Status of the LHC Machine
'2008 Agenda and Events'

A Very Eventful First Year!

O. Brüning

CERN, Geneva, Switzerland

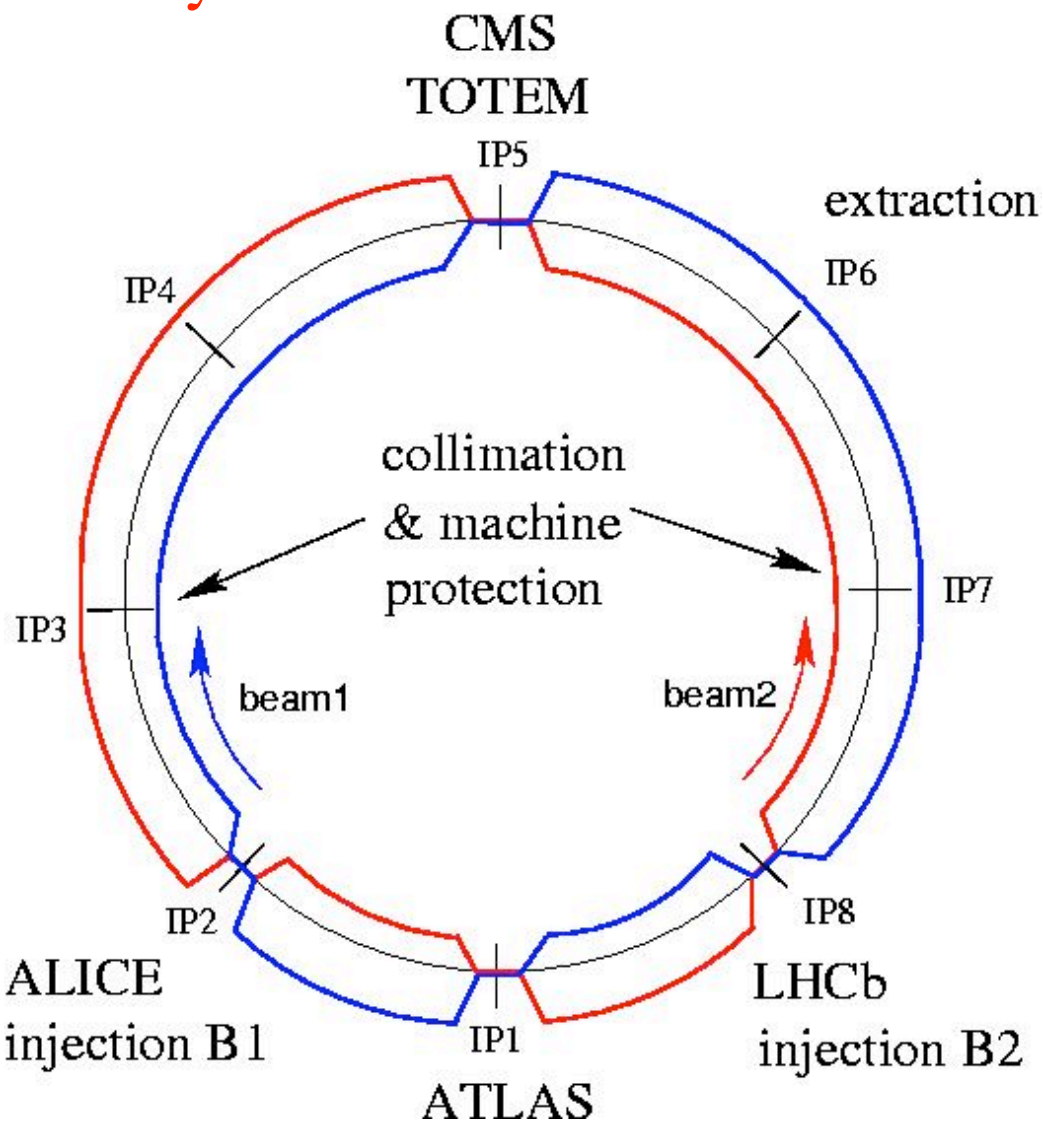
On Behalf of the whole LHC Commissioning Team

Contents

- Introduction: what is the LHC
- Status at the Beginning of 2008
- Hardware Commissioning
- Beam Commissioning
- Events at the End of September

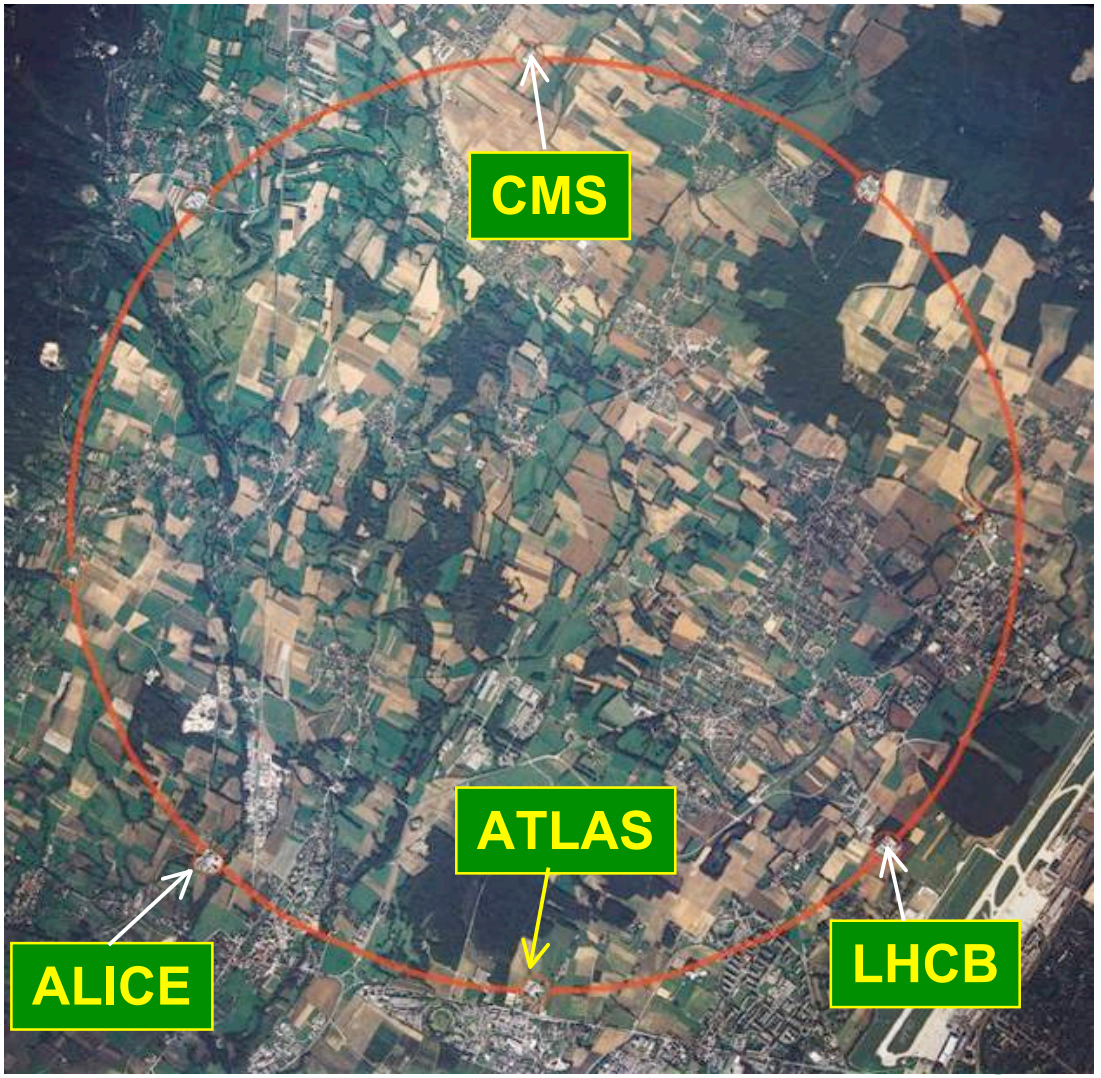
LHC Layout

- 2-in-1 magnet design
  p-p & Pb-Pb collisions
- 7 TeV p-beam energy
  ➔ > 1 TeV CM energy
  ➔ Higgs discovery
- 2 high L experiments with
  $L = 10^{34}\ cm^{-2}\ sec^{-1}$
  ➔ 2808 bunches / beam
  with 1.15 10^{11} ppb
- 2 low L experiments:
  ALICE (Pb-Pb) & LHCb

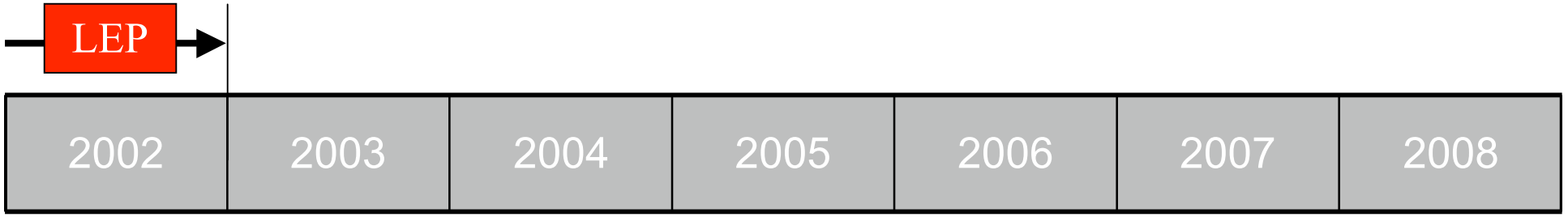


LHC Layout

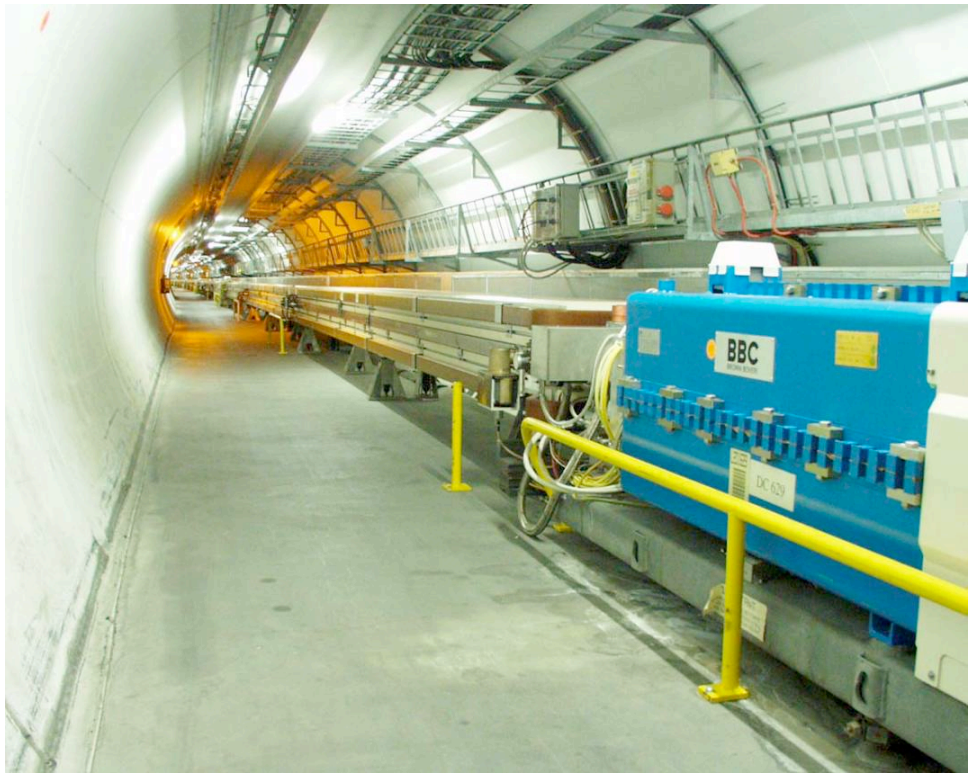
- built in old LEP tunnel
  - ➔8.4 T dipole magnets
  - ➔ 10 GJ EM energy
  - ➔ powering in 8 sectors
- 2808 bunches per beam with 1.15 10^{11} ppb
  - ➔360 MJ / beam
  - ➔crossing angle & long range beam-beam
- Combined experiment/ injection regions



LHC progress 2002-2008: Installation

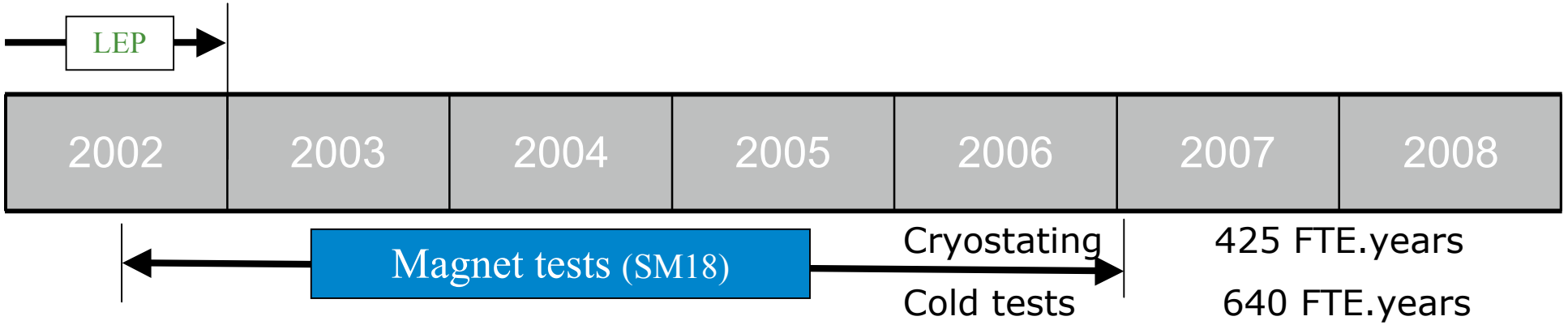


LEP Dismantling



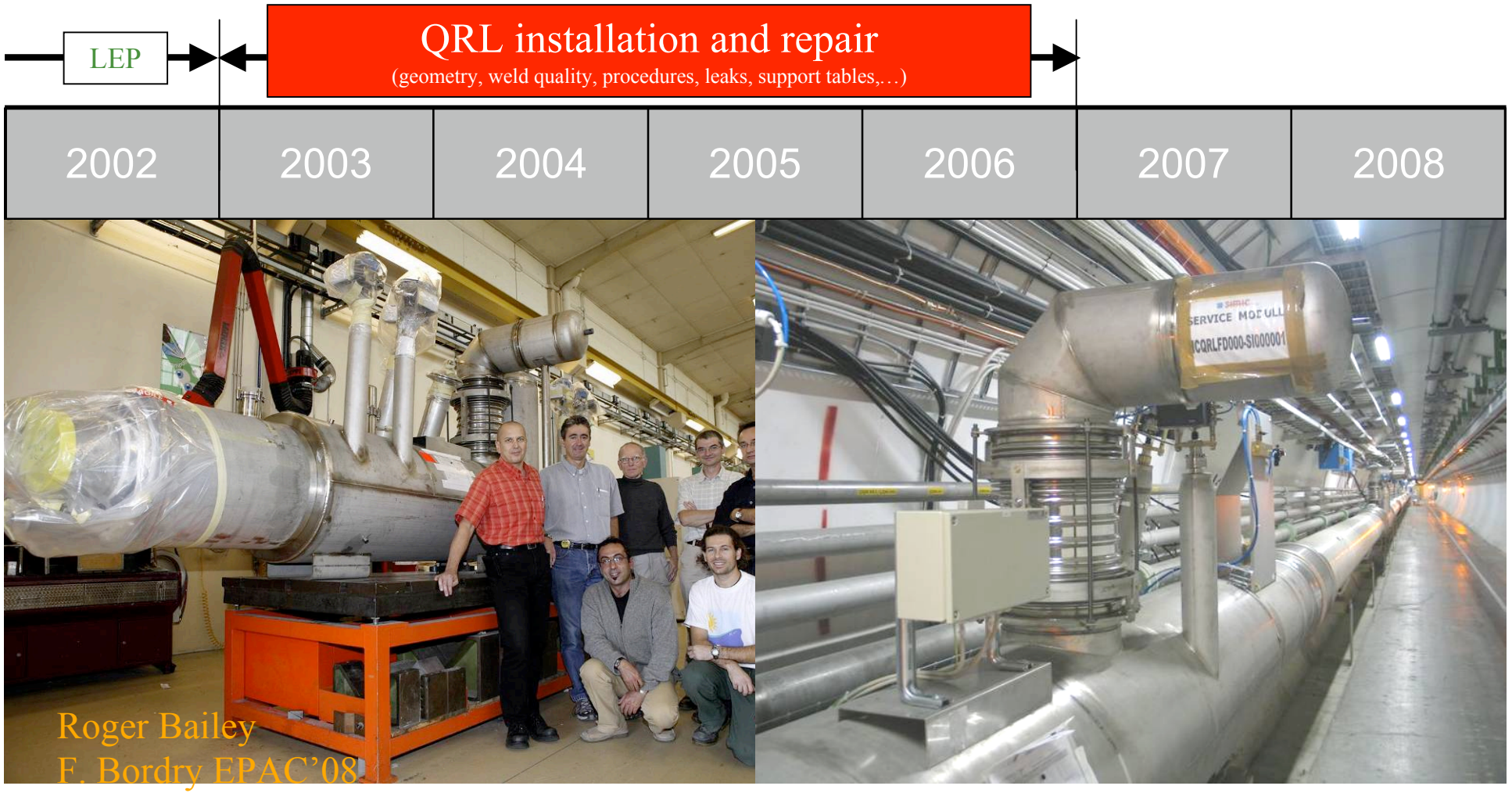
Roger Bailey
F. Bordry EPAC'08

LHC progress 2002-2008: Installation

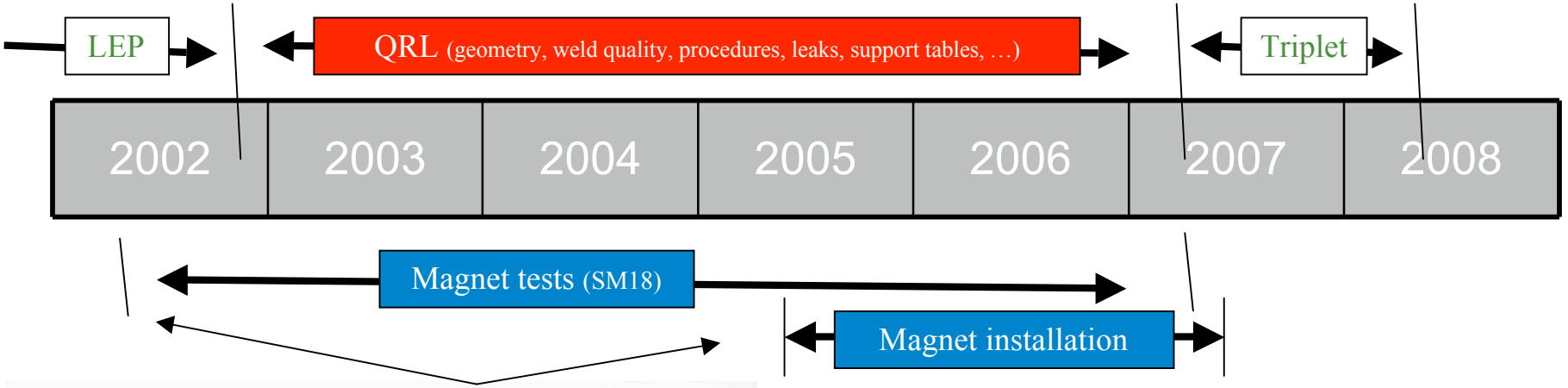


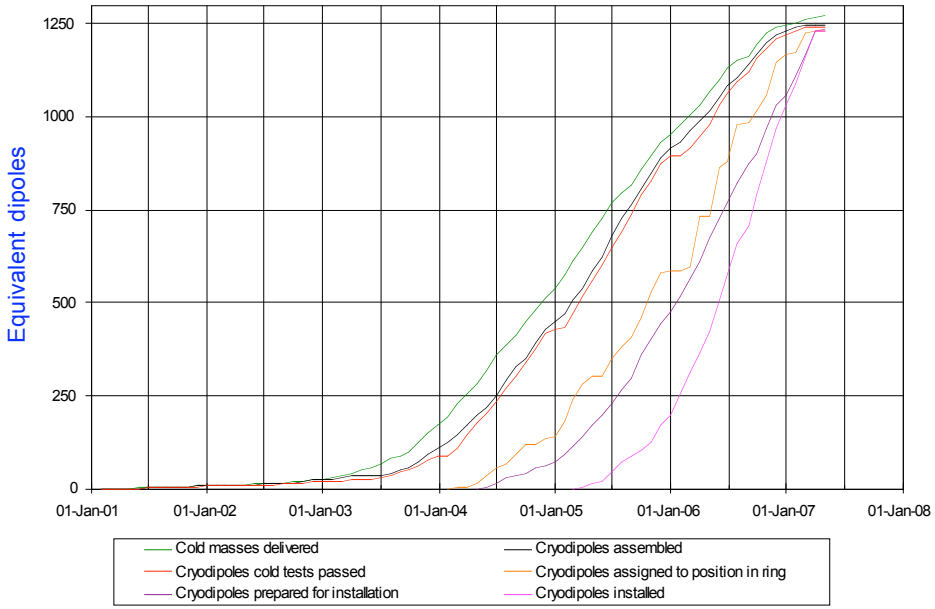
Completion of magnet cryostating & tests, 1 March 2007

