LHC Beam Diagnostics
The(a) user's point of view

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LHC Operation

Acknowledgements:
R. Jones + all colleagues that provided input and plots

Outline

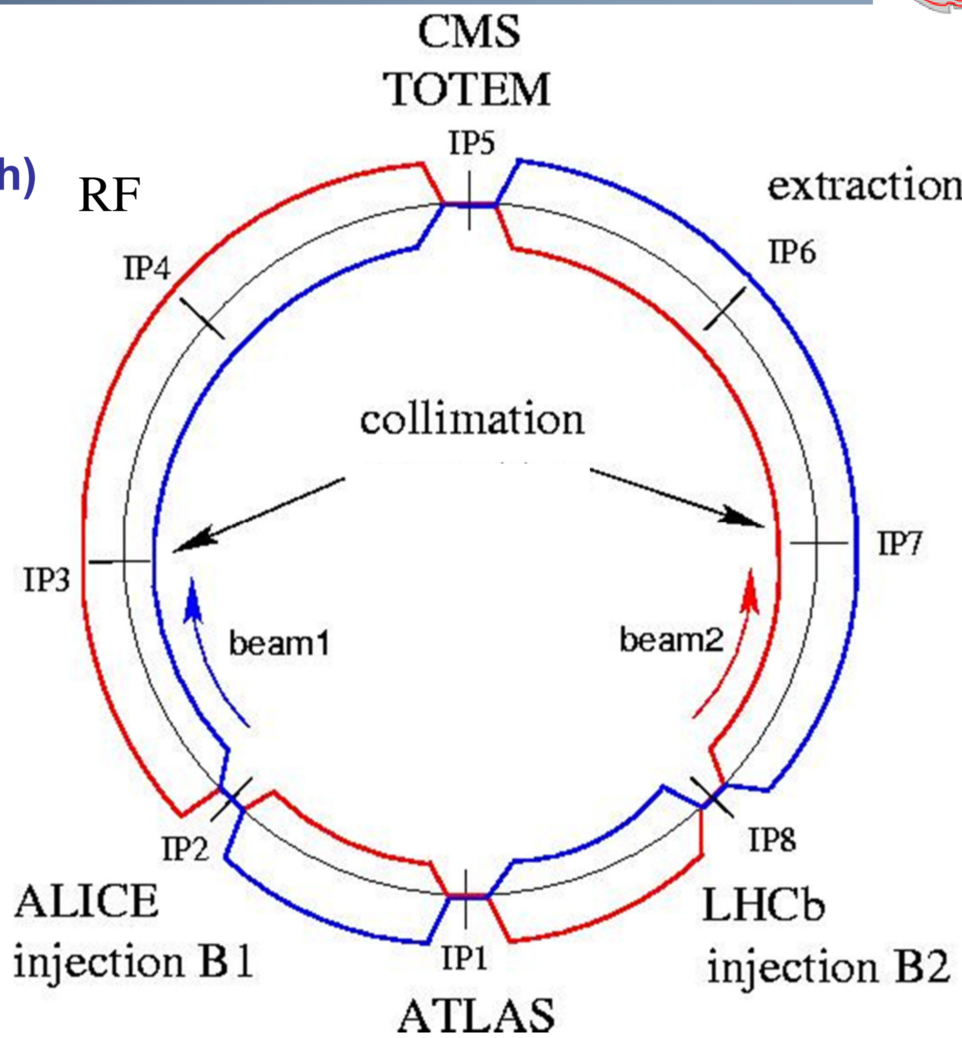
- Introduction – LHC status in 2011
- Beam position
- Beam loss
- Tune and chromaticity
- Transverse profiles
- Beam intensity and longitudinal profile
- Comments and outlook

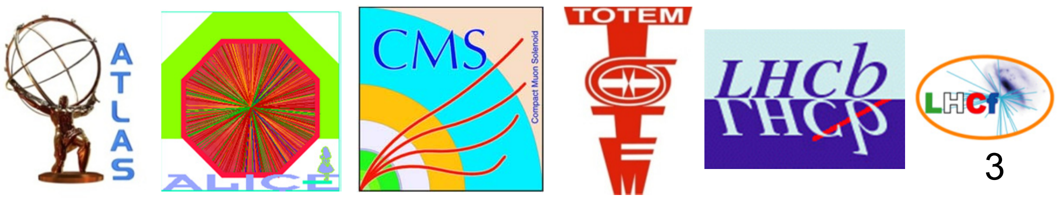
LHC layout and parameters

- 8 arcs (sectors), ~3 km each
- 8 long straight sections (700 m each)
- circumference 26.7 km
- beams cross in 4 points
- 2-in-1 magnet design with separate vacuum chambers → *p-p* collisions

- Nominal bunch spacing 25 ns

- ~8000 super-conducting magnets.
  up to 8.3 T dipole field.
- 1600 electrical circuits.





LHC layout and parameters

- 8 arcs (sectors), ~3 km each
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- circumference 26.7 km
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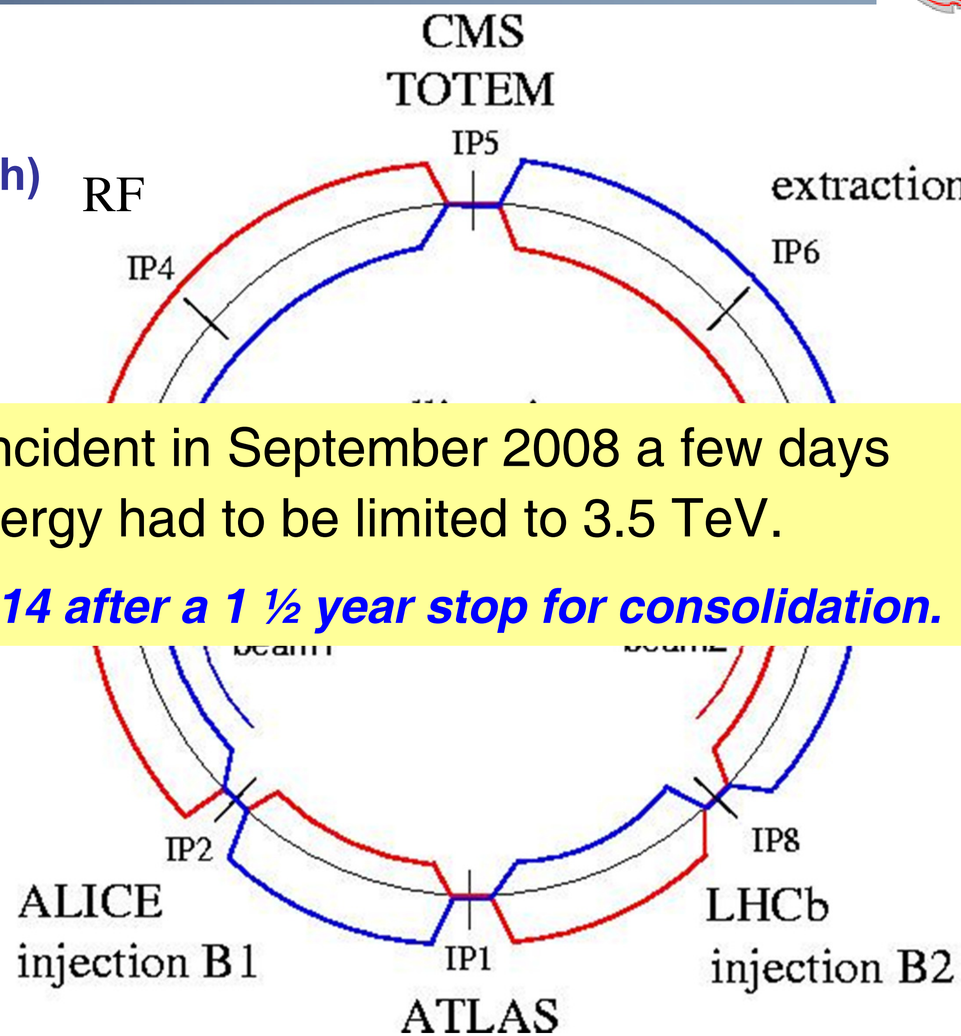
  v
- N

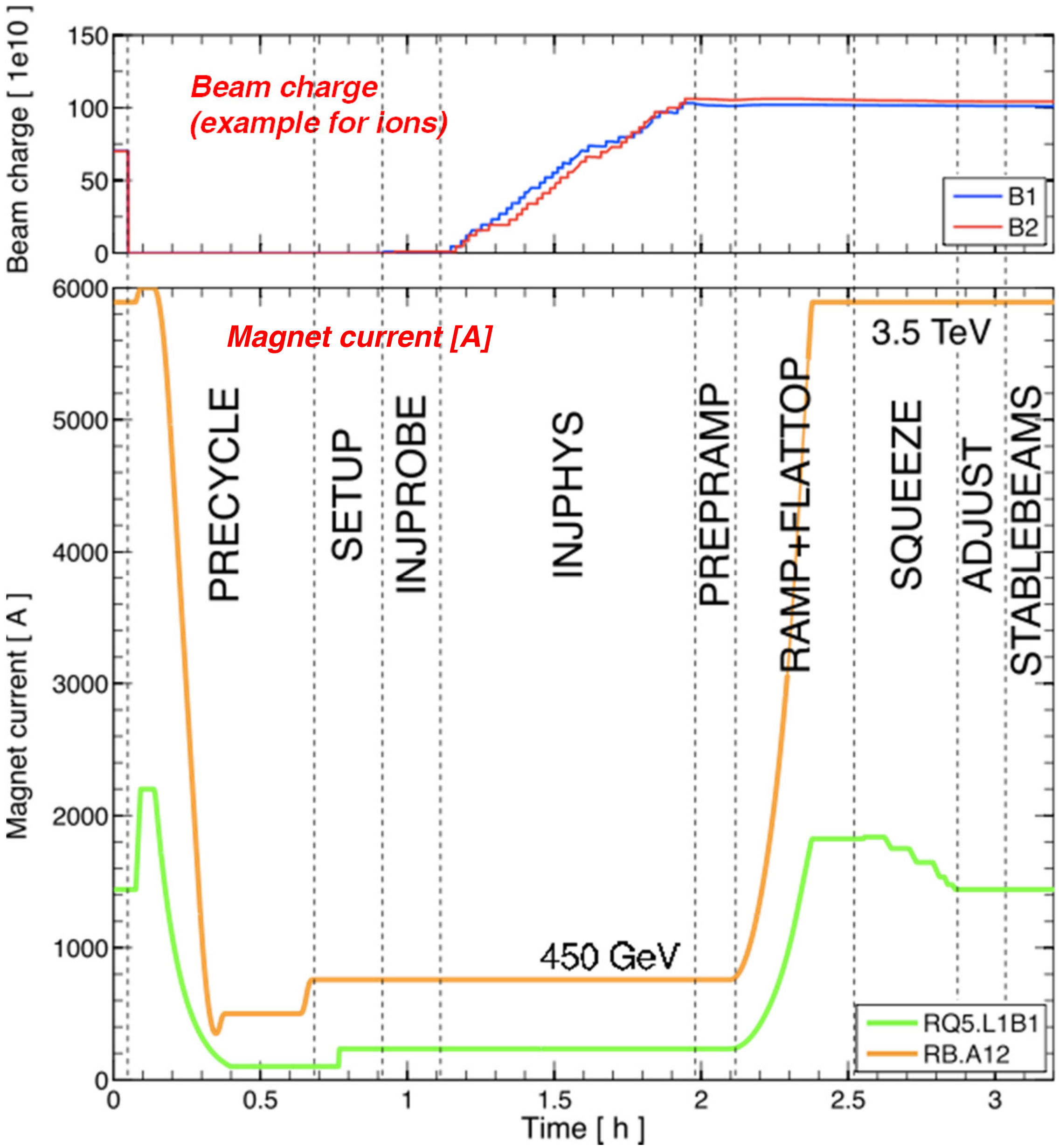
Following a severe powering incident in September 2008 a few days after startup with beam, the energy had to be limited to 3.5 TeV.

Full energy recovered end 2014 after a 1 ½ year stop for consolidation.

- ~8000 super-conducting magnets.
  up to 8.3 T dipole field.
- 1600 electrical circuits.



Operational cycle



- Cycle:
  - ***Injection***
  - ***Ramp***
  - ***Squeeze***
  - ***Collide beams***
  - ***Stable physics beams***
  - ***Ramp down/cycle***
- Presently a good turn around is performed in 3 hours – best 2h 40.

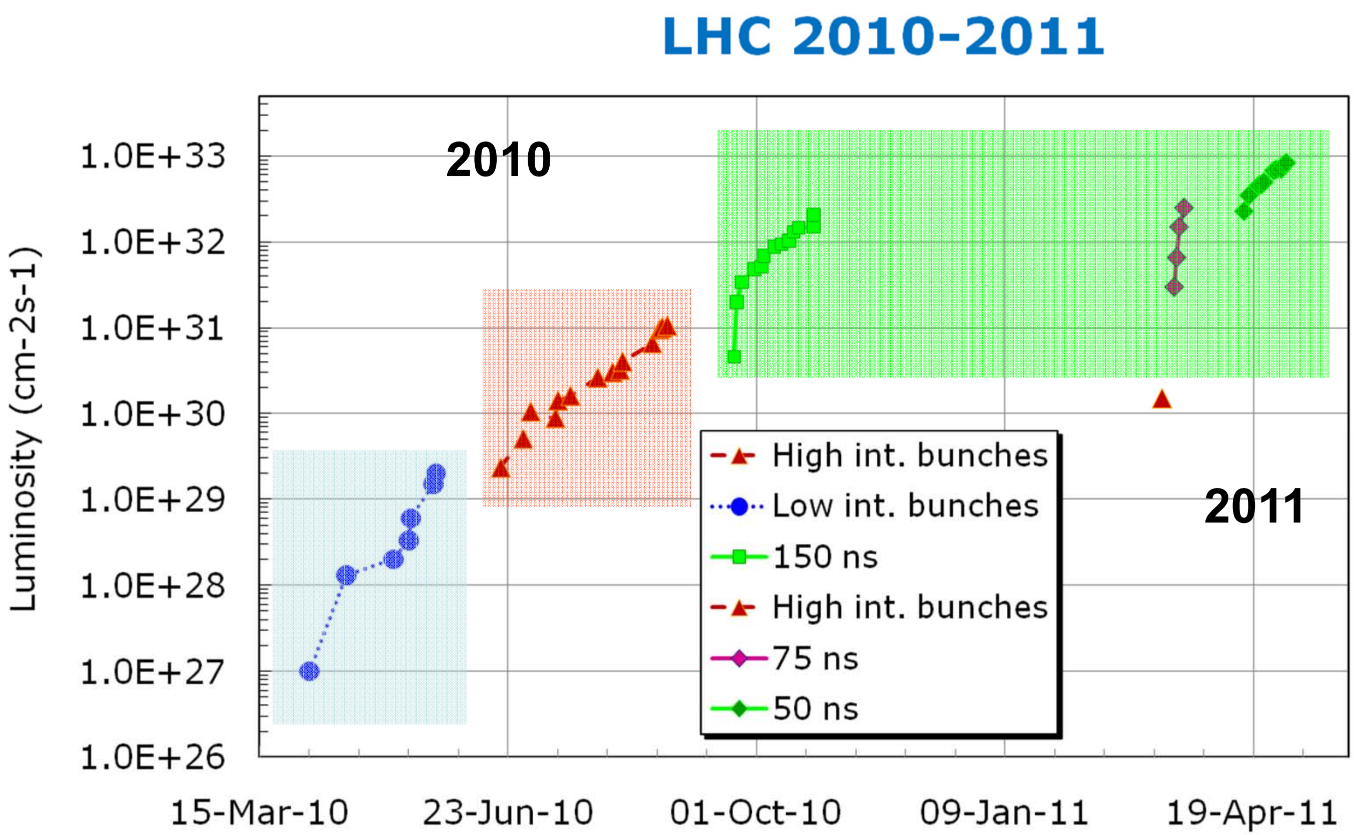
During the '**squeeze**' phase, the betatron function at the collision points (β^*) is reduced to increase the luminosity.

