Beam Instrumentation performance overview

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Abstract

The 2011 run has proven that LHC can operate safely and stably with higher bunch intensity and smaller transverse emittance than foreseen in the Technical Design Report. In this presentation the performance of the Beam Position Monitoring (BPM) system is discussed. The improvements to the system, those made during the last year and those expected to be done for 2012 run are presented. The status of the three types of devices measuring the transverse beam emittance, wire scanners (BWS), synchrotron radiation monitors (BSRT) and beam gas ionization monitors (BGI), are shown. The control room applications are reviewed and a set of improvements proposed by the operation team is presented.

INTRODUCTION

This paper describes the main issues observed with LHC Beam Instrumentation during the 2011 run and prospects for improvements during the upcoming run.

BEAM CURRENT TRANSFORMERS

During the 2010 run the DC Current Transformer (DCCT) suffered from dependency of the measurement on the filling pattern and from saturation effects [1]. A series of modifications were made to the electronics and to the DCCT itself during the technical stop in winter 2010/2011. Subsequent calibration studies performed in 2011 now show that the absolute accuracy and reproducibility has reached level better than 1%. The filling pattern dependency has also been successfully addressed as can be seen in Figure 1 which shows that the FBCT and DCCT lines agree to better than 0.5% during the whole of the filling process.

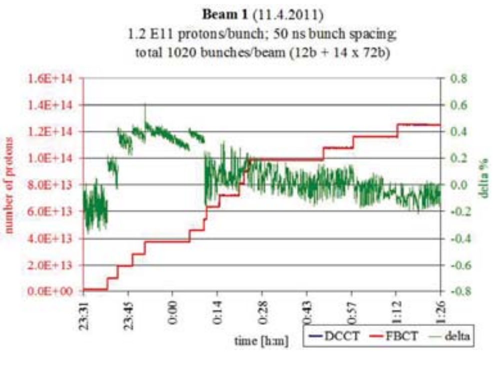

Figure 1: DCCT vs FBCT - no filling pattern dependence observed.

BEAM POSITION MONITORS

The LHC Beam Position Monitors (BPM) provide the average orbit for all bunches over many turns, bunch-by-bunch and turn-by-turn position data. These measurements are used by the orbit feedback system, for injection quality checks machine, for machine development studies and some are also directly integrated into the Beam Interlock System (BIS). The system in general worked very well, but there are nevertheless a few pending issues limiting its performance, which are discussed below.

Temperature stability

An unphysical drift of the measured orbit due to temperature variation in the electronics crates was already observed during 2009. Since then, different hardware and software efforts to mitigate this undesirable effect have been tested. Currently, the technique used to mitigate this problem consists of three phases:

- A standard BPM calibration, added to the LHC sequencer and executed before each fill, removes any accumulated temperature drifts. The OP team should remember to perform this calibration just before injection of the physics fill (ie. repeat it if the injection sequence remains blocked for whatever reason for many hours after executing the BPM calibration).
- The temperature gradient ($\mu\mathrm{m}/^{\circ}\mathrm{C}$) of each channel is calculated with test signals, by provoking a temperature change in the BPM crates by means of fan speed variation. These measurements were performed about once per month during 2011 and the gradients founds were relatively constant over year.
- During the fill, the crate temperature is monitored online and a linear correction to the position measured is applied using the gradient of each channel. This on-line correction partially compensates for the temperature variation along the fill, but not completely. The remaining temperature variations can accumulate and become noticeable especially after long fills.

Additional study of the gradient stability will be performed during 2012 aiming to find a more accurate correction.

Thermally stabilized electronics racks are considered as a long-term solution to the temperature stability issue. A prototype is being tested in SUX1 since November 2011. If the rack is found to be stable a replacement of all BPM racks will take place in Long Shutdown 2013 (LS1).

Interlock BPMs

Some BPMs (BPMSA.A4L6.B1, BPMSB.A4L6.B2, BPMSA.B4L6.B1, BPMSB.B4L6.B2, BPMSB.A4R6.B1, BPMSA.A4R6.B2, BPMSB.B4R6.B1, BPMSA.B4R6.B2) installed in IR6 are interlocked through BIS. Currently this system dumps the beam if 70 bunch measurements in 100 turns are outside of the acceptance limits. This means that the system is sensitive to a single bunch giving poor data. In case the system is in low sensitivity and a single bunch drops below $3 \cdot 10^{10}$ charges, the BPM can either stop giving readings or gives spurious readings for this bunch. The last possibility can lead to a beam dump.

A possible mitigation of this issue is the removal of 4 dB attenuators which will decrease the sensitivity threshold down to $2 \cdot 10^{10}$ charges. The drawback to this solution is the risk of generating beam dump triggers at high bunch intensity due to signal reflections. An evaluation of the maximum bunch intensity expected in 2012 is necessary to decide on the implementation of this measure.

