

LHC at the Royal Society, London, England

16th May 2011

The LHC Collider Status and Performance

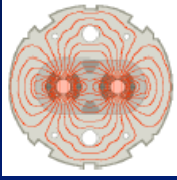
Stephen Myers

Director for Accelerators and Technology,

CERN Geneva

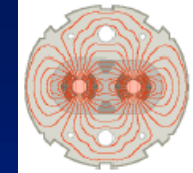


September 10, 2008; It worked!





LHC: Some of the Technical Challenges



Circumference (km)	26.7	100-150m underground
Number of 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)	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	$2.2 \cdot 10^{-6}$ loss causes quench
Beam Stored Energy (MJoules)	362	Results from high beam energy and high beam current 1MJ melts 2kg Cu
Magnet Stored Energy (MJoules)/octant	1100	Results from the high magnetic field
Sector Powering Circuit	8	1612 different electrical circuits

- Energy stored in the magnets 10 GJ (1100 MJ/octant)
- In LHC we must dump the magnetic energy in around 40 seconds i.e. stop the aircraft carrier in 40 seconds



- Energy stored in each beam 362 MJ (in 89us) 4TW (power)

Copper
 Melting point 1356 K
 Specific heat capacity 386 J kg⁻¹ K⁻¹
 Latent heat of fusion 205000 J kg⁻¹
 So 1 kg takes (1354*386+205000) J =0.73MJ
 0.73MJ could heat and melt half a tonne (500kg) of copper
 1.46MJ could heat and melt 1.5 tonne (1500kg) of copper

A very thin long hole

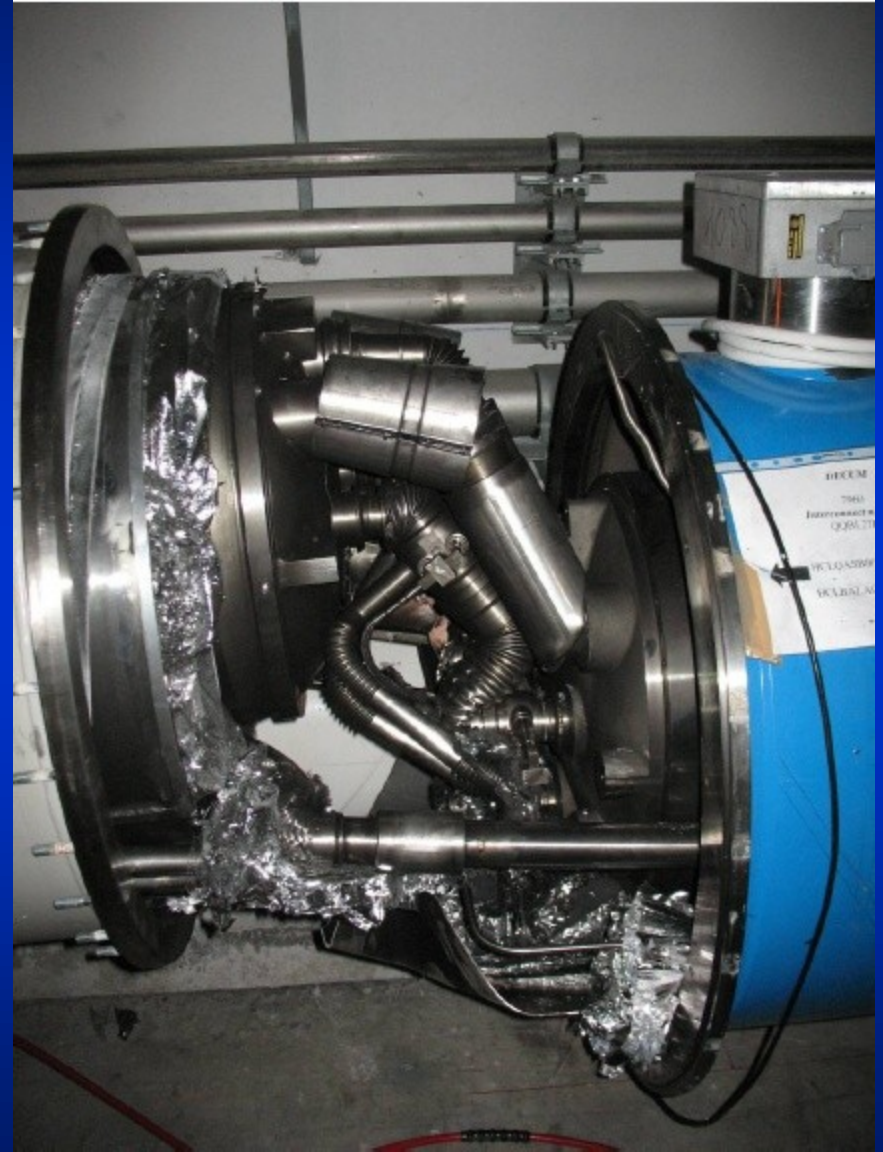
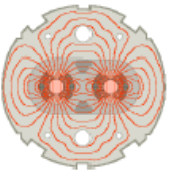
How to Deal with the LHC self Destructive Power



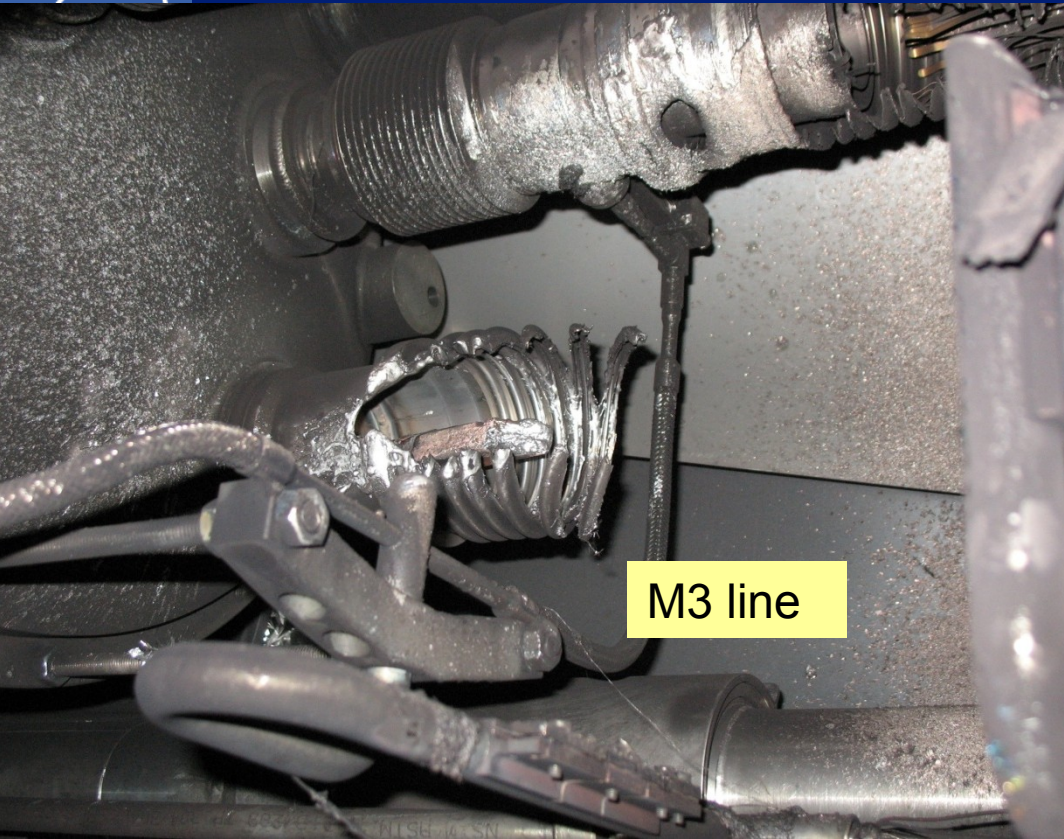
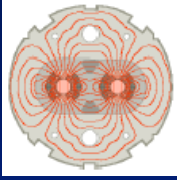
- In case of a problem the stored energy in the magnets and in the beam must be transferred to and dissipated in a safe, clearly defined place
- Magnet Protection system
 - “Quench” Protection (measures resistance)
 - Energy dump triggered and energy dissipated as heat in resistors (after of course aborting the beams)
- Machine Protection System
 - All critical elements which could provoke a beam loss are equipped with an emergency beam abort signal which triggers the beam dump system. There is also a beam loss monitoring system all around the circumference which will abort the beam if anomalous losses occur
 - **The beam dump system is the last safety net**

9 days after the successful start up

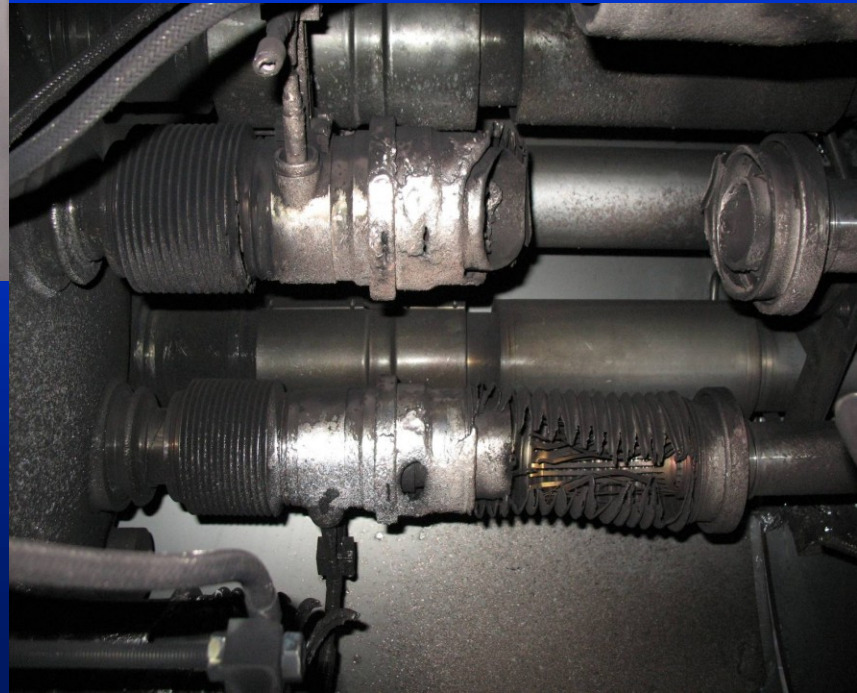
- During a few days period without beam
- Making the last step of dipole circuit in sector 34, to 9.3kA
- At 8.7kA, development of resistive zone in the dipole bus bar splice between Q24 R3 and the neighbouring dipole
- Electrical arc developed which punctured the helium enclosure

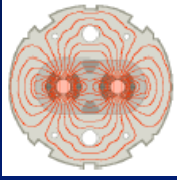


Electrical arc between C24 and Q24



V lines





Collateral damage: secondary arcs

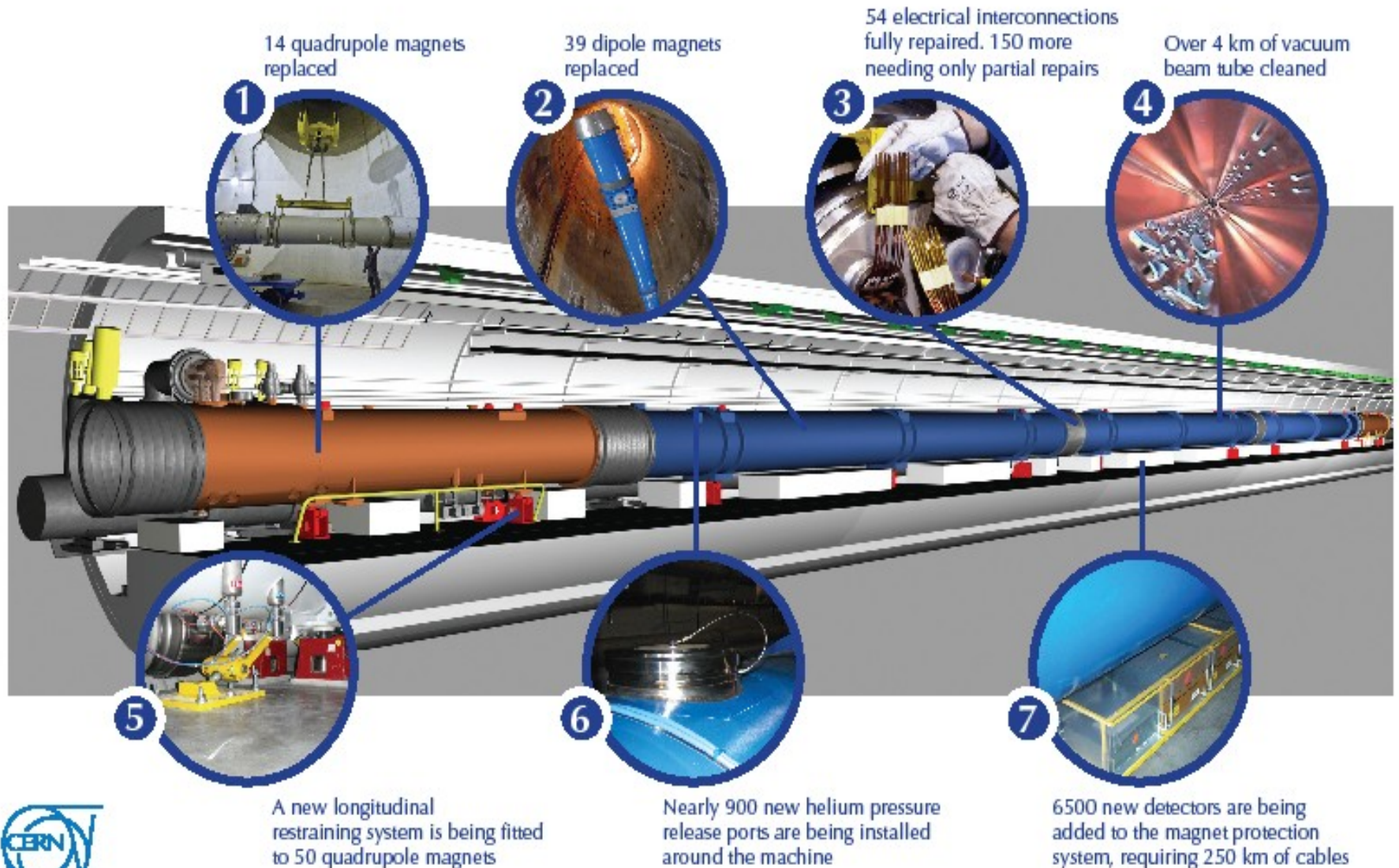


QQBI.27R3 M3 line

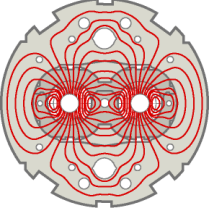
QBBI.B31R3 M3 line



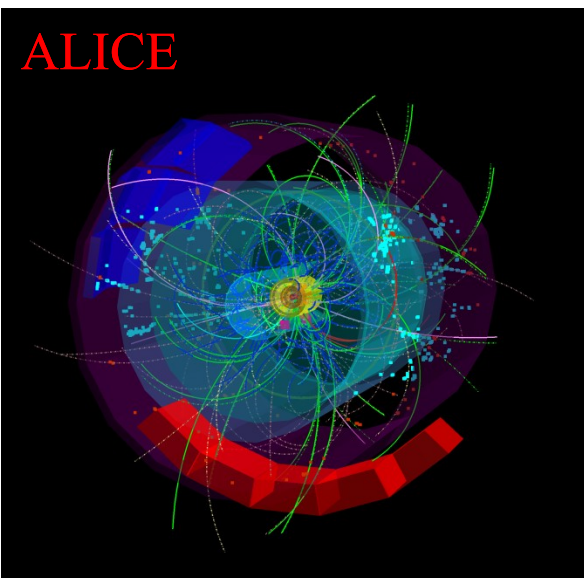
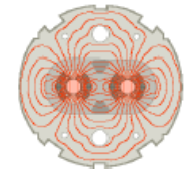
The LHC repairs in detail



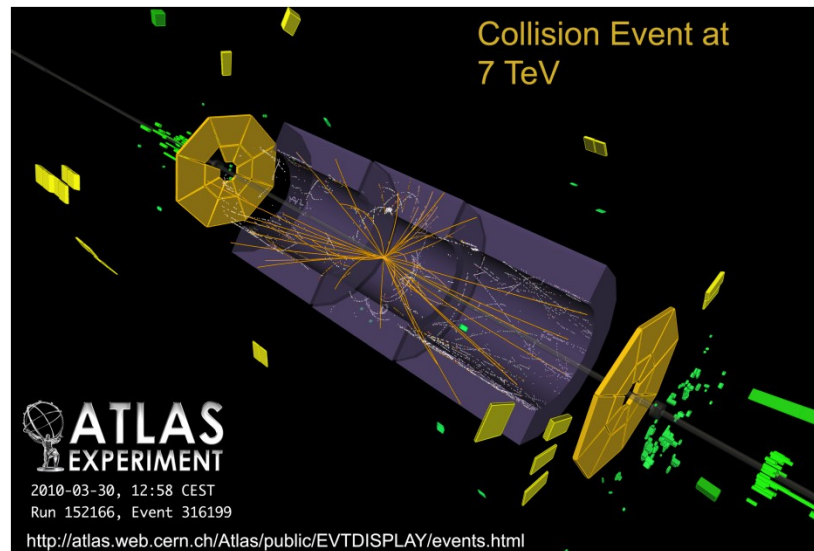
+ 8 cryogenics!



LHC: First collisions at 7 TeV on 30 March 2010



ALICE



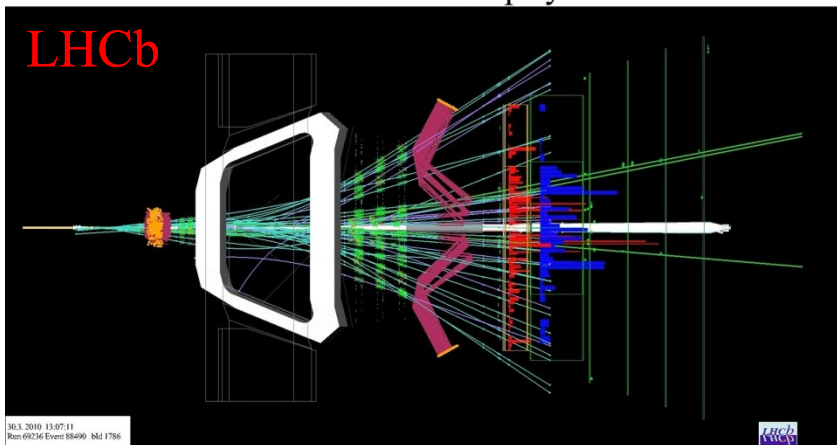
Collision Event at 7 TeV

ATLAS
EXPERIMENT

2010-03-30, 12:58 CEST
Run 152166, Event 316199

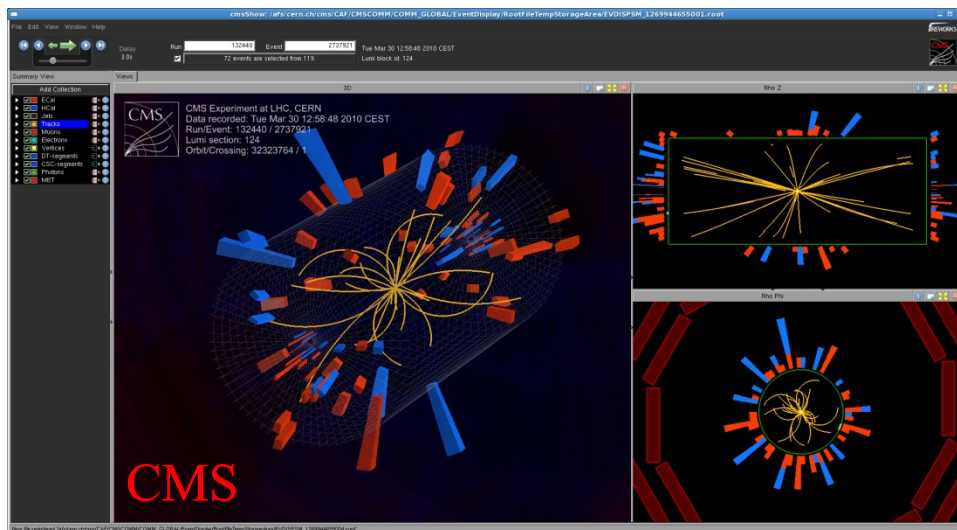
<http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html>

LHCb Event Display



LHCb

30.3.2010 13:07:11
Run 60256 Event 33490 NSL 1756



CMS



Very Cautious start: low bunch intensity and increasing the number of bunches to 13 with beta* = 2m

calculated

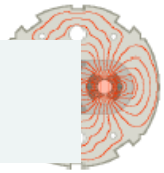
Event	TeV	OEF	β^*	Nb	lb	ltot	MJ	Nc	Peak luminosity	Date
1	3.5	0.2	10	2	1.00E+10	2.0E+10	0.0113	1	8.9E+26	30 March 2010
2	3.5	0.2	10	2	2.00E+10	4.0E+10	0.0226	1	3.6E+27	02 April 2010
3	3.5	0.2	2	2	2.00E+10	4.0E+10	0.0226	1	1.8E+28	10 April 2010
4	3.5	0.2	2	2	2.00E+10	4.0E+10	0.0226	1	1.8E+28	19 April 2010
5	3.5	0.2	2	2	2.00E+10	4.0E+10	0.0226	1	1.8E+28	15 May 2010
6	3.5	0.2	2	13	2.60E+10	3.4E+11	0.1910	8	2.4E+29	22 May 2010
7	3.5	0.2	3.5	3	1.10E+11	3.3E+11	0.1865	2	6.1E+29	26 June 2010
8	3.5	0.2	3.5	6	1.00E+11	6.0E+11	0.3391	4	1.0E+30	02 July 2010
9	3.5	0.2	3.5	8	9.00E+10	7.2E+11	0.4069	6	1.2E+30	12 July 2010
10	3.5	0.2	3.5	13	9.00E+10	1.2E+12	0.6612	8	1.6E+30	15 July 2010
11	3.5	0.2	3.5	25	1.00E+11	2.5E+12	1.4129	16	4.1E+30	30 July 2010
12	3.5	0.2	3.5	48	1.00E+11	4.8E+12	2.7127	36	9.1E+30	19 August 2010

Switch to beta* = 3.5m, design bunch intensity and increase the number of bunches to 48 (2.7MJ)

