LHC Status and Introduction to the HL-LHC

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LHC Timeline 1/3 2008

- 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.
  - However: uncertainties about the splice quality
  - Risk of thermal runaway scenarios

    ➔ decision to limit beam energy to 3.5 TeV for first operation

LHC Timeline 2/3 2009

- 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 seen before beam lost!
- December 14th 2009
  - Stable 2x2 at 1.18 TeV
  - Collisions in all four experiments with 'safe beams' (≈ 10^{10} ppb)

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

Commissioning – Strategy

- Main goal for LHC run in 2010 & 2011: integrated luminosity of 1 fb^{-1}
  - ➔ implies flat out operation with 100 pb^{-1} per month in 2011
  - ➔ implies routine operation with $L > 10^{32}$ cm^{-2} sec^{-1} in 2011!
- Main goal for 2010: Commissioning of peak luminosity of 10^{32} cm^{-2} sec^{-1}
  - ➔ not achievable with 2 10^{10} bunch intensity
  - ➔ requires ca. 800 bunches with $N_b > 8\ 10^{10}$ ppb and $\beta^* = 3.5$m

    or ca. 400 bunches with $N_b > 8\ 10^{10}$ ppb and $\beta^* = 2$m
  - ➔ implies operation with stored beam energies above 30 MJ

    compared to operation with ca. 2 MJ in Tevatron and

    operations with 13 bunches of 2 10^{10} ➔ 170 kJ

Commissioning in 2010

- Four running periods:

  1)Single bunches with low bunch intensities

  2)Single bunches with nominal bunch intensities

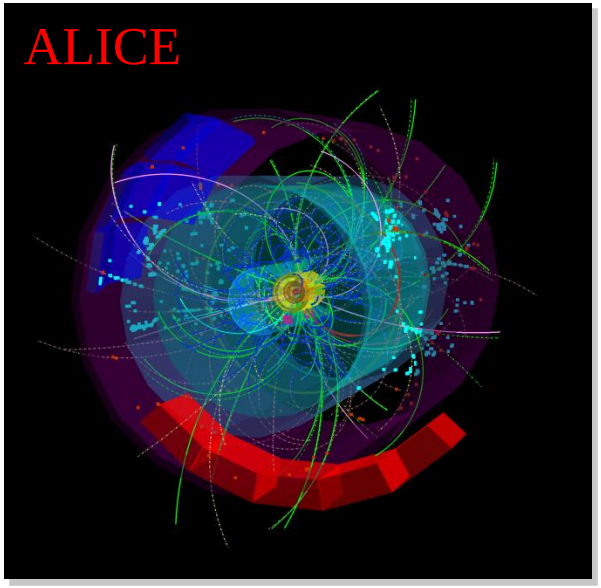
  3)Bunch trains (150ns) with nominal bunch intensities

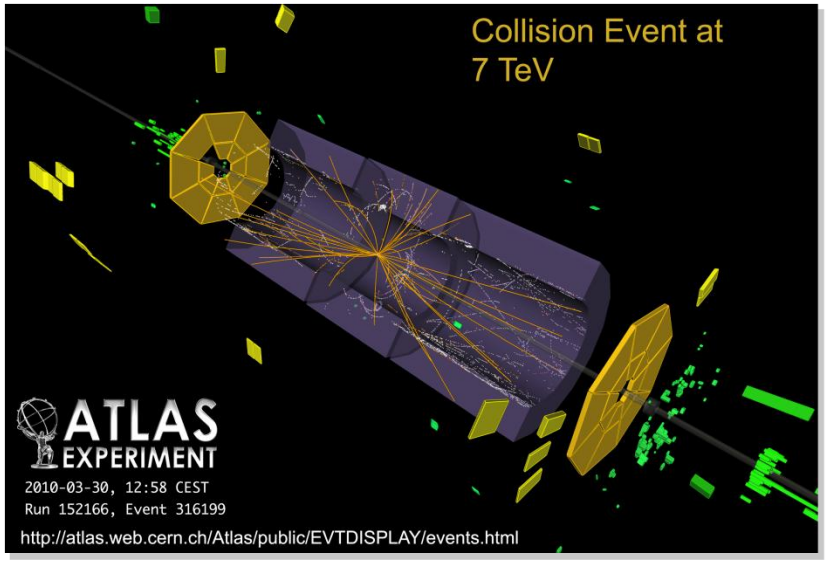
  4)Bunch trains with 50 ns bunch spacing

LHC Timeline 3/3 2010

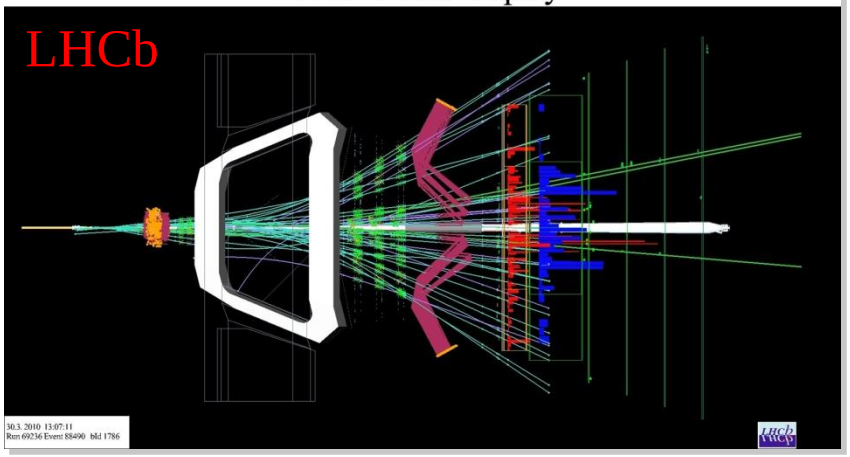
27th Feb	First injection
28th Feb	Both beams circulating
5th March	Canonical two beam operation: L ~ 10^{27} cm^{-2} sec^{-1}
8th March	Collimation setup at 450 GeV
12th March	Ramp to 1.18 TeV
15th - 18th March	Technical stop – bends good for 6 kA
19th March	Ramp to 3.5 TeV
30th March	3.5 TeV collision under ‘stable’ beam conditions

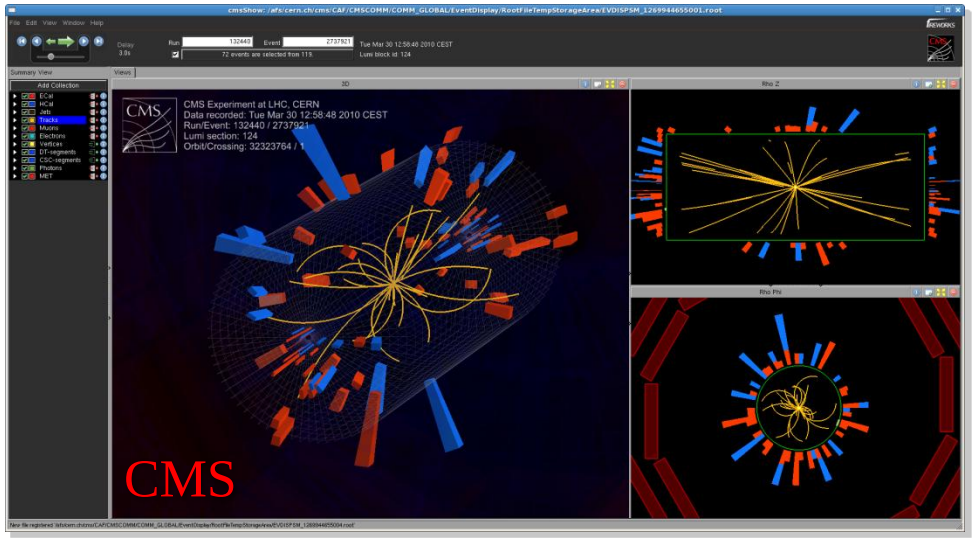
LHC: First collisions at 7 TeV on 30 March 2010





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) it was decided to change the mode of operation to high bunch intensities

Intensity ramp up for nominal bunch OP

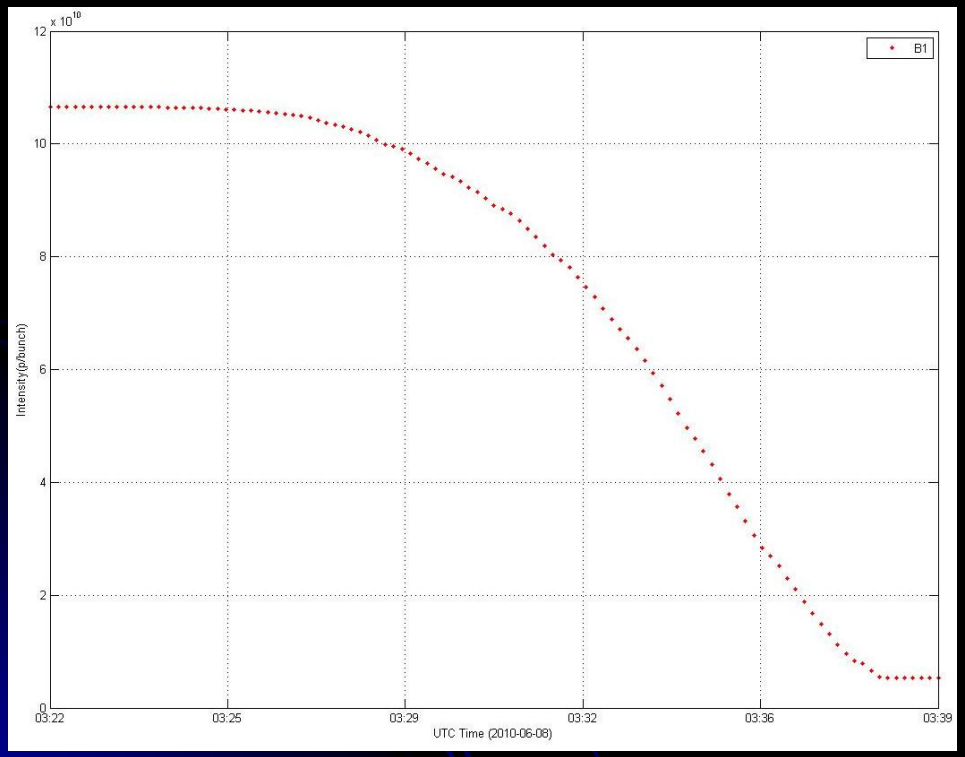
- Intensity ramp up:
  - Start with 3 x 3

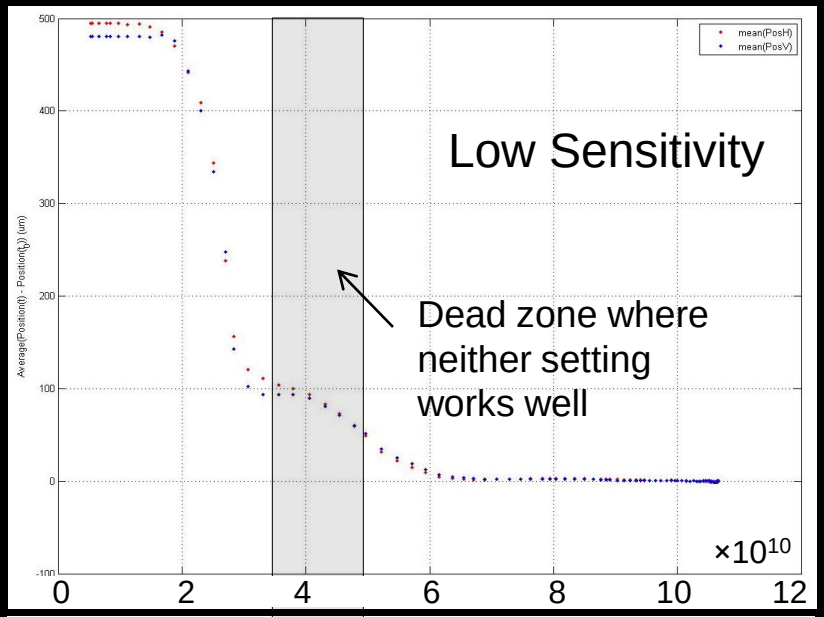
    ➔ $L \approx 5\ 10^{29}\ cm^{-2}\ sec^{-1}$
  - Move on to 6 x 6, 8 x8, 12 x 12, 24 x 24 (1.5 MJ) over 4 weeks until end of July ➔ $L \approx 4\ 10^{30}\ cm^{-2}\ sec^{-1}$
  - Plan for a stable running period in August under constant conditions.
  - Constant β^* and Xing angle.
  - Experience with machine reproducibility:

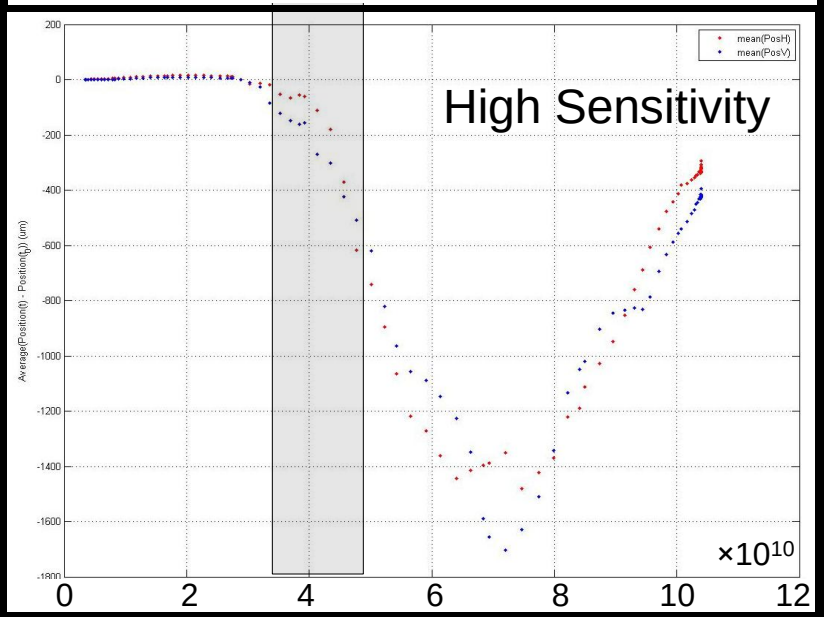
    ➔ orbit, collimation setup, etc.

1) BPM Dependence on Intensity - Beam 1

- One nominal bunch of 1×10^{11} slowly scraped away using a primary collimator
  - 2 fills – one for low sensitivity and one for high sensitivity

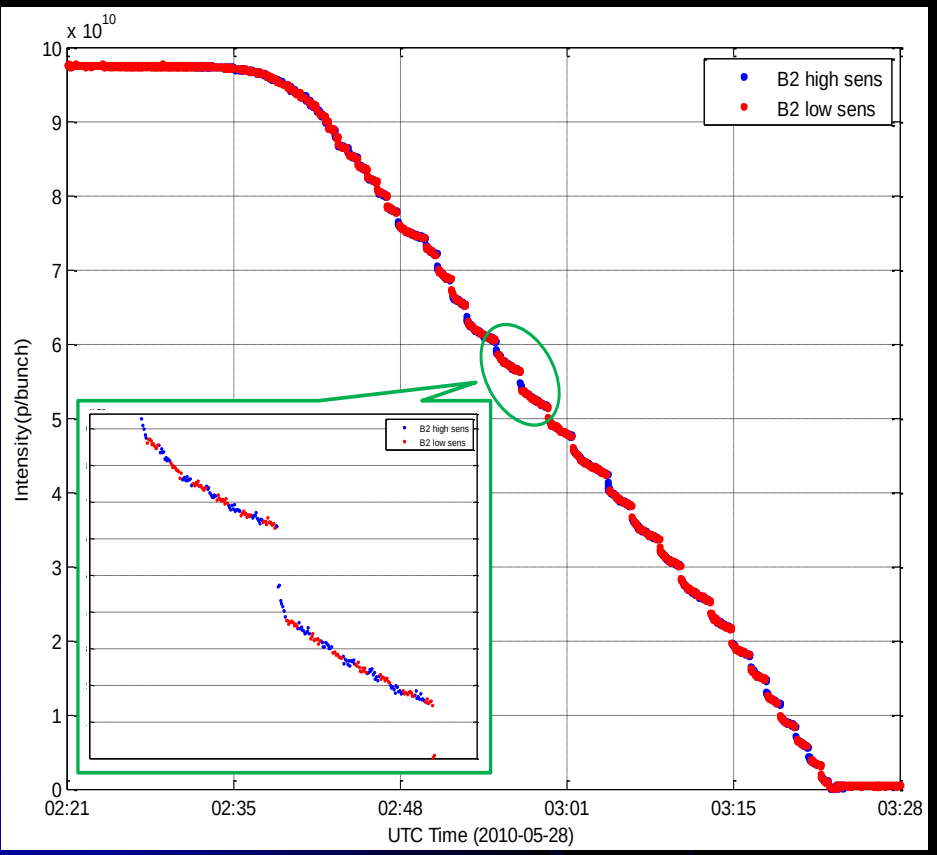


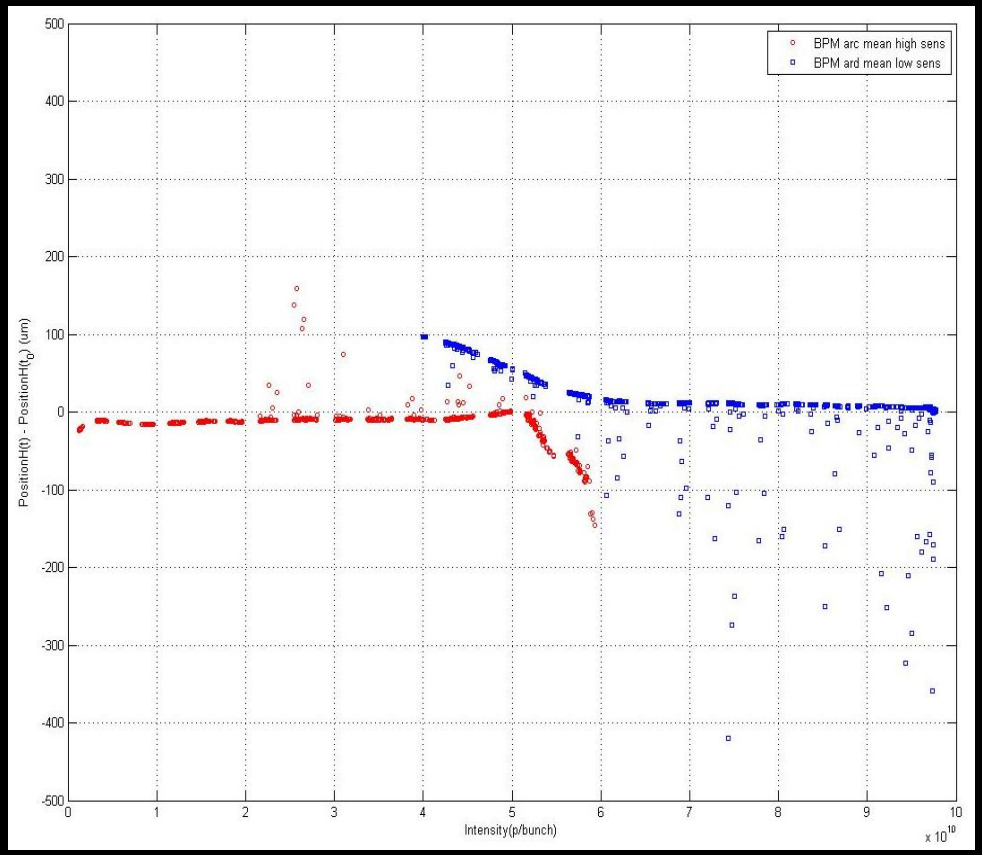




1) BPM Dependence on Intensity - Beam 2

- One nominal bunch of 1×10^{11} slowly scraped away using a primary collimator
- Sensitivity constantly changed from high to low
  - Outliers due to acquisition overlapping two sensitivity ranges
- Sensitivity ranges seen to overlap as expected at around 5×10^{10}