LHC Progress in 2010-11 at 3.5 TeV

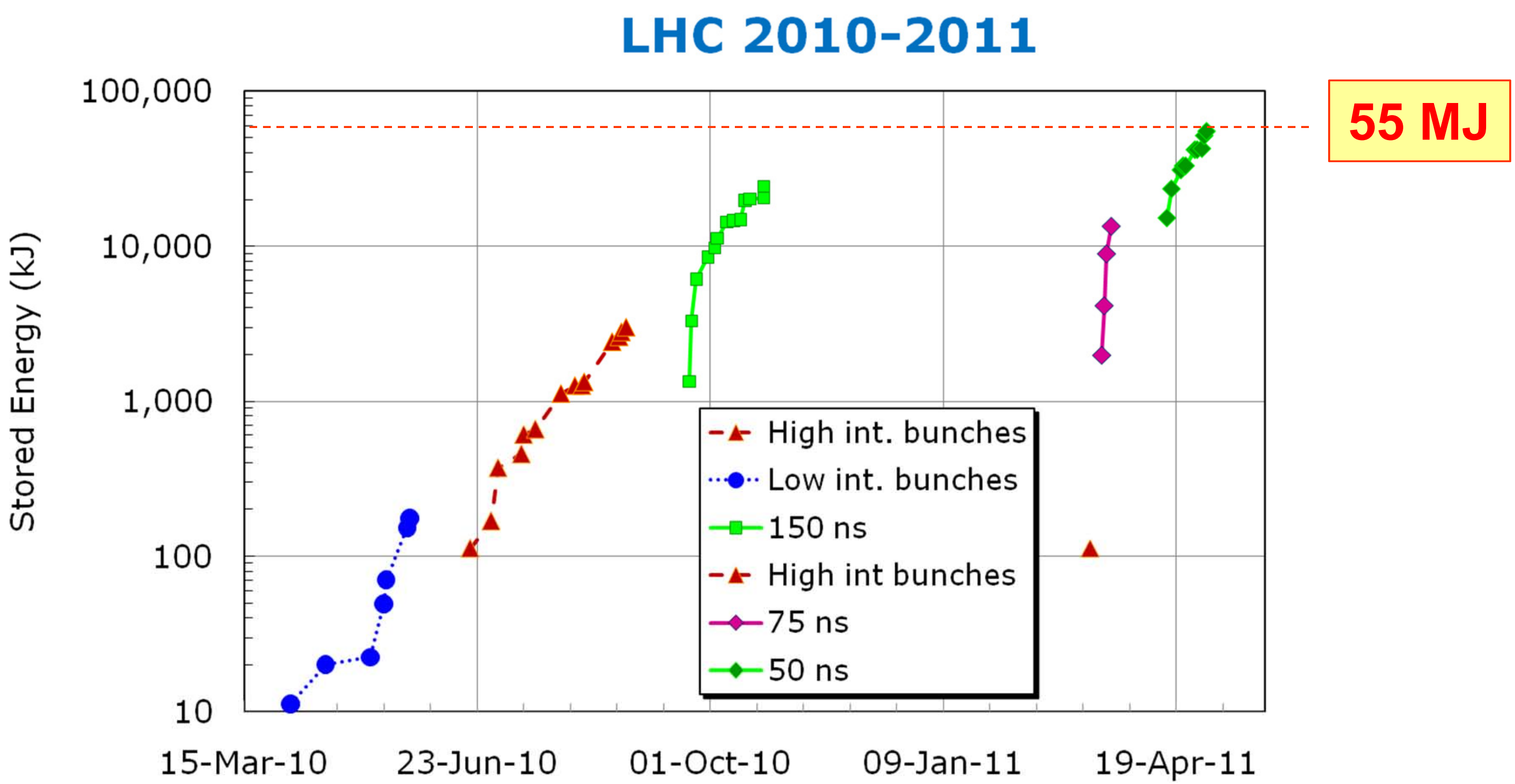
Low bunch intensity operation, first operational exp. with MPS

Ramping up to 1 MJ, stability run at 1-2 MJ

Reach out for the fb-1 !



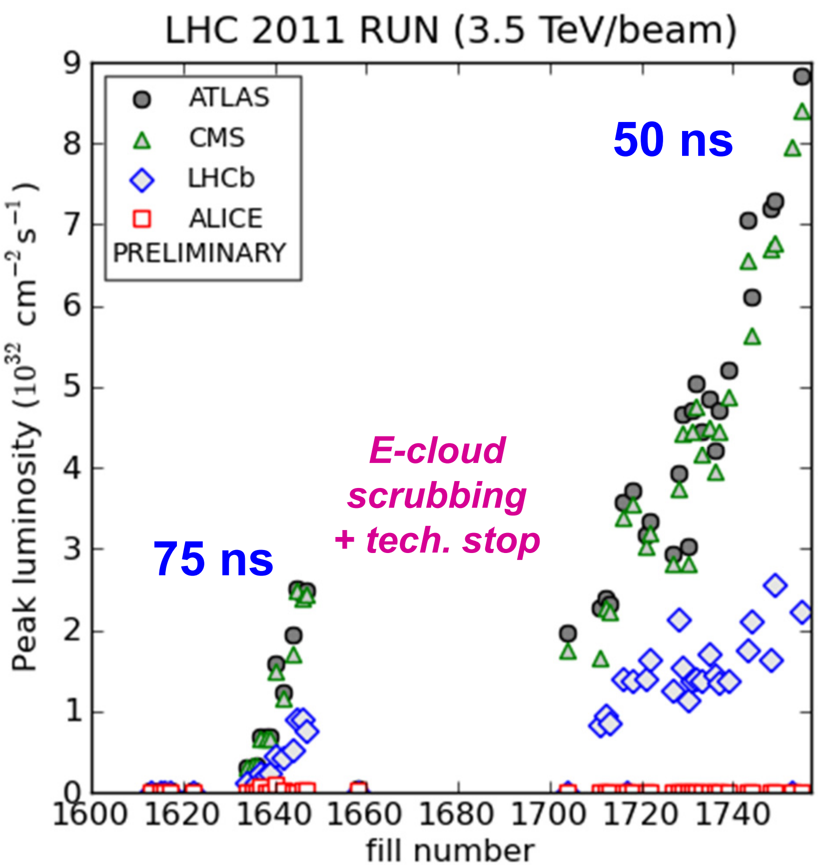
- The stored energy in each beam has been pushed to 55 MJ.
- Despite this large stored energy no magnet was ever quenched with circulating beam – very good protection by the BLMs !
    - *Quenches only occurred due to injection failures (with low intensity).*



LHC Performance in 2011

- LHC was re-commissioned with beam in 3 weeks after winter stop.

- Beam progress in 2011:
  - *After a one week 'scrubbing run' to mitigate **electron cloud effects** the LHC started operation with a bunch **spacing of 50 ns**.*
  - ***April 21st LHC exceeded the TEVATRON luminosity record of 4×10^{32} cm^{-2}-s^{-1}.***
  - *Present record: **8.5×10^{32} cm^{-2}s^{-1}** with 768 bunches.*

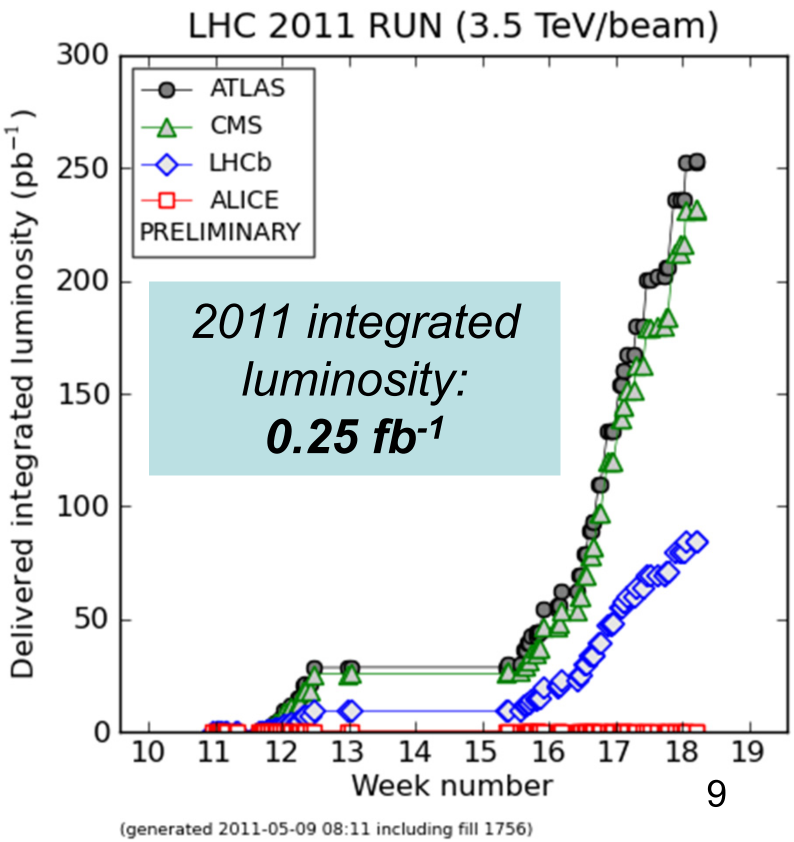


(generated 2011-05-03 11:40 including fill 1755)

Outlook for 2011

- Peak luminosities of **(1-2)×10^{33} cm^{-2}s^{-1}** are within reach, with up to ~1400 bunches. Integrated luminosities ≥ **2 fb^{-1}** in 2011 feasible.
- Possible '**Threats**' for further performance increases:
  - Vacuum (electron clouds), beam instabilities, radiation induced Single Event Upset issues in tunnel electronics.

Parameter	2011 achieved	2011 'target'	Nominal
N (p/bunch)	**1.2×10^{11}**	**>1.2×10^{11}**	**1.15×10^{11}**
No. bunches	768	~1400	2808
ε (μm rad)	**~2.8**	**<3**	**3.75**
β* (m)	1.5	1.5	0.55
L (cm^{-2}s^{-1})	**8.5×10^{32}**	**~1.5×10^{33}**	**10^{34}**



LHC is not just protons

- In this presentation the focus is set *on the performance with high intensity proton beams* – the main physics program of the LHC.
- But the LHC also has an extensive (~ 1 month/year) *ion program* – for the moment with Lead beams.
  - *Very successful Pb run in December 2010. **Switch over from proton to ion collisions in 4 days – 'perfectly' working instrumentation played an important role !***
  - *Test of p-Pb scheduled for the end of 2011.*
- The performance of the LHC instrumentation is typically equivalent between protons and ions – *modulo resolution due to intensity*. Some instruments (Schottky) actually performed better with ions than with protons.
  - *Ion bunch ~ **5×10^{9} charges***
  - *Proton bunch ~ **5×10^{9} – 1.5×10^{11} charges***

General remarks

- The LHC has many instruments – too many for me to describe them or comment on them in this presentation.
- The choice of instruments that will be discussed clearly reflects *my personal bias*, but to a large extent this overlaps with those *instruments that are used most by LHC operation*.
- There have been numerous talks and posters at this workshop that describe some of those instruments in more details !

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- ❑ Beam position
- ❑ Beam loss
- ❑ Tune and chromaticity
- ❑ Transverse profiles
- ❑ Beam intensity and longitudinal profile
- ❑ Comments and outlook

Beam position – 10^{th} September 2008

The LHC BPM system live show:

- All of CERN (and more) follows threading of the beams around the rings.
- Fantastic availability, negligible amounts of polarity errors.