LHC progress 2002-2008: Installation



LHC progress 2002-2008: Installation

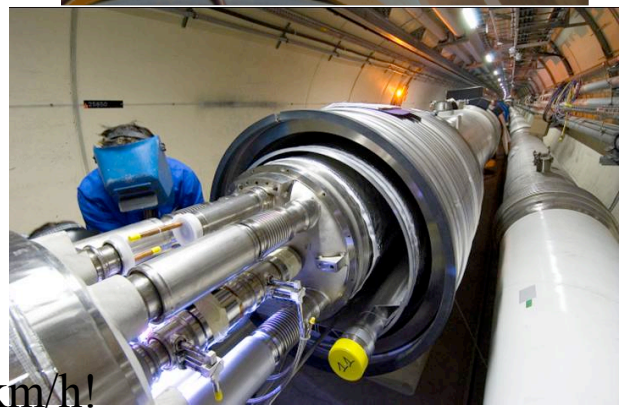


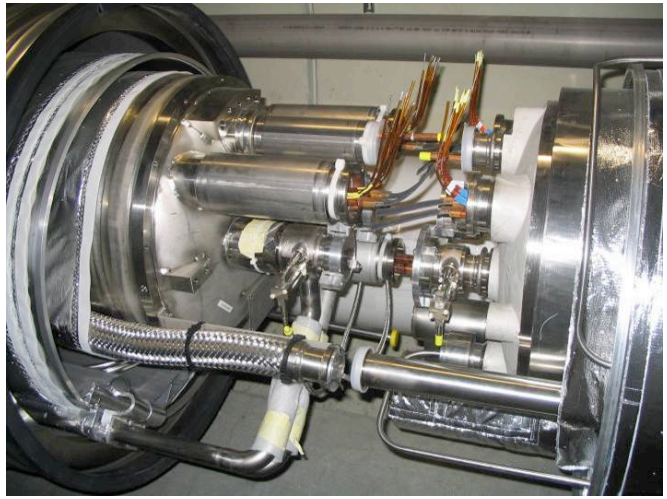


LHC Installation: a complex task

1232 dipole magnets
340 quadrupole magnets

Tight space in tunnel





Single access point:
30'000 km underground at 2 km/h!

Complex interconnections

LHC progress 2002-2008: Problems

Triplet magnets:

Pressure test failed in Sector 7-8 (Nov 2006).
The heat exchanger did not withstand the differential pressure of 9 bar.

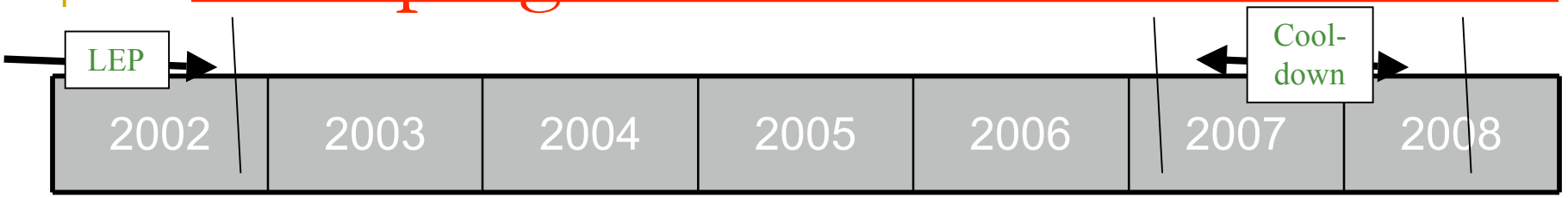
After the repair of the first heat exchanger, pressure test failed in Sector 4-5 (March 2007).
Axial movement of the Q1 cold mass due to the thrust force (12 t at 20 bar), which led to the breaking of the support system and rupture of the bellows between the first two quadrupoles.

➔Start cool down of arc without triplet!

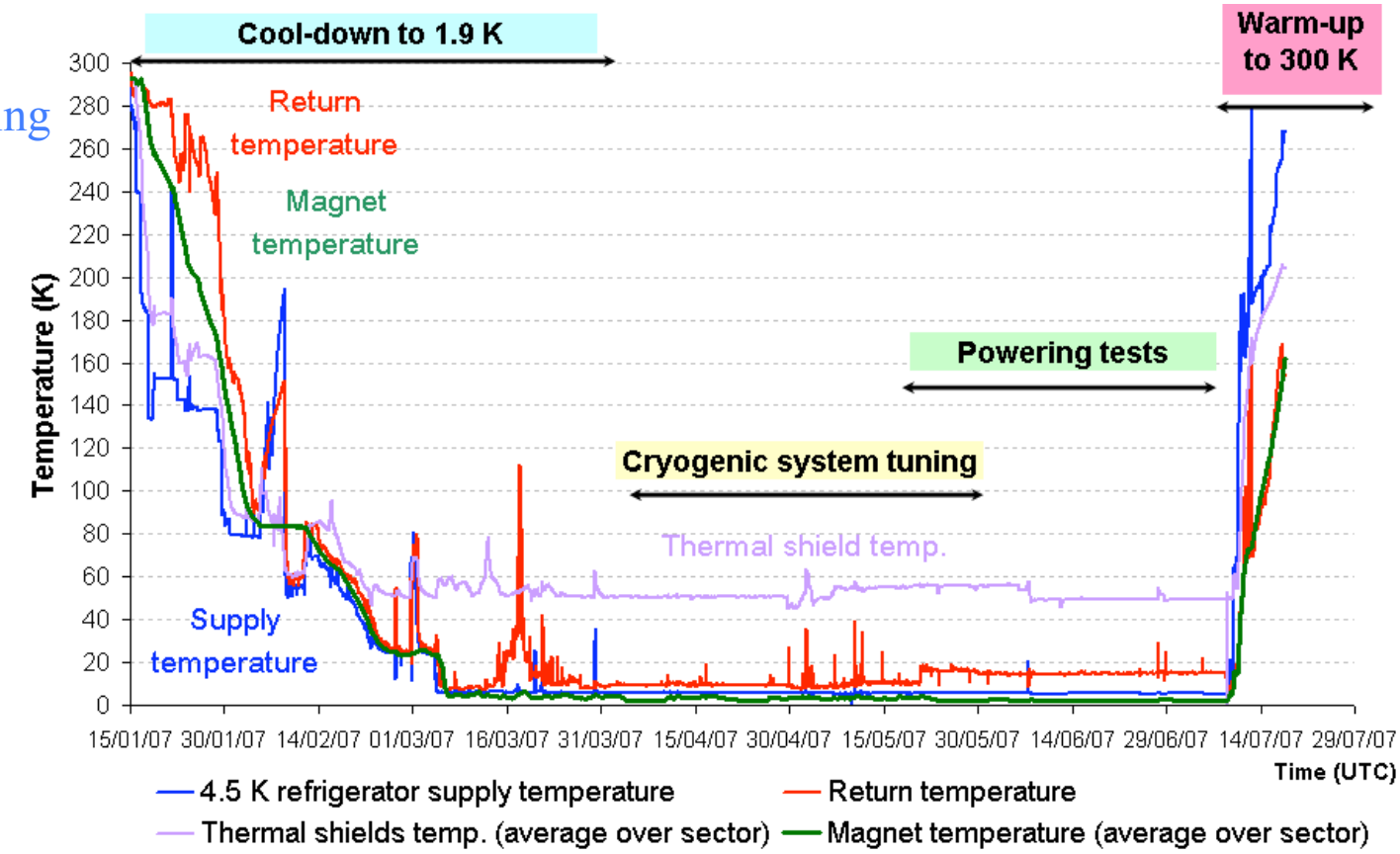
➔ warm up in two sectors!

F. Bordry EPAC'08

LHC progress 2002-2008: Cool Down

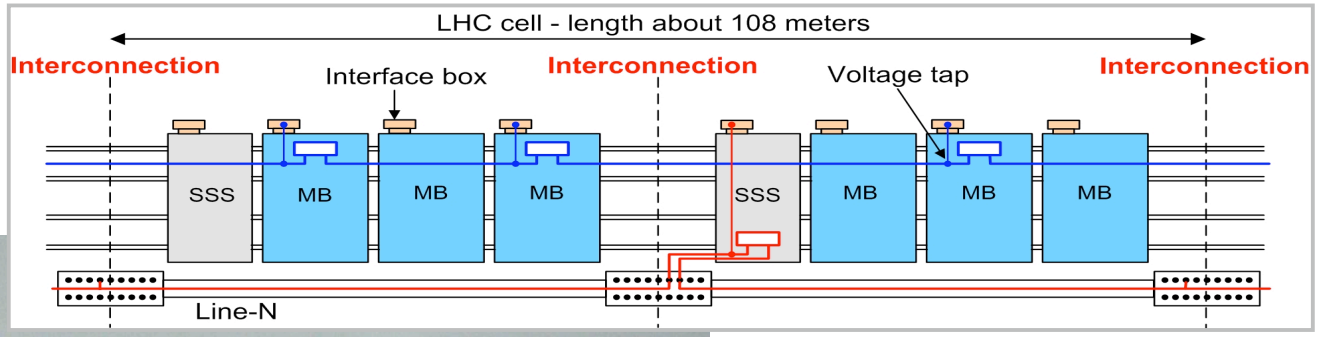


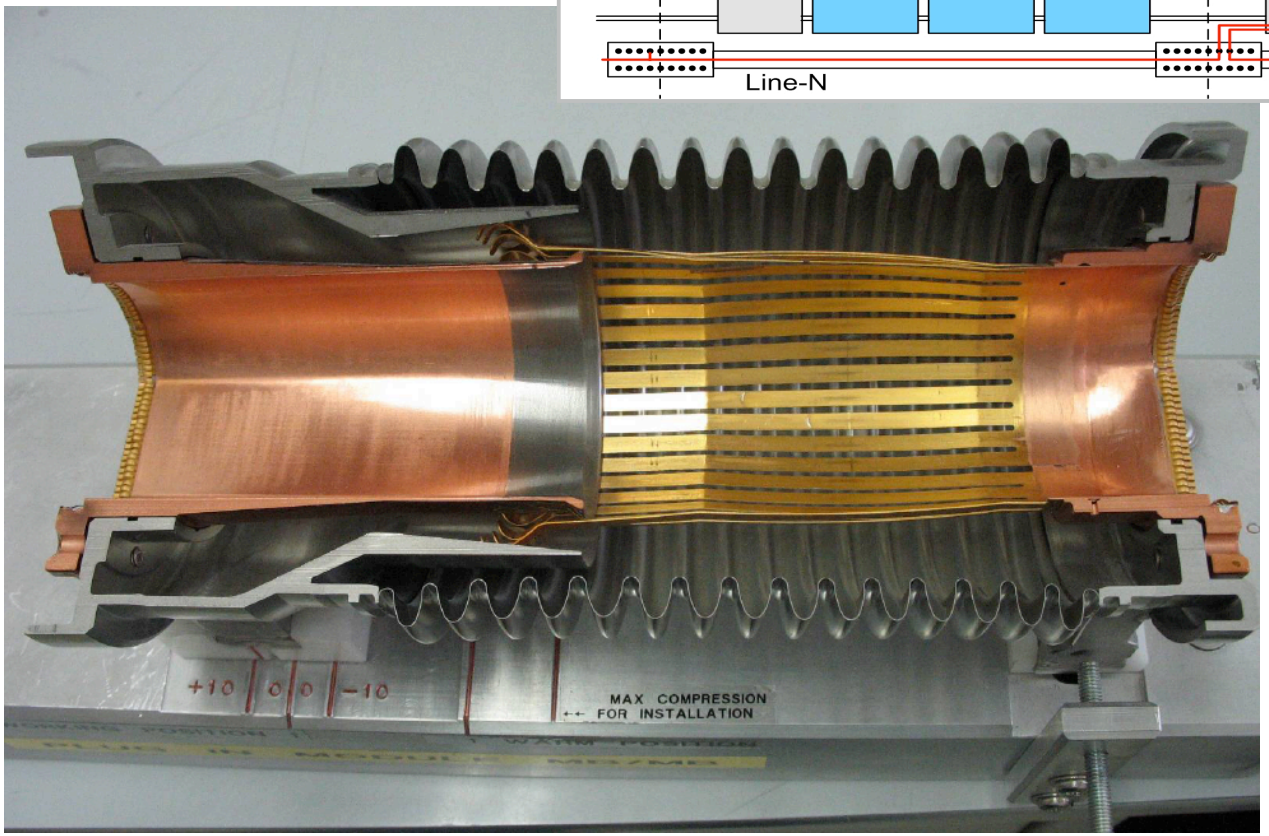
First cool down in Sector 78: fine tuning of the Cryogenics control



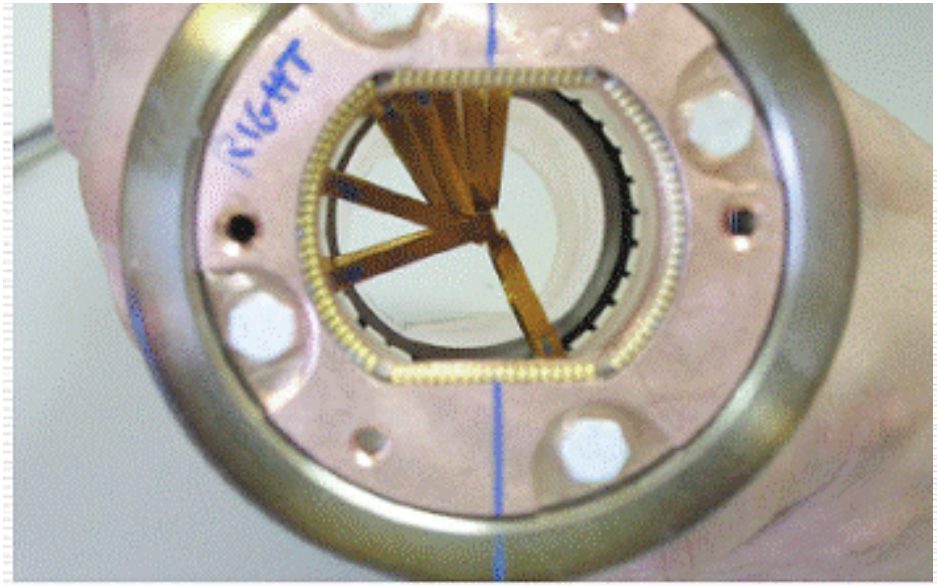
S. Claudet
LHC MAC 22

RF bellow deformations in interconnections

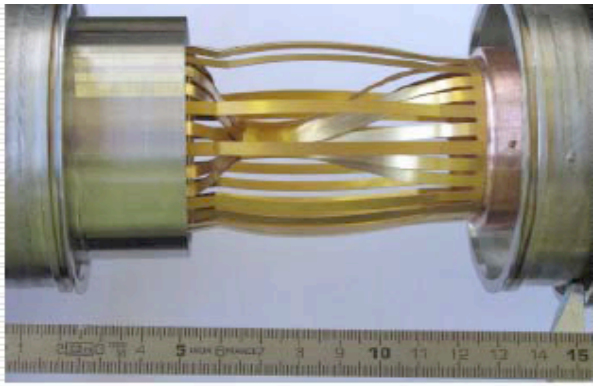


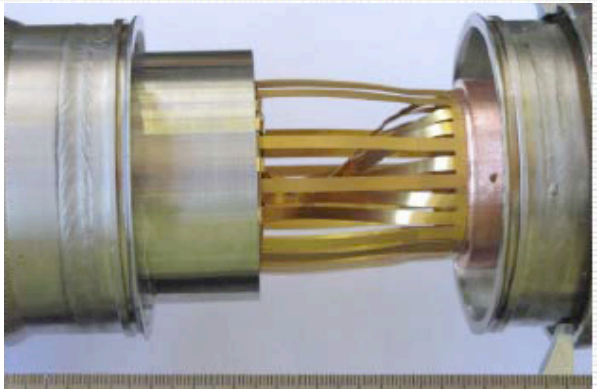


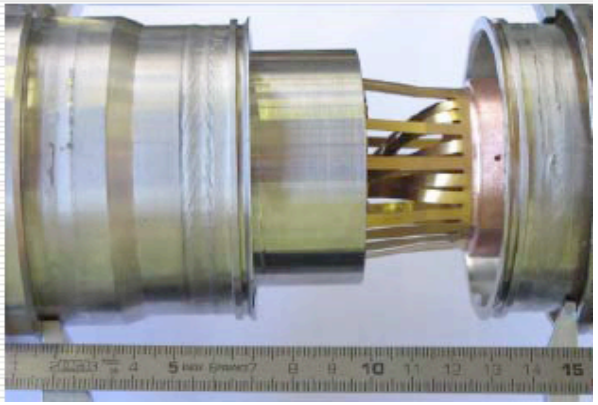
RF bellow deformations in interconnections



Not optimal conditions for the beam !





