LONGITUDINAL BEAM MEASUREMENTS AT THE LHC: THE LHC BEAM QUALITY MONITOR

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Abstract

The LHC Beam Quality Monitor is a system that measures individual bunch lengths and positions, similarly to the twin system SPS Beam Quality Monitor, from which it was derived. The pattern verification that the system provides is vital during the injection process to verify the correctness of the injected pattern, while the bunch length measurement is fed back to control the longitudinal emittance blow up performed during the energy ramp and provides a general indication of the health of the RF system. The algorithms used, the hardware implementation and the system integration in the LHC control infrastructure are presented in this paper, along with possible improvements.

SYSTEM OVERVIEW

The LHC Beam Quality Monitor (BQM) is the system that provides measurements of bunch lengths and filling pattern at the LHC. It is based on similar principles as the SPS BQM, described in [1] and [2].

The LHC BQM block diagram is shown in Figure 1. The longitudinal beam profile to be analysed is acquired from a Wall Current Monitor (WCM) of type APWL [3]. The pick-up signal is routed on a coaxial cable and through splitters until it reaches a Pickering Programmable Attenuator (PPA) and an Acqiris DC222 Analogue to Digital Converter (ADC, 8 GS/s) acquisition card. The ADC is synchronized to the RF and revolution frequencies (f_{RF} and f_{rev}) by means of a VME Trigger Unit (VTU).

The digitized WCM beam profile is analysed in a Front End Software Analysis class (FESA, C++ based, [4]). The FESA environment was developed at CERN and allows synchronization of the front end computers to the LHC timing telegram and events by means of timing receivers.

The software architecture is complicated by the fact that the OASIS software resides in the same front-end for Mountain-Range type acquisitions based on the same Acqiris ADCs. As multi-threading is not supported, the

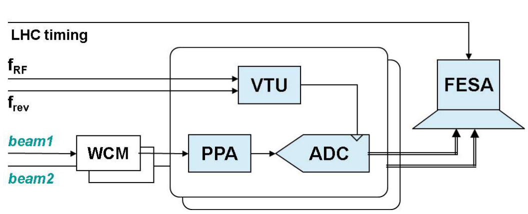

Figure 1: LHC BQM block diagram.

BQM software receives the beam profiles through an OASIS layer. This implies some limitations compared to the case in which direct access to the ADC is implemented, as in the SPS BQM.

Currently, the acquisition of one longitudinal beam profile is triggered every 55000 turns, corresponding to ≈5 s (1 turn ≈ 89 μs). A full LHC turn is acquired for every profile, i.e. a total of 800000 points are acquired at 8 GS/s.

The routines for the analysis of the beam profile are reused from the SPS BQM. A Full-Width Half-Maximum (FWHM) algorithm finds the positions of the bunches and calculates their widths [1]. The filling pattern is derived from the bunch positions calculated from the FWHM algorithm. The conversion from a FWHM measurement of the bunch width to a 4σ bunch length (which is the standard measurement) is described in the next section.

BUNCH LENGTH MEASUREMENTS

Along the signal chain from the WCM pick-up to the ADC the bunch profile is distorted. This signal deformation can be described by Transfer Functions (TF), which are used to analyse the distorted signal and could be used to reconstruct the original undistorted bunch profile. In the present software no direct recontruction is performed.

The original bunch profile is assumed to be Gaussian, and can thus be characterised by its rms width σ. The parameter of interest is the FWHM of the distorted bunch profile, FWHM', at the end of the signal chain with respect to the rms width of the original bunch profile. The signal chain TFs are used to determine the relations between FWHM' and σ for the LHC BQM acquisition chain. The TFs of the signal chain main parts are:

- the pick-up TF (-3 dB bandwidth extending from 70 kHz to 2.3 GHz [3]);
- the TF of the cabling (different cables used, for a total length ≈30 m);
- the Pickering 41-180 DC to 3 GHz Attenuator TF;
- the 3 GHz ADC acquisition board Acqiris DC-222 TF, approximated with a first order low-pass filter with a -3 dB cut-off at 3 GHz.

The expected signal at the end of the signal chain is estimated numerically. A bunch profile consisting of a Gaussian of rms width σ is used. The FWHM of the Gaussian bunch is proportional to σ through a factor $2\sqrt{2\ln 2}$.