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Beam 2 threading

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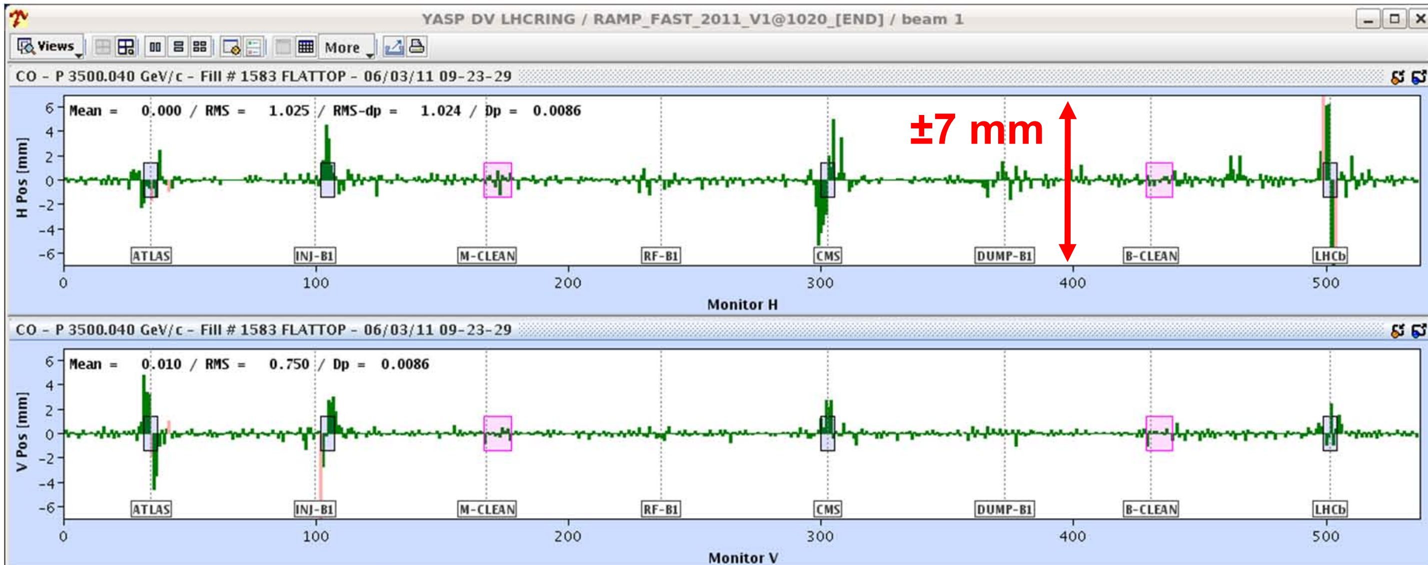
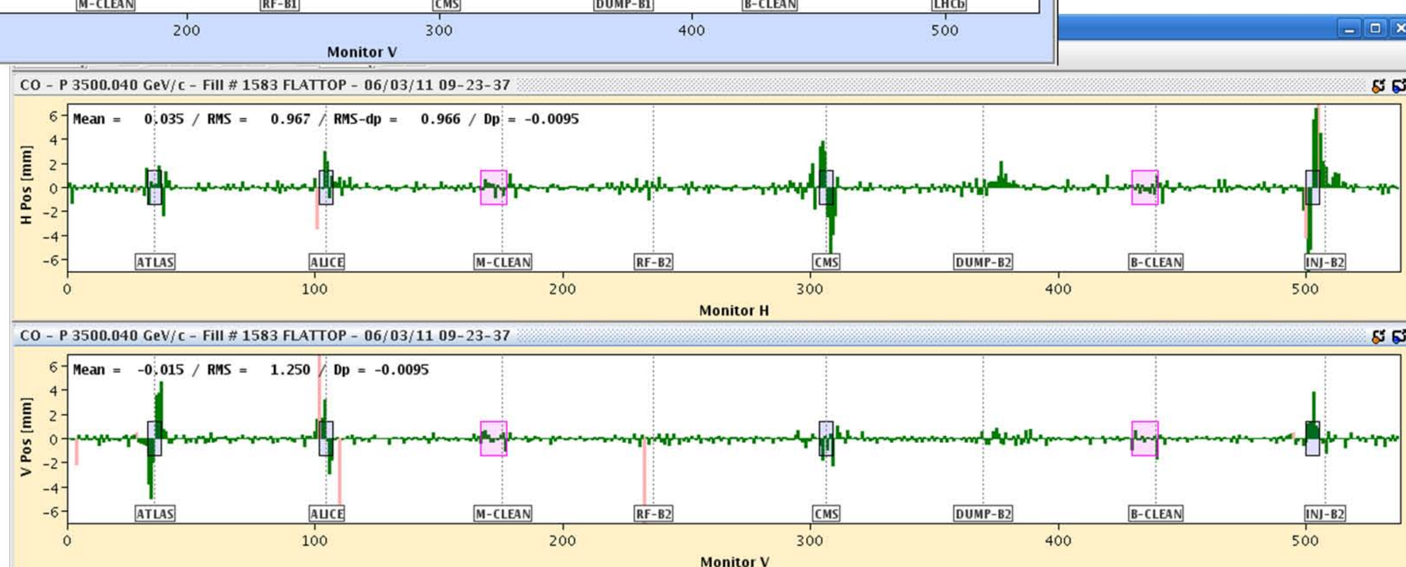
Beam 2 threading

The LHC BPM system

- 1070 button and coupler monitors – ***2140 position readings***.
- Auto-triggered orbit, excellent availability, ~2% monitors with ‘problems’.



Typical orbits



Orbit feedback

- Rather unusual for a proton ring, an orbit feedback was foreseen from the start, based on 25 Hz orbit acquisitions.
  - *~ 1 Hz bandwidth sufficient for LHC beams.*
  - *Super-conducting orbit correctors are 'slow beasts'.*
- The main role of the OFB is to maintain the beam centered within the aperture and in particular within the ~ 100 collimators.
- The OFB is based on central processing of all BPM data,
  - *incoming UDP packet stream (68 crates),*
  - *outgoing UDP packet stream to PC controllers (~50 crates),*

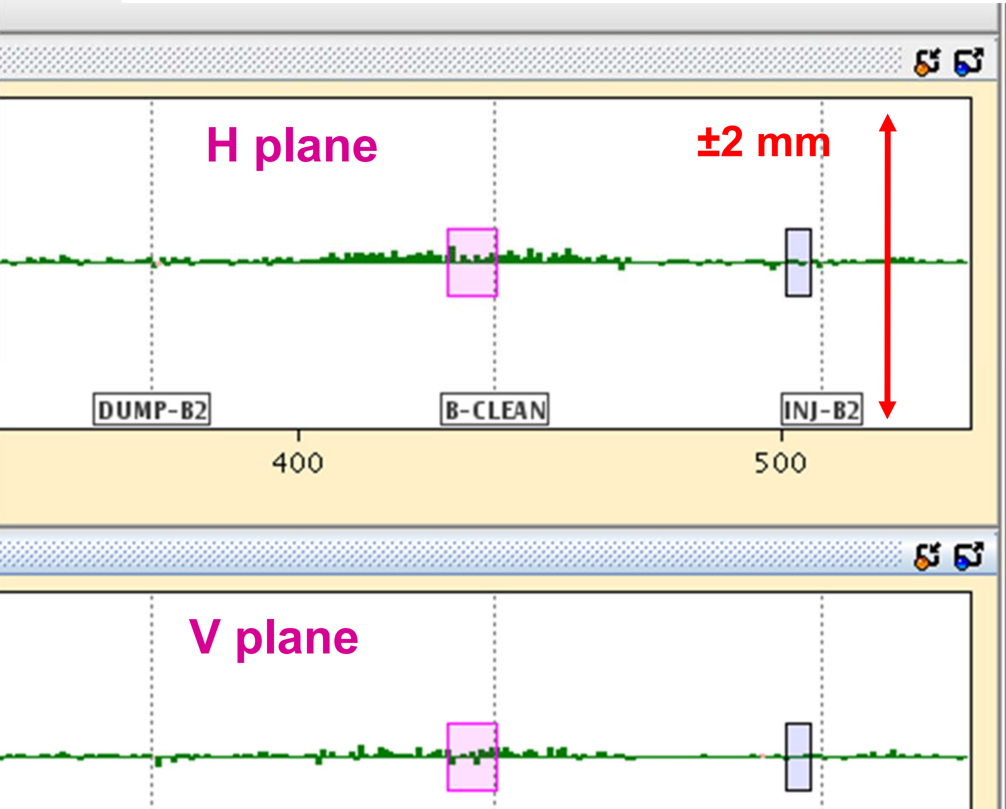
  with data exchange over Gb Ethernet.
- ***OFB*** was put into operation in April 2010 and ***performed very reliably*** since then – after the usual running in issues had been solved.
  - *Stability in ramp and squeeze of ~ 50 μm rms or better – OK.*

Orbit measurement systematics

- As we are trying to focus the beams more at the collisions points (β^* reduction), ***aperture considerations*** become more critical and the ***orbit reproducibility becomes essential***.

  Margins collimators – aperture of ~ 2 mm – going down !

- ***Crate temperature*** driven systematic errors (~ 50 μm/deg) have quickly been identified as a considerable issue for reproducibility.



  - *Under 'control ' with regular calibrations and T corrections.*

    ~ 100 μm residuals…

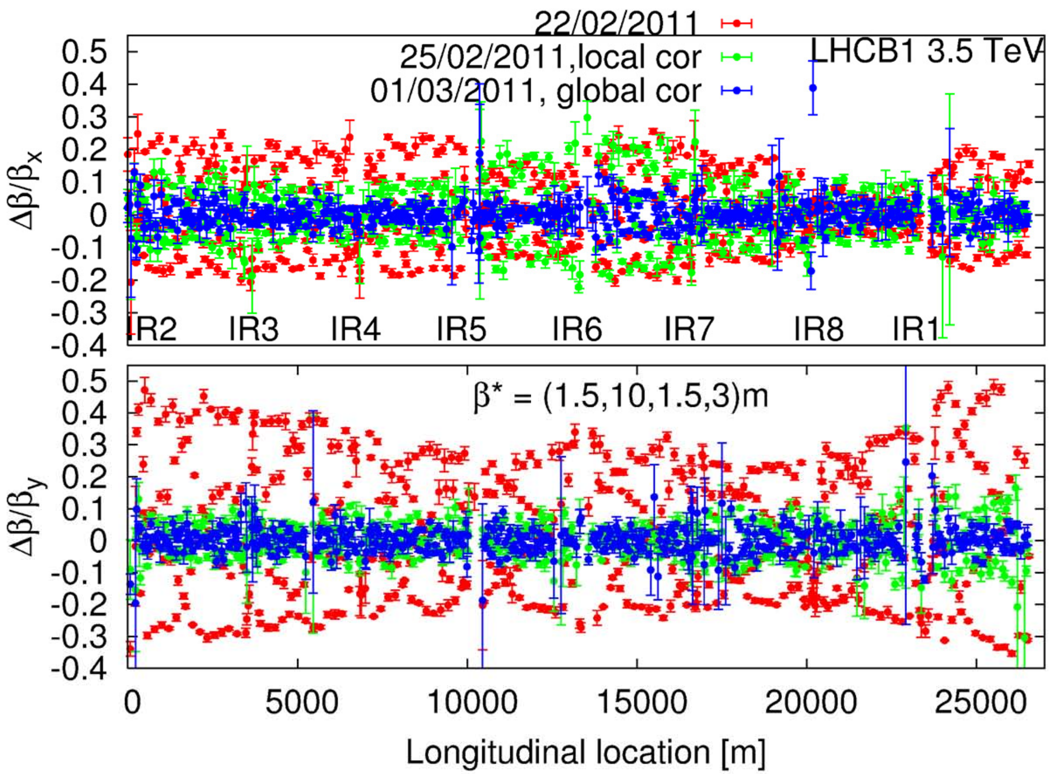
  - *Long term solution: temperature controlled racks.*

- ***Filling pattern*** effects of ~200 μm are controlled by appropriate calibrations.

  Need different beam structures for setups and physics.

Multi-turn BPM acquisitions

- The BPM system provides bunch-by-bunch and turn-by-turn acquisitions of to 100k turns x bunches per BPM/plane.
  - *So far only 4k turns used – data readout problems…*
- In combination with an ***AC-dipole excitation***, multi-turn acquisitions were used to measure and successfully correct the beta-beat.
  - *For collisions beta-beat was corrected to 5% (wrt nominal optics).*



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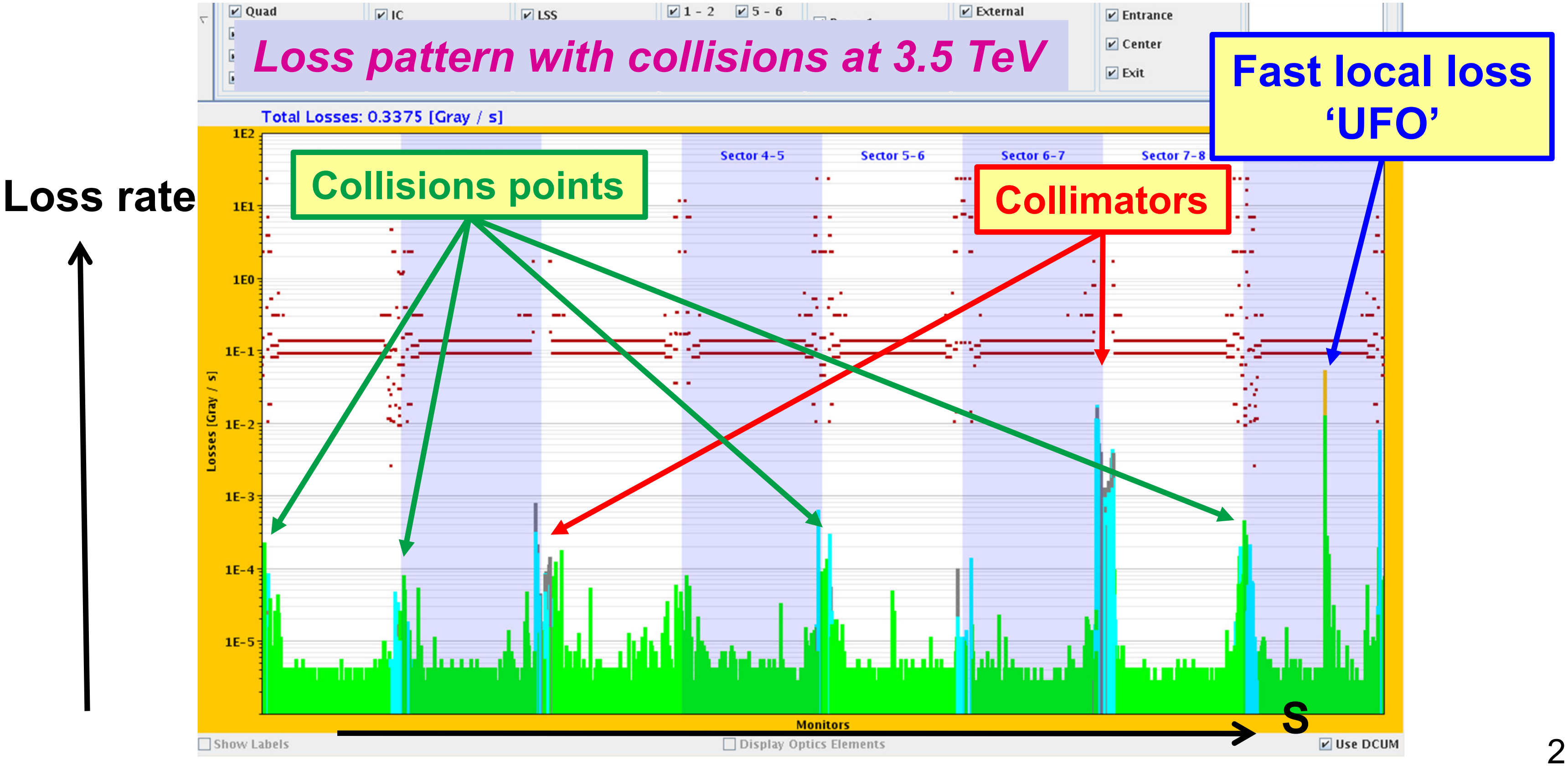
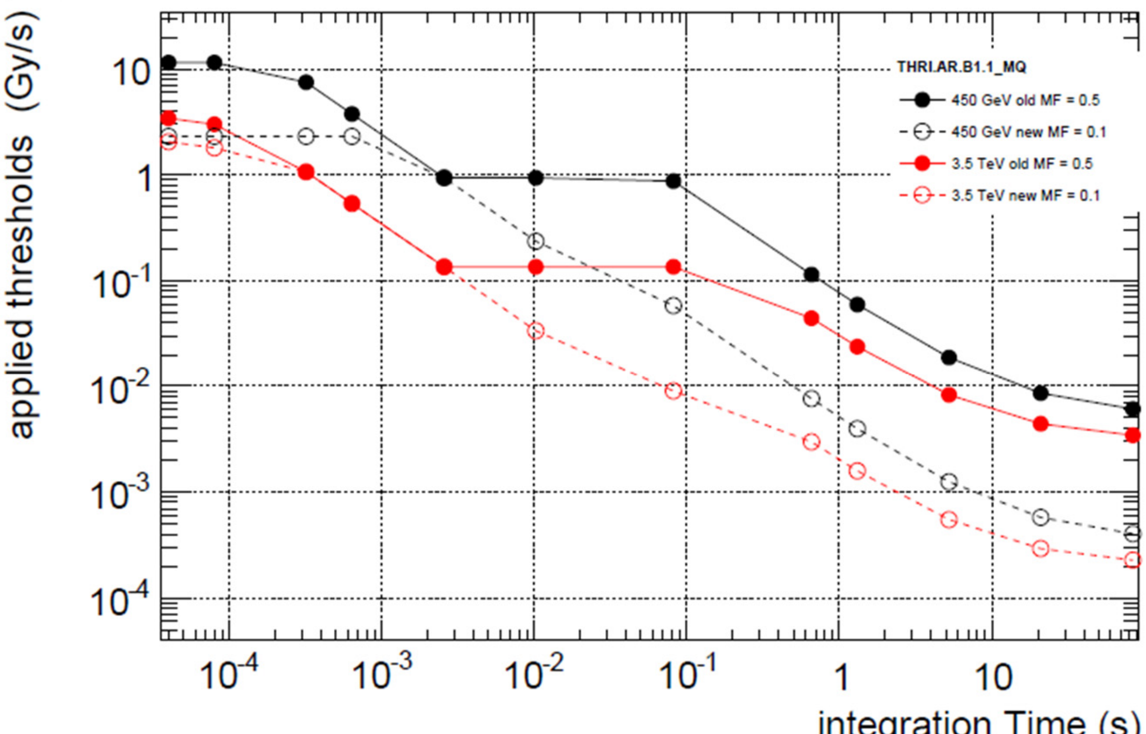
Beam Loss Monitor System

