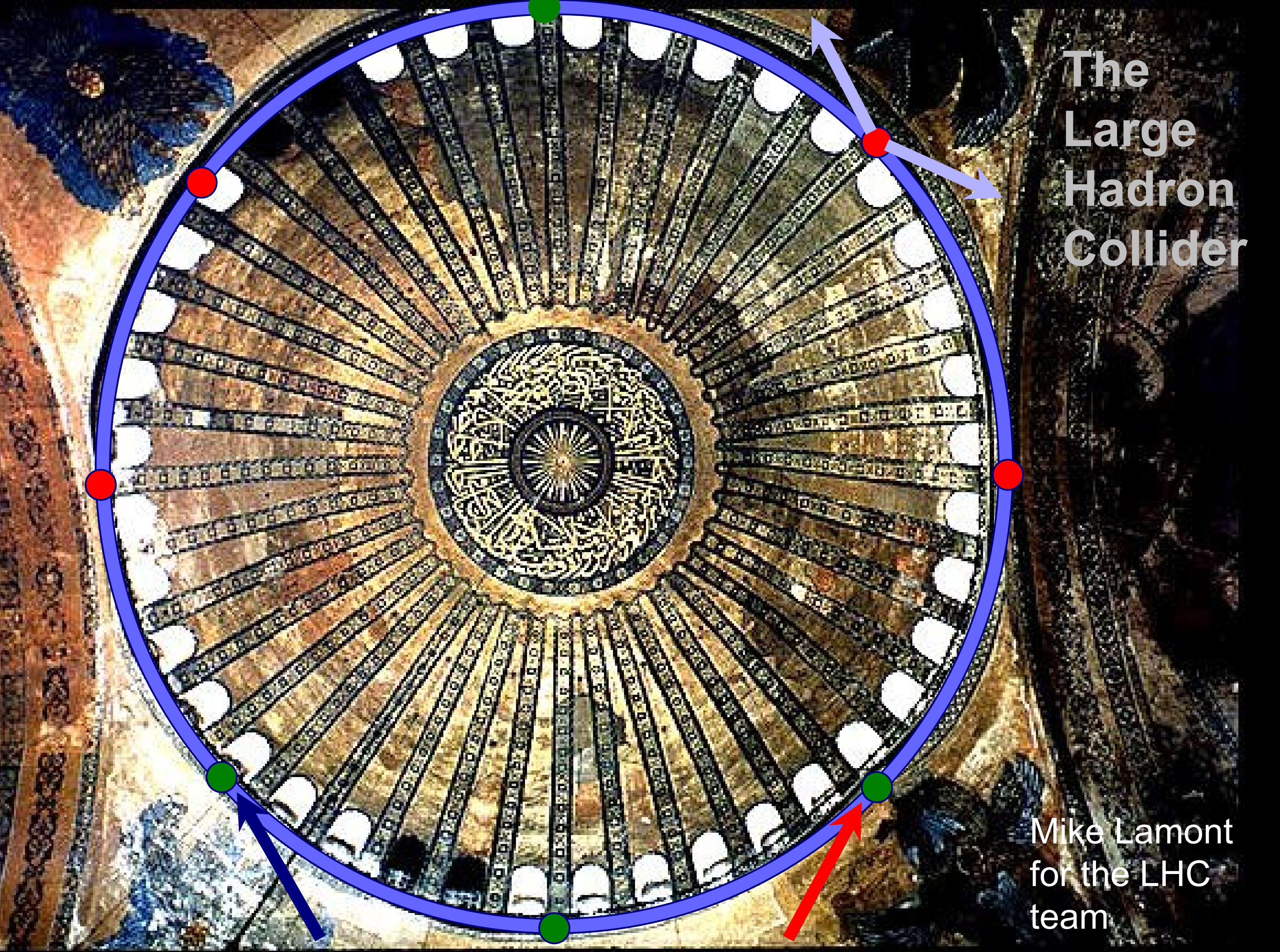
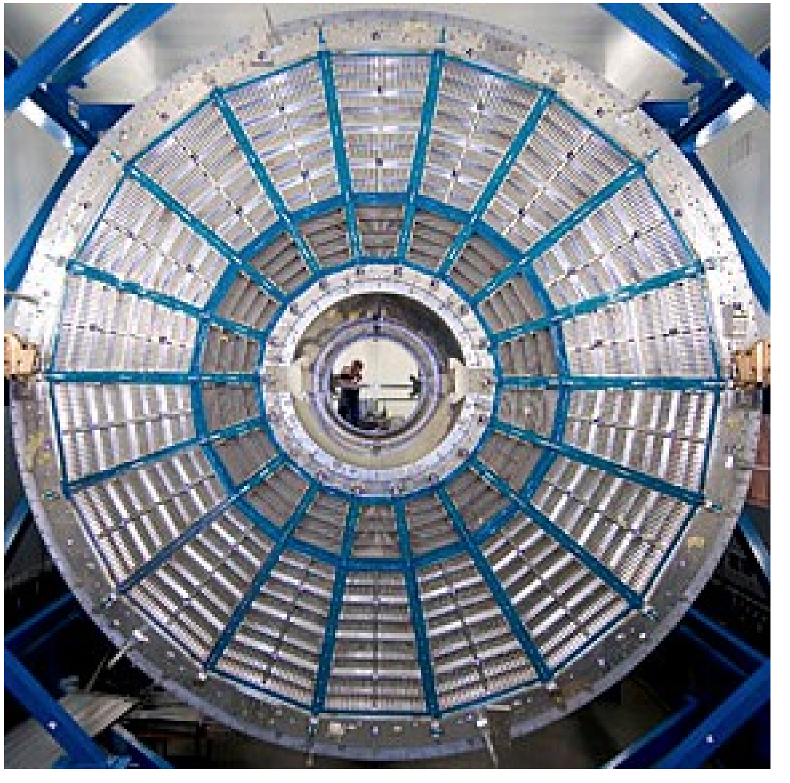


The Large Hadron Collider

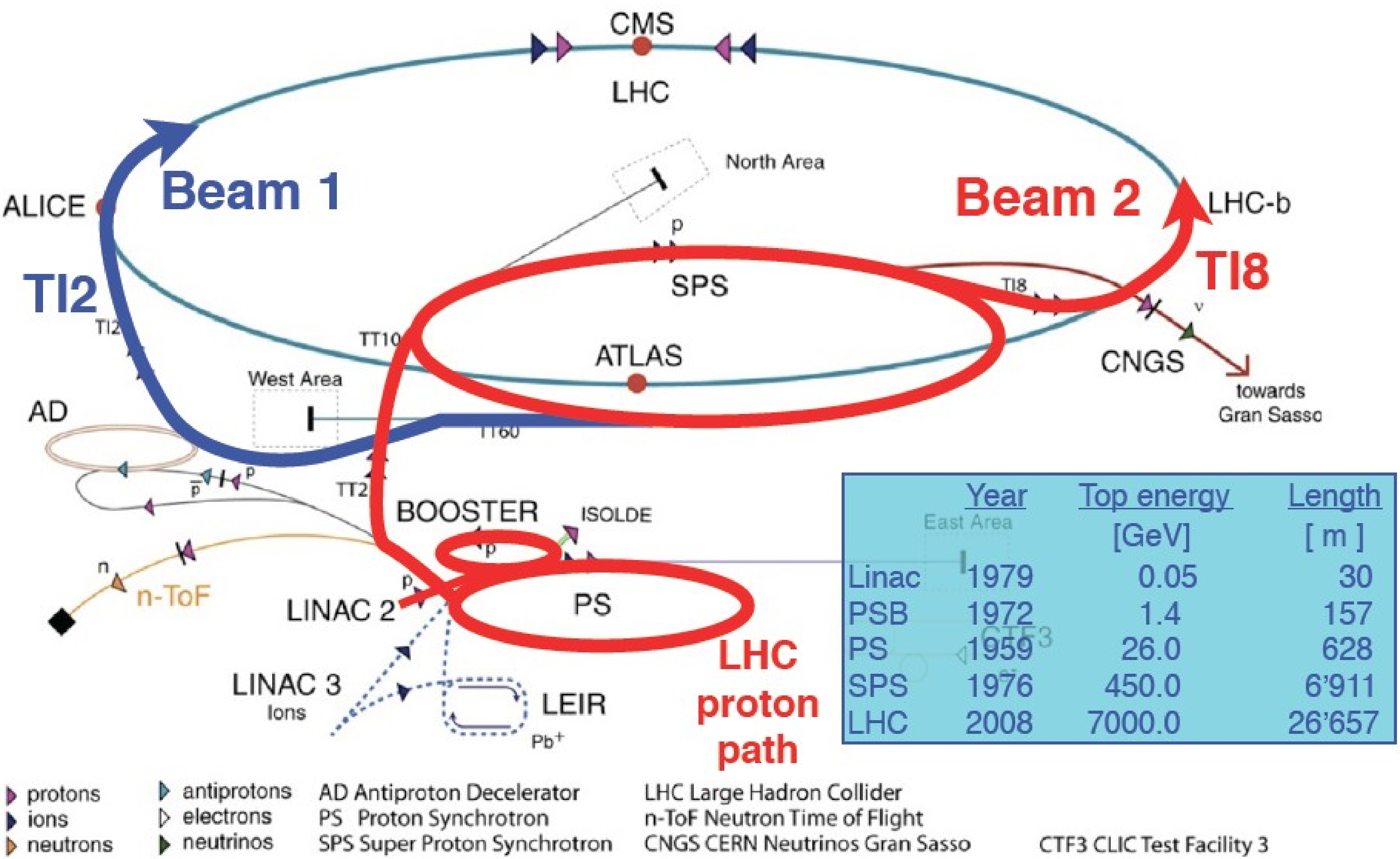
Mike Lamont for the LHC team

Overview

- Introduction
- Performance in 2010
- Progress in 2011
- Looking ahead
- Conclusions



CERN's injector complex

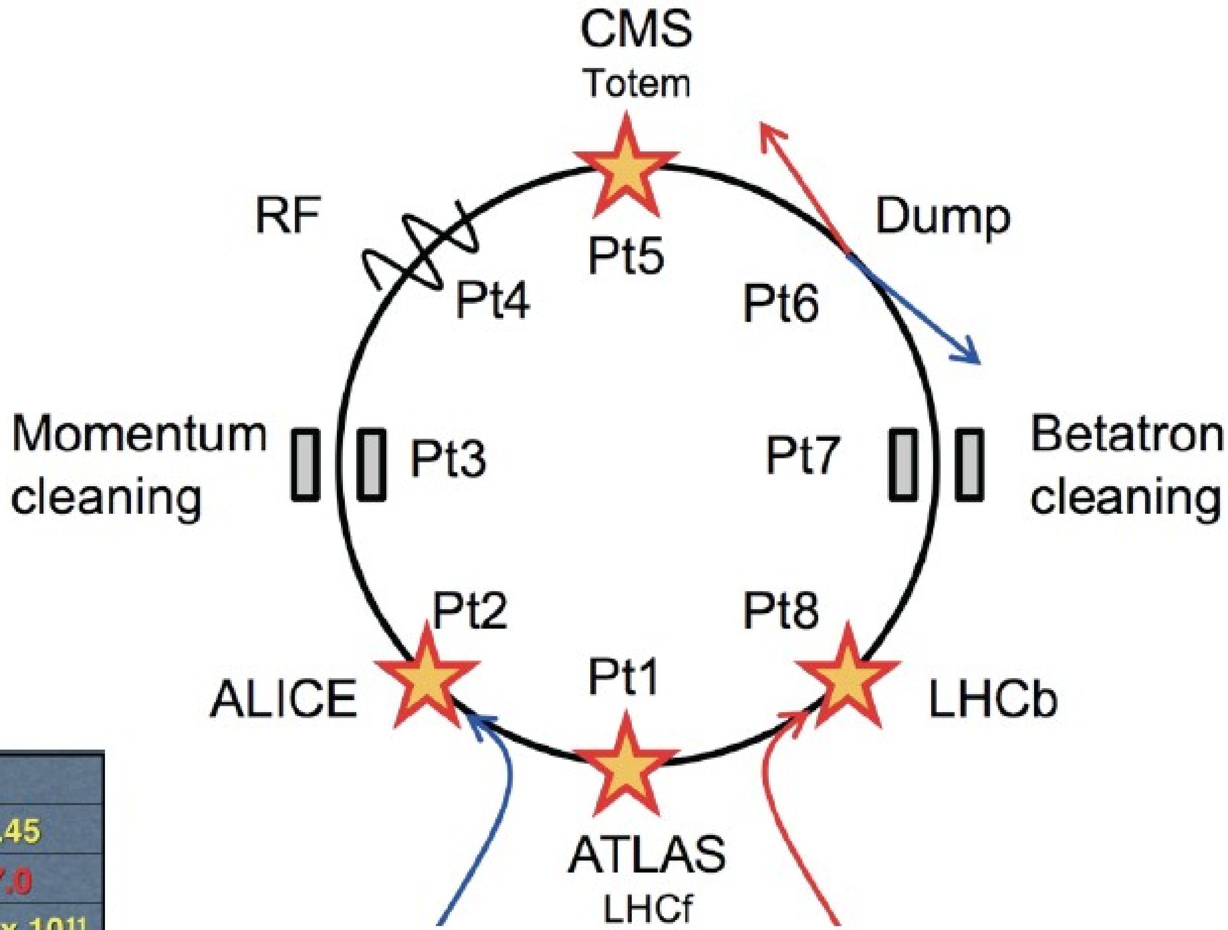


	Year	Top energy [GeV]	Length [m]
Linac	1979	0.05	30
PSB	1972	1.4	157
PS	1959	26.0	628
SPS	1976	450.0	6'911
LHC	2008	7000.0	26'657

LHC layout and accelerator systems

LHC Layout

- 8 arcs (~3 km)
- 8 straight sections (~700 m).
- Two-in-one magnet design
- 4 interaction points (IPs):
  IP1, IP2, IP5, IP8
- IP2/IP8: beam injection
- IP6: beam dump region
- IP4: RF (acceleration)
- IP3/IP7: beam cleaning



Nominal LHC parameters	
Beam injection energy (TeV)	0.45
Beam energy (TeV)	7.0
Number of particles per bunch	1.15×10^{11}
Number of bunches per beam	2808
Max stored beam energy (MJ)	362
Norm transverse emittance (μm rad)	3.75
Colliding beam size (μm)	16
Bunch length at 7 TeV (cm)	7.55

Luminosity - reminder

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

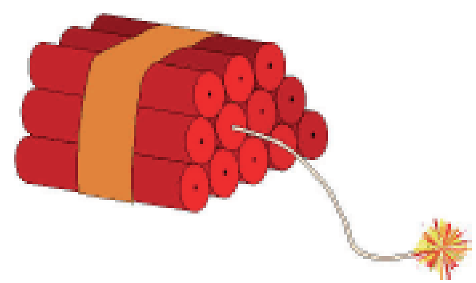
$$\sigma^* = \sqrt{\varepsilon\beta^*}$$

N	Number of particles per bunch
K_b	Number of bunches
f	Revolution frequency
σ_y	Beam size at interaction point
F	Reduction factor due to crossing angle
ε	Emittance – area in phase space occupied by beam
ε_n	Energy normalized emittance
β^*	Beta function at IP – defines beam envelope

2010 – main aims

- Lay the foundations for 2011 and the delivery of 1 fb^{-1}. Peak luminosity target $1x10^{32}\ cm^{-2}s^{-1}$
- Gain solid operational experience of injecting, ramping, squeezing and establishing stable beams
- Steady running at or around 1 MJ for an extended period
- Perform a safe, phased increase in intensity up to around 30 MJ per beam