Orbit position resolution

The resolution of the orbit determination has been improved by deploying new firmware which allows longer integration time in the asynchronous mode. For the arc BPMs this improvement has been measured during an MD and the resolution improved from 10 μm to about 1 μm. The new firmware also removes orbit sensitivity to turn-by-turn oscillations when the number of bunches in the machine is more than 100.

In order to fully profit from the new firmware the integration time should be configured according to the number of bunches in the machine, otherwise the Orbit Feedback System can be perturbed by large signal delays. There are two solutions possible:

- Integrate into sequencer.
- Make it automatic in the front-end.

The second solution will be available for 2012 start-up.

Orbit in LSS

In four out of the 8 Long Straight Sections (LSS) of the LHC, both beams travel in the same vacuum chamber, in order to allow collisions. Special stripline BPMs are used at these locations since they are directional and therefore capable of distinguishing the two beams. Unfortunately their directivity is limited to about 20 dB, provoking a cross-talk between the measurements of the two beams.

A solution proposed for this problem is to measure the orbit in synchronous mode using single bunches which do to suffer from the cross-talk issue. A firmware allowing this measurement was deployed in January 2011. In order to use it a proper mask (choice of the right bunch) must be configured for each BPM and for each filling scheme/stage. This work is in progress and an application capable of selecting proper masks is expected to be ready for 2012 start-up.

LONGITUDINAL DENSITY MONITOR

The Longitudinal Density Monitors (LDM [2]) aim to profile the whole LHC ring with 50 ps resolution. They have a high dynamic range in order to measure the charge of ghost and satellite bunches relative to the main bunch.

The method used by the LDM is single-photon counting of synchrotron light. An avalanche photodiode operated in the Geiger mode, with 50 ps resolution, is used as a detection device.

Currently the LDM are operational on both beams and are used, on a regular basis, for satellite and ghost bunch measurements. It reaches 10^5 dynamic range with integration time of 15 minutes. The data are logged in Logging DB and in SDDS [1]. An example of the measurement is presented in Figure 2.

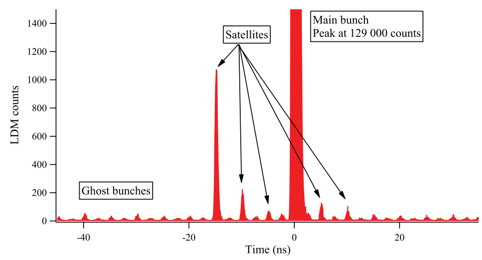

Figure 2: Longitudinal structure of ion beam at 3.5 ZTeV obtained with integration time of 10 minutes.

In 2012 the LDM will be particularly important because of the planned collision scheme for Alice, where main bunches will be colliding with satellite bunches. The improvements foreseen for the 2012 run are:

- Finalize software for fully automatic running.
- Improve online analysis and display.
- Adapt optical system in order to eliminate the dependence on the transverse bunch size.

WIRE SCANNERS

Wire scanners are the reference devices for beam emittance measurement. Therefore a lot of effort is made in order to ensure their accuracy and availability.

Consistency

The consistency of the measurements were studied during the Machine Development (MD) periods. One way to evaluate the consistency is to compare turn mode with bunch mode. This comparison, done using offline fit on profile data retrieved from the Logging DB, gave the difference between the modes as 2% RMS.

[1] SDDS stands for Self-Described Data Structure.

In the bunch mode, where wire scanner measurement is gated with a single bunch, there is a part of the signal which arrives from the preceding bunch. This part is called cross-talk and has been estimated to be about 2.5% for 50 ns bunch spacing and 8% for 25 ns bunch spacing.

Preventive maintenance

A daily cron job [2] has been put in place in order to monitor all scans made by each wire scanner. It retrieves number of erroneous scans, number of warnings sent by the system and shows which error messages have been issued. Daily control of the report and observation of the development of the rate of errors should allow preventive maintenance to be performed before equipment failure occurs.

Noise on beam 1 signal

During the 2011 run the beam 1 scanners suffered from high noise. The source of this noise has not been identified, despite the efforts and investigations performed during technical stops. During the 3rd MD a method of signal correction was developed. As the noise is low frequency it is possible to determine the noise on a given turn by acquiring the signal during the abort gap, where there is no beam present. Once acquired, this signal is subtracted from that acquired during passage of a bunch, successfully eliminating this noise. An example of this is shown in Figure 3.

