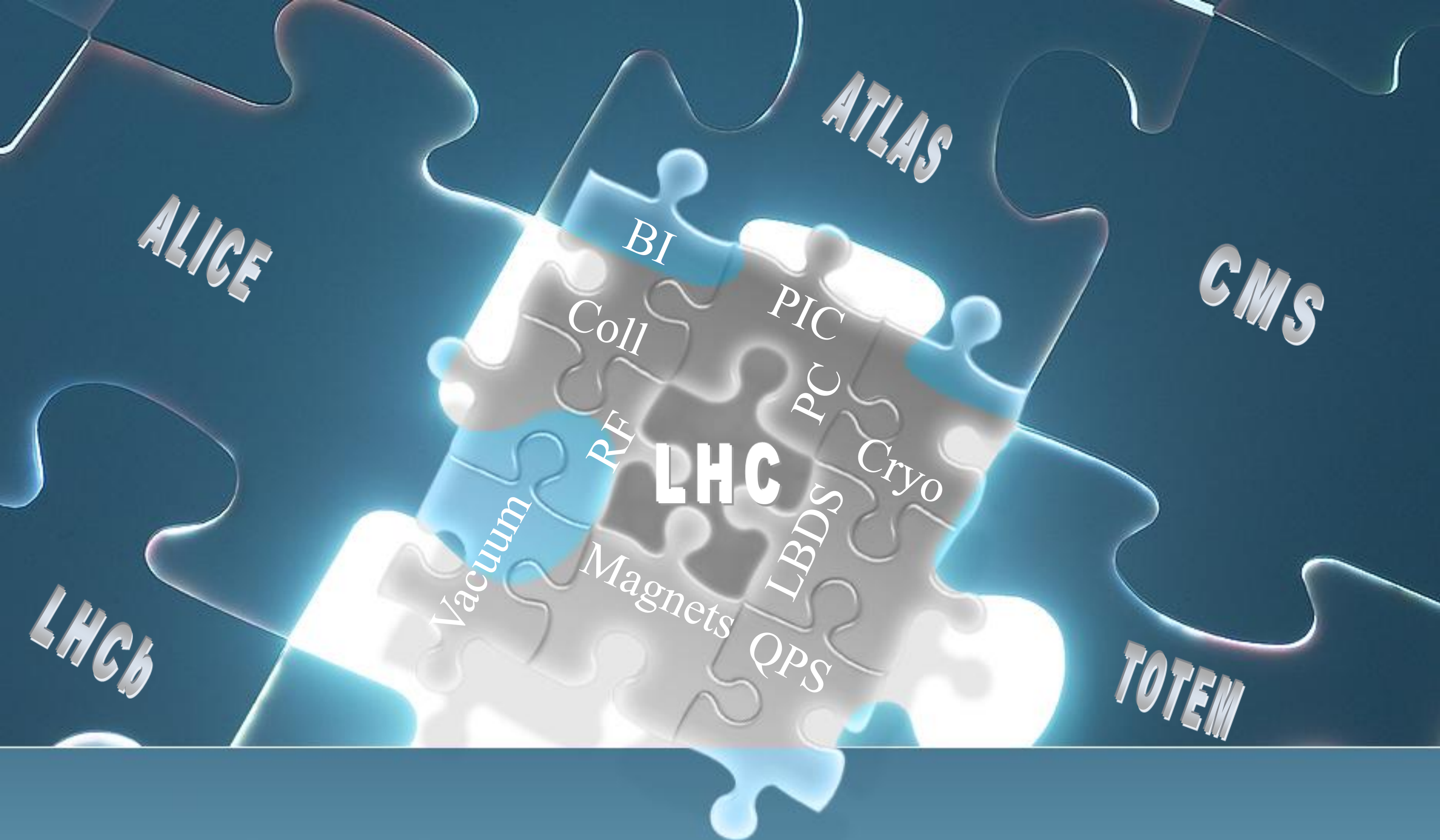

LHC Overview & Status

R. Alemany (CERN AB/OP)

Content

1. Accelerator complex
2. Energy Stored in the Magnets
   - Quench Protection System
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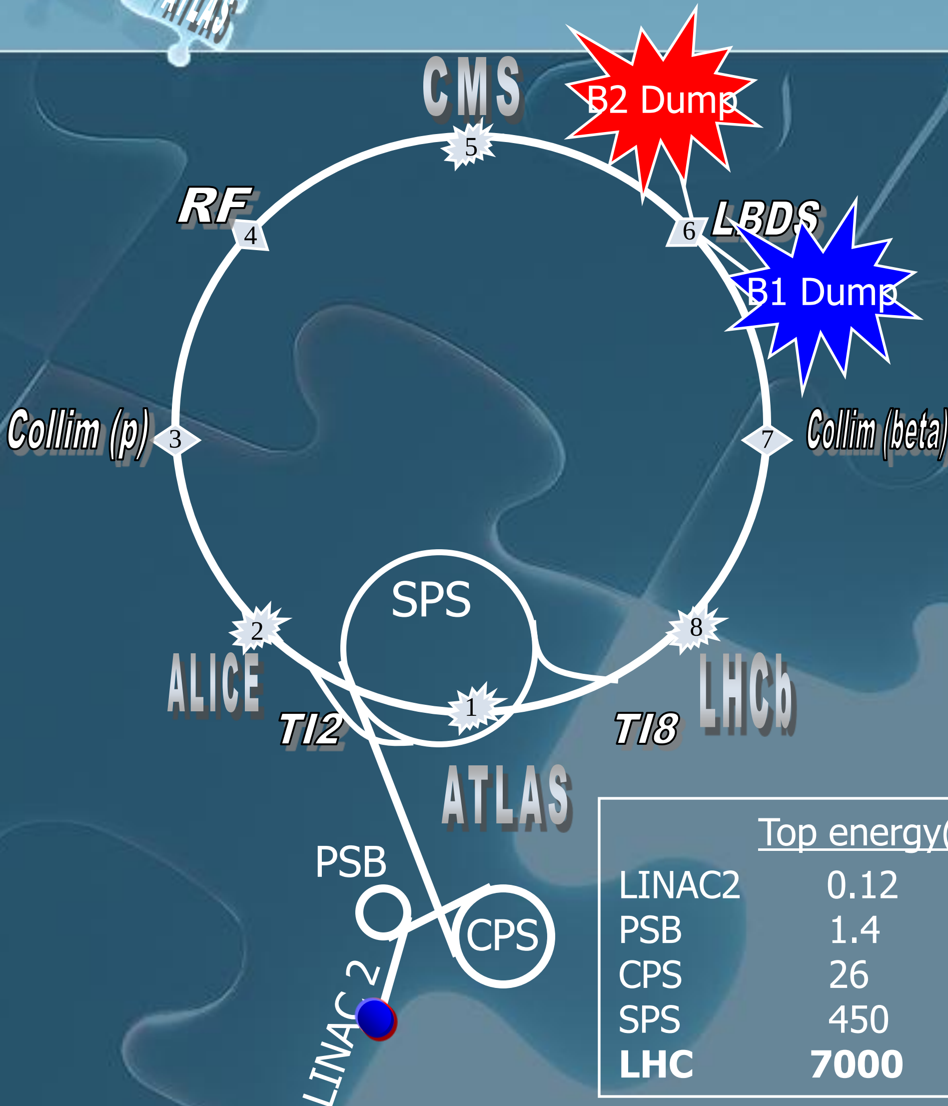
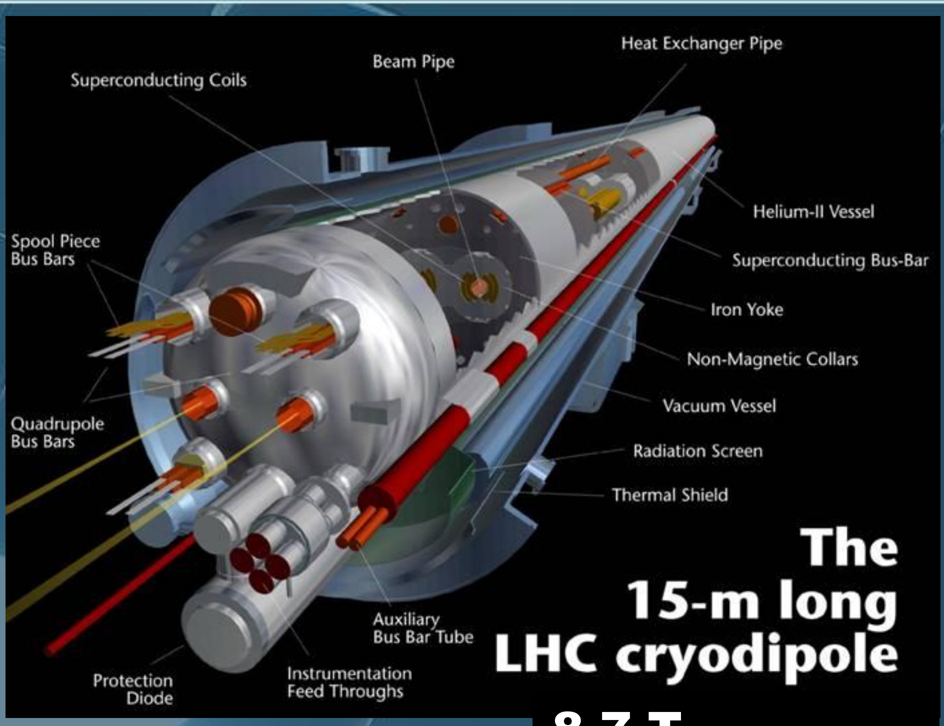
Accelerator complex for p





The 15-m long LHC cryodipole

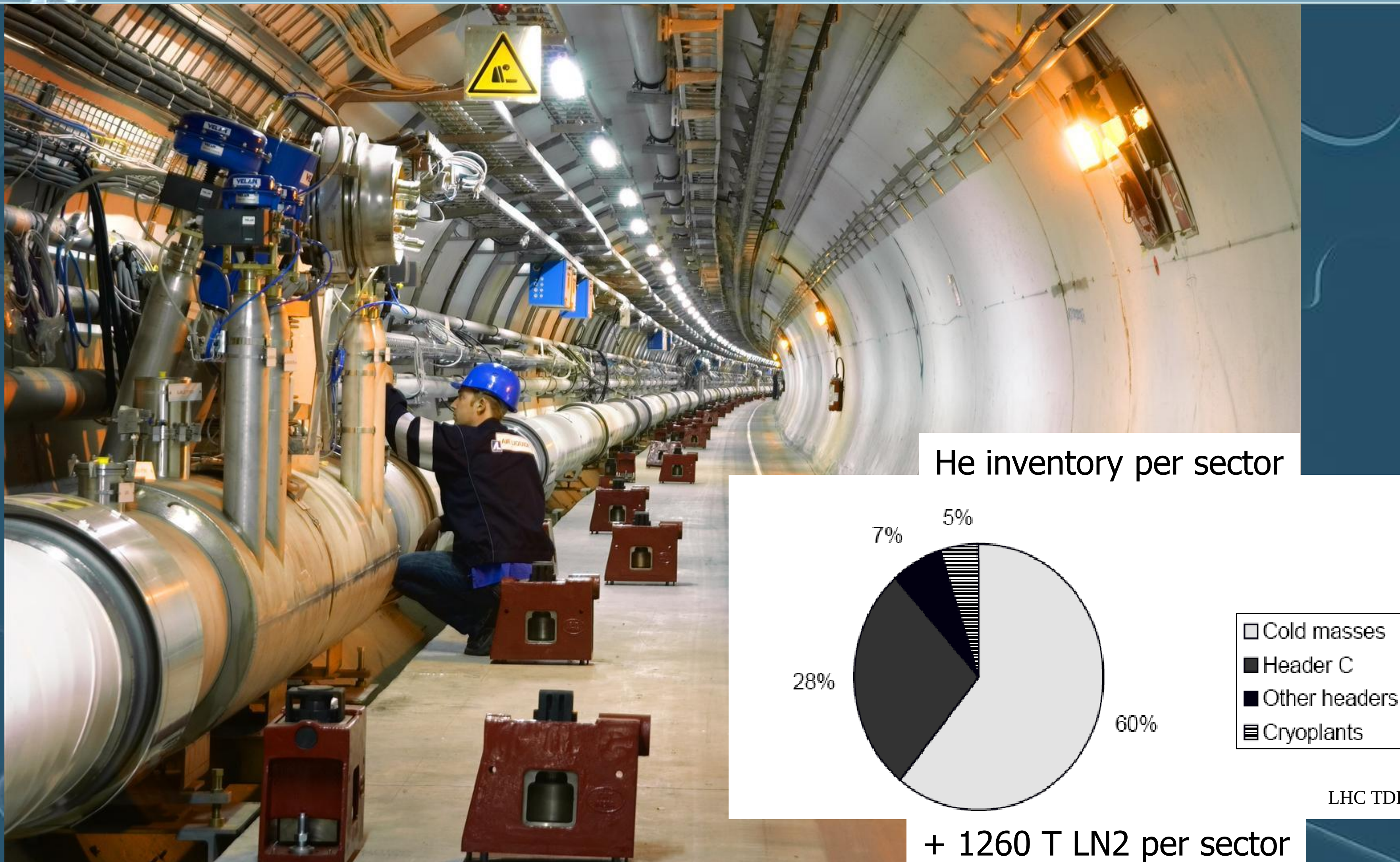
8.7 T
11.8 kA / 7 MJ
1.9 K

1232 cryodip.

	Top energy(GeV)	Circumference(m)
LINAC2	0.12	30
PSB	1.4	157
CPS	26	628 = 4 PSB
SPS	450	6911 = 11 x PS
LHC	**7000**	**26657 = 27/7xSPS**

QRL (Cryogenic Line Installation)

He inventory per sector

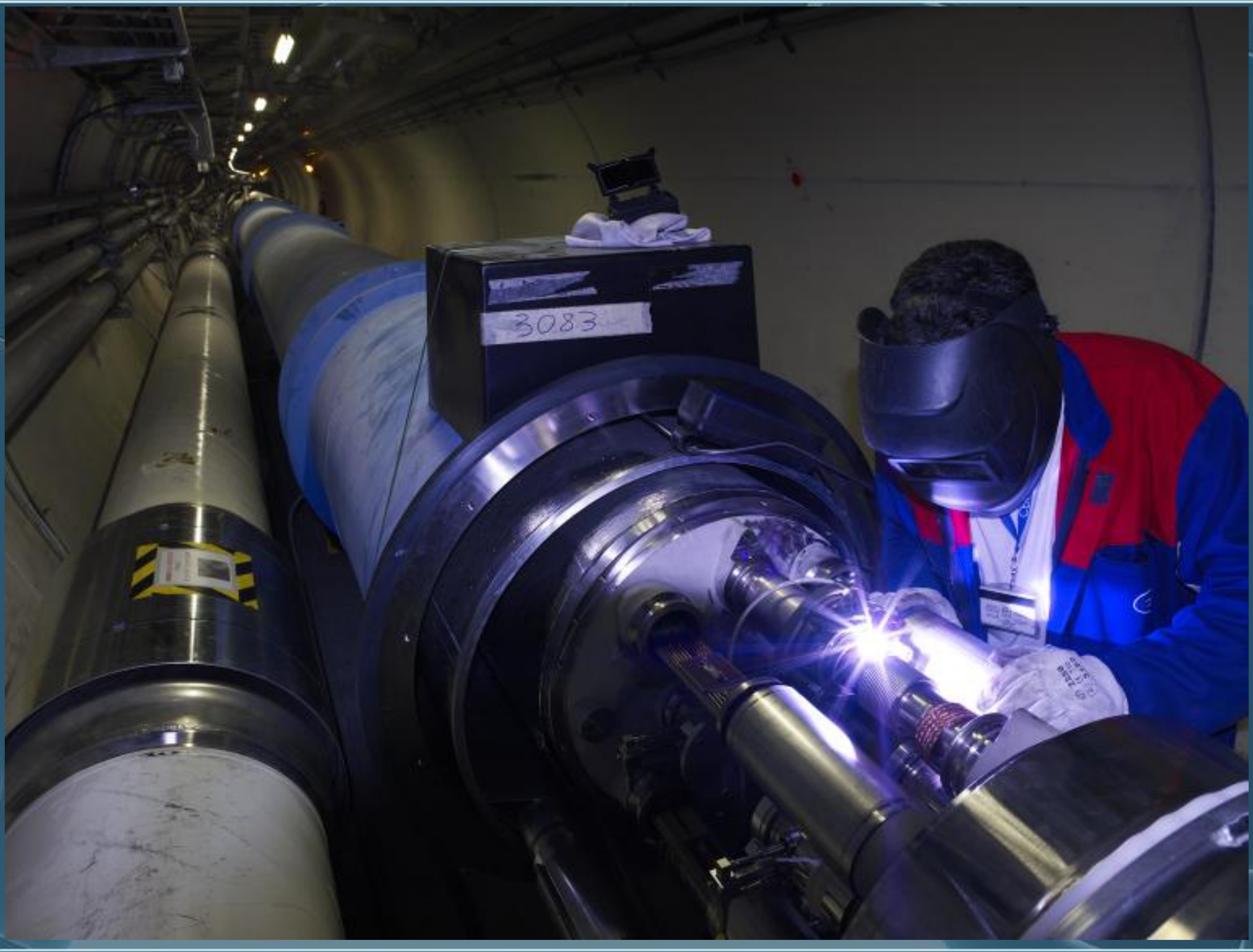


LHC TDR

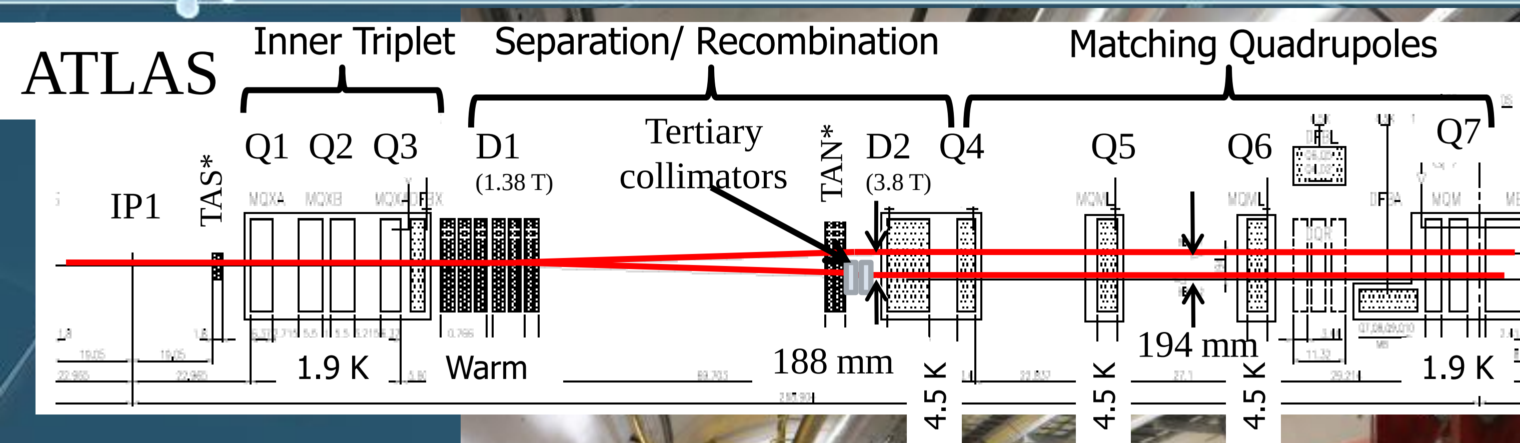
+ 1260 T LN2 per sector

LHC Dipoles Installation

Interconnection

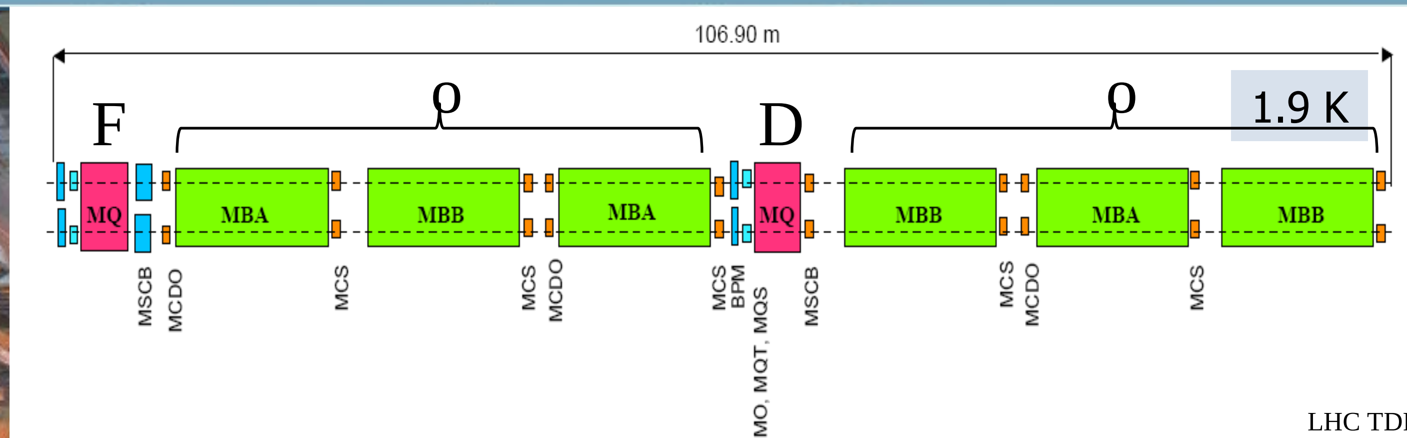


Inner Triplet



* Protect Inner Triplet (TAS) and D2 (TAN) from particles coming from the IP

LHC Arc



LHC TDR

MBB: Main Dipole
MQ: Main Quadrupole
MQT: Trim Quadrupole
MQS: Skew Trim Quadrupole
MO: Lattice Octupole
MSCB: Sextupole (Skew Sextupole)+Orbit Corrector
MCS: Spool Piece Sextupole
MCDO: Spool Piece Octupole + Decapole
(BPM: Beam Position Monitor)

~ 9000 magnets powered with ~1700 power converters

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Energy Stored in the Magnets

~ 10 Gjoule corresponds to …

… an aircraft carrier at battle-speed of 55 km/h

the energy of ~3 Tons TNT
the energy of 370 kg dark chocolate

More important than the amount of energy is …

How fast (an safe) can this energy be released?