Maximum reached is $10.7 \times 10^{30} \text{ cm}^{-2}\text{s}^{-1}$

First Operation with trains of bunches; up to 348 still with $\beta^* = 3.5\text{m}$ (3.5TeV/beam, 24MJ)

d

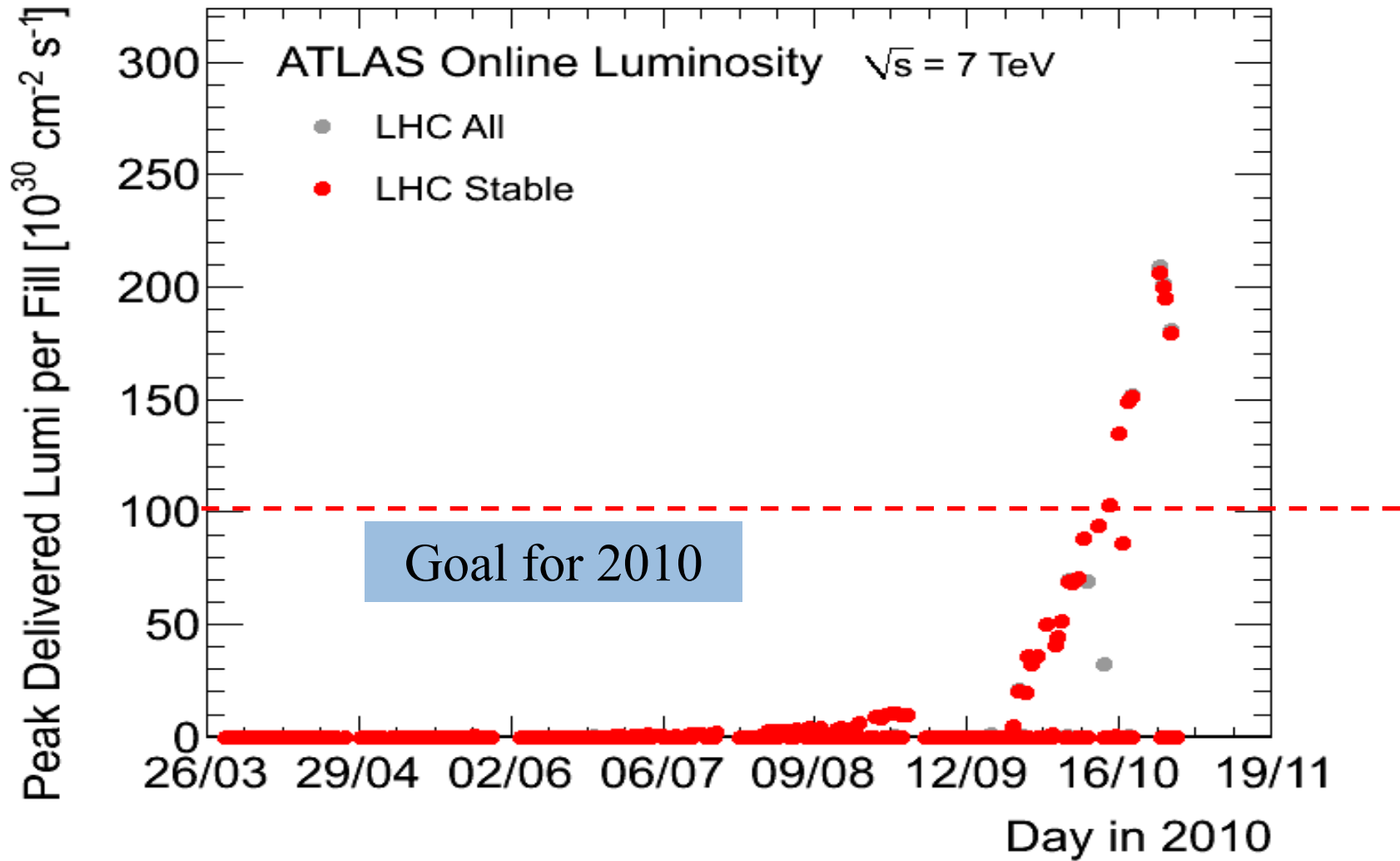
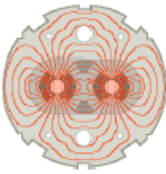


Nb	lb	MJ	Nc	Peak luminosity (design parameters)	Maximum luminosity (measured)	Pile up (from measured Lumi)	Date
56	1.10E+11	3.5	47	1.203E+31	2.000E+31	1.9054	23/09/2010
104	1.10E+11	6.5	93	2.381E+31	3.500E+31	1.7955	25/09/2010
152	1.10E+11	9.4	140	3.584E+31	5.000E+31	1.7550	29/09/2010
204	1.10E+11	12.7	186	4.762E+31	7.000E+31	1.8307	04/10/2010
248	1.10E+11	15.4	233	5.965E+31	1.030E+32	2.2158	14/10/2010
312	1.10E+11	19.4	295	7.552E+31	1.500E+32	2.5650	16/10/2010
368	1.15E+11	23.9	348	9.737E+31	2.050E+32	2.9721	25/10/2010

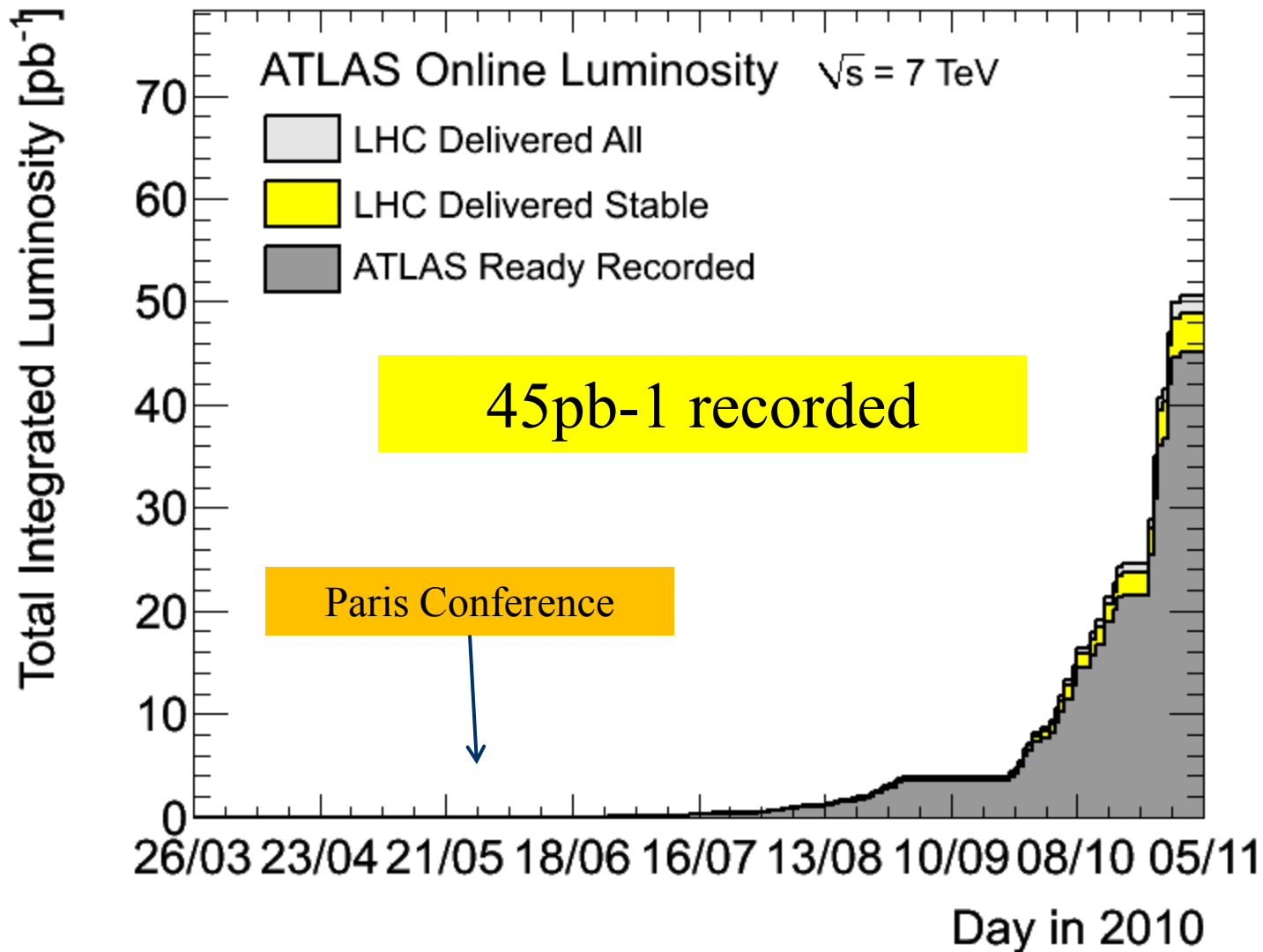
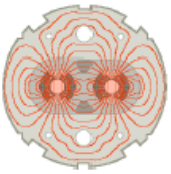
Performance Improvement by a factor of 200,000 in 7 months:



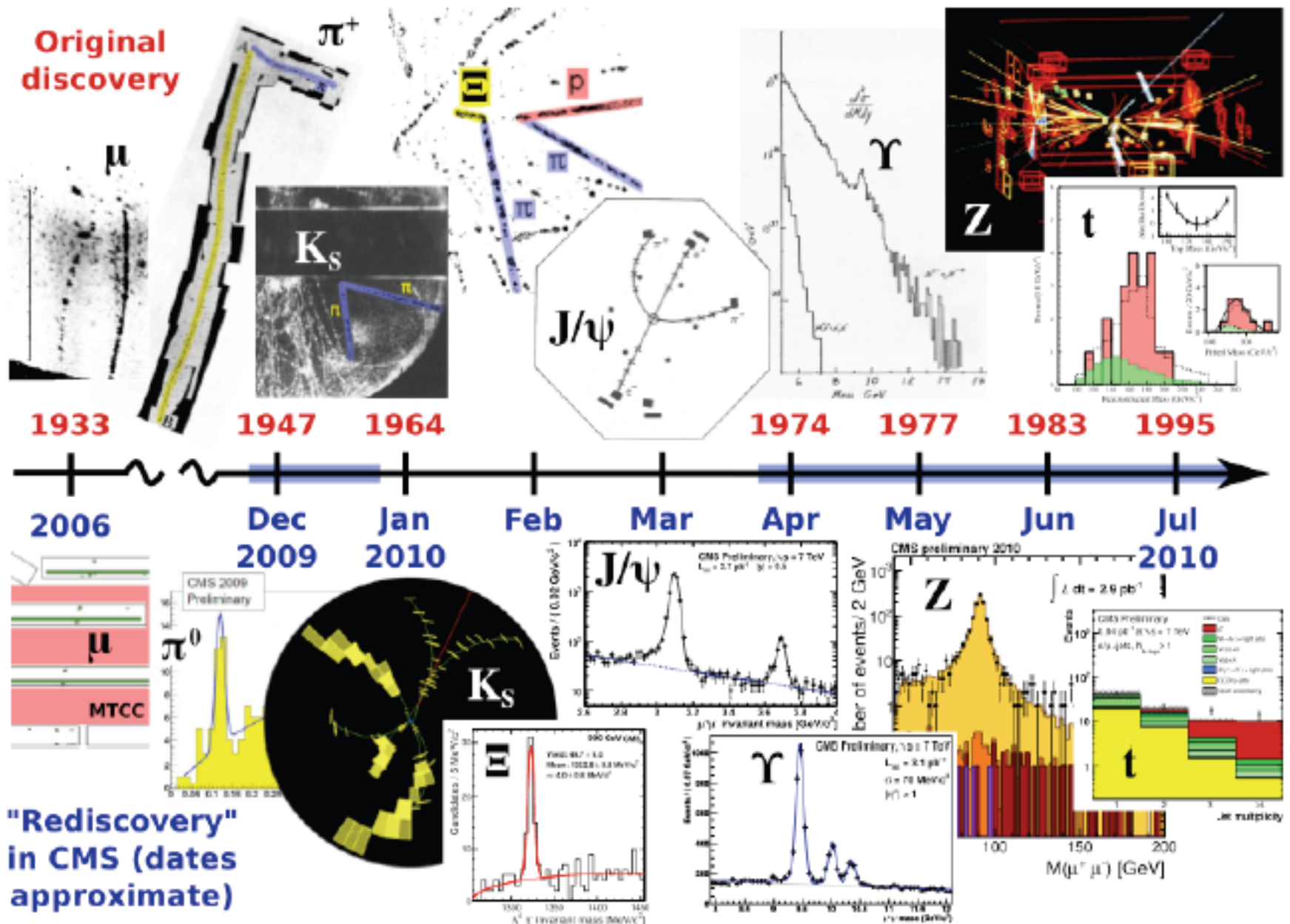
Peak Luminosity



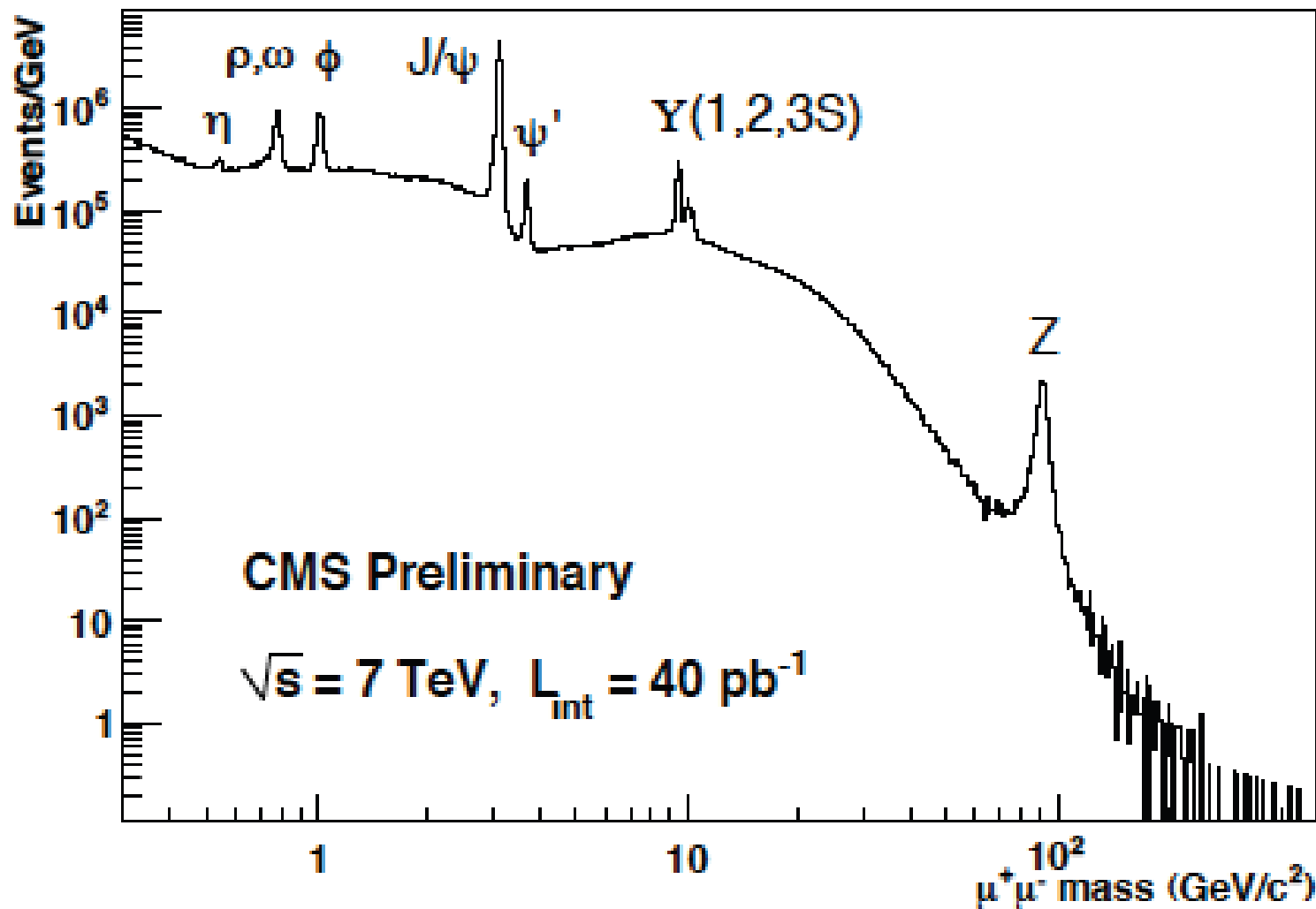
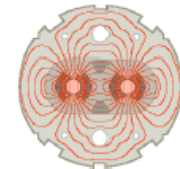
Integrated Luminosity in 2010

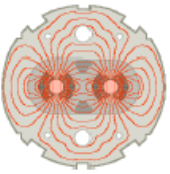


Brief History of the Standard Model



Di-electron and di-muon spectra

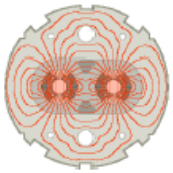




End of 2010: Collisions of lead ions



2010 Ion Run Predictions



The Injectors ready

- ***The Pb⁸²⁺ beam was injected into the LHC (first beam after the 2008 incident)***

The basic machine parameters are similar

- ***But the collimation system needed some setting up***
- ***The behavior of the beam instrumentation– the low intensities make life difficult***

It will not look as impressive as protons as far as absolute performance is concerned:

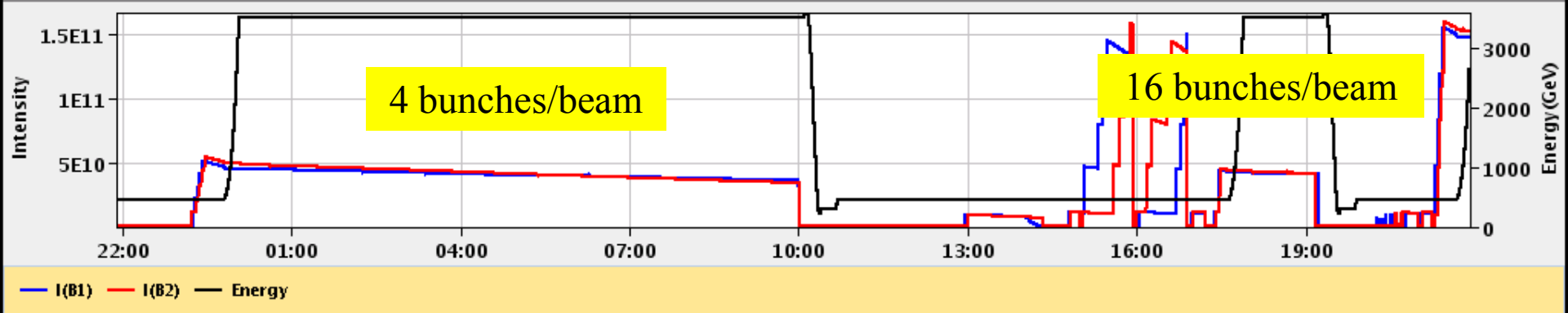
- ***Peak Luminosity $\sim 10^{+25} \text{ cm}^{-2} \text{ s}^{-1}$ (c.f. $2 \times 10^{+32}$ for protons)***
- ***Integrated Luminosity $\sim 3\text{-}10 \mu\text{b}^{-1}$ (c.f. 50,000,000 μb^{-1} for protons)***
- ***But each collision will look pretty impressive!***

Experiment Status	ATLAS	ALICE	CMS	LHCb
Instantaneous Lumi (ub.s) ⁻¹	0.00e+00	7.08e-08	0.00e+00	0.00e+00
BRAN Luminosity (ub.s) ⁻¹				0.001
Inst Lumi/CollRate Parameter				
BKGD 1	0.002	0.179	0.000	0.150
BKGD 2	2.000	0.000	0.002	1.317
BKGD 3	0.000	1.882	0.098	0.050

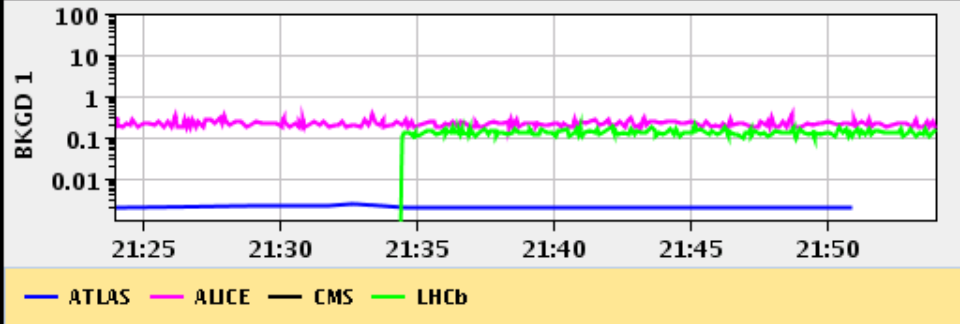
First Long Run with lead ions 8-9 Nov 2010

LHCb VELO Position OUT Gap: 58.0 mm RAMP TOTEM: STANDBY

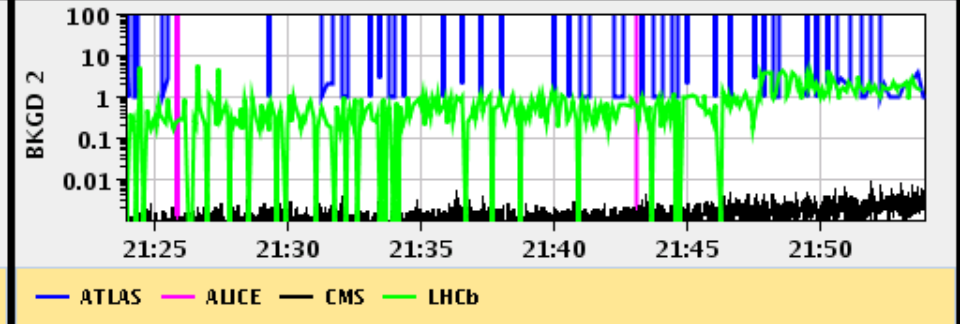
Performance over the last 24 Hrs Updated: 21:53:55