The Gaussian bunch profile is sampled at a sampling period of $\Delta t = 25$ ps. For the range of σ considered here,

$\Delta t = 25$ ps is sufficiently short to practically eliminate effects of finite sampling period. Additionally, this sampling period is much shorter than the sampling period used by the Acqiris DC-222 ADC (125 ps). The use of a considerably shorter Δt in the simulation allows to obtain relations between the parameters of interest which are more independent of uncontrolled effects, e.g. the sampling period phase shift is unknown and should be treated as an additional error. In the simulation, 25 ns is used a bunch repetition period.

The TFs mentioned earlier are applied to the train of Gaussian bunch profiles and FWHM' is calculated from the bunch profiles obtained. The baseline of the bunch train is not perfectly constant, and the maximum bunch signal is needed to calculate FWHM'. This is done once with respect to the level of the first sample within the repetition period and once with respect to the minimum sample within the repetition period. It is a way to express the possible range of FWHM' which would be obtained with the actual hardware implementation. It is then the factor of $4\sigma/\text{FWHM'}$ which determines how FWHM' has to be converted to the full 4σ bunch length of the original bunch profile.

For a better understanding of the contribution of each component of the total actual TF, the factor $4\sigma/\text{FWHM'}$ is evaluated introducing one at a time the TFs of the components in the signal chain. Figure 2 shows the case of the signal chain for beam 1 (similar results are obtained for beam 2 as the differences in the signal chains are negligible). In blue it shows $4\sigma/\text{FWHM'}$ as a function of FWHM' using only the pick-up TF. In cyan it shows $4\sigma/\text{FWHM'}$ as a function of FWHM' using the pick-up TF and the TF of part of the cabling. The yellow curve includes the pick-up TF, the cabling and the Pickering Programmable Attenuator. Finally, the green curve takes all TFs into account, including the ADC card TF. The width of the curves shown is determined by the difference of FWHM' obtained in one or the other way as described before. The width is indicative of the uncertainties due to the method of how FWHM' is determined. The dashed red line in Figure 2 shows the factor factor $2\sqrt{2\ln 2}$, which would apply for an ideal signal transmission without distortion. The magenta line is the curve used in the LHC BQM to convert FWHM' to 4σ.

The validation of the bunch length measurement was done in two independent ways. Firstly the bunch length at LHC injection was compared to the values published by the SPS BQM at SPS extraction for different bunch intensities (probes, intermediate and nominal intensity per bunch). A good agreement was found well within the precision of the measurement.

Secondly, the corrected bunch lengths derived from FWHM' (σ_{b1} and σ_{b2}) were compared to the width of the luminous region provided by the experiments (σ_{LR}) according to :

$$\sigma_{LR} = \frac{1}{2}\left(\sqrt{\sigma_{b1}^2 + \sigma_{b2}^2}\right) \quad (1)$$

One example of this comparison is depicted in Figure 3.

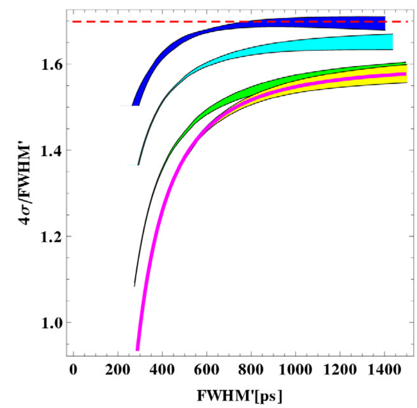

Figure 2: Calibration function.

In the top plot, the average bunch lengths for one low intensity fill. The 4σ bunch length is shown from injection to beam dump: the bunches are longest when at the flat bottom, then the bunch length shrinks during the energy ramp, then slow bunch lengthening is observed for the beams at the 3.5 TeV flat top (due to IBS and RF noise). The sharp step up and down in bunch length around 17 hours corresponds to a trip of various RF lines (5 out of 6 in use at the time for beam 1, 4 out of 6 for beam 2). During physics, the experiments publish the size of the luminous region they detect. For ATLAS and CMS that is plot in the bottom plot of Figure 3, together with the estimation from the BQM derived from Equation 1.

