LHC Machine Operational Status and Future Plans

US LHC User's Organization, FNAL
Steve Myers
(On behalf of the LHC team and international collaborators)

Topics

- Brief Recap of last two years
- Summary of luminosity performance this year
- Very Recent Progress
- Plans

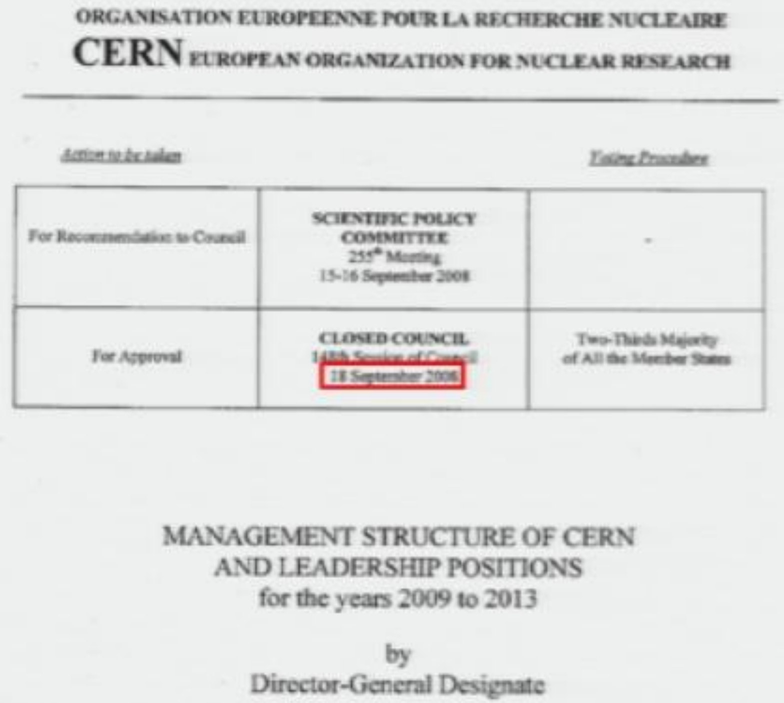
LHC: Some Technical Challenges: Recap

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 Commissioning: Recap

- 2008
  - Accelerator complete
  - Ring cold and under vacuum
- September 10th 2008
  - First beams around
- September 19th 2008
  - The incident
- 2008 – 2009
  - 14 months of major repairs and consolidation
  - New Quench Protection System for online monitoring and protection of all joints.

LHC Commissioning: Recap


ORGANISATION EUROPEENNE POUR LA RECHERCHE NUCLEAIRE

CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Action to be taken | *Voting Procedure*

For Recommendation to Council	SCIENTIFIC POLICY COMMITTEE 255th Meeting 15-16 September 2008	-
For Approval	CLOSED COUNCIL 148th Session of Council 18 September 2008	Two-Thirds Majority of All the Member States

MANAGEMENT STRUCTURE OF CERN
AND LEADERSHIP POSITIONS
for the years 2009 to 2013

by
Director-General Designate

- 2008
  - Accelerator complete
  - Ring cold and under vacuum
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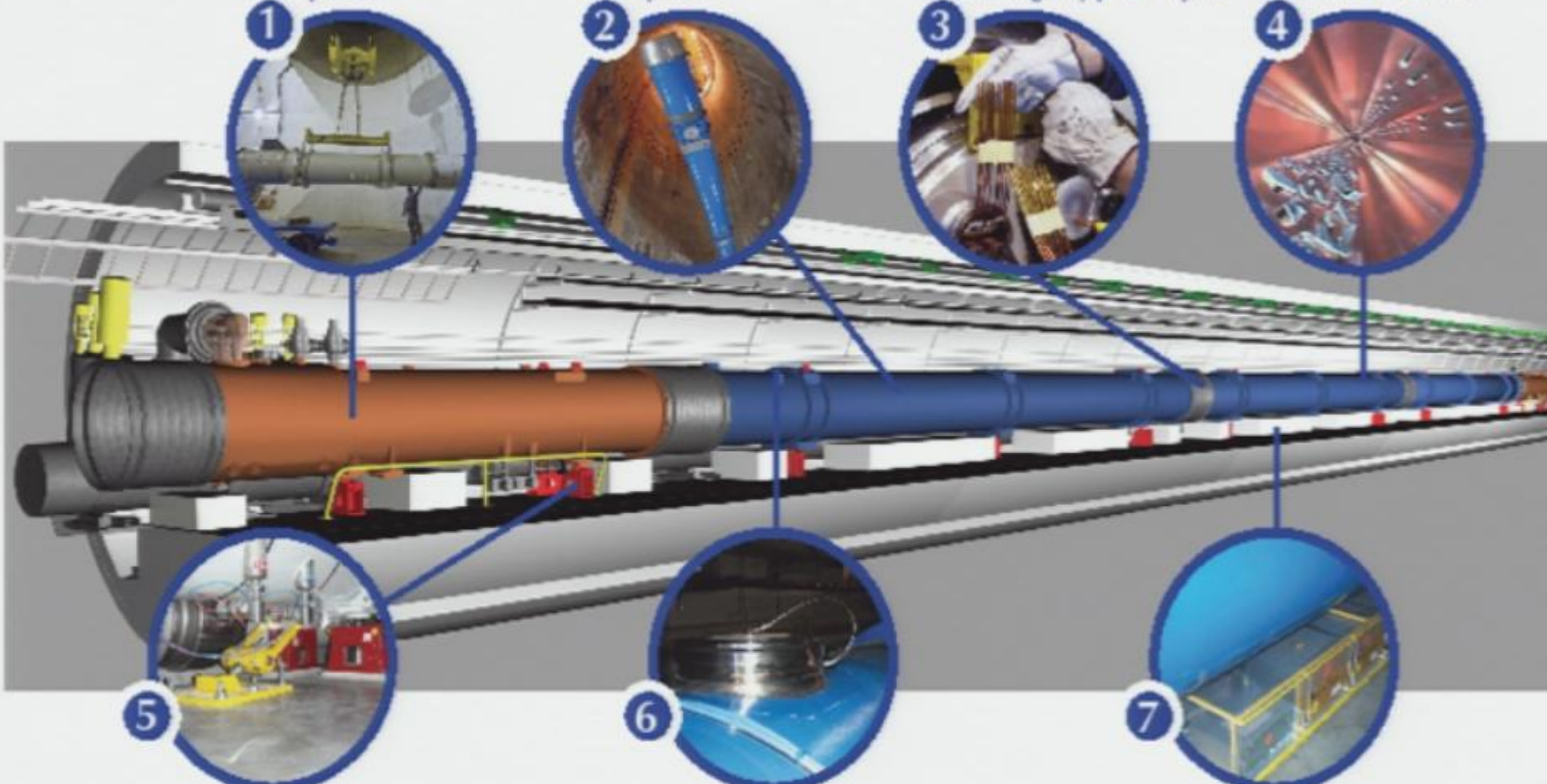
Phase 1 +2

The LHC repairs in detail



\+ 8 cryogenics!

Summary of LHC Commissioning

- November 20^{th} 2009
  - First beams around again
- November 29^{th} 2009
  - Both beams accelerated to 1.18 TeV simultaneously
- December 8^{th} 2009
  - 2x2 accelerated to 1.18 TeV
  - First collisions at 2.36 TeV cm!
- December 14th 2009
  - Stable 2x2 at 1.18 TeV
  - Collisions in all four experiments

LHC - highest energy collider

Limited to 2 kA in main circuits (1.18 TeV) during deployment and testing of new Quench Protection System

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Decided Scenario 2010-2011

Following the technical discussions in Chamonix (Jan 2010) the CERN management and the LHC experiments decided

- Run at 3.5 TeV/beam with a goal of an integrated luminosity of around $1fb^{-1}$ by end 2011
  - Implies reaching a peak luminosity of 10^{32} in 2010
- 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

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Primary Goal for 2010

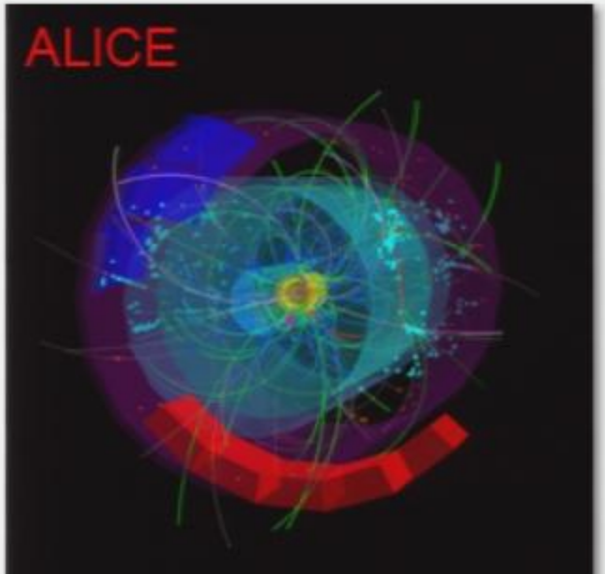
Why do we limit the beam energy to 3.5TeV in 2010-2011?

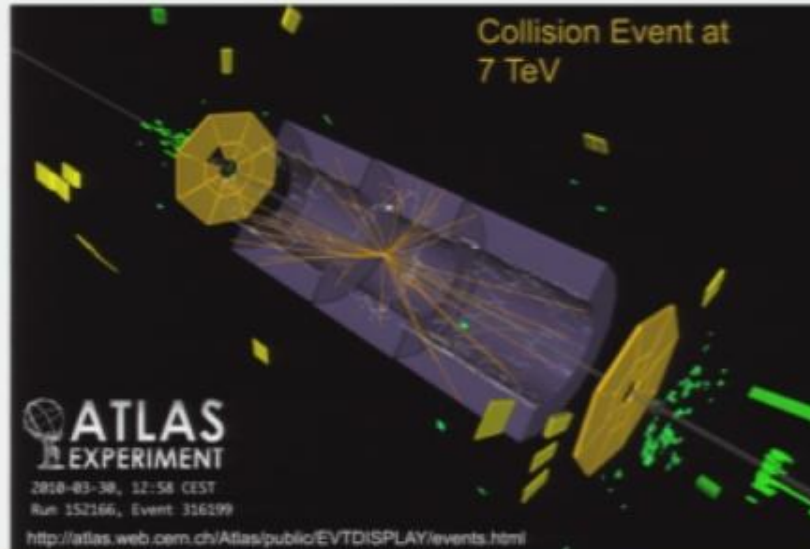
All the work we have done since November 2008 makes us certain that a repeat of September 19 can NEVER happen.

