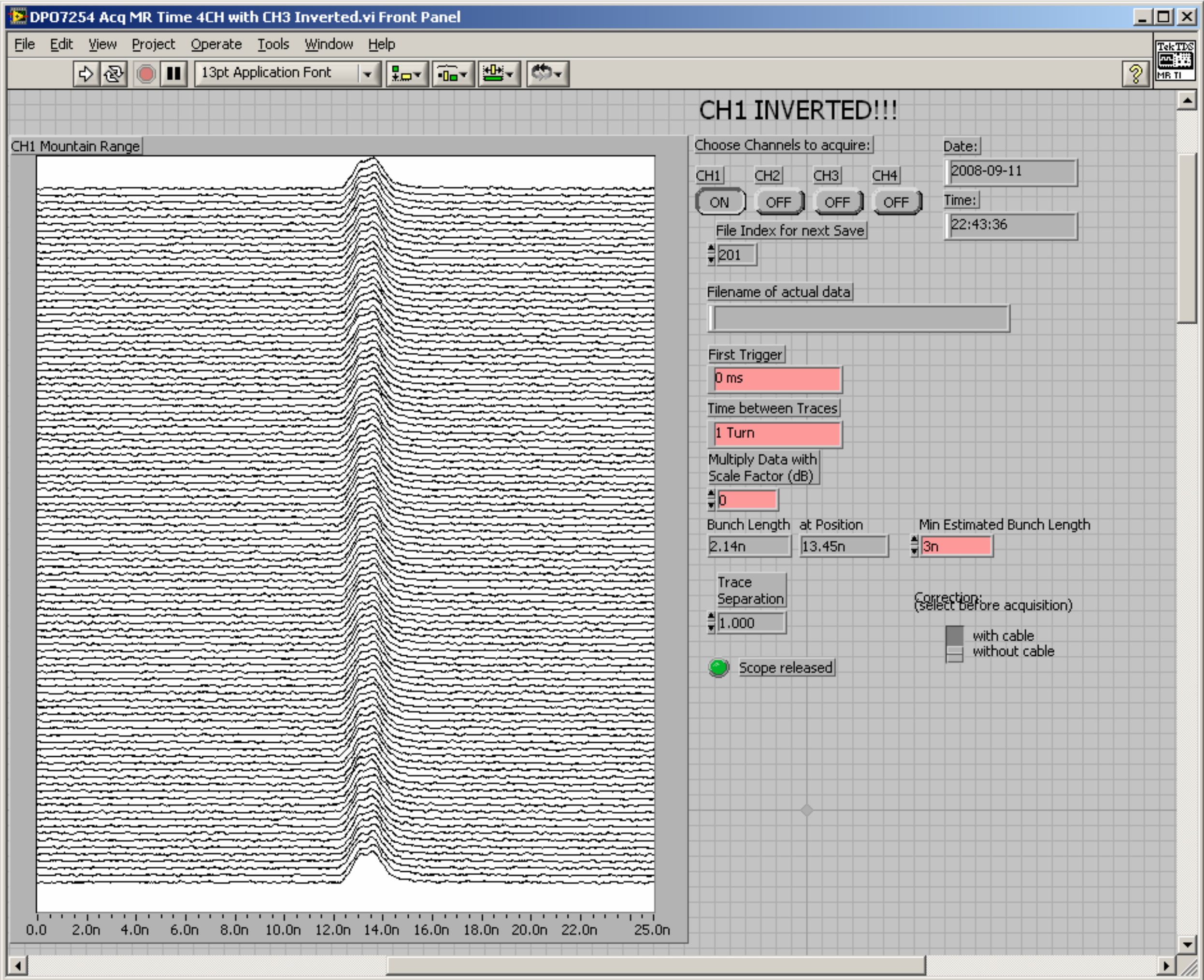
Beam transverse profile: horizontal wire scan