Energy Stored in the Magnets

If not fast and safe …

During magnet test campaign, the 7 MJ stored in one magnet were released into one spot of the coil (inter-turn short)

P. Pugnat

Energy Stored in the Magnets:
Quench & Quench Protection System

- **A Quench is the phase transition of a super-conducting to a normal conducting state**
- **Quenches are initiated by an energy release of the order of mJ:**
  - **Movement of the superconductor by several μm (friction and heat dissipation)**
  - **Beam losses:**
    - **@7 TeV 0.6 J/cm^3 can quench a dipole; this energy density can be generated by 10^7 protons**
    - **@450 GeV (injection energy), ~ 10^9 protons are needed**
  - **Failure in cooling**

Energy Stored in the Magnets:
Quench & Quench Protection System

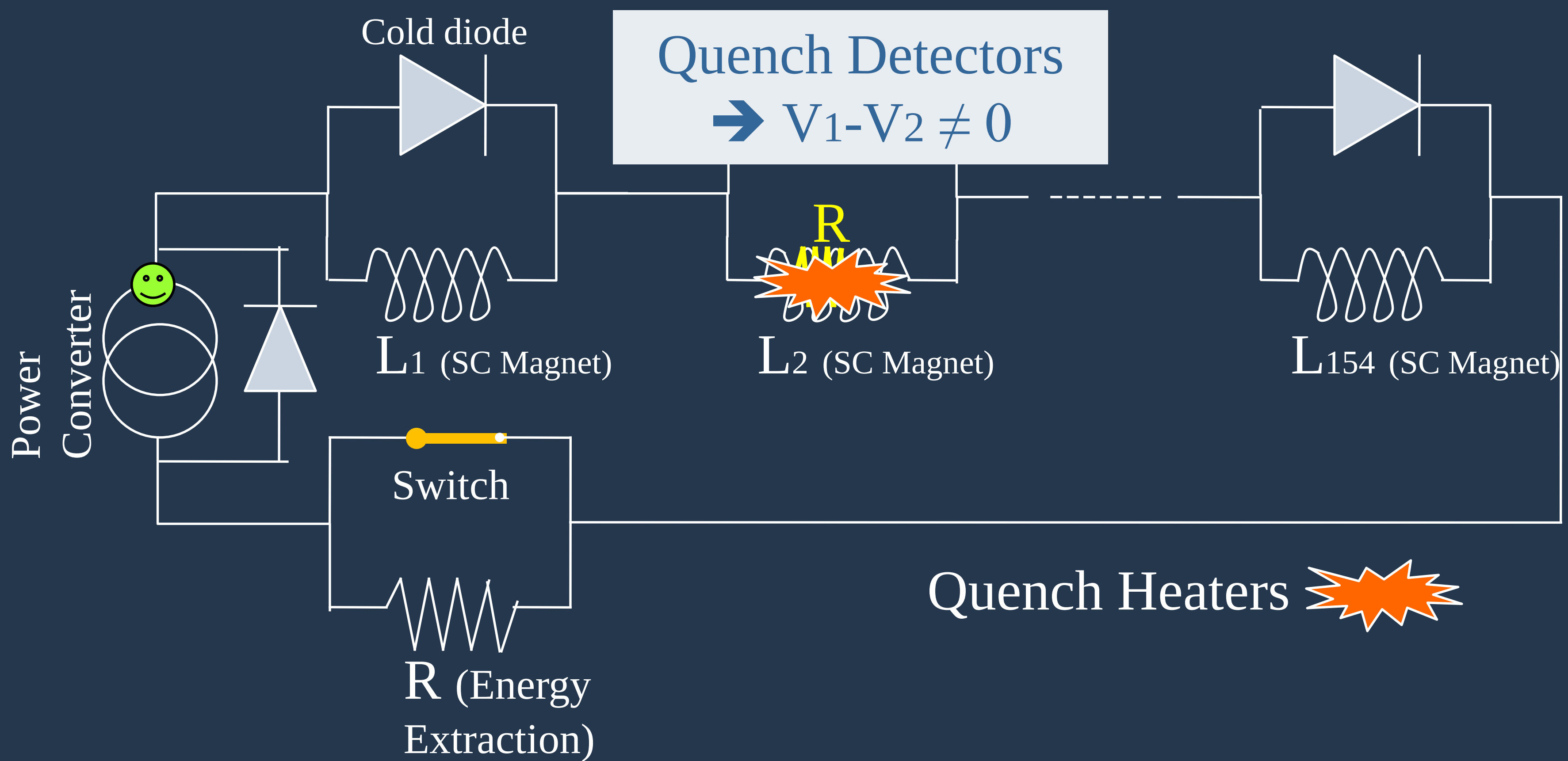
Quench Protection System

- **To limit the temperature increase after a quench**
  - **The quench has to be detected ➔ Quench Detectors***
  - **The energy is distributed in the magnet by force-quenching the coils using Quench Heaters***
  - **The stored energy is released in a controlled way ➔ Cold by-pass diodes* & Energy Extraction System**
  - **The magnet current is switched off within << 1 second ➔ Power Interlock System**
- **Failure in QPS:**
  - **False quench detection: down time of some hours** 
  - **Missed quench: damage of magnet, down time 30 days** 

*** On every SC magnet**

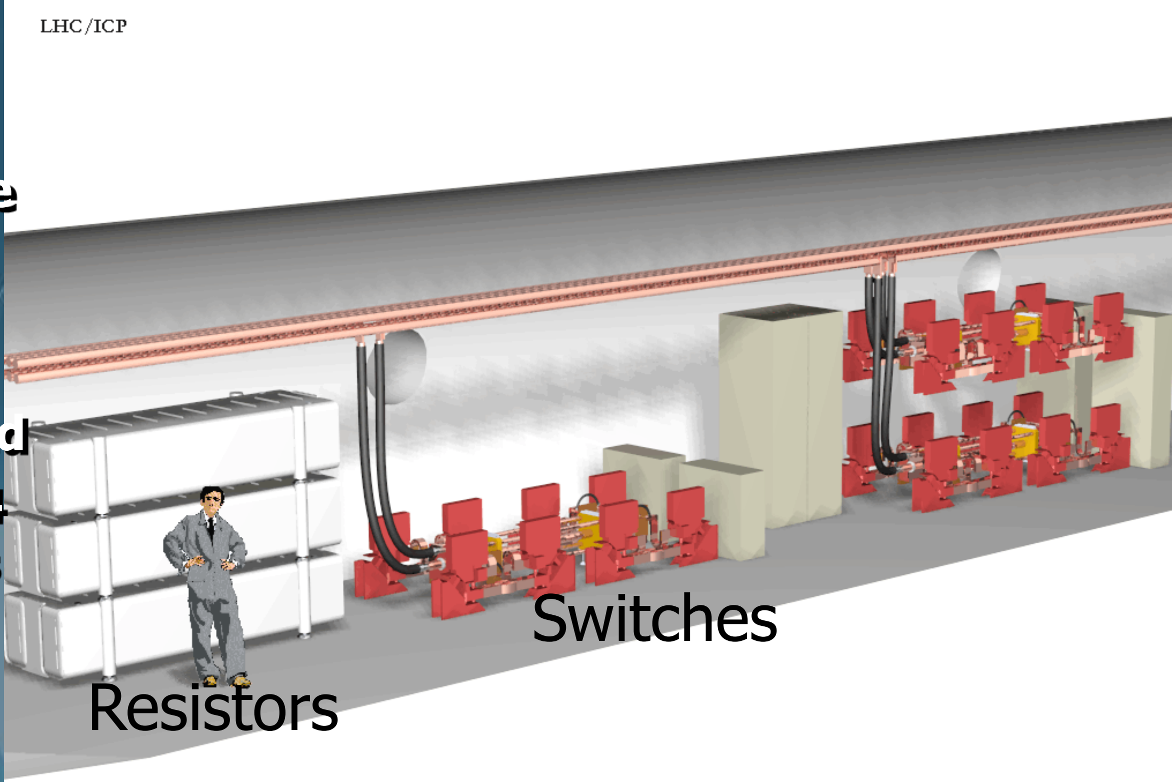
Energy Stored in the Magnets:
Quench & Quench Protection System

LHC Main Dipole System in one sector



Magnet Energy: Energy Extraction System

- During normal operation every ramp down of the magnets implies energy extraction, but this takes ~20 min ➔ too slow in case of a quench
- A dedicated Energy Extraction System for quench protection is needed
- There are 32 EES for the 24 13kA main circuits (dipoles & quadrupoles) (+ the EES for the 600 A correctors)
- This system releases the energy in 104 s for the dipoles (-125 A/s) and in 40 s for the quadrupoles (-325 A/s)

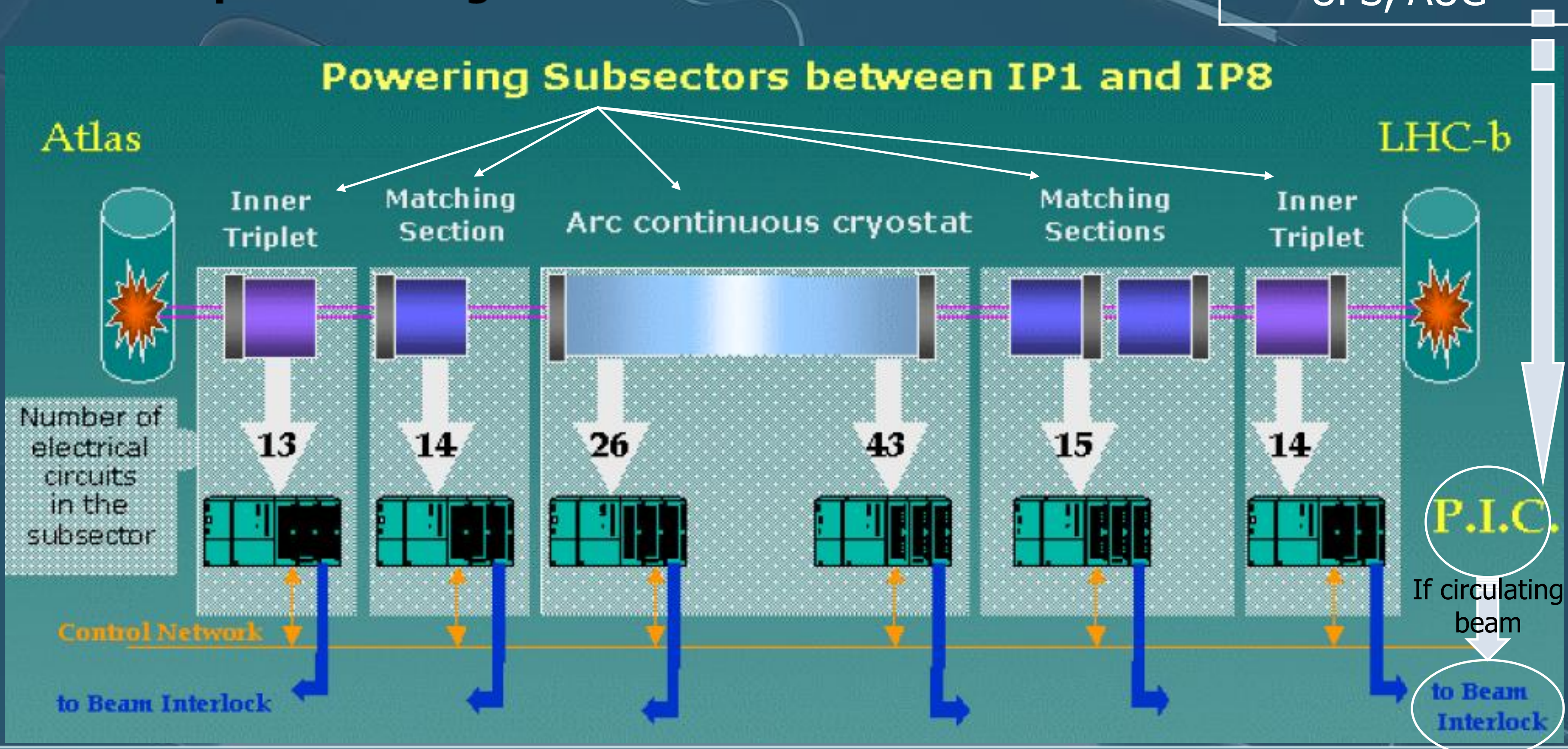


13kA Energy Extraction Facilities in the UA's for LHC Main Dipole and QF/QD circuits

Magnet Energy: Power Interlock Controller

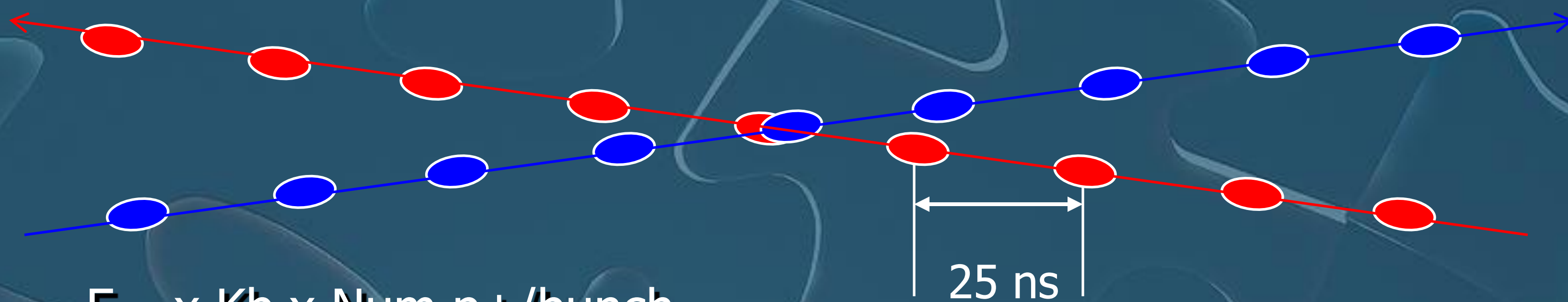
- **36 PICs in LHC for the SC magnets (warm magnets also have PICs)**
- **1 PIC per Powering Subsector**

Power Converters
QPS
Cryo
UPS, AUG



Contents

Energy Stored in the Beams



$E_{beam} = E_{p+} \times Kb \times Num\ p+/bunch$

$E_{p+} = 7$ TeV

$Kb = 2808$

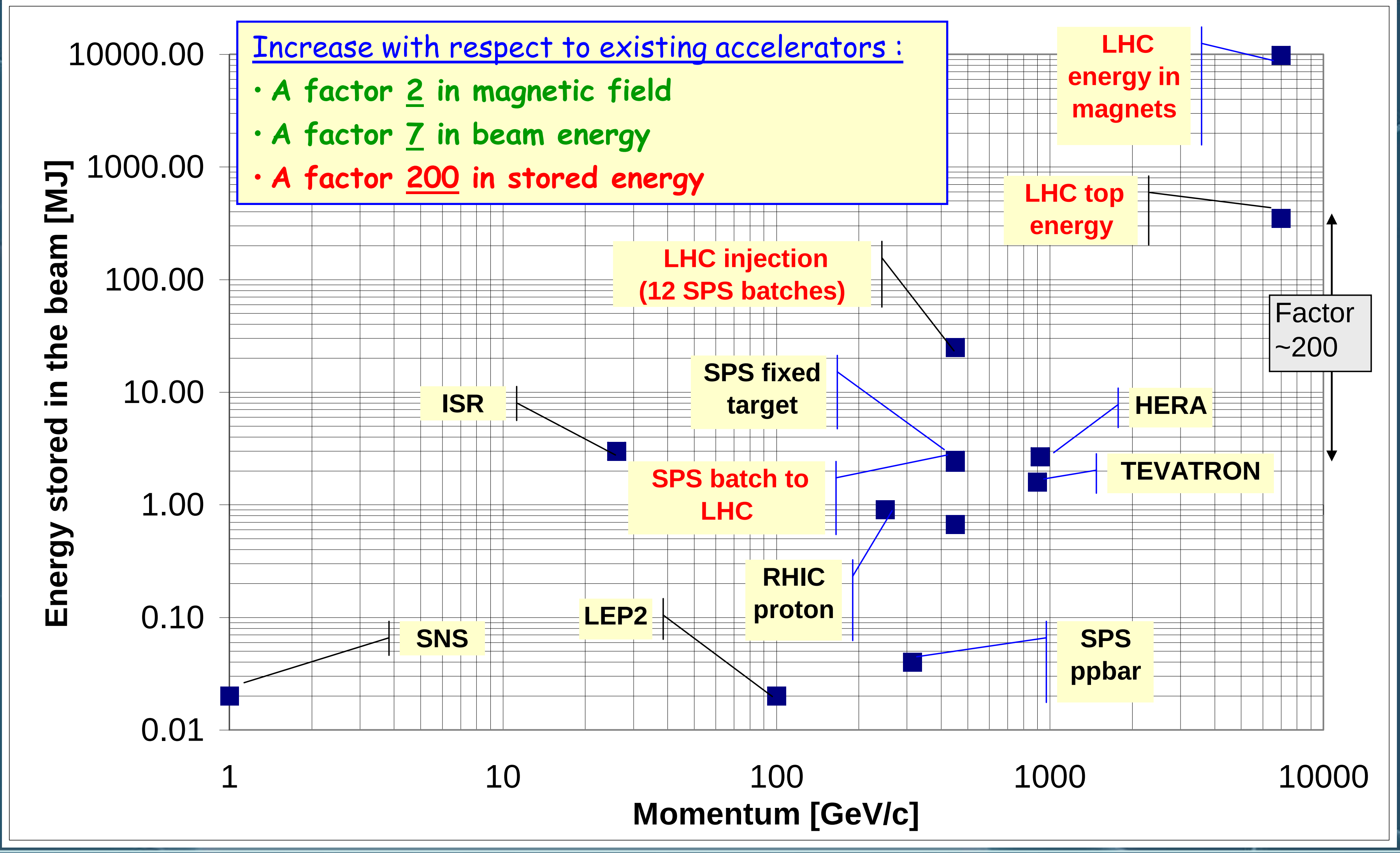
Num p+/bunch $= 1.15 \times 10^{11}$

Nominal values

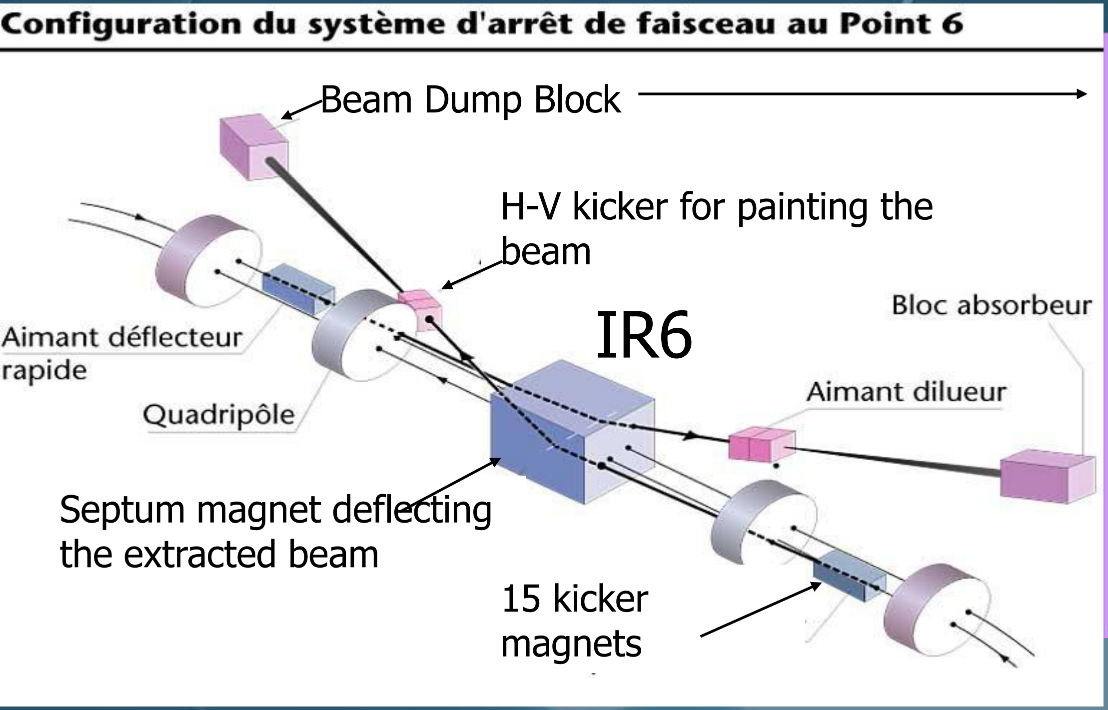
$E_{beam} = 362$ MJules

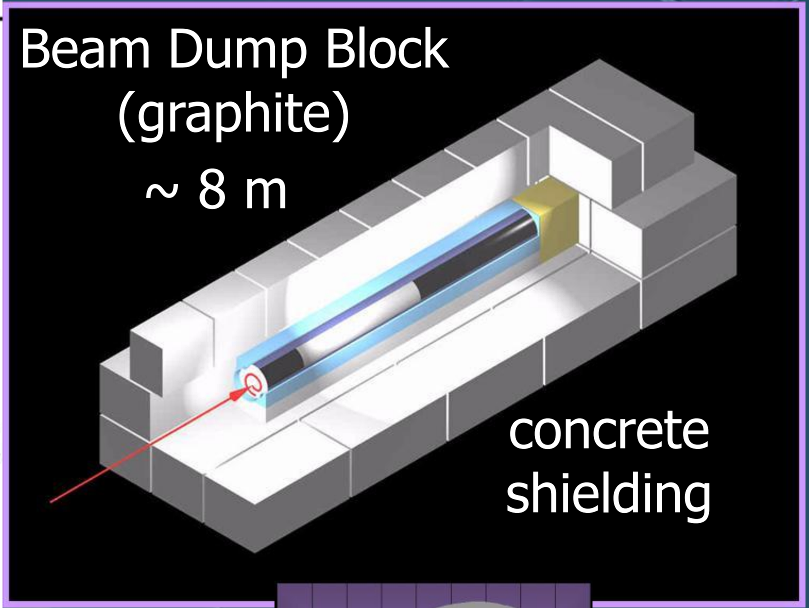
Enough to melt 500 kg of copper

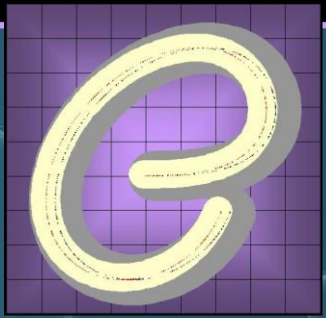
Energy Stored in the Beams



Energy Stored in the Beams: Beam Dump System

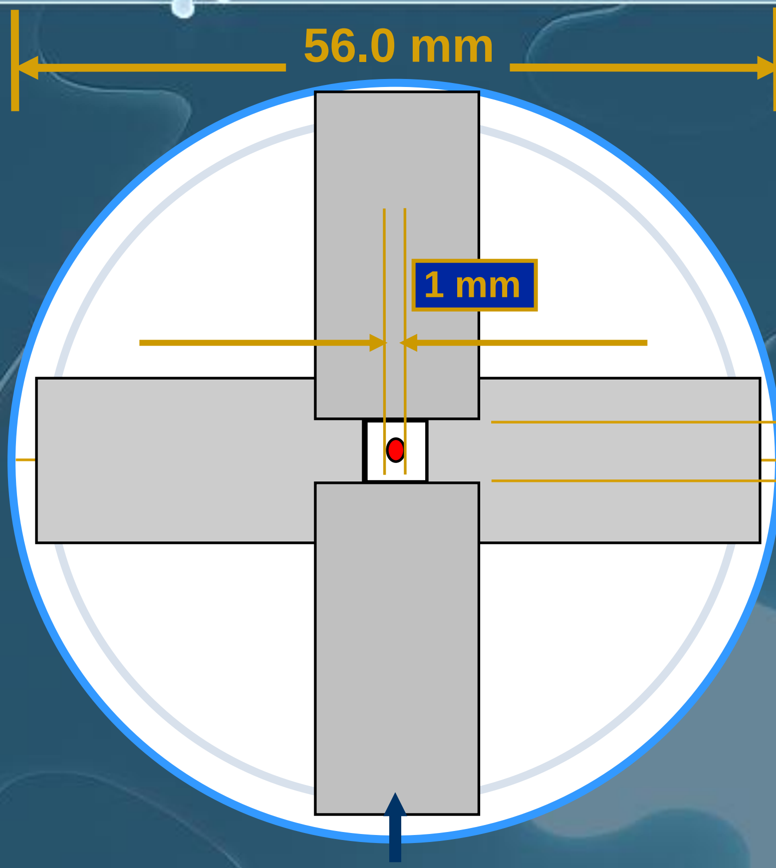






Is the only system in LHC able to absorb the full nominal beam

Energy Stored in the Beams: Collimation System



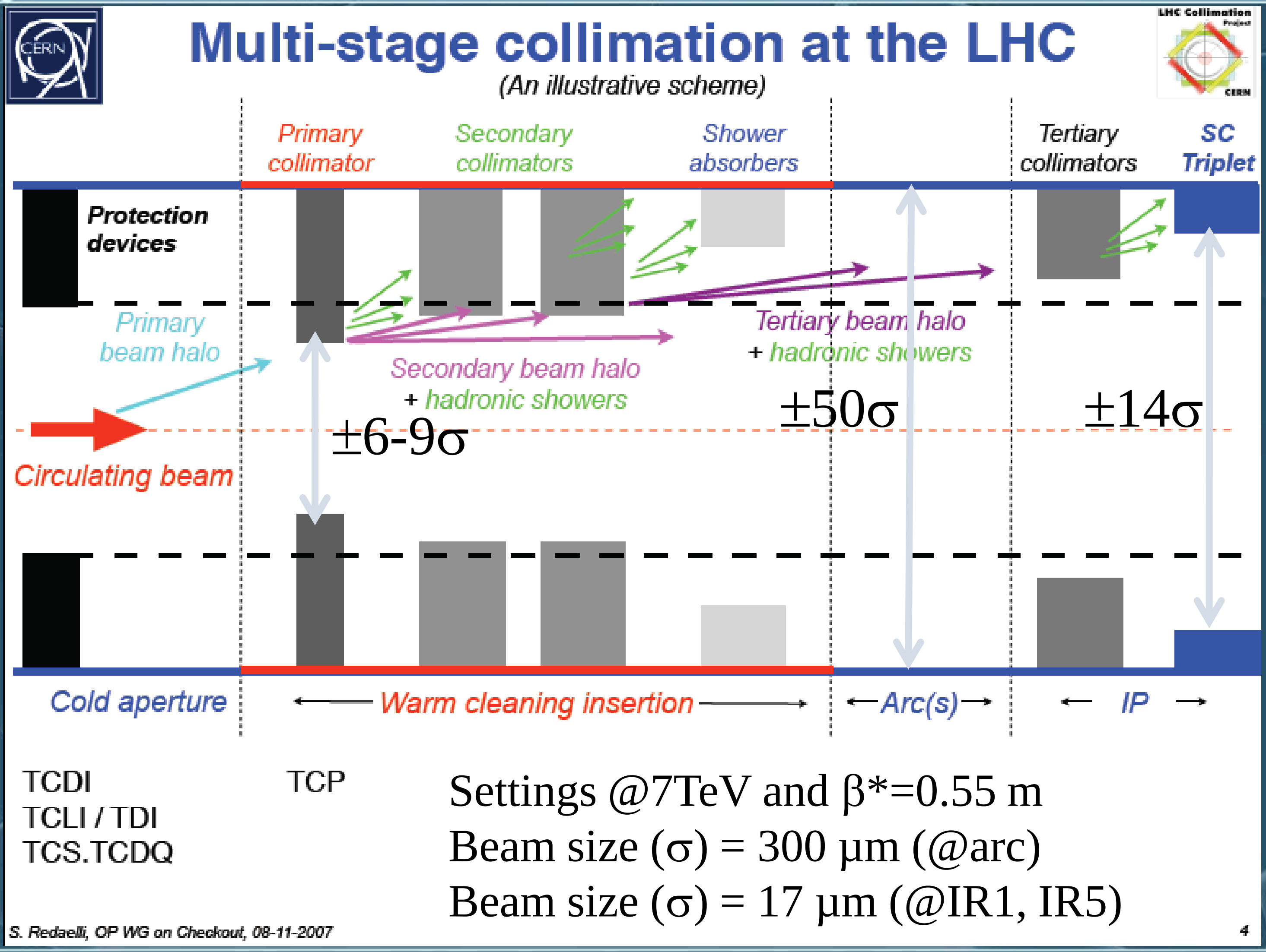
Collimation System Functionality:

1. Absorb beam halo to avoid quenches
2. Once beam losses appear they protect the equipment and experiments. If BLMCs > Threshold → Beam Interlock → Beam Dump

E.g. Settings of collimators @7 TeV with luminosity optics

Very tight settings → orbit feedback!!