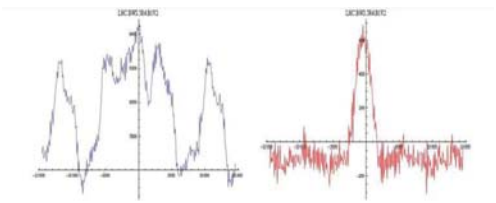

Figure 3: Illustration of noise on beam 1 wire scanner. Signal before (left plot) and after (right plot) correction.

Reproducibility

The quality of the measurement depends on the quality of the signal, which is determined, amongst other things, by the photomultiplier (PM) gain and the optical filter used. Incorrect setting of these parameters results in wrong emittance values. The measurements give coherent and accurate results if an optimal PM gain and filter is used to ensure a linear response of the system. Both settings currently require a certain level of expertise or checks by performing multiple scans (trial and error method). It has been proposed to put in place an algorithm which will make the choice of the two parameters automatic, based on beam parameters. The algorithm will be tested during the 2012 run.

[2] Cron is a time-based job scheduler in unix-like systems. It enables users to schedule jobs to run periodically at certain times or dates.

Ease of use

The existing operational application is criticized for not being ergonomic and easy to use. The most important criticism concerns automation of scans, for instance launching the horizontal/vertical scanners at the same time or performing a number of scans in a row, such as during the beam ramp.

The automation of scans will be introduced through the wire scanner server. The way the scan sequence will be launched (timing event, sequencer, modified operational application) is still to be discussed.

SYNCHROTRON LIGHT MONITOR

The two Synchrotron Light Monitors (BSRT, [3]) provide continuous emittance measurement, with the possibility of gating on a single bunch. The improvements expected for the 2012 run concern mainly the control of bunch-by-bunch scans and absolute calibration.

Bunch-by-bunch scan

A bunch-by-bunch scan example is shown in Figure 4. During 2011 the scan rate was limited to 1-3 seconds per bunch and was driven by the high level expert GUI application. On several occasions the interference of multiple GUIs opened by mistake at the same time yielded unusable results.

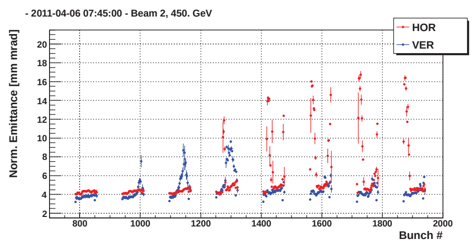

Figure 4: Example of bunch-by-bunch emittance scan with BSRT.

During the winter break or during a Technical Stop in 2012, it is foreseen to exchange of the old front-end CPUs for new ones running Linux. This should allow a dramatic increase in the bunch-by-bunch scan speed (the aim is to scan bunches with 10-25 Hz acquisition frequency).

In order to fully profit from the new hardware the scan should be driven from the FESA server and not from the expert application. This server will be available for the 2012 run. An OP application which will allow the user to set basic parameters of the scan and to display the results must be prepared in parallel. This is regarded as an OP duty.

Accuracy and absolute calibration

The real beam size σ_{beam} is estimated from the one measured with BSRT σ_{meas} according to:

$$\sigma_{meas}^2 = (MAG \cdot \sigma_{beam})^2 + \sigma_{PSF}^2 \qquad (1)$$

where MAG is the system optical magnification and σ_{PSF} is the optical point-spread function. The latter is driven by many factors, like diffraction, aberration and depth of field, that are beam energy dependent (by definition and due to the fact that at LHC the synchrotron light source changes with energy).

Both parameters, MAG and σ_{PSF}, can be determined for given camera settings (camera position, color filter) and for given beam parameters (emittance, intensity). Experience in 2011 showed that the calibration must be applied with caution. Figure 5, where wire scanner measurements are compared with BSRT, shows two cases:

- Good calibration (upper plot).
- Case where a single correction factor does not work for both small and large-emittance bunches (bottom plot).

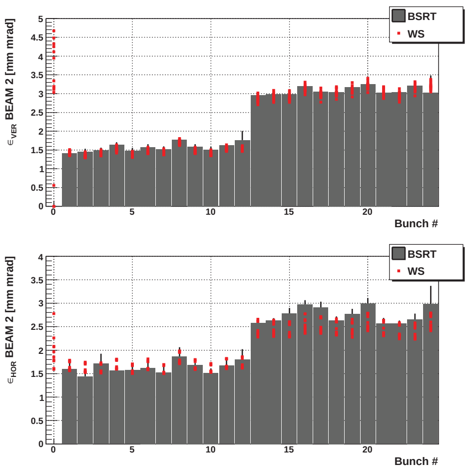

Figure 5: Examples of good and not so good agreement between wire scanner and BSRT measurements.

