# PERFORMANCE OF AND FIRST EXPERIENCES WITH THE LHC BEAM DIAGNOSTICS

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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 [1]. This included the two large, distributed, beam position and beam loss systems, as well as the scintillating and OTR screen systems, the fast and DC beam current transformer systems, the tune measurement system and the wire scanner system. The fast timing system was also extensively used to synchronise most of this instrumentation. This presentation will comment on the results to date, some of the issues observed and what remains to be done for the next LHC run.

## THE LHC BTV SYSTEM

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; a 1mm thick alumina plate (scintillator) and a 12µm 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.

### *First Results from the LHC BTV System*

During commissioning the beam was initially steered through the transfer lines and different sections of the machine using the alumina screens, producing very clear but completely saturated images (See Fig. 1).

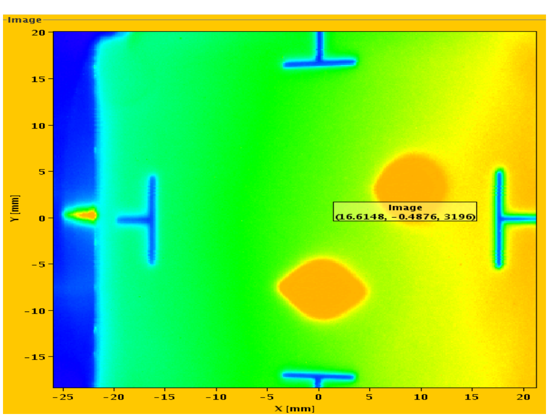


Figure 1 : The first full turn in the LHC as seen by the BTV system (10/9/2008).

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 possibility of observing OTR emission for even the lowest intensity pilot bunches ($2\times10^9$ protons) was due to the high sensitivity of the standard CCD cameras.

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

### *Outlook for the LHC BTV System*

Due to the expected radiation levels in the injection regions a gradual replacement of the standard CCD cameras with less sensitive radiation hard cameras is foreseen. This will result in losing the possibility to observe single pilot bunches in OTR mode.

## THE LHC BLM SYSTEM

The purpose of the LHC BLM system is threefold: to protect the LHC equipment from damage; to avoid beam induced magnet quenches; to observe losses for machine parameter tuning such as the adjustment of collimators. The protection requirements led to the placement of detectors at all likely loss locations, resulting in over 4000 installed monitors mainly around the quadrupole magnets and in the collimator regions. These are either 1.5 litre $N_2$ filled ionisation chambers or 10cm long Secondary Emission Monitors (SEM). 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. The BLM monitor acquisition systems for both half sectors served by a given access point are concentrated on the surface, with a redundant link to the beam interlock system transmitting the beam permit signal to the dump system.

### *Early Performance of the LHC BLM System*

Fig. 2 shows the readings of all ionisation chambers around the ring during single turn operation with Beam 1. The bias level of the acquisition is given by the current injected into each channel to continuously test their status. A variation in this test current can be seen for the individual channels as a result of different settings in the front-end electronics. This will have to be better adjusted in all front-end cards before the next running period. The large reading left of IP1 is due to the dump of the beam on the TCT collimator.

The signal to noise level can be better assessed if this bias current level is subtracted, giving a noise level two

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Figure 2 : BLM readings along the ring (logarithmic scale). In green the integrated signal from each ionisation chamber over the last 5.2 seconds updated every second. In red the corresponding threshold setting for each monitor.

orders of magnitude smaller than the signal from a pilot bunch of intensity $2\times10^9$ dumped on a tertiary collimator. This signal to noise level should be sufficient to use the loss patterns from a single pilot bunch of $5\times10^9$ to allow a subsequent safe, quenchless injection of a total intensity up to $5\times10^{11}$.

There were two beam induced triggers of the Quench Protection System (QPS) during the injection tests which allowed an attempt at quench reconstruction using the BLM system. The loss patterns observed were located near the centre of a bending magnet, in the dispersion suppressor right of IP2 and left of IP3. The impact angle was 250 µrad in one case and 730 µrad in the other. In both cases the area had sufficient BLM coverage to allow an attempt at reconstruction. 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 ~15 mJ.cm$^{-3}$ compared to the 30 mJ.cm$^{-3}$ expected.

### *Outlook for the LHC BLM System*

The incident in sector 3-4 implies that almost all BLMs in sector 3-4 will have to be dismantled. The subsequent consolidation required around the LHC means that in the other warmed sectors, at every other quadrupole magnet, some BLMs and cable trays have to be dismounted, while in the sectors remaining cold the new cable tray installation for the upgraded QPS will impact BLM installations. In addition to this unforeseen work, some consolidation was already planned to improve the system after the experience with first beam in the machine:

- Separation of the high voltage supply cables for the SEM and ionisation chambers. This aims to reduce the observed cross talk between the two systems.
- Implementation of a system to allow a full remote reset of the front-end electronics. This will involve the addition of a small mezzanine card to all front-end electronics cards.
- Noise check of the signal cable network. Any poor connections or cables will be repaired.

