LESSONS IN BEAM DIAGNOSTICS

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Abstract

This paper will concentrate on the studies carried out on LHC beam instrumentation systems during the 2011 run, the improvements made and the outlook for 2012. It will include an update on the issues resolved since 2010, such as the performance of the BCT systems, and discuss advances in the bunch by bunch measurement capability of many systems. The paper will also highlight what can be hoped for in terms of performance for 2012 and the issues which remain to be solved.

INTRODUCTION

During 2011 there was continuous development ongoing on all beam instrumentation systems. Much of this was carried out parasitically, but there were also two dedicated machine development periods where specific studies were pursued. The full results from these are reported in two MD notes [1, 2]. The overall performance and detailed improvements to be implemented for 2012 are also presented in [3].

This paper will concentrate on the main outcomes from all of these studies and on what can be expected in terms of performance for 2012. It will cover the BPM and feedback systems, the BCT systems, longitudinal density monitor and the various devices used for beam size measurement. The BLM system performed exceptionally well in 2011, and with no major changes foreseen in 2012 will not be treated here. A discussion on quench margins and related BLM thresholds are reported in a separate paper in these proceedings [4].

BPM SYSTEM

On the whole the BPM system performance in 2011 was very good with 98% of the 2152 channels operational throughout the year. The remaining 2% were masked in the orbit feedback system due to a number of different issues: systematic non-physical offsets; high noise; high error rate. Most of the masked monitors are located in the LSS regions where the pick-ups are connected to the acquisition electronics via long cables. Cable adapters, containing low pass filters, have now been installed and should reduce the rms noise on these channels.

BPM Studies

Another issue for the LSS BPMs is cross-talk on the directional pick-ups which are used to measure individual beams in the common beam pipe regions near the interaction points. The isolation between beams is only between 20-25dB, but is further improved by positioning the BPMs as far as possible from parasitic crossings. Nevertheless there is still some influence observed, and this was quantified during a machine development period by intentionally crossing 2 bunches within the BPM and then slowly dephasing one bunch relative to the other. The results are displayed in Fig 1, which shows the measured orbit with respect to the initial reference when the beams are displaced longitudinally. It can be seen that in the worst case an error of up to 400μm can be introduced into the measurement. This is rarely the case for proton beams, as the BPMs are not located exactly at parasitic crossing locations. However, when operating with protons on ions the unequal revolution frequencies will mean that these beams will periodically scan this entire range, leading to these errors being present from time to time. To ensure that this cross-talk effect is minimised for 2012 a bunch selection will be introduced to ensure that the orbit is only calculated from bunches which do not have nearby parasitic crossings at the BPM locations.

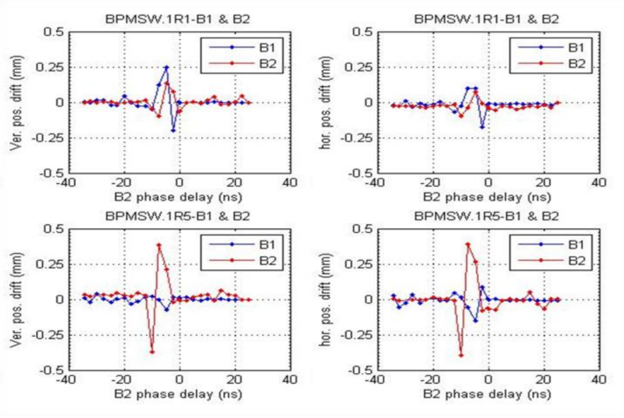

Figure 1 : Directivity of the BPMSW as a function of time between the arrival of the two bunches in the pick-up.

The default mode of operation for the LHC BPM system is the so-called ‘asynchronous mode’. This is an auto-triggered mode, completely independent of external timing. The orbit is calculated from the acquisition of the position of each bunch by means of an exponential moving average algorithm implemented as a first order infinite impulse response (IIR) digital filter in the hardware. The time constant of this filter is configurable and determines the number of passing bunches required to obtain a good average approximation. Up to now the time constant was limited to a value corresponding to a few thousand bunch triggers. This works well for small numbers of bunches, but becomes a problem as soon as the bunch number increased to over a few hundred as the BPM system is then sensitive to single turn effects. It also means that the noise on the orbit is higher than it could be, as much of the data is ignored with the 25Hz update rate to the feedback system. A new firmware is now in place which allows much longer time constants to be used. This was tested during MD time and behaved as expected, lowering the rms orbit noise from around 10µm to 1µm. Automatic filter setting was also introduced into the firmware, ensuring that the optimal time constant is used for the current filling pattern.

