FIRST YEARS EXPERIENCE OF LHC BEAM INSTRUMENTATION

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Abstract

The LHC is equipped with a full suite of sophisticated beam instrumentation which has been essential for rapid commissioning, the safe increase in total stored beam power and the understanding of machine optics and accelerator physics phenomena. This paper will comment on all of these systems and on their contributions to the various stages of beam commissioning. It will include details on: the beam position system and its use for real-time global orbit feedback; the beam loss system and its role in machine protection; total and bunch by bunch intensity measurements; tune measurement and feedback; synchrotron light diagnostics for transverse beam size measurements, abort gap monitoring and longitudinal density measurements. Issues and problems encountered along the way will also be discussed together with the prospect for future upgrades.

INTRODUCTION

The first beams circulated in the LHC on the 10th September 2008 in full view of the world's media. Nine days on, a poor superconducting splice overheated during a hardware test at high current, creating an arc which pierced the helium containment vessel with severe consequences. 14 months later, after a major magnet repair and consolidation programme, the LHC was once again cold and ready to take beam. A one month run at the end of 2009 saw the LHC quickly advance with optics, collimation and working point studies at its 450GeV injection energy. Ramp commissioning to 1.18TeV followed, ending in collisions at 1.18TeV per beam in all four of its 4 main experiments.

Further consolidation work was carried out on both the machine and experiments for the first two months of 2010, before the start of a 2 year physics run. Remarkable progress has been made since then, with the LHC now routinely declaring physics with 1380 bunches per beam, a peak luminosity above $2{\times}10^{33}$ cm^{-2}s^{-1}, above nominal bunch intensity and below nominal transverse emittance.

This rapid progress with beam commissioning and operational optimisation was in a large part helped by the very good beam instrumentation with which the LHC is equipped [1].

EARLY DIAGNOSTICS

Injection and Extraction

During commissioning, scintillating and optical transition radiation screens were used to observe and optimise the injection into the LHC and extraction into its dump lines. These also provided the image of the first full LHC turn transmitted worldwide on the 10th September 2009 (Fig. 1). The only screen which still remains in regular operation is the large 1m diameter alumina screen in the dump line, which is continually used to verify the correct functioning of the beam dump system.

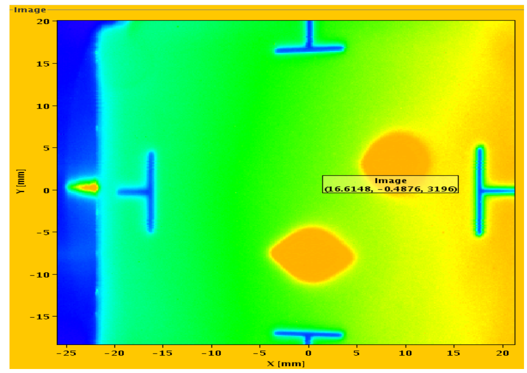

Figure 1: First full turn in the LHC (10/9/2008).

Establishing the Orbit

The LHC BPM system [2] is comprised of 1054 beam position monitors, the majority of which (912) are 24mm button electrode BPMs located in all arc quadrupole cryostats. The remaining BPMs are enlarged (34mm or 40mm) button electrode BPMs mainly for the stand alone quadrupoles, or stripline electrode BPMs used either for their directivity in the common beam pipe regions or for their higher signal level in the large diameter vacuum chambers around the dump lines.

The beam position acquisition electronics is split into two parts, an auto-triggered, analogue, position to time normaliser which sits in the tunnel and an integrator/digitiser/processor VME module located on the surface. Each BPM measures in both horizontal and vertical planes, making a total of 2156 channels.

Several parallel modes of BPM operation are possible. The beam threading mode, used for completing the first turn and closing the orbit on itself was designed to be a totally asynchronous acquisition mode, where any triggers obtained within a specified gate are stored, processed & published. From the very first shot into LHC the BPM system gave excellent results while operating in this mode. Combined with powerful orbit correction software it allowed quick diagnostics to be made on BPM polarity and machine optics errors.