Energy Stored in the Beams: Collimation System



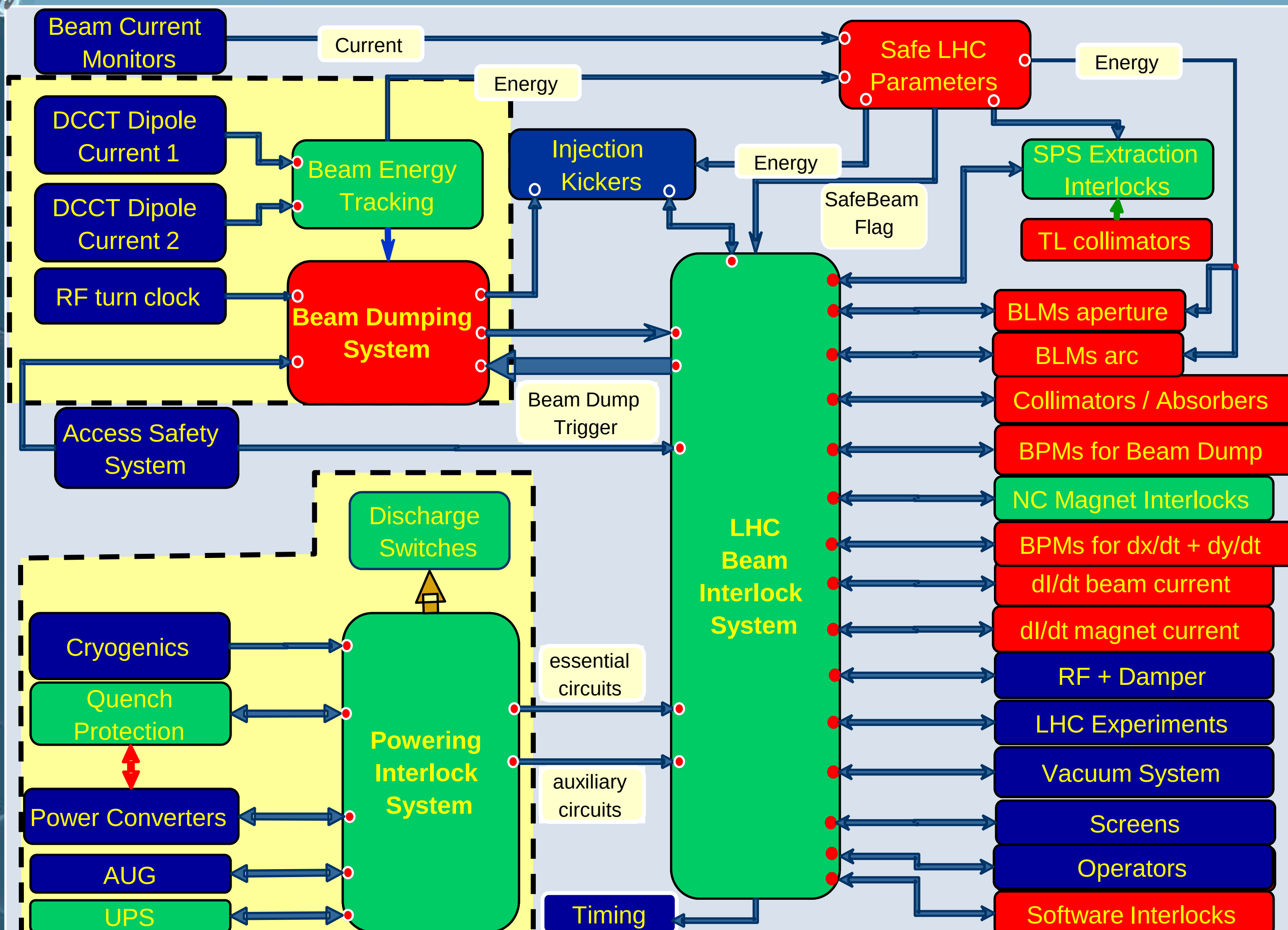
Settings @7TeV and β*=0.55 m

Beam size (σ) = 300 μm (@arc)

Beam size (σ) = 17 μm (@IR1, IR5)

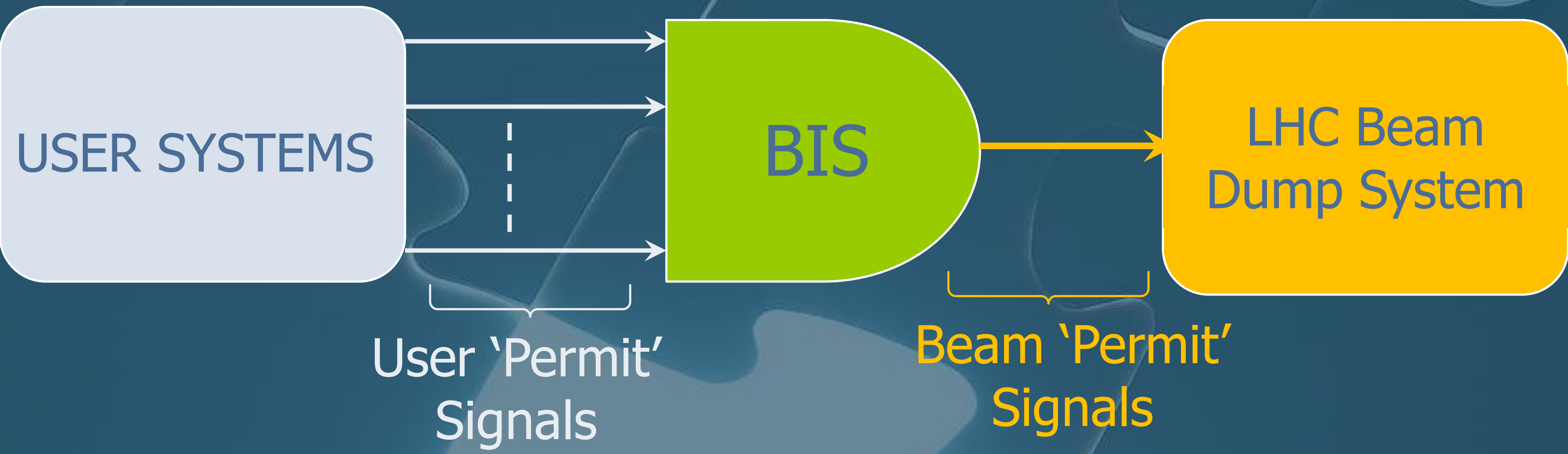
Contents

Machine Protection System



Green = ready before first beam

Machine Protection System: Beam Interlock



153 User Systems distributed over 27 km

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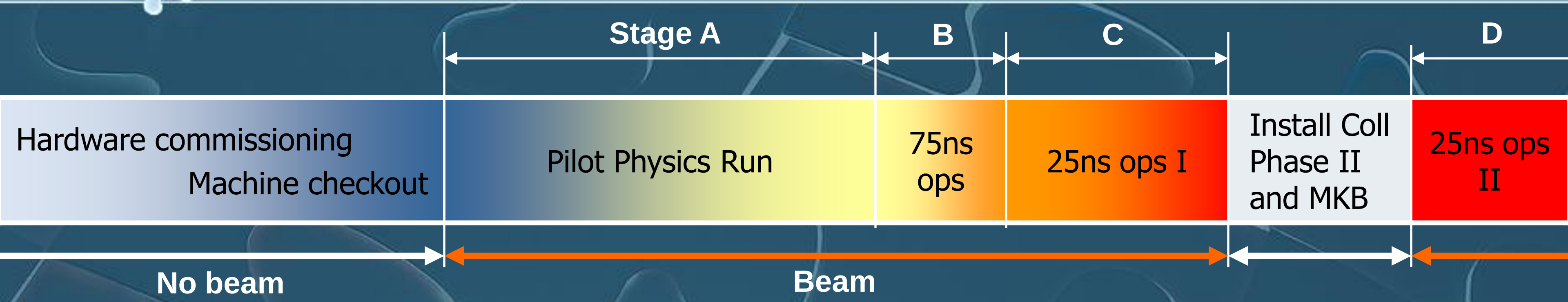
Overall Strategy for Commissioning



Hardware Commissioning

Thorough commission of technical systems:

- Magnets, vacuum, cryo, PC, quench detection, energy extraction, RF, beam instrumentation, kickers, septa, collimators, absorbers, etc.
- Services: AC distribution, water-cooling, ventilation, access control, safety, etc.

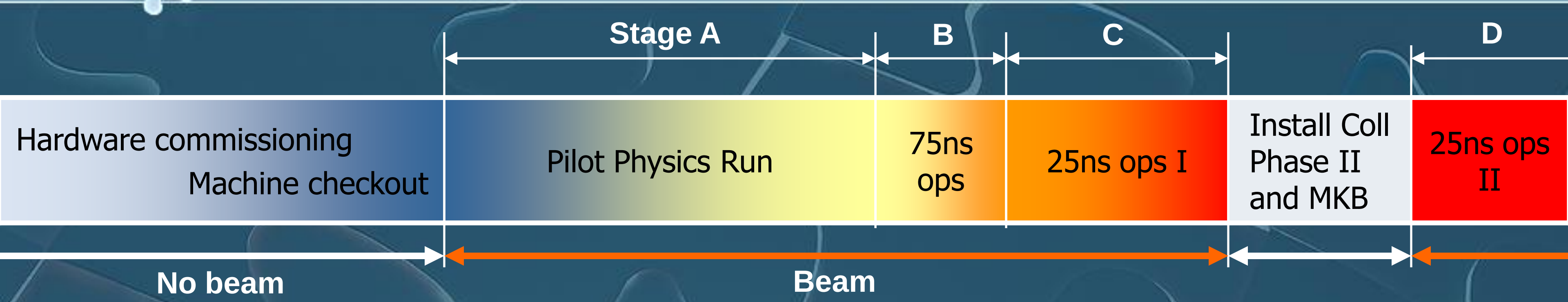
Stages:

1. Individual system test
2. Global system test

Commissioned energy:

1. 2008 ➔ Eb = 5.5 TeV (no training quenches)
2. 2009 ➔ Eb = 7 TeV ?? (magnet training required)

Overall Strategy for Commissioning



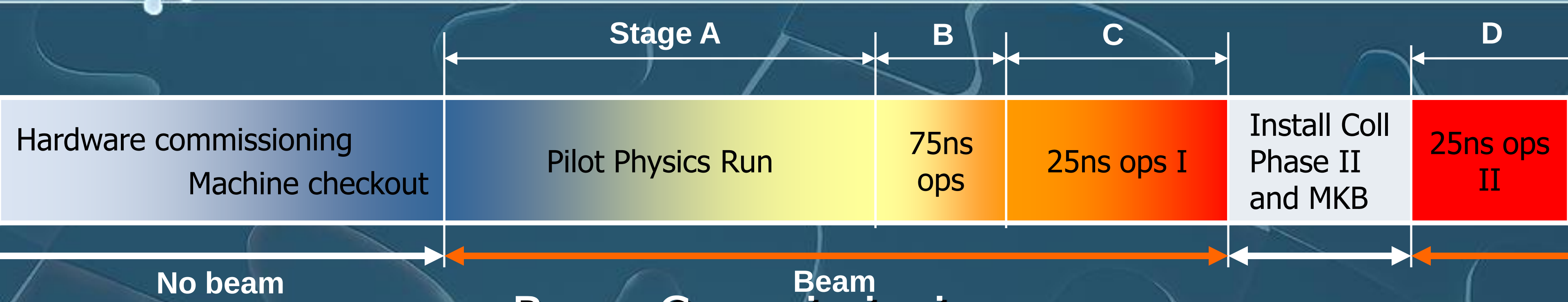
Machine Checkout

- Drive all systems through the standard operational sequence (synchronized)
- Check Control System functionality from CCC high-level software applications
- Check beam instrumentation acquisition chain
- Check timing synchronization
- Check all equipment control functionality
- Check machine protection and interlock system

Stages:

1. Individual system test. First integration into the OP group
2. Multi-system test, e.g. Machine Protection (BLM, BIS, LBDS)
3. Dry run: drive the whole machine through the nominal sequence.

Overall Strategy for Commissioning



Beam Commissioning

Stage A: Pilot physics run

- First collisions
- 43 bunches, no crossing angle, no squeeze, moderate intensities
- Push performance
- Performance limit 10^{32} $cm^{-2}s^{-1}$ (event pileup)

Stage B: 75ns operation

- Establish multi-bunch operation, moderate intensities
- Relaxed machine parameters (squeeze and crossing angle)
- Push squeeze and crossing angle
- Performance limit 10^{33} $cm^{-2}s^{-1}$ (evt pileup)

Stage C: 25ns operation I

- Nominal crossing angle
- Push squeeze
- Increase intensity to 50% nominal
- Performance limit 2 10^{33} $cm^{-2}s^{-1}$

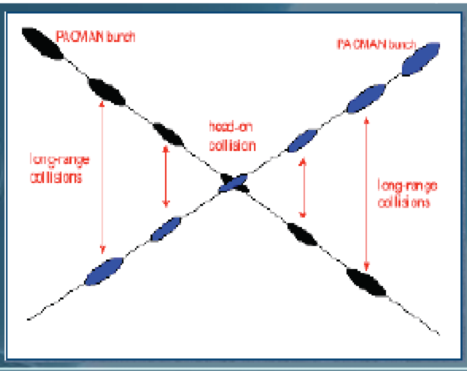
Stage D: 25ns operation II

- Push towards nominal performance
- Requires hardware updates: collimators and beam dump system
- Performance goal: 10^{34} $cm^{-2}s^{-1}$

Beam Commissioning with p^+

- LHC Design Parameters:

Design Parameters	
Lumi IP 1,5 ($cm^{-2}\ s^{-1}$)	10^{34}
Lumi IP 2,8 ($cm^{-2}\ s^{-1}$)	$5\ 10^{32}$
σ_{xy} IP 1,5 (μm)	16.7
σ_{xy} IP 2,8 (μm)	70.9
Crossing angle (μrad)	285



Nominal Settings	
E_{beam} (TeV)	7
# p^+/bunch	$1.15\ 10^{11}$
# bunches/beam	2808
E_{beam} Stored (MJ)	362
ε_n^{xy} (μm rad)	3.75
Bunch length (cm)	7.5
β^* (IP: 1,2,5,8) (m)	0.55, 0.55, 10, 10

Beam Commissioning with p^+ Stage A

- Start as simple as possible
- Change 1 parameter (kb, N, β*) at a time
- All values for:
  - nominal emittance
  - 7 TeV
  - 2 m β* (IP: 1&5)

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

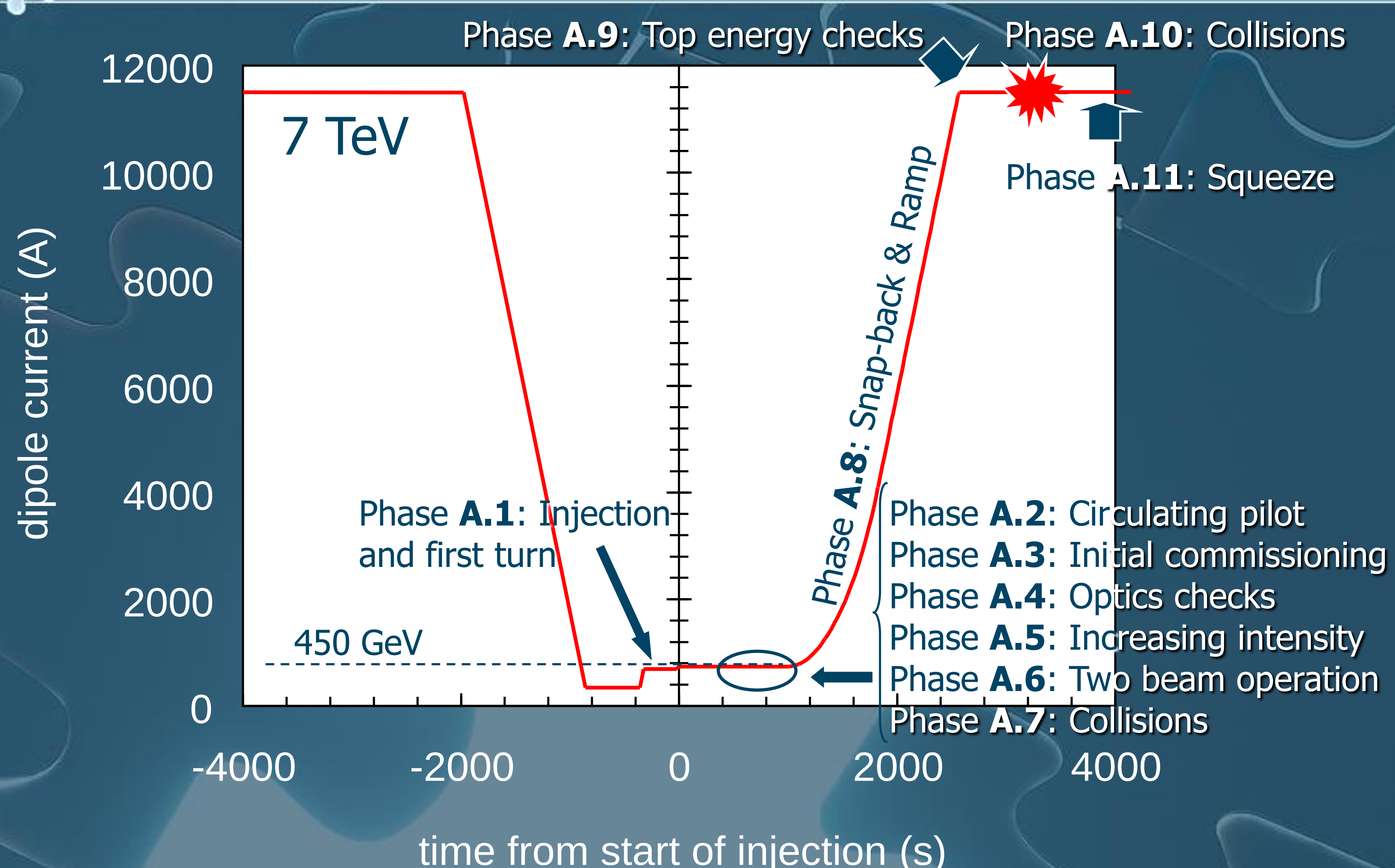
$$EvtRate/Cross = \frac{L\sigma_{TOT}}{k_b f}$$

Protons/beam ≲ 10^{13}
(LEP beam currents)

Stored energy/beam ≲ 10MJ
(SPS fixed target beam)

