The LHC accelerator: Technology and First Commissioning

Rüdiger Schmidt - CERN

430. WE-Heraeus-Seminar on "Accelerators and Detectors at the Technology Frontier"

- The LHC: “Just another collider?”
- Collision of intense particle beams
- The LHC technology
- Commissioning with beam
- 19/9/2008 incident and what followed
- Status and outlook

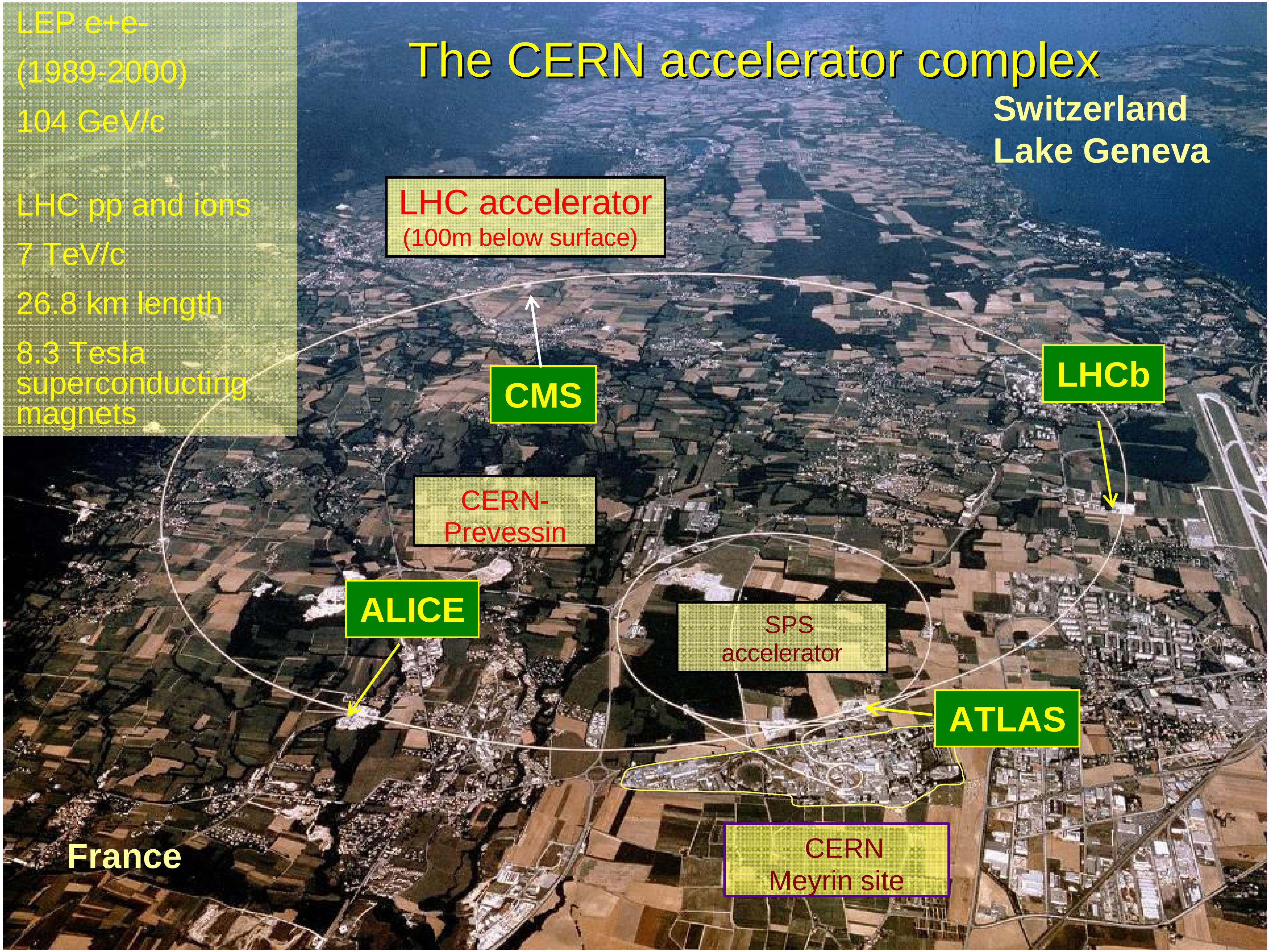
Overview LHC and its challenges

Energy and Luminosity

- Particle physics requires an accelerator colliding beams with a centre-of-mass energy substantially exceeding 1TeV
- In order to observe rare events, the luminosity should be in the order of 10^{34} [$cm^{-2}s^{-1}$] (challenge for the LHC accelerator)
- Event rate:

$$\frac{N}{\Delta t} = L[cm^{-2} \cdot s^{-1}] \cdot \sigma[cm^{2}]$$

- Assuming a total cross section of about 100 mbarn for pp collisions, the event rate for this luminosity is in the order of 10^9 events/second (challenge for the LHC experiments)
- Nuclear and particle physics require heavy ion collisions in the LHC (quark-gluon plasma ....)


The CERN accelerator complex
LEP e+e-
(1989-2000)
104 GeV/c
LHC pp and ions
7 TeV/c
26.8 km length
8.3 Tesla superconducting magnets
Switzerland
Lake Geneva
LHC accelerator
(100m below surface)
CMS
LHCb
CERN-Prevessin
ALICE
SPS accelerator
ATLAS
CERN Meyrin site
France

The LHC: just another collider ?

Name	Start	Particles	Max proton energy [GeV]	Length [m]	B Field [Tesla]	Stored beam energy [MJoule]
TEVATRON Fermilab Illinois USA	1983	p-pbar	980	6300	4.5	1.6 for protons
HERA DESY Hamburg Germany	1992	p – e+ p – e-	920	6300	5.5	2.7 for protons
RHIC Brookhaven Long Island USA	2000	Ion-Ion p-p	250	3834	4.3	0.9 per proton beam
LHC CERN Geneva Switzerland	2008	Ion-Ion p-p	7000	26800	8.3	362 per proton beam

Challenges for LHC

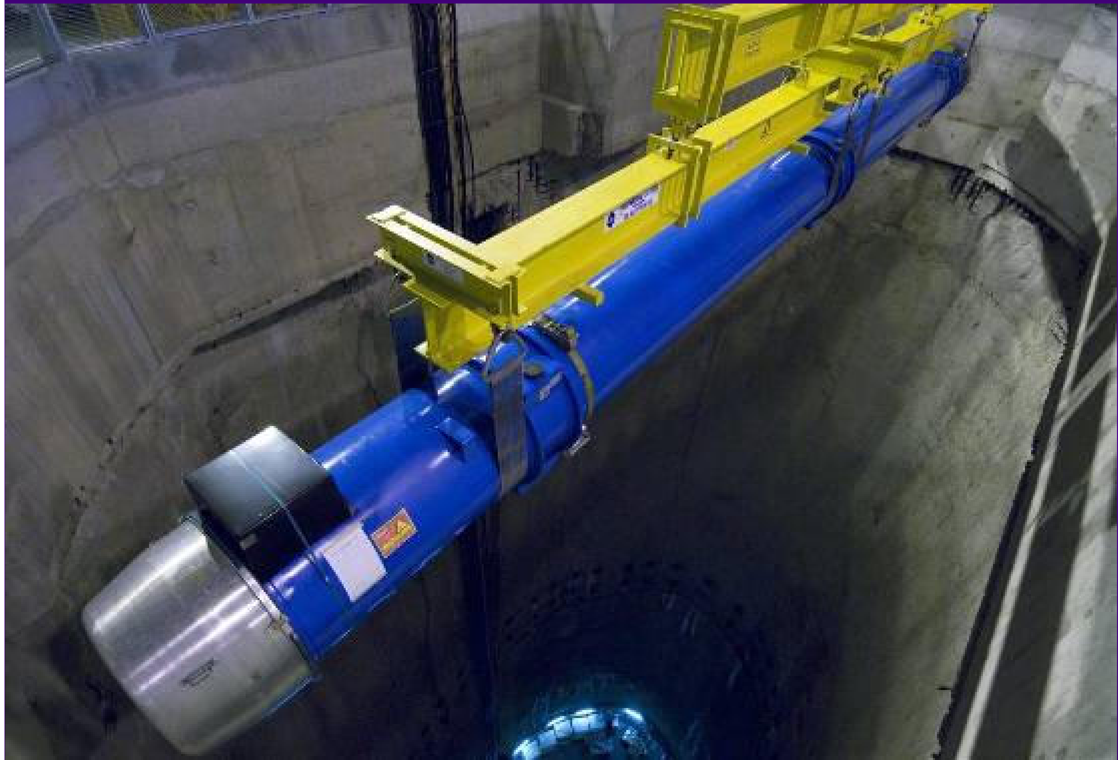
- High-field (8.3 Tesla) superconducting magnets operating at a temperature of 1.9 K with an energy stored in the magnets of 10 GJ
- Complexity of the accelerator (most complex scientific instrument ever constructed) with 10000 magnets powered in 1712 electrical circuits
- Beam-parameters pushed to the extreme
  - Energy stored in the beam two orders of magnitude more
  - Transverse energy density three orders of magnitude more
- GJoule beams running through superconducting magnets that quench with mJoule
- Consequences for several systems (machine protection, collimation, vacuum system, cryogenics, …)

A total number of 1232 dipole magnets are required to close the circle

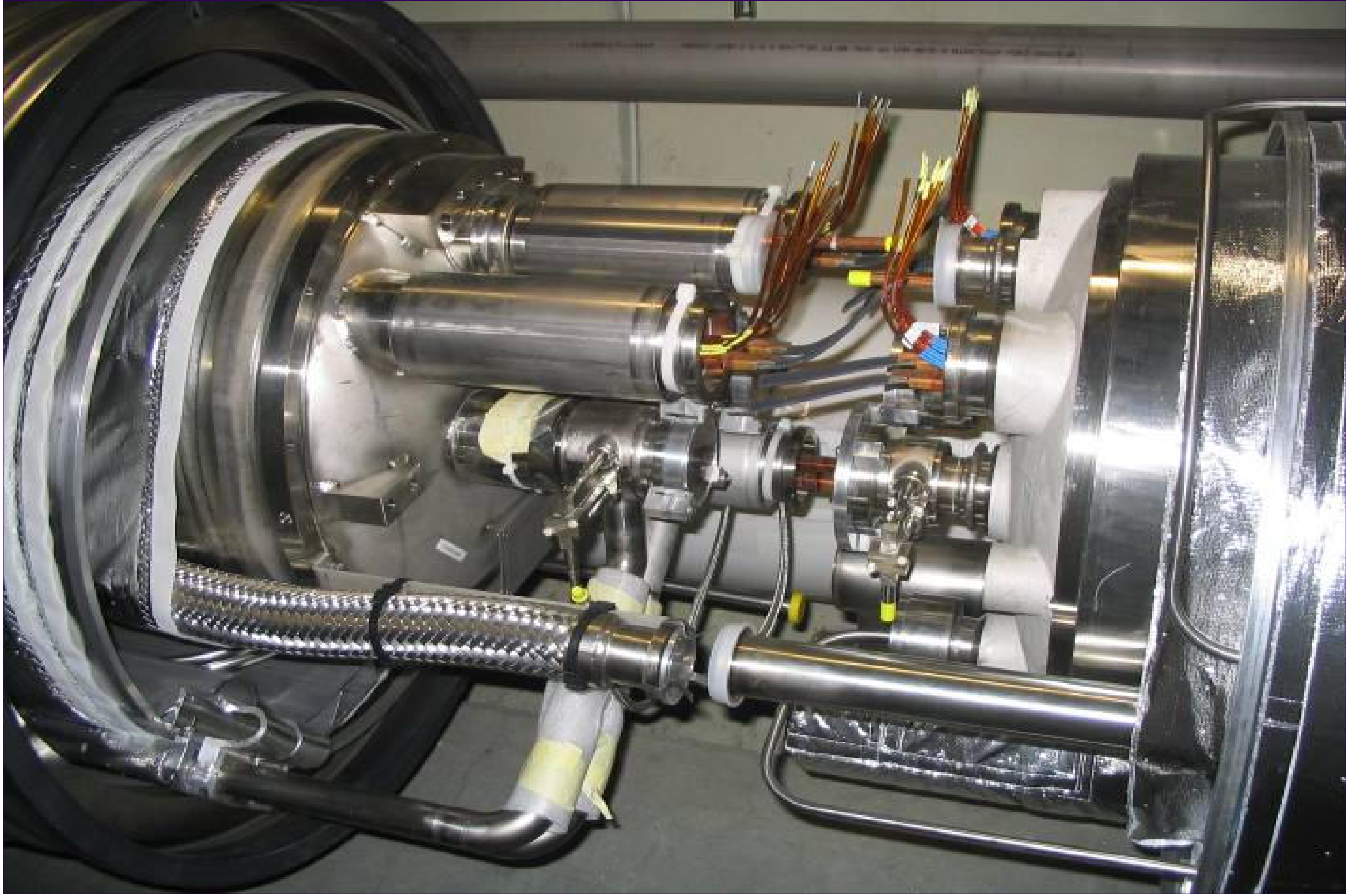
LHC dipole magnet lowered into the tunnel

First cryodipole lowered on 7 March 2005

Descent of the last magnet, 26 April 2007



Interconnecting two magnets out of 1700



Current leads with High Temperature Superconductors

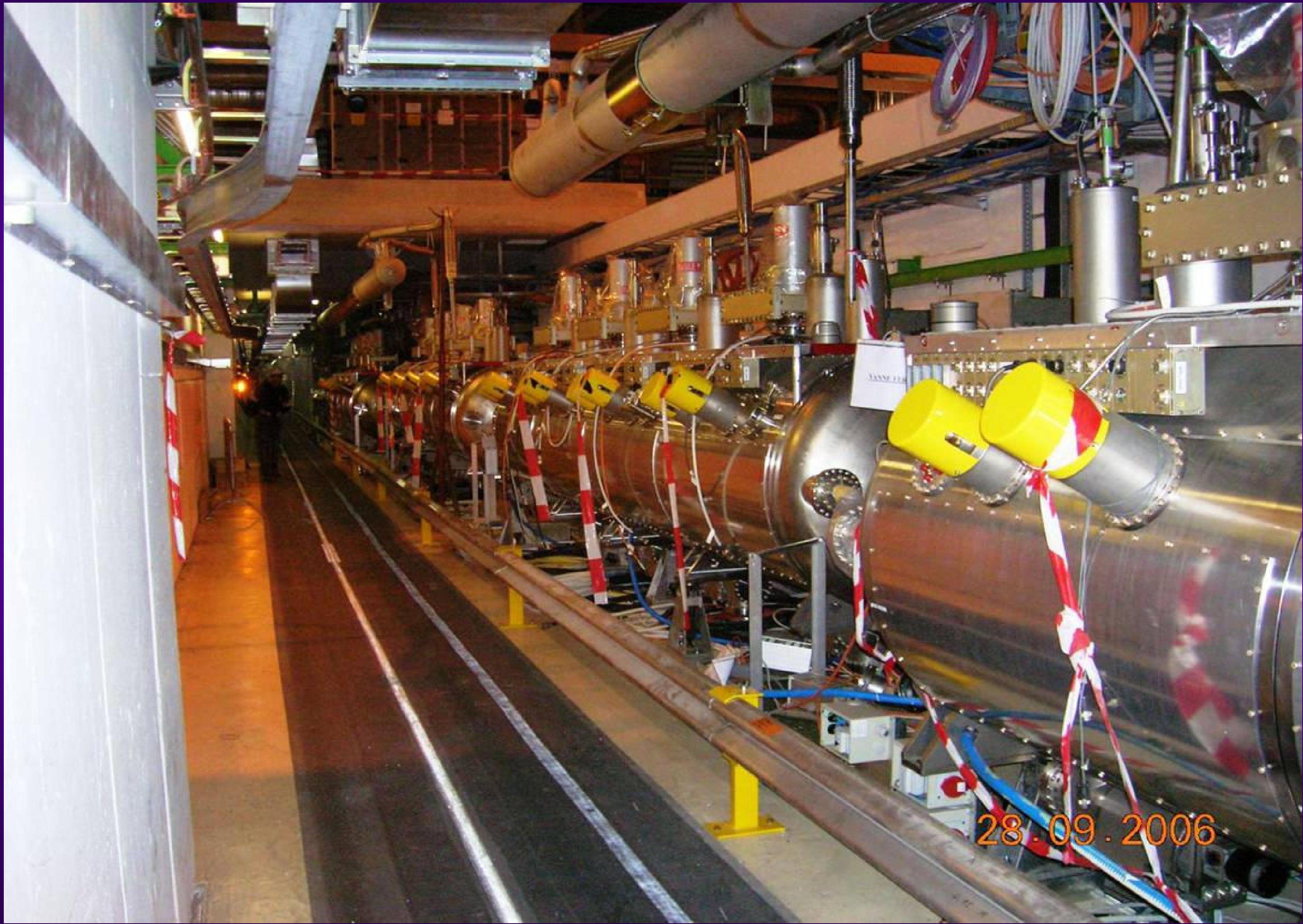
Feedboxes ('DFB'): transition from copper cable to super-conductor

Water cooled Cu cables

10

DFB with ~17 out of 1600 HTS current leads

RF cavities, four per beam with some 10 MVolt



Colliding very intense proton beams

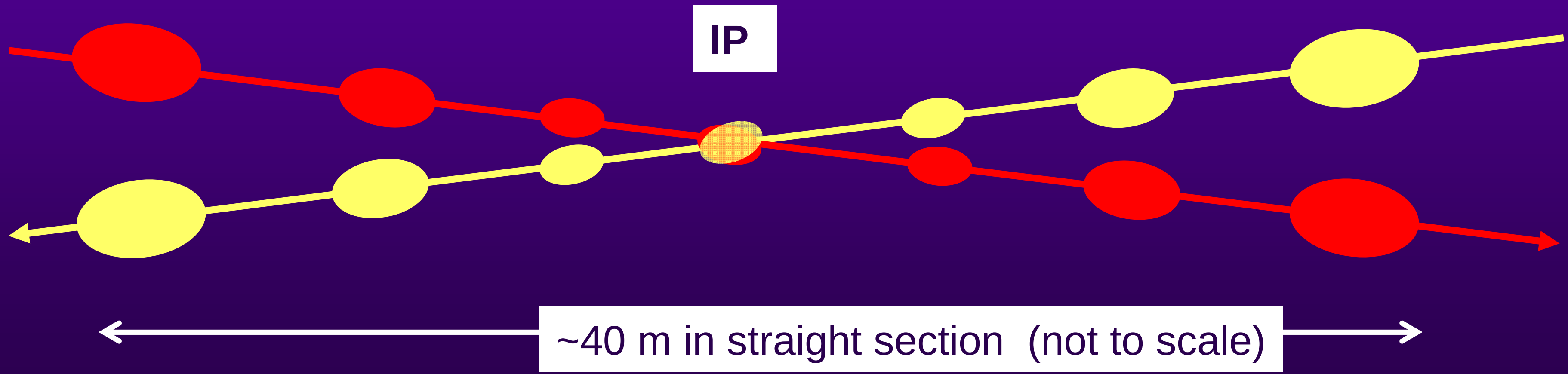
High luminosity by colliding trains of bunches