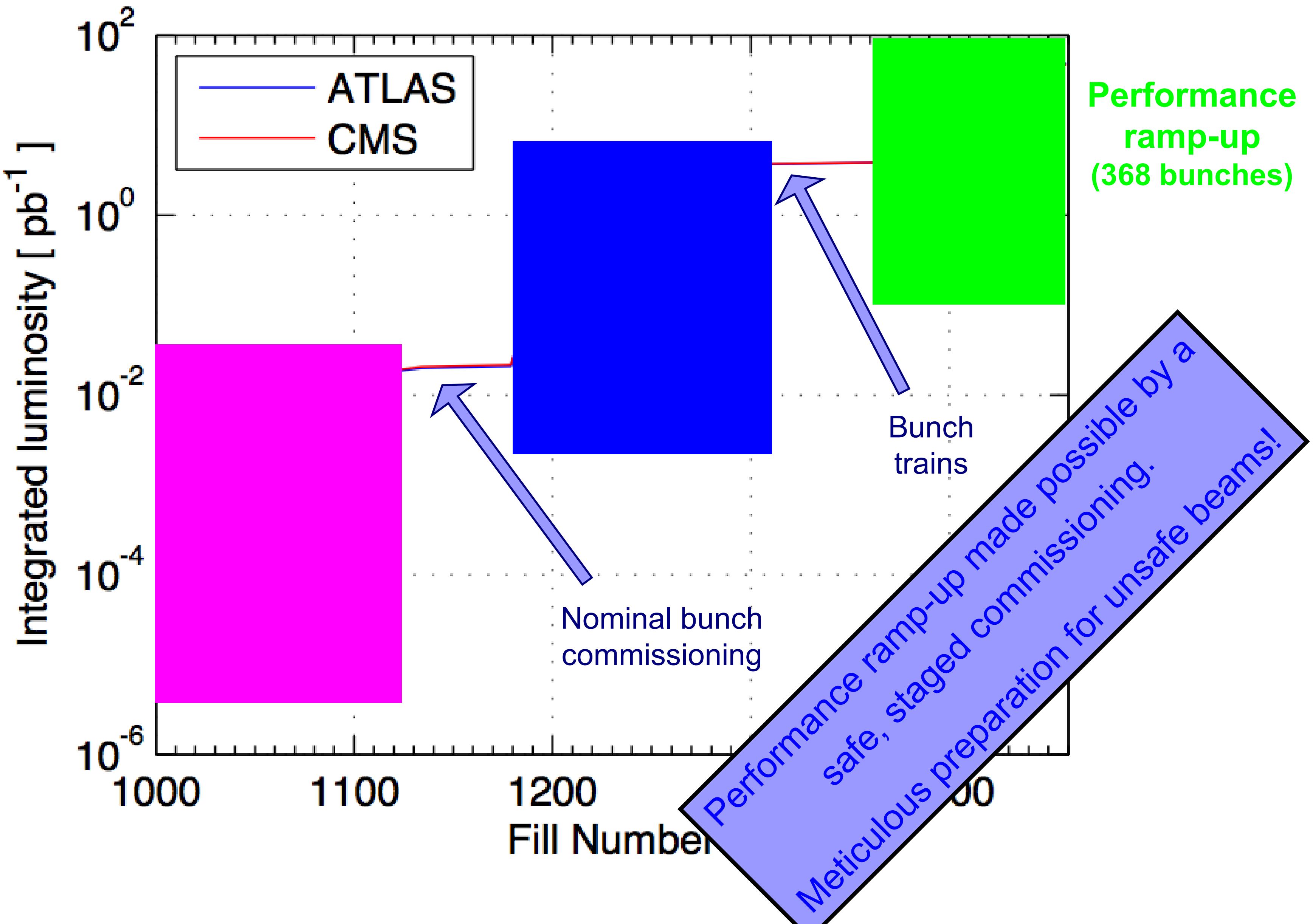
30 MJ is equivalent to ~7 kg of TNT



2010 parameters

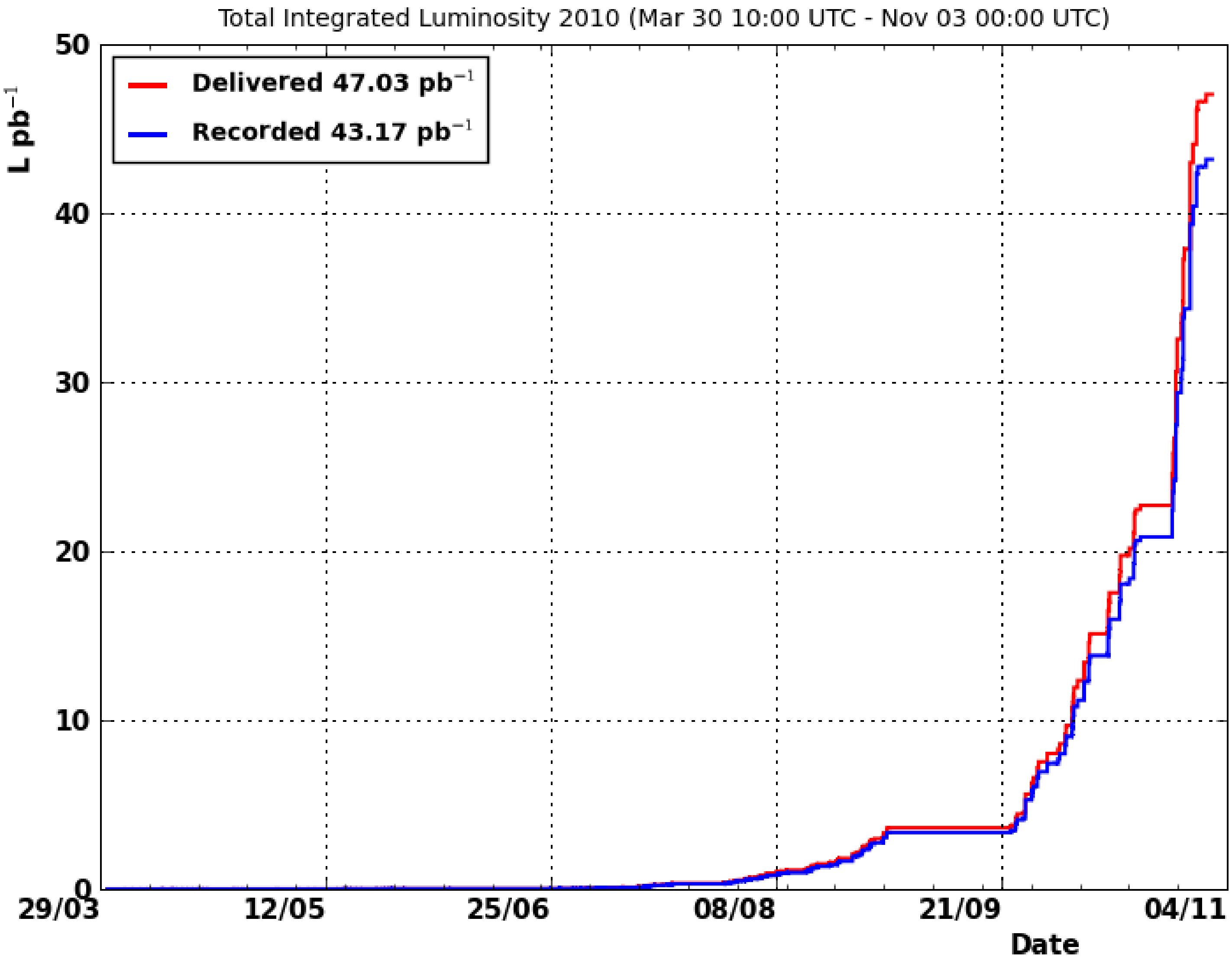
	2010	Nominal
Energy [TeV]	3.5	7
beta* [m]	3.5, 3.5, 3.5, 3.5 m	0.55, 10, 0.55, 10
Emittance [mm.mrad]	**2.0 – 3.5 start of fill**	3.75
Transverse beam size at IP [microns]	~60	16.7
Bunch intensity	1.2e11	1.15e11
Number of bunches	368 348 collisions/IP	2808
Stored energy [MJ]	28	360
Peak luminosity [$cm^{-2}s^{-1}$]	2e32	1e34

Luminosity: 3 running periods



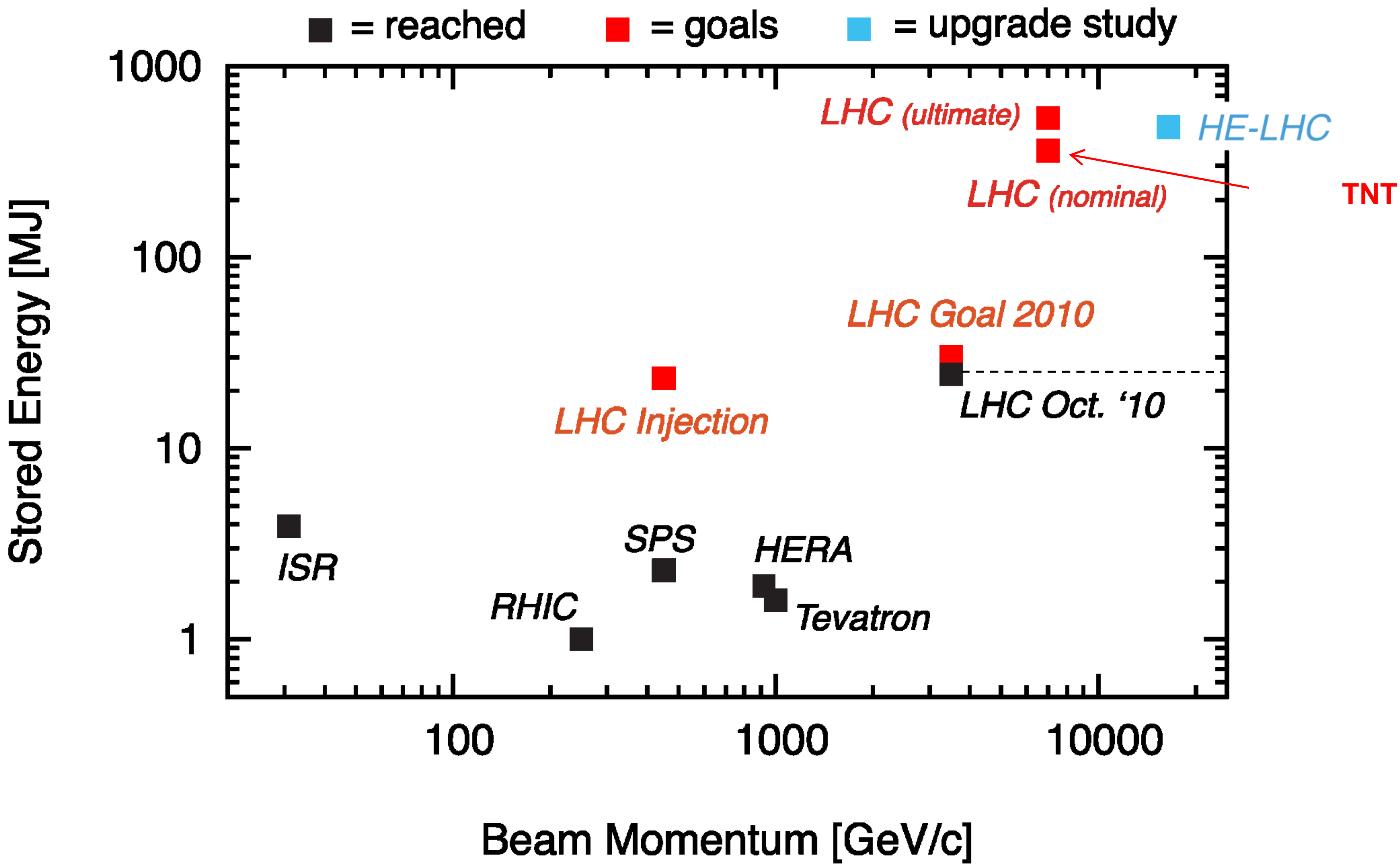
Luminosity 2010

CMS



Status LHC Stored Energy

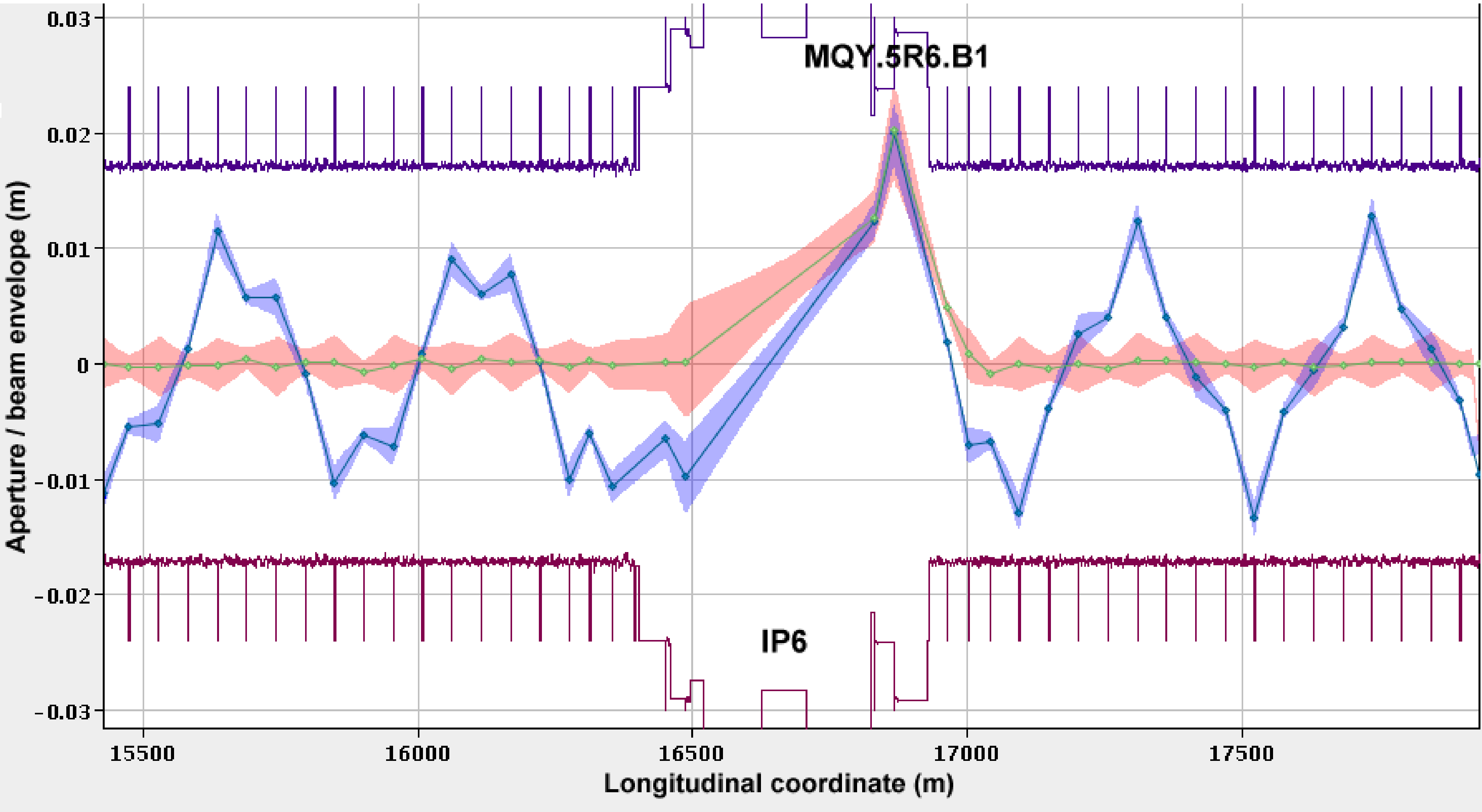
Stored energy reached at 3.5 TeV: **28.0 MJ**



Lifetimes

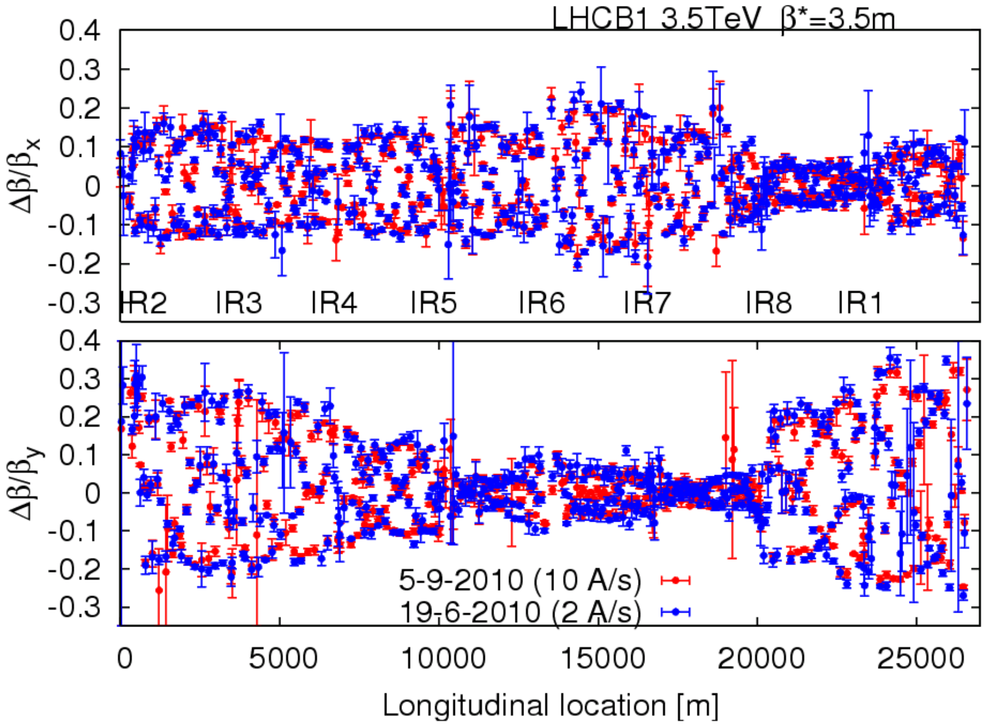
- Excellent single beam before collisions - over 300 hours
- Luminosity lifetime 15- 20 hours, better in 2011
  - Reasonably well given by emittance growth and intensity decay
  - Minimal drifts in overlap – beams very stable
- Intensity lifetime ~90 hours
  - Luminosity burn, losses on collimators
- Emittance growth (hor. ~ 30 hours, vert. ~ 20 to 40 hours)
  - Intra Beam Scattering
  - and something else – at least sometimes "the hump"