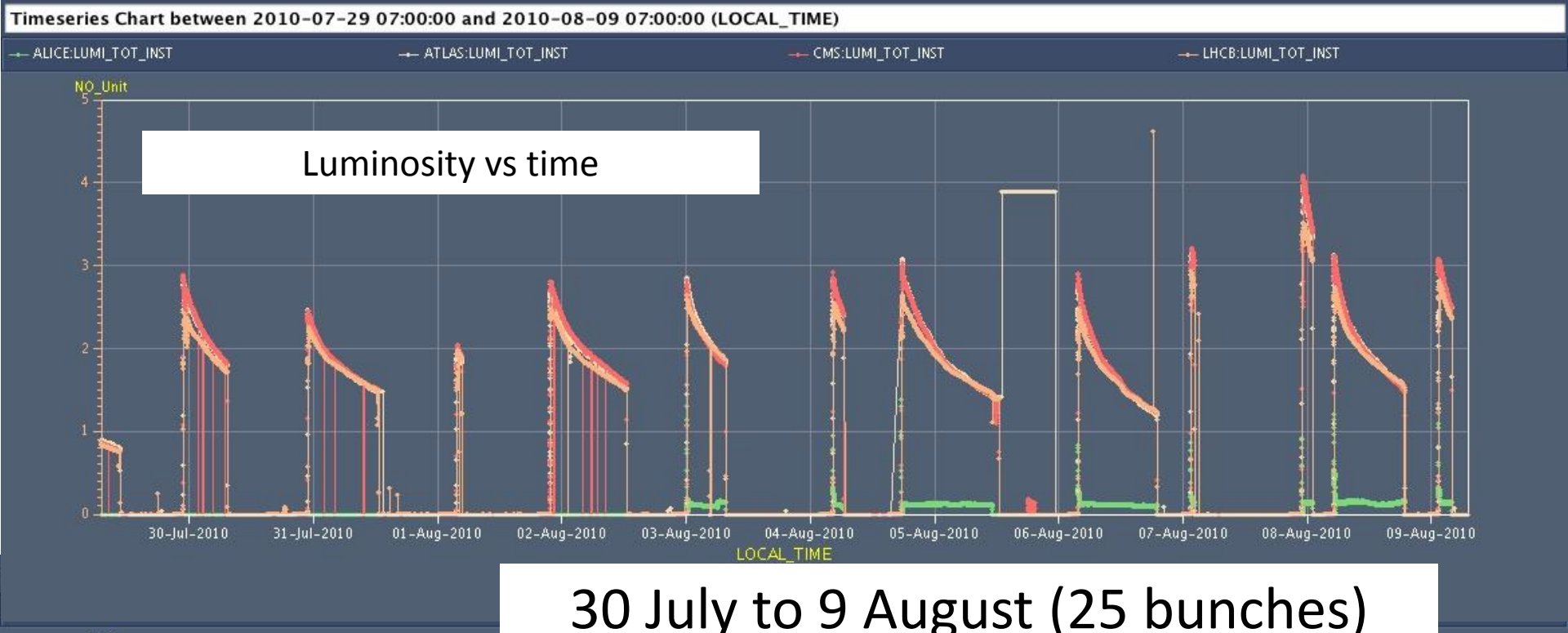


Second Running Period (High bunch Intensity

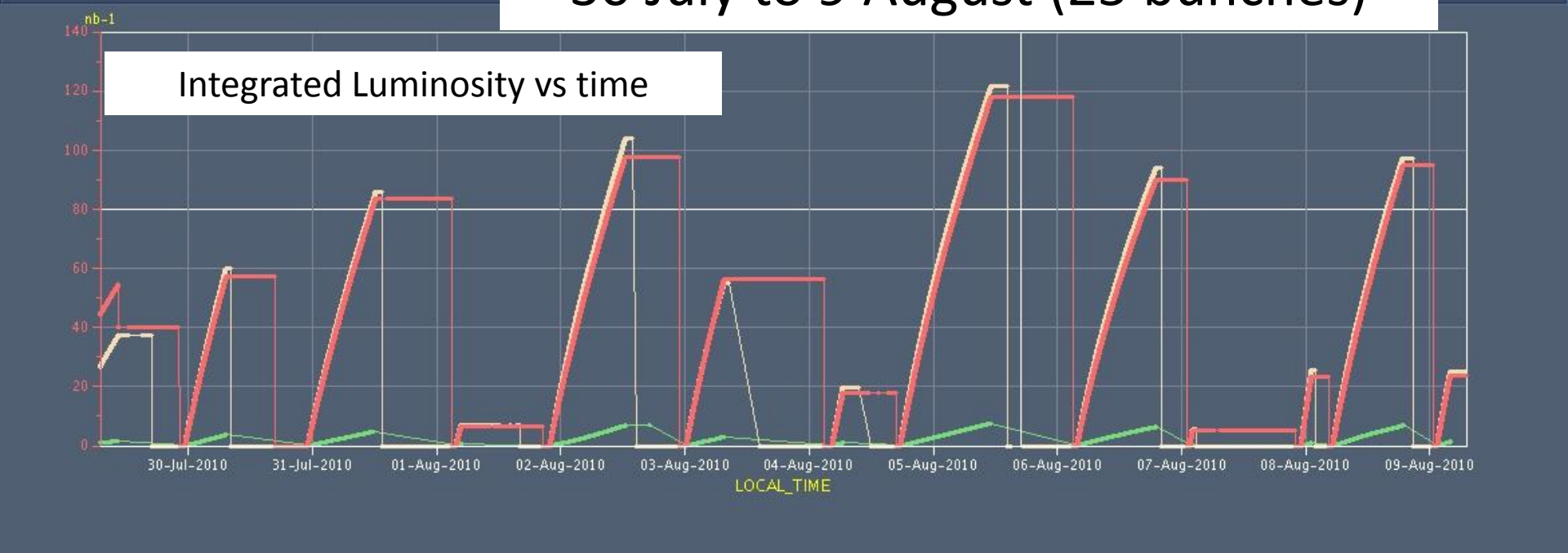
calculated

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

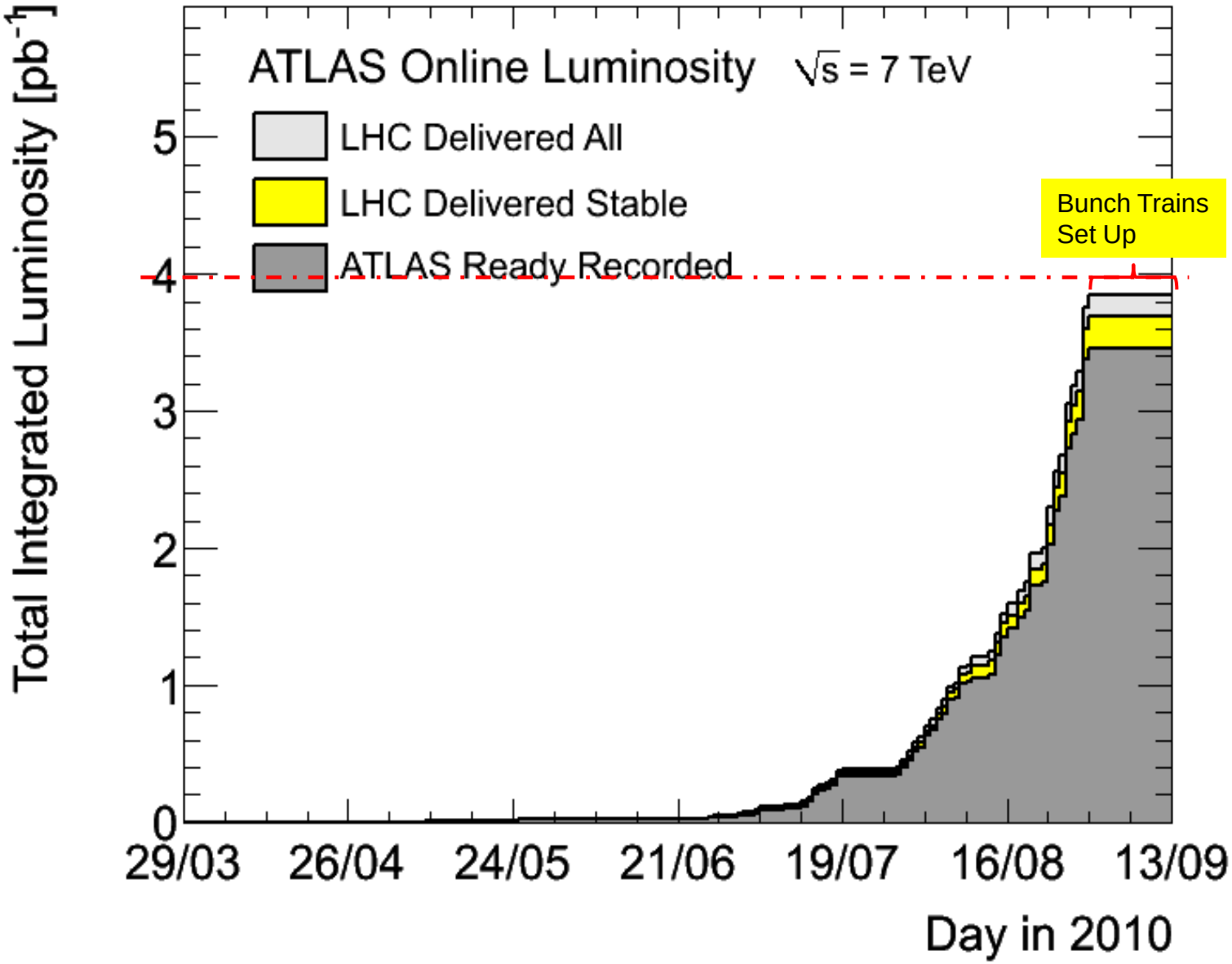
Maximum reached is 10.7×10^{30} $cm^{-2}s^{-1}$



30 July to 9 August (25 bunches)



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



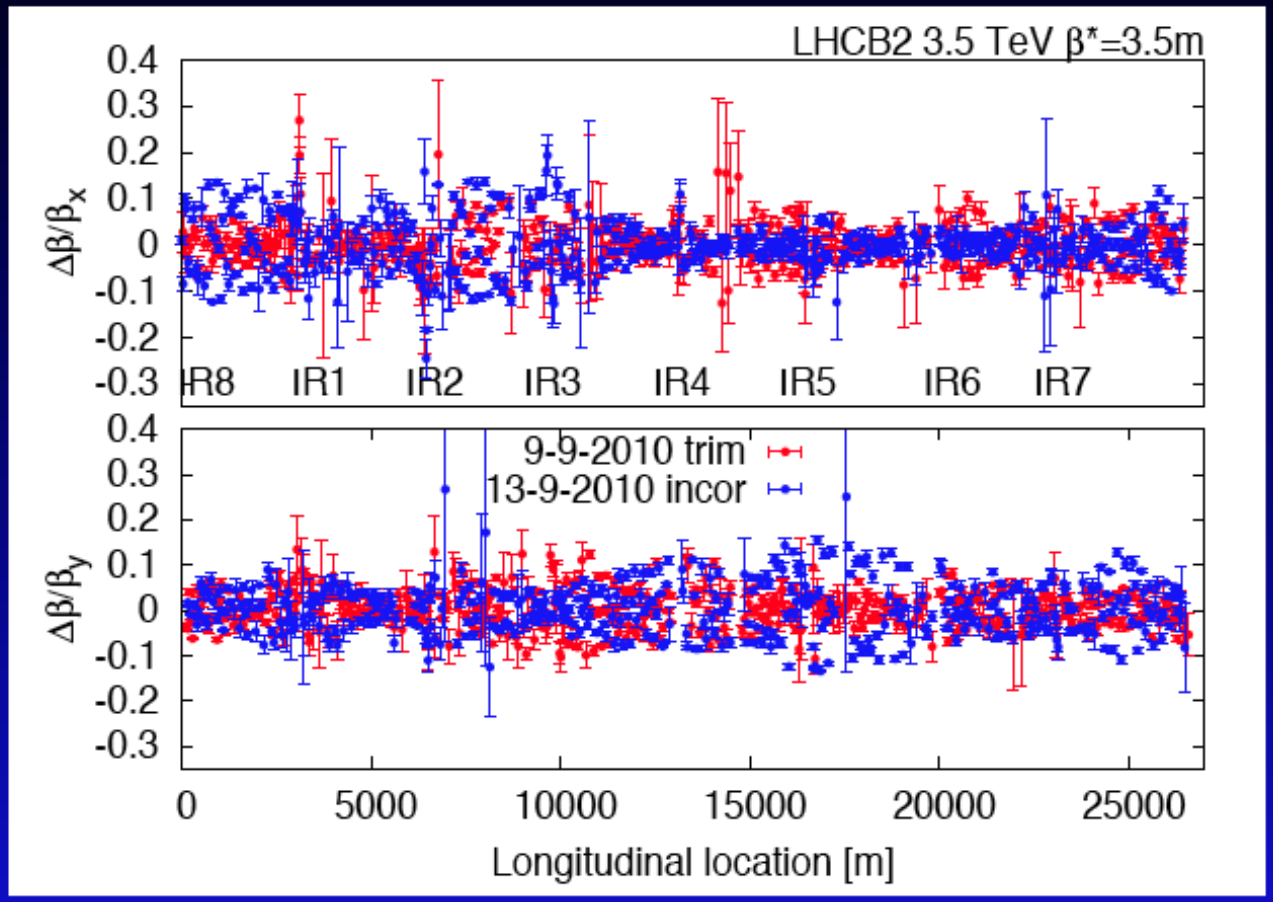
Measured 450 GeV Aperture

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
- Mechanical tolerances, closed orbit and beta-beat better than specified

Optics

Global correction (incorporated), Beam 2



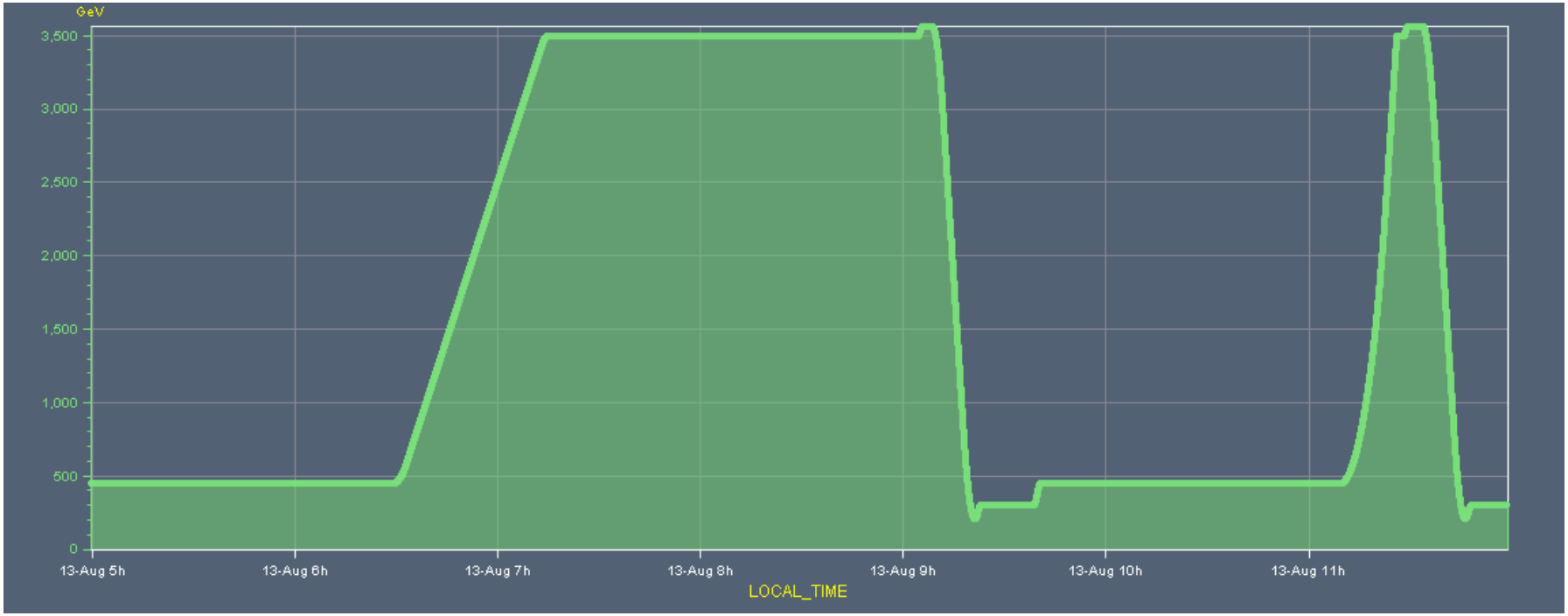
indeed ≈15%.