Number of „New Particles“
per unit of time:

$$\frac{N}{\Delta T} = L\left[cm^{-2} \cdot s^{-1}\right] \cdot \sigma\left[cm^{2}\right]$$

The objective for the LHC as proton – proton collider is a luminosity of about 10^{34} [$cm^{-1}s^{-2}$]

- LEP (e+e-) : 3-4 10^{31} [$cm^{-2}s^{-1}$]
- Tevatron (p-pbar) : some 10^{32} [$cm^{-2}s^{-1}$]
- B-Factories : > 10^{34} [$cm^{-2}s^{-1}$]



Luminosity parameters

$$L = \frac{N^2 \cdot f \cdot n_b}{4\pi \cdot \sigma_x \cdot \sigma_y}$$

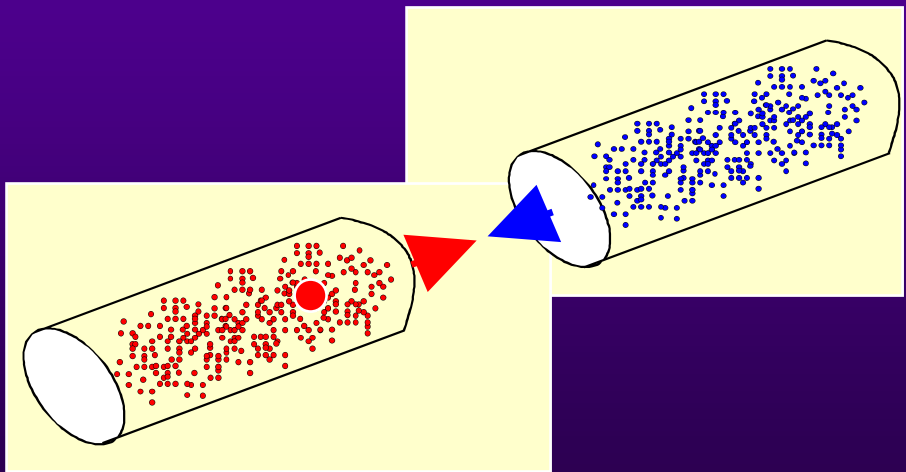
with:

$N =$ Number of protons per bunch

$f =$ revolution frequency

$n_b =$ number of bunches per beam

$\sigma_x \cdot \sigma_y =$ beam dimensions at interaction point



Beam beam interaction determines parameters

Number of protons **N** per bunch limited to about **10^{11}** due to beam-beam interaction

f = **11246 Hz**

Beam size at IP **σ** = **16 μm** for β = 0.5 m (beam size in arc σ = ~0.2 mm

$$L = \frac{N^2 \cdot f \cdot n_b}{4\pi \cdot \sigma_x \cdot \sigma_y} = 3.5 \cdot 10^{30} \cdot cm^{-2} \cdot s^{-1}$$

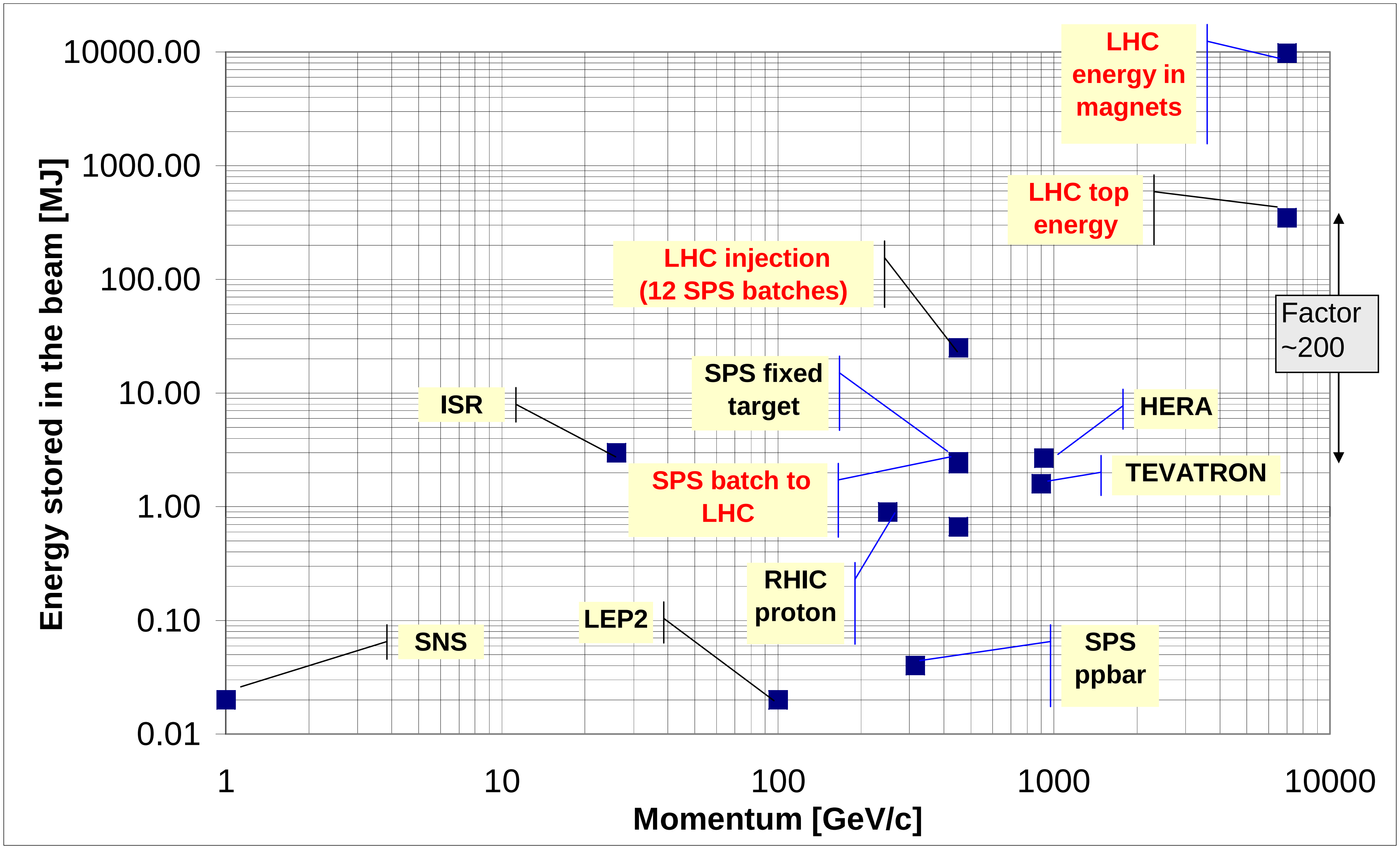
with one bunch N_b=1

with N_b = **2808 bunches** (every 25 ns one bunch)

L = 10^{34} [$cm^{-2}s^{-1}$]

=> 362 MJoule per beam

Livingston type plot: Energy stored magnets and beam

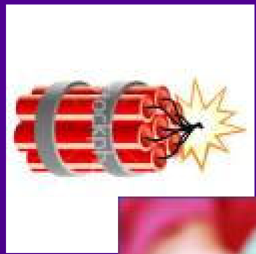


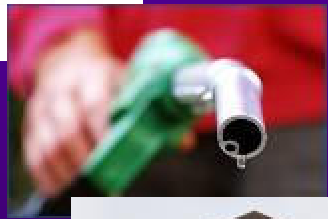
What does this mean?

The energy of an 200 m long fast train at 155 km/hour corresponds to the energy of 360 MJoule stored in one LHC beam

360 MJoule: the energy stored in one LHC beam corresponds approximately to…

- 90 kg of TNT
- 8 litres of gasoline
- 15 kg of chocolate





It's how ease the energy is released that matters most !!

Very high beam current: consequences

- Dumping the beam in a safe way
- Beam induced quenches (when 10^{-8}-10^{-7} of beam hits magnet at 7 TeV)
- Beam cleaning (Betatron and momentum cleaning)
- Radiation, in particular in experimental areas from beam collisions (beam lifetime is dominated by this effect)

- Beam instabilities due to impedance
- Synchrotron radiation at 7 TeV - power to cryogenic system
- Photo electrons - accelerated by the following bunches

- Single particle dynamics: dynamic aperture and magnet field quality, in particular in the presence of dynamic effects in superconducting magnets during the ramp

The LHC accelerator complex

Complexity due to the LHC main ring
AND due to the injector chain

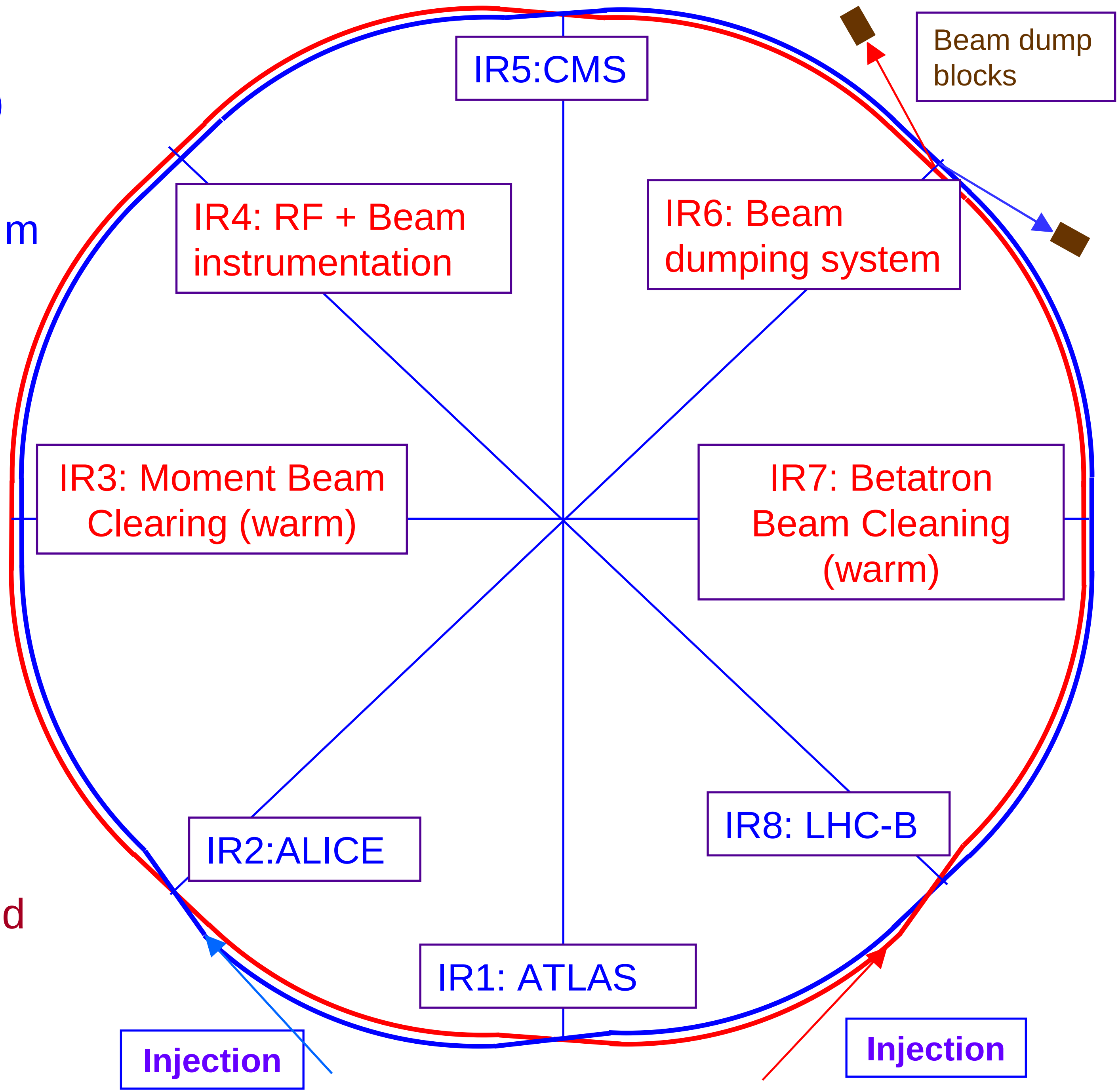
LHC Main Ring Systems

Superconducting magnets
Cryogenics
Vacuum system
Powering (industrial use of High Temperature Superconductors)

LHC Layout

eight arcs (sectors)

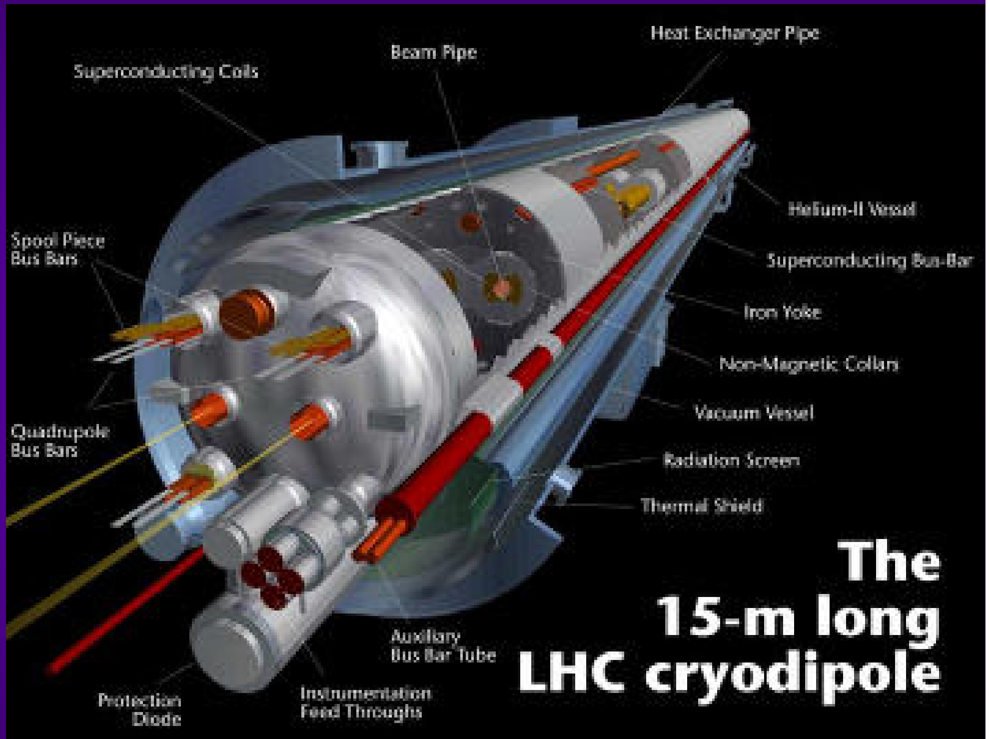
eight long straight section (about 700 m long)



each sector is independent, in terms of cooling and powering

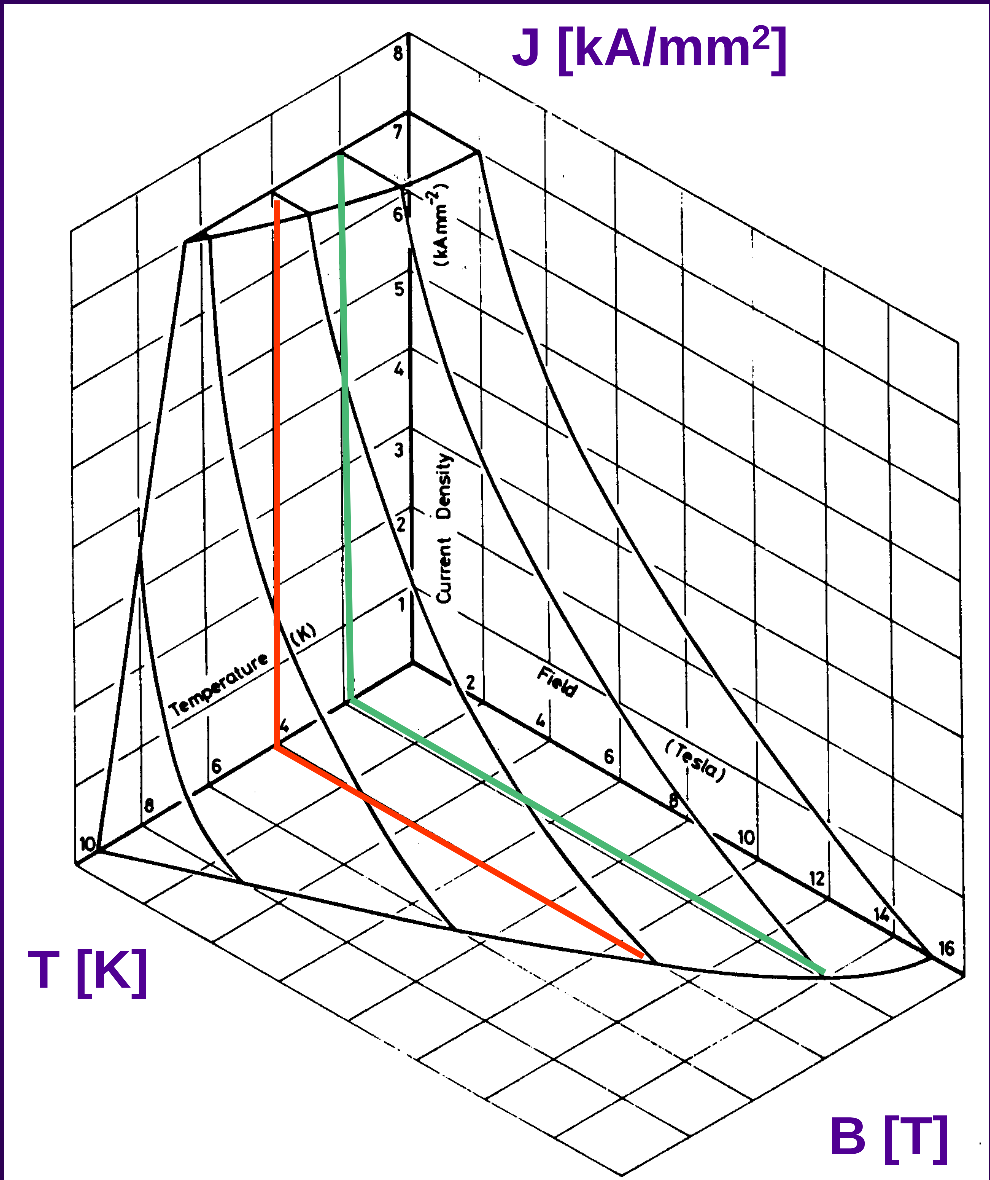
Dipole magnets for the LHC

1232 Dipolemagnets
Length about 15 m
Magnetic Field 8.3 T
Two beam tubes with an opening of 56 mm



plus many other magnets, to ensure beam stability (1700 main magnets and about 8000 corrector magnets