It has to be pointed out that bunches of "nominal" intensity are a factor 5-6 more intense, and require a controlled emittance blow up during the ramp in order not to lose Landau damping [5]. The controlled blow up changes the bunch shape, and that affects the accuracy of the BQM bunch length measurement. Punctual verifications indicate a 10-15% difference to the luminous region data. Detailed studies are ongoing.

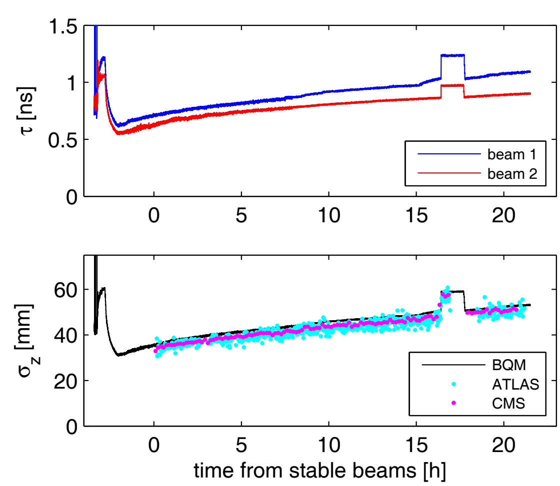

Figure 3: Bunch length and comparison with luminous region size (fill 1104, 6 bunches of about 2e10 ppb per ring).

Figure 4: Screenshot of LHC BQM GUI, indicating the number of bunches circulating in each ring and the average bunch length history (bunch lengthening at injection, ramp with blow up and slow lengthening at the flat top).

INTEGRATION

The LHC BQM was born firstly to have bunch length measurements, but has since become well integrated in the LHC controls. The average bunch length measurement is used for feedback in the controlled longitudinal emittance blow-up [5], which is vital to avoid longitudinal instabilities due to loss of Landau damping. A target value is set in the LHC software database and the blow up is active until that value is reached in the measurement.

The knowledge of the filling pattern is critical during the injection process, and it is thoroughly verified by different systems. The LHC Software Interlock System monitors the injection requests and in case beam is already present at the requested location, it does not allow the request to be executed. The LHC Injection Sequencer verifies the matching between the measured filling pattern and the database configuration before publishing the new injection request, displaying a warning in case the two are different. After the injection has taken place, the Injection Quality Check verifies the match between the request and the injected pattern to confirm whether the injection has taken place or not.

A Graphical User Interface (GUI) was developed to display the results of the BQM measurements e.g. filling pattern, bunch lengths and number of bunches per ring (see Figure 4. The history of the average bunch length, peak and product of the two is displayed over several hours. The latest bunch-by-bunch values are also displayed, while for the history a different application is available, used mainly during machine developments. The GUI also allows remote control of the PPA, which needs to be changed for different bunch intensities, i.e. pilot or nominal.

FUTURE DEVELOPMENTS

Some ideas are already on the table for possible improvements of the system. They have been accumulated over time as so far the system was unique, making developments hard to schedule. A development system is now being installed, and this will significantly ease the developments.

Initially the algorithms were optimized for speed since they were designed for the SPS BQM, and speed is not as critical in the LHC BQM. The algorithms could be then improved for deriving more information about the bunch shape, even simply by repeating the FWHM algorithm at 30% and 90% of the signal maximum. It would also be interesting to perform multiple acquisitions so to have an estimation about beam stability. Multiple acquisitions ($\approx$10) spaced $\approx$30 turns would be sufficient to get a good estimation ($\approx$70%) of both dipole and quadrupole oscillations.

At present, the acquisition is repeated every $\approx$5 s, but it is worth noting that if possible the frequency should be made higher, as this would positively impact especially on the controlled blow up performance. Additionally, a connection to the "beam in" signal, rather than the current injection event, would be favourable as it would allow to trigger on the first turn (now a delay is inserted to make sure not to measure before injection).

CONCLUSIONS

The LHC BQM is the system that provides information about bunch lengths and filling pattern of the LHC beams. The bunch length measurement was calibrated taking into account the transfer functions of all the components in the signal chain between the beam and the output of the ADC. Good agreement of the results is found with respect to SPS and experiments' measurements. The system is well integrated in the LHC controls: it gives feedback to the controlled emittance blow up and provides filling pattern information to a number of systems during the injection process. Some ideas for upgrading the system will be implemented as soon as the development system will be available.

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