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.

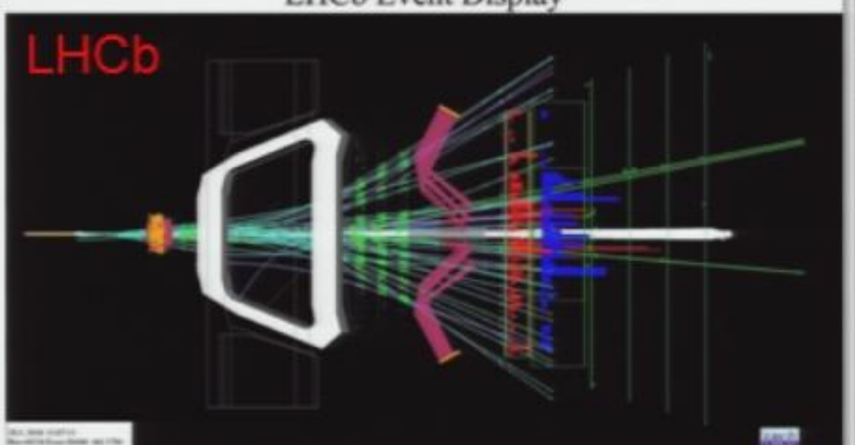
BUT in April 2009, we have uncovered a different possible failure scenario which could under certain circumstances produce an electric arc in the "copper stabilizers" of the magnet interconnects

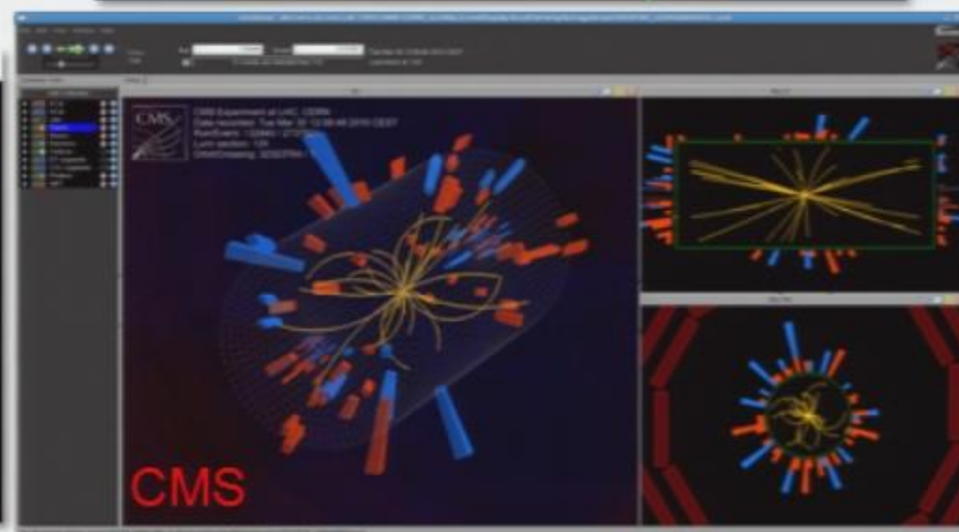
LHC: First collisions at 7 TeV on 30 March 2010





LHCb Event Display





First Running Period (low bunch intensity)

calculated

Event	TeV	OEF	β*	Nb	Ib	Itot	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	4	2.00E+10	8.0E+10	0.0452	2	3.6E+28	19 April 2010
5	3.5	0.2	2	6	2.00E+10	1.2E+11	0.0678	4	7.1E+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

> Seven Orders of magnitude below design

At this point, just ahead of the ICHEP, Paris, (based on collisions at 450 GeV with 1.1e11 ppb) we decided to change mode of operation to high bunch intensity

At the time of ICHEP, Paris

calculated

Event	TeV	OEF	β*	Nb	Ib	Itot	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
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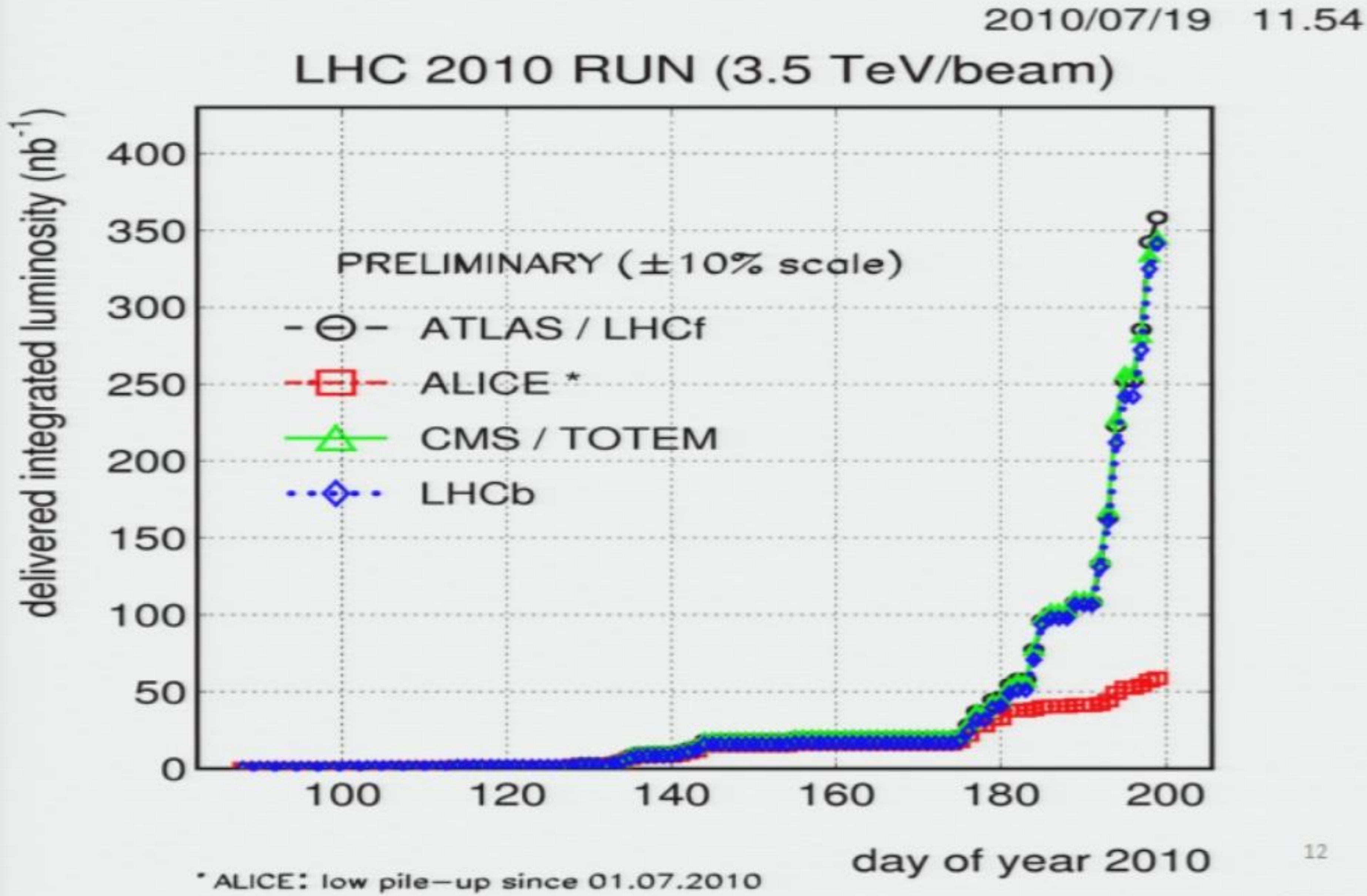
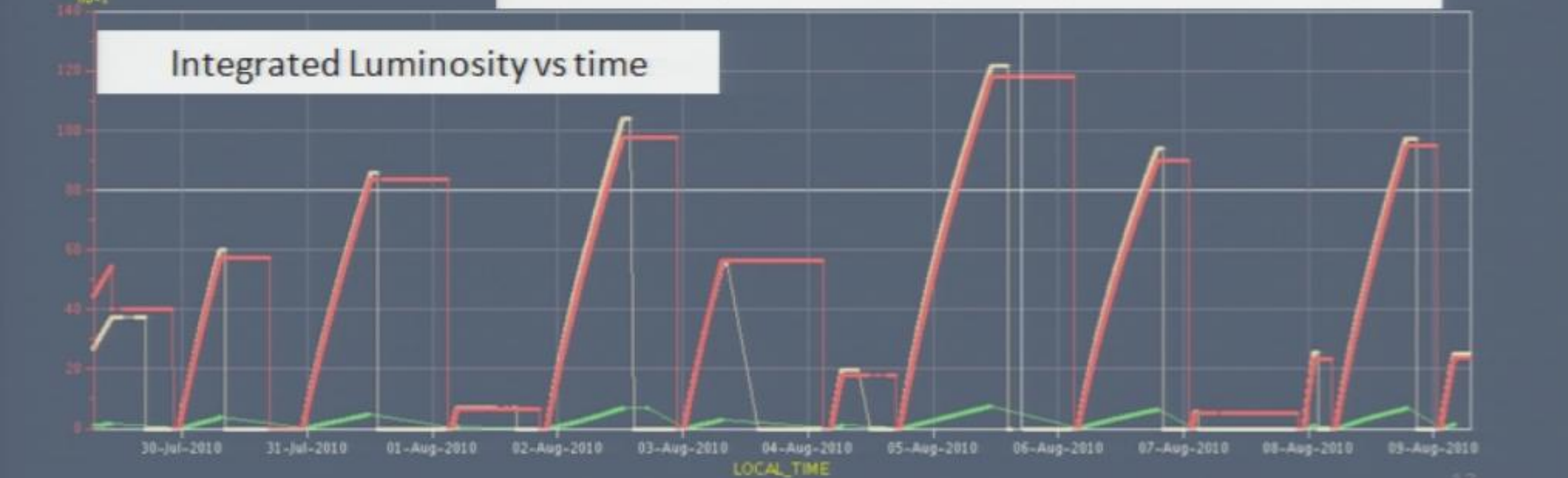
6	3.5	0.2	2	13	2.60E+10	3.4E+11	0.1910	8	2.4E+29	22 May 2010
7	3.5	0.2	3.5	3	1.10E+11	3.3E+11	0.1865	2	6.1E+29	26 June 2010
8	3.5	0.2	3.5	6	1.00E+11	6.0E+11	0.3391	4	1.0E+30	02 July 2010
9	3.5	0.2	3.5	8	9.00E+10	7.2E+11	0.4069	6	1.2E+30	12 July 2010

