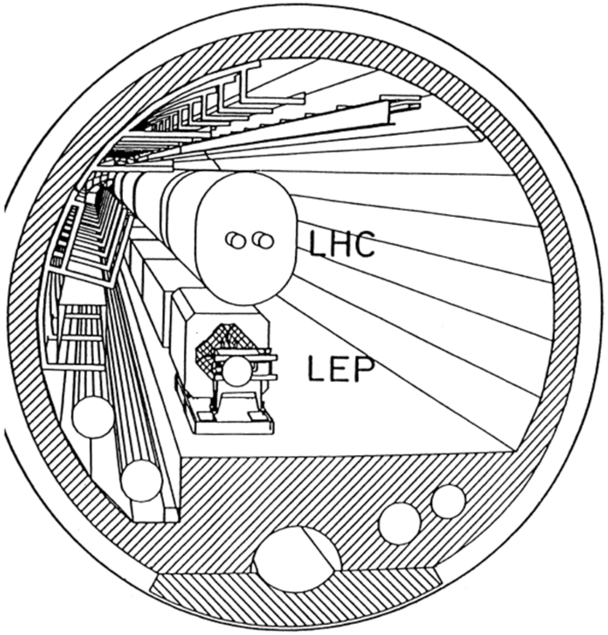
LHC - challenges in handling beams exceeding 140 MJ



LARGE HADRON COLLIDER
IN THE LEP TUNNEL

Vol. I

PROCEEDINGS OF THE ECFA–CERN WORKSHOP

held at Lausanne and Geneva,
21–27 March 1984

Organizing Committee

G. Brianti, CERN; W. Hoogland, NIKHEF;
M. Jacob, CERN; C. Joseph, Lausanne
J. Mulvey, Oxford; C. Rubbia, CERN
J. Sacton, Brussels

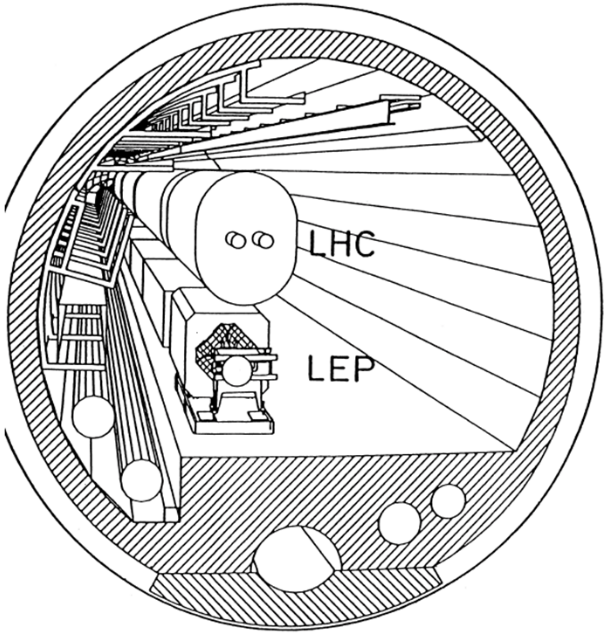
These Proceedings are dedicated

HB2012

Institute of High Energy Physics, Beijing
September 17-21, 2012

Rüdiger Schmidt, CERN
17 September 2012

…..a long history



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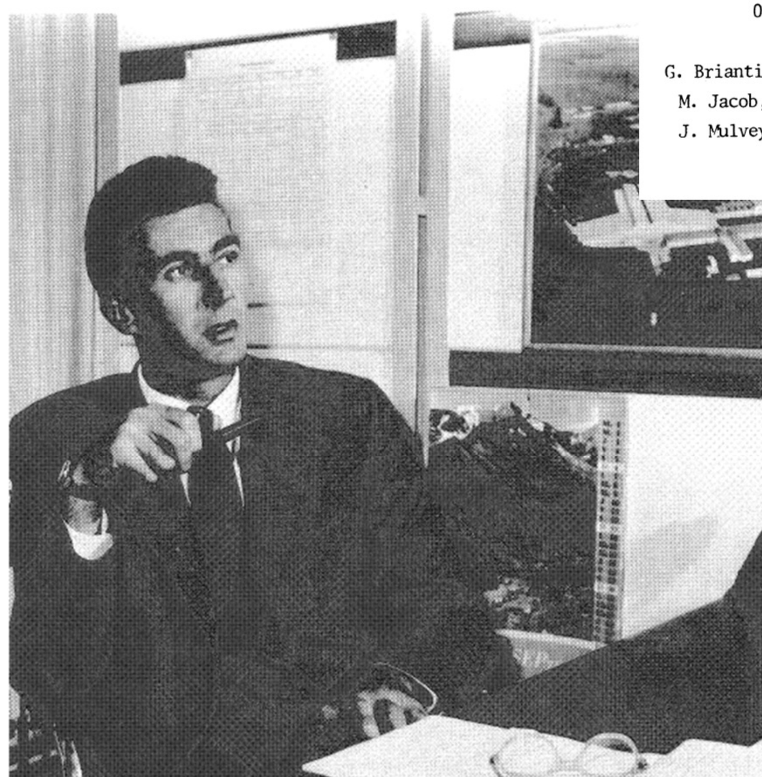

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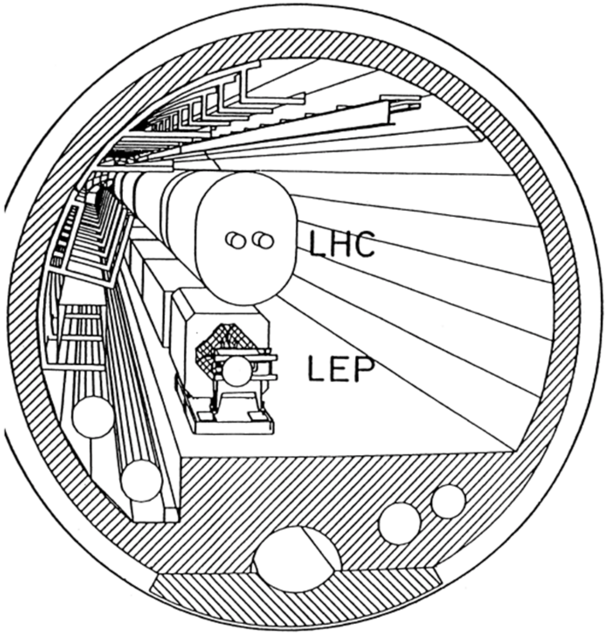
Introduction to the LHC and its challenges

Machine protection and collimation

Operational cycle and observations

Final remarks

also be big enough to accommodate another ring of magnets.



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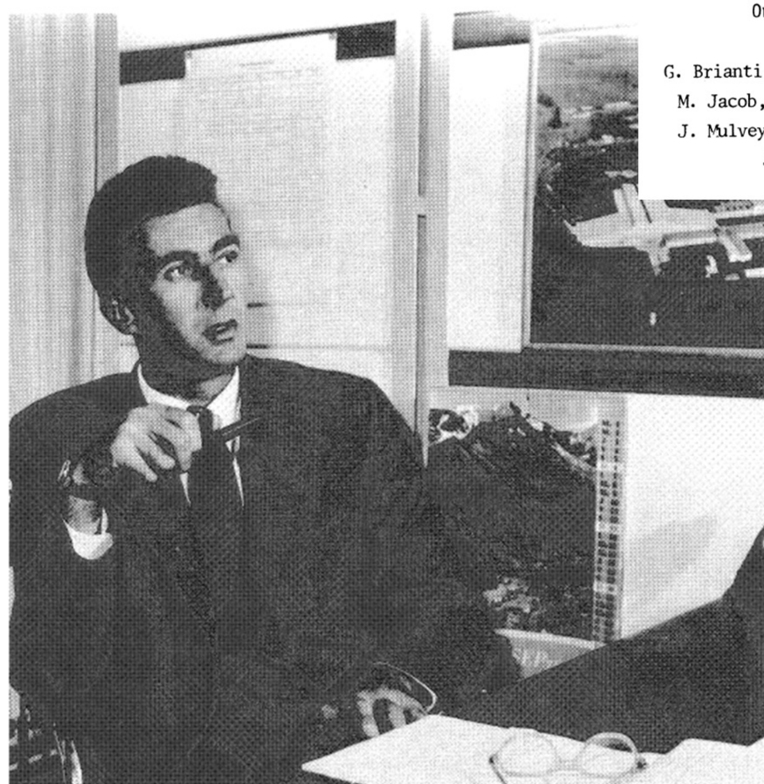

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This presentation is an introduction to LHC challenges, details are presented in a large number of presentation on LHC and its Injectors during this workshop

This presentation is on behalf of the large team working on LHC and its injectors. Acknowledgements to many colleagues for their help and material.

also be big enough to accommodate another ring of magnets.

LHC nominal versus LHC today

Nominal

- Proton momentum: **7 TeV/c**
- Peak Luminosity: 10^{34} [$cm^{-2}s^{-1}$]
- Stored energy/beam: **2808 bunches (25 ns): 362 MJoule**

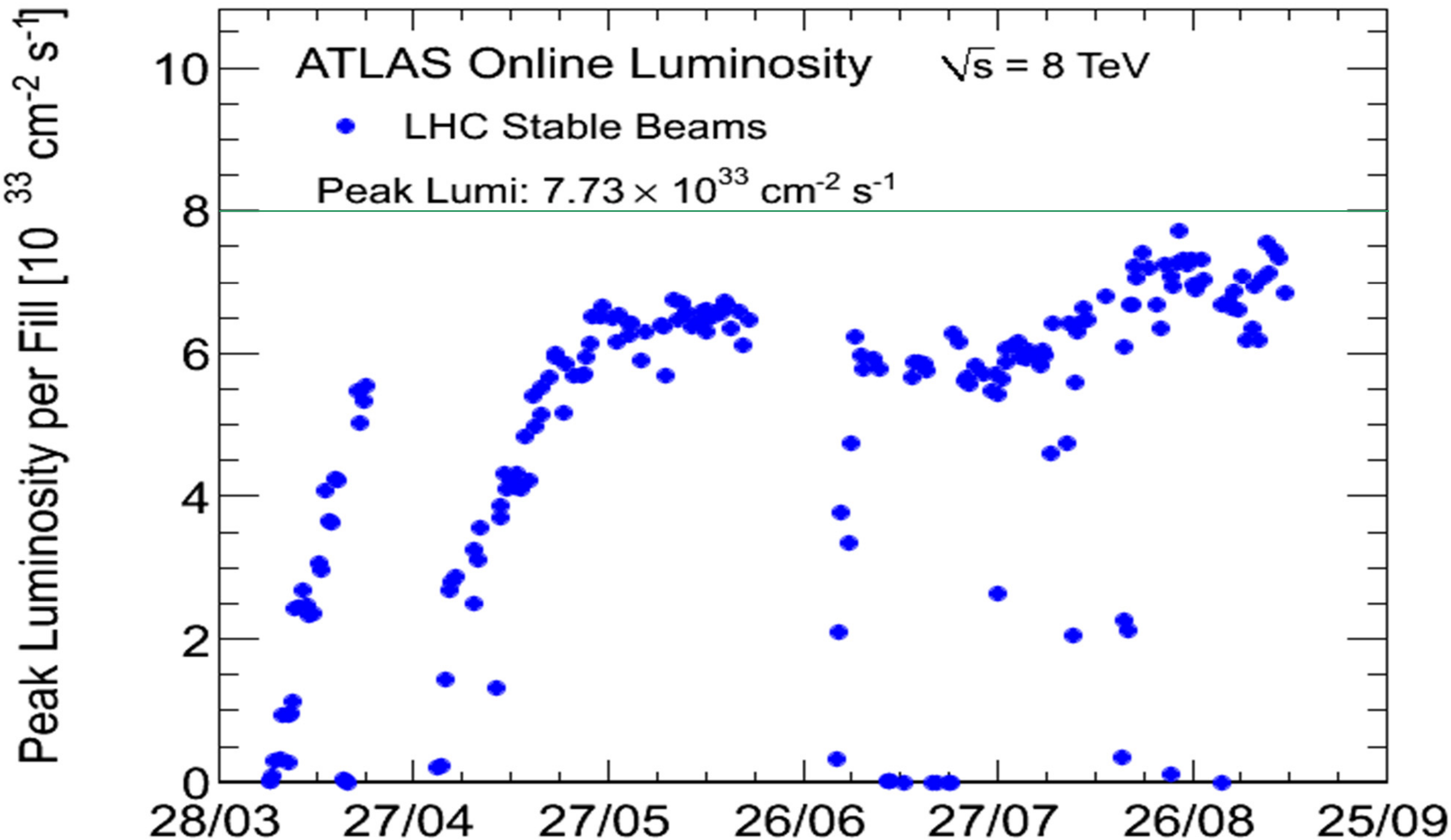
Operation in 2008-2011

- LHC start of beam operation in 2008, followed by the accident
- LHC re-start of beam operation limited to 3.5 TeV in 2009
- Successful operation in 2010 and 2011 at 3.5 TeV

Operation in 2012

- Proton momentum: **4 TeV/c**
- Peak Luminosity: $7.7 \cdot 10^{33}$ [$cm^{-2}s^{-1}$]
- Stored energy/beam: **1380 bunches (50 ns): 140 MJoule**

