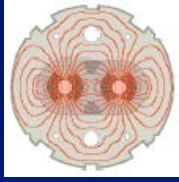


LHC Commissioning and First Operation

The LHC hardware and beam commissioning and initial operation will be reviewed both in terms of beam and hardware performance. The implemented machine protection measures and their impact on LHC operation will be presented

IPAC10, May 2010, Kyoto, Japan

Steve Myers

Director for Accelerators and Technology,

CERN Geneva

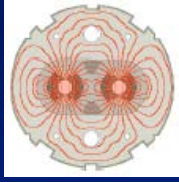
(On behalf of the LHC team and international collaborators)

Topics

- The LHC
- The Accident
- The Repair and consolidation
- Initial Commissioning
- Present status and plans

Superconducting Proton Accelerator and Collider
installed in a 27km circumference underground tunnel (tunnel cross-section diameter 4m) at CERN
Tunnel was built for LEP collider in 1985

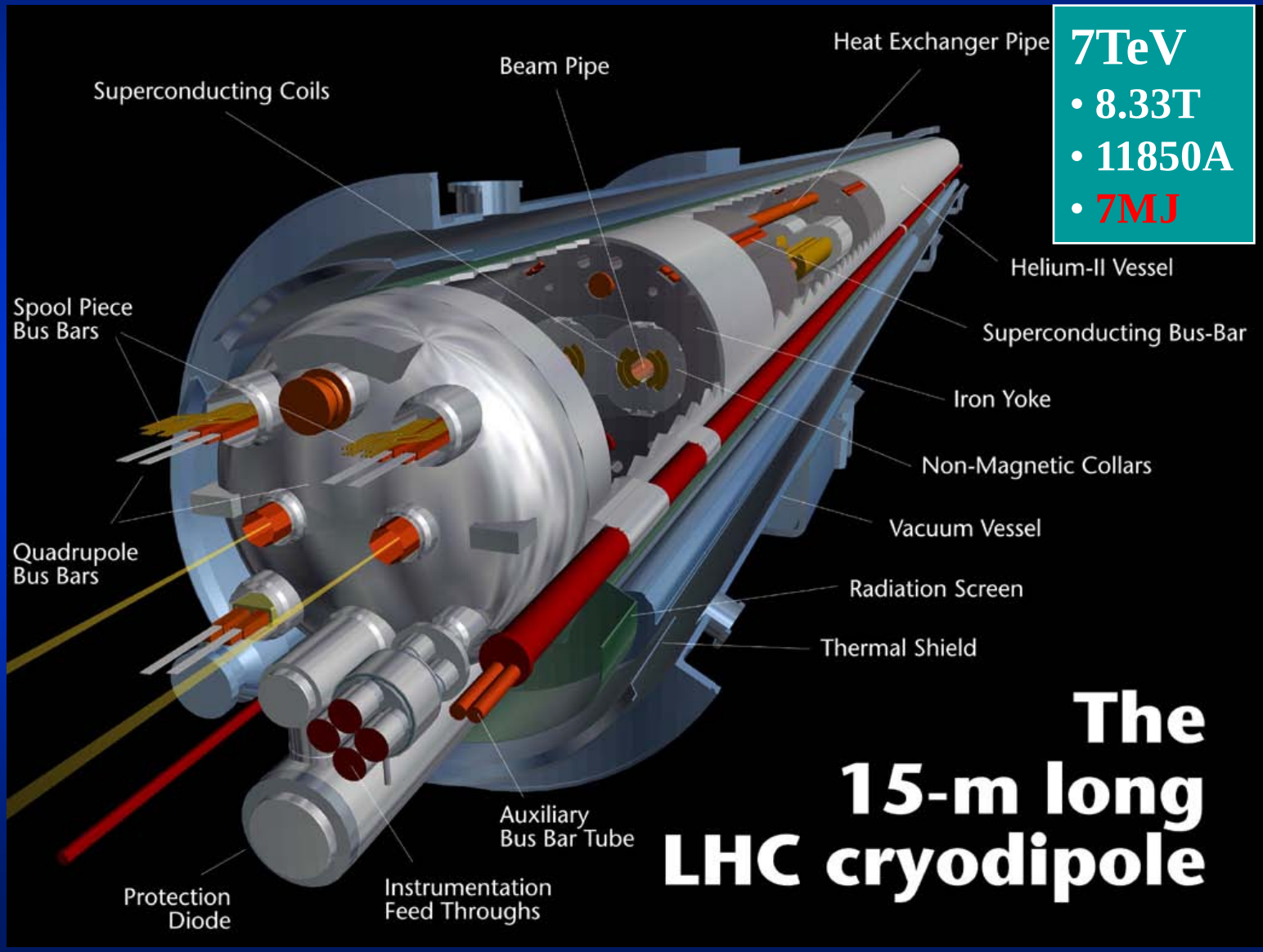
LHC: Some Technical Challenges



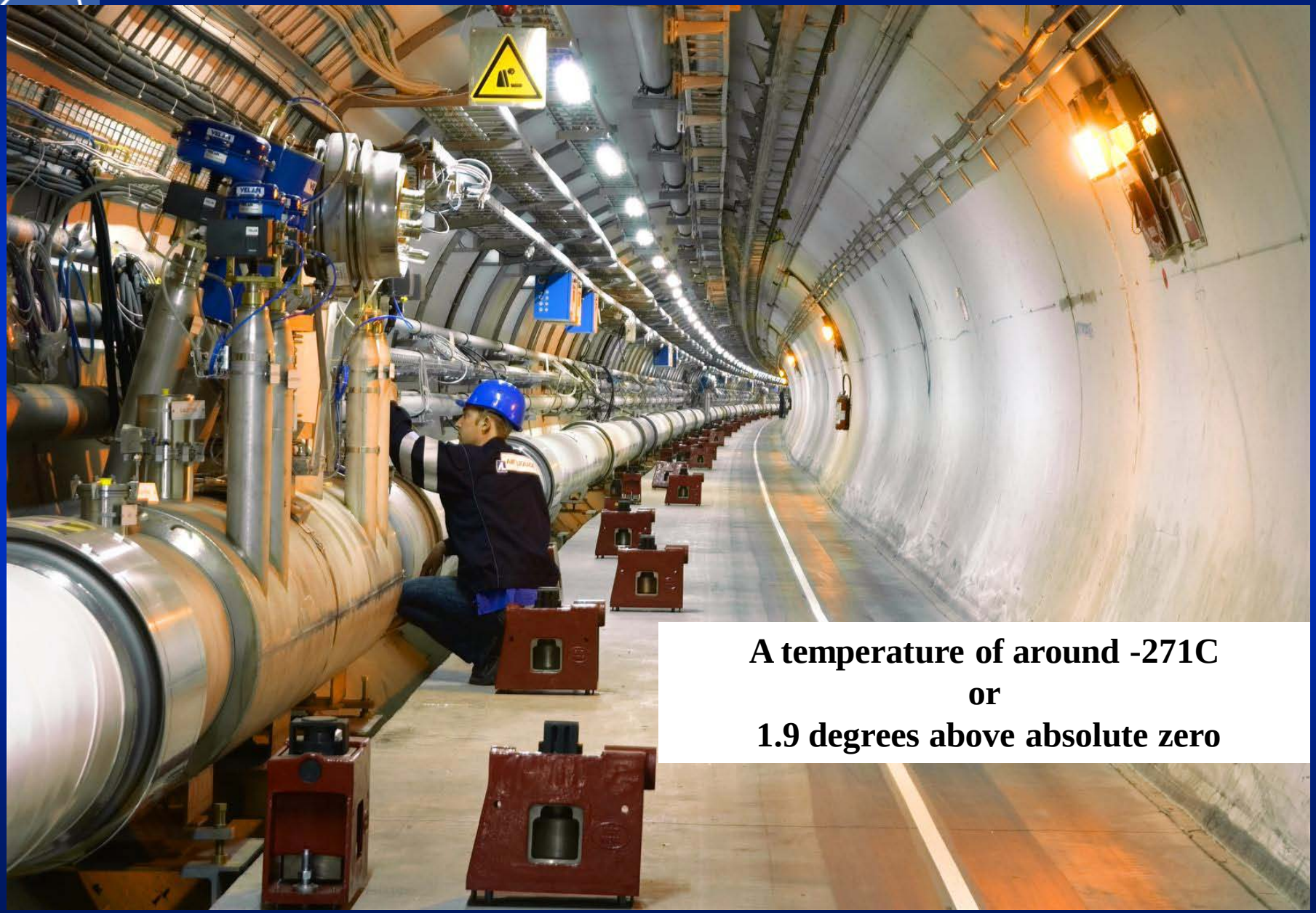
Circumference (km)	26.7	100-150m underground
Number of superconducting twin-bore Dipoles	1232	Cable Nb-Ti, cold mass 37million kg
Length of Dipole (m)	14.3	
Dipole Field Strength (Tesla)	8.4	Results from the high beam energy needed
Operating Temperature (K) (cryogenics system)	1.9	Superconducting magnets needed for the high magnetic field Super-fluid helium
Current in dipole sc coils (A)	13000	Results from the high magnetic field 1ppm resolution
Beam Intensity (A)	0.5	$2.2.10^{-6}$ loss causes quench
Beam Stored Energy (MJoules)	362	Results from high beam energy and high beam current 1MJ melts 1.5kg Cu
Magnet Stored Energy (MJoules)/octant	1100	Results from the high magnetic field
Sector Powering Circuit	8	1612 different electrical circuits

LHC dipoles (1232 of them) operating at 1.9K

Contracts by 4.7cm during cool-down



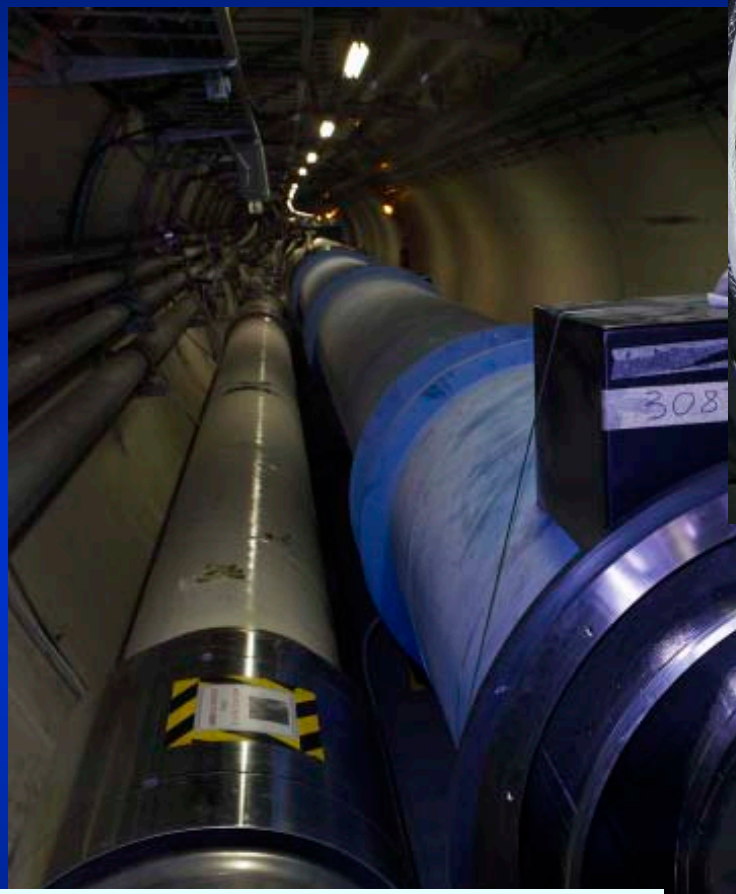
Helium distribution line (THXRA01 Serge Claudet)

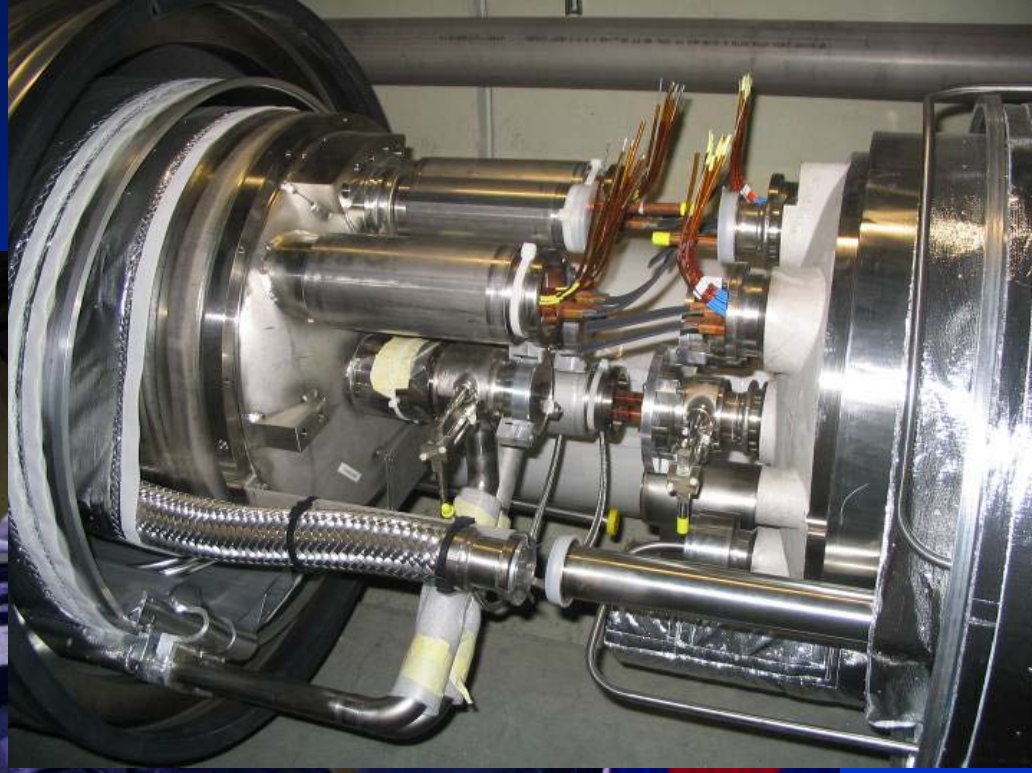


A temperature of around -271C
or
1.9 degrees above absolute zero

Magnets

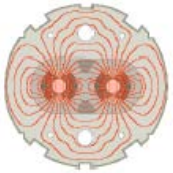
Interconnections





During cool-down of the LHC the machine contracts by 80 metres, 10m per octant

- Vacuum continuity
- Electrical connections



- The LHC
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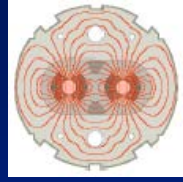
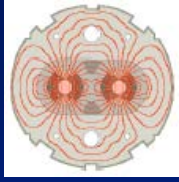
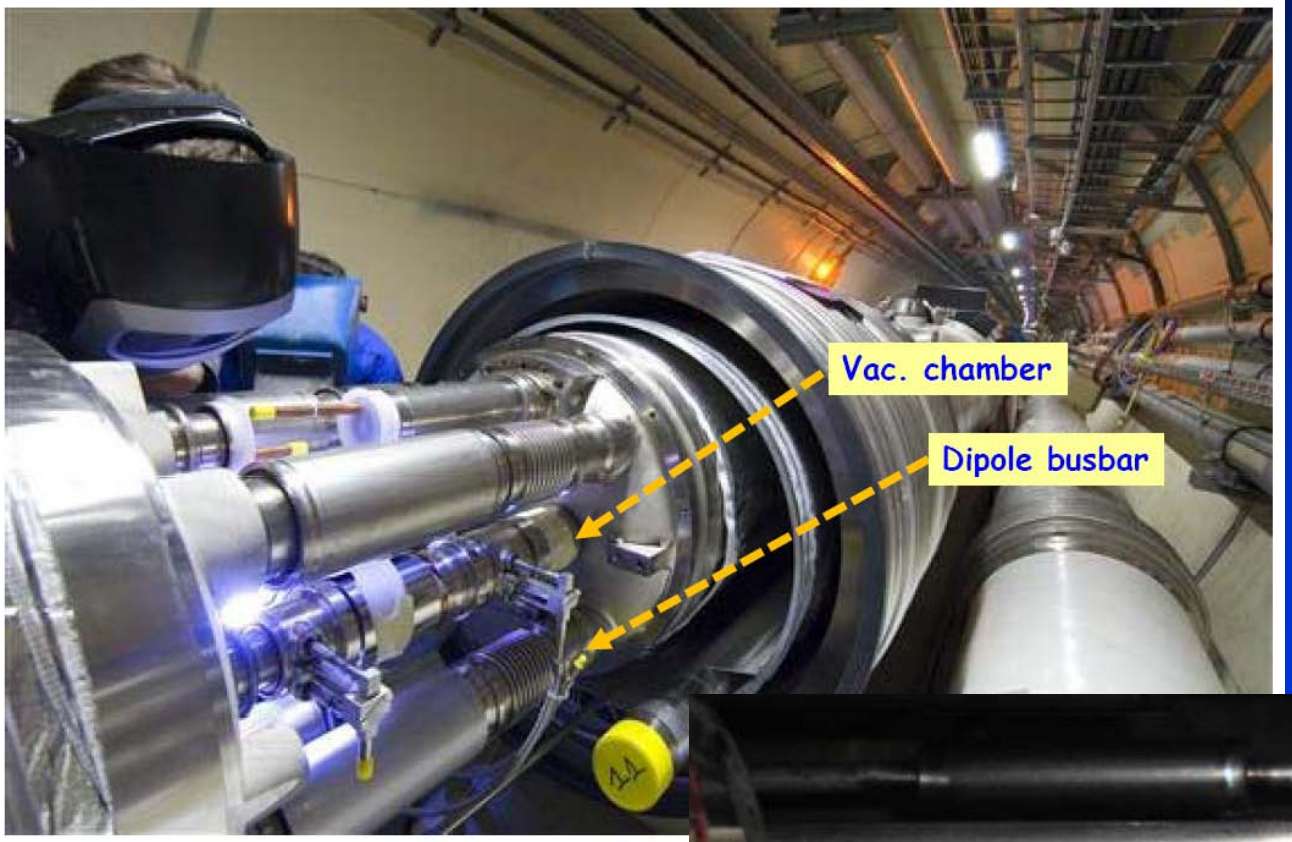
Accident of September 19th 2008

