LHC Machine Operational Status and Plans

International Workshop on Linear Colliders 2010, Geneva

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

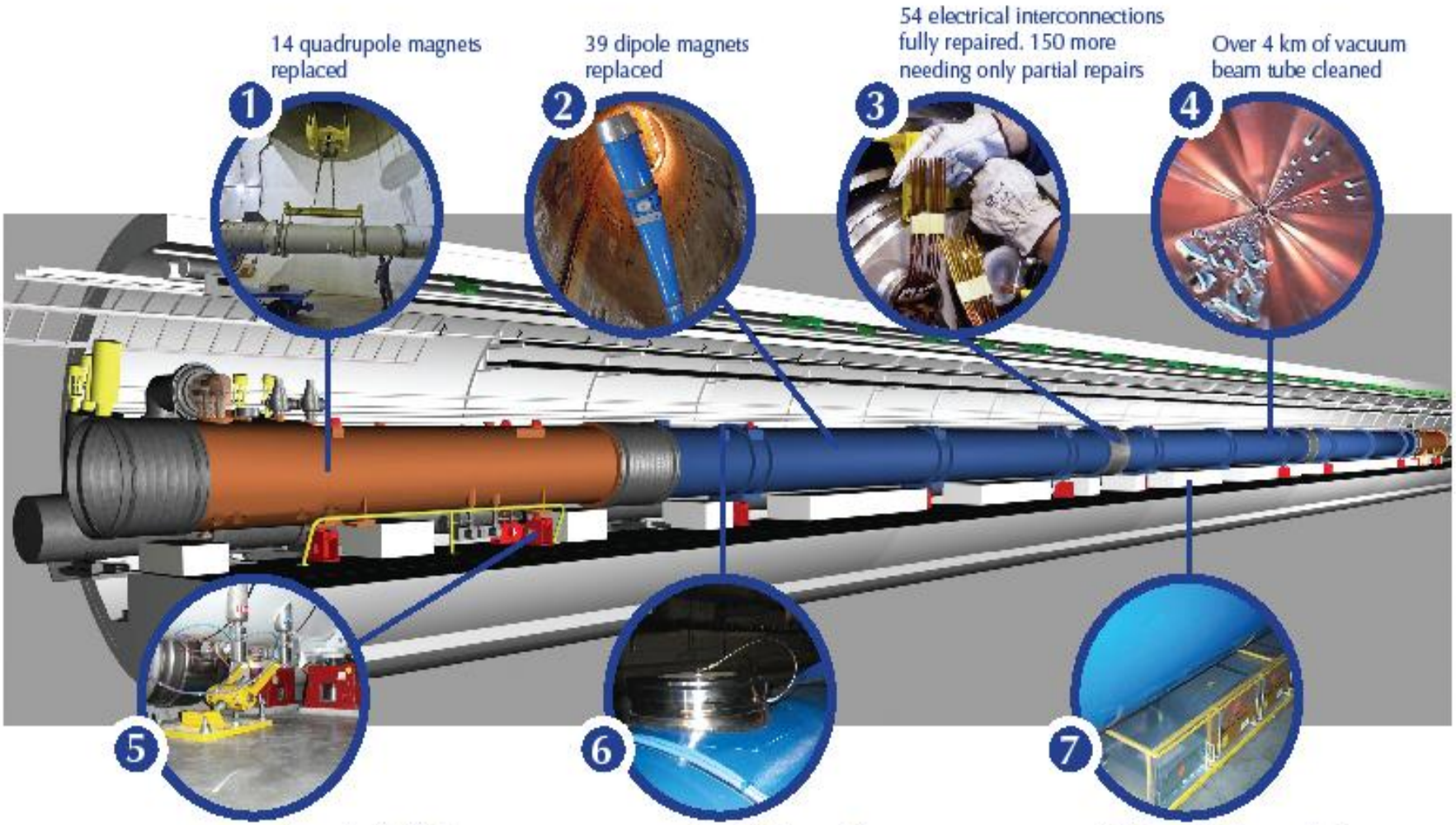
Circumference (km)	26.7	100-150m underground
Number of superconducting twin-bore Dipoles	1232	Cable Nb-Ti, cold mass 37million kg
Length of Dipole (m)	14.3	
Dipole Field Strength (Tesla)	8.4	Results from the high beam energy needed
Operating Temperature (K) (cryogenics system)	1.9	Superconducting magnets 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.

Phase 1 +2

The LHC repairs in detail



CERN

+ 8 cryogenics!

Summary of LHC Commissioning

- November 20th 2009
  - First beams around again
- November 29th 2009
  - Both beams accelerated to 1.18 TeV simultaneously
- December 8th 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

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

Primary Goal for 2010

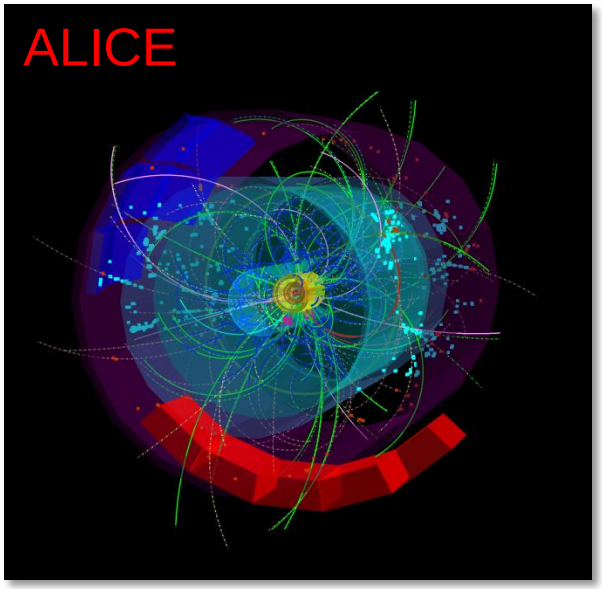
Why do we limit the beam energy to 3.5TeV in 2010-2011?

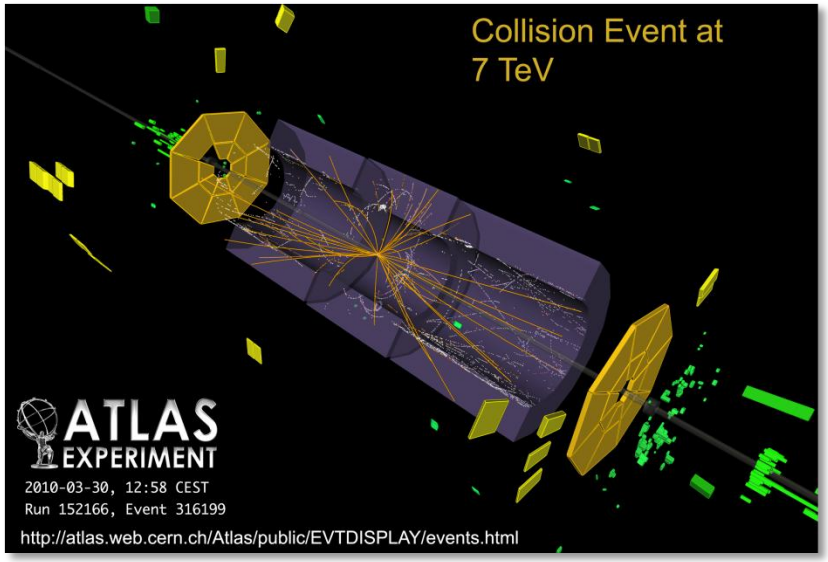
All the work we have done since November 2008 makes us certain that a repeat of September 19 can NEVER happen.

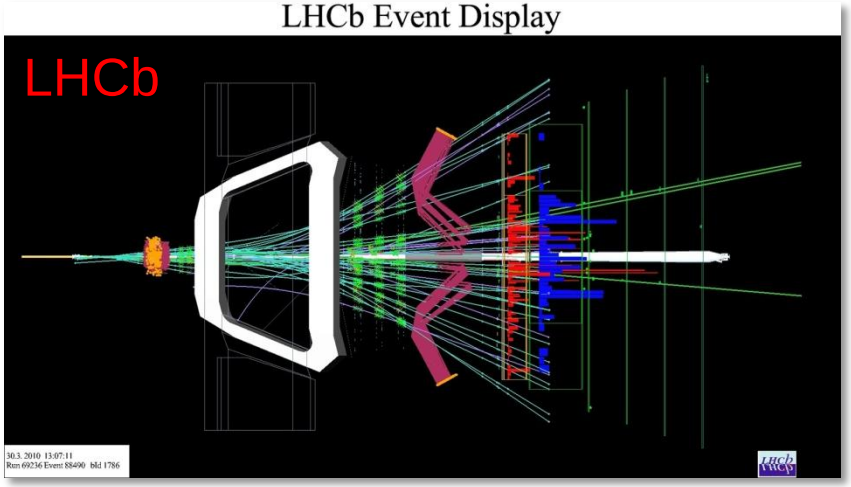
The offending connector in this incident had an estimated resistance of 220nΩ. We have measured all 10,000 inter-magnet connectors and the maximum resistance we have seen is 2.8nΩ.

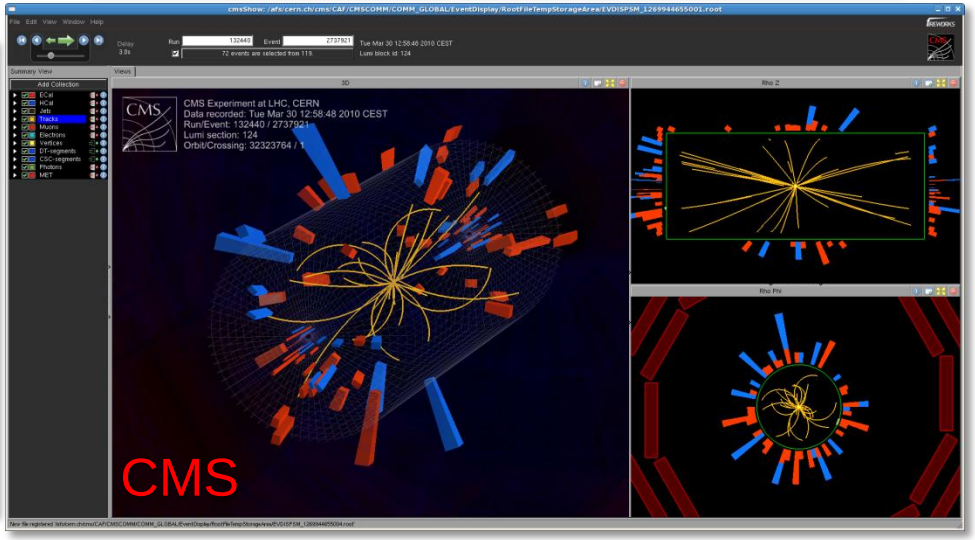
BUT in April 2009, we have uncovered a different possible failure scenario which could under certain circumstances produce an electric arc in the “copper stabilizers” of the magnet interconnects

LHC: First collisions at 7 TeV on 30 March 2010









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

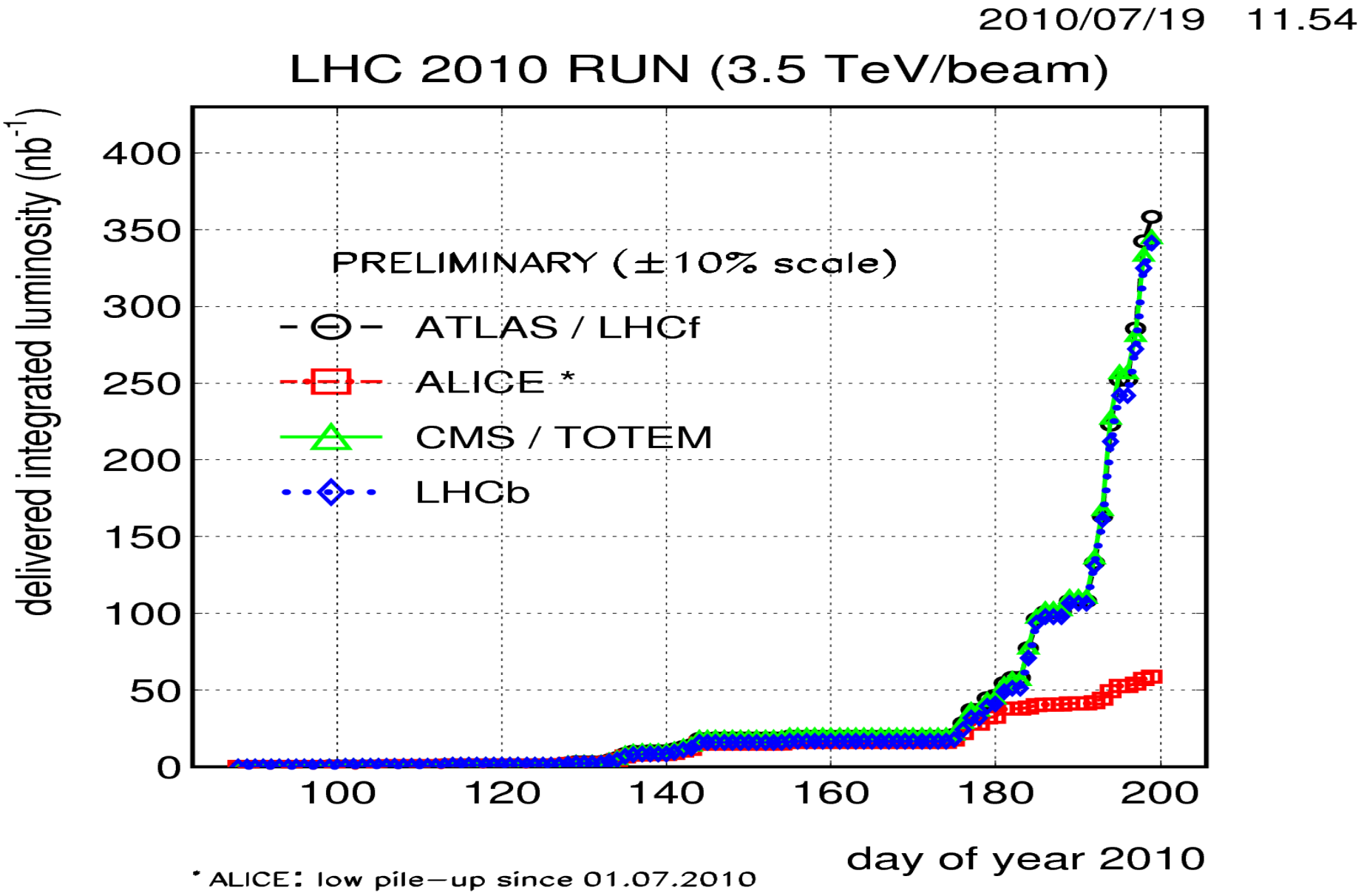
At the time of ICHEP, Paris

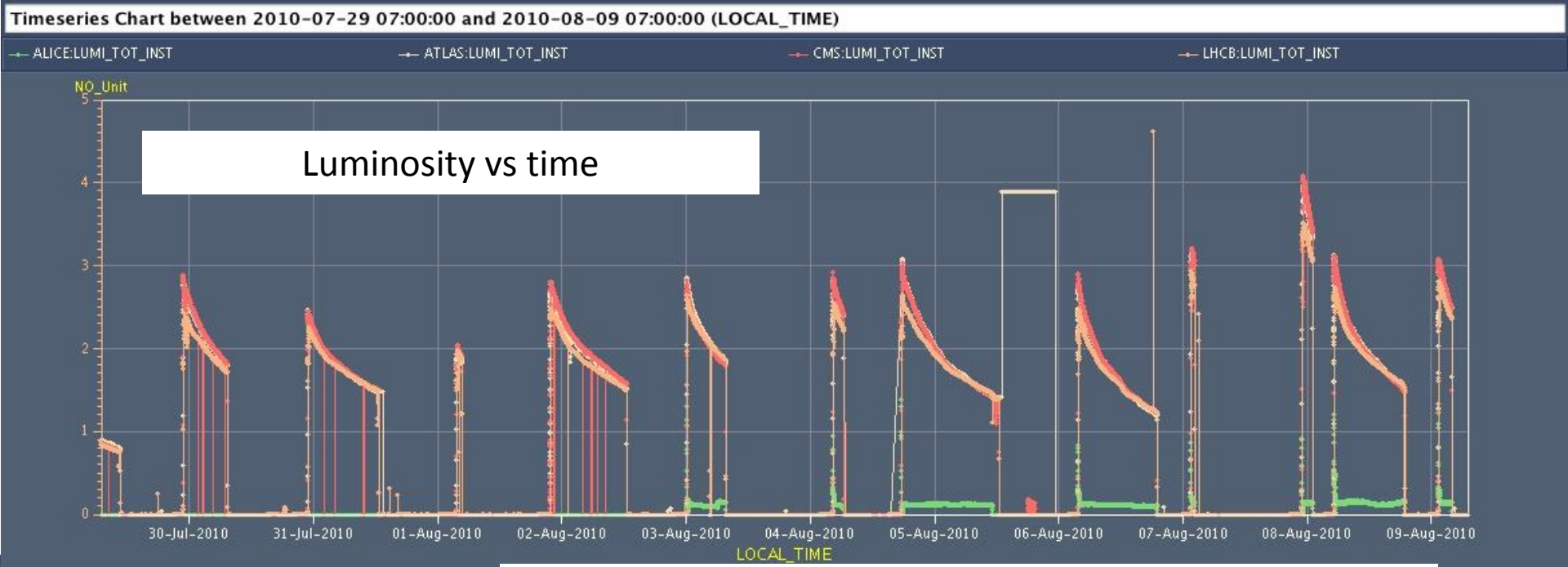
calculated

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
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