Operating temperature of superconductors (NbTi)

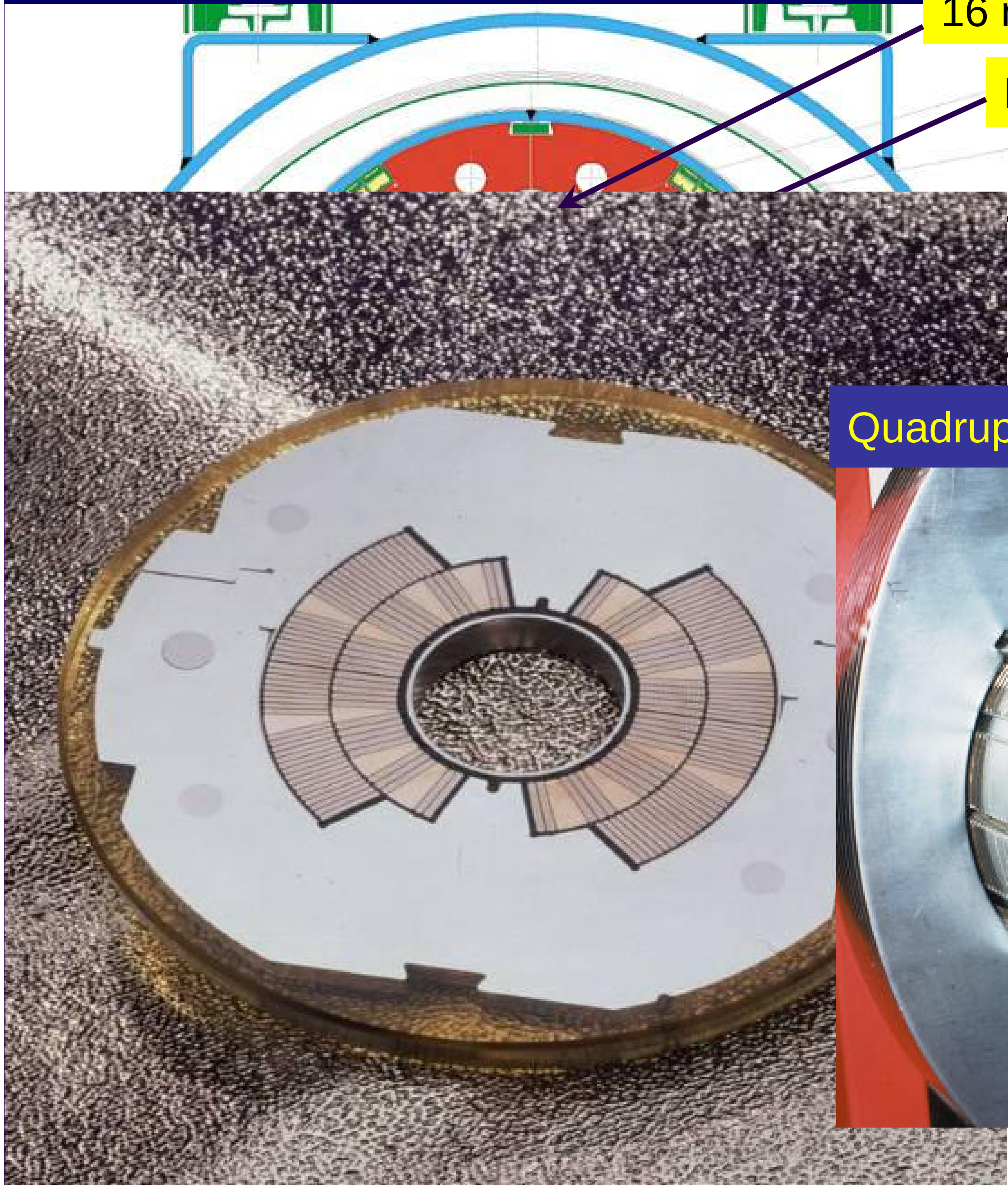


The superconducting state only occurs in a limited domain of temperature, magnetic field and transport current density

Superconducting magnets produce high field with high current density

Lowering the temperature enables better usage of the superconductor, by broadening its working range

Dipole magnet cross section



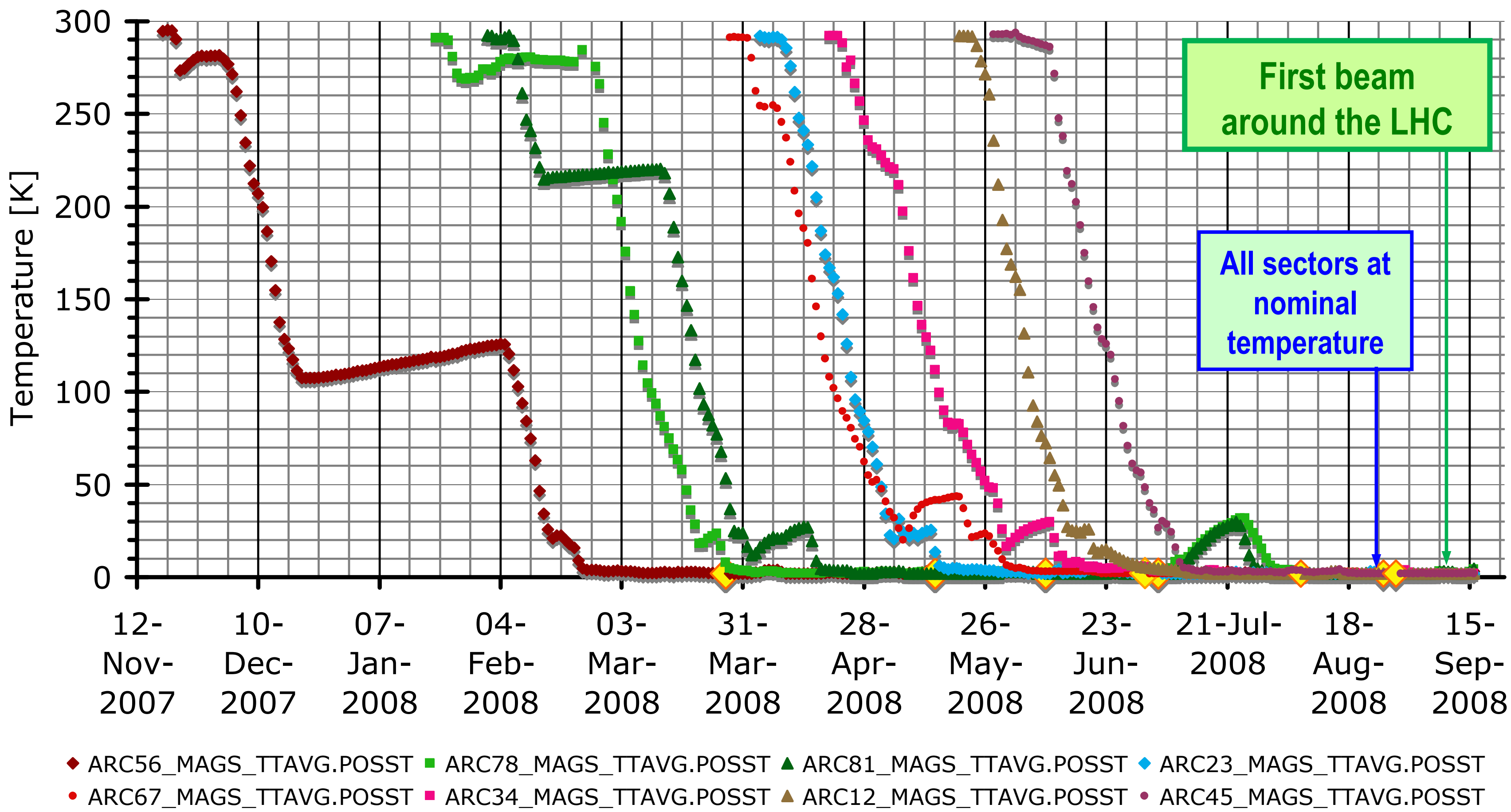
Commissioning of the LHC

Commissioning of the hardware systems

Beam commissioning

LHC Cool-down

Cool-down time ~ 4-6 weeks/sector
[sector = 1/8 LHC]



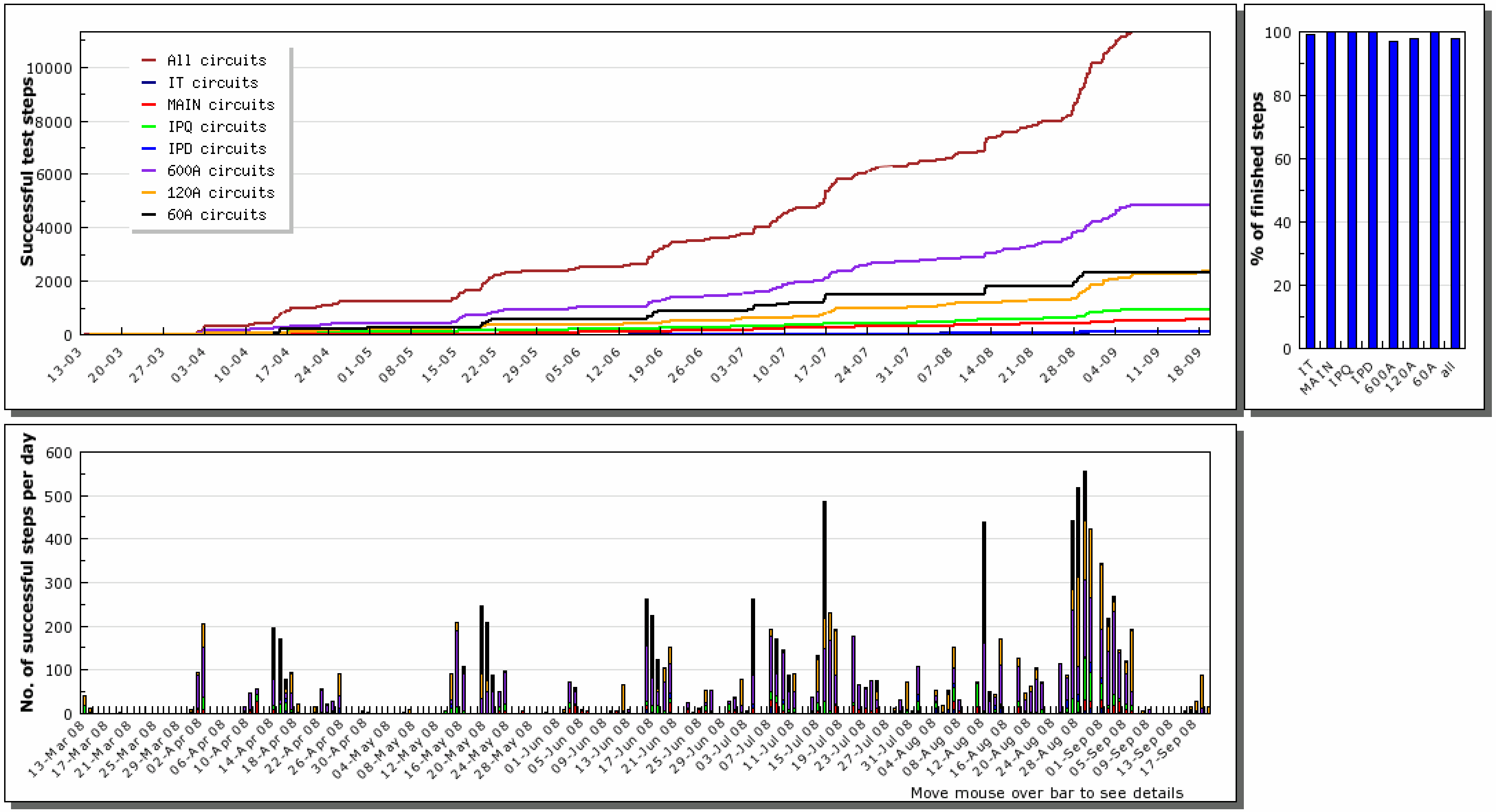
26

LHC Hardware Commissioning

April to September 2008

- (Re-)commissioning of the LHC electrical circuits (power converter, quench protection, interlocking..) following predefined test steps
- Commissioned to 5.5 TeV (5 TeV target for physics in 2008)

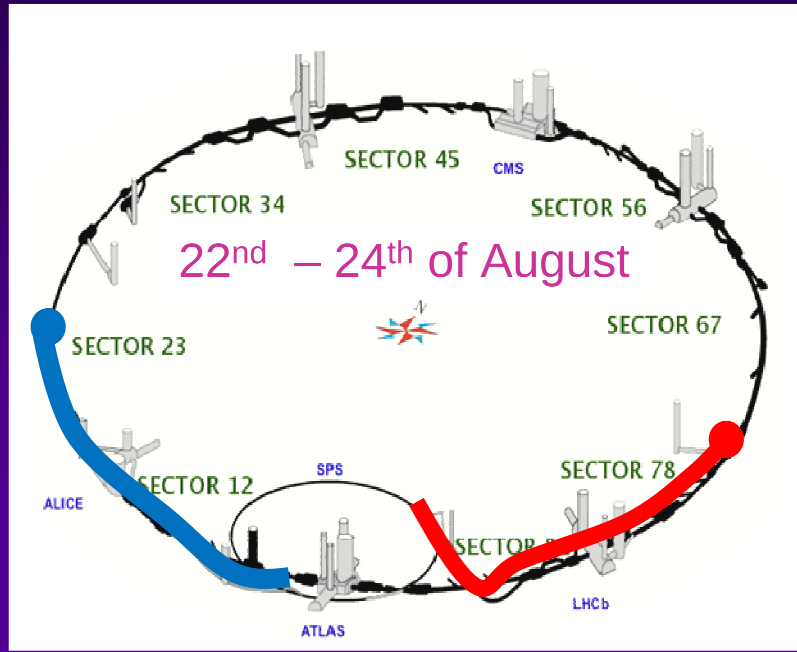
11122 out of 11321 test steps successfully executed

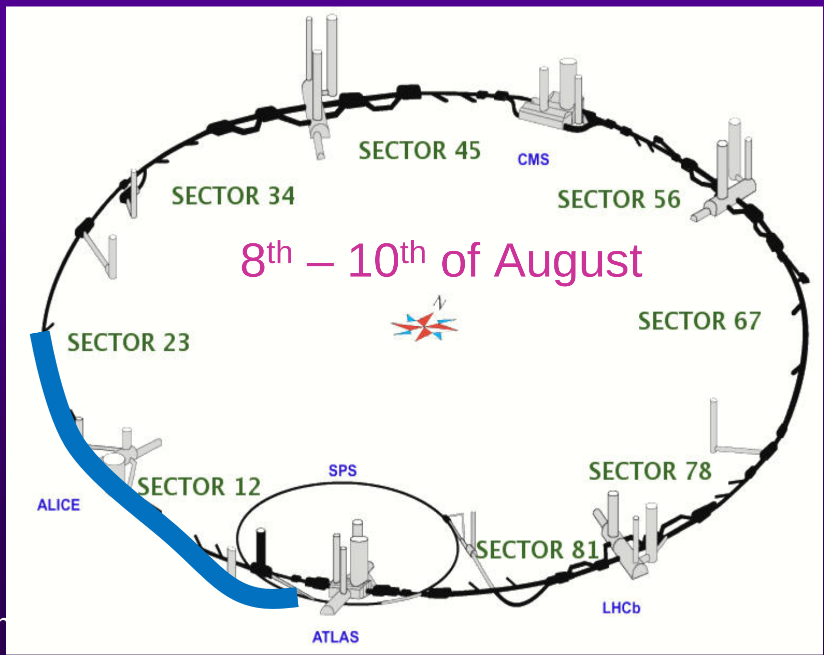


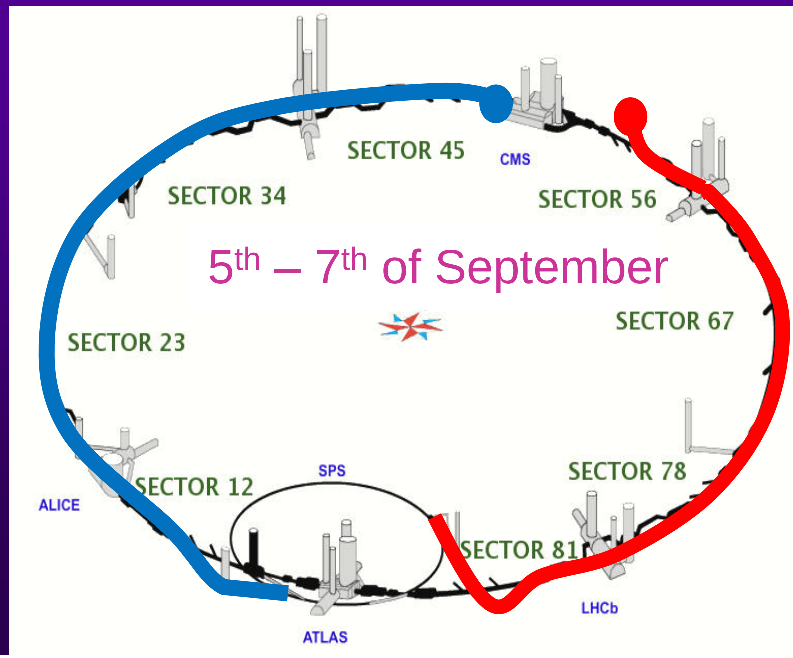
Injection tests

August – September 2008:

- Injection tests of up to 4 adjacent sectors
- Almost all HW systems involved in tests
- Essential checks for:
  - Control system
  - Beam instrumentation
  - Optics (magnetic model) and aperture







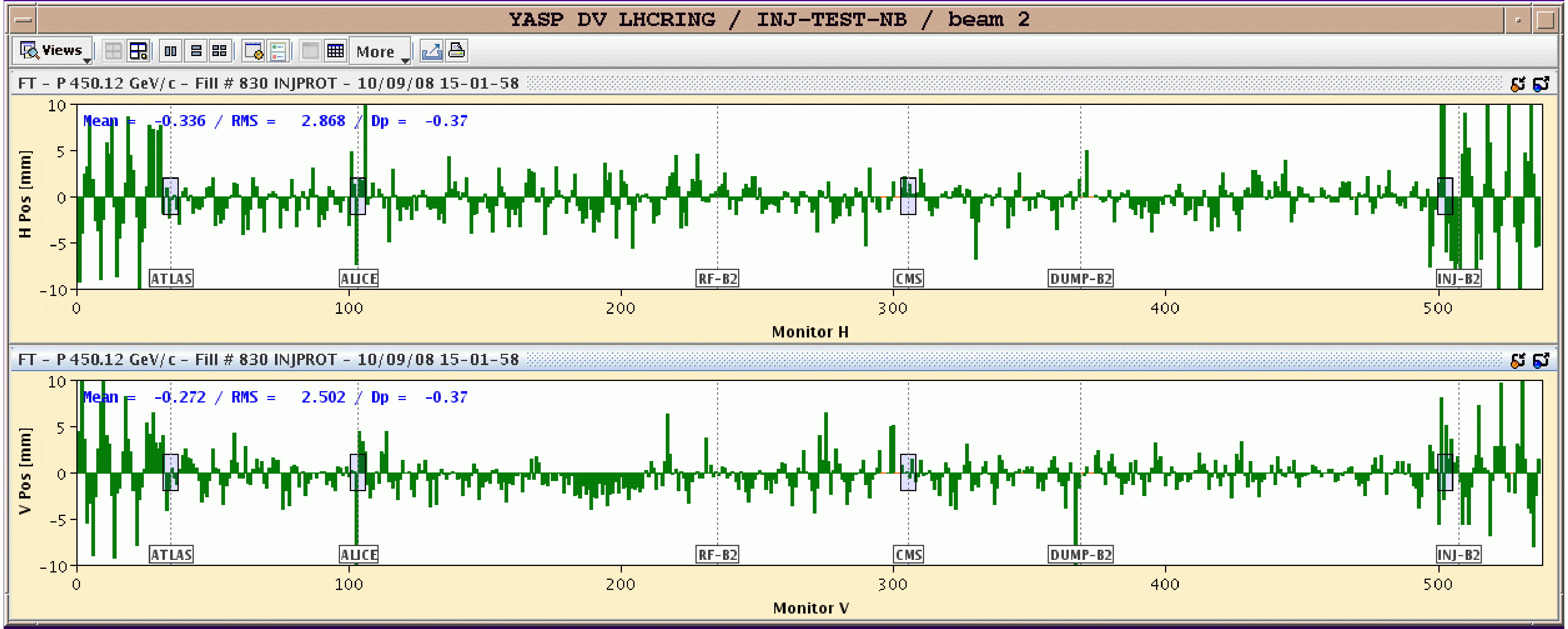
September 10th – like a dream !