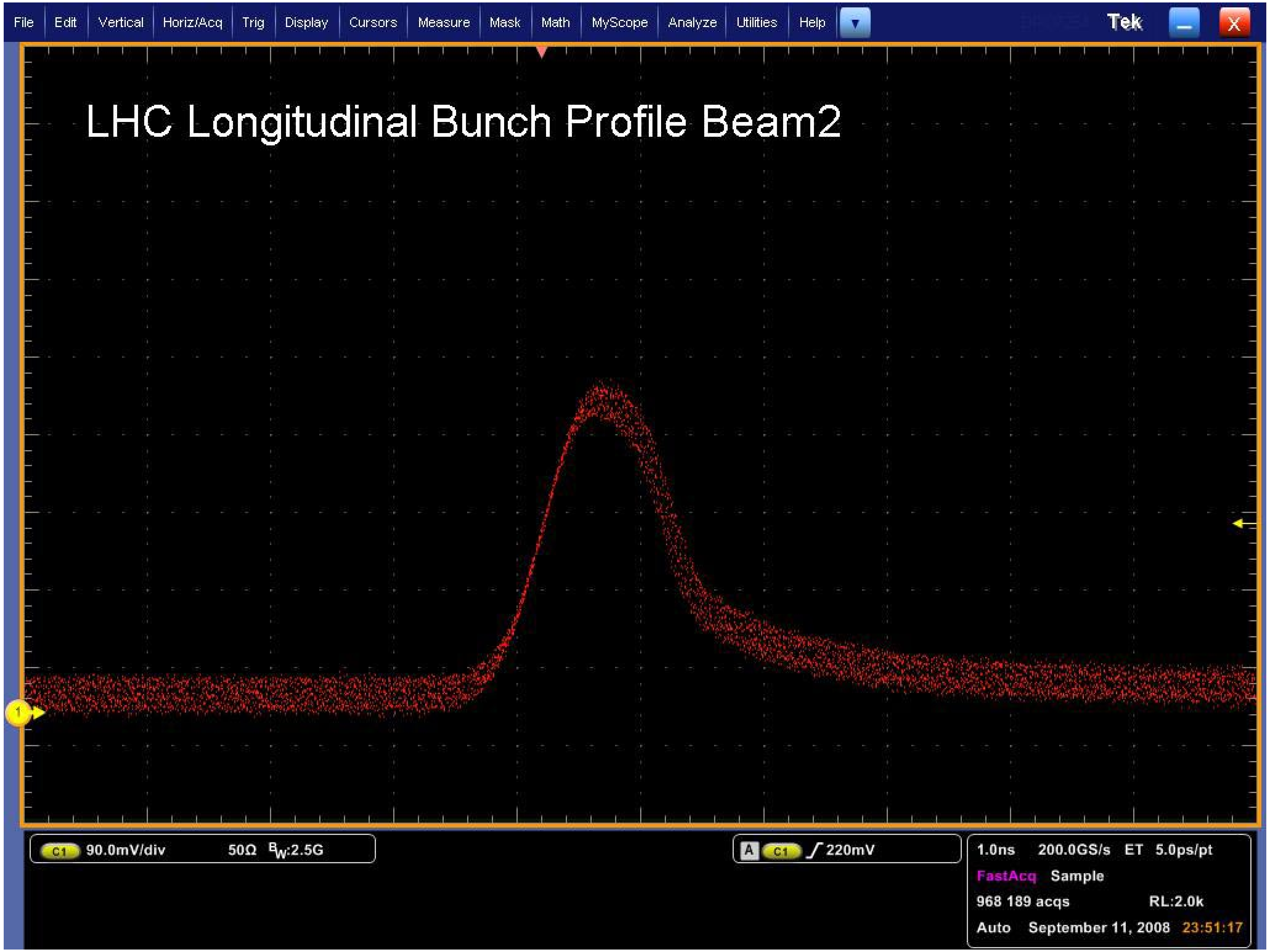


No RF, debunching in ~ 250 turns



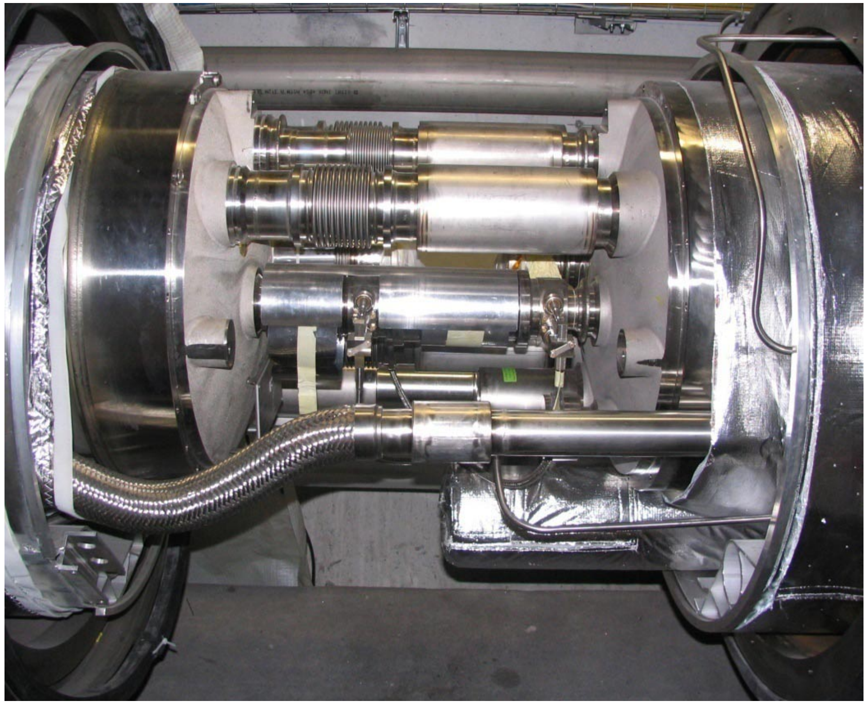
Beam capture by RF

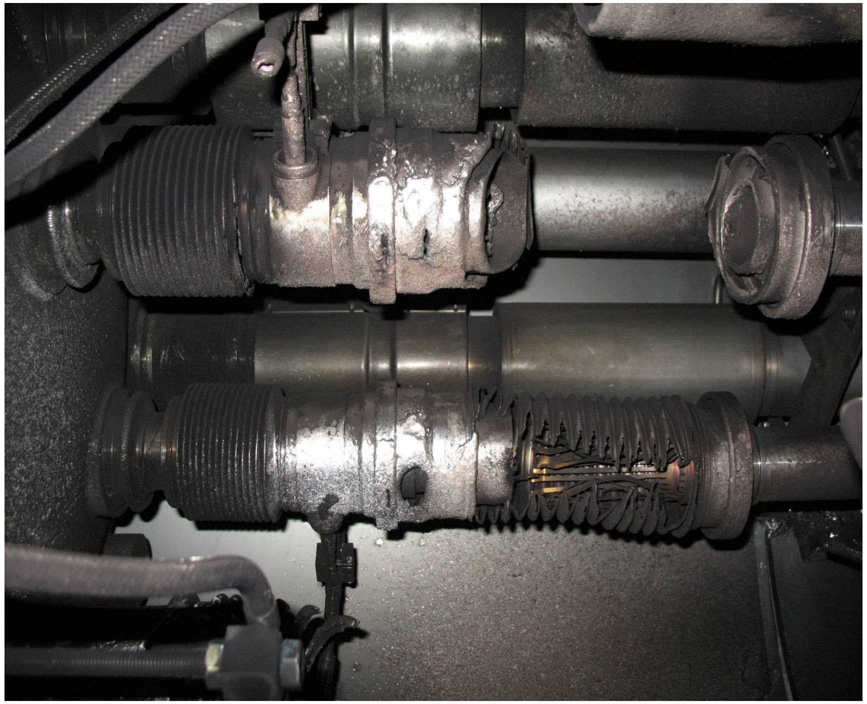




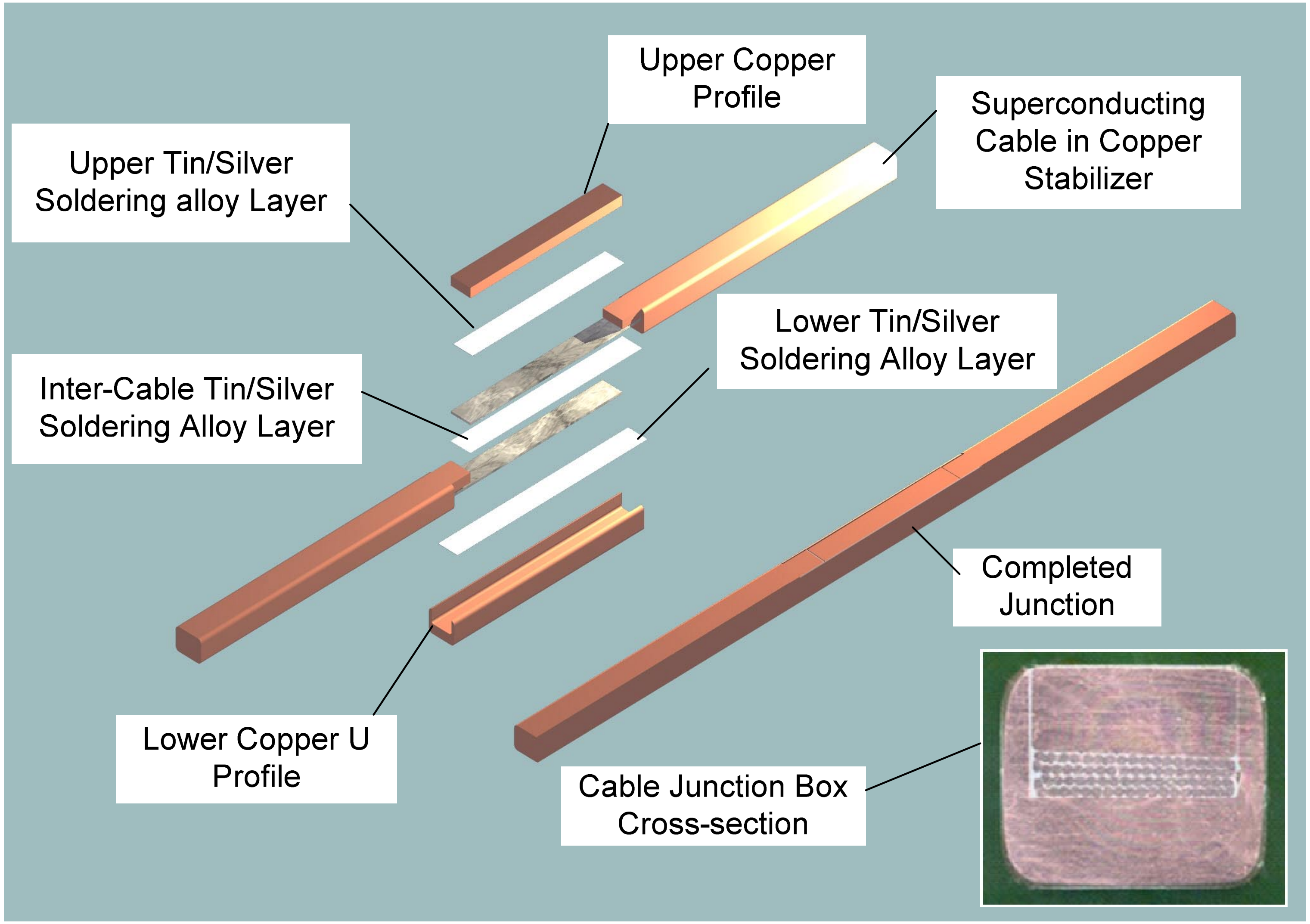
File Edit Vertical Horiz/Acq Trig Display Cursors Measure Mask Math MyScope Analyze Utilities Help
Tek
LHC Longitudinal Bunch Profile Beam2
C1 90.0mV/div 50Ω BW:2.5G
A C1 220mV
1.0ns 200.0GS/s ET 5.0ps/pt
FastAcq Sample
968 189 acqs RL:2.0k
Auto September 11, 2008 23:51:17