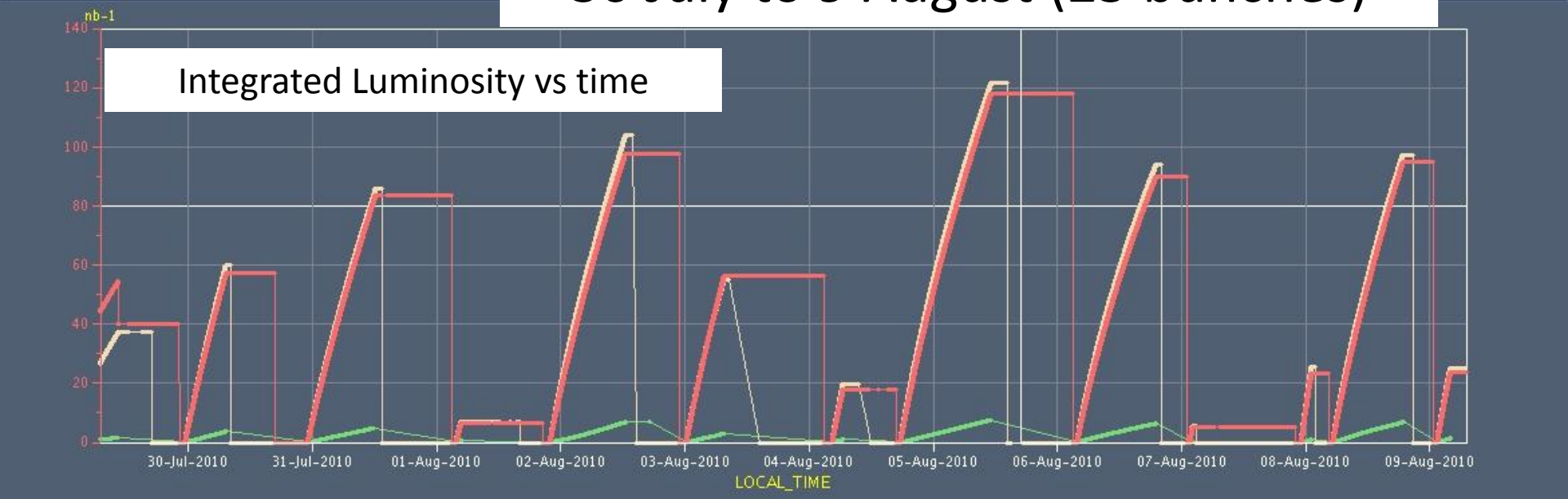
At the time of the ICHEP, Paris,

Integrated Luminosity ICHEP10 (350nb-1)





30 July to 9 August (25 bunches)



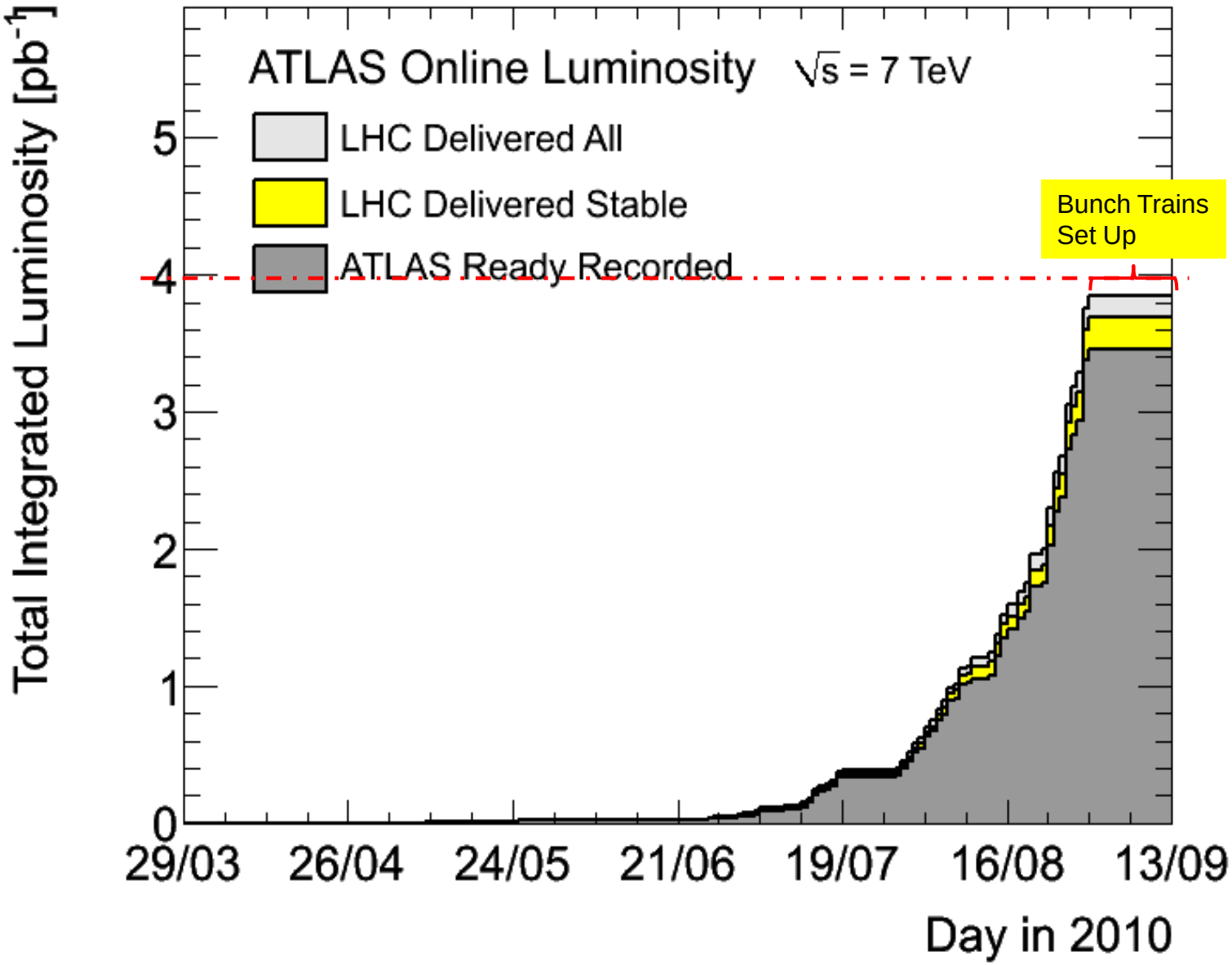
Second Running Period (High bunch Intensity

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
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 10.7×10^{30} $cm^{-2}s^{-1}$

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



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

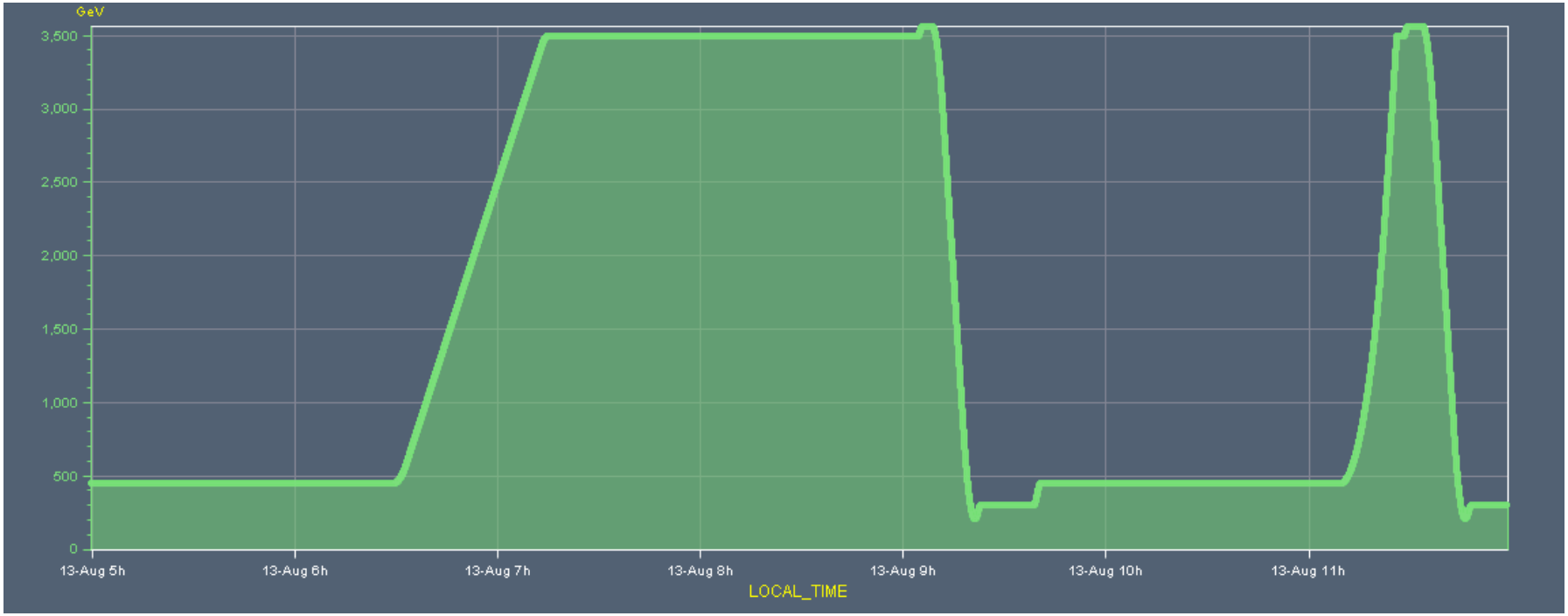
LMC 18th August.

- Parameters and Conditions
  - Nominal bunch intensity 1.1E11
  - Stick to β* = 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)

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 aperture gold mine for performance”

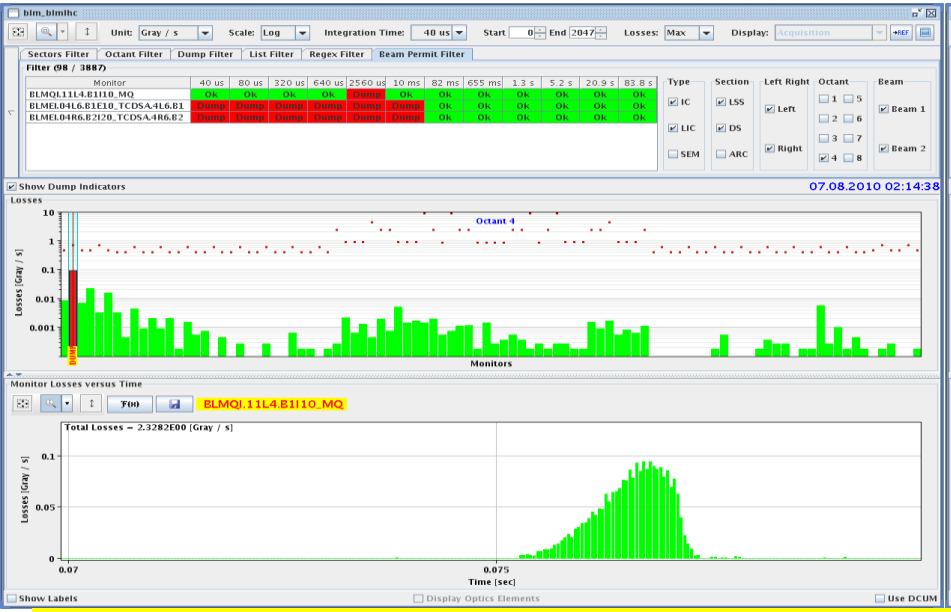
Conclusion from Aperture

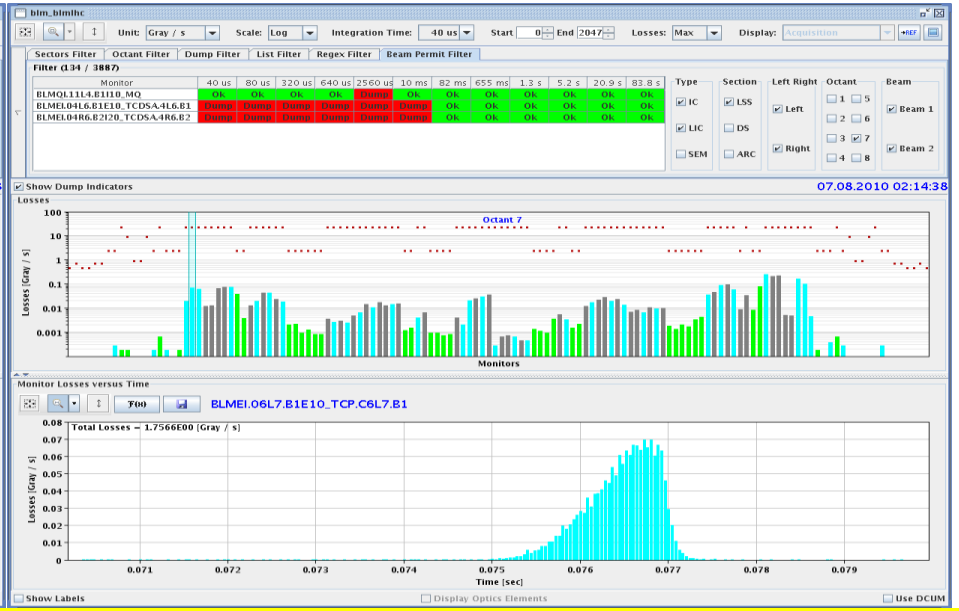
- **Plenty of aperture at triplets: > 13 σ (n1 > 10)**
- Can open tertiary collimators, e.g. to 13 σ at injection.
- **Can stay with 170 μrad crossing angle at injection.**
- Can also review settings for injection protection → Relax?
- We will measure aperture also at top energy with 3.5 m beta*. If (when) similar margins found , this will open the door for smaller beta* with same risk level.

Unexplained Beam Losses

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

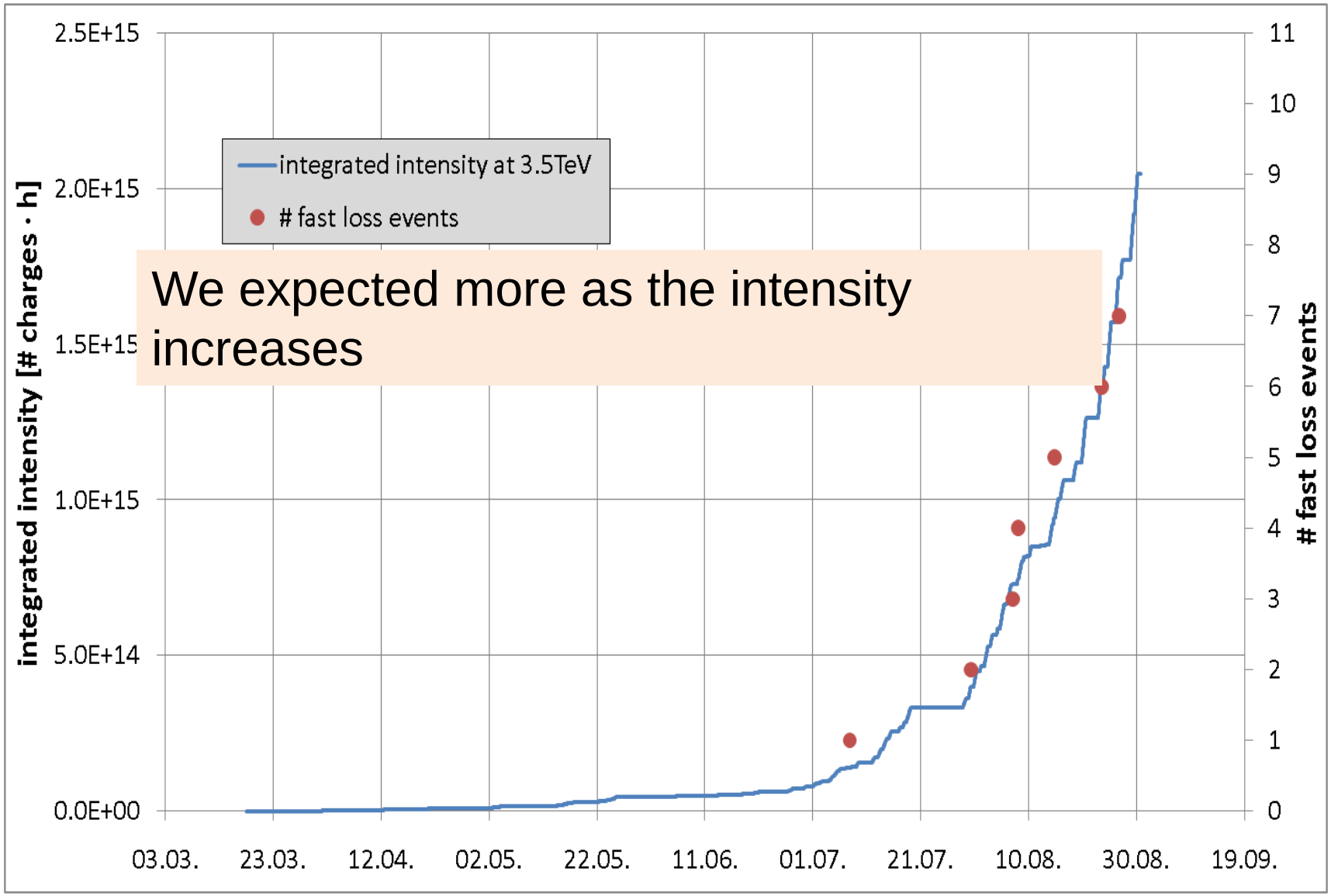




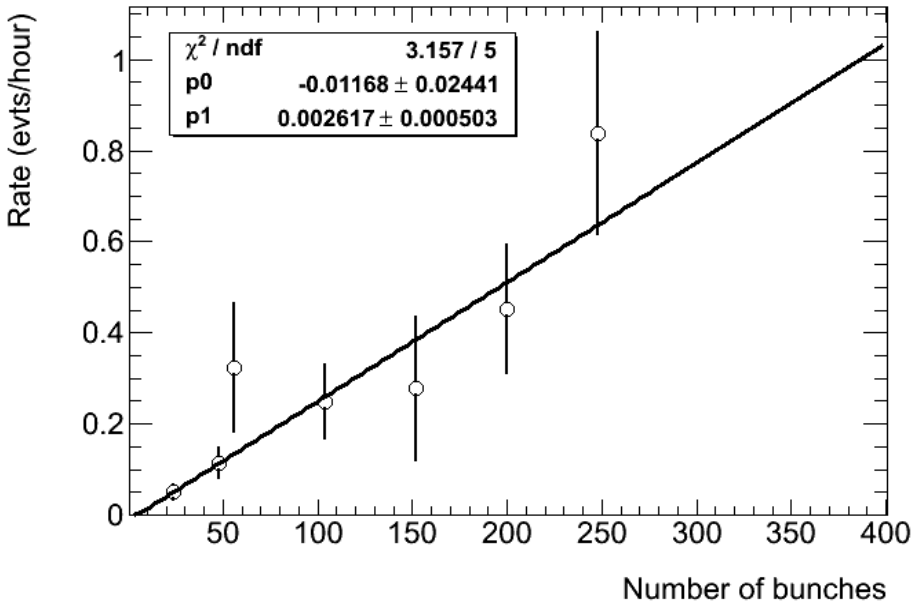
- Suspicion is that debris if falling into the beam provoking a small beam loss seen by the BLM which triggers the beam dump (machine protection works well)