- Almost ***4000 ionization chambers*** protect the LHC super-conducting magnets against quenches and damage from beam loss.
- The system has been designed with very high safety standard (SIL3) and is an ***essential component of the LHC Machine Protection System***.
  - *Smallest loss integration interval is 40 μs ~½ LHC turn.*



BLMs for Machine Protection

- The LHC BLM system will dump if a ***SINGLE** monitor goes above threshold.*
  - *This rather 'aggressive' policy did not cause unnecessary down time.*
- A large fraction of the LHC BLMs are installed on super-conducting magnets with *dump thresholds* set to ***30% of the estimated quench level loss***.
  - *In 2010 the quench thresholds were probed by experiments and by actual loss events. From this experience the thresholds were:*



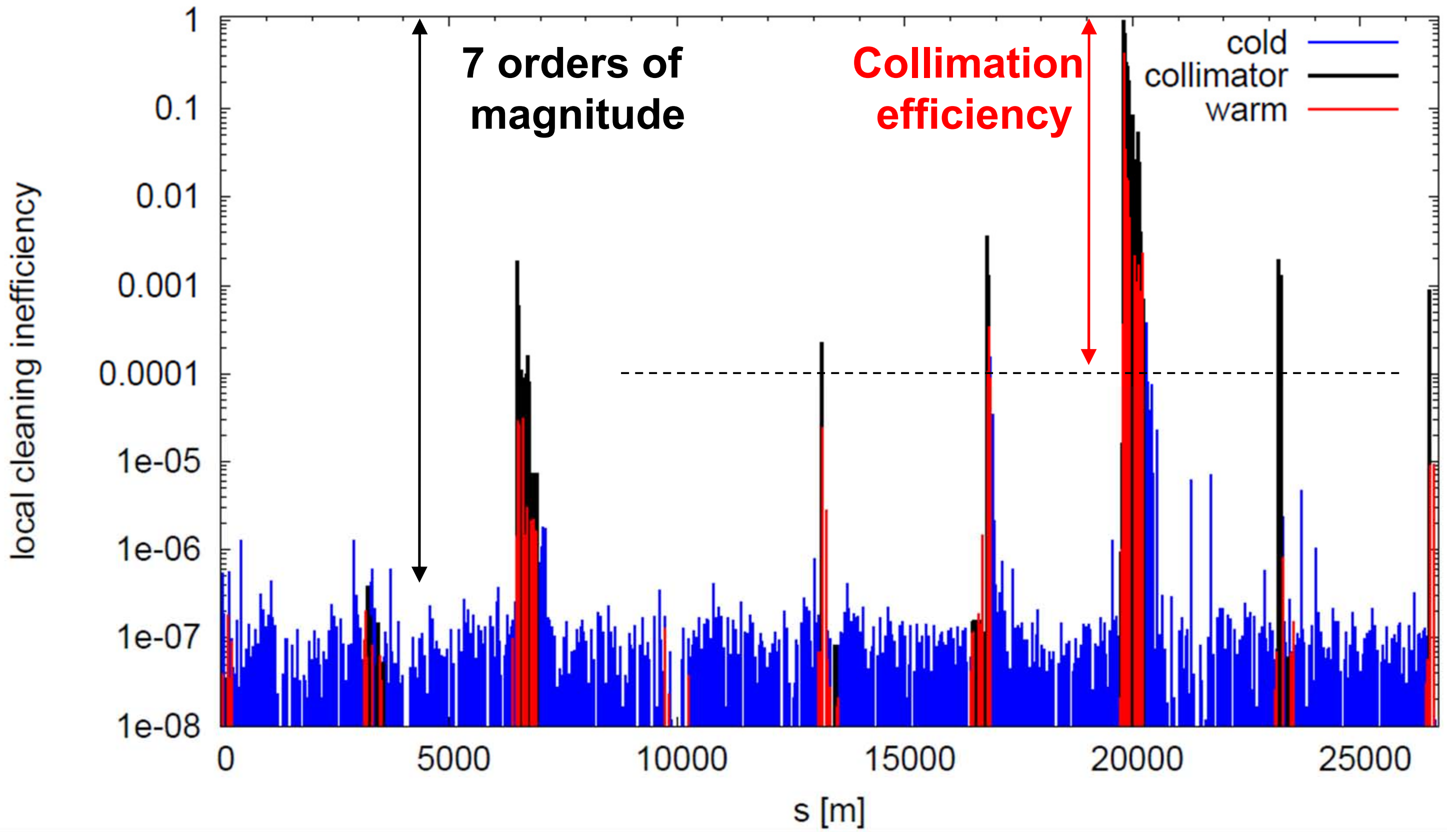
✓ ***increased** by a factor 5 for losses on the millisecond time scale,*

✓ ***reduced** by a factor ~2 for losses on the second time scale.*

Collimator loss maps

The performance of the BLM system as diagnostics for losses is probably best shown by ***the collimation loss maps***.

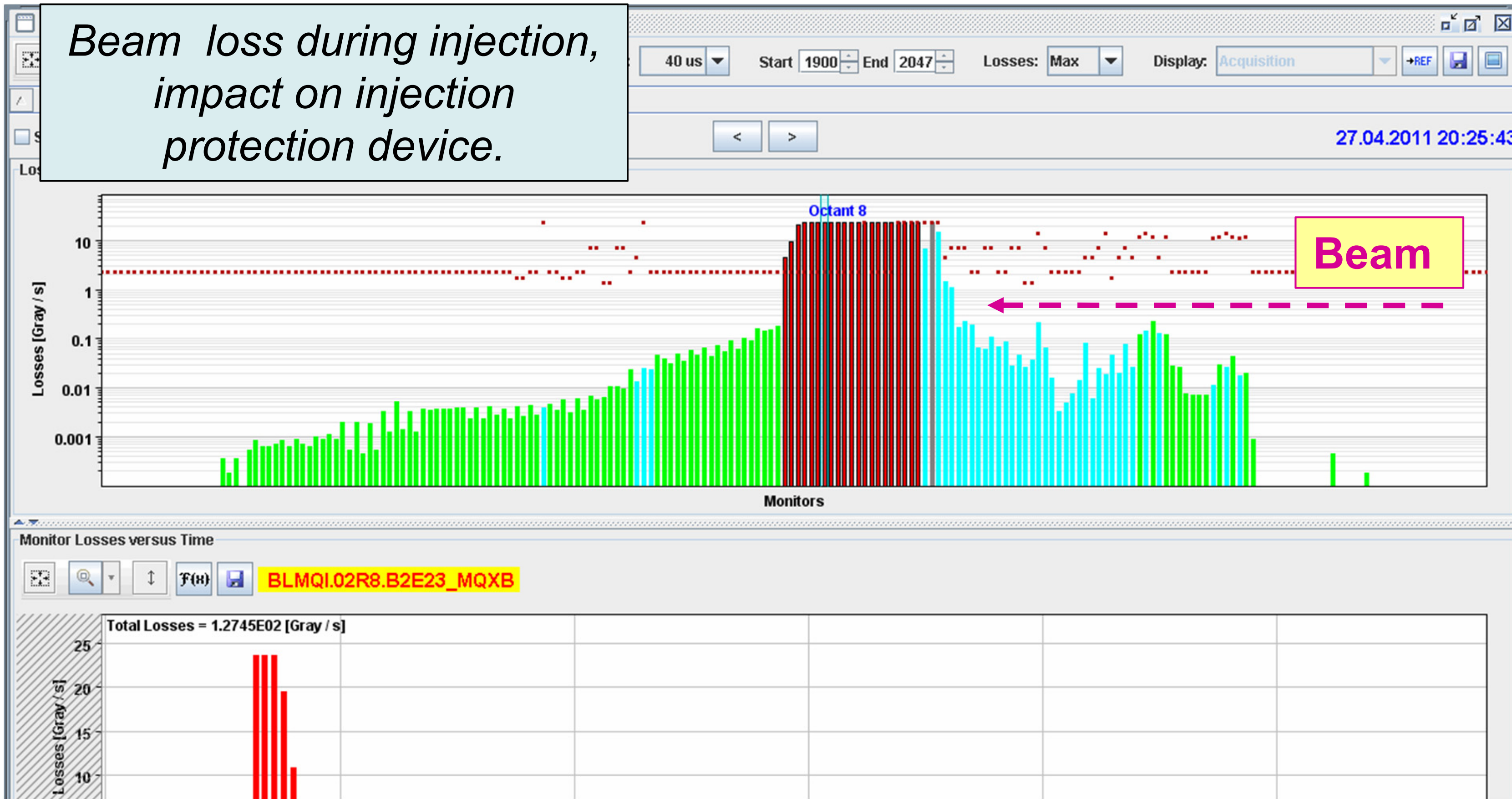
- *To assess the **performance of collimator setups**, beams of a few bunches are made to cross the 1/3 order resonance – leading to large losses.*
- *The loss pattern recorded by the BLMs is used to asses the **collimation system performance – typically 99.9x % efficiency!***



BLM saturation

One of the remaining issues of the BLM system is saturation of the loss signal (electronics) for very fast events (injection) or very high losses at collimators.

- *Smaller ionization chambers, filters….*



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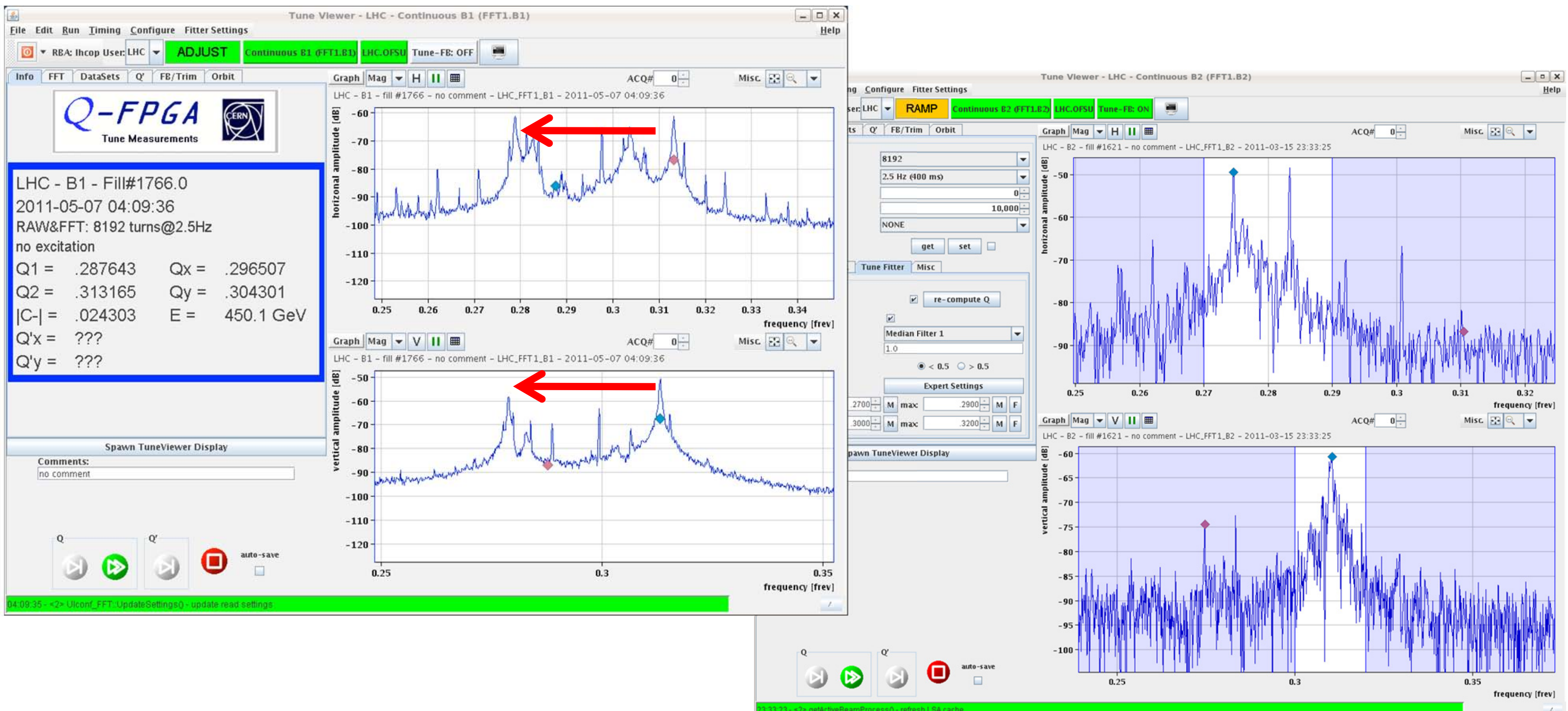
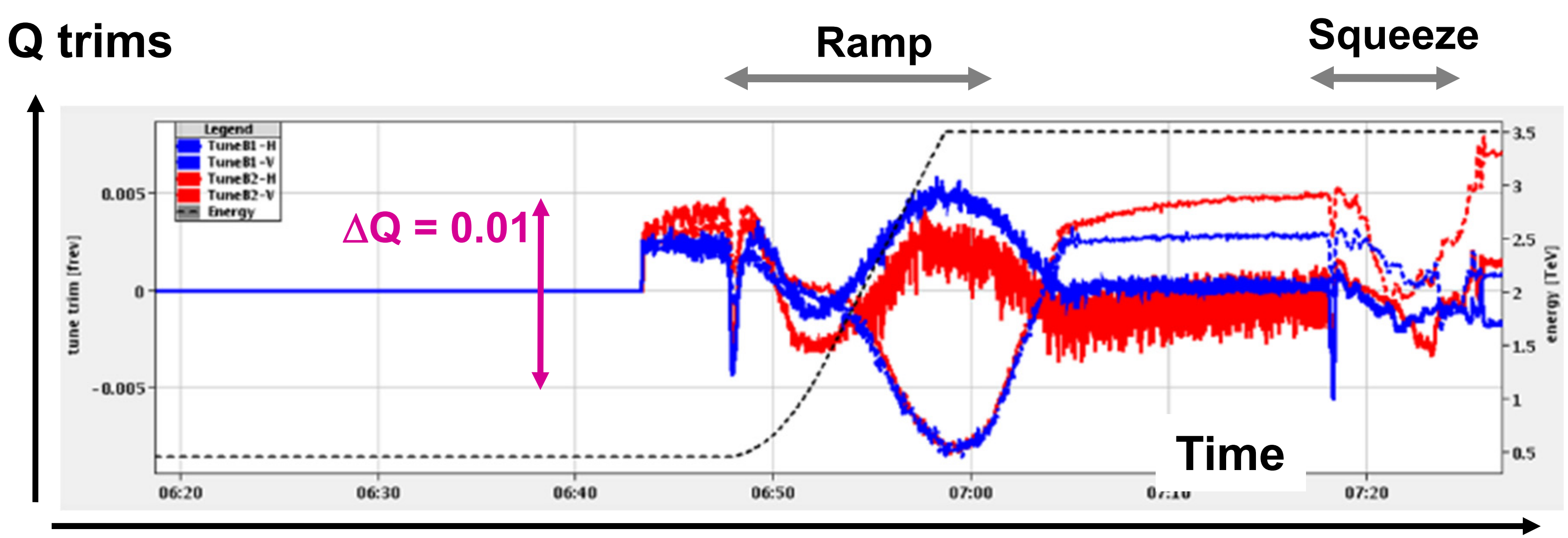
Tune

