

# LHC Machine Operational Status and Future Plans

US LHC User's Organization, FNAL

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(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 <b>superconducting twin-bore Dipoles</b>	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) ( <b>cryogenics system</b> )	1.9	Superconducting magnets needed for the high magnetic field Super-fluid helium
<b>Current in dipole sc coils (A)</b>	<b>13000</b>	Results from the high magnetic field 1ppm resolution
Beam Intensity (A)	0.5	$2.2 \cdot 10^{-6}$ loss causes quench
<b>Beam Stored Energy (MJoules)</b>	<b>362</b>	Results from high beam energy and high beam current 1MJ melts 1.5kg Cu
<b>Magnet Stored Energy (MJoules)/octant</b>	<b>1100</b>	Results from the high magnetic field
<b>Sector Powering Circuit</b>	<b>8</b>	1612 different electrical circuits

# LHC Commissioning: Recap

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

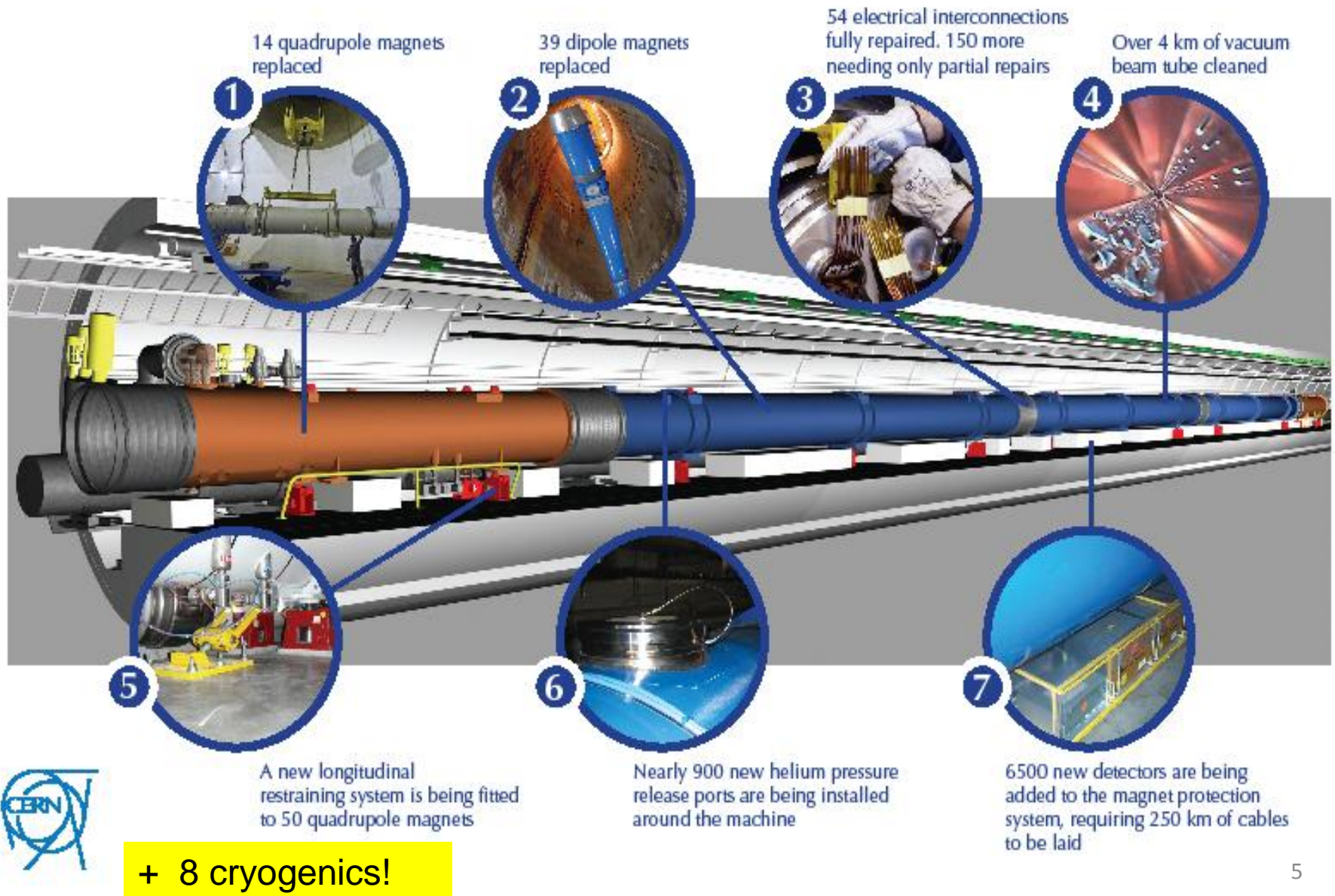
ORGANISATION EUROPEENNE POUR LA RECHERCHE NUCLEAIRE  
**CERN** EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

<i>Action to be taken</i>		<i>Voting Procedure</i>
For Recommendation to Council	SCIENTIFIC POLICY COMMITTEE 255 <sup>th</sup> Meeting 15-16 September 2008	-
For Approval	CLOSED COUNCIL 148 <sup>th</sup> Session of Council <b>18 September 2008</b>	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

# The LHC repairs in detail



# Summary of LHC Commissioning

- November 20<sup>th</sup> 2009
  - First beams around again
- November 29<sup>th</sup> 2009
  - Both beams accelerated to 1.18 TeV simultaneously
- December 8<sup>th</sup> 2009
  - 2x2 accelerated to 1.18 TeV
  - First collisions at 2.36 TeV cm!
- December 14<sup>th</sup> 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

# 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  $1\text{fb}^{-1}$  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

Primary Goal for 2010

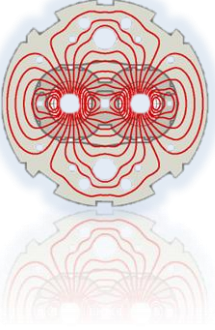
# Why do we limit the beam energy to 3.5TeV in 2010-2011?

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

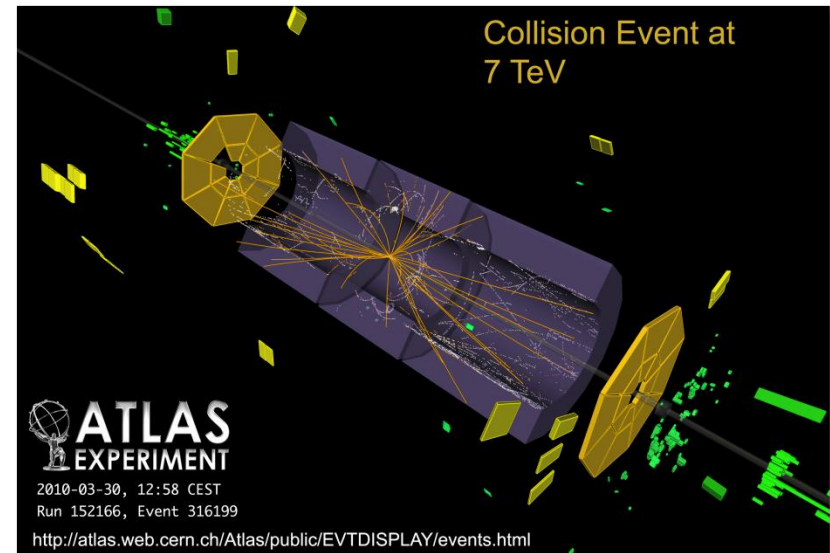
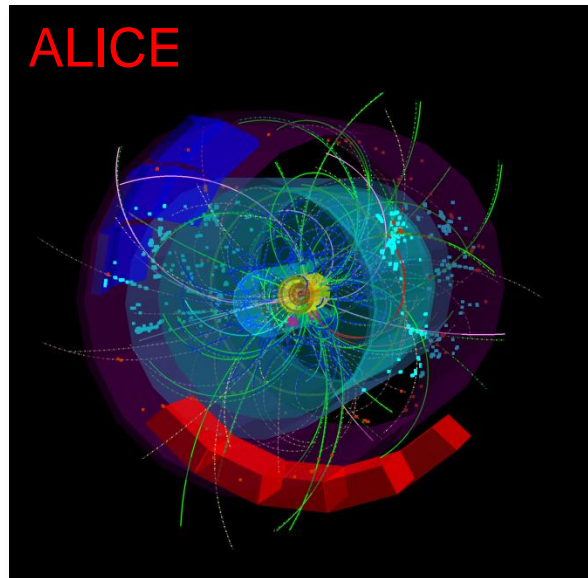
The offending connector in this incident had an estimated resistance of  $220\text{n}\Omega$ . We have measured all 10,000 inter-magnet connectors and the maximum resistance we have seen is  $2.8\text{n}\Omega$ .