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

Correlation of Number of fast Losses with beam Intensity



INTENSITY DEPENDENCE



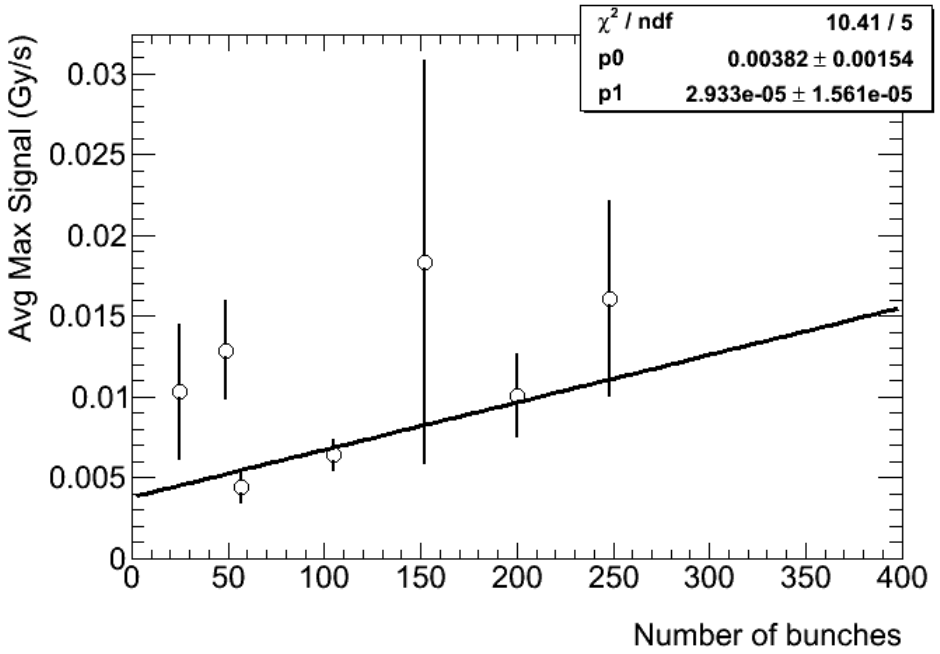
"UFO" Rate

The UFO rate seems to increase linearly with intensity:

Extrapolating

2000 Bunches => ~ 5.2 evts/hour

60% of the events used to produce this graphic were far from threshold (Signal/Threshold < 0.2)



Signal intensity (RS05)

Signal in the BLM at maximum also scales (linearly?) with intensity:

Extrapolating

2000 Bunches => ~ 0.06 Gy/s

Thresholds for cold magnets in RS05 are in the range 0.02-0.08 Gy/s

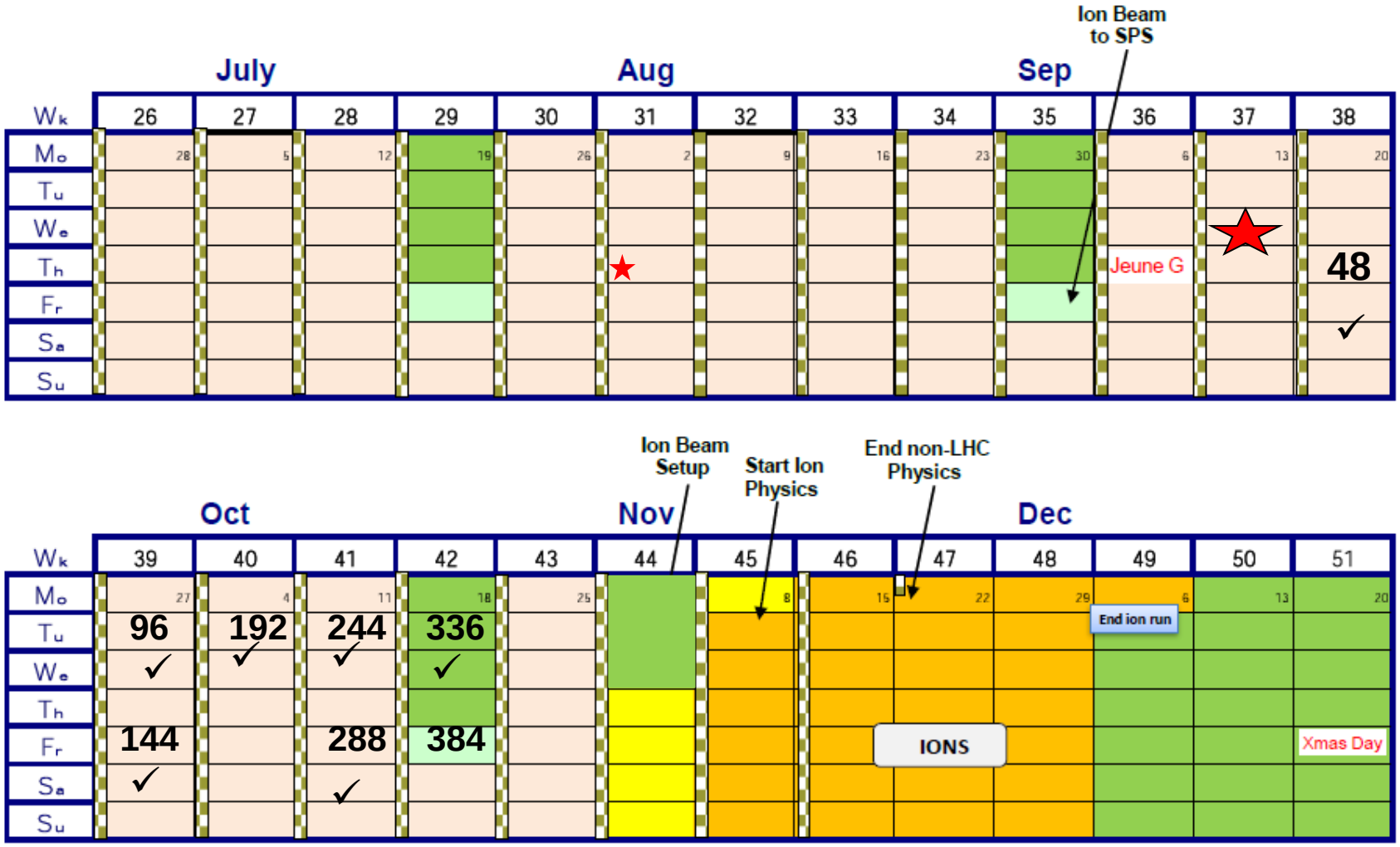
Reconsidering rate of MJ increase

- Following the external review of the machine protection system
  - Considering speeding up the increase of MJ per week to 2 instead of 1
  - Could allow some time before the ion run for slight reduction of the beta* or increase in the number of bunches
- Bunch trains (with stable beams) since Wednesday 22nd September

Intensity increase

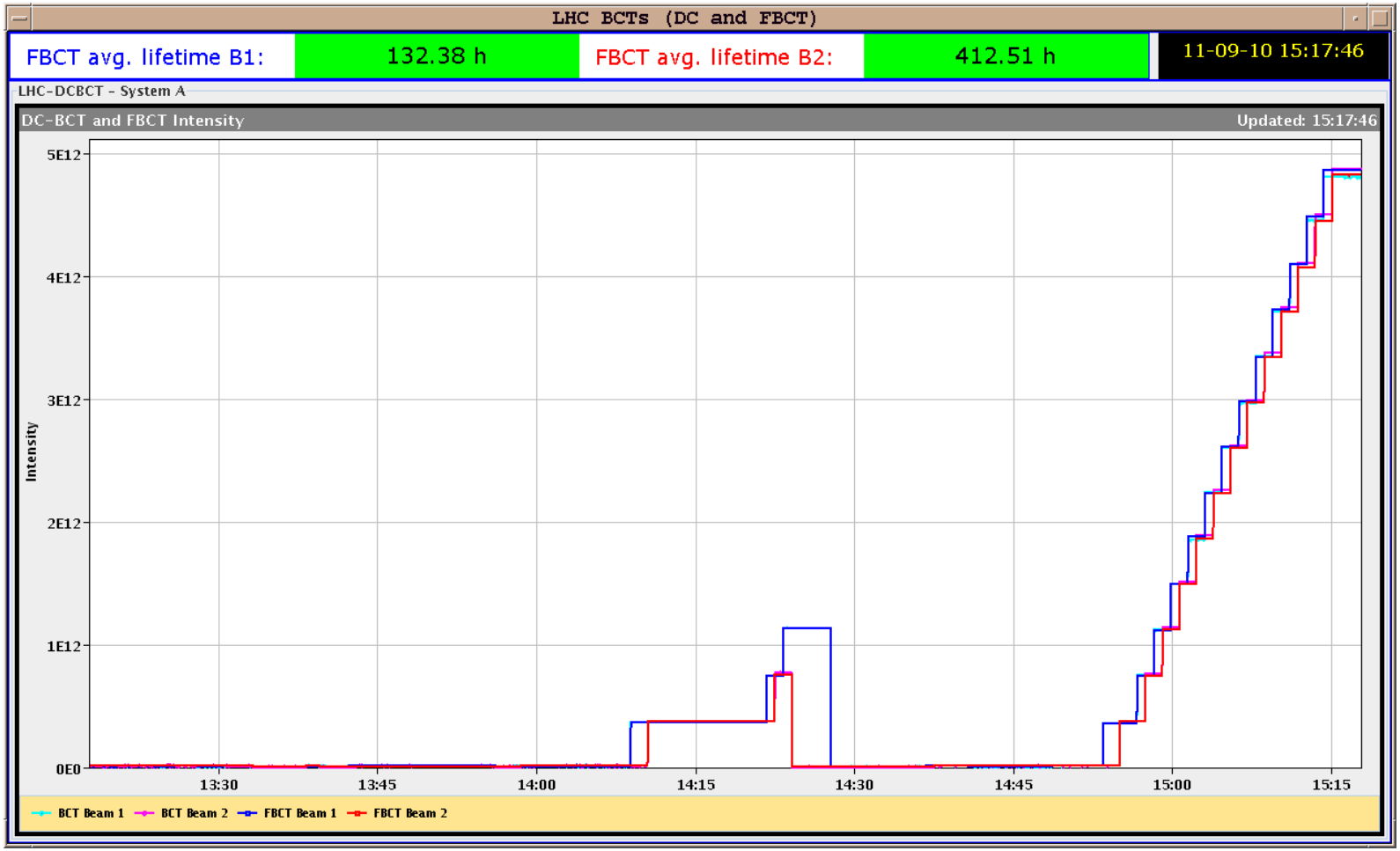
- Intensity increase roadmap
  - Start train operation with 3x8 (or equivalent) – 2 fills, stabilize the sequence. Then move on to 6x8 (or equivalent).
  - 3 fills at a given intensity. Integrated physics time of ~20 hours.
  - Intensity step 48 bunches (+- 10%).
  - A checklist will be defined with the requirements for increasing the intensity.
  - Follow up on review items – as appropriate/possible.
  - Injection: significant change as we are now injecting unsafe beam.
    - Very careful monitoring of abnormal injections.

Aggressive Schedule



Saturday 11.9

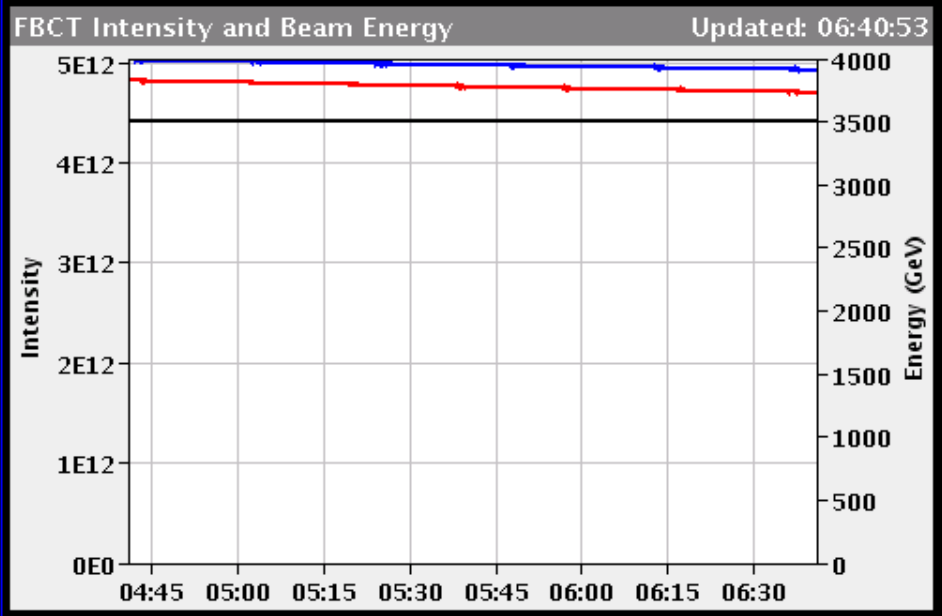
- RF setting up
  - Finally the complete injection sequence of 13x4 bunches per beam was executed and went smoothly with very little uncaptured beam

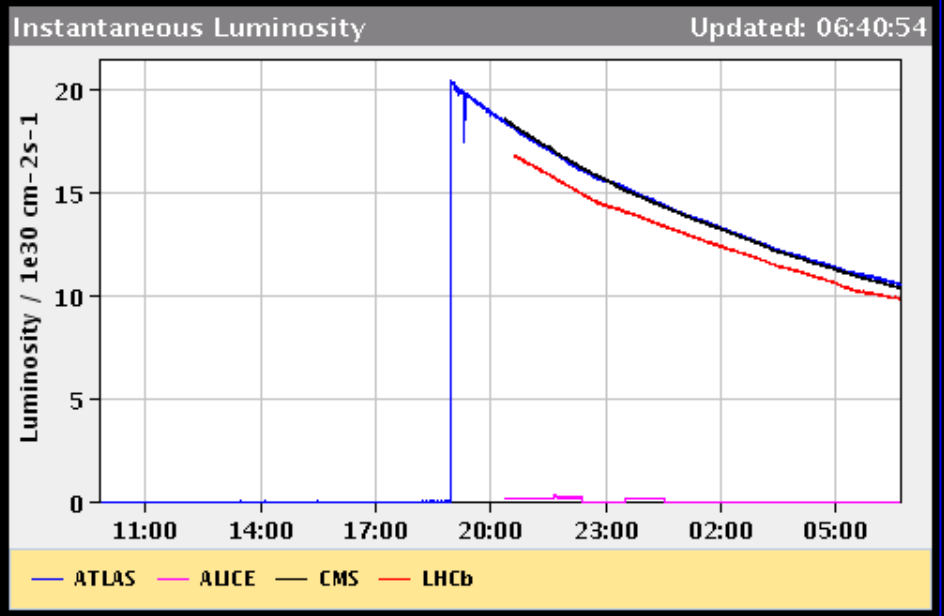


LHC Page1 | Fill: 1366 | E: 3500 GeV | 24-09-2010 06:40:53

PROTON PHYSICS: STABLE BEAMS

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





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

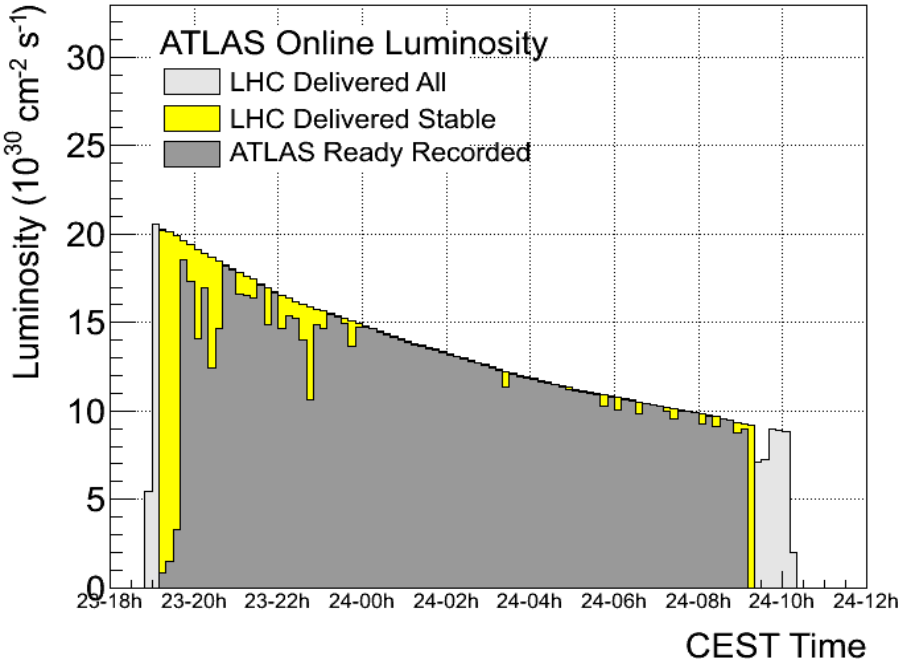
Collisions with bunch trains; 22nd September 7x8 bunches;
Luminosity = 2×10^{31}

