THE SPS BEAM QUALITY MONITOR, FROM DESIGN TO OPERATION

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Abstract

The SPS Beam Quality Monitor is a system that monitors longitudinal beam parameters on a cycle-by-cycle basis and prevents extraction to the LHC in case the specifications are not met. This avoids losses, unnecessary stress of machine protection components and luminosity degradation, additionally helping efficiency during the filling process. The system has been operational since the 2009 LHC run, checking the beam pattern, its correct position with respect to the LHC references, individual bunch lengths and stability. In this paper the algorithms used, the hardware implementation and the operational aspects are presented.

INTRODUCTION

Ideas for an SPS extraction interlock signal based on SPS longitudinal beam measurements are sketched in the LHC Design Report [1], firstly to verify that the beam is safe for downstream machine elements, and secondly to make sure that the beam is of sufficient quality to meet the LHC needs to avoid both unnecessary stress of machine protection elements and degradation of luminosity.

The system is specified to: a) verify the synchronization between the SPS and LHC frequencies, e.g. to avoid injection onto circulating beam; b) measure individual bunch phase, length and emittance in order to prevent capture problems which would stress the momentum collimation or create satellite bunches; c) check for the presence of satellite bunches created at the SPS or its injectors; d) verify the stability of the beam, as bunches that are longitudinally unstable at the time of extraction can cause capture losses in the LHC and creation of satellite bunches. Additionally, the system is specified to assess the stability of the beam as late as possible in the cycle, and the evaluation should be faster than few synchrotron periods T_s, so to avoid the development of instabilities after the measurement is performed ($T_s \approx 5$ ms at the SPS flat top in the present configuration). The SPS Beam Quality Monitor (BQM) fulfils all these requirements and triggers the SPS emergency beam dump in case any of the checks is not passed.

The system is based on an Analogue-to-Digital Converter (ADC) sampling a Wall Current Monitor signal (WCM), controlled by a Front End Software Architecture (FESA) class and synchronized to the SPS cycle and to the SPS and LHC RF and revolution frequencies. The digitized longitudinal beam profile is then analysed by means of fast algorithms to deduce individual bunch lengths, peaks and positions, stability and presence of satellite bunches.

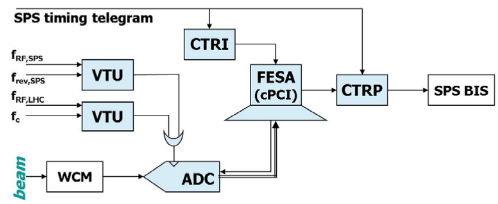

Figure 1: SPS BQM block diagram.

The system has been operational since the beginning of the 2009 LHC run, and it has become an indispensable tool helping LHC machine protection and SPS operation shift crews. It is worth mentioning that such a system improves also the LHC filling efficiency as the occasional "bad shot" from the injectors is blocked before reaching the LHC, avoiding the need to dump and refill the LHC from scratch.

The first studies on the system were presented in [2].

SYSTEM OVERVIEW

In Figure 1 the SPS BQM block diagram is sketched. A Wall Current Monitor of type APWL [3] provides the longitudinal beam profile to be analysed. It is connected by means of a coaxial cable of ≈180 m to an Acqiris ADC (DC211, 4 Gb/s, i.e. 20 points per bucket). The ADC is synchronously triggered with respect to the SPS or LHC revolution and RF frequencies in order to guarantee precise synchronization to the bucket by means of VME Trigger Units (VTUs). The digital waveform is then fetched by the CPU (Pentium III 1 GHz) on a front-end board, where a FESA class code is running (C++ based, [4]). The software includes the algorithms used for the calculation of the parameters of interest. The FESA environment also allows synchronization to the SPS machine cycles: Real Time Actions (RTA) are triggered in the cycle with 1 ms precision (e.g. injection, start of ramp, etc) by means of the SPS timing telegram and receivers (CTRI, CTRP). The output of the SPS BQM is then connected to the SPS Beam Interlock System (BIS), so that the emergency beam dump is pulled if the beam quality is not good enough. The interlock is connected in a failsafe way so that in case of malfunctioning of the SPS BQM software, the emergency dump is pulled by default.