**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**

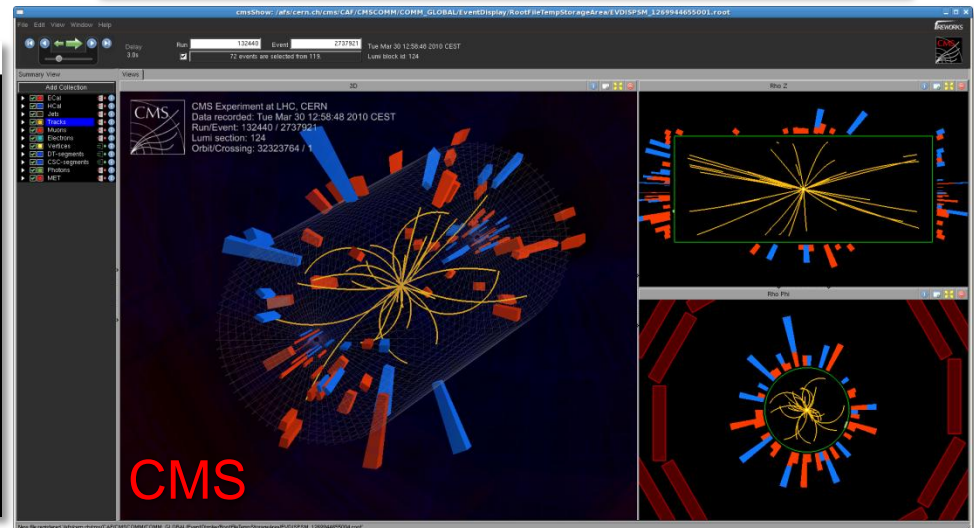
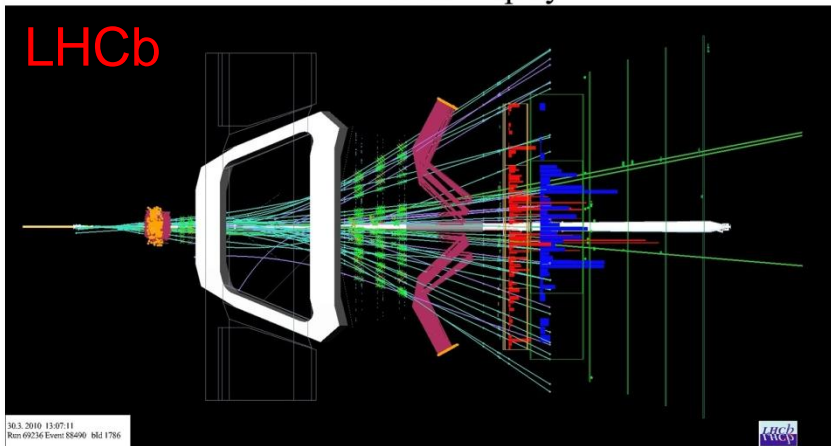




# LHC: First collisions at 7 TeV on 30 March 2010



LHCb Event Display



# First Running Period (low bunch intensity)

calculated										
Event	TeV	OEF	$\beta^*$	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	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

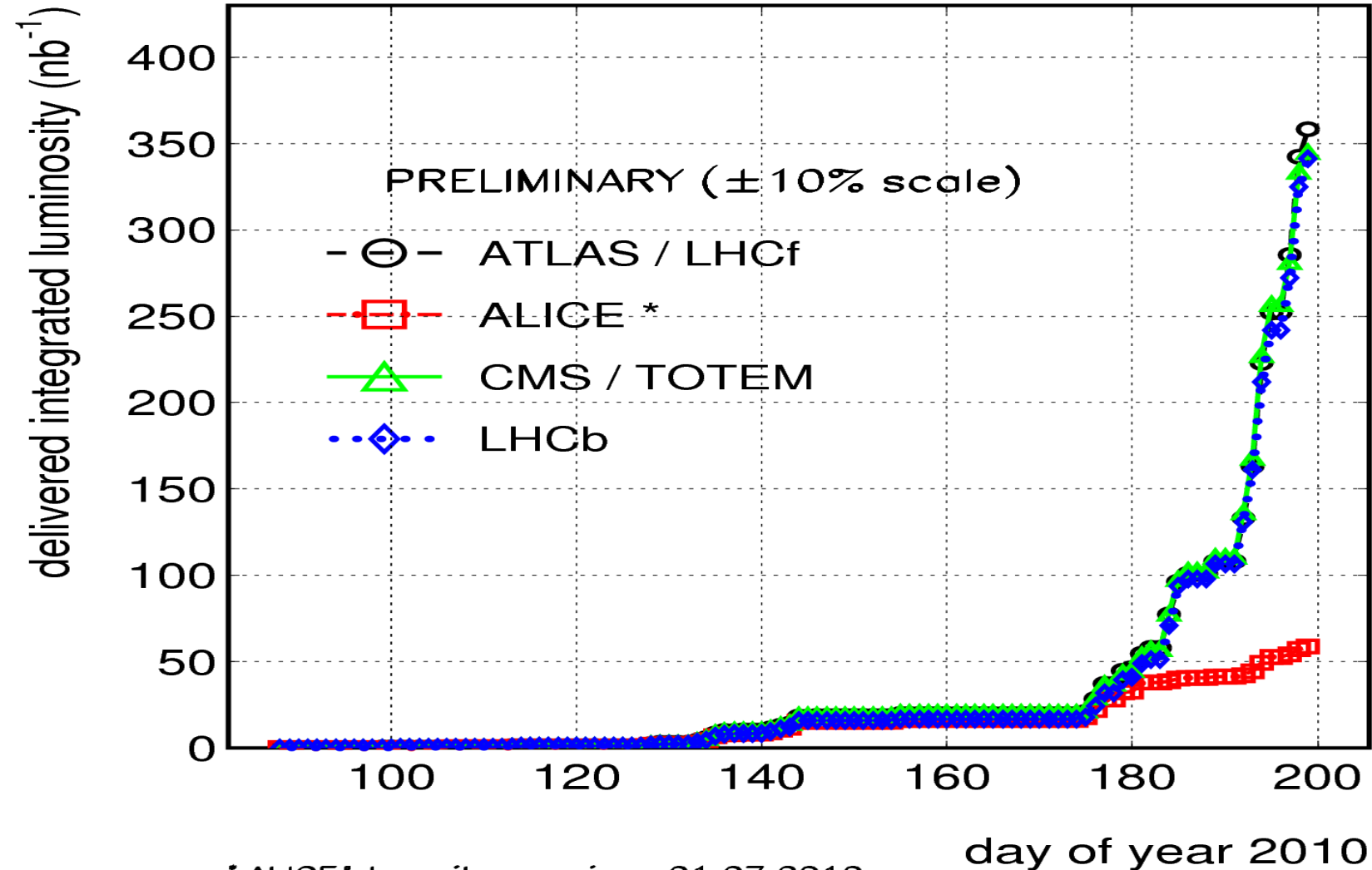
Event	TeV	OEF	$\beta^*$	Nb	lb	ltot	MJ	Nc	Peak luminosity	Date
1	3.5	0.2	10	2	1.00E+10	2.0E+10	0.0113	1	8.9E+26	30 March 2010
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3	3.5	0.2	2	2	2.00E+10	4.0E+10	0.0226	1	1.8E+28	10 April 2010
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6	3.5	0.2	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)