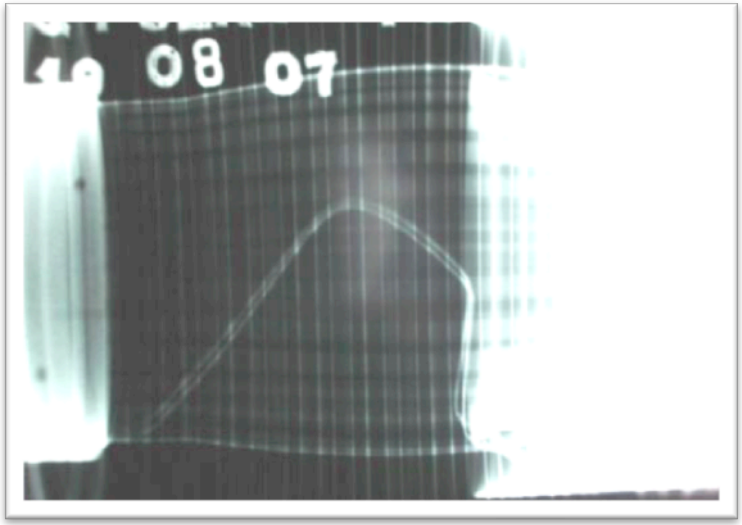


Warm

F. Bordry EPAC'08

Non-conforming contacts, simulating warm-up from cold

RF bellow deformations in interconnections



-16 PIM with buckled fingers of which 9 where unexpected.
-In total 28 PIM were replaced.
-The interconnects of the whole sector were X-rayed

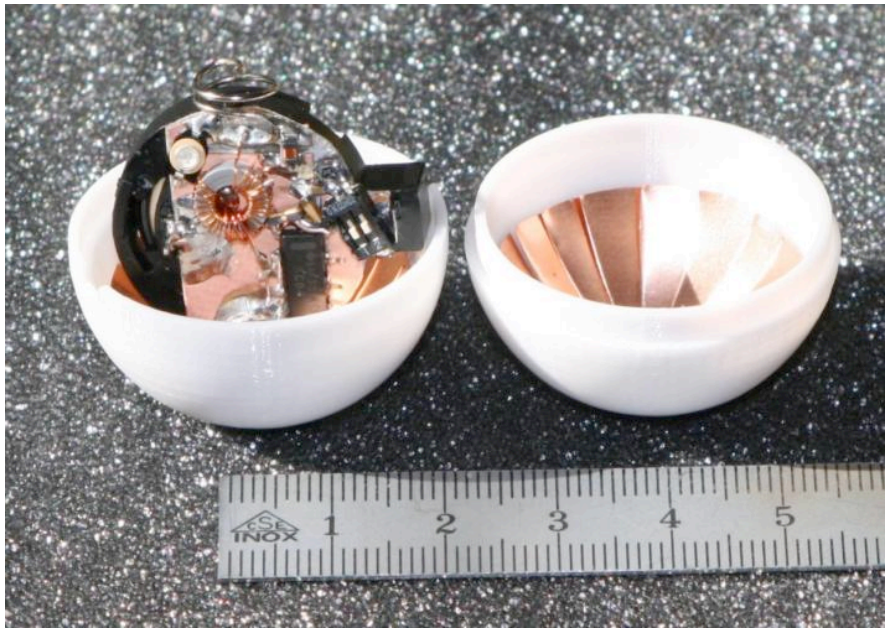
A ball is sucked in at one end of the sector :

- 34mm exterior, 30mm interior
- Total weight ~15 g (ball 8g)

RF characteristics

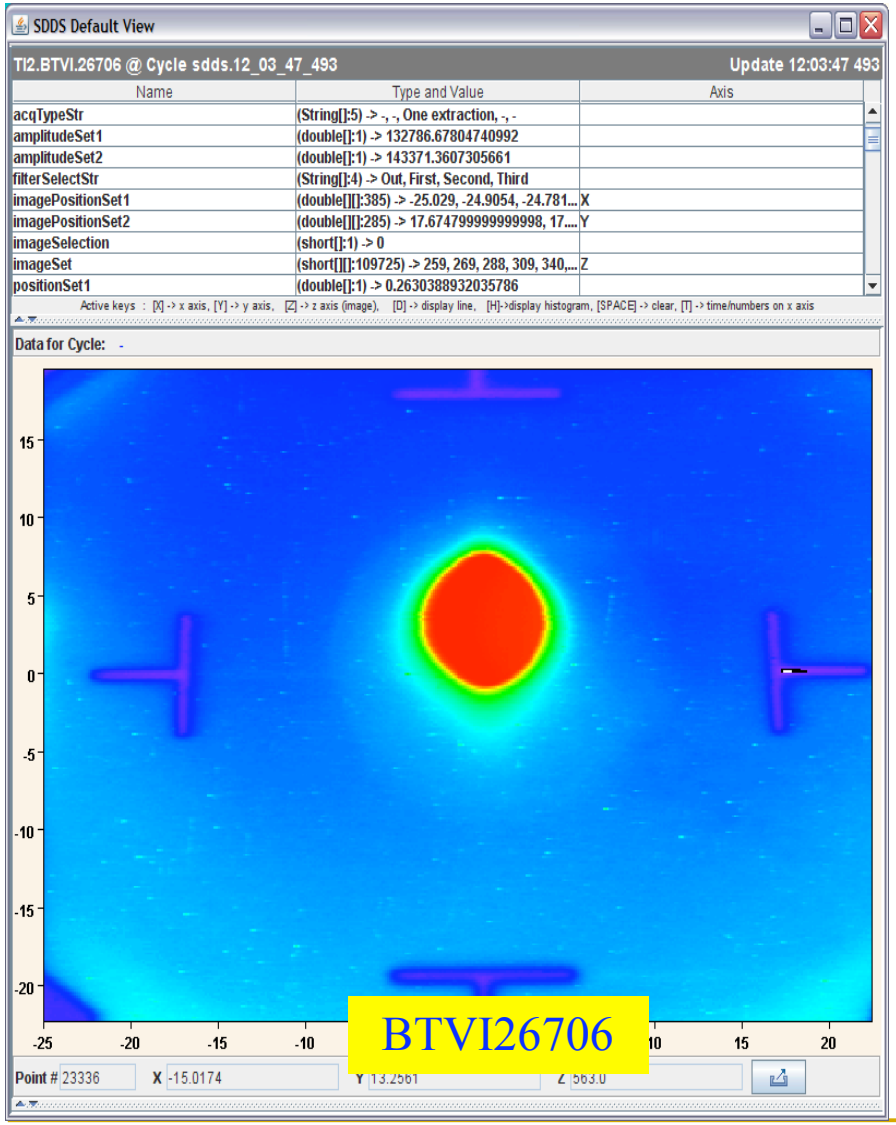
- 40MHz resonant circuit
- Generates 20V between copper electrodes
- Battery powered Over 2hr lifetime

-BPM trigger threshold at ~3mV



Good opportunity to test BPM functionality!

LHC progress 2002-2008: Transfer Lines



(TI8 test was successfully done in 2004)

First shot straight down the line at 12:03:47 on 28 October 2007

This BTV screen is the last in the part of TI2 which could be explored with beam on 28 October. It is located some 70 m after the lowest point in TI2, and some 700 m away from the temporary dump, which in turn is placed at some 50 m from the end of the TI2 tunnel, to avoid irradiating the LHC area.

Lyn Evans LHC MAC 22

Courtesy of V. Mertens

Status at the Beginning of 2008

- Installation: 2002 to 2008
- Issues related to QRL installation:
  - ➔ required partial re-installation of installed QRL line in 78
- Issues related to the triplet magnets:
  - ➔ decision to cool arc without triplets (arc 78 and 45) implied a warm up at later stage
- Hardware commissioning identified weak elements in arc 78:
  - ➔ one dipole limited to 2kA and QF/QD limited to 6.5kA
  - ➔ implied an intervention (warm up) at later stage
- Deformation of the RF fingers in the interconnects
- Successful transfer line commissioning

Main Events in 2008

- First magnet powering in the tunnel: quench tests with large 'string'; synchronous powering of complete arc system; de-training
- Machine cool down: 22. August - all sectors simultaneously at 1.8K; 30. August first cryo OK for complete machine
- Tunnel closure: 5. September - LHC access control enters operational phase
- 'Synchronization tests' with beam:

  first beam steering in injection area; first beam induced quench; inject & dump test
- Commissioning with beam:

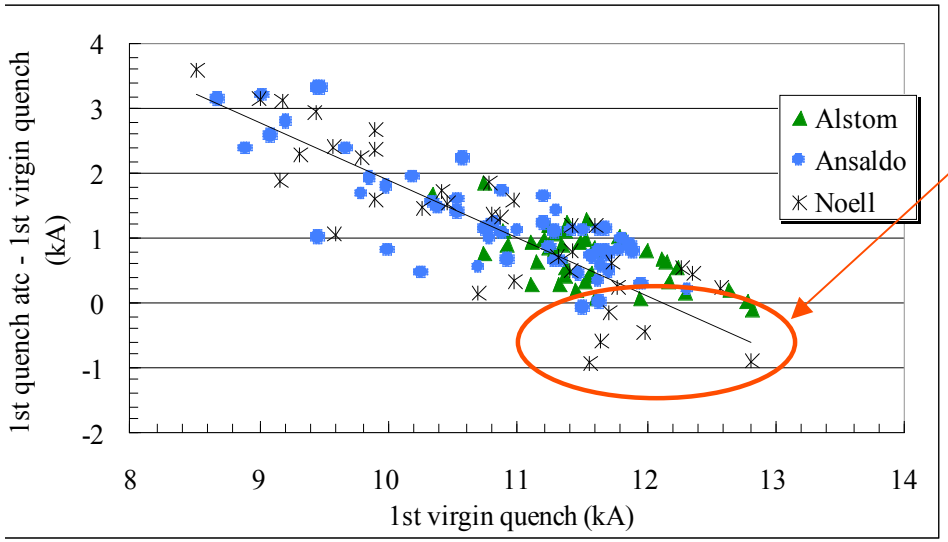
  first turn; orbit correction; aperture verification; tune measurements; optics checks; RF capture with 20 min+ beam life time
- 19. September

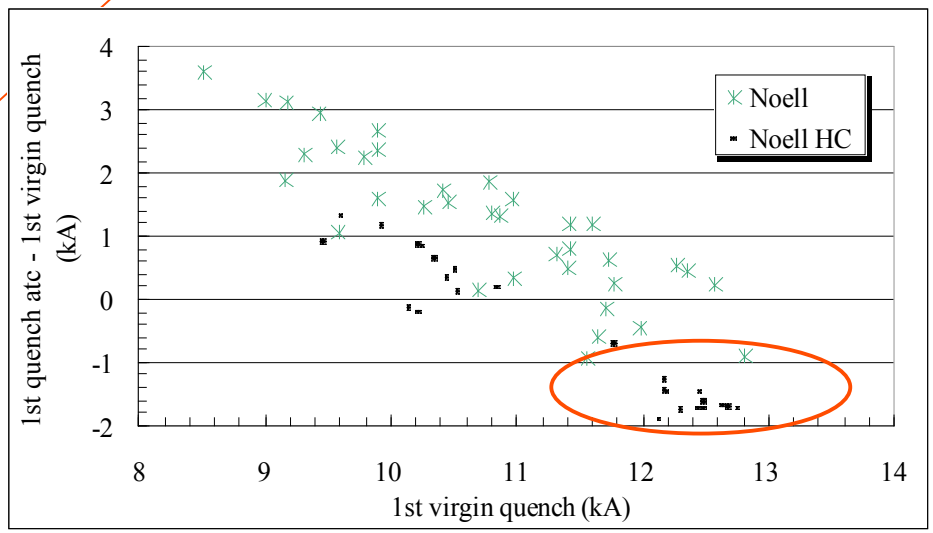
De-Training Effect for Quench Levels

- The LHC magnets have a higher quench level after thermal cycle as compared to 1st virgin quench
  - The gain is the larger the lower the 1st virgin quench

A. Siemko at MAC 23

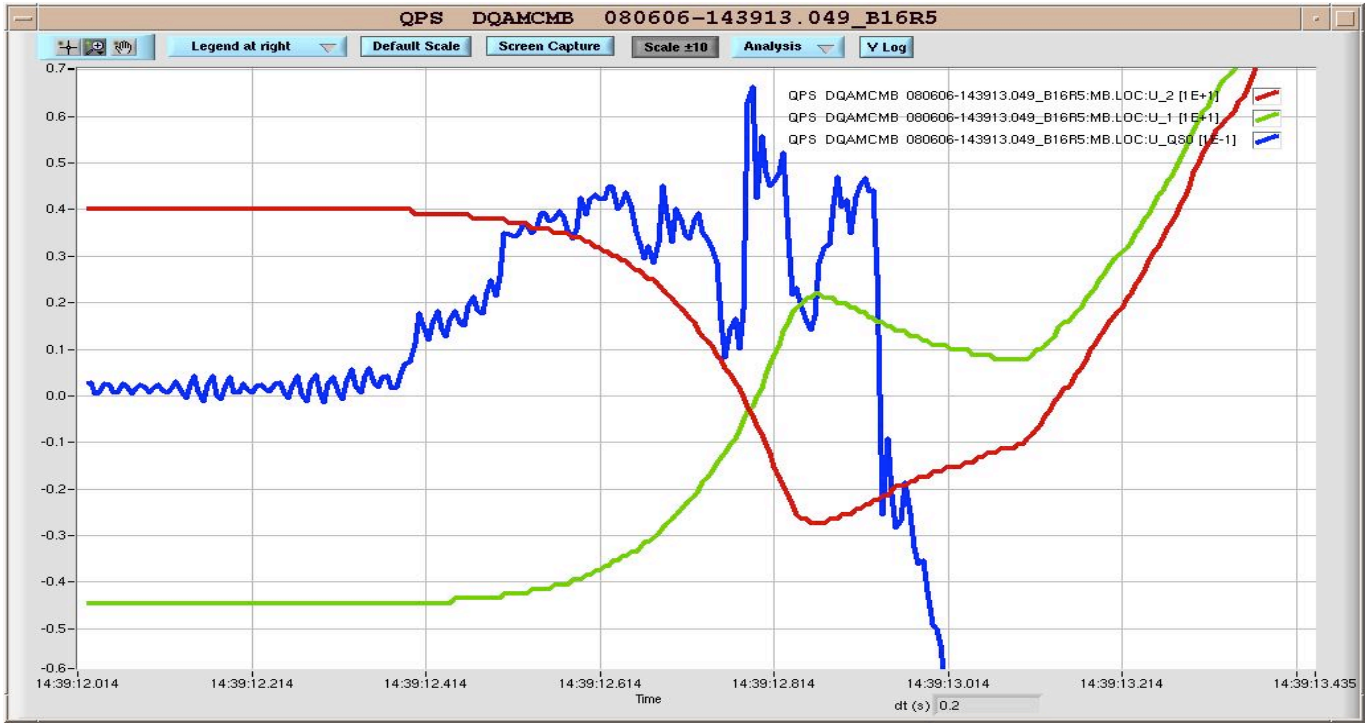
- However, Noell magnets shows some anomalous behavior





- Detraining looks worse for the Sector 56 data
- ➔ decision to perform hardware commissioning in 2008 to 5.5 TeV

Phenomenon of Symmetric Quenches

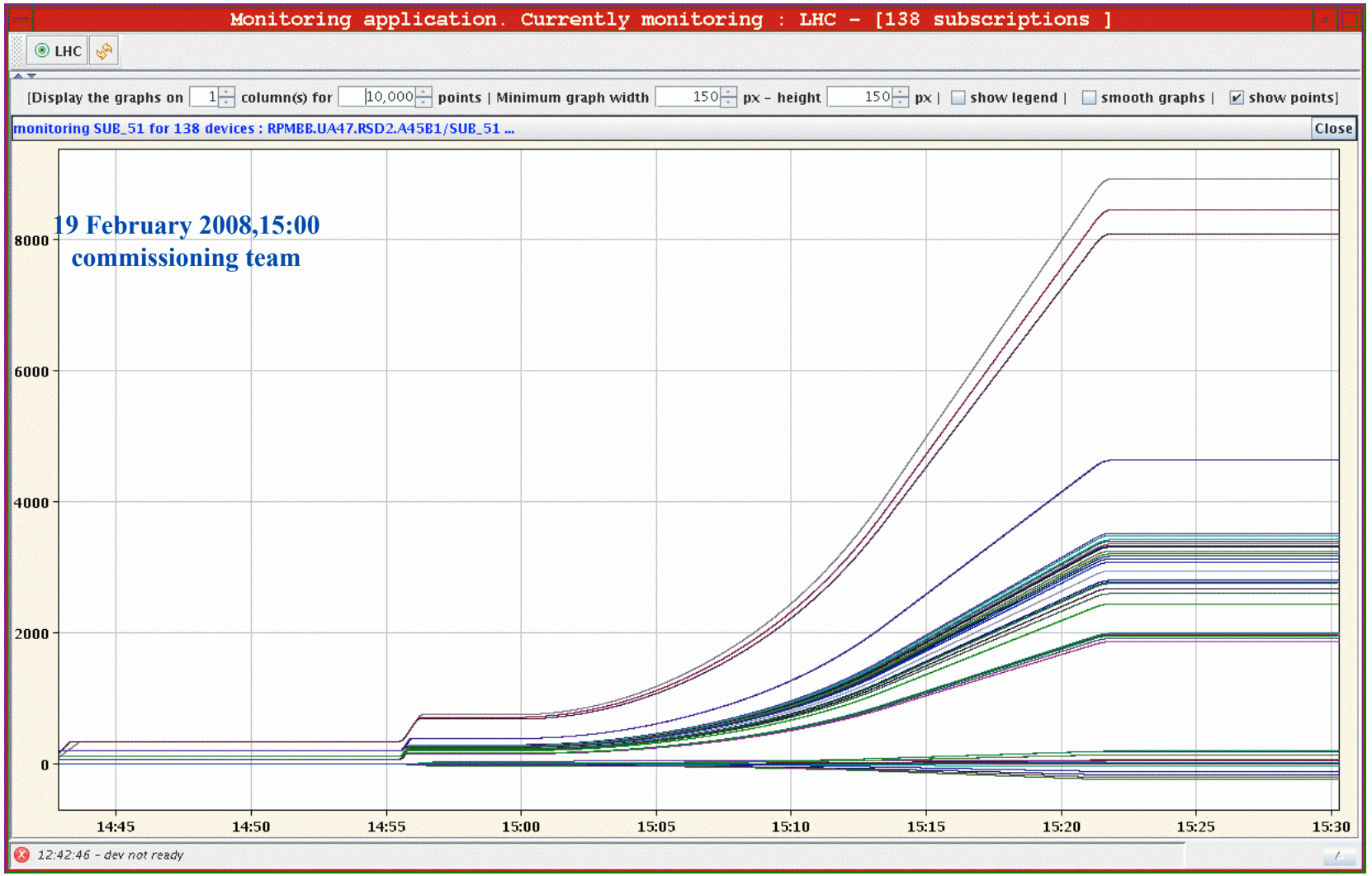


A. Siemko at
B. MAC 23

- In sector 5-6 five symmetric quenches were observed after quench propagation caused by a thermo-hydraulic wave
  - One quench (in B16.R5 at ~7.4 kA) has developed the high "MIITs" and resulting high hot spot temperature
- ⇒ required modifications to the quench protection system!