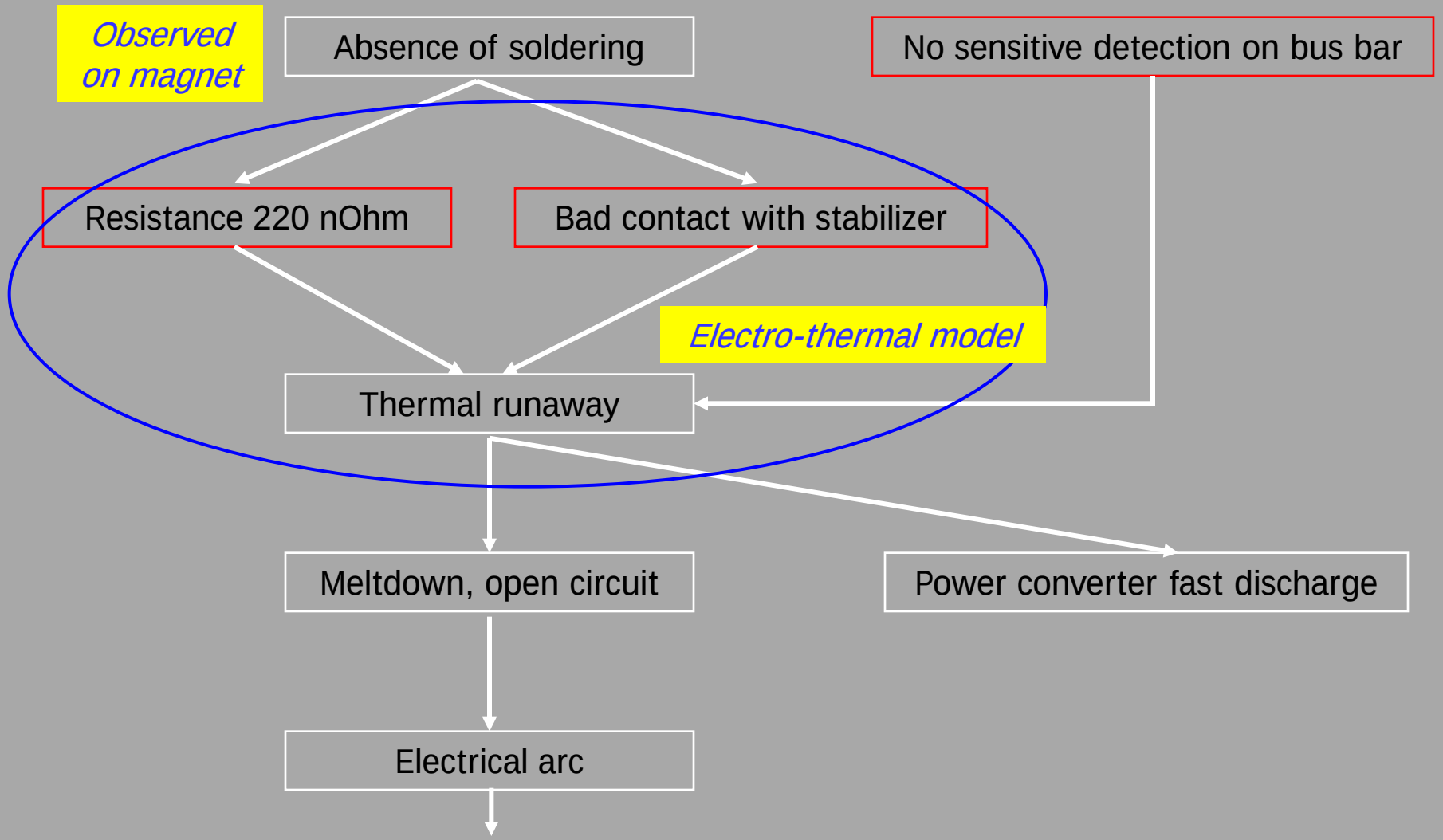


- Following a very impressive start-up with beam on September 10, 2008
  - During a few days period without beam
  - Making the last step of dipole circuit in sector 34, to 9.3kA
  - At 8.7kA, development of resistive zone in the dipole bus bar splice between Q24 R3 and the neighbouring dipole
  - Electrical arc developed which punctured the helium enclosure

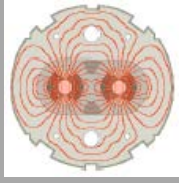


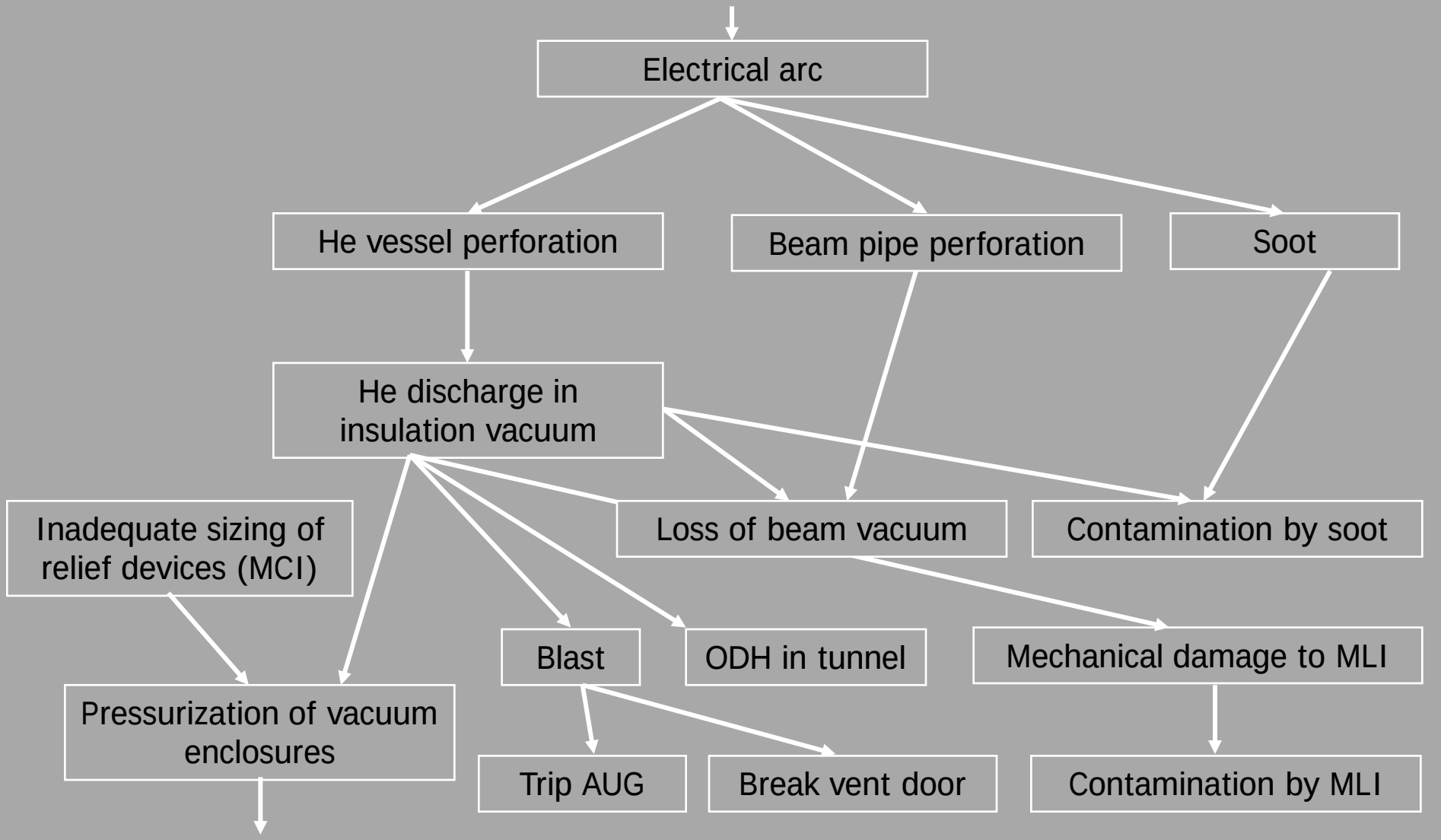

Vac. chamber
Dipole busbar

Fault tree [1/3]

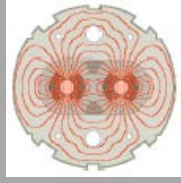


Fault tree [2/3]





Fault tree [3/3]