BPM Issues

There are two main issues remaining for the 2012 LHC run. The first is the sensitivity of the interlock BPMs in the dump region to bunches that lose a considerable amount of their initial intensity. This is typically a problem during MD periods and in particular for the 25ns scrubbing runs. The current configuration of the interlock is such that a single bunch out of tolerance for 100 turns will trigger a beam dump. This can happen if the system is in low sensitivity mode and the bunch intensity drops to around 3×10^{10}, where the system no longer functions in its optimal regime and can give spurious readings. In order to allow some more margin for manoeuvre, the attenuators connected to these pick-ups, to equalise their output signal to the level of standard arc BPMs, will be removed for the 2012 run, and should mean that a beam dump will not be triggered before the bunch intensity drops below 2×10^{10}.

The second issue which remains in 2012 is the sensitivity of the BPM surface acquisition system to temperature variations. Although the individual calibration and on-line correction of each channel has mitigated this effect to some extent, during long physics fills errors of over 100µm are still possible. This is not expected to improve before temperature controlled racks are installed during LS1.

FEEDBACKS

The operations-feedback on beam-based feedbacks at Evian'11 [5] was: “Feedbacks saved more fills than they dumped: we cannot live without them”. In 2011, 33 fills were lost directly or indirectly due to the feedback systems, accounting for 25% of the dumps during the ramp and squeeze (i.e. the periods when the feedbacks are operational). Five of these fills were lost due to feedback specific instabilities or wrong references being used, while the majority were due to the QPS system falsely indentifying the fast change in quadrupole current requested by the tune feedback system as the start of a quench. There are two reasons for this:

- The current QPS system is too sensitive to small, fast changes in magnet current
- The tune measurement system is not able to lock on to the tune without additional external excitation when the transverse damper is in operation during injection, or when the beam is more stable during the squeeze.

The first will be addressed in 2012 by increasing the QPS thresholds, a short term solution while running at 4TeV, but not viable in the long term when the energy is further increased.

The second is currently being studied by BE/BI and BE/RF with the testing of various schemes for overcoming these problems foreseen for 2012. However any novel or considerably improved system will only be operationally deployed after LS1.

Feedback Studies

At the end of 2011 a dedicated MD period was used to study the possibility of increasing the orbit feedback loop-bandwidth. This was prompted by the large orbit transients observed at the matched points during the squeeze, which the orbit feedback system was too slow to correct and could therefore not be corrected by incorporating the feedback function for feedforward.

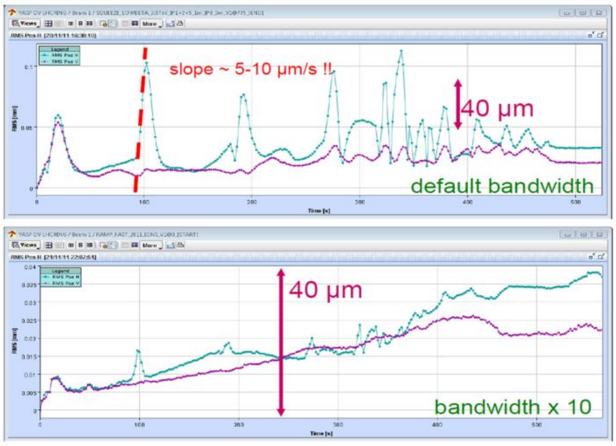

Figure 2 : Test of increasing the orbit feedback bandwidth tenfold, showing that the transients observed at the matched points during the squeeze are nicely corrected.

Fig 2 shows the results obtained, with the increased loop-bandwidth allowing the orbit transients to be corrected. The correction data could then be used to feedforward to subsequent fills further reducing the transients observed. Unfortunately it was also seen that with this loop-bandwidth the COD response is, as predicted, at its limit with one of the later fills being lost due to orbit feedback instability. Standard orbit feedback operation in 2012 will therefore maintain a modest loop-bandwidth, with the possibility of increasing it in specific runs to iron out any large, fast excursions, with the results used for feedforward.