Beam threading

Threading by sector by sector:

- One beam at the time, one hour per beam
- Collimators were used to intercept the beam (1 bunch, 2×10^9 p)
- Beam through one sector, correct trajectory, open collimator and move on

Beam 2 threading

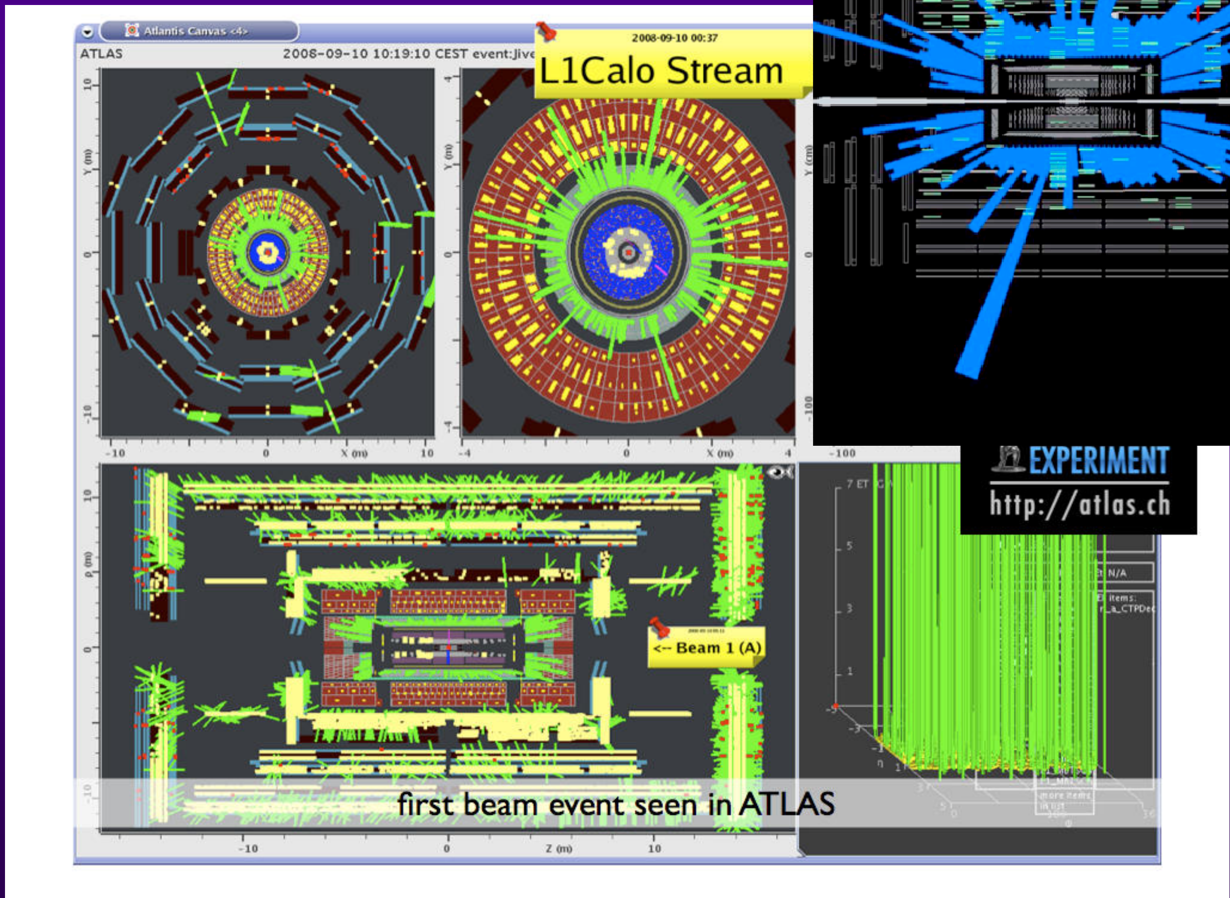


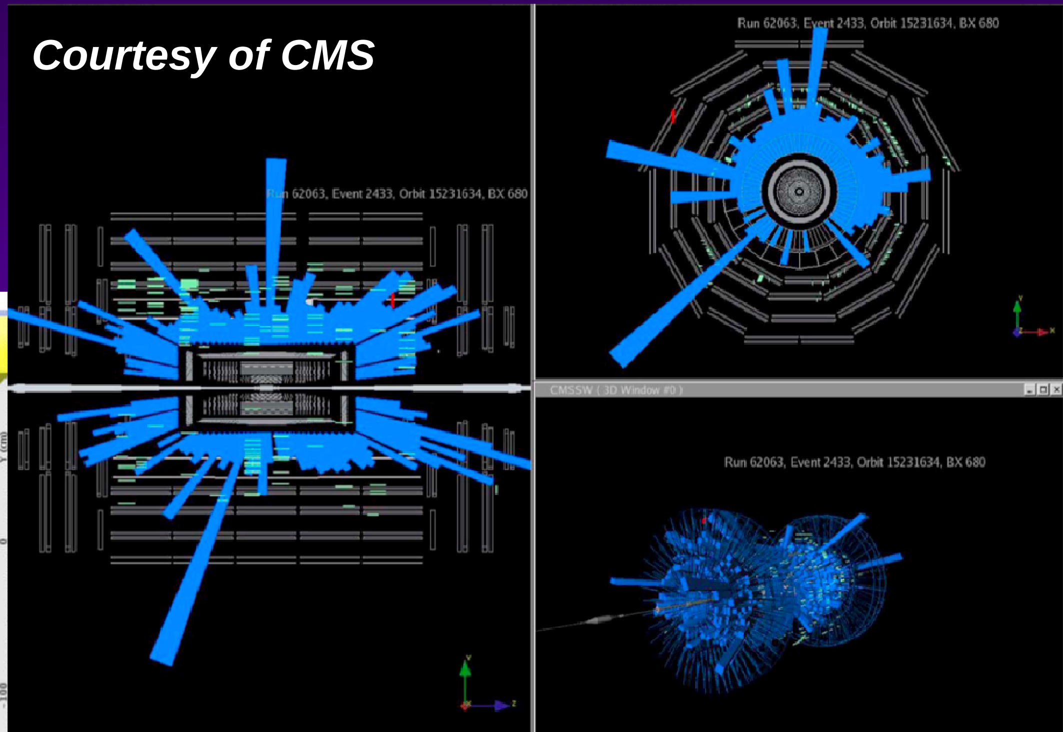
Courtesy J.Wenninger

ATLAS & CMS ‘events’

‘Beam-on-collimator’ events

Synchronized to beam timing !





Beam commissioning progress

September 10th

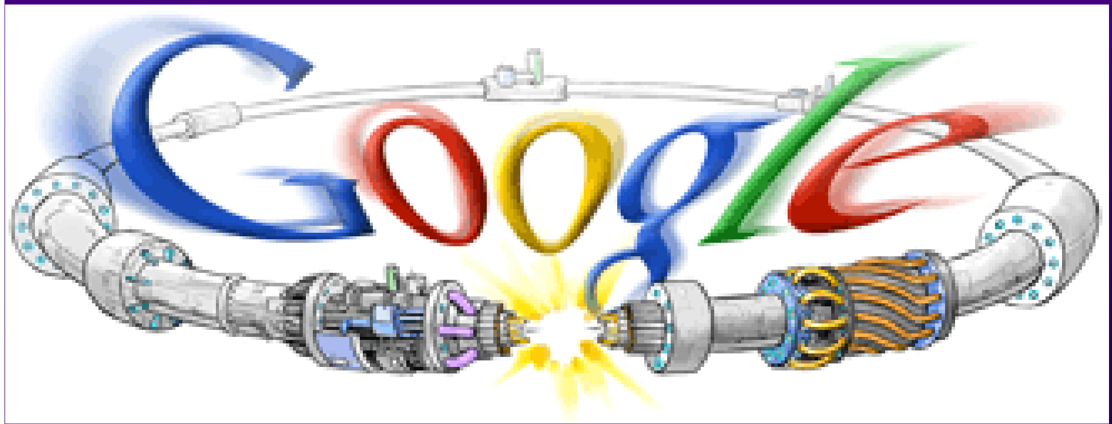
- 10:30 : Beam 1 around the ring (in ~ 1 hour). Beam makes ~ 3 turns
- 15:00 : Beam 2 around the ring, beam makes 3-4 turns
- 22:00 : Beam 2 circulates for hundreds of turns…

September 11th

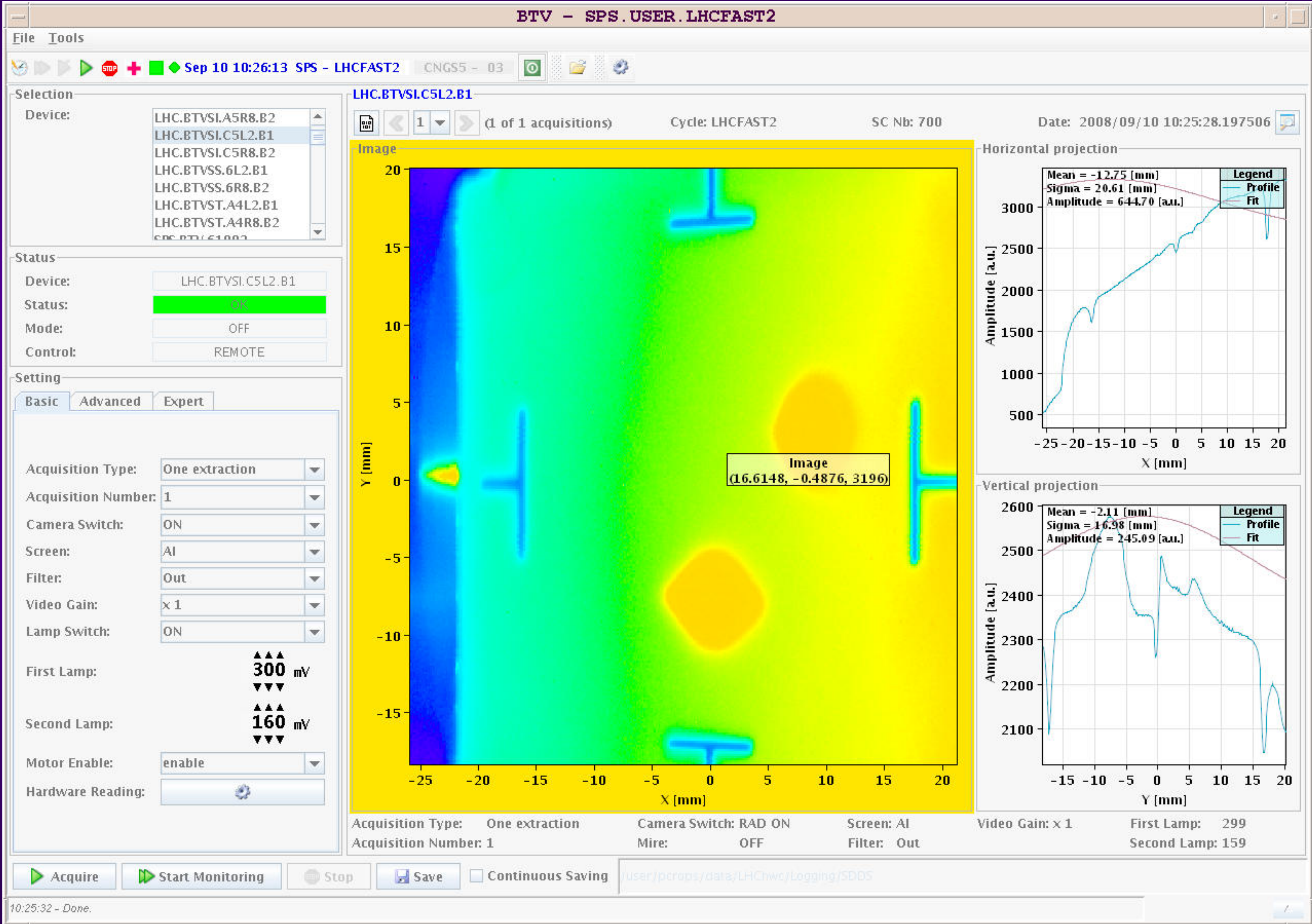
- Late evening: Beam 2 captured by RF

September 12th

- All basic instrumentation operational: Beam Position Monitors, Beam Loss Monitors, Tune, Beam Current Measurements
- Beta-beating measured