Peak luminosity evolution during 2012

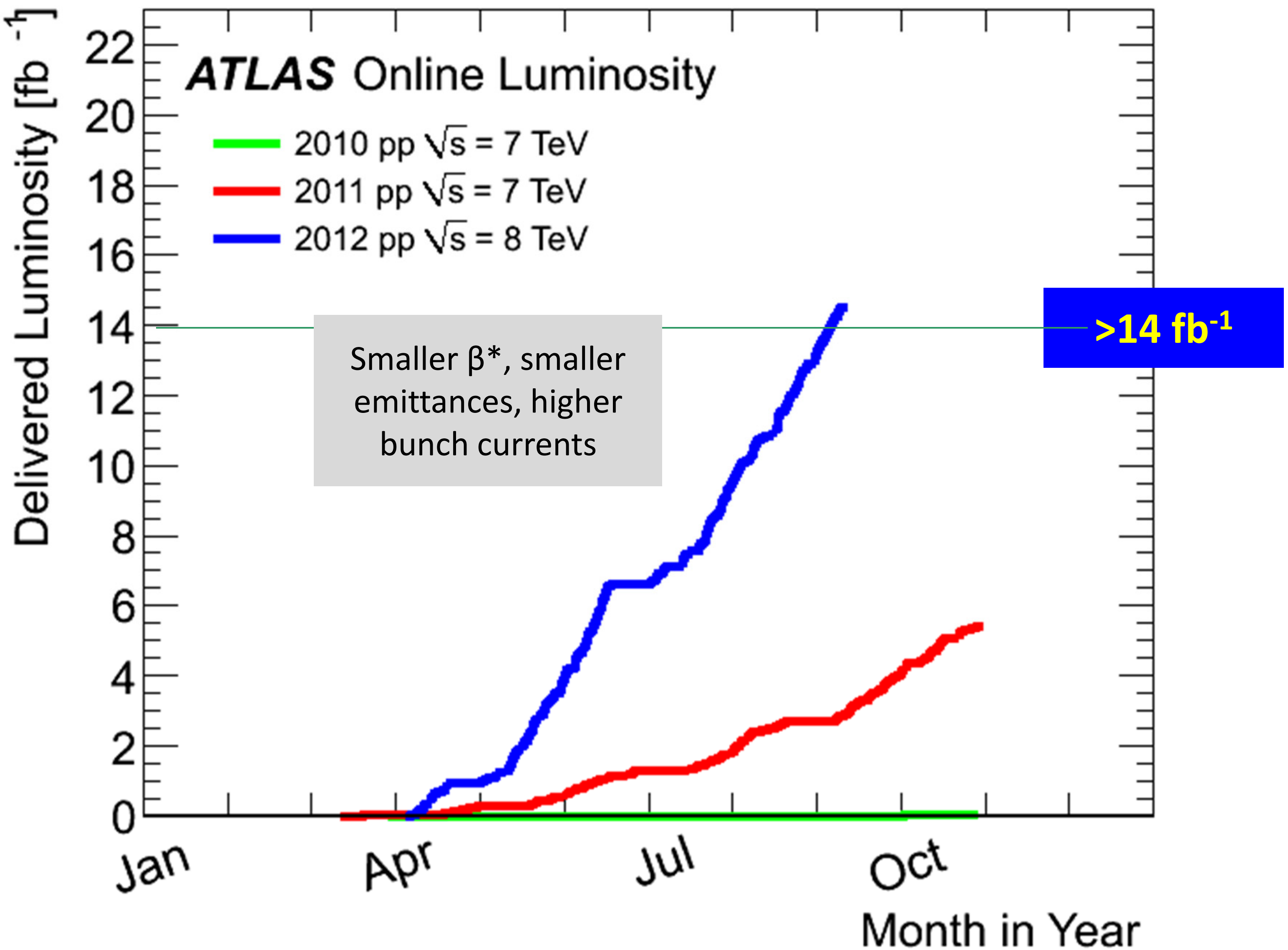


Start-up phase for machine protection

Recovering from technical stop and increase - approaching limits

Recovering from technical stop, approaching limits, changing parameters

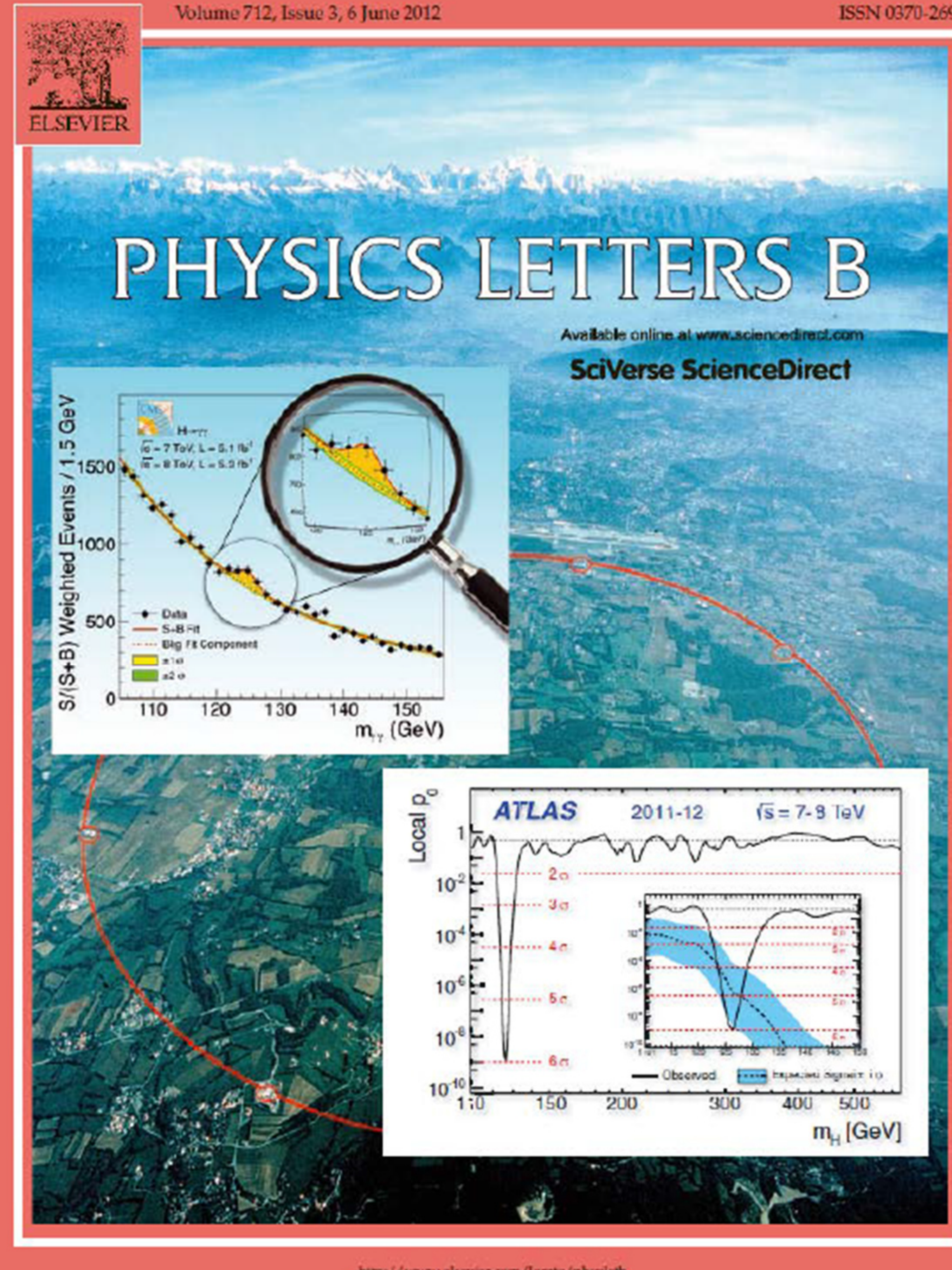
Integrated luminosity in 2012



excellent

ATLAS Collaboration, ***Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC***, Phys.Lett.B (2012)

CMS Collaboration, ***Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC***, Phys.Lett.B (2012



LHC luminosity (nominal parameters at 7 TeV)

Number of protons per bunch limited to about **1-3×10^{11}** due to the beam-beam interaction and beam instabilities, nominal **1.15×10^{11}**

Emittance given by injectors, nominal emittance constant

f = **11246 Hz**

Beam size **16 μm** for β = 0.5 m (β function)

$$L = \frac{N^2 \times f \times n_b}{4 \times \pi \times \sigma_x \times \sigma_y} = 3.5 \times 10^{30}\ [cm^{-2}\ s^{-1}]$$ for one bunch

with **2808** bunches (every 25 ns one bunch)

L = 10^{34} [cm^{-2}s^{-1}]

Role of injector complex

- The luminosity depends on the **emittance** and the **intensity per bunch (=> high brightness)**, given to a large extent by the complex chain of injectors (LINAC, Booster, PS and SPS)
- Other parameters are the number of bunches
  - Beam structure (25 ns or 50 ns bunch spacing), also defined by the injectors
  - Number of bunches in a batch (e.g. 144 bunches/batch from SPS -> LHC)
  - In total, 1380 bunches in 2012
- A large amount of work is going on to understand and improve the beam parameters in the injector complex
  - Understanding and improving present performance
  - Improvement program during the next decade

Reports related to the improvements of the injectors

- **Brightness** Evolution for LHC Beams during the 2012 Run, Bettina Mikulec (CERN, Geneva)
- Low gamma transition optics for the SPS: simulation and experimental results for **high brightness** beams, Hannes Bartosik (CERN, Geneva)
- Beam Stability and Tail Population at SPS Scrapers, Bettina Mikulec (CERN, Geneva)
- Review of longitudinal instabilities in the SPS and beam dynamics issues with high harmonic RF systems in accelerators, Elena Shaposhnikova (CERN, Geneva)
- Tune Spread Studies at Injection Energies for the CERN Proton Synchrotron Booster, Bettina Mikulec (CERN, Geneva)
- Longitudinal Beam Loss Studies of the CERN PS-to-SPS Transfer, Helga Timko (CERN, Geneva)
- Fully 3D long-term simulation of the coupling resonance experiments at the CERN PS, Ji Qiang (LBNL, Berkeley, California)

Longer term programme

- The high intensity/**high brightness** upgrade program at CERN: status and challenges, Simone Silvano Gilardoni (CERN, Geneva)
- Linac4 beam dynamics and commissioning strategy, Jean-Baptiste Lallement (CERN, Geneva)

Challenges

The LHC: just another collider ?

	Start	Type	Max proton energy [GeV]	Length [m]	B Field [Tesla]	Luminosity [$cm^{-2}s^{-1}$]	Stored beam energy [MJoule]
TEVATRON Fermilab Illinois USA	1983	p-pbar	980	6300	4.5	$4.3\ 10^{32}$	1.6 for protons
HERA DESY Hamburg	1992	p – e+ p – e-	920	6300	5.5	$5.1\ 10^{31}$	2.7 for protons
RHIC Brookhaven Long Island	2000	Ion-Ion p-p	250	3834	4.3	$1.5\ 10^{32}$	0.9 per proton beam
LHC CERN	2008	Ion-Ion p-p	7000 Now 4000	26800	8.3	10^{34} Now $6\ 10^{33}$	**362 per beam**
Factor			7	4	2	**20**	**100**

Challenges: High Luminosity and Machine Protection

- Large amount of energy stored in the beams
- Injecting beams, performing the energy ramp and bringing the beams into collisions …. without quenching or even damaging accelerator and experiments
- Dumping 130 MJ beam without quenching magnets
- Detecting all failures that could lead to uncontrolled beam losses
- Avoiding beam losses, in particular in the superconducting magnets
  - Superconducting magnets might quench when 10^{-8}-10^{-7} of beam (10^{6}-10^{7} protons) hit magnet
  - Beam cleaning using collimators (betatron and momentum cleaning) is vital during operation
- Radiation, in particular in experimental areas from beam collisions
  - Single event upset in the tunnel electronics
  - Radiation induced damaged of material (not yet observed)

Challenges: High Luminosity and Beam Dynamics

- Beam-Beam effects, head-on and long range
- Beam instabilities due to the machine impedance
  - Collimators with jaws very close to beam contribute to the impedance
  - Collimator position depends on energy and on beta function at collision point (collimators move close to the beam during energy ramp)
- Heating of components close to the beam (kickers, collimators, beam instruments, vacuum bellows, …), already (limited) damage of components
- Electron cloud effects
  - Photo electrons, generated by beam losses - accelerated by the following bunches – lead to instabilities
- Tools to fight instabilities
  - Octupoles, chromaticity, transverse damper, …
  - Head-on beam-beam effect provides stability (tune spread)

7 TeV and 2800 bunches 360 MJoule - what does this mean?

The energy of an 200 m long fast train at 155 km/hour corresponds to the energy of 360 MJoule stored in one LHC beam

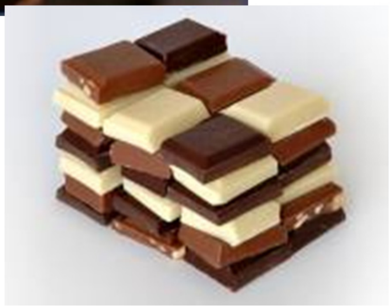
360 MJoule: the energy stored in one LHC beam corresponds approximately to…

- 90 kg of TNT
- 8 litres of gasoline
- 15 kg of chocolate

It's how easy the energy is released that matters most !!

360 MJoule - what does this mean?

The energy of an 200 m long fast train at 155 km/hour corresponds to the energy of 360 MJoule stored in one LHC beam



An experiment on hydrodynamic tunnelling of the SPS high intensity proton beam at the HiRadMat facility, Juan Blanco (CERN, Geneva)

High Energy Tests of Advanced Materials for Beam Intercepting Devices at CERN HiRadMat Facility, Alessandro Bertarelli (CERN, Geneva)

SPS experiment: Beam damage with 450 GeV proton beam

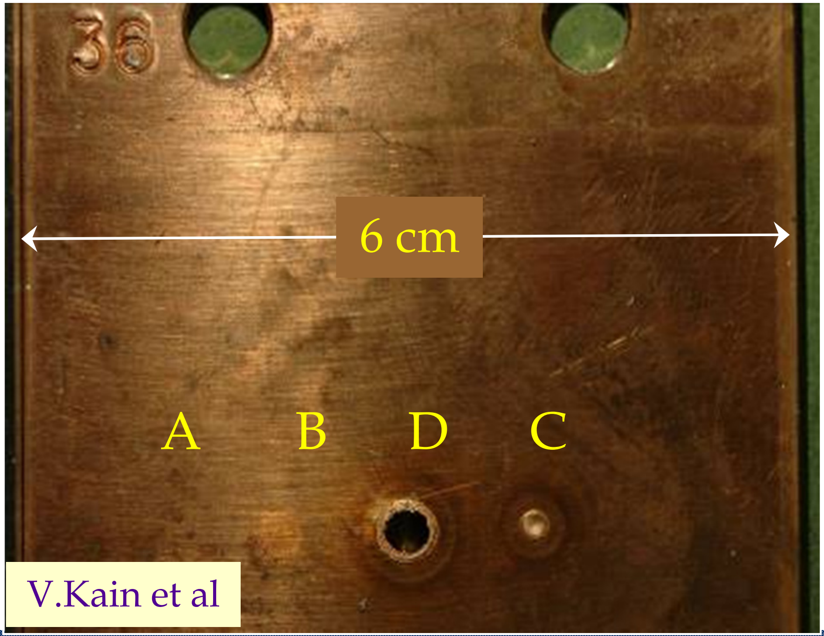
Controlled SPS experiment

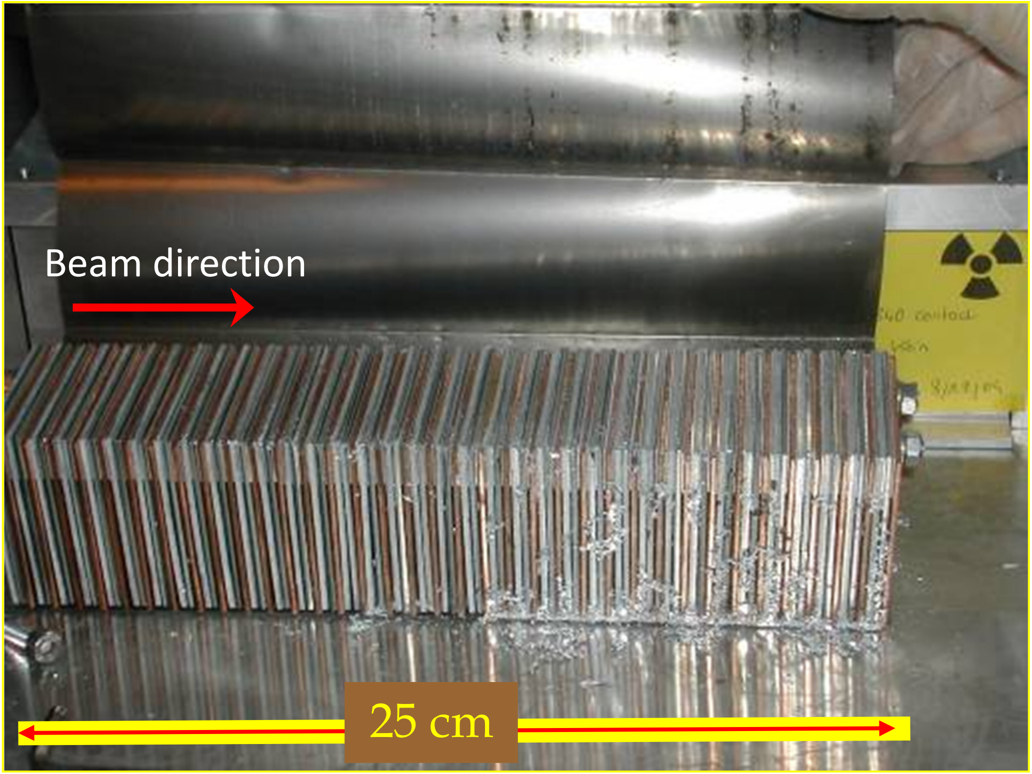
- $8 \cdot 10^{12}$ protons clear damage
- beam size $\sigma_{x/y}$ = 1.1mm/0.6mm

above damage limit for copper

- $2 \cdot 10^{12}$ protons

below damage limit for copper





- Damage limit ~200 kJoule
- 0.1 % of the full LHC 7 TeV beams
- Energy in a bunch train injected into LHC: factor of ~10 above