Once the beam started to circulate, the asynchronous orbit acquisition of the BPM system (IIR mode) could be used. This provides an update of the average orbit at 25Hz with a resolution better than ~10µm.

The BPM capture mode, allowing selected bunches to be acquired for several thousand turns, in combination with AC dipole excitation proved essential for optics measurements. For example the beta-beating could be easily measured with this technique and allowed corrections to be put in place which have reduced the residual beta-beat to less than 10%.

Tuning Machine Parameters

The base-line tune, chromaticity and coupling measurement system for the LHC relies on the diode-based, base-band-tune (BBQ) technique [3] developed for the LHC but now also used in all CERN synchrotrons.

Fig. 2 shows a typical tune spectrum captured at injection energy with no externally applied excitation. The calibration of the signal amplitude was performed by applying a known single frequency tone via a stripline kicker. The remarkable sensitivity of the BBQ system is clear, with oscillations visible down to the tens of nanometre level. This has allowed the LHC to have a continuous measurement of tune without the need for external excitation under most beam conditions.

The figure also shows a perturbation of unknown origin in the vertical plane known as "The Hump". This caused problems whenever it crossed the tune, resulting in emittance blow-up and beam-loss seen through a reduction in the lifetime. Discovering the source of this excitation was therefore a priority in 2010 with this sensitive tune system a vital tool for such analysis. It has since disappeared for the 2011 run, without a clear understanding of its origin.

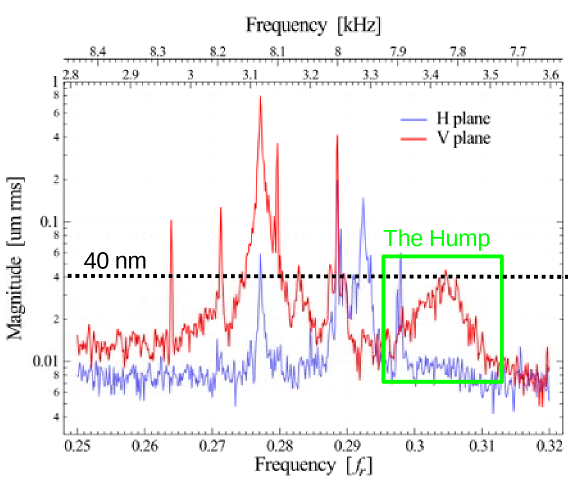

Figure 2: Typical tune spectrum resulting from residual beam oscillations. Also visible is the unknown perturbation source known as "the hump".

MACHINE PROTECTION

The main workhorse for protecting the machine from beam induced damage or quenches is the beam loss monitoring (BLM) system [4] comprised of some 4000 monitors. The signals of almost all monitors are compared with pre-defined threshold values which, if exceeded, result in a retraction of the beam permit signal and consequently a beam dump. It has also proved an invaluable tool for the alignment and verification of other protection elements such as the LHC collimators and absorbers.

The LHC BLM Acquisition System

The majority of the LHC BLMs are 50cm long, 1.5 litre, nitrogen filled ionisation chambers. These have been optimized to give an ion collection time of 85μs, i.e. less than one LHC turn. They are located around each quadrupole magnet (six per quadrupole), in the collimator regions and at other aperture restrictions in the machine. The system has been designed to cover a total dynamic range of some 10^{13}, which is achieved by combining the ionisation chambers with secondary emission monitors (SEMs) having ~30000 times smaller gain.

The same acquisition system is used for both the ionisation chambers and SEMs, and is based on current to frequency conversion. It is capable of measuring induced currents from 10pA to 1mA with linearity better than 5%. In a similar way to the BPM system only a minimum of electronics is placed in the tunnel, with a Gigabit Optical Link with cyclic redundancy transmitting the acquired signal to the surface processing electronics. The latter calculates the integrated loss values for time periods of between 80μs and 100 seconds and compares them to a table of threshold values which depend on both the loss duration and beam energy.