19 September incident at LHC sector 3 4
Electrical arc between two magnets

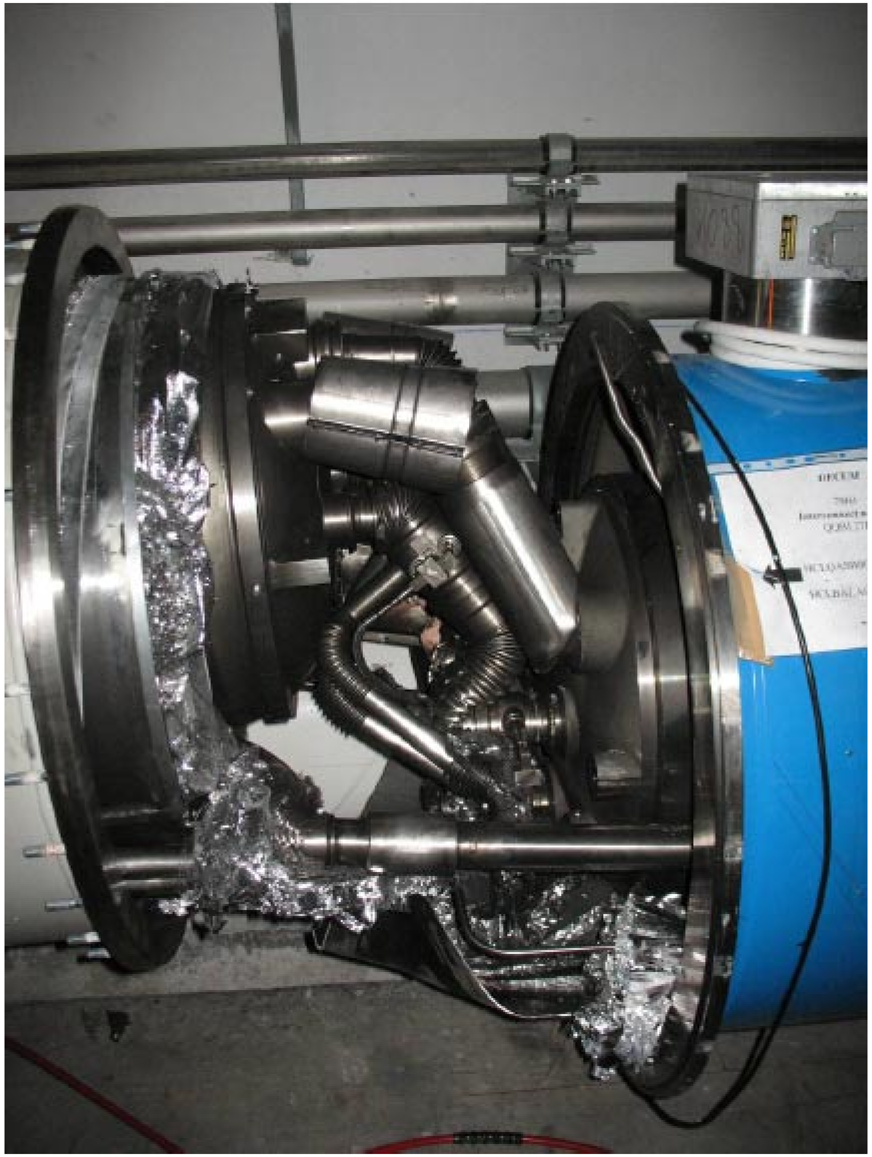




Splice in 12 kA bus bar



Collateral damage: magnet displacements



Collateral damage: ground supports

Longitudinal displacements in damaged area

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Displacements status in sector 3-4 (From Q17R3 to Q33R3) ; P3 side

Based on measurements by TS-SU, TS-MME and AT-MCS

	Q17	A18	B18	C18	Q18	A19	B19	C19	Q19	A20	B20	C20	Q20	A21	B21	C21	Q21
Cryostat	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2
Cold mass	?	?	?	?	?	?	?	?	?	?	<5	<5	<5	<5	<5	<5	<5

	Q21	A22	B22	C22	Q22	A23	B23	C23	Q23	A24	B24	C24	Q24	A25	B25	C25	Q25
Cryostat	<2	<2	<2	<2	-7	<2	<2	<2	-187	<2	<2	<2	<2	<2	<2	<2	<2
Cold mass	<5	<5	<5	<5	-25	-67	-102	-144	<5	-190	-130	-60	<5	<5	<5	<5	<5

	Q25	A26	B26	C26	Q26	A27	B27	C27	Q27	A28	B28	C28	Q28	A29	B29	C29	Q29
Cryostat	<2	<2	<2	<2	<2	<2	<2	<2	474	-4	<2	<2	11	<2	<2	<2	<2
Cold mass	<5	<5	<5	<5	<5	57	114	150?	-45	230	189	144	92? Vert	50	35	<5	<5

	Q29	A30	B30	C30	Q30	A31	B31	C31	Q31	A32	B32	C32	Q32	A33	B33	C33	Q33
Cryostat	<2	<2	<2	<2	<2	<2	<2	<2	188	<2	<2	<2	5	<2	<2	<2	<2
Cold mass	<5	<5	<5	<5	<5	19	77	148	<5	140	105	62	18	<5	<5	<5	?