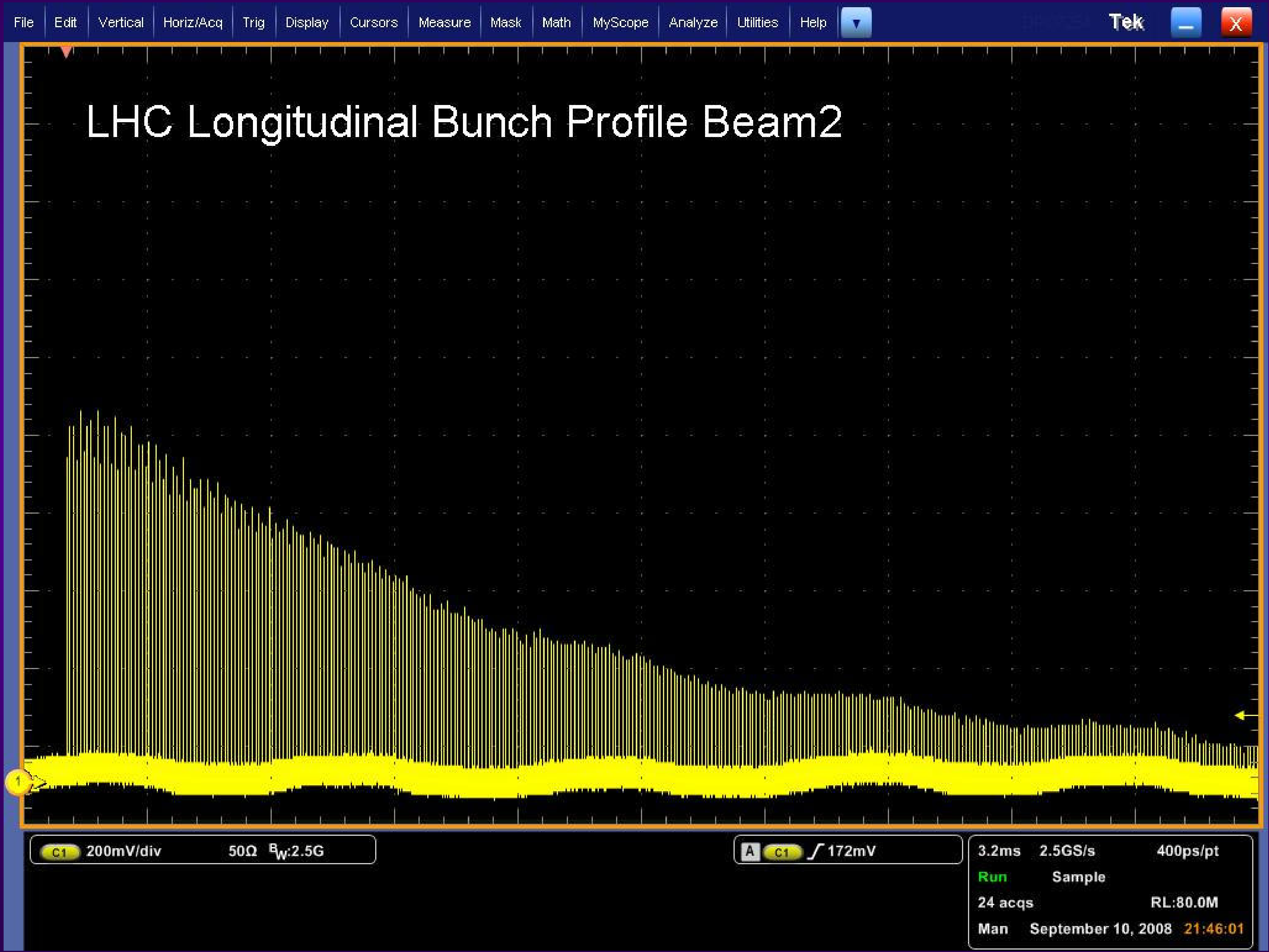


Beam on turn 1 and turn 2 on a screen



Courtesy R. Bailey

Few 100 turns

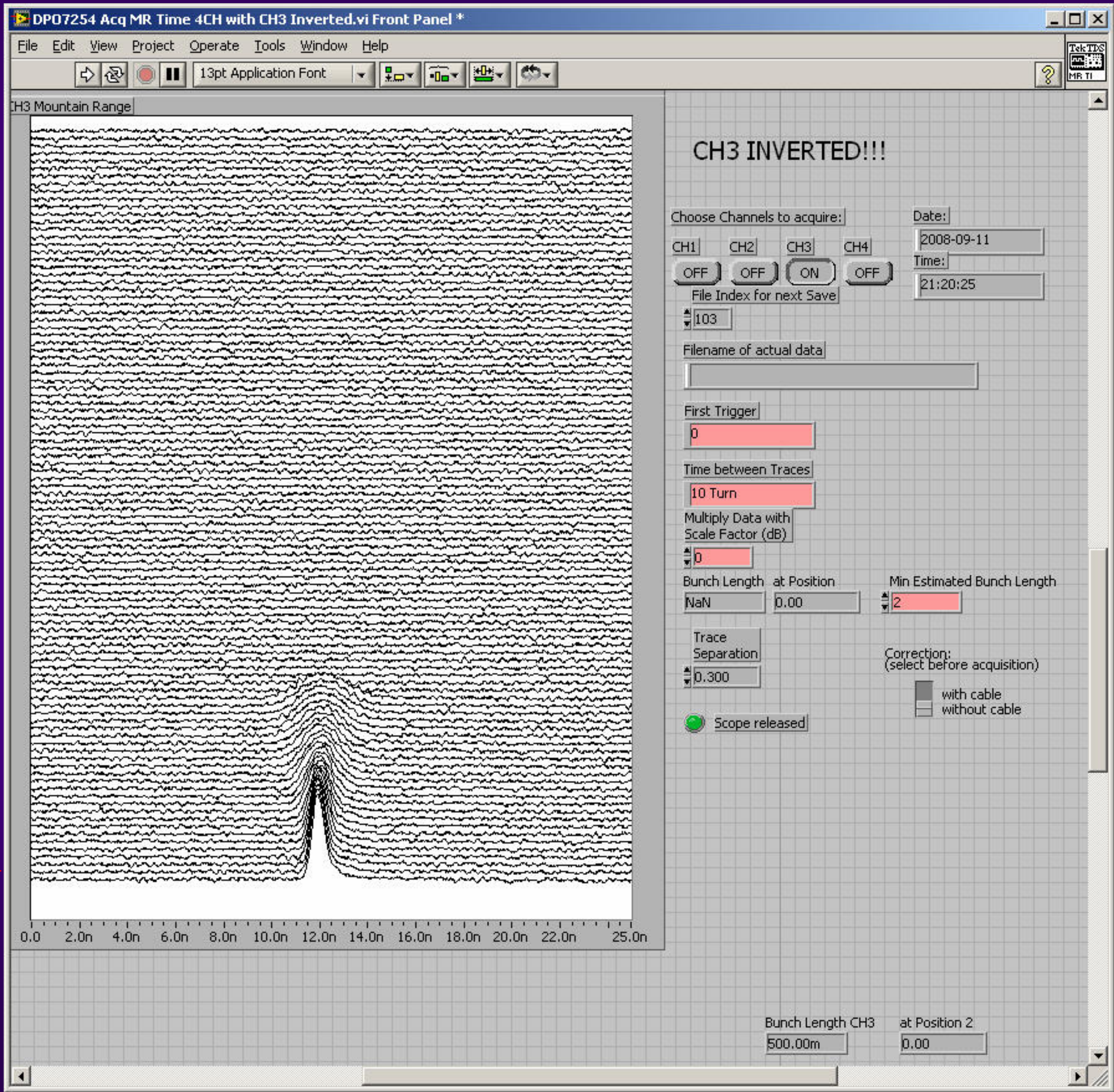


Courtesy R. Bailey

No RF, debunching in ~ 250 turns, roughly 25 ms

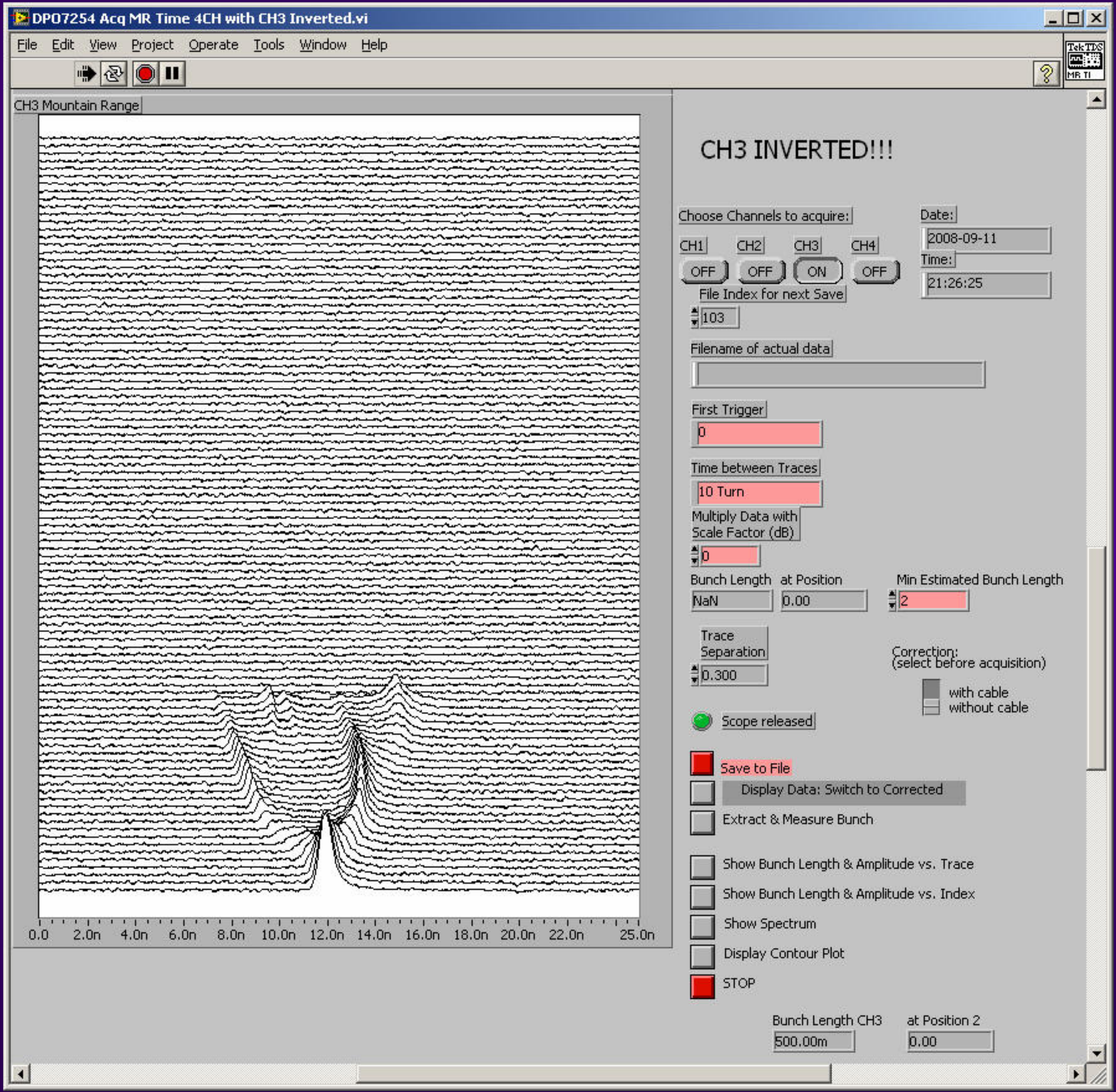
about 1000 turns

single turn



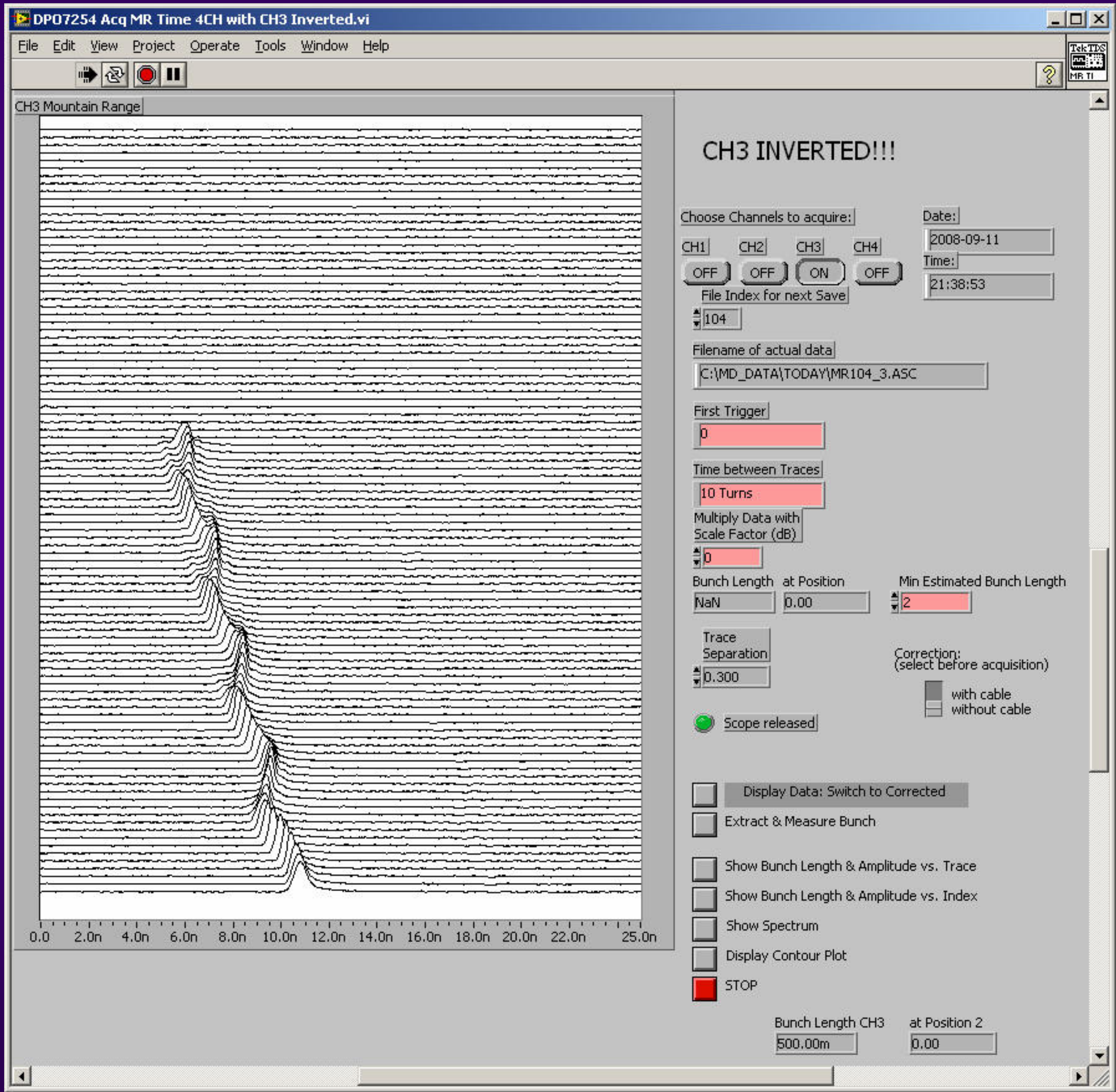
Courtesy
E. Ciapala

First attempt at capture, at exactly the wrong injection phase…



Courtesy
E. Ciapala

Capture with corrected injection phasing



Courtesy
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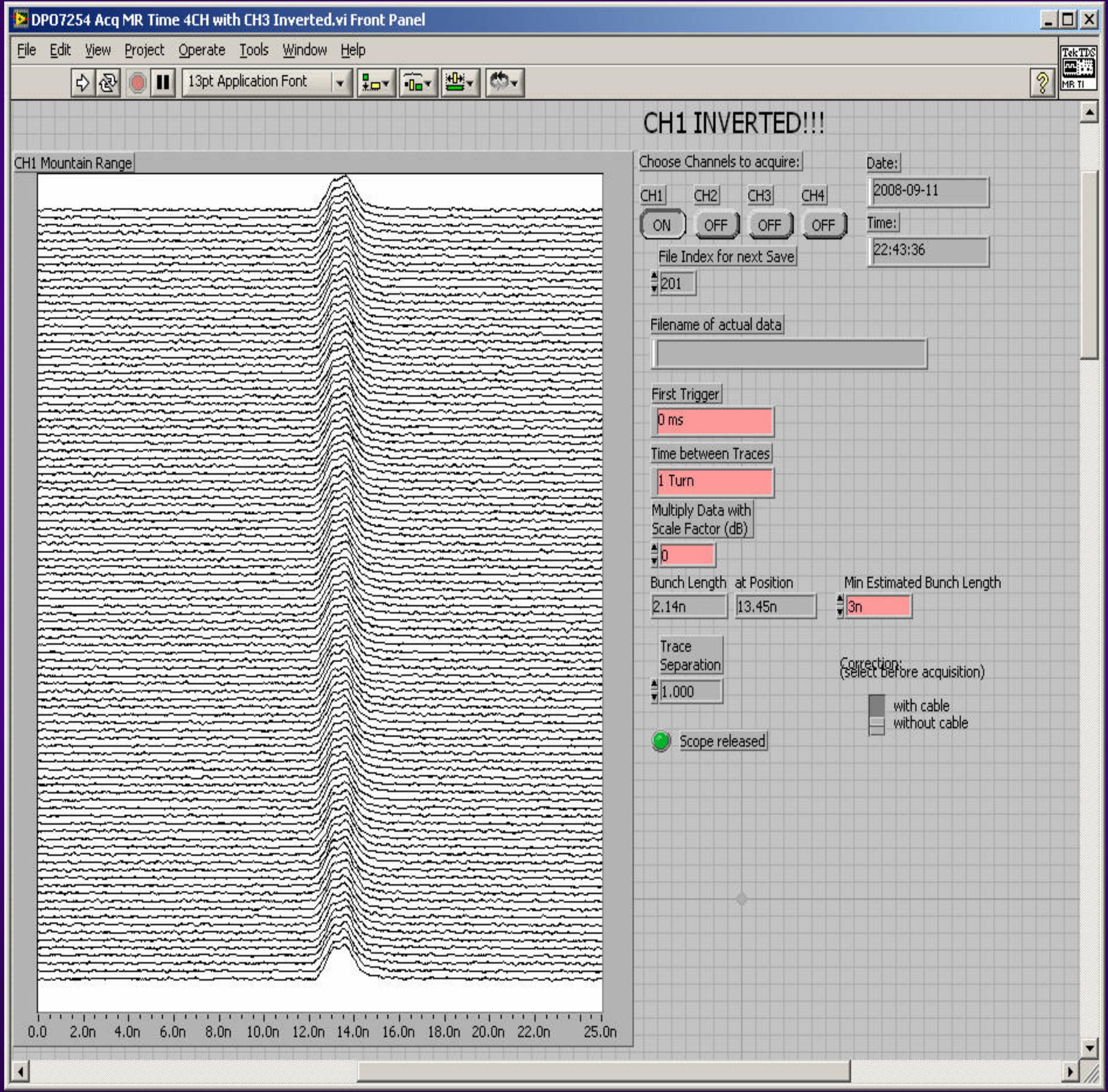
Capture with optimum injection phasing, correct reference

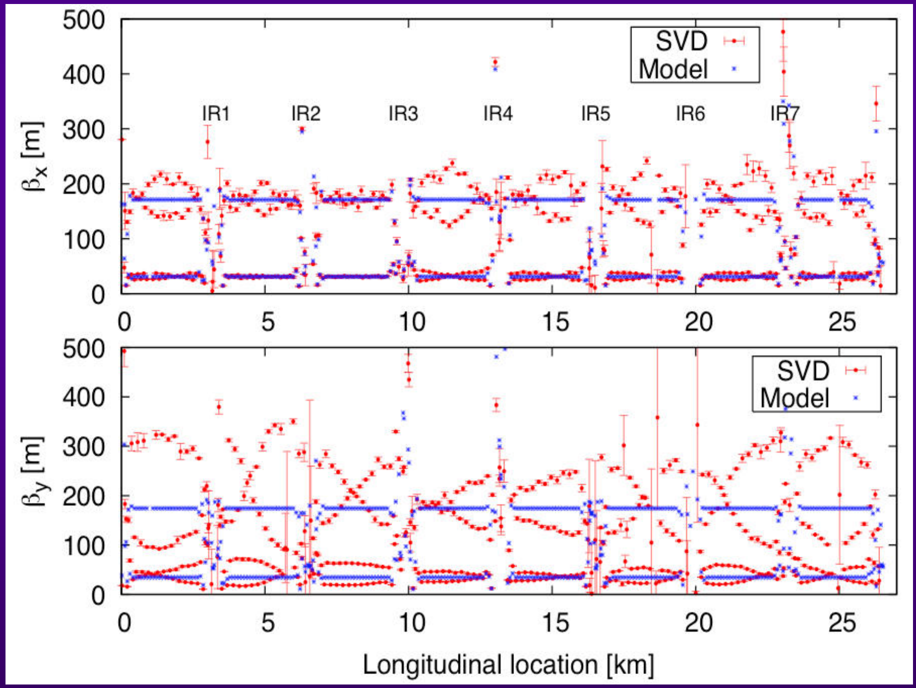


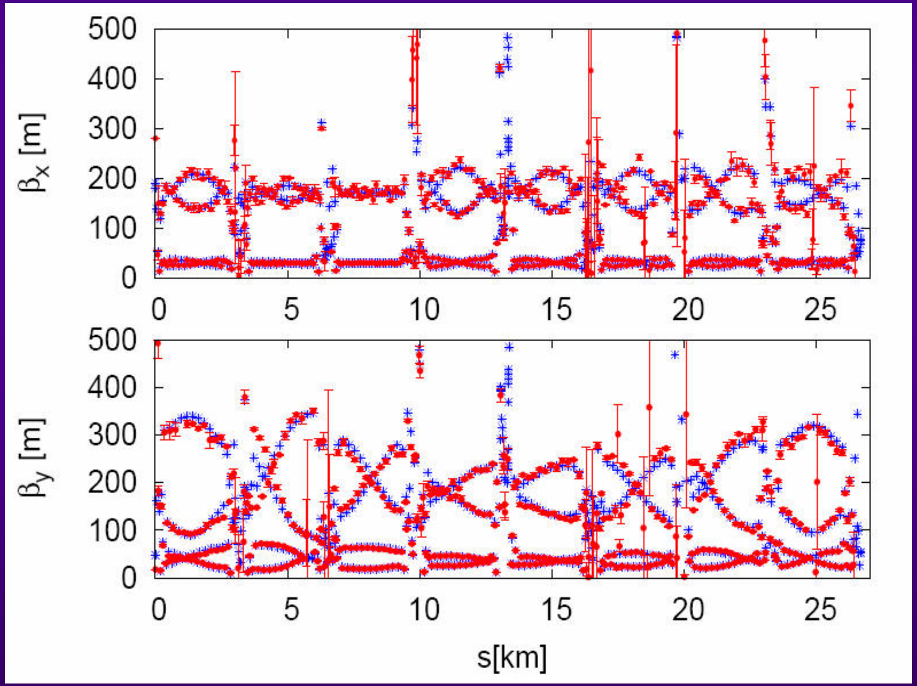
Courtesy
E. Ciapala

Magnetic model & beta-beating

A sophisticated magnetic model (FIDEL) was developed to predict settings and field errors for the LHC. FIDEL is backed by measurements and integrated into the control system for online corrections.