Aperture looks good



Optics & magnetic machine

- Optics stunningly stable

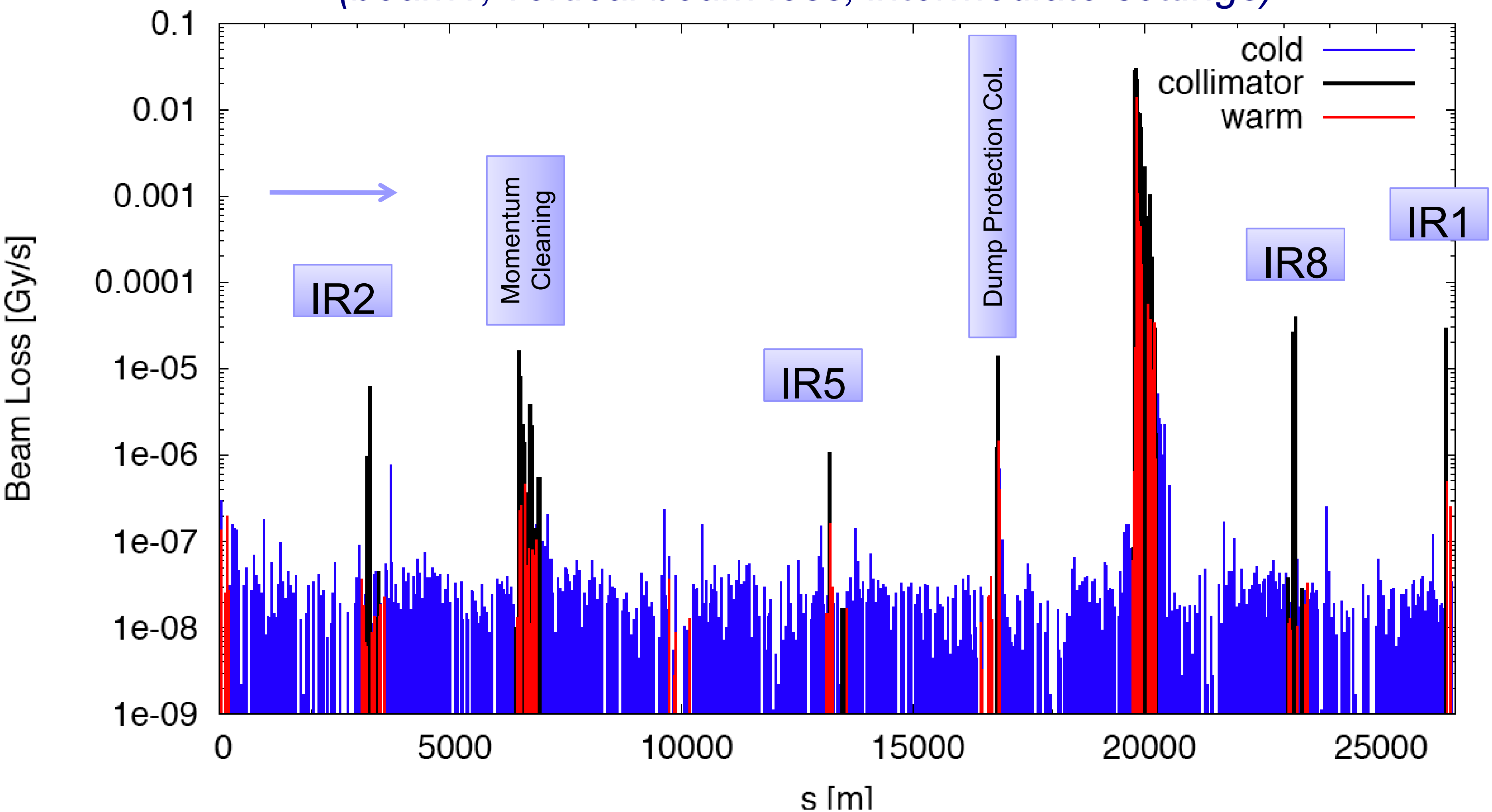


- Machine magnetically and optically well understood
  - Excellent agreement with model and machine
- Magnetically reproducible
  - Important because set-up remains valid from fill to fill

Measured Cleaning at 3.5 TeV

Making sure the hierarchy is respected

(beam1, vertical beam loss, intermediate settings)



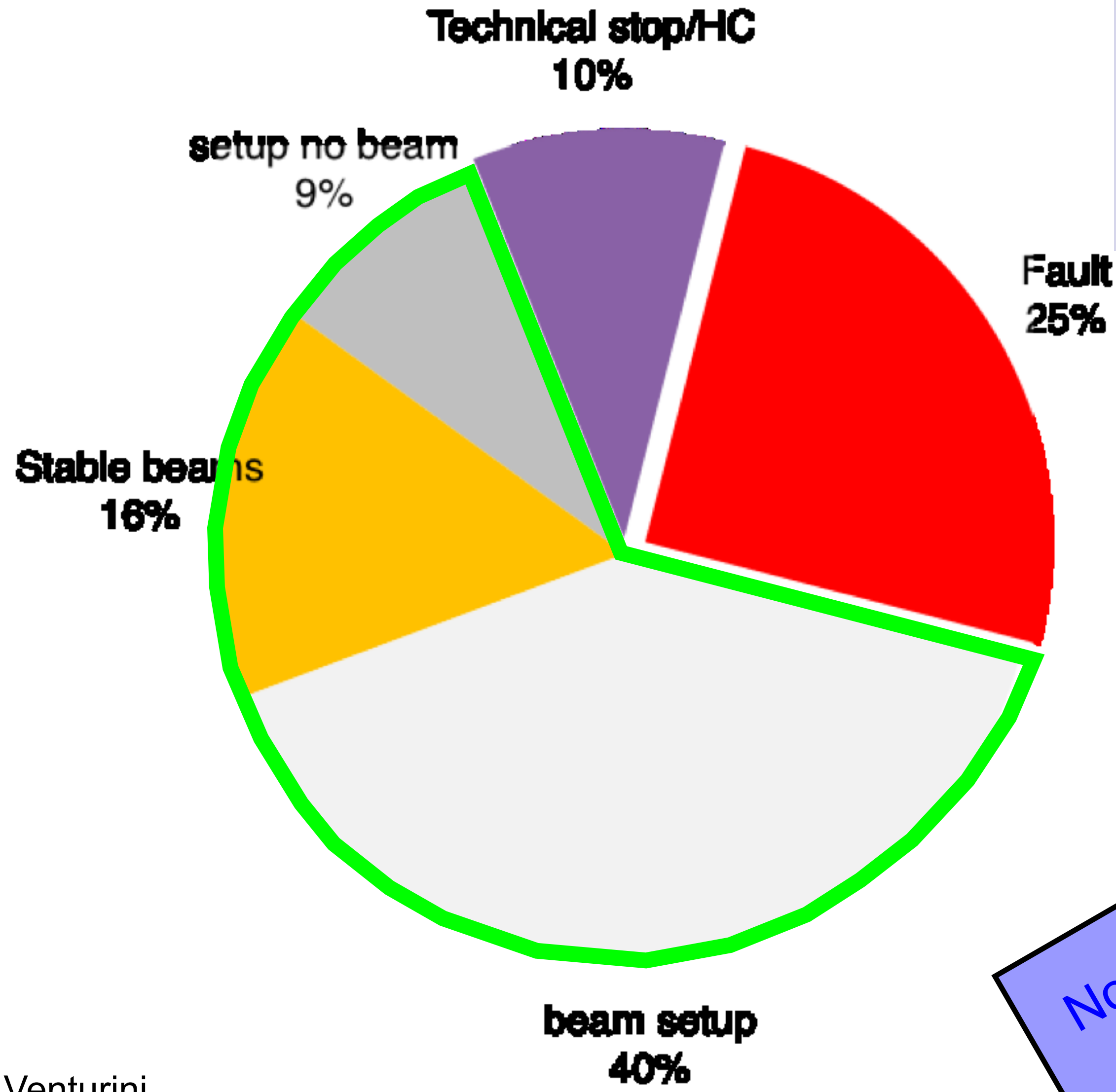
Beam cleaning efficiencies ≥ 99.98% ~ as designed

LHC 2010 - summary

- Excellent single beam lifetime
- Ramp & squeeze essentially without loss
  - No quenches with beam above 450 GeV
  - Excellent performance of Machine Protection
- Optics close to model (and correctable)
- Excellent reproducibility
- Aperture as expected
- Better than nominal from injectors
  - Emittances, bunch intensity
- Beam-beam: can collide nominal bunch currents
  - With smaller that nominal emittances – surprise!

And surprisingly good availability…

Overall LHC efficiency in 2010



65% availability

Not bad for the first year of operation!

W. Venturini

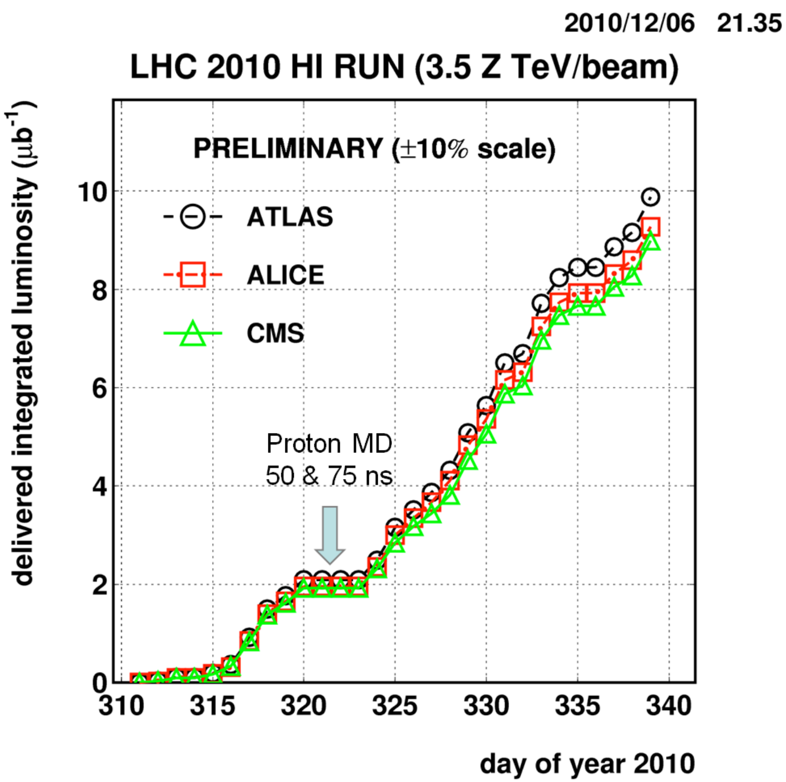
Pb run 2010

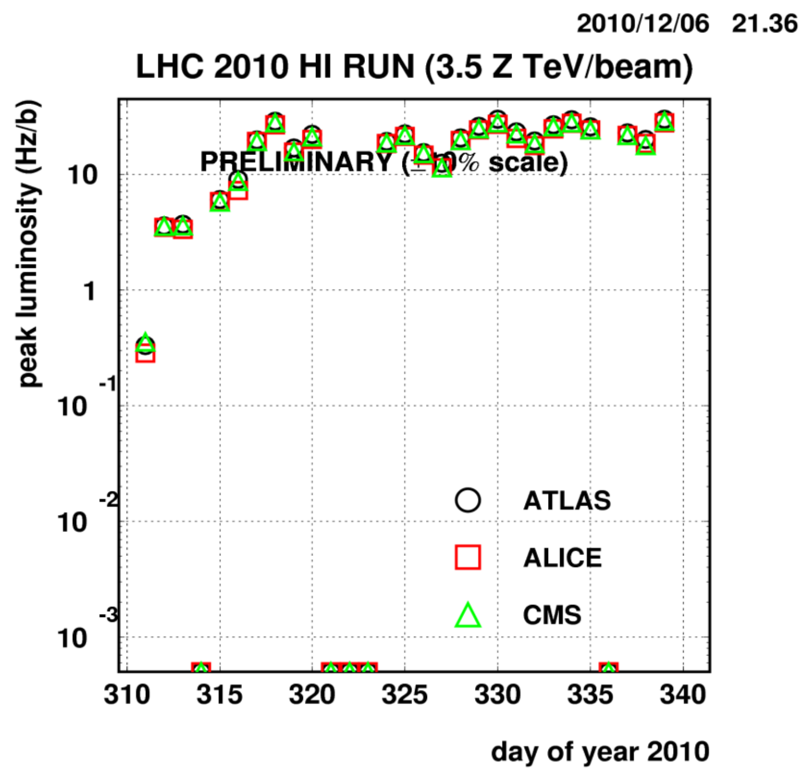
- Very fast commissioning plan worked:
  - Collisions within 50 hours of first injection
  - Profited of the experience of the proton run
  - Stable beams within 4 days (… and physics)
  - Rapid progression in number of bunches

- The LHC worked with Pb beams
  - No rapidly decaying, invisible beams
  - No quenches
  - Some new losses and radiation problems

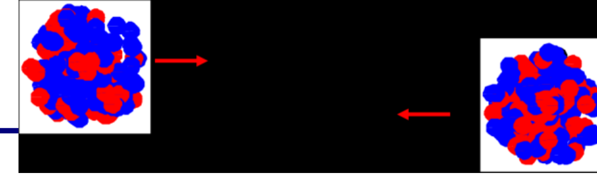
Pb run 2010 - Achievements

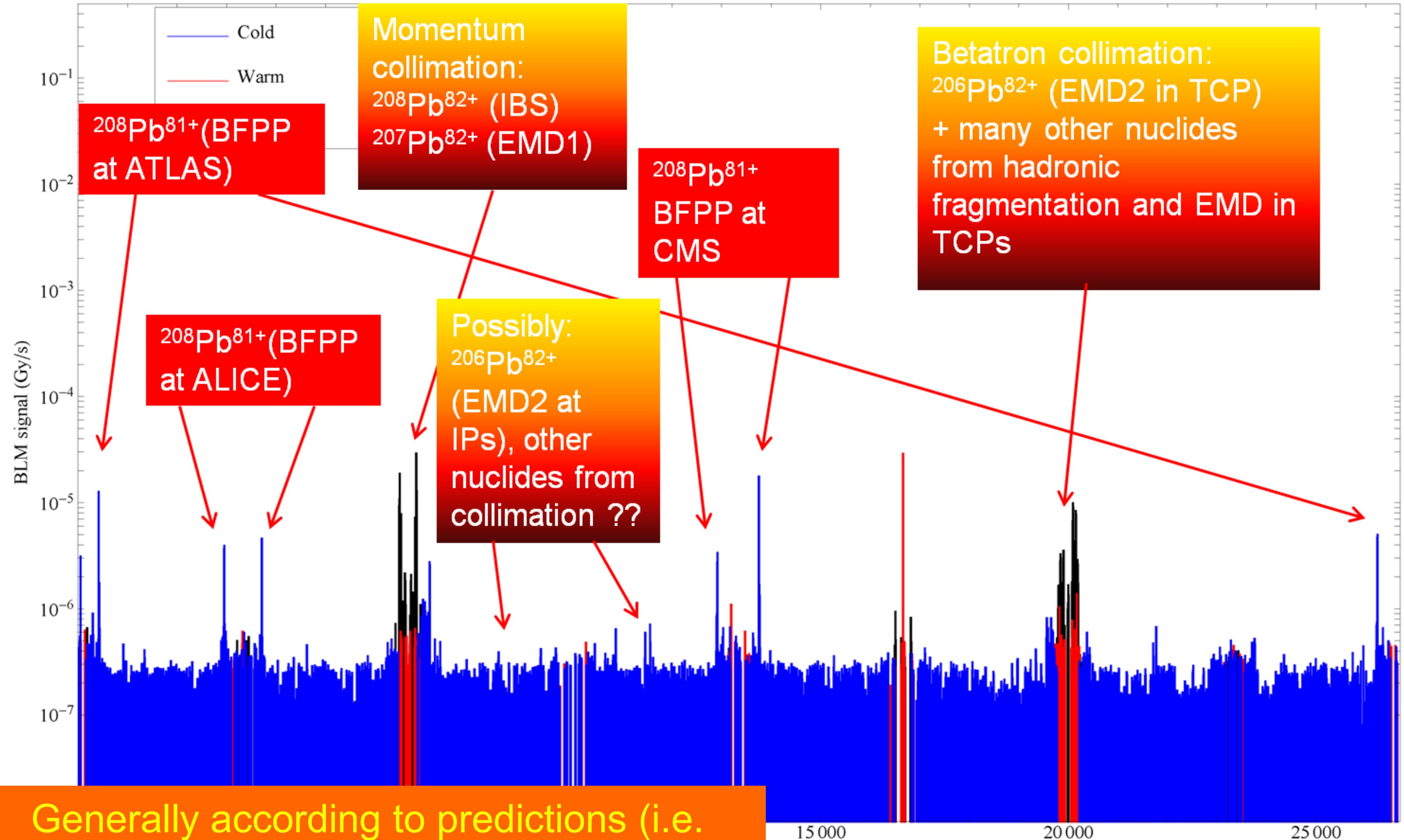
Integrated Luminosity	10 μb^{-1}
Peak Stable Luminosity Delivered	3.04×10^{25} $cm^{-2}s^{-1}$
Maximum number of bunches in collision	137
Average bunch population	1.2×10^{8} ions (>60% above nominal)





Pb run 2010: Collimation



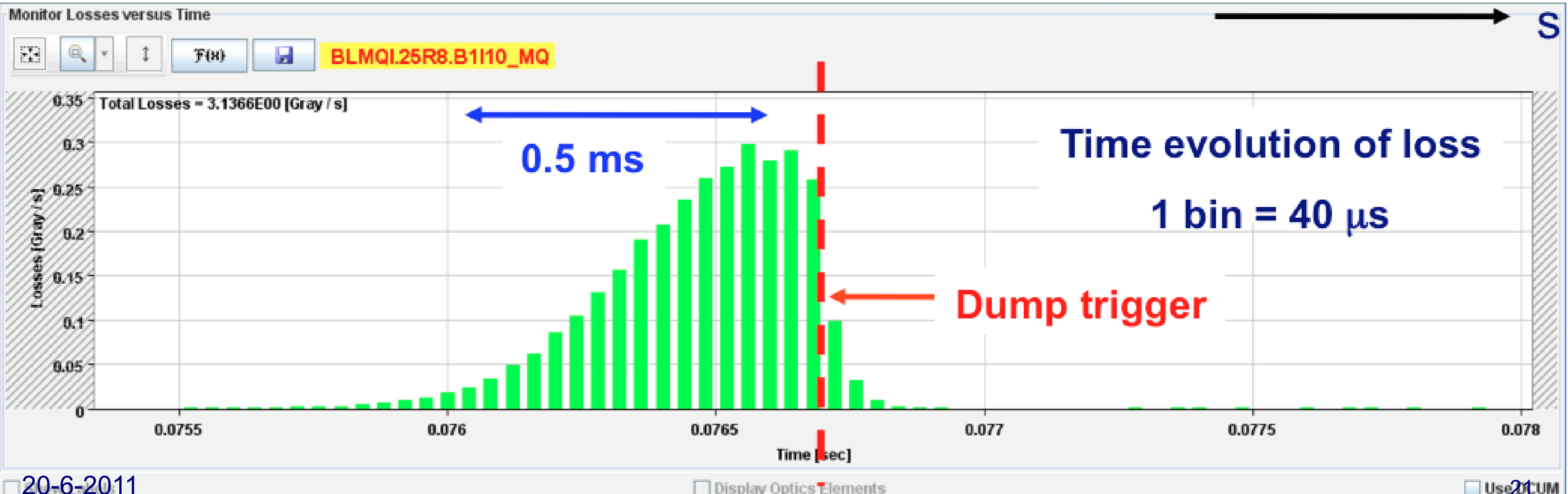


Generally according to predictions (i.e. efficiency is a factor 100-500 worse than p).