The aim for 2012 run is to publish the corrected beam sizes with 10% accuracy. Dedicated MD sessions will be fundamental to further study the accuracy of the device as a function of beam parameters as well as the settings of the cameras and optical system.

BEAM GAS IONIZATION MONITOR

During the 2011 run the Beam Gas Ionization (BGI) monitors were still in the commissioning phase. In early 2011 the camera gate and gain control have been introduced in the system, as promised at the Evian 2010 workshop. During the last month of the run, the gas injection control system, allowing local injection of small amount of neon, has been successfully tested and can now be operated by the OP crew.

Signal quality

The quality of the beam images registered by the BGI cameras degraded over time. It is suspected that the deterioration of the Multi-Channel Plates (MCPs) which are used to amplify the electron flux, is the reason for the image degradation. In the area of the image usually occupied by the beam the image became darker, which suggests that the local gain of the MCP decreased. This effect is known in the literature and heavily used MCPs should be exchanged regularly.

A procedure to correct for the gain deterioration has been put in place in the FE server, but it has its limits. Therefore an exchange of all MCPs during the winter TS has been planned. Installation of linux FE CPUs, similarly to BSRT, will allow implementation of a more advanced image processing algorithm, hopefully leading to better results in 2012.

Accuracy of emittance

During the MDs of 2011 it has been found that a correction factor, with the same form as σ_{PSF} from Equation 1, should be used for BGI. The reason for this is a larger than initially estimated electron gyroradius in the BGI magnetic field. Figure 6 shows such a correction applied to BGI data, showing a good agreement with wire scanner measurements.

A basic simulation of the electron movement in the BGI has been performed [4], but recalibration of all instruments with wire scanners must take place in the early stages of the 2012 run. An MD with inverse electric field polarity will also be prepared in order to check if ions could be used to profile the beam instead of electrons.

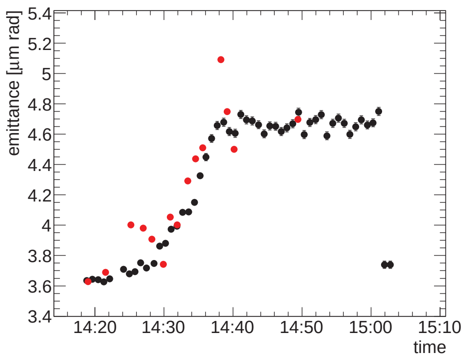

Figure 6: Evolution of the horizontal emittance of beam 1 during a ramp of the beam energy on the December 6th, 2011. BGI measurements (black dots) are shown together with wire scanner ones (red dots). The BGI measurements are presented using calibration factor of $95\ \mu\text{m/pixel}$ and $\sigma_{PSF} = 0.55\ mm$.

SCHOTTKY MONITOR

The Schottky monitor is mainly used for bunch-by-bunch tune measurements, but will also be used for measurements of other beam parameters like chromaticity or emittance. The bunch-by-bunch tune measurement, which unlike the BBQ system does not suffer from transverse damper activity, is a particular advantage of this device.

Signal quality

The Schottky signal quality has been seen to depend strongly on the beam conditions. The detectors are very sensitive to any coherent longitudinal and transverse oscillations, and the spectral content of such signals at the detection frequency of 4.8 GHz depends strongly on the bunch length and longitudinal shape. Because of this sensitivity, the Schottky signal disappears for protons as soon as the RF longitudinal blow-up starts during the ramp and only reappears some 30 minutes after reaching 3.5 TeV. For ions, the Schottky monitor gives very nice signals under nearly all beam conditions, helped by the Z^2 dependence of the Schottky signal amplitude.

During the 2011 run it was observed that the B1H channel provided the best quality signal. The goal for the 2012 run is to understand why this is and so bring the quality of the other three channels to the same level as B1H.

Bunch-by-bunch tune measurement

Providing bunch-by-bunch tune measurements is the main goal for the 2012 run. The resolution obtained so far during MD time is $2 \cdot 10^{-4}$.

SUMMARY

In summary the most interesting developments of the presented BI devices are listed.

- BPM:
  - Orbit resolution improved down to 1 μm.
  - Temperature dependence may be reduced.
  - Stripline BPMs (in the LSS) will provide good orbit measurements.
- LDM:
  - Fully automatic scan.
  - Improved fixed display
- Wire scanners:
  - Automatic PM gain and filter settings.
- BSRT:
  - Bunch-by-bunch scan will be performed 20 times faster.
  - Better accuracy of published beam size (down to 10%).
- BGI:
  - Independent continuous emittance measurement.
- Schottky:
  - Bunch-by-bunch tune measurement.

Some of the improvements will be available from the beginning of the run, while others will be introduced progressively during the year. They are all expected to help in the optimization of LHC operation in 2012.

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