Pressurization of vacuum enclosures

Pressure forces on vacuum barriers

Plastic deformation of shells

Buckling of bellows

Used to estimate max pressure reached

Rupture of supports and ground anchors

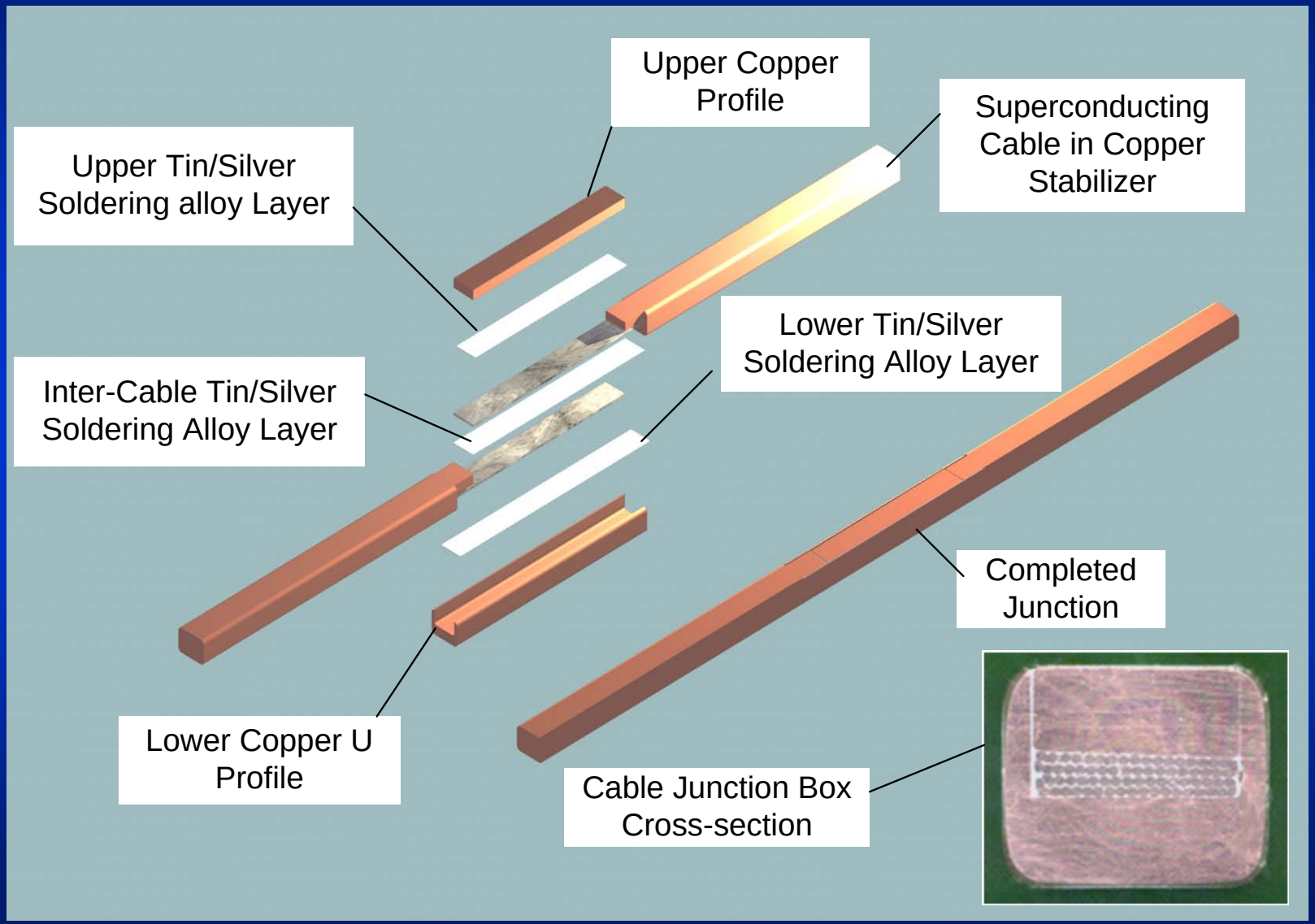
Displacement of magnets

Damage to tunnel floor

Mechanical damage to interconnects

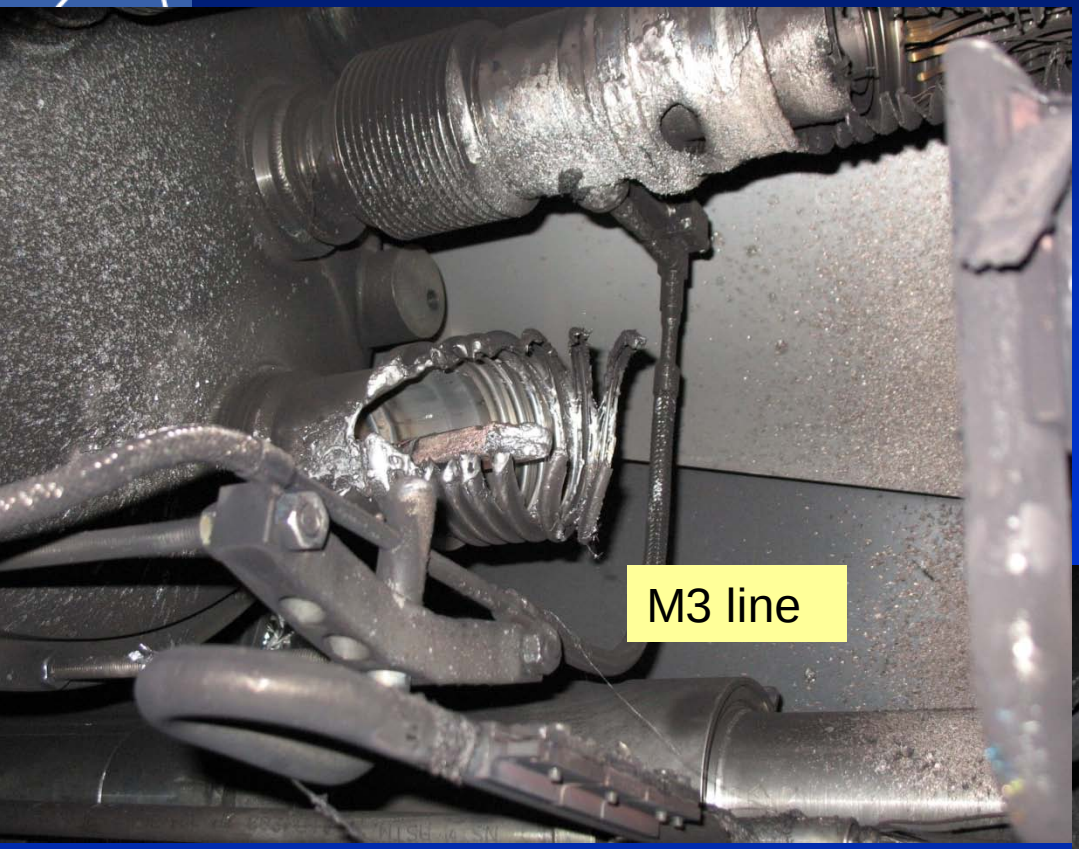
Secondary electrical arcs

Bus bar splice



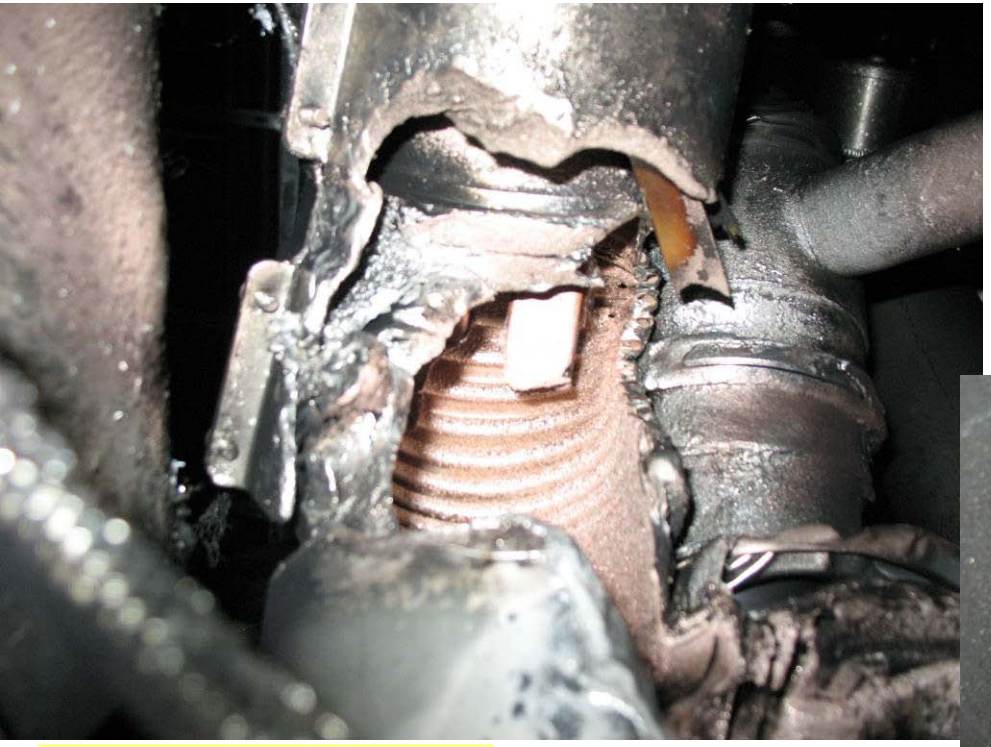
Consequences

Electrical arc between C24 and Q24



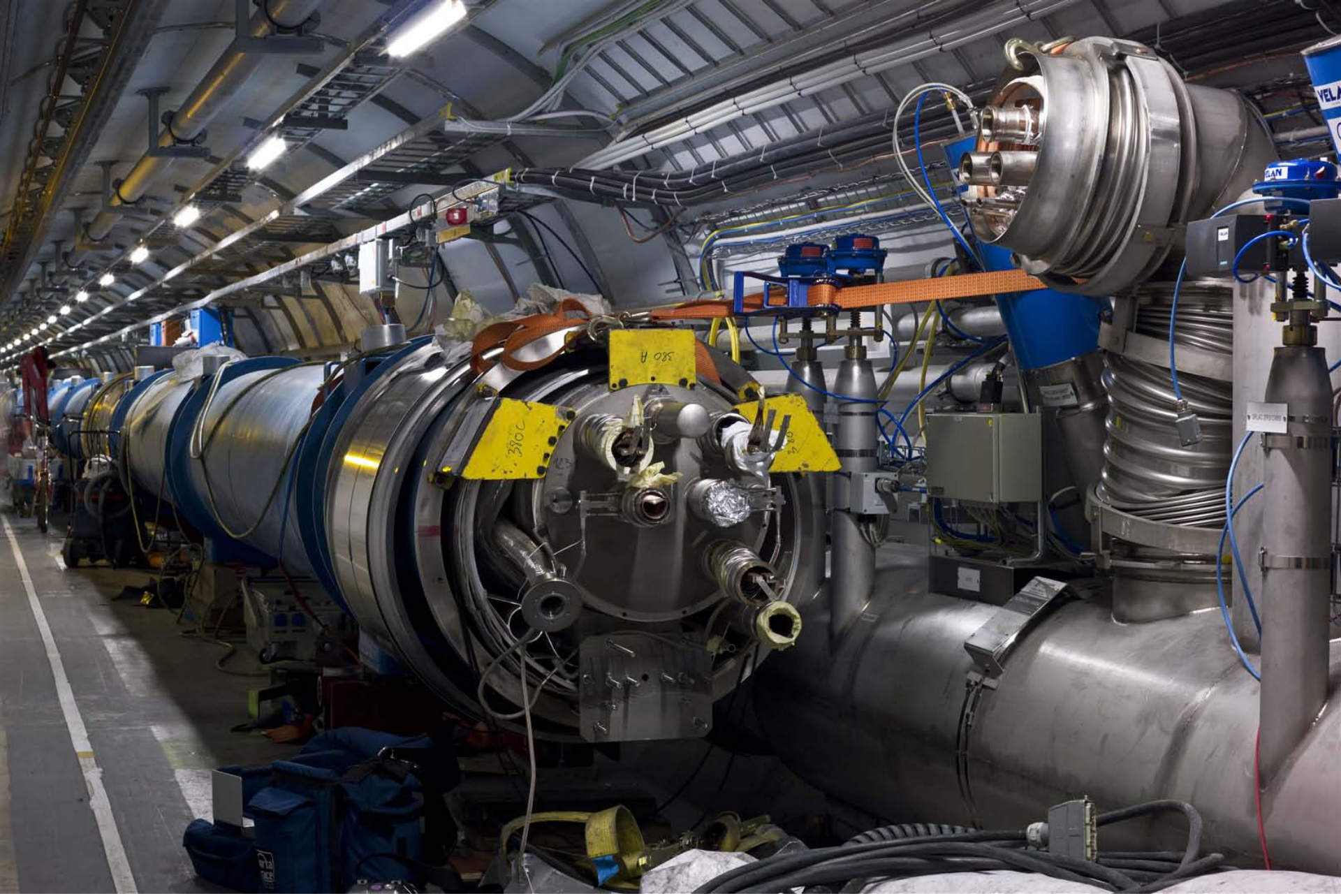
V lines

Collateral damage: secondary arcs



QQBI.27R3 M3 line

QBBI.B31R3 M3 line

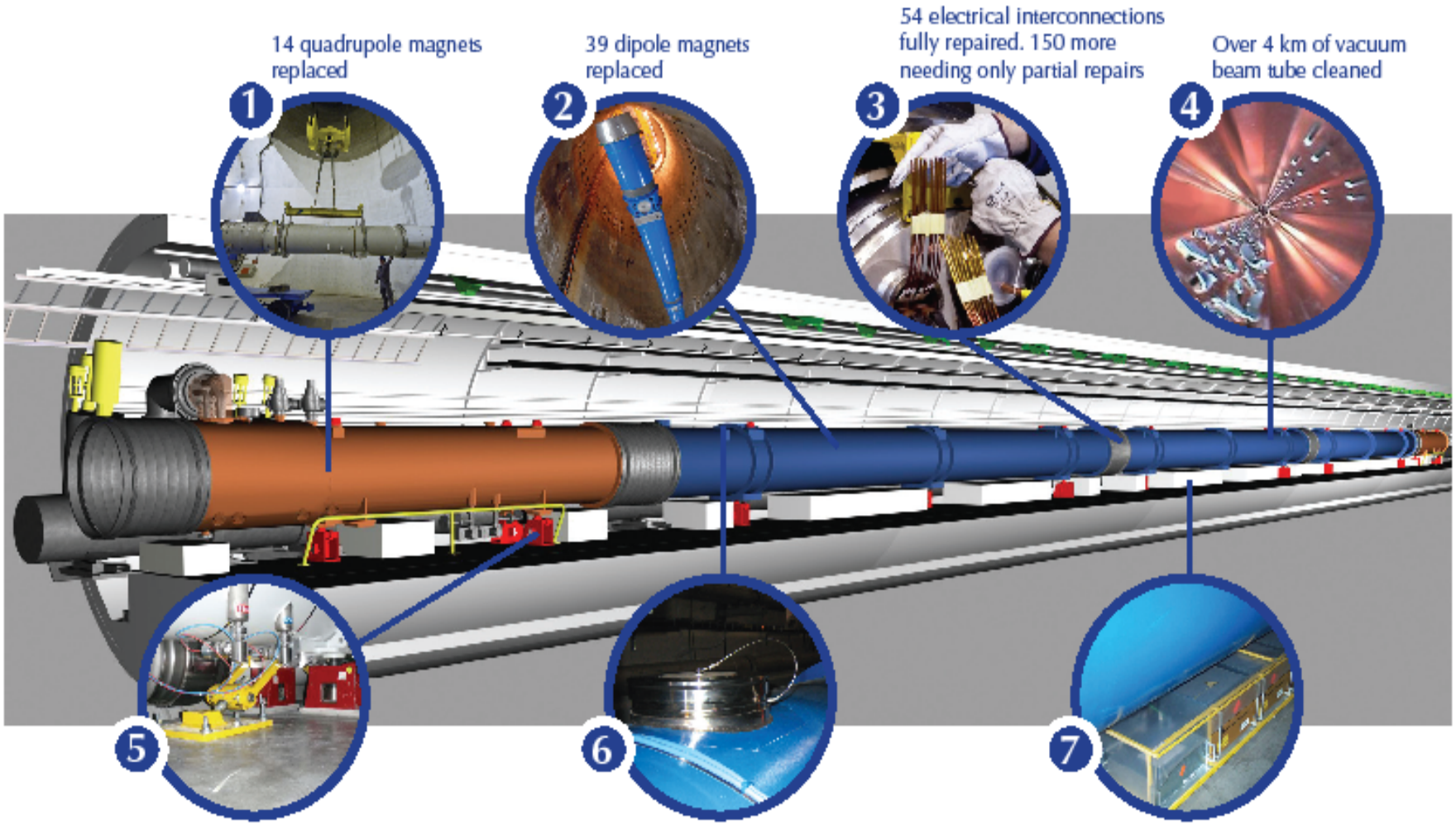


- The LHC
- Initial turn on in Septembe[illegible]08
- [illegible]ccident
- The Repair and consolidation
- Initial Commissioning
- Present status and plans

This was NOT a good time for us!!

Phase 1 +2

The LHC repairs in detail



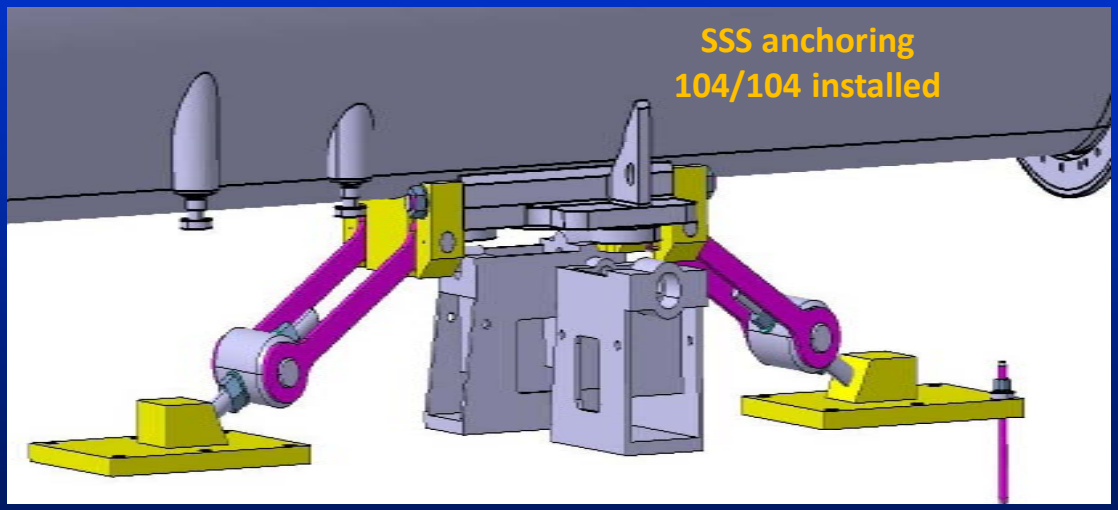
+ 8 cryogenics!

Magnet protection and anchoring

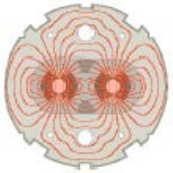
DN200 on dipoles
732/1344 installed

DN200 on ITs
24/24 installed

DN160 on SAM
92/96 installed



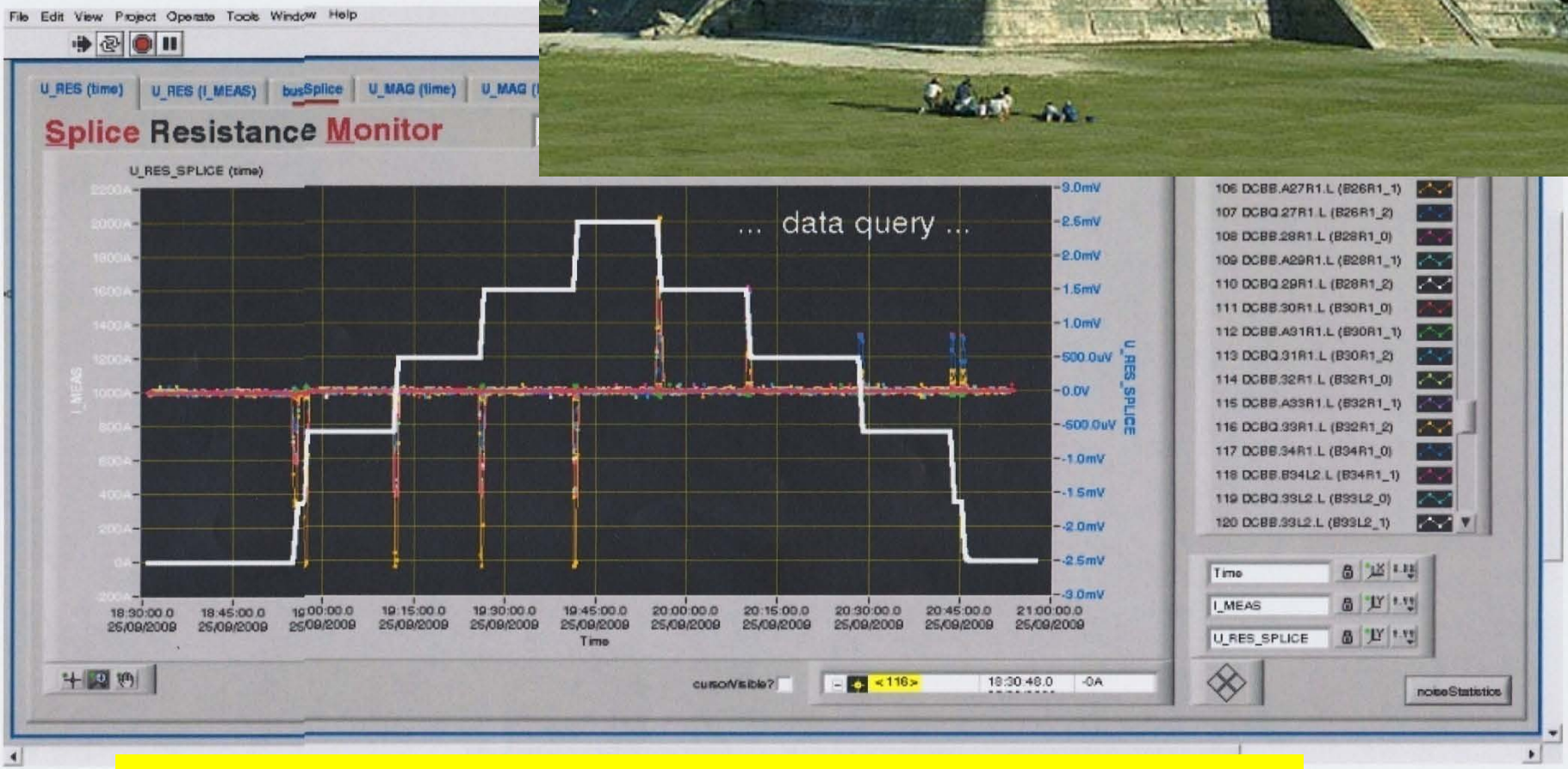
SSS anchoring
104/104 installed



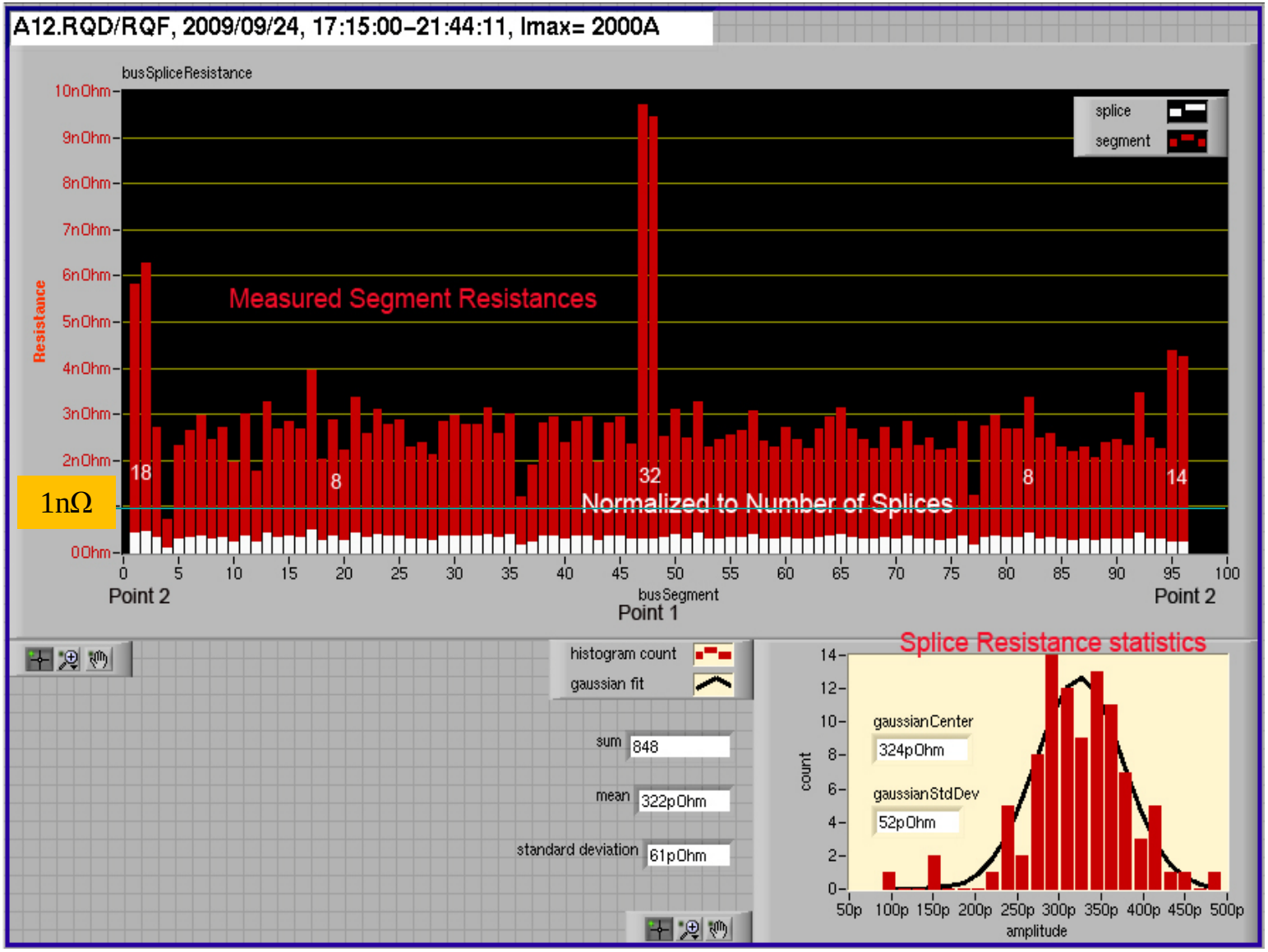
- The LHC
- Initial turn on in September 2008
- The Accident
- The Repair and consolidation
  - Hardware commissioning and preparation for operation
- Initial Commissioning
- Present status and plans

Pyramid for Splice Mapping

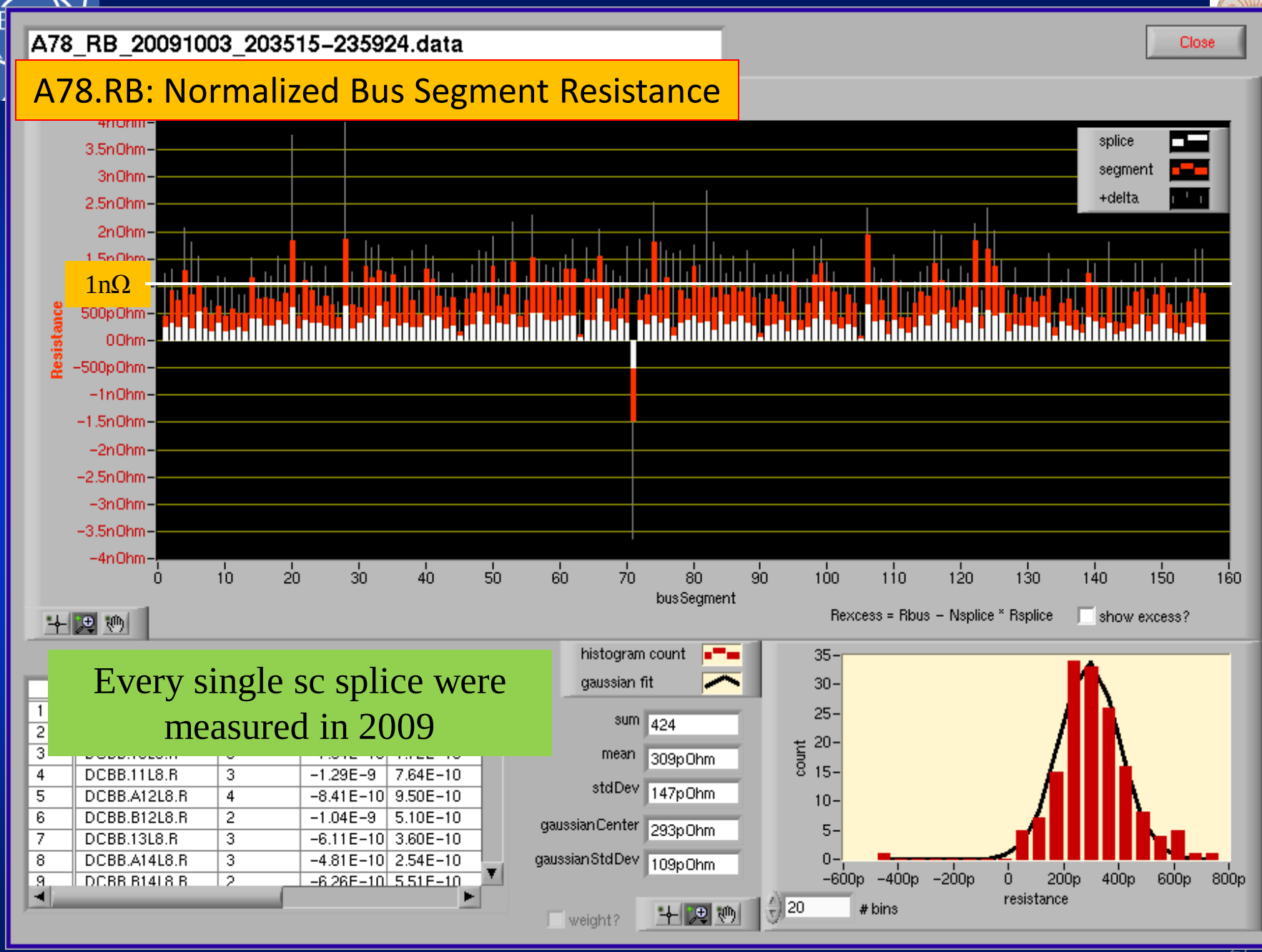
MOPEB044, Koratzinos et al
MOPEB045 Solfaroli et al
MOPEB046 Siemko et al



Current in the Dipoles as function of time


A12.RQD/RQF, 2009/09/24, 17:15:00–21:44:11, Imax= 2000A
busSpliceResistance
splice
segment
Measured Segment Resistances
Resistance
10nOhm
9nOhm
8nOhm
7nOhm
6nOhm
5nOhm
4nOhm
3nOhm
2nOhm
1nΩ
0Ohm
18
8
32
8
14
Normalized to Number of Splices
busSegment
Point 2
Point 1
Point 2
histogram count
gaussian fit
sum 848
mean 322pOhm
standard deviation 61pOhm
Splice Resistance statistics
gaussianCenter
324pOhm
gaussianStdDev
52pOhm
count
amplitude