The beam loss monitor acquisition is an integral part of the machine protection system, and for losses occurring on a time scale of less than 10ms is the only loss detection system available for the LHC. For this reason the failure rate and availability requirements are very stringent and have been evaluated using the Safety Integrity Level (SIL) approach. The system has been calculated to reach SIL3 level, corresponding to a probability of not detecting a dangerous beam loss of 10^{-3} per year. This is achieved by duplicating the signal treatment chain for all elements after the current to frequency conversion, incorporating error correction and detection techniques and constantly monitoring the availability of all monitors. Substantial radiation testing was also carried out on all components to be installed in the LHC tunnel.

LHC BLM System Performance

There were two beam induced triggers of the quench protection system during the injection tests of 2008, which allowed an attempt at quench reconstruction using the BLM system. Knowing the bunch intensity, impact location and loss distribution widths it was possible to compare the measured results with GEANT4 simulations. This showed a discrepancy of a factor ~1.5, as a result of which the threshold values for quench prevention were raised by ~50%.

The LHC BLM system is also the main tool for setting-up the collimation system, which is essential for protecting the machine against quenches and damage. At the high energy and relatively low emittances of the LHC, the damage limit is quickly reached with only a few pilot bunches of 5×10^{9} circulating in the machine.

Fig. 3 shows the measured beam loss from all monitors for an unstable beam. The large dynamic range of the BLM system is clearly visible, with the results indicating that the collimation system is performing as designed. Losses are localised to the collimator regions giving a cleaning efficiency of better than 99.98%.

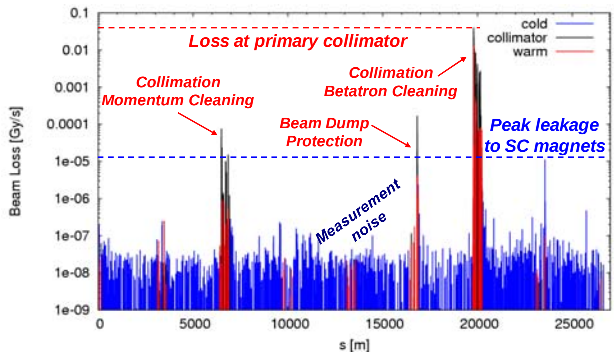

Figure 3: Beam losses throughout the LHC ring as measured during a test of the collimation system.

Observation of Fast Losses

On the evening of the 7th July 2010, the BLM system requested a beam dump as a consequence of the appearance of fast beam losses on the millisecond timescale. Since then, 28 beam dumps have been requested due to similar losses happening at different locations around the LHC, with this issue becoming one of the limiting factors for machine availability.

Detected exclusively by the BLM system it is believed that such losses originate from dust particles falling into the beam, or being attracted to it through its strong electromagnetic field. These "Unidentified Falling Objects" (UFOs) have been extensively studied using the BLM system. A search algorithm was implemented to trawl through the logging data looking for similar signatures that did not result in a beam dump. Over 5000 candidate UFO events have been observed to date, with the majority well below the abort threshold. Although the event rate is still at around 5 events per hour during physics stores, some conditioning does appear to be taking place.

Since no magnet quenches have so far been caused by these UFOs the BLM thresholds for millisecond scale losses have been progressively increased to limit the impact of UFOs on the availability of the machine.

Other Machine Protection Instrumentation

Four other beam instrumentation systems are used for machine protection: special BPMs around the dump line constantly monitor the beam position with respect to dump line protection elements; the DC beam current transformer (DCCT) provides a limit for "safe beam" in the machine; a beam position monitor equipped with special electronics detects beam presence to ensure that no high intensity beam is injected without a pilot bunch already circulating; an abort gap monitor ensures that the level of unbunched beam in the 3μs gap used for the dump kicker risetime is kept under control.