2010/07/19 11.54

## LHC 2010 RUN (3.5 TeV/beam)

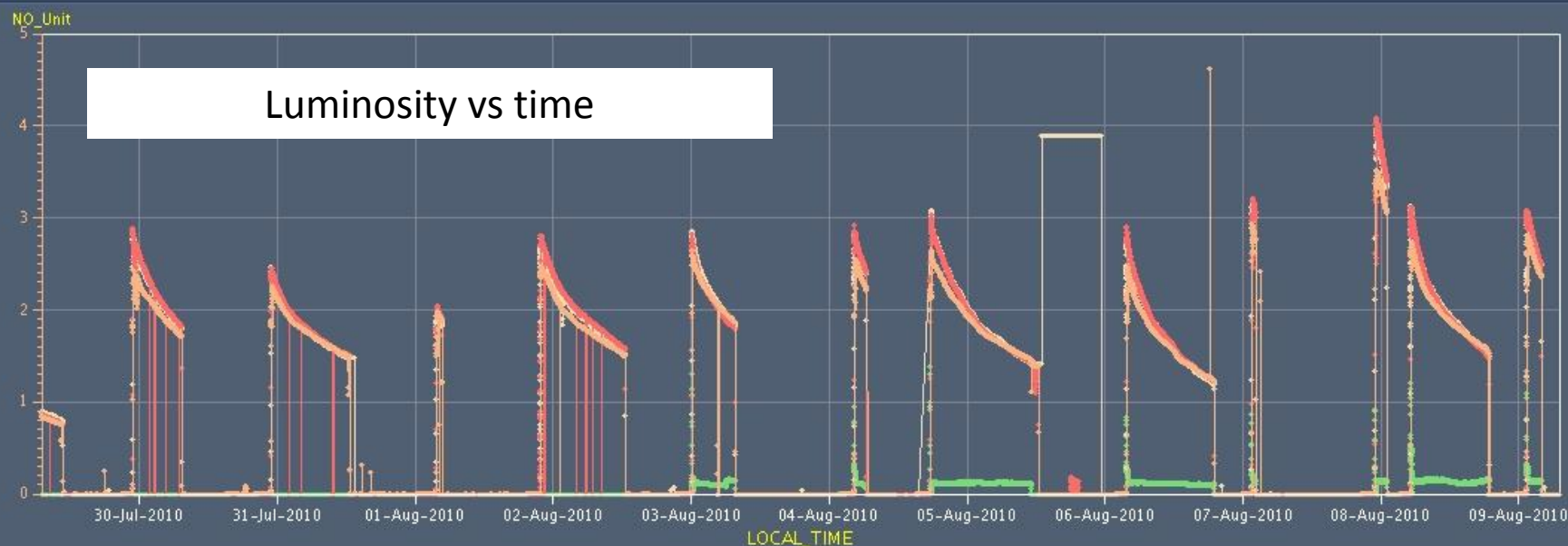


ALICE:LUMI\_TOT\_INST

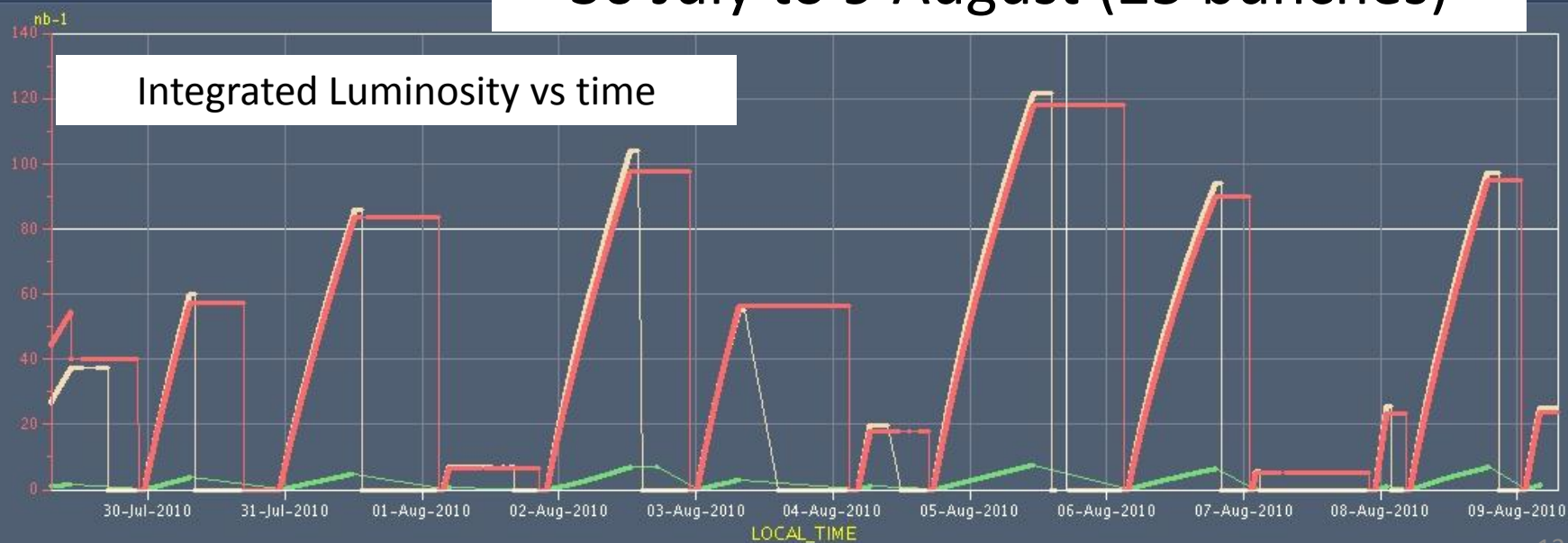
ATLAS:LUMI\_TOT\_INST

CMS:LUMI\_TOT\_INST

LHCb:LUMI\_TOT\_INST



30 July to 9 August (25 bunches)



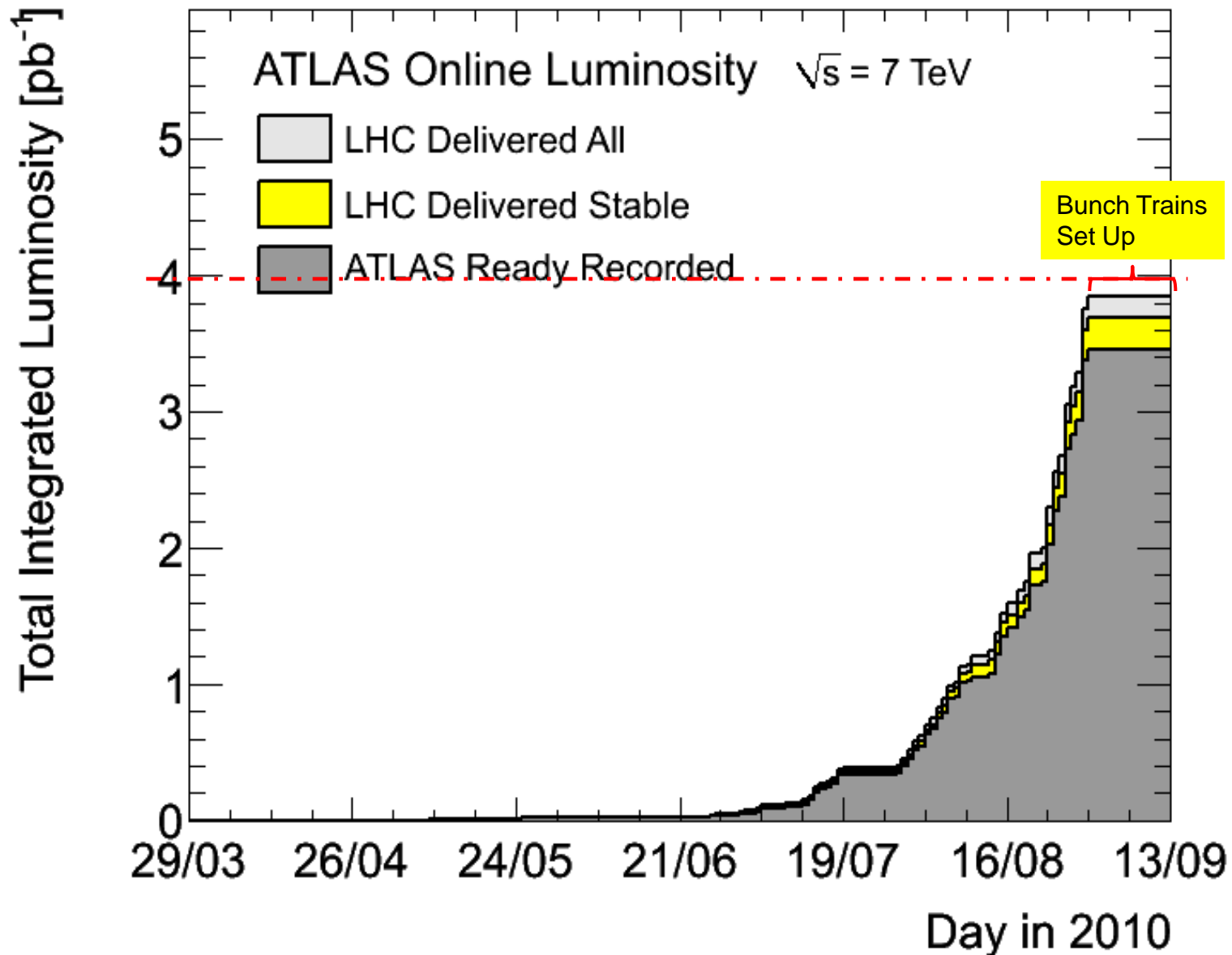
# Second Running Period (High bunch Intensity)

calculated

Event	TeV	OEF	$\beta^*$	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	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
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

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

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



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

LMC 18<sup>th</sup> August.

