LHC BEAM DIAGNOSTICS - THE USERS POINT OF VIEW

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Abstract

The LHC started up with beam in November 2009, and within less then on year its luminosity reached 2×10^{32} $cm^{-2}s^{-1}$ at 3.5 TeV in October 2010. A few weeks later, in November 2010, lead ion collisions were established within little over two days. The fast progress and successes of the LHC commissioning and early operation would not have been possible without the excellent performance of its beam instrumentation. All essential instruments worked from the first day or were commissioned in a very short time, providing rapid diagnostics for the beam parameters. Tune and orbit feedbacks that rely on high quality measurements were used early on to achieve smooth operation with minimal beam losses. This presentation will address the performance of the LHC beam instrumentation, in particular the very large beam position and beam loss monitoring systems, both composed of many thousand channels. Present limitations and future improvements will also be discussed.

LHC COMMISSIONING

The Large Hadron Collider (LHC) [1] saw in 2010 the first full year of operation at 3.5 TeV per beam, after the incident of September 2008 that required a major consolidation program in the tunnel and after a short engineering run at 1.18 TeV at the end of 2009 [2]. The choice of operating at half the design beam energy of 7 TeV per beam was taken to minimize the risk associated to superconducting splice burn-out. A design problem of the main circuit splices was indeed revealed by the massive monitoring campaign that followed the 2008 incident. A full consolidation program to overcome this energy limitation requires a long shutdown to fix all the super-conducting slices which is foreseen in 2013-2014.

After a safe operation at 3.5 TeV in 2010, the LHC roadmap for the next few years has been discussed at the LHC Performance Workshop held in January 2011 [3]. The two main outcomes are that (1) the operating energy will be maintained at 3.5 TeV in 2011 and that (2) the machine run will be extended into 2012. The goal of this two-year long running period is to maximize the LHC physics outcome by either discovering or ruling out the existence of the Higgs boson.

A schematic view of the 26.7 km-long LHC ring is given in Fig. 1 [1]. The LHC lattice has 8 arcs and 8 long straight sections (LSSs). Thanks to a two-in-one magnet design, the counter-rotating proton beams circulate in separated vacuum chambers and cross each other only in the experimental interaction regions (IRs): IR1 (that houses the experiments ATLAS and LHCf), IR2 (ALICE), IR5 (CMS and TOTEM) and IR8 (LHCb). The other straight sections are dedicated to the radio-frequency system (IR4), the beam dumping system (IR6) and the momentum (IR3) and betatron (IR7) collimation systems. The injections of the clockwise beam 1 and anti-clockwise beam 2 take place in IR2 and IR8, respectively.

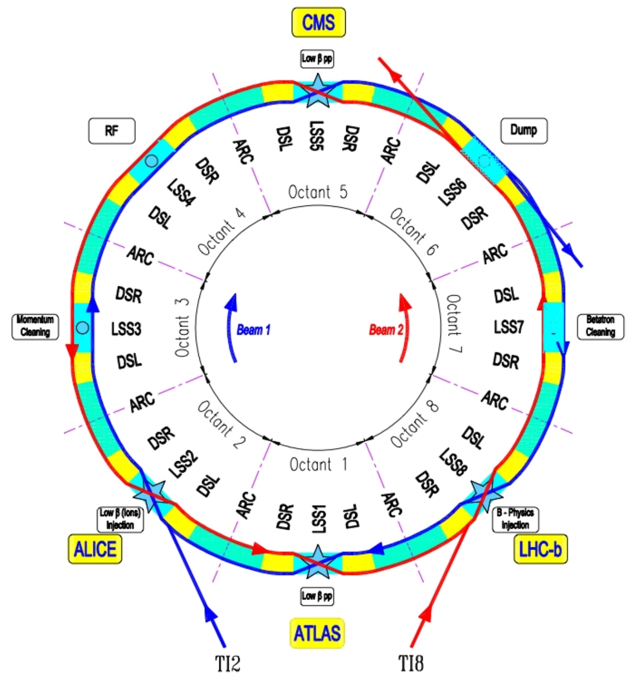

Figure 1: Illustrative layout of the 26.7 km-long LHC rings, featuring 8 arcs and 8 long straight sections (LSSs). Each LSS is surrounded by 2 dispersion suppressors (DSs) [1].