- Tune diagnostics is based on a high sensitivity BBQ (Base-Band Q) system operated in continuous FFT spectrum mode @ 2.5 Hz.
  - *Working well, but sometimes issues with our transverse feedback system that kills all coherent motion…*
  - *Resolution at the level of 10^{-4} – fine for standard control room use.*



Tune feedback

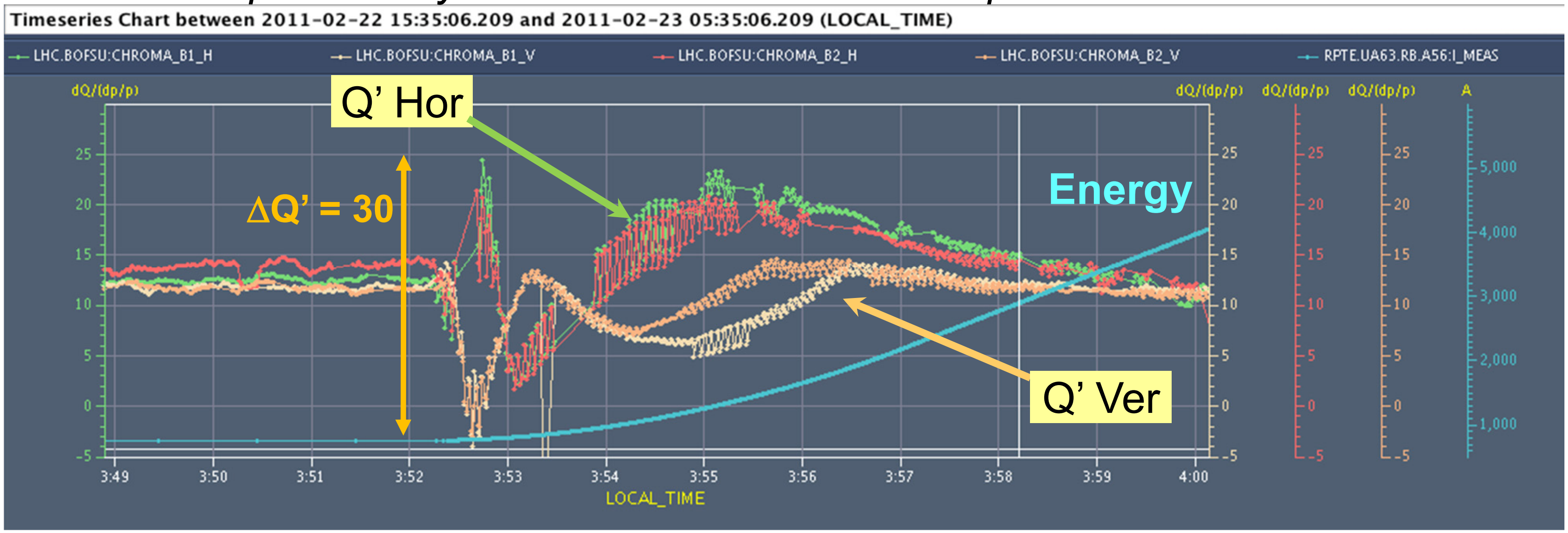
- A real-time tune feedback is used for ramp and squeeze - based on FFT acquisitions @ 2.5 Hz – ***essential tool***, even if it is possible to operate without.
  - *Sometimes **compatibility issues between tune FB and transverse feedback (TFB)** –signal quality for Q diagnostics. Compatibility with the TFB is also the reason why a PLL is not used for Q-tracking.*
  - *Too aggressive corrections lead to trips of Q trim circuits as the quench protection system erroneously interprets fast trims (voltage spikes) as quenches: has been an issue for some time - OK now.*
  - *QFB trims minimized by feed-forward…*



Chromaticity

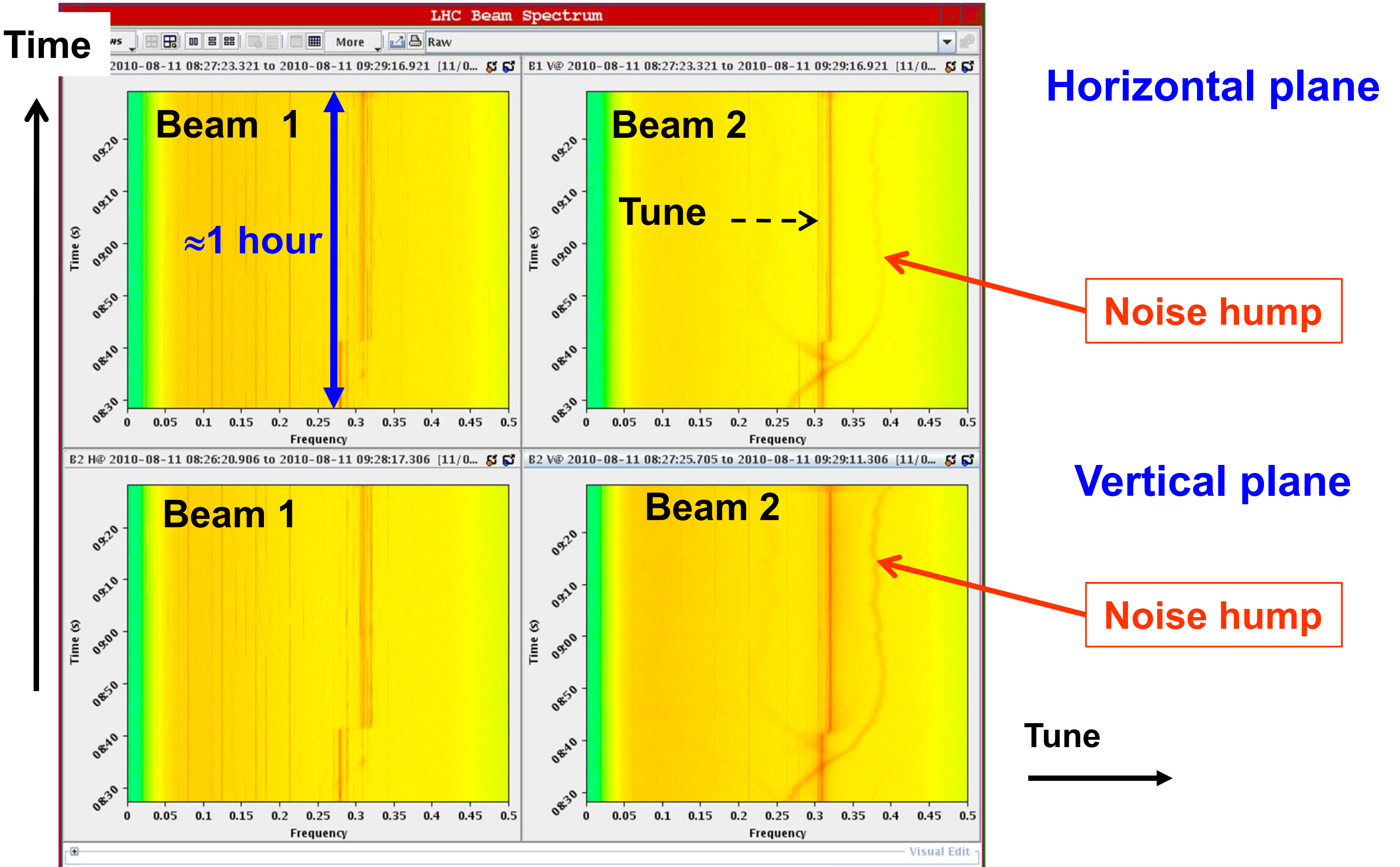
- Q' is measured using classical RF frequency modulation - $dp/p = \pm(2\text{-}4)\times10^{-4}$.
- Q' is used at every injection with pilot / moderate intensity beams.
  - *Check of feed-forward correction for the dynamic field decay of the super-conducting dipole magnets (decay of ~ 20 units of Q').*
- Ramp measurements on demand with low intensity + feed-forward.
  - *Ramp measurement with high intensity could be feasible – not done so far.*

Example of early Q' measurement in the ramp



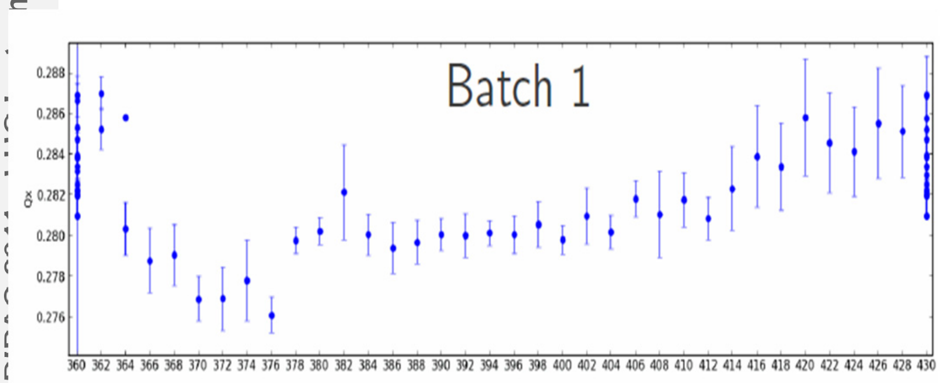
Noise on the beam

- In 2009 & 2010 the beams were periodically excited by an unknown noise source ('hump') of varying frequency – affected mostly beam2 in vertical plane.
  - *Amplitude ~ μm → emittance growth.*
- In 2012 the situation is better – not quite clear why..

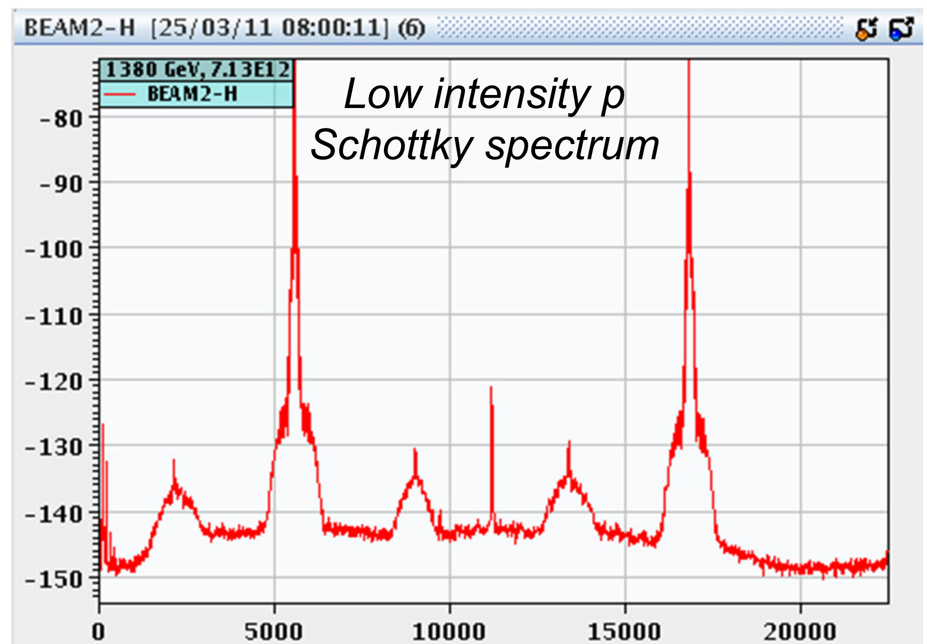


Bunch by bunch tunes - shottky

- A Schottky monitor provides tune, chromaticity, momentum spread data independently of the BBQ system.
  - *Can be gated to provide bunch-by-bunch tunes.*
- Strong and long lasting coherent longitudinal oscillations with high intensity proton beams makes measurements difficult.
  - *Requires long waiting times (~ 30 minutes) after the ramp.*
  - *Performance is good with low intensity ion beams.*



Q versus bunch number
with strong electron cloud activity.