SSS with vacuum barrier

>0 Towards P4

[mm] Values are in mm

? Not measured yet

Cold mass displacement

Cryostat displacement

Open interconnection

Electrical interruptions

Dipole in short circuit

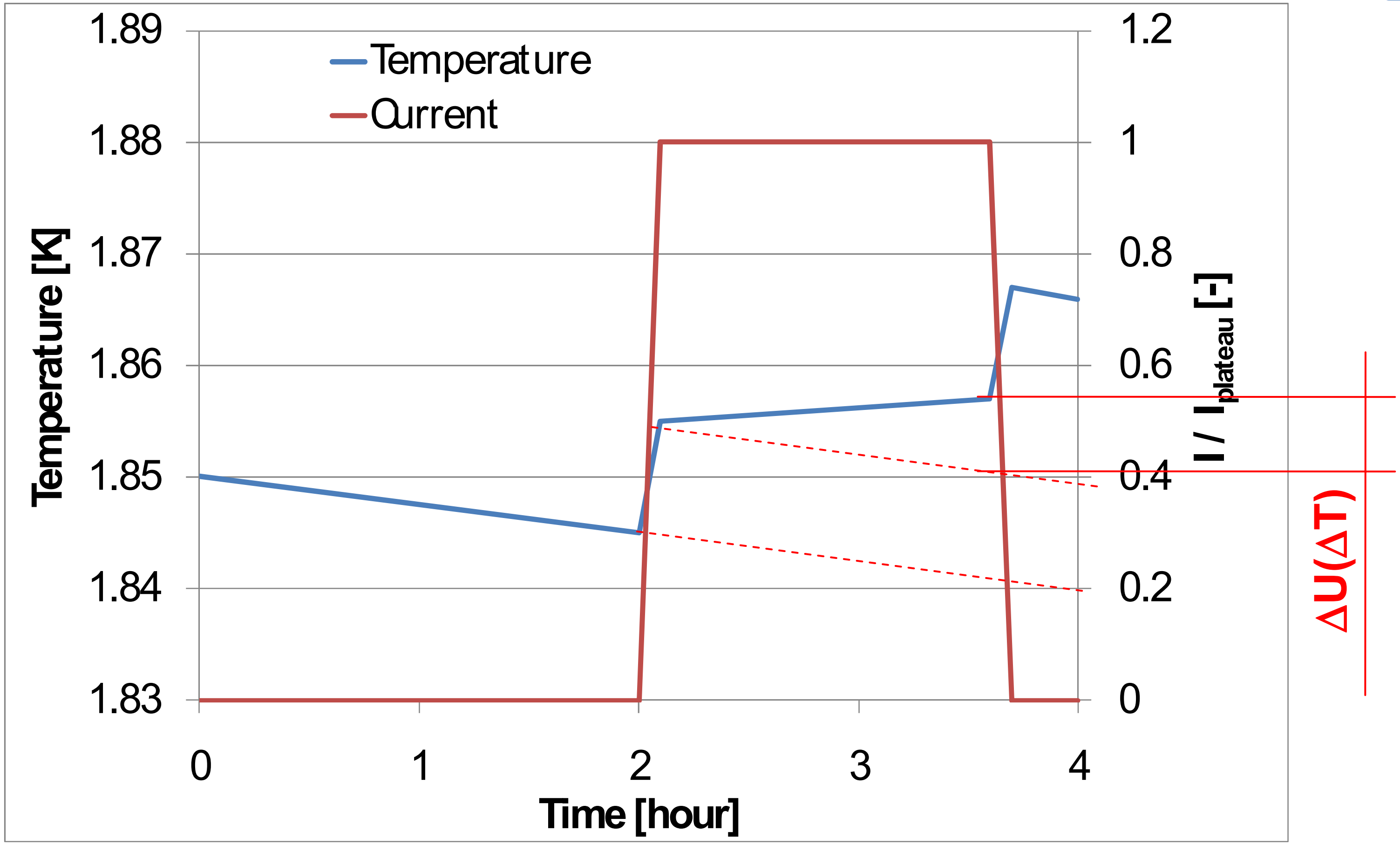
Electrically damaged IC

Buffer zones

Disconnected

Detection of resistive zones by He II calorimetry
Methodology

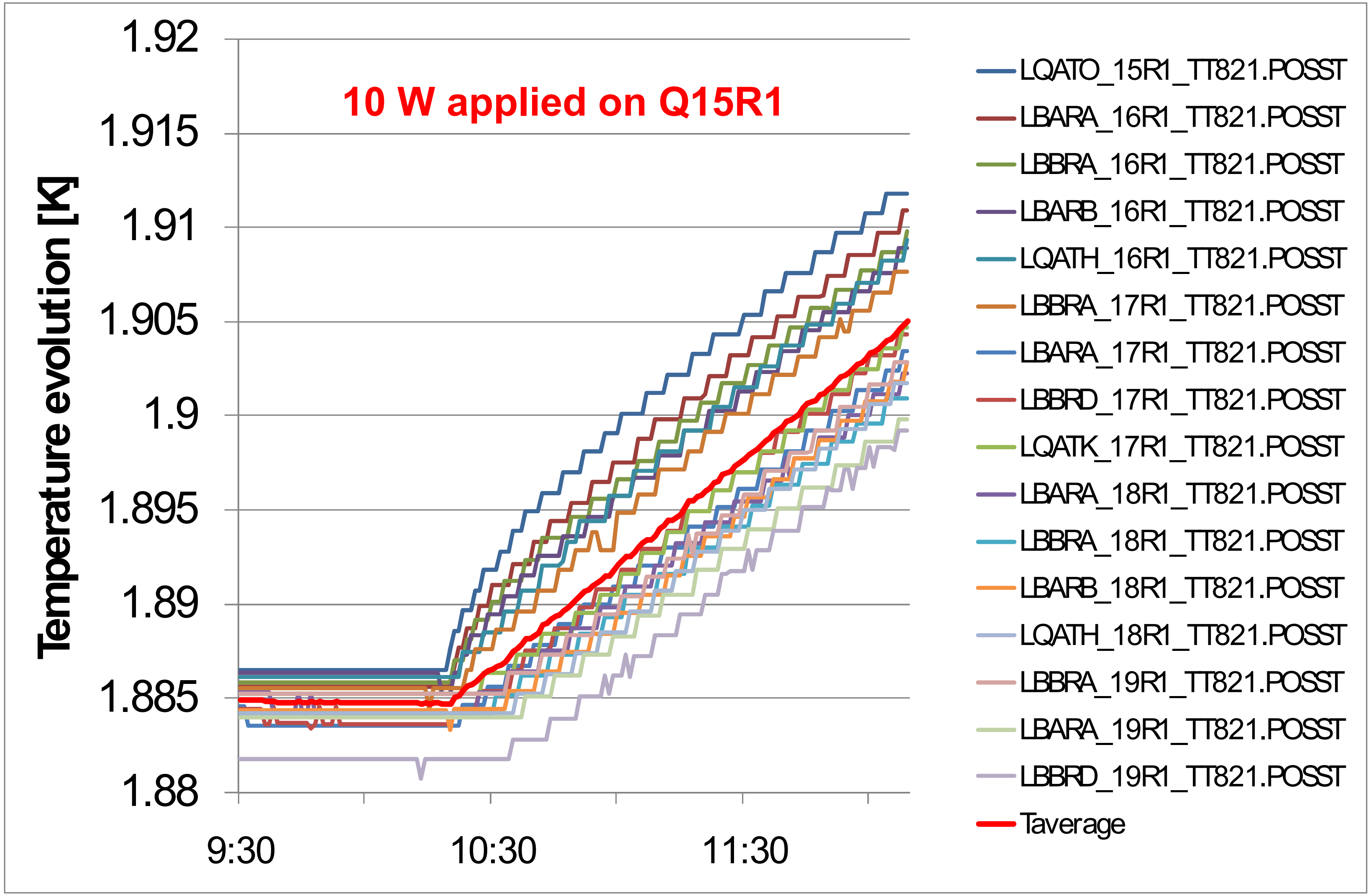
LHC 2008



1. Assessment of the baseline slope (remaining CV opening mismatch w/r to static HL)
2. Assessment of the temperature increase during powering plateau
3. Assessment of the internal energy variation (J/kg)
4. Assessment of the deposited energy assuming a mass of 26 l/m of LHeII