PROBLEMS – TWO OF THEM

UFOs – unidentified falling objects

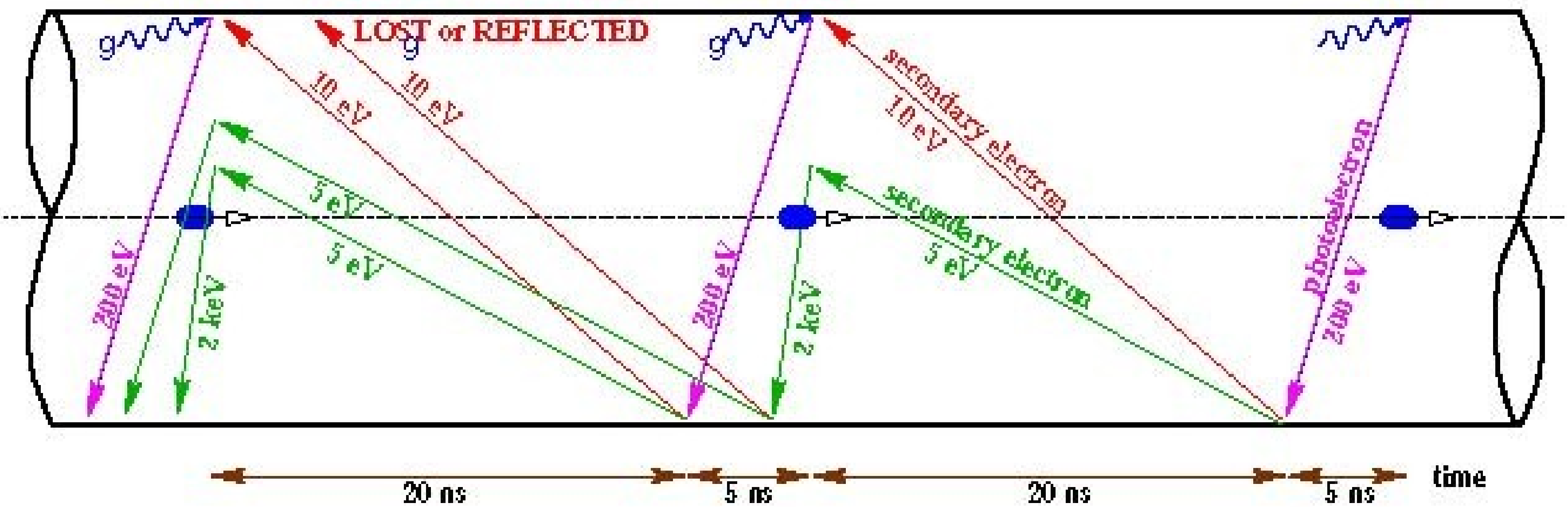
- Many sudden local losses have been recorded.
- No quench, but preventive dumps
- Rise time around of the order 1 ms.
- Potential explanation: dust particles falling into beam creating scatter losses and showers propagating downstream
- Distributed around the ring – arcs, inner triplets, IRs



Electron cloud

Reflection

Schematic of electron cloud build up in LHC arc beam pipe due to photoemission and secondary emission [F. Ruggiero]



Secondary emission yield [SEY]

- Vacuum pressure rise (background in experiments)
- Single-bunch instability
- Multi-bunch instability
- Incoherent emittance growth
- Heat load in cold arcs (quenches in the limit)

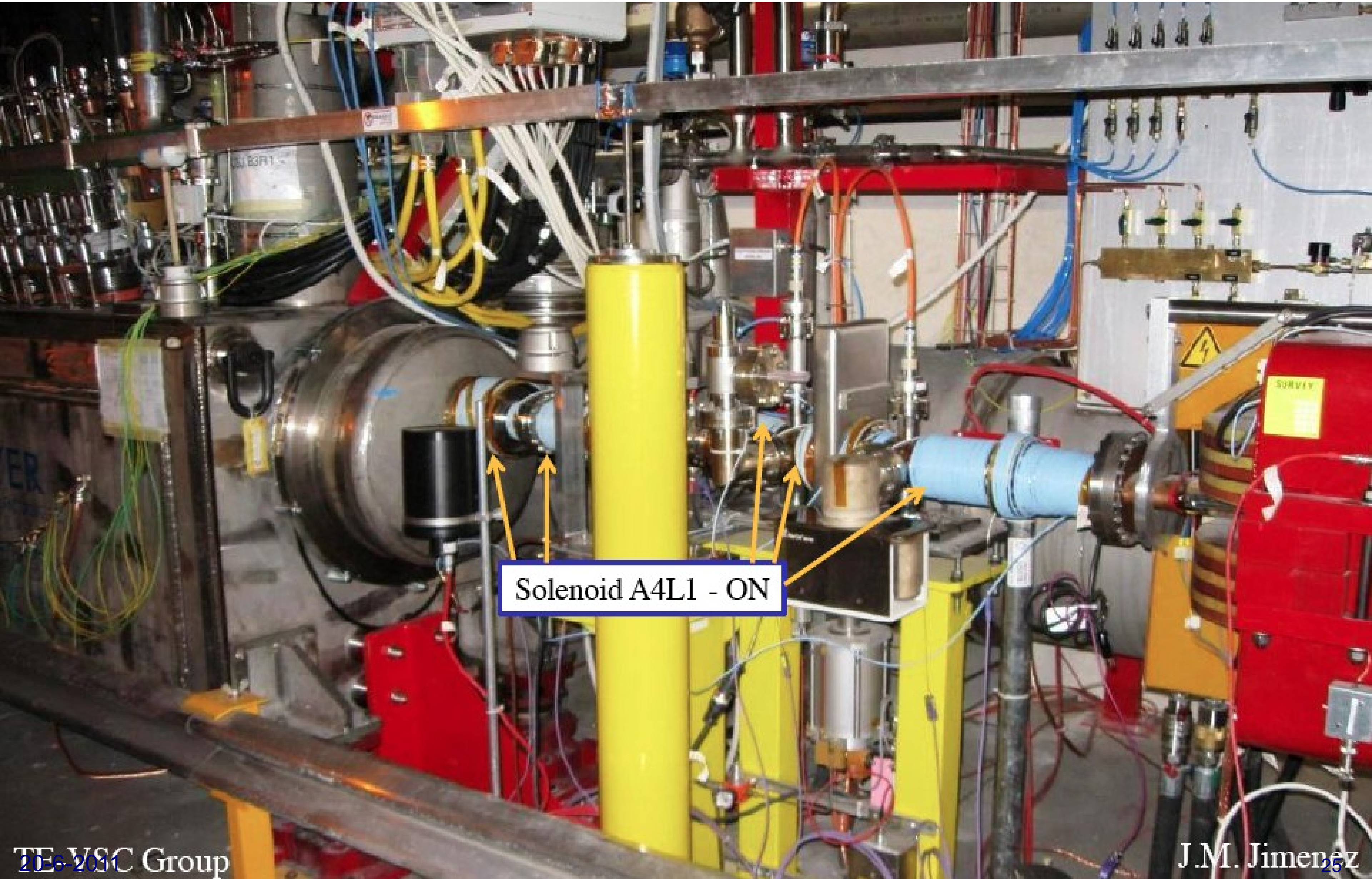
Experience in 2010

- Vacuum activity started off in regions with common beam pipe at 450 GeV as we pushed up the number of bunches with 150 ns spacing
  - Test solenoids cured problem – electron cloud
- Tried 50 ns bunch spacing
  - Things really kicked off
  - High vacuum activity in warm regions
  - Significant heat load in cold regions
  - Instabilities and beam size growth observed
  - **Surface conditioning ('scrubbing') observed**
    - Gas desorption rates and SEY drop
    - Time constant < 1 day
- Situation a lot cleaner with 75 ns
  - incoherent effects seen – emittance blow-up
  - 800+ bunches injected into both beams

Scrubbing strategy for 2011

- 2010 observations are certainly due to ~ 2 < SEY < 2.5, whereas 1.7 was usually the max value studied in the past
- Scrubbing with large emittance, high intensity 50 ns beam
- Time around 10 days including preparation and validation
- Lots of wire wrapped around warm bits during the technical stop (solenoids)

Solenoids between DFBX and D1 in IR1R



2011: main goals

fast, secure and far-reaching

- Motivation is clear!
- 1 fb^{-1} delivered to each of IP1, IP5 and IP8 at 3.5 TeV
- Challenge to deliver 1 fb^{-1} to IP8
  - Maximum luminosity : from 2e32 to 3e32 cm^{-2} s^{-1}
  - Luminosity leveling via separation required to get close
- Alice
  - pp run: 5e29 < L < 5e30 cm^{-2} s^{-1}, $\mu < 0.05$

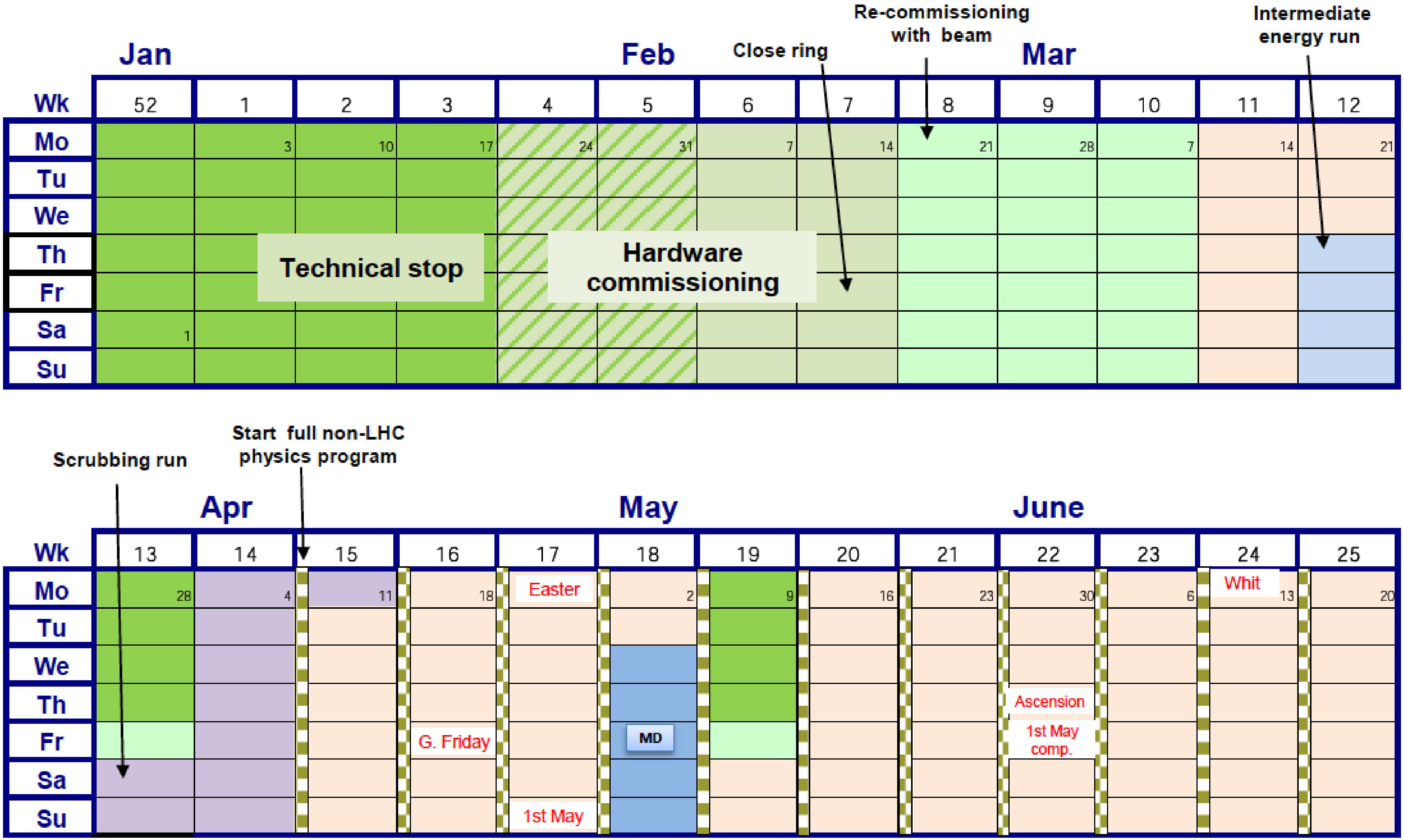
Decided on beta* = 1.5 m in Atlas, CMS; 3 m in LHCb; 10 m in Alice

Baseline scenario for 2011

- Beam commissioning: 3 weeks
  - Exit - stable beams with low number of bunches
- Ramp-up to ~200 bunches (75 ns): 2 weeks
  - Multi-bunch injection commissioning continued
  - Stable beams
- Technical Stop: 4+1 days
- Scrubbing run: 10 days including 50 ns injection comm.
- Intermediate energy run – 5 days
- Resume 75 ns operation and increase no. bunches: 3 weeks
  - 300 – 400 – 600 – 800 – 930 - MPS and OP qualification
- Physics operation 75 ns: ~930 bunches
- 50 ns remains an option if things look good

We are here!

2011 LHC schedule Q1/Q2



2011 – recommissioning

19th February	First beam, circulating beams established.
3rd March	First collisions at 3.5 TeV, beta*=1.5 m with pilot beams
5th March	Nominal bunches at 3.5 TeV, start collimator set-up, injection and beam dump set-up & validation
13th March	First stable beams, 3 bunches per beam, initial luminosity 1.6e30 cm-2s-1
18th March	32 bunches per beam, initial luminosity ~3e31 $cm^{-2}s^{-1}$
19th March	64 bunches per beam, initial luminosity ~6e31 $cm^{-2}s^{-1}$
20th March	**1.45e32 $cm^{-2}s^{-1}$ with 75 ns**

Fast re-commissioning, improvements across the board.