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

LMC 18th August.

- Parameters and Conditions
  - Nominal bunch intensity 1.1 10^{11}
  - smaller than nominal emittances: 2.5μm ←→ 3μm (3.75μm)
  - Stick to β* = 3.5 m in all IPs with 175 μrad crossing angle
  - Commission bunch trains
    - New setup for injection process (crossing angle)
    - Complete re-do of the whole machine protection set-up
  - Go to 150 ns bunch spacing
  - Commission faster ramp (10 A/s)

Test ramp 10 A/s



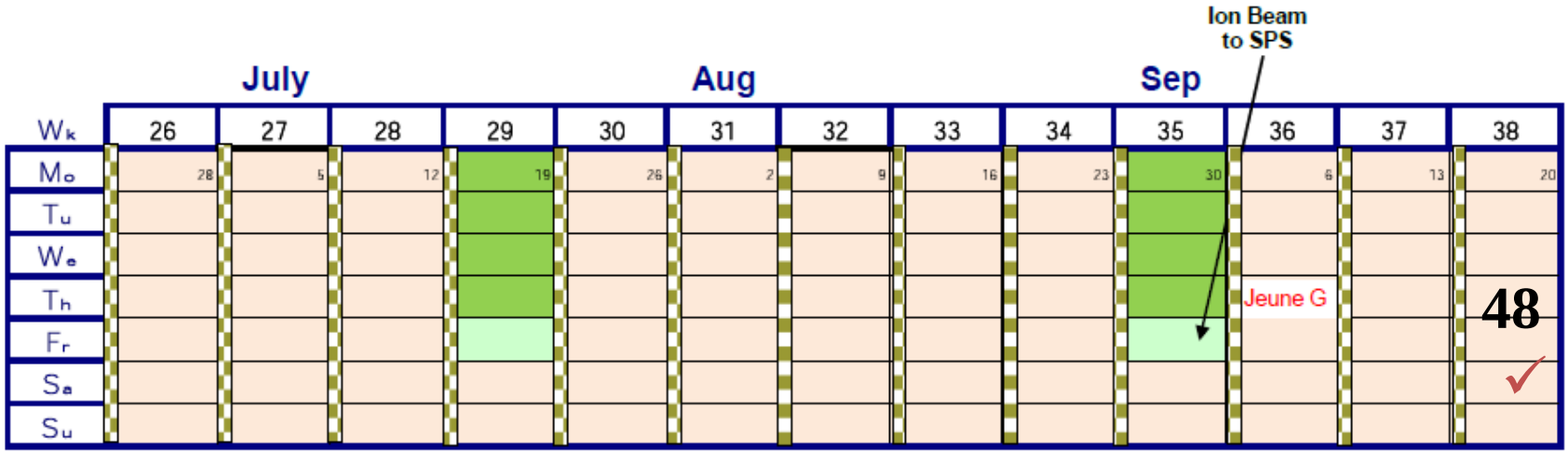
1st attempt reached 1.7TeV
2nd attempt perfect ramp up to 3.5TeV

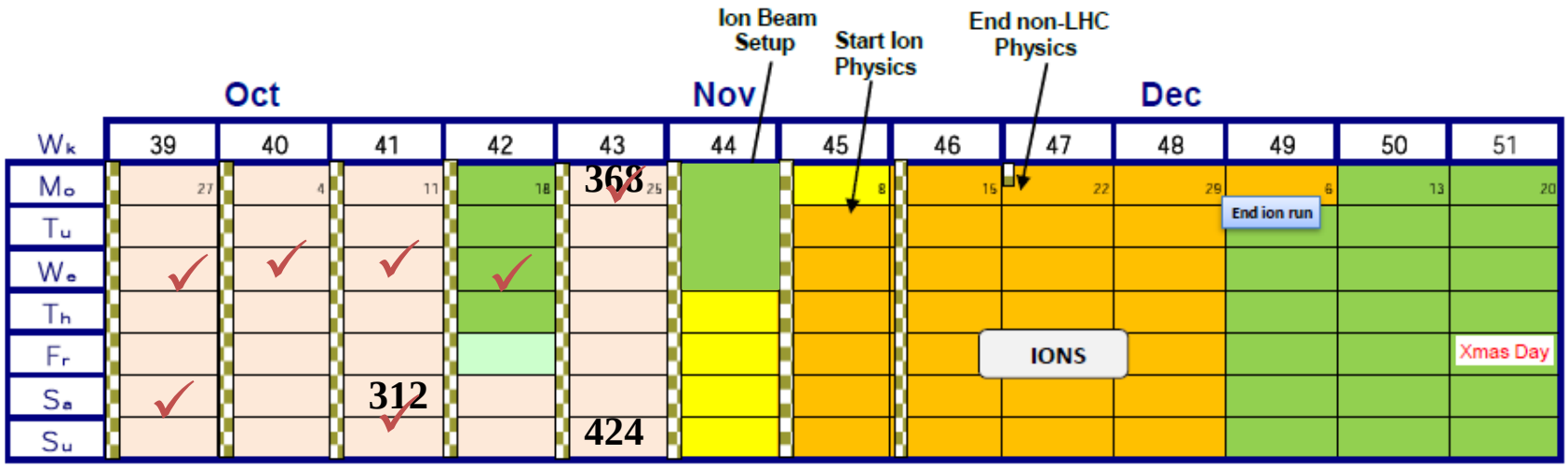
Ramp duration reduced from 46 to 16 minutes

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

Bunch Train Schedule





Collisions

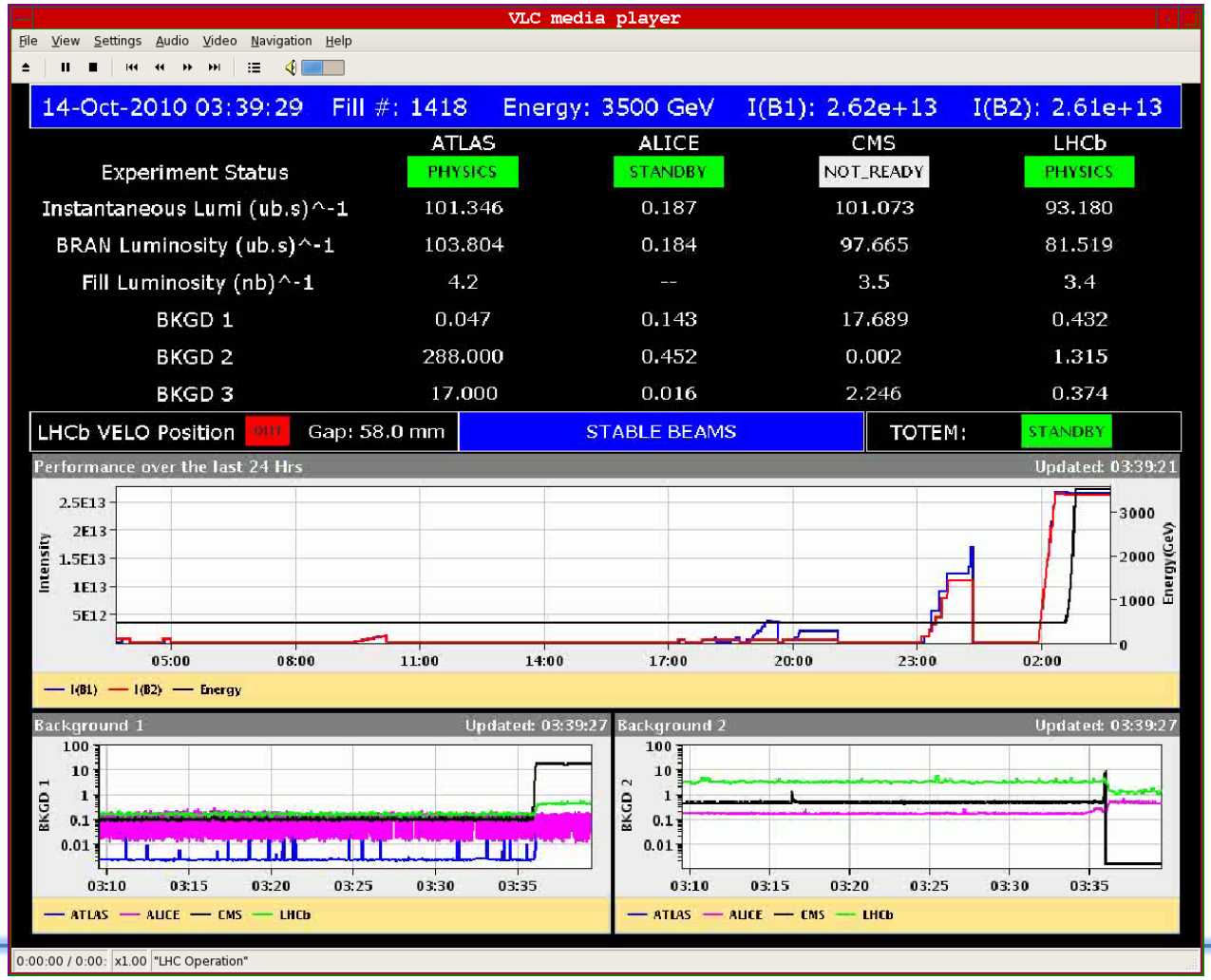
Fill	# bunch	N bunch [10^{11} p]	$\varepsilon_{H/V\ B1}$ @inj [μm]	$\varepsilon_{H/V\ B2}$ @inj [μm]	L_{peak} [10^{32} $cm^{-2}s^{-1}$]	$\varepsilon_{H/V}$ @coll. from lumi [μm]	Stable beams [h]	L_{int} [pb^{-1}]	Reason for dump	$\varepsilon_{H/V}$ @end of coast (from Lumi scan) [μm]
1408	248	1.02	-	-	0.94	2.5	9.5	>2.4	Prog.	3.8/3.9
1410	256	1.04	1.5/1.3	1.4/1.6	1.3	1.8	0	0	BLM on MQW	-
1418	248	1.04	1.7/1.6	2.1/2.2	1.03	2.4	8.5	>2.4	PC IT.R1	-
1422	16	0.78	2.4/2.6	2.6/3.2	0.018	3.9	5.5	0.03	LBDS	-
1424	312	1.13	2.0/1.9	2.2/2.4	1.35	2.6	1	0.4	UFO LHCb BCM	-
1427	312	0.89	2.0/1.8	2.2/2.4	0.86	2.6	9.5	2.3	Prog.	3.2/3.1
1430	312	1.15	-	-	1.48	2.4	0.6	0.3	UFO Pt.4	-

- Typical emittances in collision 2.5 μm
  - ➔ ca. 50% higher than nominal beam-beam parameter!!!

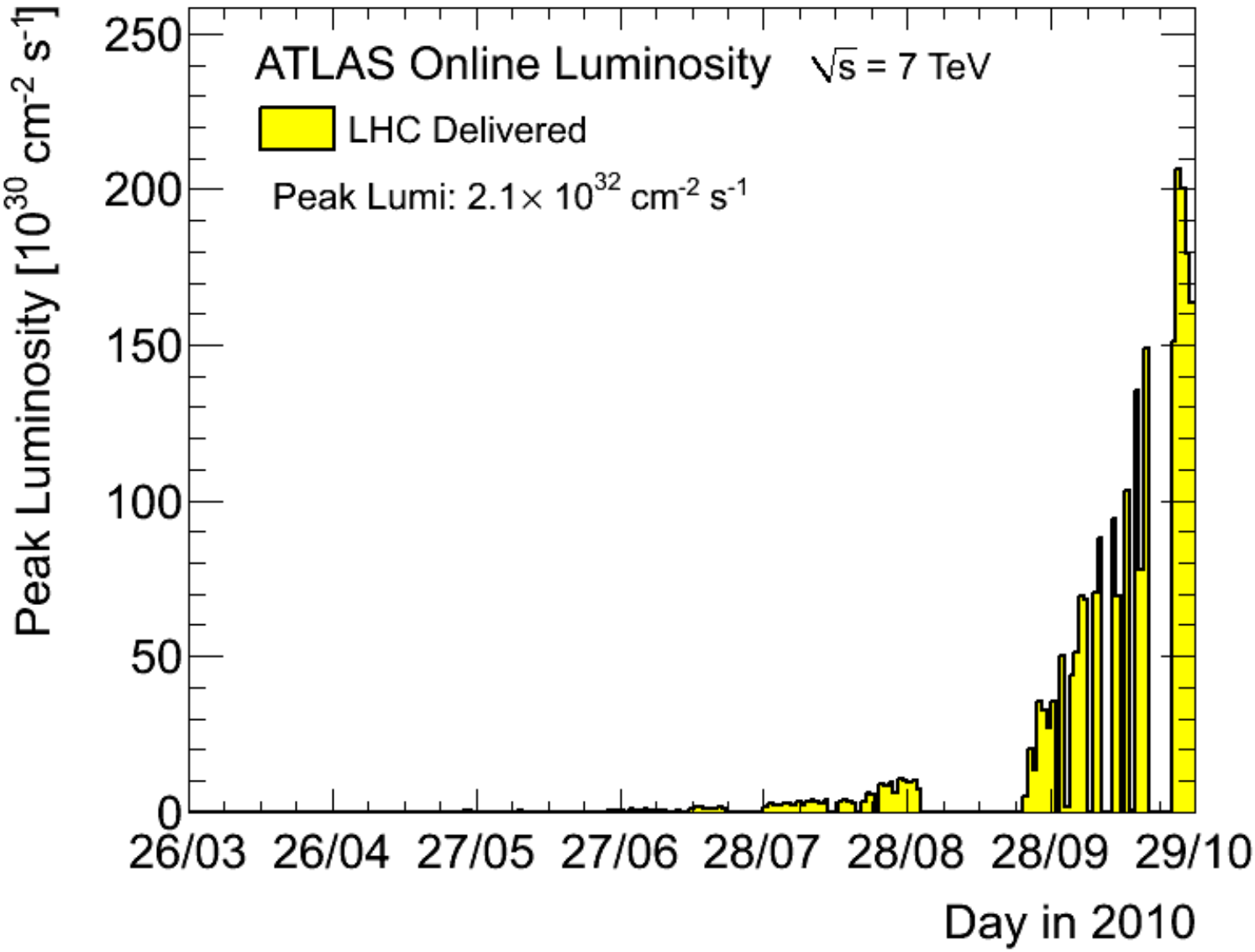
LHC protons 2010: mission accomplished

250 bunches with ca. 2.6 10^{13} ppb

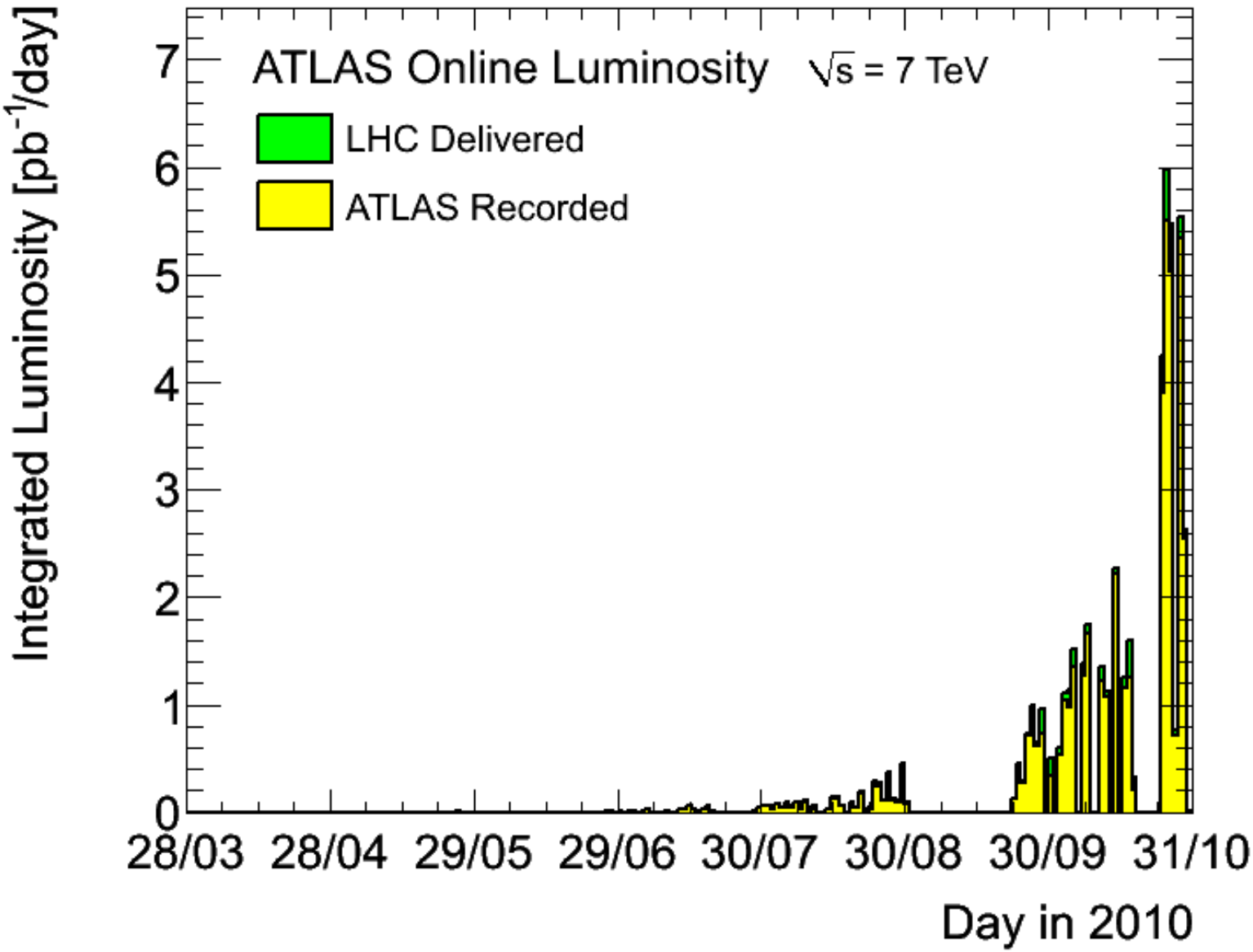
$L_0 > 10^{32}$ cm^{-2} s^{-1} ➔ Emittance in collision < 3 μm