Detection of resistive zones by He II calorimetry
Experimental validation

LHC 2008



Detection of resistive zones by He II calorimetry
Experimental validation

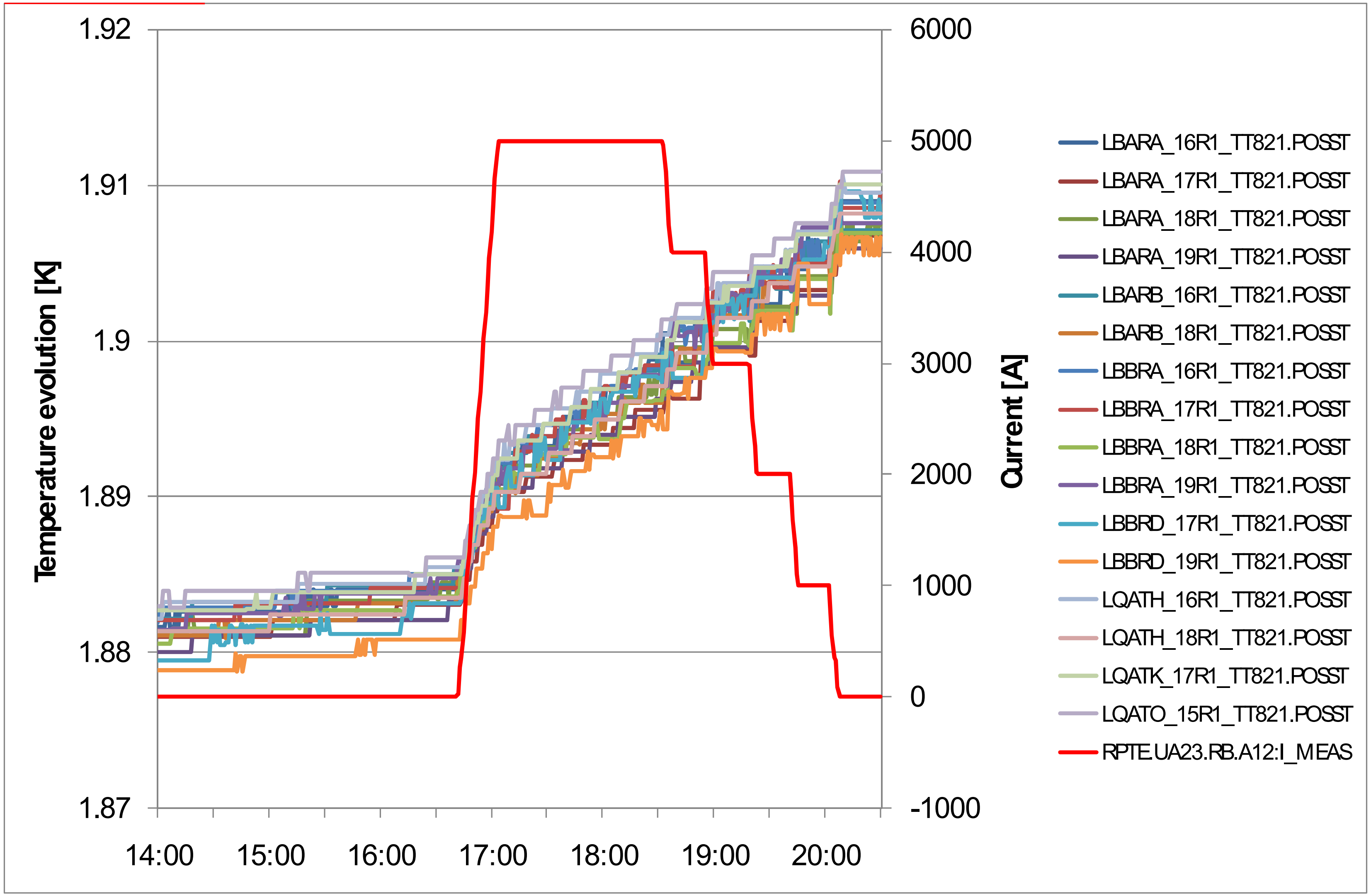
LHC 2008

	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]	**10.0**	

→ The power variation calculated by He II calorimetry is 10.0 W, corresponding to the applied electrical power

→ The method is validated and able to resolve ~ W

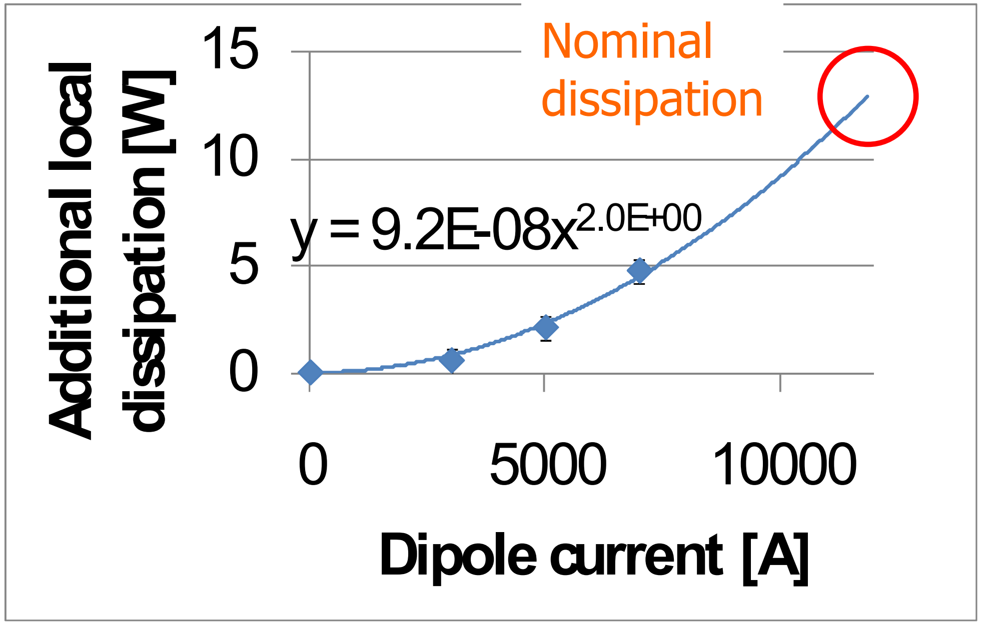
Calorimetry during 15R1 powering @ 5000A



The 15R1 case: additional heat dissipation due to a bad splice

Current	Total (measured)		Nominal Splices*	Add. local dissipation	Uncertainty
[A]	[mW/m]	[W]	[W]	[W]	[W]
3000	4.4	1.0	0.4	0.6	0.6
5000	14.9	3.2	1.1	2.1	0.6
7000	32.2	6.9	2.1	4.8	0.6

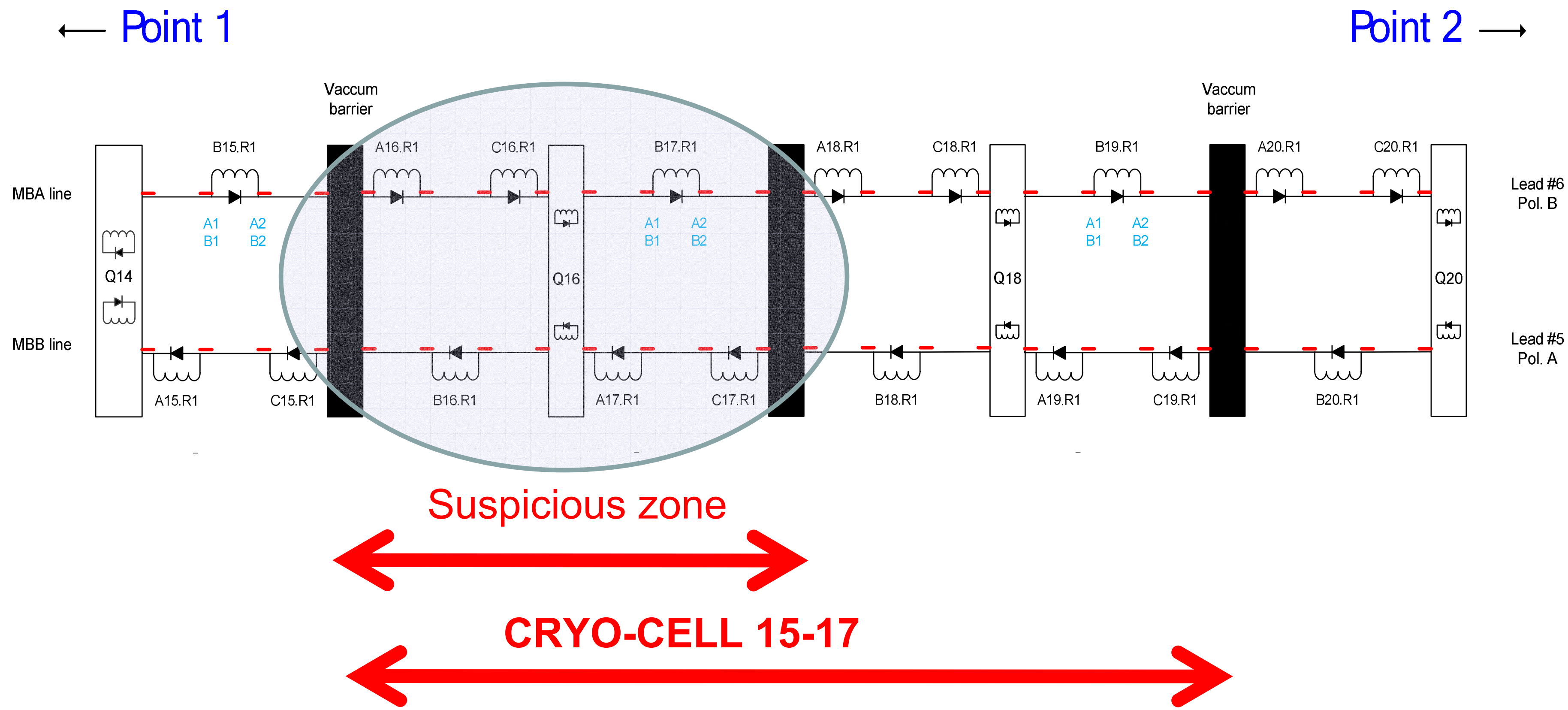
*: Calculated on the basis of 0.33 nW per splice and verified with the 5000 A plateaus