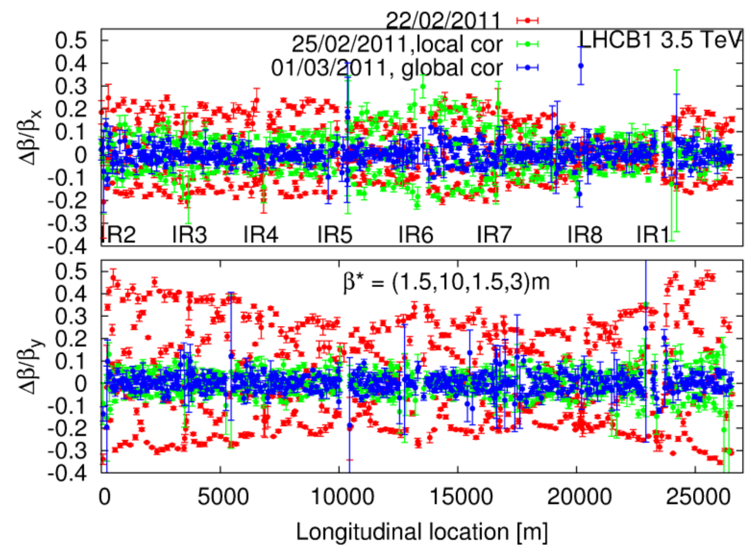
Operation cycle now well optimized: faster ramp & squeeze, much fewer manual actions required by shift crews

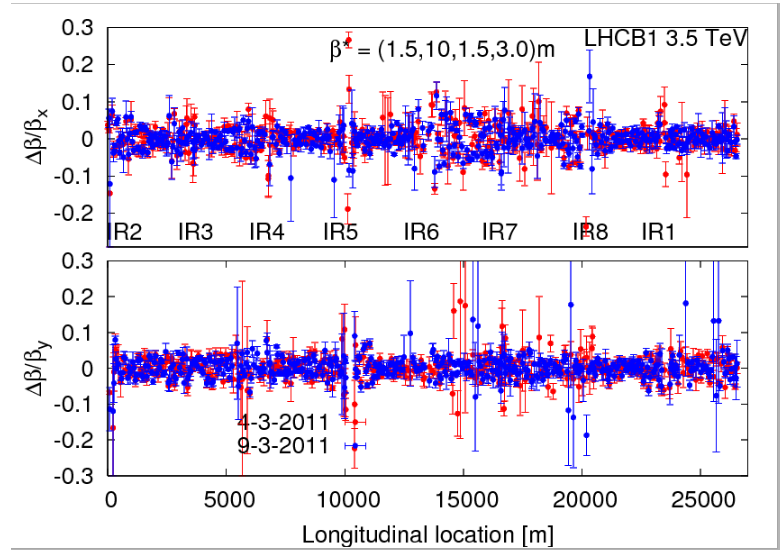
Machine still beautiful

- Beta beating corrected down to 5-10%!!
- Confirmed stability of the optics
- 'Final' β^* values from K-modulation:

Beam/plane	IR5	IR1
B1H	1.50	1.53
B2H	1.48	1.57
B1V	1.52	1.50
B2V	1.52	1.57

- Errors around 4-10%
- Aperture: global > 12 σ, triplet > 14.5 σ





Scrubbing run

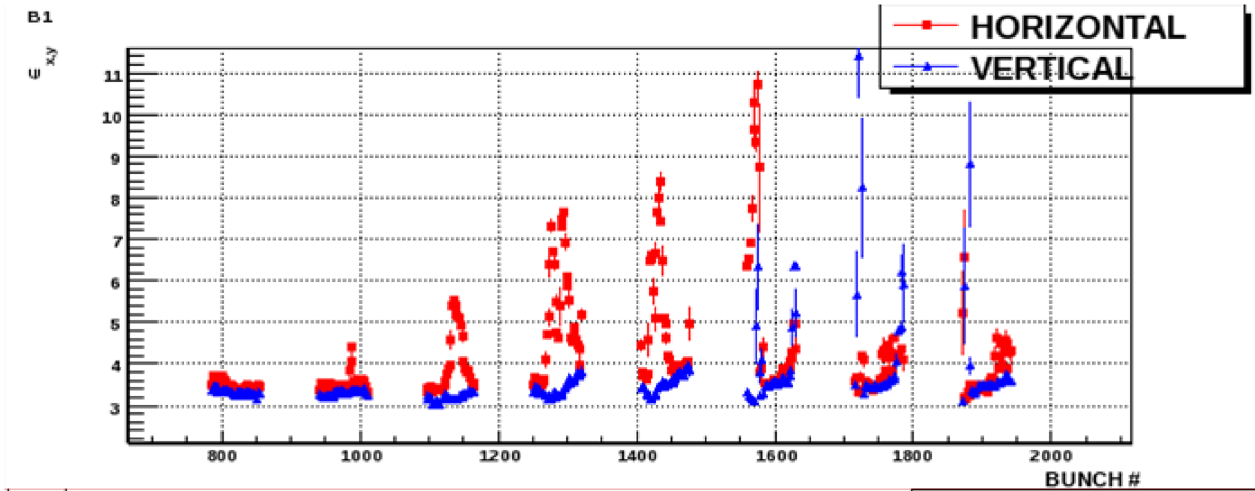
- Impressive progression in spite of several technical problems not related to the scrubbing (> 3 days lost).
- 5 days of scrubbing
- All solenoid off (experiments and vacuum solenoids at warm sections)

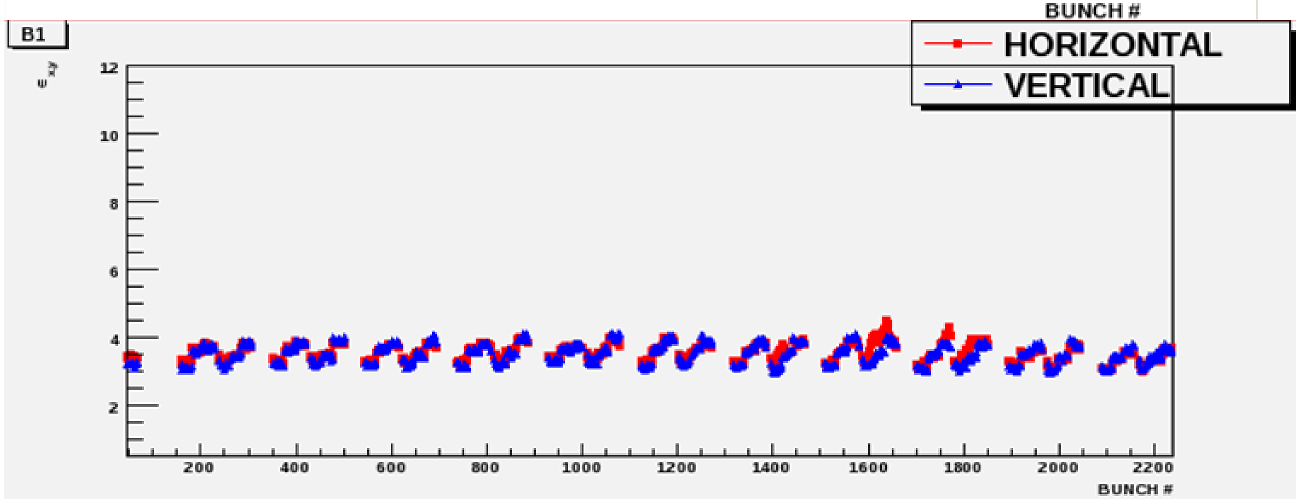
Date	Bunches B1+B2
Tue 5th April	300+300
Wed 6th April	408+336
Sat 8th April	588+588
Sun 9th April	804+804
Mon 10th April	1020+1020

- Careful increase in intensity (in steps of 200 bunches) monitoring cryogenics, vacuum, machine protection and particularly RF
  - Limited to 72 bunches/train by injection performance
- Reached 1020 bunches per beam at the end of the scrubbing run ➔ more than 10^{14} protons per ring

Scrubbing: effect on beam

Started like this – 300 bunches

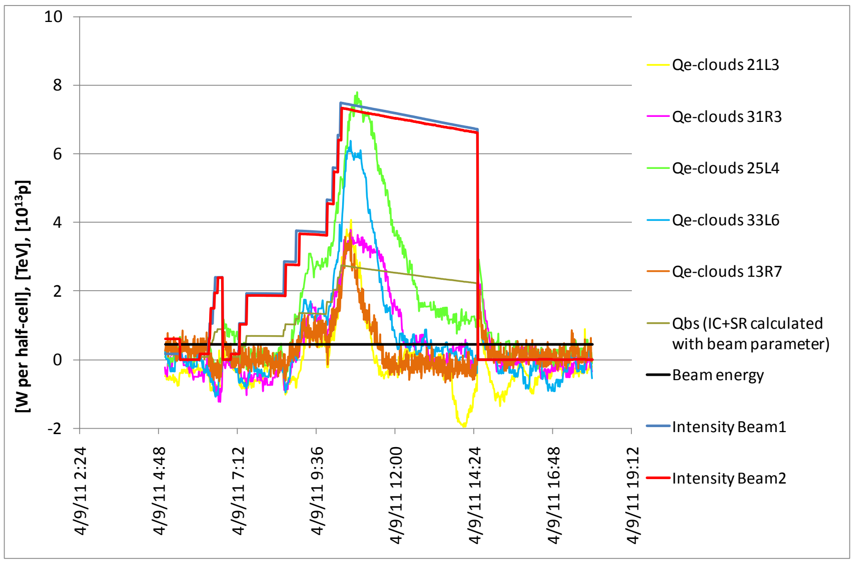


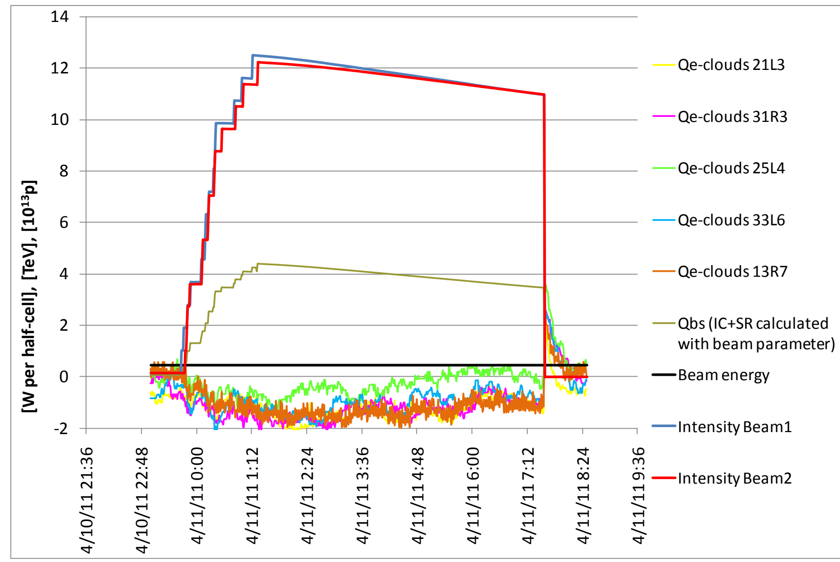


804 bunches some hours of scrubbing

Scrubbing: Heat-loads in the arcs

- Impressive reduction of the heat load in few hours: results consistent with SEY reduction from 2.5 to <1.8





L. Tavian

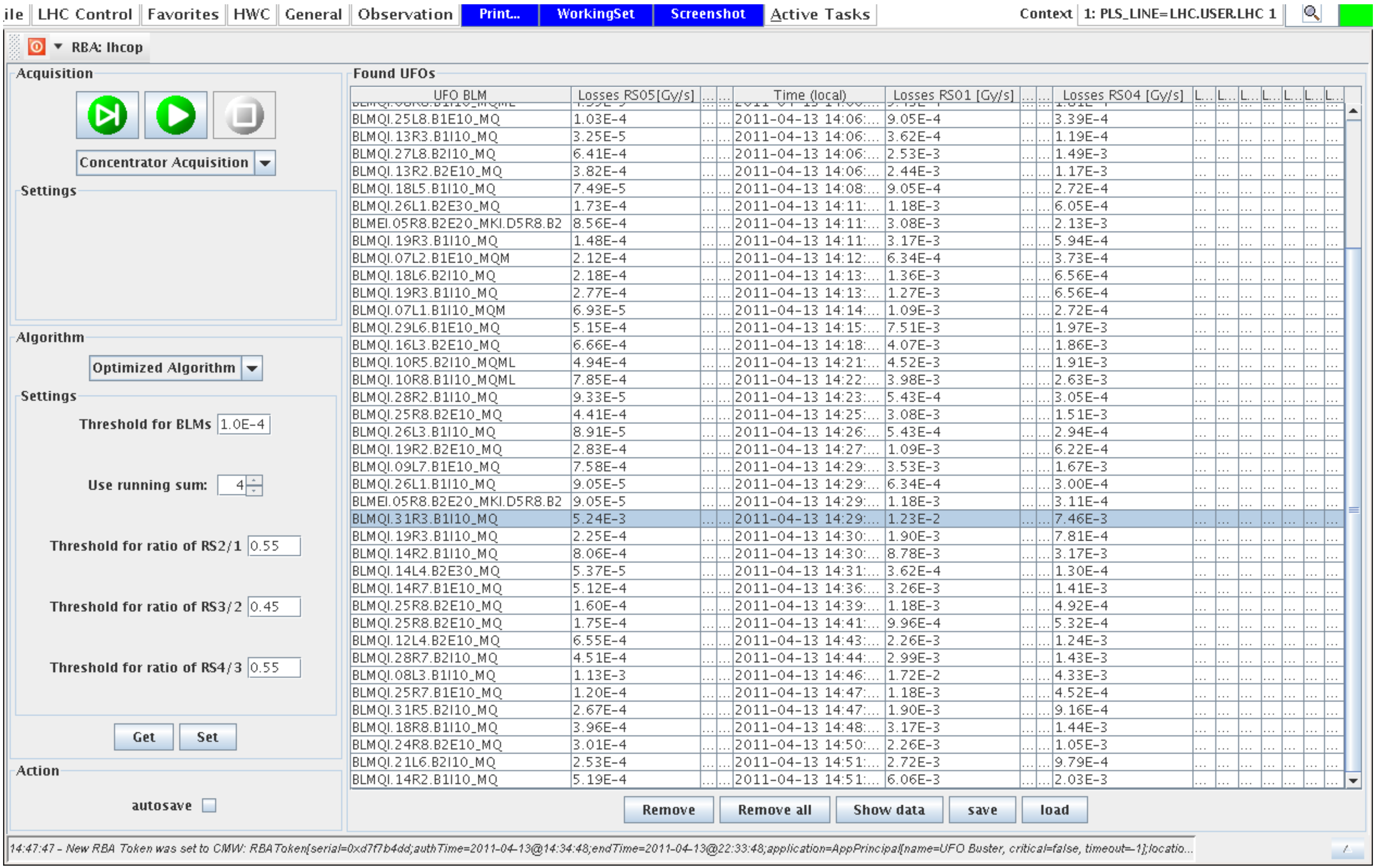
Decision taken to go with 50 ns bunch spacing after encouraging scrubbing run

Next step – increasing the number of bunches

Issues include:

- Running with higher total beam intensity requires much finer control of the beam parameters plus…
- More UFOs
- More SEUs
- RF Power Couplers (present limitation)
- RF wave-guide flashover (linked to UFOs)
- HOM heating of Injection kickers, cryo, collimators.. (total intensity and bunch length dependence)

UFO's: coming thick and fast



UFO BLM	Losses RS05[Gy/s]	...	...	Time (local)	Losses RS01 [Gy/s]	...	...	Losses RS04 [Gy/s]	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	...	...	...	...	...	...	...
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BLMQI.10R5.B2I10_MQML	4.94E-4	...	...	2011-04-13 14:21:...	4.52E-3	...	...	1.91E-3	...	...	...	...	...	...	...
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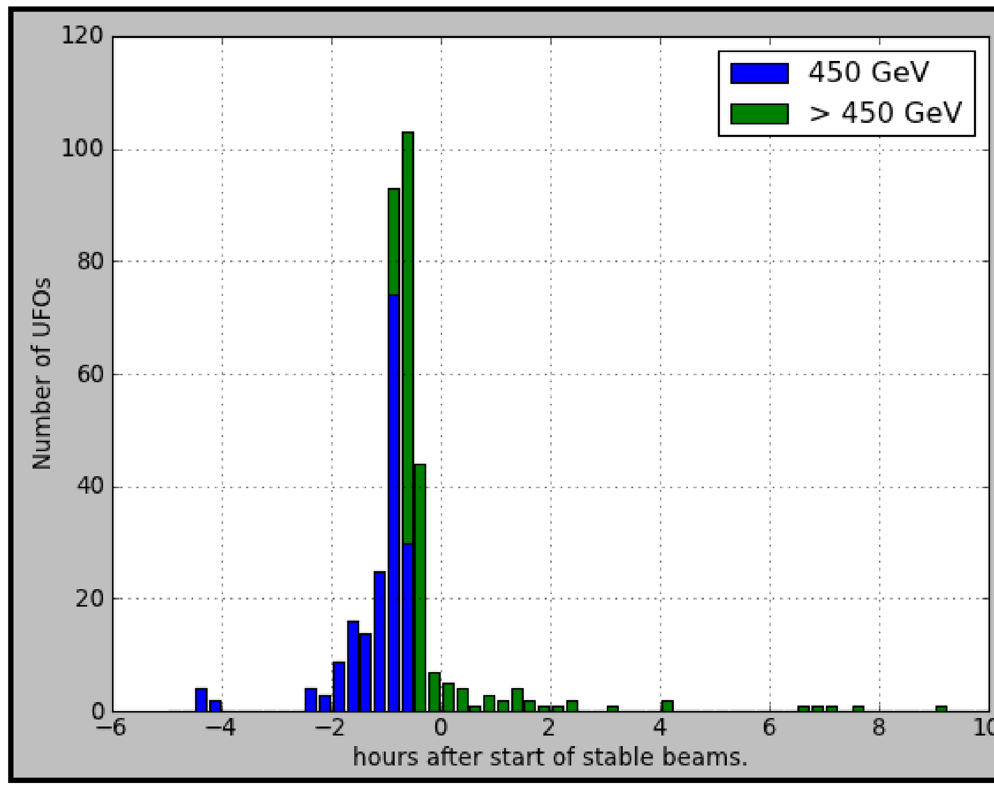
BLMQI.12L4.B2E10_MQ	6.55E-4	...	...	2011-04-13 14:43:...	2.26E-3	...	...	1.24E-3	...	...	...	...	...	...	...
BLMQI.28R7.B2I10_MQ	4.51E-4	...	...	2011-04-13 14:44:...	2.99E-3	...	...	1.43E-3	...	...	...	...	...	...	...
BLMQI.08L3.B1I10_MQ	1.13E-3	...	...	2011-04-13 14:46:...	1.72E-2	...	...	4.33E-3	...	...	...	...	...	...	...
BLMQI.25R7.B1E10_MQ	1.20E-4	...	...	2011-04-13 14:47:...	1.18E-3	...	...	4.52E-4	...	...	...	...	...	...	...
BLMQI.31R5.B2I10_MQ	2.67E-4	...	...	2011-04-13 14:47:...	1.90E-3	...	...	9.16E-4	...	...	...	...	...	...	...
BLMQI.18R8.B1I10_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.B2I10_MQ	2.53E-4	...	...	2011-04-13 14:51:...	2.72E-3	...	...	9.79E-4	...	...	...	...	...	...	...
BLMQI.14R2.B1I10_MQ	5.19E-4	...	...	2011-04-13 14:51:...	6.06E-3	...	...	2.03E-3	...	...	...	...	...	...	...

