FIRST RESULTS FROM THE LHC BEAM INSTRUMENTATION SYSTEMS

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Abstract

During the 2008 LHC injection synchronisation tests and the subsequent days with circulating beam, the majority of the LHC beam instrumentation systems were capable of measuring their first beam parameters. This included the two large distributed systems, beam position and beam loss, as well as the scintillating and OTR screens, the fast and DC beam current transformers, the tune monitors and the wire scanners. The fast timing system was also extensively used to synchronise most of this instrumentation. This paper will comment on the results to date.

LHC START–UP

In September 2008 a circulating proton beam was established for the first time in the large hadron collider (LHC) at CERN. The availability of high quality beam instruments from day one allowed rapid progress in establishing the circulating beam.

Before attempting to thread the beam for the first time in the collider, several dry runs and synchronisation tests were performed in the summer months of 2008. The extensive testing of all the different instruments and of the related control system were of paramount importance for the successful start–up of LHC.

BEAM POSITION SYSTEM (BPM)

The LHC BPM system [1] consists of 1054 beam position monitors of which 912 are 24 mm button electrodes installed in the arc quadrupole cryostats (SSS). The remaining monitors are either enlarged (34 mm or 40 mm) button electrodes for the stand alone quadrupoles or stripline electrodes used for their directivity in the common beam pipe regions and for their higher signal level in the large diameter vacuum chambers of 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 the horizontal and vertical plane, resulting in a total of 2156 electronic channels. The lower limit for correct BPM triggering is $1.5\ 10^9$ protons per bunch.

The beam threading mode (FIFO) was used to provide the first turn position data to the operator GUI. This is a totally asynchronous acquisition mode, where any triggers obtained within a specified gate are recorded.

As this mode does not require the adjustment of any timing signal, it provided very useful data from the very first shot into LHC. Combined with powerful software it allowed quick diagnostics to be made on BPM polarity and machine optics errors leading to a very rapid threading of the beam in the two rings.

Once the beam started to circulate for more than 1 second, the orbit acquisition mode could also be used. This provided an update of the average bunch position every second. Figure 1 shows the results of some 15 minutes worth of horizontal orbit data, with similar results obtained in the vertical plane. It can be seen that the rms noise on the measurement for the majority of the machine is between 5 µm and 15 µm.

The alternating high/low noise peaks follow the beta function (45° BPM sampling), indicating that a large fraction of these fluctuations are due to the beam. The resolution of the BPM system in orbit mode with a single pilot bunch is therefore ~ 5 µm.

Figure 1 also shows oscillations and drifts of the orbit, that have since been traced to temperature fluctuations in the acquisition racks.

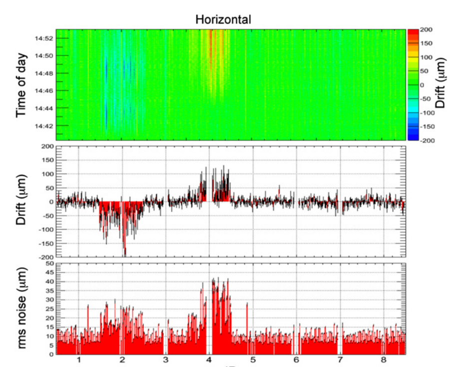

Figure 1: BPM orbit stability in high sensitivity mode.

THE LHC BEAM LOSS SYSTEM (BLM)

The LHC BLM system [2] consists of 4000 monitors, mainly ionisation chambers, installed around the quadrupole magnets and in the collimator regions. This system covers three purposes: to avoid damage to the machine, to avoid beam induced magnet quenches and to help tune machine parameters such as the collimator aperture. The signals from the monitors are used to trigger the beam dump if the readings exceed pre–defined threshold values.

Figure 2 shows the readings of all ionisation chambers around the ring during single turn operation with Beam 1. The noise level is two orders of magnitude smaller than the signal from a pilot bunch of intensity $2\ 10^9$ being dumped on a tertiary collimator left of IP5. This signal to noise level should be sufficient to use the loss patterns from a single pilot bunch of 5 10^9 to allow a subsequent safe, quenchless injection of a total intensity up to 5 10^{11}.

There were two beam induced triggers of the quench protection system during the injection tests, which allowed an attempt at quench reconstruction using the BLM system. The loss pattern observed in each case was very different, with one occurring at the end of a main dipole magnet and the other occurring in the middle of a dispersion suppressor magnet. Knowing the bunch intensity, impact location and loss distribution widths, it was possible to constrain the simulations to give an estimate of the energy deposited in the coil. This was found to be $\sim$ 15 mJ cm^{-3} compared to the 30 mJ cm^{-3} expected.