BCT SYSTEMS

During the 2010 run the DC Current Transformer (BCTDC) suffered from a dependency of the measurement on the filling pattern and from saturation effects [6]. As the circulating current is an important parameter for the absolute luminosity calibration of the LHC experiments, a very fruitful collaboration was started between the BI Group and the Experiments to pin down all possible error sources. In addition, a series of modifications were made to the electronics and to the BCTDC itself during the technical stop in winter 2010/2011.

Operation in 2011 showed that the saturation issues and the filling pattern dependency have been successfully addressed. Fig 3 shows the total intensity as measured by the fast BCT and DC BCT during LHC filling in 2011. It can be seen that the fast and DC BCT readings now agree to better than 0.5% during the whole of the filling process. In addition, calibration studies performed throughout 2011 show that the absolute accuracy and reproducibility for the BCTDC has reached a level better than 0.3%.

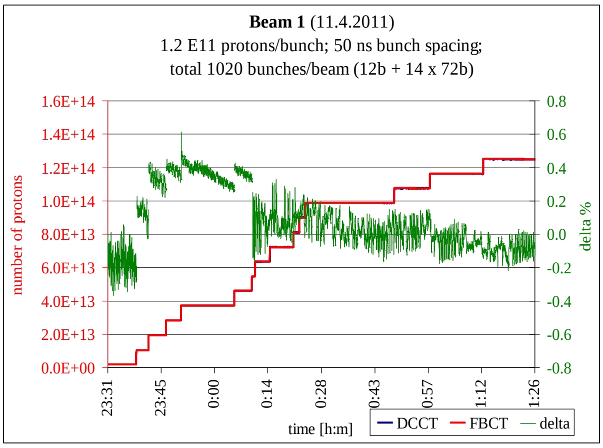

Figure 3 : Comparison of fast and DC BCT measurements and their relative error during physics filling in 2011.

Some improvements were also made to the fast BCT system, notably the addition of 70MHz low-pass filters to mitigate the effect of bunch length variation on the measurement, while still maintaining a bunch by bunch capability. The bunch position dependence of the measurement coming from the commercial toroid used is not solved, and represents an error of 1% per mm. Fortunately the orbit is well controlled in this region, limiting this effect and keeping the overall error well below the 1% level. A new toroid is currently under development to address this issue and it is hoped to test this in the LHC during 2012.

Complete testing of the dI/dt electronics will also be ongoing in 2012 with the aim of fully qualifying the electronics before LS1.

SYNCHROTRON LIGHT SYSTEMS

Longitudinal Density Monitor

The LHC Longitudinal Density Monitor (LDM) [7] 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. 4 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.

The LDM is also relied upon to cross check the ghost and satellite populations as measured by the experiments during van de Meer scans for luminosity calibration. Ensuring a sufficiently low level is important to validate the cross-calibration of the DC and fast BCTs.

For 2012 it is foreseen to finalise the LDM software to provide fully automatic tuning along with an operational application to be developed by BE/OP. The optical system will be adapted to eliminate any dependence on the transverse bunch size, and a detailed study of the LDM accuracy for ghost and satellite populations will also be carried out.

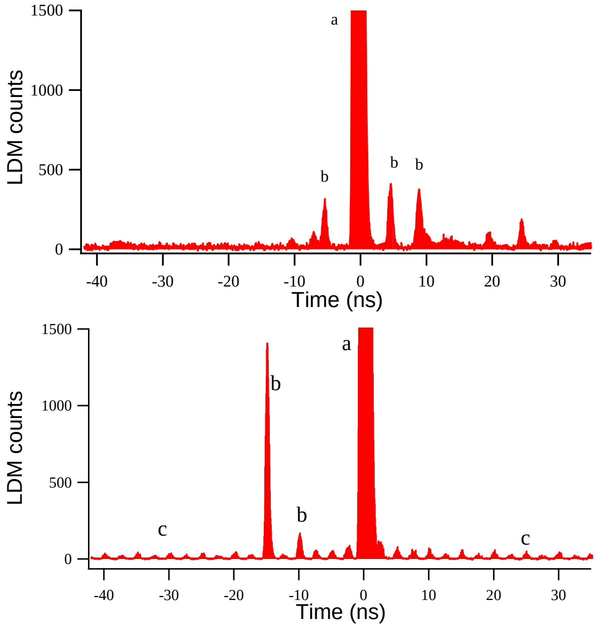

Figure 4 : LDM plots for protons (above) and lead ions (below). a) main bunch with peak at 1.3 x 10^5 counts, b) satellites, and c) ghost bunches.