Figure 2 shows the SPS energy ramp for an operational LHC cycle in the SPS, and the time at which WCM acquisitions (blue squares) and RTAs (red circles) are performed. One full SPS ring profile acquisition is performed at every injection to verify injected beam parameters. This

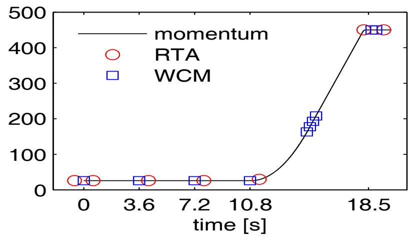

Figure 2: Nominal LHC filling cycle at the SPS (4 PS injections).

gives information about too long or too short bunches at injection. Multiple consecutive acquisitions are performed during the ramp to verify the correctness of the beam pattern and the presence of satellite bunches. These acquisitions have to be performed after the last injection but early enough in the cycle, since this is the most time consuming computation. Only 12 profiles are acquired of about 45% of the SPS circumference due to memory limitations in the present ADC. Finally, as late as possible in the cycle, 8 profiles are acquired to verify bunch parameters before extraction (e.g. bunch length), stability and position with respect to the LHC references (verifying the LHC-SPS rephasing).

Four RTAs exist: a) to setup the ADC acquisition before the first injection; b) to readout the ADC waveform, calculate the bunch parameters after each injection and setup the ADC for the next acquisition; c) to readout the ADC waveforms acquired during the ramp, calculate the beam pattern, verify the presence of satellite bunches and setup the last acquisition; d) to readout the data from the last acquisition and perform the final analysis (bunch length, stability, position, etc) so to inhibit extraction if needed.

ALGORITHMS

Three main types of computations are used for the BQM SPS, namely: 1) the Full-Width Half-Maximum (FWHM) algorithm for the evaluation of bunch lengths, 2) two types of stability checks, 3) the pattern and satellite bunch detection algorithm. The FWHM algorithm was already introduced in [2]. It is chosen for its simplicity which allows for extremely short evaluation times before extraction. The raw FWHM bunch length is corrected for cable dispersions by the use of a calibration function in the form of a second degree polynomial. The calibration function was derived by comparing waveforms taken through the BQM acquisition chain and through a second chain including a fast scope connected to the same pick-up via a fibre optic link (bandwidth $\geq$ 3 GHz).

The stability evaluation is based on concepts presented in [2]: 8 profiles are acquired at an appropriate sub-multiple of the synchrotron period (34 turns) in order to make sure to sample possible instabilities. The number of profiles is limited to 8 due to the bus transfer speed, and the FWHM algorithm is applied only on the first frame. Subtraction between frames allows detecting shape changes (see Figure 3) which can identify mainly dipole oscillations, but also quadrupole oscillations. Due to the little time available, the subtraction is performed only in small intervals around the positions of the bunches (derived by the FWHM algorithm performed on the first frame). Additionally, the bunch peaks for different frames provide information about possible quadrupole oscillations. Results from these algorithms were compared to an analysis based on Gaussian fit parameter variations: the two equivalently detect dipole and quadrupole, but the BQM algorithms additionally detect also rigid dipole oscillations.

The beam pattern is verified by comparing the bunch positions with the requested pattern (information provided for each cycle by the LHC Injection Sequencer). Any extra, missing or misplaced bunch makes the check fail.