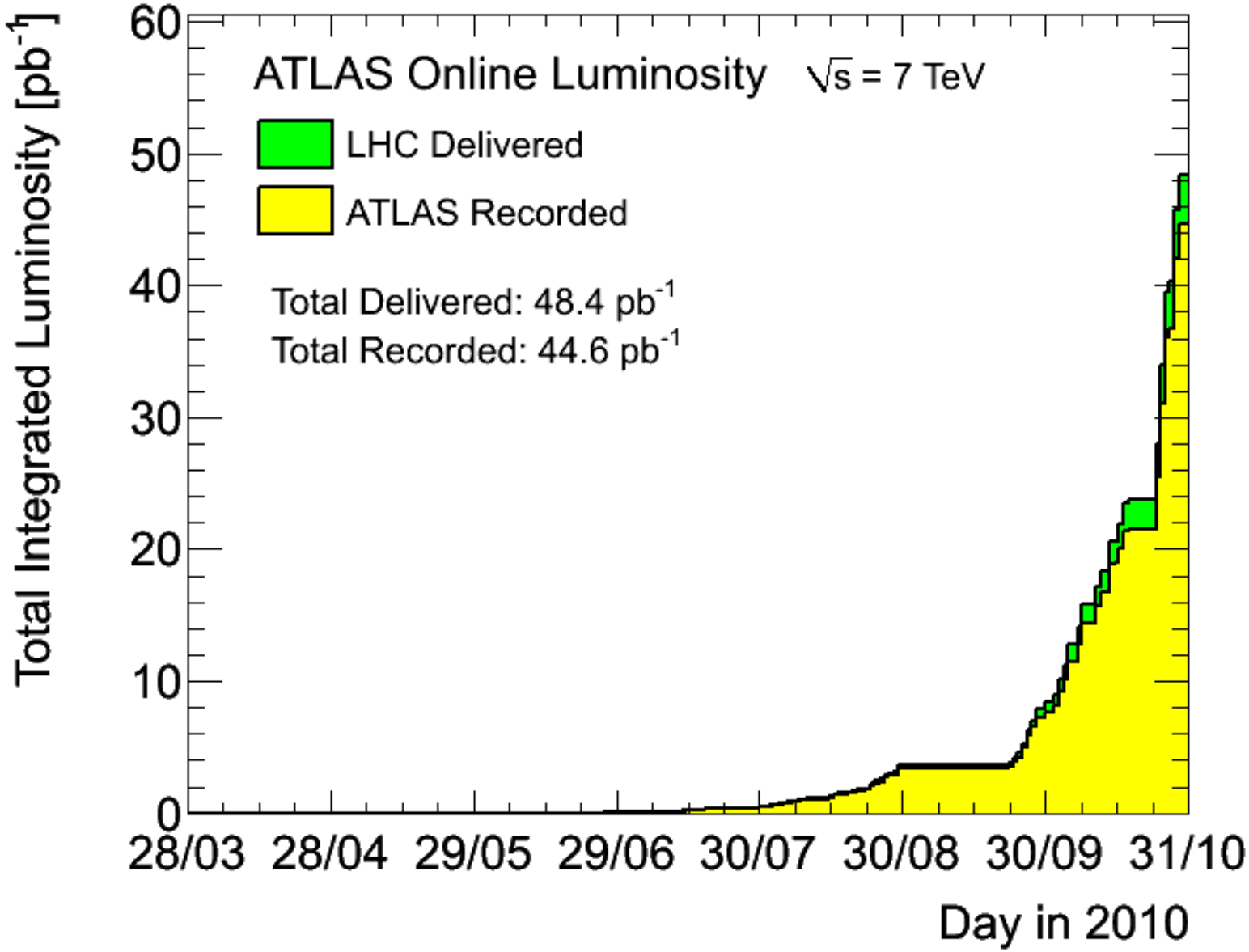
1/11/2010 (delivering up to 2 10^{32} cm^{-2} sec^{-1} peak with 368)



1/11/2010 (approaching 6pb-1 per day)



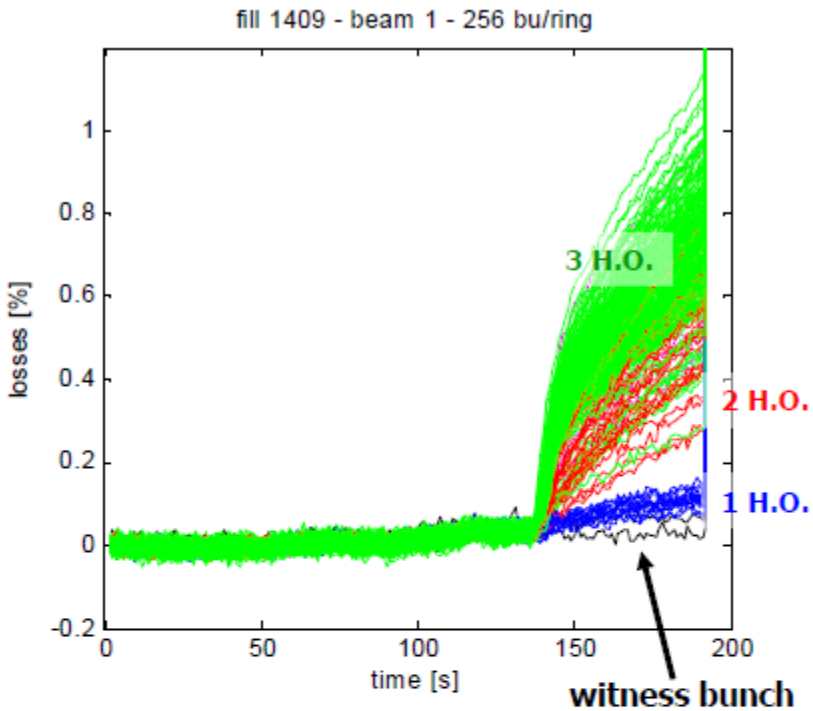
1/11/2010 (approaching 50pb-1)

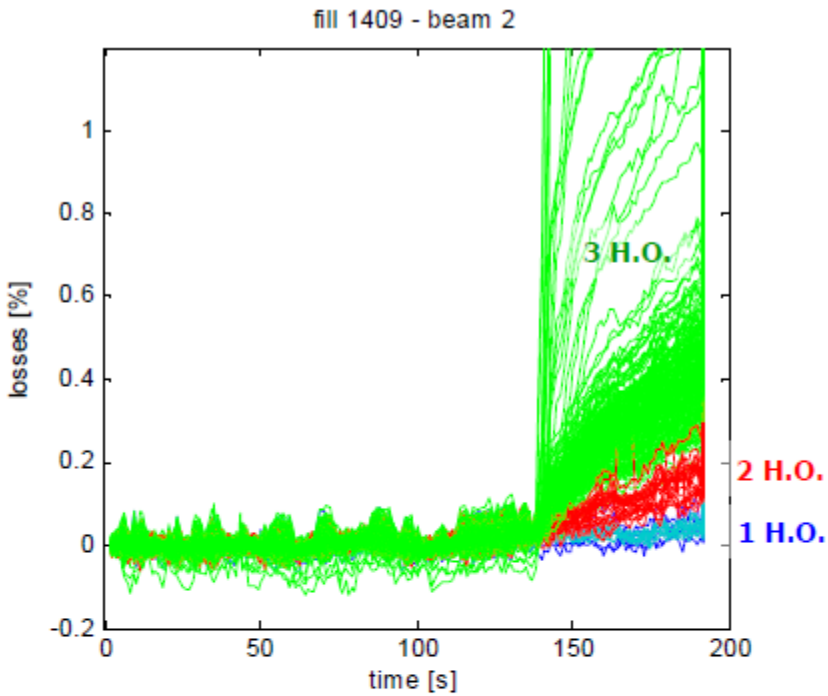


Observations & Events

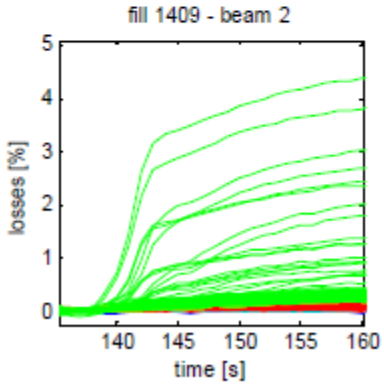
- Beam-Beam: beam-beam parameter > $3\ 10^{-3}$ ➔ $6\ 10^{-3}$
- UFOs
- Vacuum effects for bunch trains above 200 bunches
- Aperture limitation at injection region

Beam-Beam: Bunch by bunch





- beams dumped right after colliding (~1 minute)
- clear dependence of losses on number of H.O. collisions
- some bunches b2 lose up to 5% in the first few seconds
  - 12 out of 14 biggest losers from first 3 16-bunch injections
    - 10th 11th 12th 13th in the 16-bunch train

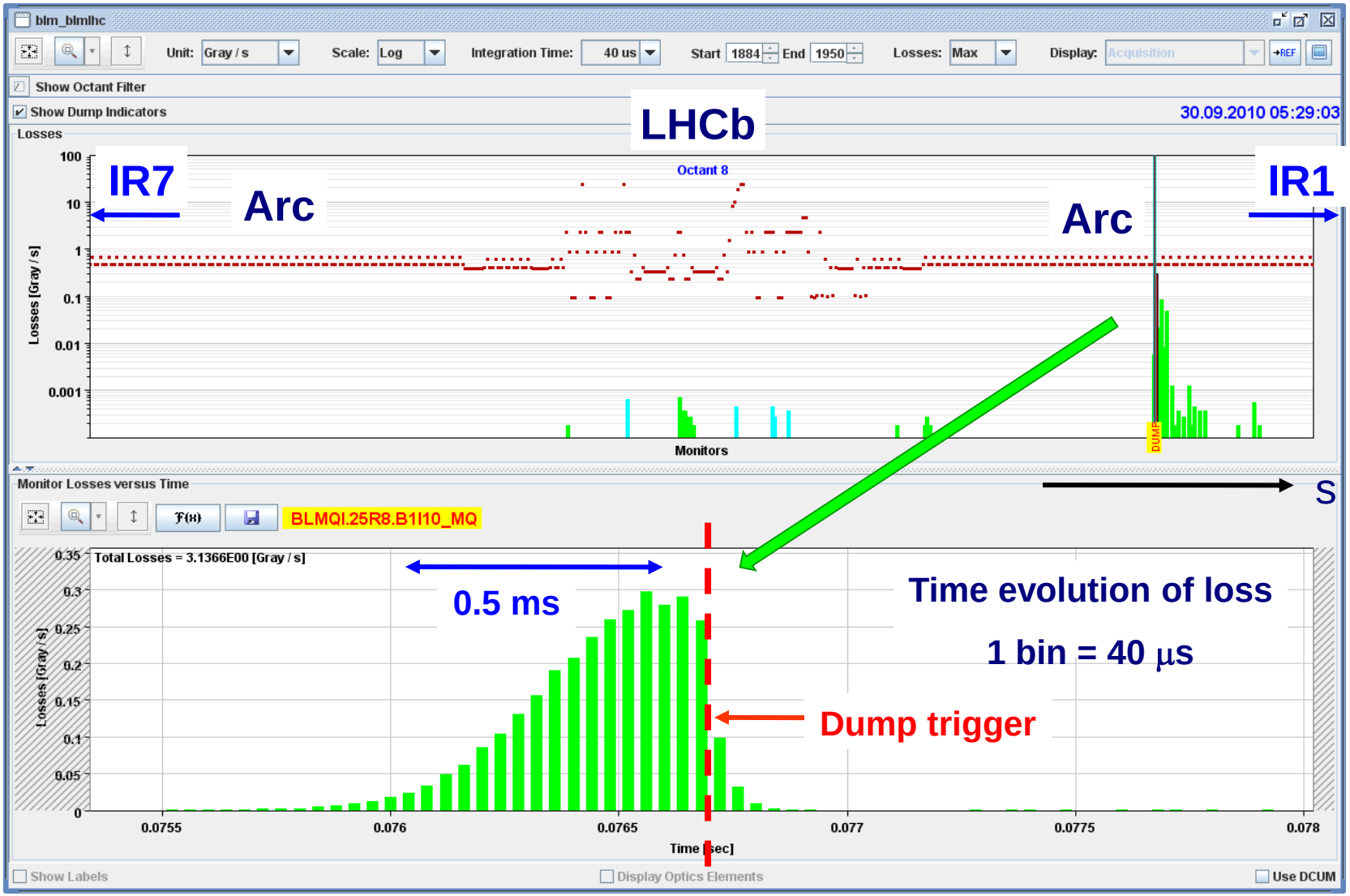


IPs: 1 5 2 8 - 1 5 8 - 1 5 2 - 1 5 - 2 8 - 8 - 2

giulia papotti (BE/OP/LHC)