A78.RB: Normalized Bus Segment Resistance



Every single sc splice were measured in 2009

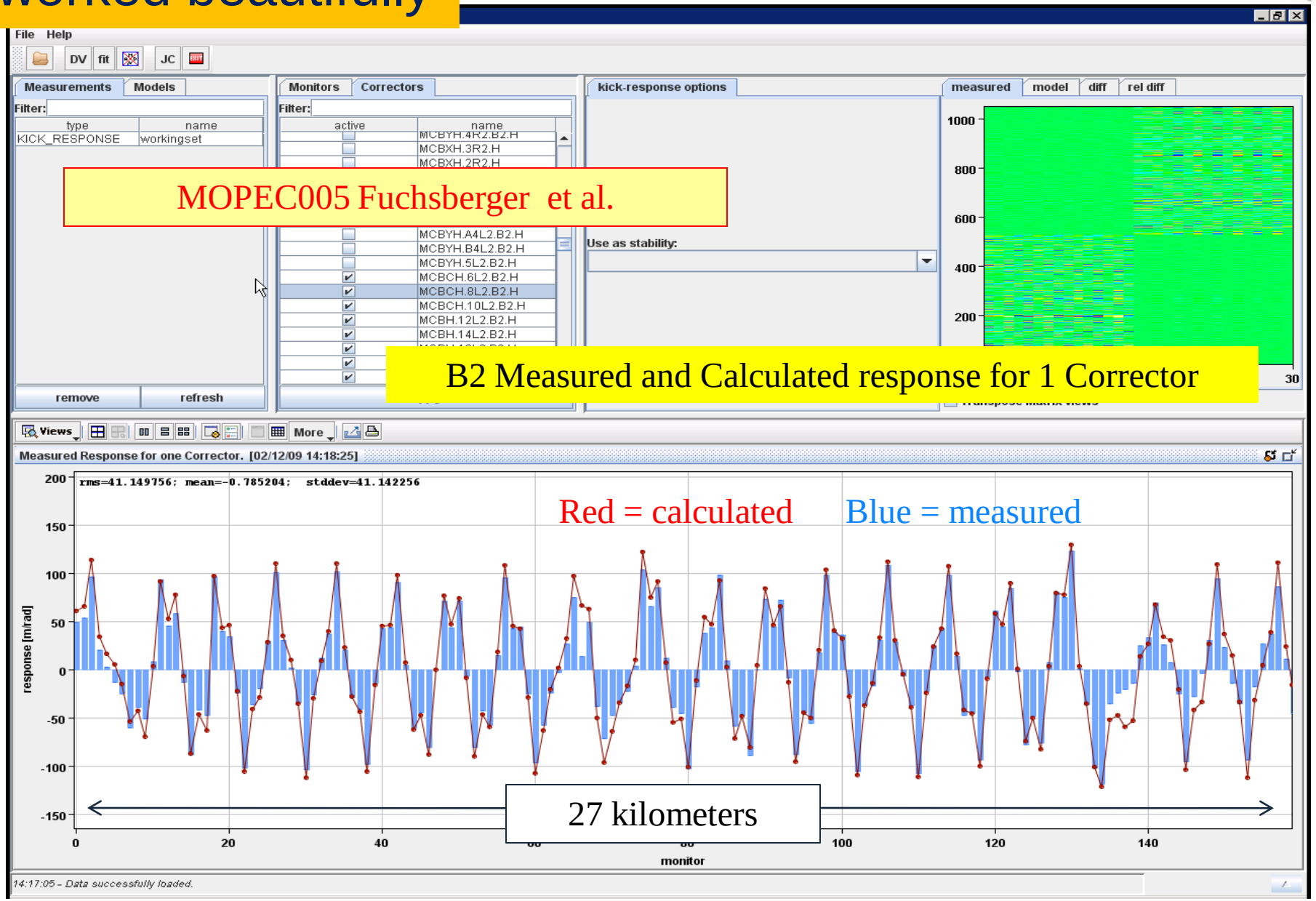
4	DCBB.11L8.R	3	-1.29E-9	7.64E-10
5	DCBB.A12L8.R	4	-8.41E-10	9.50E-10
6	DCBB.B12L8.R	2	-1.04E-9	5.10E-10
7	DCBB.13L8.R	3	-6.11E-10	3.60E-10
8	DCBB.A14L8.R	3	-4.81E-10	2.54E-10
9	DCBB.B14L8.R	2	-6.26E-10	5.51E-10

Milestones before Christmas 2009

Date	Day	Achieved
Nov 20	1	Each beam circulating. Key beam instrumentation working.
Nov 23	4	First collisions at 450 GeV. First ramp (reached 560 GeV).
Nov 26	7	Magnetic cycling established (reproducibility).
Nov 27	8	Energy matching.
Nov 29	10	Ramp to 1.18 TeV.
Nov 30	11	Experiment solenoids on.
Dec 04	15	Aperture measurement campaign finished. LHCb and ALICE dipoles on.
Dec 05	16	Machine protection (Injection, Beam dump, Collimators) ready for safe operation with pilots.
Dec 06	17	First collisions with STABLE BEAMS, 4 on 4 pilots at 450 GeV, rates around 1Hz.
Dec 08	19	Ramp colliding bunches to 1.18 TeV
Dec 11	22	Collisions with STABLE BEAMS, 4 on 4 at 450 GeV, > 10^{10} per bunch, rates around 10Hz.
Dec 13	24	Ramp 2 bunches per beam to 1.18 TeV. Collisions for 90mins.
Dec 14	25	Collisions with STABLE BEAMS, 16 on 16 at 450 GeV, > 10^{10} per bunch, rates around 50Hz.
Dec 16	27	Ramp 4 on 4 to 1.18 TeV. Squeeze to 7 m.

All systems worked beautifully

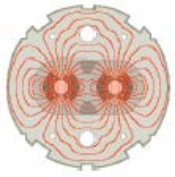
Optics Checks (2nd Dec)



MOPEC005 Fuchsberger et al.

B2 Measured and Calculated response for 1 Corrector

Why are we limiting the beam energy to 3.5TeV in 2010-2011?

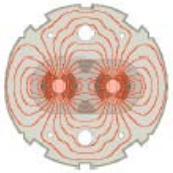


All the work we have done since November 2008 makes us certain that a repeat of September 19 can NEVER happen.

The offending connector in this incident had an estimated resistance of 220nΩ. We have measured all 10,000 inter-magnet connectors and the maximum resistance we have seen is 2.8nΩ.

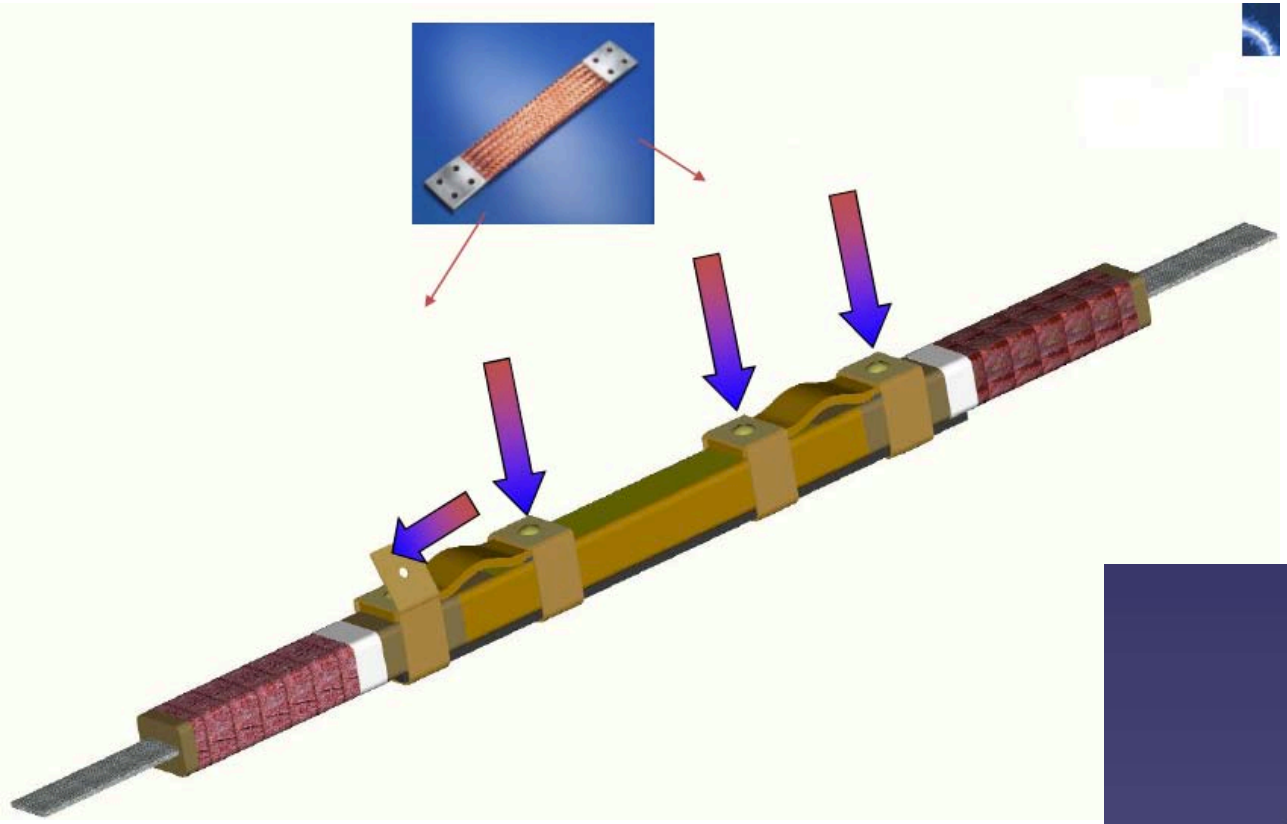
BUT in April 2009, we have uncovered a different possible failure scenario which could under certain circumstances produce an electric arc in the “copper stabilizers” of the magnet interconnects

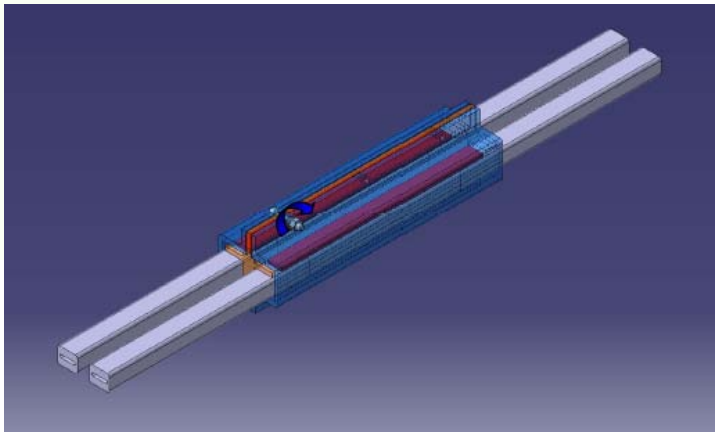
Decided Scenario 2010-2011



- Run at 3.5 TeV/beam up to a integrated luminosity of around $1fb^{-1}$.
- Then consolidate the whole machine for 7TeV/beam (during a shutdown in 2012)
- From 2013 onwards LHC will be capable of maximum energies and luminosities

Clamped and shunted

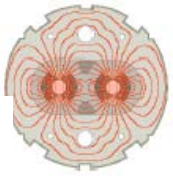




MOPEB042 Bertinelli et al.

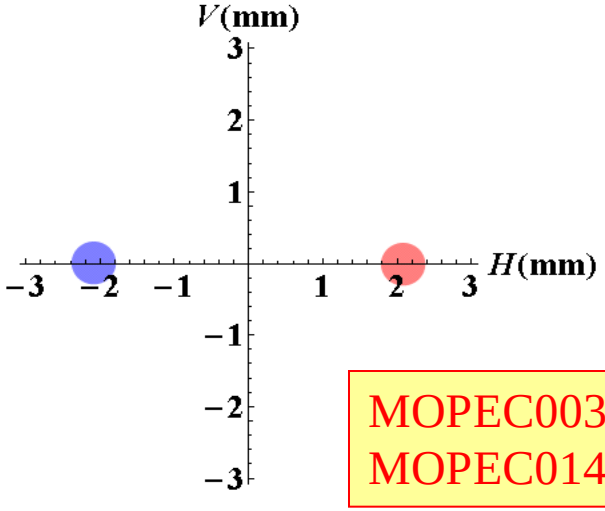
First Collisions at 7TeV cm March 30, 2010

Media foresaw this at 09:17 precise!!



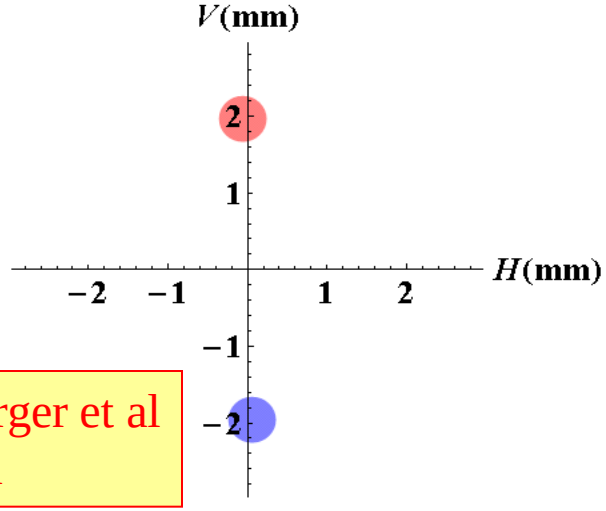
ATLAS IP Separation

H = 4.173 mm : V = 0.035 mm



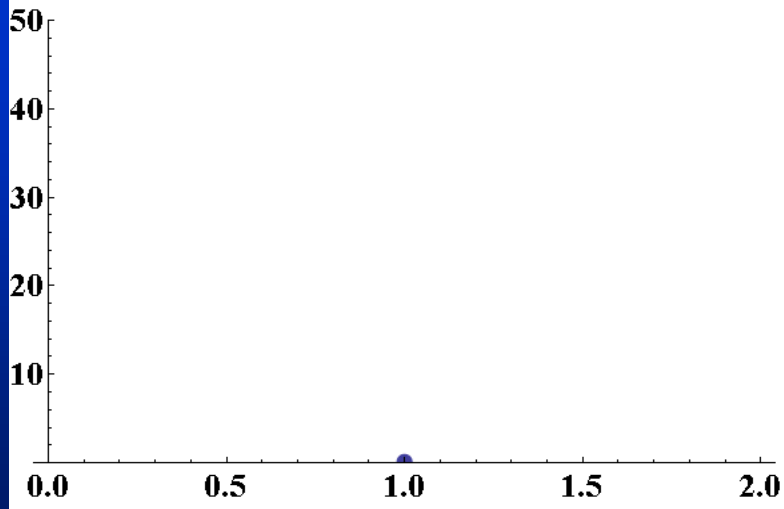
CMS IP Separation

H = 0.130 mm : V = 3.925 mm

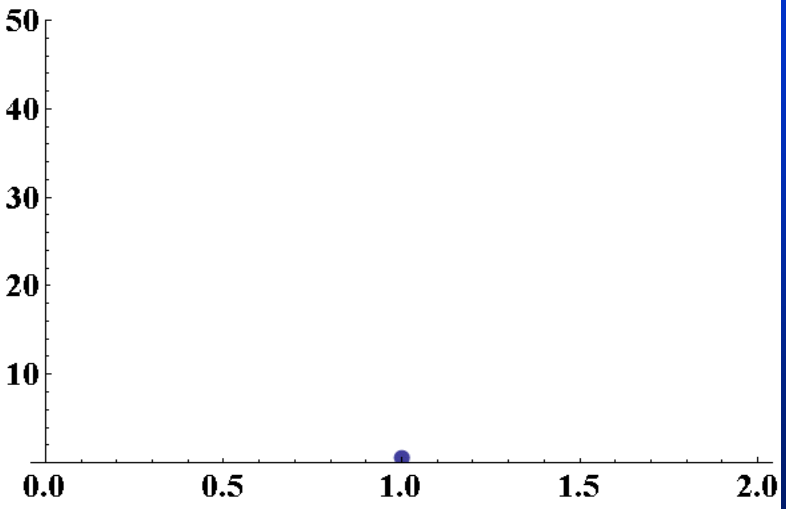


MOPEC003/4 Fuchsberger et al
MOPEC014 White et al

ATLAS Coll Rate Evol



CMS Coll Rate Evol



30/3/2010

11:15 injected again
12:38 : At 3.5 TeV

OP Vistars - Mozilla Firefox

File Edit View History Bookmarks Tools Help

http://op-webtools.web.cern.ch/op-webtools/vistar/vistars.php?usr=LHC1

Most Visited | Scientific Linux CERN | CERN IT Departme... | CERN Home Page | Linux distributions

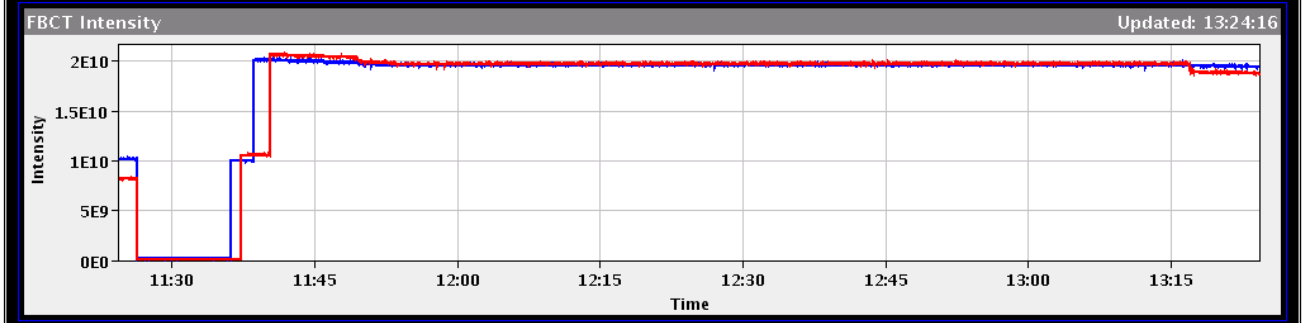
CERN - AB - OP eLogbook - Vi... | CERN - AB - OP eLogbook - Vi... | CERN - AB - OP eLogbook - Vi... | CERN - AB - OP eLogbook - Vi... | OP Vistars

LHC1 — OP Vistars

LHC Page1 | Fill: 1005 | E: 3500 GeV | 30-03-2010 13:24:16

PROTON PHYSICS: STABLE BEAMS

Energy:	3500 GeV	I(B1):	1.88e+10	I(B2):	1.68e+10



Comments 30-03-2010 13:22:57 :

Stable beams!

BIS status and SMP flags	B1	B2
Link Status of Beam Permits	true	true
Global Beam Permit	true	true
Setup Beam	true	true
Beam Presence	true	true
Moveable Devices Allowed In	true	true
Stable Beams	true	true

LHC Operation in CCC : 77600, 70480 | PM Status B1 ENABLED | PM Status B2 ENABLED

Done

Since the first Collisions

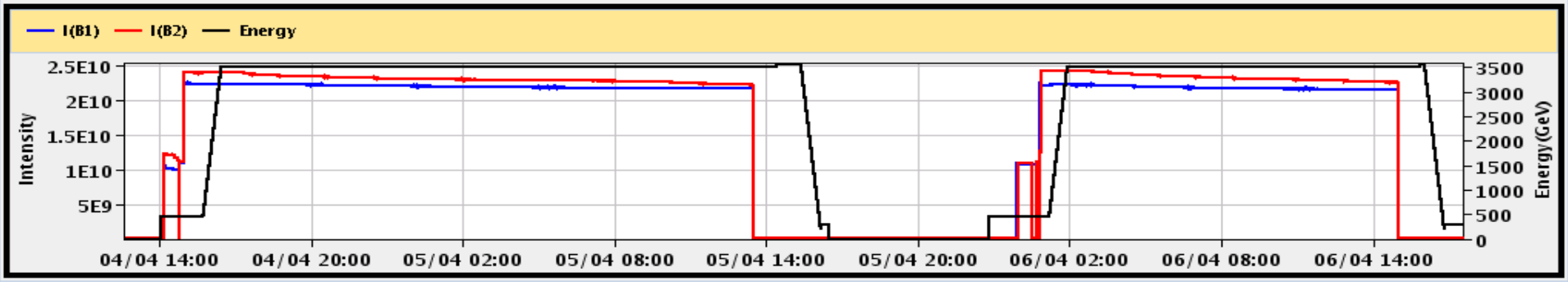
A very good 48 hour period!