Synchrotron Light Cameras

The total synchrotron light power in the LHC is shared between the Abort Gap Monitor, the Longitudinal Density Monitor and a camera dedicated to transverse profile measurement (BSRT). 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, a continuous integration of all incoming light every 20ms or a gated acquisition down to 25ns.

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.

The gated mode was implemented in 2011, was driven by the high level expert GUI application and allowed a scan rate of 1-3 seconds per bunch. With over 1000 bunches in the machine for physics fills, this implied a total measurement time of up to 1 hour. For 2012 it is foreseen to upgrade the front-end CPUs and related software to allow a ten times faster scan speed.

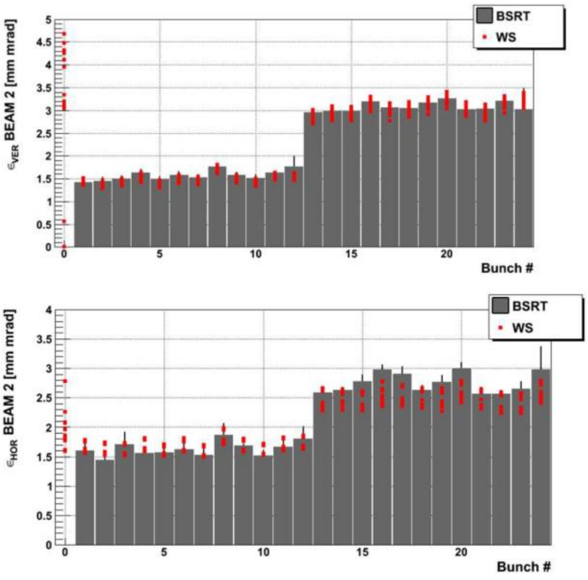

Figure 5: Examples showing good (upper plot at 450GeV) and not so good (lower plot at 3.5TeV) agreement between wire-scanner and BSRT measurements.

Much machine development time was devoted to understanding the accuracy and absolute calibration of the BSRT. The real beam size σ_{beam} is estimated from the measured beam size according to:

$$\sigma^2_{meas} = (MAG \cdot \sigma_{beam})^2 + \sigma^2_{PSF}$$

where MAG is the system optical magnification and σ_{PSF} is the optical point-spread function. The latter is dependent on many factors including diffraction, aberration and depth of field. These are all beam energy dependent due to the changing spectrum of the synchrotron light and the change in source from the undulator to the D3.

Both parameters, MAG and σ_{PSF}, can be determined for given camera settings (camera position, colour filter) and for given beam parameters (emittance, intensity). Experience in 2011, however, showed that the calibration must be applied with caution. Fig 5, where wire scanner measurements are compared with the BSRT, shows a case at injection where good agreement was found for both small and large emittance bunches, and also a case at 3.5TeV where a single correction factor does not work. This indicates a scaling factor in addition to the correction in quadrature, which was later confirmed by correlating the correction factor with the beta function.

The aim for the 2012 run is to publish corrected sigmas within an error of ±10% at both injection & top energy. To achieve this it will be necessary to fully understand all sources of errors by re-analysing in detail all the data from the 2011 MDs and performing new MDs to determine the magnification at 450 and 4000 GeV via closed orbit bumps, verify that with such magnifications the correction factors work for all bunch sizes, and exclude any dependence on intensifier gain.

WIRE SCANNERS

The wire scanners are vital for the cross calibration of all the other beam size measurement devices. Scans are, however, only possible with low intensity beam due to limits imposed by the energy deposition that can be handled by the wire and on the quench margins of the downstream magnets.

The Beam 1 scanners were found to suffer from high noise, the source of which has to date not been identified despite investigations performed during several technical stops. A method of signal correction was therefore developed to subtract the noise contribution. As the noise is low frequency it is possible to determine its influence on a given turn by acquiring the signal during the abort gap, where there is no beam present. Once acquired, this signal can be subtracted from the bunch signal acquired on the same turn, successfully eliminating this noise.