OPTIMISATION OF OPERATION I

Beam Based Feedbacks

During the LHC design phase the expected large perturbations combined with the tight tolerances imposed on chromaticity led this to be considered as the most critical parameter for real-time control in the LHC. However, in response large losses occurring during the initial ramps due to tune drifts, the commissioning of tune feedback followed by orbit feedback [5] were given priority and thus operated for almost every fill from an early stage. In addition, the excellent knowledge of the magnetic transfer functions of the final machine have allowed both chromaticity and coupling to be controlled to a sufficient degree through feedforward alone.

Tune Feedback

The tune feedback is based on the BBQ mentioned previously, with the tune calculated from a real-time FFT spectrum analysis. This system reaches an equivalent turn by turn sensitivity of ~30nm, and with ever-present residual tune oscillations in the order of 100nm to 1μm visible on nearly all LHC beams this provided ample signal for reliable tune feedback.

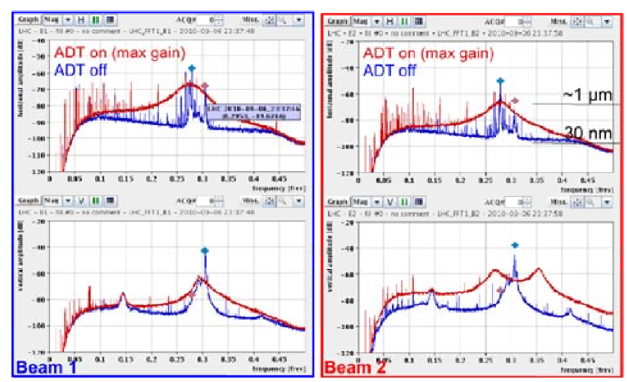

Figure 4: Comparison of tune signals with transverse damper on (red) and off (blue).

However, as soon as the transverse damper was required to deal with instabilities due to the increasing intensity of the beams, the additional noise introduced by this system often swamped the residual tune oscillations (Fig. 4). The only solution found to date for cohabitation of these two systems is to run the transverse damper at a lower gain in the critical periods during ramp and squeeze when the tune feedback is expected to operate.

Orbit Feedback

Commissioning and characterisation of the LHC orbit feedback system started very early on in 2010. The system, using a regularised SVD approach, has a closed loop bandwidth of 0.1Hz and is continually supplied with orbit data from the BPM system at 25Hz. A comparison of the orbit drifts observed with and without feedback during energy ramps to 3.5TeV is shown in Fig. 5.

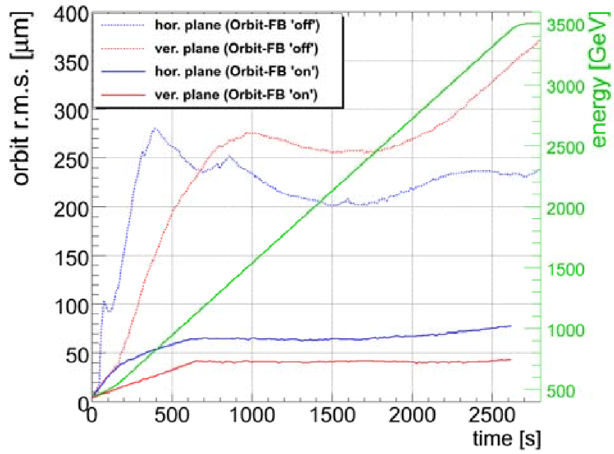

Figure 5: Comparison of orbit stability and drift with and without orbit feedback

The orbit feedback can maintain orbit stabilities of typically better than 70µm globally and 20µm in the arcs compared to orbit perturbations of up to about 1mm without orbit feedback. Most of the remaining orbit variations are due to programmed dynamic reference changes around the experimental insertions during ramp and squeeze.

The main performance limitation of the orbit feedback is linked to an observed systematic BPM dependence on temperature that initially caused errors on orbit measurement of greater than 300µm. This is now suppressed to the order of 100µm by post-processing, measuring the acquisition crate temperature and applying temperature corrections to the data. A full temperature control of the acquisition racks is foreseen to be implemented for this system in the future.