06-Apr-2010 17:27:13 Fill #: 1023 Energy: 297.4 GeV I(B1): 1.55e+08 I(B2): 7.01e+07

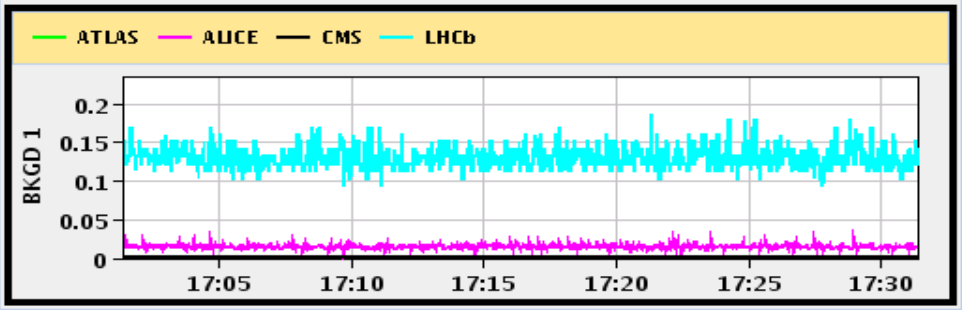
	ATLAS	ALICE	CMS	LHCb
Experiment Status	STANDBY	NOT READY	STANDBY	STANDBY
Instantaneous Luminosity	0.000e+00	0.000e+00	0.000e+00	8.989e-04
BRAN Count Rate	3.229e-07	4.059e-32	2.086e-11	1.635e-32
BKGD 1	0.002	0.014	0.002	0.131
BKGD 2	0.000	0.000	0.002	0.002
BKGD 3	0.000	0.005	0.003	0.037

LHCf STANDBY Count(Hz): 0.000 | LHCb VELO Position OUT Gap: 58.0 mm | TOTEM: CALIBRATION

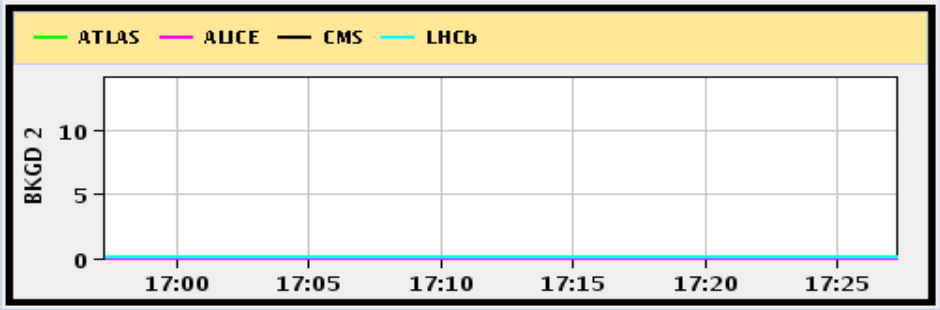
Performance over the last 12 Hrs



Background 1



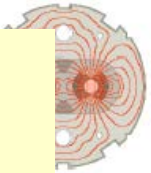
Background 2



Fill 1022

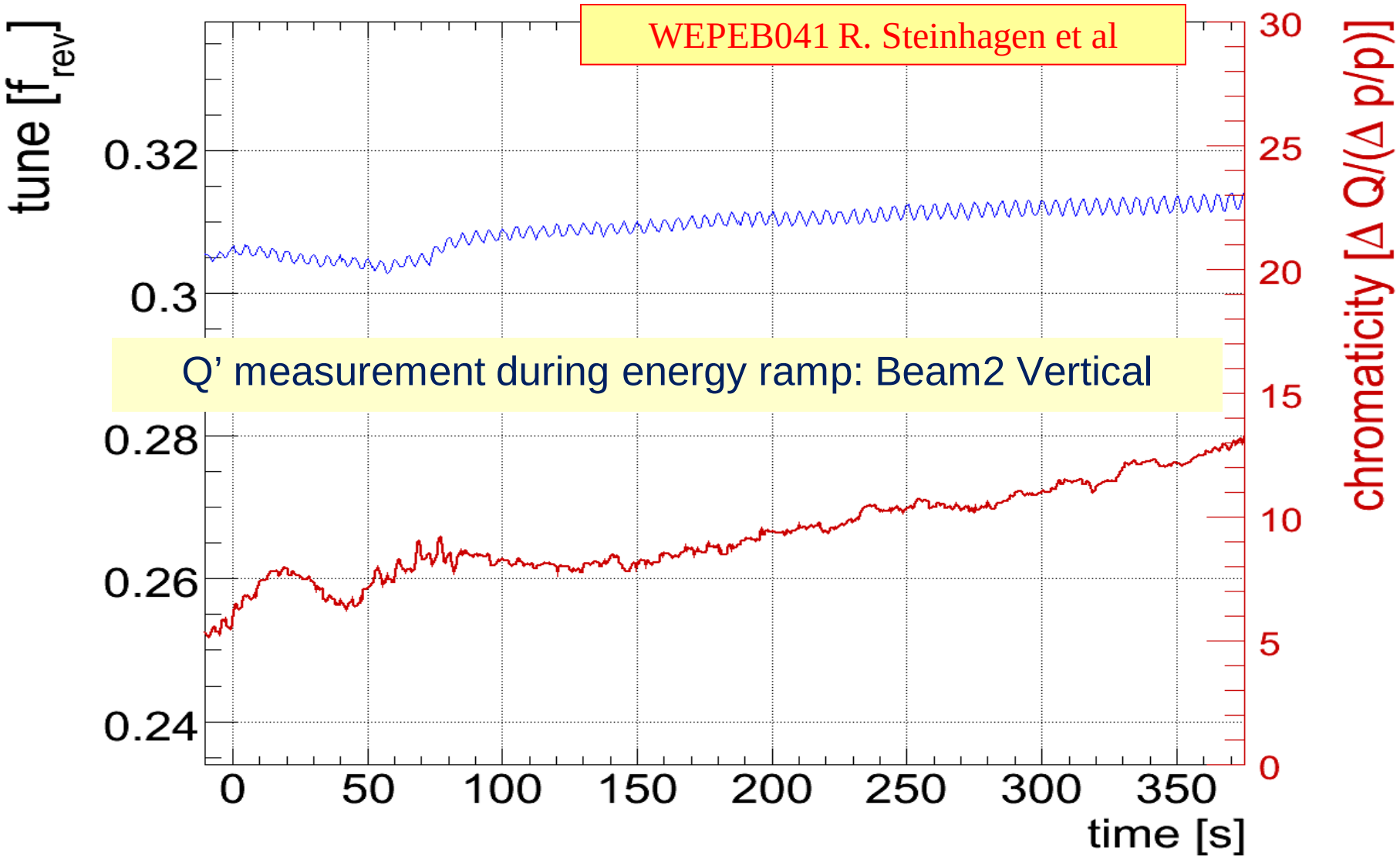
- Single beam lifetimes:
  - Beam 1: 990 hours
  - Beam 2: 730 hours
  - Very good beam-gas, negligible luminosity burn, negligible diffusion
- Luminosity lifetime
  - 40 – 50 hours
  - Mainly from gentle beam blow-up (tau ~ 40 hours for B2V)
  - Beam tune shift ~ 0.0015 (one plane, 2 real collision points, reduced emittances)

Magnetic model MOOCRA01 Todesco et al



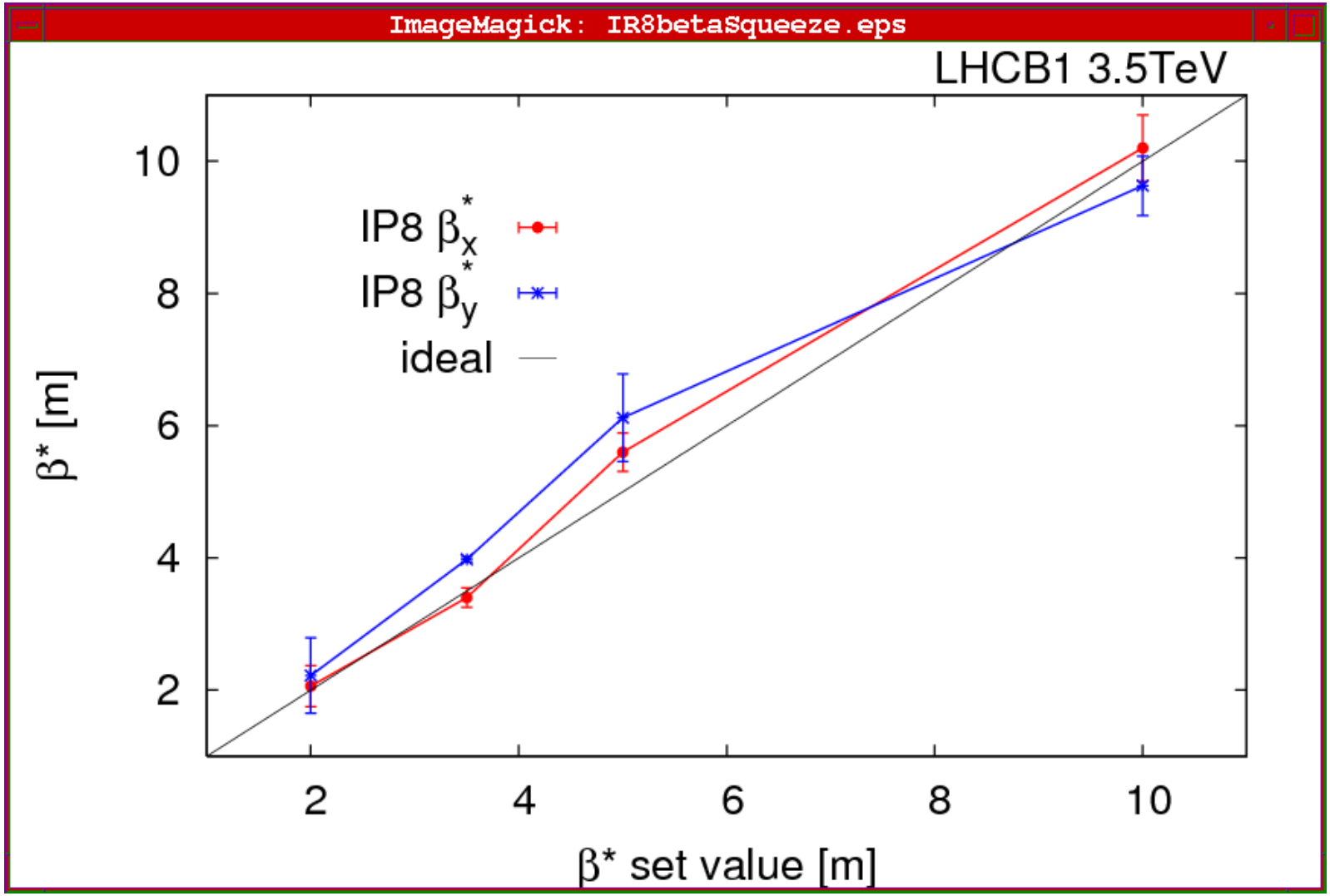
- The knowledge of the magnetic model of the LHC is remarkable and has been one of the key elements of a very smooth beam commissioning
- Tunes, energy matching, optics remarkably close to the model already
- Bodes very well for the future.

Tuesday 13.4.


WEPEB041 R. Steinhagen et al
Q' measurement during energy ramp: Beam2 Vertical
tune [f_rev]
0.32
0.3
0.28
0.26
0.24
0
50
100
150
200
250
300
350
time [s]
30
25
20
15
10
5
0
chromaticity [Δ Q/(Δ p/p)]

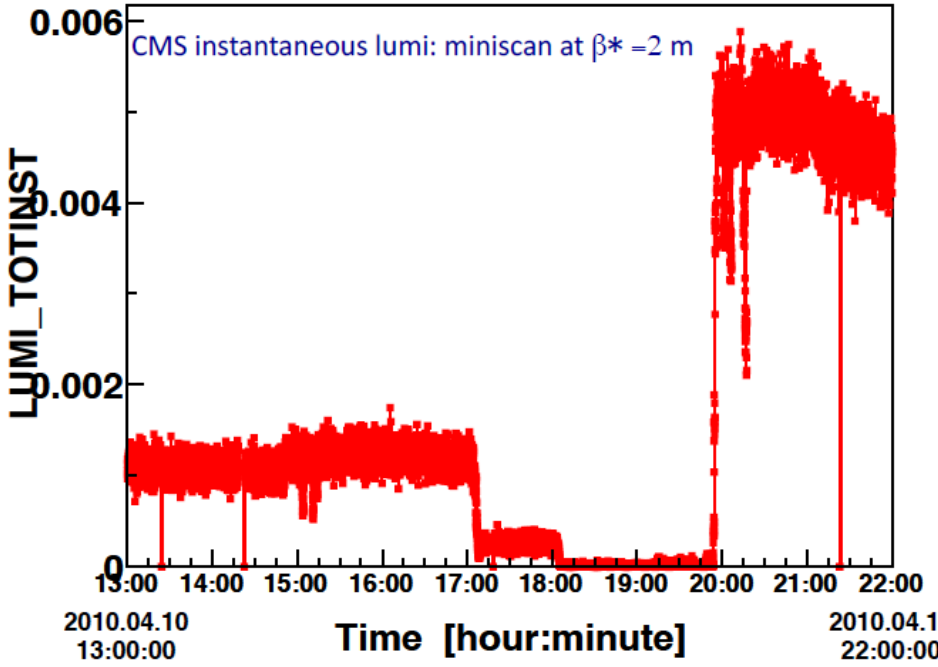
Tuesday 13.4.

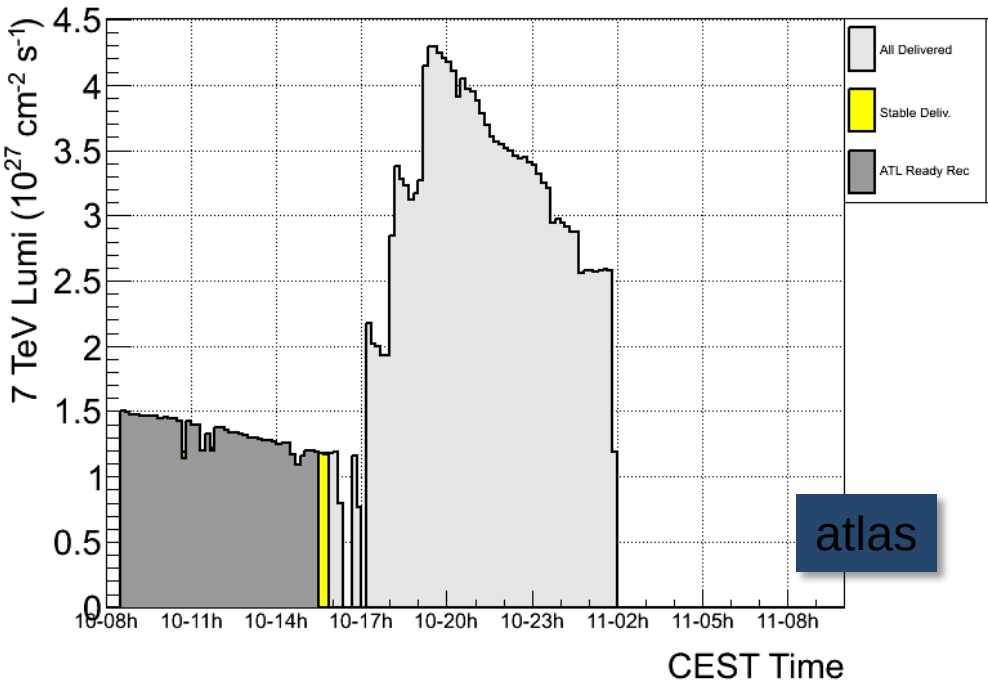
- β^* during squeeze to β^* = 2m in IR8:



IP1&5 lumi vs squeeze

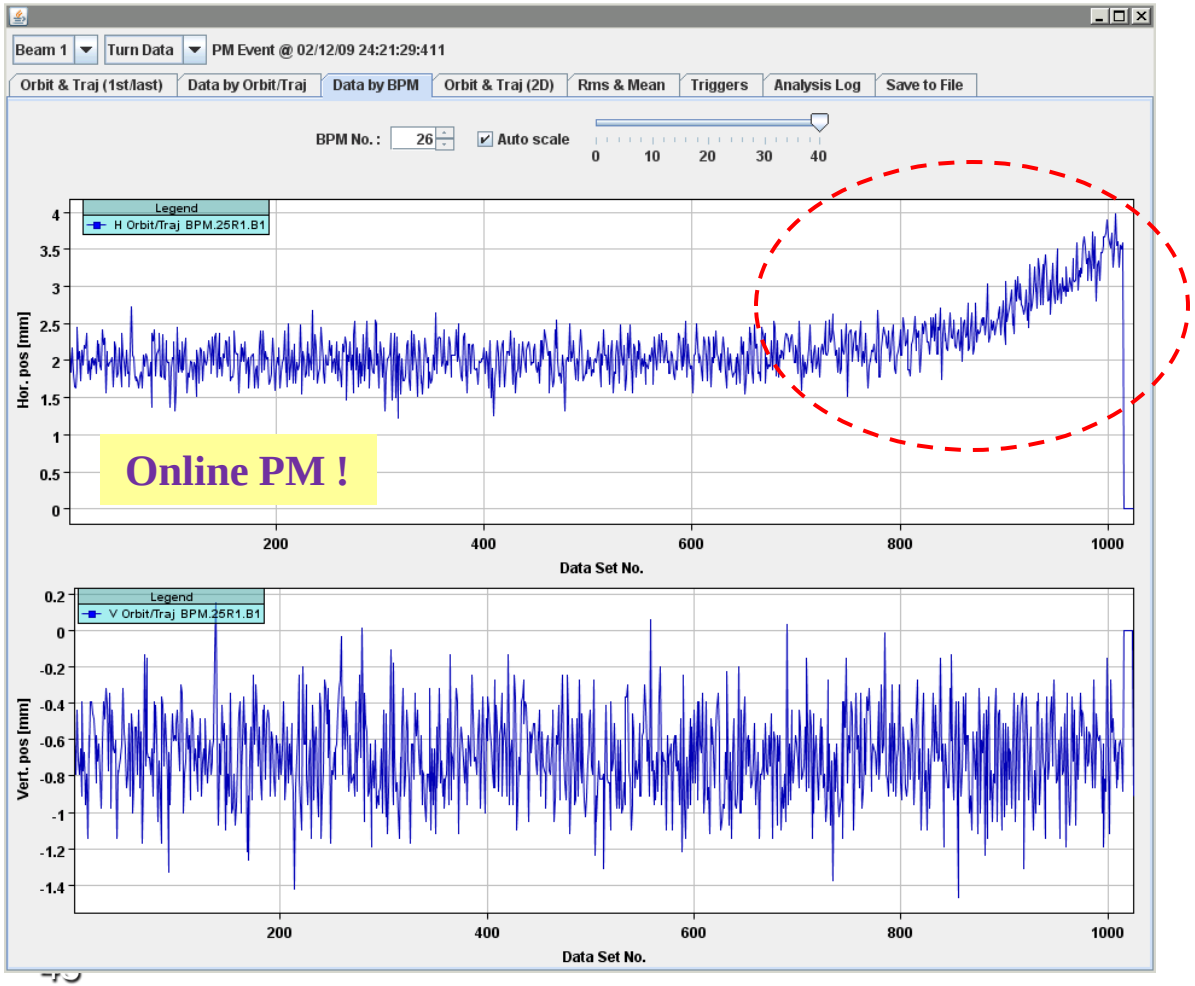
- Raw (online) lumi plots on 10 apr 2010, during the squeeze to 2m in IP1 and IP5
- Factor gained (raw numbers):
  - ~4.5 in Pt5 (after min scan)
  - ~4 in Pt1
- Not corrected for lumi decay over the ~5h of squeeze and mini scans





FMCM Beam Tests for D1 IR1/5

- Low intensity beam test.
- Trajectory evolution after OFF send to RD1.LR1, with FMCM masked.
- Beam dumped by BLMs in IR7.