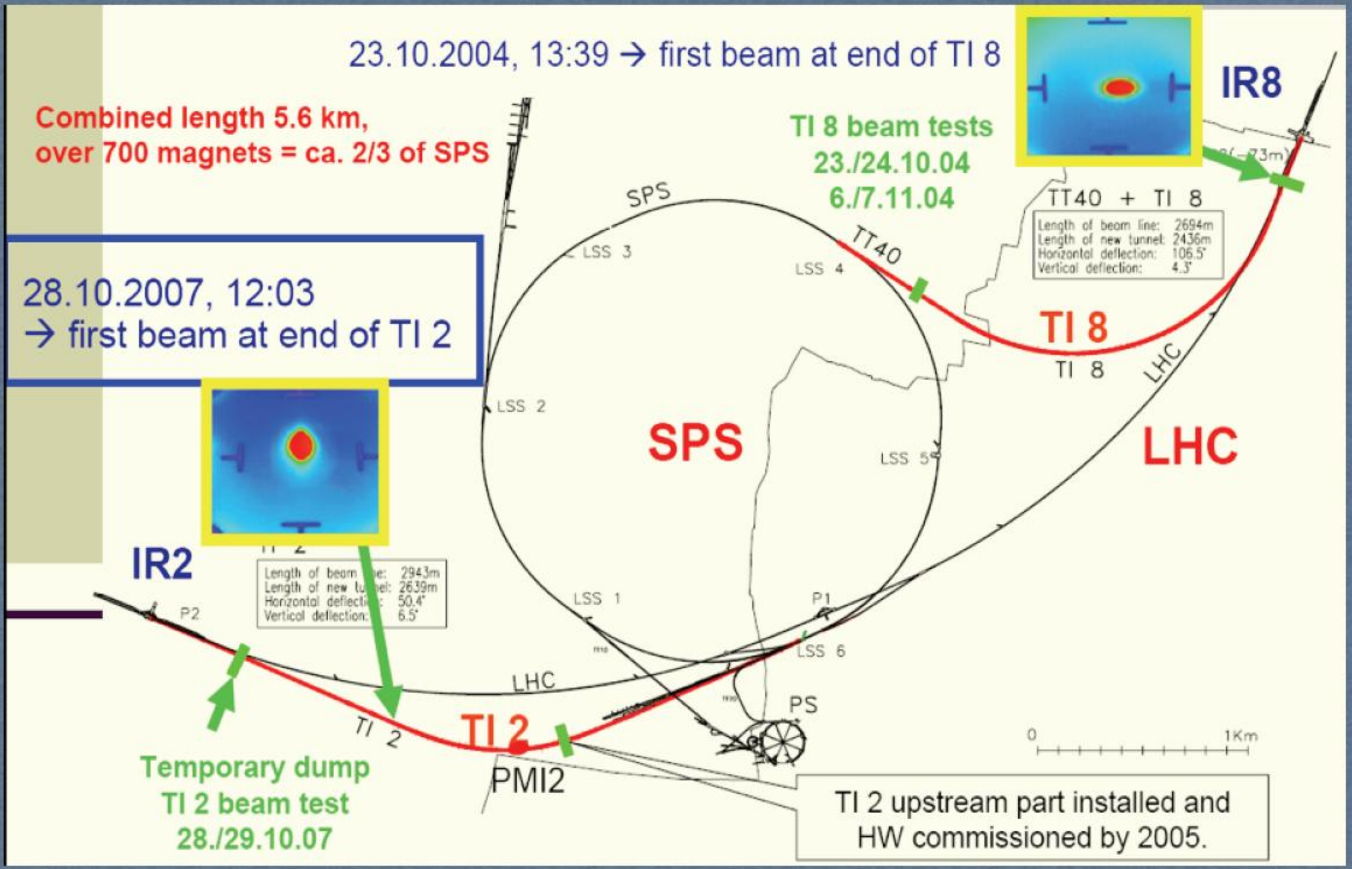
Parameters			Beam levels		Rates in 1 and 5		Rates in 2	
k_b	N	β* 1,5 (m)	I_{beam} proton	E_{beam} (MJ)	Luminosity ($cm^{-2}s^{-1}$)	Events/ crossing	Luminosity ($cm^{-2}s^{-1}$)	Events/ crossing
1	10^{10}	11	$1\ 10^{10}$	10^{-2}	$1.6\ 10^{27}$	<< 1	$1.8\ 10^{27}$	<< 1
43	10^{10}	11	$4.3\ 10^{11}$	0.5	$7.0\ 10^{28}$	<< 1	$7.7\ 10^{28}$	<< 1
43	$4\ 10^{10}$	11	$1.7\ 10^{12}$	2	$1.1\ 10^{30}$	<< 1	$1.2\ 10^{30}$	0.15
43	$4\ 10^{10}$	2	$1.7\ 10^{12}$	2	$6.1\ 10^{30}$	0.76	$1.2\ 10^{30}$	0.15
156	$4\ 10^{10}$	2	$6.2\ 10^{12}$	7	$2.2\ 10^{31}$	0.76	$4.4\ 10^{30}$	0.15
156	$9\ 10^{10}$	2	$1.4\ 10^{13}$	16	$1.1\ 10^{32}$	3.9	$2.2\ 10^{31}$	0.77

Beam Commissioning with p+ Stage A



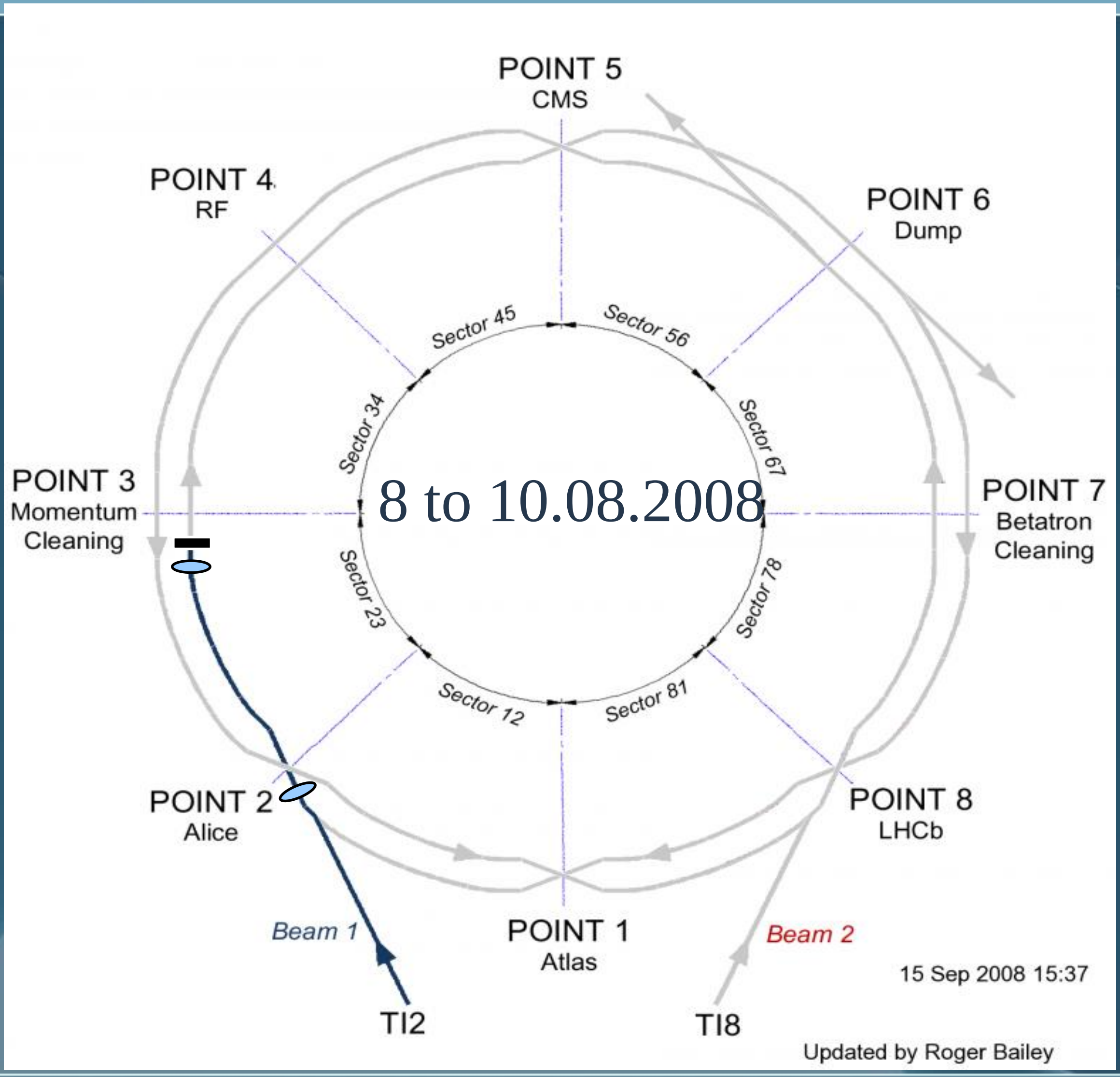
Beam Commissioning in the Transfer Lines

Transfer line commissioning



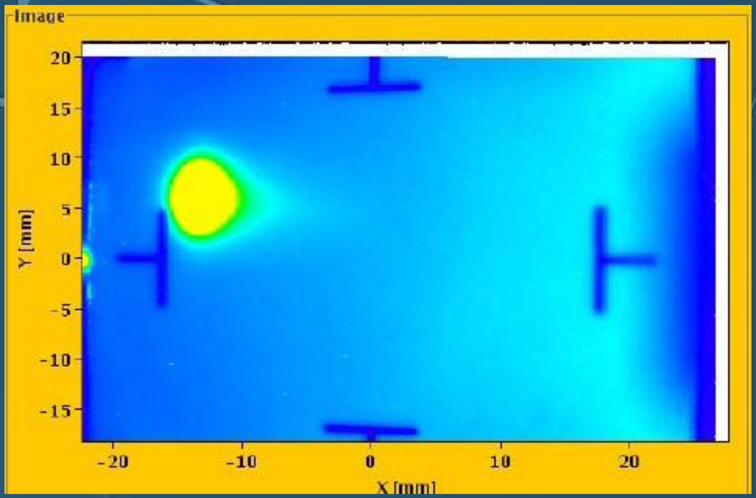
Courtesy of J. Uythoven

Injection Test 1



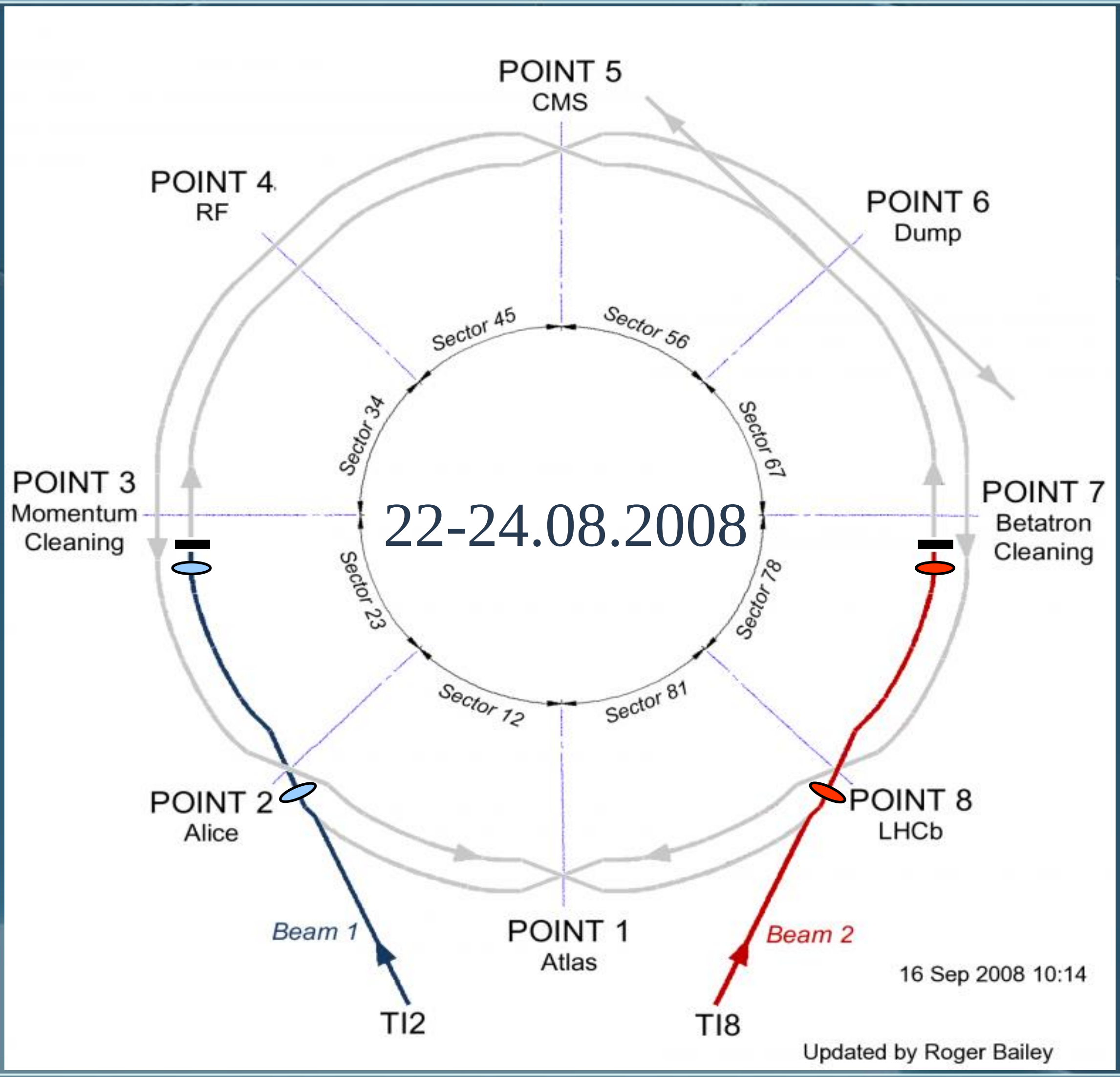
Injection Test 1

- Achieved
  - Synchronization SPS – LHC
  - **Beam 1** injected IP2
  - Through to collimators in IP3 first shot
  - Trajectory correction
  - Kick-response measurements
  - Off-energy measurements (dispersion)
  - Explored the aperture
  - Quench



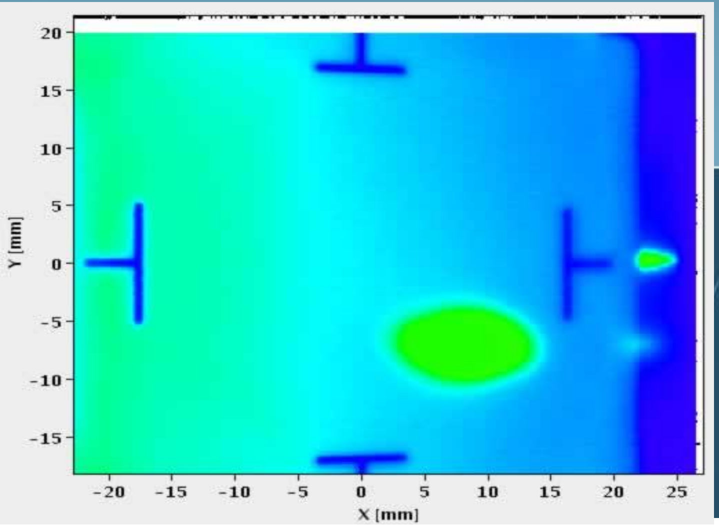
- Discovered
  - Aperture restriction in the injection line
    - Traced to misaligned vacuum pump
  - Optics problem IP3
    - Polarity convention QTL

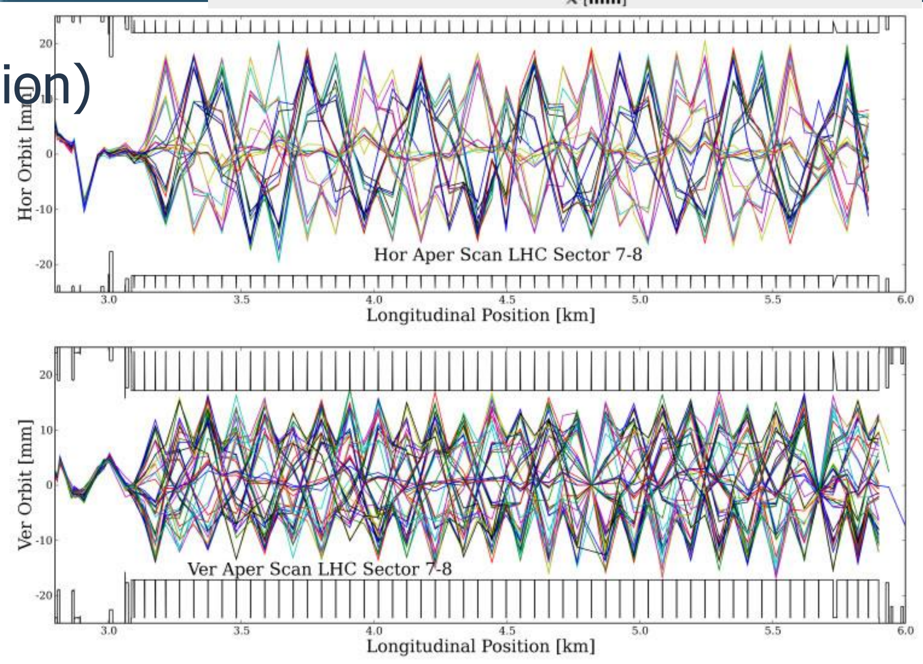
Injection Test 2



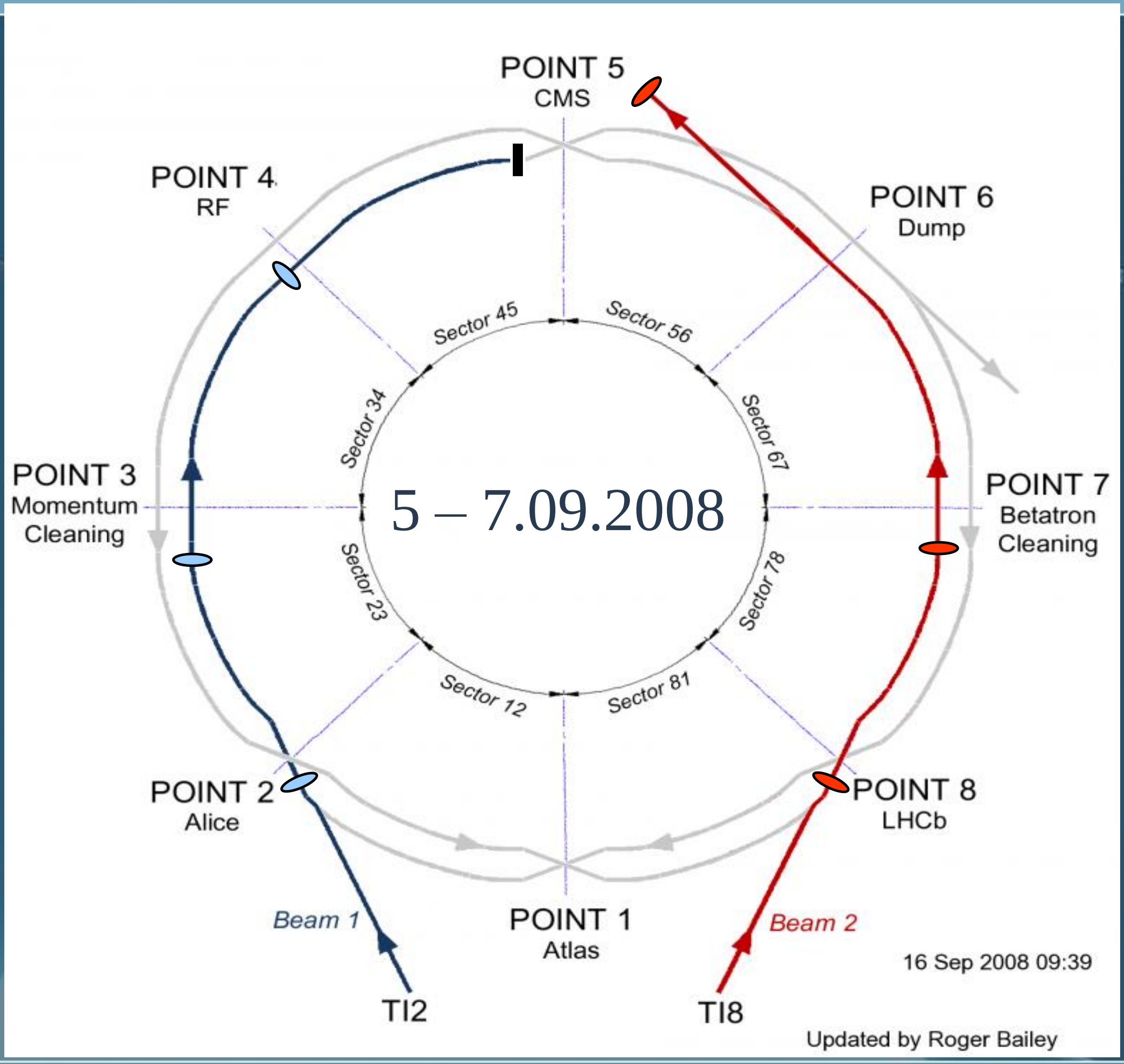
Injection Test 2

- Achieved
  - Beam 2 injected IP8
  - Through to collimators in IP7 first shot
  - Trajectory correction
  - Kick-response measurements
  - Off-energy measurements (dispersion)
  - Explored the aperture
  - Beam 1 injected IP2
  - Through to collimators in IP3
  - Aperture in injection region OK
  - Polarity correction confirmed
  - Interleaved injection
- Discovered
  - Optics problem at the end of the TI8 line





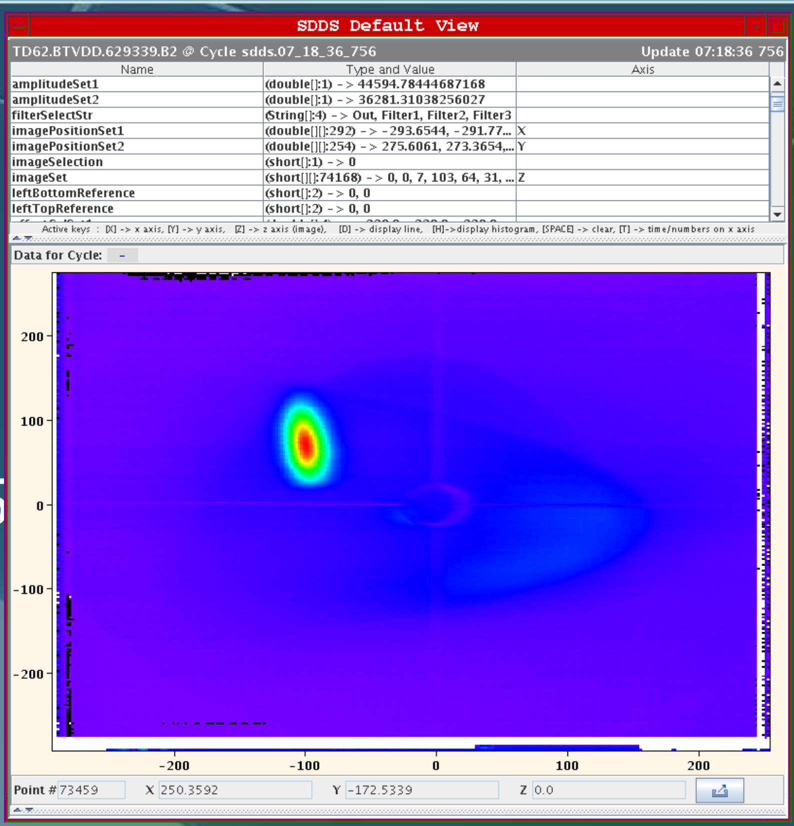
Injection Test 3



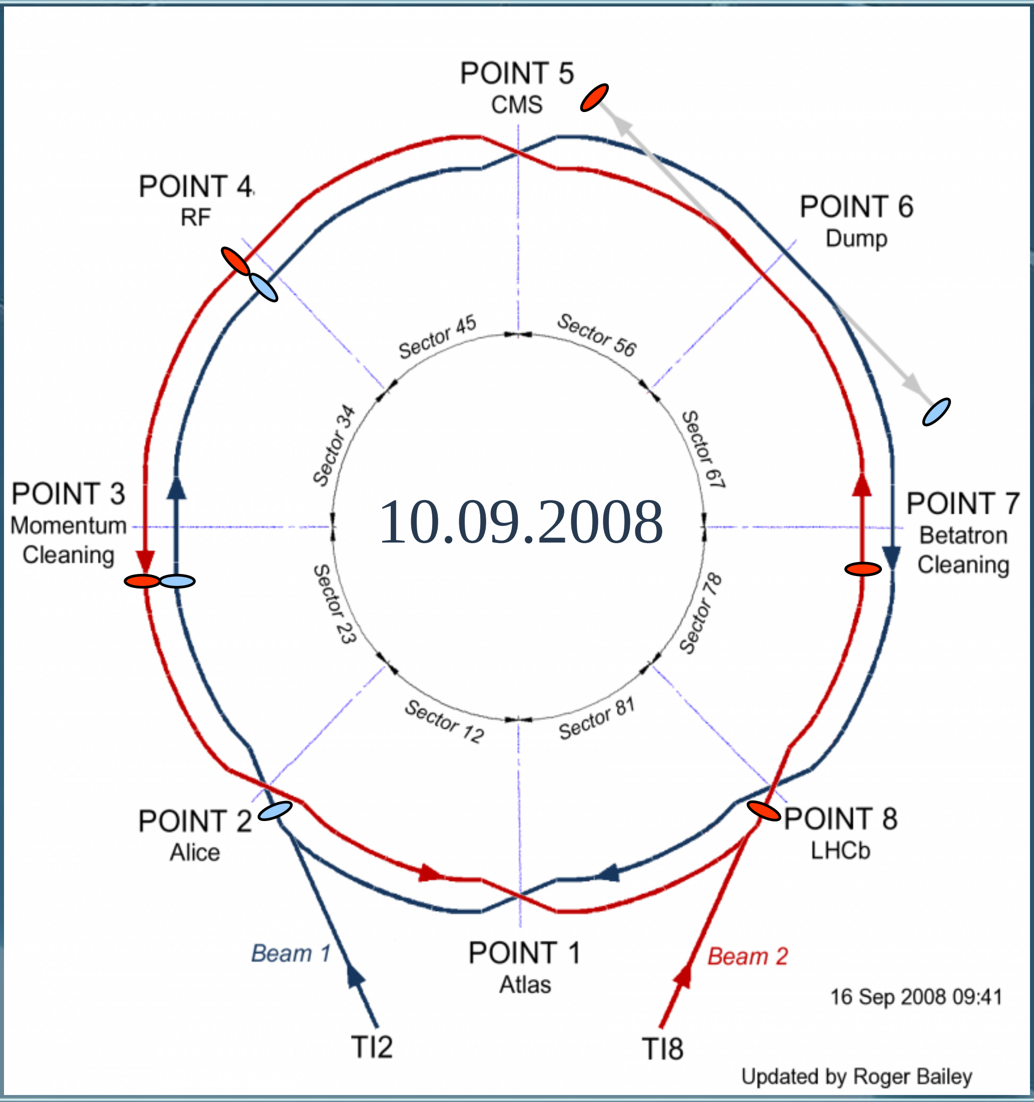
Injection Test 3

- Achieved
  - Beam 2 injected IP8
  - Threaded to dump in IP6
  - Steered then inject and dump
  - Beam 1 injected IP2
  - Threaded through to coll in IP5