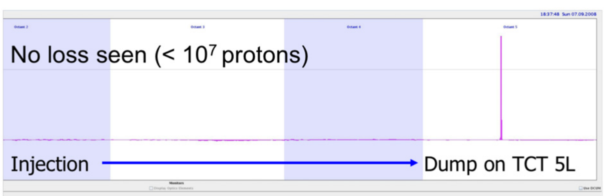

Figure 2: BLM, beam injection from IP2 to IP5.

THE LHC SCREENS SYSTEM (BTV)

There are a total of 37 TV beam observation systems (BTV) of 7 different types installed in the LHC. Each BTV station is equipped with two screens: one being a 1 mm thick alumina plate (scintillator) and the second a 12 µm thick titanium foil (to produce Optical Transition Radiation OTR). The alumina plates are very sensitive and can observe single bunches of well below 10^9 particles, but due to their thickness significantly perturb the beam. The number of photons emitted by the OTR is much less than that of the alumina screen, on the other hand the perturbation to the beam is minimal allowing multiple monitors to be used at the same time as well as multi–turn observation.

During the commissioning the beam was initially steered through the transfer lines and the different sections of the machine using the alumina screens, most of the time producing very clear but completely saturated images (See Fig. 3).

After this first step the OTR screens replaced the alumina screens as they reduced the blow–up of the beam, reduced the radiation due to beam losses and produced images well suited for analysis with good linearity and no saturation.

The BTV monitors performed well and were extensively used during all the synchronization tests as well as for the first beam in the LHC. They provided a quick, reliable tool for the operators in this initial commissioning phase.

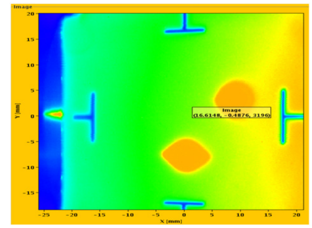

Figure 3: BTV, the first full turn in the LHC.

THE LHC TUNE, CHROMATICITY AND COUPLING MEASUREMENT SYSTEMS

The LHC tune, chromaticity and coupling measurement system [3] consists of three independent acquisition chains per beam and relies on the diode–based, base–band–tune (BBQ) technique now used in all CERN synchrotrons. Each BBQ system consists of two diode peak–detectors per plane, an analogue front–end and a digital acquisition and processing system that provides either real–time spectra (FFT) or phase–locked loop (PLL) functionality.

Of the three systems per beam, the first is dedicated to continuous, passive, beam spectra observation and observes any residual beam oscillations or externally produced beam excitation. The second system is for on–demand tune measurement, with excitation provided using either the dedicated kickers or fast frequency sweeps (chirp signals) via the LHC transverse damper. The third system is dedicated to PLL tune operation, again using the transverse damper as excitation source.

While the PLL hardware has been commissioned, the limited time did not permit a PLL setup with beam. Excitation via the tune kickers was also not attempted. All measurements were therefore performed using passive observation of residual beam oscillations.

Figure 4 shows the tune spectra and corresponding turn–by–turn data before and after correction of the horizontal tune for beam 2, which was initially close to the half–integer resonance. The shift in the horizontal tune and increased number of detected turns (i.e. lifetime) after the tune trim are clearly visible. The availability of this system at a very early stage, capable of tune measurement with a limited number of turns, provided a means to quickly adjust the injection tunes. This allowed the beam to circulate long enough to attempt the first RF beam capture.

This system was also used in conjunction with chirp excitation via the transverse damper. This allowed a first estimate to be produced for coupling in the LHC, with the measured value found to be $|C| \sim 0.07$. Although no direct measurement of chromaticity was attempted, it was possible to estimate its value from the ratio of the tune and synchrotron sideband amplitudes. This gave a chromaticity of $Q'_H \sim Q'_V \sim 32$.

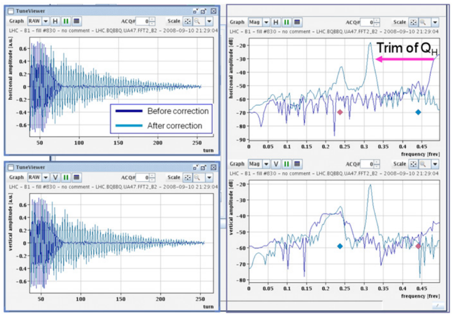

Figure 4: BBQ, first tune measurement and correction.