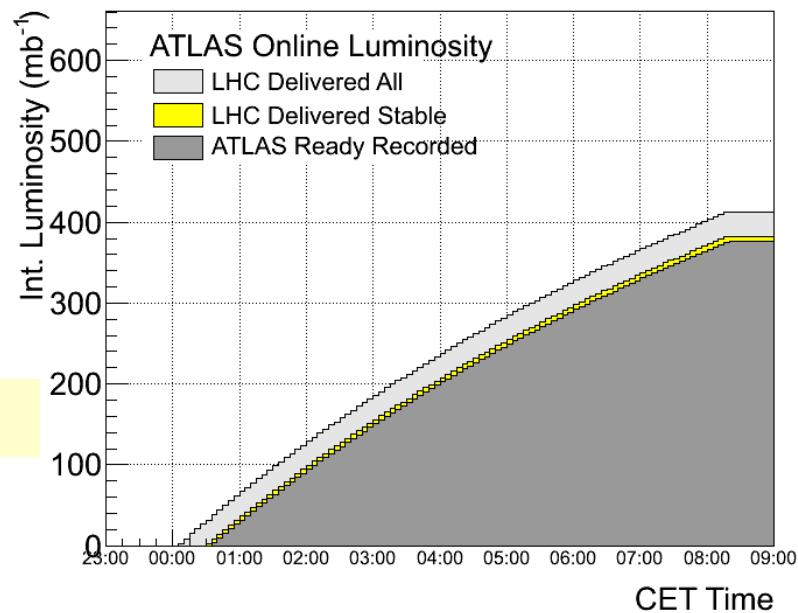
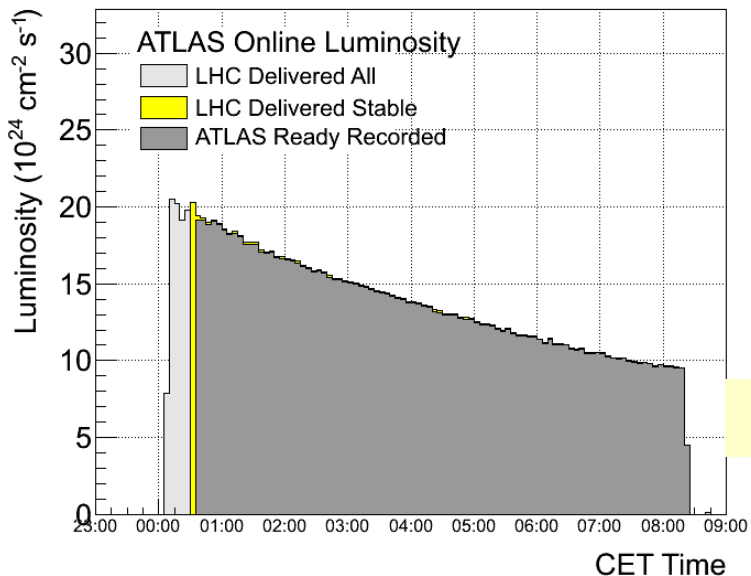


Background 1 Updated: 21:53:55

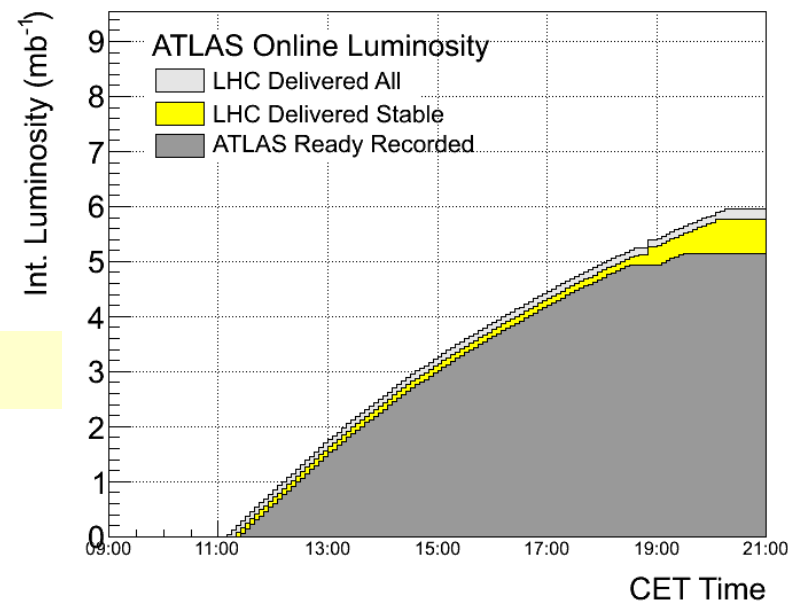
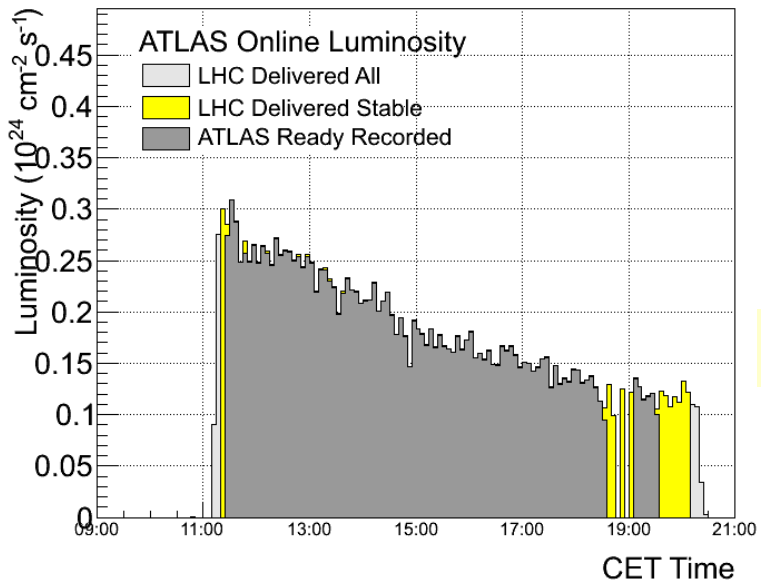


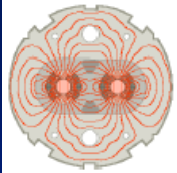
Background 2 Updated: 21:53:55



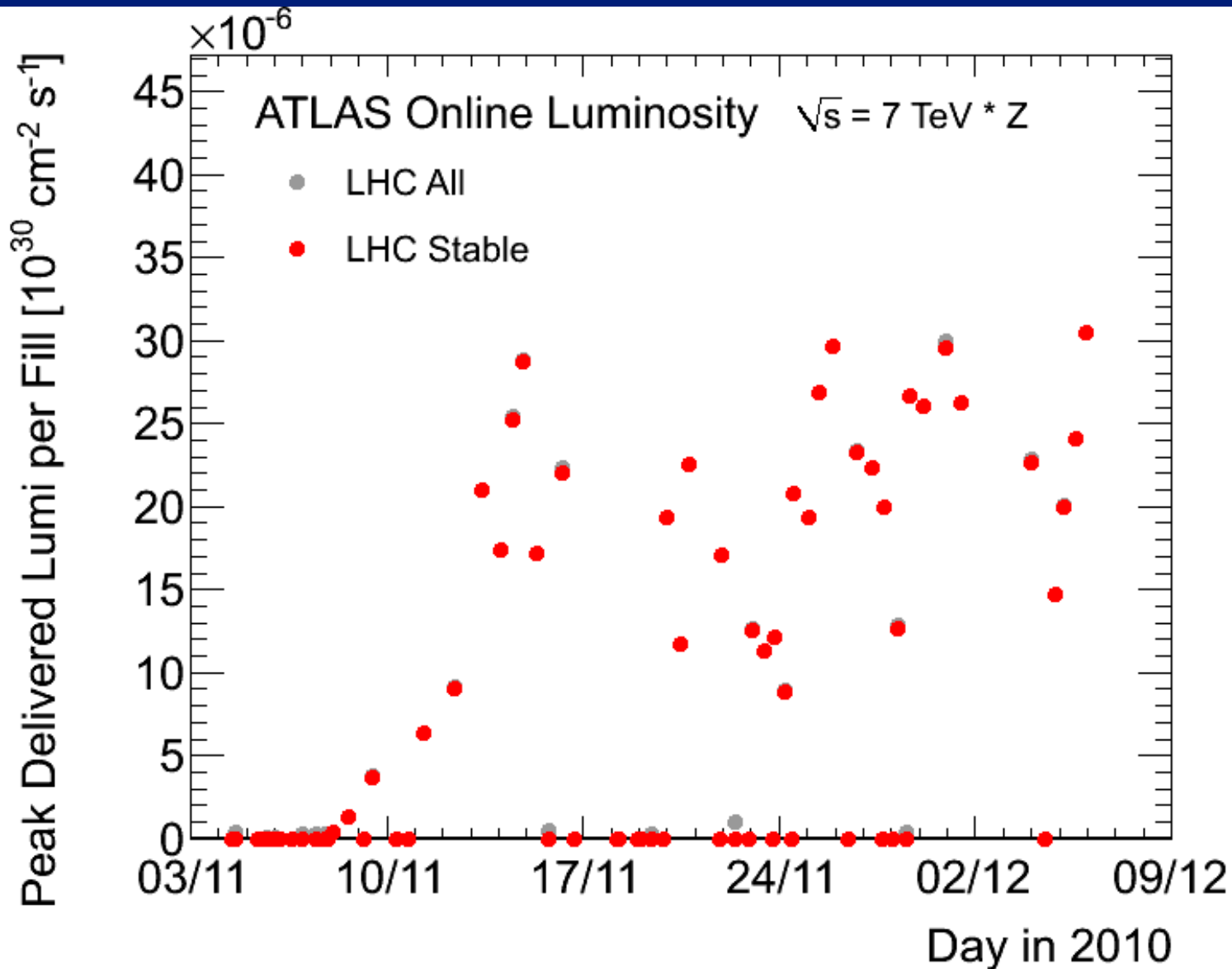


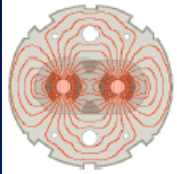
6 days of ion operation (x 100 increase)



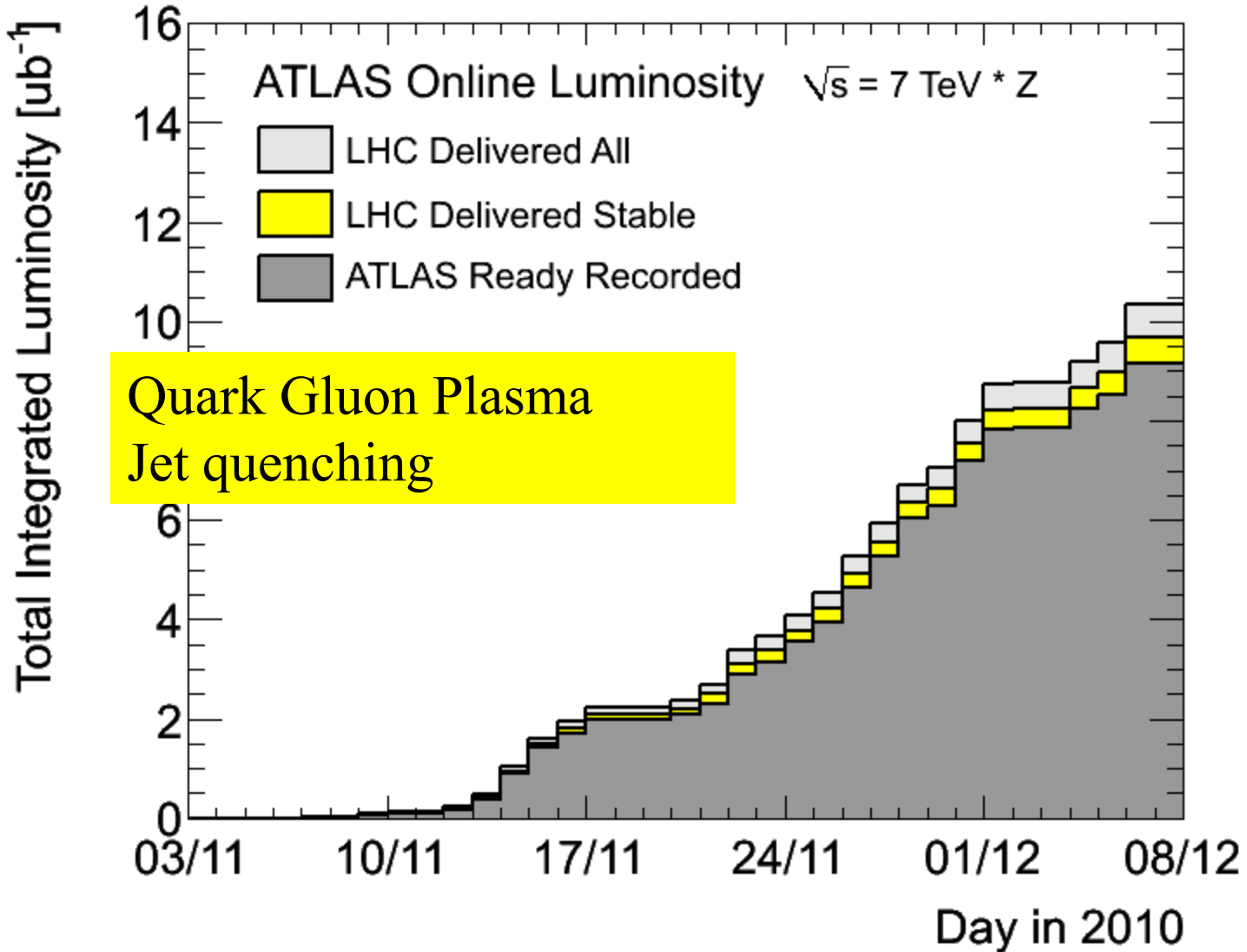


Evolution of the Peak Luminosity with lead Ions





Integrated Luminosity with lead Ions



2011 LHC schedule

Jan

Feb

Close ring

Re-commissioning
with beam

Mar

This SPC 3 periods

1. Physics re-established with 75ns and increasing the number of bunches,
2. Intermediate energy run at 1.38 TeV/beam + Scrubbing Run
3. Start of going by steps towards 900b + TS + (MD)

11	12
14	21

Intermediate energy run (date t.b.c.)

Scrubbing run (date t.b.c.)

Start full non-LHC physics program

Apr

May

June

Wk	13	14	15	16	17	18	19	20	21	22	23	24	25	
Mo	28	4	11	18	Easter	2	9	Today	16	23	30	6	13	20
Tu														
We														
Th										Ascension				
Fr					G. Friday									
Sa														
Su					1st May									

Period 1: Restablishing Physics at 75ns bunch spacing

200 bunches; 75ns; 24bpi

LHC Page1

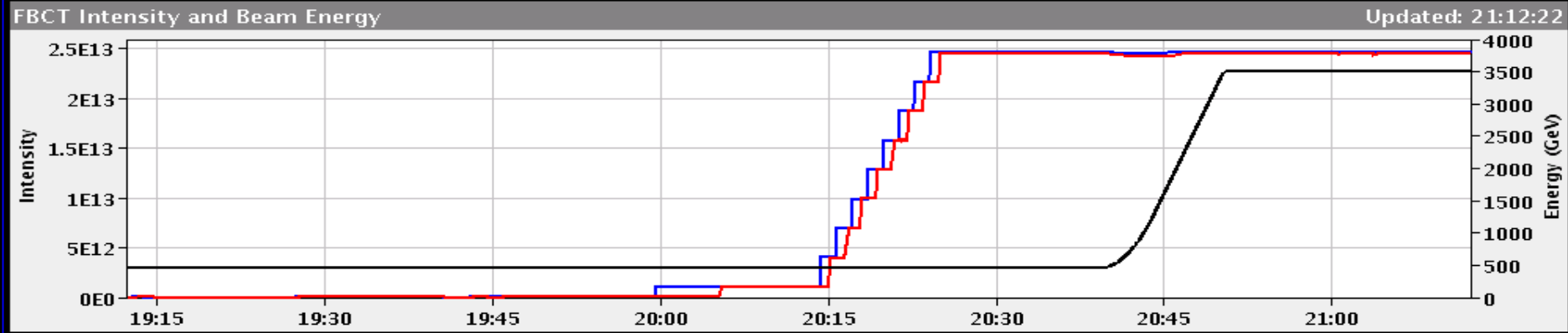
Fill: 1645

E: 3500 GeV

22-03-2011 21:12:25

PROTON PHYSICS: ADJUST

Energy: 3500 GeV I(B1): 2.48e+13 I(B2): 2.44e+13



Comments 22-03-2011 20:22:16 :

filling

next fill with 200 bunches

BIS status and SMP flags

B1 B2

Link Status of Beam Permits	true	true
Global Beam Permit	true	true
Setup Beam	false	false
Beam Presence	true	true
Moveable Devices Allowed In	false	false
Stable Beams	false	false