- Discovered
  - Optics problem in IP7
    - Polarity convention on Q6
  - Optics problem in IP4
    - Polarity convention



10th of September

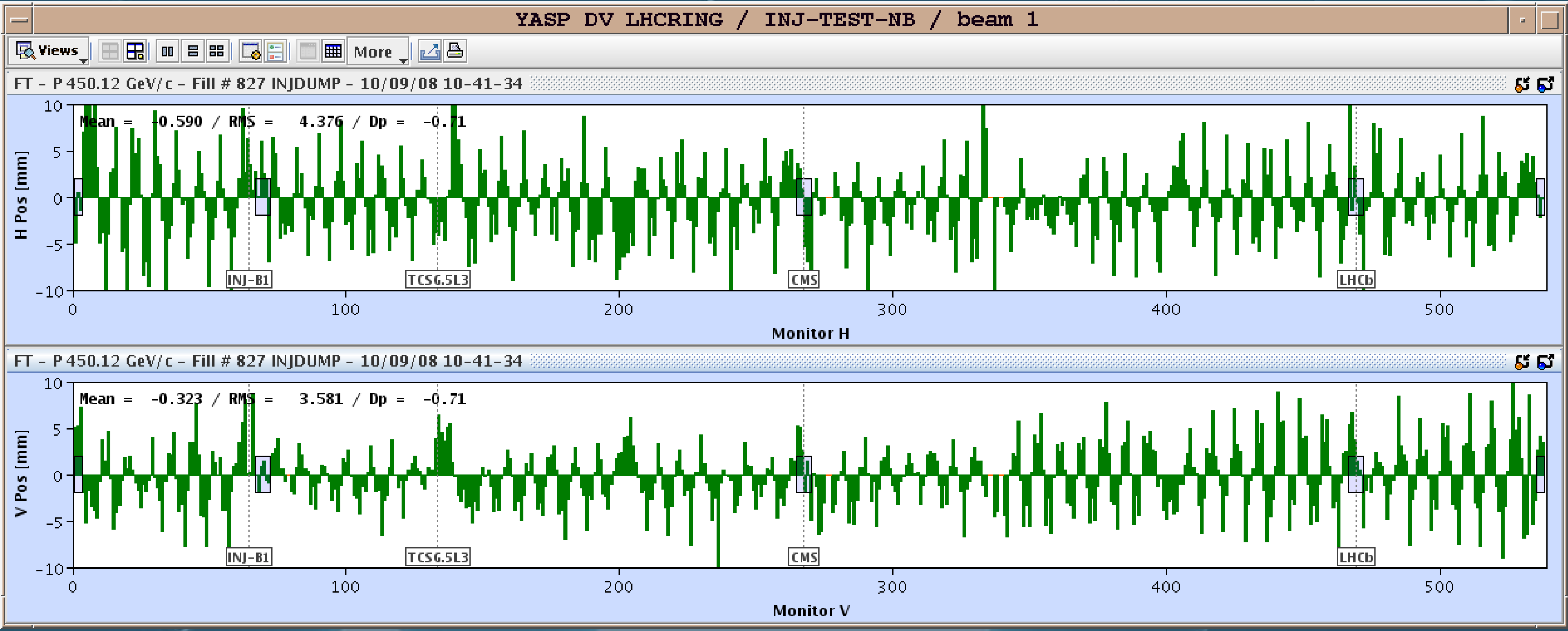


10th of September

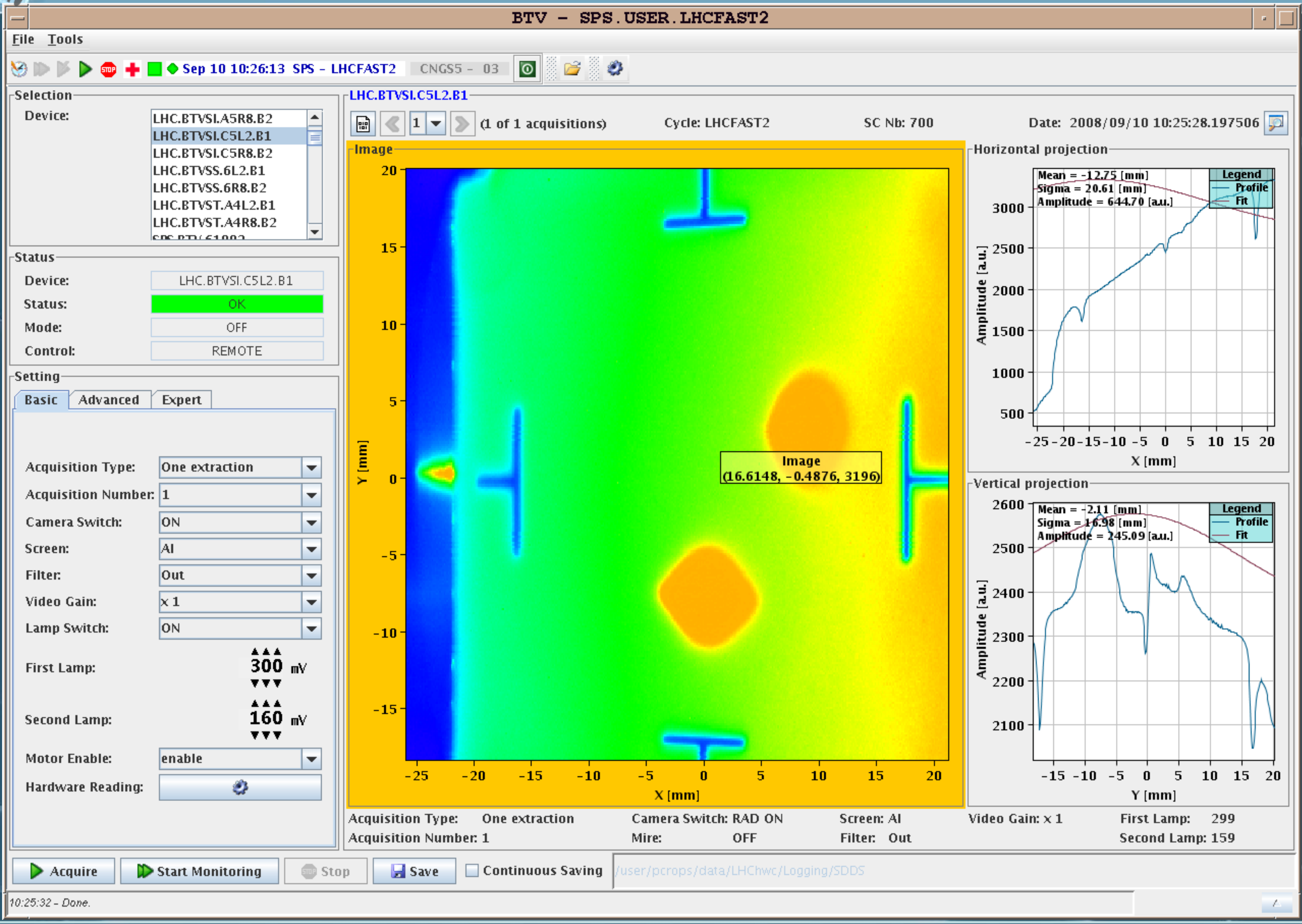
- Achieved
  - Beam 1 injected IP2
  - Threaded around the machine in 1h
  - Trajectory steering gave 2 or 3 turns

  - 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

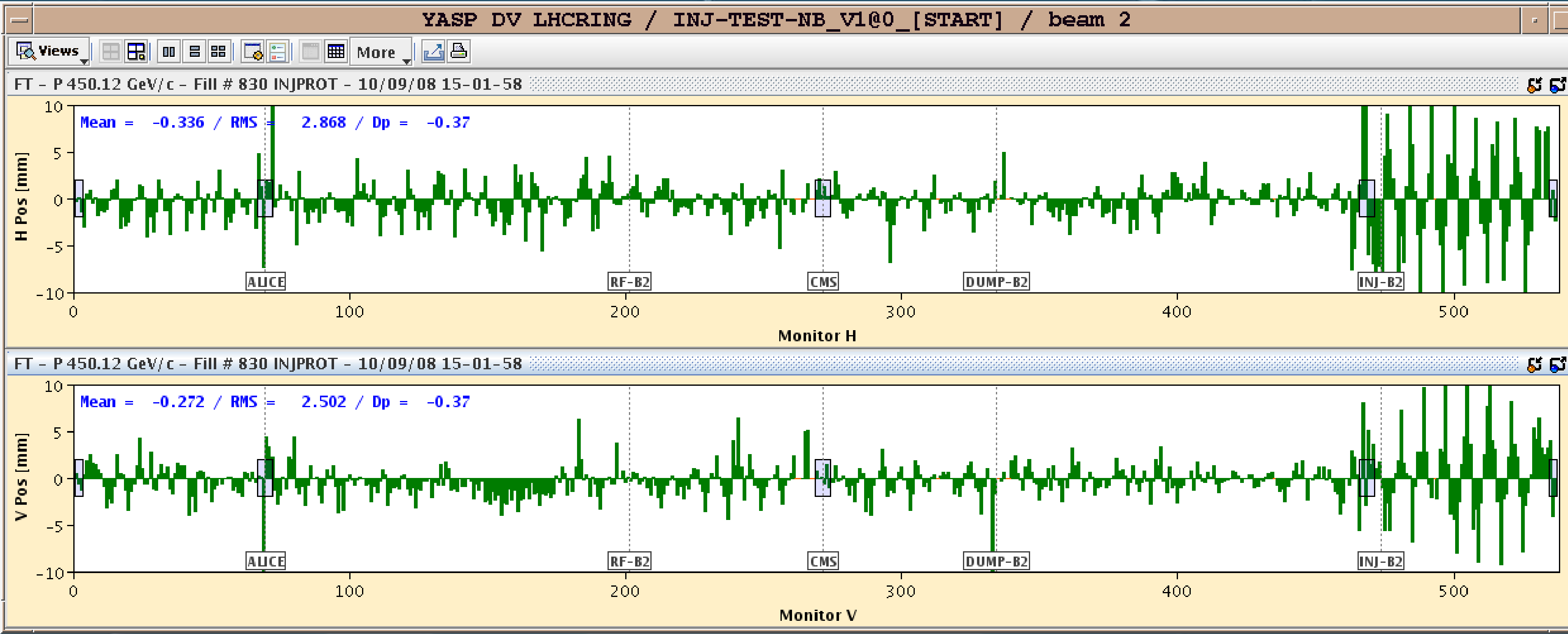
Beam 1 – First turn trajectory



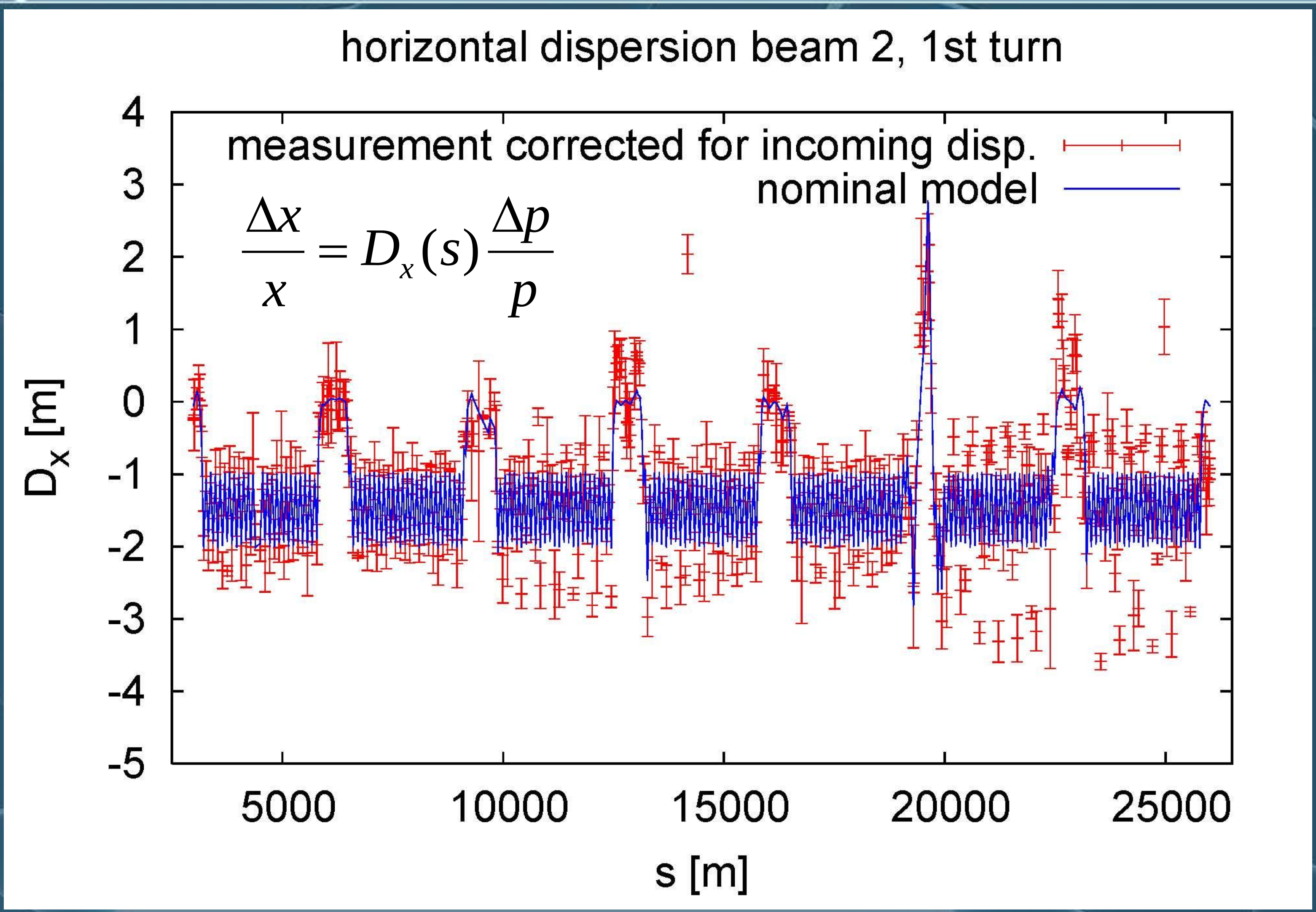
Beam 1 on TDI screen – 1^{st} and 2^{nd} turns



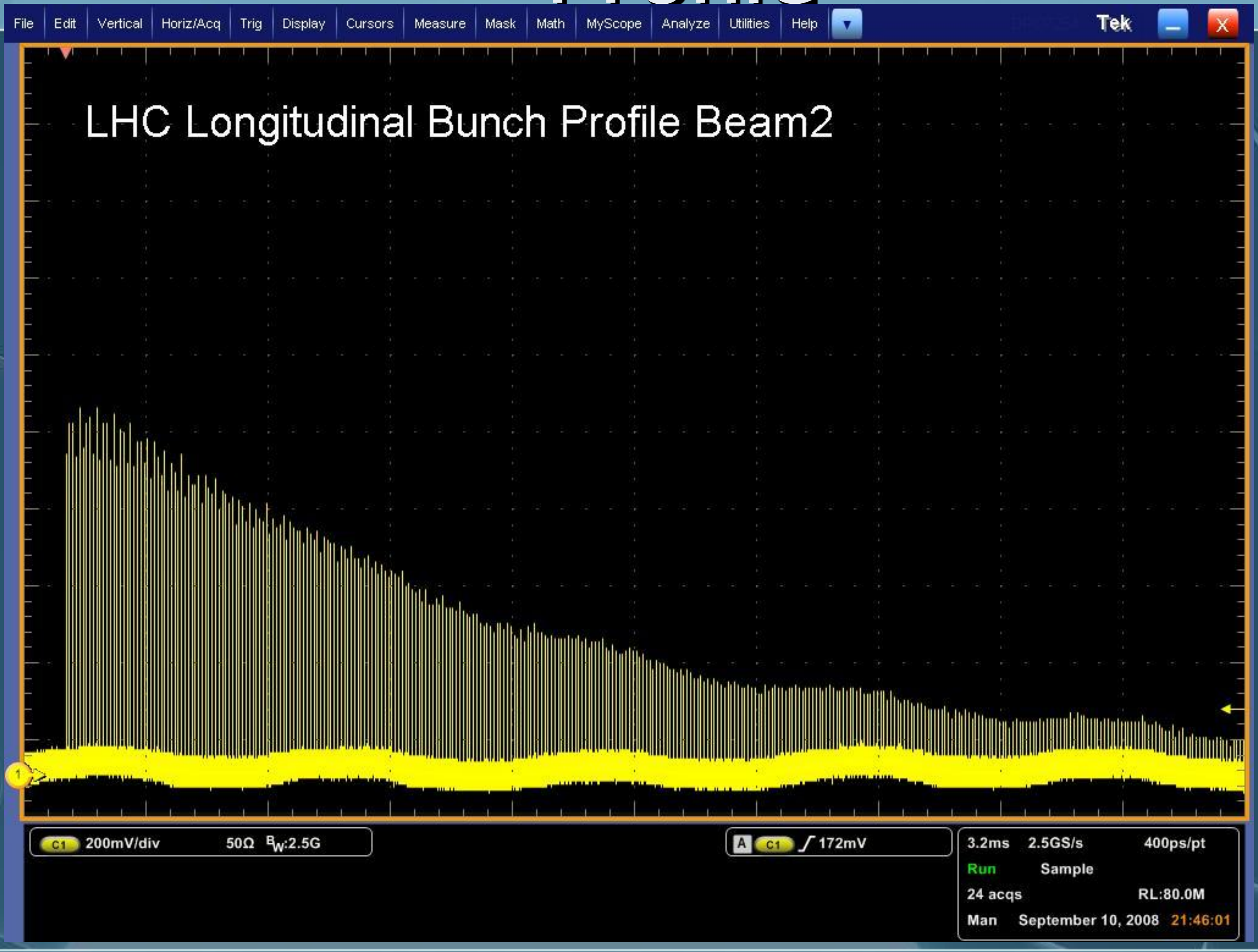
Beam 2 – First turn trajectory



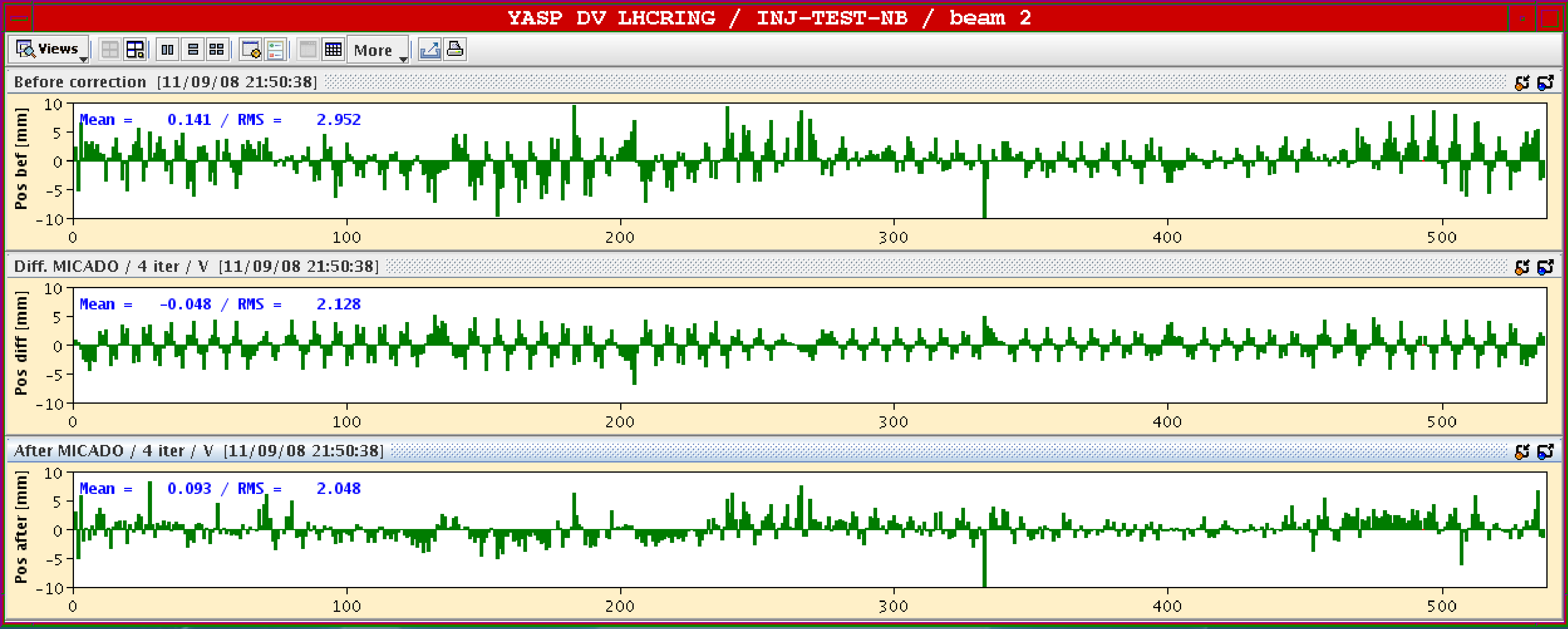
Beam 2 – first turn dispersion measurement