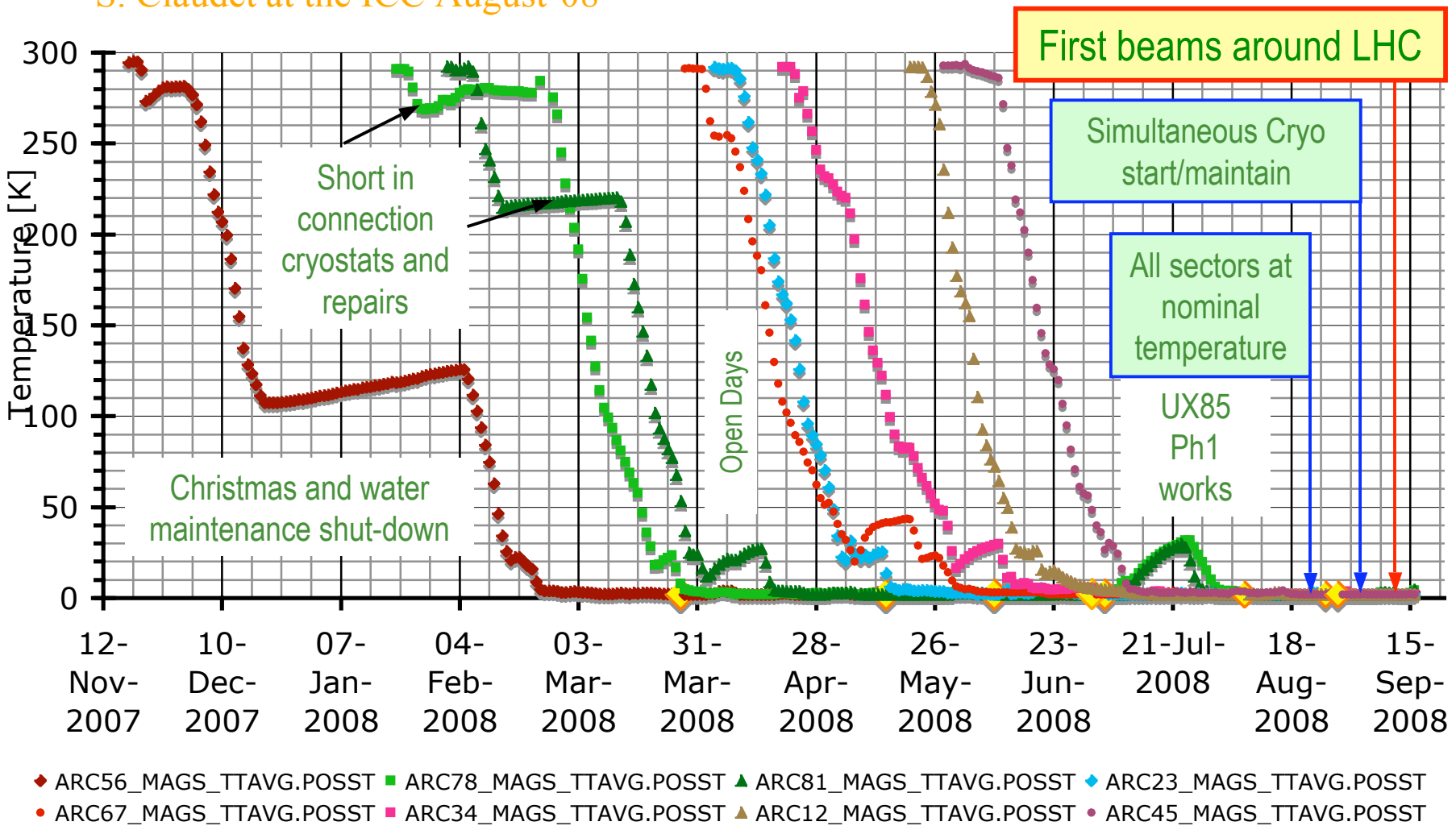
Ramp of 138 power converters to a current equivalent to 5.3 TeV

(including all high current magnets realistic LHC optics)



First cool-down of LHC sectors

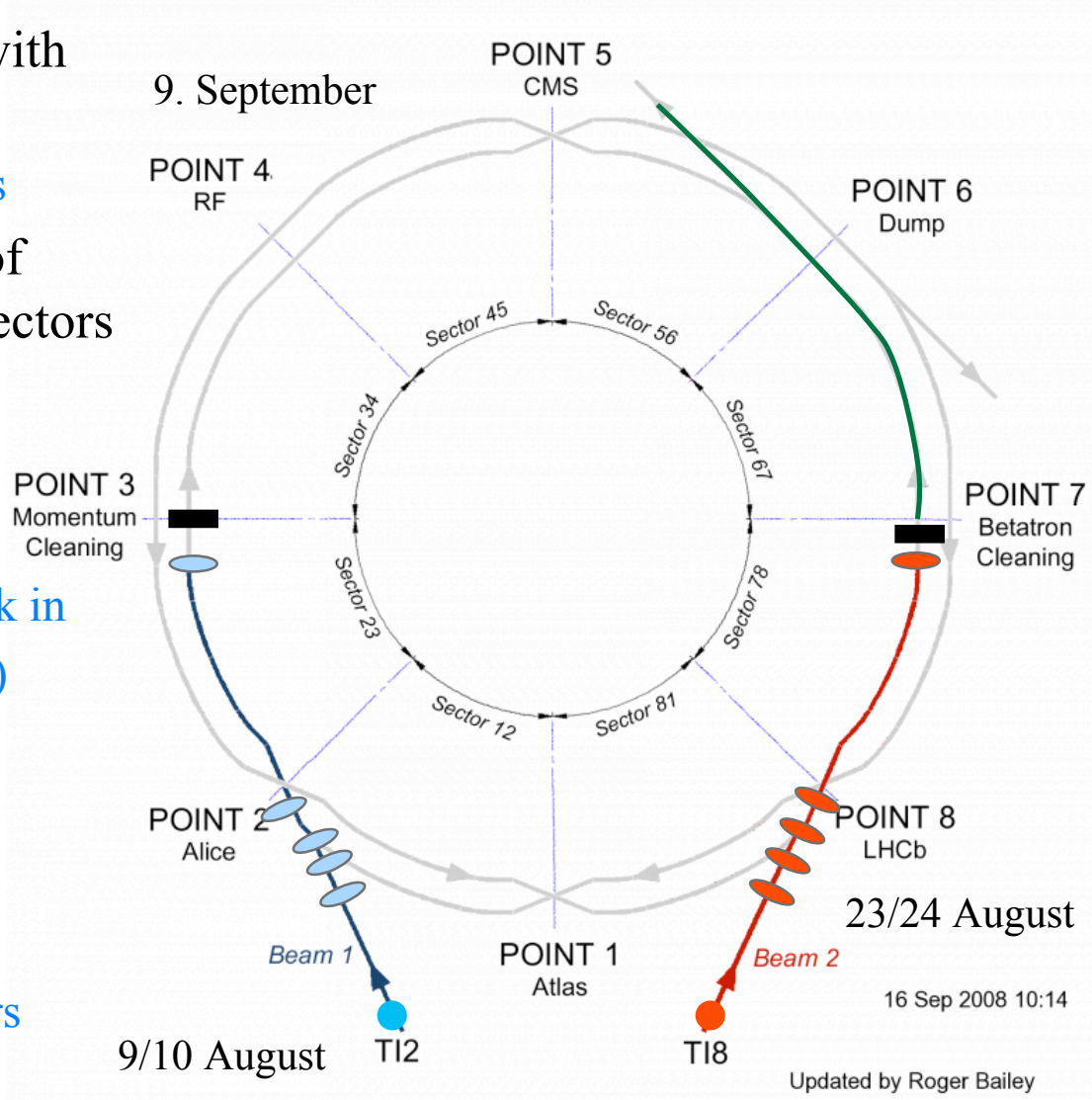
S. Claudet at the ICC August'08



Cooling sectors + Cryo tuning + Powering activities

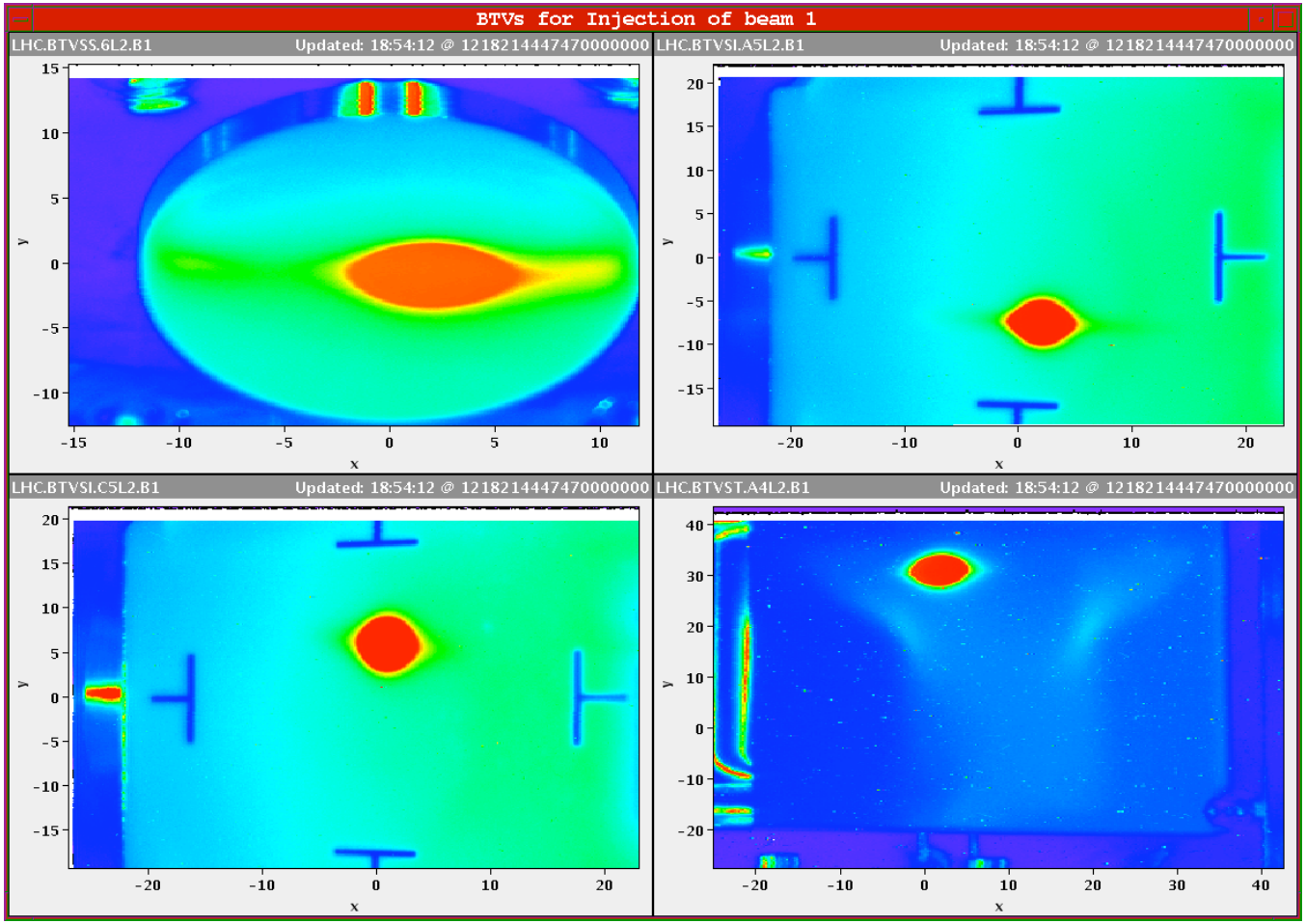
Synchronization Tests With Beam

- Synchronize SPS extraction with LHC injection kickers
  - Adaptation of timing controls
- Magnet polarity verification of injection line and first LHC sectors
  - Sorted out several polarity errors (data base)
- Aperture scans
  - Identified aperture bottle neck in injection area (vacuum valve)
  - First beam induced quench
- BPM & BLM verification
  - Concentrators, data base, thresholds
  - Sorted out several BPM errors
- Inject & dump mode
  - Dump kicker timing



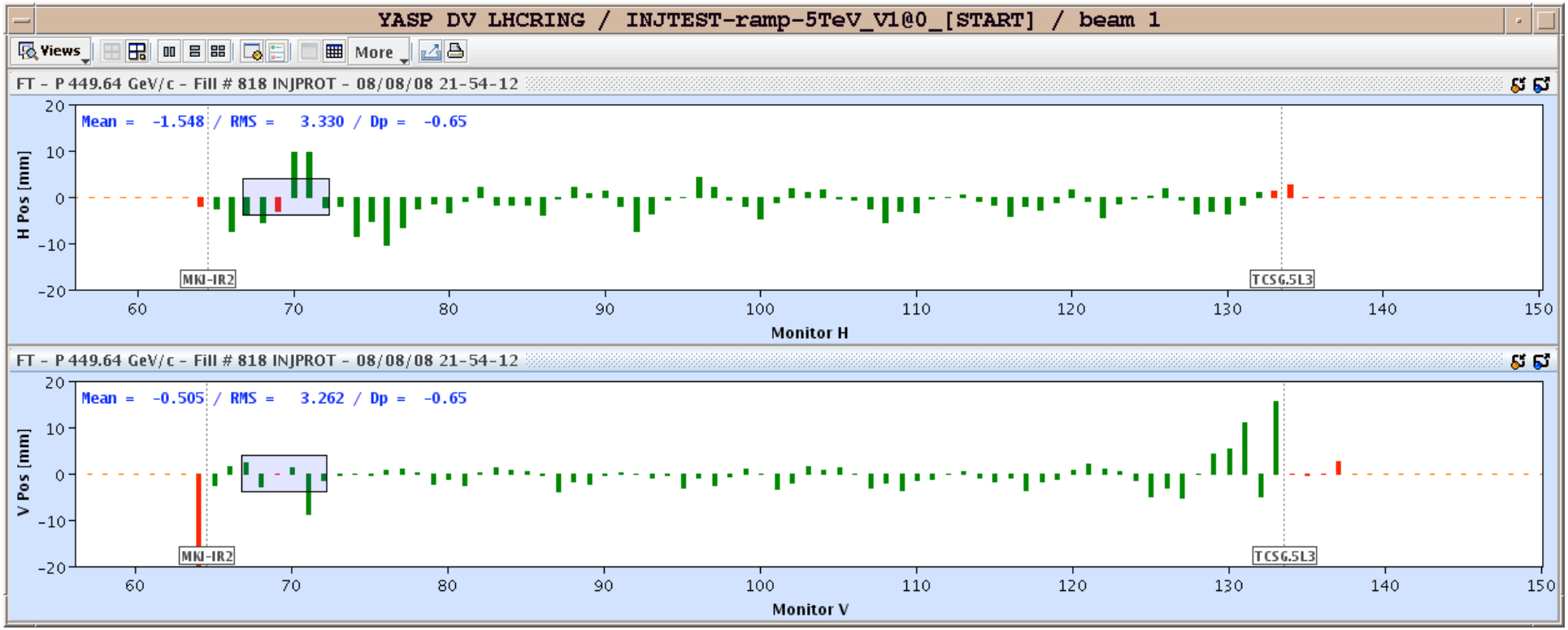
Synchronization Tests With Beam

- First Beam in the LHC: Injection area (Sept, kicker and TDI)



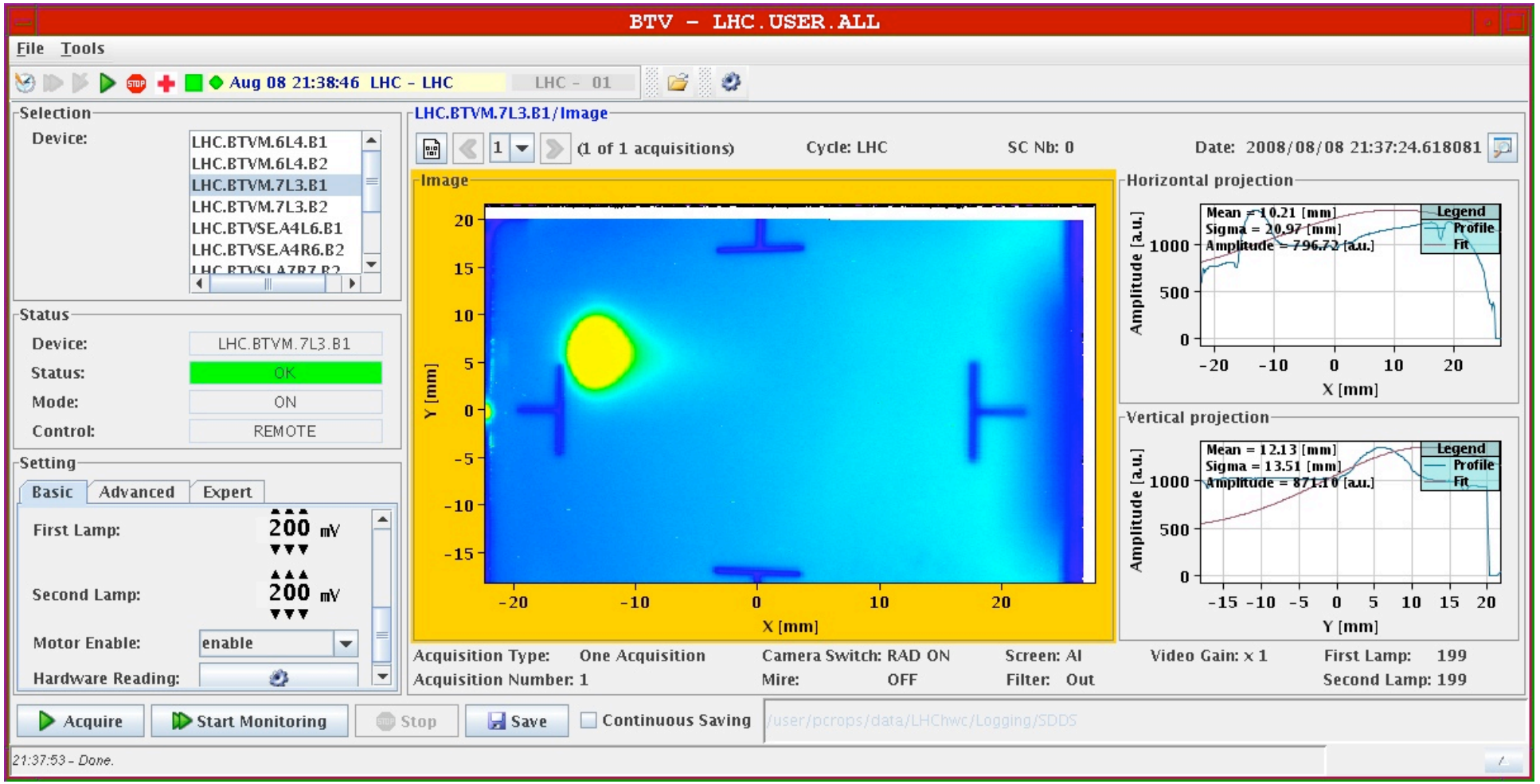
Synchronization Tests With Beam

- First Beam to IR3: First trajectory steering onto collimator in IR3



Synchronization Tests With Beam

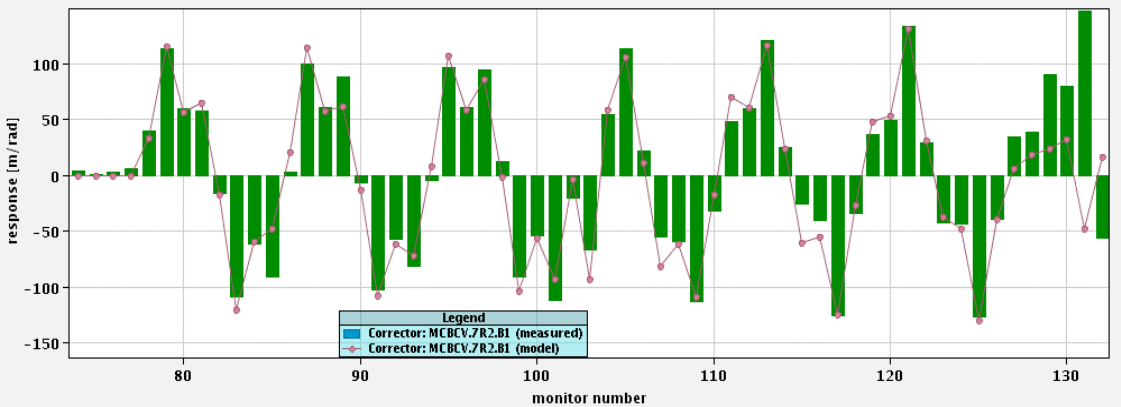
- First Beam to IR3: Beam stopped on collimator jaw