At the time of the ICHEP, Paris,

Integrated Luminosity ICHEP10 (350nb-1)



30 July to 9 August (25 bunches)



Second Running Period (High bunch Intensity)

calculated

Event	TeV	OEF	β*	Nb	Ib	Itot	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	4	2.00E+10	8.0E+10	0.0452	2	3.6E+28	19 April 2010
5	3.5	0.2	2	6	2.00E+10	1.2E+11	0.0678	4	7.1E+28	15 May 2010
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7	3.5	0.2	3.5	3	1.10E+11	3.3E+11	0.1865	2	6.1E+29	26 June 2010
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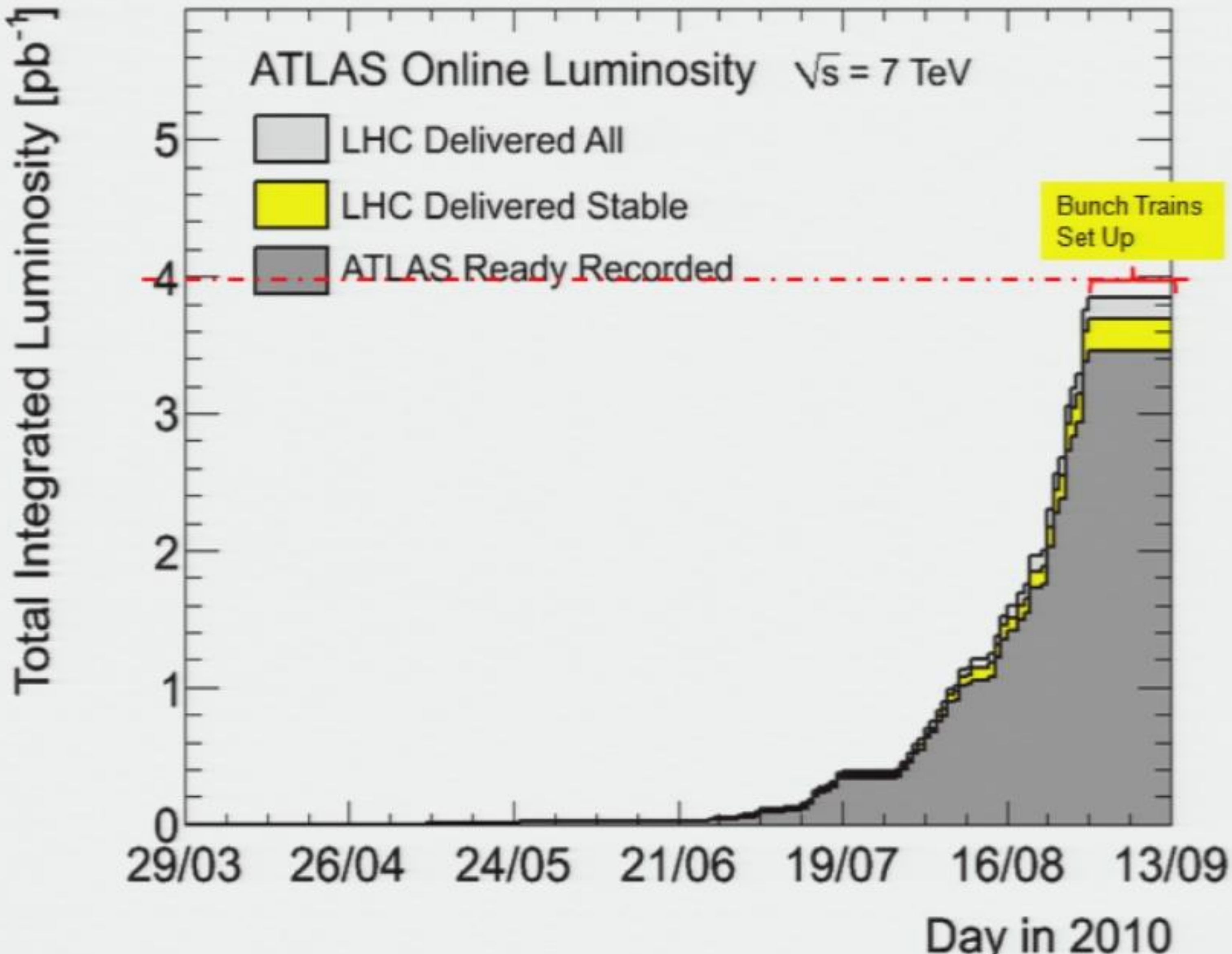
9	3.5	0.2	3.5	8	9.00E+10	7.2E+11	0.4069	6	1.2E+30	12 July 2010
10	3.5	0.2	3.5	13	9.00E+10	1.2E+12	0.6612	8	1.6E+30	15 July 2010
11	3.5	0.2	3.5	25	1.00E+11	2.5E+12	1.4129	16	4.1E+30	30 July 2010
12	3.5	0.2	3.5	48	1.00E+11	4.8E+12	2.7127	36	9.1E+30	19 August 2010

Maximum reached is 10.7×10^{30} $cm^{-2}s^{-1}$

Approaching $4pb^{-1}$ (move to bunch trains)



Plan for getting to 10^{32} before ion run

LMC 18th August.

- Parameters and Conditions
  - Nominal bunch intensity 1.1E11
  - Stick to $\beta^* = 3.5$ m in all IPs
  - Commission bunch trains
    - Complete re-do of the whole machine protection set-up
  - Go to 150 ns bunch spacing
  - Commission faster ramp (10 A/s)

Additional work for bunch trains

- Completely new set up of all phases of LHC under the new conditions needed for safe operation with high intensity bunch trains
  - Beam transfer (collimation)
  - Emittance control in injectors and during ramp in LHC
  - Transverse damper set up with lower noise
  - Injection with crossing angles (collimators and unsafe beam),
  - Accumulation with crossing angle; long discussions about magnitude of crossing angle
  - Ramp with 10A/s
  - Squeeze (changing crossing angles to collision values)
  - Collisions with crossing angles (collimation)
  - (Aperture measurement)

Test ramp 10 A/s

1st attempt reached 1.7TeV
2nd attempt perfect ramp up to 3.5TeV

Ramp duration reduced from 46 to 16 minutes

Measured 450 GeV Aperture

Beam / plane	Limiting element	Aperture [σ]
Beam 1 H	Q6.R2	12.5
Beam 1 V	Q4.L6	13.5
Beam 2 H	Q5.R6	14.0
Beam 2 V	Q4.R6	13.0

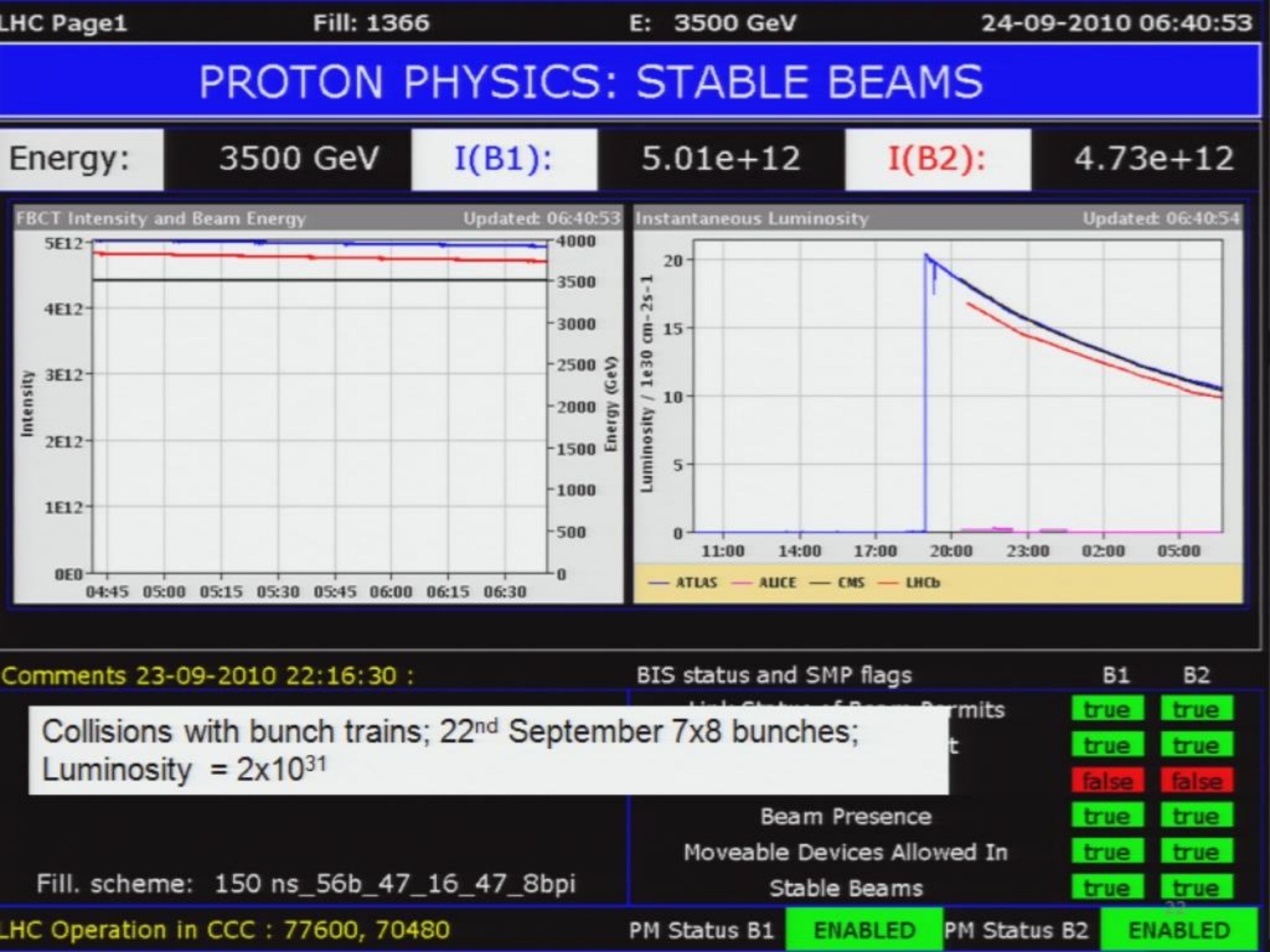
- Predicted aperture bottlenecks in triplets (n1=7) do not exist.
- "Measured" n1 = 10 – 12 (on-momentum) instead design n1 = 7
- "We discover the performance gold mine of aperture"