Some additional work is also foreseen on the BLM software, notably:

- The design of an application to allow the BLM threshold settings to be loaded and checked in the database.
- The test of a software package for handling machine critical settings along with the definition of procedures for manipulation of those settings.

## THE LHC BPM SYSTEM

The LHC BPM system is comprised of 1054 beam position monitors, the majority of which (912) are 24mm button electrode BPMs located in all arc quadrupole cryostats (SSS). 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 [2] 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.

### *First Results from the LHC BPM System*

The beam threading mode 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 stored, processed & published. From the very first shot into LHC the BPM system gave excellent results whilst operating in this mode. Combined with the powerful on-line optics software available it allowed quick diagnostics to be made on BPM polarity and machine optics errors.

### *Test of the Intensity Limit for the BPM System*

The LHC BPM system can work in one of two sensitivity ranges – high or low. The threshold for the sensitivity change is conceived such that any reflections at the level of -20dB do not retrigger the system. In the high sensitivity setting the BPM system was foreseen to work correctly with bunch intensities in the range $2\times10^{9}$ to $2\times10^{10}$ protons, with the low sensitivity working from $2\times10^{10}$ to $2\times10^{11}$ protons. In order to test the lower limit for auto-trigger detection the bunch intensity was varied from below $1\times10^{9}$ to around $3\times10^{9}$, while counting the number of correctly triggered BPMs in the arc of Sector 2-3. Fig. 3 shows the results obtained, along with the predicted performance of a typical electronics channel measured in the laboratory. The lower limit for correct BPM functioning can therefore be stated as being $1.5\times10^{9}$ protons per bunch.

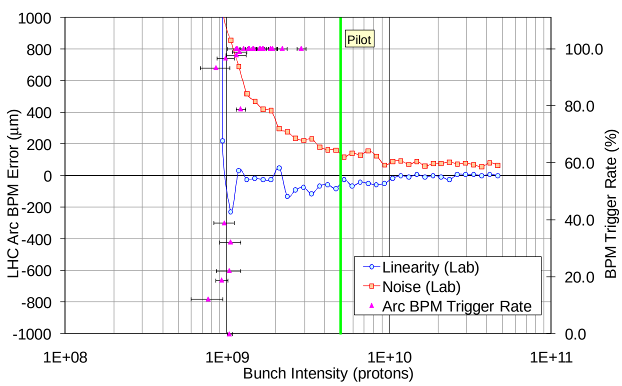


Figure 3 : BPM auto-trigger threshold determination – HIGH sensitivity mode (10/8/2008).

### *Early Performance of the LHC BPM System*

The performance of the LHC BPM system has been characterised for very low intensity, single bunch operation both in trajectory and orbit mode. From the trajectory analysis of 31 injections during the synchronisation tests for Beam 1 the overall rms variation in position over a timescale of some ten minutes was generally seen to be between 150-400µm. This order of magnitude is consistent with the electronic noise estimations shown in Fig. 3 for bunch intensities in the range $2\times10^{9}$ to $5\times10^{9}$ protons.

Once the beam started to circulate for more than 1 second, the asynchronous orbit acquisition of the BPM system (IIR mode) could be used. This provides an update of the average orbit over the last few thousand bunch positions every second. The data for this mode is routed via the orbit feedback controller, which republishes it to external clients. This allowed much of the acquisition module of the orbit feedback system to be tested and debugged with real data. The operator GUI was capable of retrieving and displaying this data, providing a continuous update of the orbit at 1Hz.

Fig. 4 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 5µm and 15µm. The alternating high/low noise peaks follow the beta function (with 45° BPM sampling), indicating that a large fraction of this noise results from the beam itself, induced by the known corrector dipole power converter current ripple. The resolution of the BPM system in orbit mode with a single pilot bunch is therefore better than ~5µm.

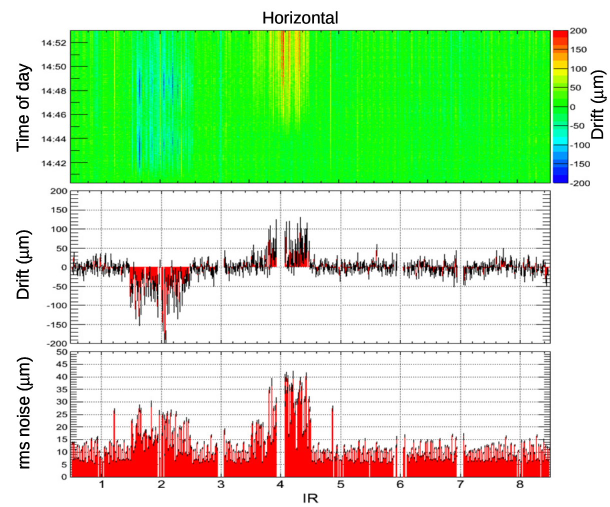


Figure 4 : Orbit stability – HIGH sensitivity mode (12/9/2008).