Figure 2 illustrates the peak luminosity progression that characterized the 2010 run and the early part of the 2011 run. Three different running periods can be identified:

(1) Initial commissioning and luminosity run with reduced intensity (blue shaded area);
(2) operation with up to 48 bunches of intensity above the nominal value of 1.15×10^{11} p (red shaded area);
(3) operation with bunch-train injections at 150 ns spacing in 2010, up to a total of 368 bunches, for luminosity performance ramp-up; operation with bunch-train injections at 75 ns and then 50 ns spacing in 2011, up to a total of 768 bunches (status mid-May 2011, green shaded area).

The main LHC design parameters, the 2011 achievements and the forecast for 2011 are given in Table 1. To

Table 1: LHC Parameters for Proton Operation, the Second Column Indicates the Present Achievements in 2011

Parameter	Value		
	Design	2011	2011 target
Beam energy [TeV]	7.0	3.5	3.5
Peak luminosity [10^{32}cm^{-2}s^{-1}]	100	8.5	10–15
Stored energy [MJ]	362	55	≈100
Bunch intensity [10^{10}p]	11.5	12	12–14
Number of bunches	2808	768	1400
Bunch spacing [ns]	25	50	50-75
Norm. transv. emittance [μm]	3.5	2.8	2.5
β^* in IR1/IR5 [m]	0.55	1.5	1.5
β^* in IR2 [m]	10.0	10.0	10.0
β^* in IR8 [m]	10.0	3.0	3.0

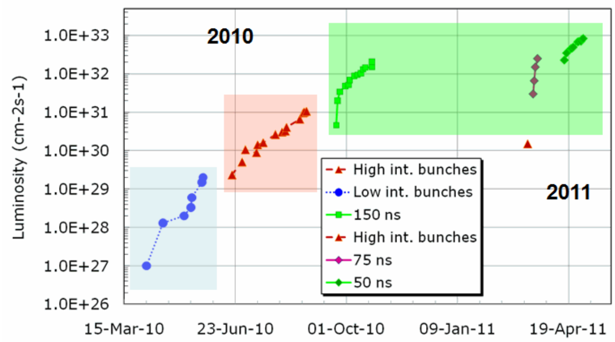

Figure 2: Record luminosity as a function of time in 2010 and 2011.

minimize the electron-cloud effects measured in 2010 [3] a scrubbing run took place in the first half of April 2011, after which operation started with high intensity beams based on 50 ns bunch spacing. Figure 3 illustrates the luminosity progression in 2011. On April 21st 2011 the LHC luminosity exceeded for the first time the TEVATRON luminosity record. Only two weeks later the LHC luminosity exceed the TEVATRON record by more than a factor two. The present integrated luminosity in 2011 is 0.25 fb^{-1}, well on the way to a total of a few fb^{-1}.

LHC BEAM INSTRUMENTATION

In this document the focus is set on the performance with high intensity proton beams which is the main physics program of the LHC. But the LHC also has an extensive (≈1 month/year) ion program, for the moment with Lead (Pb) beams. A very successful Pb-Pb run took place in December 2010. The switch over from proton to ion collisions was done in 4 days and perfectly working instrumentation played an important role in this fast turn-over of the LHC. Another Pb-Pb run will take place in November 2011, followed by a first test of mixed p-Pb operation.