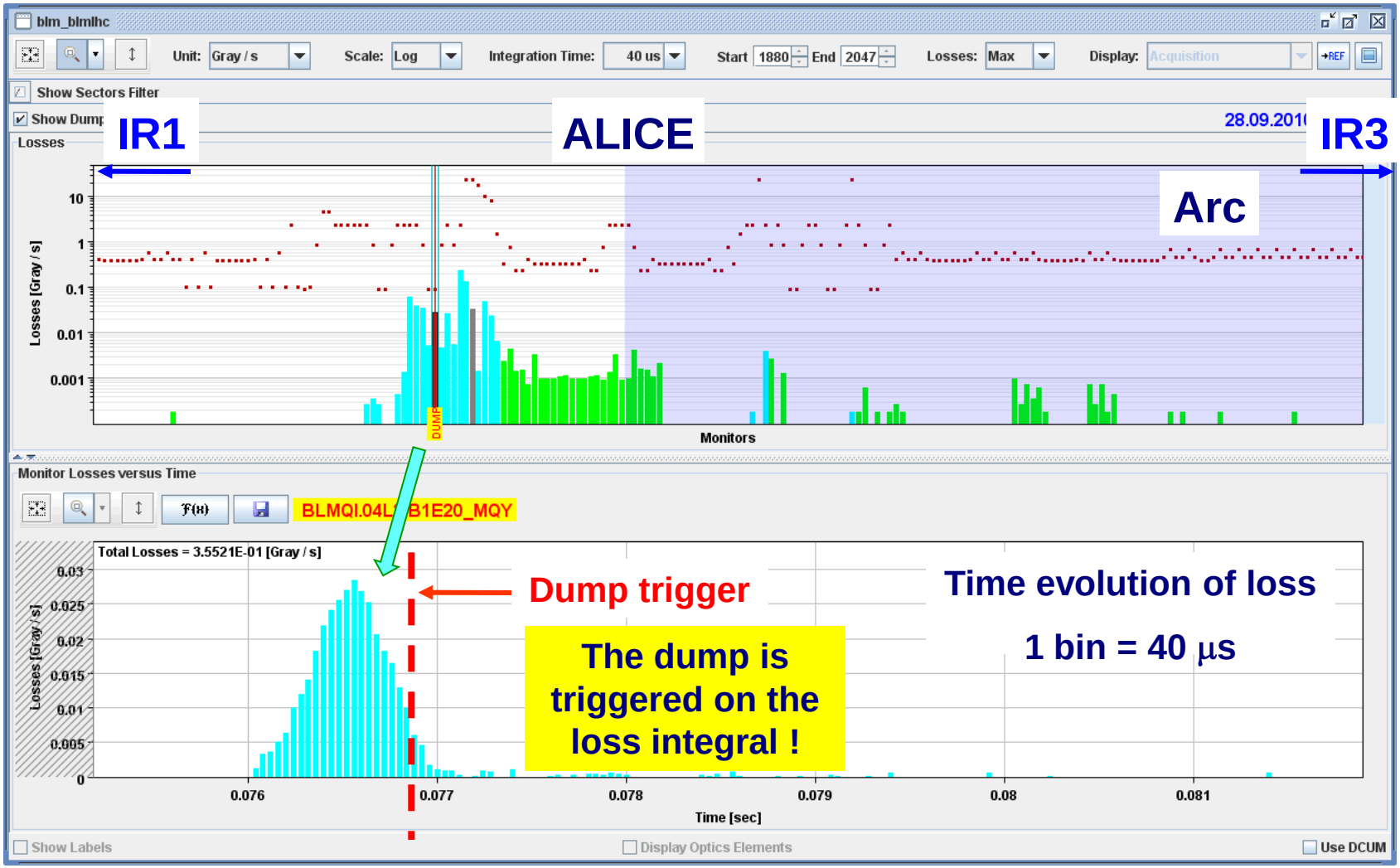
UFOs: Unidentified Falling Objects

Beam loss monitor post-mortem

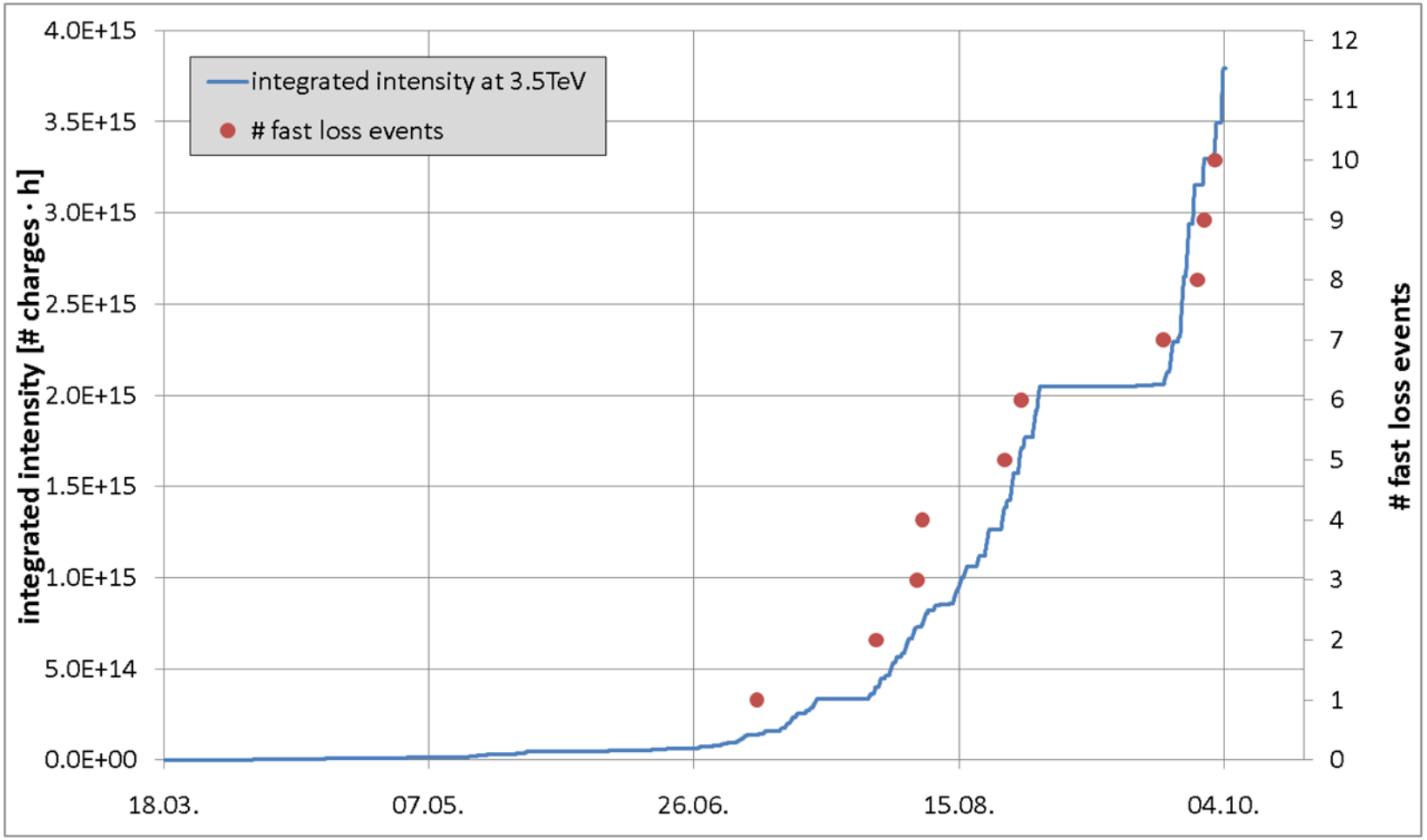


UFOs: Dump on integrated loss

About 50% of the UFOs lead to dumps while the loss is decaying…

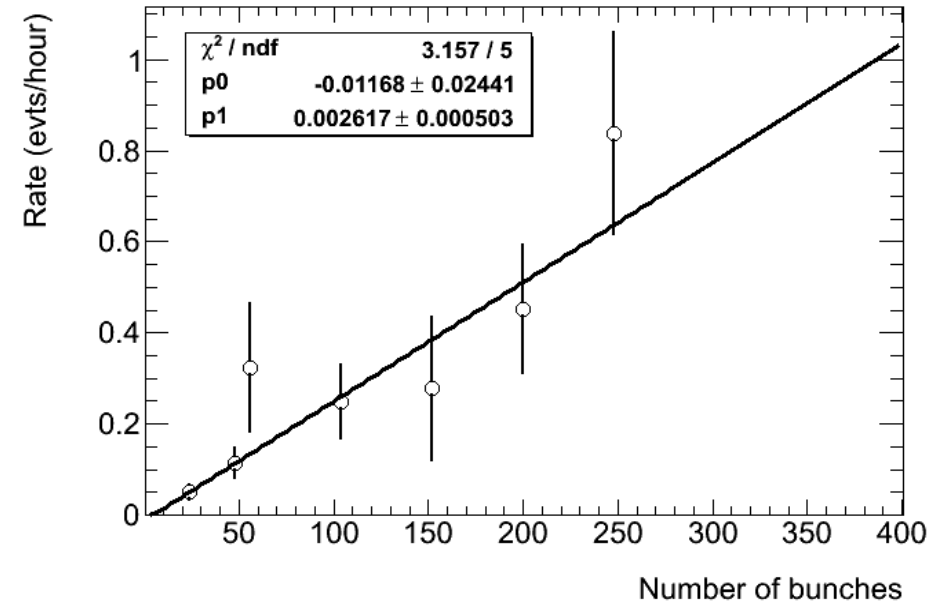


UFOs versus time



Excluded Totem UFOs

UFOs: INTENSITY DEPENDENCE



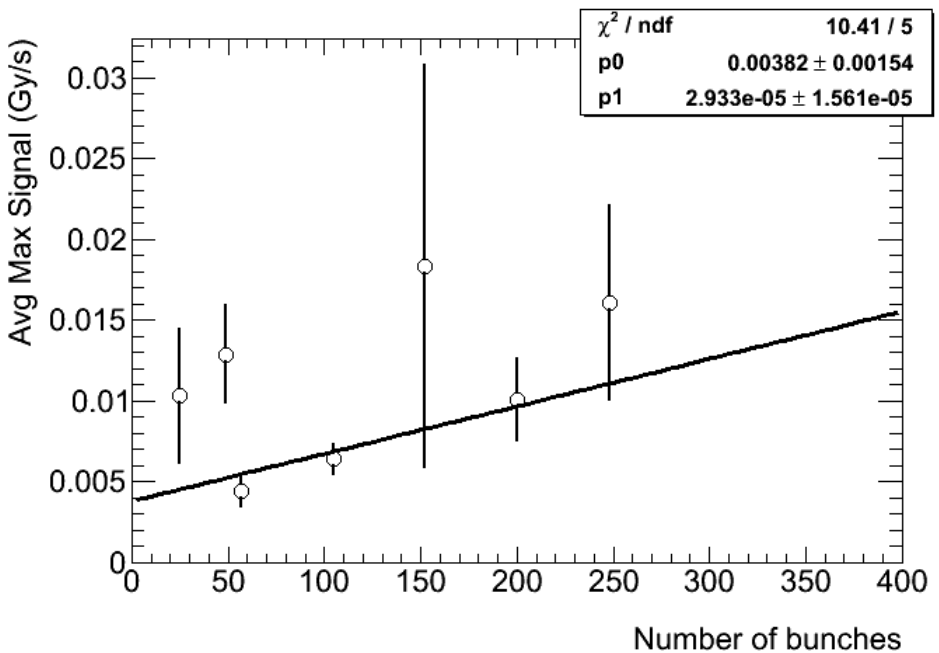
"UFO" Rate

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

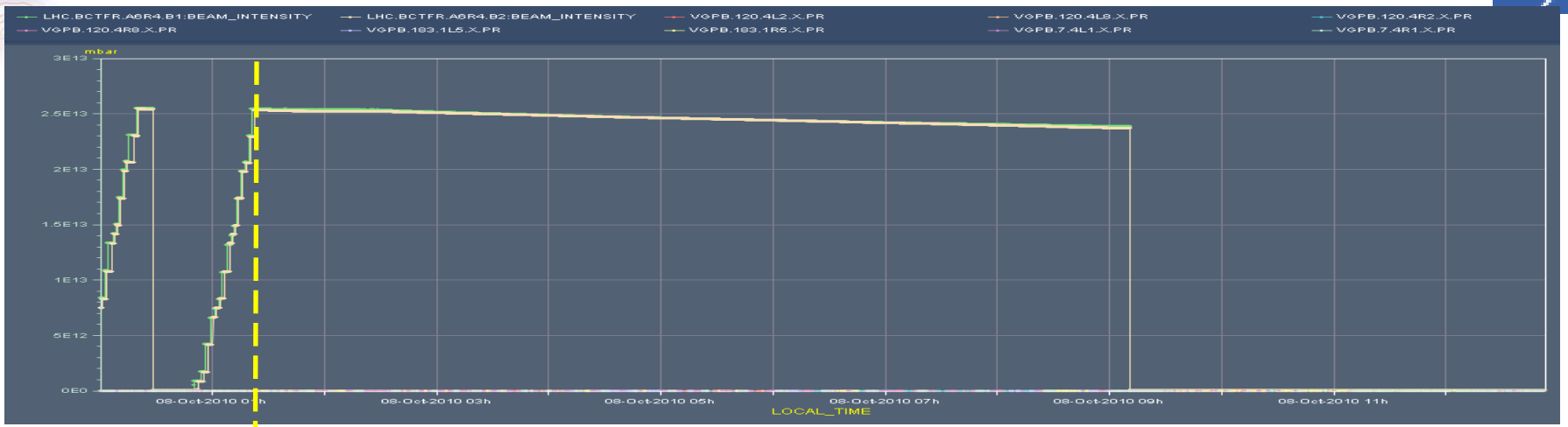
2000 Bunches => ~ 0.06 Gy/s

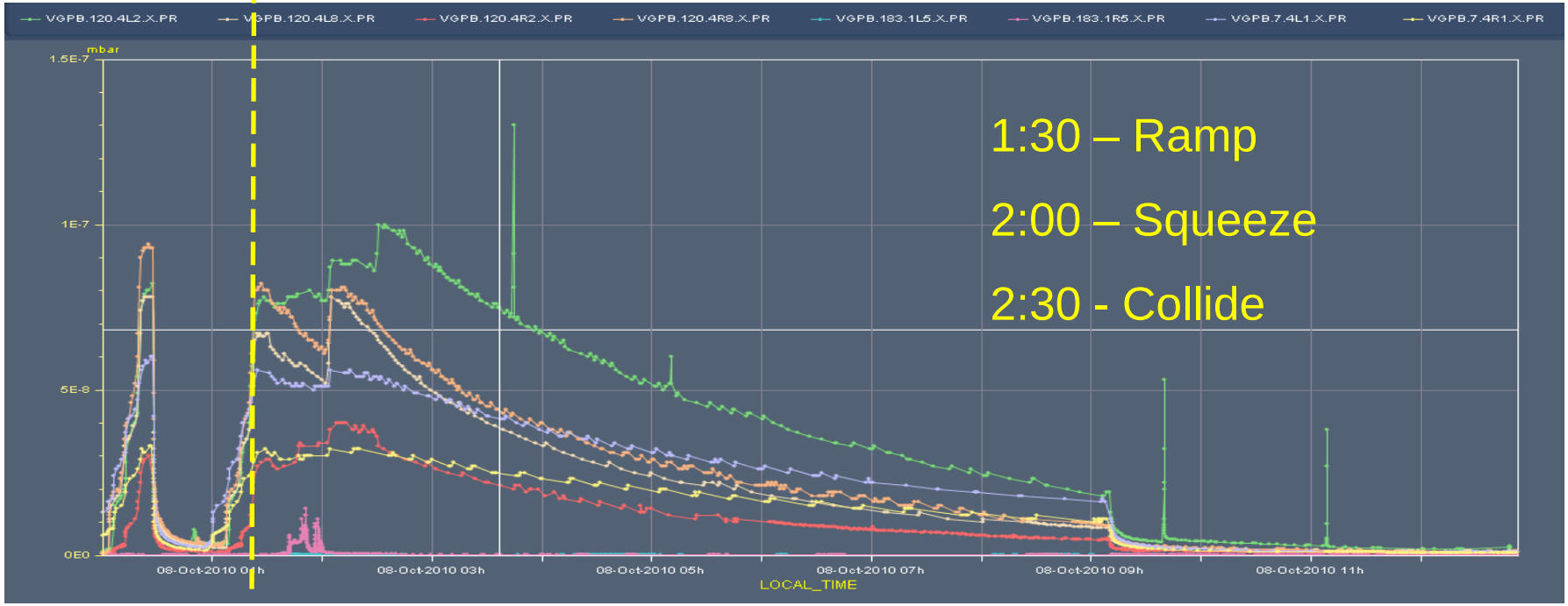
Thresholds for cold magnets in RS05 are in the range 0.02-0.08 Gy/s

Vacuum near the Experiments

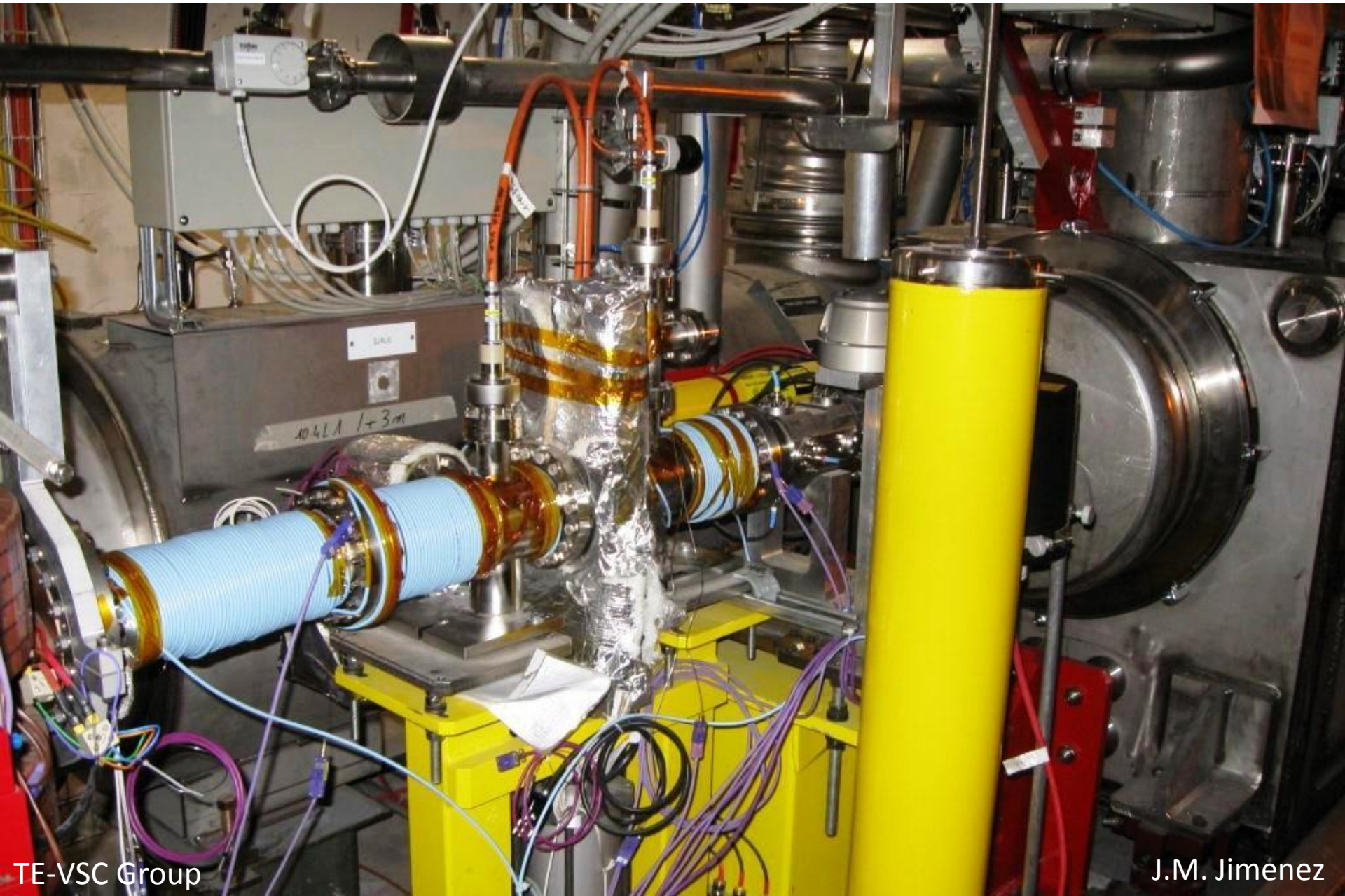
- Vacuum activity in the common beam chamber of all experiments.
- Local pressure bump around ± 60 m from the IP.
  - Uncoated segment of vacuum chamber at the warm-cold transition of inner triplets
- Pressure rise driven by the presence of both beams
  - *Higher backgrounds.*
  - *Driven by beam and bunch intensity*
    - *Possibly higher order mode heating from the beam.*
    - *Possibly due to synchrotron light heating desorption D1/D2 and Quads*
    - *Possibly Electron Cloud*
    - *NOT due to some beam losses as nothing on BLMs*
  - *Same order of magnitude everywhere (towards 10^{-7} mbar).*
  - *Gets worse when beam intensity goes up*
  - *Improves when running at same beam intensity*
    - *Cleaning effect*
- *Valves will close if $p > 4 \cdot 10^{-7}$ mbar in 2 out of 3 gauges. Still ok.*