→ Local resistance: ~90 nohms confirmed by electrical measurement !

→ Nominal dissipation 13 W: OK w/r to the cooling loop capacity margin

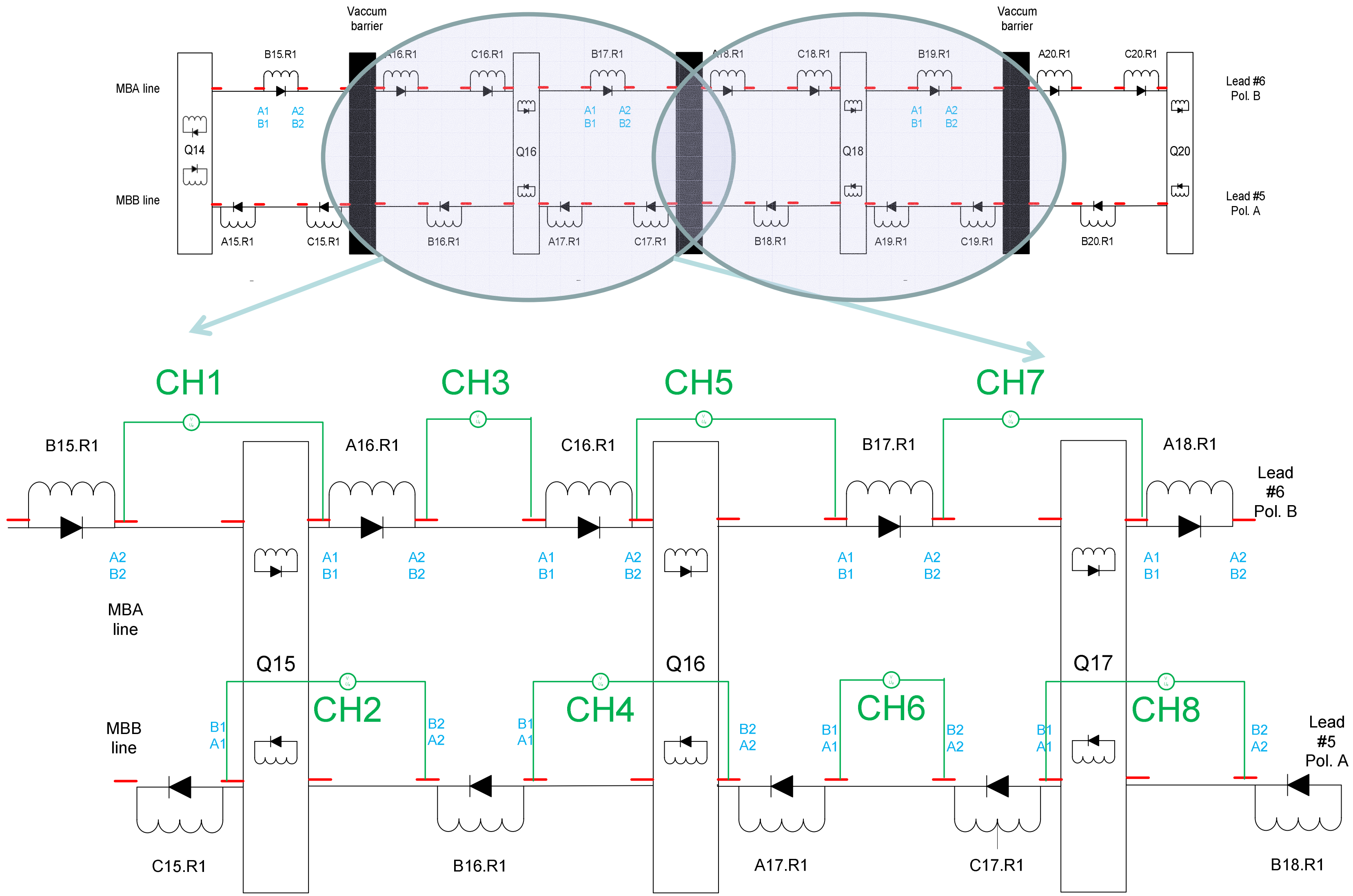
Schematic of the RB circuit in Sector 1-2 half-cells 14 to 20



Installation of 8 nanovoltmeters for monitoring interconnections in half cells 15&16 Sector 1-2

LHC 2008

← Point 1 Point 2 →



Results of resistance measurements

LHC 2008

Half-cells 15&16

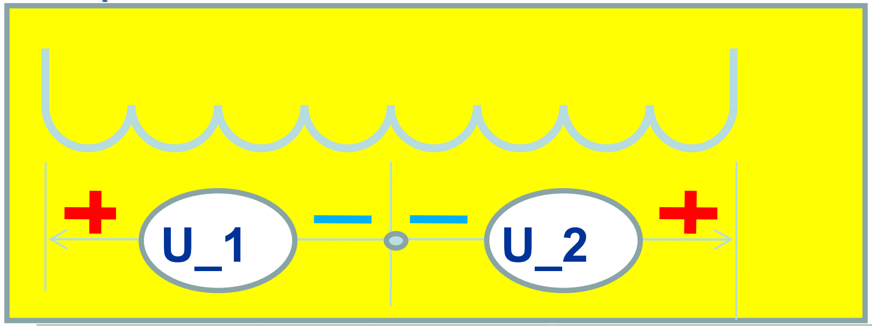
Channel	Resistance	No of splices	R/ Splice
CH1	1.18	3	0.39
CH2	1.07	3	0.36
CH3	0.75	2	0.38
CH4	0.97	3	0.32
CH5	0.96	3	0.32
CH6	0.48	2	0.24
CH7	1.13	3	0.38
CH8	1	3	0.33
		Average	0.34
		St Dev	0.05