Beam losses

Particles are lost due to a variety of reasons

- Beam-gas interaction
- Losses from collisions
- Losses due to the beam halo touching the aperture
- Losses due to instabilities
- Losses due to failures (e.g. power converters, RF, controls, ….)
- End of a physics fill

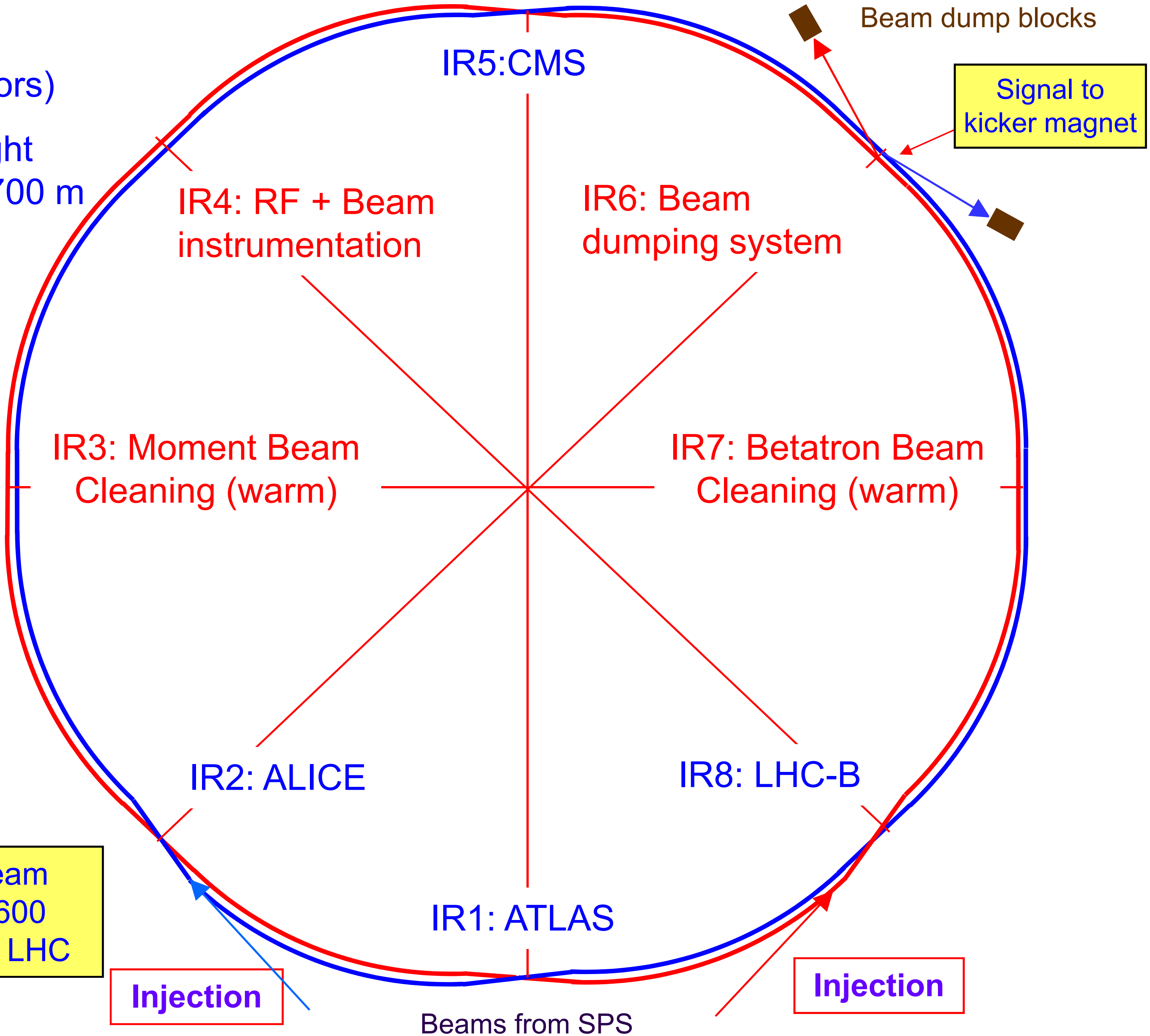
- **Continuous beam losses** are inherent to the operation of accelerators
  - Taken into account during the design of the accelerator
- **Accidental beam losses** are due to a multitude of failures mechanisms
  - The number of possible failures leading to accidental beam loss is (nearly) infinite
  - Any failure must result in beam dumps to avoid uncontrolled beam loss

Machine protection and collimation

LHC Layout

eight arcs (sectors)

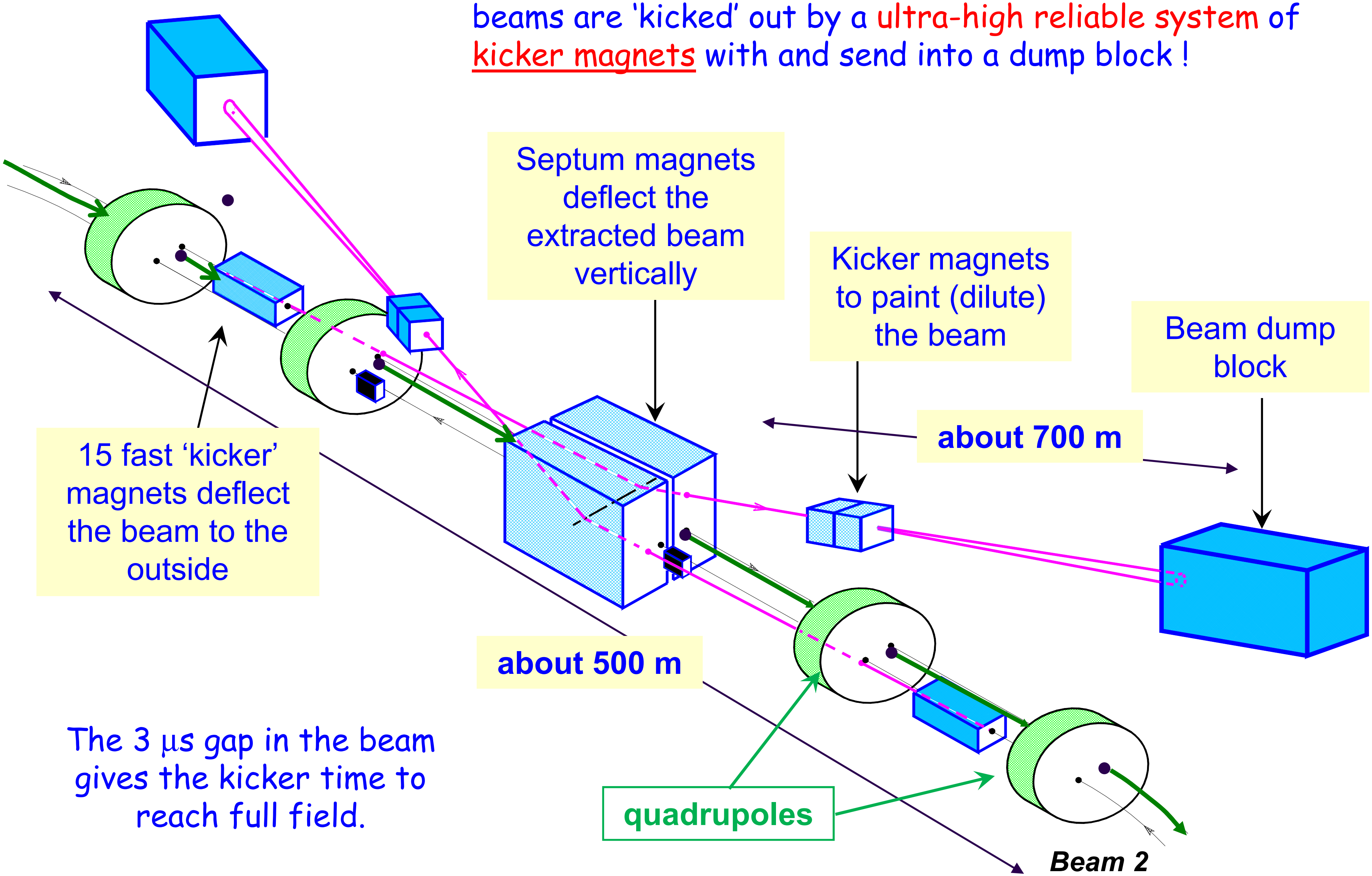
eight long straight section (about 700 m long)



Detection of beam losses with >3600 monitors around LHC

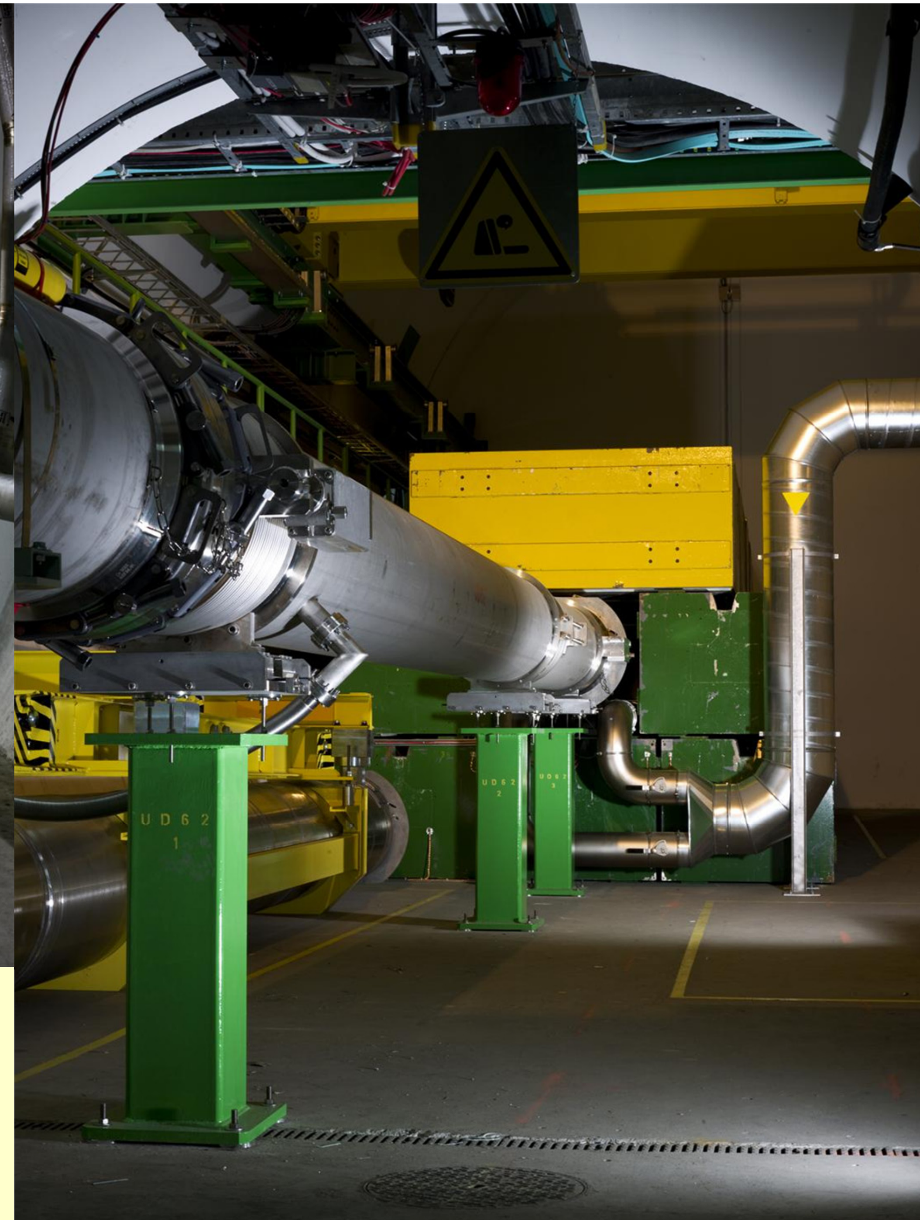
Layout of beam dump system

To get rid of the beams (also in case of emergency!), the beams are 'kicked' out by a ultra-high reliable system of kicker magnets with and send into a dump block !



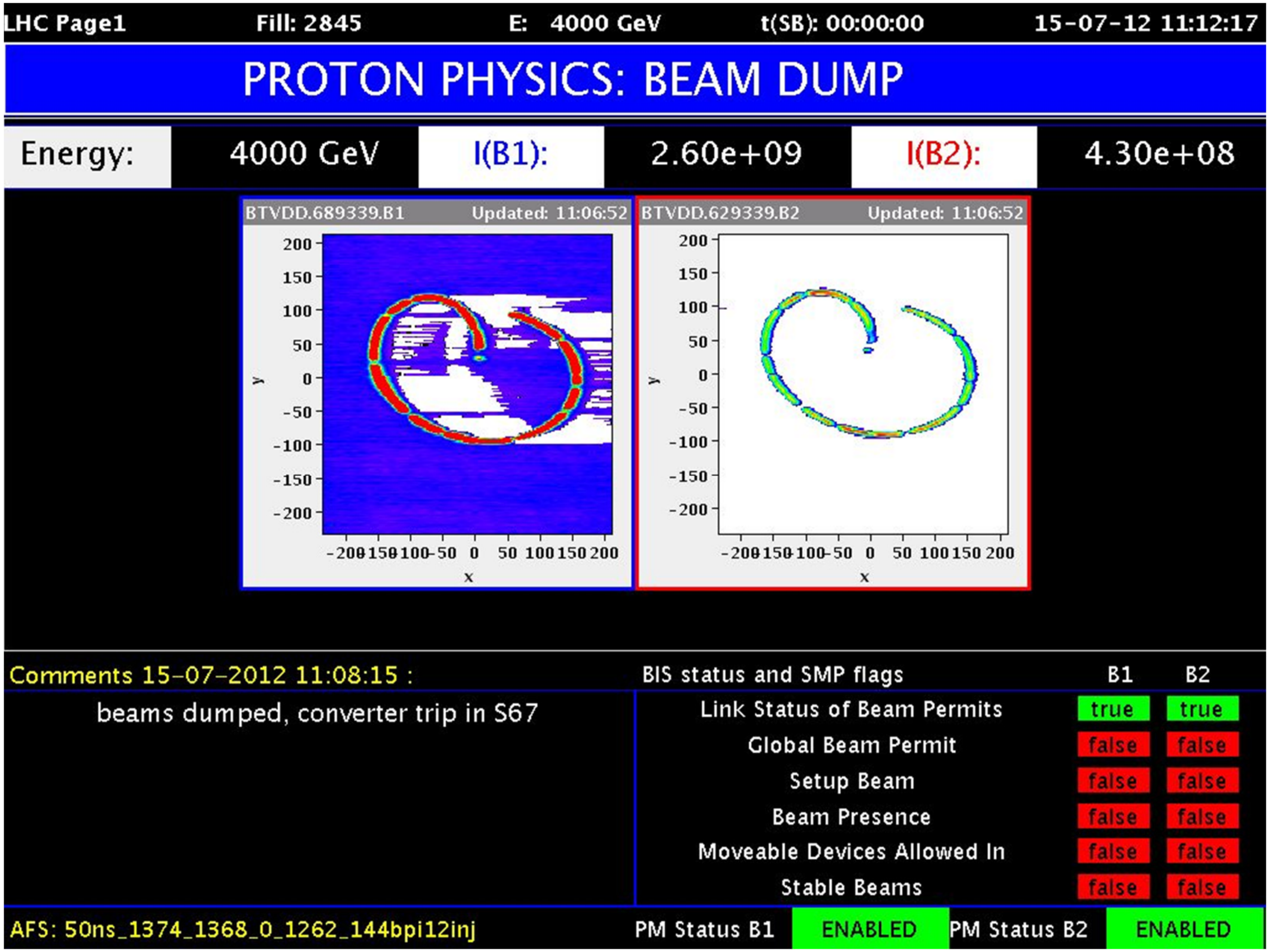
The 3 μs gap in the beam gives the kicker time to reach full field.