Beta-beat tolerance : 20%





- Horizontal beating ≤ 30%
- Vertical beating up to 90-100%

Large source of beating identified as cabling problem (beam1-beam2).

Courtesy J.Wenninger

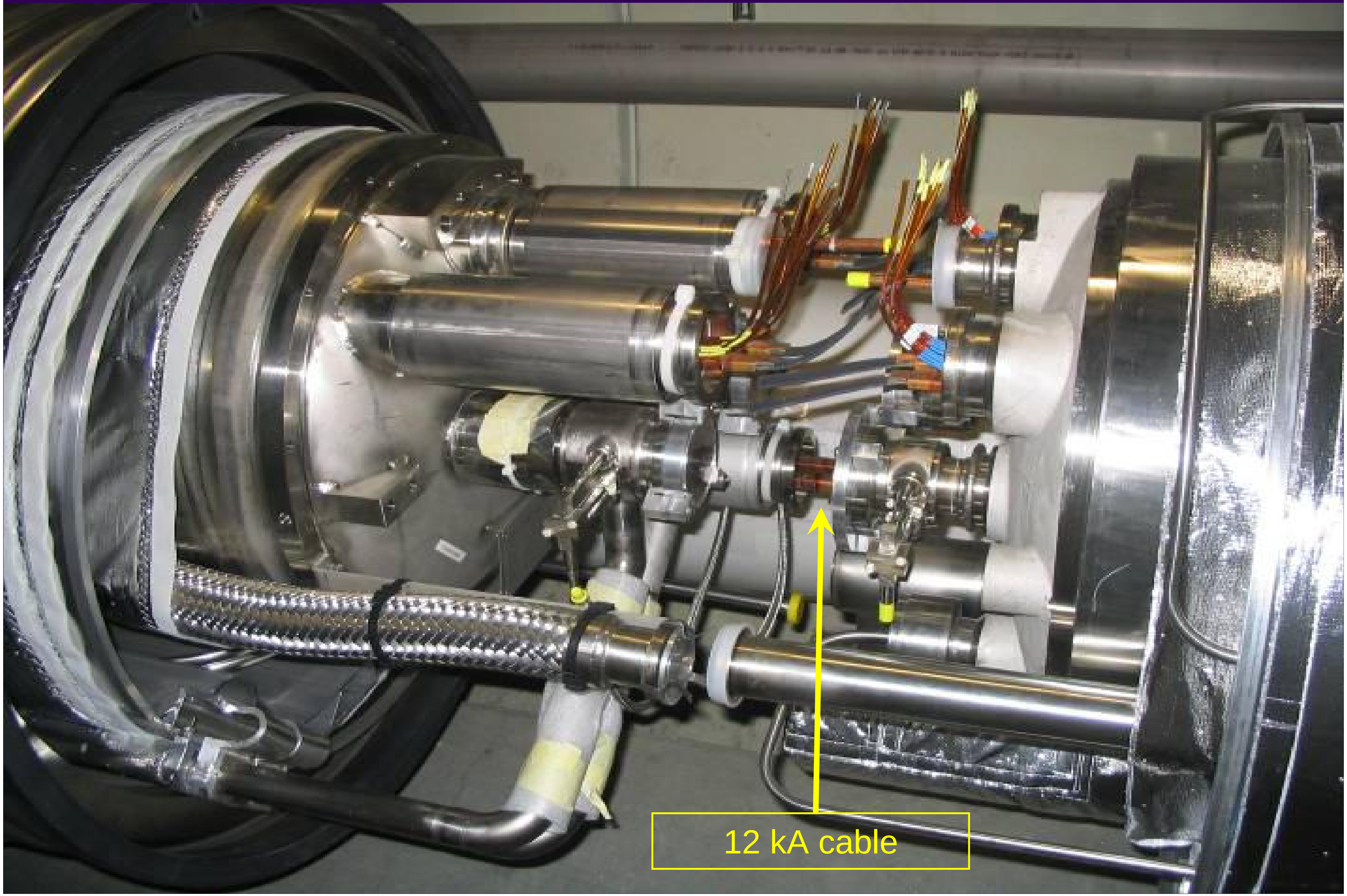
September 19th Incident

REPORT OF THE TASK FORCE ON THE INCIDENT OF 19TH SEPTEMBER 2008 AT THE LHC
Ph.Lebrun et al., LHC Project Report 1168, 2009

Event sequence

- Last commissioning step of the main dipole circuit in sector 34: ramp to 9.3 kA (5.5 TeV), as seven sectors before
- At 8.7 kA an electrical fault developed in a dipole bus bar interconnection between a quadrupole and dipole
- *Later correlated to a local resistance of ~220 nOhm – nominal value 0.35 nOhm*
- An electrical arc developed which punctured the helium enclosure and the beam vacuum tube
- Secondary arcs developed along the sector
- Around 400 MJ from a total of 600 MJ were dissipated in the cold-mass and in electrical arcs
- Large amounts of helium were released into the insulating vacuum, in total 6 tons were released

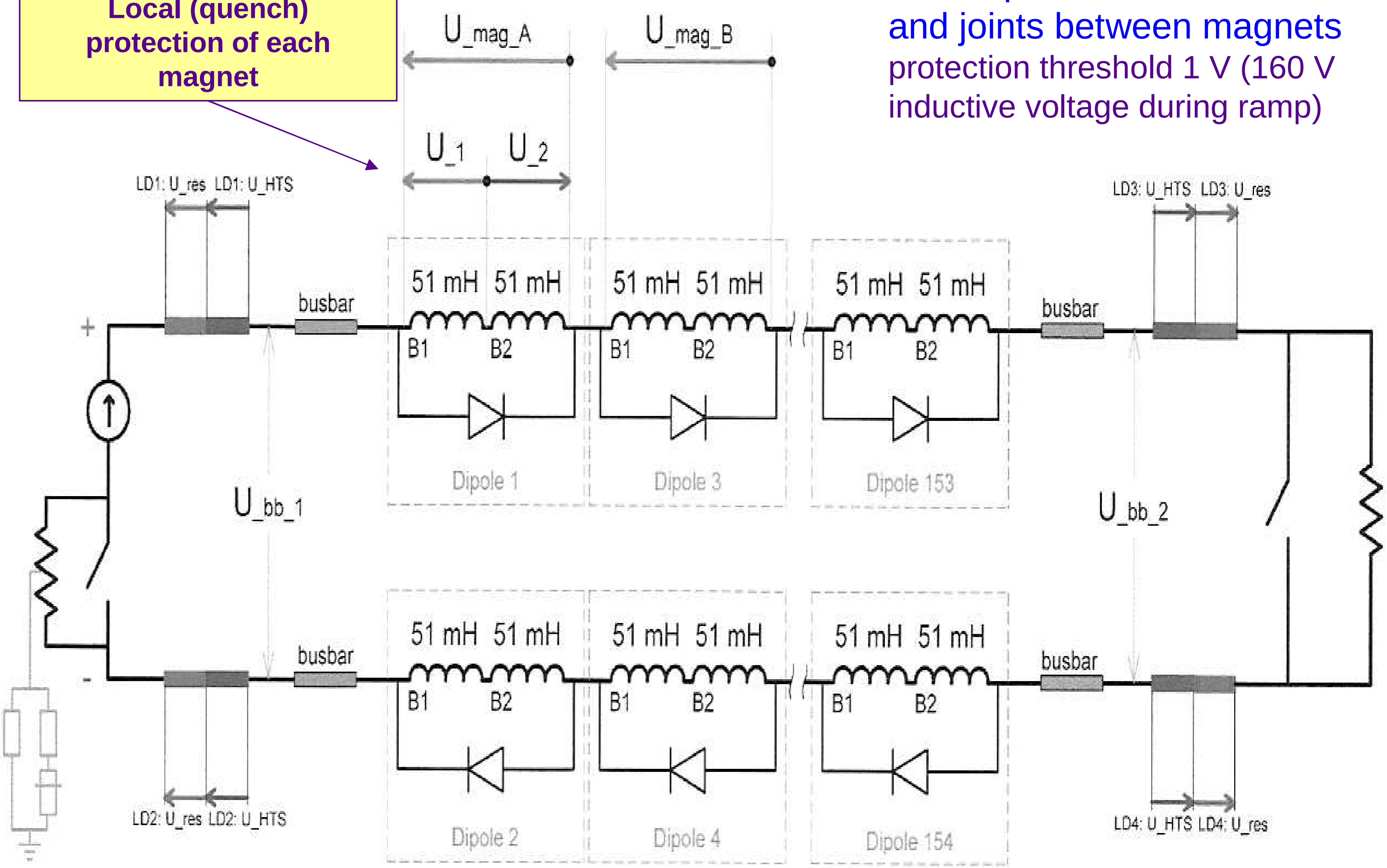
Rupture of high current cable between two magnets



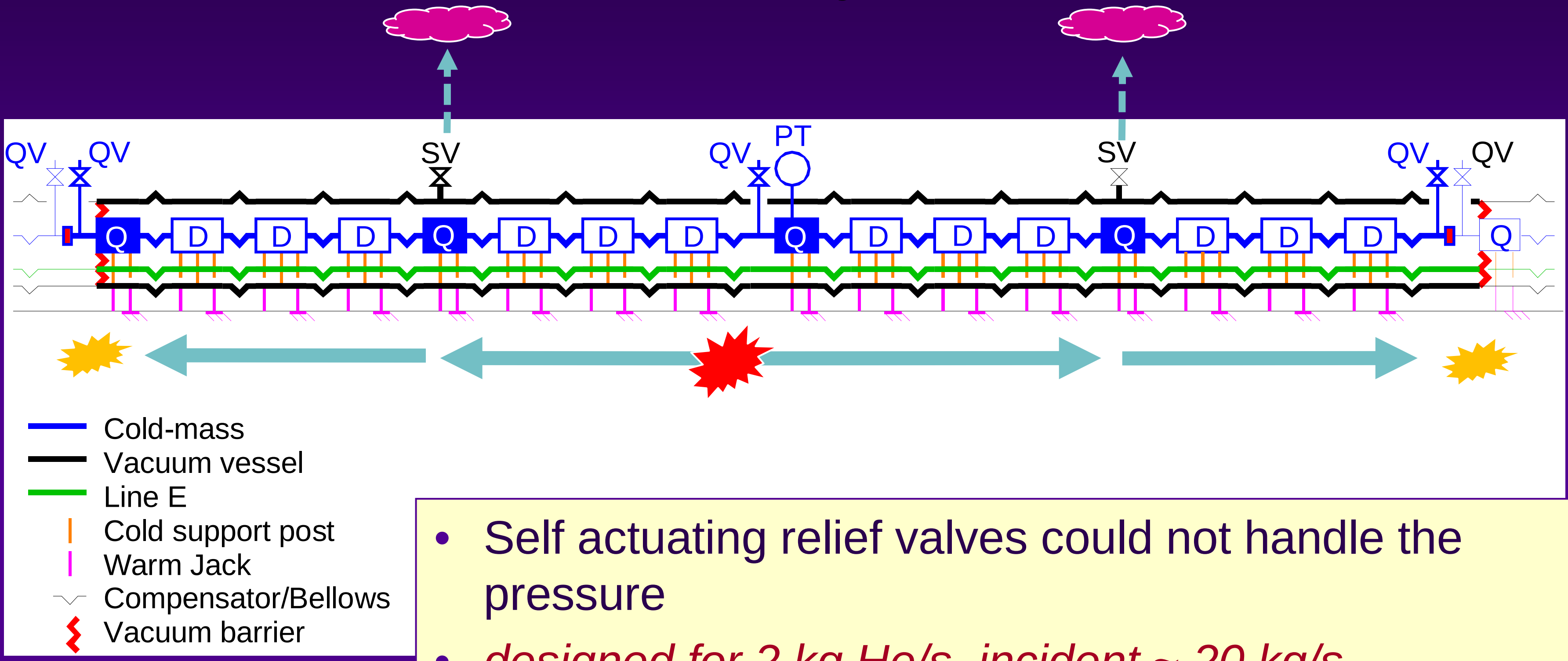
Schematic of the main dipole circuit

Local (quench) protection of each magnet

Global protection of the busbar and joints between magnets
protection threshold 1 V (160 V inductive voltage during ramp)

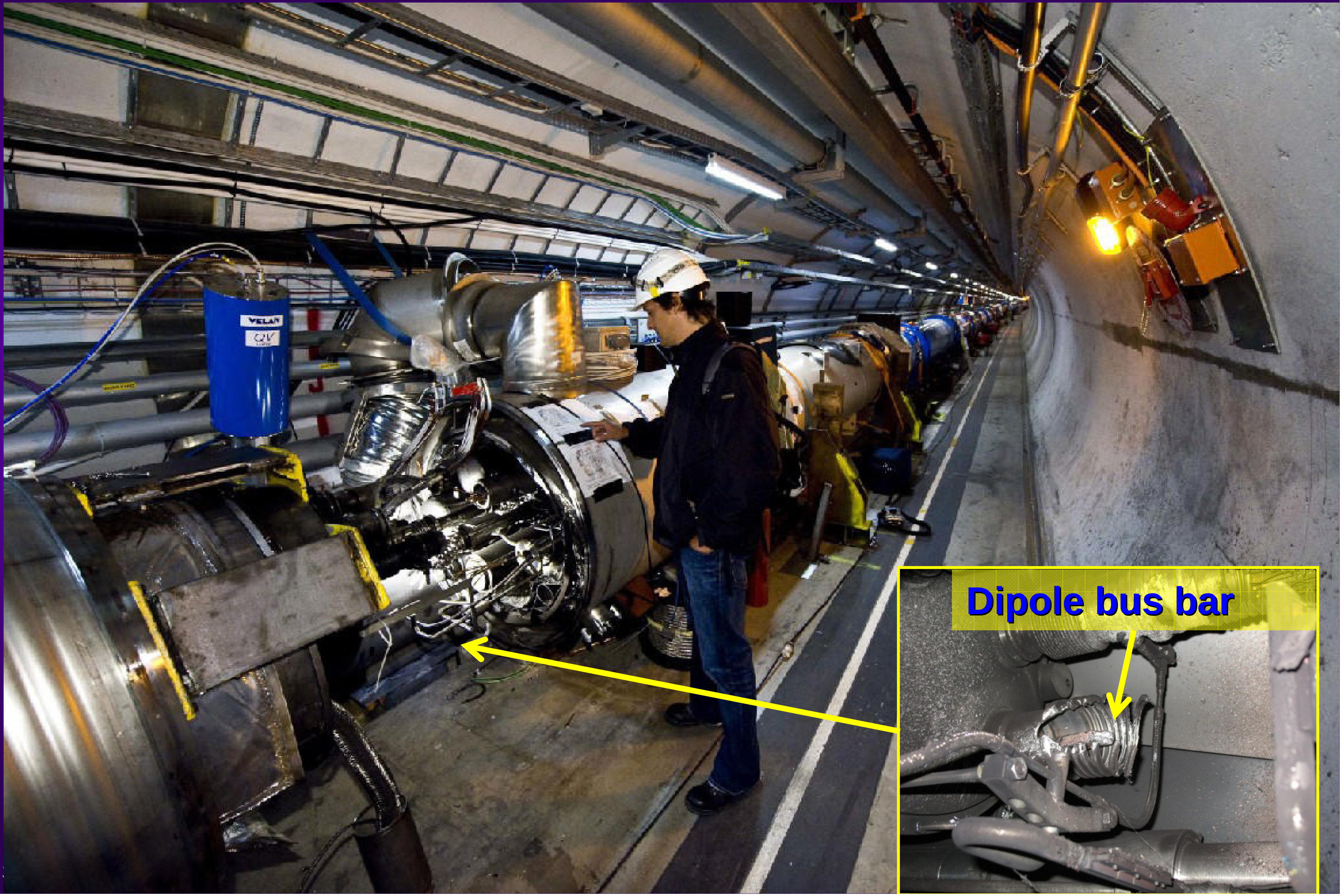


Pressure inside the cryostats

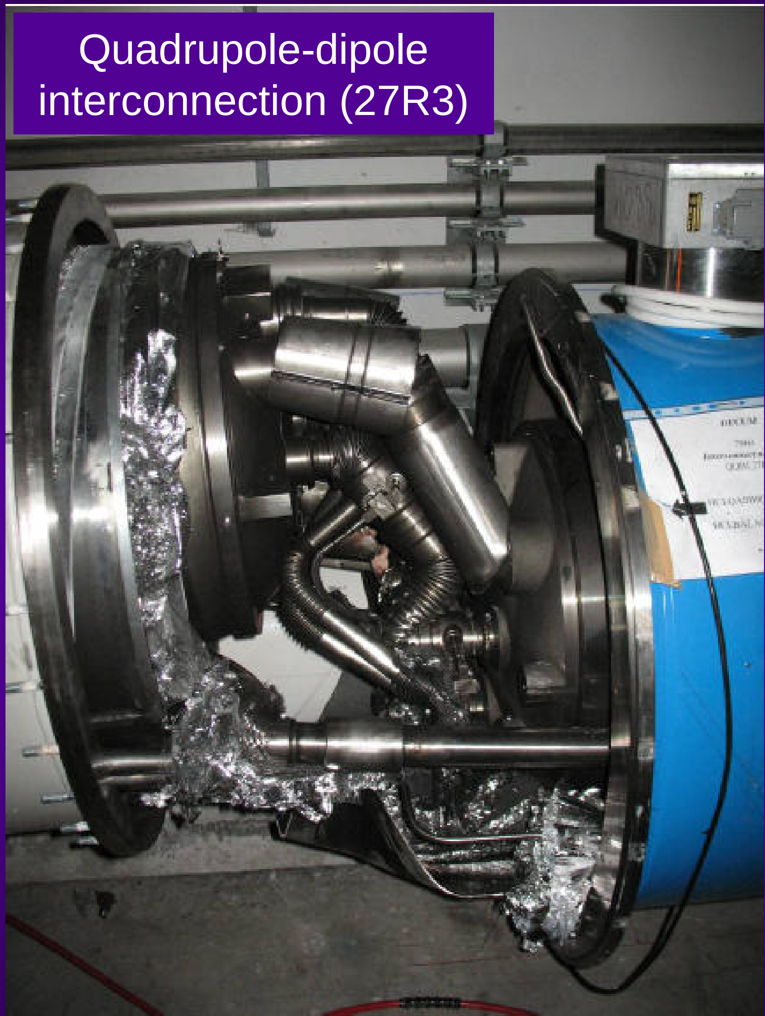


- Self actuating relief valves could not handle the pressure
- *designed for 2 kg He/s, incident ~ 20 kg/s*
- Large forces exerted on the vacuum barriers (every 2 cells, 230 m)
- *designed for a pressure of 1.5 bar, incident ~ 10 bar*
- Several quadrupoles displaced by up to ~50 cm
- Connections to the cryogenic line damaged in some places