An oscillation of the position in Point 2 and a drift of the position in Point 4 are also clearly visible. These variations were traced to changes in the air temperature of the surface electronics racks in these locations and may be unacceptable for nominal LHC operation. Investigations are therefore underway to try to eliminate this problem.

### *Outlook for the LHC BPM System*

The main consequences of the Sector 3-4 incident are:

- The dismounting, test and re-installation of the BPMs and electronics in the damaged area.
- The test of all BPM electrodes in-situ for contamination after cleaning.
- The addition of spring clamps on the BPM ports for all sectors remaining cold, which implies the disconnection & re-connection of over 2000 external BPM cables.

Due to these interventions, over half of the machine will have to be re-commissioned. A BPM intensity card [3] will also be installed throughout the machine to allow each BPM to give intensity information.

## THE LHC TUNE, CHROMATICITY AND COUPLING MEASUREMENT SYSTEMS

The LHC base-line tune, chromaticity and coupling measurement system consists of three independent acquisition chains per beam and relies on the diode-based, base-band-tune (BBQ) technique developed for the LHC and now also used in all CERN synchrotrons. The layout of these systems is described in detail in [4].

Of the three systems per beam, the first is dedicated to passive beam spectra observation and ensures a continuous data logging for post-mortem analysis, passive beam quality monitoring and fixed displays in the control room. This passive system observes any residual beam oscillations or externally produced beam excitation.

The second system is intended for 'on-demand' tune measurement, with excitation provided using dedicated tune kickers or fast frequency sweeps ('chirp' signals) via the LHC transverse damper.

The third system is dedicated to Phase Locked Loop (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.

### *First Results from the LHC Q, Q' & |C| Systems*

An extensive report on all the initial results from these systems can be found in [5]. Fig. 5 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.

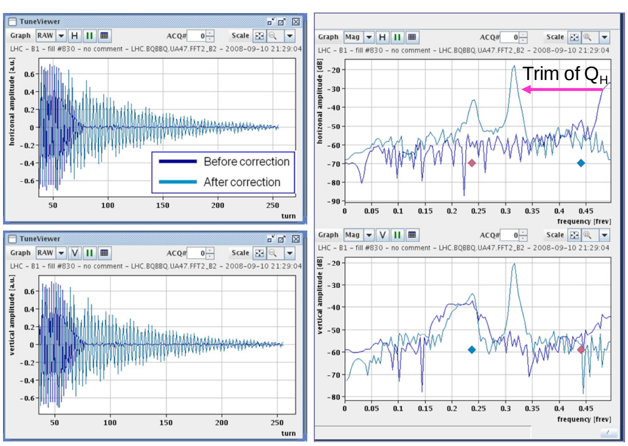


Figure 5 : First measurement and correction of tune using the LHC BBQ system.

This system was also used in conjunction with chirp excitation via the transverse damper giving a first estimate for coupling in the LHC, which was found to be $|C| \approx 0.07$.

### *Outlook for the LHC Q, Q' & |C| Systems*

The next step required to fully commission the LHC tune, chromaticity and coupling systems will be to turn on and optimise the PLL tune systems. This will allow chromaticity measurement via RF modulation and also the first attempts at tune, coupling and chromaticity feedback.

The other special transverse and longitudinal monitors, namely the head-tail/instability monitors, the wall current monitors and the Schottky monitors remain to be fully commissioned.

## 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 LHC BCTDC Systems*

The DC current transformers (BCTDC) measure the mean current of the circulating beam. Because of their operational importance, two independent systems are installed per ring. Four ranges, provided simultaneously, are used to cover the entire beam dynamic range from a few $10^9$ to $5\times10^{14}$ protons (~3μA to ~900mA) [6].

### *First Results from the LHC BCTDC System*

The main application used to view the BCTDC acquisition was a fixed display which was refreshed once per second. Fig. 6 shows such an acquisition for Beam 2 on September 12$^{th}$ 2008, with 4 successive injections of a single pilot bunch ranging in intensity from $3.5\times10^9$ to $6\times10^9$ protons and circulation times of 100 seconds to 40 minutes. The BCTDC used for this measurement was the operational system (A) while the spare (B) was kept for test and development. The automatic range selection was set to the highest sensitivity with a full scale of $5\times10^{11}$ protons.