Dump line



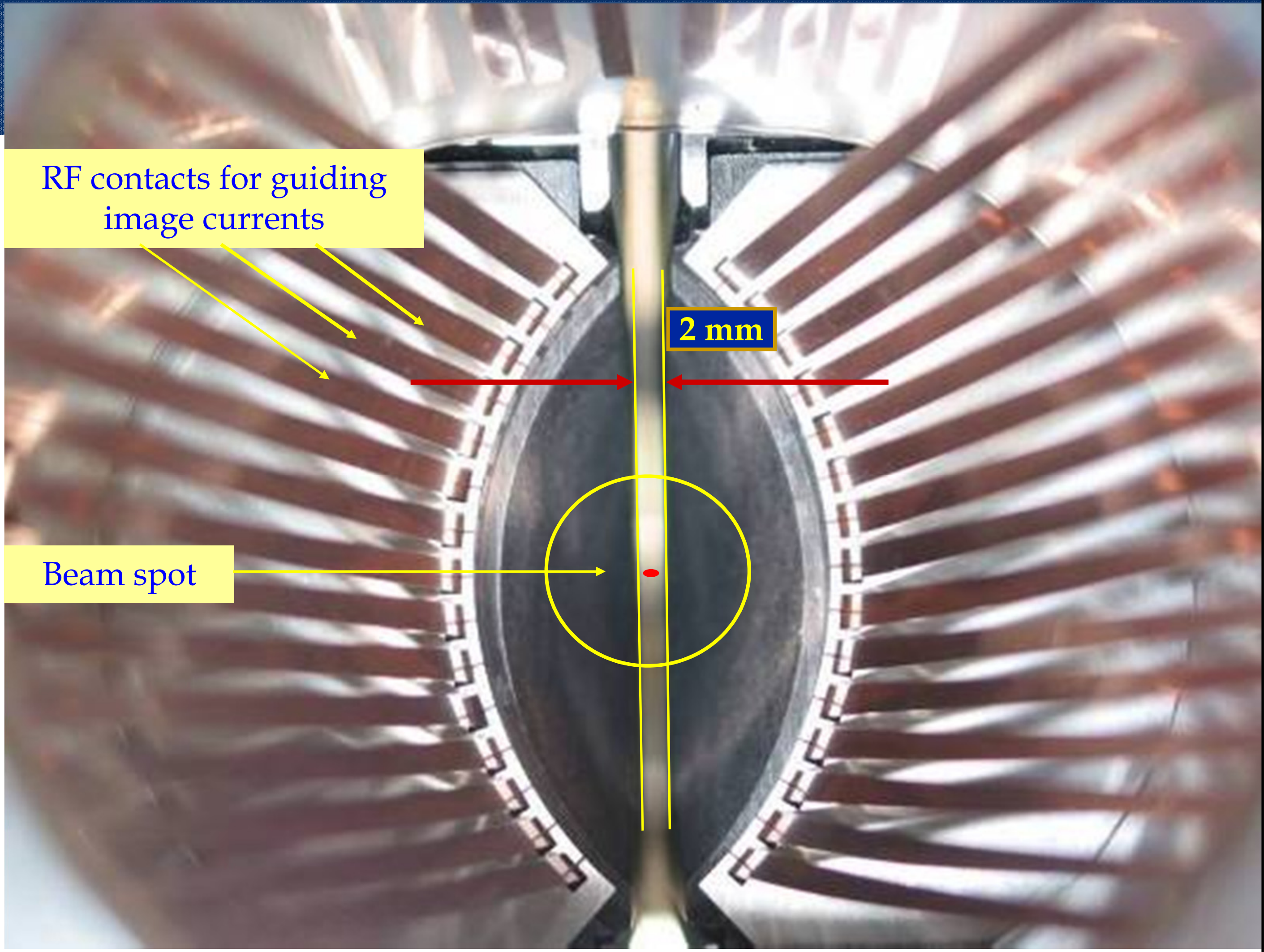
Beam dump line and graphite absorber at the end

Beam dump with 1380 bunches

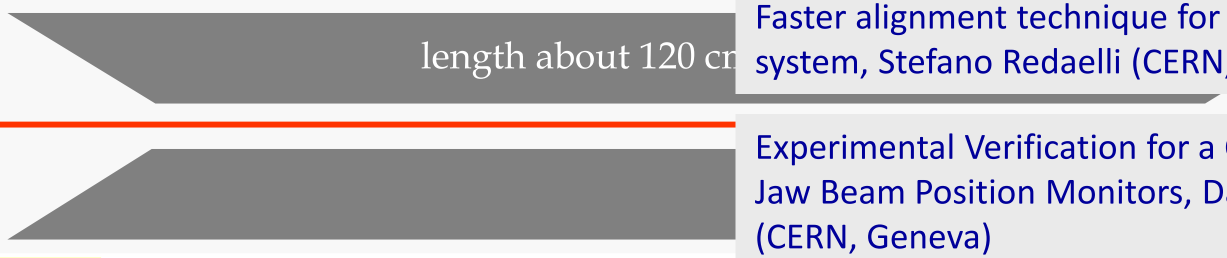


Beam spot at the end of the beam dumping line, just in front of the beam dump block

View of a two sided collimator



about 100 collimators are installed in LHC



Faster alignment technique for the LHC collimation system, Stefano Redaelli (CERN, Geneva)

Experimental Verification for a Collimator with In-Jaw Beam Position Monitors, Daniel Wollmann (CERN, Geneva)

Betatron beam cleaning

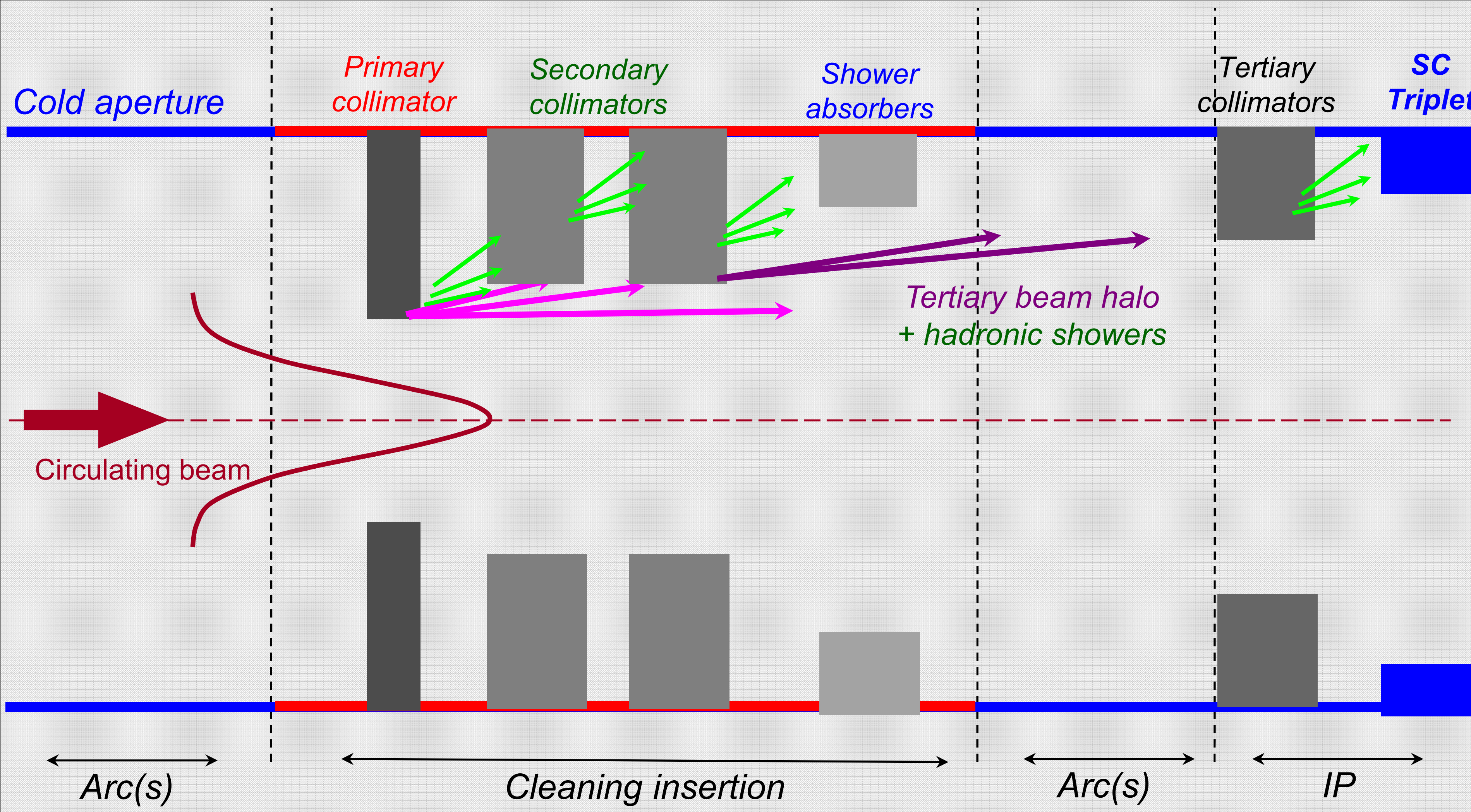
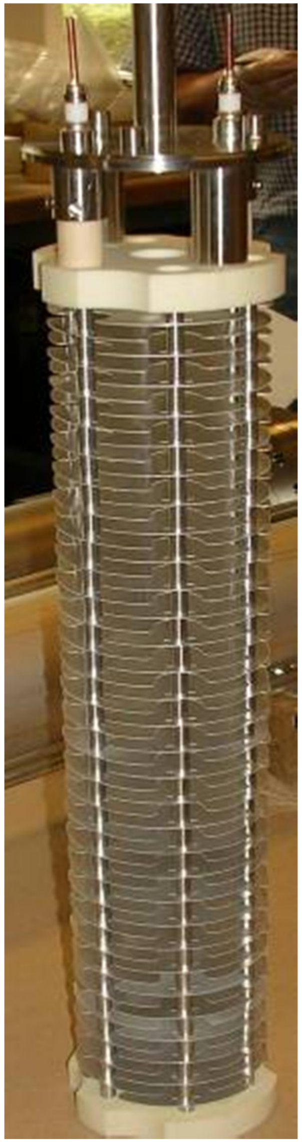


Illustration drawing

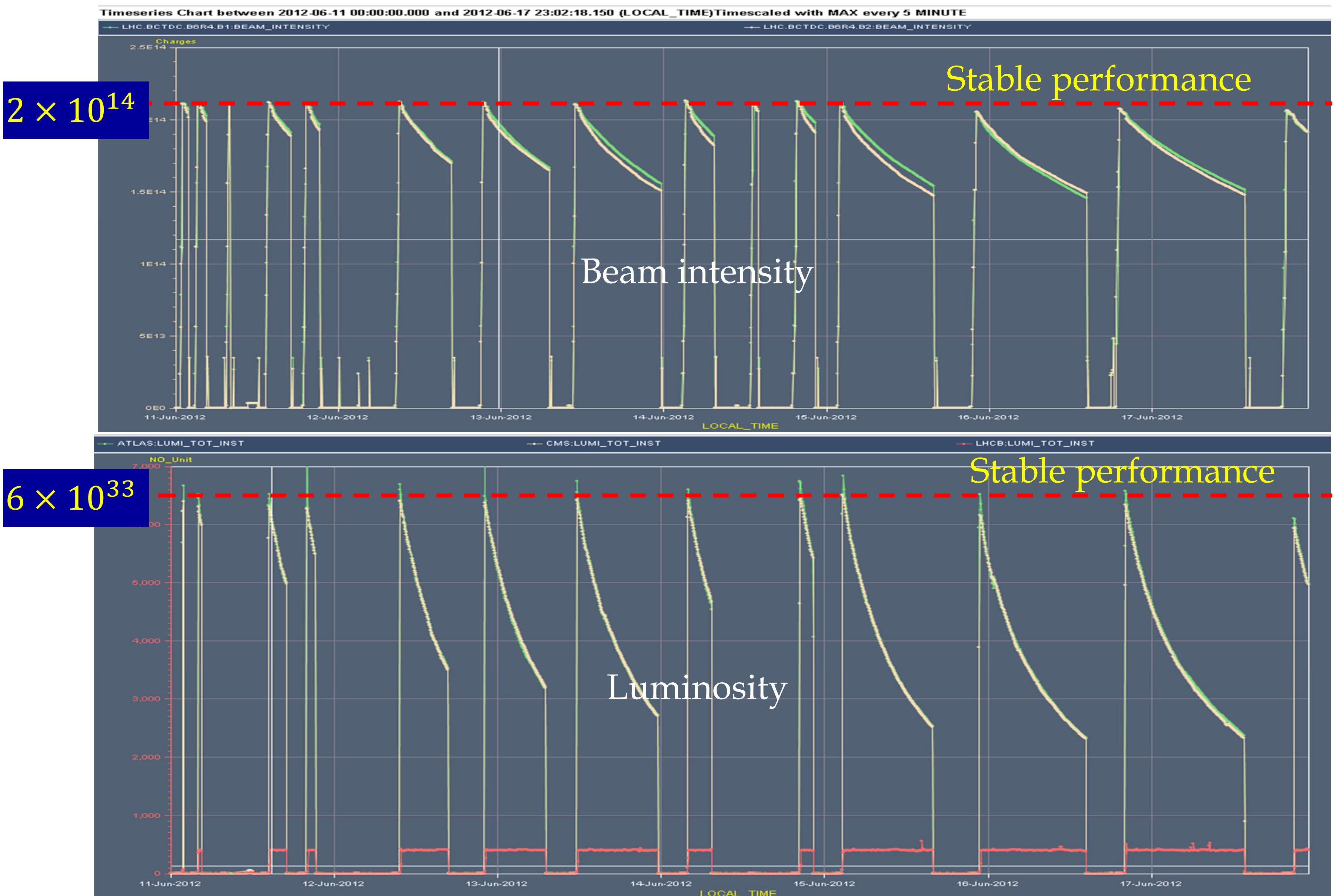
Beam Loss Monitors

- Ionization chambers to detect beam losses:
  - Reaction time ~ ½ turn (40 μs)
  - Very large dynamic range (> 10^6)
- ~3600 chambers distributed over the ring to detect abnormal beam losses and if necessary trigger a beam abort (happened many times…)