Fill. scheme: 150 ns_56b_47_16_47_8bpi

BIS status and SMP flags	B1	B2
rmits	true	true
t	true	true
	false	false
Beam Presence	true	true
Moveable Devices Allowed In	true	true
Stable Beams	true	true

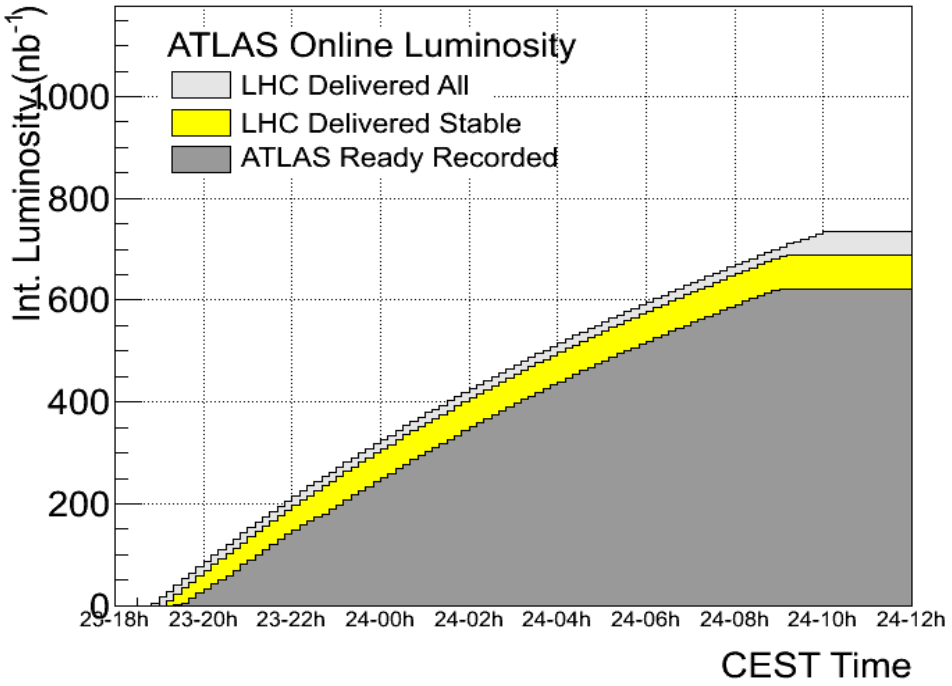
LHC Operation in CCC : 77600, 70480

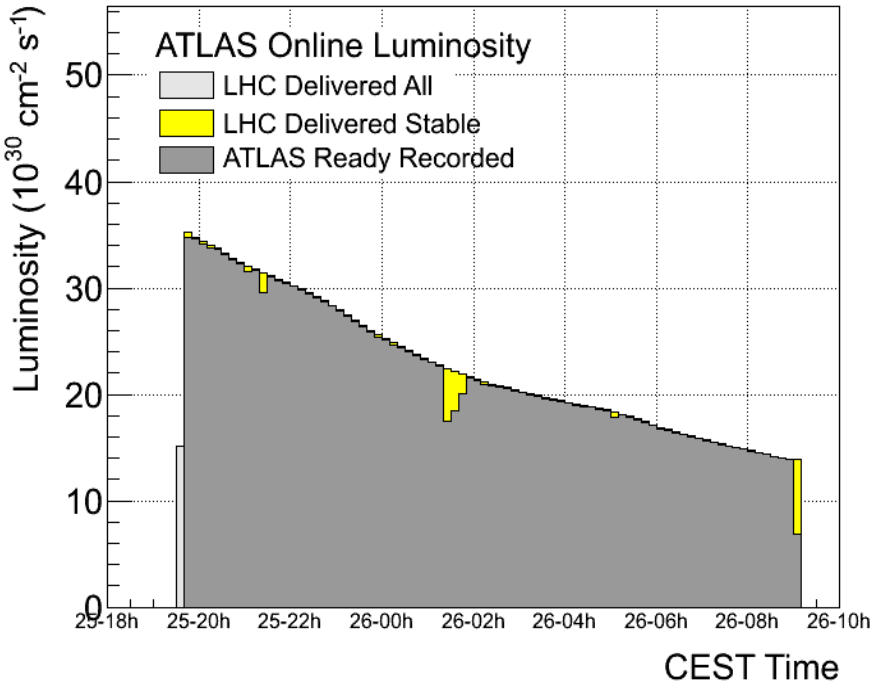
PM Status B1: ENABLED | PM Status B2: ENABLED



September 23
48 bunches; bunch trains

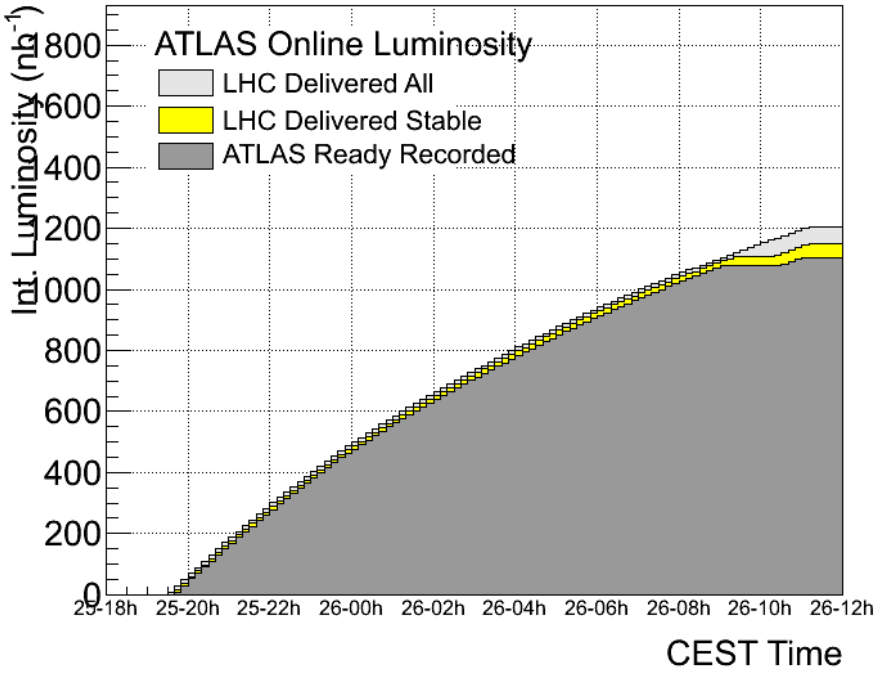
This was a “turning point” fill as it showed that a head-on beam-beam tune shift of ~.02 total was possible (cf design of .01)





September 25/26
104 bunches

1pb-1 in a single fill



PERFORMANCE AS OF THIS MORNING

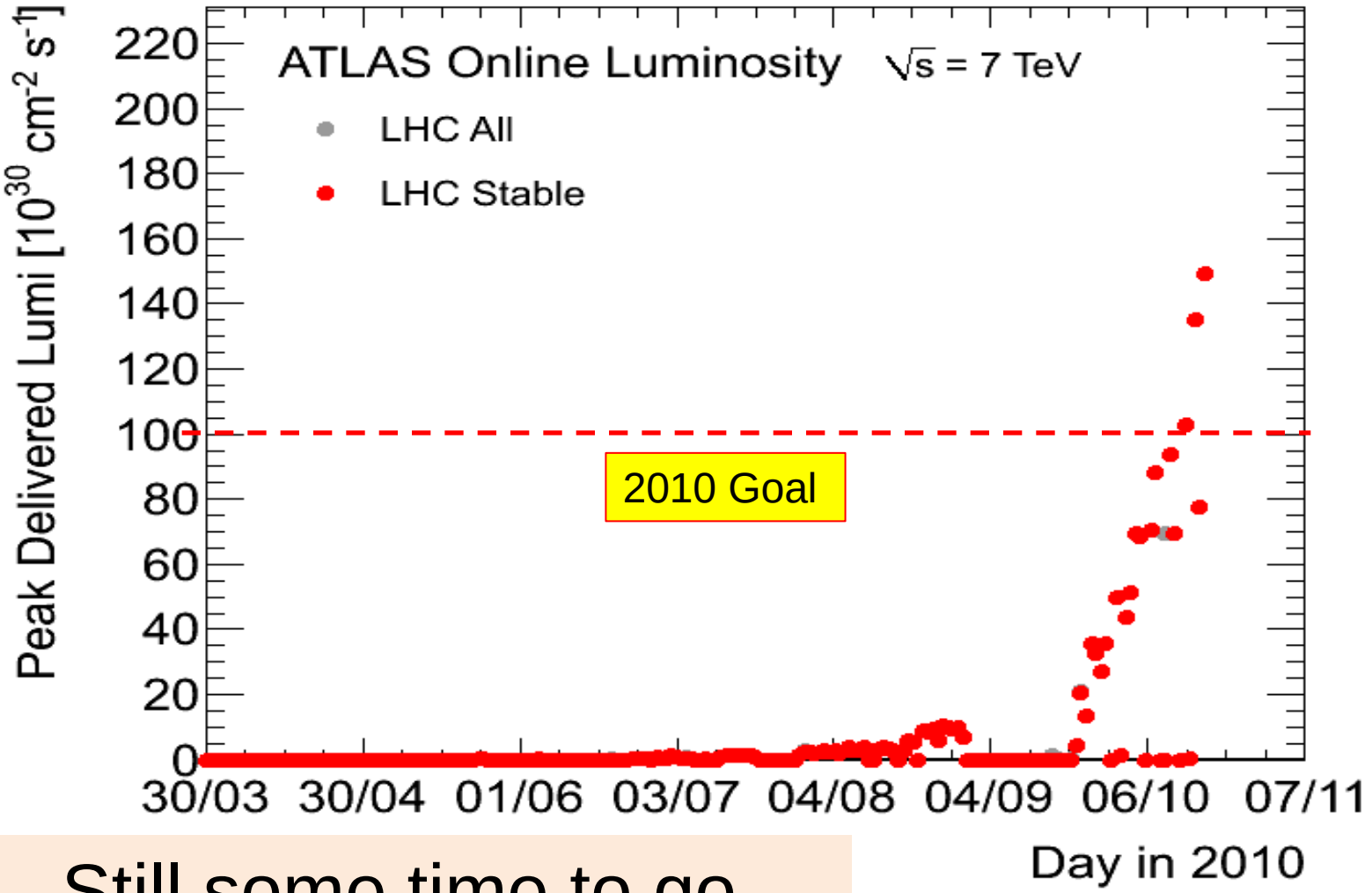
Last Fill with 302 (293 colliding) bunches per beam

Third Running Period (bunch trains)

Nb	Ib	MJ	Nc	Peak luminosity (design parameters)	Maximum luminosity (measured)	Beam-beam shift from measured Lumi	Date
56	1.10E+11	3.5	47	1.203E+31	2.000E+31	0.0157	23/09/2010
104	1.10E+11	6.5	93	2.381E+31	3.500E+31	0.0139	25/09/2010
152	1.10E+11	9.4	140	3.584E+31	5.000E+31	0.0132	29/09/2010
204	1.10E+11	12.7	186	4.762E+31	7.000E+31	0.0139	04/10/2010
248	1.10E+11	15.4	233	5.965E+31	1.030E+32	0.0164	14/10/2010
312	1.10E+11	19.4	295	7.552E+31	1.500E+32	0.0188	16/10/2010

Still some time to go

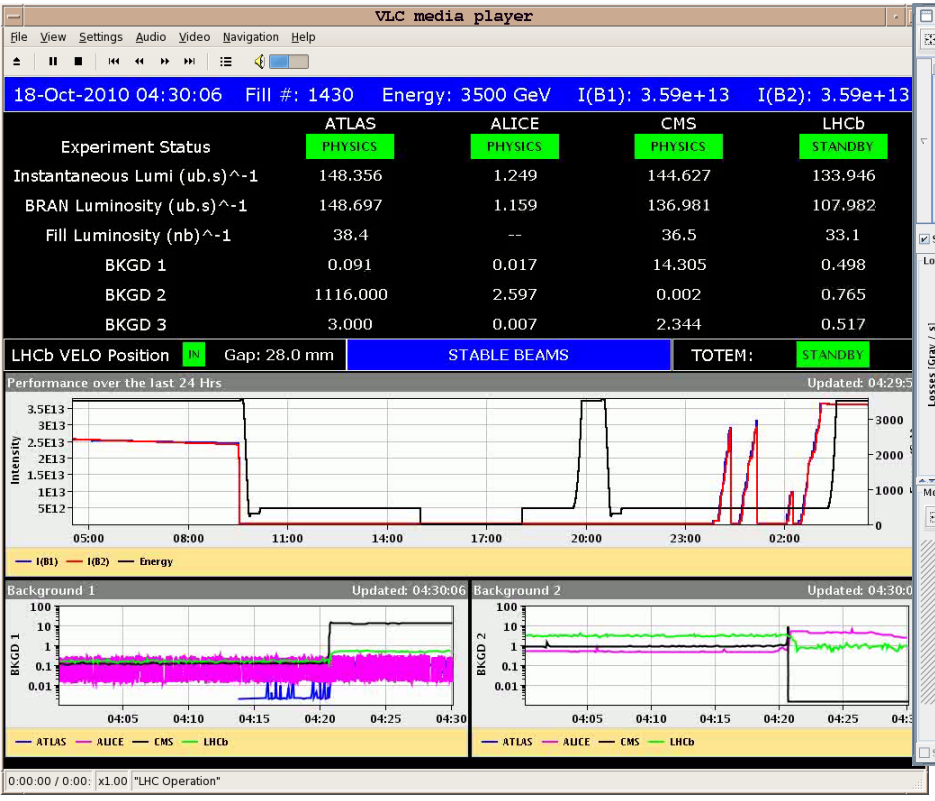
2010 Goal Exceeded!