OPTIMISATION OF OPERATION II

Bunch by Bunch Measurements

One of the main specifications for most of the LHC beam instrumentation systems was the ability to perform bunch by bunch measurements at up to 40MHz. This has proven invaluable in diagnosing and curing issues such as RF capture problems, injector beam quality issues and instabilities as well as providing useful data for routine machine optimisation.

Synchrotron Light Monitor

The unprecedented energies reached in the LHC allow synchrotron light diagnostics to be used with both protons and heavy ions. One synchrotron light monitor (BSRT) per beam is therefore installed to continuously monitor the beam in the LHC. The total synchrotron light power is shared between the Abort Gap Monitor, the Longitudinal Density Monitor and a camera dedicated to transverse profile measurement. The latter is a Proxitronic Nanocam HF4 S 25N NIR intensified via a multichannel plate between the photocathode and the camera sensor. It can currently be used in one of two operational modes: continuous integration of all incoming light every 20ms; gated acquisition down to 25ns every 20ms.

The continuous mode is used to integrate the beam signal over all bunches and hence gives the average horizontal and vertical profile. In gated mode, the acquisition of profiles for a single bunch is possible. By moving the gate from one bunch to the next one can scan the entire LHC bunch train to give individual profiles from which the bunch by bunch emittance can be calculated. Wire scanner measurements are used with few bunches in the machine for cross-calibration of the BSRT.

The gated mode has been extensively used in trying to minimise and equalise the emittance. The minimisation of emittance leads to increased luminosity, while equalising the emittance reduces blow-up due to beam-beam effects.

Fig. 6 shows an example of bunch by bunch emittance measurements during the scrubbing run used to condition the machine against electron cloud effects at the start of 2011. Instabilities leading to increased emittance are clearly visible on one beam towards the end of the injected batches. The BSRT was invaluable in quantifying the improvements made during the course of this conditioning. It has also been used to detect non-uniformity in the emittance of the beam coming from the LHC injectors, leading to an optimisation campaign which resulted in much better emittance uniformity.

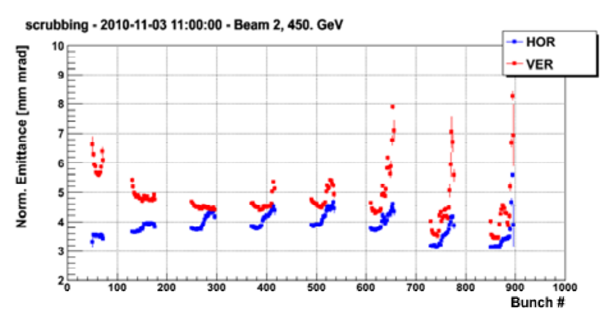

Figure 6: Bunch by bunch emittance showing the blow-up of some bunches due to electron cloud instabilities.

Longitudinal Density Monitor

The LHC Longitudinal Density Monitor (LDM) [6] is a single-photon counting system measuring synchrotron light by means of an avalanche photodiode detector (APD). It is able to longitudinally profile the whole ring with a resolution of ~50 ps. On-line correction for the effects of the detector deadtime, pile-up and afterpulsing allow a dynamic range of 10^5 to be achieved.

Measurements were taken with the LDM during both proton and lead ion runs. It has proven a very useful tool to optimize the injector chain and understand RF capture issues in the LHC. Fig. 7 shows that in the case of protons, almost all the satellites are spaced at 5 ns intervals, and believed to originate in the LHC injector chain where lower RF frequencies are used. In the case of heavy ions, small ghost bunches spaced at 2.5 ns (i.e. occupying the LHC RF buckets) are spread around the ring in addition to the larger 5 ns satellites near a main bunch. This was found to come from modulation of the LHC RF voltage at injection to optimize capture for newly injected bunches, which led some particles from previously injected bunches to leak out of their buckets. These particles were subsequently recaptured once the RF voltage was again increased.