Operational cycle and observations

Beam Intensities and Luminosity, 11-18/6/2012

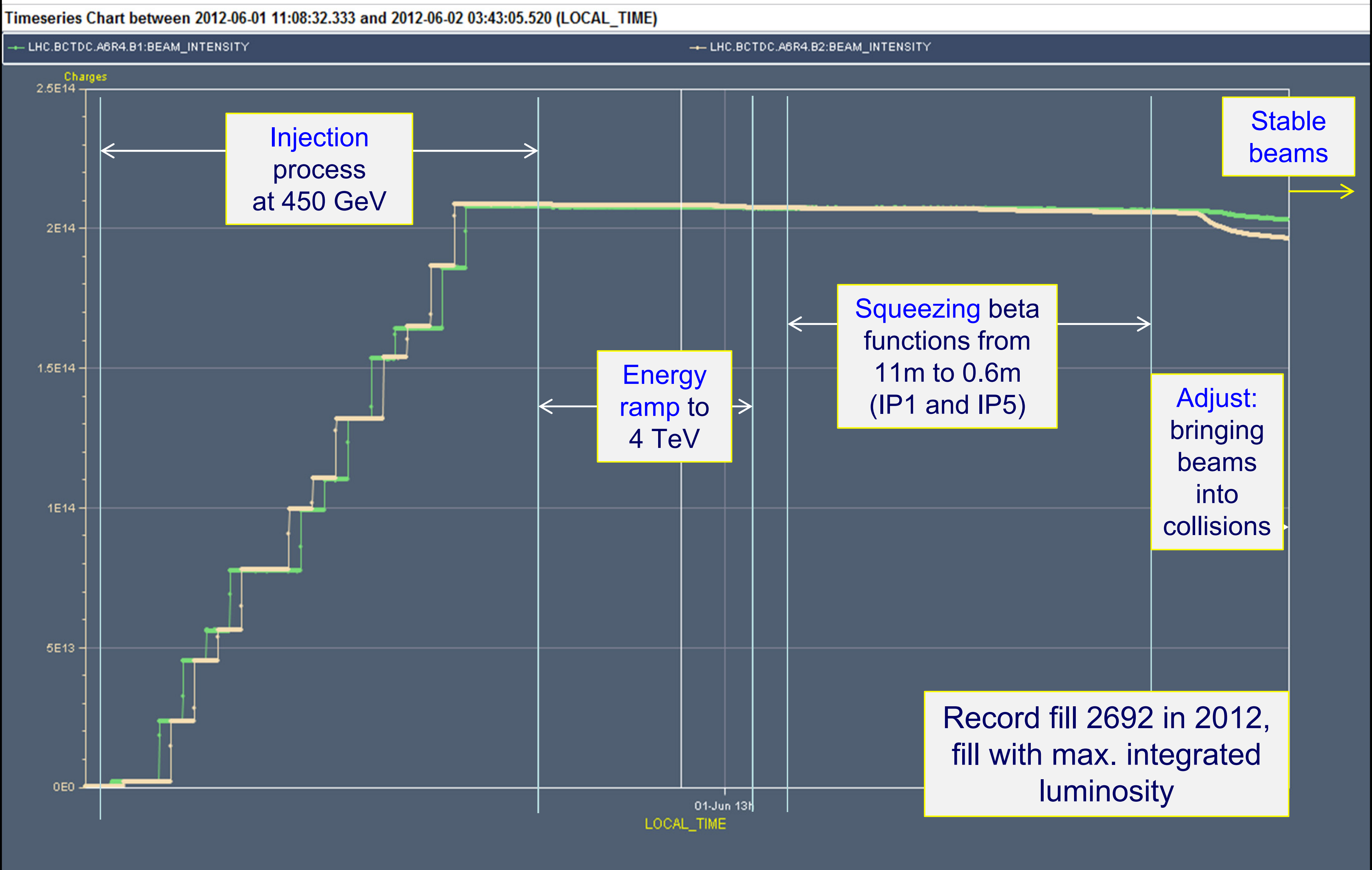


Overview of fills

Fill	Duration	Ibeam	Lpeak [e30 cm-2s-1]	Lint [pb-1]	Dump
2723	2:26	2.03E+14	6406	46.06	Trip of ROD.A81B1, SEU?
2724	1:13	2.03E+14	6329	25.905	Electrical perturbation
2725	7:04	2.05E+14	6520	115.5	Trip of S81
2726	8:58	2.05E+14	6499	142.5	Electrical perturbation, FMCM
2728	11:41	2.06E+14	6525	171.5	**Operator dump**
2729	3:28	2.06E+14	6502	67.7	BLM self trigger
2732	1:52	2.06E+14	6592.5	40	QPS trigger RQX.R1, SEU?
2733	12:34	2.06E+14	6674	183	Triplet RQX.L2 tripped.
2734	15:33	2.01E+14	6257.5	203.5	**Operator dump**
2736	17:29	2.02E+14	6465.5	233	**Operator dump**
2737	3:36	1.99E+14	6021	66.1	RF Trip 2B2
Total	**51.1%**			**1301**	

51 % of time in stable beams; total of **1.3 fb-1** in one week !

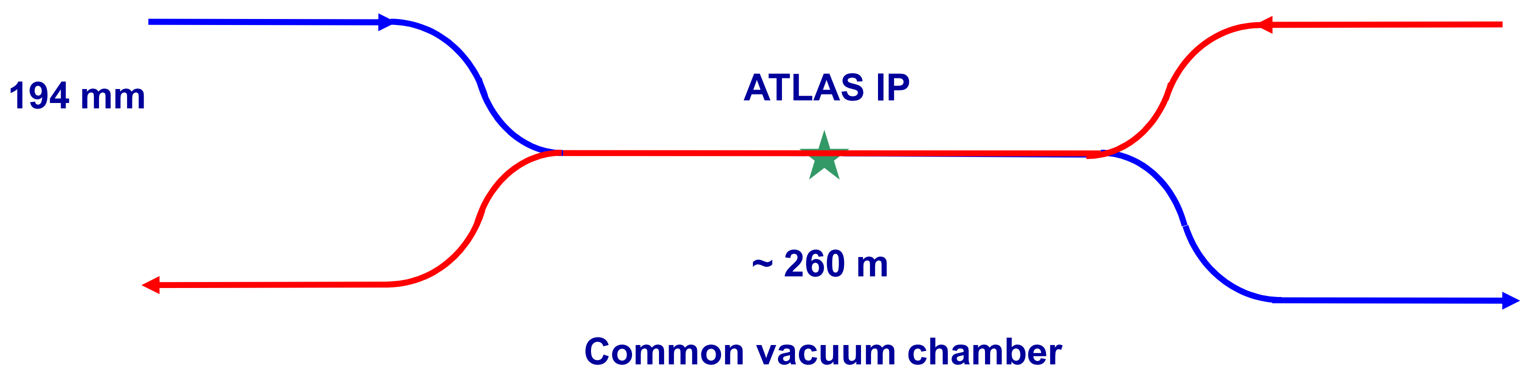
LHC operational cycle



Excellent fill 2195 in 2011

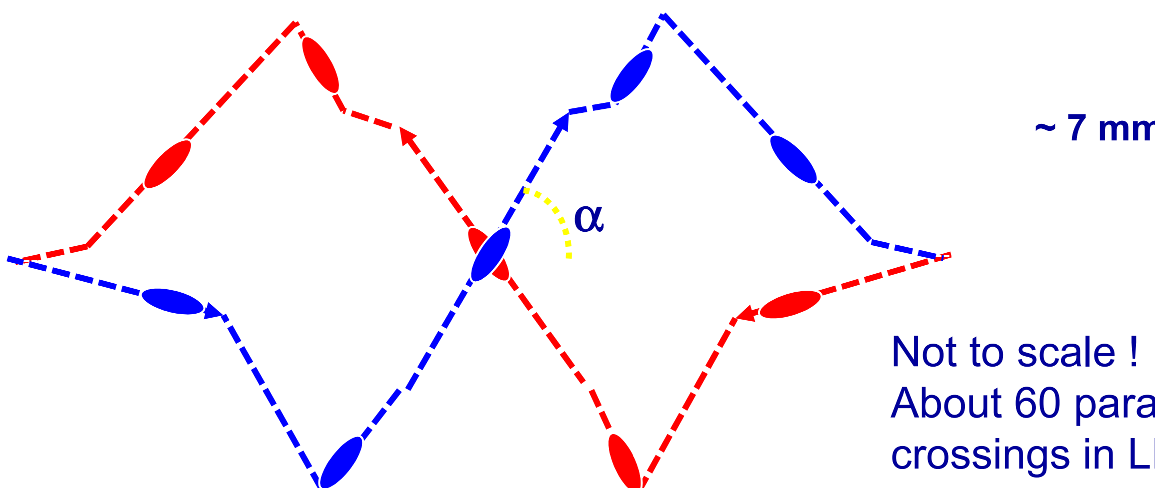
Separation and crossing: example of ATLAS

Horizontal plane: the beams are combined and then separated



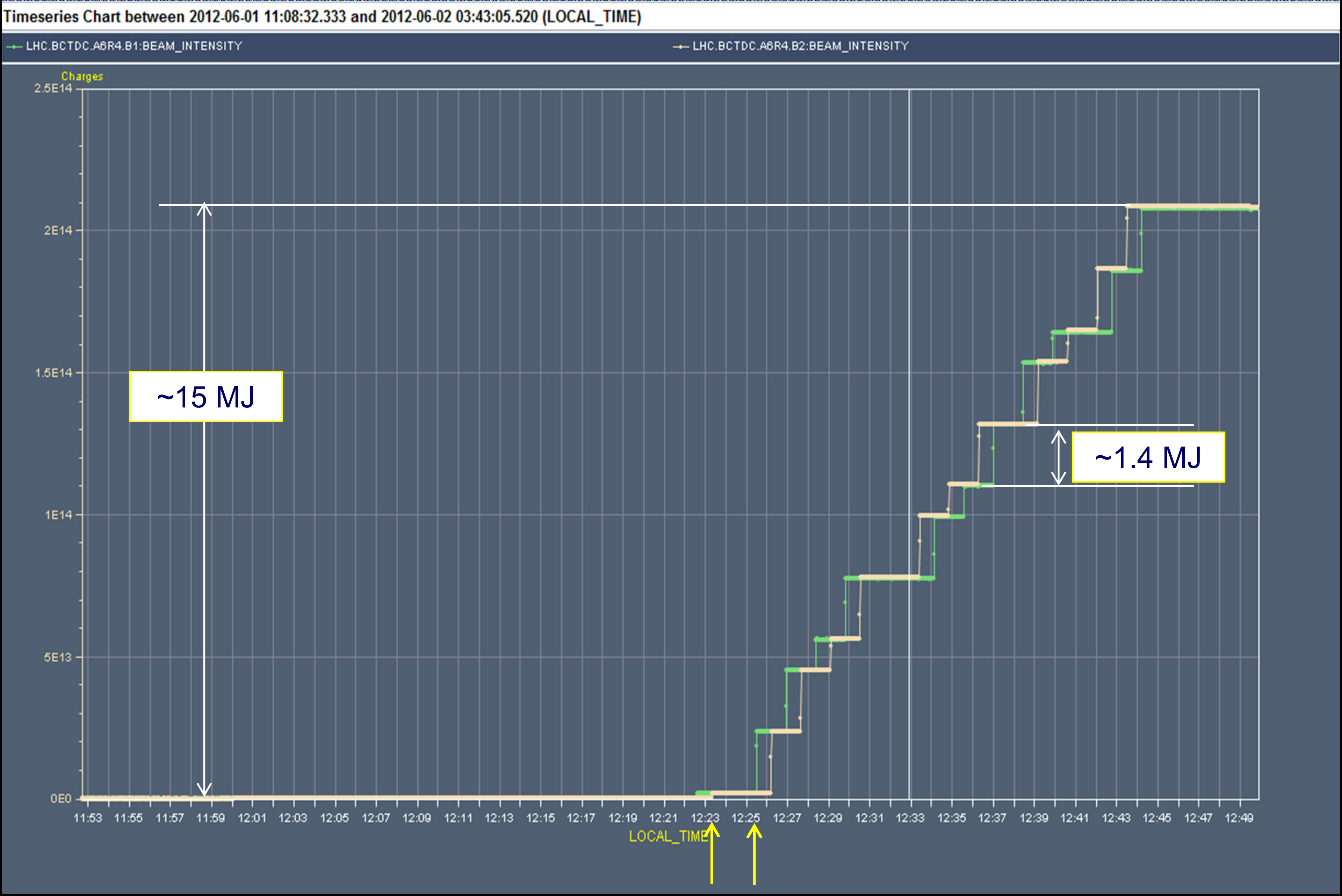
Vertical plane: the beams are deflected to produce a crossing angle at the IP to avoid undesired encounters in the region of the common vacuum chamber