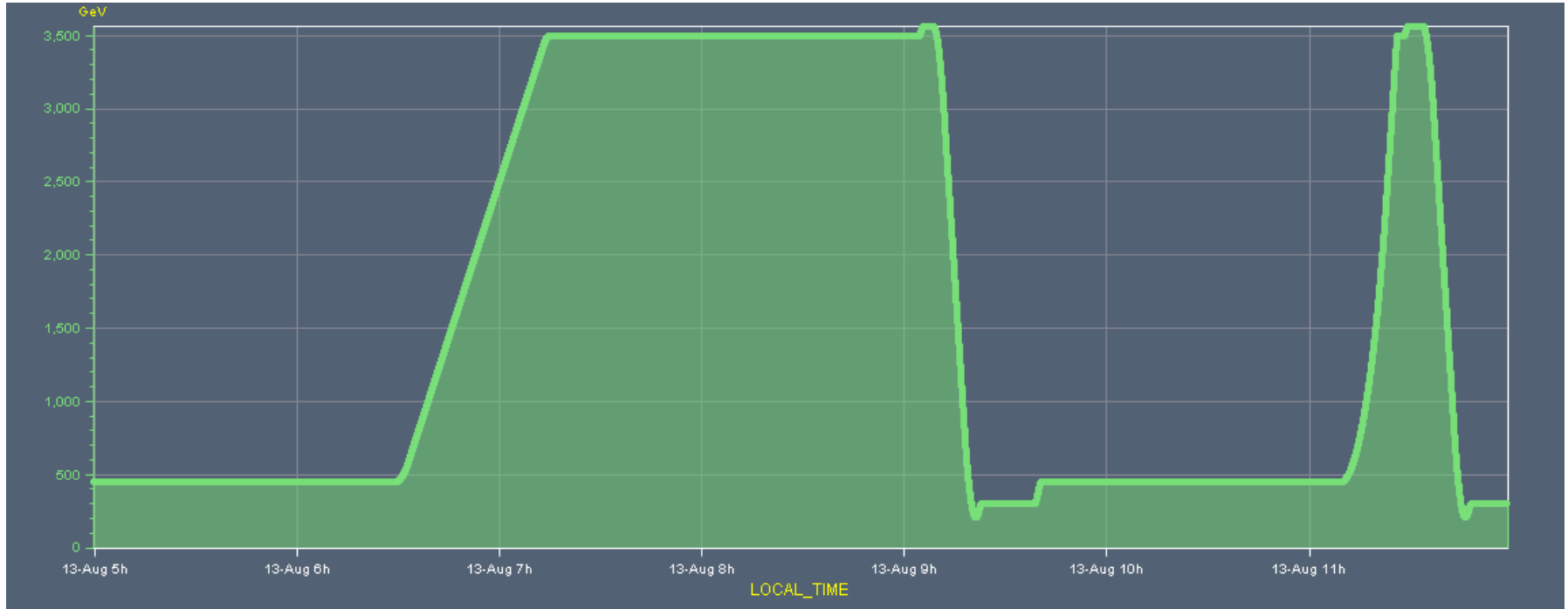
- Parameters and Conditions
  - Nominal bunch intensity  $1.1\text{E}11$
  - Stick to  $\beta^* = 3.5$  m in all IPs
  - Commission bunch trains
    - Complete re-do of the whole machine protection set-up
  - Go to 150 ns bunch spacing
  - Commission faster ramp (10 A/s)



# 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



1<sup>st</sup> attempt reached 1.7TeV  
2<sup>nd</sup> attempt perfect ramp up to 3.5TeV

Ramp duration reduced from 46 to 16 minutes

# Measured 450 GeV Aperture

Beam / plane	Limiting element	Aperture [ $\sigma$ ]
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

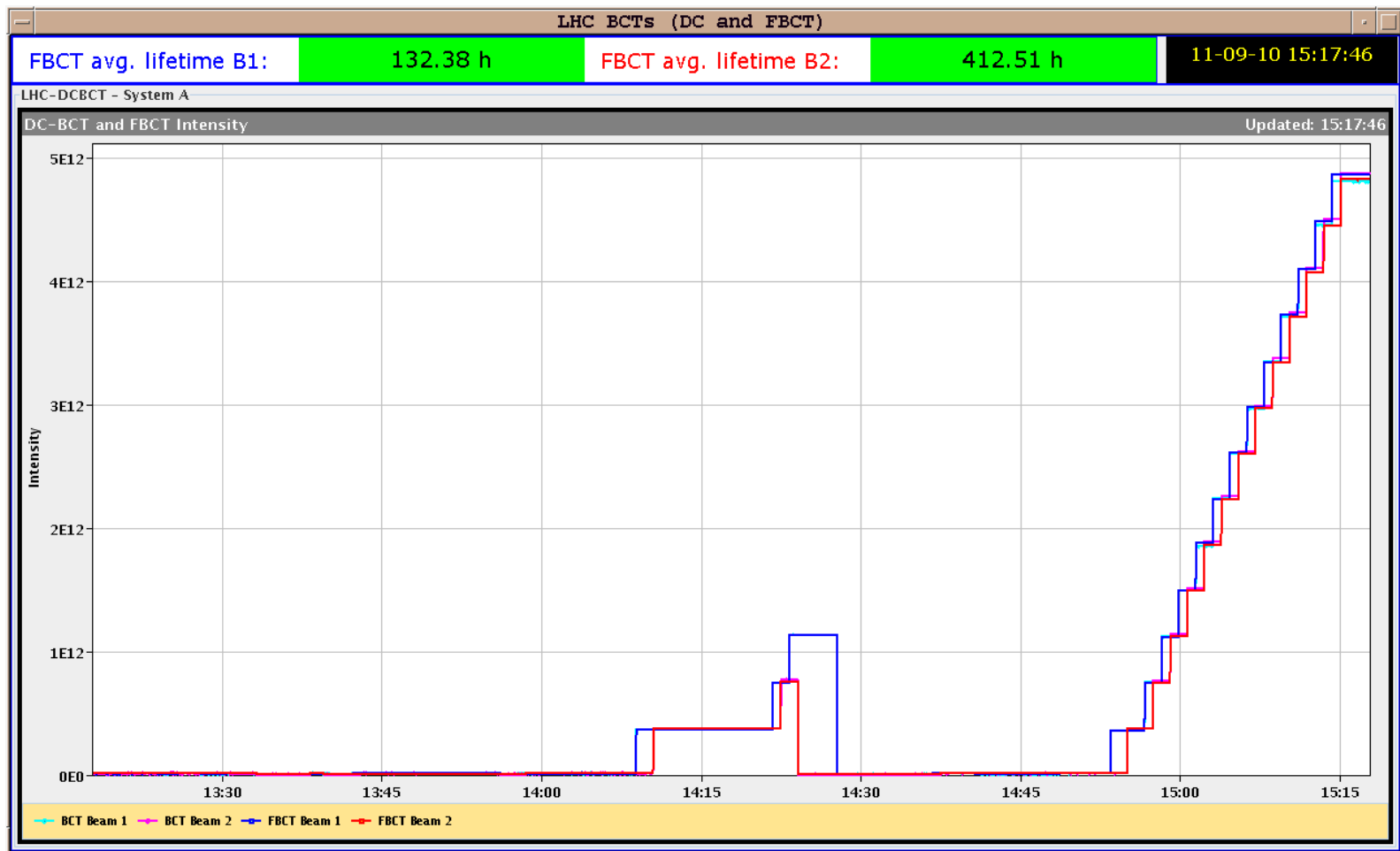
- Predicted aperture bottlenecks in triplets ( $n_1=7$ ) do not exist.
- “Measured”  $n_1 = 10 - 12$  (on-momentum) instead design  $n_1 = 7$
- “We discover the performance gold mine of aperture”

# 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

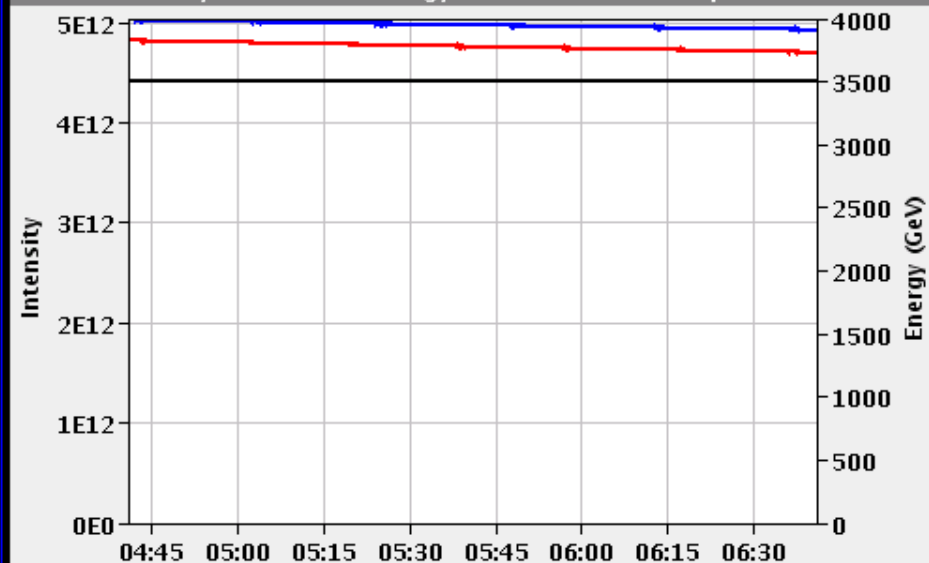
- RF setting up
  - Finally the complete injection sequence of 13x4 bunches per beam was executed and went smoothly with very little uncaptured beam