Half-cells 17&18

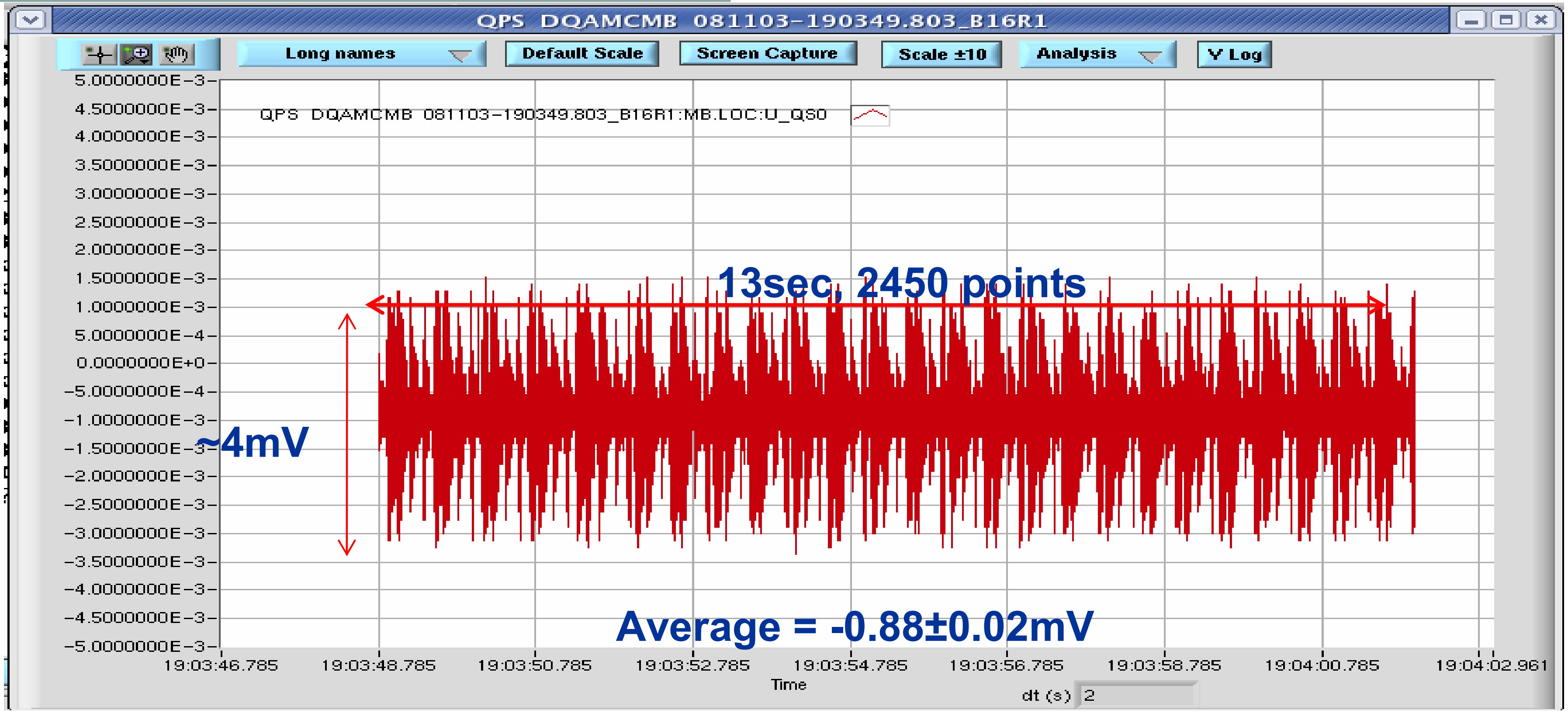
Channel	Resistance	No of splices	R/ Splice
CH11	1.069	3	0.36
CH12	1.14	3	0.38
CH13	0.694	2	0.35
CH14	0.81	3	0.27
CH15	0.99	3	0.33
CH16	0.75	2	0.38
CH17	1.175	3	0.39
CH18	0.98	3	0.33
		Average	0.35
		St Dev	0.04

Sector A12: A15R1 – C19R1

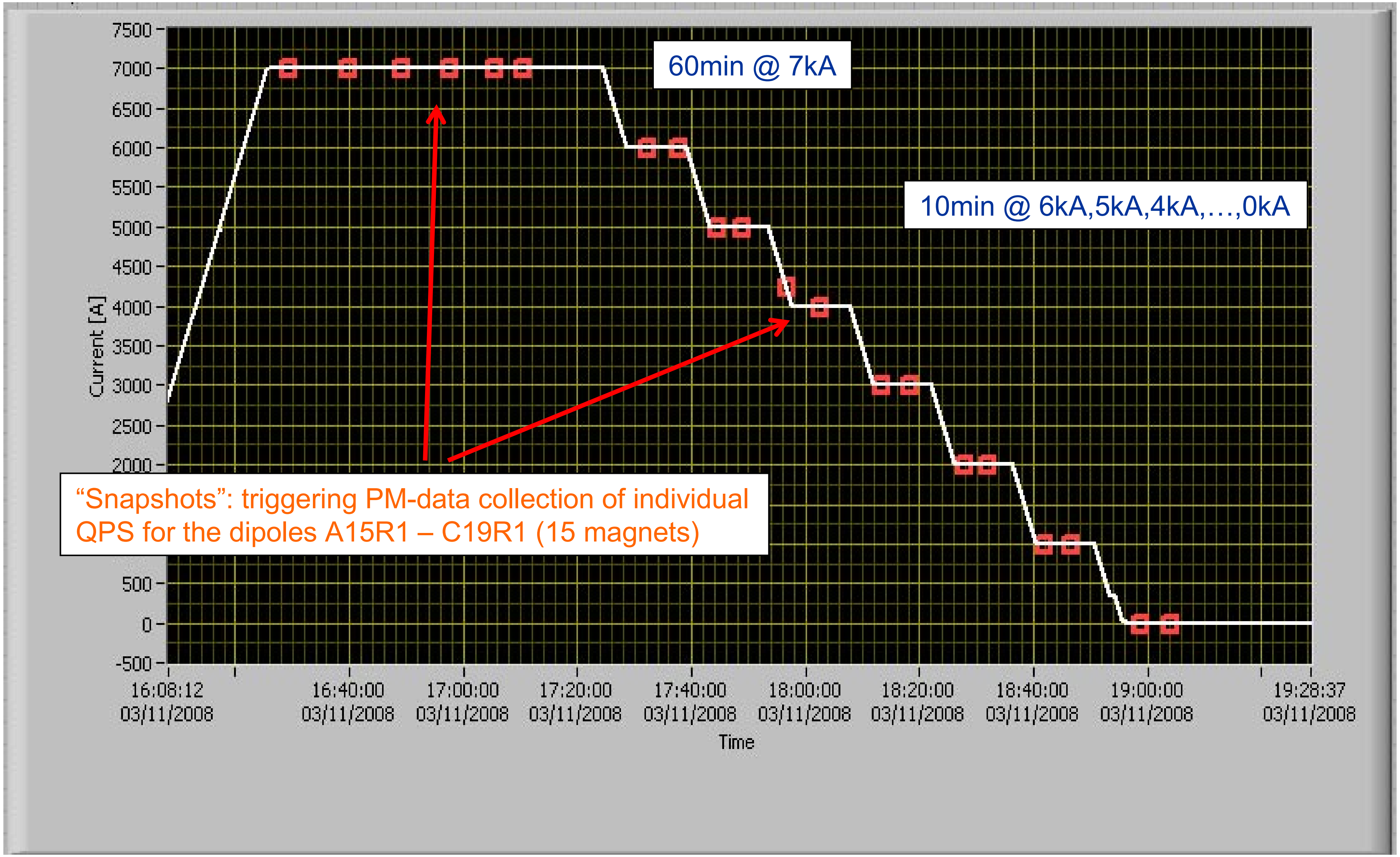
Internal splice measurements by « snapshot »



U_QS0 => -(U_1+U_2)
Sampling Rate = 5ms
Resolution = 0.125mV
Quench Threshold = 100mV@10ms