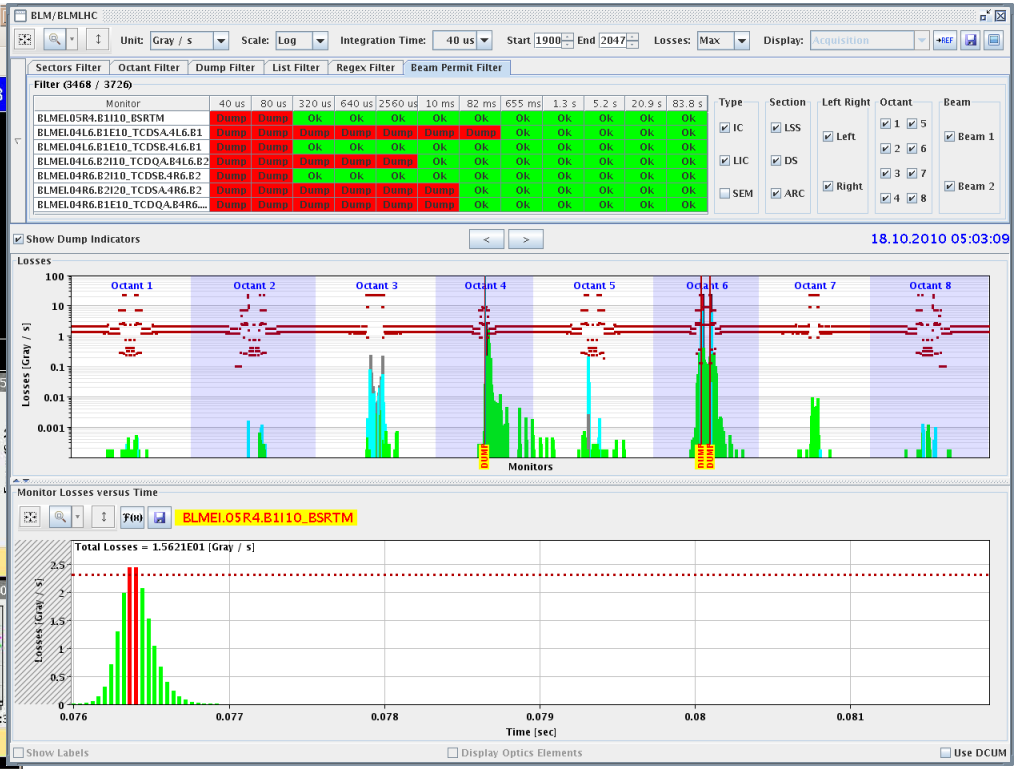


Still some time to go

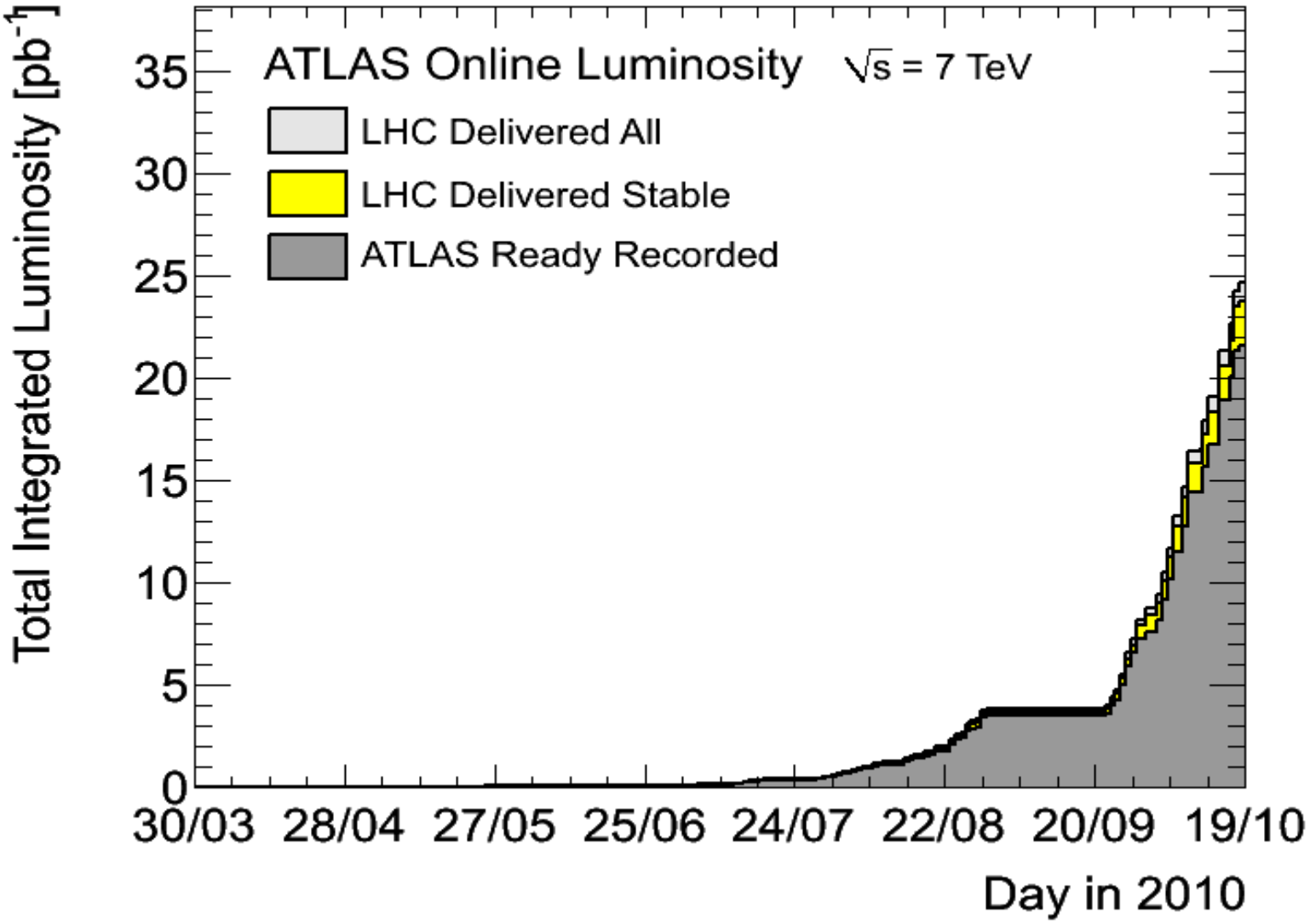
Stable beams #1430

- $3.6x10^{13}$ p/beam in collision (~20 MJ/beam)
- L_0~$1.5x10^{32}$ cm^{-2} s^{-1} ➔ Emittance in collision 2.4 um
- Damped by UFO event after **0.5 hour (~250 nb^{-1}).** UFO event on beam 1 close to BSRT in point 4 (just above threshold)

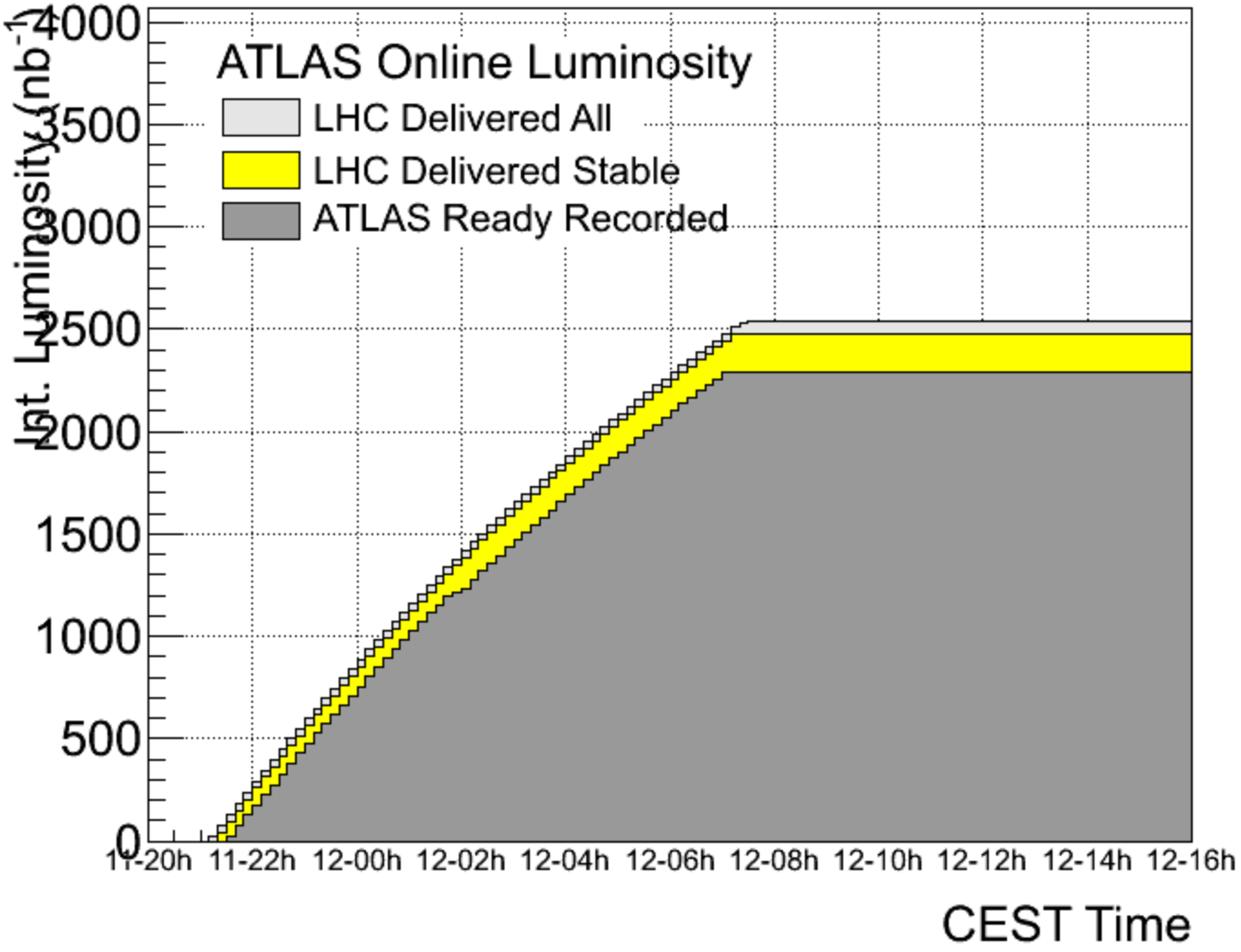




18/10/2010 (approaching 25pb-1)



Highest Integrated Luminosity Fill so Far



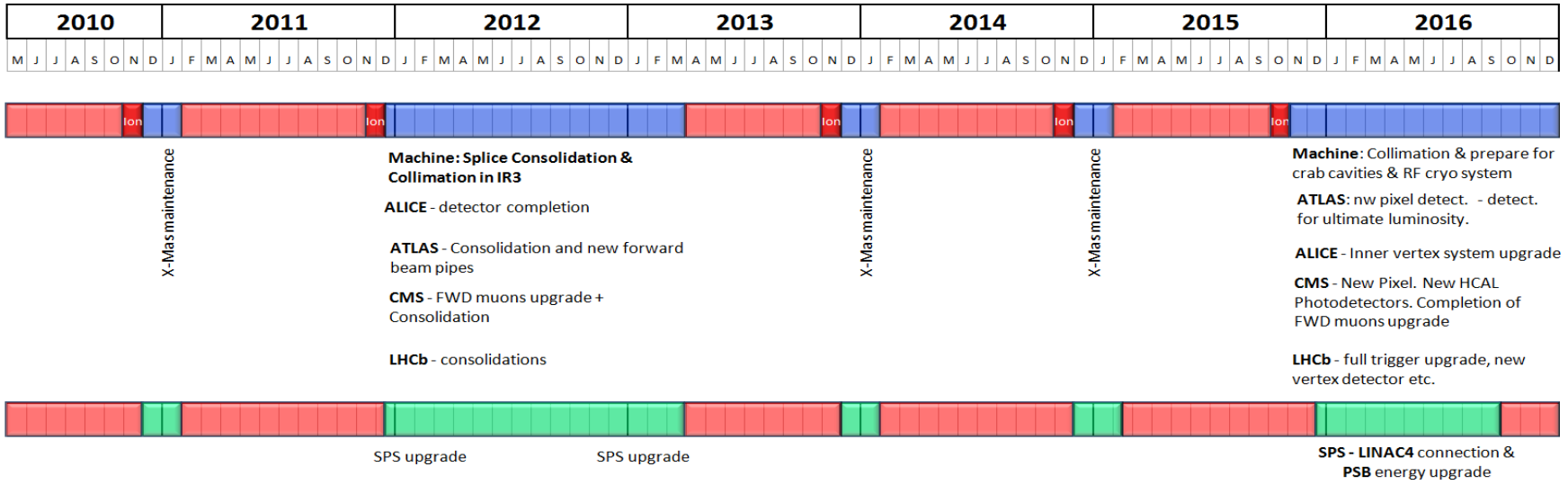
Plans for 2011

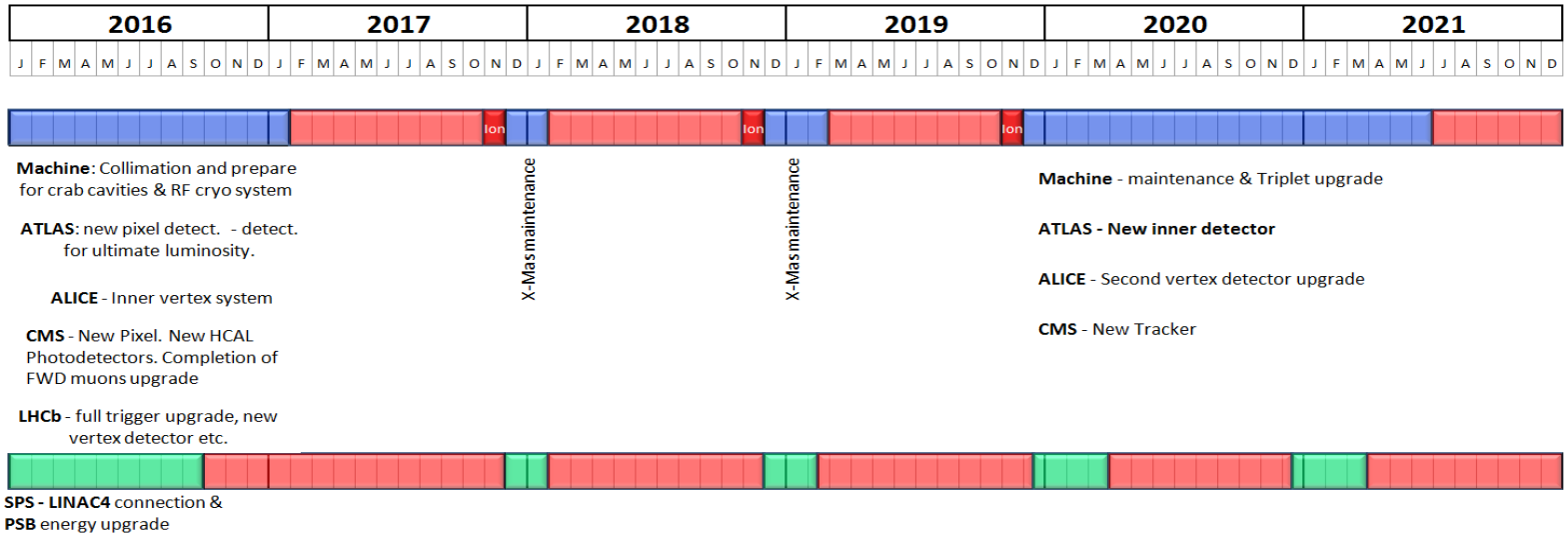
- Running Conditions in 2011 (Chamonix January 2011)
  - Maximum beam energy
  - Bunch spacing
  - Integrated luminosity evaluation (goal set is $1fb^{-1}$)

Summary: What did we learn in 2010

- LHC is magnetically very reproducible on a month to month time scale
- Head on beam-beam limit
- Aperture
- Not a single magnet quench due to beam
- UFOs
- Injection Studies
- Debunched beam
- Electron cloud, vacuum and background
- Machine protection
  - Set up is long
  - Quench levels for fast and slow losses

The 10 year technical Plan





Third Running Period (bunch trains)

Nb	Ib	MJ	Nc	Peak luminosity (design parameters)	Maximum luminosity (measured)	Beam-beam shift from measured Lumi	Date
56	1.10E+11	3.5	47	1.203E+31	2.000E+31	0.0157	23/09/2010
104	1.10E+11	6.5	93	2.381E+31	3.500E+31	0.0139	25/09/2010
152	1.10E+11	9.4	140	3.584E+31	5.000E+31	0.0132	29/09/2010
204	1.10E+11	12.7	186	4.762E+31	7.000E+31	0.0139	04/10/2010
248	1.10E+11	15.4	233	5.965E+31	1.030E+32	0.0164	14/10/2010
312	1.10E+11	19.4	295	7.552E+31	1.500E+32	0.0188	16/10/2010

Still some time to go

Acknowledgements

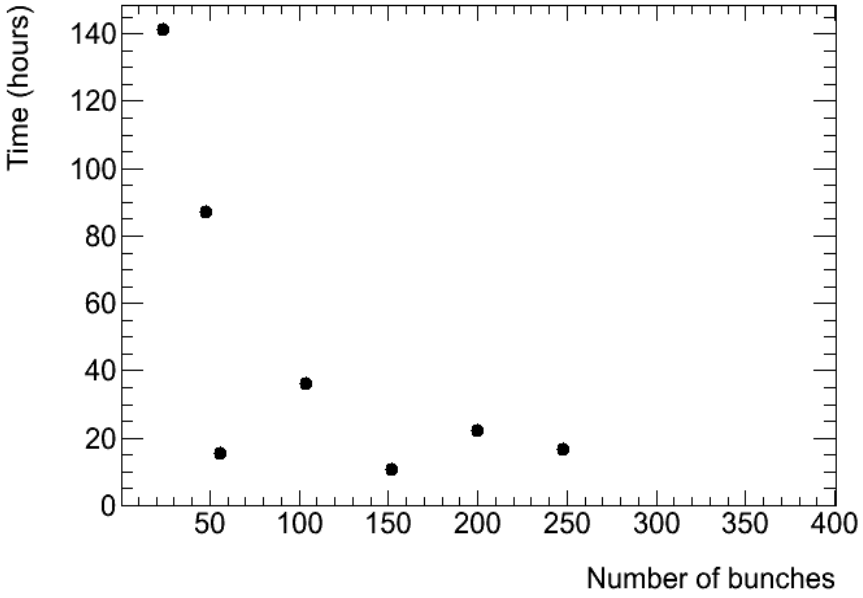
The superb progress and performance of the LHC machine and its injectors is due to the excellence, hard work and dedication of the CERN staff and our collaborators.

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

Thank You

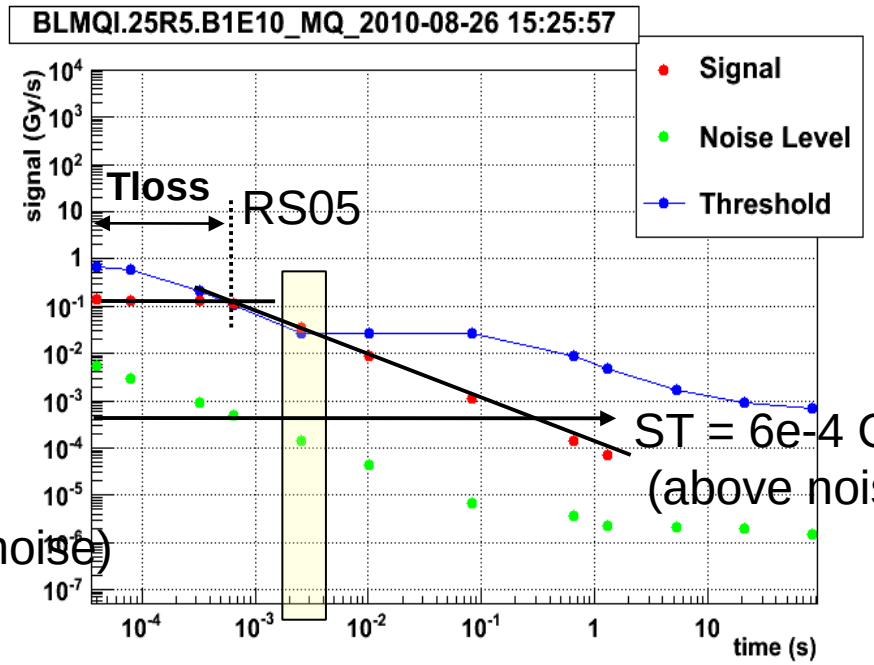
SPARES

SEARCH FOR “UFO”s



Scan in logging database for UFO-like
events. All fills with stable beams from 30/07 until 12/10 included in the analysis.