AFS: 75ns_200b_194_178_188_24bpi9inj

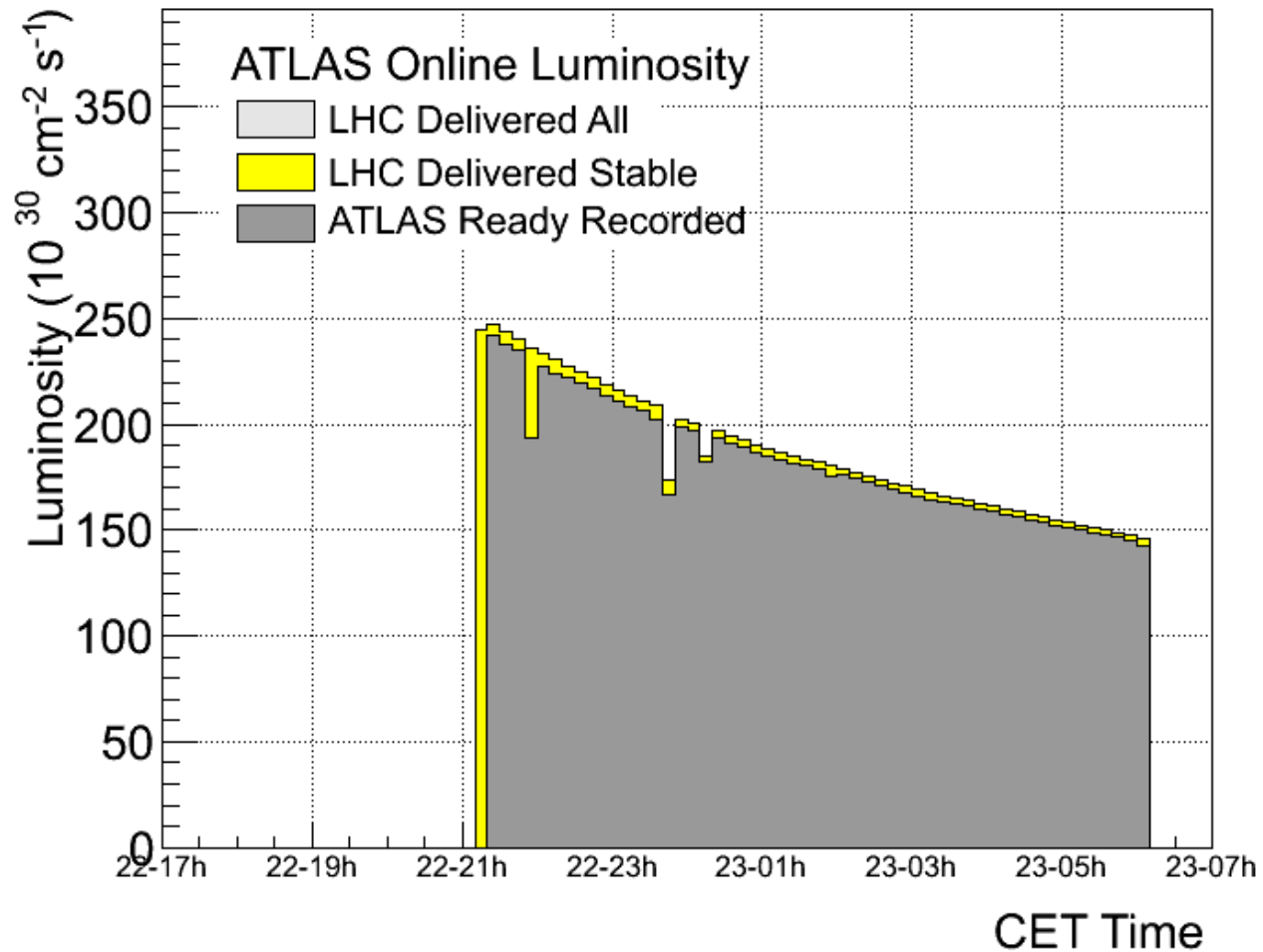
PM Status B1

ENABLED

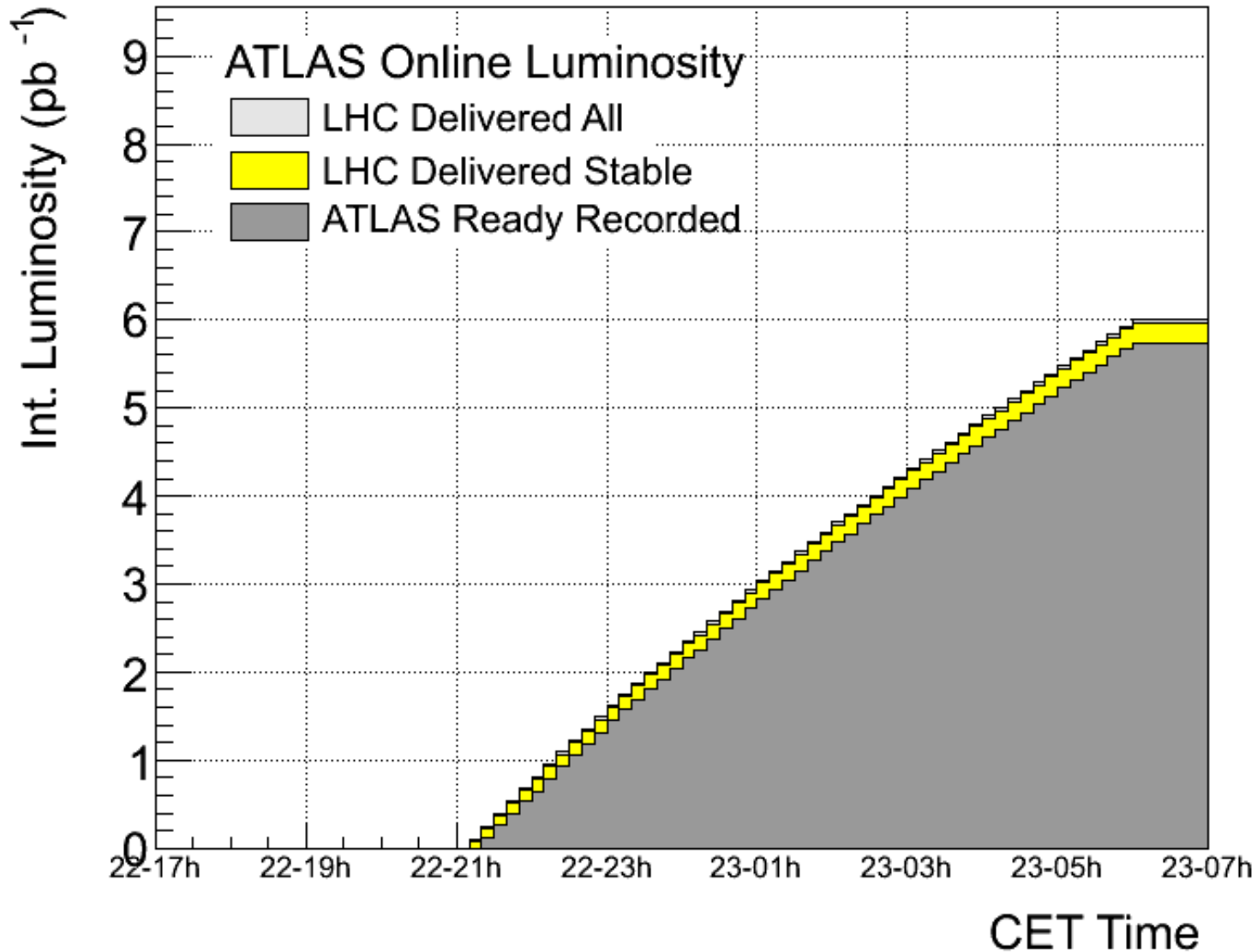
PM Status B2

ENABLED

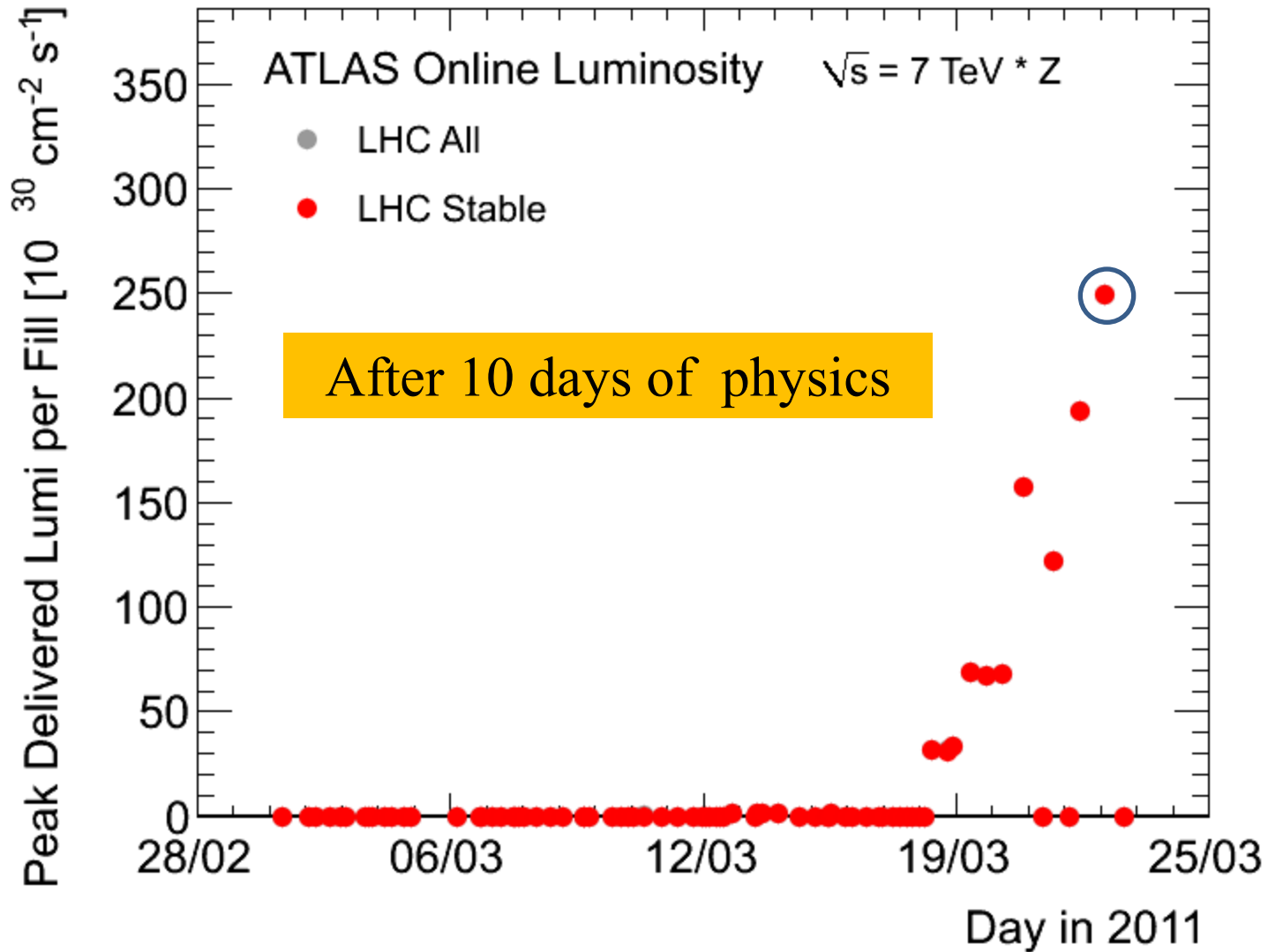
Best fill 1st Period; Luminosity with time



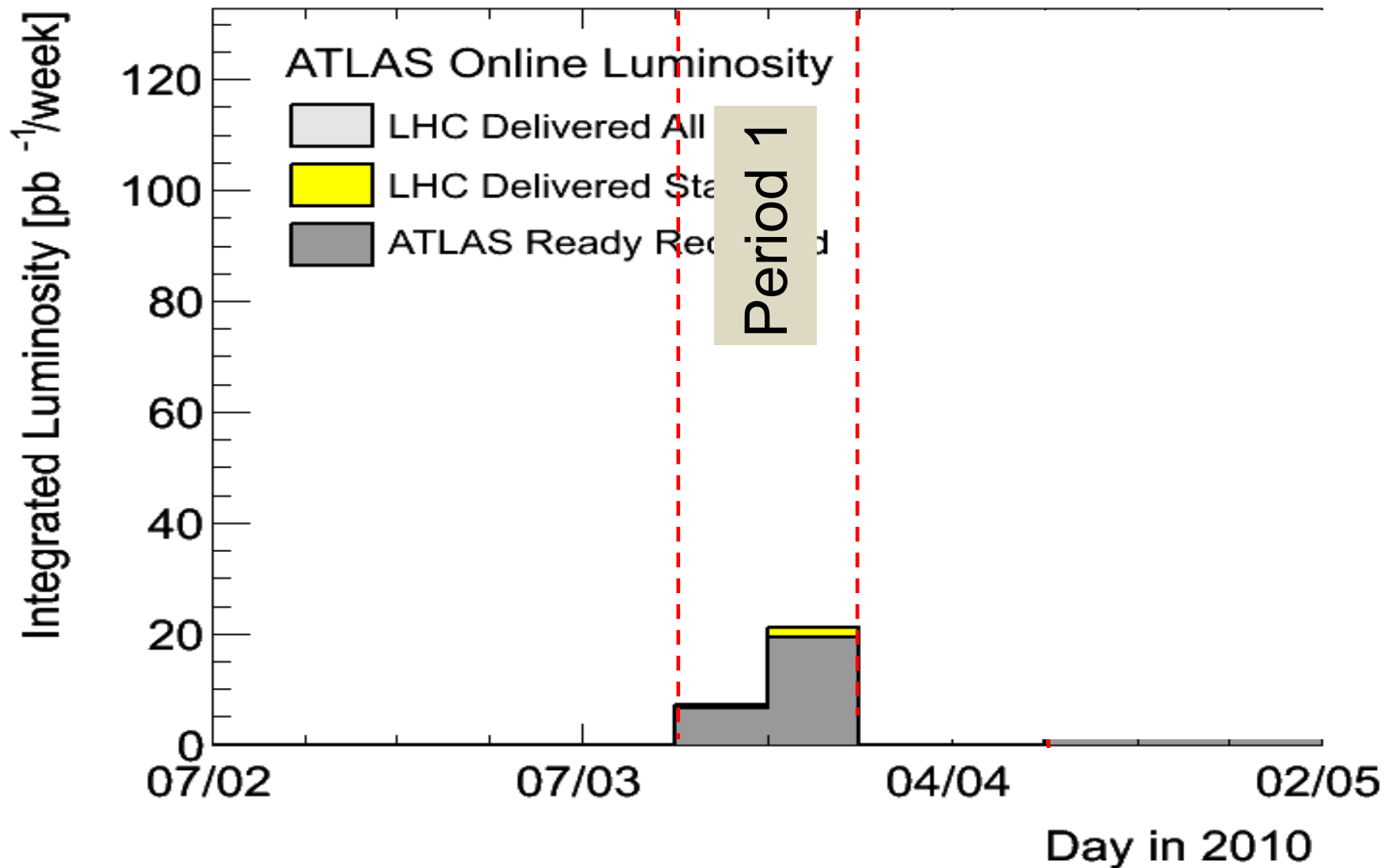
1st Period: Best Integrated Luminosity



First Record Fill of 2011 (on March 23)



1st Period



2nd Period (a) Intermediate Energy Run at 1.38TeV/beam

Accomplished without too much bother;

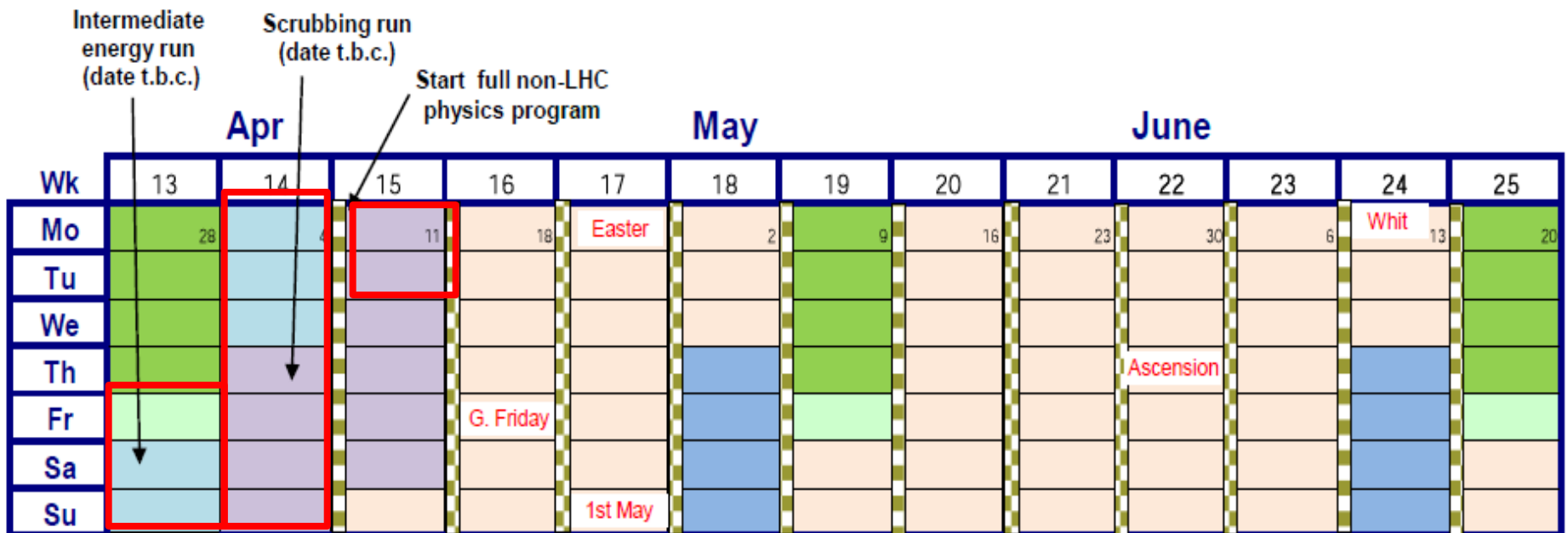
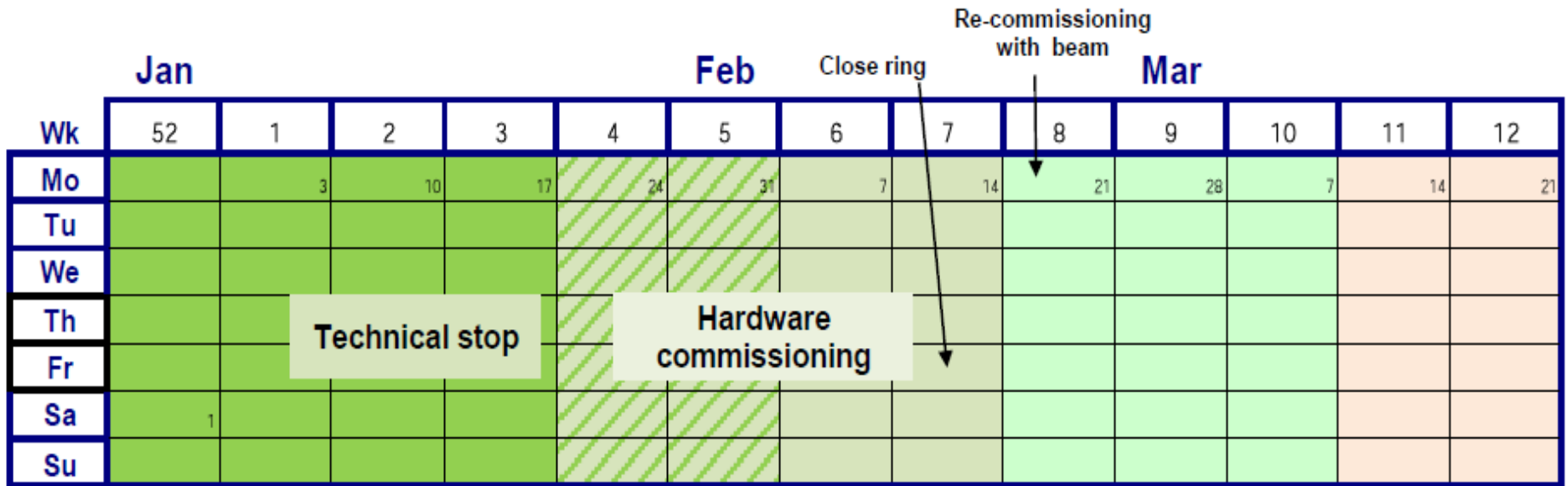
Done in 4 days 25th March – 28th March
BEFORE the Technical stop

2nd Period (b)

Scrubbing Run at 450 GeV/beam.

10 days or real scrubbing foreseen,
but because of technical hiccups
took 12 days of calendar time

2011 LHC schedule

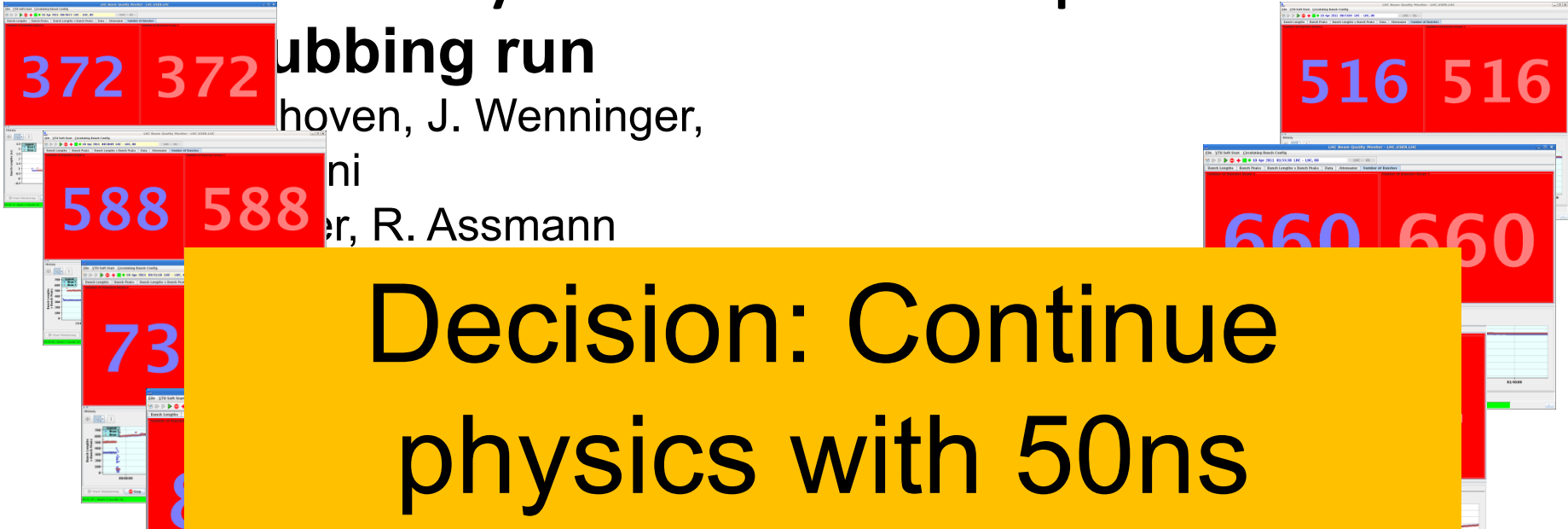


Scrubbing: only 5 effective days

- Intensity progression – 50 ns
 - Above 600 bunches beam stability became an issue and slowed down temporarily (many dumps) the progression.
 - Tune shifts with intensity, RF tuning...
 - All dumps well captured by MPS.
 - No issues with HOM power for RF.

Date	Bunches B1+B2
Tue 5 th April	300+300
Wed 6 th April	408+336
Sat 8 th April	588+588
Sun 9 th April	804+804
Mon 10 th April	1020+1020

Summary of week 14 & part of 15



Decision: Continue physics with 50ns



3rd Period: Increasing the number of bunches

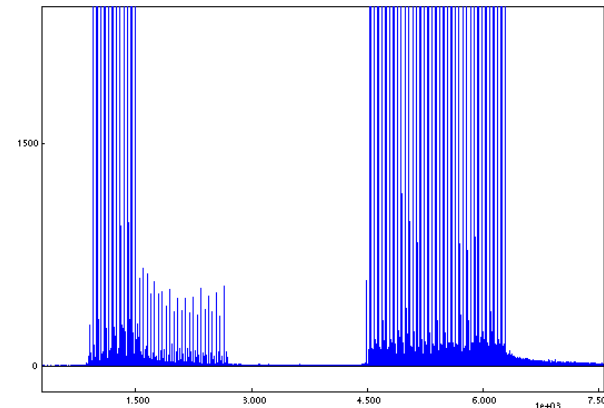
Issues encountered with Higher Intensities

- Requires much finer control of the beam parameters
 - Chromaticity, gain of feedback and use of Landau octupoles
 - Injection quality
- Many more UFOs: not yet serious

The Basics: Injection Quality



small parasitic bucket population $\approx 1\%$



UFO's: 90 in 90 minutes

[file](#) [LHC Control](#) [Favorites](#) [HWC](#) [General](#) [Observation](#) [Print...](#) [WorkingSet](#) [Screenshot](#) [Active Tasks](#)
Context 1: PLS_LINE=LHC.USER.LHC 1