Synchronization Tests With Beam

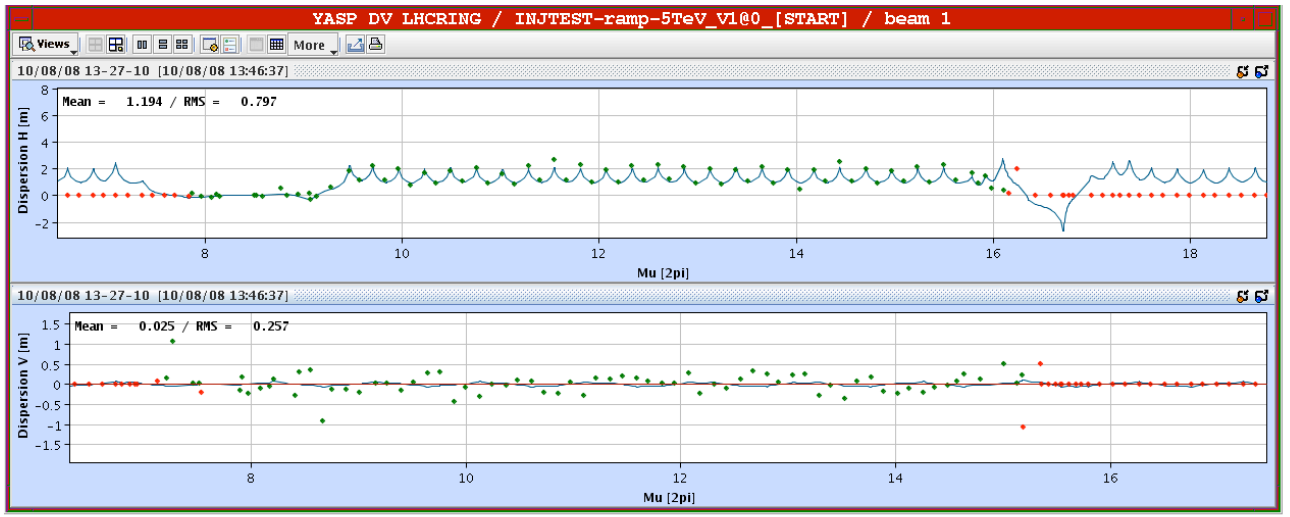
- First Beam to IR3: Kick response ➔ excellent fitting tools!

V. Kain
J. Wenninger



- First Beam to IR3: Dispersion orbit measurement ➔ polarity errors

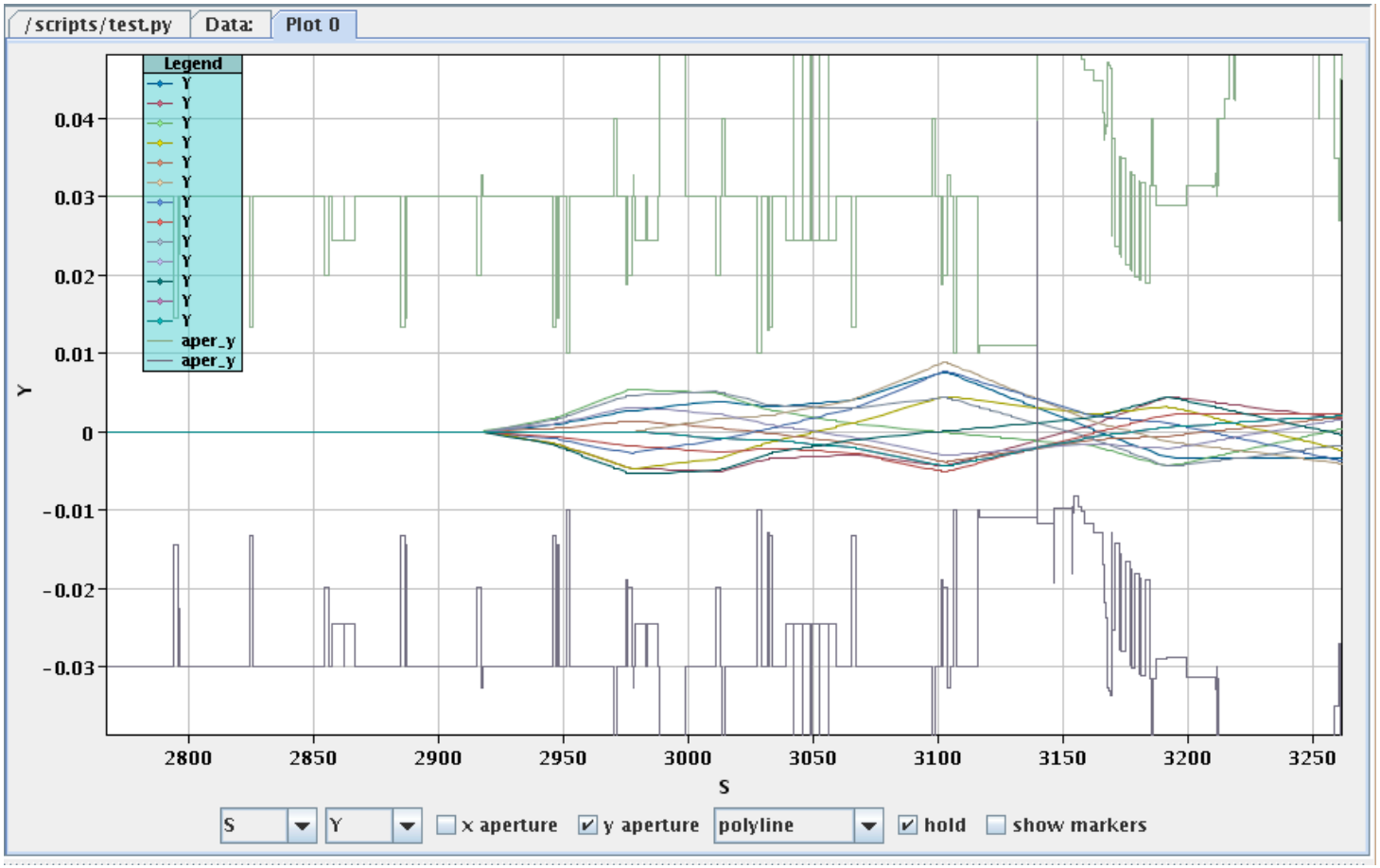
V. Kain
J. Wenninger



Synchronization Tests With Beam

- Injection region aperture verification: Aperture limitation due to vacuum valve

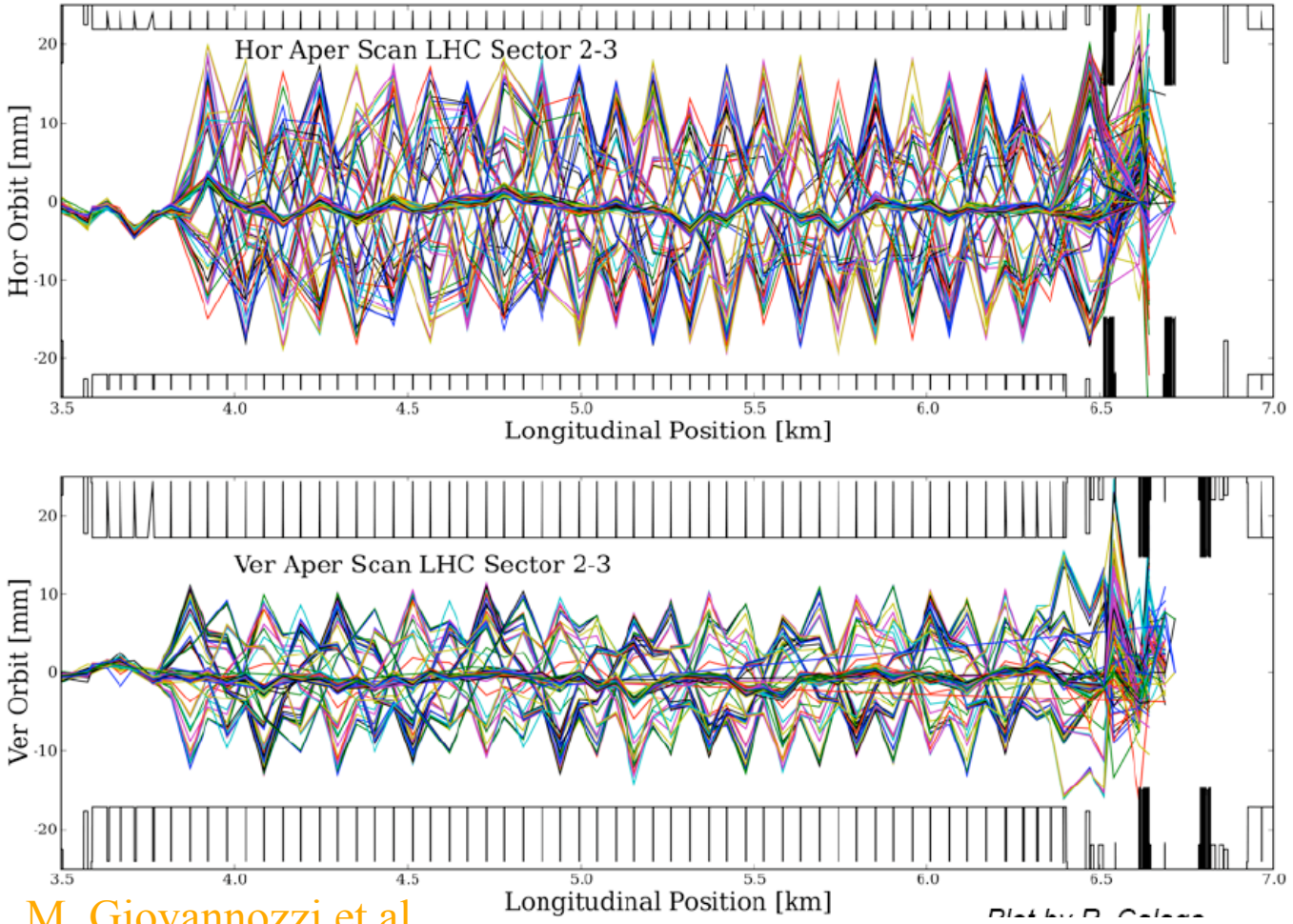
B. Goddard



- MADX online model Ilia Agapov

Synchronization Tests With Beam

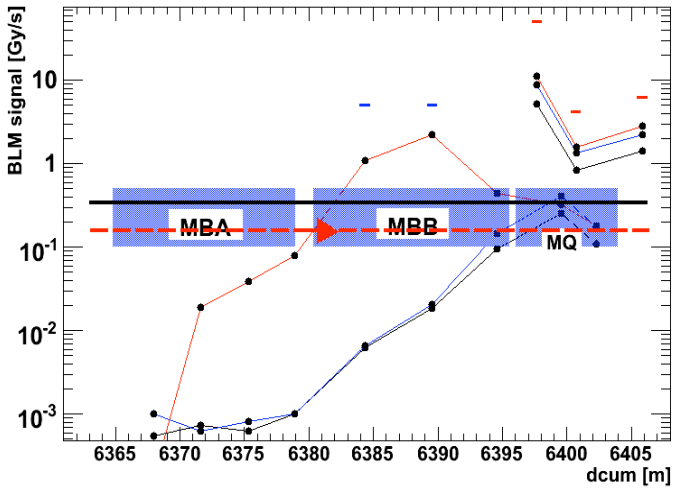
- Arc aperture verification: Kick measurements ➔ aperture and coupling

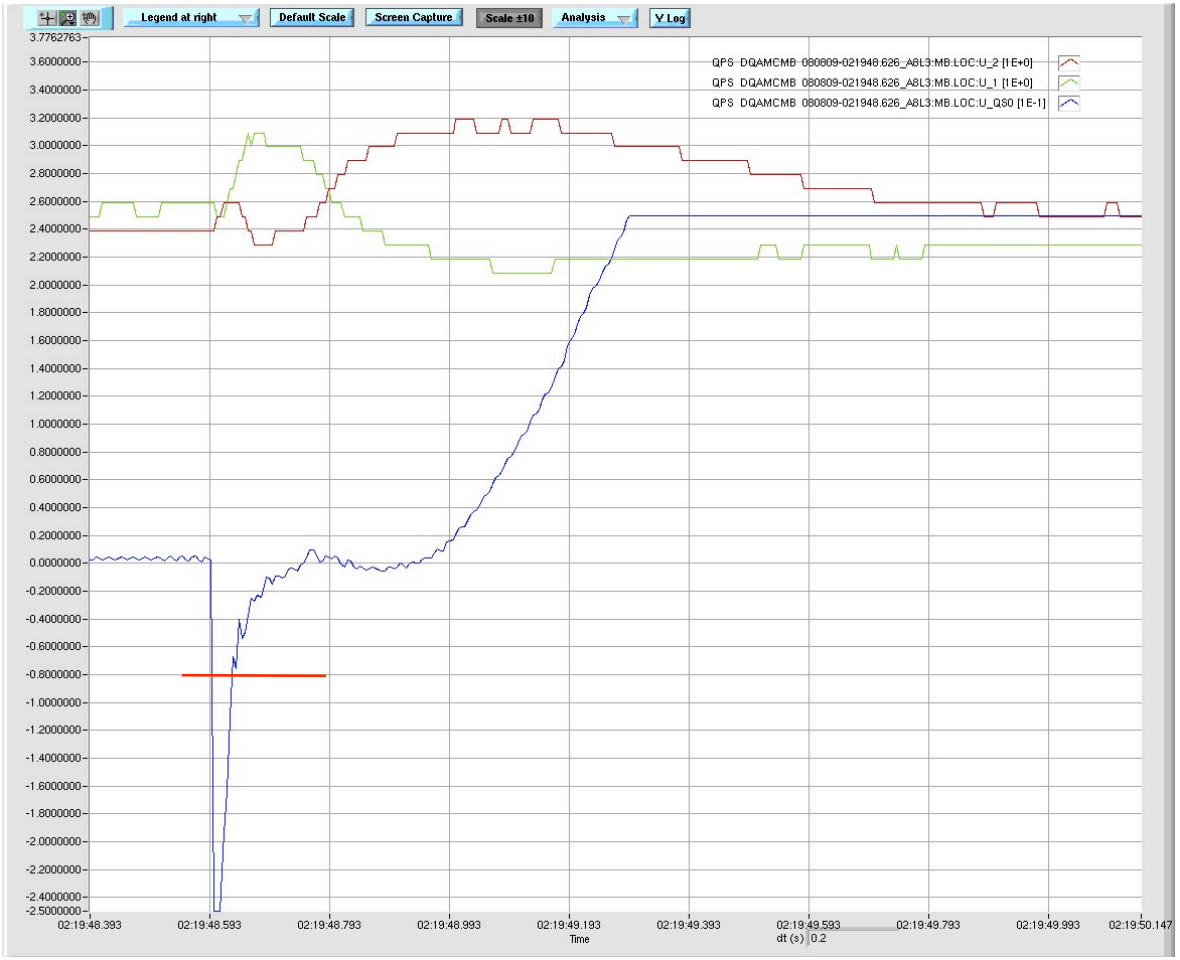


R. Callaga, M. Giovannozzi et al.

Synchronization Tests With Beam

- First Beam to IR3: First trajectory corrections and beam induced quench:





Summary Synchronization Tests

- **Extremely useful exercise:** last minute fixes to software (timing), powering data base (polarities), functionality checks (BPM and BLM), Removal of aperture bottle necks (vacuum valve alignment)

- **First beam induced quench:** BLM calibration!, verification of 'safe beam' intensities