~330 hours of stable beam

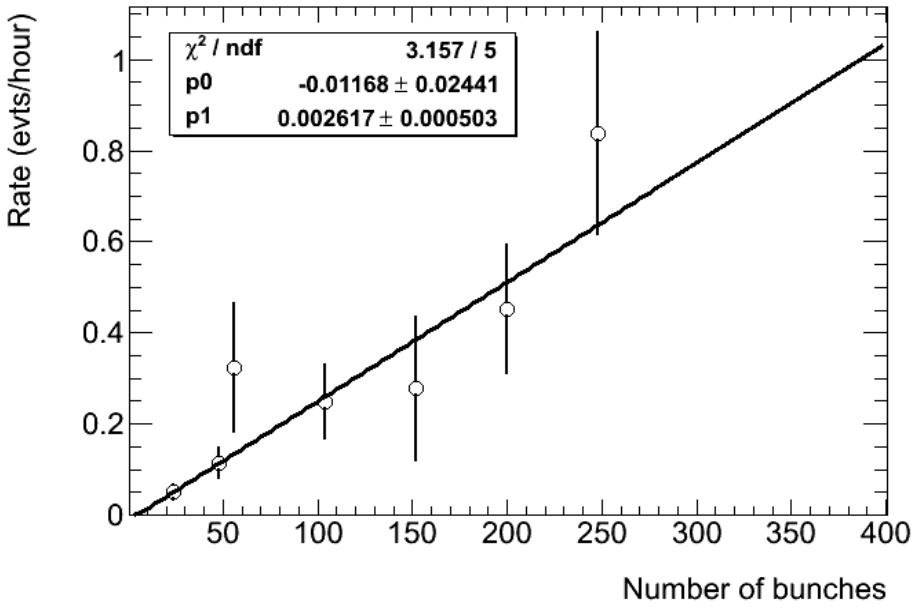


“UFO” losses typically ~1ms.
Duration of the losses estimated from the graphic RS vs time with a ~30% accuracy

Analysis based on RS05:

- Clusters of at least 3 blms within 40 m and signal higher than ST (above noise)
- Signal in TCPs > ST

INTENSITY DEPENDENCE



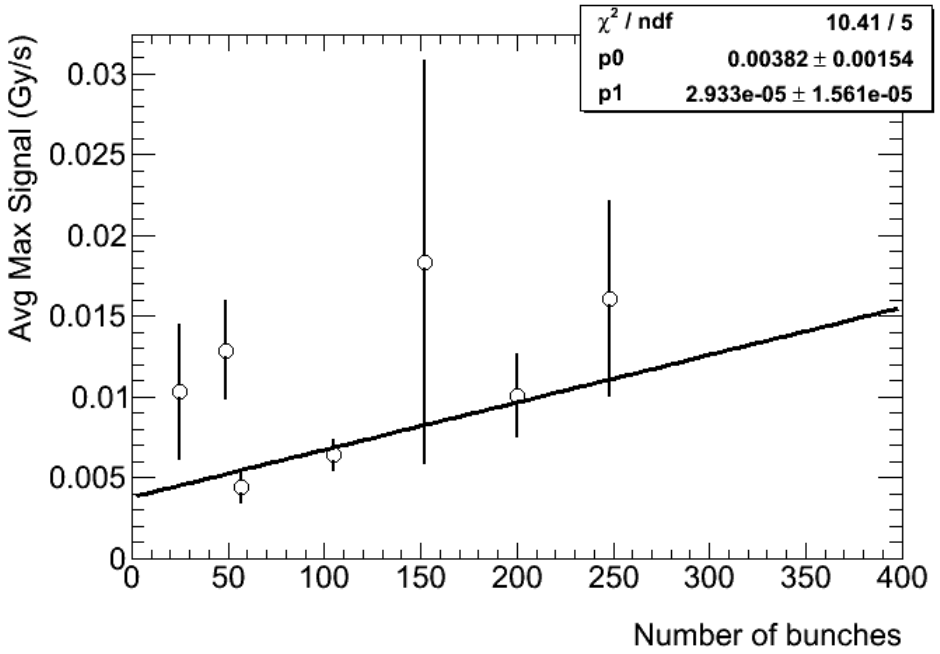
"UFO" Rate

The UFO rate seems to increase linearly with intensity:

Extrapolating

2000 Bunches => ~ 5.2 evts/hour

60% of the events used to produce this graphic were far from threshold (Signal/Threshold < 0.2)



Signal intensity (RS05)

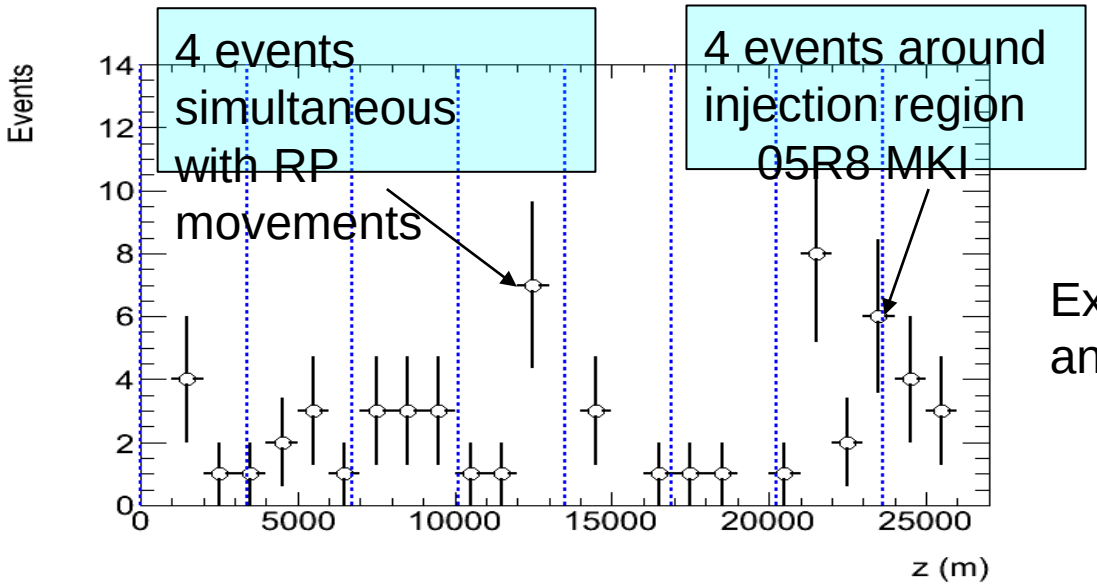
Signal in the BLM at maximum also scales (linearly?) with intensity:

Extrapolating

2000 Bunches => ~ 0.06 Gy/s

Thresholds for cold magnets in RS05 are in the range 0.02-0.08 Gy/s

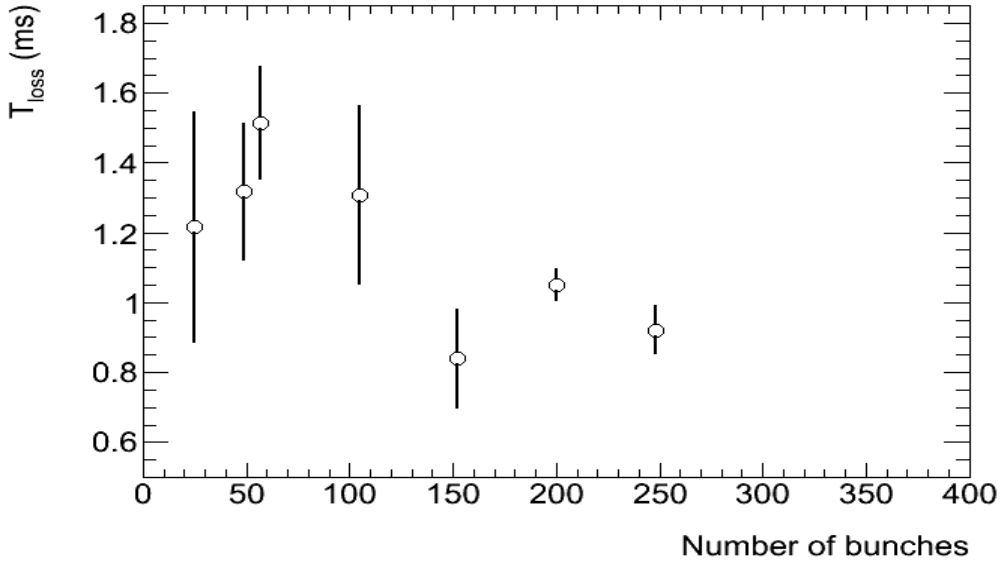
LOSS DURATION AND LOCATION



Location

Map of losses (1km/bin)

Excess of events around IP5 (Rps) and IP8 (injection)



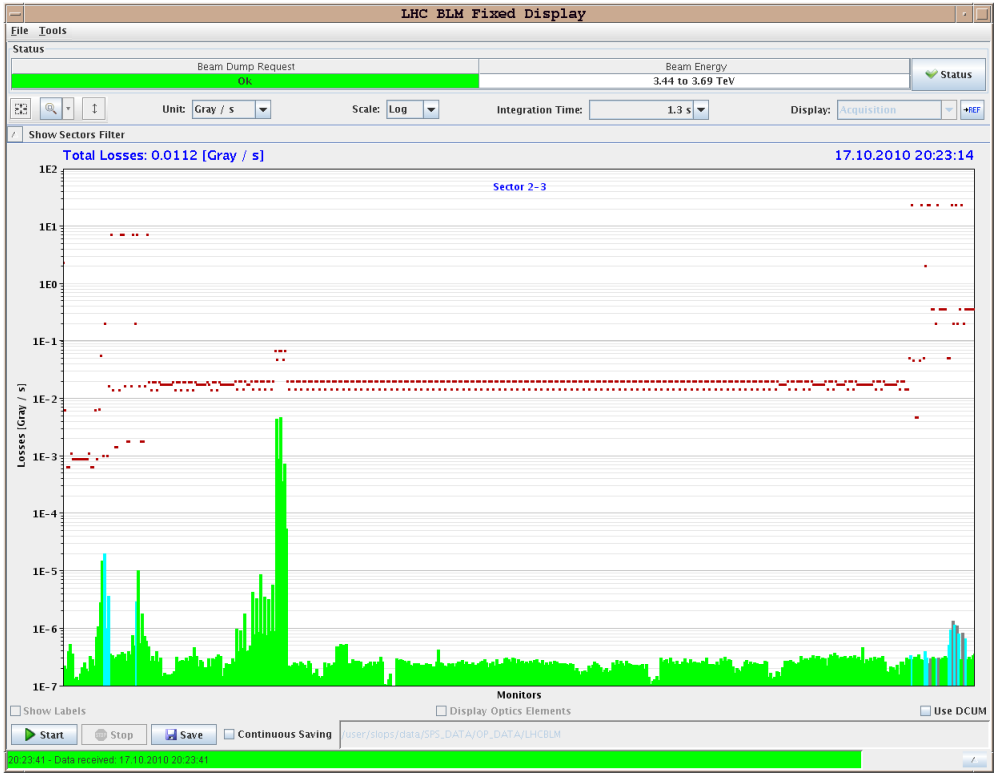
Loss duration

Tendency to decrease as intensity increases:

NB = 24 ----> Tloss =1-3 ms
NB = 248 ----> Tloss = 0.6-2.4 ms

Quench test (17/10)

- Quench test:
  - Beam intensity:
    B1: 2.38x10^{10} p ($\varepsilon_{H/V}$=6/7 μm)
    B2: 2.05x10^{10} p ($\varepsilon_{H/V}$=11/13 μm)
  - bump at MQ14.R2 vertical positive (B2)
  - Total loss ~1x10^{10} p in 7.3 s
  - Losses about a factor 10 below the threshold values (see plot). The thresholds were increased by a factor 3 before test.
  - QPS thresholds exceeded on MQ14.R2



Preliminary conclusion: BLM thresholds should be decreased by a factor 3 (or more) to avoid QPS triggers ➔ to be analyzed in detail

B. Dehning, J. Wenninger et al.

Injection issues - summary

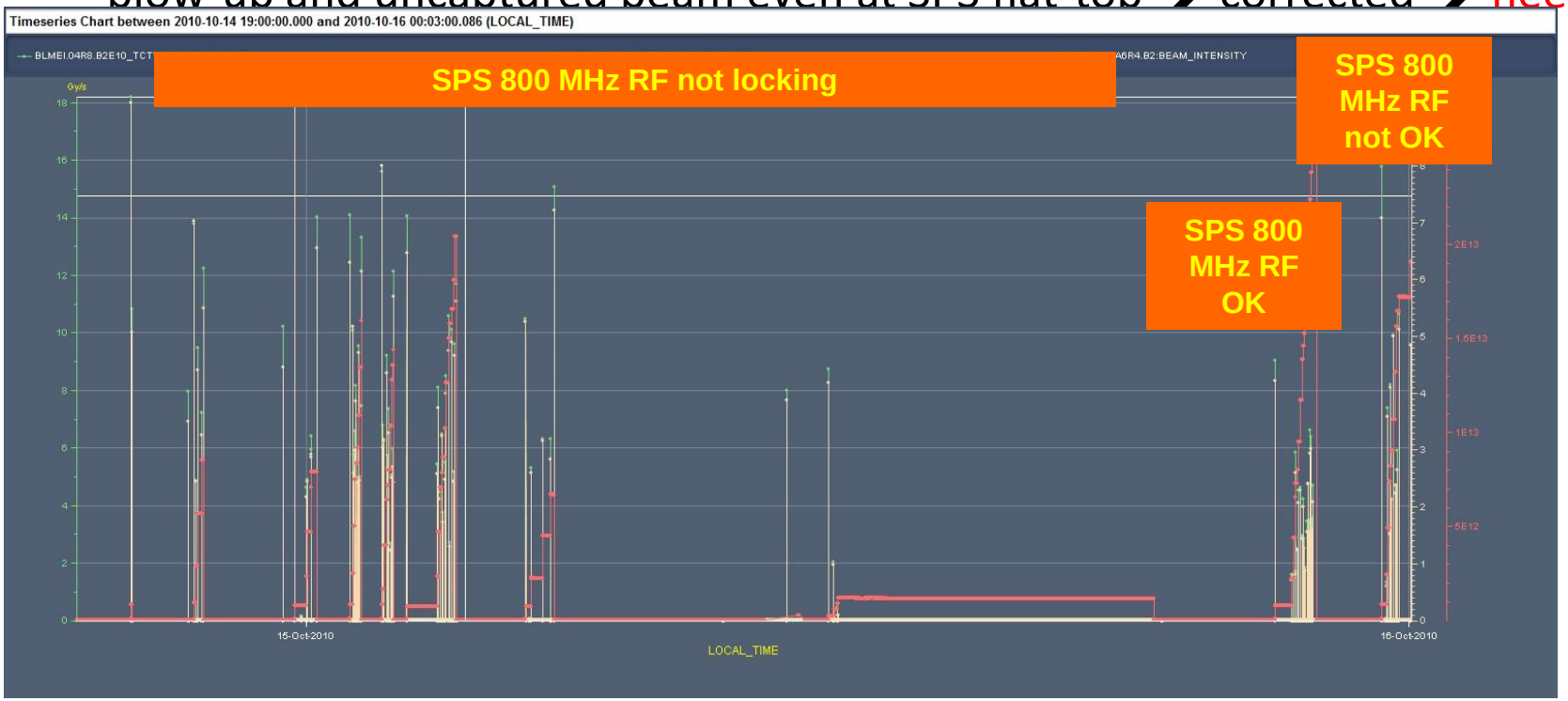
- Un-captured beam from SPS
  - Thursday-Friday night
  - Swept across TDI by injection kick – dumped by LHCb
  - Tracked down to 800 MHz in SPS

- Obstruction in MSI at IP2 leading to losses at B1 injection
  - Deterioration observed in 2 occasions: Fri 08/10 and & Sat 16/10

- Capture losses in LHC
  - Very dependent on longitudinal beam quality from the injection (150 ns is not good in that respect)
  - Very (too?) low tolerances in LHC – general issue with fast losses at 450 GeV – dumping beam after the event