Incident location



Collateral damage : displacements

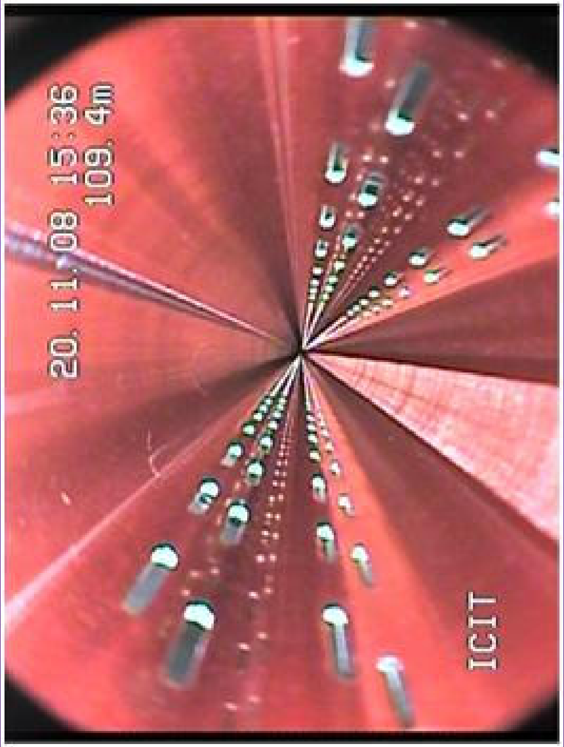
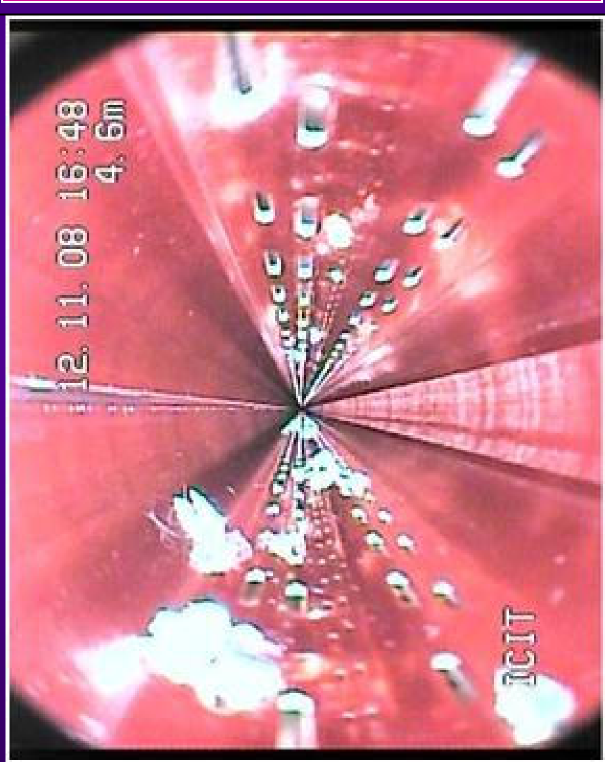
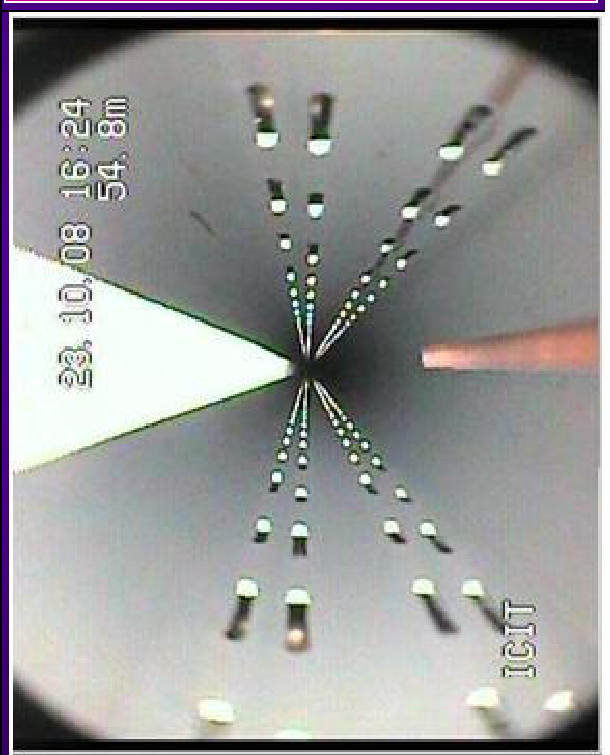

Quadrupole-dipole interconnection (27R3)

Quadrupole support

- **39 dipoles** out of 154
- **14 quadrupole** short straight sections (SSS) out of 52

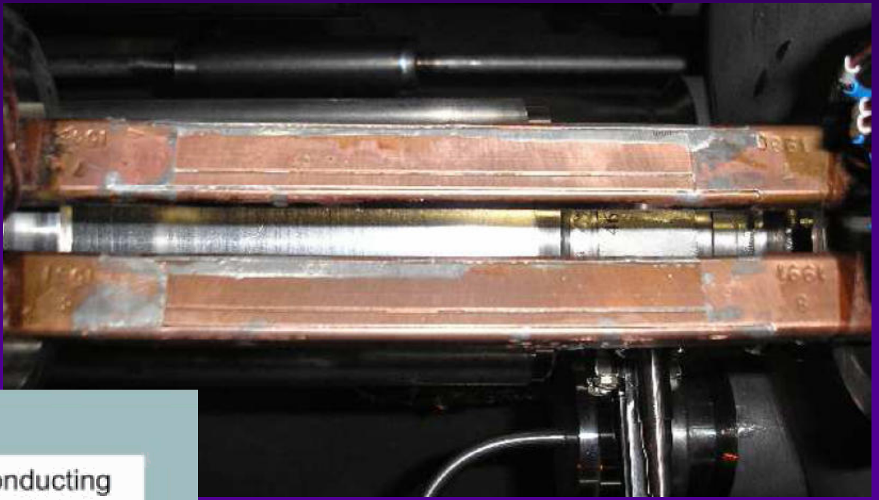
…had to be moved to the surface for control, repair or replacement

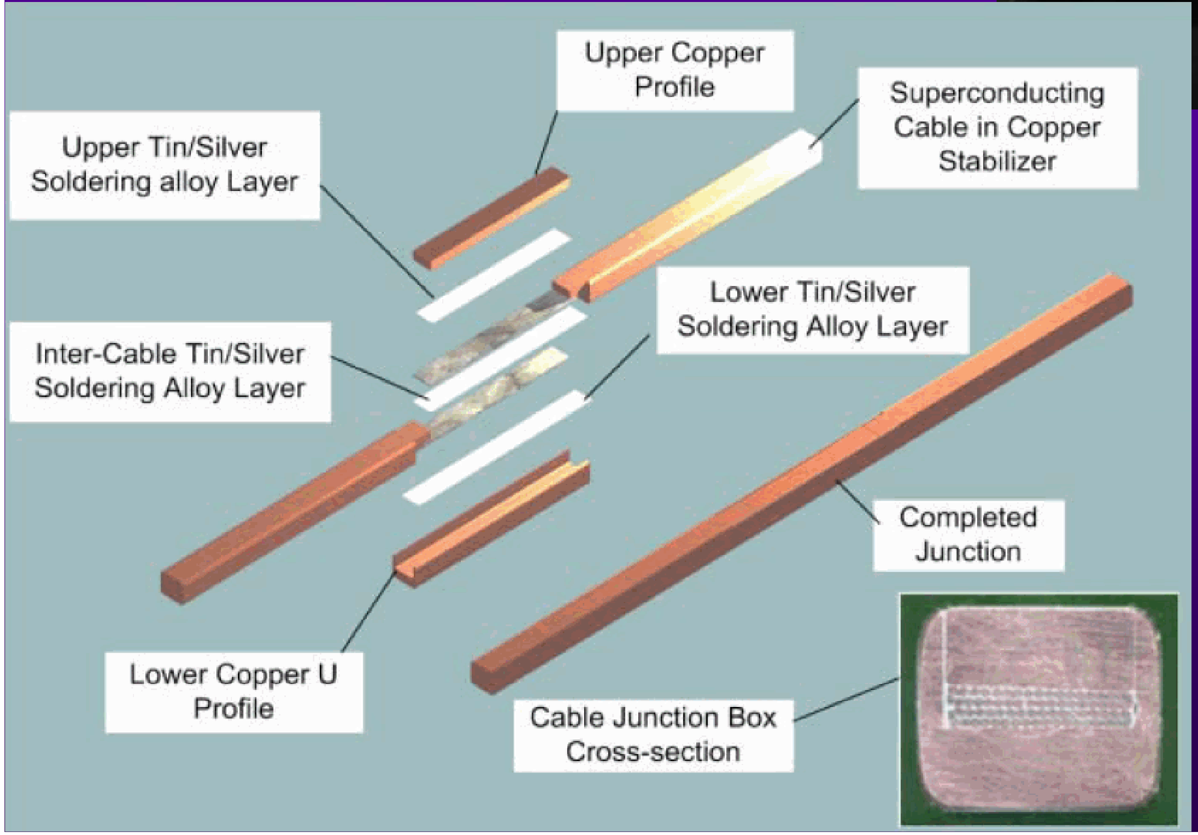
Collateral damage : beam vacuum

Beam screen with clean Copper surface.	Beam screen contaminated with multi-layer magnet insulation debris.	Beam screen contaminated with sooth.
		
	≈ 60% of the chambers	**≈ 20% of the chambers**

Busbar joint: most likely cause of incident

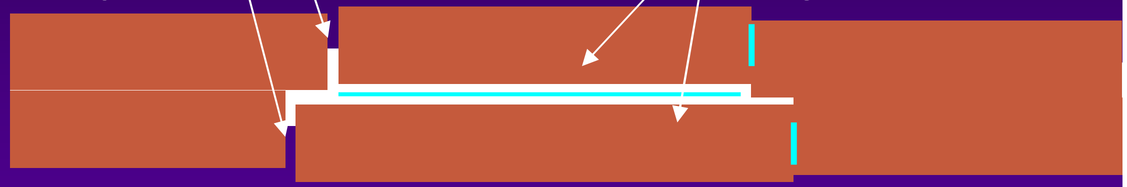
- Bus bar joint is brazed
- Joint resistance ~0.35 nΩ
- Joints are not clamped
- Global protection of the entire busbar (154 dipoles) with a threshold of 1 V



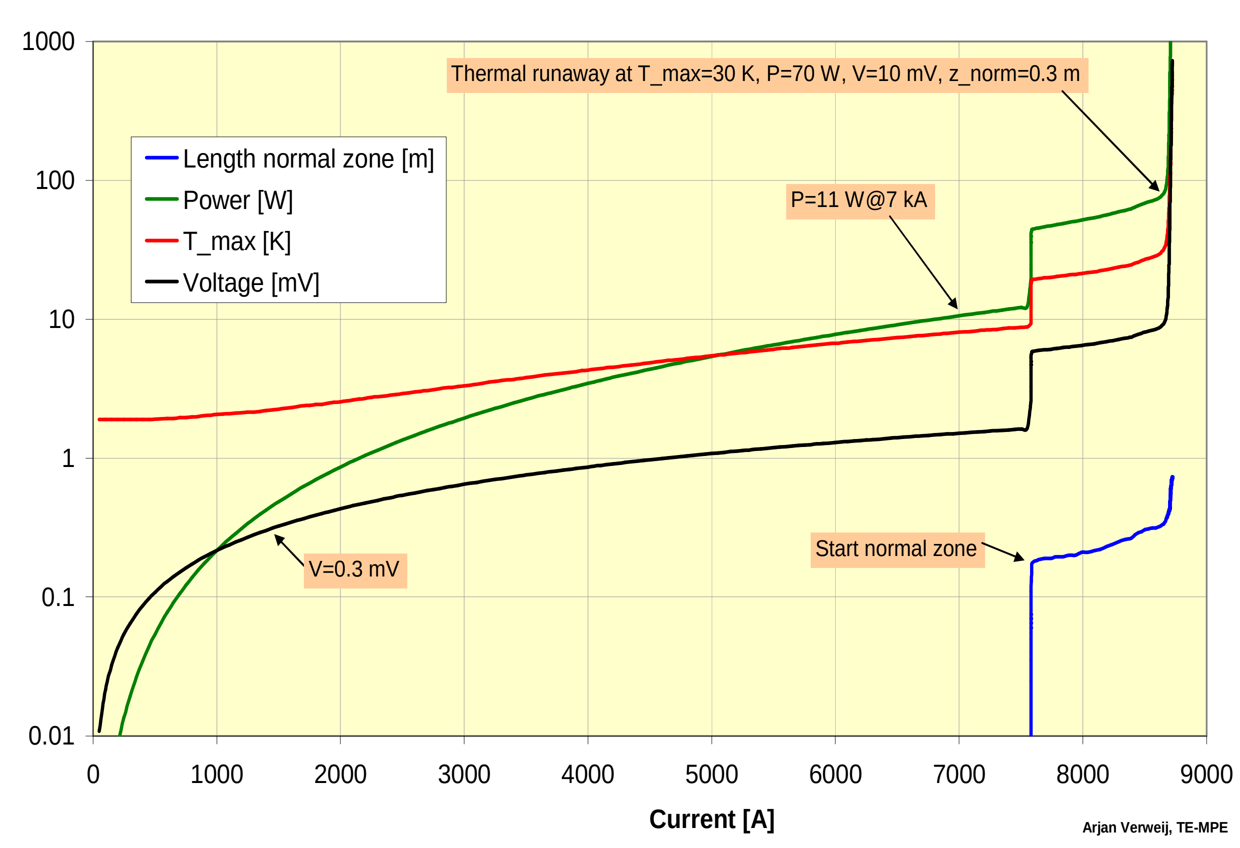


- Visual inspection after brazing
- A fraction of the joints were tested with an ultra-sound technique. Development came too late for tests in sector 34, but it is not sure that the fault would have been detected

Joint contact scenario



- Joint model with poor electrical contact, R ~ 220 nΩ.
- Simulation of the last 'fatal' ramp: thermal run-away around 8700 A.
- Protection threshold of **1 V** of the QPS not adequate.
- Threshold of ~ **0.3 mV** is required to adequately protect the busbar against such incidents.

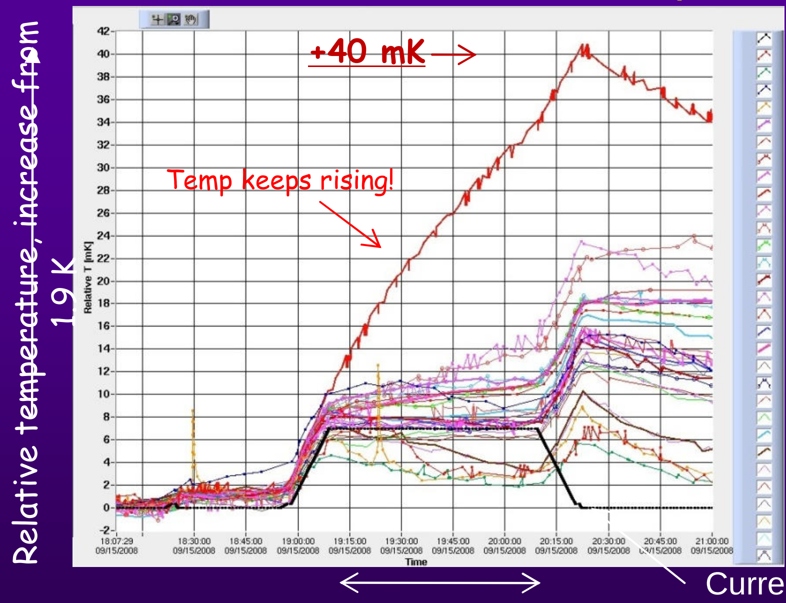


What about the other joints?