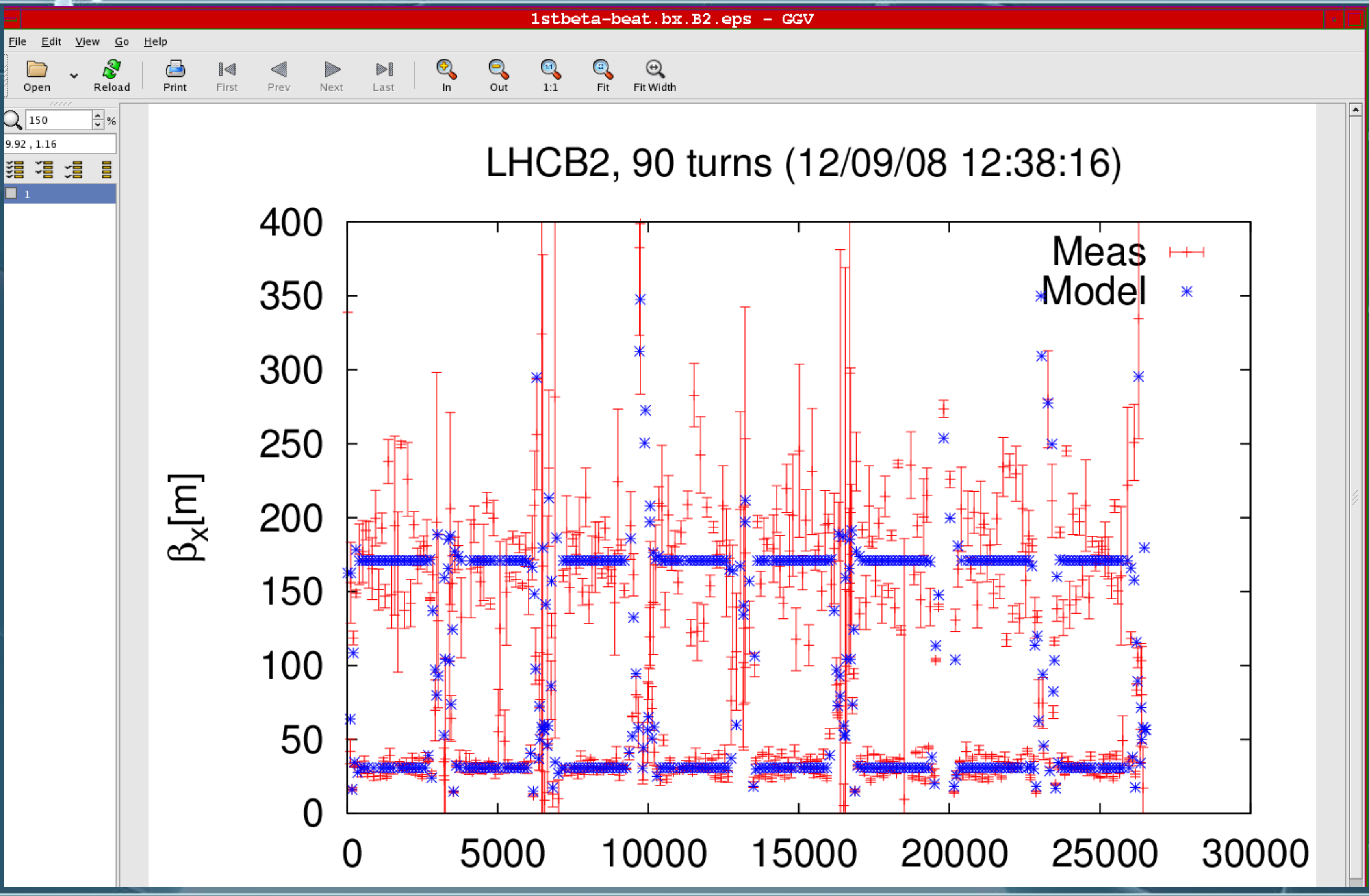
Beam 2: Longitudinal Bunch Profile



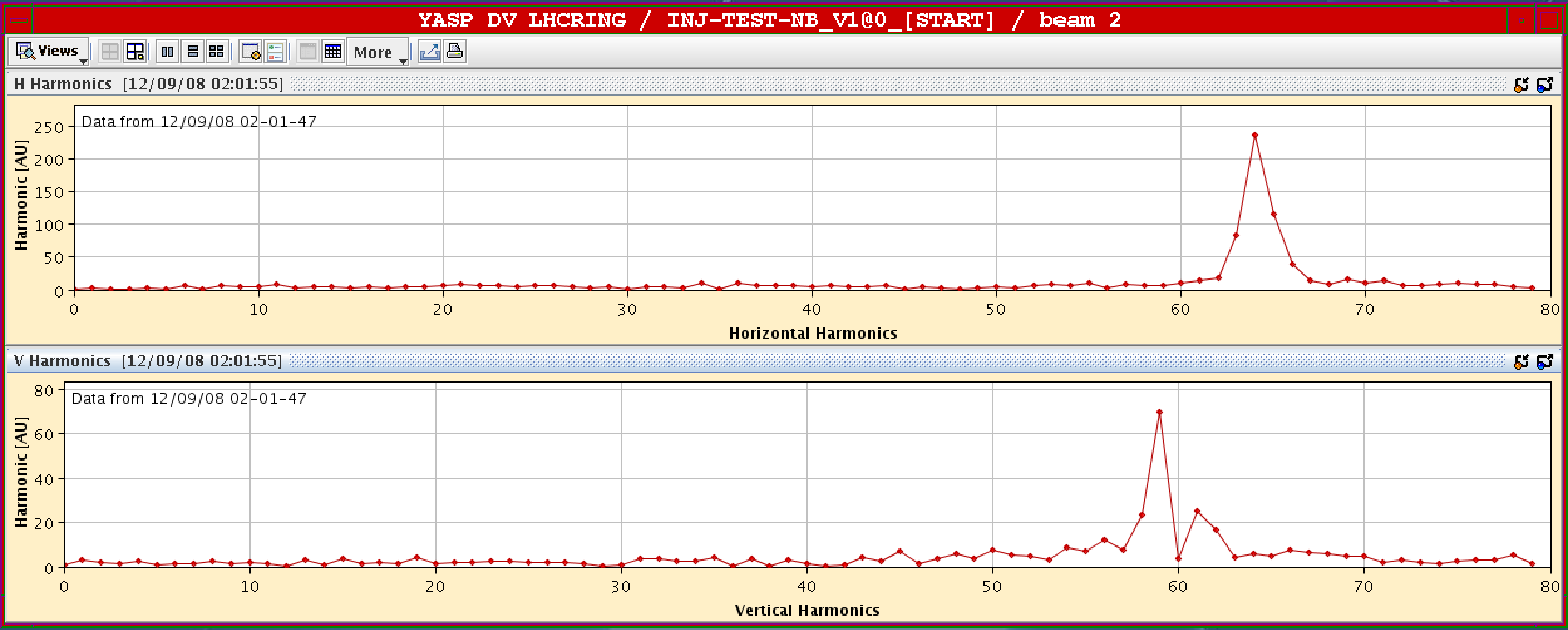
Beam 2 closed orbit



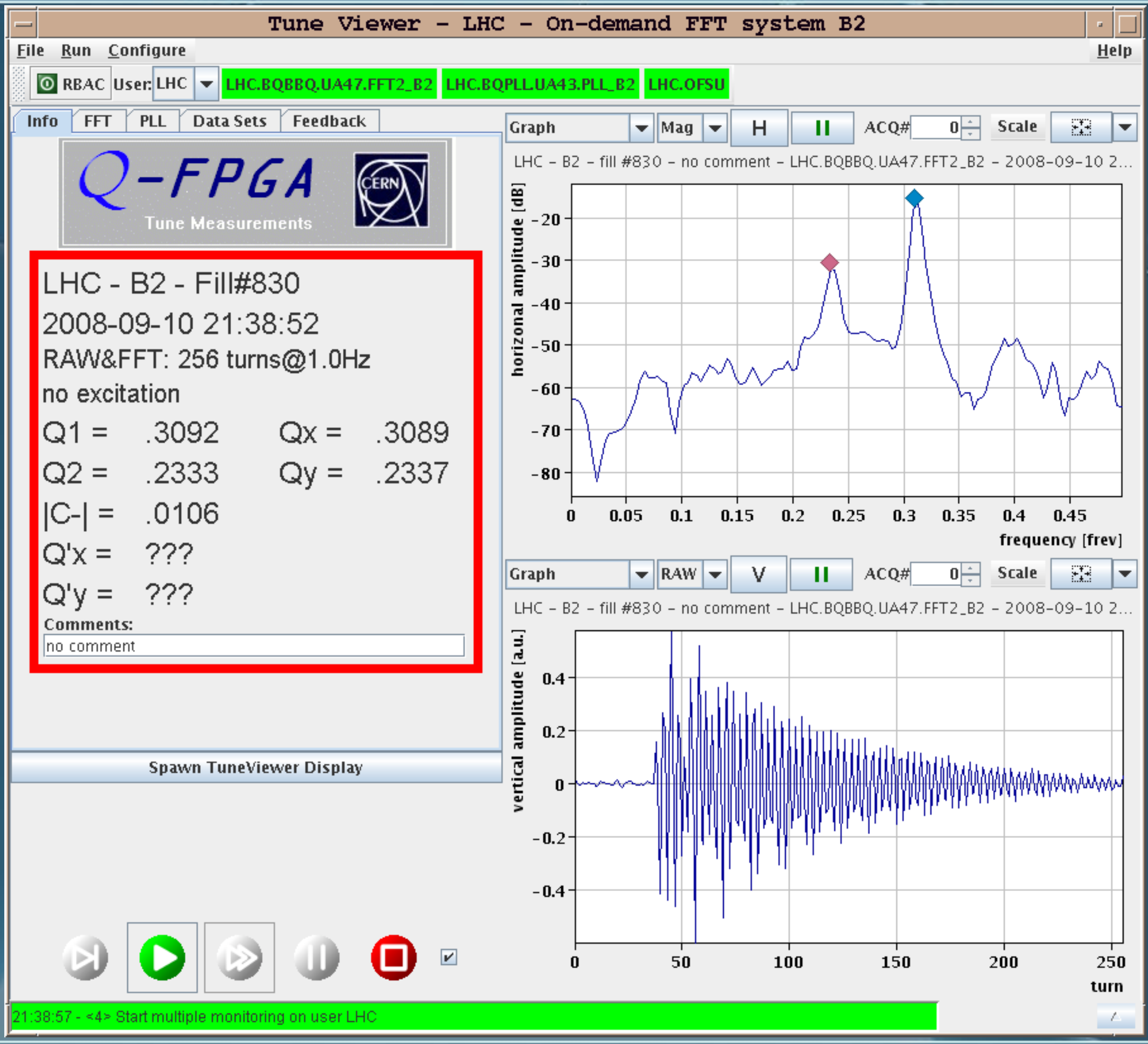
Beam 2 beta measurement



Beam 2 integer tunes

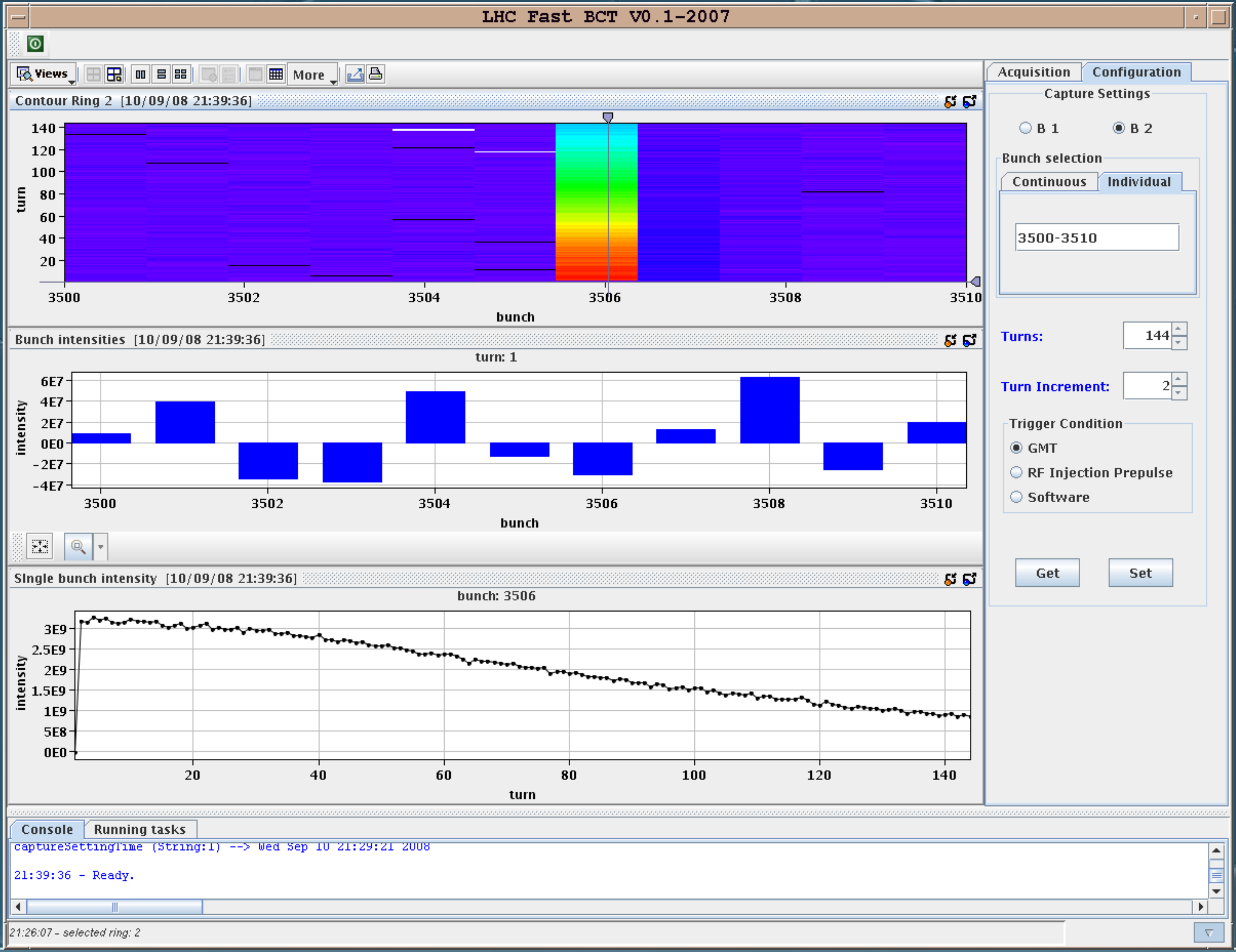


Beam 2 tunes

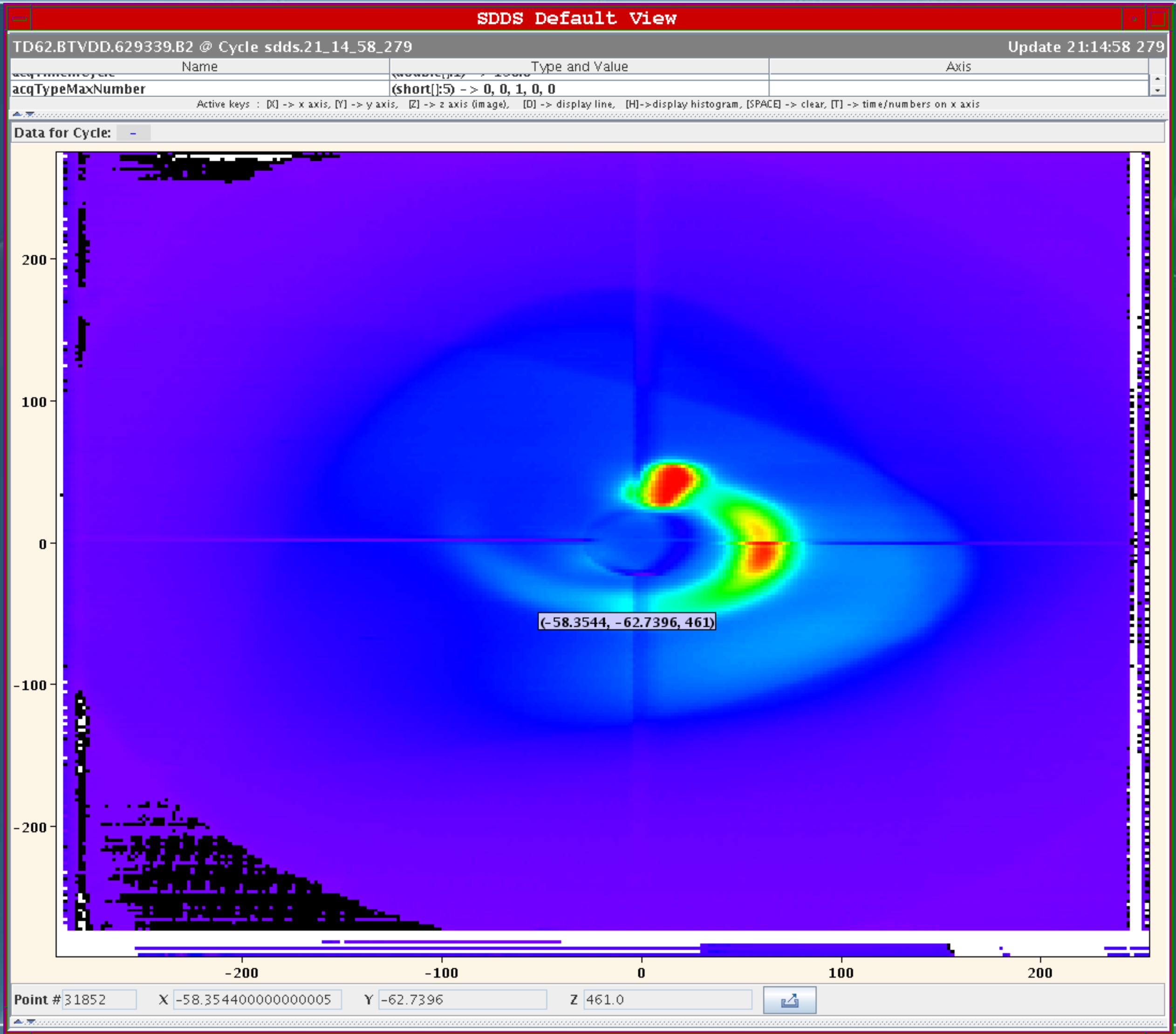


Tune Viewer - LHC - On-demand FFT system B2
File Run Configure
Help
RBAC User: LHC
LHC.BQBBQ.UA47.FFT2_B2
LHC.BQPLL.UA43.PLL_B2
LHC.OFSU
Info FFT PLL Data Sets Feedback
Q-FPGA
Tune Measurements
LHC - B2 - Fill#830
2008-09-10 21:38:52
RAW&FFT: 256 turns@1.0Hz
no excitation
Q1 = .3092 Qx = .3089
Q2 = .2333 Qy = .2337
|C-| = .0106
Q'x = ???
Q'y = ???
Comments:
no comment
Spawn TuneViewer Display
Graph Mag H ACQ# 0 Scale
LHC - B2 - fill #830 - no comment - LHC.BQBBQ.UA47.FFT2_B2 - 2008-09-10 2...
horizonal amplitude [dB]
frequency [frev]
Graph RAW V ACQ# 0 Scale
LHC - B2 - fill #830 - no comment - LHC.BQBBQ.UA47.FFT2_B2 - 2008-09-10 2...
vertical amplitude [a.u.]
turn
21:38:57 - <4> Start multiple monitoring on user LHC

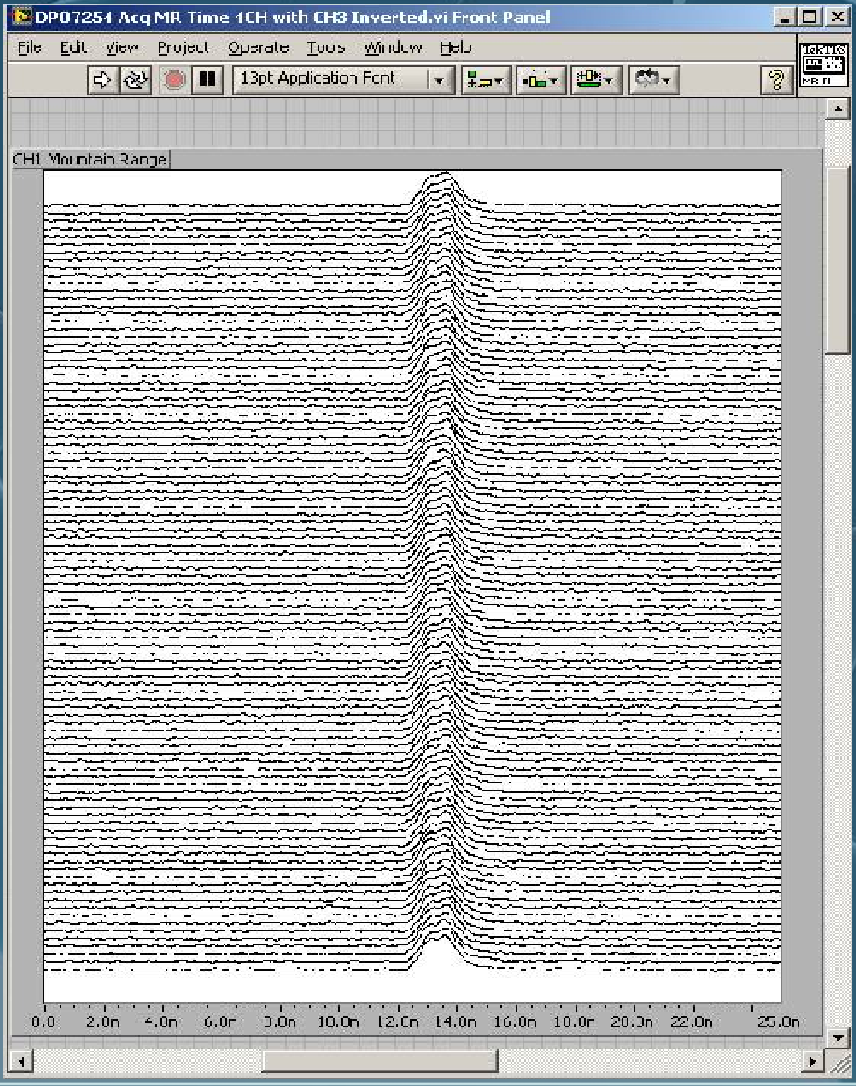
Beam 2 fast BCT (Beam Current Transformer)