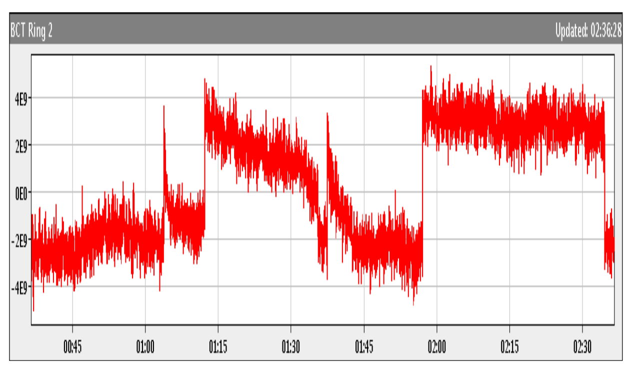


Figure 6 : First circulating beam in ring 2 seen by BCTDC A (12/9/2008).

The noise on the signal corresponds to an rms of $7\times10^8$ protons for a one second integration time, which is equivalent to 1.3μA. A similar value is found for the slow fluctuations observed over several hours. This result is very good and meets expectations, although it is also a reminder that the BCTDC can only measure single pilot bunches with a limited accuracy of around 20%. A small, negative offset of ~$2.5\times10^9$ (4.5µA) was also observed and will be automatically corrected for in the future.

### *The LHC Fast BCT (BCTFR/BCTFD) Systems*

The LHC fast BCT systems are capable of measuring bunch to bunch intensity on a turn by turn basis [7]. Four such systems are installed in the LHC ring – one operational system and a hot spare for each beam. Each system has two parallel measurement bandwidths acquiring simultaneously with two different gains. Similarly two systems per beam are installed in the LHC dump lines. The dump line fast BCTs do not measure bunch to bunch, but give only the total intensity.

### *First Results from the BCTFR System*

During the early injection tests where the beam passed through LSS4R, and in the subsequent commissioning with circulating beam 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 $2\times10^9$ to $6\times10^9$ 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. There are still numerous things to be addressed before the full functionality of the system is reached, including commissioning of the lifetime algorithm and items related to the machine-protection system such as safe beam flag transmission and fast beam current decay monitoring. The detectors and acquisition chains of the fast BCTs in the dump line still remain to be commissioned.

## THE LHC WIRESCANNER SYSTEMS

A total of 8 linear wire scanners are installed in the LHC for measuring the transverse density profile of the beam. Each beam is equipped with 2 wire scanners in both horizontal and vertical planes, with one available for operation and the other intended as a fully functional back-up. The scanning speed of these systems is 1 $ms^{-1}$.

### *First Results from the BWS System*

Only beams with very low intensity were available for testing the LHC wirescanners ($2\times10^9$ to $6\times10^9$ protons circulating at 450 GeV). The first profiles were obtained with the electronics working in turn by turn mode, which does not distinguish between individual bunches. Due to the low intensity the measured profiles are quite noisy, but still well defined. Shown in Fig. 7 is the vertical profile acquired for Beam 2.

### *Outlook for the LHC Wirescanner System*

It is intended to implement the individual bunch acquisition mode ready for use during the next LHC run. This will use the standard BI Digital Acquisition Board (DAB64x) fitted with the 40MHz integrator mezzanine cards of the fast BCT system. In this mode a profile can be produced for one or several arbitrarily selected bunches.

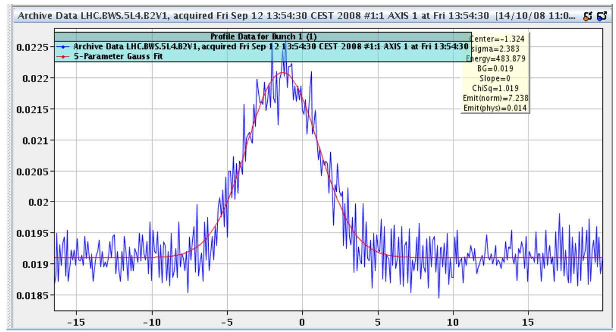


Figure 7 : Vertical wire scan on a single circulating pilot bunch (12/9/2008).

## 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 BI Group with the help of many other Groups & external collaborators.

There is still a lot of work remaining to be done, however. A near complete re-commissioning of the BPM and BLM systems will be required after major interventions both in sector 3-4, and in the other sectors being consolidated as a result of the sector 3-4 incident. There are significant improvements being made to the synchrotron light monitor optical layout after the initial installation experience and it is also foreseen to install the three remaining US-LARP collision rate monitors (fast ionisation chambers) for the high luminosity interaction regions.

## REFERENCES

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