RBA: lhcop

Acquisition

Concentrator Acquisition ▼

Settings

Found UFOs

UFO BLM	Losses_RS05 [Gy/s]	Time (local)	Losses_RS01 [Gy/s]	Losses_RS04 [Gy/s]	L	L	L	L	L	L	L	L	L	L	L
BLMQI.25L8.B1E10_MQ	1.03E-4	2011-04-13 14:06...	9.05E-4	3.39E-4	...	...	...	...	...	...	...	...	...	...	...
BLMQI.13R3.B1110_MQ	3.25E-5	2011-04-13 14:06...	3.62E-4	1.19E-4	...	...	...	...	...	...	...	...	...	...	...
BLMQI.27L8.B2110_MQ	6.41E-4	2011-04-13 14:06...	2.53E-3	1.49E-3	...	...	...	...	...	...	...	...	...	...	...
BLMQI.13R2.B2E10_MQ	3.82E-4	2011-04-13 14:06...	2.44E-3	1.17E-3	...	...	...	...	...	...	...	...	...	...	...
BLMQI.18L5.B1110_MQ	7.49E-5	2011-04-13 14:08...	9.05E-4	2.72E-4	...	...	...	...	...	...	...	...	...	...	...
BLMQI.26L1.B2E30_MQ	1.73E-4	2011-04-13 14:11...	1.18E-3	6.05E-4	...	...	...	...	...	...	...	...	...	...	...
BLMEI.05R8.B2E20_MKI.D5R8.B2	8.56E-4	2011-04-13 14:11...	3.08E-3	2.13E-3	...	...	...	...	...	...	...	...	...	...	...
BLMQI.19R3.B1110_MQ	1.48E-4	2011-04-13 14:11...	3.17E-3	5.94E-4	...	...	...	...	...	...	...	...	...	...	...
BLMQI.07L2.B1E10_MQM	2.12E-4	2011-04-13 14:12...	6.34E-4	3.73E-4	...	...	...	...	...	...	...	...	...	...	...
BLMQI.18L6.B2110_MQ	2.18E-4	2011-04-13 14:13...	1.36E-3	6.56E-4	...	...	...	...	...	...	...	...	...	...	...
BLMQI.19R3.B1110_MQ	2.77E-4	2011-04-13 14:13...	1.27E-3	6.56E-4	...	...	...	...	...	...	...	...	...	...	...
BLMQI.07L1.B1110_MQM	6.93E-5	2011-04-13 14:14...	1.09E-3	2.72E-4	...	...	...	...	...	...	...	...	...	...	...
BLMQI.29L6.B1E10_MQ	5.15E-4	2011-04-13 14:15...	7.51E-3	1.97E-3	...	...	...	...	...	...	...	...	...	...	...
BLMQI.16L3.B2E10_MQ	6.66E-4	2011-04-13 14:18...	4.07E-3	1.86E-3	...	...	...	...	...	...	...	...	...	...	...
BLMQI.10R5.B2110_MQML	4.94E-4	2011-04-13 14:21...	4.52E-3	1.91E-3	...	...	...	...	...	...	...	...	...	...	...
BLMQI.10R8.B1110_MQML	7.85E-4	2011-04-13 14:22...	3.98E-3	2.63E-3	...	...	...	...	...	...	...	...	...	...	...
BLMQI.28R2.B1110_MQ	9.33E-5	2011-04-13 14:23...	5.43E-4	3.05E-4	...	...	...	...	...	...	...	...	...	...	...
BLMQI.25R8.B2E10_MQ	4.41E-4	2011-04-13 14:25...	3.08E-3	1.51E-3	...	...	...	...	...	...	...	...	...	...	...
BLMQI.26L3.B1110_MQ	8.91E-5	2011-04-13 14:26...	5.43E-4	2.94E-4	...	...	...	...	...	...	...	...	...	...	...
BLMQI.19R2.B2E10_MQ	2.83E-4	2011-04-13 14:27...	1.09E-3	6.22E-4	...	...	...	...	...	...	...	...	...	...	...
BLMQI.09L7.B1E10_MQ	7.58E-4	2011-04-13 14:29...	3.53E-3	1.67E-3	...	...	...	...	...	...	...	...	...	...	...
BLMQI.26L1.B1110_MQ	9.05E-5	2011-04-13 14:29...	6.34E-4	3.00E-4	...	...	...	...	...	...	...	...	...	...	...
BLMEI.05R8.B2E20_MKI.D5R8.B2	9.05E-5	2011-04-13 14:29...	1.18E-3	3.11E-4	...	...	...	...	...	...	...	...	...	...	...
BLMQI.31R3.B1110_MQ	5.24E-3	2011-04-13 14:29...	1.23E-2	7.46E-3	...	...	...	...	...	...	...	...	...	...	...
BLMQI.19R3.B1110_MQ	2.25E-4	2011-04-13 14:30...	1.90E-3	7.81E-4	...	...	...	...	...	...	...	...	...	...	...
BLMQI.14R2.B1110_MQ	8.06E-4	2011-04-13 14:30...	8.78E-3	3.17E-3	...	...	...	...	...	...	...	...	...	...	...
BLMQI.14L4.B2E30_MQ	5.37E-5	2011-04-13 14:31...	3.62E-4	3.10E-4	...	...	...	...	...	...	...	...	...	...	...
BLMQI.14R7.B1E10_MQ	5.12E-4	2011-04-13 14:36...	3.26E-3	1.41E-3	...	...	...	...	...	...	...	...	...	...	...
BLMQI.25R8.B2E10_MQ	1.60E-4	2011-04-13 14:39...	1.18E-3	4.92E-4	...	...	...	...	...	...	...	...	...	...	...
BLMQI.25R8.B2E10_MQ	1.75E-4	2011-04-13 14:41...	9.96E-4	5.32E-4	...	...	...	...	...	...	...	...	...	...	...
BLMQI.12L4.B2E10_MQ	6.55E-4	2011-04-13 14:43...	2.26E-3	1.24E-3	...	...	...	...	...	...	...	...	...	...	...
BLMQI.28R7.B2110_MQ	4.51E-4	2011-04-13 14:44...	2.99E-3	1.43E-3	...	...	...	...	...	...	...	...	...	...	...
BLMQI.08L3.B1110_MQ	1.13E-3	2011-04-13 14:46...	1.72E-2	4.33E-3	...	...	...	...	...	...	...	...	...	...	...
BLMQI.25R7.B1E10_MQ	1.20E-4	2011-04-13 14:47...	1.18E-3	4.52E-4	...	...	...	...	...	...	...	...	...	...	...
BLMQI.31R5.B2110_MQ	2.67E-4	2011-04-13 14:47...	1.90E-3	9.16E-4	...	...	...	...	...	...	...	...	...	...	...
BLMQI.18R8.B1110_MQ	3.96E-4	2011-04-13 14:48...	3.17E-3	1.44E-3	...	...	...	...	...	...	...	...	...	...	...
BLMQI.24R8.B2E10_MQ	3.01E-4	2011-04-13 14:50...	2.26E-3	1.05E-3	...	...	...	...	...	...	...	...	...	...	...
BLMQI.21L6.B2110_MQ	2.53E-4	2011-04-13 14:51...	2.72E-3	9.79E-4	...	...	...	...	...	...	...	...	...	...	...
BLMQI.14R2.B1110_MQ	5.19E-4	2011-04-13 14:51...	6.06E-3	2.03E-3	...	...	...	...	...	...	...	...	...	...	...

Algorithm

Optimized Algorithm ▼

Settings

Threshold for BLMs 1.0E-4

Use running sum: 4

Threshold for ratio of RS2/1 0.55

Threshold for ratio of RS3/2 0.45

Threshold for ratio of RS4/3 0.55

Get Set

Action

autosave

Remove Remove all Show data save load

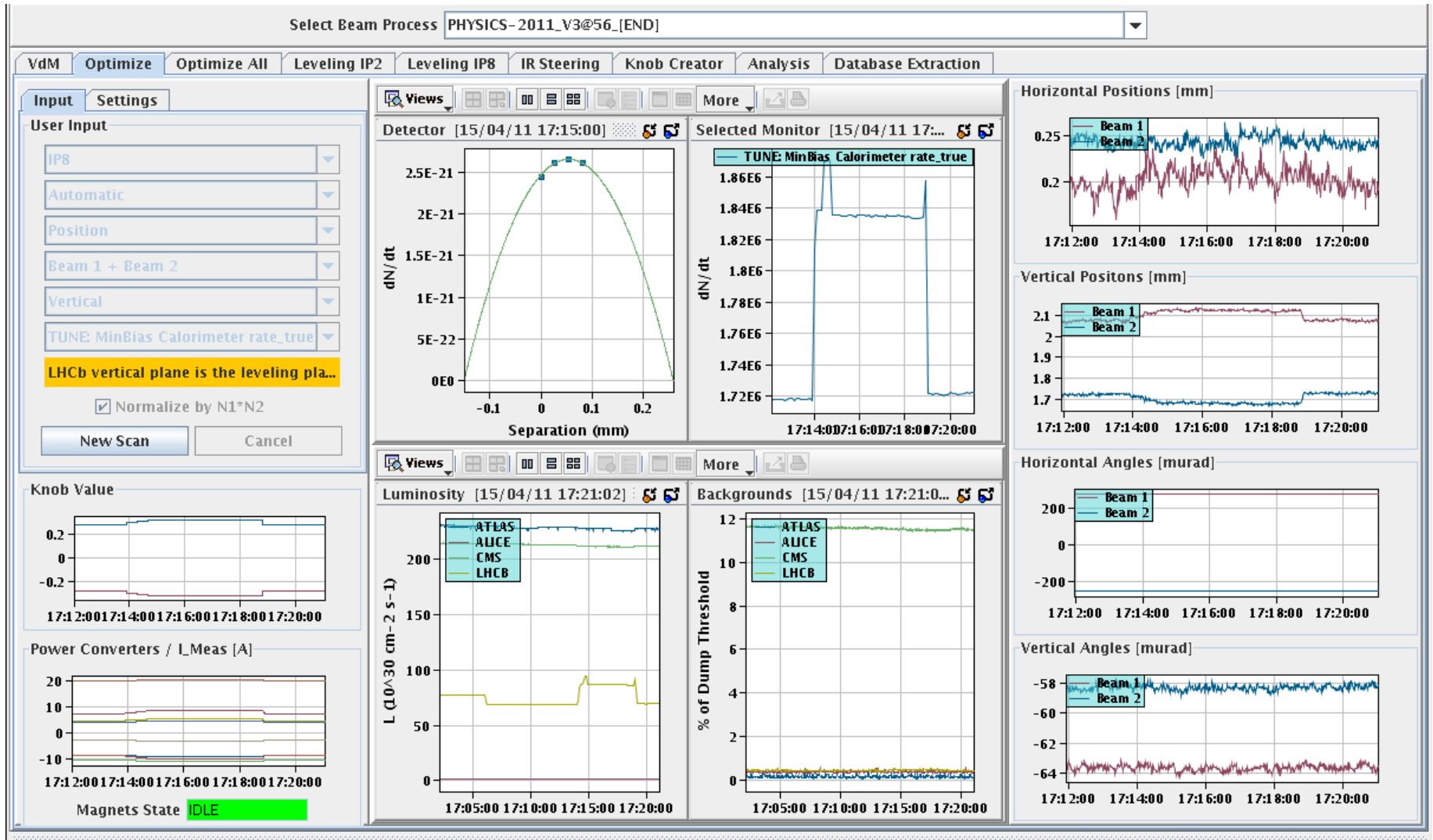
14:47:47 - New RBA Token was set to CMW: RBA-Token[serial=0xd7f7b4dd;authTime=2011-04-13@14:34:48;endTime=2011-04-13@22:33:48;application=AppPrincipal[name=UFO Buster, critical=false, timeout=1];locatio...

3rd Period: Increasing the number of bunches

Issues with Machine Protection

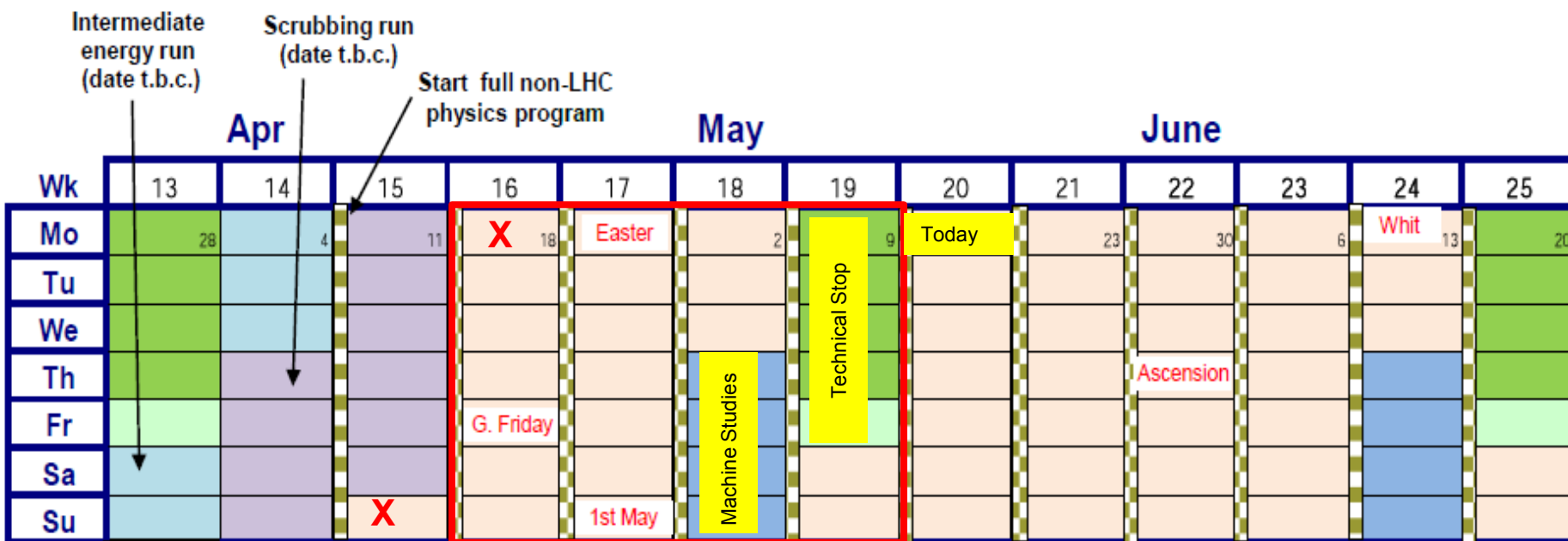
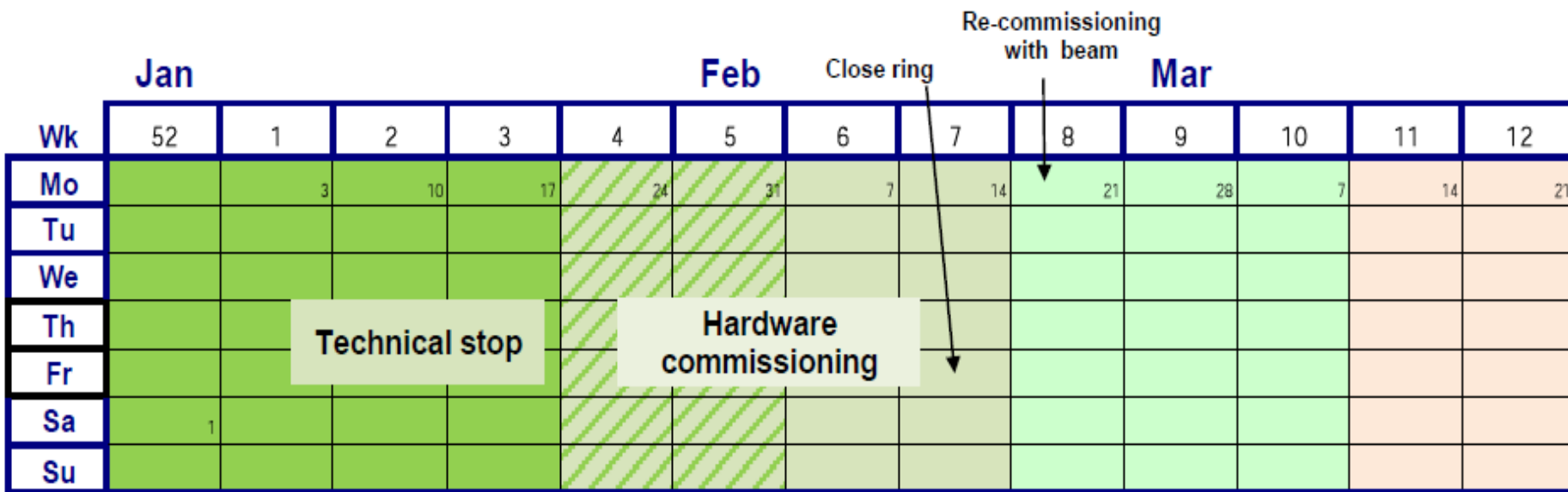
1. Collimation loss of hierarchy at 450 GeV
 - Due to order in which the loss maps were performed
2. 72 bunches
 - Last bunch of previous injection got kicked; low intensity and higher emittance
 - BPMs position calibration is sensitive to bunch intensity
 - Dump interlock measures local position of all bunches
3. **HTS quench (7th April)**
4. **Injection Kicker Flashover (18th April)**

Lumi leveling test 15th April: now operational

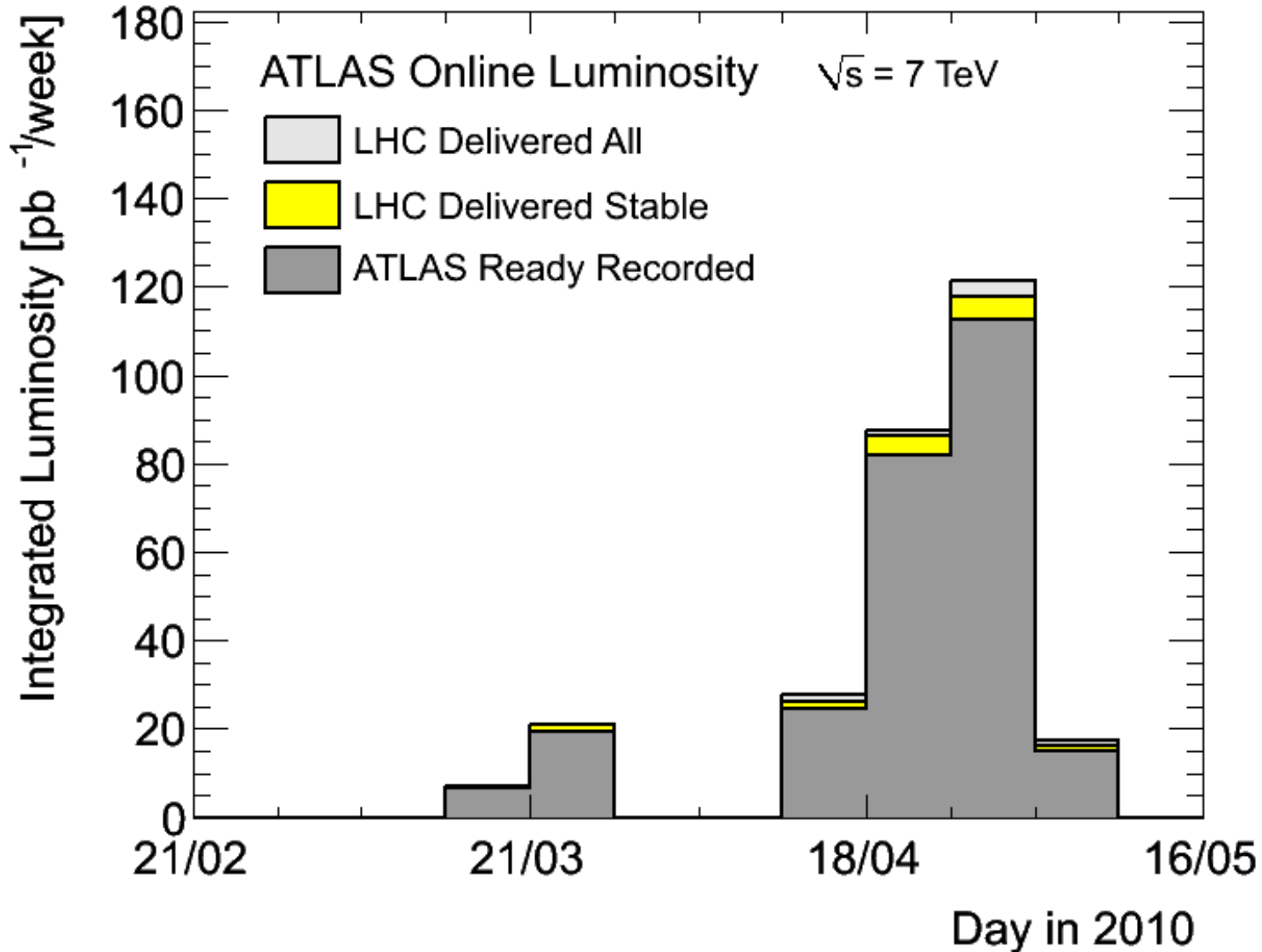


LHCb

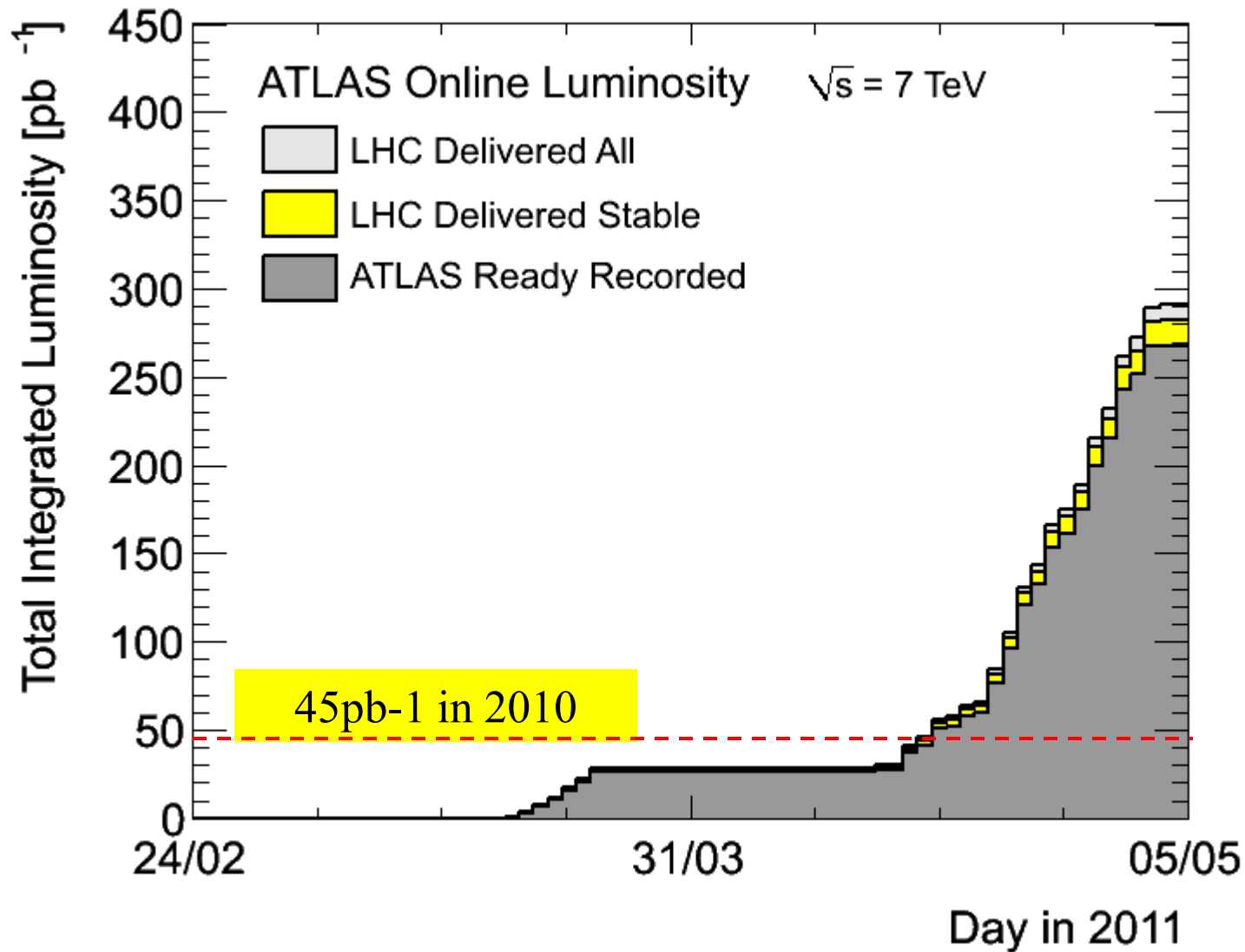
2011 LHC schedule

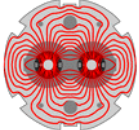


2011: Weekly summary of Integrated Luminosity



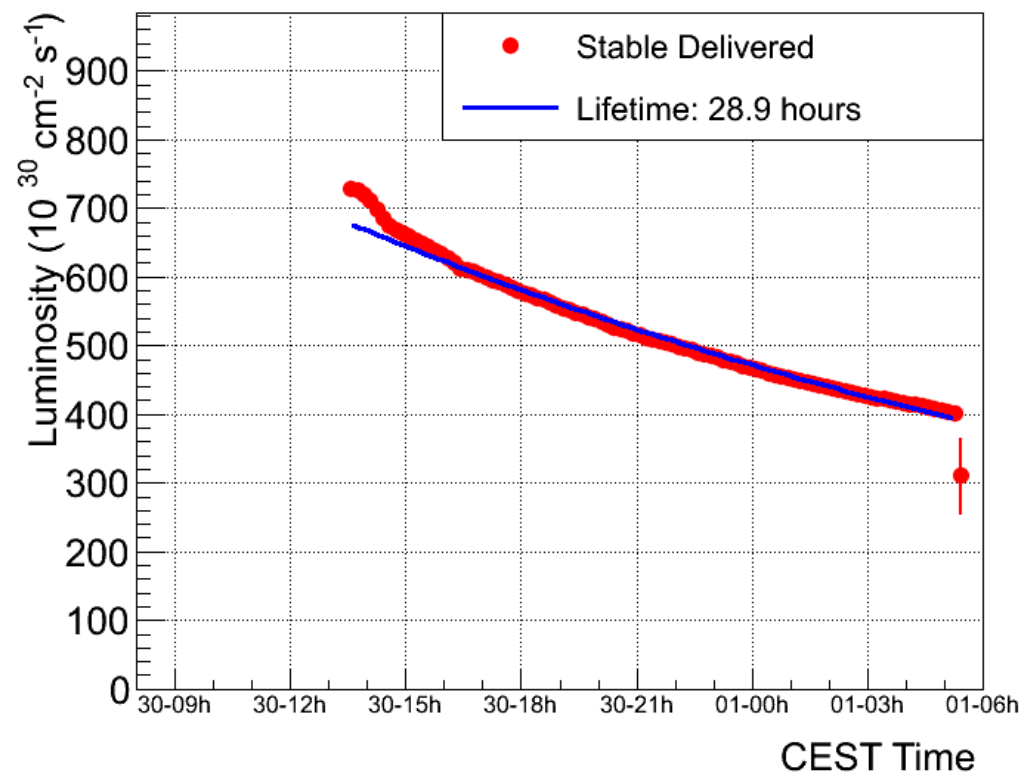
2011: Evolution of Integrated (to 2nd May)