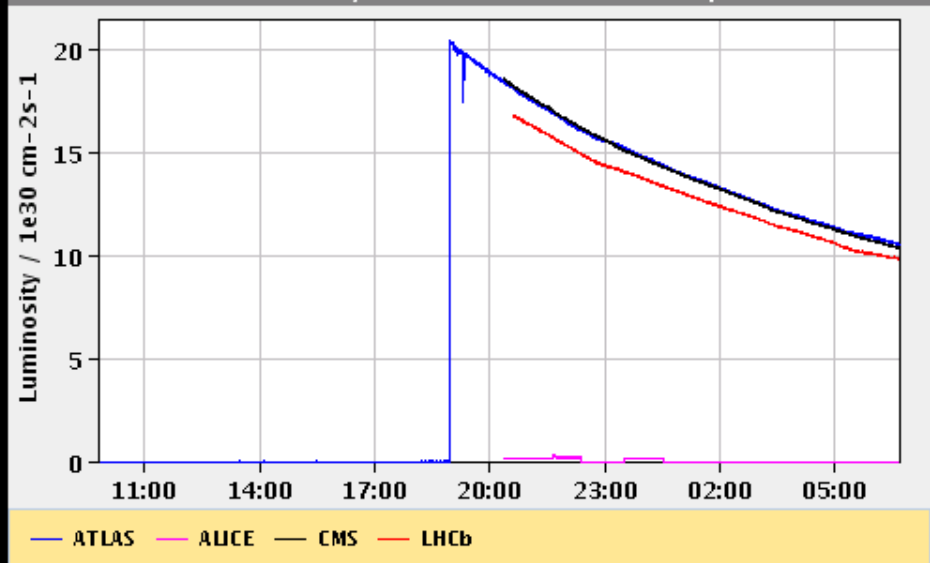
# PROTON PHYSICS: STABLE BEAMS

Energy: 3500 GeV I(B1): 5.01e+12 I(B2): 4.73e+12

FBCT Intensity and Beam Energy Updated: 06:40:53



Instantaneous Luminosity Updated: 06:40:54



Comments 23-09-2010 22:16:30 :

Collisions with bunch trains; 22<sup>nd</sup> September 7x8 bunches;  
Luminosity =  $2 \times 10^{31}$

Fill. scheme: 150 ns\_56b\_47\_16\_47\_8bpi

LHC Operation in CCC : 77600, 70480

BIS status and SMP flags

Link Status of Beam Permits

B1

B2

true true

true true

false false

Beam Presence

true true

Moveable Devices Allowed In

true true

Stable Beams

true true

PM Status B1

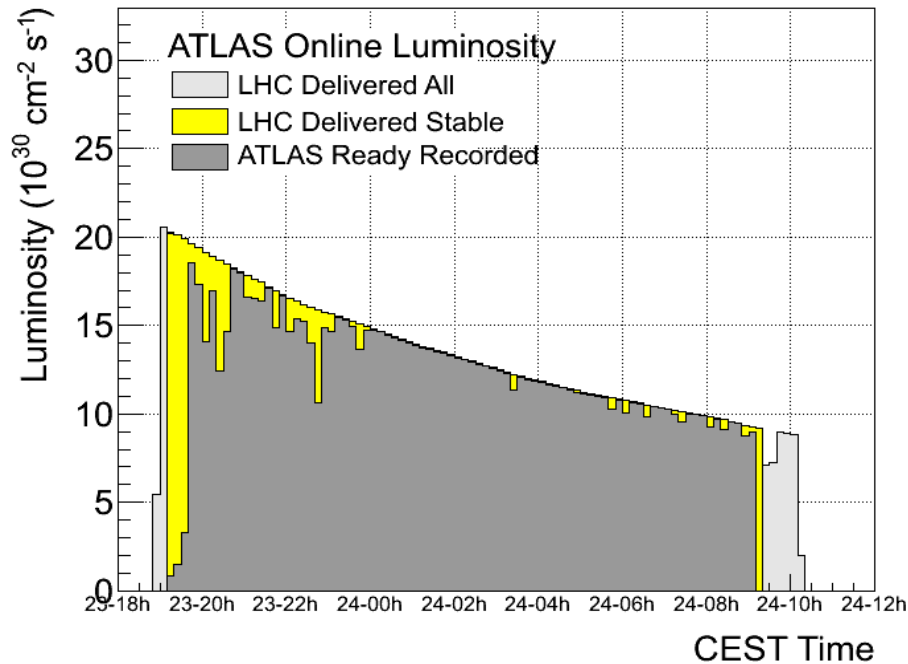
ENABLED

PM Status B2

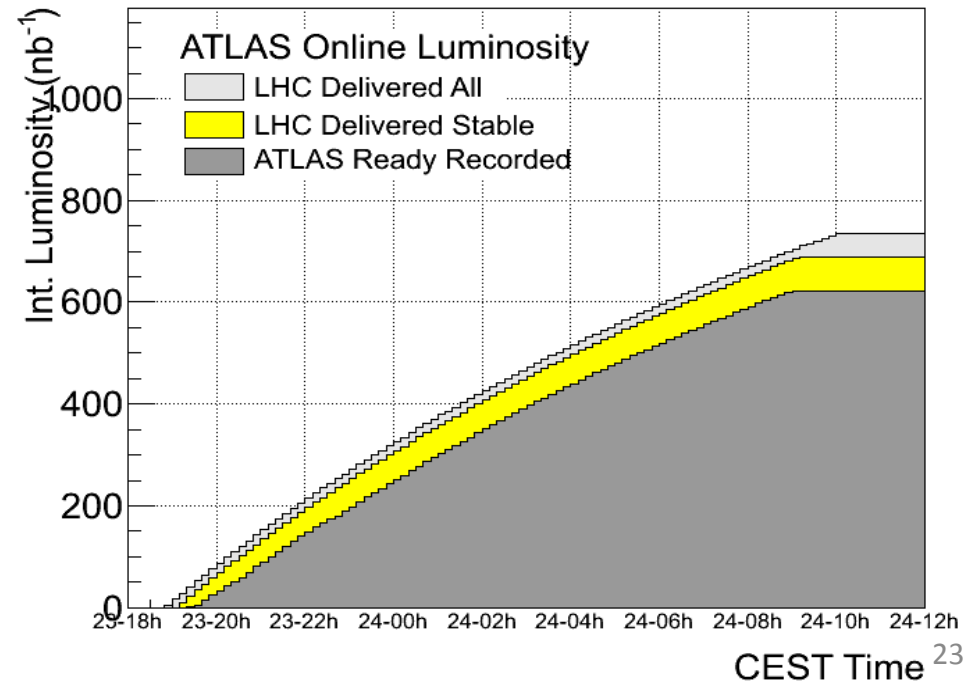
ENABLED

# September 23

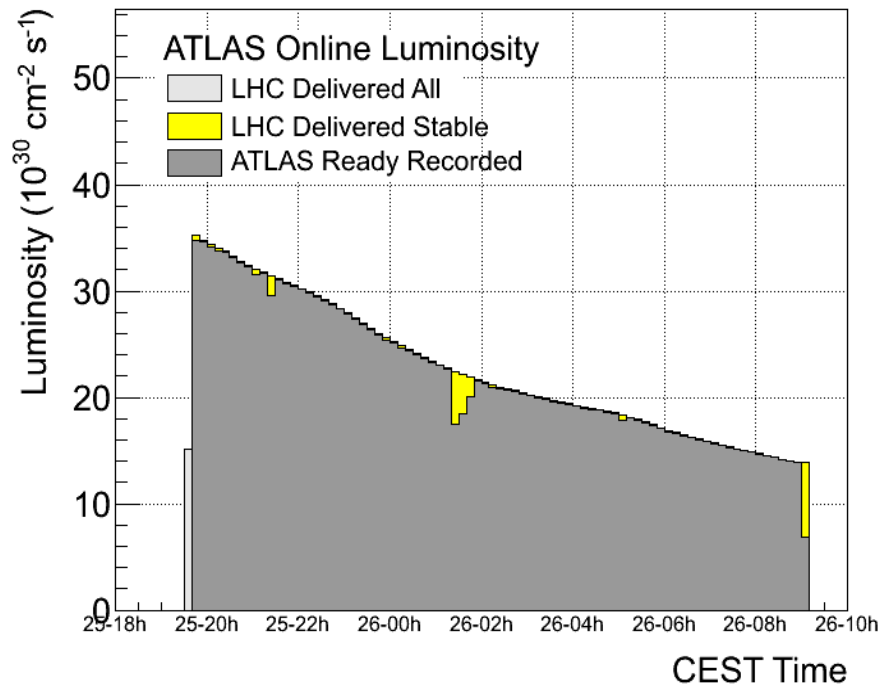
## 48 bunches; bunch trains



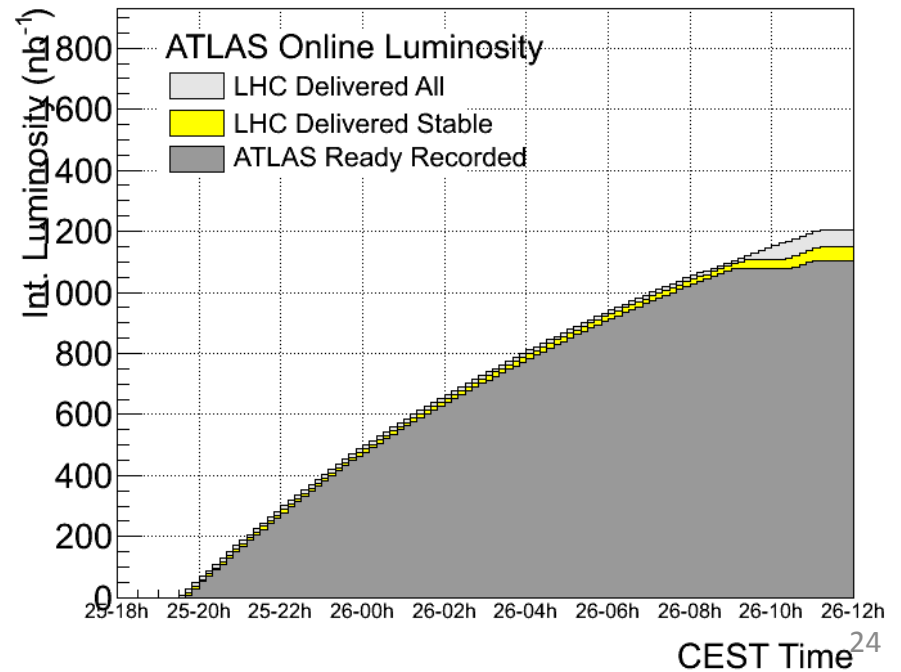
This was a “turning point” fill as it showed that a head-on beam-beam tune shift of  $\sim .02$  total was possible (cf design of  $.01$ )