~90 in 90 minutes – happily most below threshold

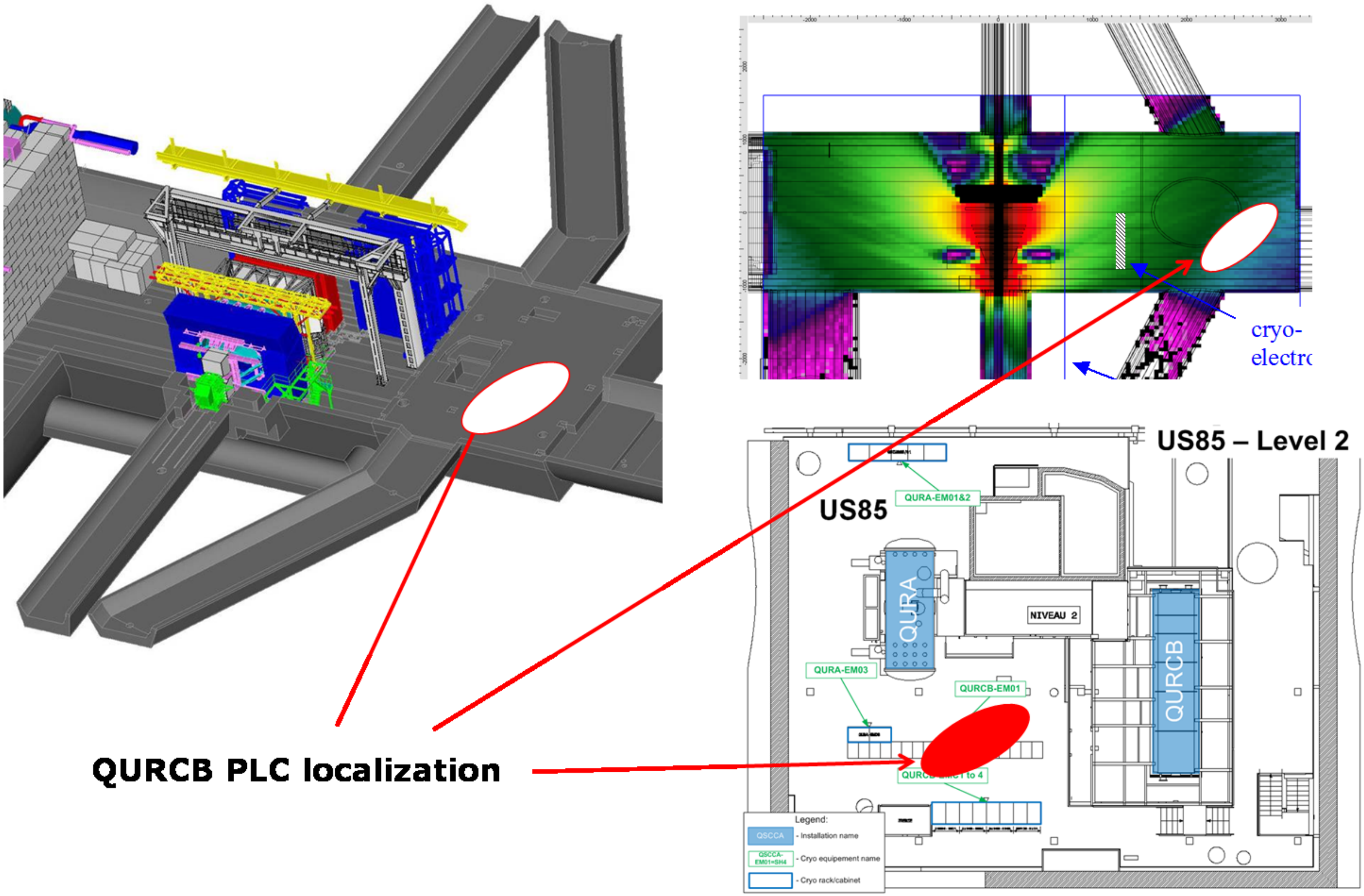
UFO around injection region

679 UFOs around the injection kickers caused **9 beam dumps.**

Most of the UFOs around the kickers occur before going to stable beams.



Radiation to electronics (SEUs etc.)



Cryogenics controls implicated (among others)

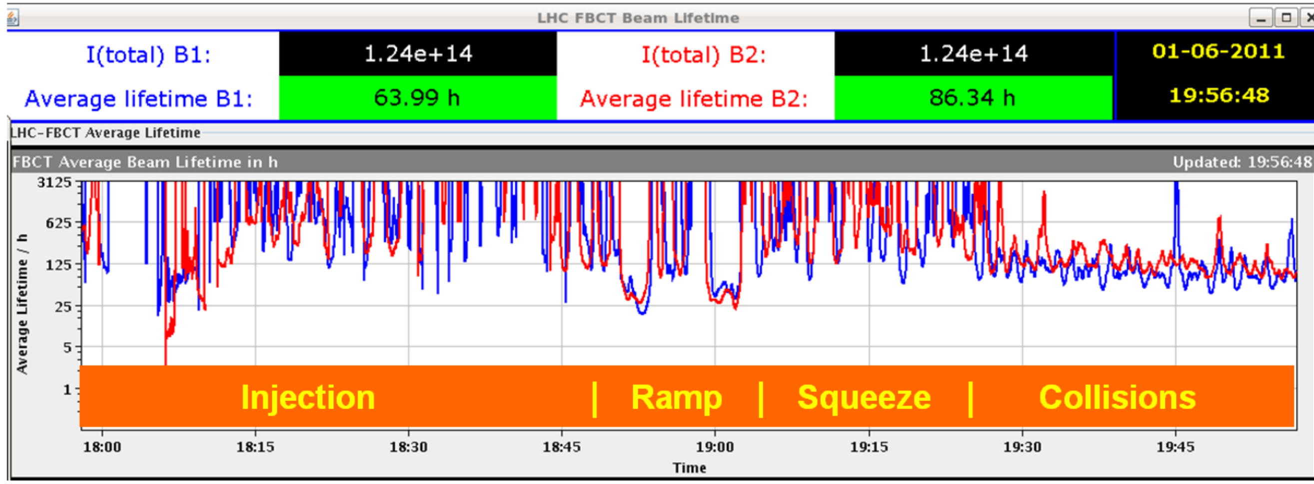
Increasing intensity – machine protection

- Collimation loss of hierarchy at 450 GeV
  - Orbit. Regular loss maps performed
- 72 (108/144) bunches from SPS
  - Beam quality from injector very important
  - 144 bunches per injection from SPS > 1 MJ down the lines
- High temperature superconducting current lead quenched (7th April)
  - Invoked quench of 11 magnets
- Injection Kicker Flashover (18th April)
  - Not pretty, heavy beam loss

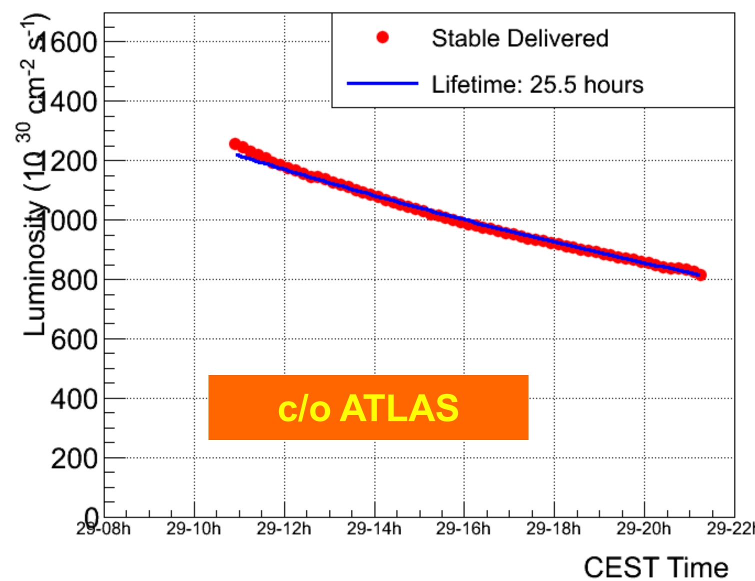
However…

Lifetimes during a fill (1092 bunches)

- Very good lifetime during the whole process
- Hardly visible when we go in collision

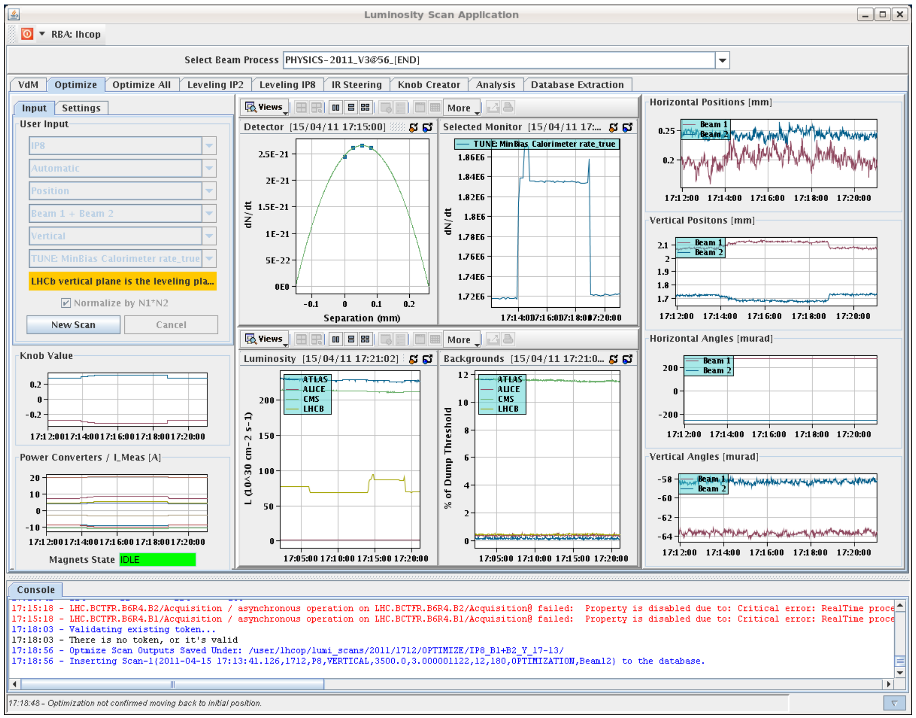


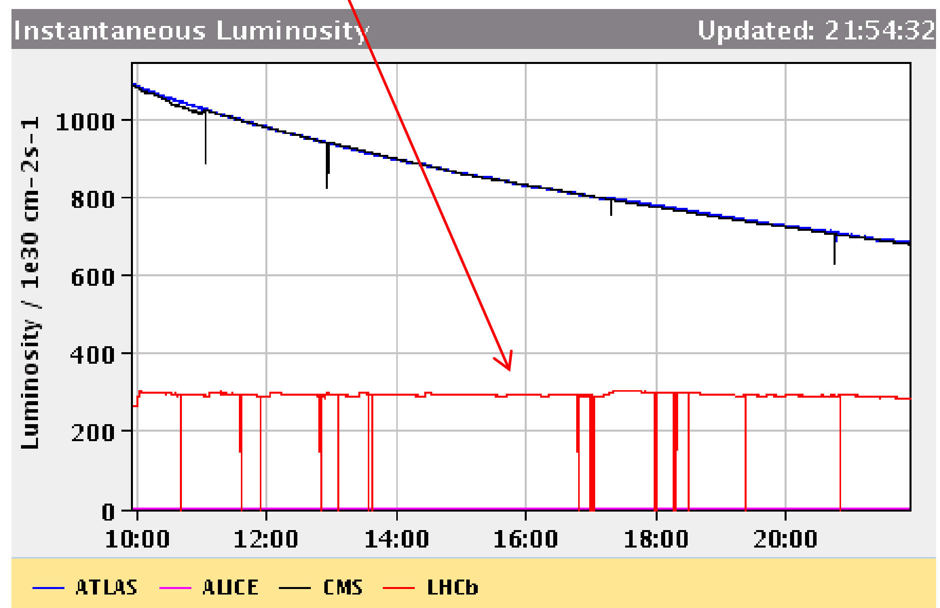
- Luminosity lifetime > 20 hours



IP8 Luminosity leveling operational

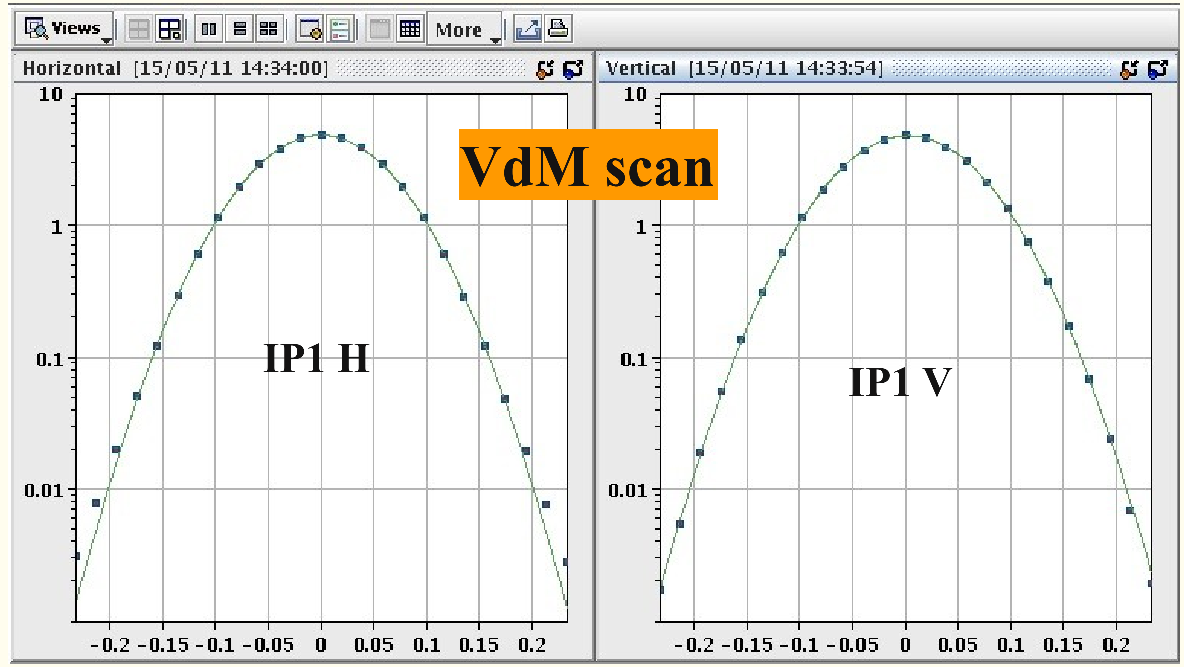
Needed to get to 1 fb^{-1} in LHCb given the limit in peak luminosity





LHC precision front

- absolute luminosity normalization
- low, well understood backgrounds
- precision optics for ATLAS-ALFA and TOTEM



precise measurement of the luminous region + beam intensity --> absolute luminosity and cross section calibration

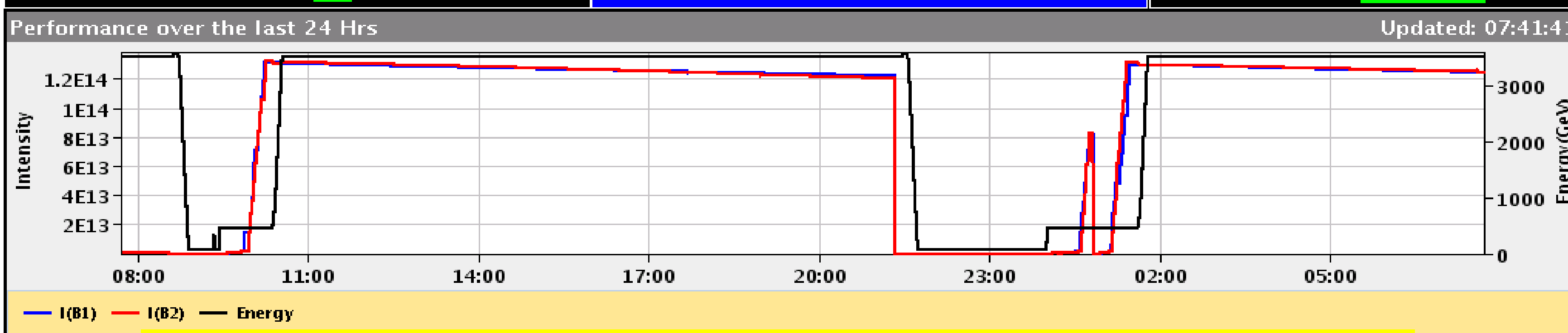
currently ~ 5 % level,

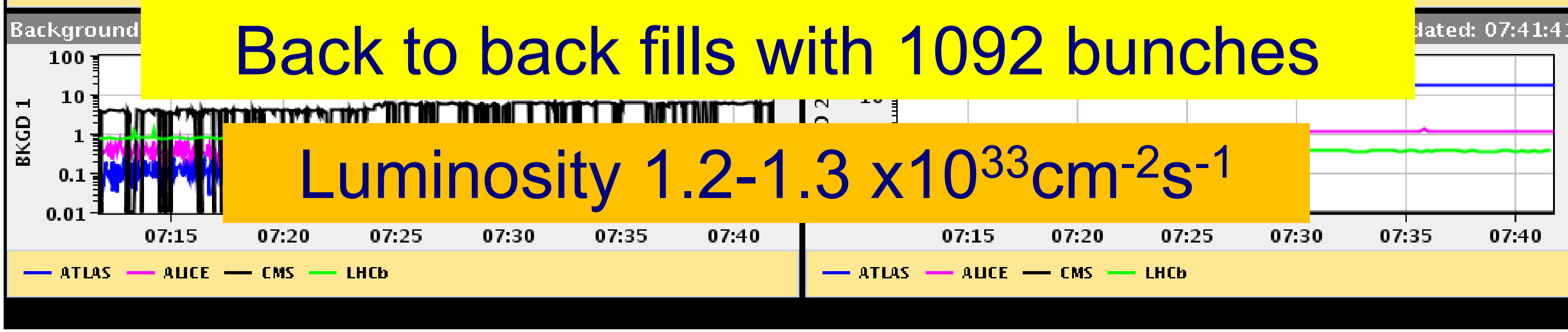
And we've been producing some luminosity