THE LHC BCT SYSTEM

Beam current transformers of two different kinds provide intensity measurements for the beams circulating in the LHC rings, as well as for the transfer lines from the SPS to LHC and from LHC to the dumps.

The DC current transformers (BCTDC) are based on the principle of magnetic amplifiers and measure the mean current of the circulating beam. Two independent systems (A and B) are installed per ring. Four ranges, provided simultaneously, are used to cover the entire beam dynamic range from a few 10^9 to $5\ 10^{14}$ protons ($\sim 3\ \mu A$ to ~ 900 mA).

Figure 5 shows such an acquisition for system A of beam 2, with 4 successive injections of a single pilot bunch ranging in intensity from $3.5\ 10^9$ to $6\ 10^9$ protons and circulation times of 100 seconds to 40 minutes.

The noise on the signal corresponds to an rms of $7\ 10^8$ protons for a one second integration time, which is equivalent to 1.3 µA. A similar value is found for the slow fluctuations observed over several hours. A small, negative offset of $\sim 2.5\ 10^9$ (4.5 µA) was also observed and will be automatically corrected for in the future.

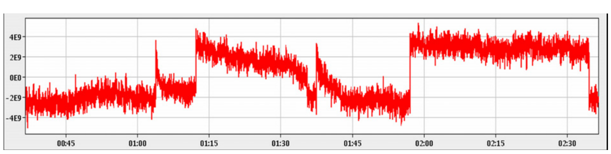

Figure 5: BCTDC, first circulating beam in ring 2.

The LHC fast BCT systems are capable of measuring bunch to bunch intensity on a turn by turn basis. Four such systems are installed in the LHC ring, one operational system and a hot spare for each beam. Similarly two systems per beam are installed in the LHC dump lines. Each system has two parallel measurement bandwidths acquiring simultaneously with two different gains.

During the LHC commissioning the fast BCT was used in capture mode, triggered by the RF pre–injection pulse, to observe the LHC pilot bunch with intensities ranging from $2\ 10^9$ to $6\ 10^9$ protons. This short time with beam in the LHC was very useful to verify the correct functioning of the complete acquisition chain from detector to the operator GUI.

THE LHC WIRESCANNER SYSTEMS

A total of 8 linear wire scanners are installed in LHC for measuring the transverse density profile of the beam: 2 horizontal and 2 vertical devices per beam. The scanning speed of all these systems is $1\ m\,s^{-1}$. Only beams with very low intensity were available for testing the LHC wirescanners ($2\ 10^9$ to $6\ 10^9$ protons circulating at 450 GeV). Due to the low intensity the measured profiles are quite noisy, but still well defined. Shown in Fig. 6 is the vertical profile of Beam 2. The beam size sigma was measured to be 2.4 mm corresponding to a normalised emittance of 7.2 µm rad. This is about twice the LHC nominal emittance at injection energy the reason for which is not yet understood.

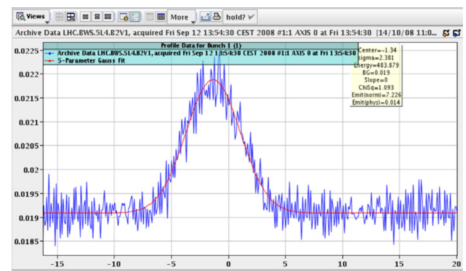

Figure 6: BWS, vertical scan of a circulating pilot bunch.

SUMMARY

The first few days of LHC running proved to be a very successful time for all the beam instrumentation systems. This was in no small part thanks to the years of planning, installation, testing and hardware commissioning carried out by all members of the beam instrumentation group with the help of many other CERN Groups & external collaborators.

The restart in 2009 will entail a full re–commissioning of the already tested systems. This will be followed by systematic measurements and fine timing adjustments for which there was no time last year. Once this is complete, work will resume on the commissioning of the remaining systems: synchrotron light monitors, rest gas ionisation monitors, PLL tune and chromaticity measurement, beam based feedback systems, Schottky monitors and finally the collision rate monitors.

REFERENCES

[1] D. Bishop et al., "The LHC Orbit and Trajectory System", 6th DIPAC, 5 – 7 May 2003, Mainz, Germany, pp. 187.

[2] B.Dehning et al., "The LHC Beam Loss Measurement System", 22nd PAC, Albuquerque, NM, USA, 25 – 29 Jun 2007, pp.4192

[3] R. J. Steinhagen et al, "First Results from the LHC BBQ Tune and Chromaticity Systems", LHC–Performance–Note–007 (2009).