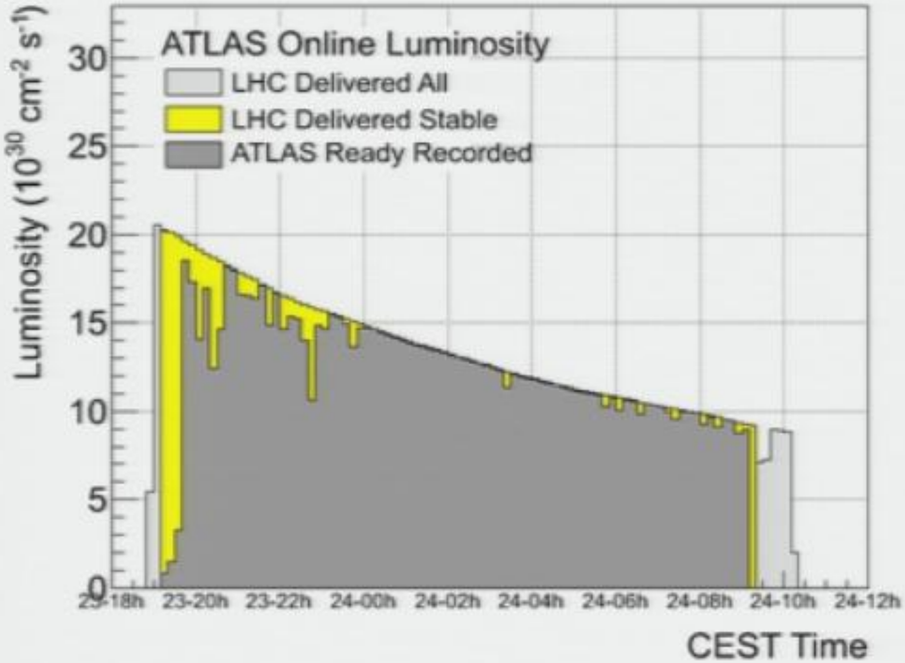
Planning the Intensity increase

- Intensity increase roadmap
  - Intensity step 48 bunches (+- 10%). (3MJ per step)
  - 3 fills at a given intensity. Integrated physics time of ~20 hours.
  - A checklist of the requirements (sine qua non) for increasing the intensity..
  - Injection: significant change as we are now injecting unsafe beam.
    - Very careful monitoring of abnormal injections.

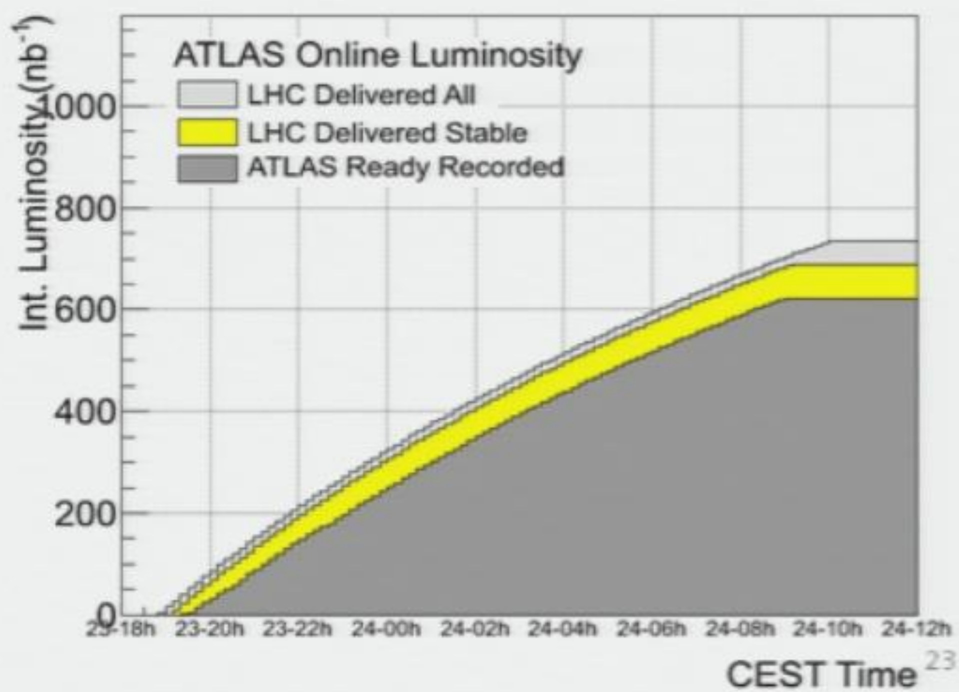
Saturday 11.9 Bunch Trains

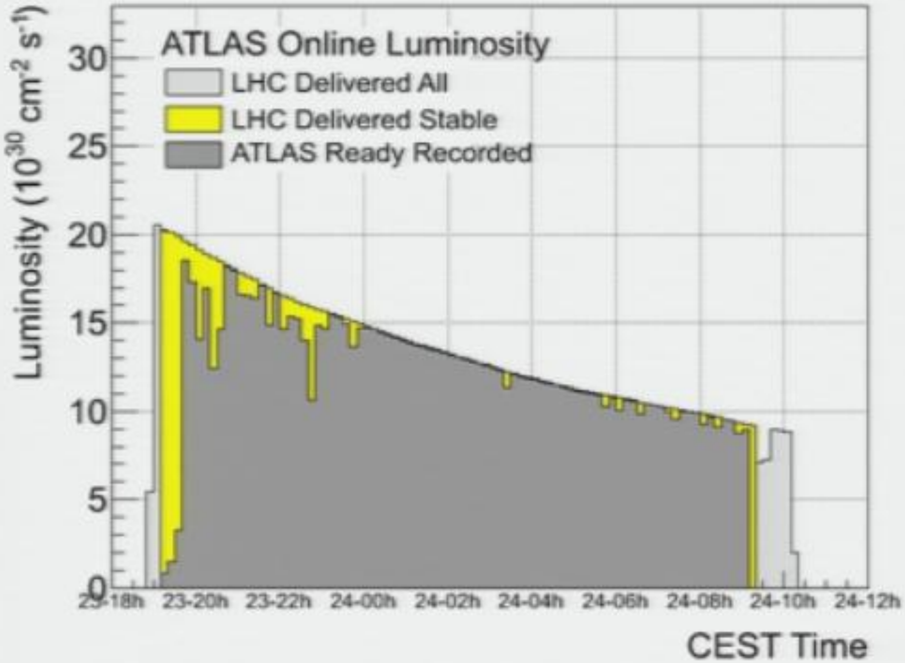
- RF setting up
  - Finally the complete injection sequence of 13x4 bunches per beam was executed and went smoothly with very little uncaptured beam


LHC Page1
Fill: 1366
E: 3500 GeV
24-09-2010 06:40:53
PROTON PHYSICS: STABLE BEAMS
Energy:
3500 GeV
I(B1):
5.01e+12
I(B2):
4.73e+12
FBCT Intensity and Beam Energy
Updated: 06:40:53
Intensity
Energy (GeV)
Instantaneous Luminosity
Updated: 06:40:54
Luminosity / 1e30 cm-2s-1
ATLAS
ALICE
CMS
LHCb
Comments 23-09-2010 22:16:30 :
Collisions with bunch trains; 22nd September 7x8 bunches;
Luminosity = 2x10^31
Fill. scheme: 150 ns_56b_47_16_47_8bpi
BIS status and SMP flags
B1
B2
Beam Presence
Moveable Devices Allowed In
Stable Beams
true
false
LHC Operation in CCC : 77600, 70480
PM Status B1
ENABLED
PM Status B2
ENABLED