30-May-2011 07:41:43 Fill #: 1816 Energy: 3500 GeV I(B1): 1.24e+14 I(B2): 1.25e+14

	ATLAS	ALICE	CMS	LHCb
Experiment Status	PHYSICS	PHYSICS	NOT_READY	PHYSICS
Instantaneous Lumi (ub.s)^-1	957.572	0.574	945.849	296.325
BRAN Luminosity (ub.s)^-1	930.163	0.970	1009.494	83.206
Fill Luminosity (nb)^-1	20925.5	11.1	21066.8	5766.5
BKGD 1	0.179	0.392	6.482	0.779
BKGD 2	17.508	1.174	0.002	0.381
BKGD 3	8.419	1.398	3.268	1.087

LHCb VELO Position IN Gap: -0.0 mm STABLE BEAMS TOTEM: STANDBY

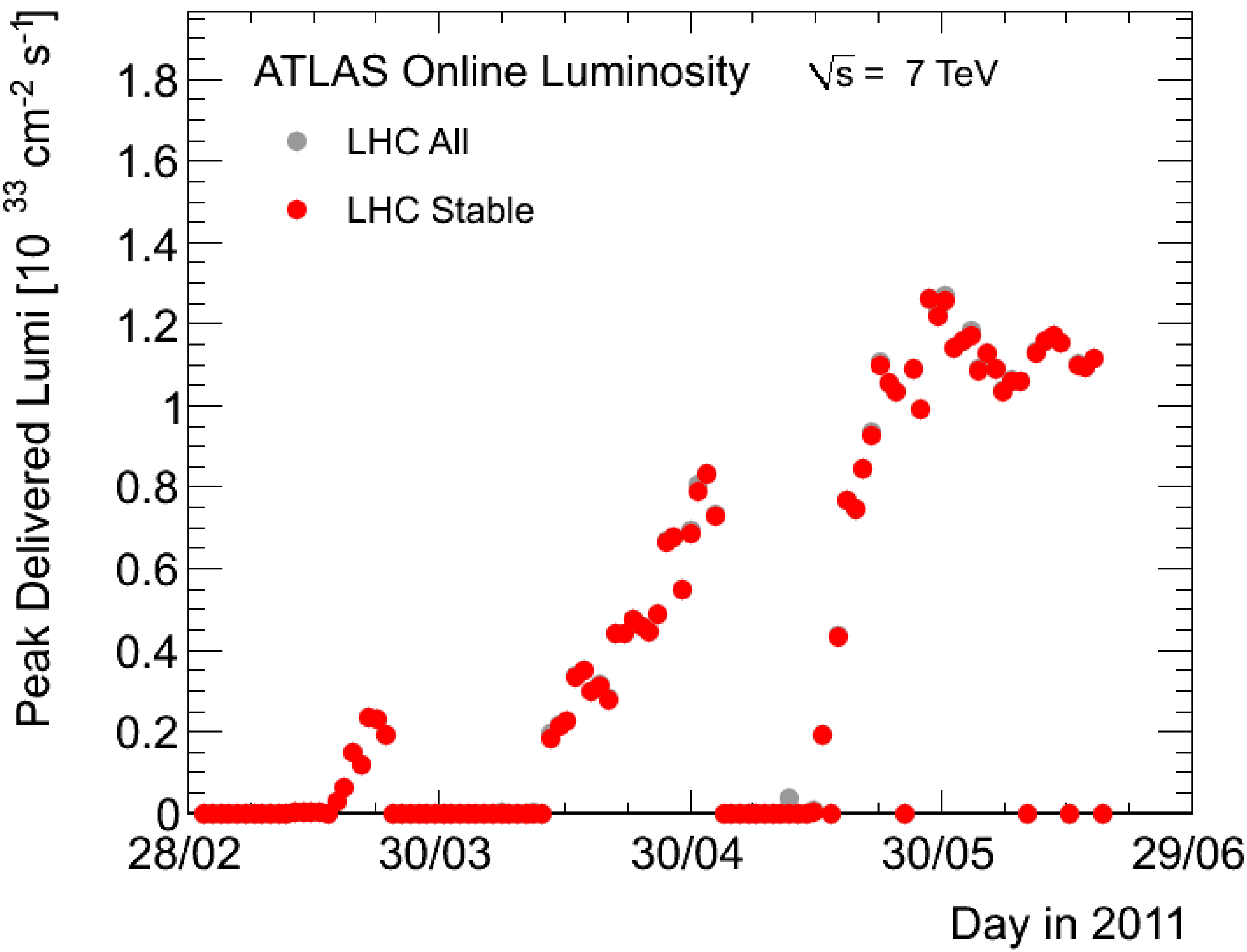


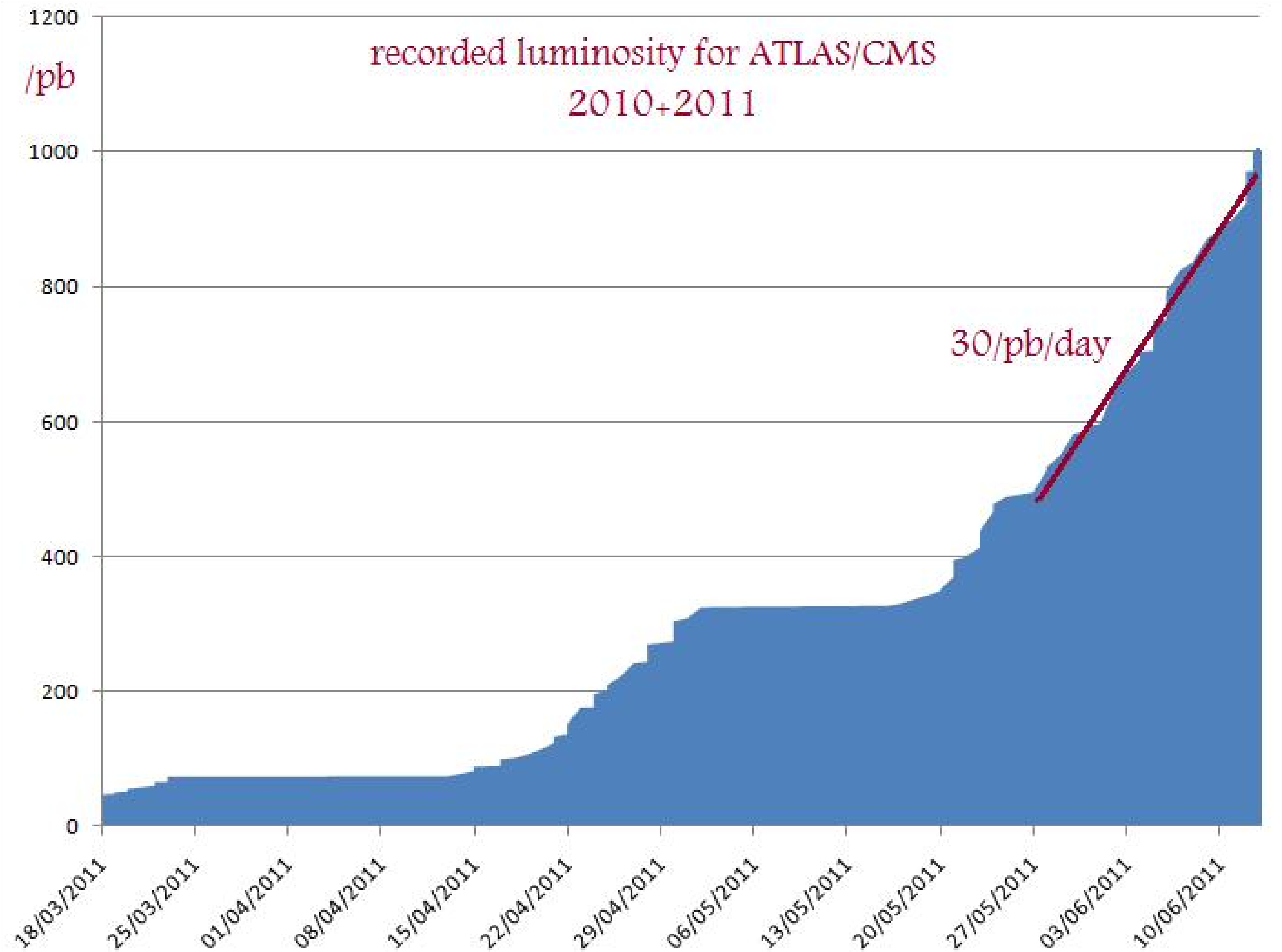


Back to back fills with 1092 bunches

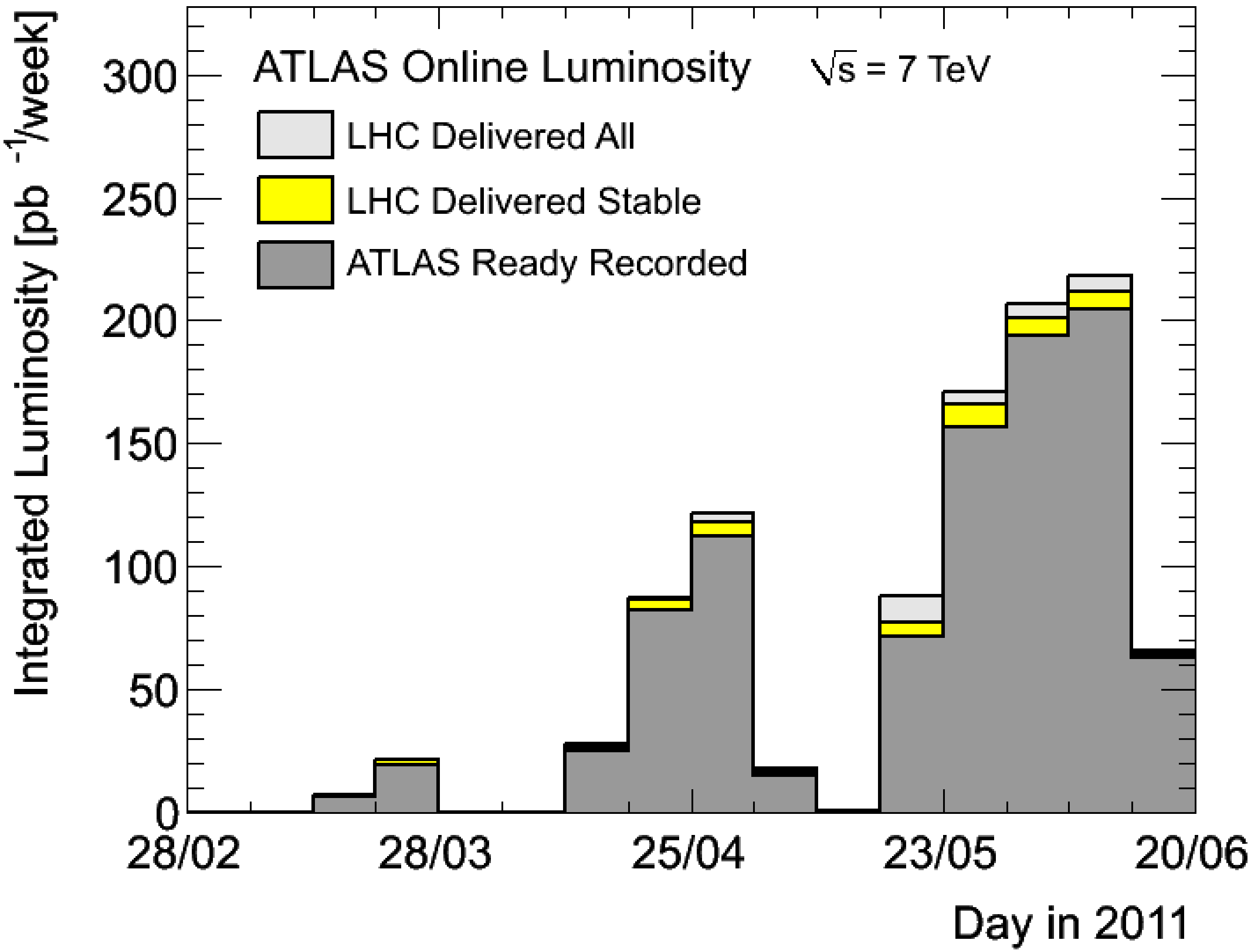
Luminosity 1.2-1.3 $x10^{33}cm^{-2}s^{-1}$

Peak Luminosity

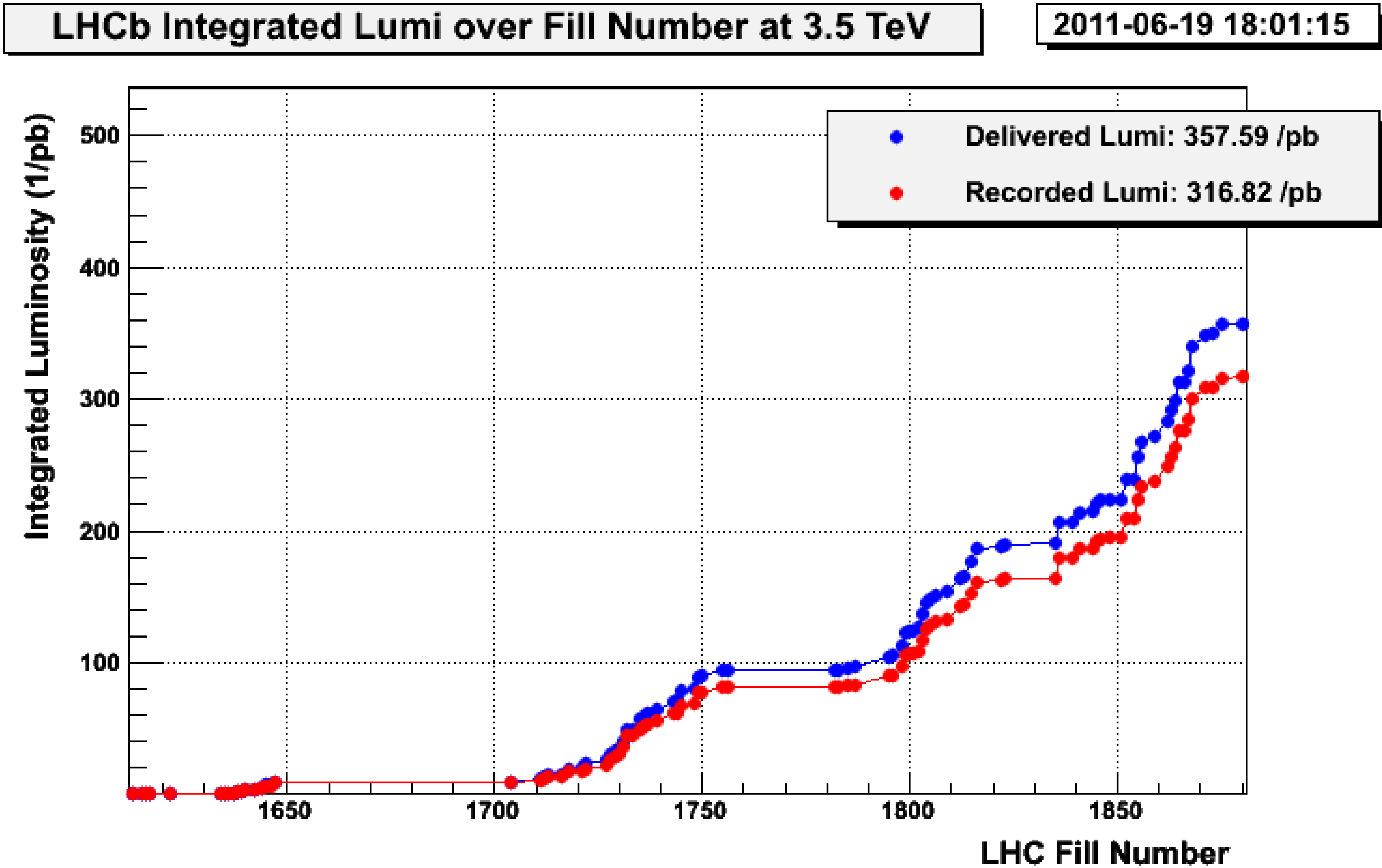



recorded luminosity for ATLAS/CMS
2010+2011
/pb
1200
1000
800
600
400
200
0
30/pb/day
18/03/2011
25/03/2011
01/04/2011
08/04/2011
15/04/2011
22/04/2011
29/04/2011
06/05/2011
13/05/2011
20/05/2011
27/05/2011
03/06/2011
10/06/2011