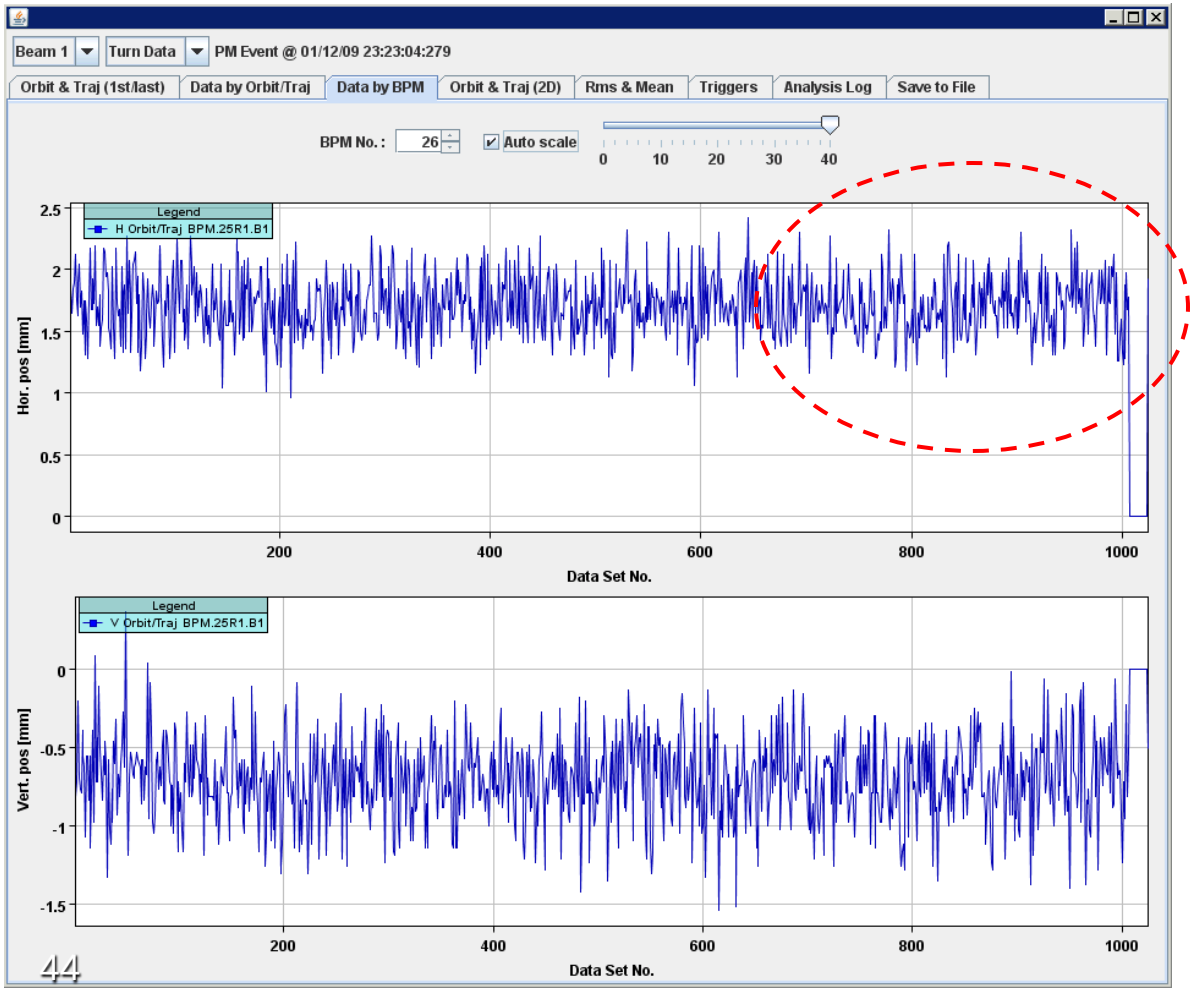


- Trajectory over 1000 turns at a BPM.
- Position change of ~1.5 mm over last 250 turns.

TUOCMH03 Schmidt and Wenninger

FMCM beam tests

- Low intensity beam test.
- Trajectory evolution after OFF send to RD1.LR1, with FMCM active.
- Beam dumped by FMCM.



- Trajectory over 1000 turns at a the same BPM.
- No position change visible within resolution.

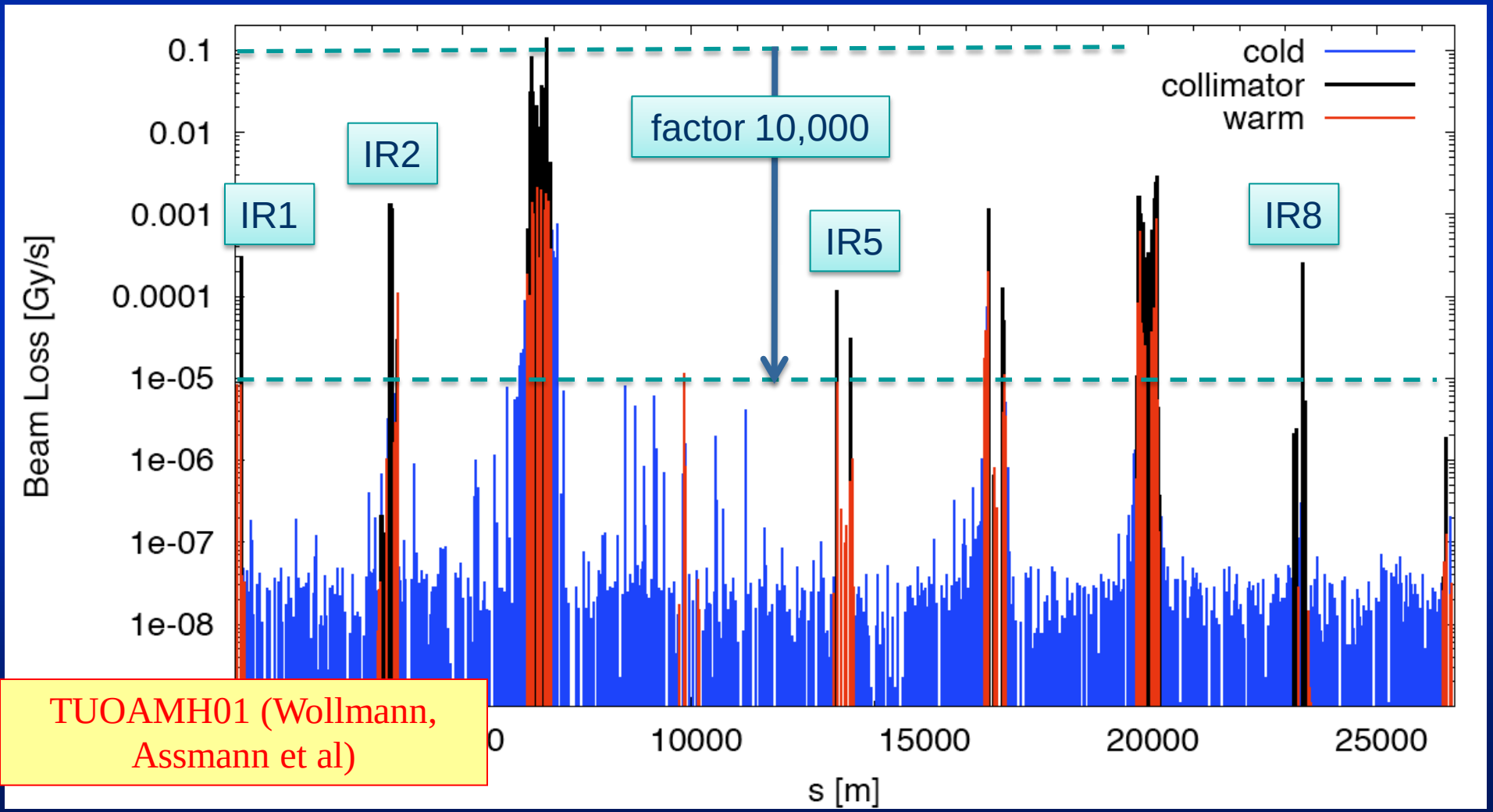
>> The redundant protection is working

LHC Design Bunch Intensity: Thursday 15.4.2010

- Higher intensity
  - Over-injection working well
  - Over-injected 1.1E11, with collimators at nominal 4.5 sigma settings.
  - Emittance at 1E11: 2.5 um H, 2,3 um V.

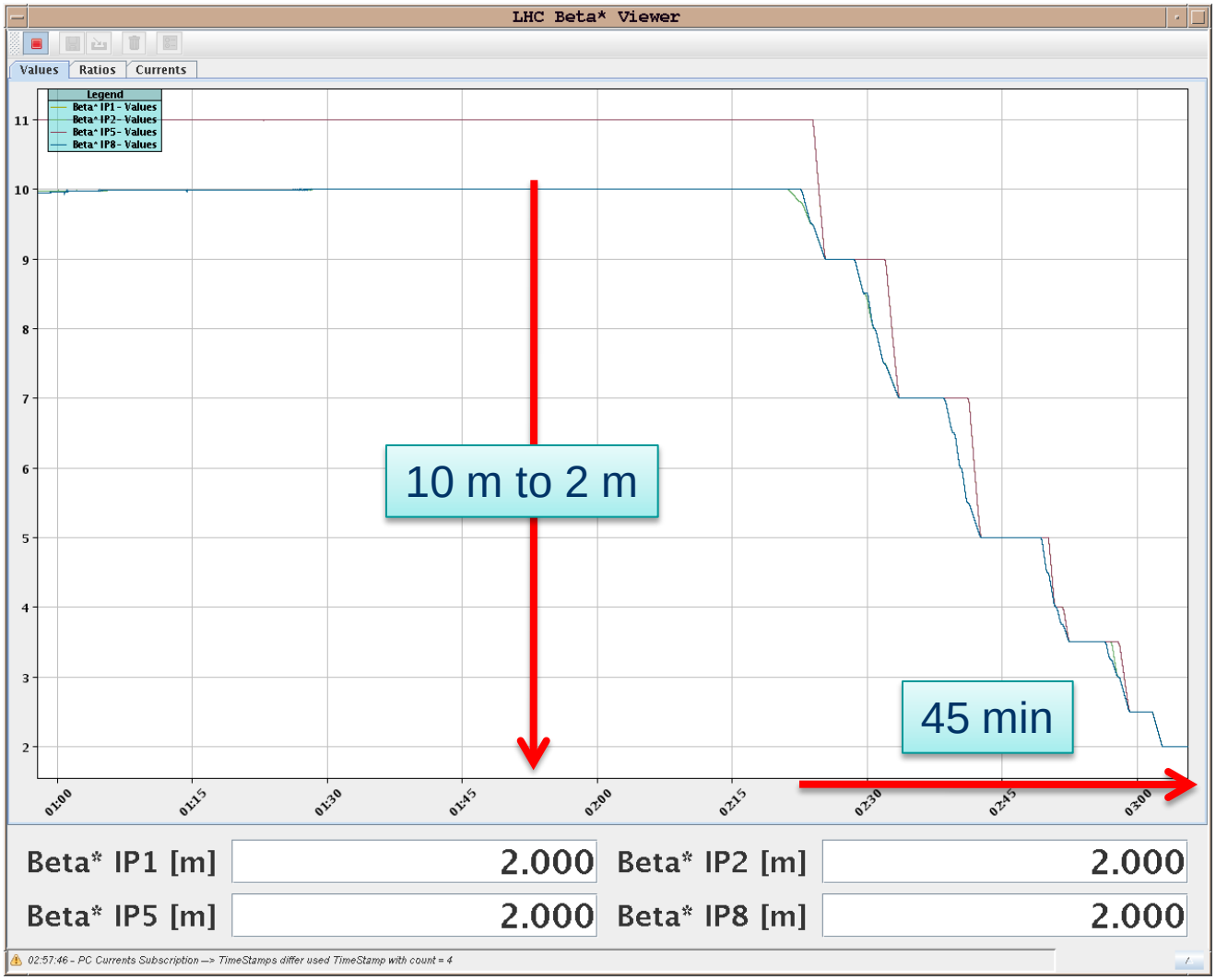
Qualification: Off-momentum collimation

Loss map for off-momentum error. All OK. See expected low leakage to experimental IR's. OK for stable beams from coll.

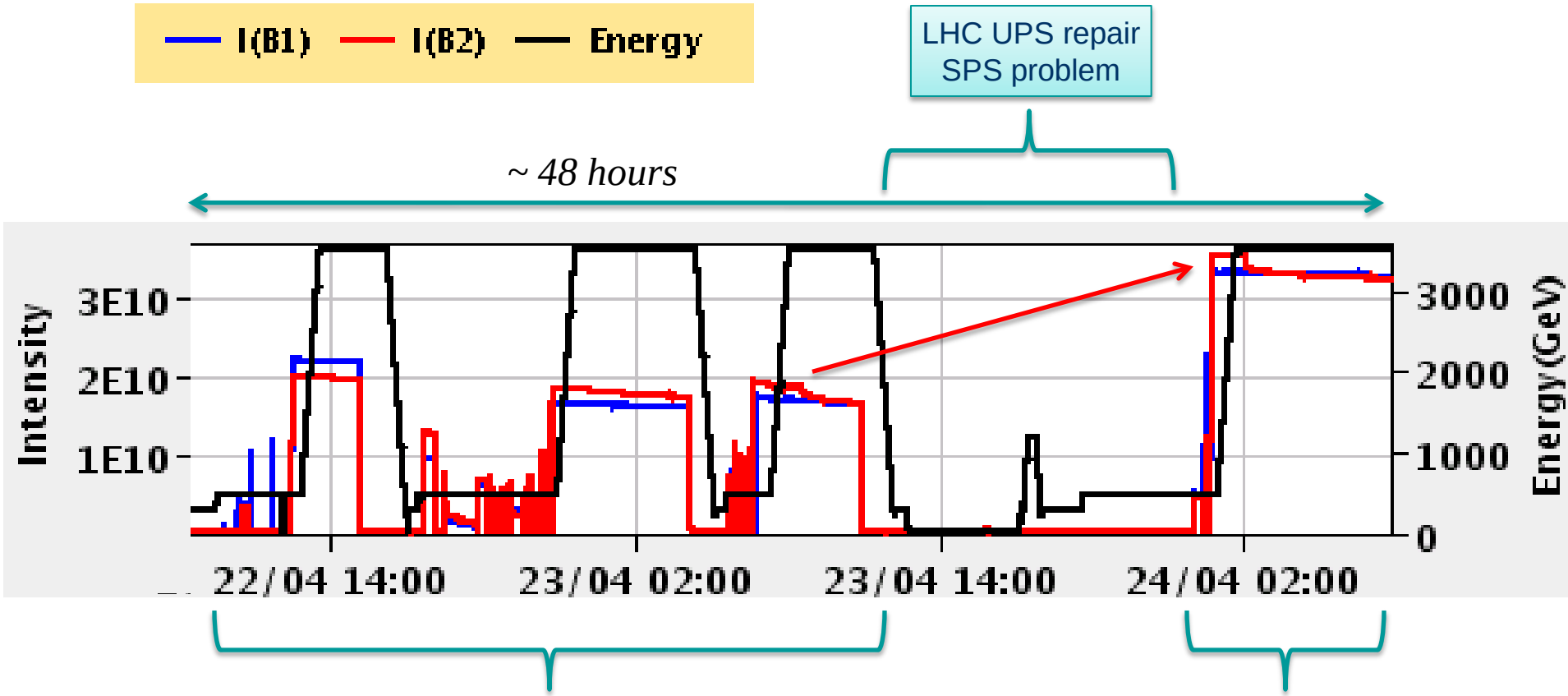


TUOAMH01 (Wollmann, Assmann et al)

Squeeze to 2 m: Fast and Smooth



Ramp & Squeeze Start to Work Smoothly



Ramp & squeeze @ 3.5 TeV qualification:
…last 2 fills w/o problem, lost on purpose…
Transverse damper commissioning @ 450 GeV

Ramp & squeeze for physics @ 3.5 TeV with higher intensity

Saturday 24/4/2010

OP Vistars – Mozilla Firefox

File Edit View History Bookmarks Tools Help

http://op-webtools.web.cern.ch/op-webtools/vistar/vistars.php?usr=LHC1

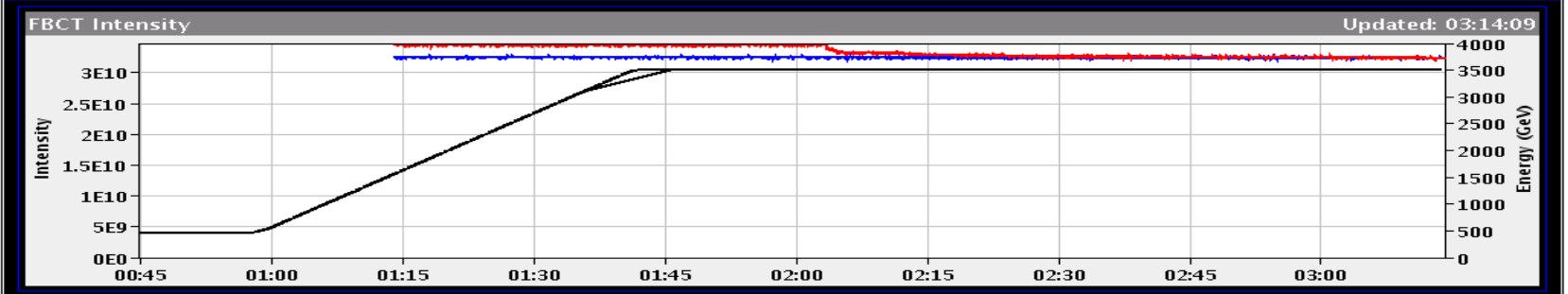
Most Visited | Scientific Linux CERN | CERN IT Departme... | CERN Home Page | Linux distributions

LHC1 — OP Vistars

LHC Page1	Fill: 1058	E: 3500 GeV	24-04-2010 03:14:09

PROTON PHYSICS: STABLE BEAMS

Energy:	3500 GeV	I(B1):	2.75e+10	I(B2):	3.22e+10



Comments 24-04-2010 03:04:01 :

injection scheme 3x3 bunches:

B1 buckets: 1, 8941, 17851

B2 buckets: 1, 8911, 17851

All IPs to 2m!!! Preparing stable beams

BIS status and SMP flags	B1	B2
Link Status of Beam Permits	true	true
Global Beam Permit	true	true
Setup Beam	true	false
Beam Presence	true	true
Moveable Devices Allowed In	true	true
Stable Beams	true	true

LHC Operation in CCC : 77600, 70480

PM Status B1: ENABLED PM Status B2: ENABLED

by E.Matli

Stable beams

Done

Performance 3.5 TeV

IP	Beta* (x, beam 1)	Beta* (y, beam 1)	Beta* (x, beam 2)	Beta* (y, beam 2)
1	2.28 m	2.02 m	1.92 m	2.10 m
2	2.07 m	1.85 m	2.09 m	2.12 m
5	2.05 m	2.02 m	1.92 m	2.58 m
8	2.07 m	1.86 m	2.24 m	1.72 m

24-Apr-2010 05:32:51 Fill #: 1058 Energy: 3500.3 GeV I(B1): 3.28e+10 I(B2): 3.25e+10