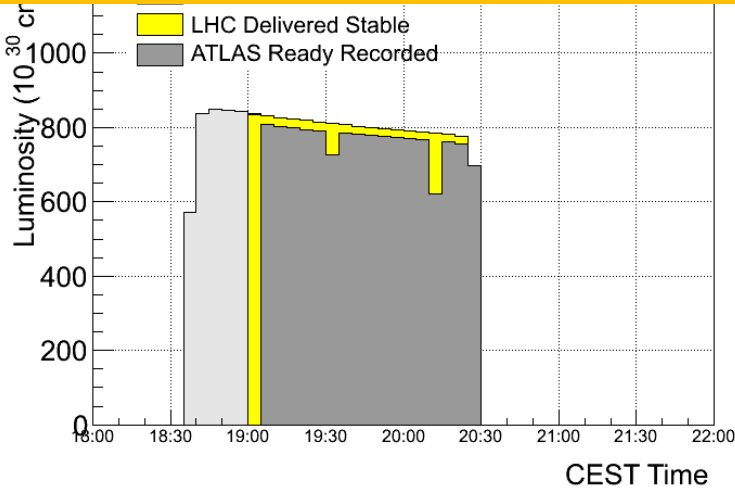
Fill 1749 – overnight (1—2 May)

Peak luminosity	~6.9 e32
Integrated luminosity	~29.7 pb-1
Stable beams	15 hours 53 minutes
Colliding bunches	598
Average emittance from luminosity	~2.5 micron

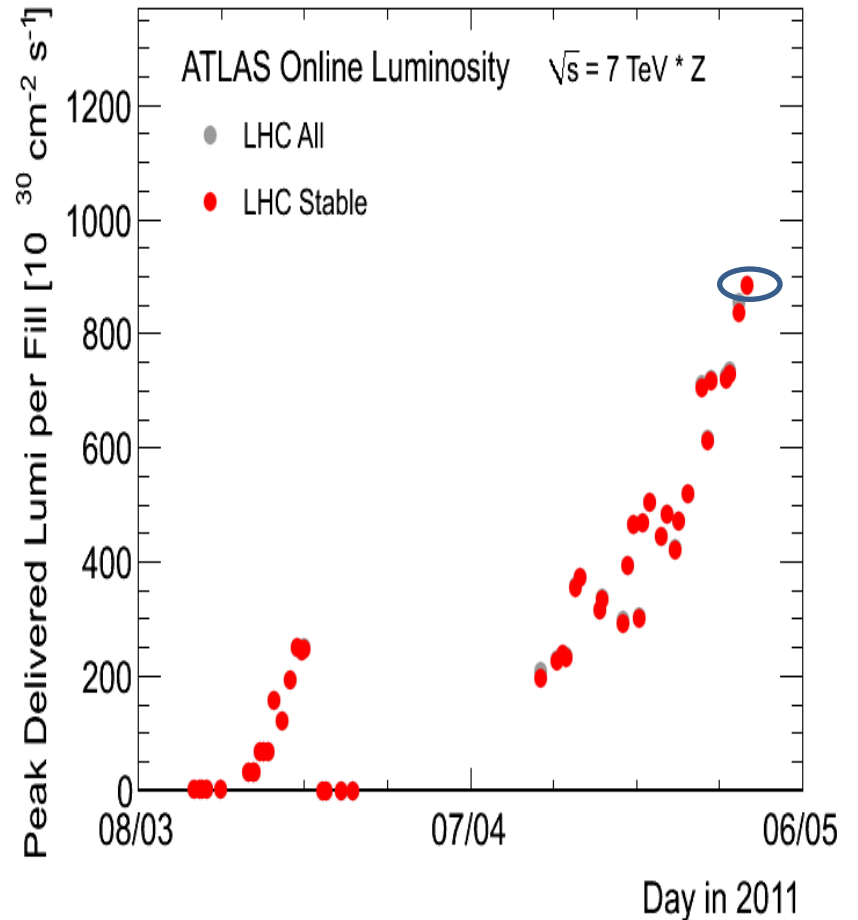
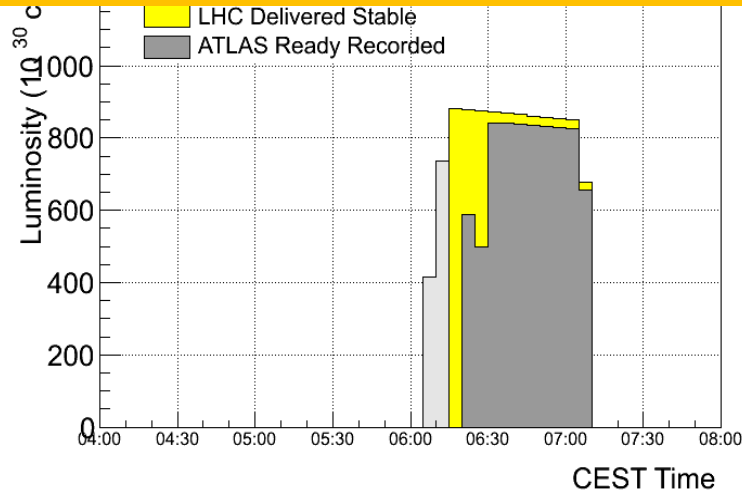


2 fills with 768 bunches/beam

Sunday May 01; $0.84 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$



Monday May 02, $0.88 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$



MD1

Some highlight ...

- MDs prove excellent performance potential of LHC:
 - No head-on beam-beam limit encountered with 3 times nominal brightness. Total tune shift: 0.03 with ATLAS/CMS collisions.
 - ATS injection optics with different integer tunes fine to 3.5 TeV.
 - Collimation system reached tighter settings with better cleaning efficiency.
 - Impedance and instabilities under control.
- Operational improvements:
 - 90m optics for ALFA and TOTEM works fine.

43% of design

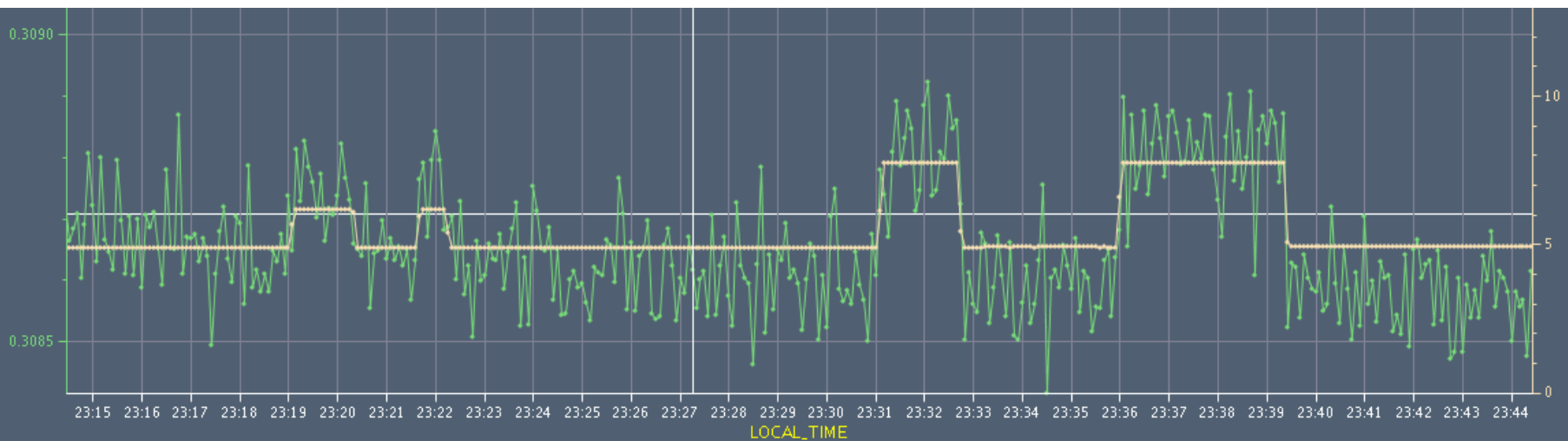
Beam-beam limit

50% above design

- Collided high intensity beams (**1.7 E11**) and small emittances (smaller than **1.5 um**) in IP1 and IP5.
- First attempt achieved **tune shifts 0.01 per IP**, vertical blowup of emittance.
 - Blowup most likely due to 10th order resonance.
- In final attempt reduced vertical tune to end up below 10th order after putting beams in collision. No more blowup observed, **tune shifts per IP in excess of 0.015** (with initial emittance below 1.2 um).
 - ↑ Factor of 4.5 above design
- Collisions in IP1 and IP5, optimized and no more blowup.
- No limit found for head-on beam-beam effects for the intensities investigated so far (no long range yet).

Vertical tune shift – collimator movement

- Clearly seen in vertical plane when moving collimators out by 4 sigma and back in, etc...
- Magnitude: ~ 0.0003



Next Period 4.5 weeks of
physics before the summer
conferences



Stop Press: Back in Physics Sunday

LHC Page1

Fill: 1783

E: 3500 GeV

15-05-2011 13:44:41

PROTON PHYSICS: STABLE BEAMS

Energy:

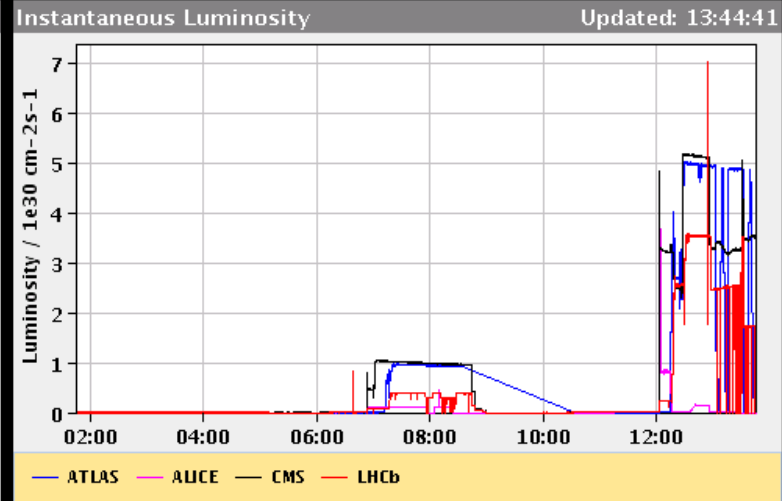
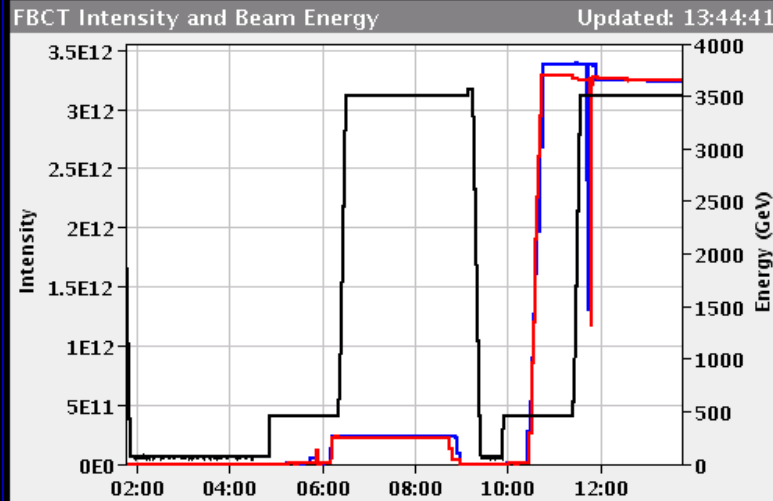
3500 GeV

I(B1):

3.23e+12

I(B2):

3.24e+12



Comments 15-05-2011 12:53:21 :

All IPs optimized
 Starting VdM scan in IP1
 We separate the others by the lumi
 region range

BIS status and SMP flags

B1

B2

Link Status of Beam Permits **true** **true**
 Global Beam Permit **true** **true**
 Setup Beam **false** **false**
 Beam Presence **true** **true**
 Moveable Devices Allowed In **true** **true**
 Stable Beams **true** **true**

AFS: Single_38b+1small_14_16_22_4bpi11inj

PM Status B1

ENABLED

PM Status B2

ENABLED

Stable Beams Today 2 E32, 228 bunches

LHC Page1

Fill: 1785

E: 3500 GeV

16-05-2011 14:01:29

PROTON PHYSICS: STABLE BEAMS

Energy:

3500 GeV

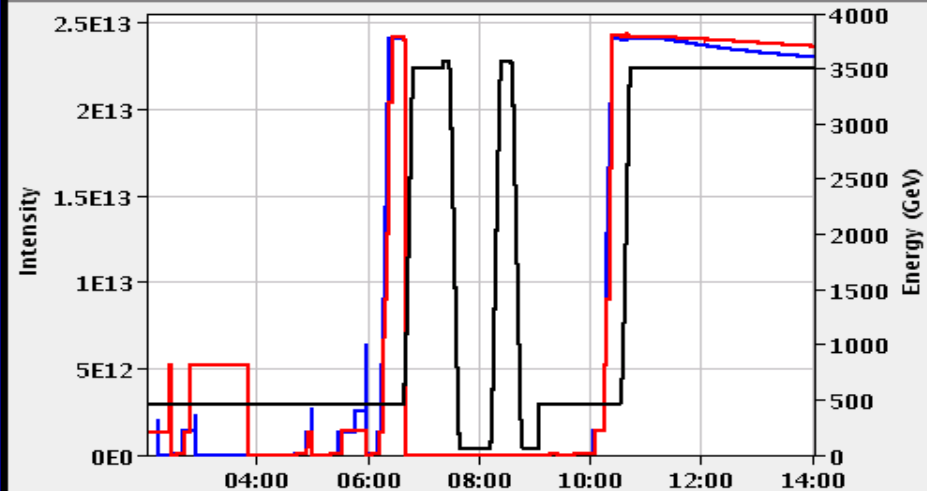
I(B1):

2.32e+13

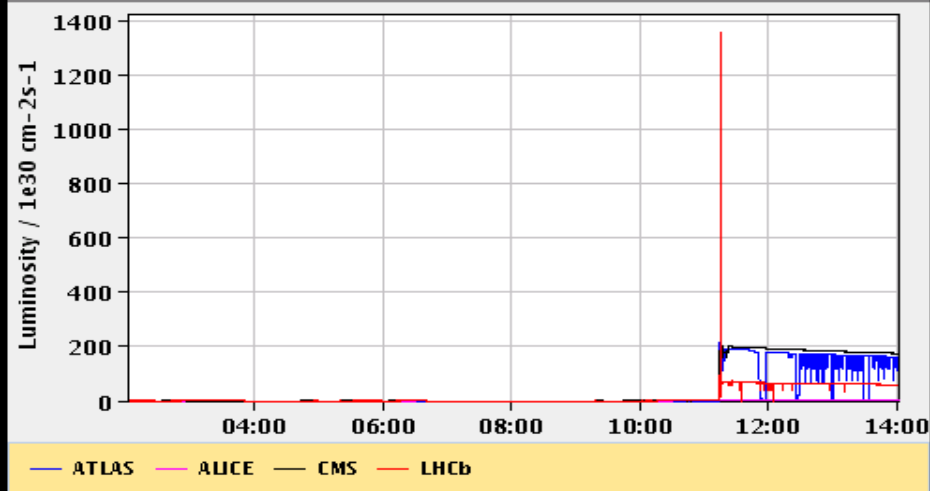
I(B2):

2.38e+13

FBCT Intensity and Beam Energy Updated: 14:01:26



Instantaneous Luminosity Updated: 14:01:28



Comments 16-05-2011 12:18:53 :

STABLE BEAMS

IP1 length scale calibration on-going

fill with 50ns for PHYSICS (228b)

BIS status and SMP flags

	B1	B2
Link Status of Beam Permits	true	true
Global Beam Permit	true	true
Setup Beam	false	false
Beam Presence	true	true
Moveable Devices Allowed In	true	true
Stable Beams	true	true

PM Status B1

ENABLED

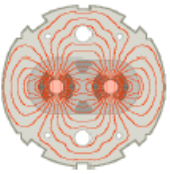
PM Status B2

ENABLED

AFS: 50ns_228b+1small_214_12_180_36bpi_8inj



Next Years



Physics data-taking until end of 2012

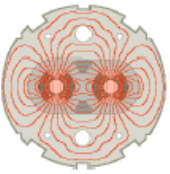
- Start taking advantage of the performance possibilities arising from the machine studies (July 2011 performance review, following MD2)
 - beam beam, aperture, emittance, intensity (pile-up)
- Following measurements of the copper stabilizers during the Christmas stop we will re-evaluate the maximum energy for 2012 (Chamonix 2012)

Long Shutdown in 2013

- repair/upgrade the magnet interconnects for operation at 6.5-7 TeV/beam
- install new collimation system in DS zone?



Longer Term



HL-LHC: Luminosity Upgrade (x5 with “levelling”)

HE-LHC: Possible energy increase of the LHC

Topics to be covered by Rolf Heuer
tomorrow afternoon

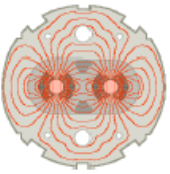
Summary



- Right on Track
- Intensity, peak and Integrated luminosity go very rapidly
- Successfully implemented luminosity leveling for LHCb
- Recently a few “near misses” causing sleepless nights
 - HTS protection fault for DFBs
 - Injection kicker flashover
- **We must remain vigilant!!**
- How to continue for the rest of 2

Warning Shots

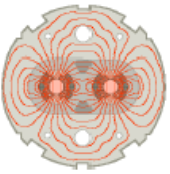




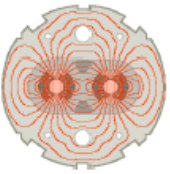
Thank you for your attention



Longer Term

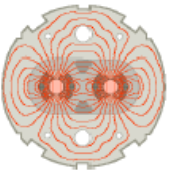


**HL-LHC: Luminosity Upgrade (x5
with “levelling”)**



Luminosity Upgrade Scenario

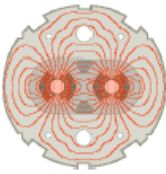
- For LHC high luminosities, the luminosity lifetime becomes comparable with the turn round time \Rightarrow Low efficiency
- Preliminary estimates show that the useful integrated luminosity is greater with
 - a peak luminosity of $5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ and a longer luminosity lifetime (by **luminosity levelling**)
 - than with 10^{35} and a luminosity lifetime of a few hours
- Luminosity Levelling by
 - Beta*, crossing angle, crab cavities, and bunch length
 - ??? Off steering



First Thoughts on an Energy Upgrade



Hardware for the Upgrade



- New high field insertion **quadrupoles**
- Upgraded **cryo system** for IP1 and IP5
- Upgrade of the intensity in the **Injector Chain**
- **Crab Cavities** to take advantage of the small beta*
- **Single Event Upsets**
 - **SC links** to allow power converters to be moved to surface
- **Misc**
 - Upgrade some correctors
 - Re-commissioning DS quads at higher gradient
 - Change of New Q5/Q4 (larger aperture), with new stronger corrector orbit, displacements of few magnets
 - Larger aperture D2