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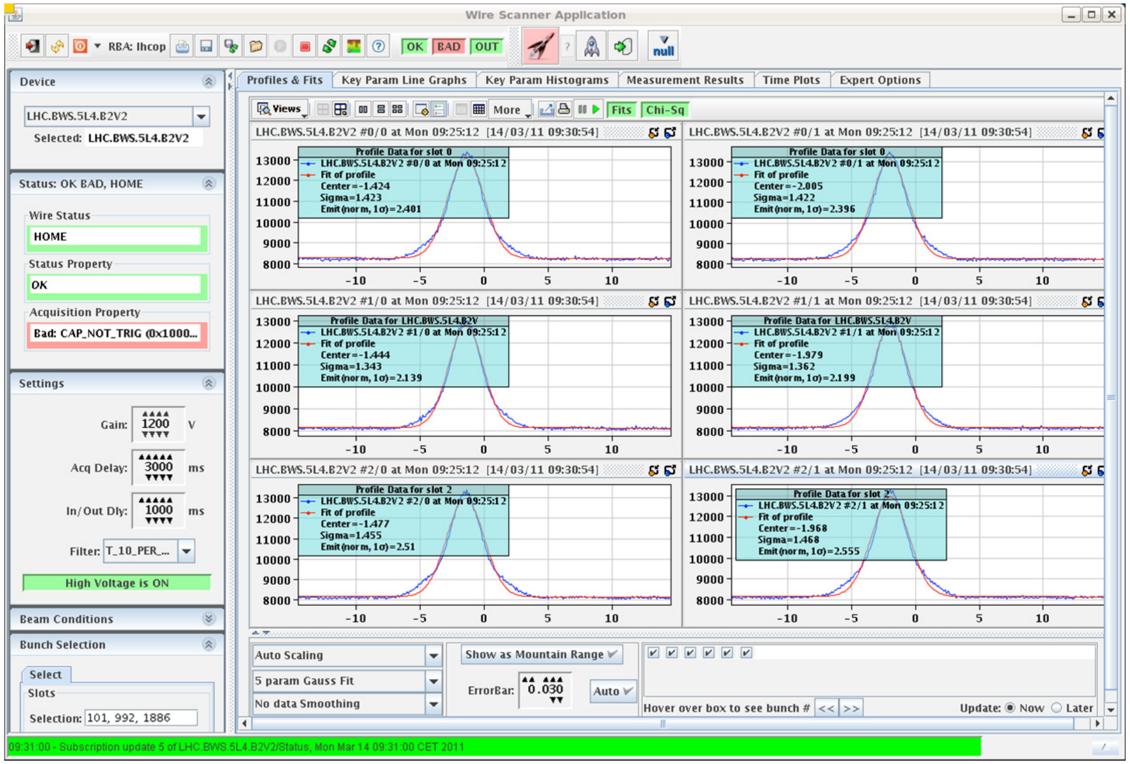
Wire scanner

- Wire-scanners have long been the workhorse for emittance measurements for operations, but their range is limited to low intensity due to risk of damage (injection) or quench (3.5 TeV) – max. ~150 bunches.
  - *Wire scans can presently only be used at start of filling and for machine experiments with moderate intensity.*
- **Wire scanners are our reference devices for absolute emittance measurements.**

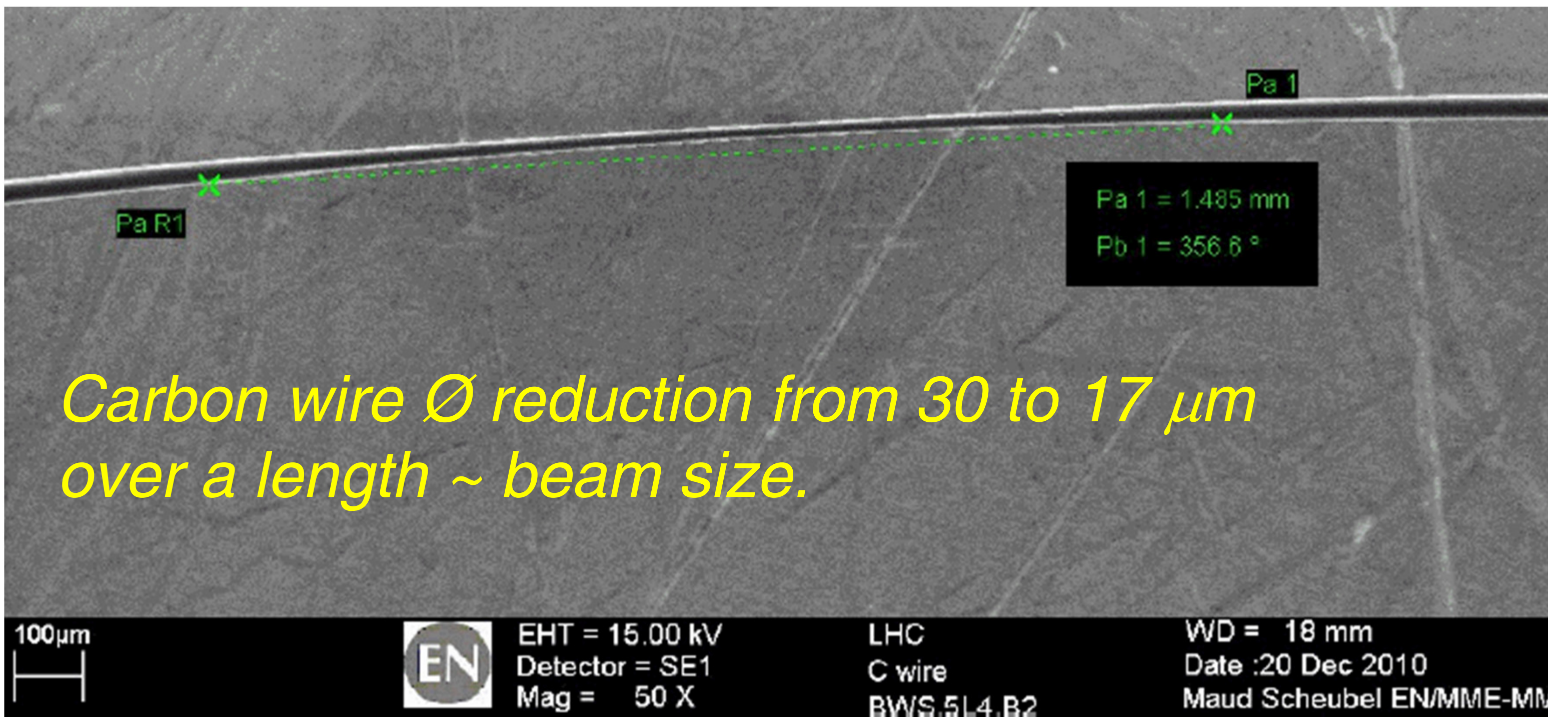
Example of bunch by bunch wire scans



Victim of the LHC beams

The only (known) damage to LHC equipment from the beam.

- *Beam 2 wire-scanner almost evaporated during a quench test when the wire speed was reduced to 5 cm/s (from 1 m/s) to quench a magnet.*
- *Almost fatal to the wire – the magnet seems to be in good shape!*



Courtesy M. Scheubel/A. Lechner

Light from hadrons

- A the LHC we have a unique privilege to be able to observe proton and ion beams in real-time using synchrotron light.
  - *Beam instabilities and kicks can we observed by eye on the TV screens.*
- My BI colleagues are working on the absolute calibration. For the moment this instrument is mostly used to relative measurements : *emittance growth and bunch by bunch emittance.*

Synchrotron light from Pb ions

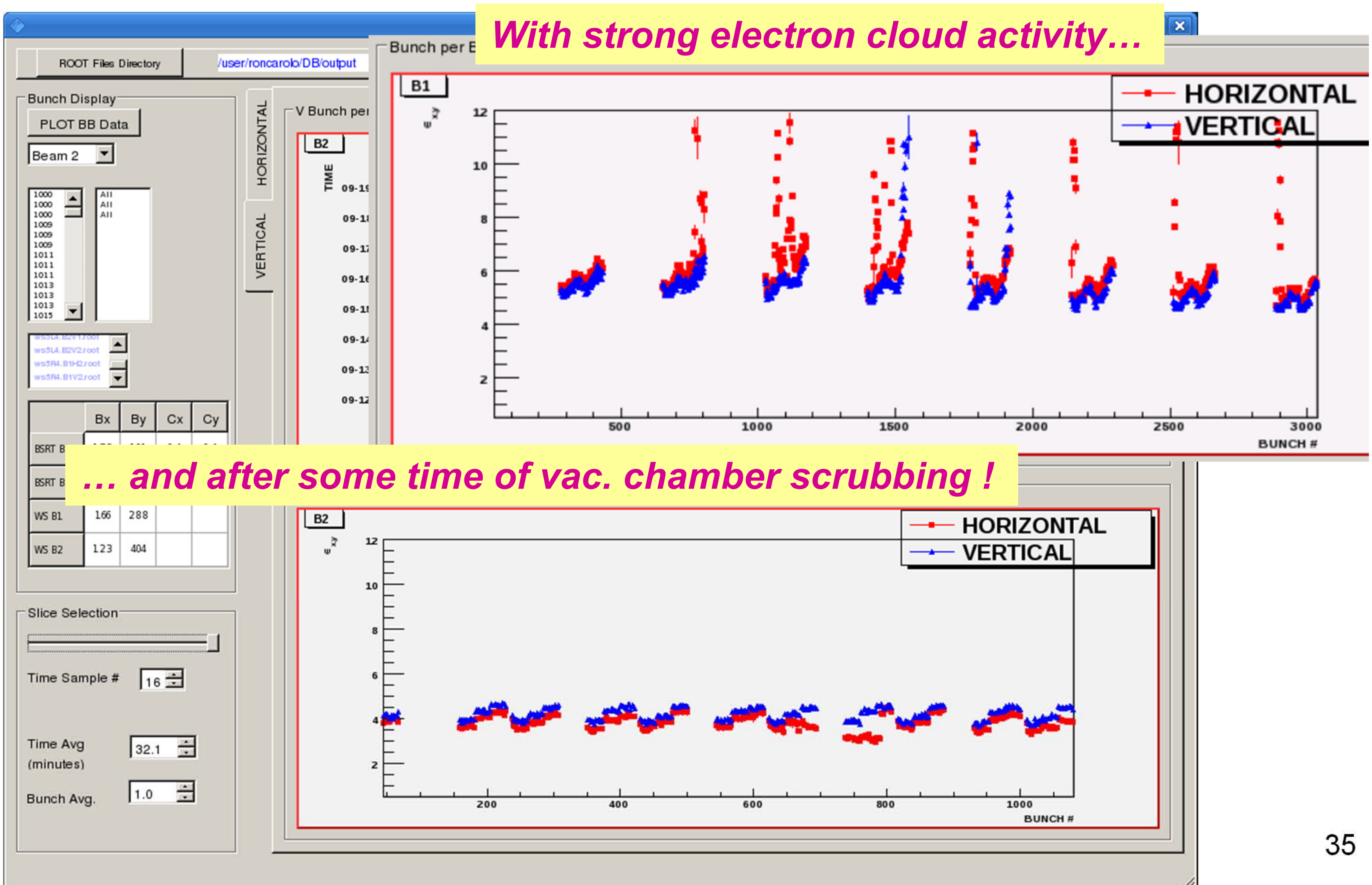
Light source

- *Super-conducting undulator from injection to 1-1.2 TeV*
- *Dipole field from ~1 TeV.*

A unique tool for a hadron collider !

Bunch by bunch emittance

Example of bunch by bunch emittance diagnostics with 804 bunches / beam



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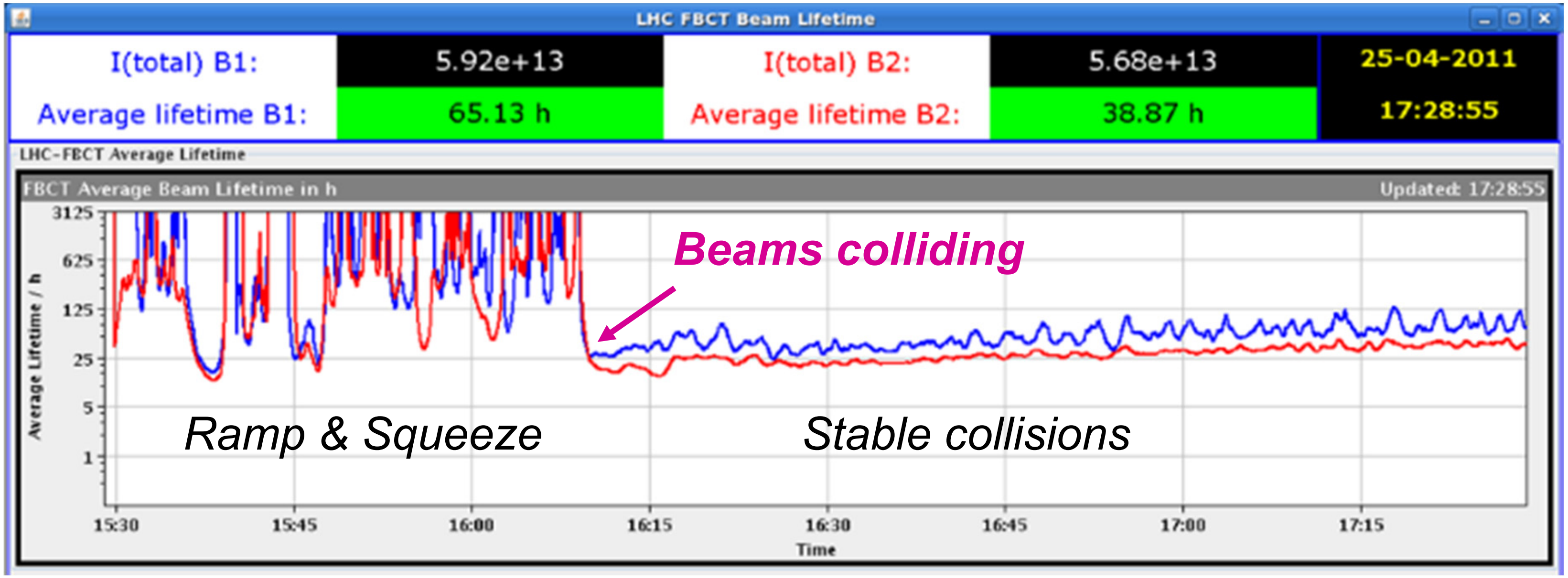
Beam intensity and longitudinal profiles

DC and bunch-by-bunch (fast) BCTs are of course a MUST.