Vacuum over fill





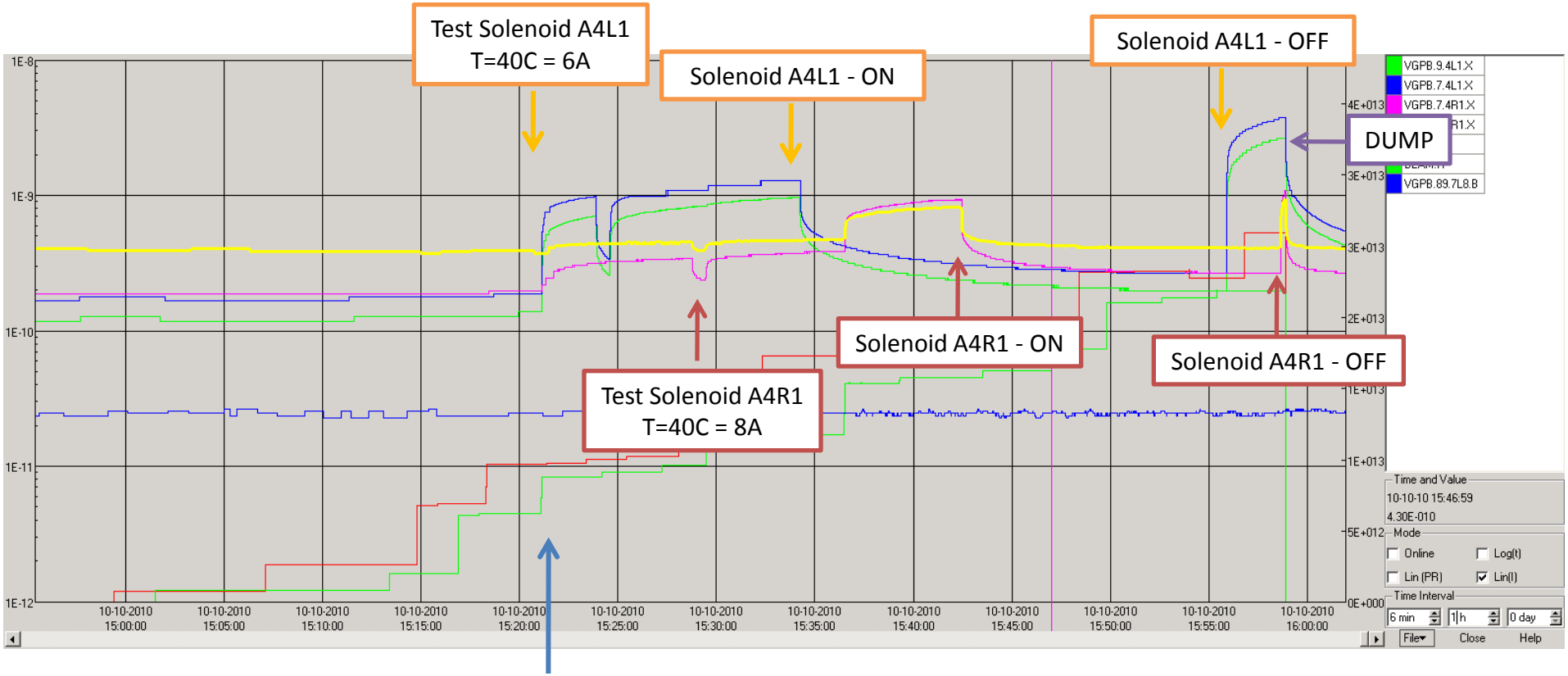
Solenoids between DFBX and D1 in IR1L



TE-VSC Group

J.M. Jimenez

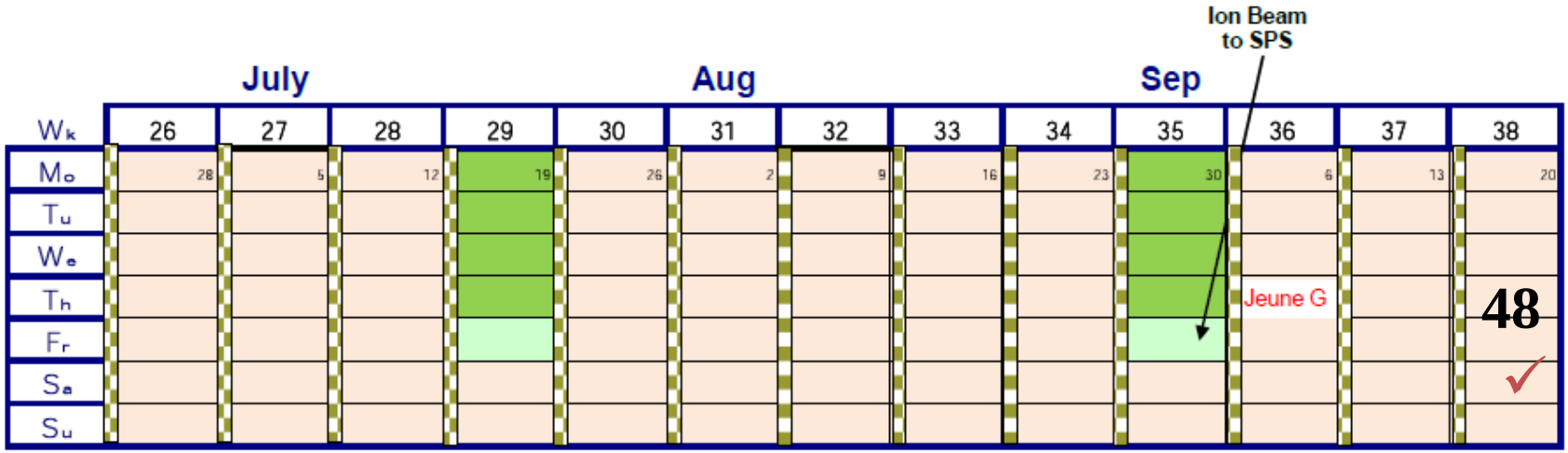
Injection Study with train of 24 Bunches
10/10/10 – 15:00

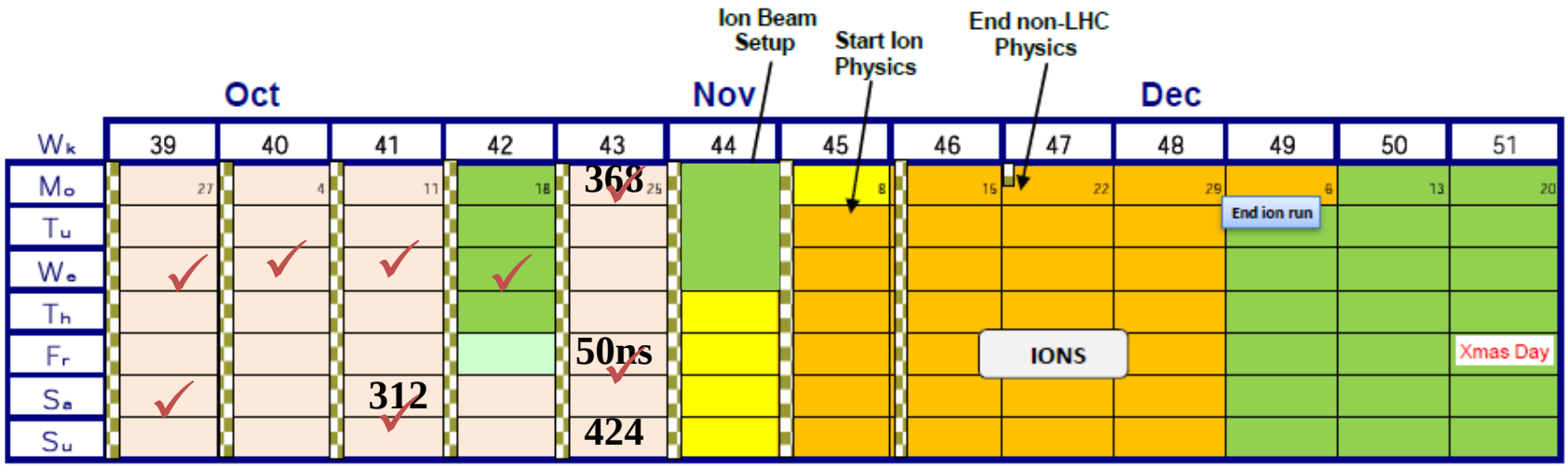


Start increase pressure on both lines when the number of protons in the machine is about:
Beam B=1E13
Beam R=8E12

J.M. Jimenez

Bunch Train Schedule



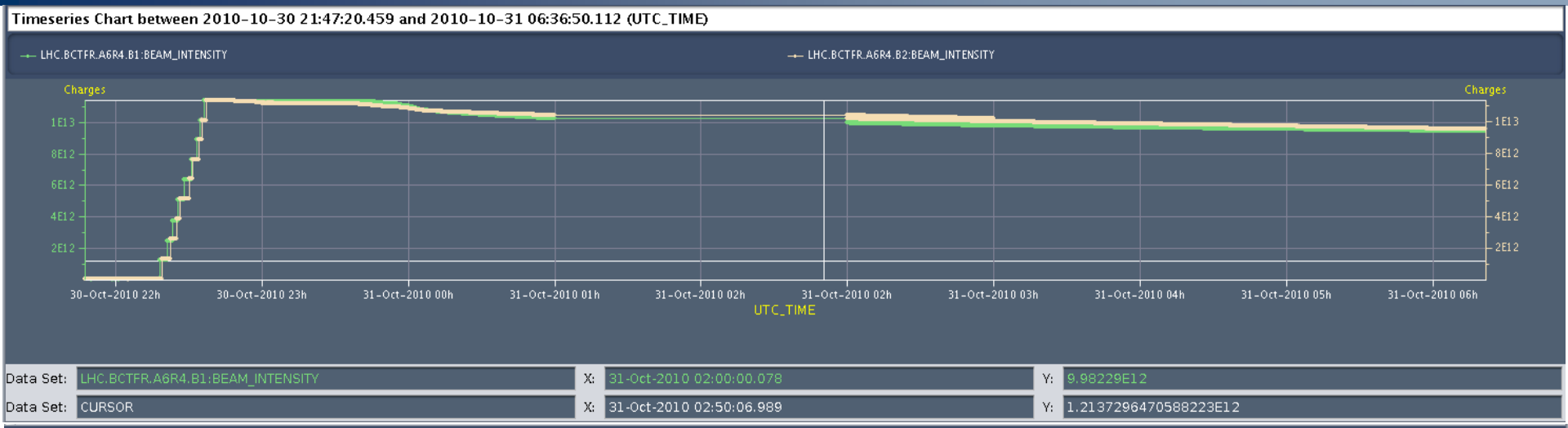


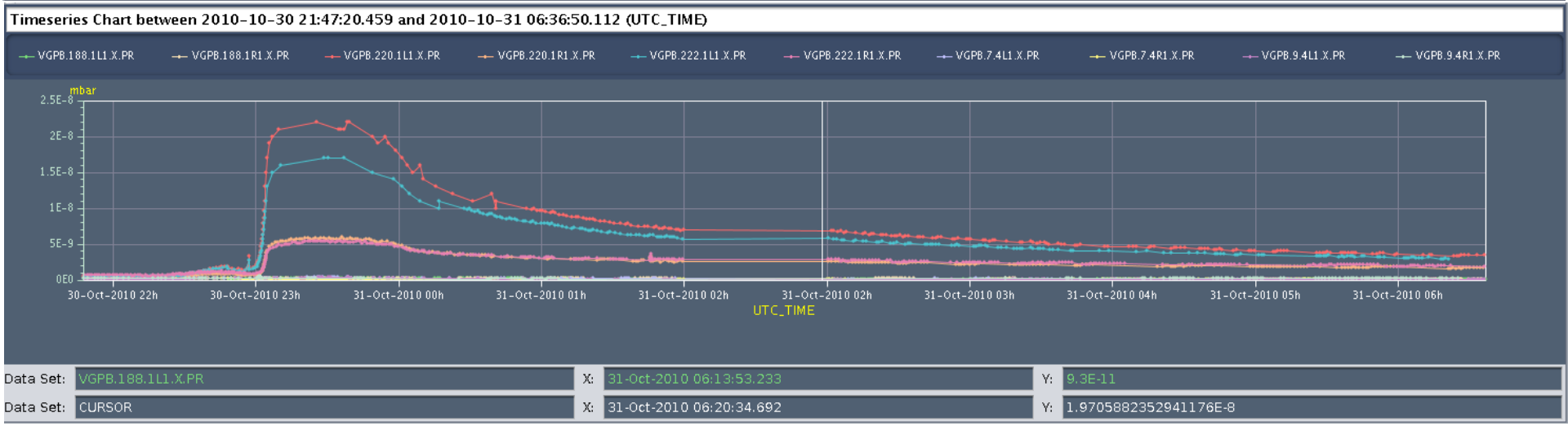
50ns bunch spacing operation: 30/31.10.

- 00h47: Start ramp. 109b. 50ns. ~1.1e11 p / bunch.
- 02h24: Stable beams. Fill 1459.
  - well separated trains of 12x50ns ➔ vacuum OK
  - Lumi ~2e31.
  - Emittance ~3 um (from lumi).
  - Negative chromaticity at end of squeeze: Losses at warning level of BLM's.
  - 30-40% bunch to bunch intensity spread.
- 07h30: Adjust. End-of-fill studies.

- Big rises in pressure when moving to 24x50ns
- Pressure goes with number of batches injected