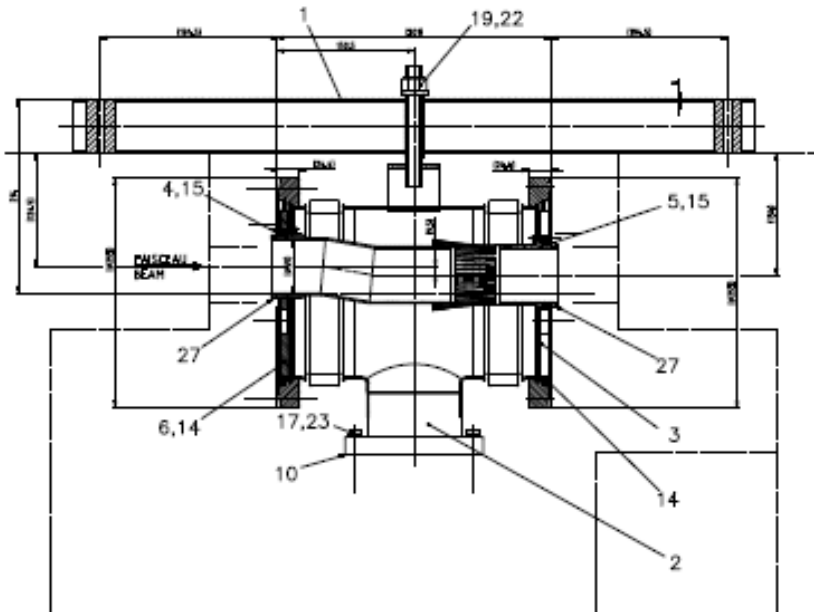
Injection losses Thu-Fri night

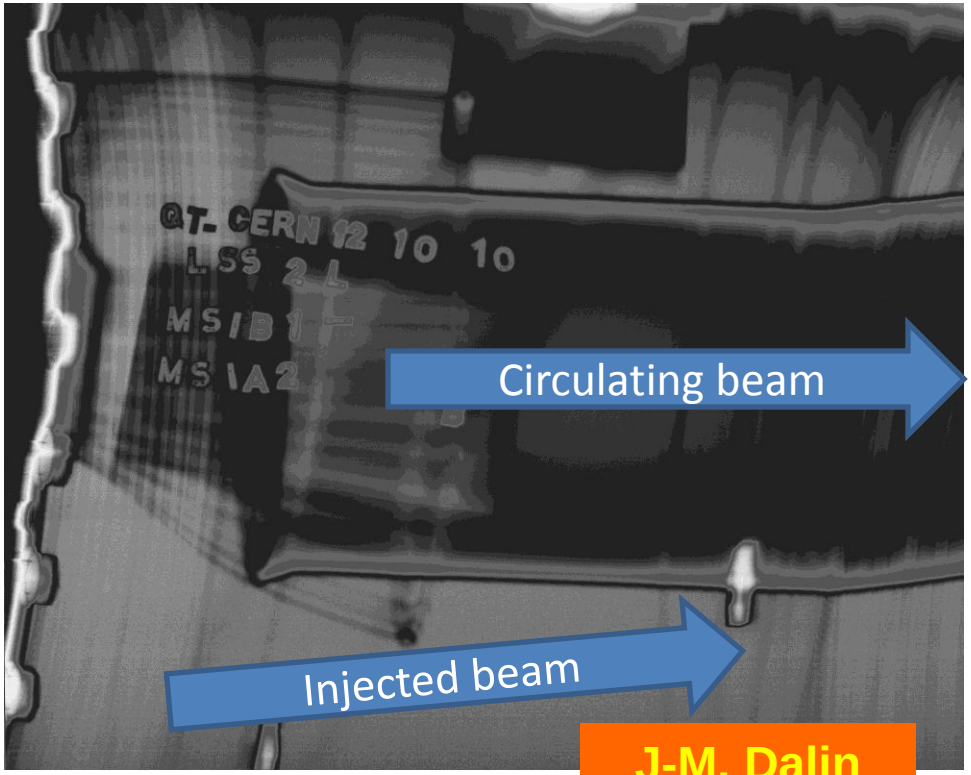
- Thorough verification of the beam quality in the SPS started in the night and continued during the morning (T. Bohl): found 800 MHz RF frequently not locking to reference (given by main RF system) ➔ source of noise, blow-up and uncaptured beam even at SPS flat-top ➔ corrected ➔ need



Injection losses B1

- Radiation survey and X-ray (Tue 12/10) have evidenced a clear aperture restriction at the transition between the injection septa MSIB/MSIA due to a non-conformity in the mounting of the interconnection

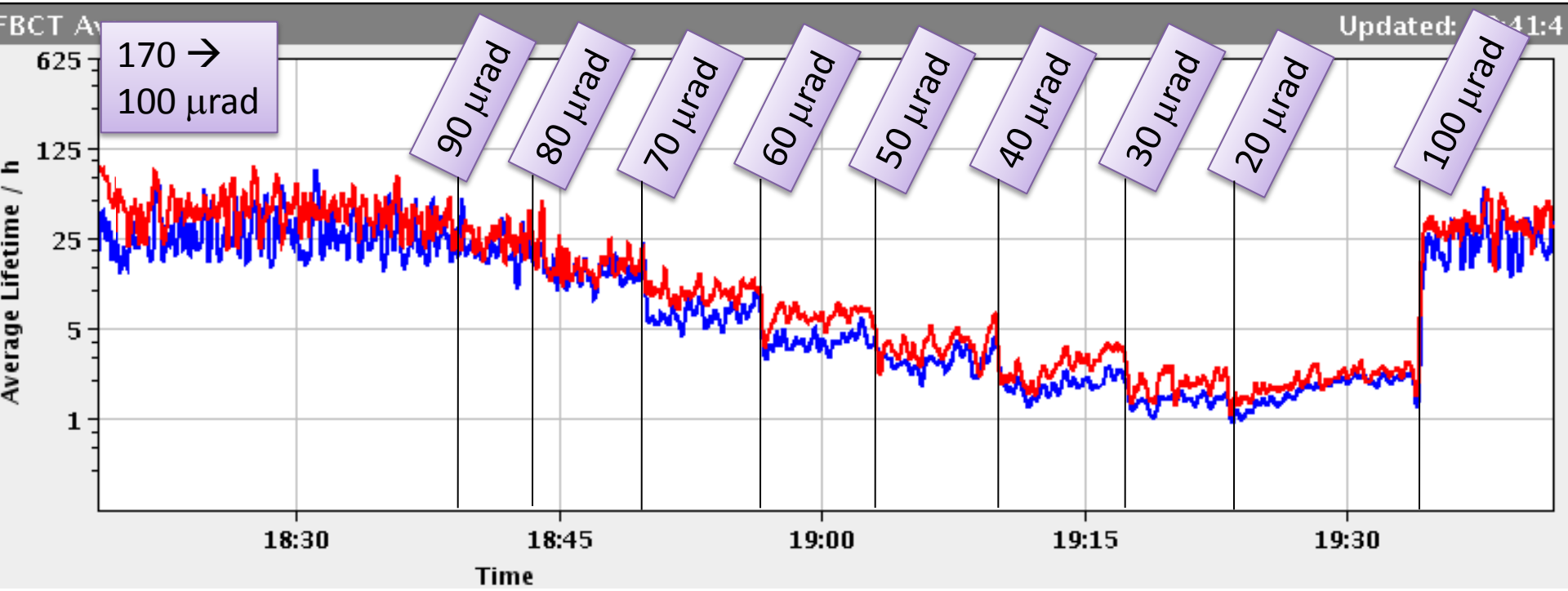




SPARES 2

Lifetime when Reducing Crossing Angle

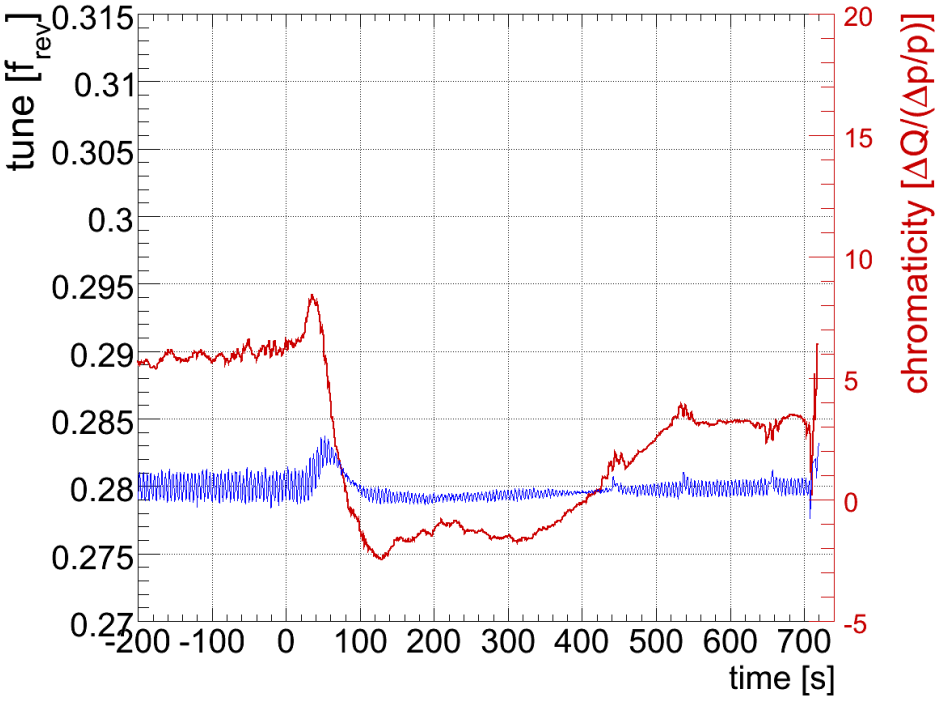
3 batches of 8 bunches each, spacing 150 ns → up to 6 LR interactions per bunch



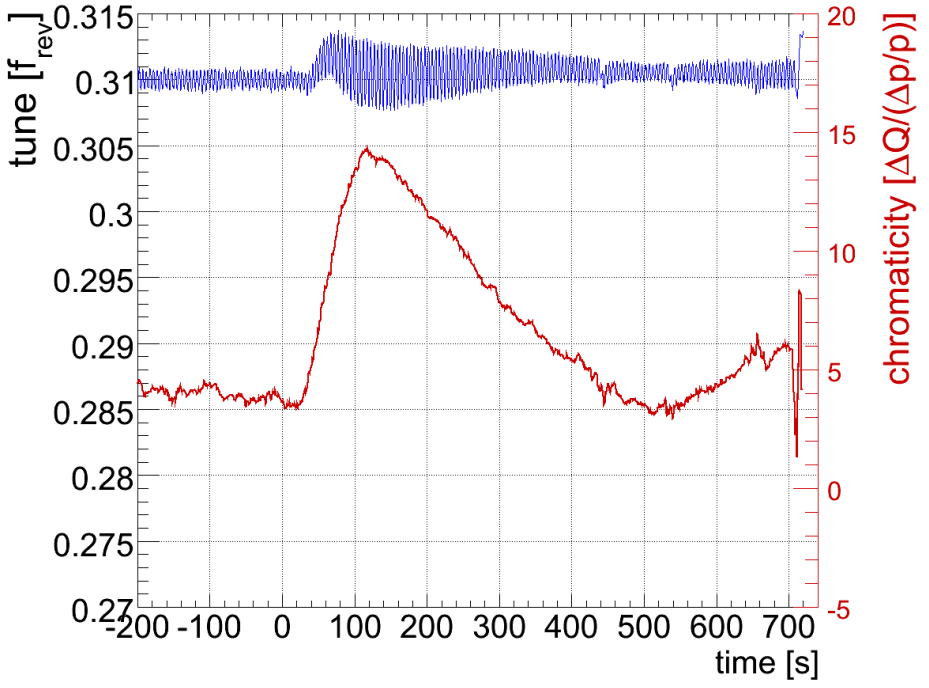
Conclusion: **Minimum required crossing angle is 100 µrad in 2010.**

Test ramp at 10 A/s

Orbits, Tunes and Chromaticities measured and automatically corrected during the ramp and stored and fed forward for next ramp