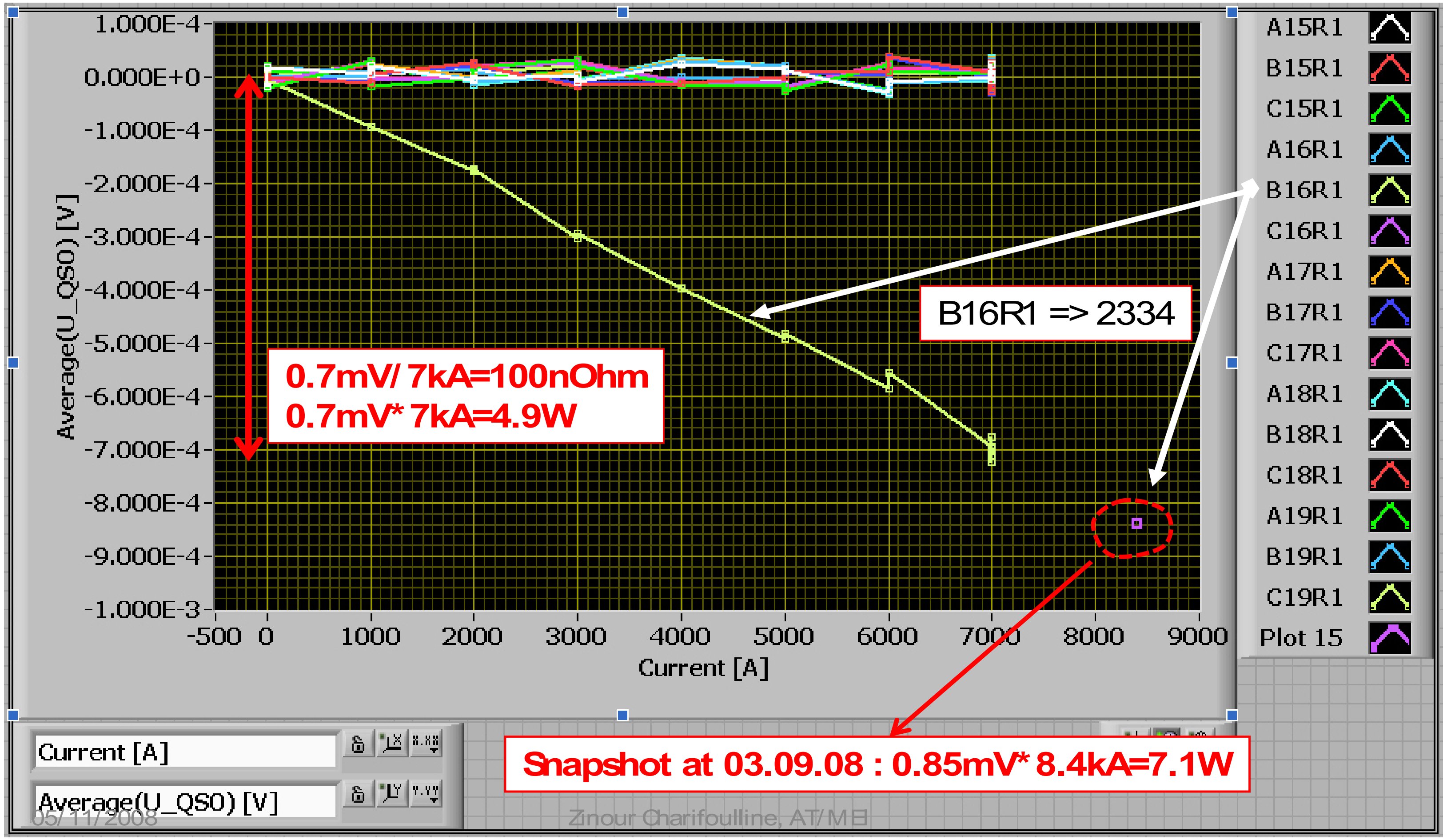
Sector A12: A15R1 – C19R1
Internal splice measurements by « snapshot »



Courtesy Z. Charifoulline

100 nΩ resistance in dipole B16.R1
in the splice between the two apertures

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



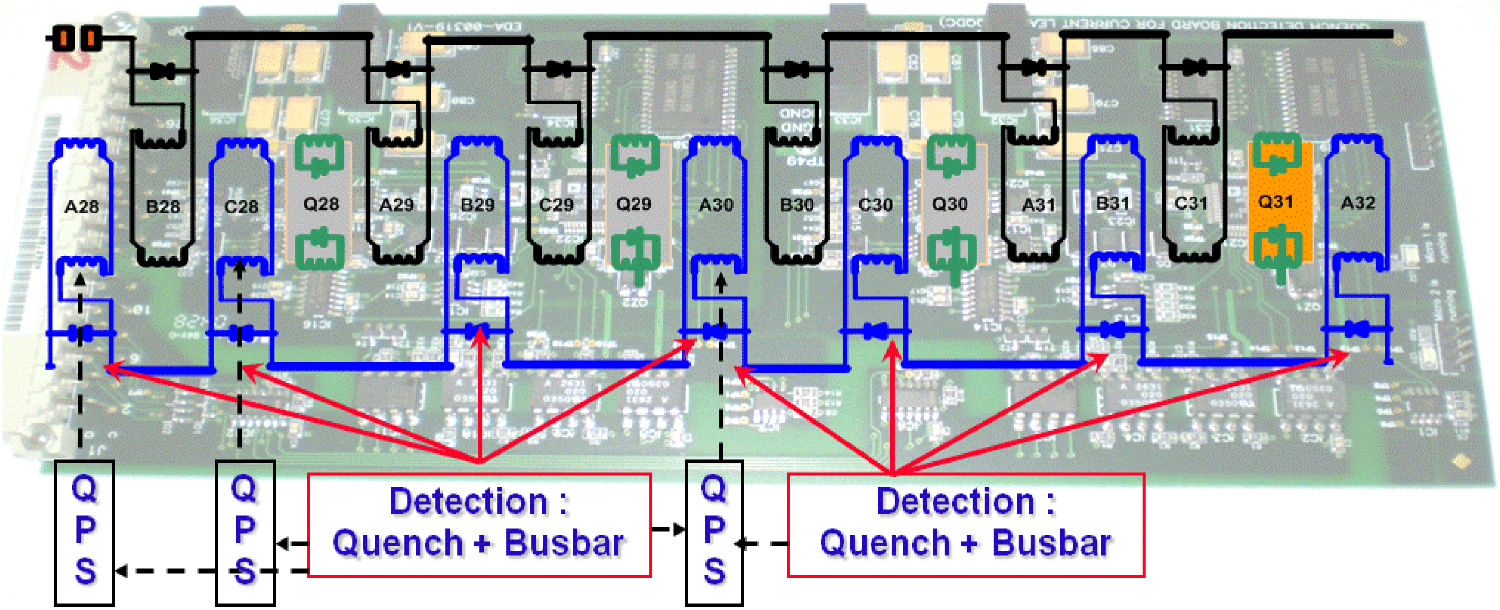
Snapshot measurements on all 154 dipoles in S 67 and 78

B32.R6 shows 47 nΩ joint resistance between poles of one aperture

LHC 2008

Results from provoked massive Post-Mortem of all dipoles in sectors 67 & 78

Design of new protection system for LHC Bus Bars



Splices measured in the LHC with 0.1 nΩ accuracy
3000 times more sensitive protection (0.3 mV) tested experimentally
180 km of instrumentation cable to install
Manufacturing of > 6000 electronic boards and 450 crates launched

Repair status

- 53 magnets (39 dipoles and 14 SSS) to be removed from the tunnel
- All fully disconnected
- 47 magnets removed by end 2008, leaving 6 for 2009
- 4 dipoles reinstalled by end 2008

19 September incident at LHC sector 3 4
Magnet removal from the tunnel

19 September incident at LHC sector 3 4
Magnet repair in SMI2

LHC 2008

The plan for 2009

the milestones