	α (μrad)
ATLAS	-145 / ver.
ALICE	90 (145) / ver.
CMS	120 / hor
LHCb	-220 /hor

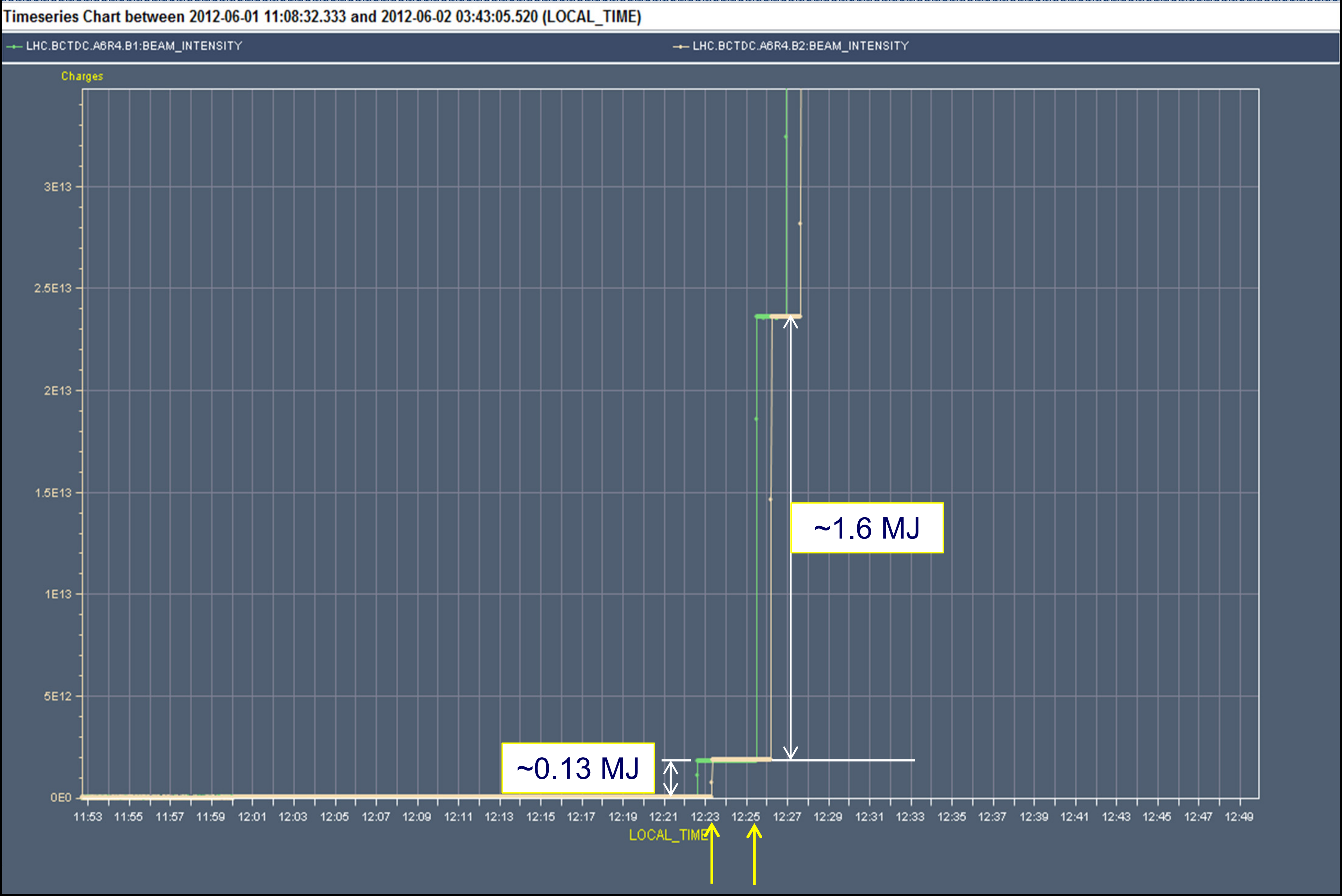


Not to scale !
About 60 parasitic crossings in LHC for 50 ns

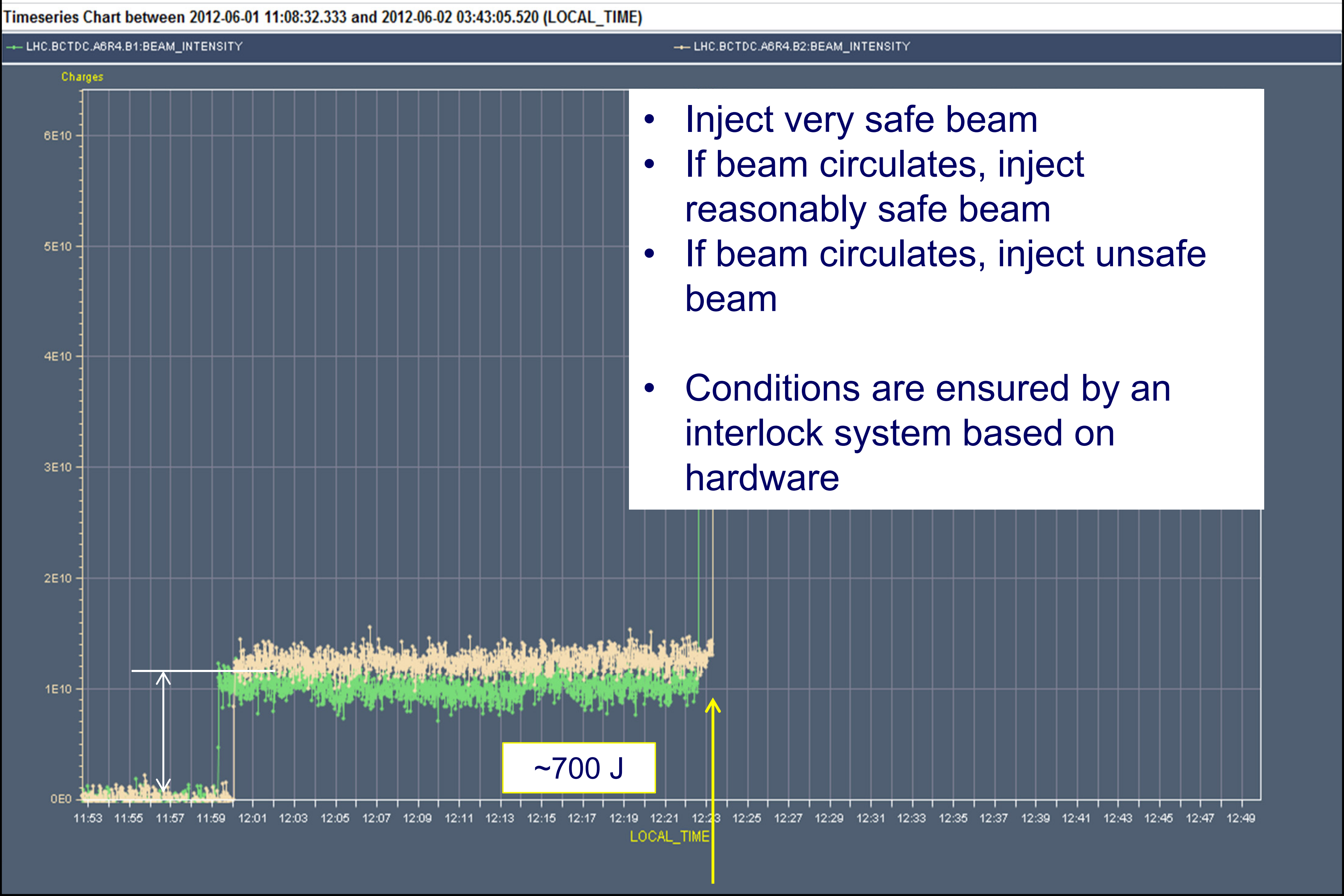
Injecting 1370 bunches - in batches of 144 bunches



Zoom: injection of first batch with 12 bunches



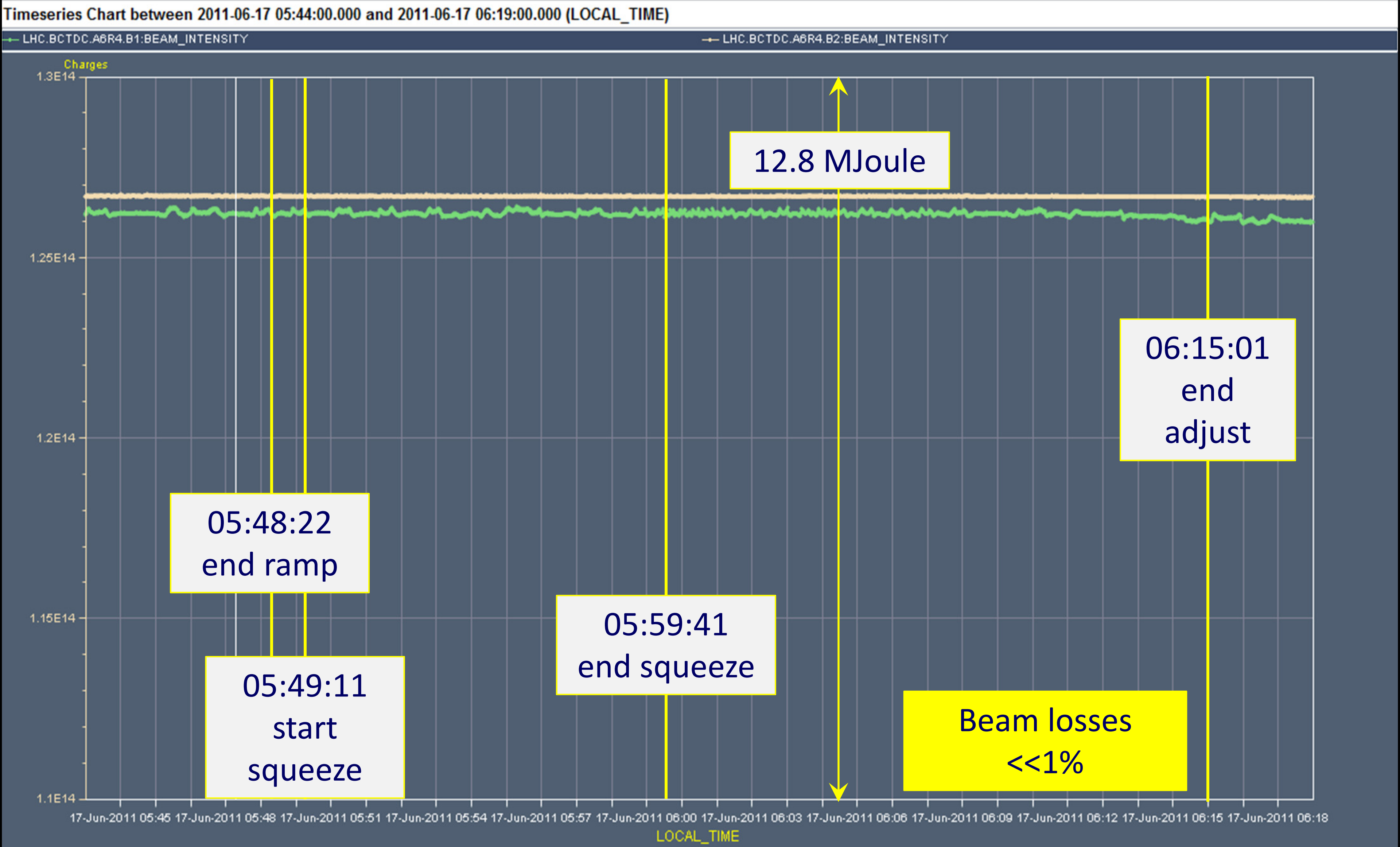
Zoom: injection of first bunch with pilot bunches



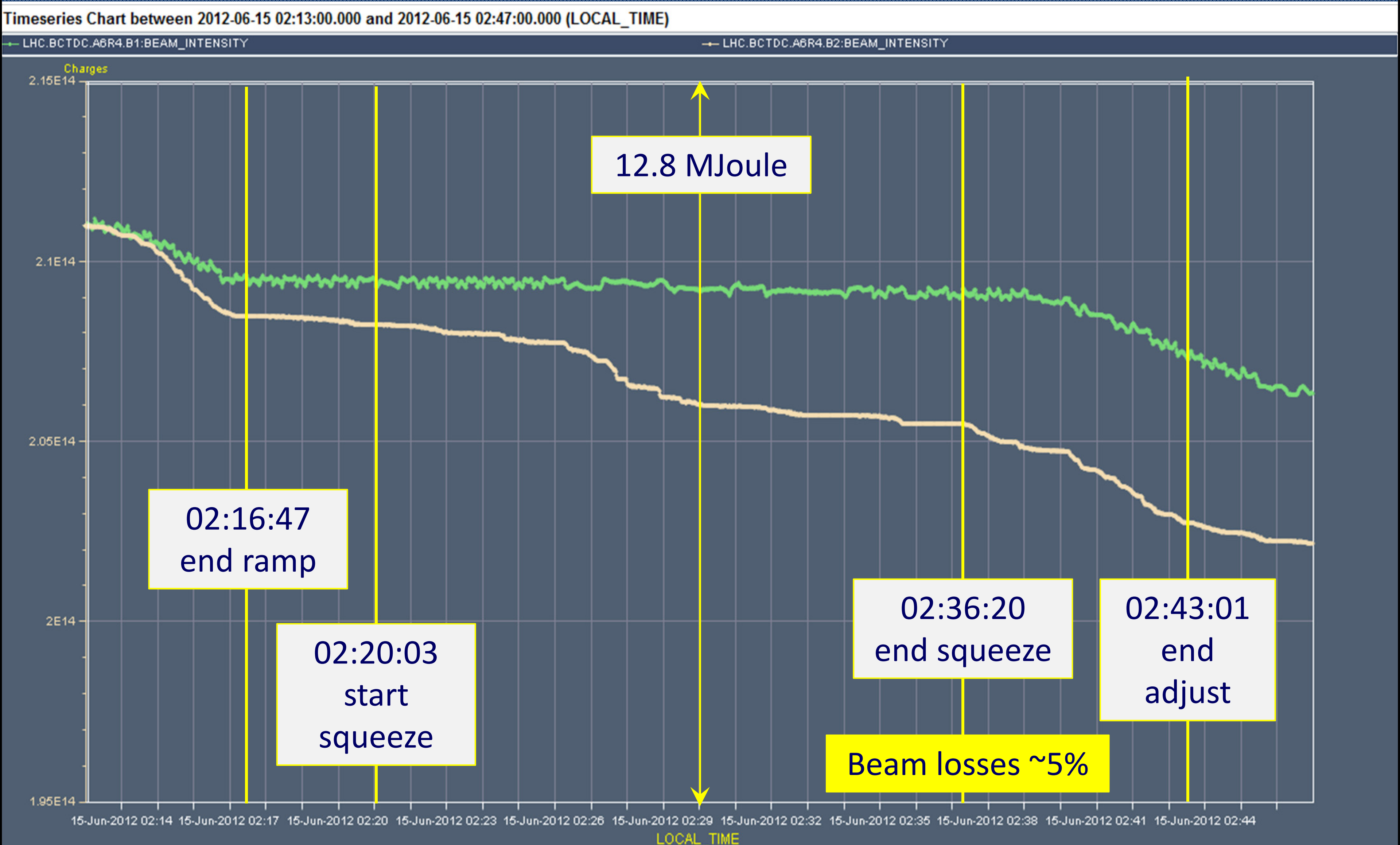
- Inject very safe beam
- If beam circulates, inject reasonably safe beam
- If beam circulates, inject unsafe beam

- Conditions are ensured by an interlock system based on hardware

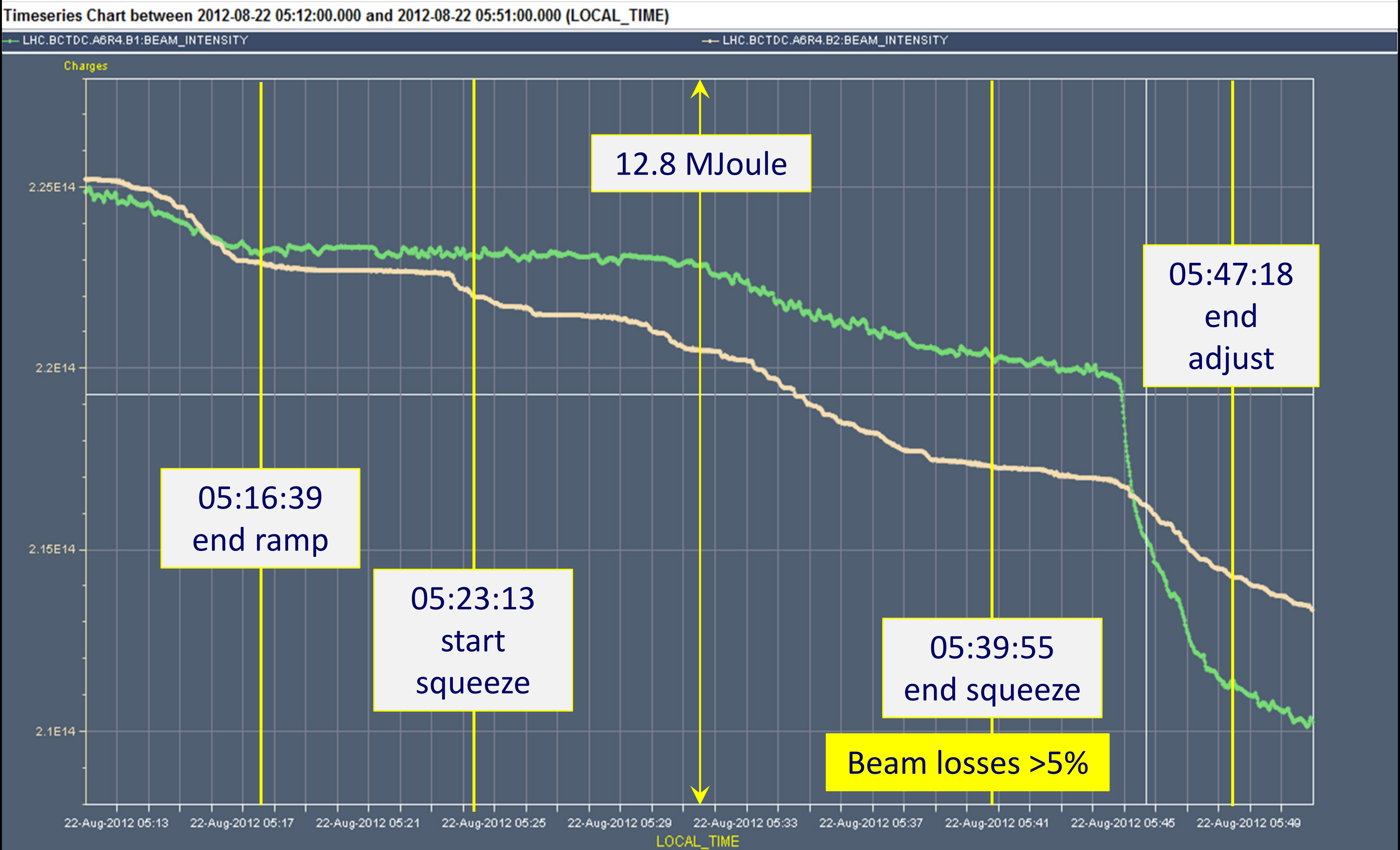
June 2011, Fill 1875, 3.5 TeV, 2011, 1092 bunches