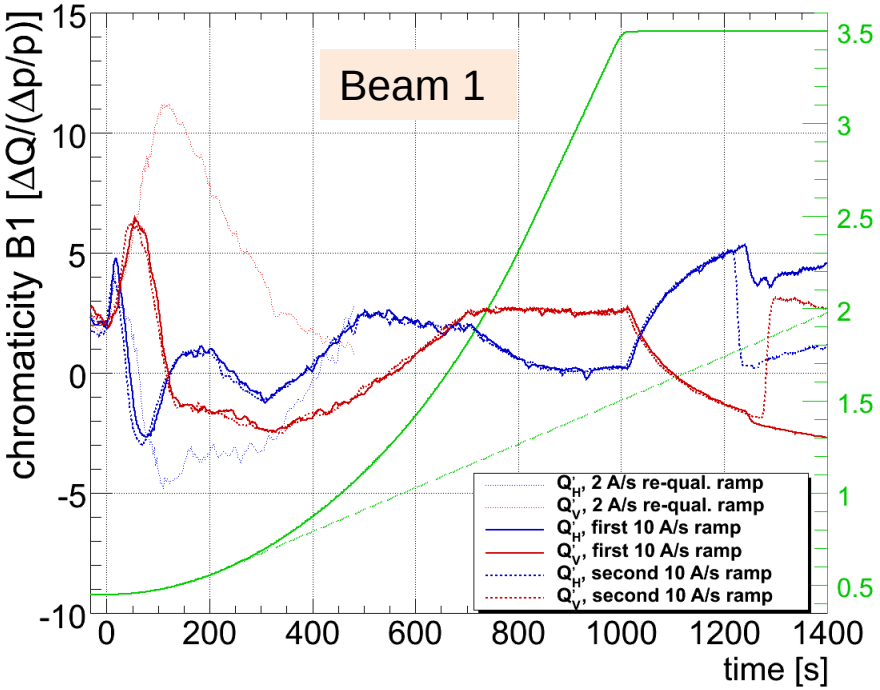
B1 horizontal

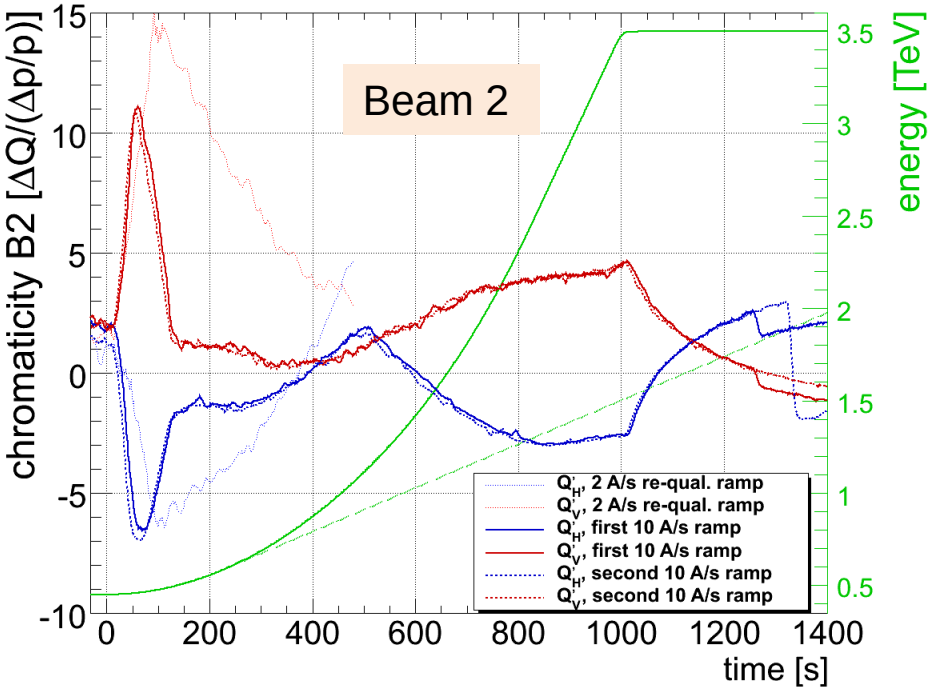


B1 vertical

Ramp with 10 A/s

- Chromaticity during the ramp reproducible

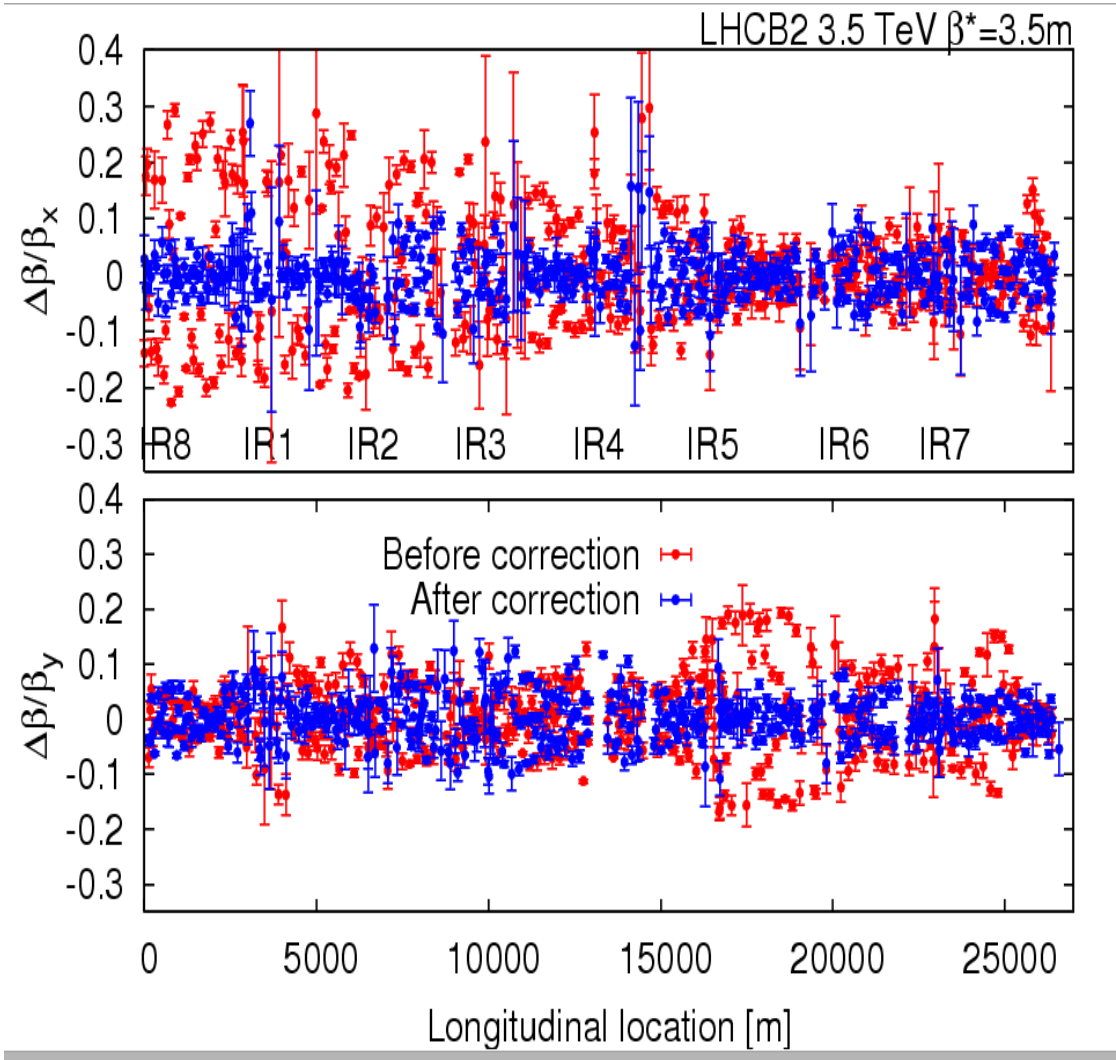




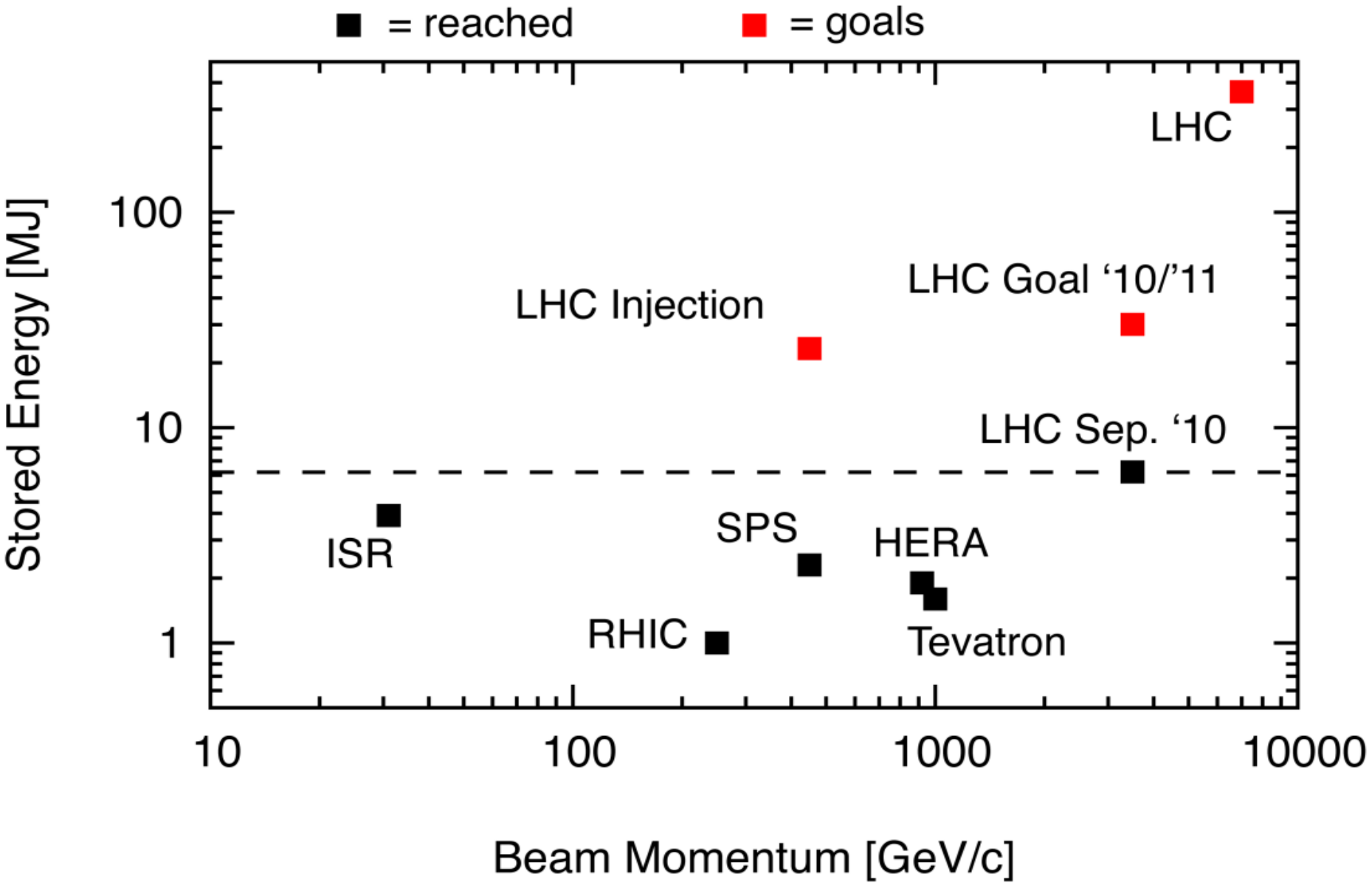
Correction of Beta beating (Wednesday 8th Sep)

- Squeeze B2
- Brief optics studies on B2
  - Global correction
  - 100 quads !
  - Impressive results !

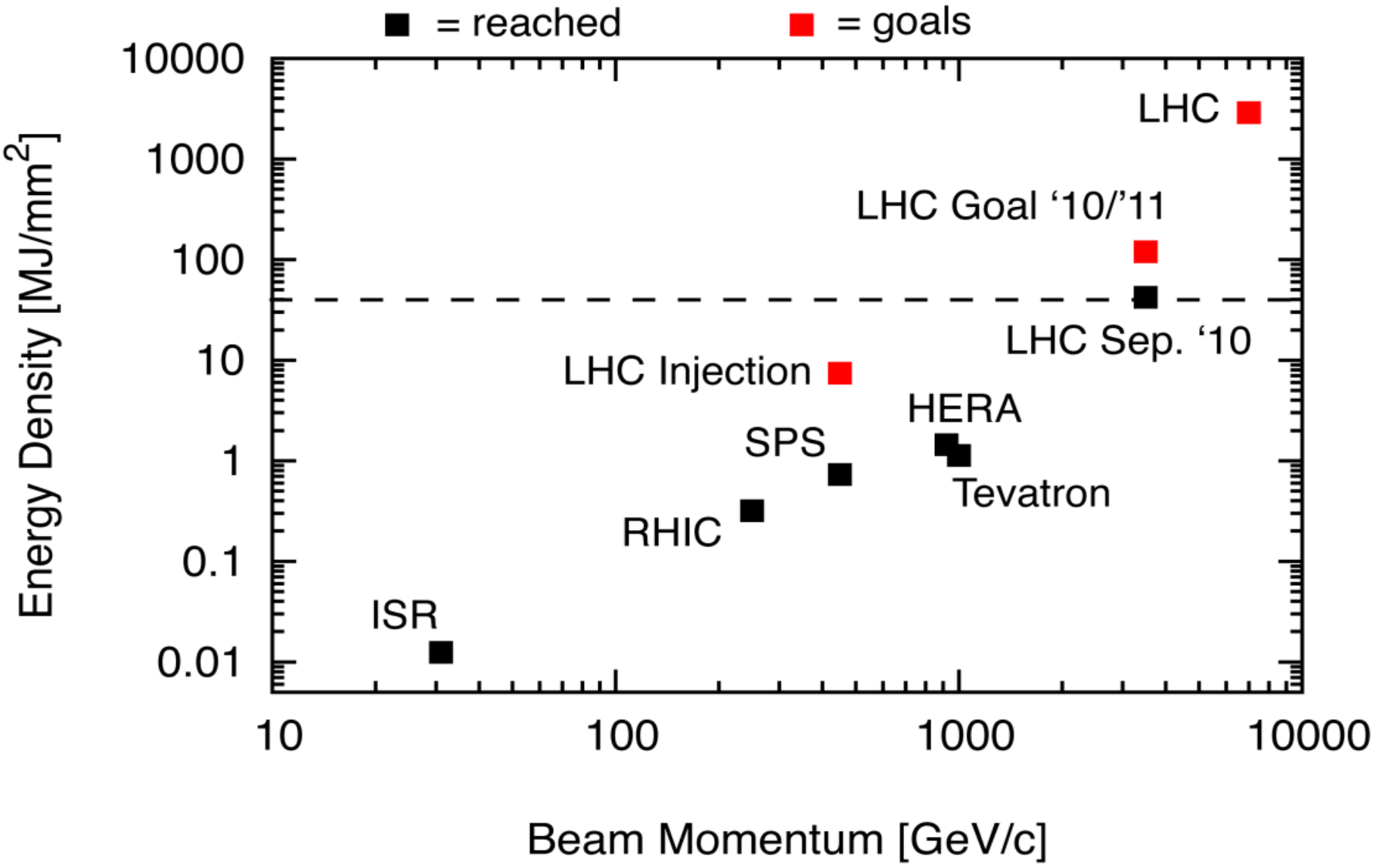
IP1	**3.22 0.22**	**3.62 0.40**
IP2	**3.83 0.61**	**3.43 0.26**
IP5	**3.67 0.07**	**3.28 0.25**
IP8	**3.26 0.10**	**3.51 0.09**



Stored Beam Energy



Energy Density in Beams

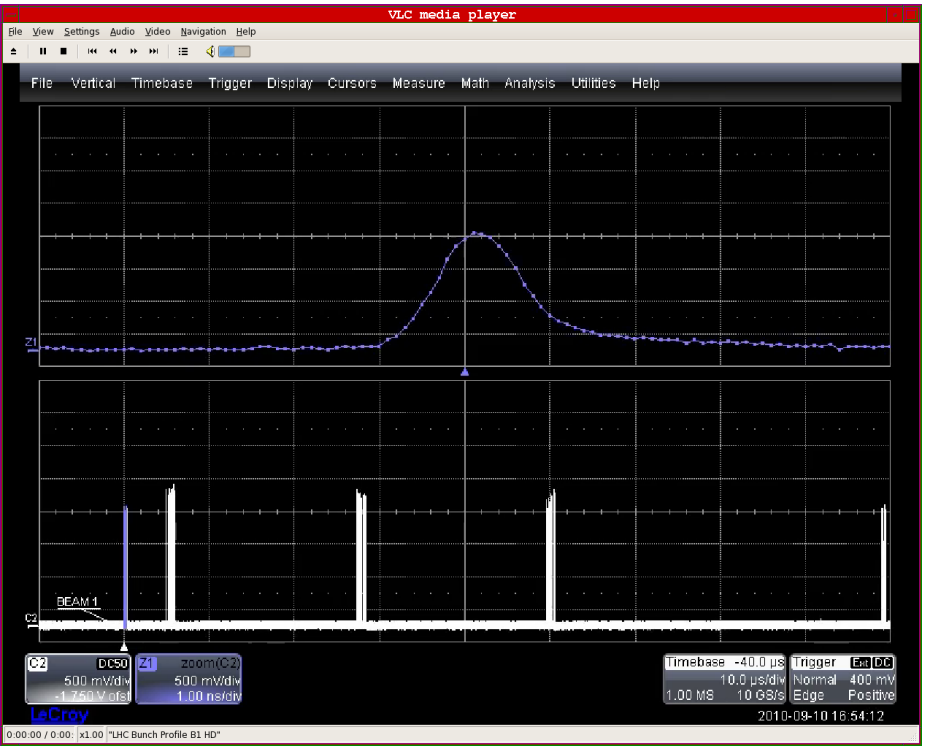


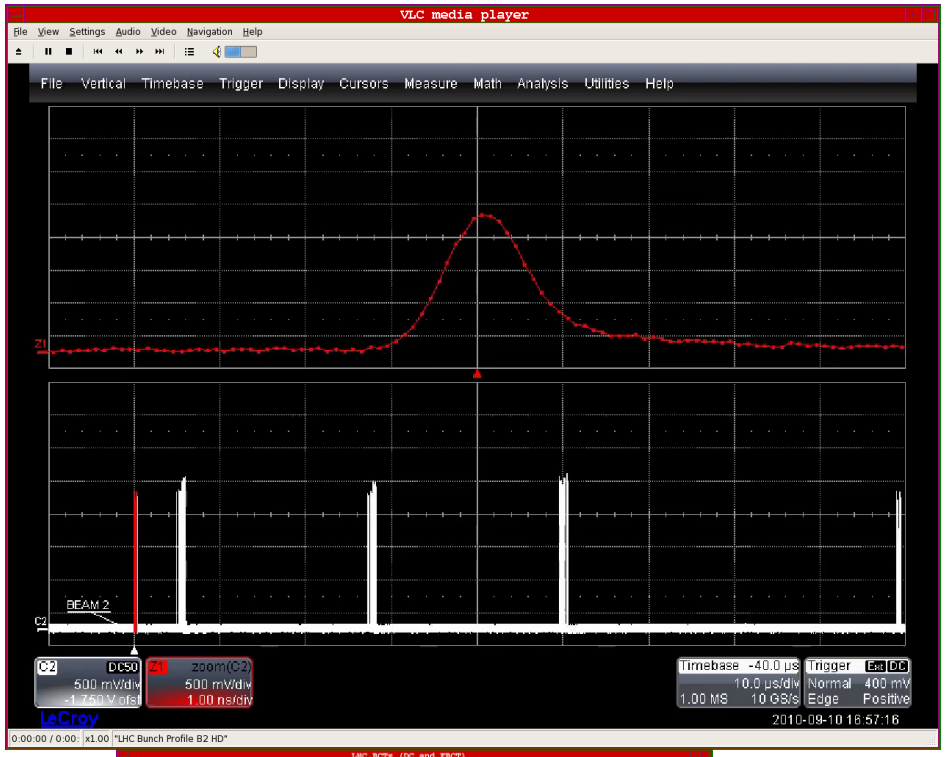
Update on UFOs (fast BLM event in SC regions)

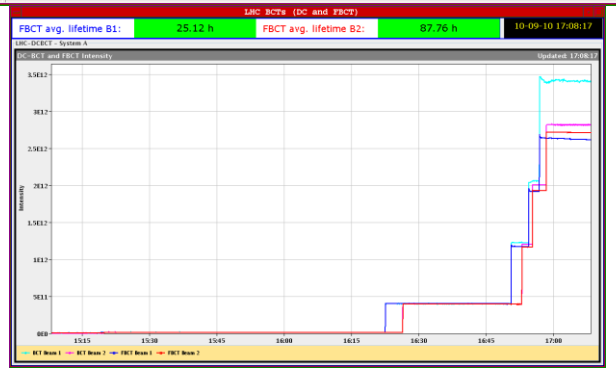
- 7 beam dumps due to fast (~ ms scale) losses in SC regions, triggered by the BLMs
- Search for similar events, but that did not trigger a beam dump, using the data logged in TIMBER.
  - The analysis was concentrated on the period with 24 and 48 bunches.

Friday 10.9

- 17.00 Inject 1 train of 4, then 3 trains of 8, both beams







Crossing angles

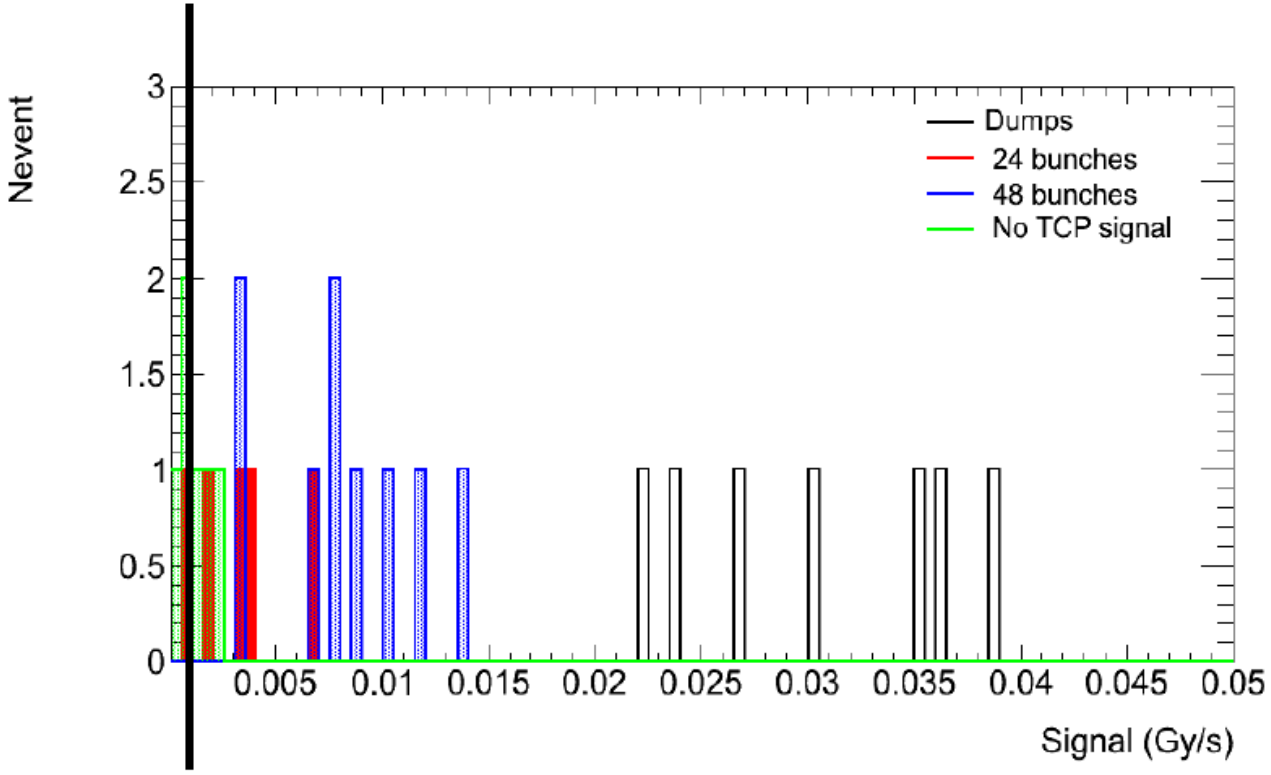
- External crossing angles
  - IR1: -170 μrad at inj./ramp and -100 μrad in squeeze/collision
  - IR2: +170 μrad at inj./ramp and +110 μrad squeeze+collision
  - IR5: +170 μrad at inj./ramp and +100 μrad in squeeze/collision
  - IR8: -170 μrad at inj./ramp and -100 μrad in squeeze/collision

- Good for beam-beam (do we need it for 150ns ?)
- Bad for aperture and MP (are we ready to do this ?)

- Strategy
  - Start with nominal angles at injection
  - Measure IR apertures
  - Test parasitic beam-beam with lower angles
  - Decide based on this

Sub-threshold UFOs

- Total of 228.6 hours of stable beam have been analyzed:
  - 141.3 hours (24 bunches) ==> 0.0566 evts/hour
  - 87.3 hours (48 bunches) ==> 0.1260 evts/hour



Distribution along the ring