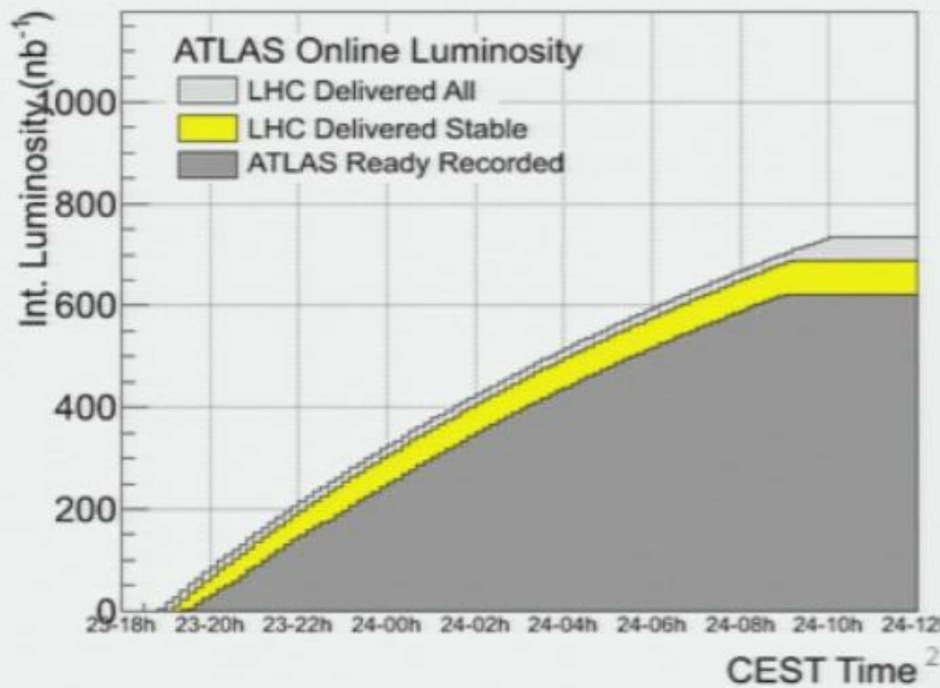
September 23
48 bunches; bunch trains



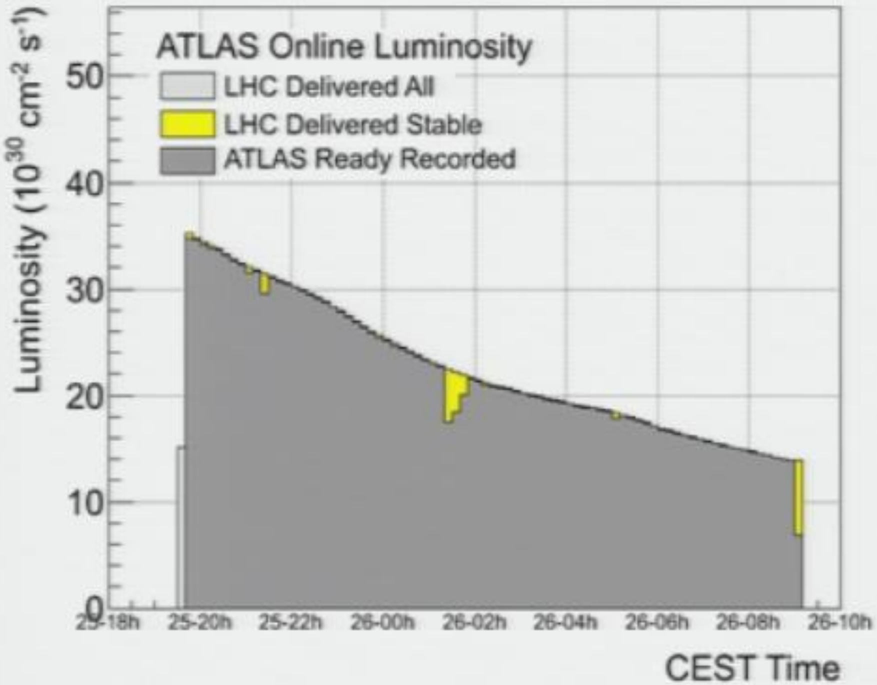


September 23
48 bunches; bunch trains

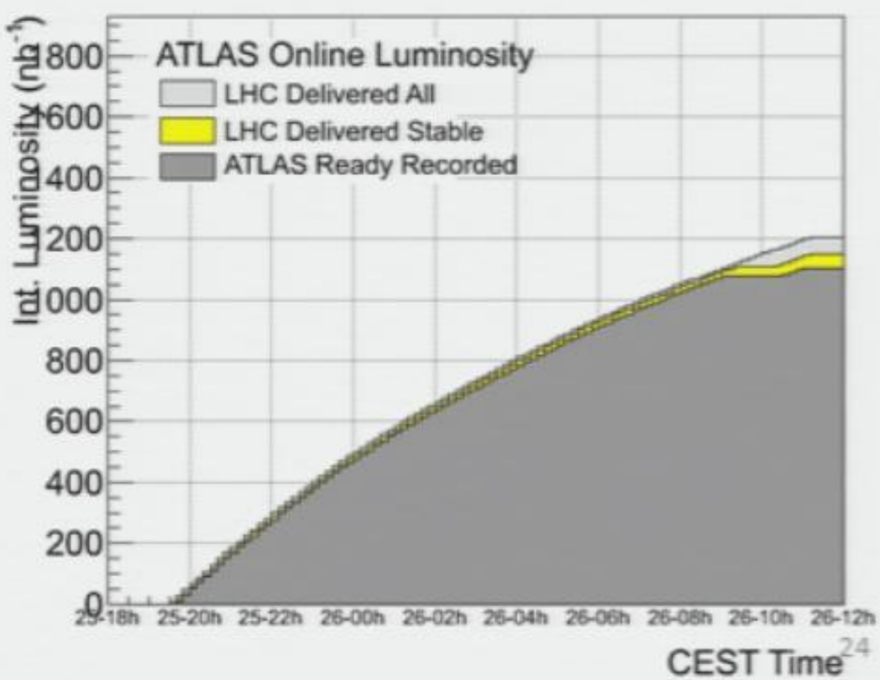
This was a “turning point” fill as it showed that a head-on beam-beam tune shift of ~.02 total was possible (cf design of .01)



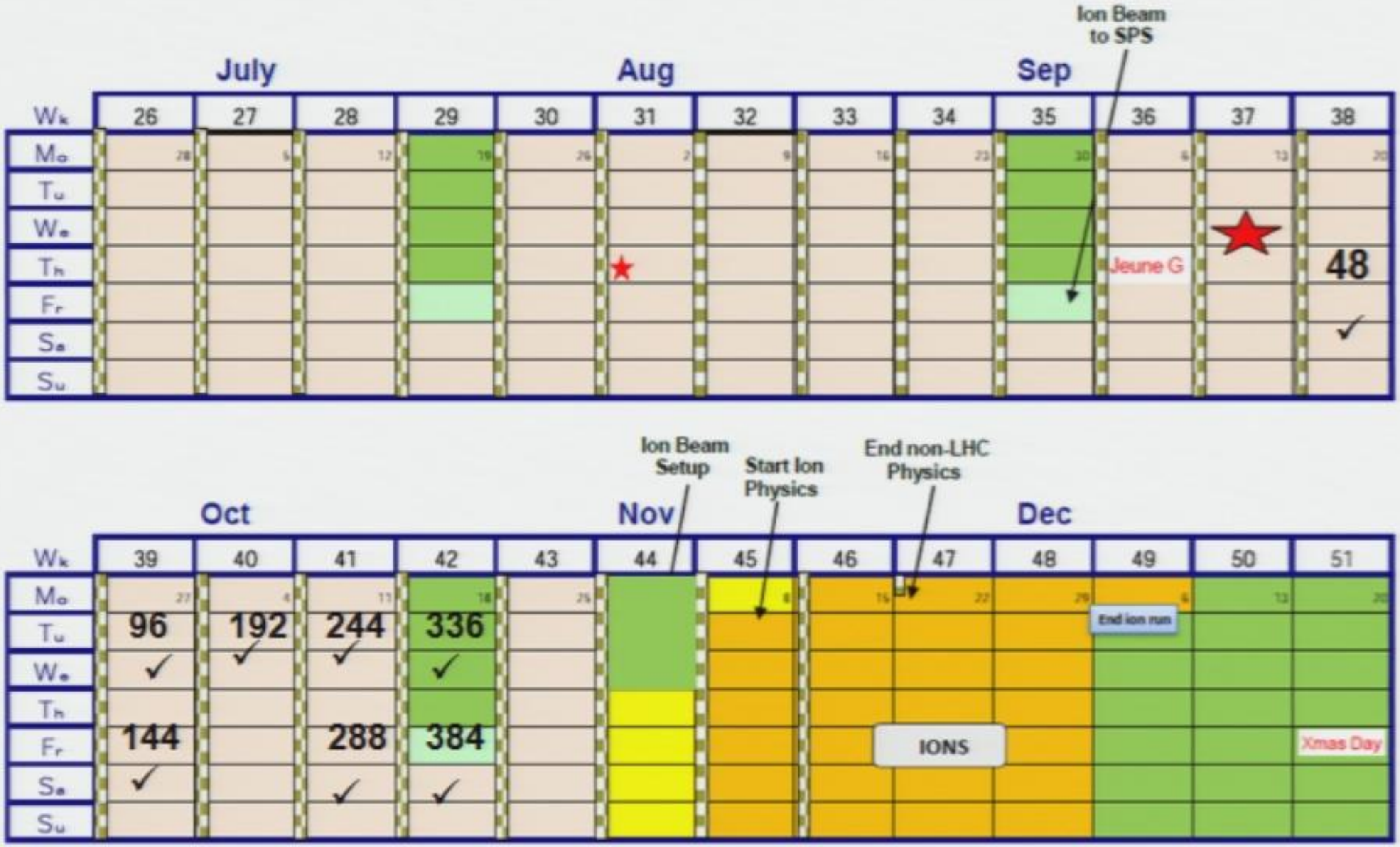
September 25/26
104 bunches



1pb-1 in a single fill



Aggressive Schedule



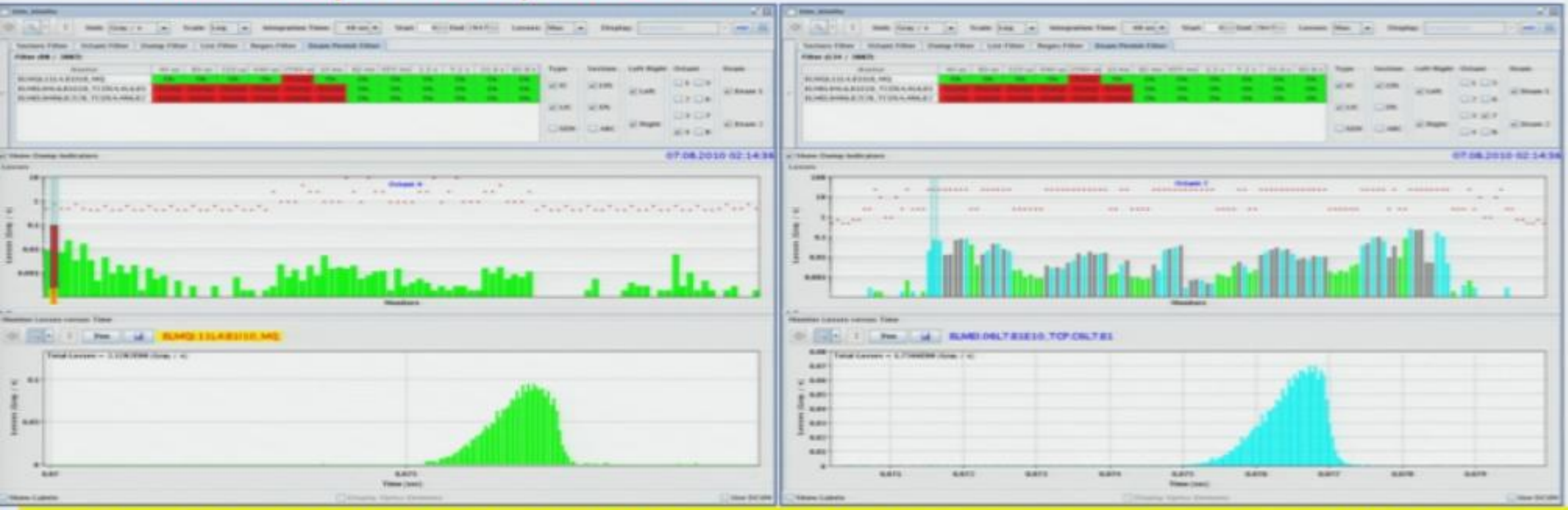
Some Issues

- Vacuum around the IPs (Nb above 300)
- UFOs
- Injection sensitivity B1 (chamber installed wrong way around 2 years ago!!)