The performance of the LHC instrumentation is typically equivalent between protons and ions, except for resolution

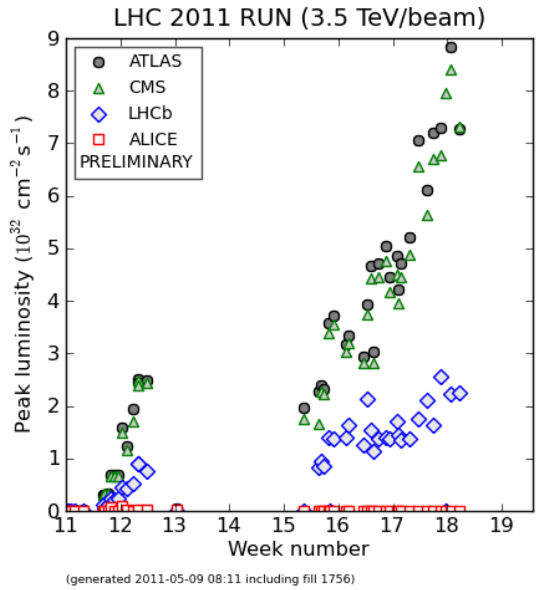

Figure 3: Peak luminosity as a function of week in 2011 recorded by the LHC experiments. Courtesy of M. Ferro-Luzzi.

effects due to lower intensity. Some instruments (for example Schottky monitor) actually performed better with ions than with protons. The typical ion bunch charge is of $2-7\times10^9$ to be compared to proton bunch charges in the range of 2×10^9 to 1.5×10^{11}.

BEAM POSITION SYSTEM

The LHC Beam Postion Monitor system [4] consists of 1070 dual plane button and coupler position monitors, and provides 2140 beam position readings. The orbit acquisitions are auto-triggered and the system availability is excellent. There are typically only around 2% monitors with problems.

On the official start up day of the LHC in September 2008, all of CERN (and many more people from the outside) followed live the threading of the beams around the rings. This took about 1 hour for each beam, and the completed first turn of beam 2 is shown in Fig. 4. The threading was extremely successful thanks to the quasi prefect performance of the BPM system on that first day. The number of channel that were found to have problems at commissioning (horizontal-vertical inversion, sign) was at the level of few percent.

Rather unusual for a proton ring, an orbit feedback (OFB) was foreseen from the start, based on 25 Hz orbit acquisitions to ensure that the high intensity proton beams would remain well centered in the over 100 collimators. For a machine with super-conducting magnets a 1 Hz bandwidth is sufficient. The OFB is based on central processing of all BPM data with with data transfer from and to the front end computers by UDP packets over Gb Ether-

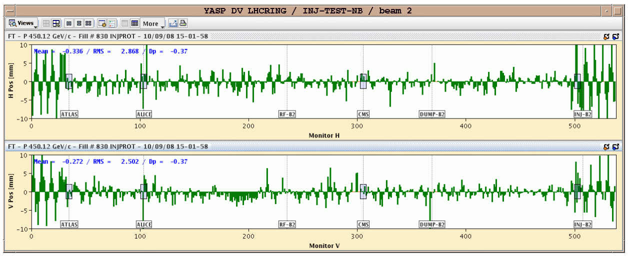

Figure 4: The very first turn of LHC beam 2 after successful threading in September 2010. The beam is injected on the right side of the image.

net. The OFB was put into operation in April 2010 and performed very reliably since then, after minor running-in issues had been solved. The rms orbit stability in ramp and squeeze is at the level of 0.1 mm or better which is adequate for the present operating conditions [5].

To boost the luminosity by a reduction of β^*, aperture considerations become more and more critical, and the orbit reproducibility becomes essential to ensure that the super-conducting magnet aperture is adequately protected. The margins between collimators and apertures are presently at the level of 2 mm, and the margins will go down in the future. Crate temperature driven systematic errors ($\approx$ 50 µm/deg) have quickly been identified as a considerable issue for the reproducibility of the orbit, with shifts of up to 0.5 mm over a time span of a few hours. The problem is now under control with regular calibrations and online temperature correction of the raw position data. The remaining residual errors are at the level of 0.1 mm. A long term solution with temperature controlled racks is being evaluated [4]. Besides the crate temperatures, filling pattern effects of $\approx$ 0.2 mm have been identified. Those effects are controlled by appropriate calibrations that emulates the filling pattern of the machine.