- *Bunch-by-bunch intensity losses are used to understand beam-beam effects and collective instabilities.*
- *Absolute calibration of DCCTs to below 1% and cross-calibration to fast BCTs is of great interest to the experiments.*
  - *In 2010 this was hampered by dependence of the DCCT on filling pattern and bunch length, and position dependence of fast BCTs. DCCT issue solved in 2011 – absolute calibration below 1%.*



Bunch by bunch intensity

In a machine with such high intensity, beam-beam effects etc, bunch by bunch intensity is essential.

- *Bunch-by-bunch intensity losses are used to understand beam-beam effects and collective instabilities.*

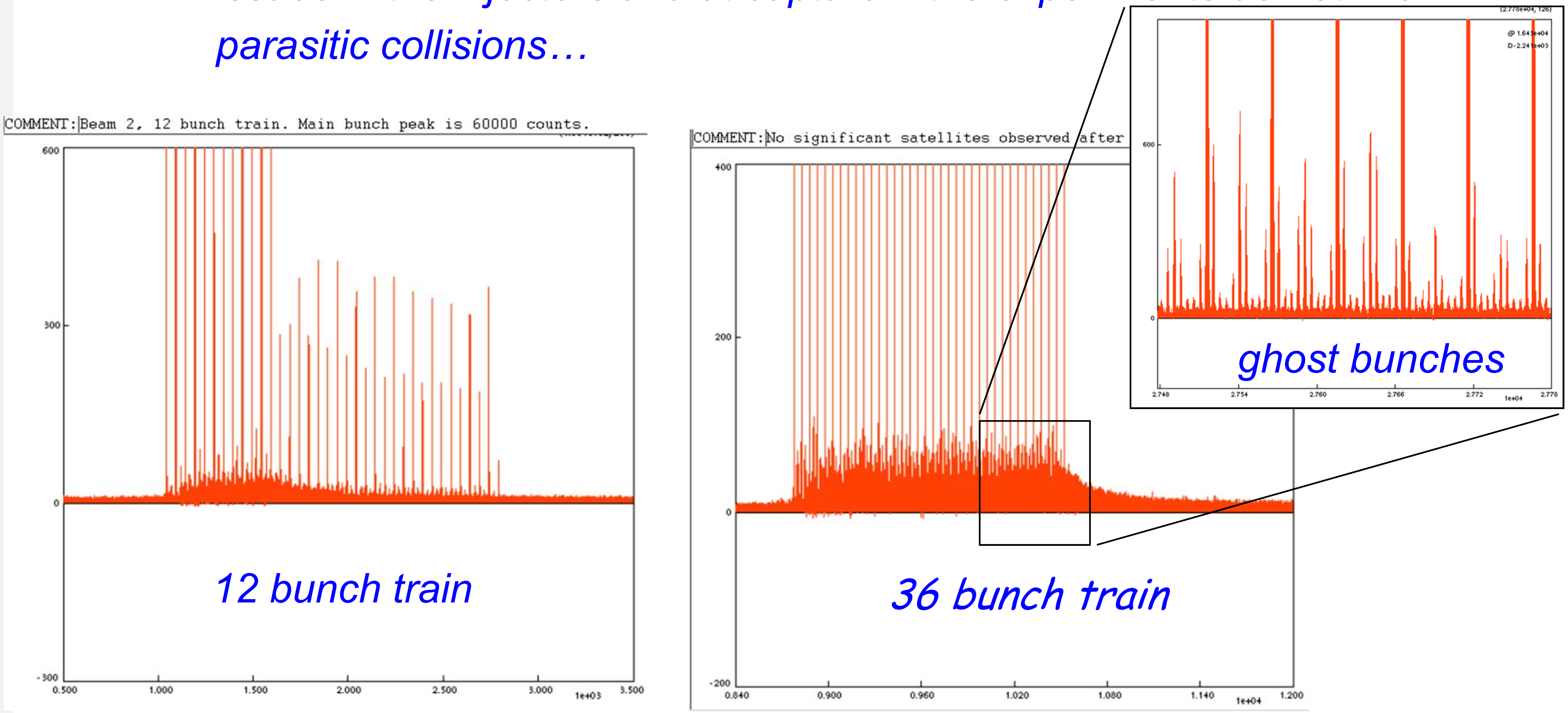
Bunch intensity

Bunch-by-bunch intensity losses

Structures reflect beam-beam and emittance differences

A longitudinal profile monitor based on photon counting (same source as synchrotron light monitor) is beginning to provide high resolution data of the longitudinal structure of the beams !

- *Still 'under construction' but extremely promising to understand RF issues in the injectors and at capture – the experiments do not like parasitic collisions…*



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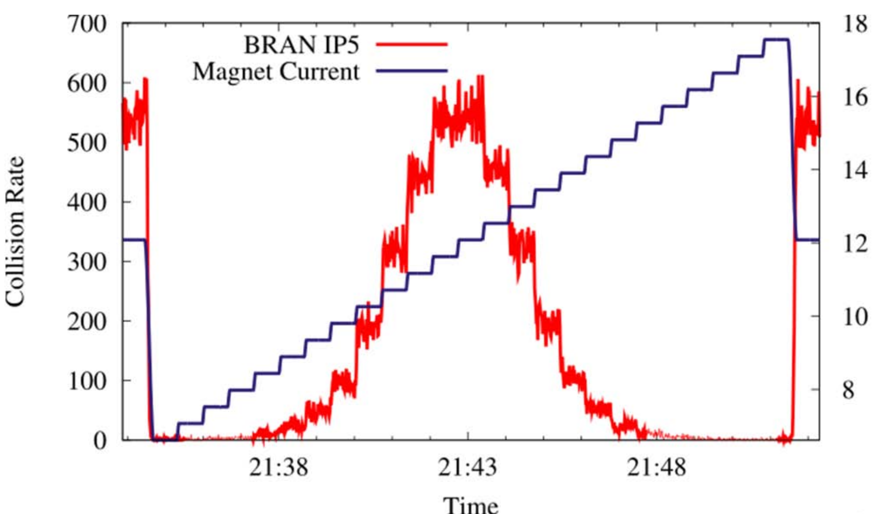
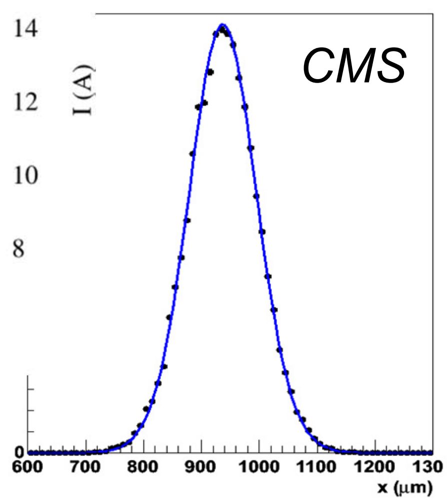
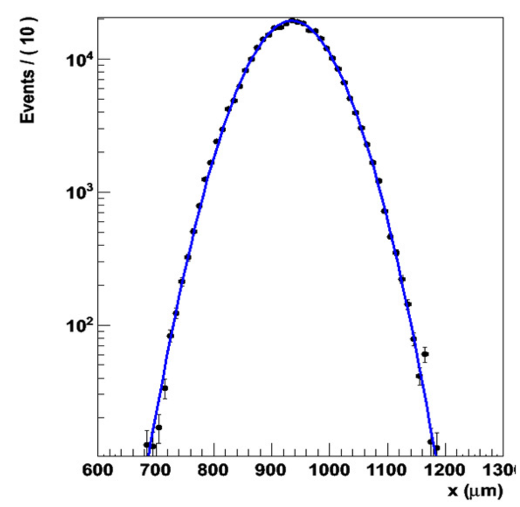
Luminosity is what they want !

- The LHC machine has its own 'simple' luminosity monitors (ionization chambers and CdTe detectors) – presently only used as backup. Beam operation is relying on the luminosity data from the experiments.
  - *Luminosity optimization scans are performed in both planes every time we bring the beams into collisions - $\approx\pm1$ sigma corrections.*
- An effort to provide an *absolute calibration of the luminosity at the level of a few %* based on Van de Meer scans is in progress – *BCT accuracy is essential.*



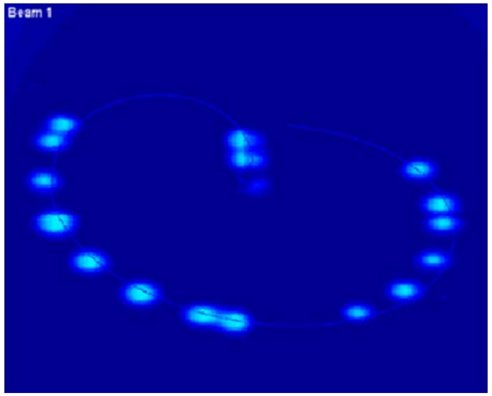


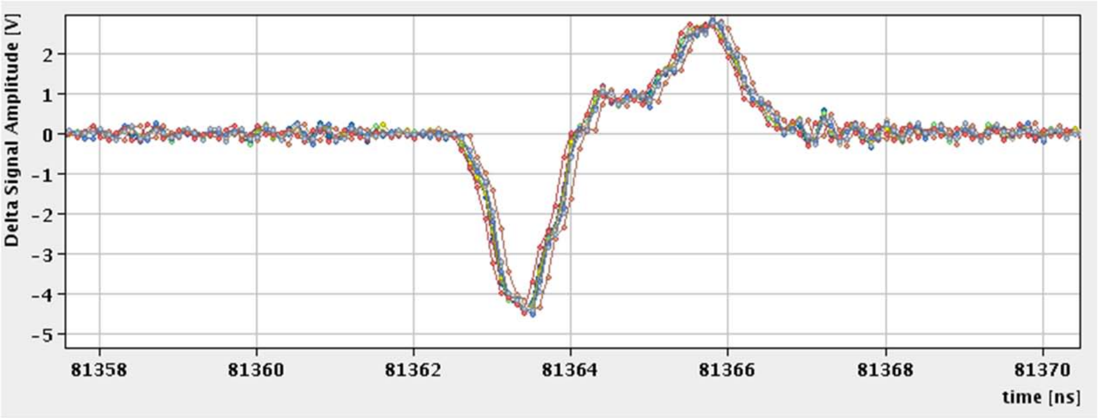


And much more…

There are more instrumentation around that I cannot cover here – apologies to my colleagues:

- Beam screens (OTR) for matching and dump diagnostics.
- Bunch length measurements,
- Gas ionization profile monitors,
- Head-tail monitors,
- Diamond detectors for bunch-by-bunch losses,
- …

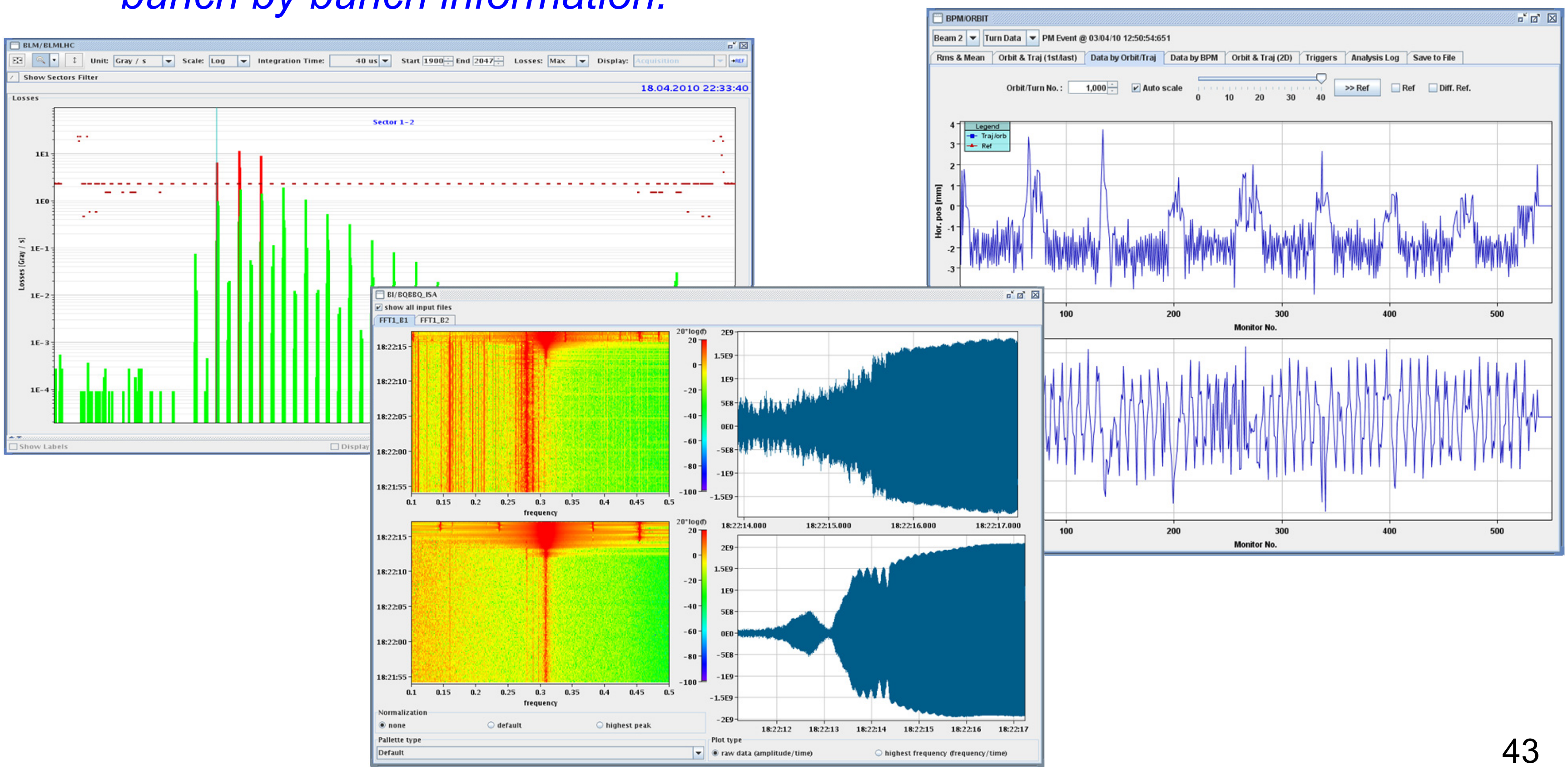




Post-mortem

All essential BI systems (BPM, BLM, BCT, BBQ) provide post-mortem data that is collected and archived for every beam dump.

- *Essential to diagnose dumps, from beam instabilities, kicker mis-fires, fast beam losses etc.*
- *Turn by turn resolution is the standard – we are now interested to add bunch by bunch information.*



Red Herring of LHC BI

Is there an instrument that was installed and where it is clear that it is of (almost) no use?

An external review of the LHC instrumentation in ~2002 ***recommended to add intensity measurements to every BPM*** (position signals are normalized).