(UFOs) Unidentified Falling Objects

Losses with almost identical loss characteristics

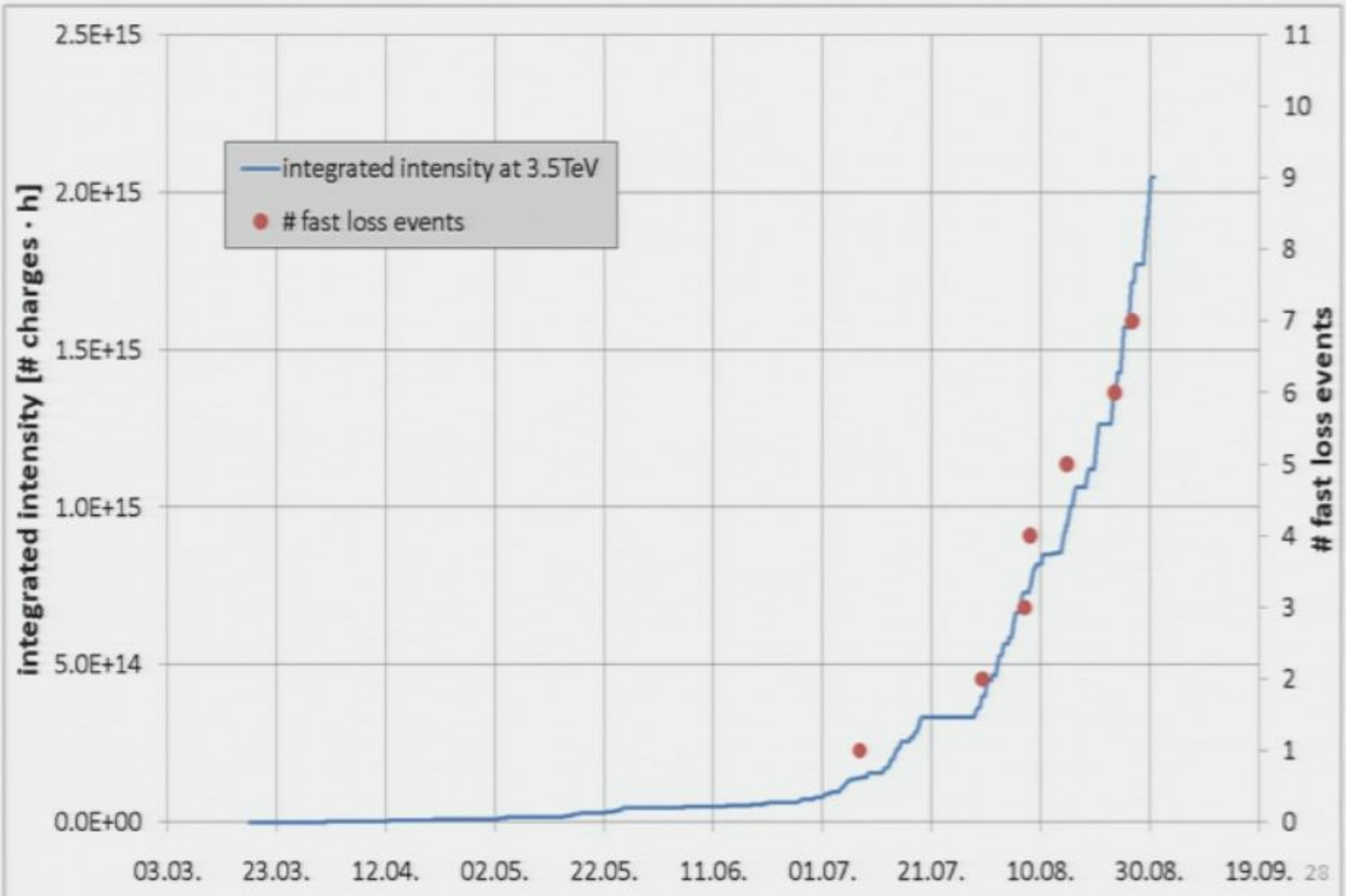
- 5 unexplained beam losses (dump provoked by the Beam loss monitoring system)
- 1 unexplained beam loss while moving Roman Pots
- 1 beam loss provoked by a wire scan



- Suspicion is that debris if falling into the beam provoking a small beam loss seen by the BLM which triggers the beam dump (machine protection works well)

Proposal to verify the thresholds of the BLMs by doing a “quench” test.

Correlation of Number of fast Losses with beam Intensity



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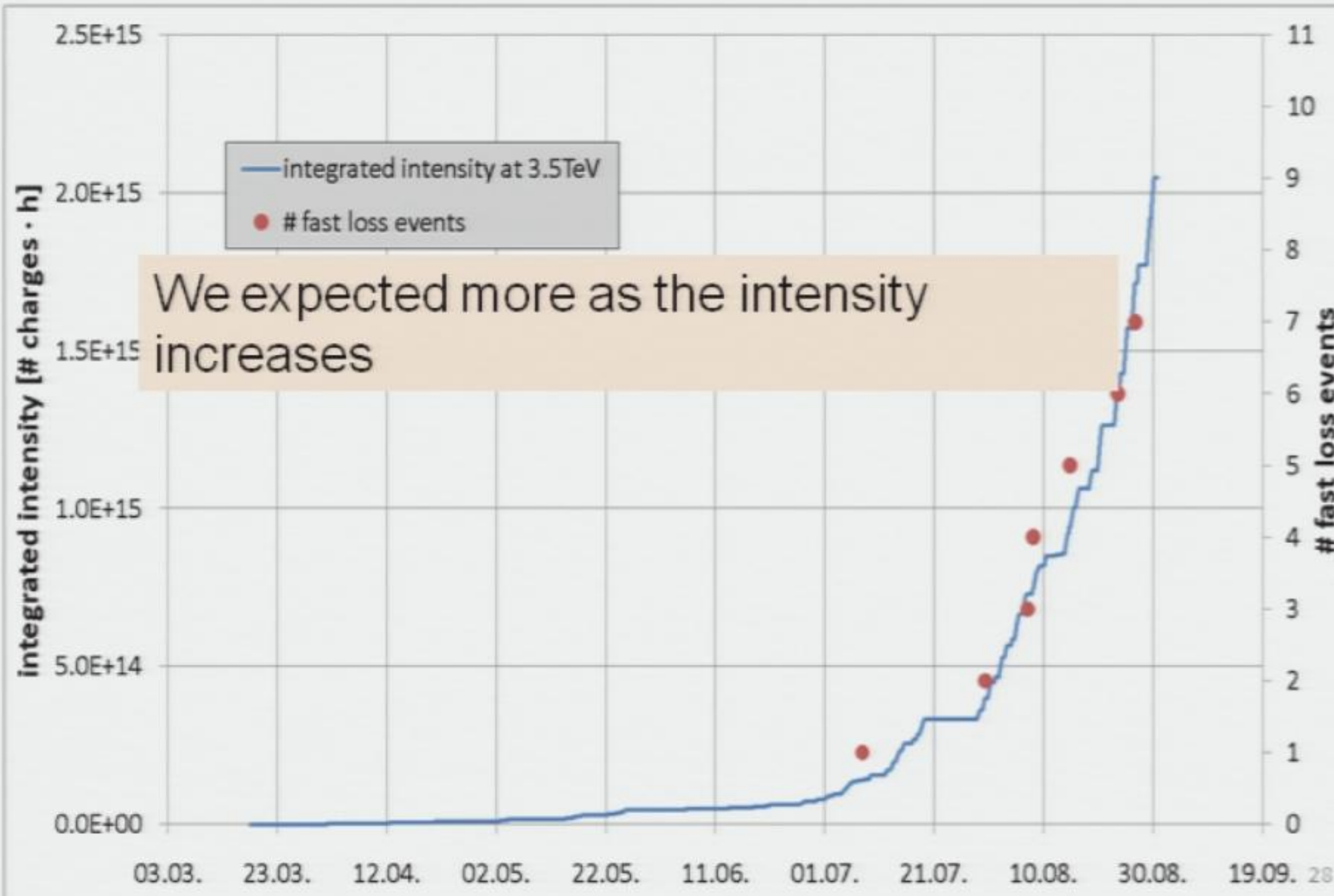


Update as of this morning (05:00 am)