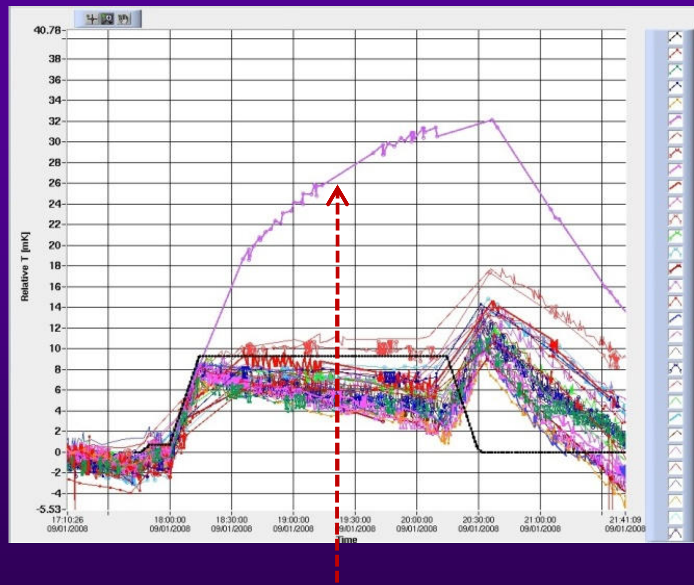
Calorimetric data

- Logged cryogenic data revealed a temperature anomaly of some 40mK in the cell of the incident during a previous (lower current) powering cycle
- Date from other powering tests indicated another anomaly in sector 12. Calorimetry suggested a ~**100nΩ resistance**

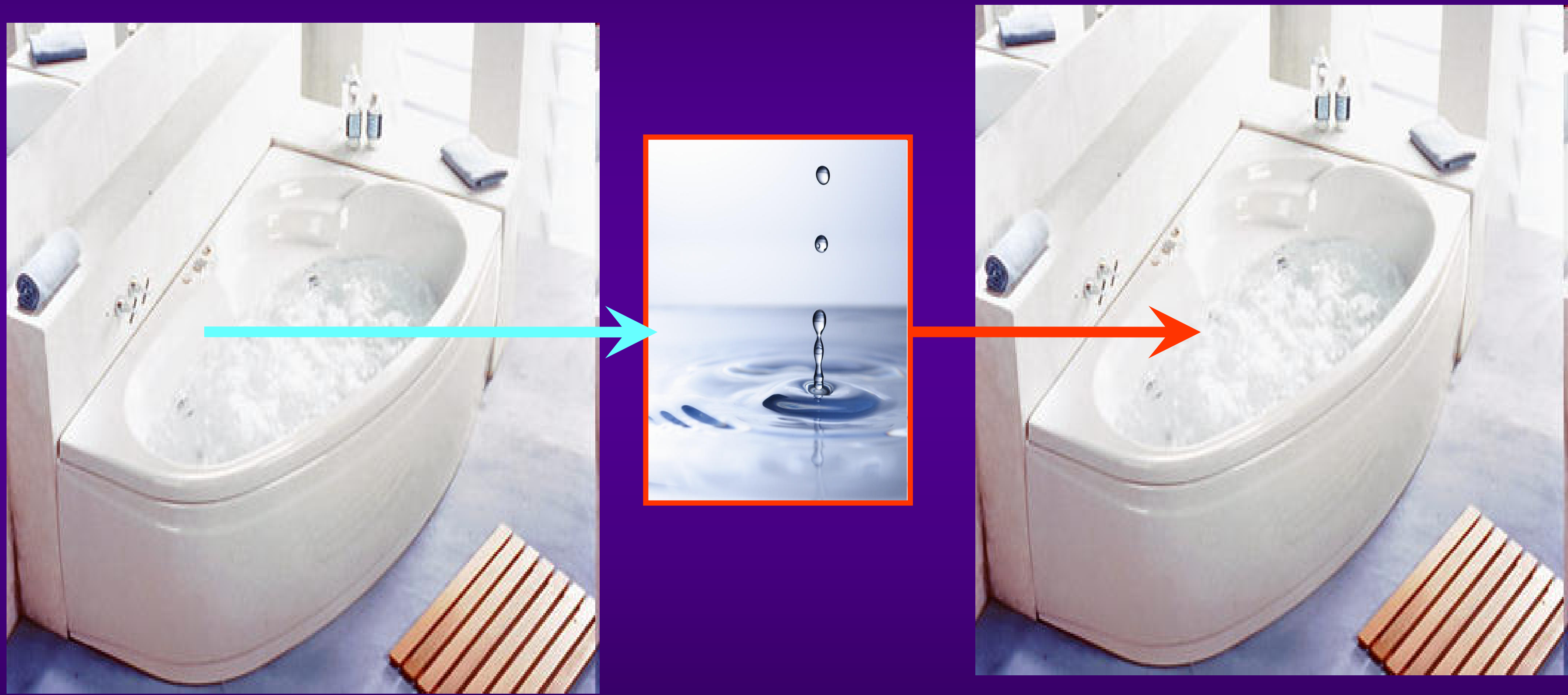
ΔT (mk) 7 kA test on Sector 3-4, Sept 15th



9.3 kA test on Sector 1-2, Sept 1st



measuring 2 W in 400 tons – few mK



Calorimetric and electrical measurements

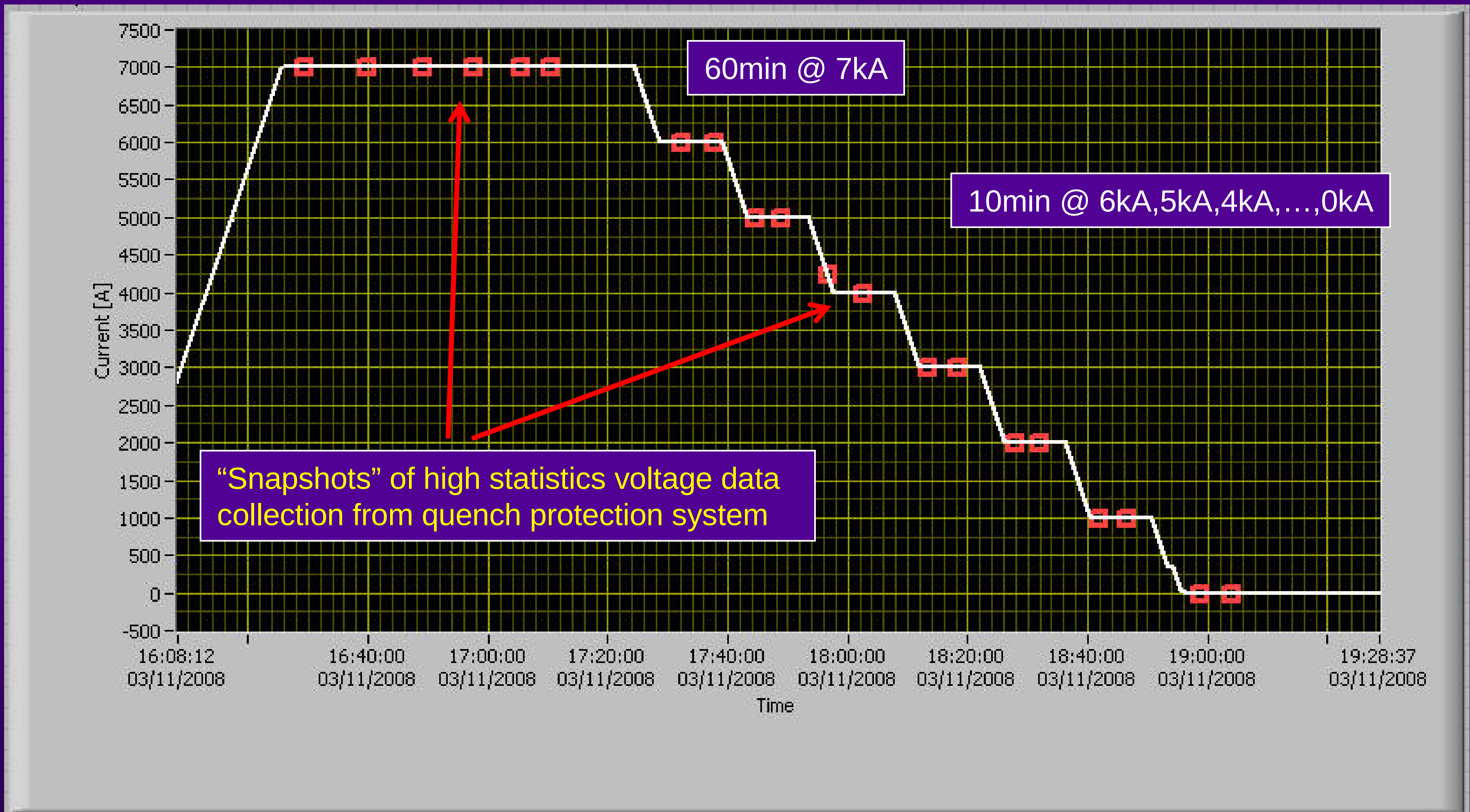
- Calorimetric measurement techniques were developed, with the possibility to localize anomalous resistances down to **~40 nΩ within a cryogenic cell of 220 m length**
  - *Systematic calorimetric tests were launched on all available sectors*
- High precision voltage measurements were employed to measure all interconnection resistances (<u>resolution < 1 nΩ</u>) in suspected cells
- The quench protection system data was collected and averaged over long time intervals for a number of current steps to localize magnets with abnormal internal resistances

<u>Outcome of the test campaign:</u>

- **2** magnets were localized with **<u>internal</u>** resistances of **50** and **100nΩ**
  - *Both magnets have been replaced*
  - *Both magnets were tested to 13 kA on test stands before!*

Electrical measurements

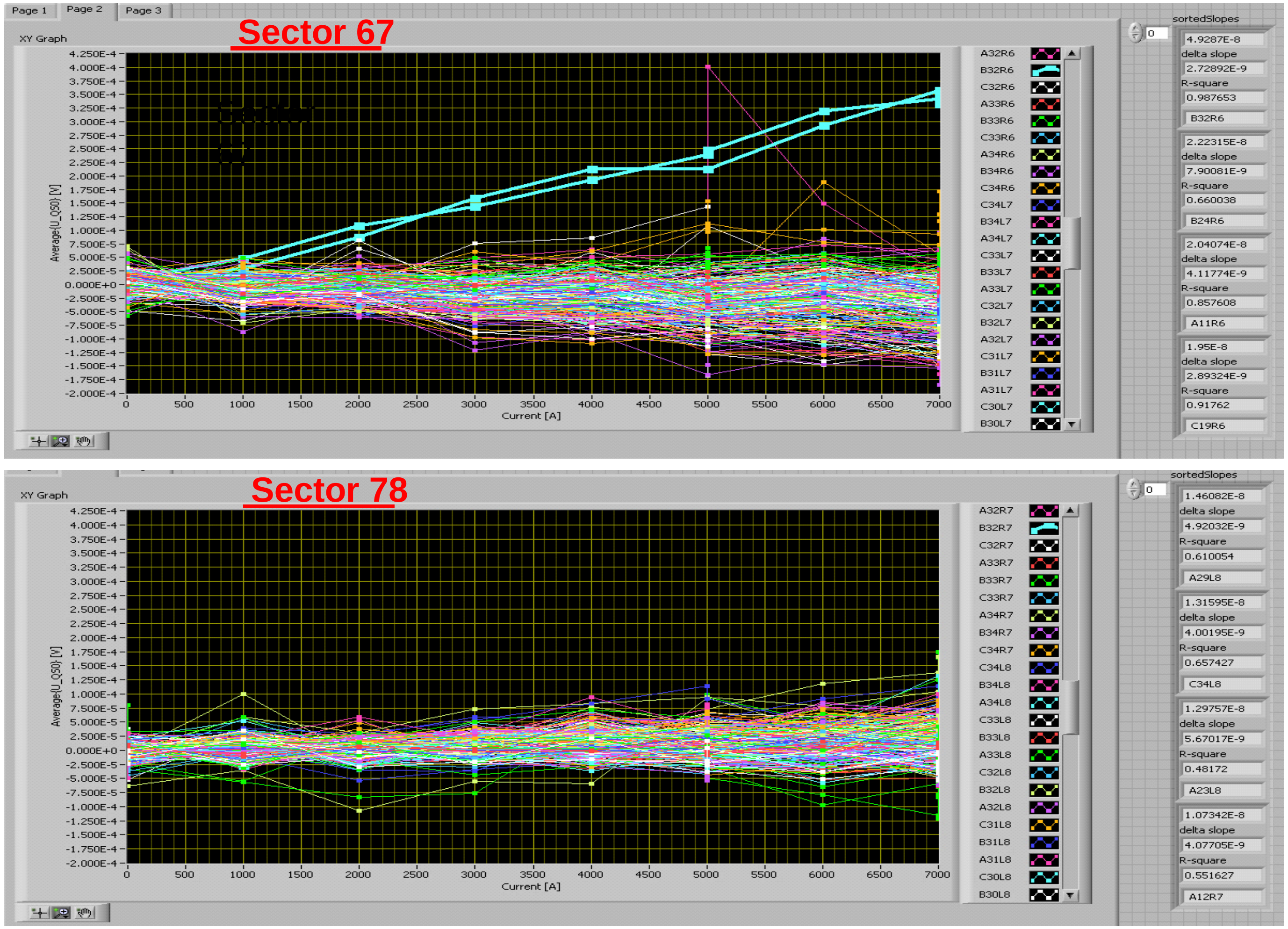
Ramps to different magnet currents and precisely measuring the voltage



Electrical measurements

Voltage

Results from measurements of all dipoles in sectors 67 & 78



Current (max = 7000 A)

Repair and consolidation

Repair

39 dipoles and 14 quadrupoles short straight sections (SSS) brought to surface for repair or replacement.

- all dipoles and most SSS back in the tunnel (last two SSS for this week)

The 2 dipoles with large internal resistance in other sectors were replaced and inspected

- Lack of solder on joint, not correctly done

The vacuum chambers are cleaned in situ

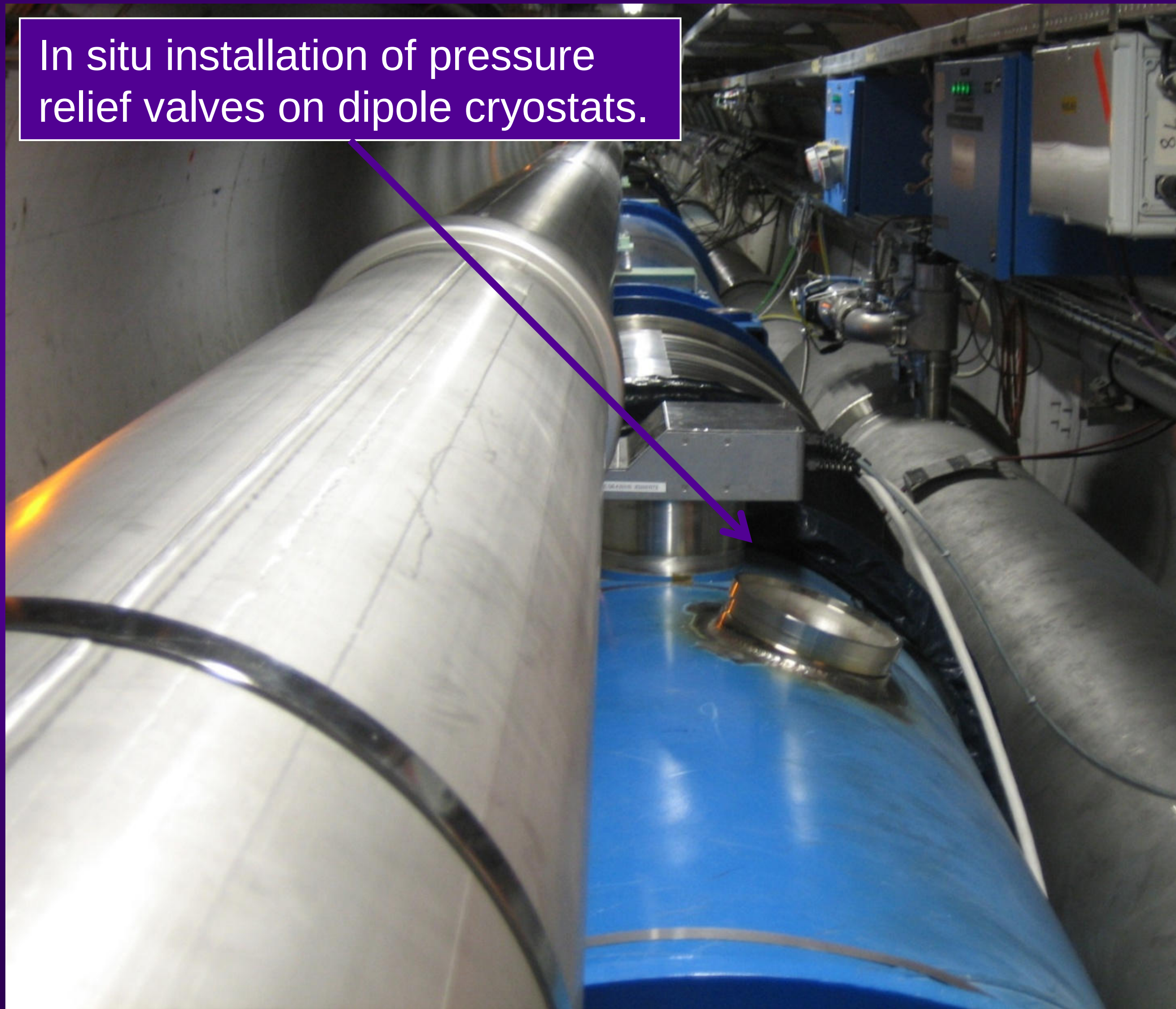
- Majority of magnets remain in place
- Cleaning of sooth with special cleaning head
- Removal of Multi Layer Insulation debris by venting and pumping

Consolidation and improvements

- Major upgrade of the quench protection system
  - Protection of all dipole and quadrupole interconnections
  - Protection against symmetric quenches of the beam1 and beam2 apertures
  - High statistics measurement accuracy to < 1 nOhm
  - Installation of > 200 km of cables, production of thousands of electronic boards.
- Reinforcement of the quadrupole/SSS supports
- Improvement of the pressure relief system to cope with a maximum He flow of 40 kg/s in the arcs (maximum conceivable flow, 2 x incident)
  - Warm sectors: 20 cm diameter relief valves added on every dipole cryostat
  - Cold sectors: all ports equipped with spring relief system
  - Straight sections: relief valves added on cryostats

Pressure relief valves on dipoles

In situ installation of pressure relief valves on dipole cryostats.



LHC run 2009/2010

Planning for 2009 / 2010

- The commissioning of the technical systems should restart in June / July 2009
- Beam commissioning is planned to start in September / October
- If things go well, we intend to operate the LHC at an energy of 5 TeV/beam
- The physics run will start this year, and continue (with a two weeks stop around Christmas) until autumn next year
- This should provide a lot of useful data to the physics experiments

LHC Experiments Desiderata

- 50-100 pb^{-1} of *good* data at $\sqrt{s}$ = 10 TeV.
  - *Many new limits set on hypothetical particles.*
- 200-300 pb^{-1} of *good* data at $\sqrt{s}$ = 10 TeV.
  - *Start competing with Tevatron on Higgs masses ~ 160 GeV/c^2.*
- 1 fb^{-1} of *good* data at $\sqrt{s}$ = 10 TeV.
  - *Higgs discovery possible ~ 160 GeV/c^2.*
- Limit event pile-up (and therefore intensity/bunch).

Outlook

- With (low intensity) beam the LHC is a wonderful machine
  - All key systems were operational
  - Remarkable performance of the beam instrumentation
- The incident in sector 34 revealed a weakness in the protection of the bus-bars and in the pressure relief systems
  - Quench protection system upgrade under way
  - Improvements of the pressure relief system
- Repair is progressing well, re-commissioning of the hardware will start mid-June
- Beam commissioning will resume in September 2009
  - Followed by a 1 year run at 5 TeV
- Do not forget: due to the high stored energy, LHC operation will never be without risk

Acknowledgement

The LHC accelerator is being realised by CERN in collaboration with institutes from many countries over a period of more than 20 years

Main contribution come from the USA, Russia, India, Canada, special contributions from France and Switzerland

Industry plays a major role in the construction of the LHC

Thanks for a lot of material from Jörg Wenninger, as well as slides from others colleagues: R.Assmann, R.Bailey, L.Bottura, E.Ciapala, L.Evans, B.Goddard