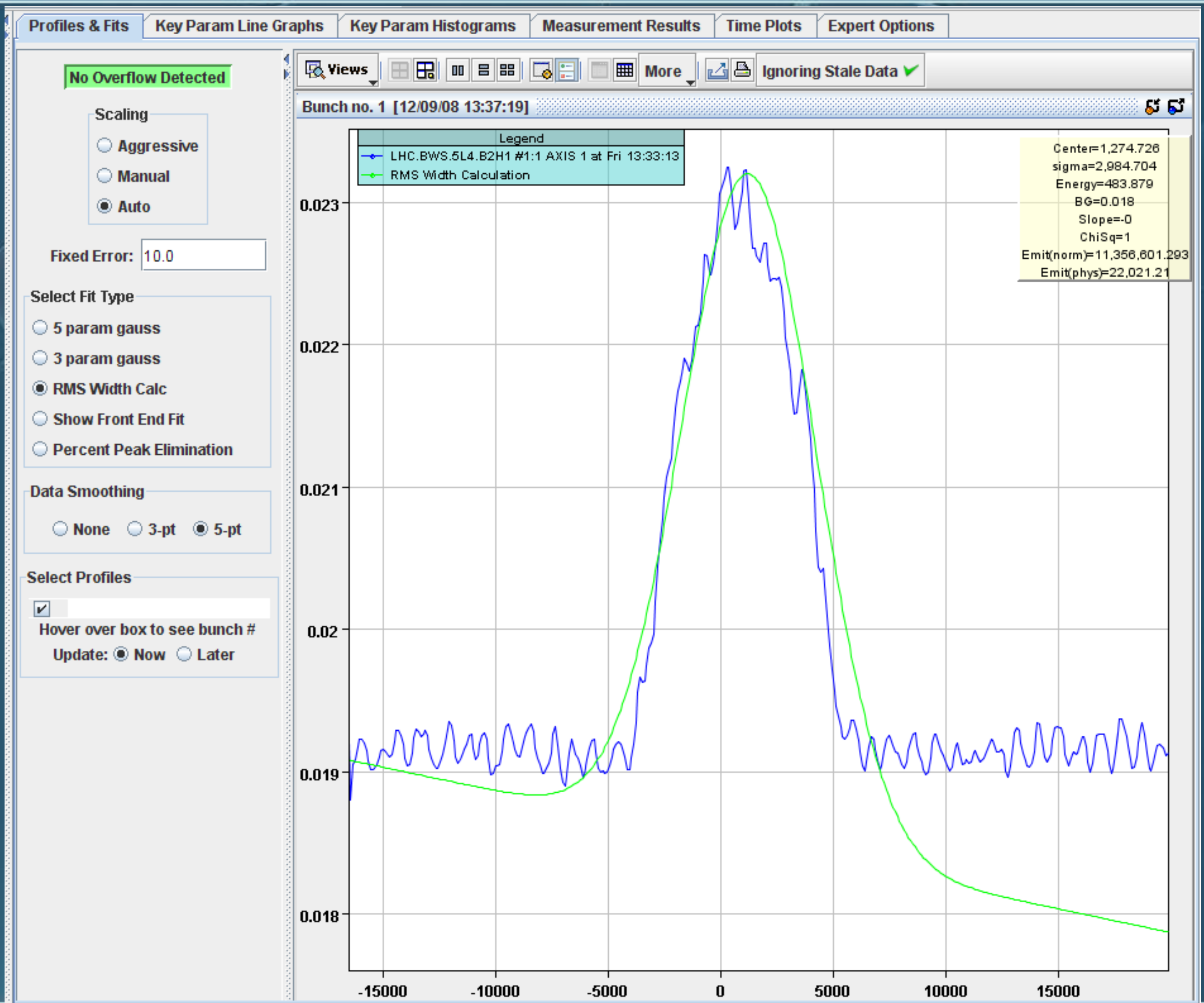
Beam dilution sweep on dump block



Beam 2 captured – mountain range display



Beam 2 wire scanner



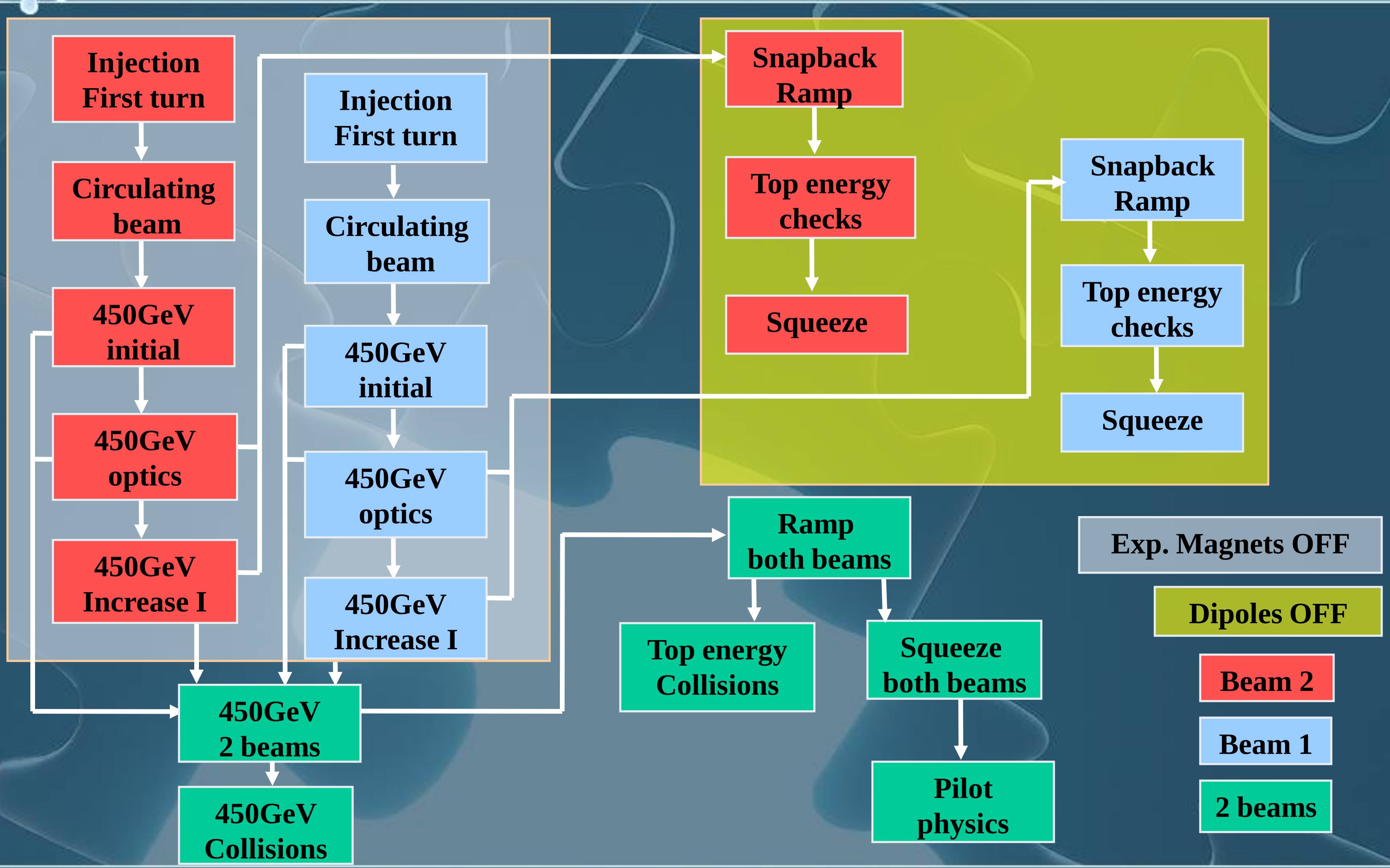
Fast start 10, 11 and 12

- All done in 3 days
- Made possible by
  - Meticulous preparation
    - Magnetic model data
    - Sophisticated settings generation
    - Dry runs
    - Injection tests
  - Powerful control system (LSA)
  - Powerful instrumentation working very quickly
  - Logging a multitude of parameters

- Allowed
  - early look at several machine parameters
  - systematic check of orbit system

Beam Commissioning with p+

Phase A: commissioning plans



Beam Commissioning with p+
Stage B: Intermediate physics run

$$F = 1/\sqrt{1+\left(\frac{\theta_c \sigma_z}{2\sigma^*}\right)^2}$$

- Relaxed crossing angle (250 μrad)
- Start un-squeezed
- Then go to where we were in stage A
- All values for
  - nominal emittance
  - 7 TeV
  - 10 m β* in points 2 and 8

Protons/beam ≈ few 10^{13}

Stored energy/beam ≤ 100 MJ

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
936	$4\ 10^{10}$	11	$3.7\ 10^{13}$	42	$2.4\ 10^{31}$	<< 1	$2.6\ 10^{31}$	0.15
936	$4\ 10^{10}$	2	$3.7\ 10^{13}$	42	$1.3\ 10^{32}$	0.73	$2.6\ 10^{31}$	0.15
936	$6\ 10^{10}$	2	$5.6\ 10^{13}$	63	$2.9\ 10^{32}$	1.6	$6.0\ 10^{31}$	0.34
936	$9\ 10^{10}$	1	$8.4\ 10^{13}$	94	$1.2\ 10^{33}$	7	$1.3\ 10^{32}$	0.76

Beam Commissioning with p+ Stage C&D: 25 ns Operation

- Nominal crossing angle (285 μrad)
- Start un-squeezed
- Then go to where we were in stage B
- All values for
  - nominal emittance
  - 7 TeV
  - 10m β^* in points 2 and 8

Protons/beam ≈ 10^{14}

Stored energy/beam ≥ 100 MJ

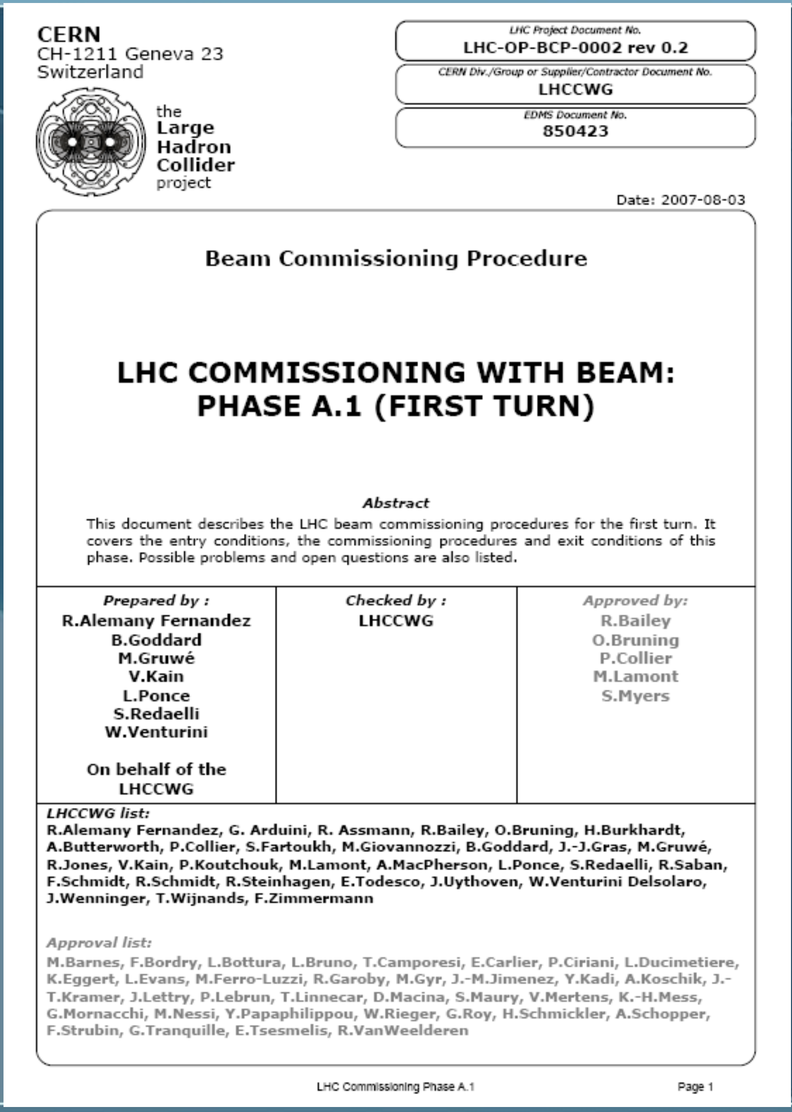
Parameters			Beam levels		Rates in 1 and 5		Rates in 2 and 8	
k_b	N	β^* 1,5 (m)	I_{beam} proton	E_{beam} (MJ)	Luminosity ($cm^{-2}s^{-1}$)	Events/ crossing	Luminosity ($cm^{-2}s^{-1}$)	Events/ crossing
2808	$4\ 10^{10}$	11	$1.1\ 10^{14}$	126	$7.2\ 10^{31}$	<< 1	$7.9\ 10^{31}$	0.15
2808	$4\ 10^{10}$	2	$1.1\ 10^{14}$	126	$3.8\ 10^{32}$	0.72	$7.9\ 10^{31}$	0.15
2808	$5\ 10^{10}$	2	$1.4\ 10^{14}$	157	$5.9\ 10^{32}$	1.1	$1.2\ 10^{32}$	0.24
2808	$5\ 10^{10}$	1	$1.4\ 10^{14}$	157	$1.1\ 10^{33}$	2.1	$1.2\ 10^{32}$	0.24
2808	$5\ 10^{10}$	0.55	$1.4\ 10^{14}$	157	$1.9\ 10^{33}$	3.6	$1.2\ 10^{32}$	0.24
Nominal			$3.2\ 10^{14}$	362	10^{34}	19	$6.5\ 10^{32}$	1.2

Contents

1. Accelerator complex
2. Energy Stored in the Magnets
   - Quench Protection System
   - Power Interlock System
   - Energy Extraction
3. Energy Stored in the Beams
   - Beam Dump System
   - Collimation System
4. Machine Protection System
5. Overall Strategy for Commissioning:
   - HW Commissioning
   - Machine Checkout
   - Beam Commissioning
     - Stage A
     - Stage B
     - Stage C&D
6. **Documentation & Human Resources**
7. Conclusions

Documentation

- Hardware Commissioning Coordination
  - http://hcc.web.cern.ch/hcc/
- Machine Checkout
  - http://wikis/display/LHCOP/LHC+Machine+Checkout
- LHC Commissioning Procedures
  - http://lhccwg.web.cern.ch/lhccwg/overview_index.htm



CERN
CH-1211 Geneva 23
Switzerland

the Large Hadron Collider project

LHC Project Document No.
LHC-OP-BCP-0002 rev 0.2

CERN Div./Group or Supplier/Contractor Document No.
LHCCWG

EDMS Document No.
850423

Date: 2007-08-03

Beam Commissioning Procedure

LHC COMMISSIONING WITH BEAM: PHASE A.1 (FIRST TURN)

Abstract

This document describes the LHC beam commissioning procedures for the first turn. It covers the entry conditions, the commissioning procedures and exit conditions of this phase. Possible problems and open questions are also listed.

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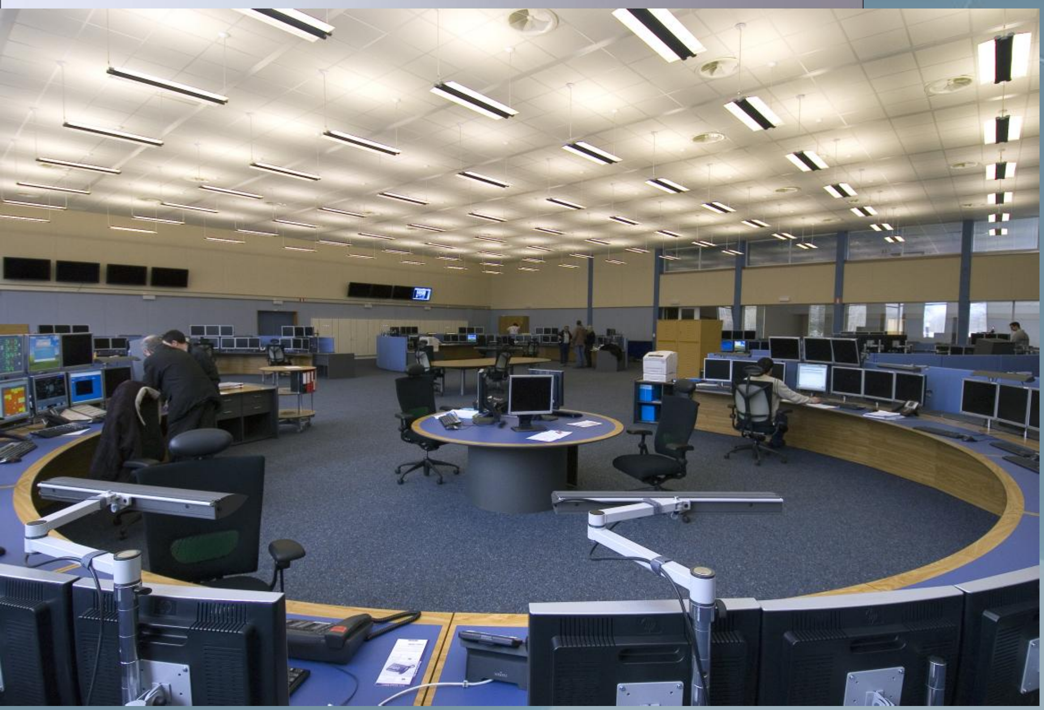
LHC Commissioning Phase A.1 Page 1

Human Resources

Beam Commissioning



Machine Coordinators

Engineers In Charge (EIC)

Operators

Commissioners In Charge (CIC)

HWC Team

Summary

- The LHC commissioning is divided in three steps:
  - Hardware Commissioning
  - Machine Checkout
  - Beam Commissioning
- To tackle the machine unprecedent complexity and potential danger (energy stored in the magnets and in the beam), each step is divided in well defined phases
- The success of the commissioning relies, among other things, upon:
  - Carefull elaboration of procedures (Documentation)

Acknowledges

The content of this presentation has been elaborated from material coming from the

LHC Commissioning Working Group

and

Hardware Commissioning Coordination Group

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 neighboring dipole

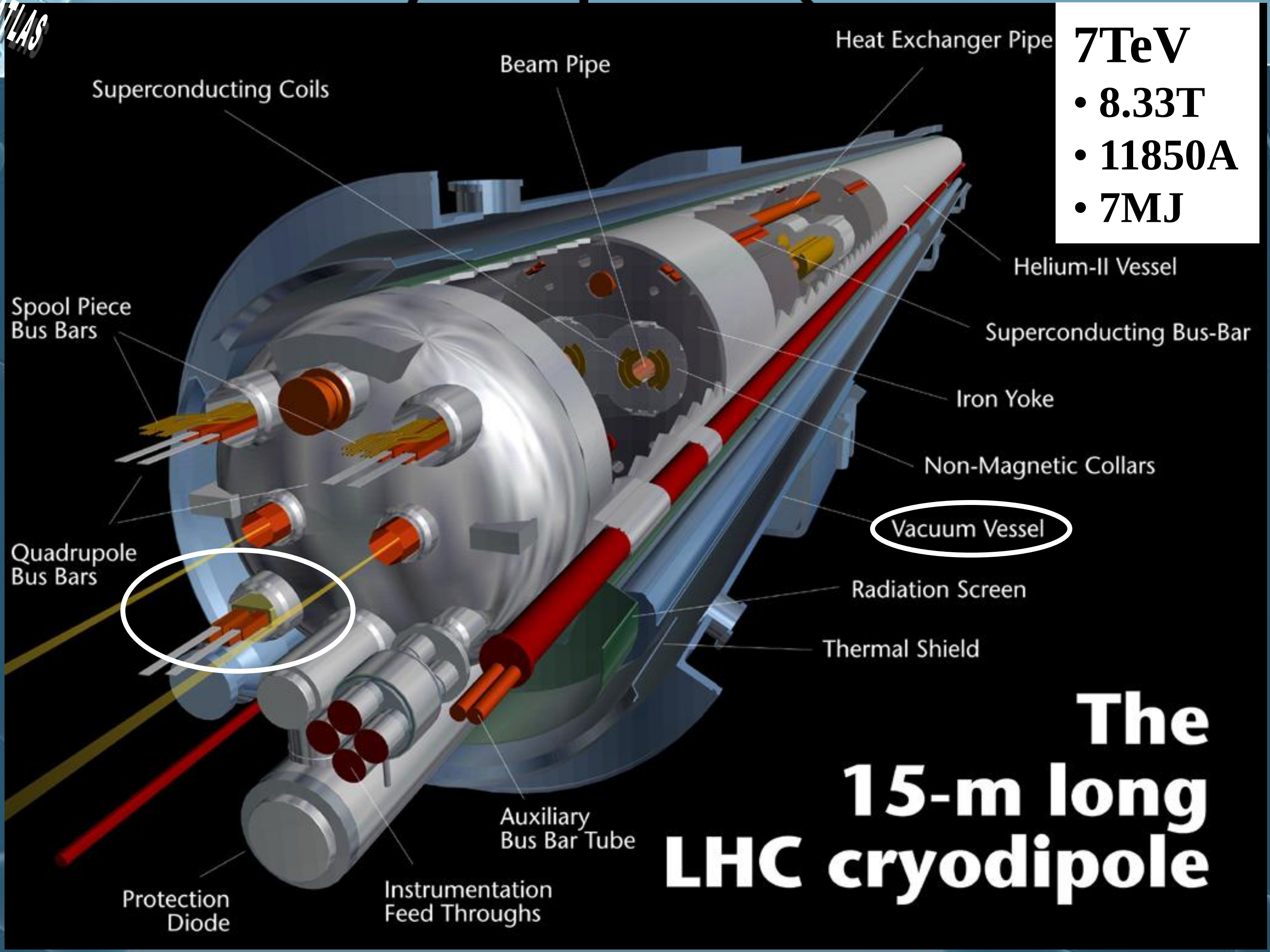
- Electrical arc developed which punctured the helium enclosure
- Helium released into the insulating vacuum

- 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

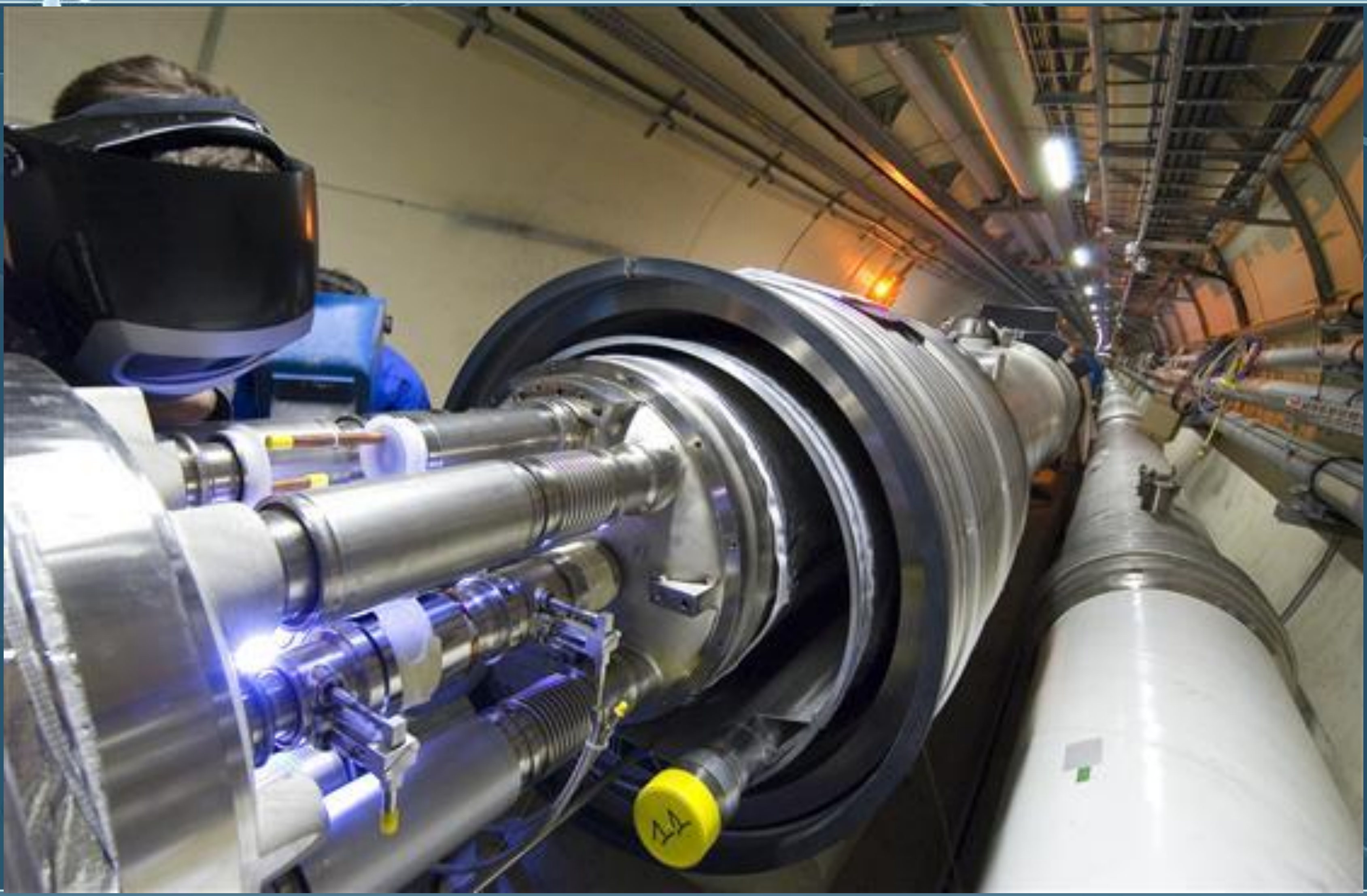
LHC cryodipole (1232 of them)

7TeV

- **8.33T**
- **11850A**
- **7MJ**



All have to be interconnected (quads too)