The BPM system also provides bunch-by-bunch and turn-by-turn acquisitions of to 100'000 (turns $\times$ bunches) per BPM and per plane. So far only 4000 turns are used due to data readout and concentration problems. In combination with an AC-dipole excitation, multi-turn acquisitions were used to measure and successfully correct the beta-beating. Figure 5 shows the beta-beating with respect to the nominal model in collisions at 3.5 TeV before and after correction.

BEAM LOSS MONITORING SYSTEM

Almost 4000 ionization chambers protect the LHC against beam induced damage and in particular the LHC super-conducting magnets against beam induced quenches. The system has been designed with very high safety standard (SIL3) and is an essential component of the LHC Machine Protection System [6]. The system is protecting the magnets against loss on time scale ranging from 40 µs (corresponding to $\approx$ 1/2 LHC turn) to 80 seconds.

The LHC BLM system dumps the beams as soon as

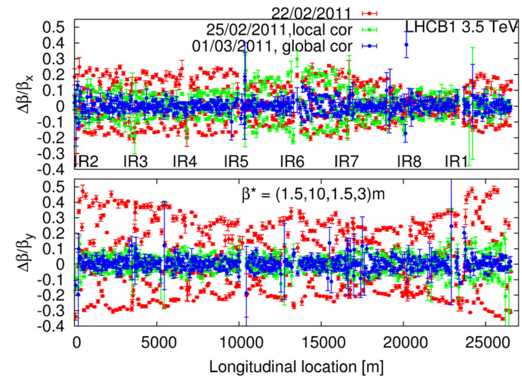

Figure 5: Example of beta-beating measurements for beam 1 using multi-turn acquisitions before and after correction at 3.5 TeV.

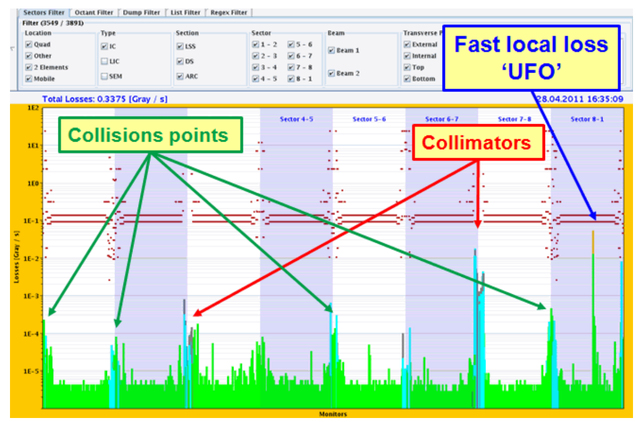

Figure 6: Loss rates along the LHC ring during stable collisions. In this example a short (millisecond duration) loss is visible on the right, probably due to dust particles.

a SINGLE monitor exceeds its interlock threshold. This rather aggressive policy did not cause unnecessary down time so far, and provided excellent and highly redundant protection. A large fraction of the 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 and reduced by a factor 2 for losses on the second time scale with respect to the initial estimates [3, 5].

Figure 6 shows the typical losses during stable high intensity collisions. The losses are contained within the highly efficient collimation system and near the experiments.

One of the remaining issues of the BLM system is the saturation of the loss signal (electronics) for very fast events (injection) or very high losses at collimators. This issue is being addressed with smaller ionization chambers and signal filters.