Very Long Term Objectives: Higher Energy LHC



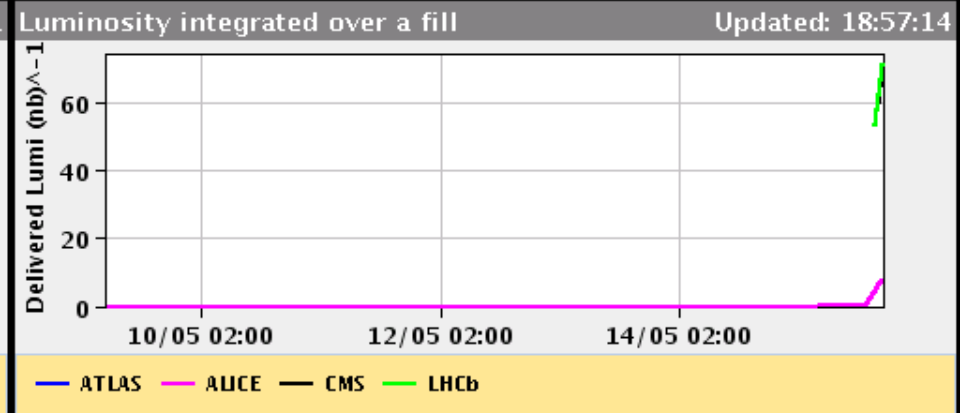
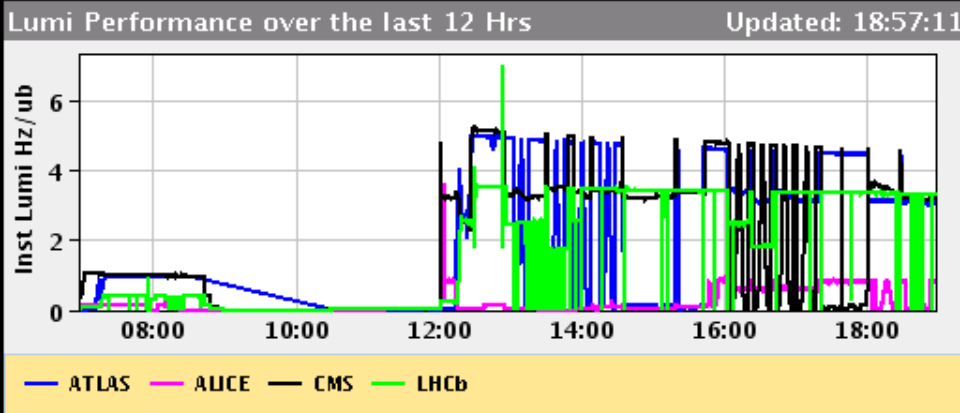
Preliminary HE-LHC - parameters

	nominal LHC	HE-LHC
beam energy [TeV]	7	16.5
dipole field [T]	8.33	20
dipole coil aperture [mm]	56	40-45
#bunches / beam	11248	1404
bunch population [10^{11}]	1.15	1.29
initial transverse normalized emittance [μm]	3.75 (x), 1.84 (y)	3.75 (x), 1.84 (y)
number of IPs contributing to the luminosity	3	2
maximum total beam size at IP [μm]	0.01	0.01
IP beta function [m]	0.55	1.0 (x), 0.43 (y)
full crossing angle [mrad]	285 ($9.5 \sigma_{x,y}$)	175 ($12 \sigma_{x0}$)
stored beam current [mA]	362	479
SR power [MW]	3.6	62.3
longitudinal damping time [h]	12.9	0.98
events per bunch crossing	19	76
peak luminosity [$\text{cm}^{-2}\text{s}^{-1}$]	1.0	2.0
beam lifetime [h]	46	13
integrated luminosity over 10 h [fb^{-1}]	0.3	0.5

Very preliminary with large error bars

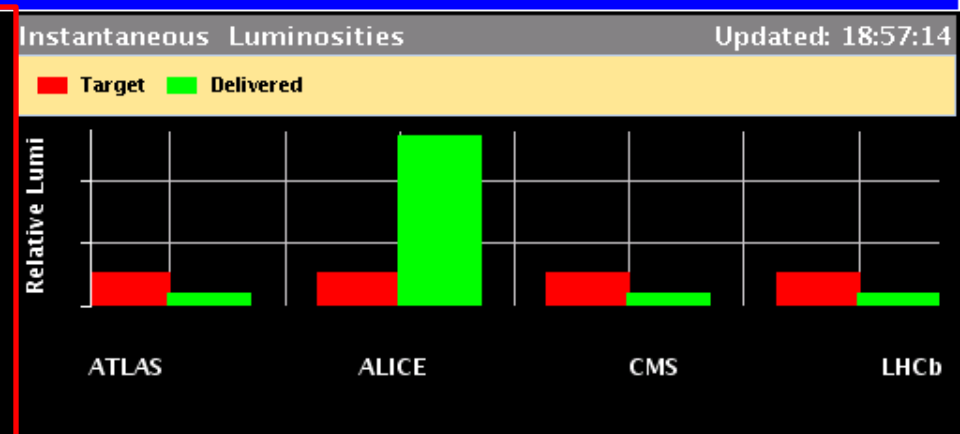
HE-LHC – main issues and R&D

- **high-field 20-T dipole** magnets based on Nb_3Sn , Nb_3Al , and HTS
- **high-gradient quadrupole magnets** for arc and IR
 - **fast cycling SC magnets** for 1-TeV injector
- **emittance control** in regime of strong SR damping and IBS
- cryogenic handling of **SR heat load** (first analysis; looks manageable)
 - dynamic **vacuum**



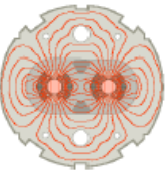
STABLE BEAMS

	Luminosity (ub.s) ⁻¹	Fill Lumi (nb) ⁻¹
ATLAS	3.07	68.5
ALICE	0.79	7.3
CMS	3.18	69.0
LHCb	3.33	71.0

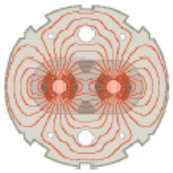


ALICE Target Instantaneous Lumi = 0.148 Hz/ub

LHCb Target Instantaneous Lumi = 10.460954 Hz/ub



Life-cycle

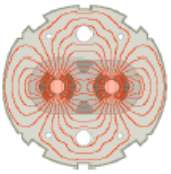


- 1983: Preliminary Performance Estimates for the LHC (S.Myers and W. Schnell, 11th April 1983)
 - 1984: Kick off meeting to discuss ideas for an accelerator to collisions at very high energy
 - 1996: Final decision for the LHC, the most complex instrument ever constructed
 - 10 September 2008: Start of commissioning with beam
 - 19 September 2008: Series of beam losses and damage
 - 19 November 2009: Resumption of beam operation
 - December 2009: First collisions at 2.38 TeV
- Today, successful operation, providing millions of particle collisions for the LHC experiments
- About 2030: The LHC physics programme to be finished ?

A 50 Years Adventure



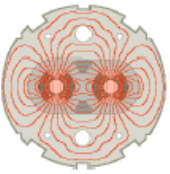
Event of 7th April



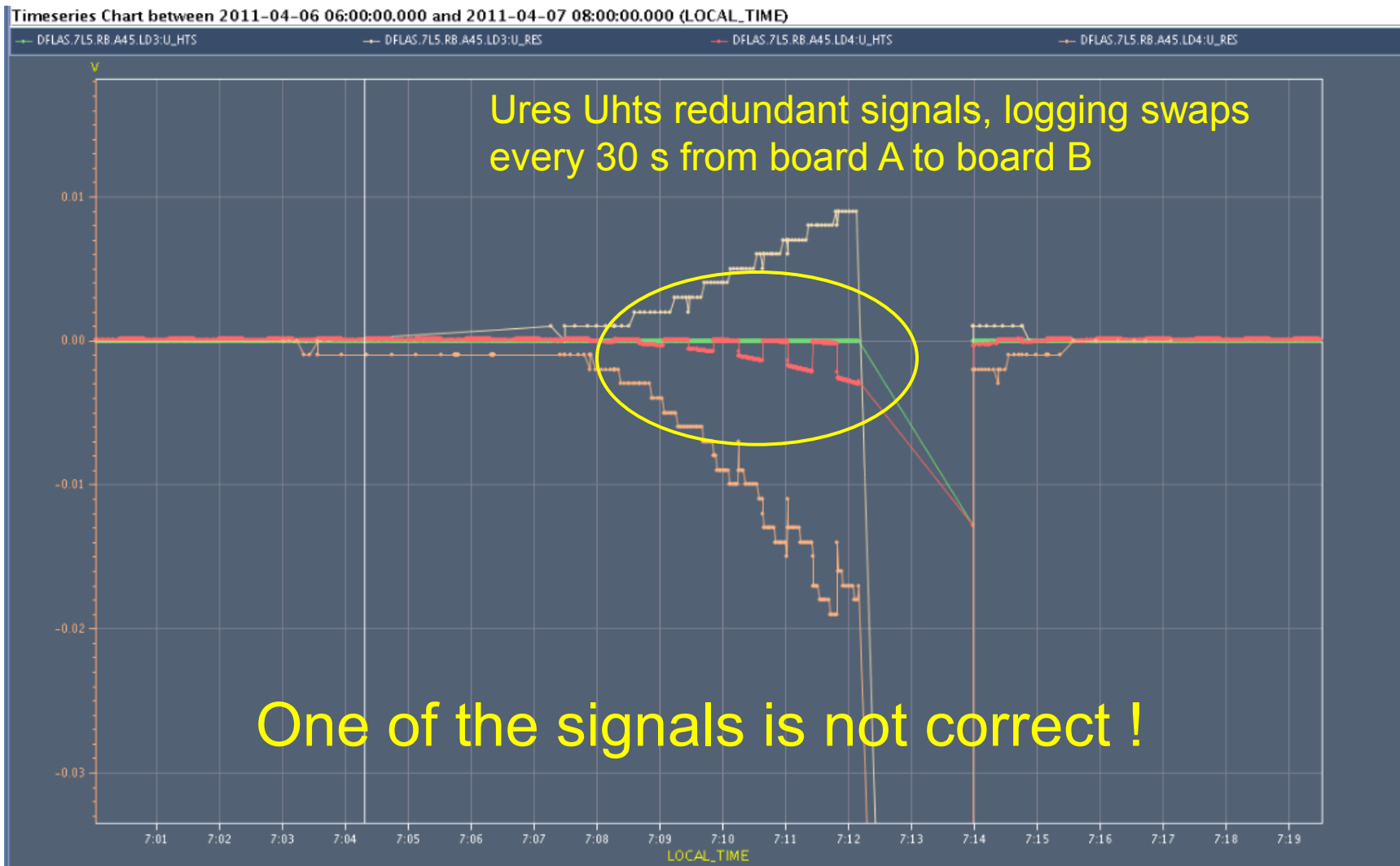
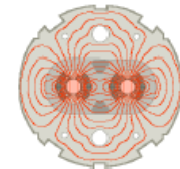
- Thursday afternoon (7th April) all **powering was stopped** in the LHC following the discovery of a worrying cabling problem affecting the QPS system protecting the HTS current leads.
- Followed by an extensive verification campaign.
- Lost about 2 days.

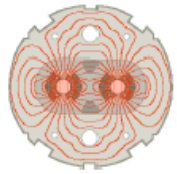


HTS quench (sc link)- what happened



- QPS tripped the RB circuit in sector 45 on Thursday around 07:00.
First time ever quench of HTS current lead
- The HTS quenched due to a lack of cooling in the DFB
 - Faulty electronics board corrupted the temperature feedback loop
- Protection by the QPS monitoring the current leads.
 - Logging of the two HTS signals showed that only one of the two measurements was correct, the other was measuring a short circuit
- **An identical fault on the redundant signal would have left the system unprotected and could lead to beyond repair damage to the DFB. No spares**
- **Decided to stop powering magnets**
 - To validate other circuits





What was swapped...?

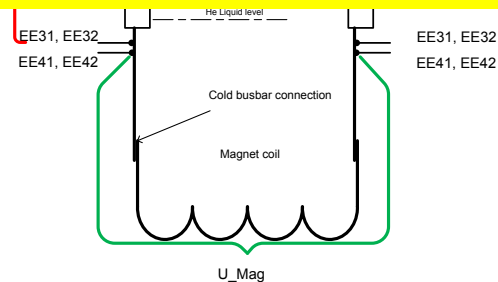
- What was found swapped in RB.A45, Lead#2 on DFBAI (L5)?
EE22 (pin 15) and EE42 (pin16)
of cable between PE and QPS controller

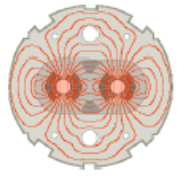


This connection had been like this since 2005

Are all connections like this?

Stop operation until all connections are verified





From the logging

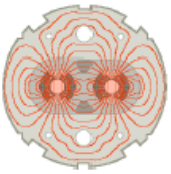
- Analysis of the logging data from old ramps allowed the QPS team to verify the correctness of the signals for other 13 kA circuits
- Verification of U_RES & U_HTS on all IPQs, IPDs, ITs using dedicated powering cycles by the QPS team
 - **Verification of boards A & B**



Example of a healthy channel: both boards move in unison during a ramp



Verification - Friday 8th April



- In the late afternoon all high current circuits except the 600 A circuits had been checked.
 - Acceptable risk for 600 A circuits.
- All tests showed the presence of the expected signals.
- **Green light for powering from TE/MPE in the evening.**

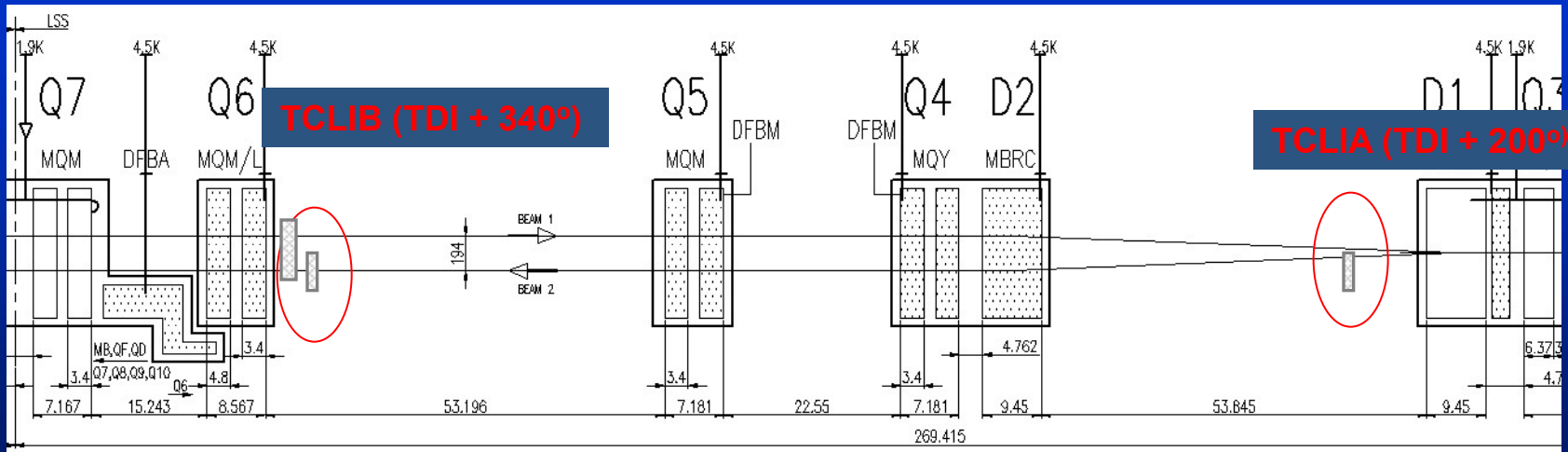
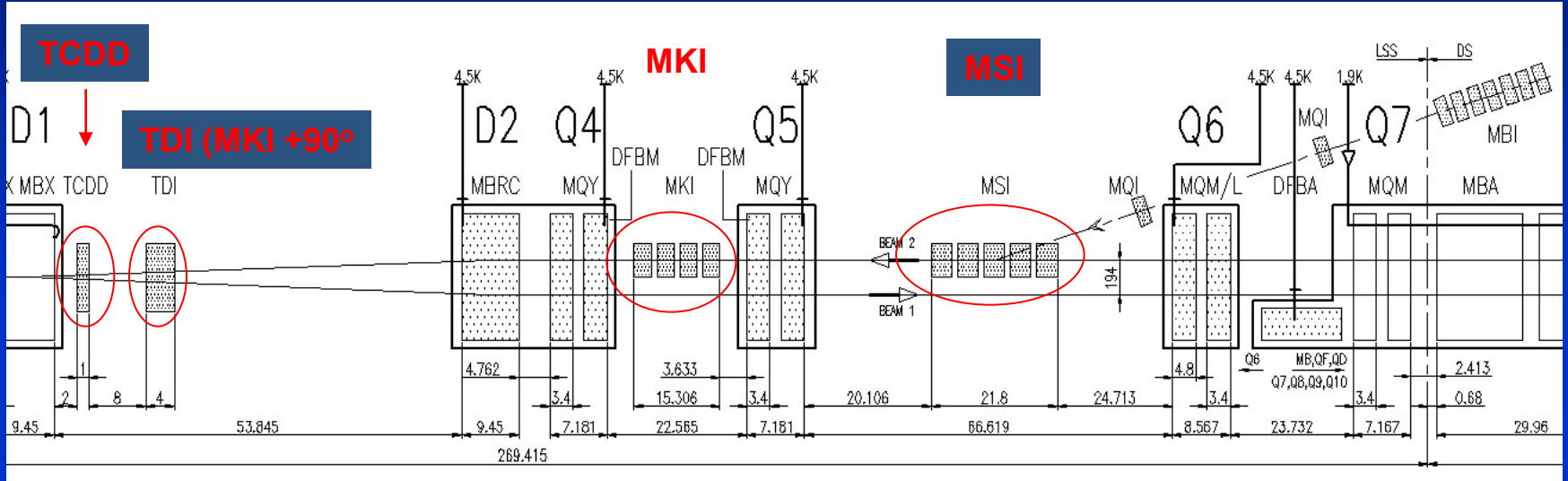
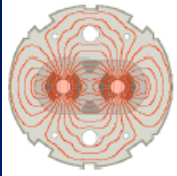
Among all the high current circuits we happen to quench exactly the one circuit with a cabling problem !!

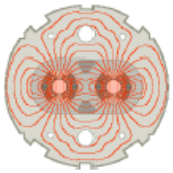
Event of 18th April

- **Flashover (high voltage breakdown) on B2 MKI magnet D (first one seen by the beam) while injecting 72b**
- **Extensive beam losses through P8 and arc 78: result**
 - Kicker interlocked off
 - Quench heaters fired on 11 magnets
 - Vacuum valves closed
 - **Several very anxious hours....**



Overview of injection region (IR8)





LHC Injection Quality Check - Playback

File Mask Playback Help

RBA: goddard

Injection IR2 Injection IR8

2011-04-18 0:06:43.550: BCTs/BQMs cannot verify injection. BQMs show no bunches injected. MKI analysis was bad. BLM analysis was bad. Insufficient BP...

BEAM EXTRACTION INJECTION KICKER BEAM LOSS MONITORS RF BUCKET CHECK INJECTION OSCILLATIONS TRANSFER LINE

2011-04-18 0:06:43.555: Too many bad points to determine result.

	RMS_H	P2P_H	RMS_V	P2P_V
2028	0.0000	0.0000	0.0000	0.0000
2030	0.0000	0.0000	0.0000	0.0000
2118	0.0000	0.0000	0.0000	0.0000
2120	0.0000	0.0000	0.0000	0.0000
2122	0.0000	0.0000	0.0000	0.0000
2124	0.0000	0.0000	0.0000	0.0000

Horizontal oscillations Vertical oscillations

Bad bunch acceptance: 0.25 Bad BPMs acceptance: 0.5

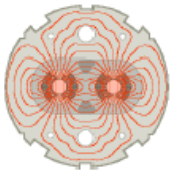
Get LSA references Set references

Bunch within thresholds.

Get last result: B1 Get last result: B2 Playback Previous Event Next Event Show data dump

00:43:43 - BCTs/BQMs cannot verify injection. BQMs show no bunches injected. MKI analysis was bad. BLM analysis was bad. Insufficient BPM data. MKI analysis gave warnings.

Bunch 36 in first injected batch OK -> breakdown after 1.8 us



LHC Injection Quality Check - Playback

File Mask Playback Help

RBA: goddard

Injection IR2 Injection IR8

2011-04-18 0:06:43.550: BCTs/BQMs cannot verify injection. BQMs show no bunches injected. MKI analysis was bad. BLM analysis was bad. Insufficient BP...

BEAM EXTRACTION INJECTION KICKER BEAM LOSS MONITORS RF BUCKET CHECK INJECTION OSCILLATIONS TRANSFER LINE

2011-04-18 0:06:43.555: Too many bad points to determine result.

	RMS_H	P2P_H	RMS_V	P2P_V
2028	0.0000	0.0000	0.0000	0.0000
2030	0.0000	0.0000	0.0000	0.0000
2118	0.0000	0.0000	0.0000	0.0000
2120	0.0000	0.0000	0.0000	0.0000
2122	0.0000	0.0000	0.0000	0.0000
2124	0.0000	0.0000	0.0000	0.0000

Horizontal oscillations

Vertical oscillations

Bad bunch acceptance: 0.25 Bad BPMs acceptance: 0.5

Get LSA references Set references

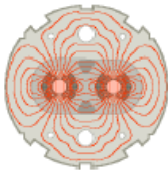
Bunch within thresholds.

Get last result: B1 Get last result: B2

Playback Previous Event Next Event Show data dump

00:43:43 - BCTs/BQMs cannot verify injection. BQMs show no bunches injected. MKI analysis was bad. BLM analysis was bad. Insufficient BPM data. MKI analysis gave warnings.

Bunch 1 in 2nd injected 36b batch +/-5 mm oscillations -> breakdown before 4 us



LHC Injection Quality Check - Playback

File Mask Playback Help

RBA: goddard

Injection IR2 Injection IR8

2011-04-18 0:06:43.550: BCTs/BQMs cannot verify injection. BQMs show no bunches injected. MKI analysis was bad. BLM analysis was bad. Insufficient BP...

BEAM EXTRACTION INJECTION KICKER BEAM LOSS MONITORS RF BUCKET CHECK INJECTION OSCILLATIONS TRANSFER LINE

2011-04-18 0:06:43.555: Too many bad points to determine result.

	RMS H	P2P H	RMS V	P2P V
2178	0.0000	0.0000	0.0000	0.0000
2180	0.0000	0.0000	0.0000	0.0000
2182	0.0000	0.0000	0.0000	0.0000
2184	0.0000	0.0000	0.0000	0.0000
2186	0.0000	0.0000	0.0000	0.0000
2188	0.0000	0.0000	0.0000	0.0000

Horizontal oscillations

Vertical oscillations

Bad bunch acceptance: 0.25 Bad BPMs acceptance: 0.5

Get LSA references Set references

Bunch within thresholds.