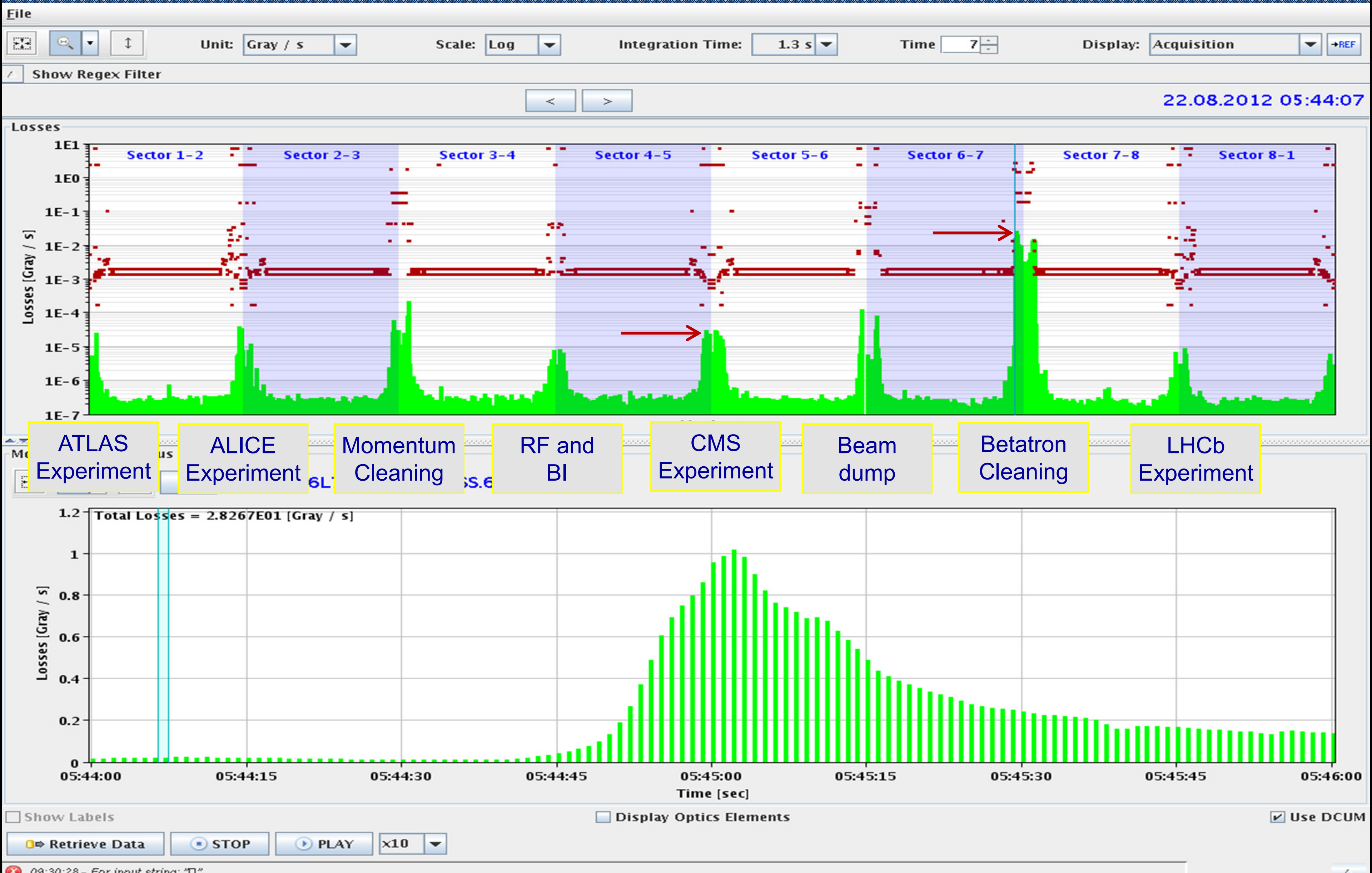
June 2012, Fill 2733, 4 TeV, 2012, 1380 bunches/beam



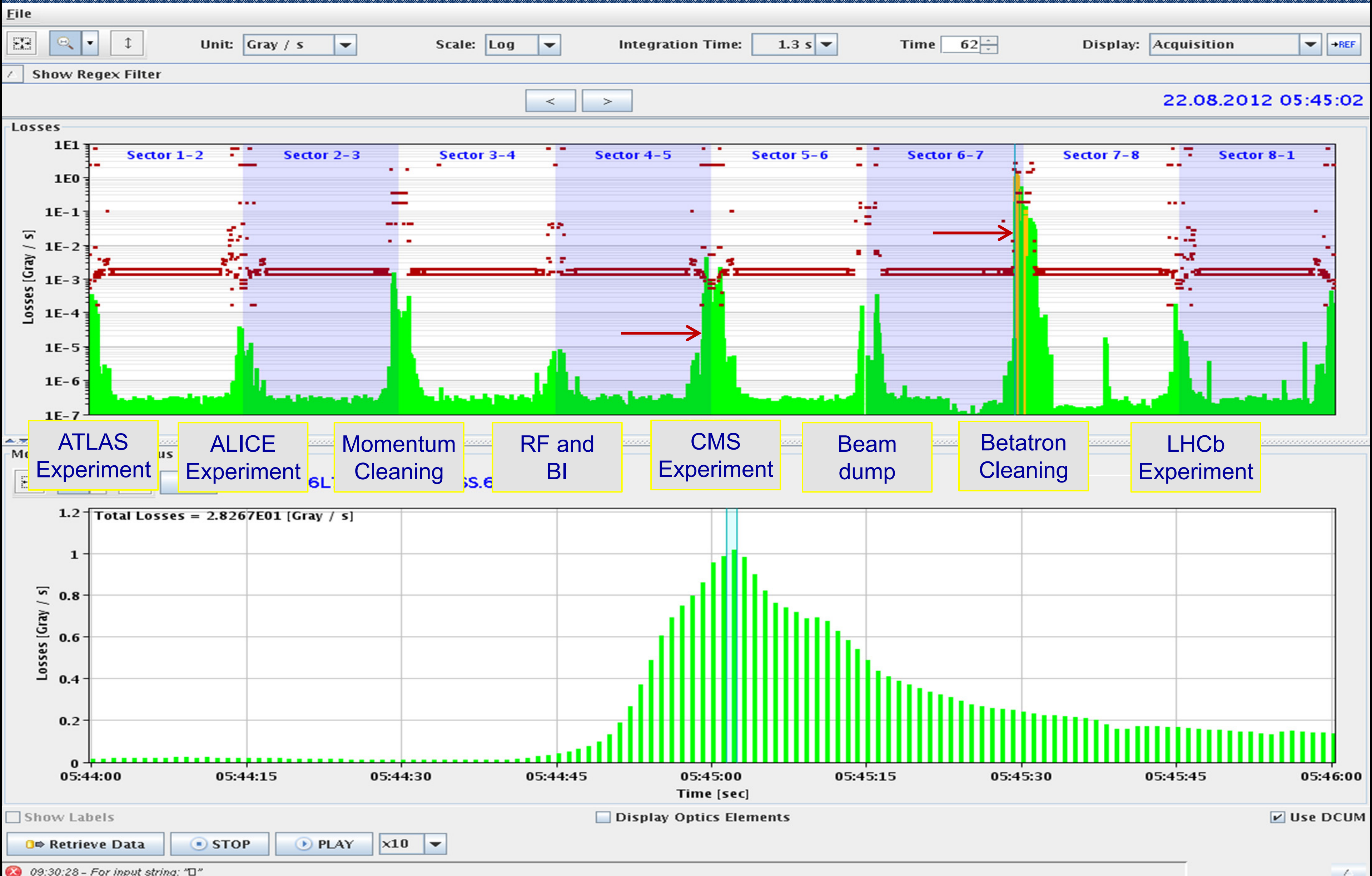
August 2012, Fill 2993, 4 TeV, 2012, 1374 bunches



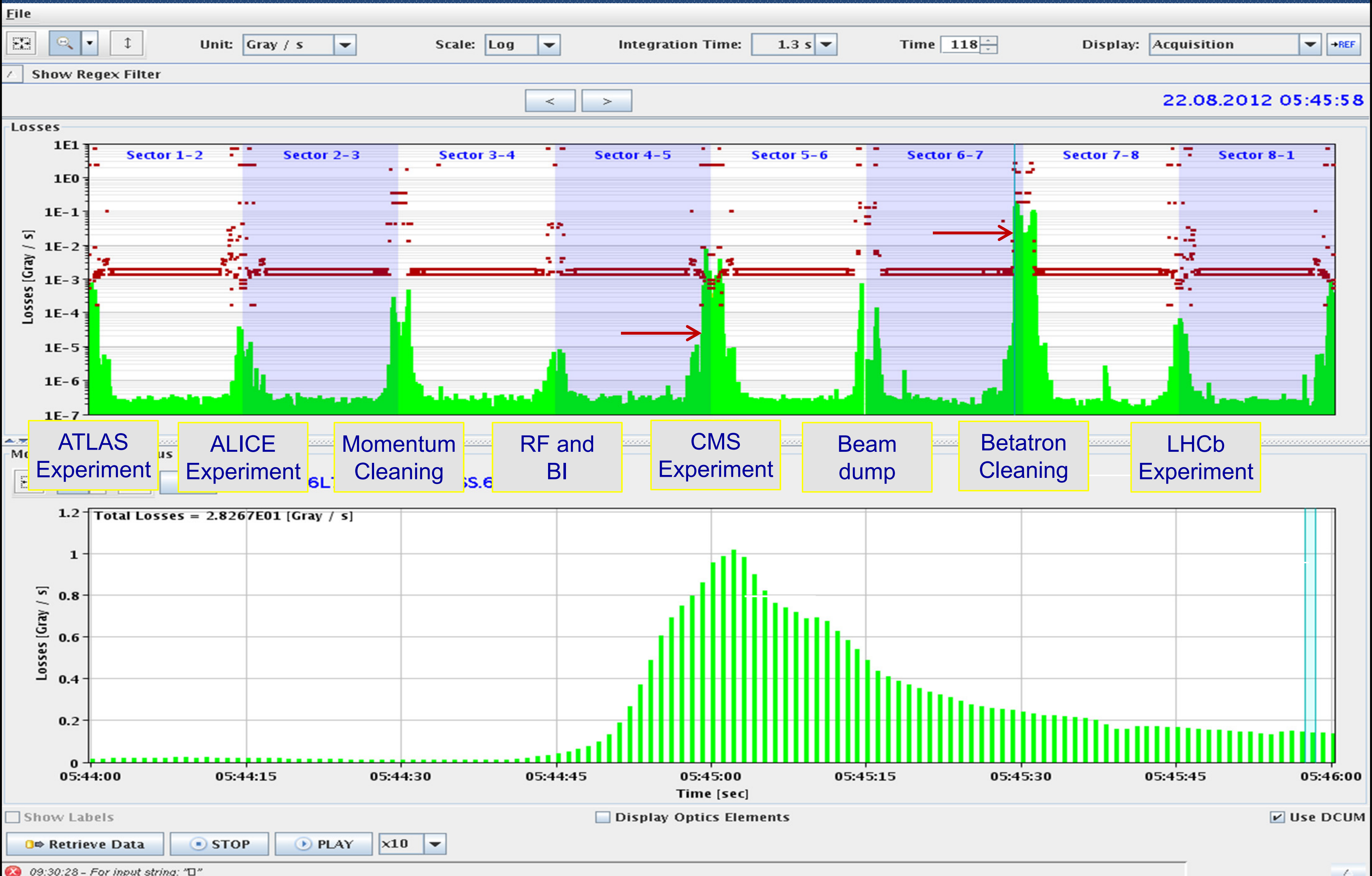
beam losses before bringing beams into collisions



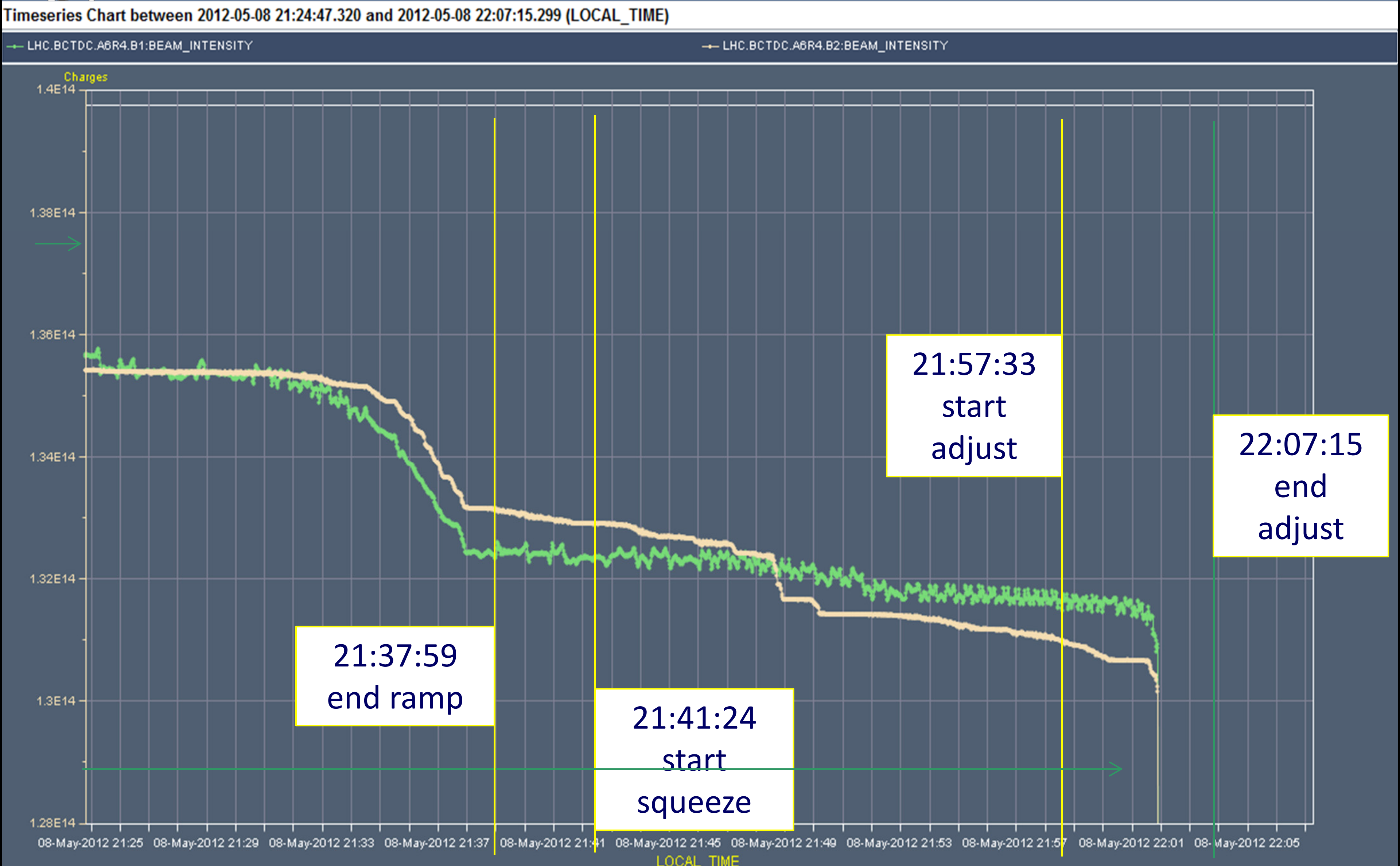
beam losses when bringing beams into collisions