September 25/26  
104 bunches



1pb-1 in a single fill





# Aggressive Schedule

	July				Aug				Sep				
W <sub>k</sub>	26	27	28	29	30	31	32	33	34	35	36	37	38
M <sub>o</sub>	28	5	12	19	26	2	9	16	23	30	6	13	20
T <sub>u</sub>													
W <sub>e</sub>													
T <sub>h</sub>						★					Jeune G	★	48
F <sub>r</sub>													✓
S <sub>a</sub>													
S <sub>u</sub>													

Ion Beam to SPS

	Oct					Nov		Dec						
W <sub>k</sub>	39	40	41	42	43	44	45	46	47	48	49	50	51	
M <sub>o</sub>	27	4	11	18	25		8	15	22	29	6	13	20	
T <sub>u</sub>	96	192	244	336							End ion run			
W <sub>e</sub>	✓	✓	✓	✓										
T <sub>h</sub>														
F <sub>r</sub>	144		288	384									Xmas Day	
S <sub>a</sub>	✓		✓	✓										
S <sub>u</sub>														

Ion Beam Setup

Start Ion Physics

End non-LHC Physics

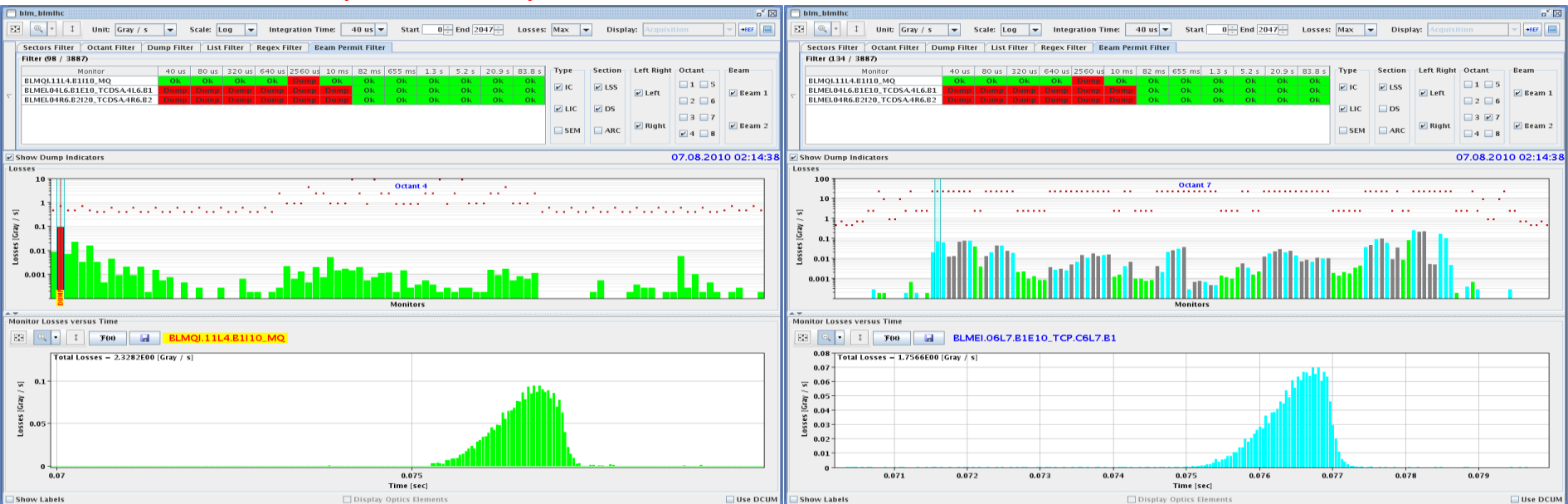
IONS

# Some Issues

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

## Losses with almost identical loss characteristics

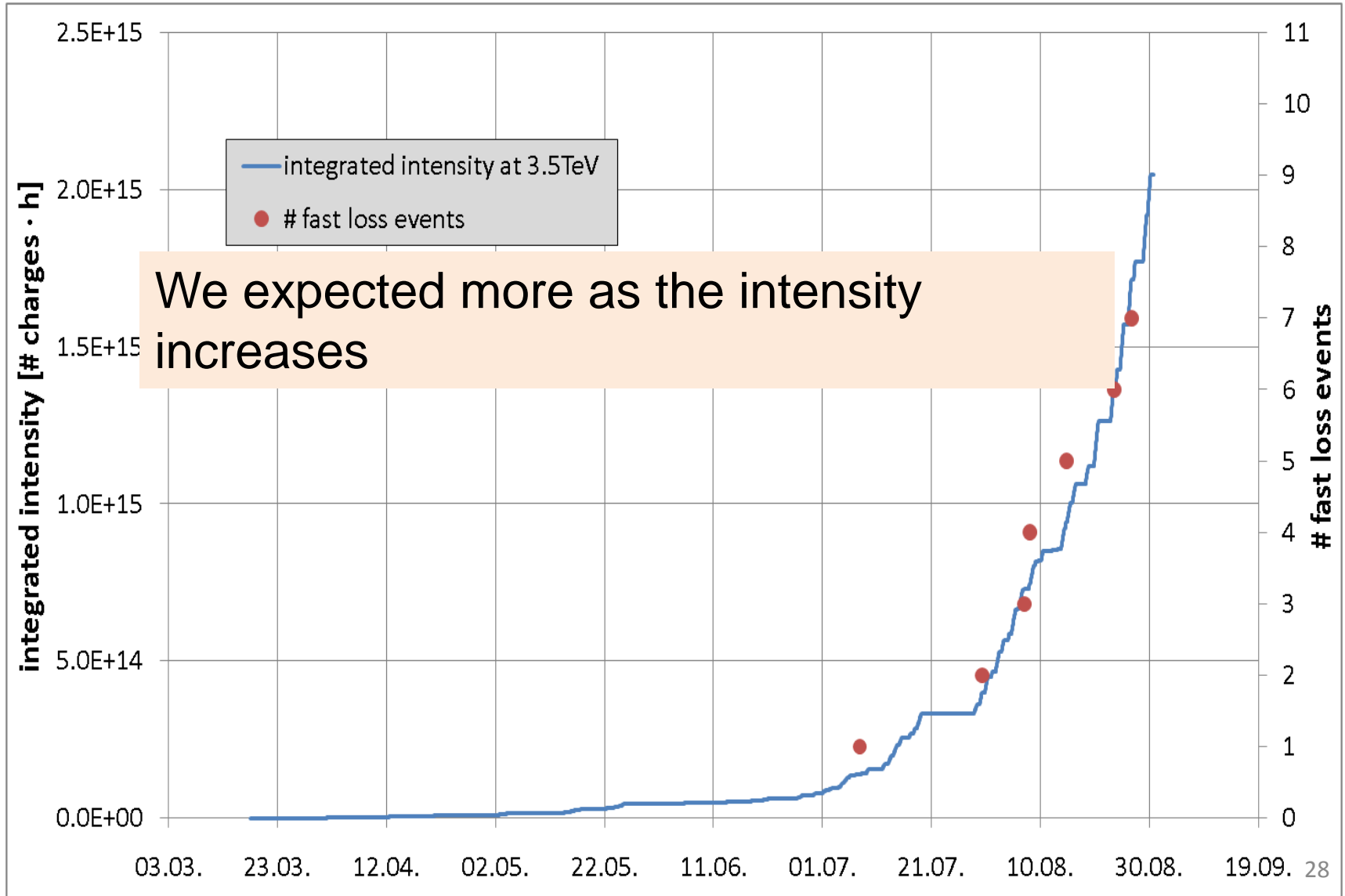
- 5 unexplained beam losses (dump provoked by the Beam loss monitoring system)
- 1 unexplained beam loss while moving Roman Pots
- 1 beam loss provoked by a wire scan



- 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



Update as of this morning (05:00 am)