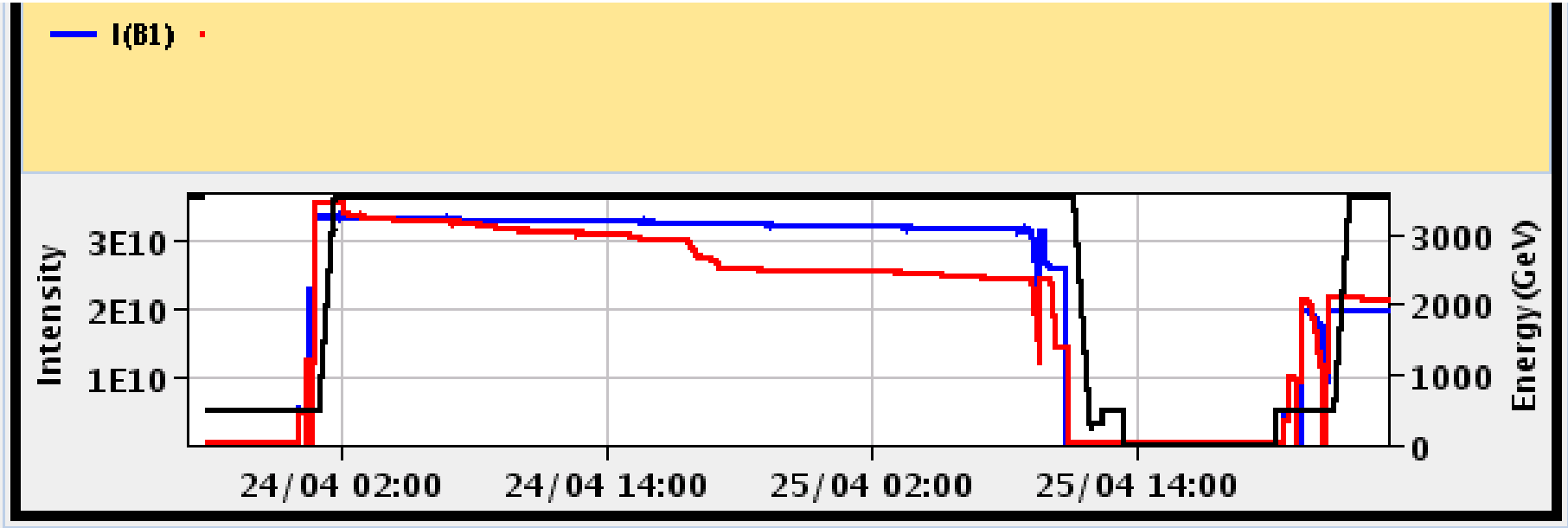
	ATLAS	ALICE	CMS	LHCb
Experiment Status	PHYSICS	PHYSICS	PHYSICS	PHYSICS
Instantaneous Luminosity	1.284e-02	1.147e-02	1.444e-02	1.497e-02
BRAN Count Rate	1.966e+02	1.159e+02	3.518e+02	3.810e+02
BKGD 1	0.048	0.014	0.040	0.141
BKGD 2	5.000	24.770	5.608	2.321
BKGD 3	0.000	0.005	0.003	0.045

LHCf PHYSICS Count(Hz): 5.400 | LHCb VELO Position IN Gap: 0.0 mm | TOTEM: STANDBY

All experiments: $L > 1.1 \times 10^{28}\ cm^{-2}\ s^{-1}$

factor ~10 achieved, as predicted

New Record Fill



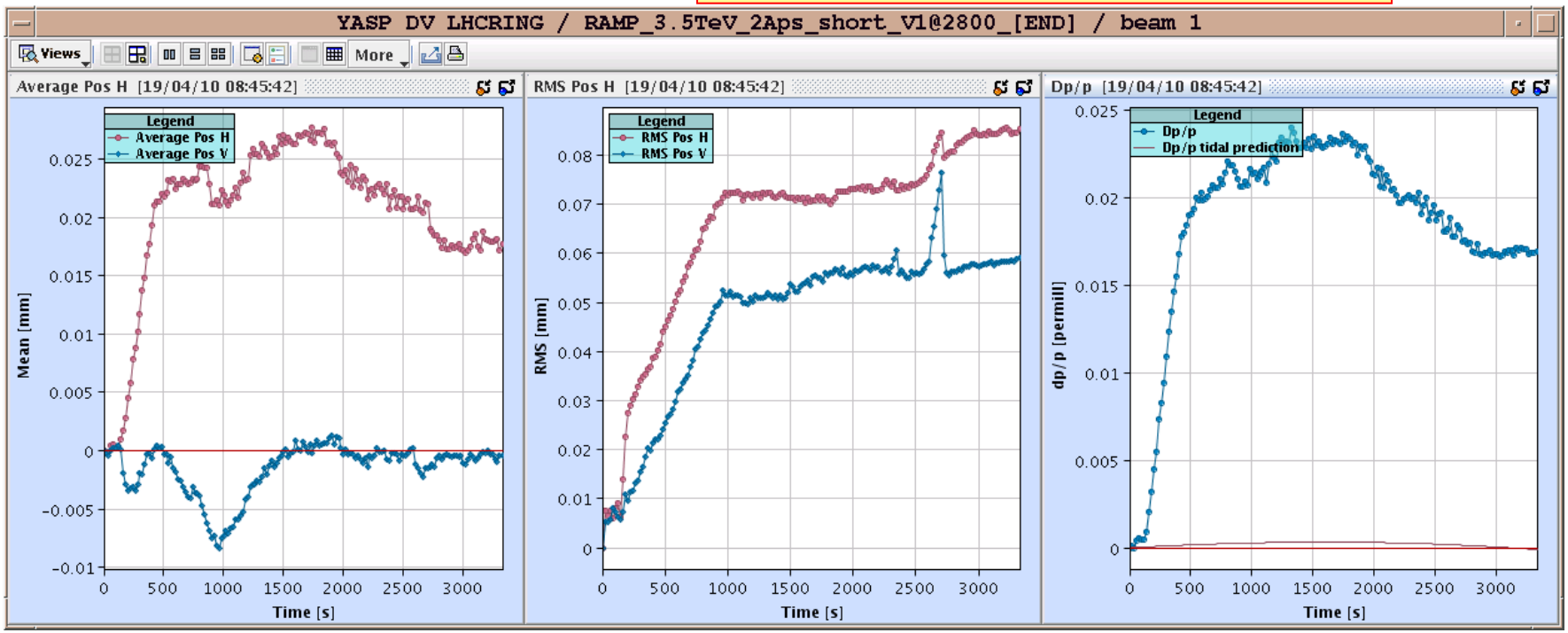
Fill length:	**30 h**
First time:	**with unsafe beam.**
Luminosity	**> 1.1e28 Hz/cm^2**
First time:	**3 bunch scheme**
First time:	**end of fill studies and dump.**

One order of magnitude increase in luminosity

Just 4 more to go before the long shutdown!!!

Orbit Feedback in Operation

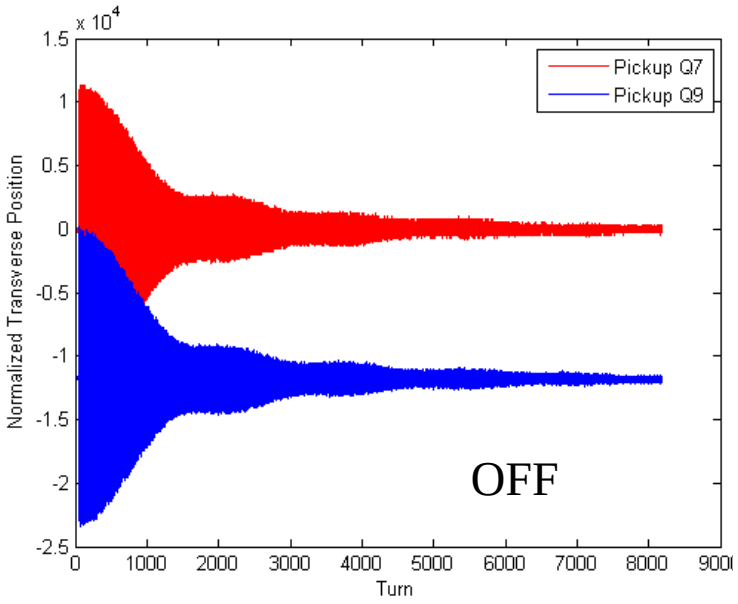
WEPEB041 R. Steinhagen et al



Maximum orbit change during energy ramp: **0.08 mm**

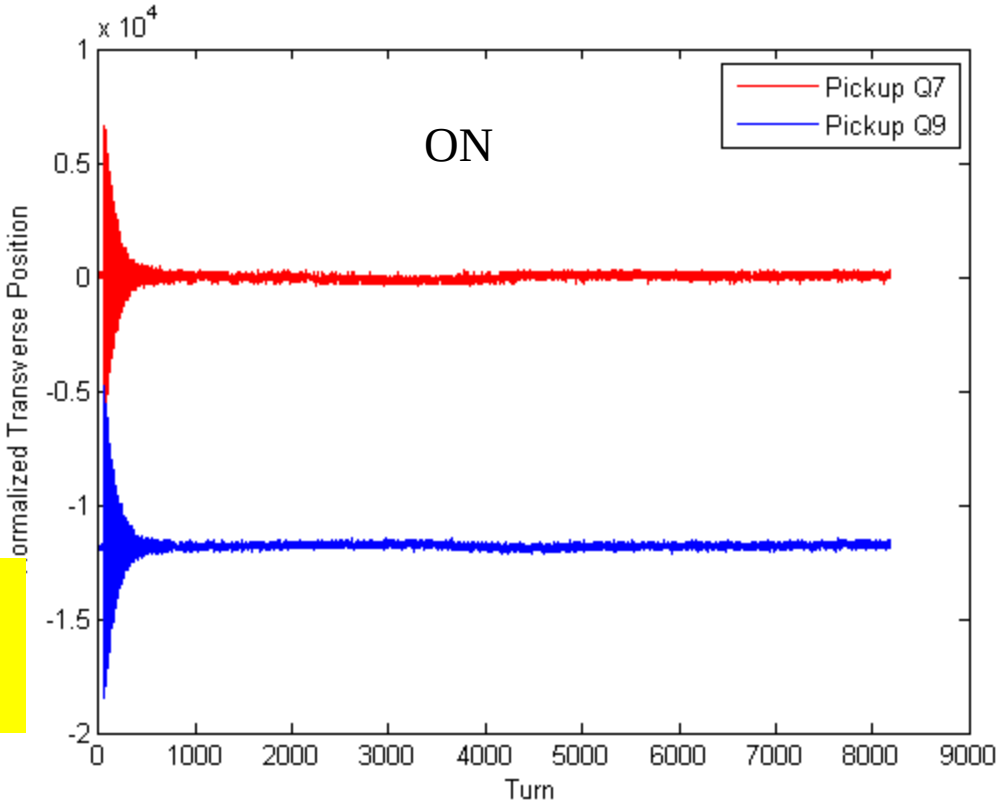
Ralph Steinhagen et al

Transverse Damper: Damping Beam Excitations



Crucial device to keep emittance growth under control!

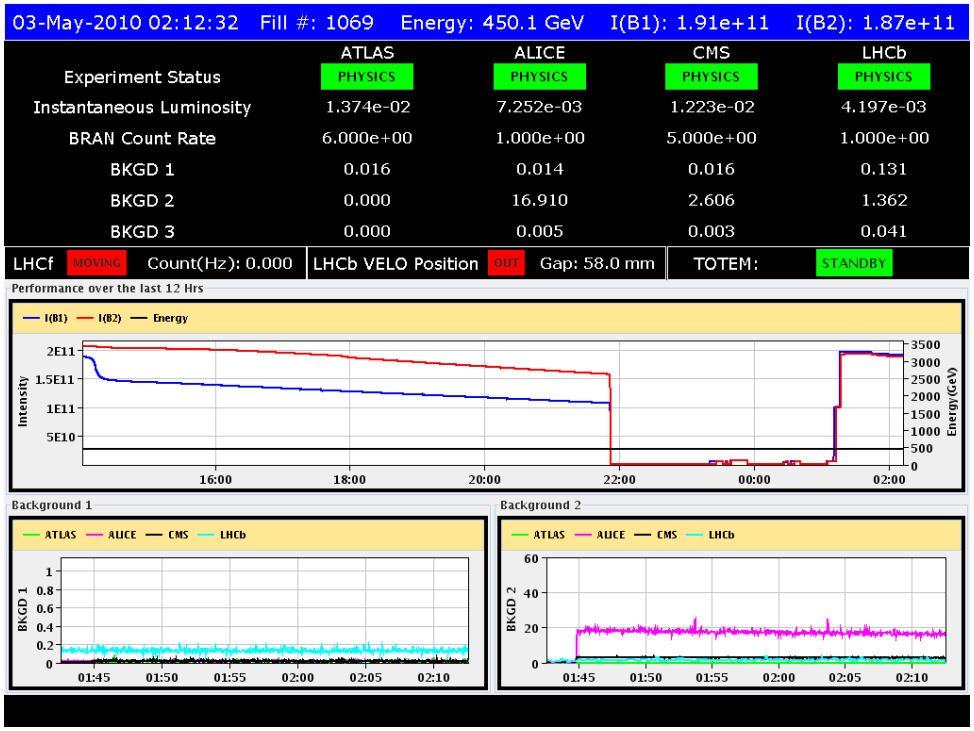
Wolfgang Hoefle et al

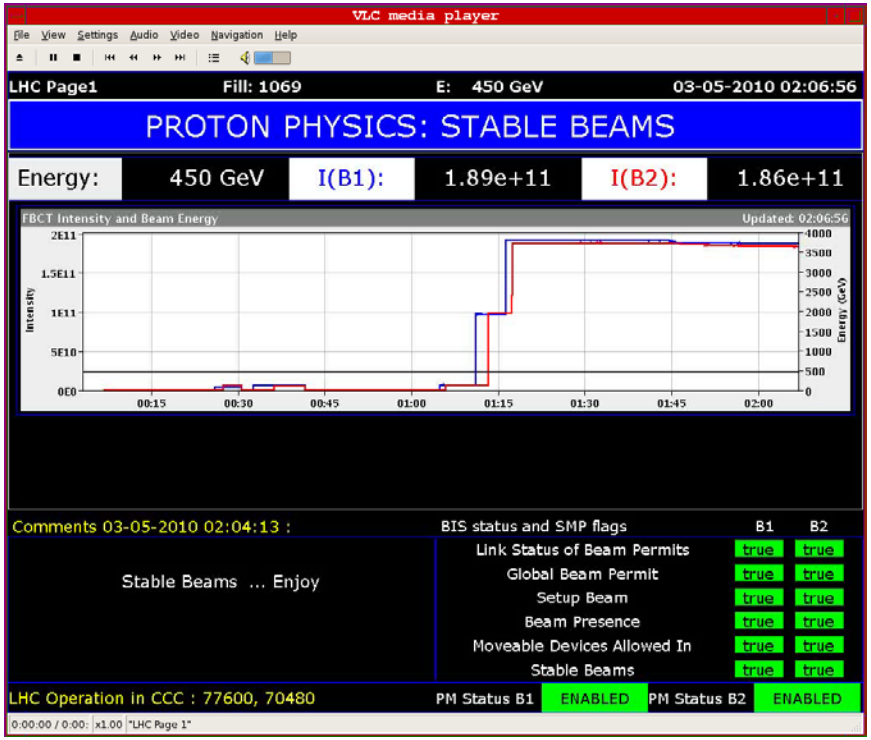


Transverse Damper will stabilize against the Hump

Collisions with design current at 450GeV

Sunday 02/05/2010 Stable beams at design current per bunch at 450GeV





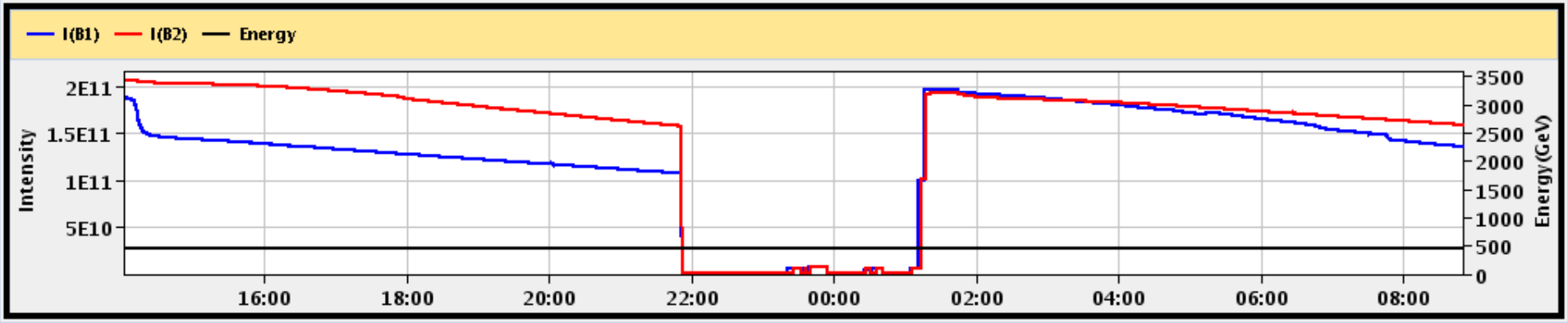
02:04 Stable beams for the second time after LHCb polarity switch and some troubles at injection

03-May-2010 08:49:21 Fill #: 1069 Energy: 450.1 GeV I(B1): 1.35e+11 I(B2): 1.59e+11

	ATLAS	ALICE	CMS	LHCb
Experiment Status	PHYSICS	PHYSICS	PHYSICS	PHYSICS
Instantaneous Luminosity	4.080e-03	2.376e-03	3.276e-03	2.314e-03
BRAN Count Rate	0.000e+00	0.000e+00	5.000e+00	1.000e+00
BKGD 1	0.015	0.013	0.010	0.122
BKGD 2	0.000	5.000	0.774	0.850
BKGD 3	0.000	0.005	0.003	0.047

LHCf PHYSICS Count(Hz): 0.000 | LHCb VELO Position IN Gap: 20.0 mm | TOTEM: STANDBY