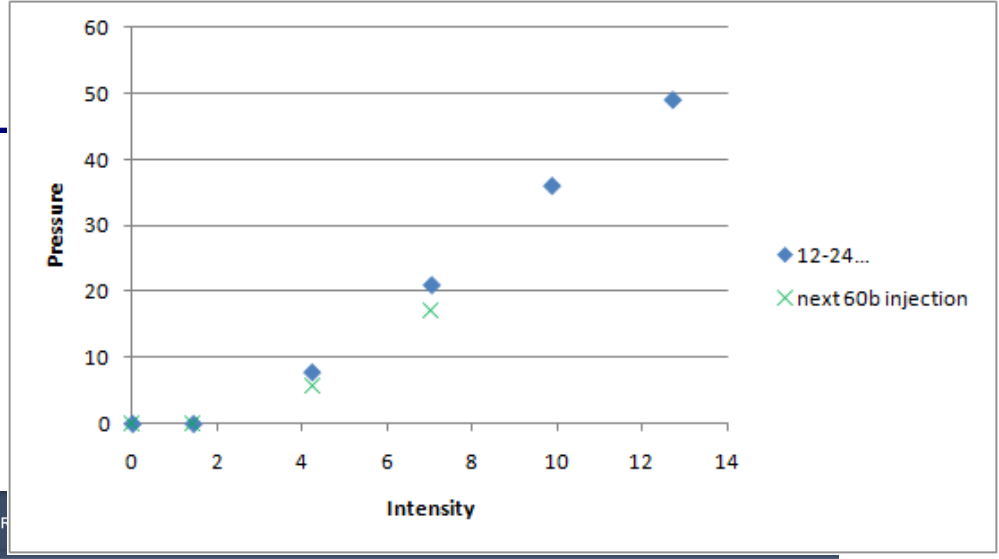
Vacuum IR1





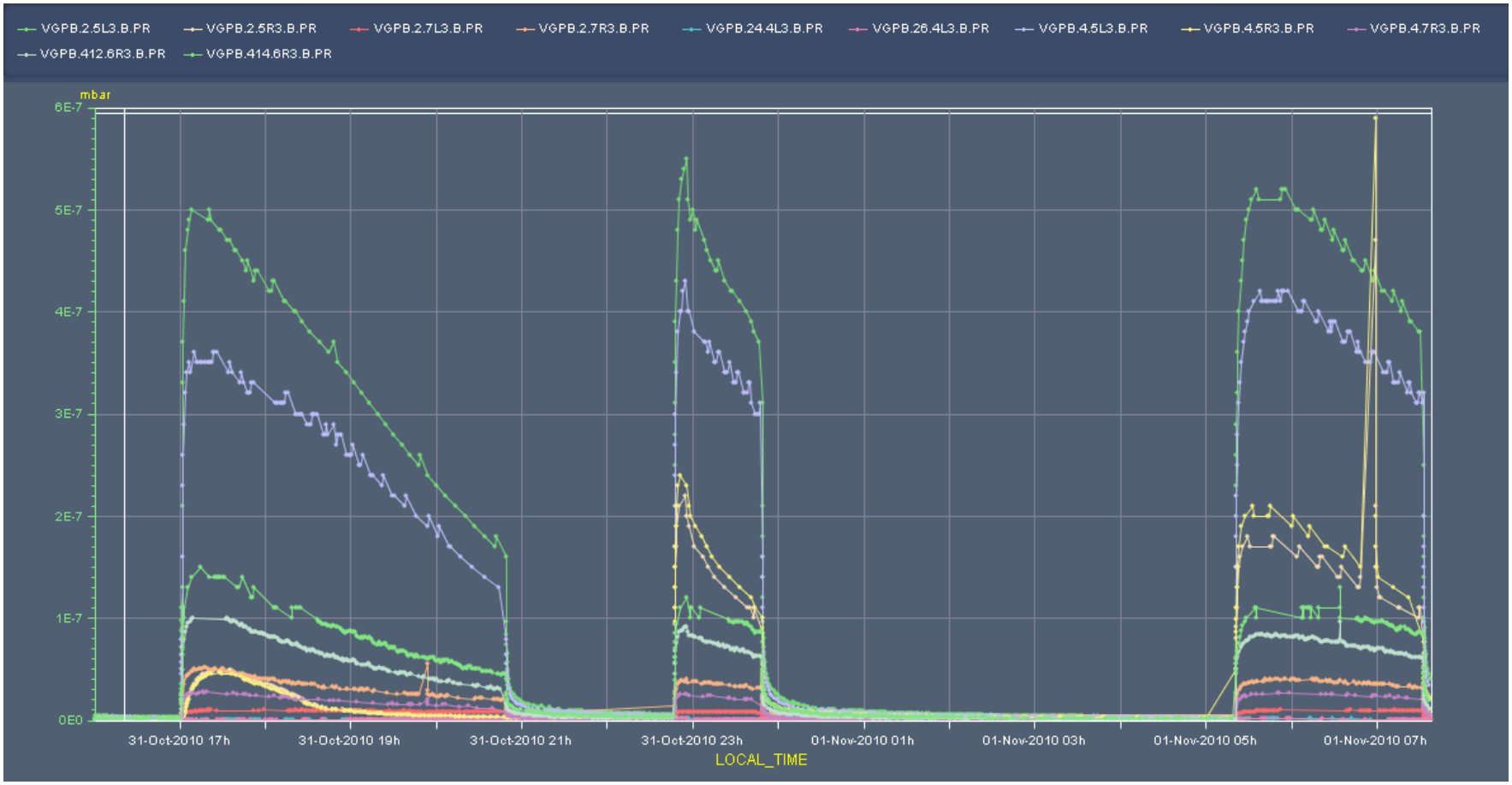
R. Alemany

6L7 – beam 1


Pressure
Intensity
12-24...
next 60b injection

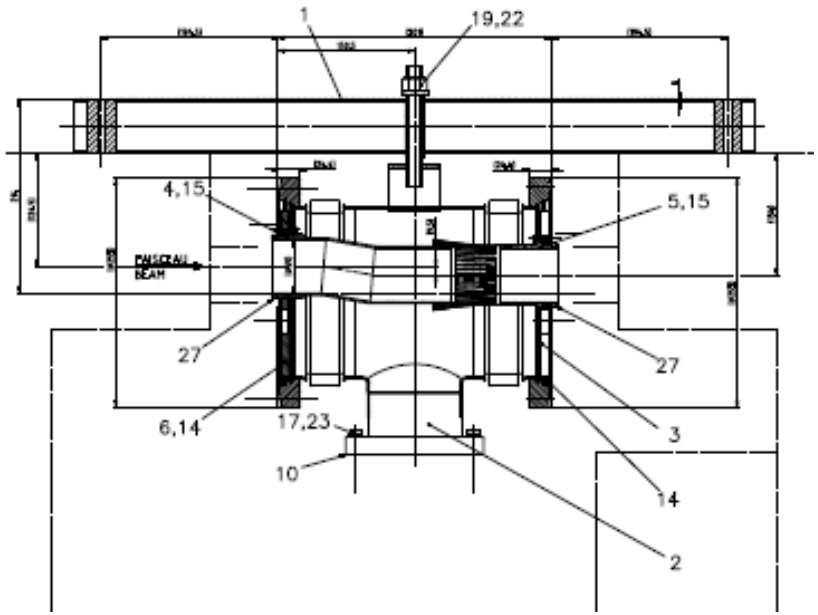

LHC.BCTFR.A6R4.B1:BEAM_INTENSITY
VGPB.77.6L7.B.PR
VGPB.773.6L7.B.PR
Charges
mbar
31-Oct 11h
31-Oct 12h
31-Oct 13h
UTC_TIME

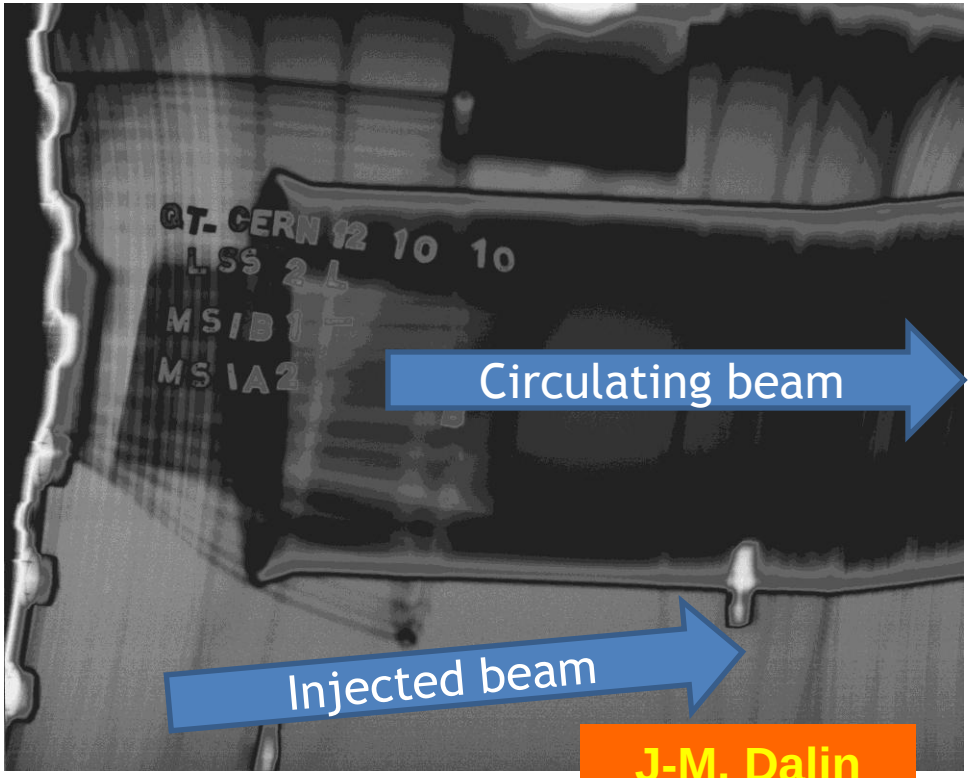
Cleaning


VGPB.2.5L3.B.PR
VGPB.2.5R3.B.PR
VGPB.2.7L3.B.PR
VGPB.2.7R3.B.PR
VGPB.24.4L3.B.PR
VGPB.26.4L3.B.PR
VGPB.4.5L3.B.PR
VGPB.4.5R3.B.PR
VGPB.4.7R3.B.PR
VGPB.412.6R3.B.PR
VGPB.414.6R3.B.PR
mbar
6E-7
5E-7
4E-7
3E-7
2E-7
1E-7
0E0
31-Oct-2010 17h
31-Oct-2010 19h
31-Oct-2010 21h
31-Oct-2010 23h
01-Nov-2010 01h
01-Nov-2010 03h
01-Nov-2010 05h
01-Nov-2010 07h
LOCAL_TIME

Aperture limitation: 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





J-M. Dalin

LHC Upgrade Plans and New Initiatives in 2008

CERN New Initiatives

LHC Insertion:

- ➔ LHC IR Upgrade –Phase I project lead by Ranko Ostojic
- ➔ LHC sLHC / Phase 2 IR upgrade lead by Lyn Evans

LHC collimation:

- ➔ Phase 2 collimation project lead by Ralph Assmann

LHC injector complex:

- ➔ LINAC4 project lead by Maurizio Vretenar
- ➔ PS2 design study lead by Michael Benedikt
- ➔ LSPL design study lead by Roland Garoby
- ➔ SPS upgrade study team lead by Elena Shaposhnikova

Outcome of Chamonix 2010

- Decision to consolidate all LHC splices in one go:
  - ➔ shutdown in 2012 for splice repair
  - ➔ followed by new hardware commissioning
  - ➔ Phase 1 IR upgrade in 2013-14 would imply 2 long shutdowns in a row

- Estimation of integrated luminosity with new schedule
  - ➔ old plan for Phase 1 IR upgrade implies triplet replacement long before end of magnet lifetime (ca.10 fb^{-1} versus 500 fb^{-1})
  - ➔ decision to 'delay' Phase 1 IR upgrade (merged with Phase 2)

- Planning of injector complex upgrade
  - ➔ have to consolidate existing injector complex for at least 10+ years
  - ➔ decision to hold PS2 & SPL plans and to launch alternative upgrade studies: PSB energy upgrade and SPS e-cloud and TMCI remedies

New Studies and Taskforces

- The Chamonix 2010 discussions led to five new task forces:

  -Planning for a long shut down in 2012 for splice consolidation

  -Long term consolidation planning for the injector complex

  -SPS upgrade task force

  ➔ accelerated program for SPS upgrade

  -PSB upgrade and its implications for the PS (e.g. radiation etc)

  -LHC High Luminosity project

  ➔ investigate planning for ONE upgrade by 2018-2020

- Launch of a dedicated study for doubling the beam energy in the LHC ➔ HE-LHC

New Project Structure at CERN

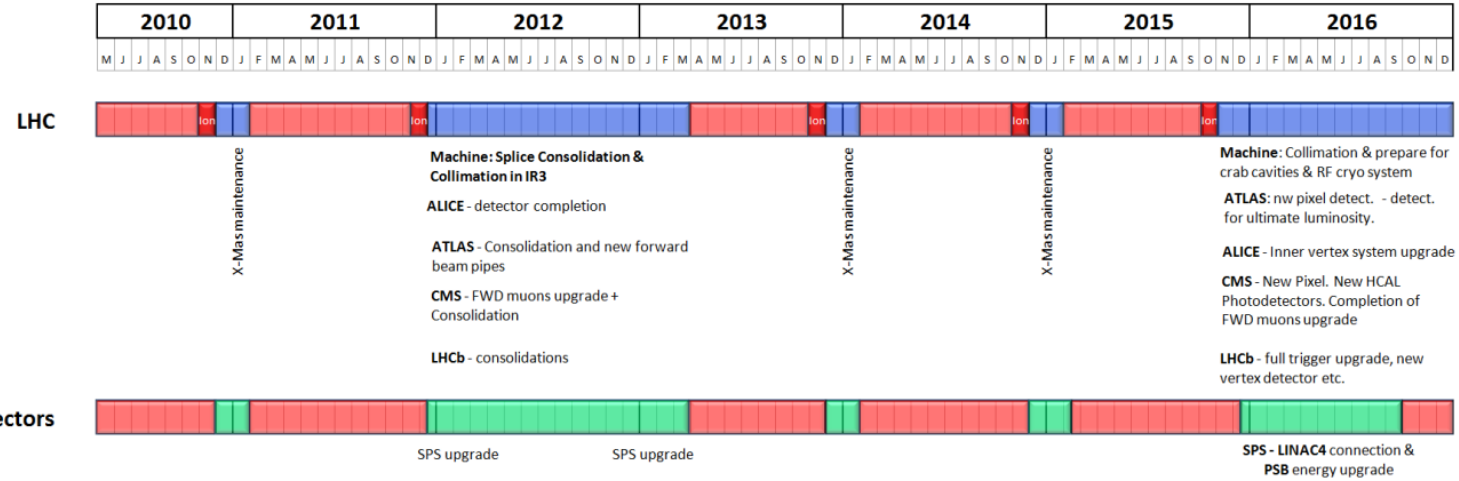
- High Luminosity LHC Projects: L. Rossi
  - ➔ prepare for operation at 5 10^{34} cm^{-2} sec^{-1}
  - ➔ prepare for integrated luminosity of 3000 fb^{-1}
  - ➔ Implementation by 2018 - 2020

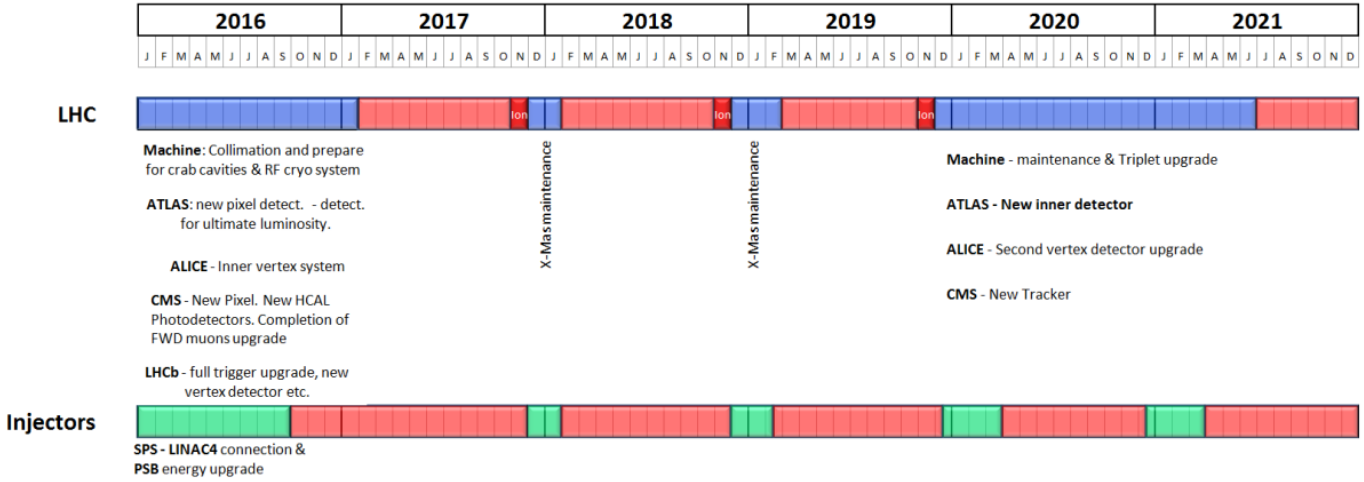
- LHC Injector Upgrade Project: R. Garoby
  - ➔ remove bottlenecks in the PS and SPS
  - ➔ investigate options for PSB upgrade (energy)

- LHC Consolidation Project: S. Baird
  - ➔ have to consolidate existing injector complex for at least 15+ years

- Linear Collider Project: Steinar Stapnes

CERN plan for coming years





Stop INJ in 2012
No shutdown in 2015 to maximize Physics

Nobody will be surprised if instalaltion of HL equipment will shift 1 year…

Situation at CERN

- New CERN plan endorsed by special SPC and FC of end of August
- Reduction in budget is acceptable to preserve the physics plan
- LHC is even reinforced
  - New plan on Collimation in IR3 accepted (if compatible), to be confirmed in next Chamonix workshop
  - Key technologies for the upgrade are kept funded and even increased (but: we suffer lack of personnel)
  - The next big shutdown is 1 year later (2016)
    - We buy time to be really prepared to use it

General features of Design Study

- 10 M€ total cost over 4 years: July 2011-June2015
- Reimbursement by EU
  - We aim at 40% reimbursement by EU (budget details are still being sorted out)
    - **CERN offers free personnel for WPs, but will be reimbursed 100% for management. Exception for fellows.**
    - This setup makes it hopefully very attractive for other partners: possibility of 50% reimbursement for Universities ?
- Close collaboration with EuCard (and other programs) for technical development
  - Most of resources on personnel
  - Some hardware, especially for orphan items
- Trying to attract contributions from other labs:
  - Non EU labs can participate (but no EU funds)

HL-LHC Structure:

Tentative Work Package list:

1)Communication & management: L. Rossi
2)Optics, Layout and Beam Physics: O. Brüning
3)Magnet Design: E. Todesco
4)Crab Cavity Design: E. Ciapala & E. Jensen
5)IR Collimation: R. Assmann
6)Machine Protection: J. Wenninger
7)Machine Experiment Interface: A. Ball
8)Superconducting Link: A. Ballarino

HL-LHC Work Package 2:

Tentative Task List:

1) Communication & management:

2) Optics & Layout:

- NbTi solutions with and without local CC; L^*; round and flat beams; 2-in-1
- Nb_3Sn solutions with and without local CC; L^*; round and flat beams; 2-in-1
- Novel solutions for correction of chromatic aberrations (a la SF & PR)
- IR4 layout and solution with global CC

  ➔ magnet parameters (aperture and length)

3) Single particle studies and tools:

- DA studies and FQ specifications
- Correction strategy and corrector specifications

  ➔ magnet parameters (FQ and corrector elements)

HL-LHC Work Package 2 Brainstorming

Tentative Task List:

4) Collective Effects:

- Impedance estimates for new layout (collimator and aperture dependent)
- IBS estimates for different beam configurations
  - ➔ beam separation; optimum configuration (flat beams vs round beams)

5) Beam-Beam Effects:

- BB long range compensation schemes
- BB limit for round and flat beams and coupling tolerances for flat beams
- Head-on BB compensation schemes and options

6) Beam Parameters and Luminosity optimization:

- L reduction and leveling (CC and poor man leveling via x-ing angle)
- Evaluation of operation experience of first 2 year LHC operation
- Options for beam parameter variation for L optimization during run (e.g. Q)
  - ➔ beam parameter set (ε_n, N_b, σ_s etc.)