Weekly


ATLAS Online Luminosity
√s = 7 TeV
LHC Delivered All
LHC Delivered Stable
ATLAS Ready Recorded
Integrated Luminosity [pb -1/week]
300
250
200
150
100
50
0
28/02
28/03
25/04
23/05
20/06
Day in 2011

LHCb



LHCb Integrated Lumi over Fill Number at 3.5 TeV
2011-06-19 18:01:15
Delivered Lumi: 357.59 /pb
Recorded Lumi: 316.82 /pb
Integrated Luminosity (1/pb)
500
400
300
200
100
1650
1700
1750
1800
1850
LHC Fill Number

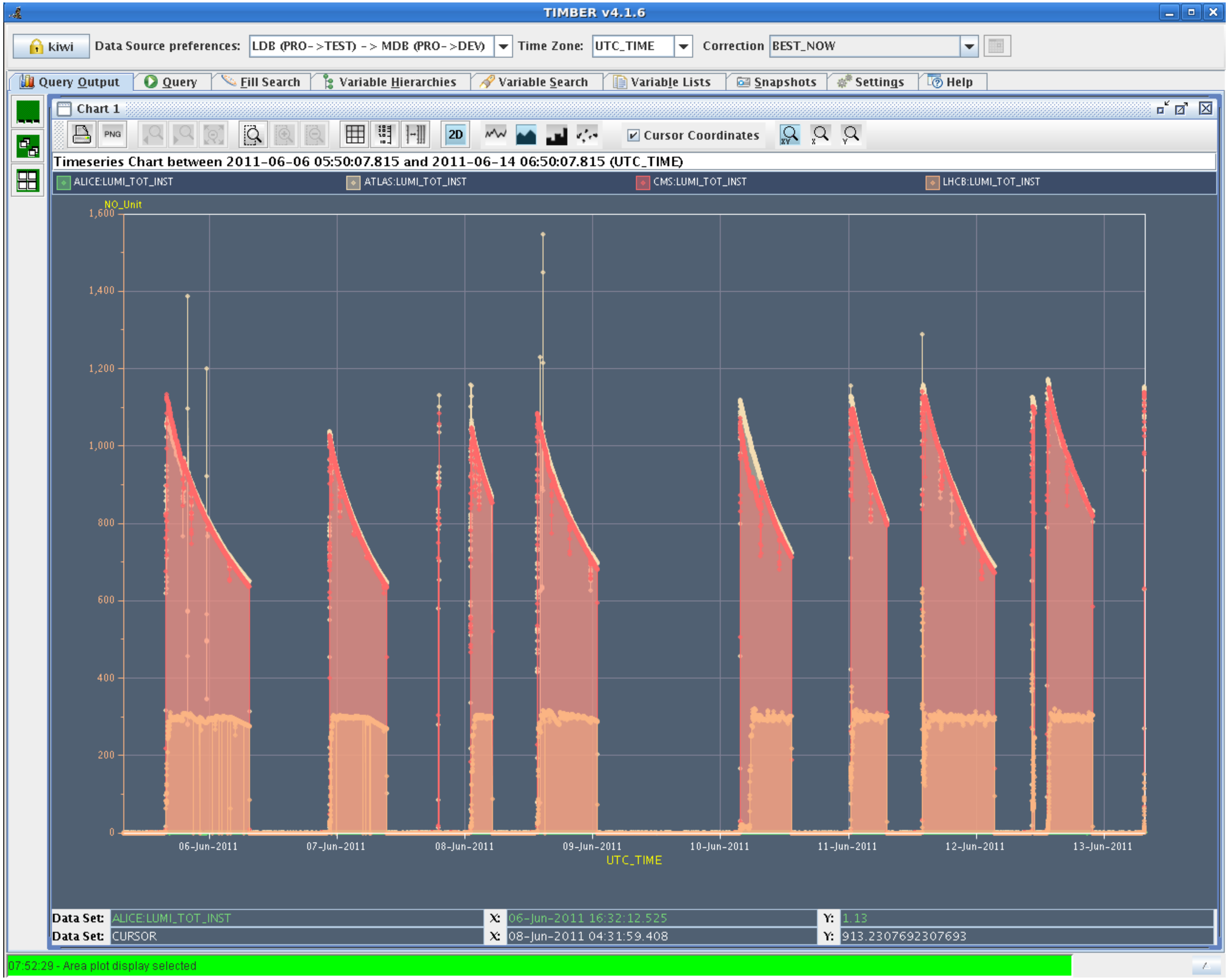
Status

Integrated Luminosity to date (IR1-5/IR8)	1.06 fb^{-1}/0.36 fb^{-1}
Peak Stable Luminosity Delivered	1.26×10^{33} $cm^{-2}s^{-1}$
Maximum number of bunches at 450 GeV/c	1308
Maximum number of bunches in collision	1092
Maximum intensity in collision	1.3×10^{14} p/beam
Maximum stored energy	73 MJ/beam
Average bunch population	1.2×10^{11} p
Emittance in collision	~2.5 μm
Maximum Luminosity Delivered in one day	56 pb^{-1}
Maximum Luminosity Delivered in one week	239 pb^{-1}

Week 23 – the week before last!

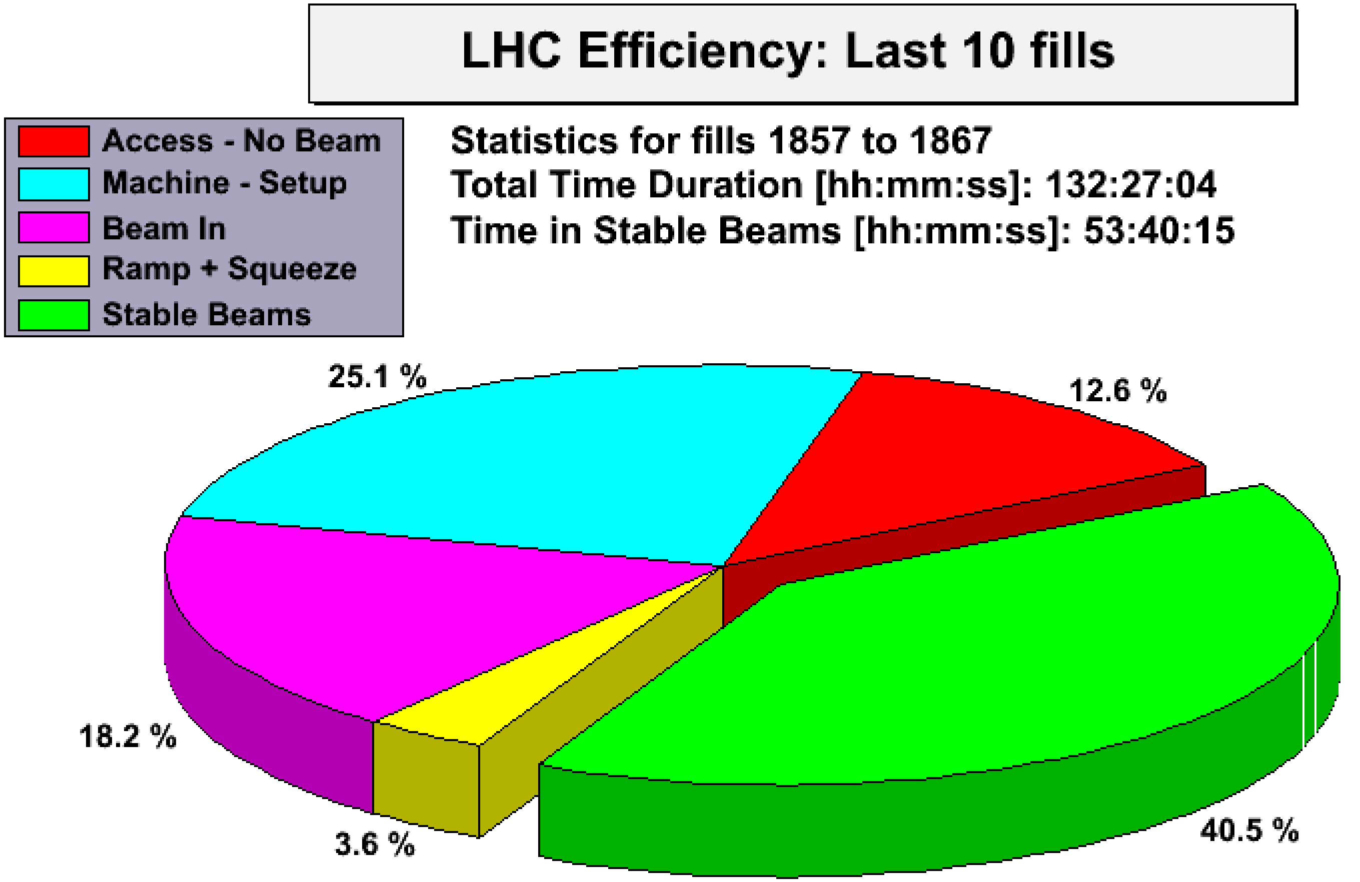
Date	Fill number	Time in stable beams	Int. lumi [pb^{-1}]	Cause of dump
Mon 6th	1854	9m	.59	trip of RQ6.L2
Mon-Tues	1855	14h21m	41.3	RTQX2.R1 - FGC
Tue-Wed	1856	10h50m	31.0	Alice dipole trip
Wed	1858	0		Big UFO IP2
Wed-Thu	1859	3h56m	13.4	Electrical glitch
Thu	1862	11h12m	32.4	Trip RSQSX 400 V PS
Thu - Sat	1863	9h43	30.8	PLC DFB-cryo MS L1
Sat - Sun	1864	6h48	23.1	D2.L1 bus bar quench
Sun - Mon	1865	13h36m	42.6	Collimator controls
Mon	1866	20m	1.3	RF Total Voltage Intlk B1
Mon 14th	1867	8h14m	28.8	RF module trip

Week 23



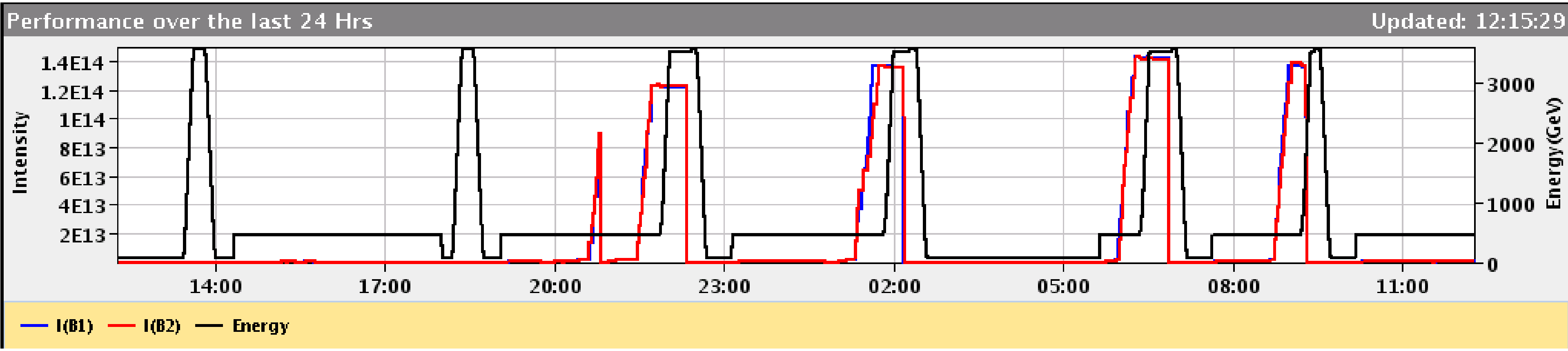
TIMBER v4.1.6
kiwi
Data Source preferences: LDB (PRO->TEST) -> MDB (PRO->DEV)
Time Zone: UTC_TIME
Correction BEST_NOW
Query Output
Query
Fill Search
Variable Hierarchies
Variable Search
Variable Lists
Snapshots
Settings
Help
Chart 1
Cursor Coordinates
Timeseries Chart between 2011-06-06 05:50:07.815 and 2011-06-14 06:50:07.815 (UTC_TIME)
ALICE:LUMI_TOT_INST
ATLAS:LUMI_TOT_INST
CMS:LUMI_TOT_INST
LHCB:LUMI_TOT_INST
NO_Unit
1,600
1,400
1,200
1,000
800
600
400
200
0
06-Jun-2011
07-Jun-2011
08-Jun-2011
09-Jun-2011
10-Jun-2011
11-Jun-2011
12-Jun-2011
13-Jun-2011
UTC_TIME
Data Set: ALICE:LUMI_TOT_INST
X: 06-Jun-2011 16:32:12.525
Y: 1.13
Data Set: CURSOR
X: 08-Jun-2011 04:31:59.408
Y: 913.2307692307693
07:52:29 - Area plot display selected

Week 23


LHC Efficiency: Last 10 fills
Access - No Beam
Machine - Setup
Beam In
Ramp + Squeeze
Stable Beams
Statistics for fills 1857 to 1867
Total Time Duration [hh:mm:ss]: 132:27:04
Time in Stable Beams [hh:mm:ss]: 53:40:15
25.1 %
12.6 %
18.2 %
3.6 %
40.5 %

It is not always easy! A day in June.

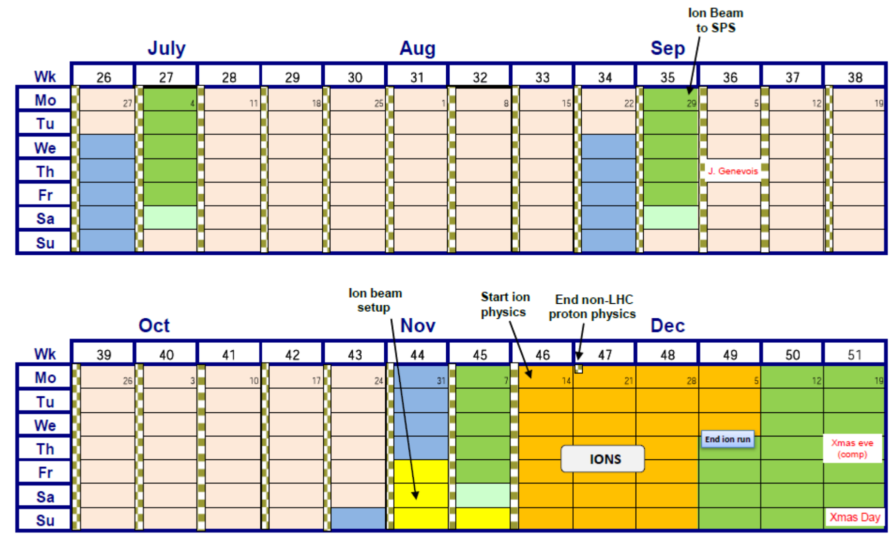
Cryo S56
Injection preparation for 144b
Cryo S34
UFO IR2
QPS noise → quench
RF arc
Collimator temperature



And let's not mention last week.

Outlook for 2011 (protons)

- 110 more days at $>10^{33}$ $cm^{-2}s^{-1}$ and an efficiency for physics (Hubner factor) of 0.2 gives another 2 to 3 fb^{-1}
- Main known unknowns: UFOs and SEU



25 ns studies to come during MDs (to sort out injection and beam stability issues) and possibly an operational development period to validate scrubbing and future operation

Outlook for 2011 (Pb)

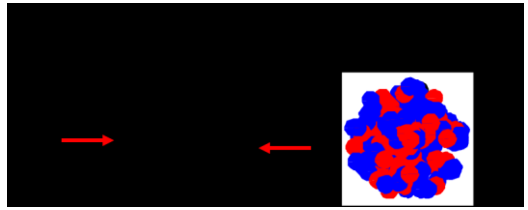
- Number of bunches vs. bunch population
  - Possibility to reach 540 bunches but likely limited to nominal bunch population

- Optics
  - Take over ATLAS and CMS β* from protons
  - Squeeze ALICE to same value β*= 1.5 m - 2 days setup

- Could reach peak luminosities in the range of 1 to 1.4×10^{26} $cm^{-2}s^{-1}$ and integrate 30 to 50 μb^{-1}

- Short run more sensitive to any prolonged machine problems

Testing p-Pb in 2011



- Important to resolve uncertainties regarding feasibility, Pb intensity limit from unequal revolution frequencies at injection, ramp
  - Modulation of long-range beam-beam, transverse feedback, tune-control …
- Crucial questions are related to injection and ramping
  - Effects of protons (say 10% of nominal) on one Pb bunch
  - Inject few Pb bunches against some convenient p filling scheme
  - Possible in 2011 (OK in 2012)
  - Detailed planning of MD being worked out

2012

- Physics data-taking until end of 2012
- Following measurements of the copper stabilizers resistances during the Christmas stop, we will re-evaluate the maximum energy for 2012 (Chamonix 2012)
- Baseline is probably 50 ns
  - Better emittances from injectors with potential to push lower, better performance for a given total beam intensity
  - Possible to push up bunch intensity
  - But first see what 25 ns brings…

Given up making predictions of integrated luminosity!

Conclusions

- The LHC is a beautiful machine (although some times temperamental) – a real testament to those that built it.
- High intensity was known to require more careful control of the machine parameters and to potentially bring a host of other issues into play
  - Work very much in progress
- 50 ns has proven to be a good choice - more potential
- > 1 fb-1 delivered to ATLAS and CMS
- ~0.36 fb-1 delivered to LHCb
- How much higher in peak luminosity we can go for ATLAS and CMS will depend on extent of UFOs, SEUs etc.
  - Aiming for 1380 bunches…