beam losses after bringing beams into collisions

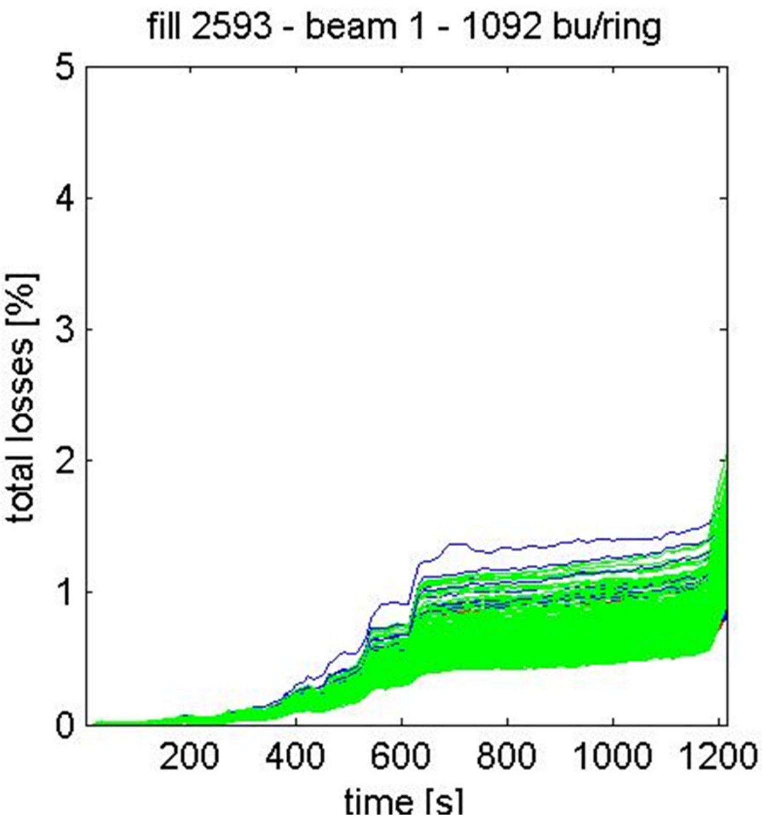


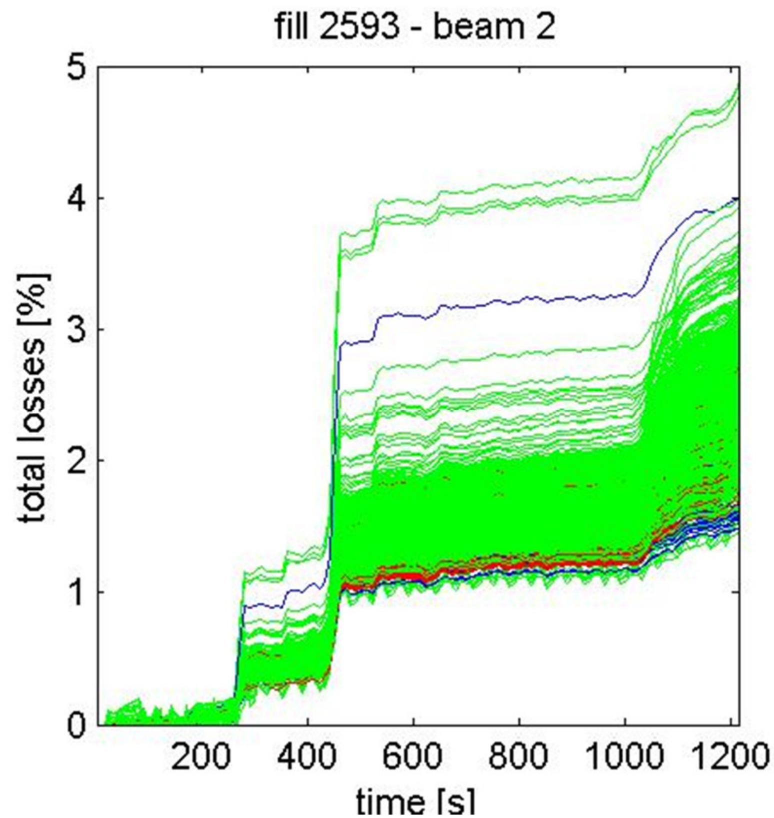
Fill 2602, also a typical fill in 2012…….



Bunch loss pattern for fill 2593

- Typical beam loss pattern – no all bunches are affected in the same way (e.g. few bunches that are not colliding)





Operating closer to the limits

- Initially, the BLM thresholds were set to dump the beams when the beam power loss exceeded about 50 kW
- By gaining experience we observed that the cleaning worked very well and there was no risk to quench magnets
- The thresholds of the BLMs for beam losses in the range of few seconds was increase, to allow for beam power losses of up to 200 kW
- This has been done for «slow» beam losses, with time constants of about one second and more
- There is still some margin, the power deposition in the collimation insertion can go up to a value between 500 kW – 1 MW

Beam losses at LHC and its injector, Laurette Ponce (CERN, Geneva)

Colliding High Brightness Beams in the LHC, Tatiana Pieloni (CERN, Geneva)

LHC impedance model: experience with high intensity operation in the LHC, Benoit Salvant (CERN, Geneva)

Quench tests at the LHC with collimation losses at 3.5 TeV, Stefano Redaelli (CERN, Geneva)

An object falls into the beam

Detection of 'unidentified falling objects' at LHC, Eduardo Nebot Del Busto (CERN, Geneva)

Bunch to Bunch Diagnostics with Diamond Detectors at the LHC, Maria Hempel (BTU, Cottbus)

Accidental beam losses during collisions

Unit: Gray / s | Scale: Log | Integration Time: 1.3 s | Start 490 End 511 | Losses: Max | Display: Acquisition

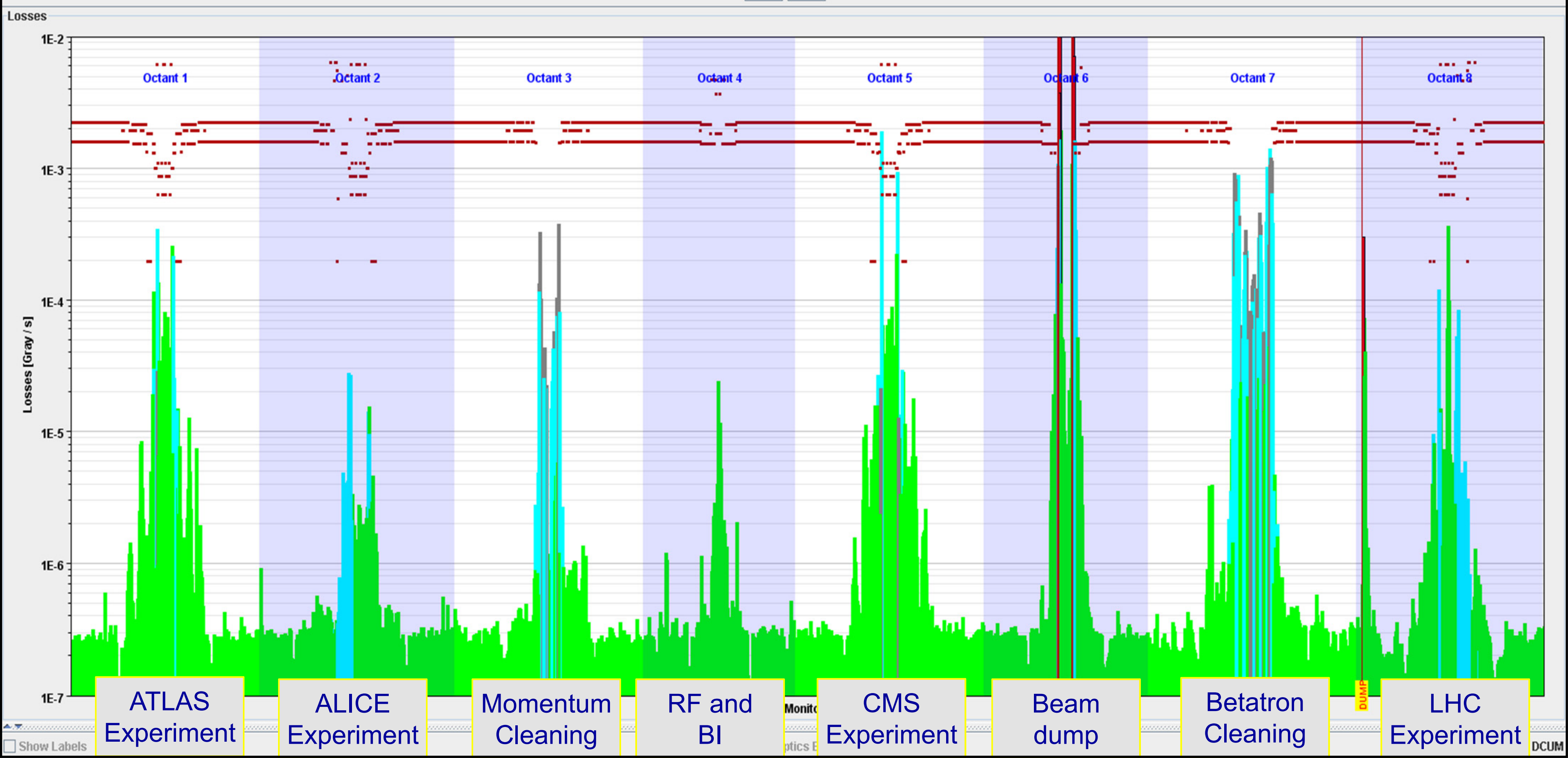
Sectors Filter | Octant Filter | Dump Filter | List Filter | Regex Filter | Beam Permit Filter

Filter (3550 / 3892)

Monitor	40 us	80 us	320 us	640 us	2560 us	10 ms	82 ms	655 ms	1.3 s	5.2 s	20.9 s	83.8 s
BLMQI.31L8.B1E10_MQ	Dump	Dump	Dump	Dump	Dump	Dump	Ok	Ok	Ok	Ok	Ok	Ok
BLMEI.04L6.B1E10_TCDSA.4L6.B1	Dump	Dump	Dump	Dump	Dump	Dump	Dump	Ok	Ok	Ok	Ok	Ok
BLMEI.04L6.B1E10_TCDSB.4L6.B1	Dump	Dump	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok
BLMEI.04L6.B2I10_TCDQA.B4L6.B2	Dump	Dump	Dump	Dump	Dump	Dump	Ok	Ok	Ok	Ok	Ok	Ok
BLMEI.04R6.B2I10_TCDSB.4R6.B2	Dump	Dump	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok
BLMEI.04R6.B2I10_TCDSA.4R6.B2	Dump	Dump	Dump	Dump	Dump	Dump	Dump	Ok	Ok	Ok	Ok	Ok
BLMEI.04R6.B1E10_TCDQA.B4R6.B1	Dump	Dump	Dump	Dump	Dump	Dump	Ok	Ok	Ok	Ok	Ok	Ok

Type: IC, LIC, SEM | Section: LSS, DS, ARC | Left Right: Left, Right | Octant: 1, 2, 3, 4, 5, 6, 7, 8 | Beam: Beam 1, Beam 2

Show Dump Indicators | 30.07.2011 23:53:11



Zoom one monitor: beam loss as a function of time

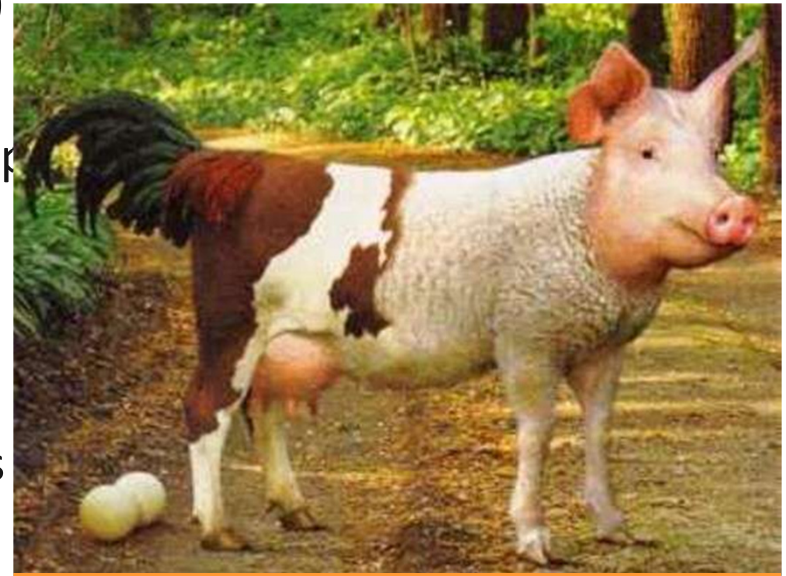
Final remarks

Longitudinal beam dynamics – excellent performance of the RF system

- Performances and future plans of the LHC RF,
  Philippe Baudrenghien (CERN, Geneva)
- Batch-by-batch longitudinal emittance blow-up in the LHC,
  Philippe Baudrenghien (CERN, Geneva)
- Measurements of the LHC longitudinal resistive impedance with beam,
  Juan Esteban Muller (CERN, Geneva)

Excellent performance of the transverse damp

- Fighting transverse instabilities
- Damping injection oscillations
- Cleaning of beam abort gap
- Produce beam losses on selected bunches hierarchy
- Measuring betatron tunes



Swiss German animal: Eierlegendewollmilchsau

What we learned.....

- High-intensity operation close to beam instability limits
- Established β* reach (aperture, collimation, optics)
- Luminosity levelling via offset tested – works fine in LHCb!
- Head-on beam-beam effect is not a limitation
- Long range beam-beam effects have to be taken seriously
  - Need separation of 10 -12 σ (otherwise bad lifetime and beam loss)
- As small as possible emittances are good
- Instabilities were observed… and to some extent understood
  - For small beam offsets at collision point while going into collisions, ….
  - Impedances (kicker, collimator heating), collective effects, ...
- Availability of such ultra-complex machine
  - Single Event Upsets, vacuum pressure increase, UFOs, cryogenics, magnet protection system, ...
  - Vigorous follow-up and consolidation

LHC Operation after the shutdown 2013/14

- Energy 6.5 TeV during 2015
- Bunch spacing 25 ns (in case of problem fall back to 50 ns)
- Beta-function at experiments ~0.5 m
- Pile-up of events in the experiments– assume acceptable
  - Depends on bunch spacing and squeeze beyond 0.5 m
  - Beta* luminosity-levelling to mitigate the initial large pile-up
- Performance could be impacted by
  - UFOs at higher energy and with 25 ns bunch spacing
  - Radiation to electronics – SEU's
  - Electron cloud & high energy & at 25 ns
  - Long-range beam-beam & smaller crossing angle & at 25 ns
  - Single- and bunch-by-bunch beam instabilities (impedances...)
- It should be possible to achieve nominal luminosity of 10^{34} [$cm^{-2}s^{-1}$] or more

Summary

- Operation in 2012 is at 4.0 TeV
- In 2012 the peak luminosity exceeded 7.5×10^{33} $cm^{-2}s^{-1}$ in ATLAS and CMS with beams of 50 ns spacing
  - The stored energy of the beams exceeded by a factor ~50 that of existing or previous machines
  - No beam induced magnet quench with stored beams
- Integrated luminosity for 2012 is in excess of 14 fm^{-1}, hope to reach more than 20 fm^{-1} until the end of the run in February 2013
- The consolidation of the splices between magnet will be done in 2013/14 , to restart autumn 2014/ 2015 at about 6.5 TeV
- UFOs could become a limitation for the availability of LHC at 6.5 TeV