Get last result: B1 Get last result: B2

Playback Previous Event Next Event Show data dump

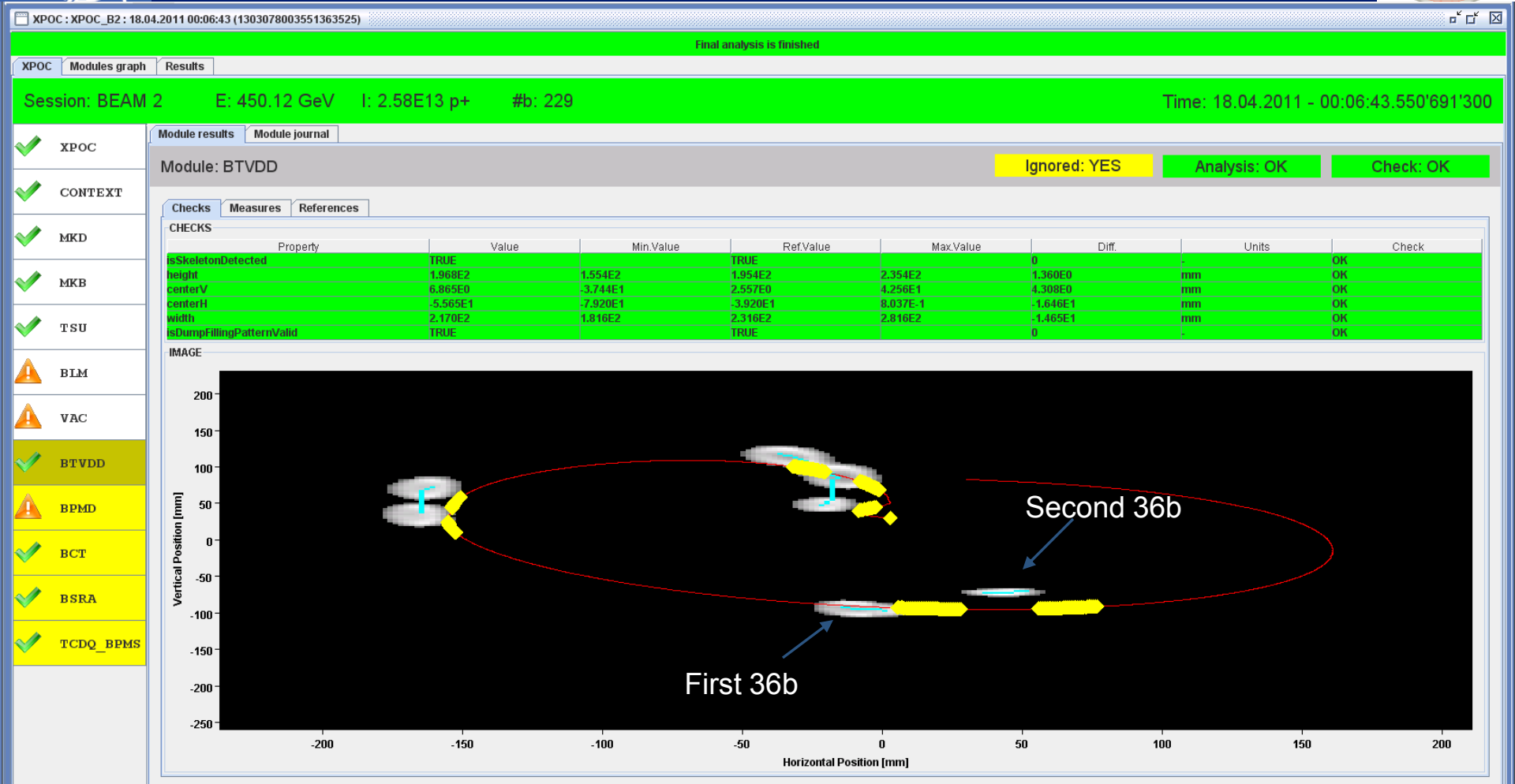
00:43:43 - BCTs/BQMs cannot verify injection. BQMs show no bunches injected. MKI analysis was bad. BLM analysis was bad. Insufficient BPM data. MKI analysis gave warnings.

All 36b of 2nd batch were badly kicked

From the trajectory, can say that the beam was on LOWER TDI jaw and overkicked, i.e. breakdown in second half of magnet (LHCb signals support this)

Grazing incidence – BPMs triggering in arc mean that more than 2e10 p+/b transmitted

From IQC

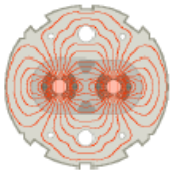


See the two batches clearly on the BTVDD – 2nd batch with lower intensity and vertically offset

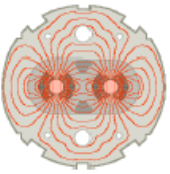
FBCT in bump line records 2.58e13 p+ dumped – ‘missing’ about 2e12 p+, almost exactly half of 36b batch – perfect grazing



Measures proposed and taken

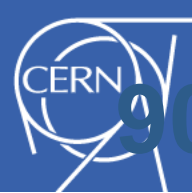


- **New SIS to prevent injection if MKI pressure $>1e-9$ (will have to get some experience with this)**
- **Checked carefully TDI alignments in P2 and P8, especially with respect to TCLI openings**
 - No anomalies found
- **New Fixed Display in CCC with MKI pressures**
- **Vacuum sublimation made on MKI2 and MKI8**
- **Production of 2nd spare MKI speeded up**

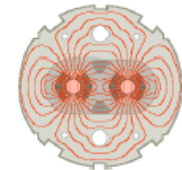


Conclusion

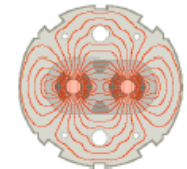
- Had a real breakdown in MKI8.D, between two 36b trains in a 72b batch
- 36b overkicked and grazed lower jaw of TDI/TCLI
 - About half of this intensity was transmitted into LHC ($2e12$)
- **Known worst case scenario for injection protection**
 - Showers caused quenches and LHCb trips
 - No damage (magnets, MKI, LHCb, TDI)
 - Protection works – factor 8 to go to real worst-case
 - Setting up and positioning of these devices critical
 - BLMs need more dynamic range
- Production of 2nd new spare MKI accelerated



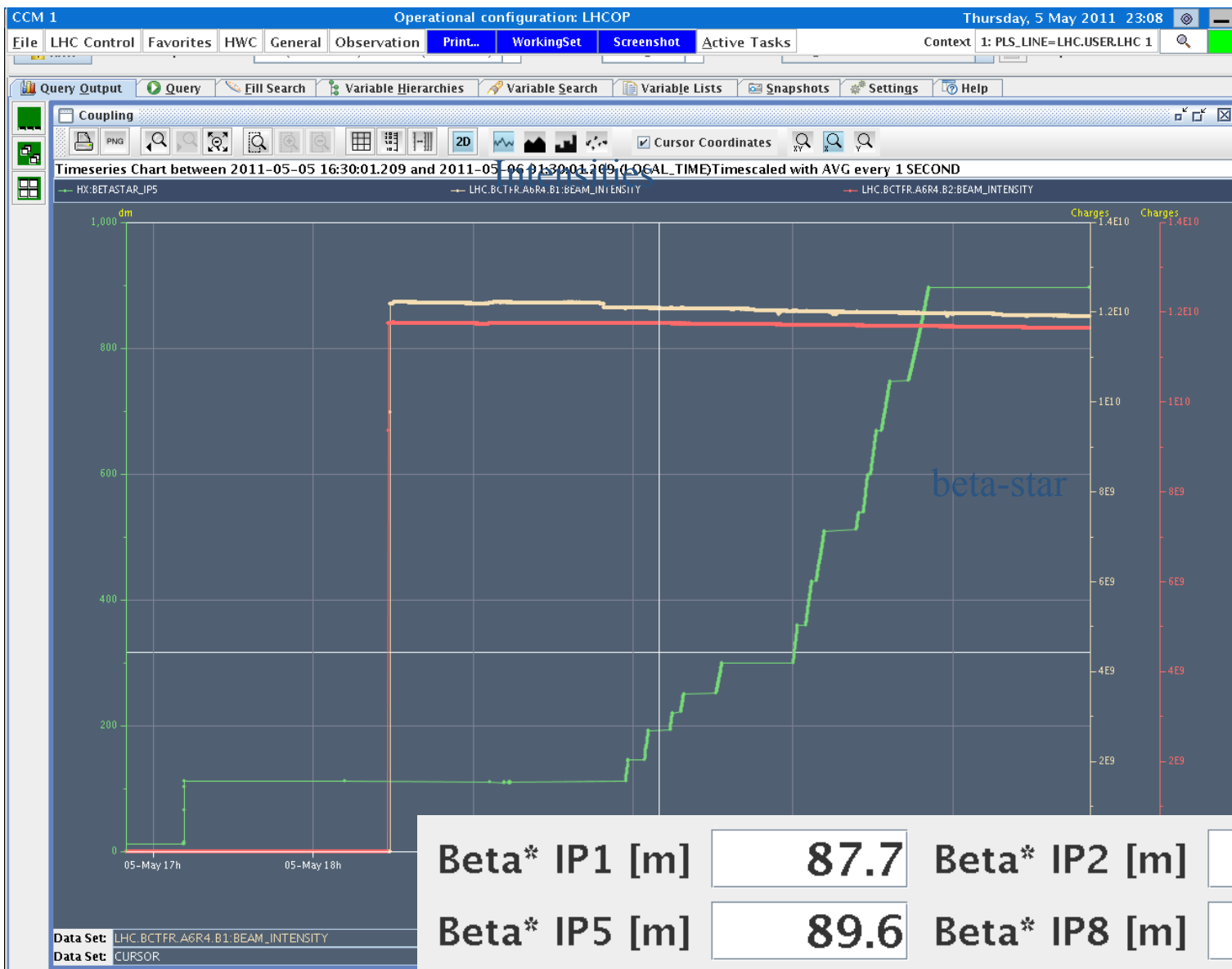
90 m Unsqueeze

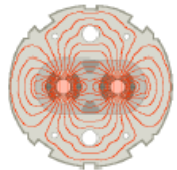


- **Demonstrate feasibility of simultaneous un-squeeze of IPs 1 & 5 with external tune compensation using main quads.**
 - Orbit and tune feedbacks were kept ON for all the beta* changes.
 - Coupling measurements, corrections, incorporated into functions.
 - Chromaticity & orbit adjusted (real-time trims into the LSA).
- **Everything worked as expected. Few minor hiccups.**
- **B-beat measurements with AC dipole carried out at flat-top, at 30m and (more extensively) at 90m.**
- **Primary collimators were closed to 10 sigma's as a safety measure prior to the AC dipole measurements.**
- **At flattop local & global coupling corrections: local**



90 m: Intensities and Beta*



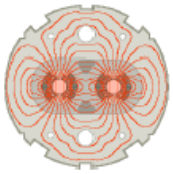


New ATS Optics

- **New injection optics (ATS optics) tested and ramped successfully up to 3.5 TeV**
 - crossing scheme off (TCT, TDI, TCLI opened with probe beam)
 - successful injection and dump test
 - damper new settings OK (with new phases of the ATS optics)
 - no emittance blow up during the ramp
 - **new integer tunes measured at injection 62/60 (instead of 64/59)**
 - CO, tune, coupling, chromaticity measured and corrected at injection and flat top
 - new tune, chroma and coupling knobs operational
 - orbit and tune feed-back successful during the ramp.
 - beta-beat measurement
 - 30% at injection, 10-15% at flat top w/o any specific correction
 - H and V dispersion measured
 - H: +/- 50 cm (compared to 2 m) for Dx at injection, +/- 20 cm at flat top.
 - V: 15-20 cm peak at injection, about 10 cm at flat top.

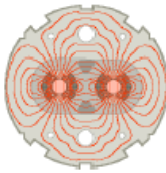


New ATS Optics



- **Next steps:**
 - **inject and ramp with crossing scheme (170 μ rad, 2 mm in all IP's kept constant during the ramp).**
 - **pre-squeeze to $b_{star}=1.2$ m w/o crossing scheme.**
 - **measure/correct the off-momentum beta-beating, and non-linear chromaticity.**
 - **switch on the crossing scheme at $b_{star}=1.2$ m and measure/correct the spurious dispersion.**

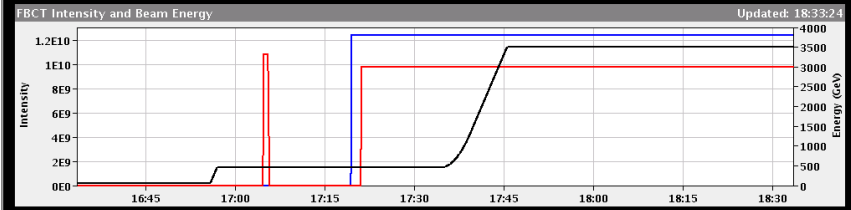
ATS New Injection Orbit – Ramp,



LHC Page1 Fill: 1769 E: 3500 GeV 07-05-2011 18:33:24

MACHINE DEVELOPMENT: FLAT TOP

Energy: 3500 GeV I(B1): 1.22e+10 I(B2): 7.82e+09



Comments 07-05-2011 18:33:05 :

ATS MD

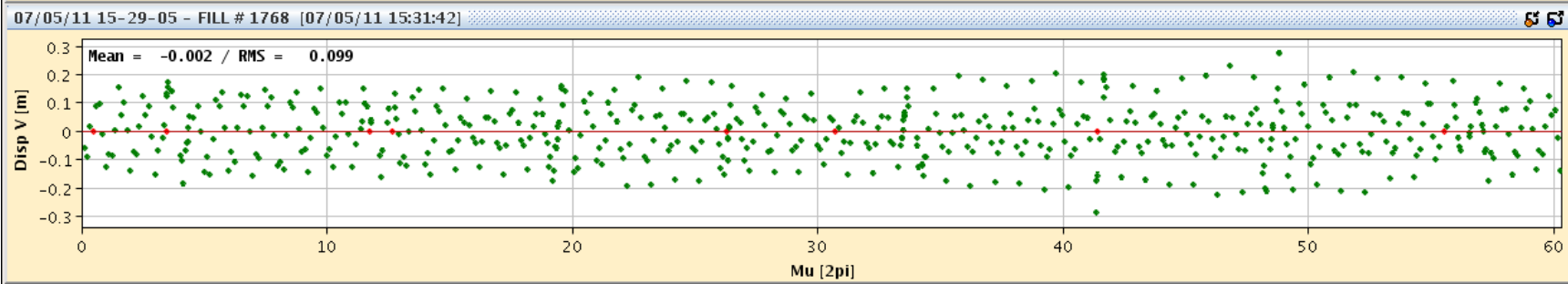
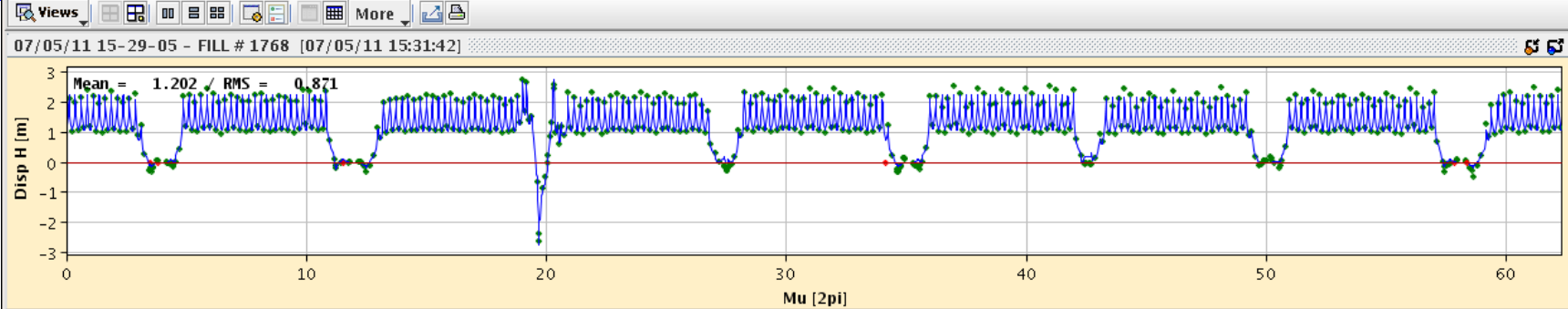
ATS measurements at 3.5 TeV completed!

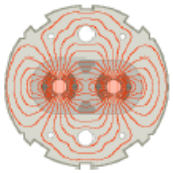
BIS status and SMP flags		B1	B2
Link Status of Beam Permits		false	false
Global Beam Permit		true	true
Setup Beam		true	true
Beam Presence		true	true
Moveable Devices Allowed In		false	false
Stable Beams		false	false

Excellent transmission of intensity through the ramp.

Dispersion B2.

AFS: alt YASP DV LHC RING / RAMP_ATS_3.5TeV_2011_V1@0_[START] / beam 2



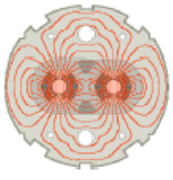


Nominal collimation, single b tune shift (Coll, Imp.)

- Initial blow-up tests with transverse damper.
- Injection scraping during short delay from injectors.
- Nominal 3.5 TeV collimation settings achieved for b1 & b2:
 - TCP = 5.7 sigma (nom), TCSG = 6.7 sigma (nom)
 - TCLA = 9.7 sigma (nom), IP6 = 7.2/7.7 sigma (nom)
- Octupoles trimmed to 350A for beam 1.
- For b1 moved towards nominal 7 TeV settings. Limited by TCSG losses close to IP7. Valid setup reached:
 - TCP = 4.0 sigma (nom), TCSG = 6.0 sigma (nom)
 - TCLA = 8.0 sigma (nom), IP6 = 7.0/7.5 sigma (nom)
 - Smallest gap: 2.2 mm
 - Beam lifetime: > 100 hours
 - Tune shift measured: $\sim 2e-4$
 - Efficiency measured: $3e-5 - 1e-4$



Settings b1 first loss-maps



VLC media player

LHC Collimators | Beam: B1 | Set: HW Group:LHC COLLIMATORS 07-05-2011 23:11:00

L(mm) MDC	IP1	PRS R(mm)					
4.3	TCLA.7R3.B1	-4.43	2.2	TCSG.D5R7.B1	-2.78		
24.87	TCL5R1.B1	-25.13	2.44	TCSG.E5R7.B1	-2.54		
10.25	TCTH.4L1.B1	-9.92	7.19	TCTH.4L5.B1	-13.02		
8.73	TCTVA.4L1.B1	-5.46	7.28	TCTVA.4L5.B1	-6.97	3.07	TCSG.6R7.B1
	IP2		24.87	TCL5R5.B1	-25.15	1.97	TCLA.A6R7.B1
4.69	TCTH.4L2.B1	-6.25		IP6		2.72	TCLA.B6R7.B1
20.02	TDI.4L2	-20.07	6.16	TCDQA.A4R6.B1		4.26	TCLA.C6R7.B1
4.64	TCTVB.4L2	-6.88	5.58	TCSG.4R6.B1	-4.2	1.85	TCLA.D6R7.B1
0.71	TCDD.4L2	-0.7		IP7		1.74	TCLA.A7R7.B1
24.96	TCLIA.4R2	-25	1.45	TCP.D6L7.B1	-0.72	8.9	TCTH.4L8.B1
24.86	TCLIB.6R2.B1	-24.98	1.03	TCP.C6L7.B1	-2.01	5.34	TCTVB.4L8
	IP3		0.63	TCP.B6L7.B1	-1.94		TI2
4.12	TCP.6L3.B1	-4.32	1.62	TCSG.A6L7.B1	-2.32	1.42	TCDIV.20607
2.74	TCSG.5L3.B1	-4.34	1.9	TCSG.B5L7.B1	-2.74	2.66	TCDIV.29012
1.29	TCSG.4R3.B1	-3.62	2.24	TCSG.A5L7.B1	-2.51	3.76	TCDIH.29050
2.74	TCSG.A5R3.B1	-3.55	1.6	TCSG.D4L7.B1	-1.48	2.4	TCDIH.29205
3	TCSG.B5R3.B1	-4.14	3.17	TCSG.B4L7.B1	-1.18	3.37	TCDIV.29234
6.64	TCLA.A5R3.B1	-7.64	2.99	TCSG.A4L7.B1	-1.26	2.96	TCDIH.29465
6.22	TCLA.B5R3.B1	-7	2.96	TCSG.A4R7.B1	-1.32	9	TCDIV.29509
6.17	TCLA.6R3.B1	-6.1	2.74	TCSG.B5R7.B1	-2.22		

0:00:00 / 0:00: | x1.00 "LHC Collimators B1"

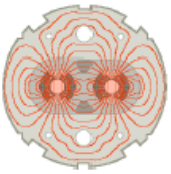
VLC media player

LHC Collimators | Beam: B2 | Set: HW Group:LHC COLLIMATORS 07-05-2011 23:11:12

L(mm) MDC	IP1	PRS R(mm)					
8.2	TCTVA.4R1.B2	-6.04	10.34	TCTH.4R5.B2	-9.88	3.02	TCSG.B5R7.B2
9.25	TCTH.4R1.B2	-10.92		IP6		2.04	TCSG.A6R7.B2
25.31	TCL5L1.B2	-24.68	4.96	TCSG.4L6.B2	-5.14	1.15	TCP.B6R7.B2
	IP2		6.06	TCDQA.A4L6.B2	-2.4	1.86	TCP.C6R7.B2
3.74	TCTVB.4R2	-7.77		IP7		2.2	TCP.D6R7.B2
4.85	TCTH.4R2.B2	-6.1	3.05	TCLA.A7L7.B2	-1.91		IP8
	IP3		2.6	TCLA.D6L7.B2	-2.2	24.92	TCLIB.6L8.B2
4.42	TCLA.7L5.B2	-4.43	4.39	TCLA.C6L7.B2	-2.91	25.02	TCLIA.4L8
5.63	TCLA.6L5.B2	-6.6	3.84	TCLA.B6L7.B2	-3.66	6.29	TCTVB.4R8
5.31	TCLA.B5L3.B2	-7.96	2.3	TCLA.A6L7.B2	-1.84	20	TDI.4R8
7.36	TCLA.A5L3.B2	-6.93	3.96	TCSG.6L7.B2	-3.59	0.7	TCTH.4R8.B2
3.08	TCSG.B5L3.B2	-4	3.12	TCSG.E5L7.B2	-2.36		TI8
2.54	TCSG.A5L3.B2	-3.78	2.57	TCSG.D5L7.B2	-2.92	1.08	TCDIH.87441
2.09	TCSG.4L3.B2	-2.75	3.6	TCSG.B5L7.B2	-1.86	6.54	TCDIV.87645
3.46	TCSG.5R3.B2	-3.55	1.66	TCSG.A4L7.B2	-3.11	6.02	TCDIV.87804
4.58	TCP.6R3.B2	-3.84	1.98	TCSG.A4R7.B2	-2.88	1.54	TCDIH.87904
	IP5		1.76	TCSG.4R7.B2	-3.3	2.64	TCDIH.88121
24.55	TCL5L5.B2	-25.44	1.4	TCSG.D4R7.B2	-2	7.31	TCDIV.88123
			3.3	TCSG.A5R7.B2	-2.02		



Reminder: Start up scenario



75 ns beam re-commissioning – Scrub with 50 ns – 75/50 ns operation

- ❑ Recommissioning with 75 ns bunch spacing - 3 w
- ❑ Increase bunch number (~300b?) – 2 w
- ❑ Scrub with 50ns when needed - 1.5 w

After scrubbing experience, decide on 50/75 ns

- ❑ 50/75 ns operation and increase bunch number -2.5w 300 – 400 –
600 – 800 – 936 -??1404 MP and OP qualification –
- ❑ Physics operation 50/75 ns – 936/1404 b
- ❑ (Back up: restore 150 ns operation – couple days)

❑ Other possible start up scenari were discussed