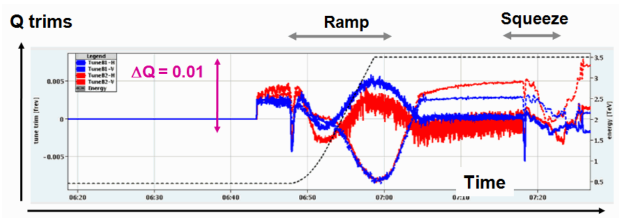

Figure 7: Real-time trims applied by the QFB during a ramp and a squeeze phase.

TUNE AND CHROMATICITY

Tune diagnostics is based on a high sensitivity BBQ (Base-Band Q) system operated in continuous FFT spectrum mode at 2.5 Hz. This system is working well, except for occasional issues with the LHC transverse feedback system that sometimes 'kills' all coherent motion, hiding the tune peak. Under normal conditions the tune resolution is at the level of 10^{-4}, adequate for normal operation.

A real-time tune feedback (QFB) is used for ramp and squeeze, based on the FFT acquisitions at 2.5 Hz. This is an essential tool, although it is possible to operate without QFB if corrections are fed forward properly. Compatibility issues between QFB and transverse feedback have been a recurrent problem, leading to poor signal quality for tune tracking. Compatibility with the TFB is also the reason why a PLL is not used for tune tracking. Too aggressive corrections by the QFB lead to trips of the tune trim circuits as the Quench Protection System erroneously interprets very fast trims (in fact the resulting voltage spikes) as quenches. In general QFB trims are minimized by feed-forward of the corrections. An example of QFB trims during a ramp and a squeeze are shown in Fig. 7.

The chromaticity is measured using classical RF frequency modulation with a range of $dp/p = \pm(2-4)\times 10^{-4}$. It is measured at every injection with pilot beams or moderate intensity beams to verify the feed-forward corrections that are applied with 2011 for the dynamic field decay of the super-conducting dipole magnets (variation of $\approx$ 20 units of Q over 1 hour on the injection plateau) [5]. Continuous measurements in the ramp are performed 'on demand' with low intensity. Corrections are then fed forward and are sufficiently stable. Ramp measurement with high intensity beam have never been tested.

A Schottky monitor provides tune, chromaticity, momentum spread data independently of the BBQ tune system [7]. It can be gated to provide bunch-by-bunch tunes which is of great interest for the study of instabilities and beam-beam effects. Strong and long lasting coherent longitudinal oscillations make measurements difficult with high intensity proton beams; long waiting times ($\approx$ 30 minutes) are needed after the ramp before signals of sufficient quality can be observed. On the other hand the performance is good with low intensity ion beams.

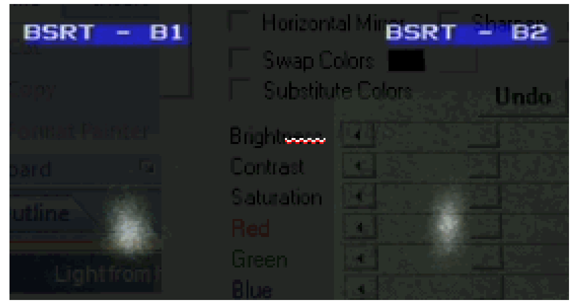

Figure 8: Synchrotron light from Pb ions at 3.5 TeV.

PROFILE MONITORS

Wire-scanners have long been the workhorse for emittance measurements for LHC operations, but their range is limited to low intensity due to risk of damage (injection) or quench (3.5 TeV). Wire scans can presently only be made at start of filling and for machine experiments with moderate intensities. Nevertheless wire scanners remain the reference devices for absolute emittance measurements [5].

A the LHC beam operation crews have the unique privilege to be able to observe proton and ion beams in real-time using synchrotron light [8]: beam instabilities and kicks can be observed by eye on TV screens, see Fig. 8. The light source is a super-conducting undulator from injection to 1.2 TeV, a dipole fringe field above 1 TeV. For the moment this instrument is mostly used for relative measurements like emittance growth and bunch by bunch emittance, as the absolute calibration is not yet sufficiently accurate.