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

⇒ reached 50pb-1 delivered

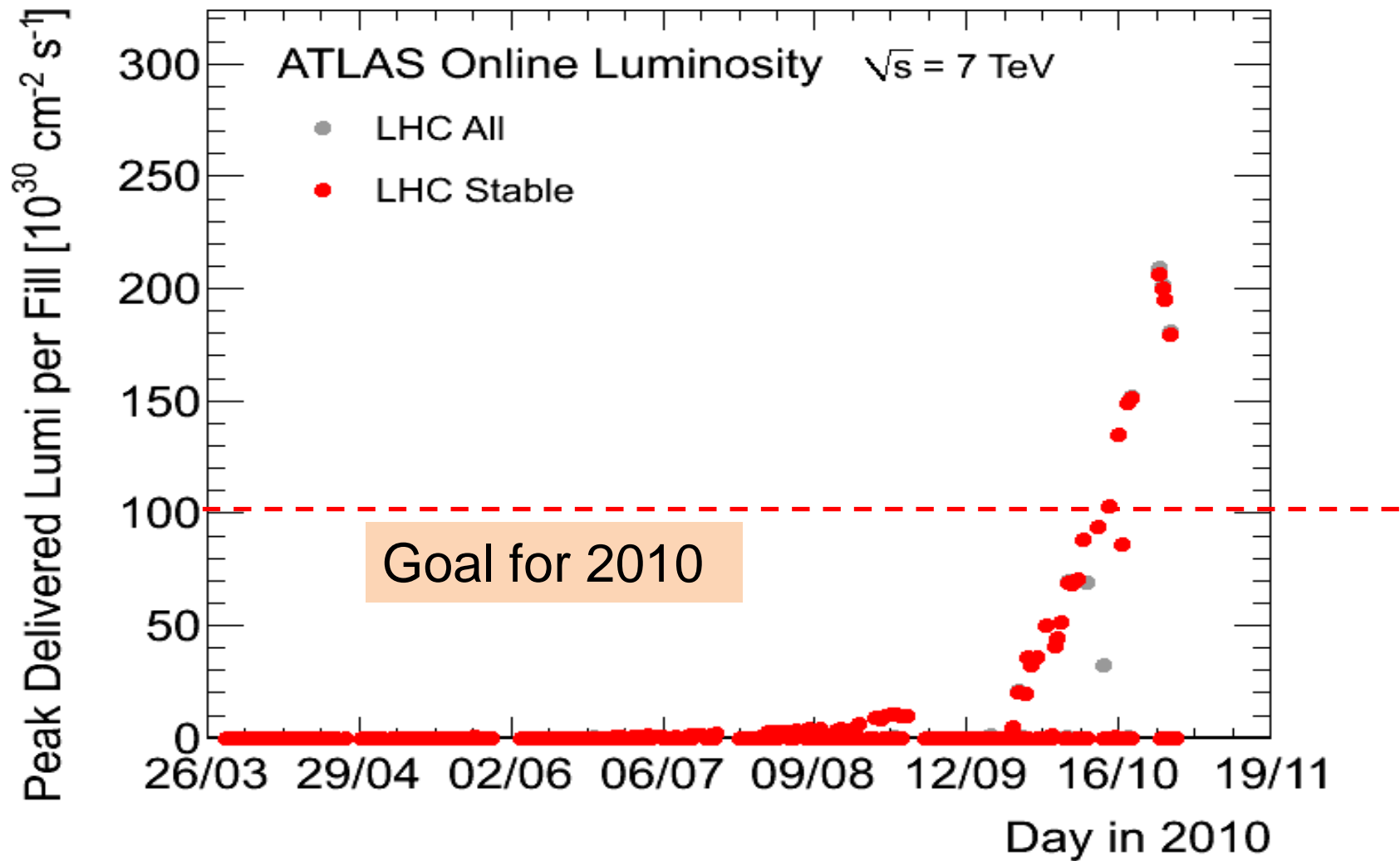
⇒ now move to 50ns bunch spacing to prepare for 2011

# Running with Bunch Trains (Parameters)

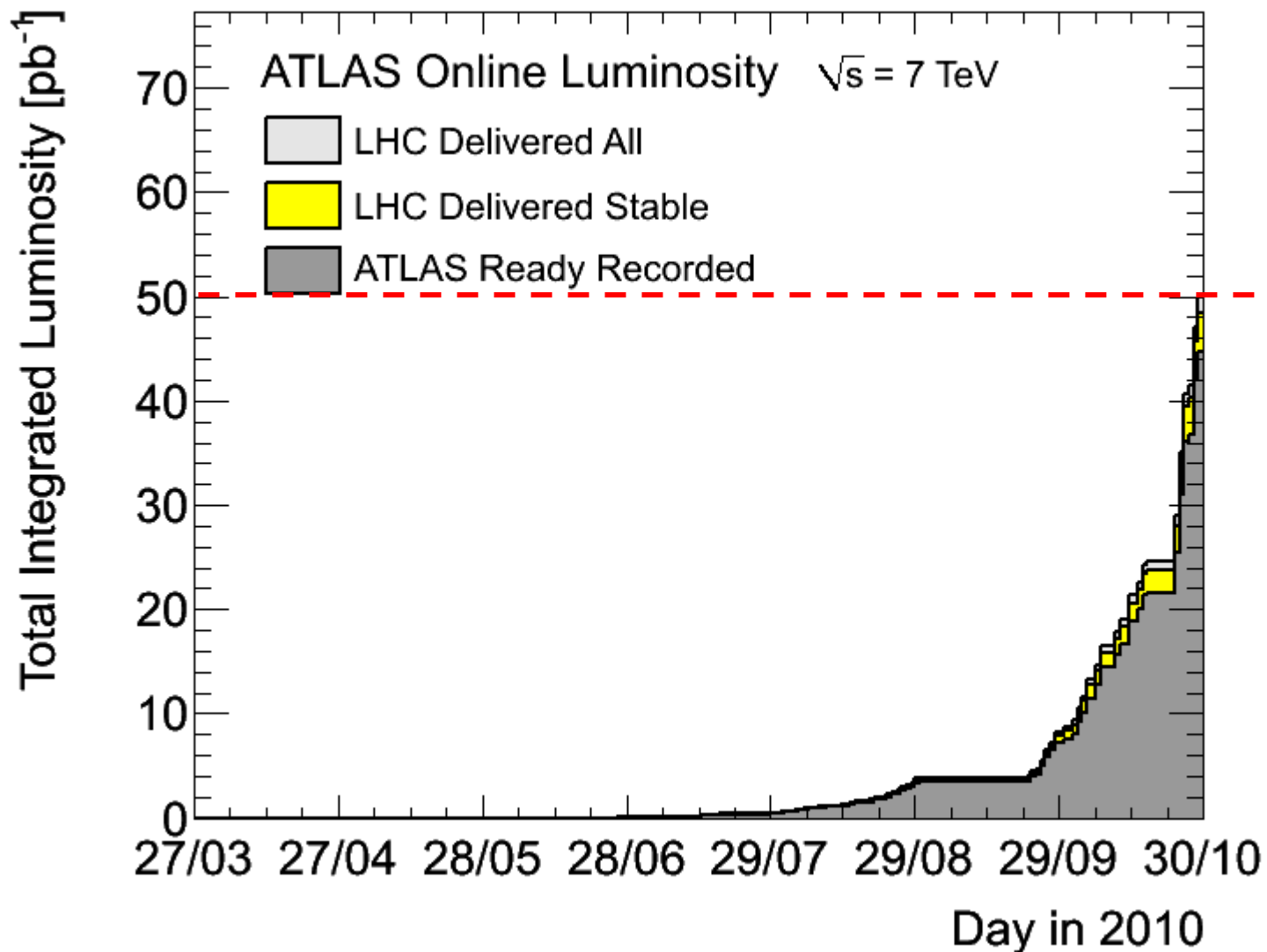
Nb	lb	MJ	Nc	Peak luminosity (design parameters)	Maximum luminosity (measured)	Pile up (from measured Lumi)	Date
56	1.10E+11	3.5	47	1.203E+31	2.000E+31	1.9054	23/09/2010
104	1.10E+11	6.5	93	2.381E+31	3.500E+31	1.7955	25/09/2010
152	1.10E+11	9.4	140	3.584E+31	5.000E+31	1.7550	29/09/2010
204	1.10E+11	12.7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