⇒ Last Fill with 368 (348 colliding) bunches per beam

⇒ reached 50pb-1 delivered

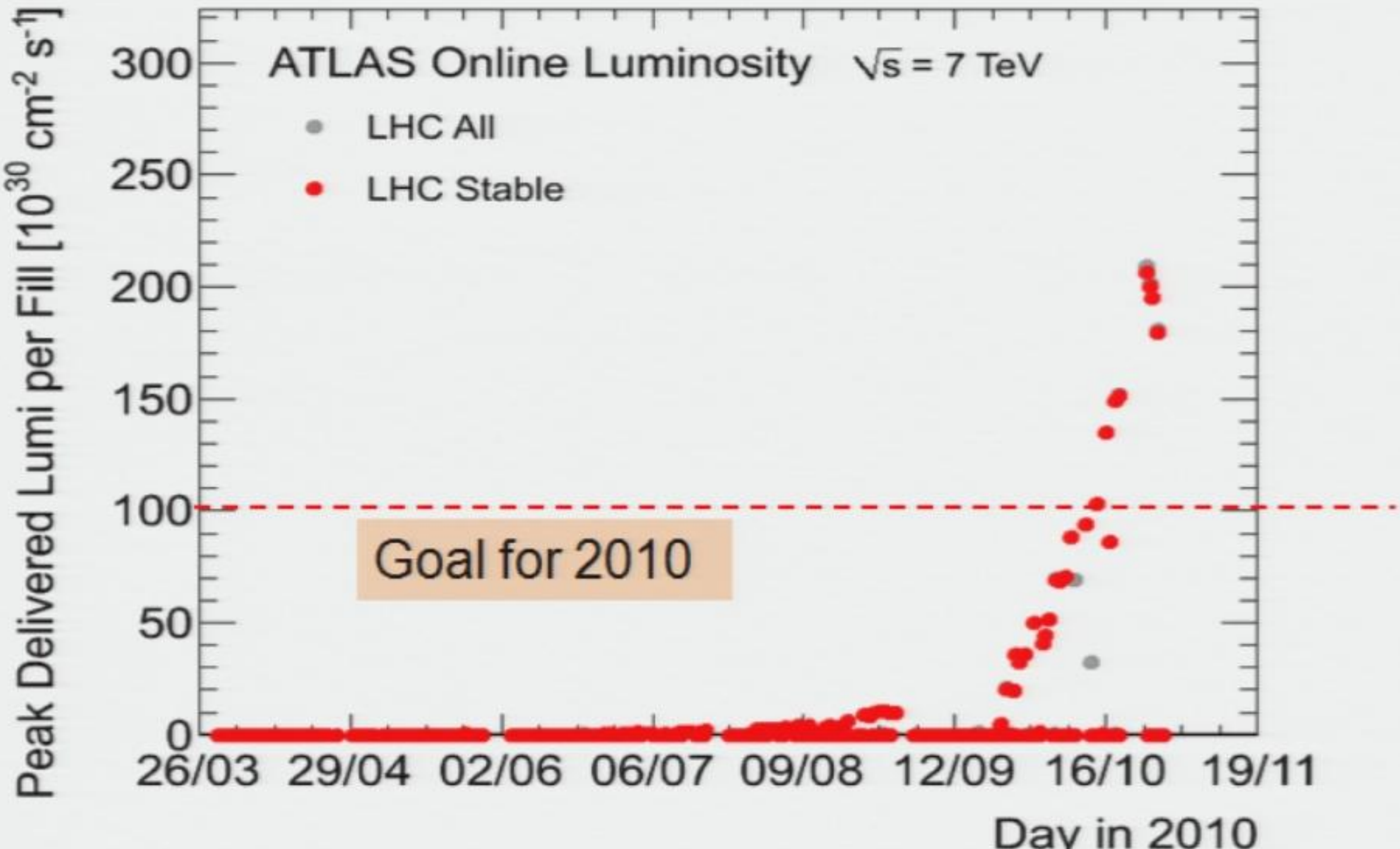
⇒ now move to 50ns bunch spacing to prepare for 2011

Running with Bunch Trains (Parameters)

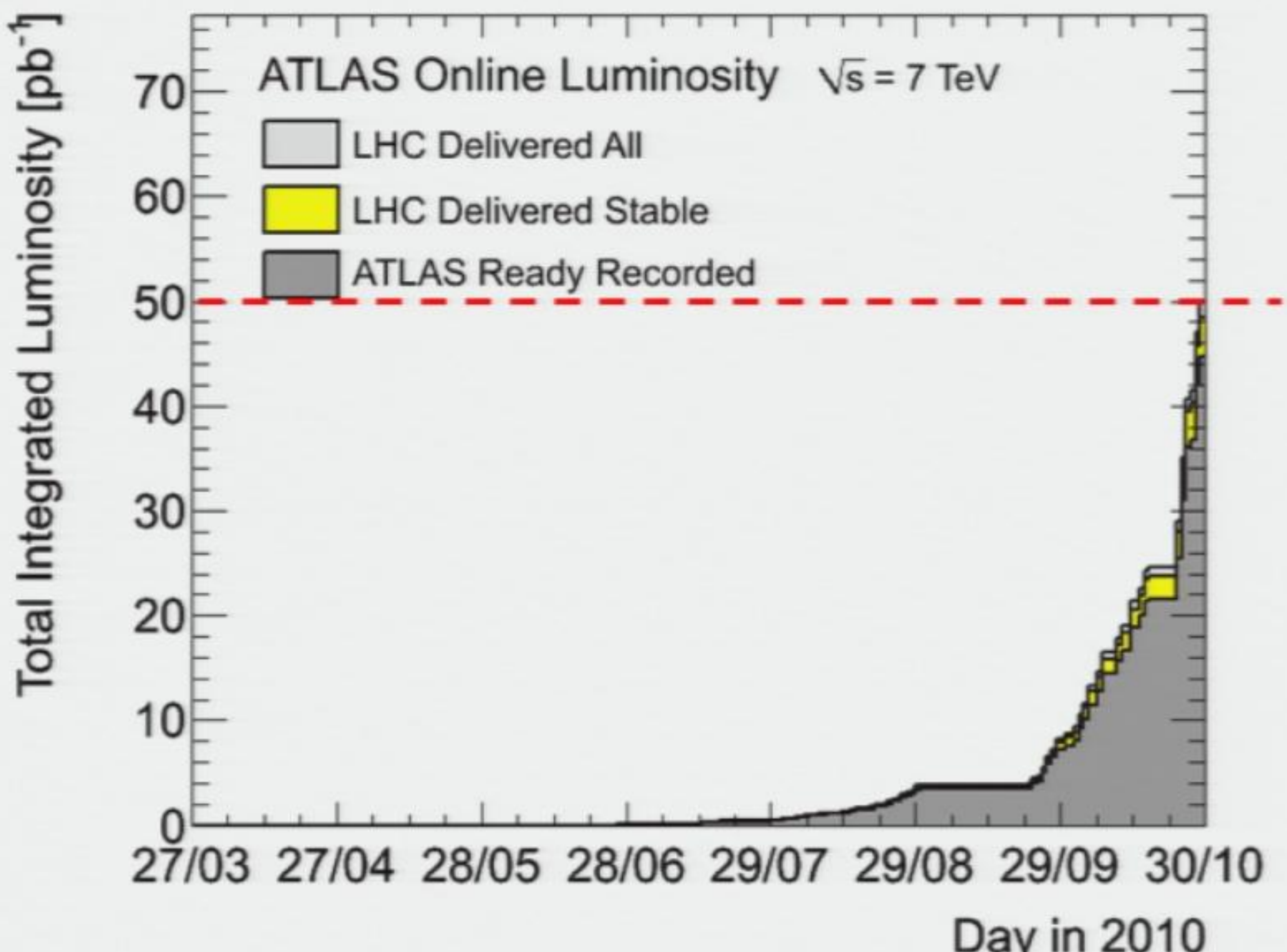
Nb	Ib	MJ	Nc	Peak luminosity (design parameters)	Maximum luminosity (measured)	Pile up (from measured Lumi)	Date
56	1.10E+11	3.5	47	1.203E+31	2.000E+31	1.9054	23/09/2010
104	1.10E+11	6.5	93	2.381E+31	3.500E+31	1.7955	25/09/2010
152	1.10E+11	9.4	140	3.584E+31	5.000E+31	1.7550	29/09/2010
204	1.10E+11	12.7	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

24MJ stored beam energy and $2.05 \times 10^{32} cm^{-2} s^{-1}$

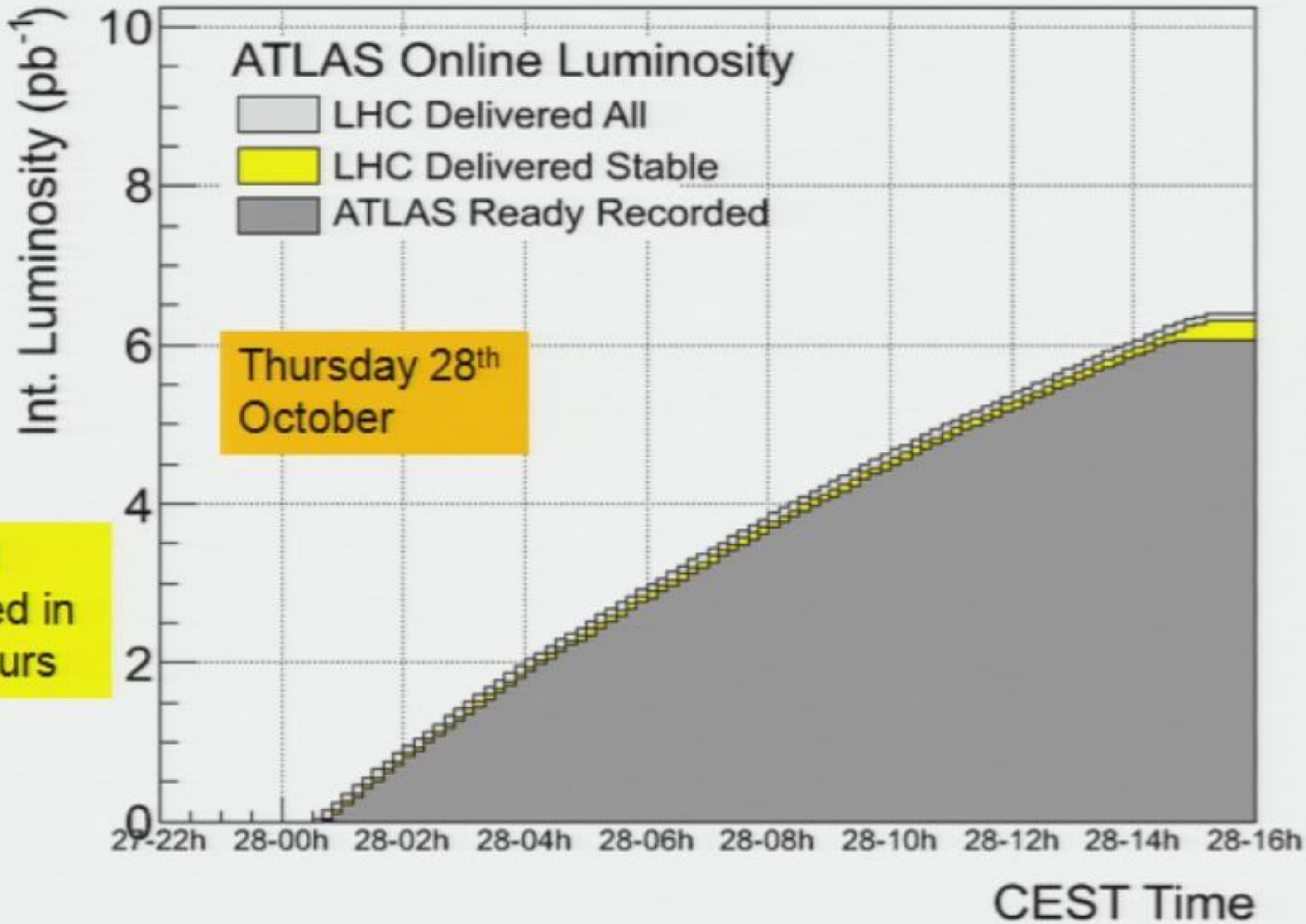
Peak Luminosity



28/10/2010 (approaching 50pb-1)