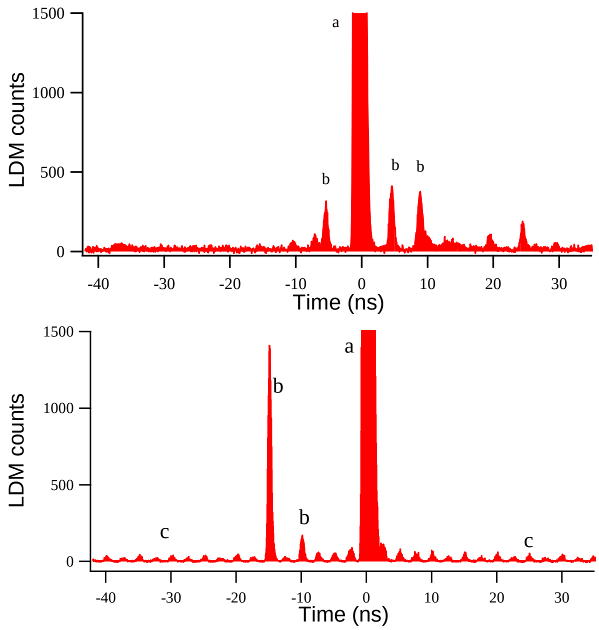

Figure 7: LDM plots for protons (above) and lead ions (below). a) main bunch with peak at 1.3 x 10^5 counts, b) satellites, and c) ghost bunches.

HELPING THE EXPERIMENTS

Absolute Luminosity Calibration

During the 2010 and 2011 LHC runs a series of dedicated fills were used for luminosity calibration measurements at each of the LHC experiments. A major contribution to the final precision of these luminosity calibration campaigns originated from the uncertainty on the accuracy of the bunch current population estimation as determined by the LHC beam current transformers [7].

While the operational needs of the LHC were quickly covered by the standard LHC fast and DC BCTs, the subsequent needs of the LHC Experiments for detector calibration required a lot more effort. In 2010 the error contribution from uncertainty in the bunch populations as measured by the BCTs was estimated to be 3% and dominated the total error on the luminosity determination.

Reducing this overall error took a lot of work and patience, firstly to determine the error sources and secondly to improve or mitigate them. The main issues observed in 2010 were the following:

- Bunch pattern dependency and saturation of the DCCT. The sources were found to be in the DCCT feedback loop and front-end amplifiers respectively. Improvements to the image current bypass and the front-end electronics during the 2010/11 winter technical stop have solved these issues for all the operational beams used in 2011.

- Bunch length dependence of the fast BCT. This was mitigated by using 70MHz lowpass filters that still allow bunch-by-bunch measurements at 40MHz.

- Bunch position dependence of the fast BCTs. This effect, at the level of 1% per mm, was not at all expected, but is now understood to come from the toroid itself. A new monitor is in preparation but will not be available for installation before the long LHC shutdown foreseen in 2013. Fortunately, the beam orbit at the BCT locations is kept sufficiently stable during standard physics fills to limit this effect to well below the 1% level.

- Satellite bunches and unbunched beam. Due to the position dependence of the fast BCT the only means of providing an accurate calibration for bunch by bunch measurements was via cross calibration with the DCCTs. This depends on a good knowledge of the amount of unbunched beam and of the particle population outside the main bunches. By the use of well defined and optimized conditions during the measurement campaign this could be kept to a minimum and verified by cross-checking these populations using the LDM and the LHC experiments themselves.

The improvements and progress made since 2010 lead us to believe that the uncertainty in the measured bunch to bunch populations is now well below this 3%, which will hopefully be verified in a new luminosity calibration campaign foreseen for autumn 2011.

FUTURE DEVELOPMENTS

Several new systems are under test or design to further improve the diagnostic capabilities of LHC instrumentation. Collimators with in-built BPMs are being designed with the aim of speeding-up collimator set-up and providing a continuous verification of jaw to beam position at the micron level, while fast BLMs based on diamond detectors are under development for the observation of bunch by bunch losses. Together with improvements to the existing systems it is hoped that the LHC beam instrumentation will continue to help maintain a safe and fully optimised LHC machine.

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