With the quality of the LHC beam loss system it seems rather clear that we will never use this… (and we have never used it so far).

A few years ago – DIPAC03 @ Mainz

Challenges for LHC and Demands on Beam Instrumentation

J. Wenninger

CERN Accelerator and Beams Division
Operations group

- The LHC machine
- Dynamic effects from SC magnets
- Beam-beam and luminosity
- Machine protection and collimation
- Electron clouds

Let's have a look at my summary from 2003…

Summary of 2003 – viewed from 2011

- The LHC is a complex collider with a tremendously high beam power.
- All instruments must cover a wide dynamic range of intensities. ✓
- Bunch-by-bunch diagnostics is required from most instruments ✓

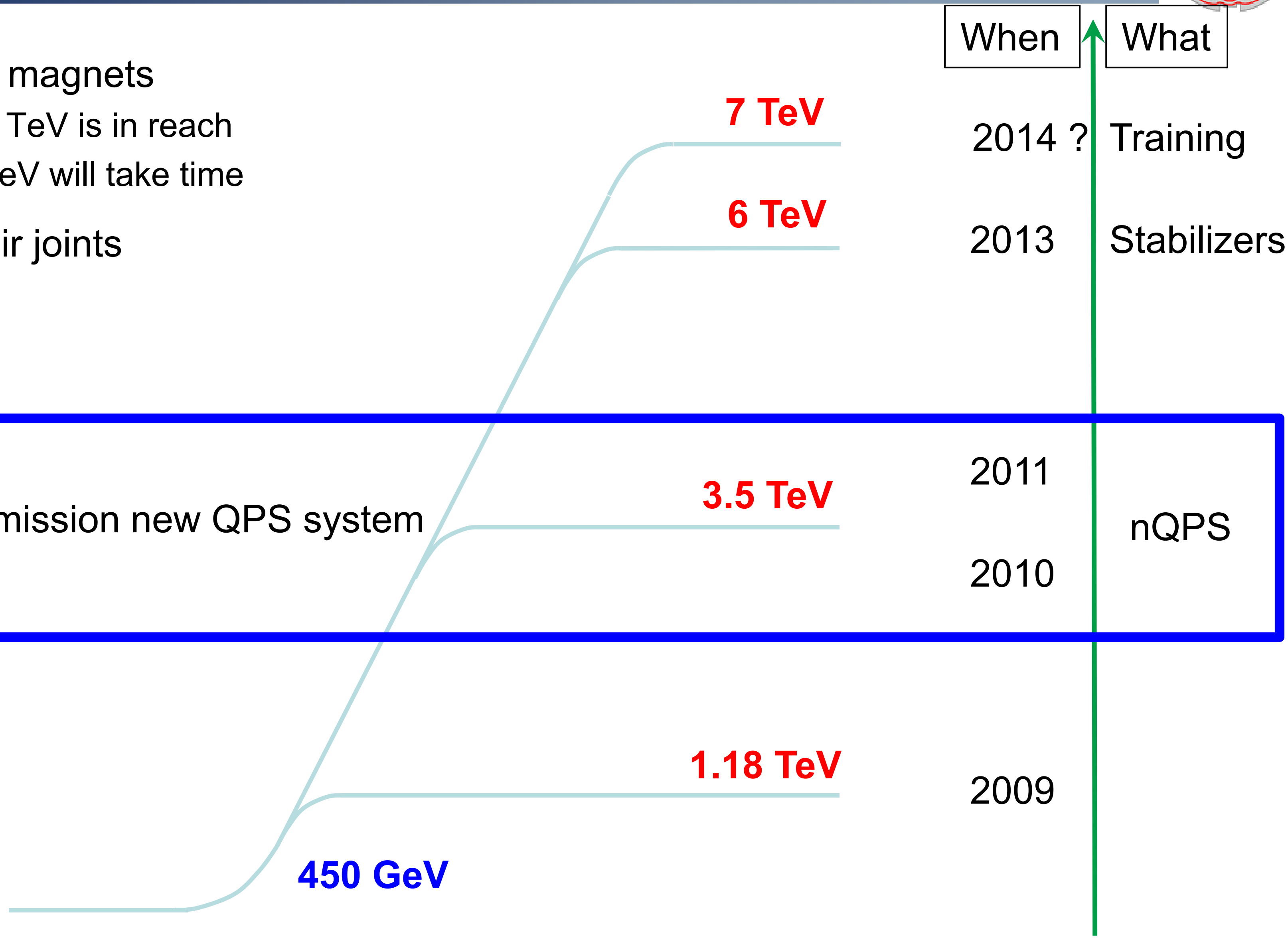
  but we have the challenge to extract & exploit the data
- Many critical measurements (Q,Q'…) must be performed without significant emittance degradation. ✓

  got away with self-excitation of the beam…
- Luminosity monitors and all instrumentation installed in cleaning sections must cope with very high radiation doses. ✓

  ok for moment (component testing) – other systems have suffered
- The LHC can only be operated …
  - efficiently with excellent diagnostics. ✓✓ *but improvements are possible*
  - safely with a high performance and failsafe beam loss system. ☆☆☆

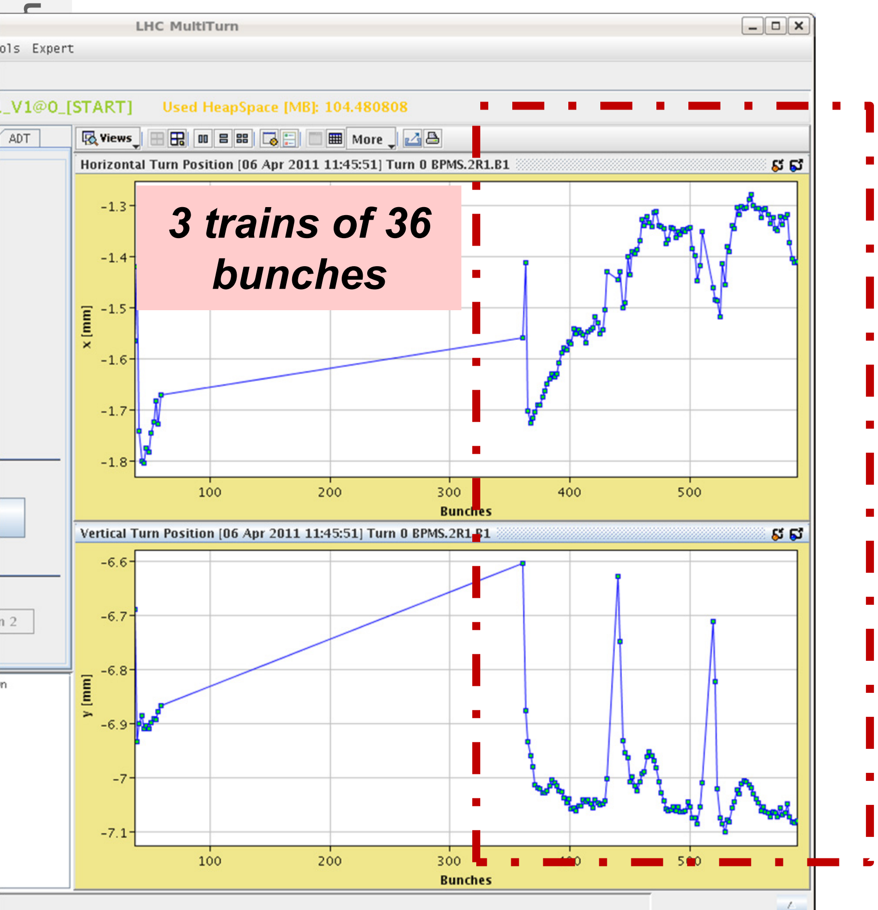
LHC target energy: the way up

- Train magnets
  - 6.5 TeV is in reach
  - 7 TeV will take time
- Repair joints
- Commission new QPS system



Orbit systematics – bunch pattern

- Like many BPM systems, the LHC electronics has a systematic dependence on bunch pattern / filling scheme.
  - *Unfortunately we have to setup the LHC with few **isolated bunches** (for example collimators and we operate with **trains of bunches**.*



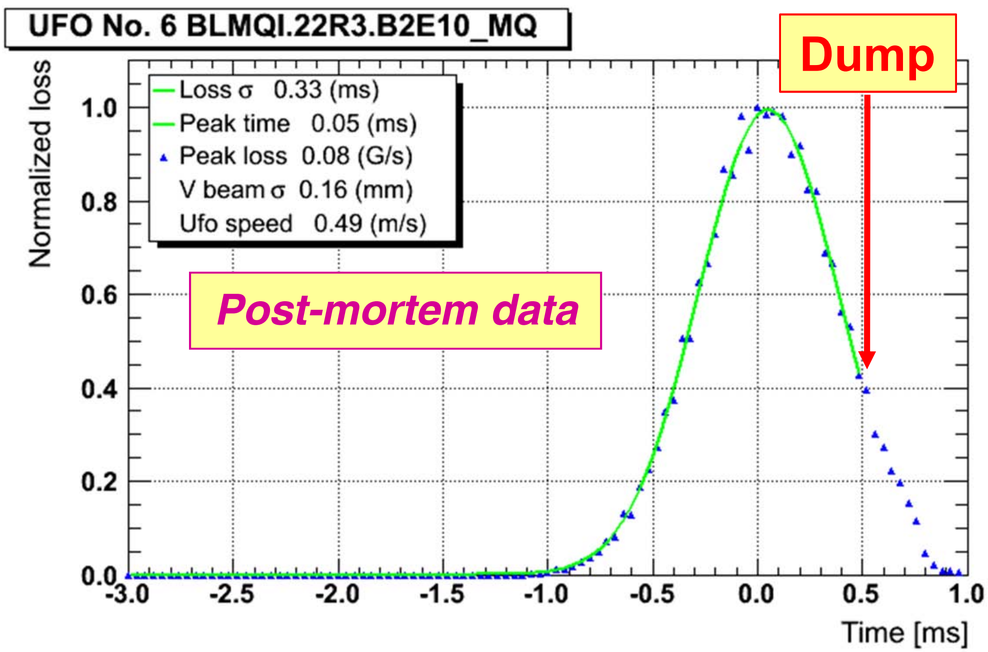
- *The BPM calibration system is able to simulate the different conditions – average effects are absorbed in calibration constants - OK.*
- *Bunch by bunch orbits are however subject to large systematic errors.*

Eventually the reproducibility of the orbit may be one of the limiting factors of LHC performance !

BPMs embedded in collimators

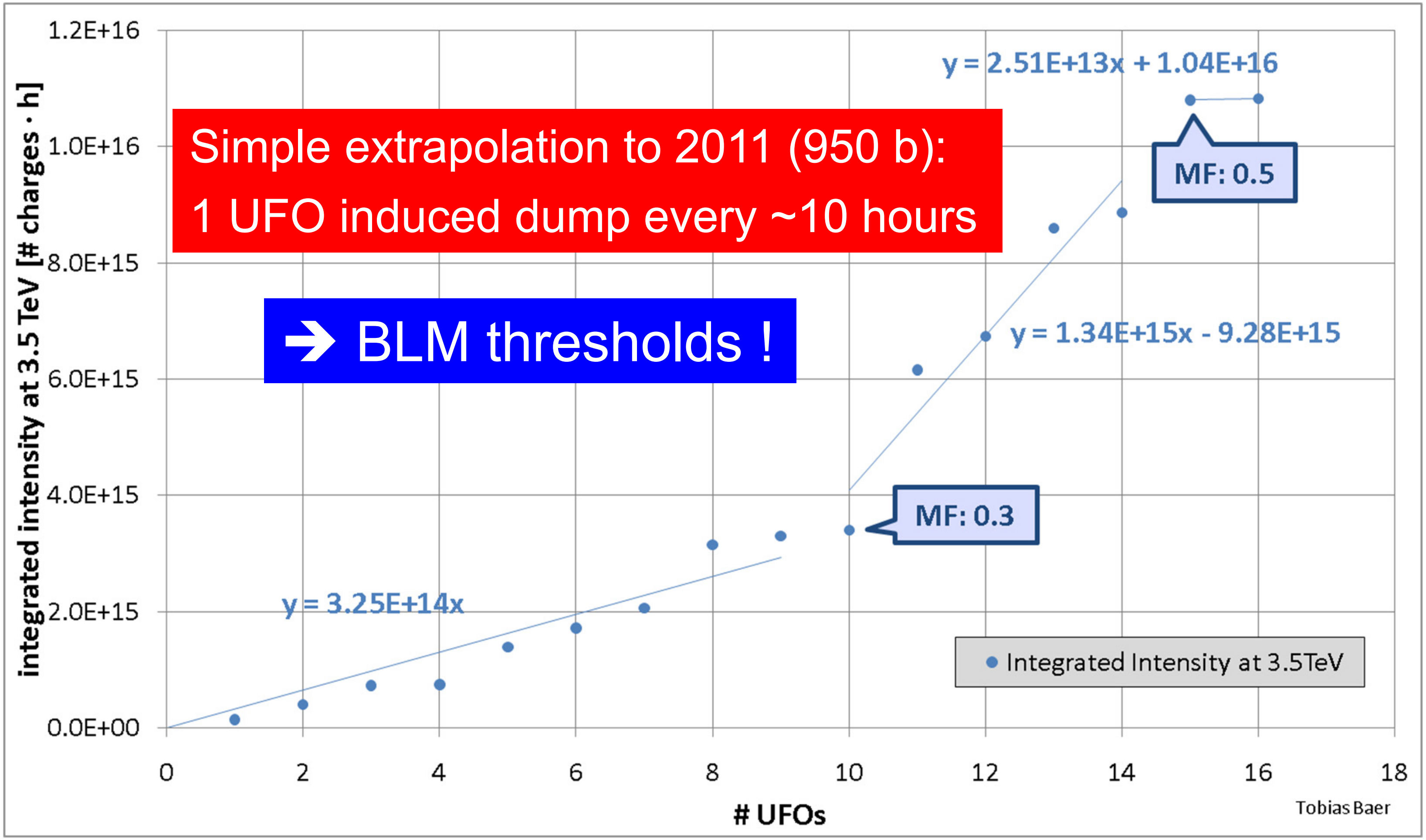
Surprise, surprise !

- Very fast beam loss events (~ ms) in cold regions of the machine have been **THE surprise** of 2010 – nicknamed UFOs (acronym borrowed from nuclear fusion community).
  - *18 beam dumps at 3.5 TeV by UFO-type events*
- Most likely small (10's μm) objects (dust…) 'entering' the beam.
  - ***The factor 5 increase of the BLM thresholds has allowed us to control such dumps in 2011 – one single dump.***
  - *Fast online detection and measurement of such events is being put in place…*



UFO rate

After the increase of the BLM Monitor Factor by a factor of 3 there were about **4.1 times fewer UFO related beam dumps.**



Courtesy T. Baer