Interconnections

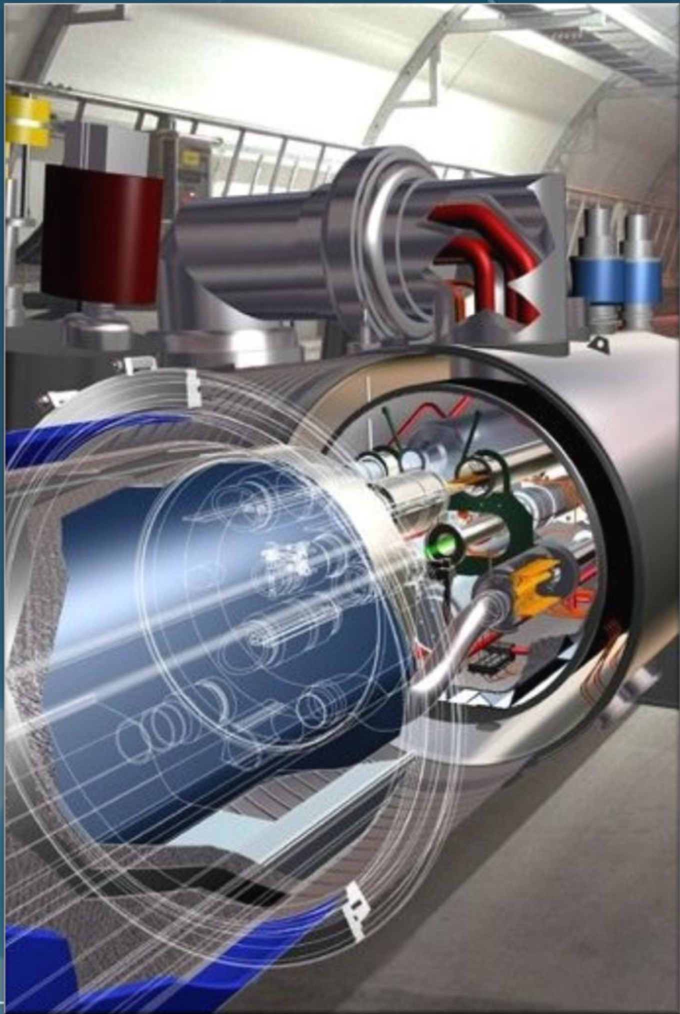
Interconnections the superconducting magnets of LHC means:

- 1695 magnet-to-magnet interconnects
- 224 magnet to QRL interconnects

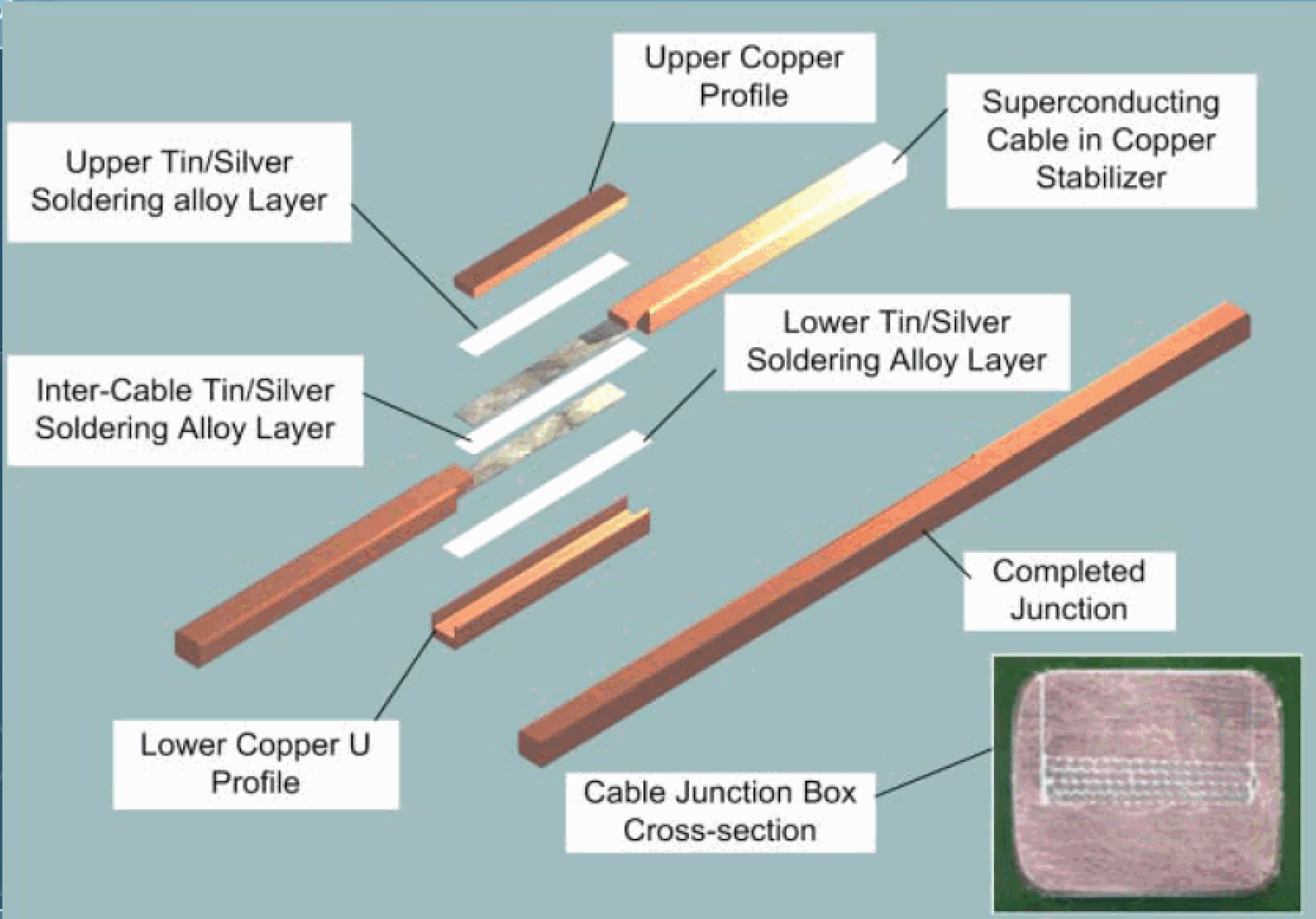
Each magnet to magnet interconnect consists of:

- ✓ 18 assembly actions divided in 9 interventions
- ✓ 5 leak tightness check
- ✓ 5 electrical tests
- ✓ 1 RF test

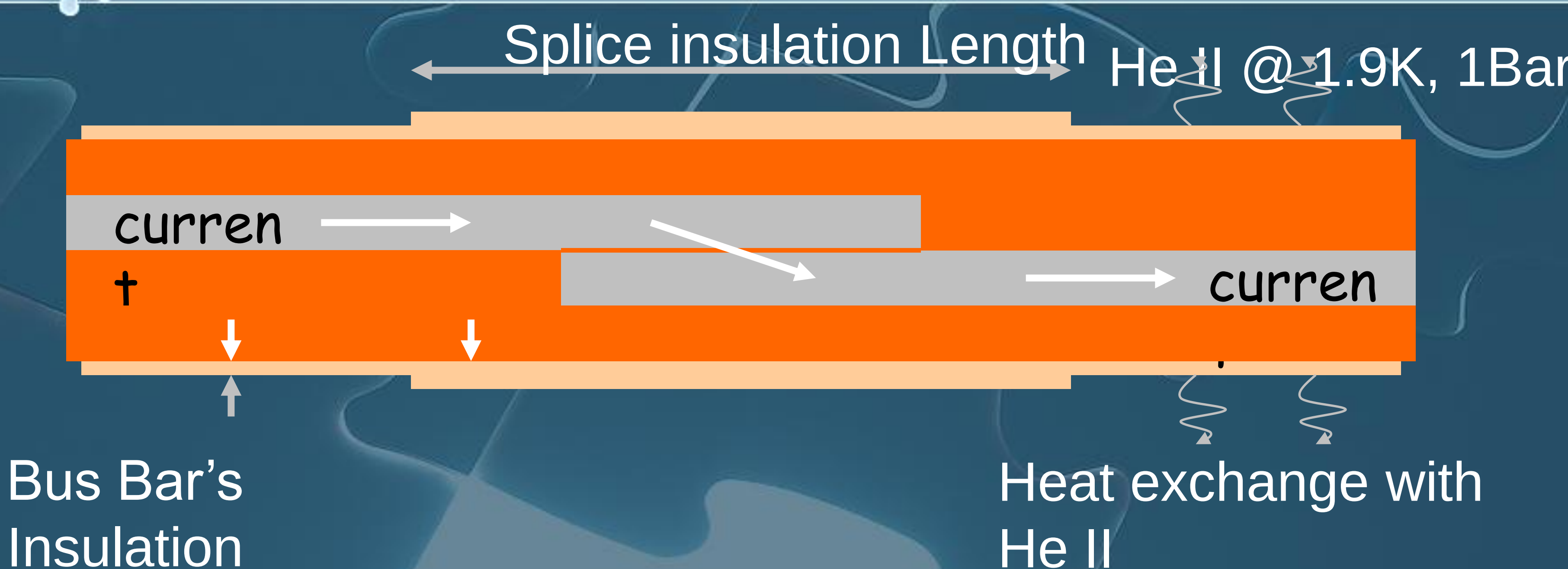
For each sector this is:
1964 assembly interventions
226 electrical tests on sub-assemblies
70 vacuum tests on sub-assemblies
14 RF test on sub-assemblies



Bus bar interconnection

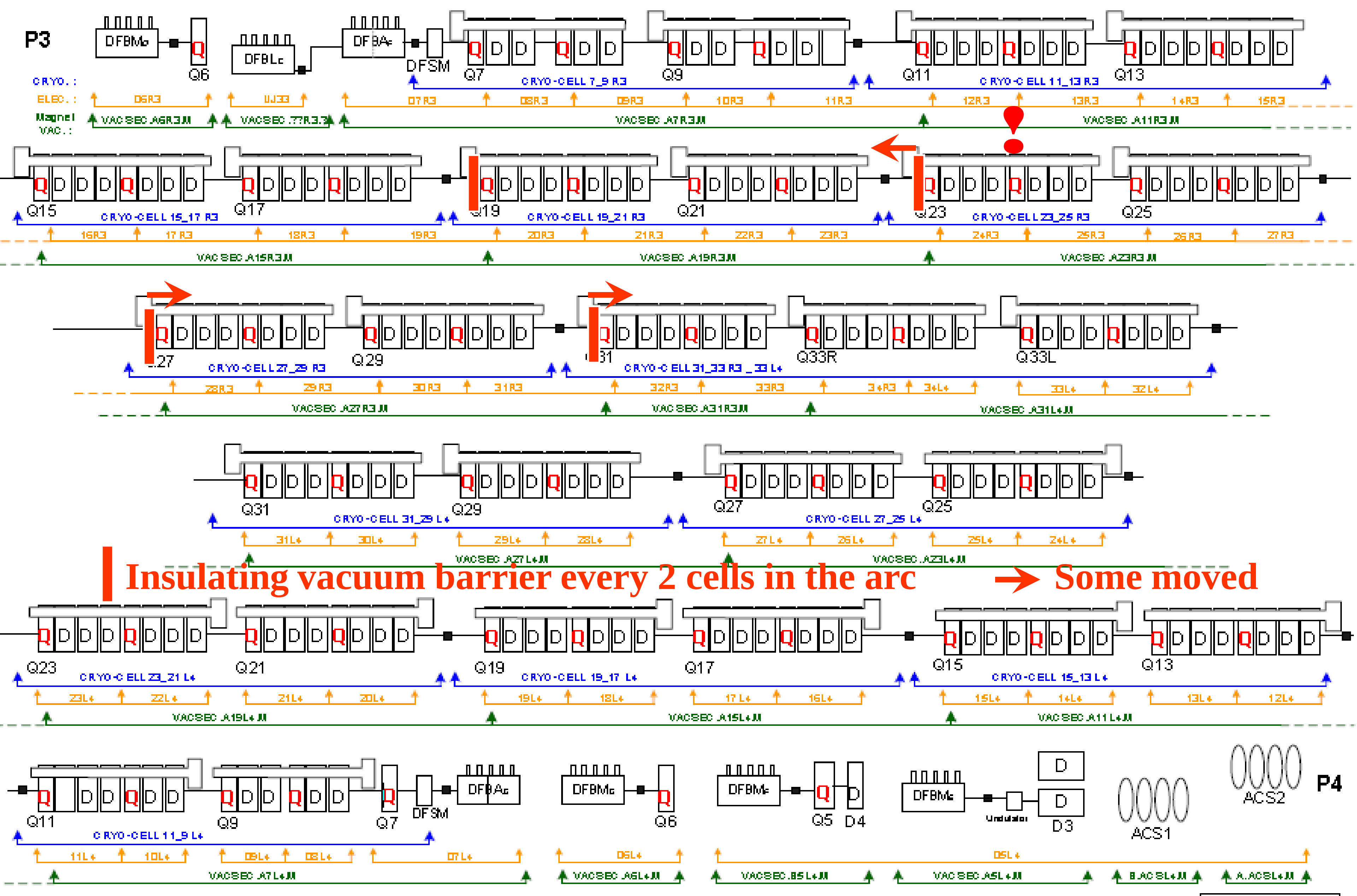


Hypothesis



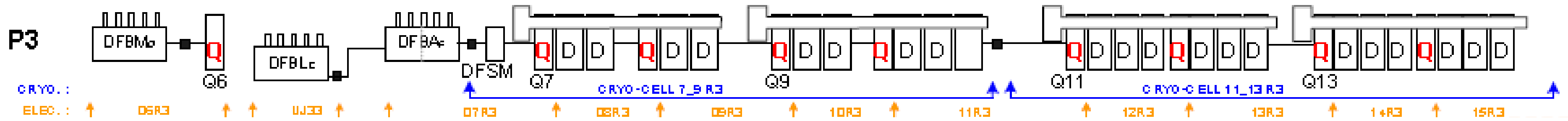
- Temperature increase due to an excessive resistance
- Superconductor quenches and becomes resistive at high current (temperature increase due to the resistance).
- Up to a certain current, the Copper can take it (cooled by the He II).
- Beyond a certain current, ‘run-away’ of the temperature, splice opens, electrical arc …

Consequences



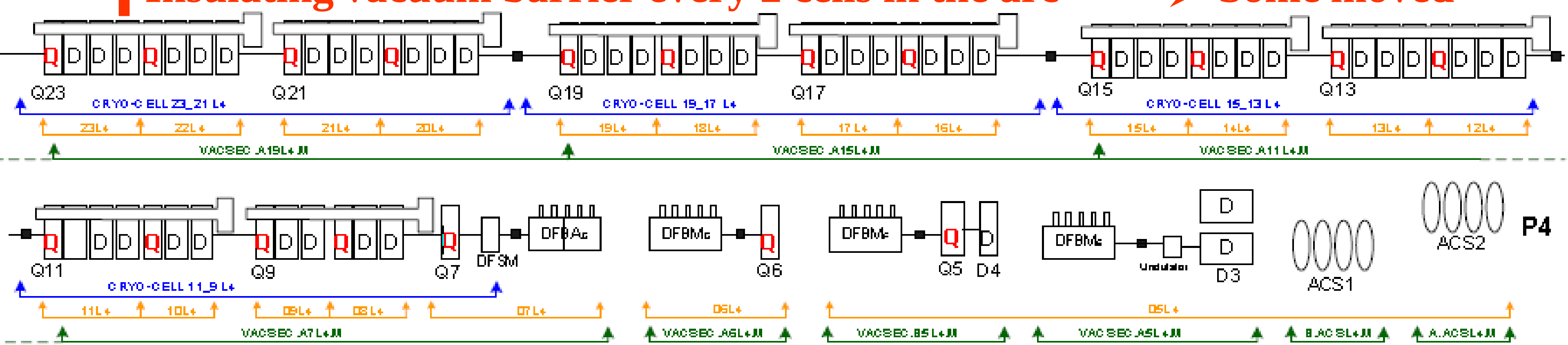
Insulating vacuum barrier every 2 cells in the arc → Some moved

Consequences



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

Insulating vacuum barrier every 2 cells in the arc → Some moved

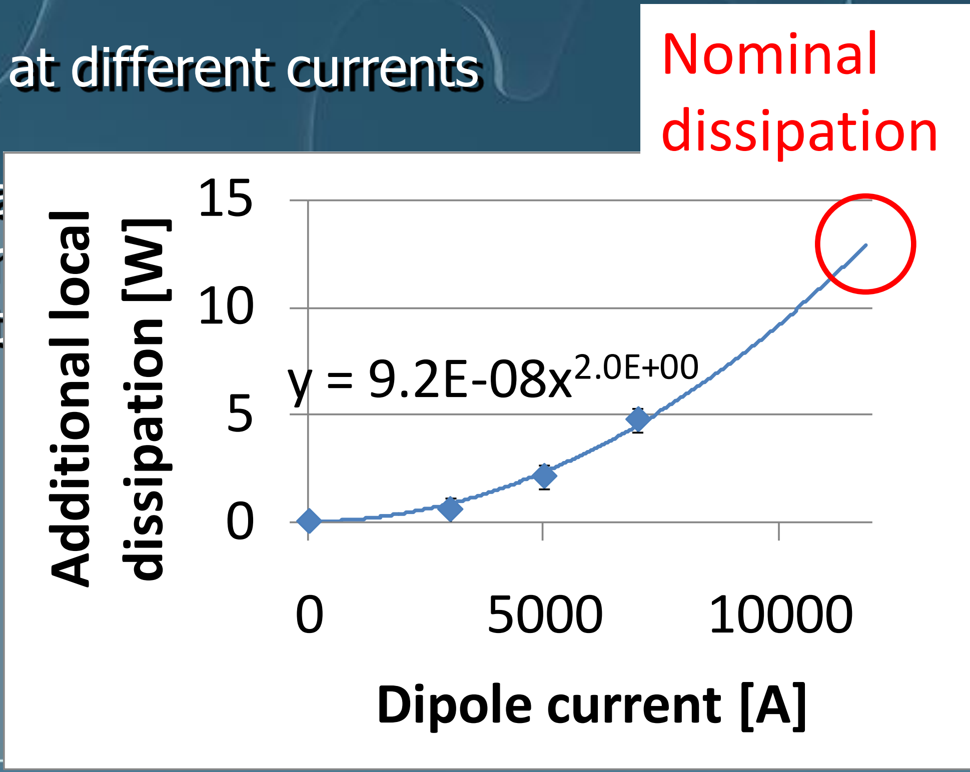


Repair

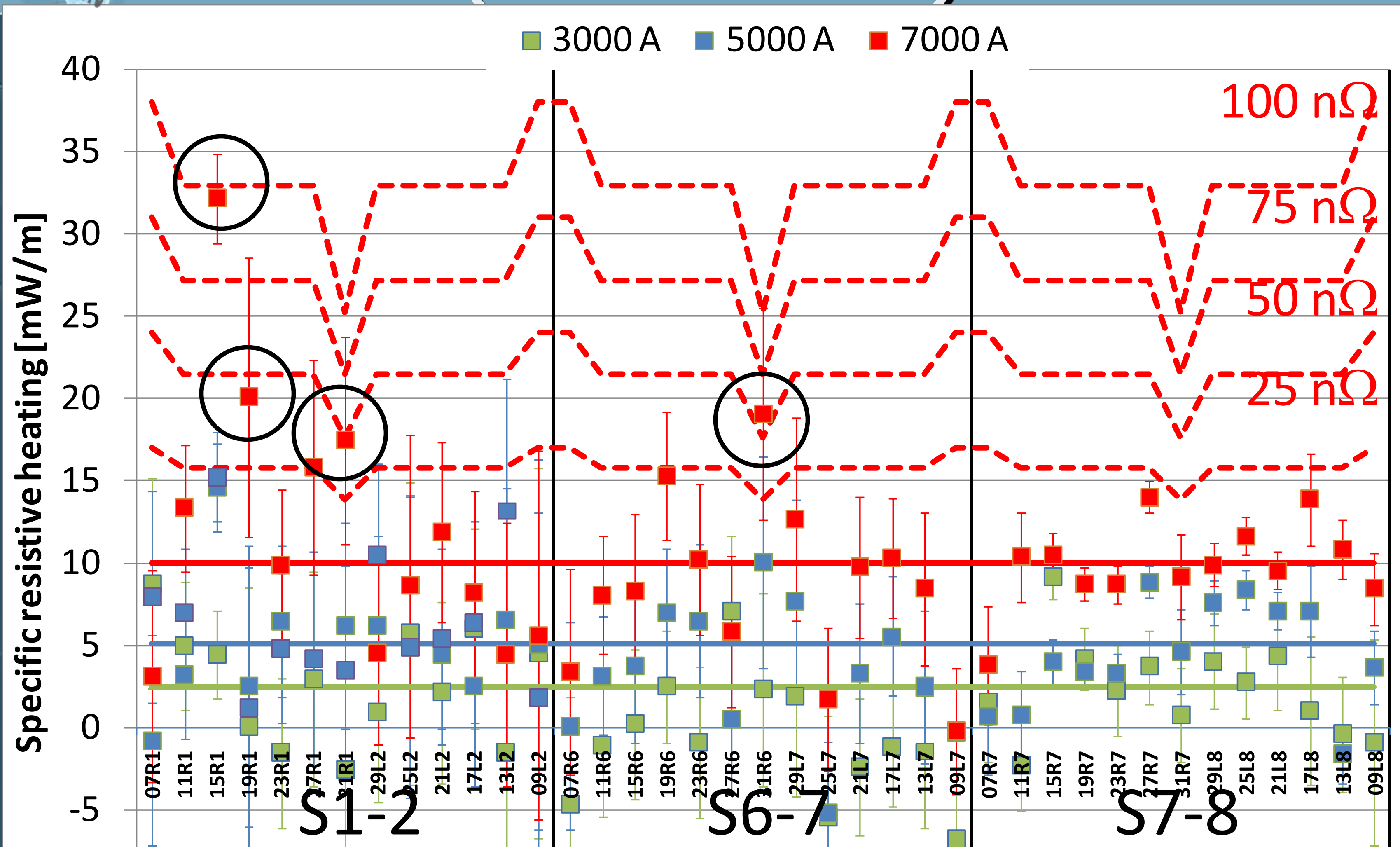
- Present strategy assumes treating all magnets Q19 to Q31
- May have to treat slightly further outside this zone (to Q33)
- Nearly all the components are at CERN
- Critical components are beam screens and SSS bottom trays
- Estimate for magnets (preliminary) November 08 to March 09
- Then have to finish interconnection, cool down, power test

Outside sector 34

- All data from hardware commissioning carefully scrutinized
- Anomalous cryogenic behaviour found in sector 12 at 7kA
  - Higher than nominal heat load in cryogenic sector 15 R1
- Controlled tests made late October at different currents
- Calorimetric measurements
  - Measure temperature increase a
  - Derive rate of energy depositior
  - Fit Energy deposition vs current
  - Deduce equivalent resistance



Calorimetric results so far (November)



- 3 sectors, 4 suspicious cases

Electrical results so far (November)

- Electrical measurements
  - Dedicated electronics needed for inter-magnet splices
  - QPS system used for internal magnet splices

  - S12 15R1
    - All inter-magnet splices measured to be similar, around 0.3nΩ
    - Magnet B16.R1 measured to have 100nΩ !!!
  - S12 19R1
    - Nothing found; traced to a feature of cryogenic system
  - S12 31R1
    - Nothing found; calorimetric fit in any case is very poor

  - S67 31R6
    - Magnet B32.R6 measured to have 45nΩ !!!

  - S78
    - Nothing found

Other measures

- From the analysis of the incident, the following modifications and consolidations are under consideration:
  - Upgrade of the quench protection system for protection against symmetric quenches (was already in the pipeline before Sector 34 incident)
  - Upgrade of the quench protection system for precision measurements and protection of all interconnects
  - Modifications of commissioning procedure to include calorimetric information and systematic electrical measurements
  - Addition of pressure release valves on EVERY dipole cryostat
    - note that this probably requires warming up

Strategy for implementing this is not yet finalised

Timescales for restart will be determined by

- Efficiency of logistics of magnets removal / installation
- Efficiency of magnet repair
- Efficiency of beam pipe repair / cleaning
- Efficiency of interconnection activities
- Strategy adopted to ensure no repeat is possible
- Time to cool down
- Time to re-commission power circuits