Highest Integrated Luminosity Fill so Far



6.3pb-1 delivered in 14.5 hours

Summary: What did we learn in 2010

- LHC is magnetically very reproducible on a month to month time scale
- Head on beam-beam limit higher than forseen
- Aperture better than foreseen
- Not a single magnet quench due to beam
- Careful increase of the number of bunches OK
- Electron cloud and vacuum
- Machine protection
  - Set up is long
  - Quench levels for fast and slow losses needs optimized
  - UFOs

Plans for 2011

- Running Conditions in 2011 (Chamonix January 2011)
  - Maximum beam energy
  - Bunch spacing 50ns (max bunches 1404)
  - Integrated luminosity evaluation (goal set is $1fb^{-1}$)

Luminosity Upgrade

Upgrades: Foreword

New Studies were launched more than one year ago

- Performance Aim
  - To maximize the useful integrated luminosity over the lifetime of the LHC
- Targets set by the detectors are:
  3000fb^{-1} (on tape) by the end of the life of the LHC
  → 250-300fb^{-1} per year in the second decade of running the LHC

- Goals
  - Check the coherence of the presently considered upgrades wrt
    - accelerator performance limitations,
    - Detector needs,
    - manpower resources and,
    - shutdown planning including detectors

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 5×10^{34} cm^{-2} 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

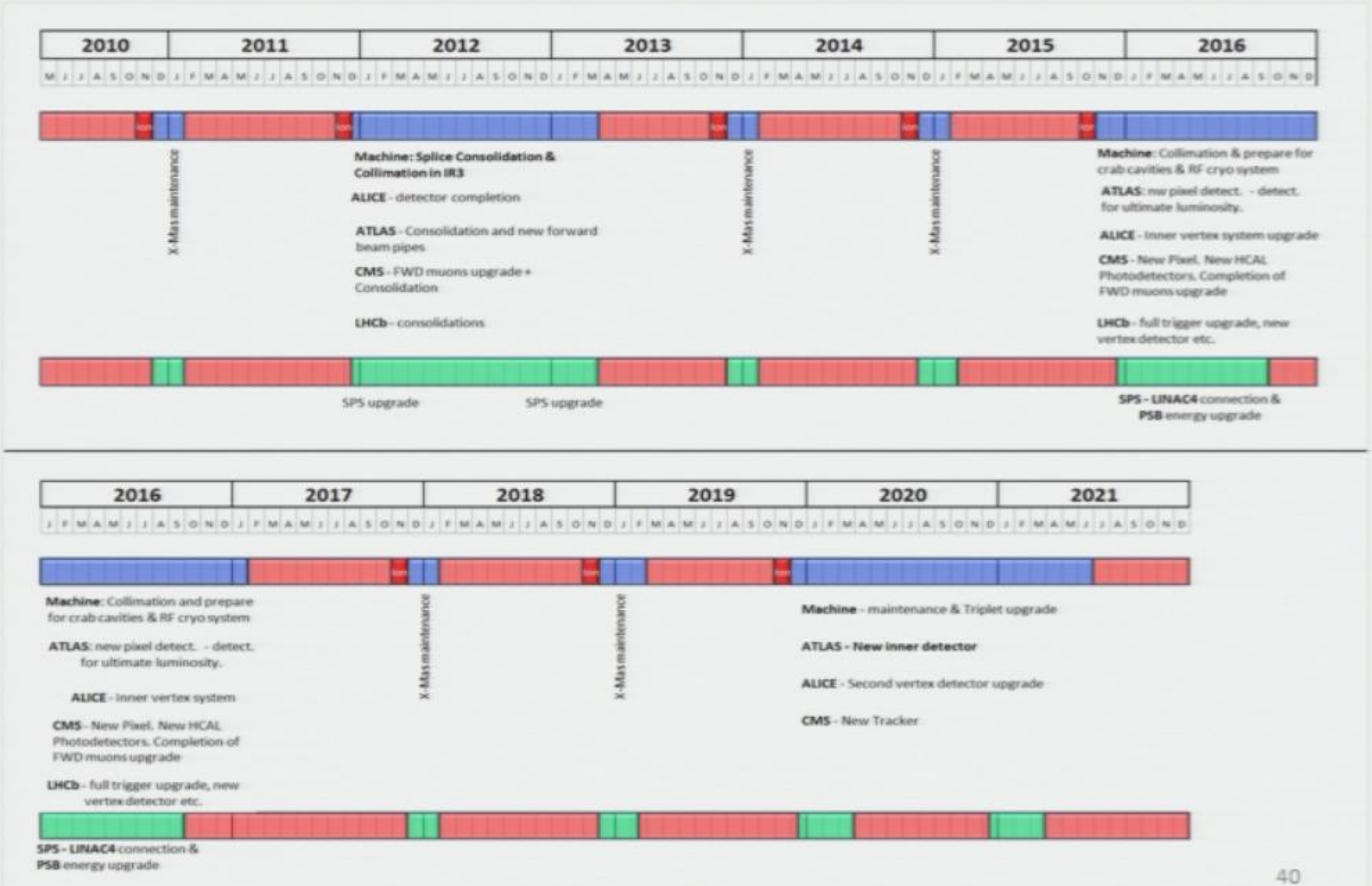
Detector physicists have indicated that their detector upgrades are significantly influenced by the choice between peak luminosities of 5×10^{34} and 10^{35}.

- Pile up events
- Radiation effects

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

The 10 year technical Plan



First Thoughts on an Energy Upgrade

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	2808	1404
bunch population [10^{11}]	1.15	1.29
initial transverse normalized emittance [μm]	3.75	3.75 (x), 1.84 (y)
number of IPs contributing to tune shift	3	2
maximum total beam-beam tune shift	0.01	0.01
IP beta function [m]	0.55	1.0 (x), 0.43 (y)
full crossing angle [μrad]	285 (9.5 $\sigma_{x,y}$)	175 (12 σ_{x0})
stored beam energy [MJ]	362	479
SR power per ring [kW]	3.6	62.3
longitudinal SR emittance damping time [h]	12.9	0.98
events per crossing	19	76
peak luminosity [10^{34} cm^{-2}s^{-1}]	1.0	2.0
beam lifetime [h]	46	13
integrated luminosity over 10 h [fb^{-1}]	0.3	0.5

Very Long Term Objectives: Higher Energy LHC

Preliminary HE-LHC - parameter

Very preliminary with large error bars

	nom	HE-LHC
beam energy [TeV]		16.5
dipole field [T]		20
dipole coil aperture [mm]		40-45
#bunches / beam		1404
bunch population [10^{11}]		1.29
initial transverse normalized em [μm]		3.75 (x), 1.84 (y)
number of IPs contribut	3	2
maximum total bear	0.01	0.01
IP beta function	0.55	1.0 (x), 0.43 (y)
full crossing	285 (9.5 $\sigma_{x,y}$)	175 (12 σ_{x0})
stored b	362	479
SR pc	3.6	62.3
longitu amping time [h]	12.9	0.98
events pe	19	76
peak lumin cm^{-2}s^{-1}]	1.0	2.0
beam lifetime	46	13
integrated luminosity over 10 h [fb^{-1}]	0.3	0.5

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***

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It is a great personal pleasure to acknowledge the success of this wonderful team.

Thank You for your attention

Luminosity Dependence on Beam Parameters (2011)

Year	TeV	OEF	β*	Nb	Ib	MJ	Normalized Emittance	Peak luminosity	Beam beam Shift	Pile up	Physics Days	Integrated (fb-1/year)
2010	3.50	0.25	3.50	368	1.15E+11	23.9	1.7	2.0E+32	0.0204	2.9	12.0	0.05
2011	4.00	0.25	3.50	400	1.15E+11	29.7	1.7	2.6E+32	0.0204	3.5	180.0	1.02
2011	4.00	0.25	2.00	400	1.15E+11	29.7	1.7	4.6E+32	0.0204	6.1	180.0	1.79
2011	4.00	0.25	2.00	400	1.30E+11	33.6	1.9	5.3E+32	0.0206	7.0	180.0	2.05
2011	4.00	0.25	2.00	600	1.30E+11	50.4	1.9	7.9E+32	0.0206	7.0	180.0	3.07
2011	4.00	0.25	2.00	800	1.30E+11	67.2	1.9	1.1E+33	0.0206	7.0	180.0	4.10
2011	4.00	0.25	2.00	800	1.30E+11	67.2	1.9	1.1E+33	0.0206	7.0	180.0	4.10
2011	4.00	0.25	2.00	800	1.60E+11	82.7	1.7	1.8E+33	0.0284	11.9	180.0	6.94
2011	4.00	0.25	2.00	1000	1.60E+11	103.3	1.7	2.2E+33	0.0284	11.9	180.0	8.67
2011	4.00	0.30	2.00	1000	1.60E+11	103.3	1.7	2.2E+33	0.0284	11.9	180.0	10.41
2011	4.00	0.30	1.50	1000	1.60E+11	103.3	1.7	3.0E+33	0.0284	15.9	180.0	13.87