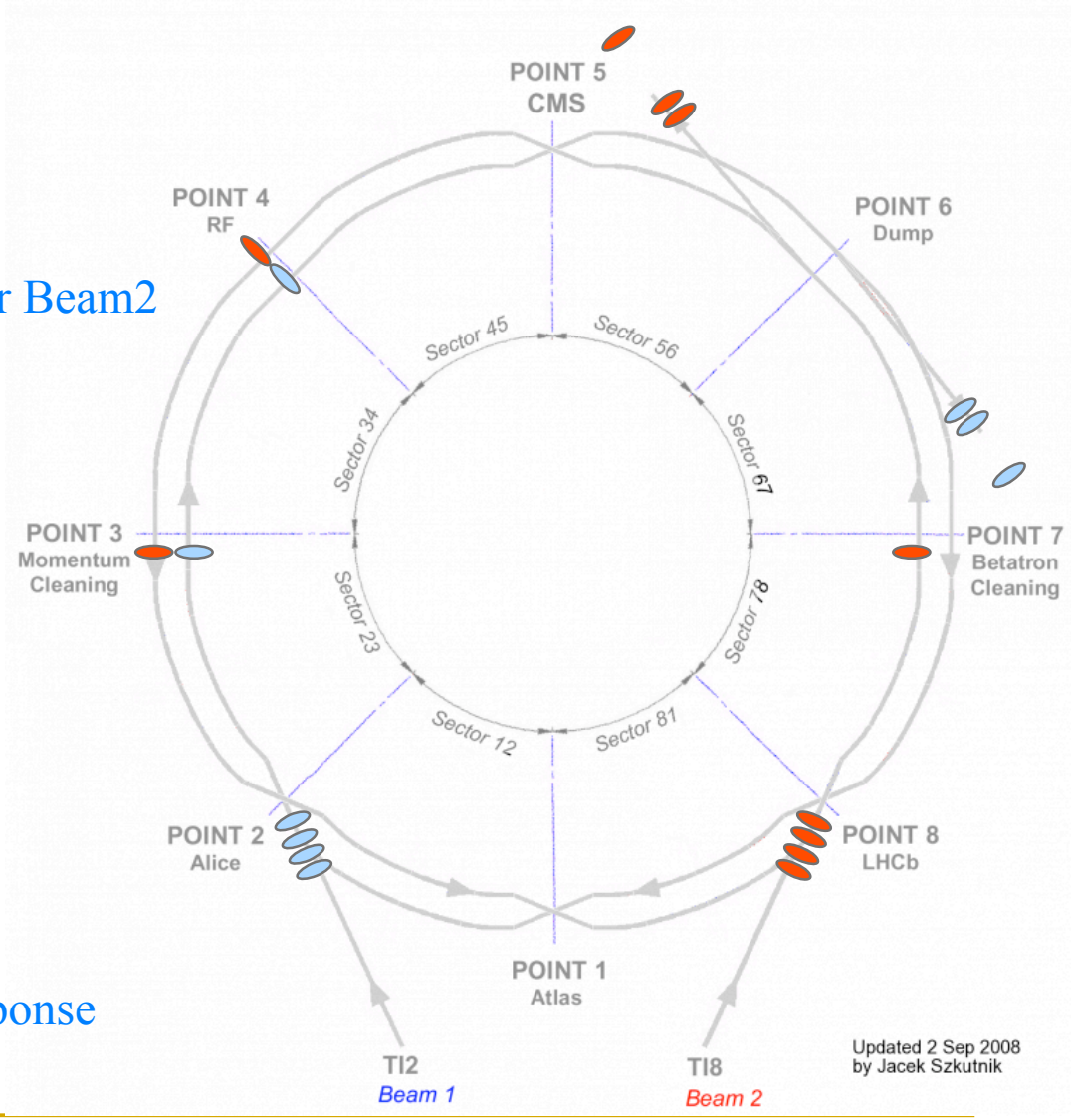
- **Tools:** extremely useful due to availability of excellent analysis tools (YASP, MADX online model; fitting tools for kick response & BPM data analysis); successful validation of LSA

- **Procedures:** validation of key procedures (synchronous powering of circuits and collimators); access system and beam interlock system

LHC Startup 10. September

LHC Beam Commissioning:

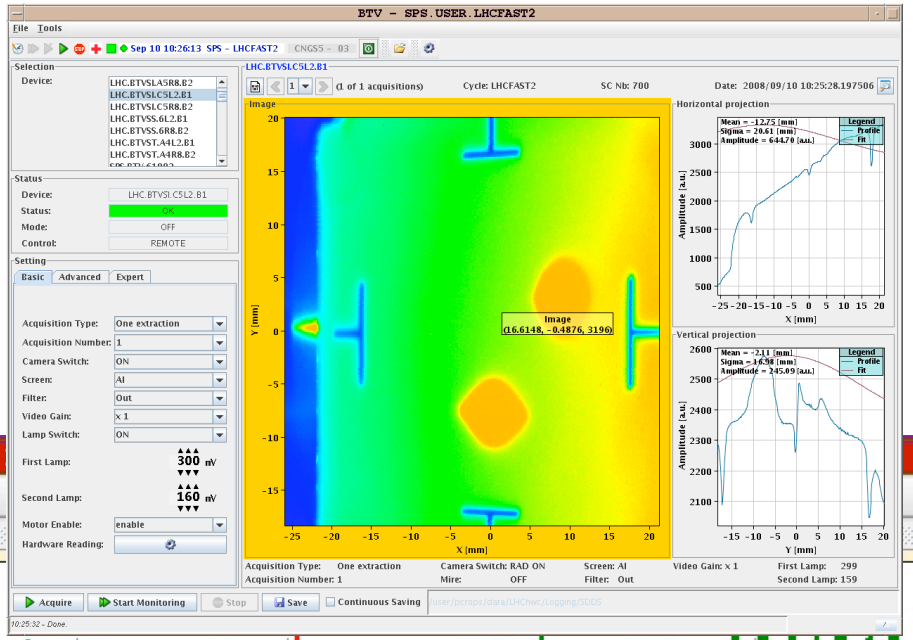
- 10. September:
  - Established 1. Turn for Beam 1
  - Established 1. Turn for Beam 2
  - Established circulating beam for Beam2
- Following days:
  - RF capture Beam 2;
  - Klystron based RF system!
  - Noise + feedback loops
- First beam measurements
  - Orbit correction
  - Tune & coupling measurement
  - Optics verification via kick-response

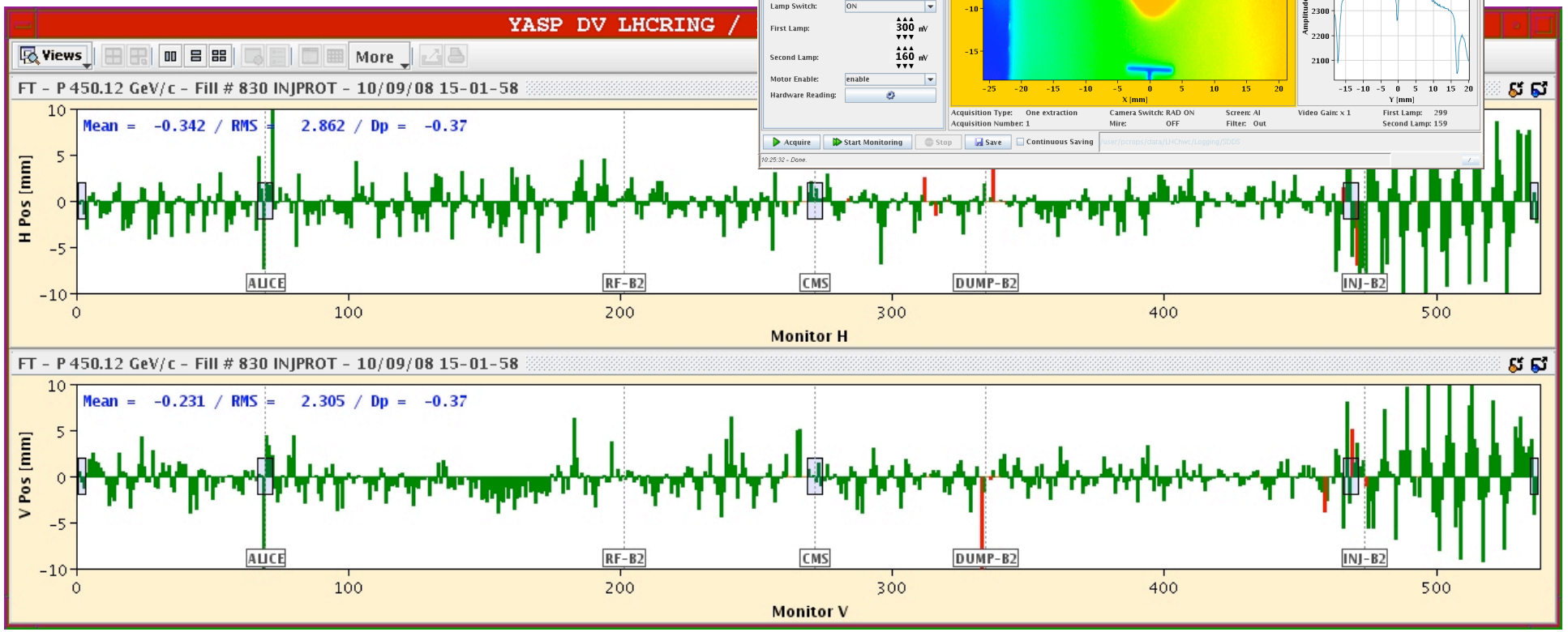


First Turn

- First & Second Turn on screen
- First Turn on BPM system

Jörg Weninger
Courtesy of Roger Bailey





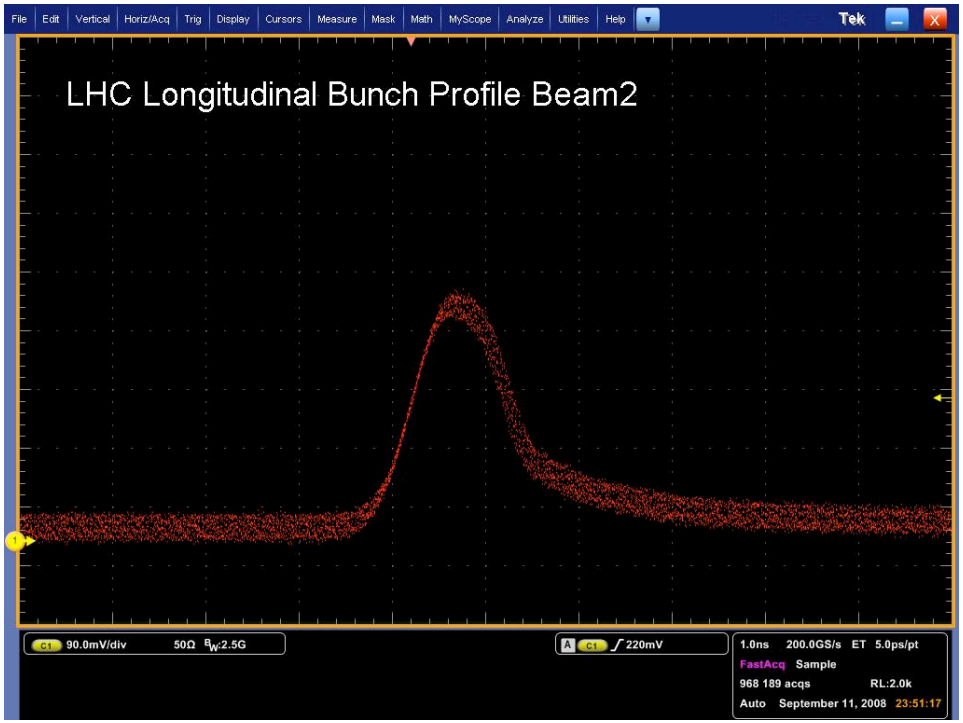
Closed Orbit and Kick Response for Full Machine

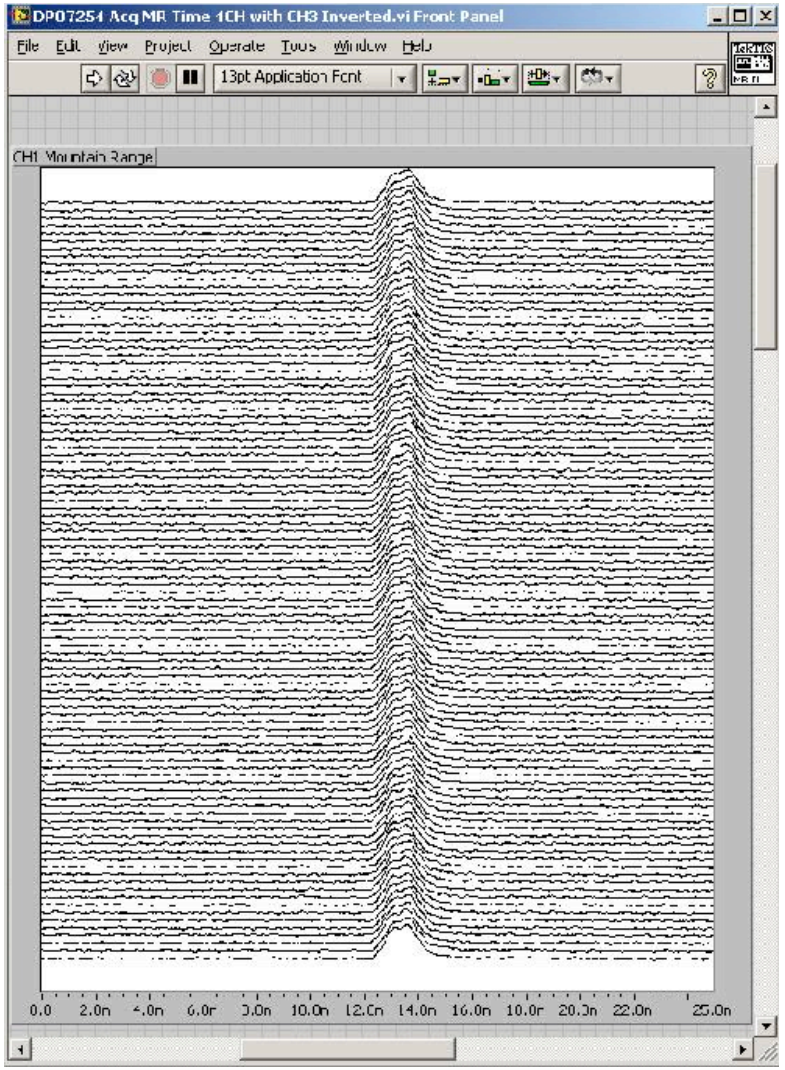
YASP by Jörg Weninger

RF Capture:

- Captured Beam Current
- Mountain Range display

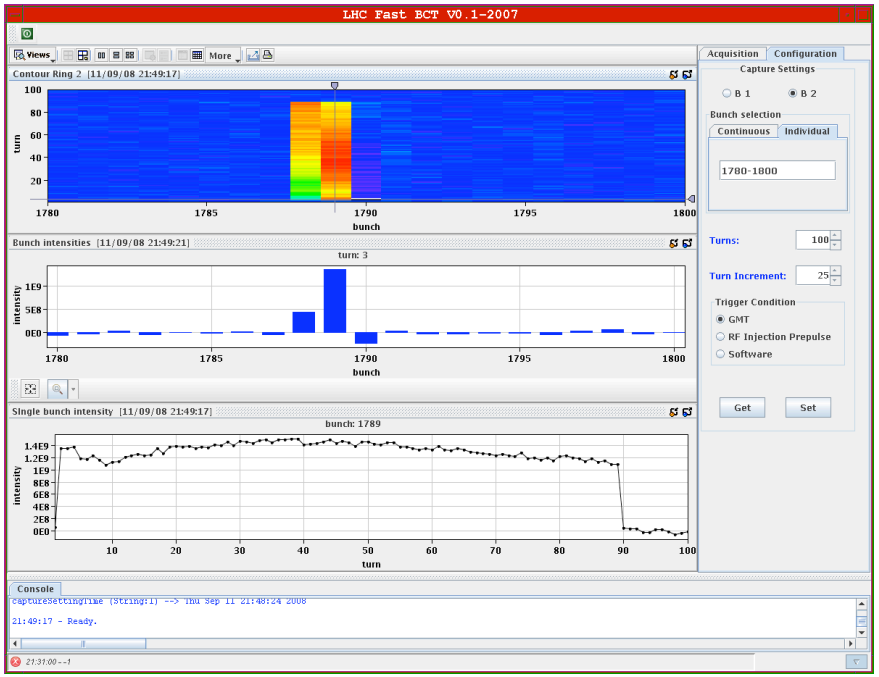
Ed Chiapal

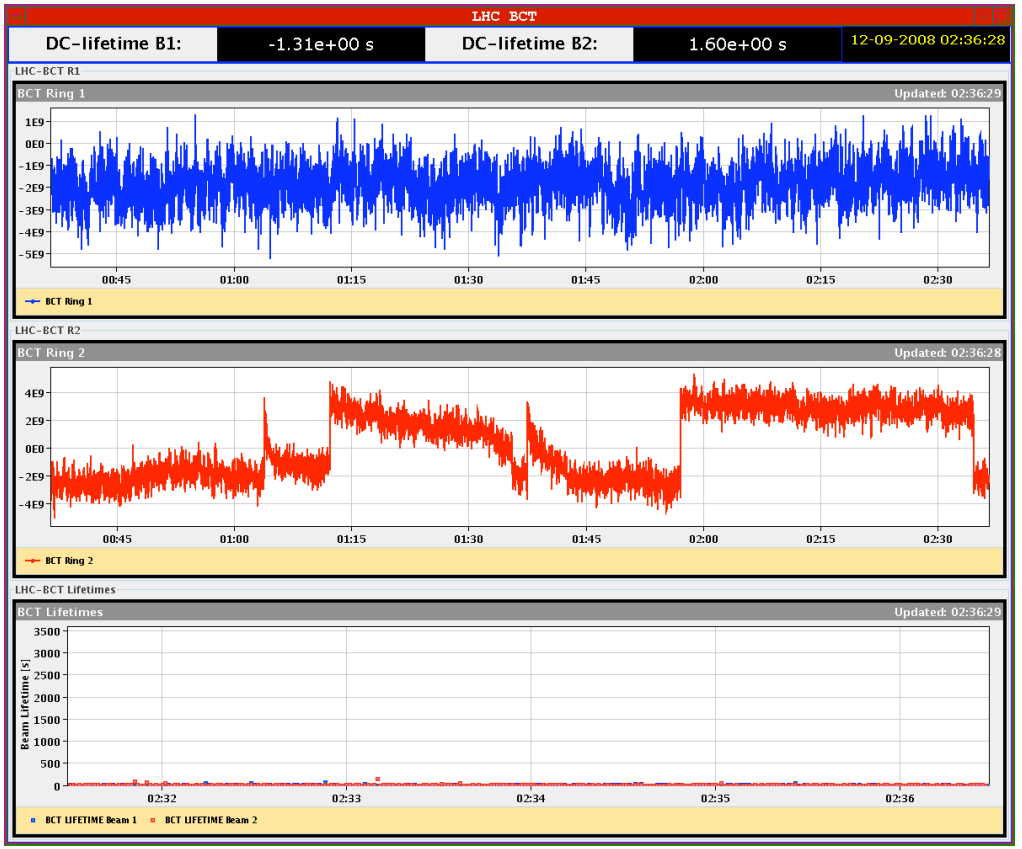




Beam Current Transformer and Beam Lifetime:

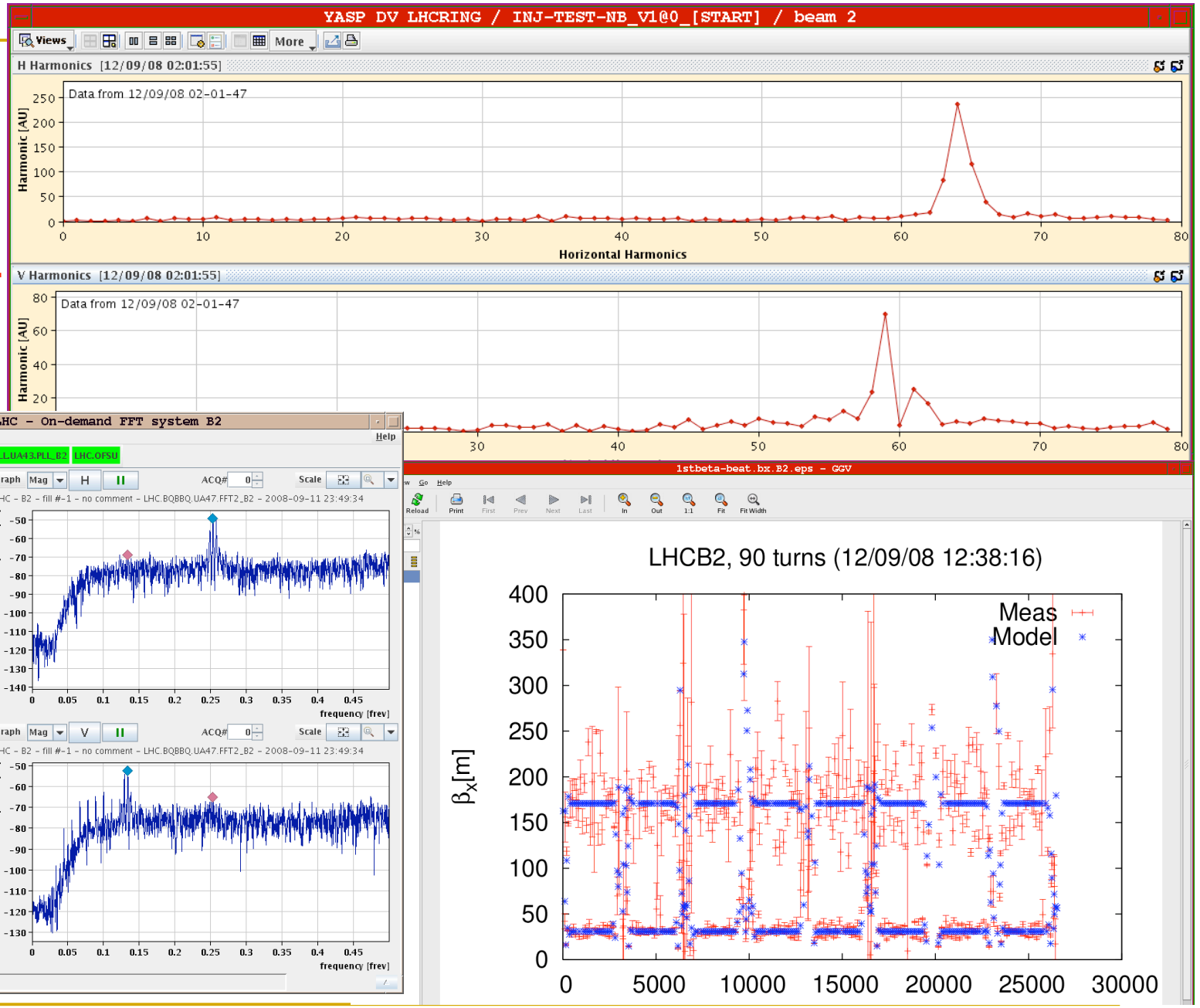
- BCT versus bunch number and time: ca. ½ h beam lifetime!





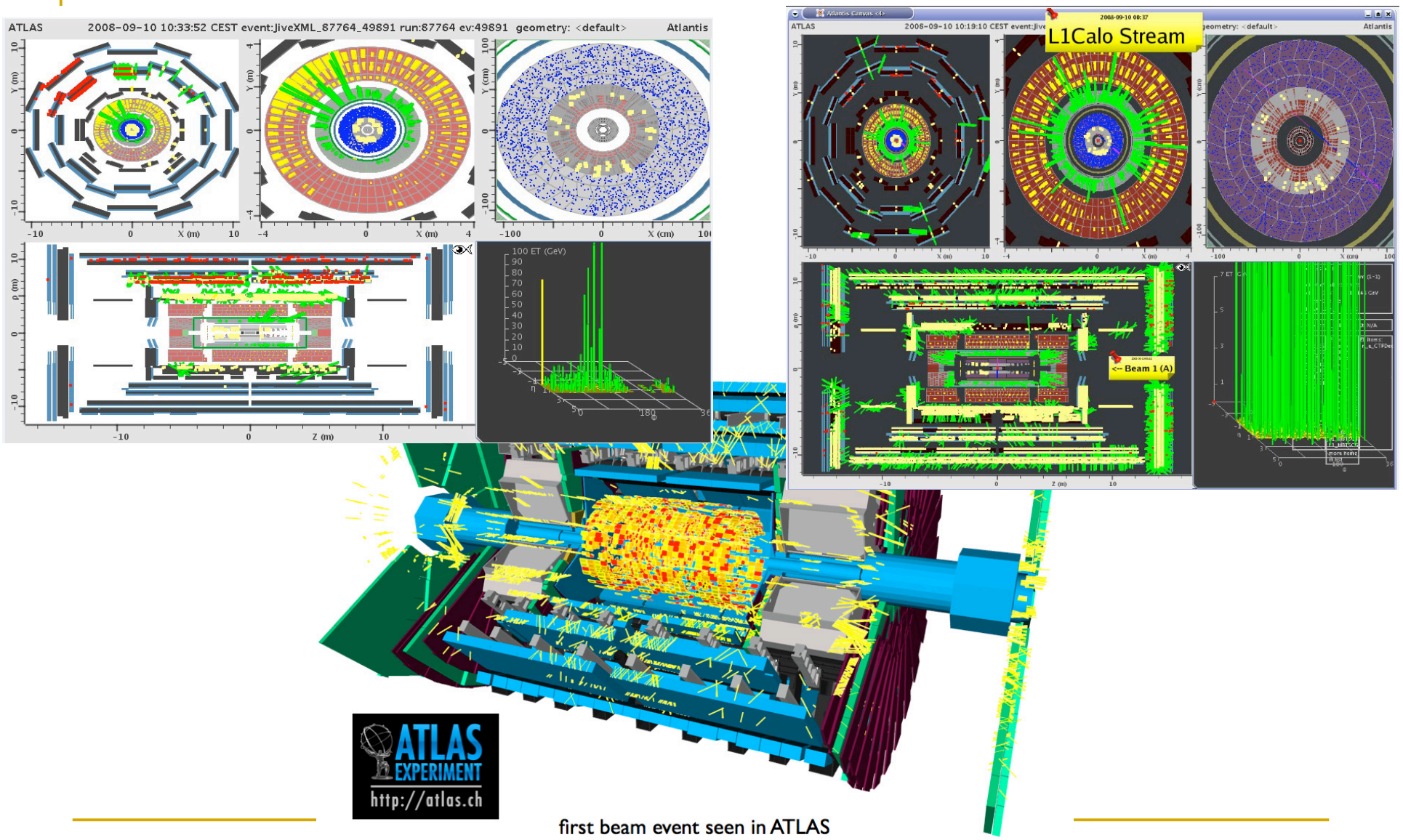
Tune and β-beat:

Jörg Weninger
R. Steinhagen



R. Thomas

First Beam Seen by the Experiments



first beam event seen in ATLAS

Summary Beam Commissioning

- Extremely successful start-up!! Made possible by:
  - Meticulous preparation
  - Accurate magnetic model
  - Dry runs (parallel 'operation' and hardware commissioning)
  - Synchronization tests
  - Powerful control system and tools and
  - a highly motivated team!!!
- Beam Commissioning stopped on Friday 12. September:
  - Transformer failure on Friday evening (12 MVA)
  - Loss of cryogenics in point 8 (➔Arcs 78 and 81)
  - Replacement could be found in CMS installation
  - Several days of access in LHC site
  - Ready for beam by 18. September (started injection tests for Beam 1)

LHC Incident in Sector 34

CERN Press Release from 20.9.2008:

Geneva, 20 September 2008. During commissioning without beam of the final LHC sector (Sector 34) at high current for operation at 5 TeV, an incident occurred at mid-day on Friday 19 September resulting in a large helium leak into the tunnel. Preliminary investigations indicate that the most likely cause of the problem was a faulty electrical connection between two magnets which probably melted at high current leading to mechanical failure. CERN's strict safety regulations ensured that at no time was there any risk to people.

CERN Press Release from 23.9.2008:

Investigations at CERN following a large helium leak into sector 3-4 of the Large Hadron Collider (LHC) tunnel have indicated that the most likely cause of the incident was a faulty electrical connection between two of the accelerator's magnets. Before a full understanding of the incident can be established, however, the sector has to be brought to room temperature and the magnets involved opened up for inspection. This will take three to four weeks. Full details of this investigation will be made available once it is complete.

LHC Incident in Sector 34

Assessment as of October 2008:

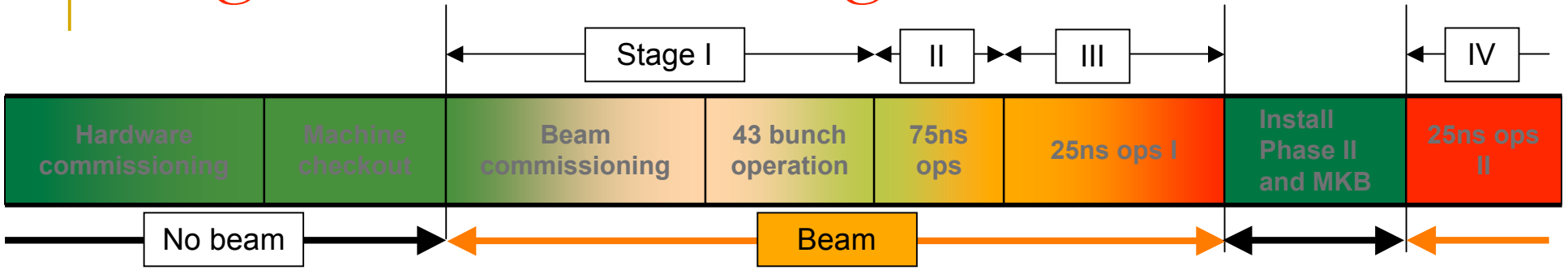
- ➔ Loss of ca. 6T of He inventory (ca.½ of the arc inventory).
- ➔ Ca. 250 MJ of stored electromagnetic energy was 'missing' in the dump resistors and diodes of the quench protection system
- ➔ 4 short straight sections (unit of a quadrupole + corrector magnets) are affected by the incident and need to be repaired on surface
- ➔ Of the order of 10 dipole magnets might be affected by the incident and need to be inspected on the surface.
- ➔ Most likely cause was a bad splice between magnets
- ➔ Means for detecting similar problems in the future are currently under study

Impact on Operation Schedule:

- ➔ LHC operation stopped 3 month before planned operation stop.
- ➔ General shutdown work at CERN was advanced by 2 month (early October).
- ➔ Start-up in 2009 advanced to 1. May instead of 1. June.
- ➔ Net loss of ca. 2 month of LHC operation due to September incident.

Spare Transparencies

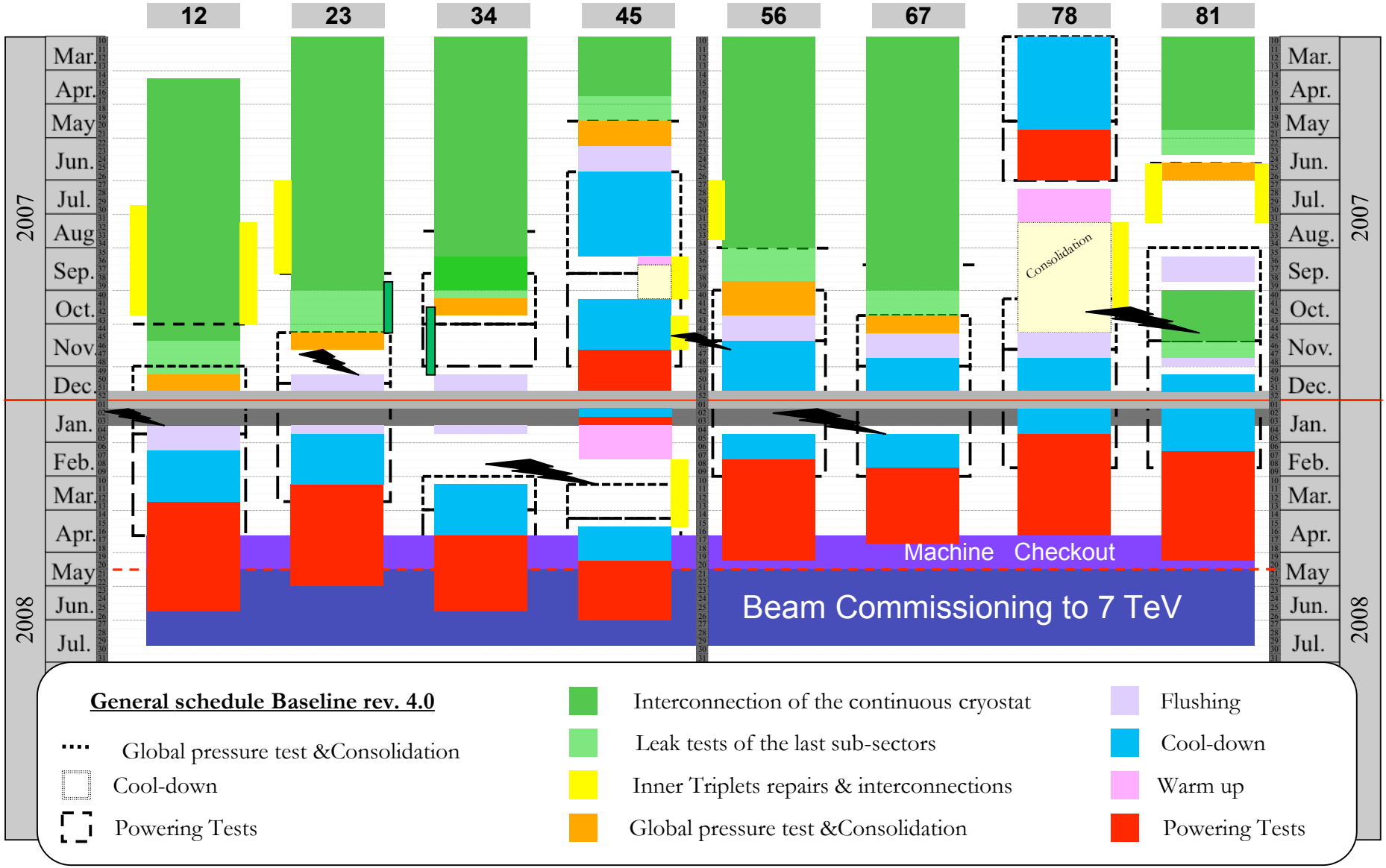
Staged Commissioning Plan for Protons



- Pilot physics run
  - First collisions
  - 43 bunches, no crossing angle, no squeeze, moderate intensities
  - Push performance (156 bunches, partial squeeze in 1 and 5 ➔ $L \approx 10^{31}$ cm^{-2} sec^{-1})
- 75ns operation
  - Establish multi-bunch operation, moderate intensities
  - Relaxed machine parameters (squeeze and crossing angle)
  - Push squeeze and crossing angle ➔ $L \approx 10^{33}$ cm^{-2} sec^{-1} (event pile up rate)
- 25ns operation I
  - Nominal crossing angle
  - Push squeeze
  - Increase intensity to 50% nominal ➔ $L \approx 2\ 10^{33}$ cm^{-2} sec^{-1}
- 25ns operation II
  - Push towards nominal performance

Courtesy of Roger Bailey

Commissioning Plans for 2008



Parameter evolution and rates

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

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

All values for nominal emittance, 10m β* in points 2 and 8

All values for 936 or 2808 bunches colliding in 2 and 8 (not quite right)

	Parameters			Beam levels		Rates in 1 and 5		Rates in 2 and 8	
	k_b	N	β* 1,5 (m)	I_{beam} proton	E_{beam} (MJ)	Luminosity ($cm^{-2}s^{-1}$)	Events/ crossing	Luminosity ($cm^{-2}s^{-1}$)	Events/ crossing
5 TeV	43	$4\ 10^{10}$	11	$1.7\ 10^{12}$	1.4	$8.0\ 10^{29}$	<< 1	Depend on the configuration of collision pattern	
5 TeV	43	$4\ 10^{10}$	3	$1.7\ 10^{12}$	1.4	$2.9\ 10^{30}$	0.36		
5 TeV	156	$4\ 10^{10}$	3	$6.2\ 10^{12}$	5	$1.0\ 10^{31}$	0.36		
5 TeV	156	$9\ 10^{10}$	3	$1.4\ 10^{13}$	11	$5.4\ 10^{31}$	1.8		
7 TeV	936	$4\ 10^{10}$	11	$3.7\ 10^{13}$	42	$2.4\ 10^{31}$	<< 1	$2.6\ 10^{31}$	0.15
7 TeV	936	$4\ 10^{10}$	2	$3.7\ 10^{13}$	42	$1.3\ 10^{32}$	0.73	$2.6\ 10^{31}$	0.15
7 TeV	936	$6\ 10^{10}$	2	$5.6\ 10^{13}$	63	$2.9\ 10^{32}$	1.6	$6.0\ 10^{31}$	0.34
7 TeV	936	$9\ 10^{10}$	1	$8.4\ 10^{13}$	94	$1.2\ 10^{33}$	7	$1.3\ 10^{32}$	0.76
7 TeV	2808	$4\ 10^{10}$	11	$1.1\ 10^{14}$	126	$7.2\ 10^{31}$	<< 1	$7.9\ 10^{31}$	0.15
7 TeV	2808	$4\ 10^{10}$	2	$1.1\ 10^{14}$	126	$3.8\ 10^{32}$	0.72	$7.9\ 10^{31}$	0.15
7 TeV	2808	$5\ 10^{10}$	1	$1.4\ 10^{14}$	157	$1.1\ 10^{33}$	2.1	$1.2\ 10^{32}$	0.24
7 TeV	2808	$5\ 10^{10}$	0.55	$1.4\ 10^{14}$	157	$1.9\ 10^{33}$	3.6	$1.2\ 10^{32}$	0.24

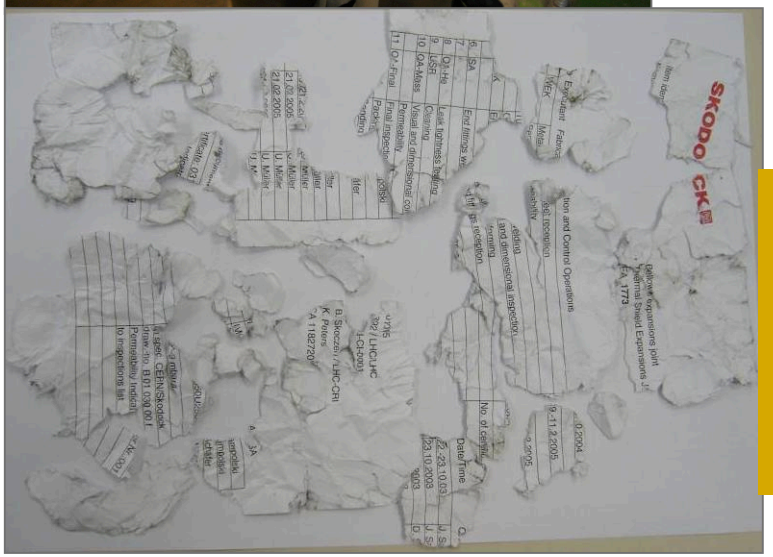
LHC progress 2002-2008: Problems

QRL line:

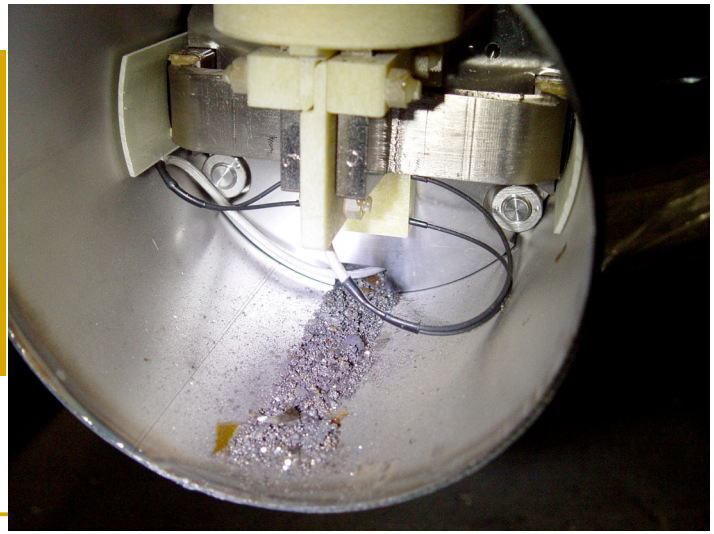
- Cracks in the injection moulded components were found in both pipe elements and service modules of the first installed elements. The faults required replacement of these components in all QRL elements already build (Sector 7-8).
- The repair was made at CERN. Sector 7-8, which was already partially installed, had to be be re-installed.
- The repair work required a strong compression of the initial schedule

LHC progress 2002-2008: Cool Down

Dust Debris
Kapton
Reports

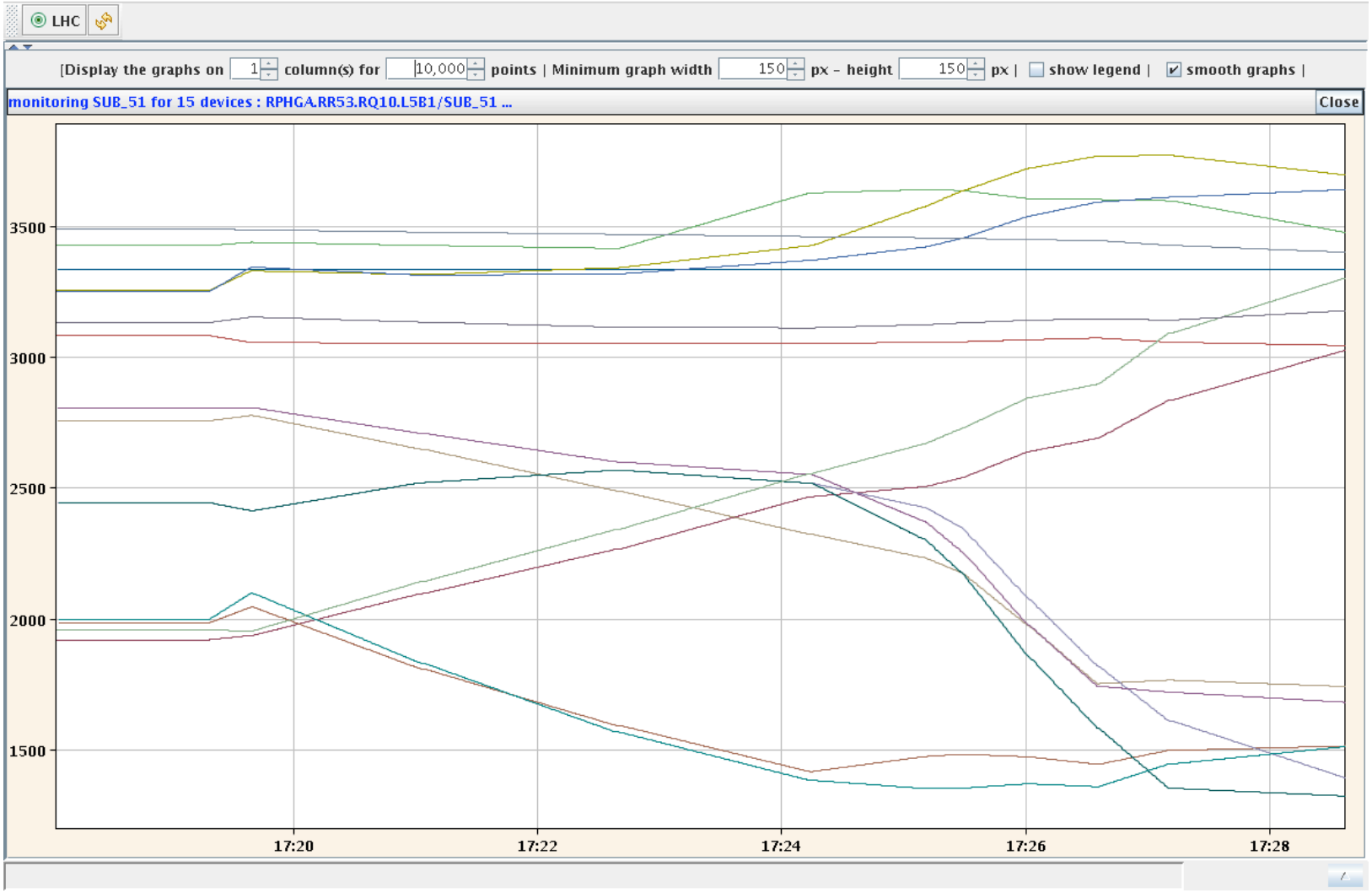


And
possible
shorts in
diodes !



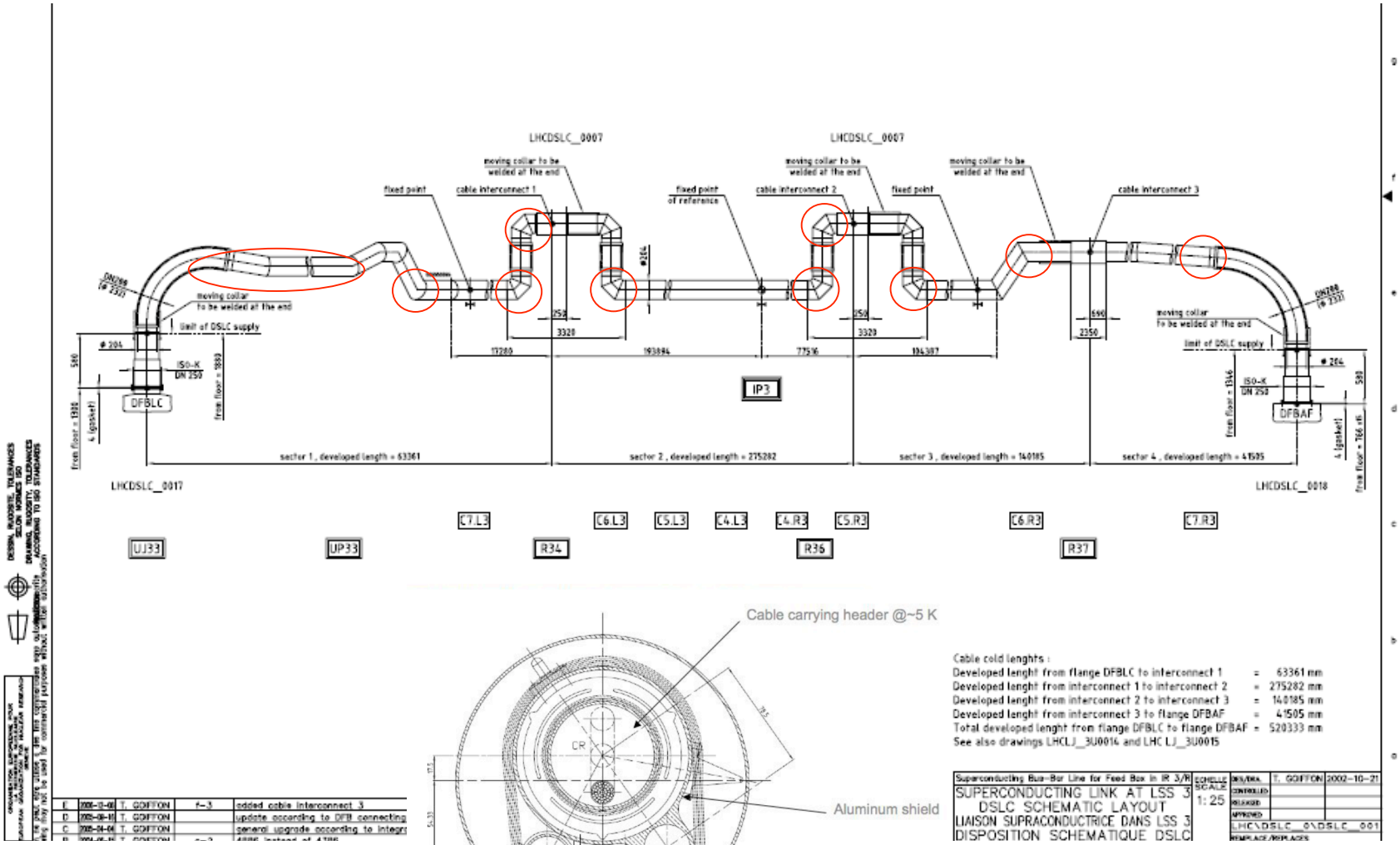
S. Claudet LHC MAC 22

Low-beta squeeze (15 independent quadrupole circuits)



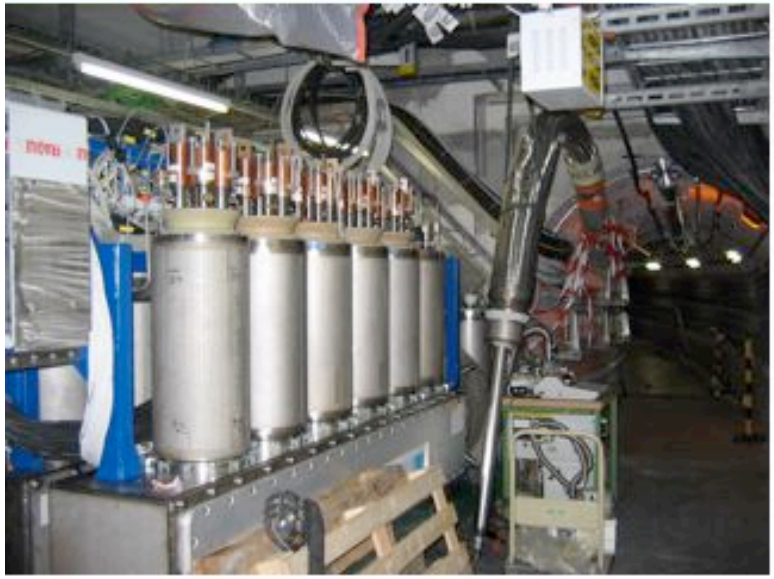
Superconducting links (DSL)

Few hundred meters link between DFBL's and stand-alone magnets



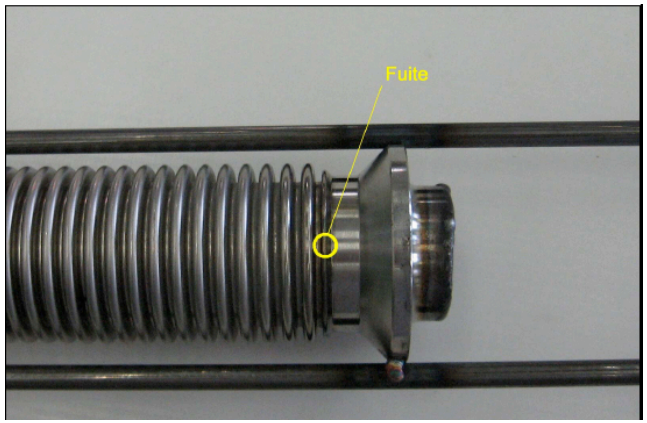
Description: visual

DSL Project



Start of section-1 at the DFBLC in UJ33

First interconnect after about 63 m, "Omega12"
Between sections 1-2 in the main tunnel



Problems with leaks at the factory-made welds on belows

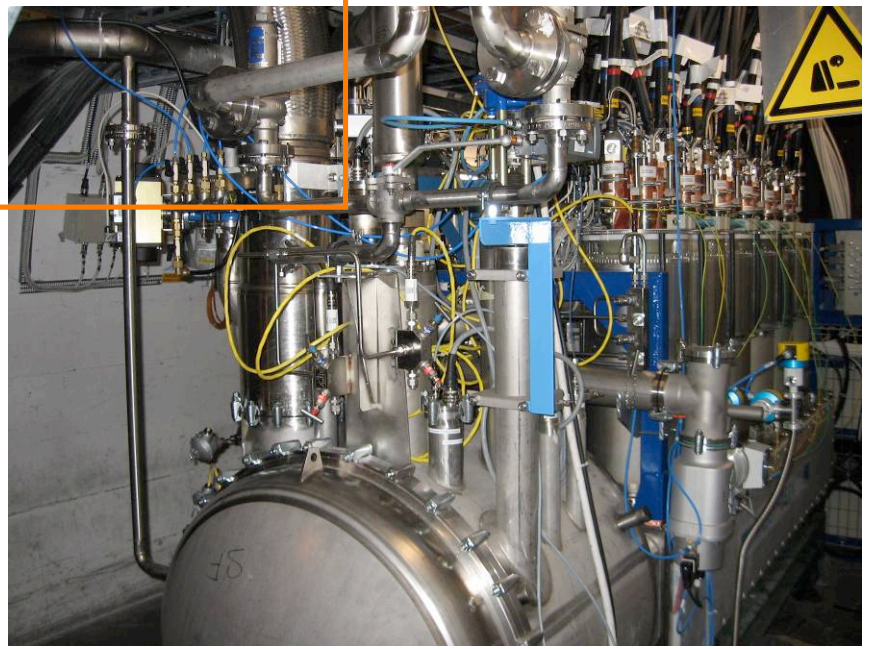
S. Claudet LHC MAC 22

Many non conformities from contractor, repaired by CERN

=> Impact on sector 3-4

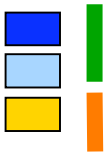
S. Claudet at LHCP 18.9.
Coordinated by A. Perin

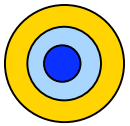
The DFBLC and DSLC in UJ33



Cable layout

Layer 1 (inner) Wires 1-10:
Layer 2: 11-26:
Layer 3 (outer layer) 27-48:





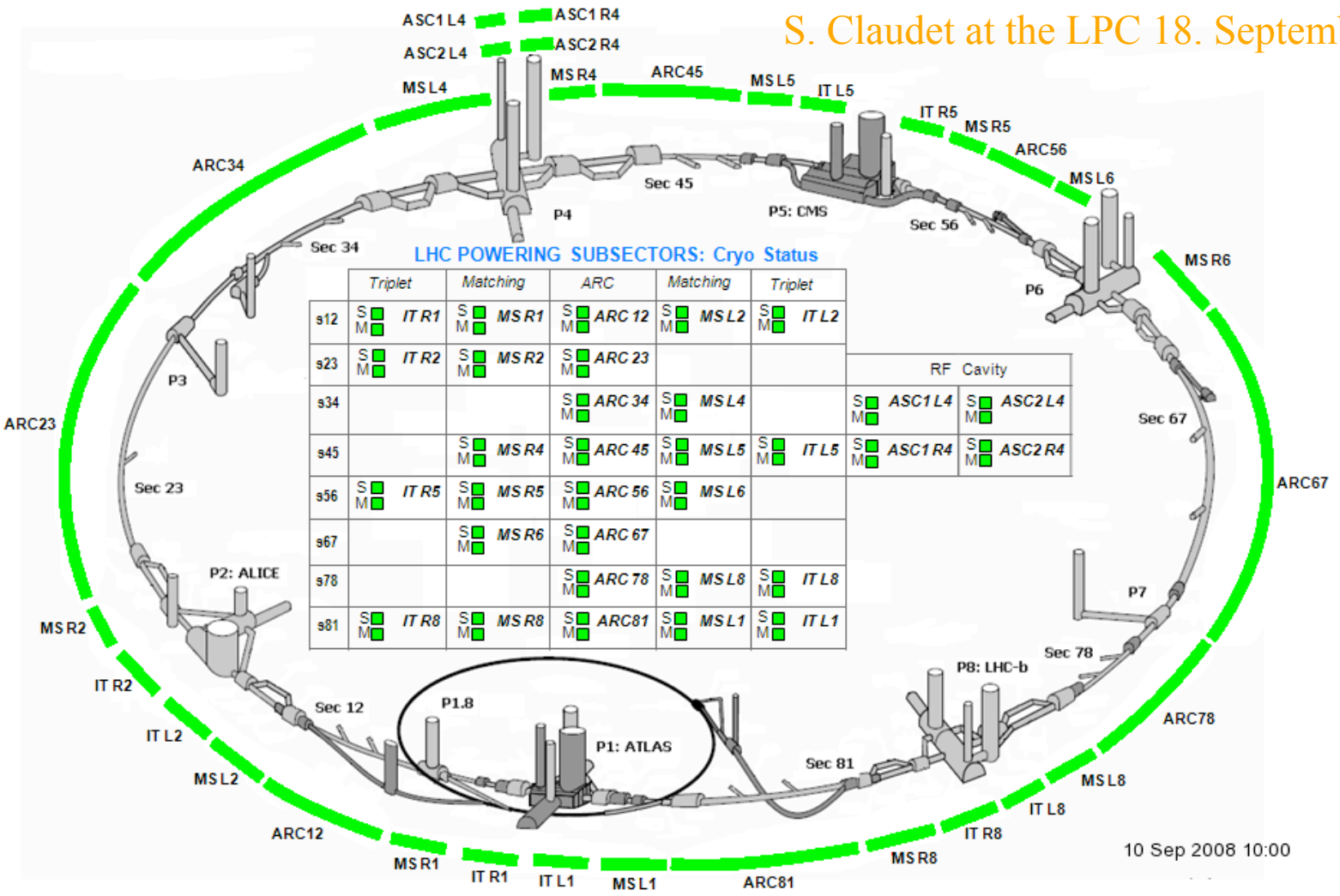
Cryo instrumentation tuned for larger Helium mass-flow

=> Stable operation now at 9-10 g/s (w.r.t 4.5 g/s before)

Improvement for powering above expectations !

LHC Cryogenics on 10. September

S. Claudet at the LPC 18. September'08



The cryogenic infrastructure