LHC Injector Upgrade Project:

Areas for USLARP involvement:

1)Turn by turn profile monitor for PSB
2)Space charge studies for the PSB and PS
3)Wide bandwidth feedback system for the SPS
4)Impedance calculations and measurements
5)Instability studies and estimates
6)e-cloud mitigation

Reserve Transparencies

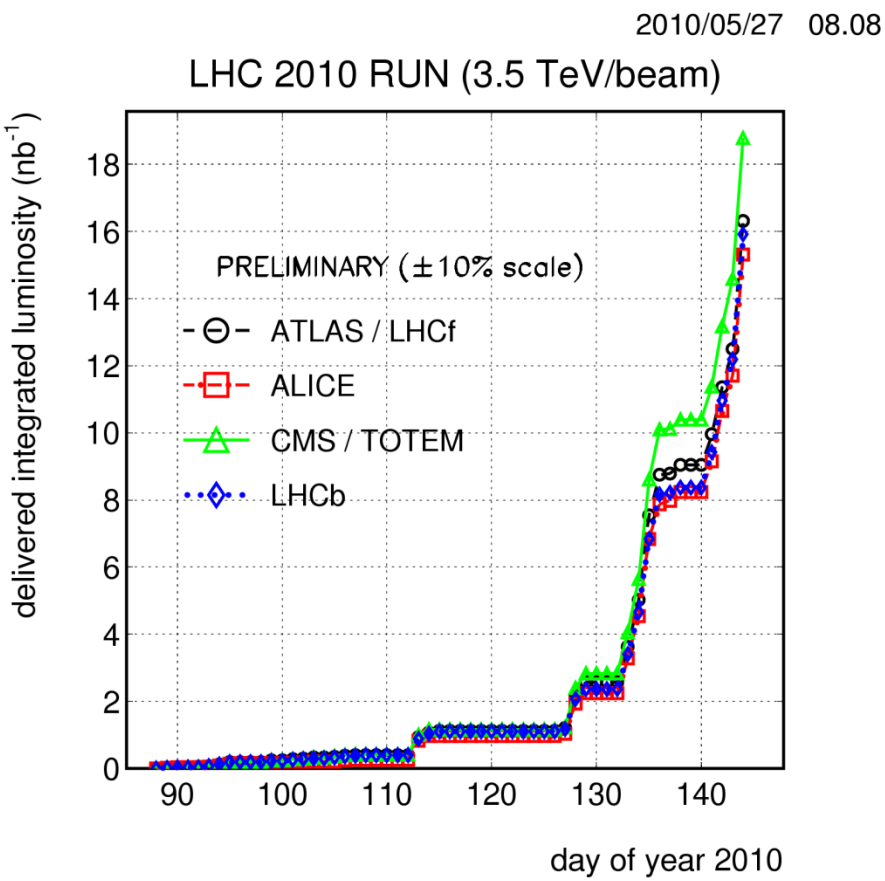
LHC Performance Optimization

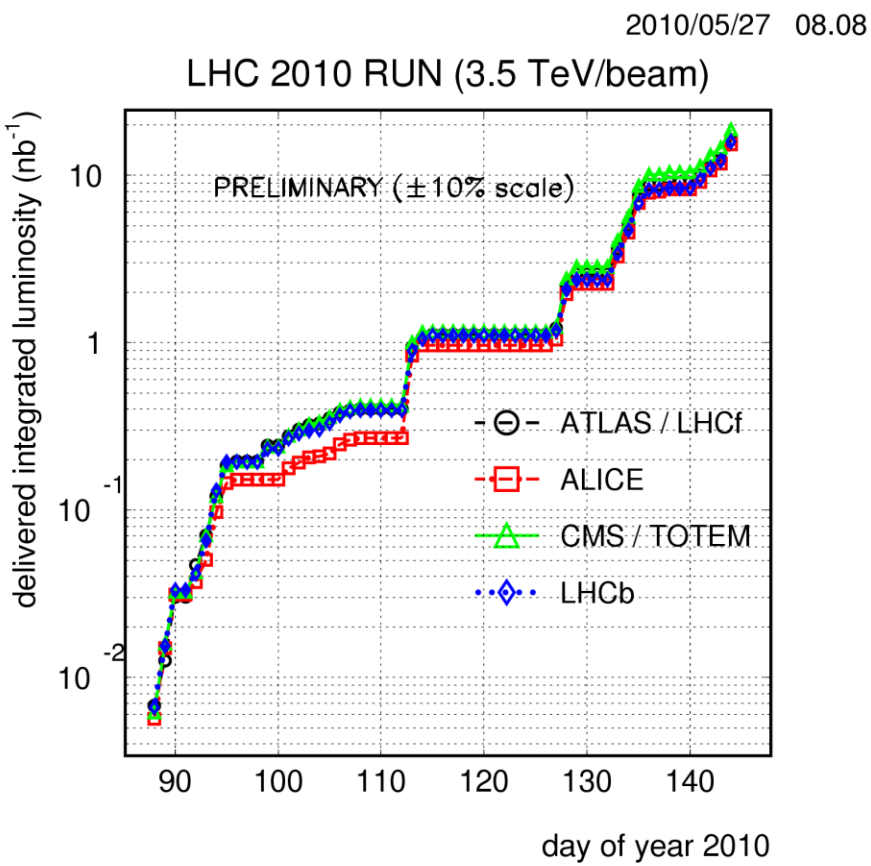
- example for small emittance scheme:

Parameter	nominal	ultimate	small emittance
N	1.15E+11	1.70E+11	1.70E+11
n_b	2808	2808	1404
beam current	5.84E-01	8.63E-01	4.32E-01
bunch spacing [ns]	25	25	50
x-ing angle [rad]	3.00E-04	3.50E-04	5.0E-04
beam separation [σ]	7.36	8.59	15
β^* [m]	0.55	0.55	0.55
ε_n [m]	3.75E-06	3.75E-06	2.50E-06
ε_L [eVs]	2.51	2.21	3.62
energy spread	1.00E-04	1.00E-04	1.24E-04
bunch length [m]	7.50E-02	7.50E-02	9.90E-02
IBS horizontal [h]	80	50	30
IBS longitudinal [h]	61	30	42
Piwinski parameter	6.77E-01	7.89E-01	1.41E+00
geom. reduction	8.28E-01	7.85E-01	4.81E-01
beam-beam / IP	3.10E-03	4.35E-03	4.00E-03
Luminosity	1 10E+34	2 10E+34	1 10E+34

Integrated luminosity

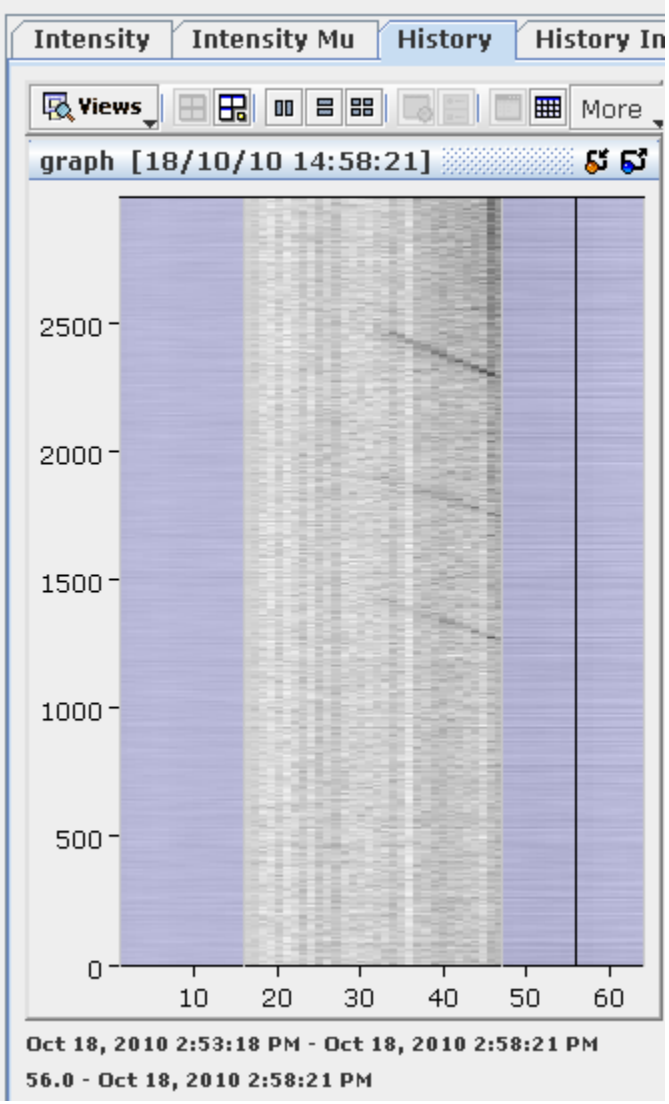
Courtesy M. Ferro-Luzzi



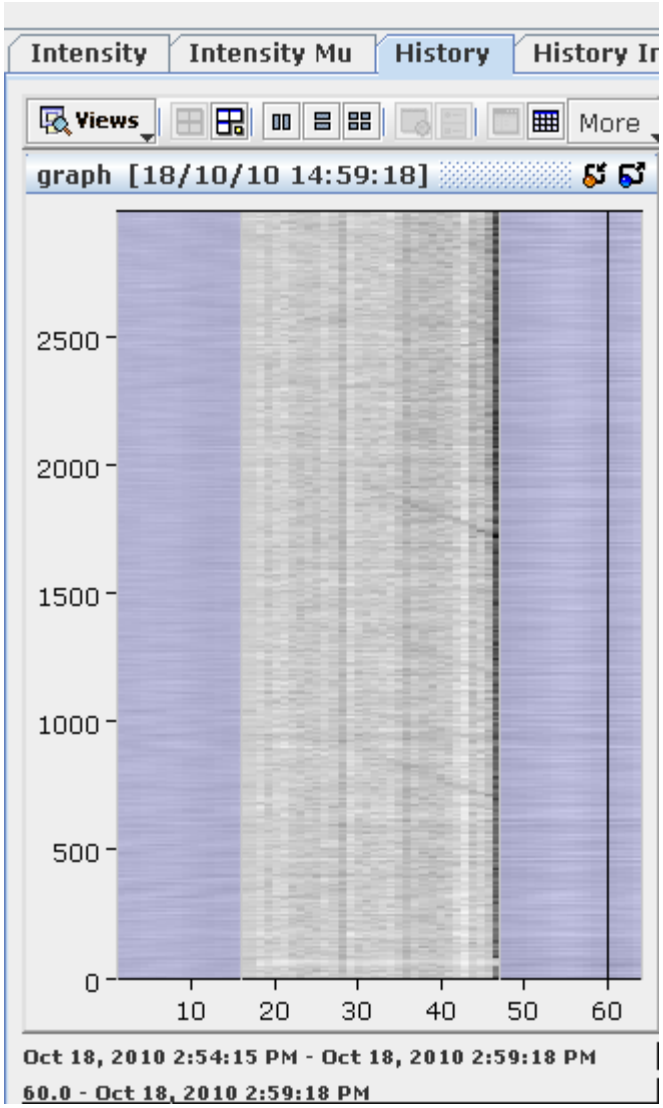


Abort Gap monitor

Adam Jeff – Andrea Boccardi



Beam 1



Beam 2

M. Lamont

3.5 TeV: run flat out at ~100 pb^{-1} per month

	Nb	ppb	Total Intensity	MJ	beta*	Peak Lumi	Int Lumi per month [pb^{-1}]
50 ns	432	7 e10	3 e13	17	2.5	7.4 e31	~63 (34)
Pushing intensity limit	796	7 e10	5.1 e13	31	2.5	1.4 e32	~116 (63)

16% nominal

Should be able to deliver around 1 fb^{-1}

Performance Tables

Limitations are highlighted in yellow; values to be demonstrated are in italic.

LHC INJECTORS WITH LINAC2		Nominal LHC Double Batch	Expected Maximum Double Batch	Original proposal, 1997 Nominal	Original proposal, 1997 Ultimate
PSB out ($\varepsilon^* \leq 2.5\ \mu m$)	ppr	1.62 x10^{12} *(1bunch/ring)* ↓ *(6 bunches, h=7)*	1.8 x10^{12} *(1bunch/ring)* ↓ *(6 bunches, h=7)*	1.05 x10^{12} *(1bunch/ring)* ↓ *(8 bunches, h=8)*	1.8 x10^{12} *(1bunch/ring)* ↓ *(8 bunches, h=8)*
PS out, per pulse	ppp	9.72 x10^{12}	10.8 x10^{12}	8.4 x10^{12}	14.4 x10^{12}
PS out, per bunch ($\varepsilon^* \leq 3\ \mu m$)	ppb	1.35 x10^{11} *(72 bunches)* ↓ *15% loss*	1.5 x10^{11} *(72 bunches)* ↓ *15% loss*	1.0 x10^{11} *(84 bunches)* ↓ *no loss*	1.7 x10^{11} *(84 bunches)* ↓ *no loss*
SPS out	ppb	1.15 x10^{11}	*1.27 x10^{11}*	1.0 x10^{11}	1.7 x10^{11}

M. Vretenar @ Chamonix 2010

LHC INJECTORS WITH LINAC4		Nominal LHC Single batch	Maximum Single batch	Maximum Double batch	Single batch + PS h=14, 12 bunches scheme
PSB out ($\varepsilon^* \leq 2.5\ \mu m$)	ppr	3.25 x10^{12} *(2bunch/ring)* ↓ *(6 bunches, h=7)*	3.6 x10^{12} *(2bunch/ring)* ↓ *(6 bunches, h=7)*	1.8 x10^{12} *(1bunch/ring)* ↓ *(6 bunches, h=7)*	*3.6 x10^{12} (3bunch/ring)* ↓ *(12 bunches, h=14)*
PS out, per pulse	ppp	9.72 x10^{12}	*10.8 x10^{12}*	*12.3 x10^{12} (scaled 1998 limit, 206ns bunches)*	*14.4 x10^{12} (lower ΔQ in single batch)*
PS out, per bunch ($\varepsilon^* \leq 3\ \mu m$)	ppb	1.35 x10^{11} *(72 bunches)* ↓ *15% loss*	*1.5 x10^{11} (72 bunches)* ↓ *<15% loss*	*1.7 x10^{11} (72 bunches)* ↓ *20% loss*	*2.0 x10^{11} (72 bunches)* ↓ *20% loss*
SPS out	ppb	1.15 x10^{11}	*>1.3 x10^{11}*	*1.37 x10^{11}*	*1.6 x10^{11}*

Goal:

Nominal intensity in single batch: shorter filling time, lower losses and emittance growth.

Potential for ultimate intensity out of PS in double batch.

Potential for > ultimate with a new PS scheme (in PSB: new recombination kicker, new RF gymnastics).

SPS: present achievements

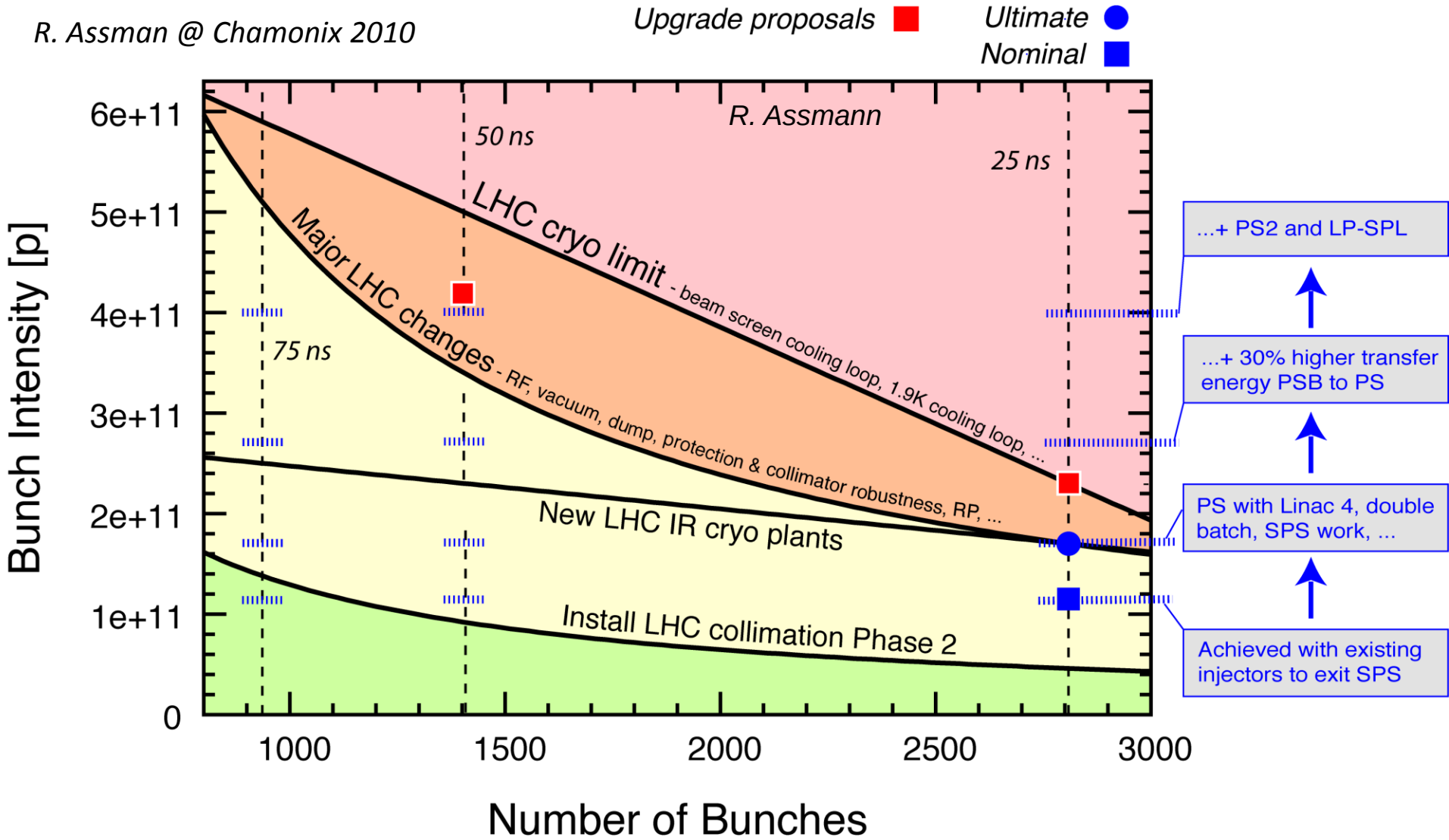
E. Chaposhnicova @ Chamonix 2010

Parameters	SPS record at 450 GeV/c		LHC request 25 ns	
	25 ns	FT	nominal	ultimate
bunch intensity/10^{11}	**1.2**	0.13	1.2	**1.8**
number of bunches in SPS	288	4200	288	288
total intensity/10^{13}	3.5	**5.3**	3.5	5.2
long. emittance [eVs]	0.7	0.8	<1.0	<1.0
norm. H/V emitt. [μm]	**3.6**	8/5	**3.5**	3.5

→ SPS upgrade is necessary for intensity above nominal LHC

Summary of LHC Intensity Limits (7 TeV)

R. Assman @ Chamonix 2010



Ideal scenario: no imperfections included!

Note: Some assumptions and conditions apply…