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

# Peak Luminosity

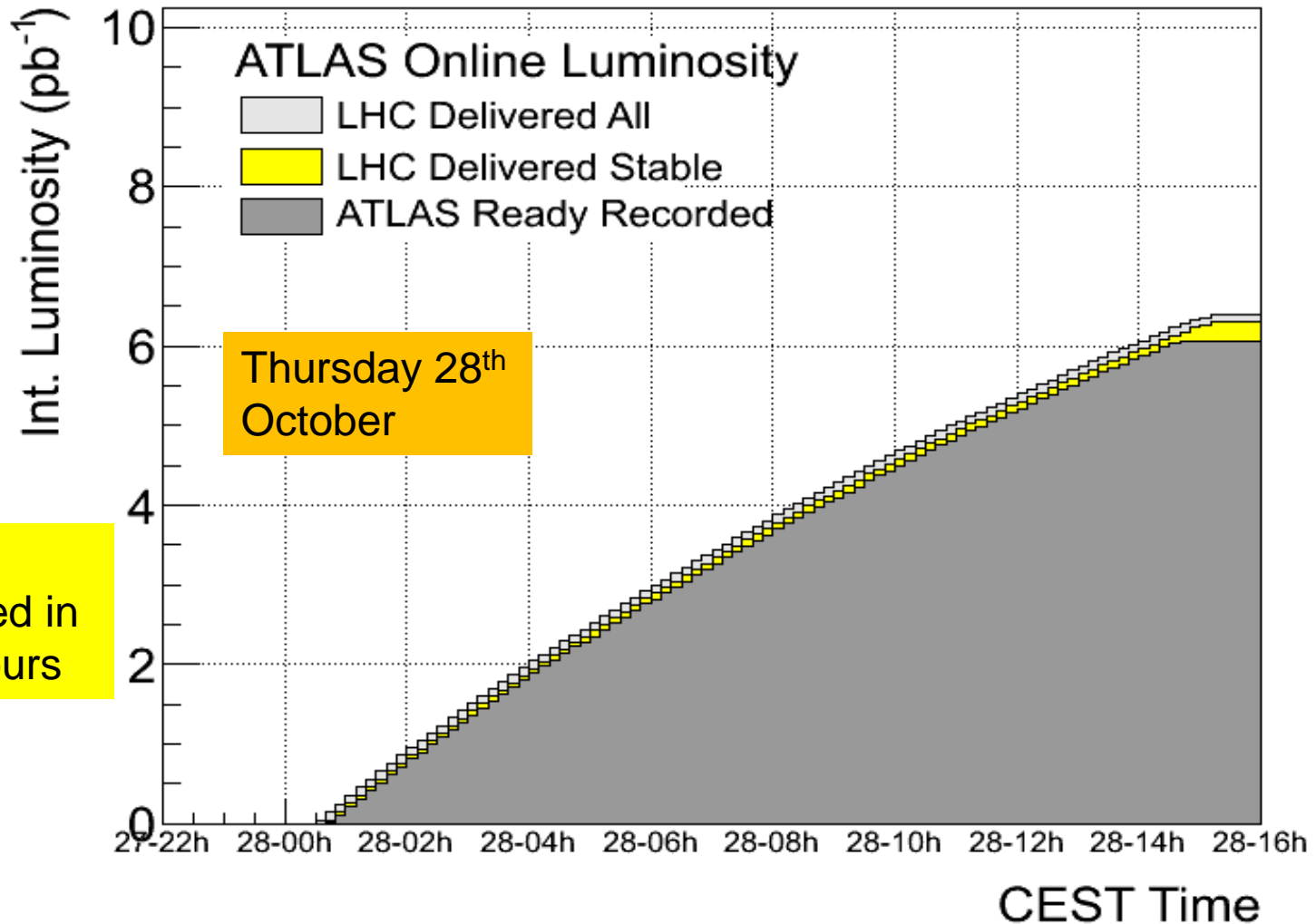


28/10/2010 (approaching 50pb<sup>-1</sup>)





# 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 foreseen
- 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  $1\text{fb}^{-1}$ )

# 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<sup>-1</sup> (on tape) by the end of the life of the LHC**
  - 250-300fb<sup>-1</sup> 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  $5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$  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

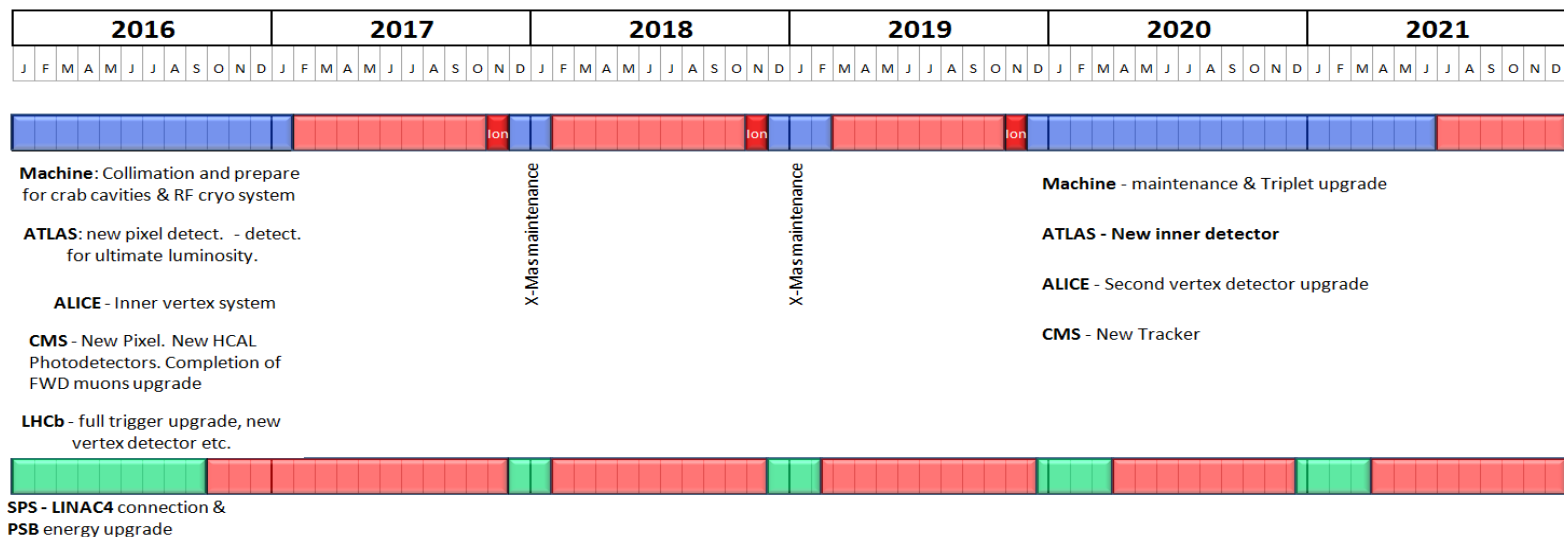
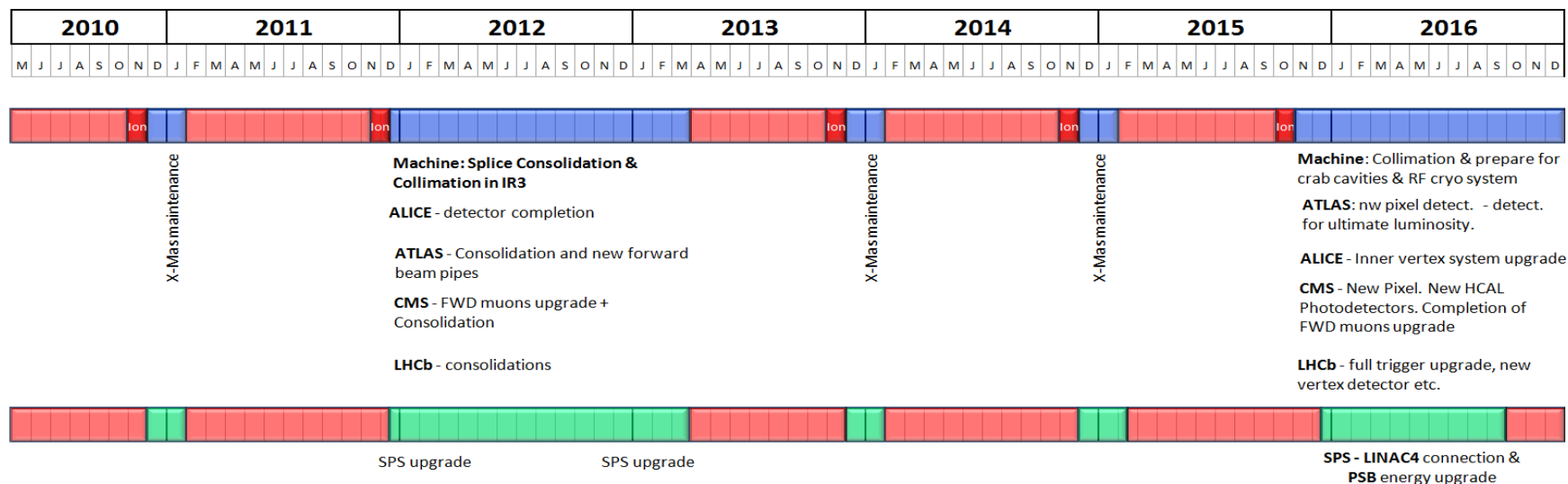
Detector physicists have indicated that their **detector upgrades** are significantly influenced by the choice between **peak** luminosities of  $5 \times 10^{34}$  and  $10^{35}$ .

- 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	<b>16.5</b>
dipole field [T]	8.33	<b>20</b>
dipole coil aperture [mm]	56	40-45
#bunches / beam	1124	<b>1404</b>
bunch population [ $10^{11}$ ]	1.15	1.29
initial transverse normalized emittance [ $\mu\text{m}$ ]	3.75 (x), 1.84 (y)	3.75 (x), 1.84 (y)
number of IPs contributing	3	2
maximum total beam size [mm]	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	<b>479</b>
SR power [MW]	3.6	<b>62.3</b>
longitudinal damping time [h]	12.9	<b>0.98</b>
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 [ $\text{fb}^{-1}$ ]	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**

# Acknowledgements

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Thank You for your  
attention