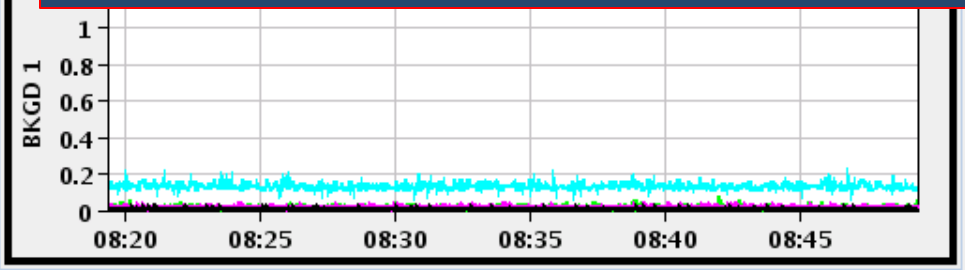
Performance over the last 12 Hrs

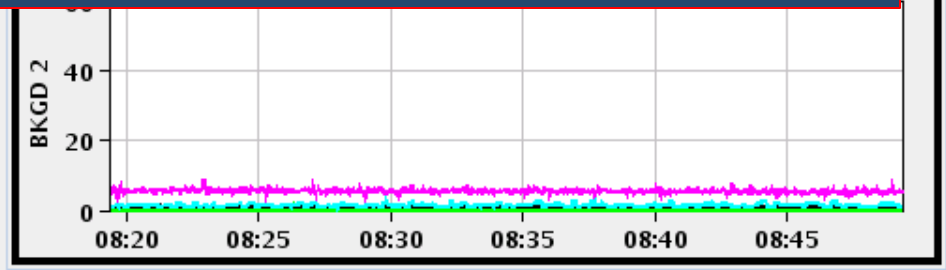


Background 1

Background 2

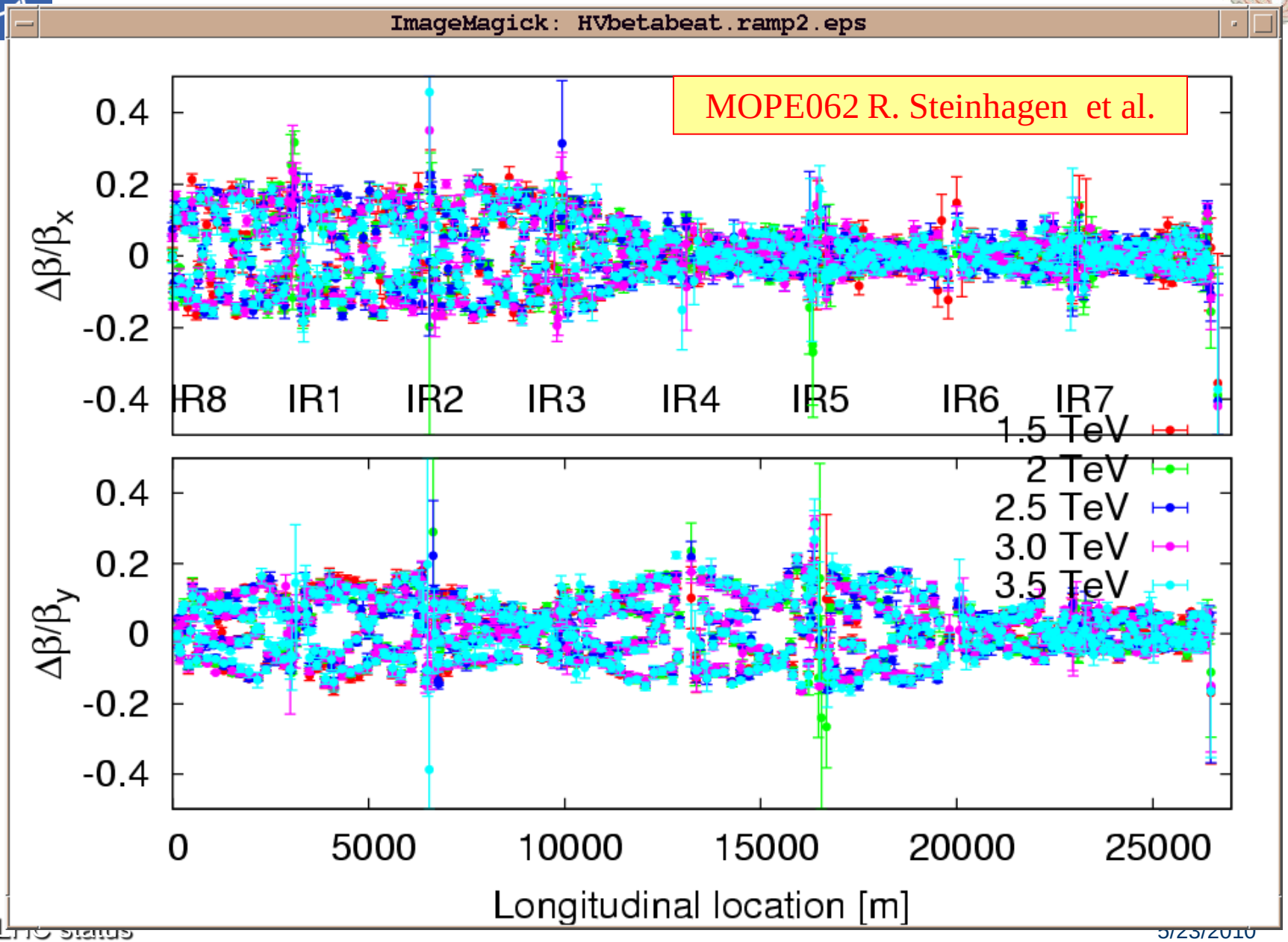
Second fill with better lifetime conditions for B1 after RF phase loop adjustment.





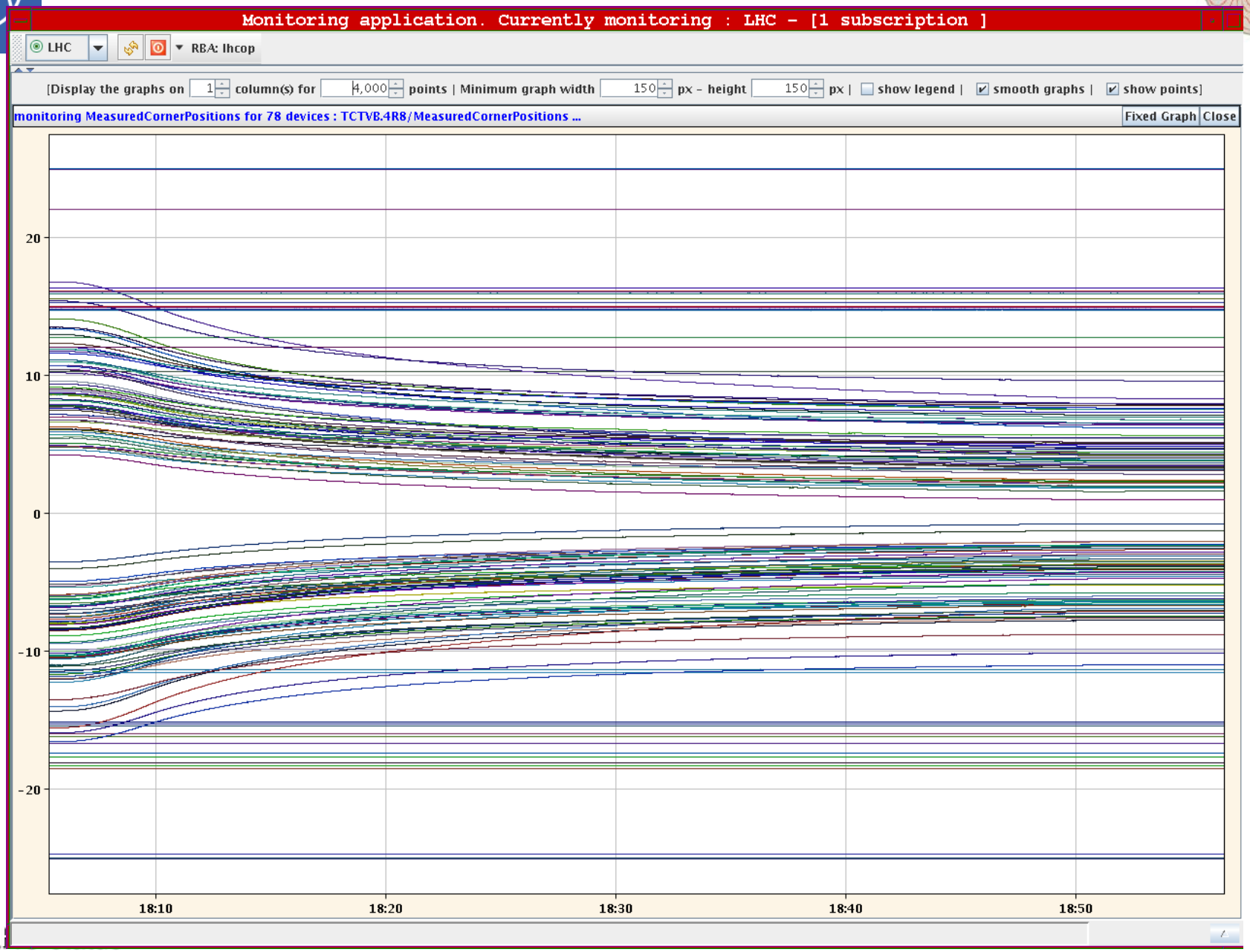
Peak and Integrated Luminosity

Ramps for Beta Beat: 1.5 TeV ➔ 3.5 TeV



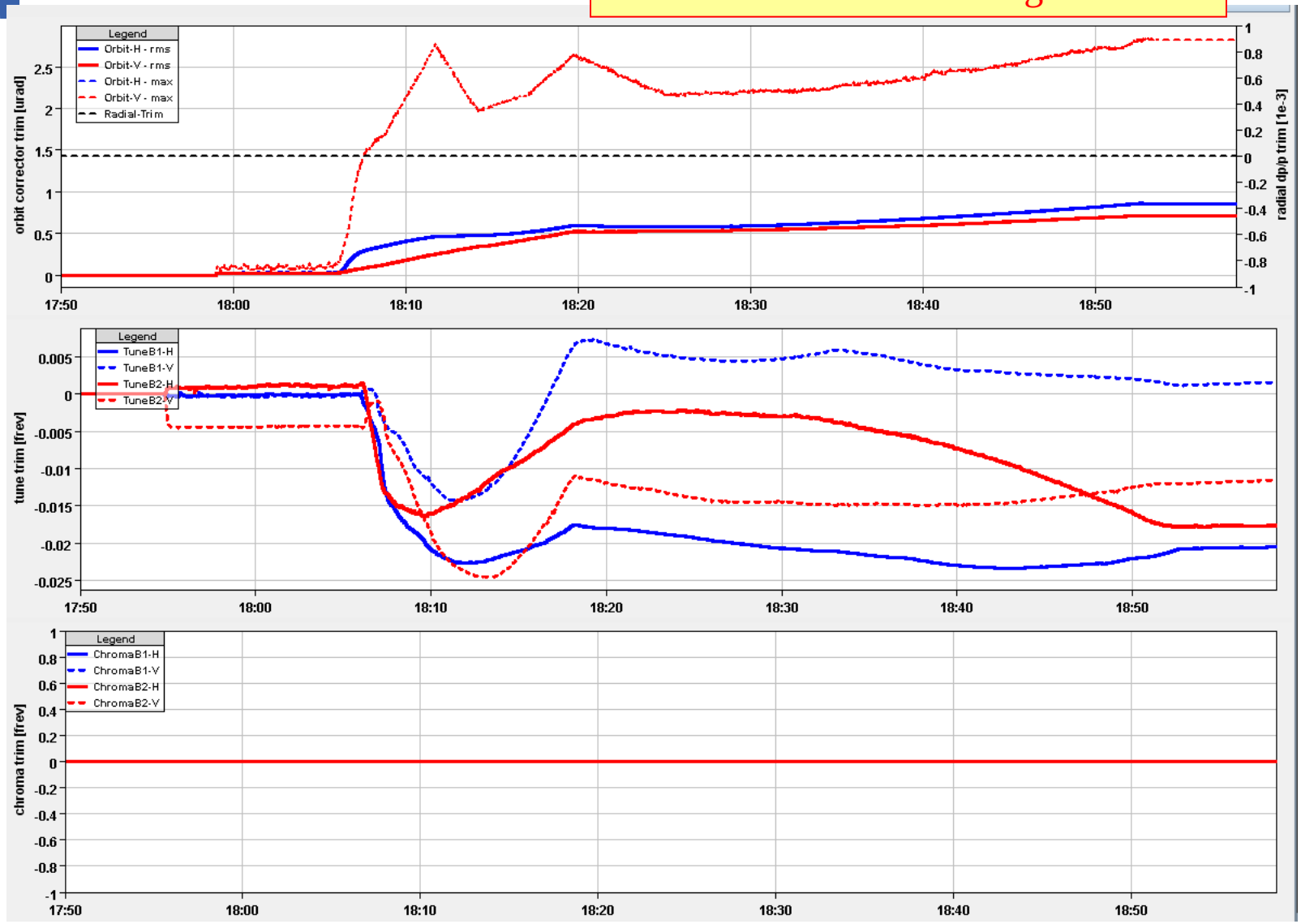
Closing Collimators During Ramp

R. Assmann



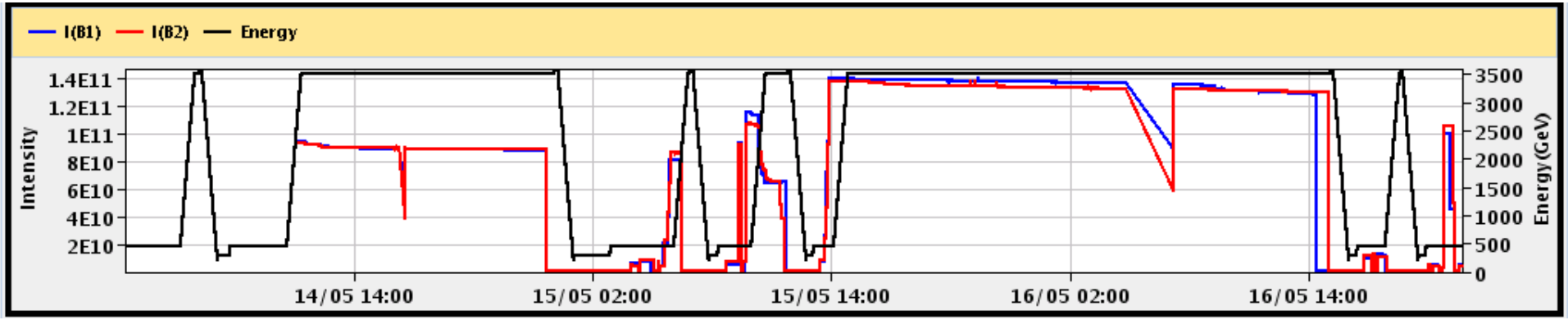
Orbit and Tune Feedback in Operation

WEPEB041 R. Steinhagen et al



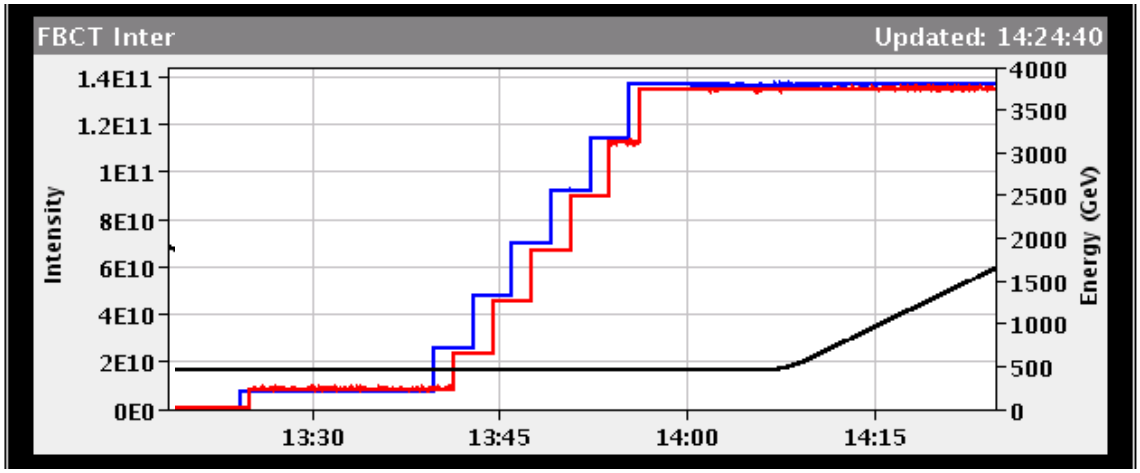
Pushing Number of 2e10 Bunches

2 x 2e10 ➔ **4 x 2e10** **6 x 2e10** per beam

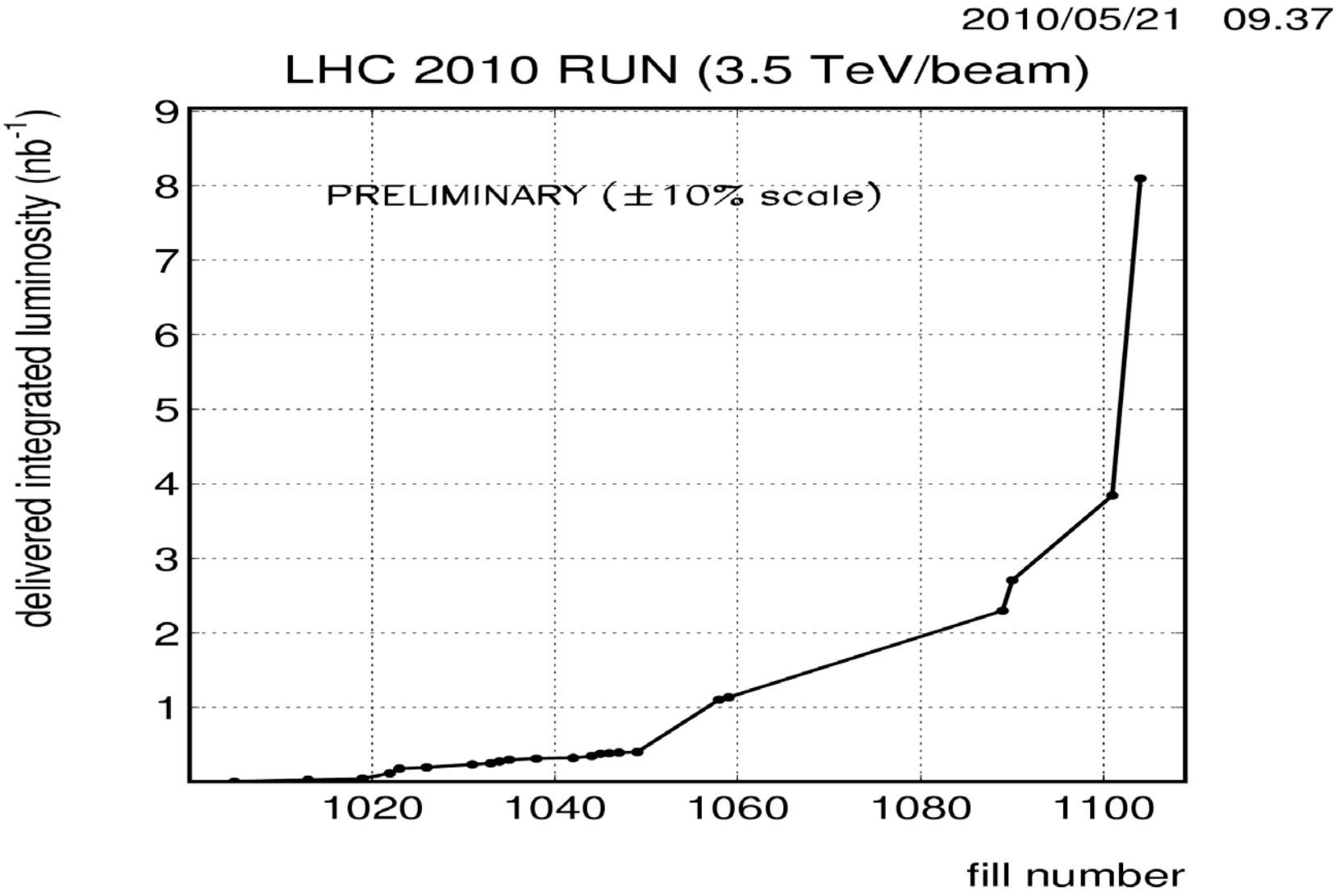


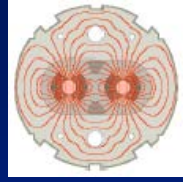
48 hours

Allowed doubling the integrated luminosity for 2010 within 48 hours!



Integrated Luminosity versus Time

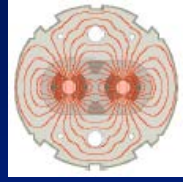




Acknowledgements

The work summarized here is the result of work carried out by hundreds if not thousands of scientists, engineers and technicians both employed by CERN and **very importantly by the many institutes which collaborate with CERN.**

It is a great personal pleasure to acknowledge the incredible contributions and dedication of such a wonderful team.



Thank you for your attention

and please wish us good luck for the future