In addition to this operational improvement implemented towards the second half of the 2011 run, the following studies were performed:

- *Consistency checks*
  A comparison of turn versus bunch mode showed that both gave the same beam size to within 2%.
- *Bunch by bunch cross talk measurements*
  For 25ns spacing the residual signal from one bunch to the next was found to be ~8%, while for 50ns spacing this reduces to ~2.5%.
- *Ease of use*
  Finding the optimal photomultiplier gain and filter settings is not straightforward, but is very important to obtain accurate measurements. Systematic studies were therefore performed to check the system linearity for various settings.

The main goals for 2012 will be to investigate ways to select the photomultiplier gain and filter settings to fit with the currently injected beam and machine conditions.

In addition the possibility of performing automatic scans at regular intervals throughout the injection, ramp and squeeze will be investigated with BE/OP.

REST GAS IOINISATION MONITOR - BGI

During the 2011 run the LHC rest gas ionisation monitors (BGI) were still in the commissioning phase. Nevertheless, control of these devices is now fully integrated in the operational controls system, including the gas injection allowing a local injection of small amounts of neon.

The quality of the beam images captured by the BGI degraded over time, the suspicion being an ageing of the Multi-Channel Plates (MCPs) used to amplify the electron flux. This effect was visible as a darkening of the area usually occupied by the beam profile, suggesting a decrease of the local MCP gain. This effect is known in literature and heavily used MCPs should be exchanged regularly. This has been carried out for the monitors on beam 1 during the 2011/2012 winter technical stop, but not for beam 2 due to issues encountered with the vacuum seal quality during the beam 1 intervention. A procedure to correct for the gain deterioration has also been put in place on the front-end server, although this has its own limitations when the degradation is too large.

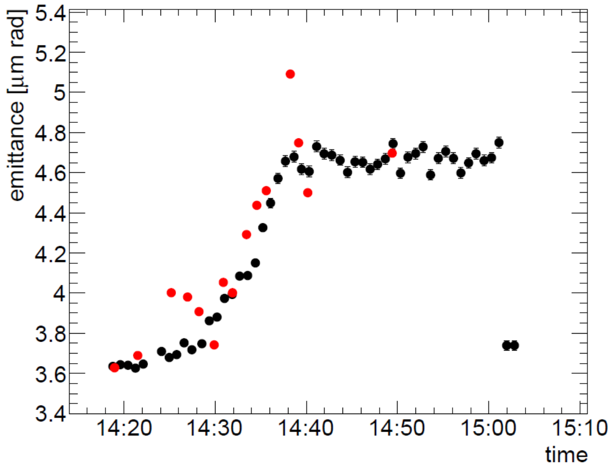

Figure 6: Evolution of the horizontal emittance of beam 1 during an energy ramp on the December 6th 2011. BGI measurements (black dots) and wire scanner (red dots).

During the 2011 MD periods it was found that a correction factor, with the same form as the σ_{PSF} used for the BSRT, should also be used for BGI. The reason for this is a larger than initially estimated electron gyroradius in the BGI magnetic field. Fig 6 shows such a correction applied to BGI data, showing a good agreement with wire scanner measurements.

An MD with inverted electric field polarity will be prepared for 2012 in order to check if the rest gas ions can be used to give better beam profiles than the electrons, which are currently collected.

OTHER BI SYSTEMS

In addition to the instruments described in some detail in this paper, developments continued on all the other LHC beam instrumentation systems. A very brief summary of their current status is listed below:

- Abort Gap Monitor - used for monitoring with studies ongoing to increase its reliability.
- Schottky - works well for ions but suffers from strong coherent signals with protons.
- Head-Tail Monitor – system was operational in 2011 with an automatic instability trigger added.
- Wall Current Monitor - work on-going to improve the overall frequency response of system.
- Diamond Beam Loss Detectors - installed in the collimation and injection regions allowing losses to be distinguished on a bunch by bunch basis.
- BTV Screens - recent issues found with the RF fingers on 5 out of 6 of these devices. The monitors are now disabled via a software interlock and should only be used if absolutely necessary in 2012.

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