BEAM INTENSITY

In a machine with such high intensities, collective instabilities and beam-beam effects, bunch by bunch intensity is clearly essential to assess the losses for different bunches in the trains. The bunch-by-bunch BCT provides intensity information for each 25 ns bunch slot, while a DC BCT (DCCT) provides precision absolute intensity information. The absolute calibration of DCCTs to below 1% and cross-calibration to the fast BCTs is of great interest to the experiments for the absolute luminosity determination. In 2010 this was hampered by a dependence of the DCCT on filling pattern and bunch length, and a beam position dependence of the fast BCTs. The DCCT issue was solved in 2011, the absolute calibration is now below 1% [9].

A longitudinal profile monitor based on photon counting (same light source as the synchrotron light monitor) is starting to provide high resolution data of the longitudinal structure of the beams. This instrument is still under construction, but it is extremely promising to understand RF issues in the injectors and at capture that lead to the creation of ghost bunches [9].

LUMINOSITY

The LHC machine has its own luminosity monitors (ionization chambers and CdTe detectors) but in regular operation they are only used as backup [10]. Shift crews are relying on the luminosity data from the experiments for daily operation, in particular for the luminosity optimization at the start of every period with stable colliding beams. Corrections of up to one beam sigma at the IP have to be applied every time the beams are brought into collisions.

An effort to provide an absolute calibration of the luminosity at the level of a few percent is under way using Van de Meer scans. This requires an excellent accuracy of the BCTs, see the previous section [9].

OTHER INSTRUMENTS

There are more instrumentation installed at the LHC that cannot be covered here:

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

POST-MORTEM FUNCTIONALITY

All essential instruments (BPMs, BLMs, BCTs, tune) provide post-mortem data in the form of circular buffers that are frozen when the beam dump is triggered. This data is collected and archived for every beam dump, it covers typically the last seconds of the beam before the dump with turn resolution. This functionality is essential to diagnose dumps from beam instabilities, kicker mis-fires, fast beam losses etc. Fig. 9 for example shows the beam loss monitor signal with a resolution of 40 µs that led to a beam dump from a fast loss, probably due to a dust particle, as recorded by the BLM system post-mortem.

CONCLUSION

The beam commissioning and first two years of LHC beam operation have been very successful, with a rapid increase of the luminosity and the stored energy of the beams. This progress would not have been possible without the overall excellent performance of the LHC beam instrumentation. Various issues have been identified and solved during the commissioning (BPM and BCT systematics, BLM thresholds, software issues etc), keeping up with the increased requirements of the machine.

In the near future improvements are expected on profile monitor absolute calibrations, Schottky monitors, longitudinal density monitors. With the LHC now running trains of nearly 1000 bunches, the challenge of extracting and exploiting bunch-by-bunch information is also being addressed.

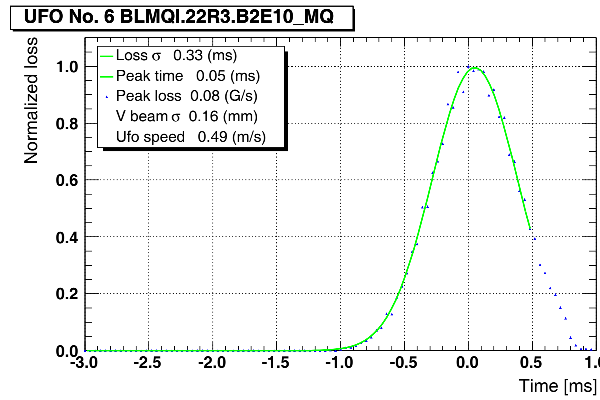

Figure 9: Time evolution of a fast beam loss that triggered a beam dump (from the beam loss) from . One bin corresponds to a 40 µs time interval.

ACKNOWLEDGMENTS

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