Satellite bunches are defined as small portions of captured beam in buckets which are supposed to be empty. They can e.g. be caused by non-negligible injection phase error in the SPS. Multiple acquisitions (for consecutive turns) are averaged by taking into account the ADC trigger jitter and by re-interpolating to have exactly 20 points per bucket. The averaged waveform is then used to reconstruct the position of the bucket edges. At the bucket edges there is no beam as the acquisition is done during the ramp (no debunched beam). Bucket edges are used to force the

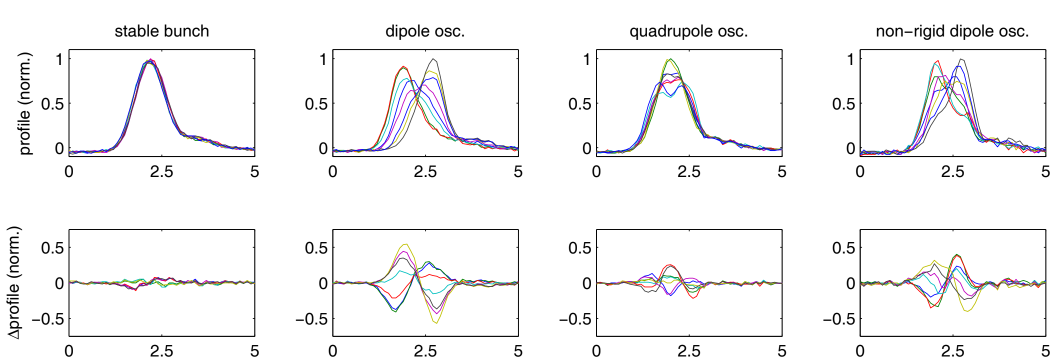

Figure 3: Example of bunch profile acquisitions and stability algorithm for both stable and unstable bunches. Top: 8 superimposed bunch profiles for stable and unstable bunches. Bottom: differences between the first profile and the others.

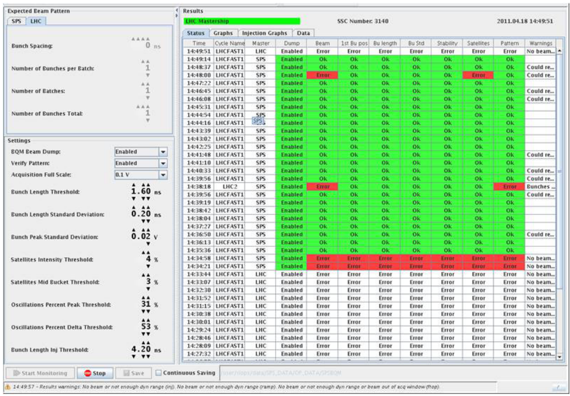

Figure 4: Screenshot of SPS BQM GUI. On the left, the settings can be changed. On the right, each line shows the analysis results for a cycle: all checks green allow extraction, any one check not passed prevents extraction (red).

beam profile to zero and compensate for the DC cut-off of the WCM (-3 dB bandwidth from 70 kHz to 2.3 GHz). If the mid-bucket value of the beam profile is above threshold, then a satellite bunch is detected. Additionally, the signal in the bucket is integrated to identify possible hollow bunches (a separate threshold is used). The detection of any number of satellite bunches causes the beam not to be extracted. The satellite bunch detection algorithms can at present reliably detect signals that are about 3% of the main bunches, better precision can be reached by hardware improvements.

INTEGRATION AND FUTURE DEVELOPMENTS

A Graphical User Interface (GUI) was developed to ease the display of results and the change of settings. A screenshot of the GUI is shown in Figure 4. It is worth noting that the acceptance thresholds can be modified by the operation shift crews through the GUI, e.g. bunch length or satellite bunch amplitude. Guidelines are given and followed, small changes are allowed for having some operational flexibility to cope with exceptional situations.

While the core of the system has remained unchanged since it first became operational in 2009, small improvements were performed in 2010 and 2011 mostly to add new interlocking checks. New checks with respect to the original design are: minimum bunch length at the flat top (required for LHC Machine Developments); bunch equality (e.g. to improve luminosity, as unequal bunches lead to a deterioration of the performance); bunch length at SPS injection (too short bunches can create stability problems). Moreover, the pattern verification can be masked to allow for special flexibility during machine development periods.

The present performance is limited by the hardware which reuses components previously purchased for other purposes. The maximum number of acquisitions is limited by the ADC memory, and affects the satellite bunch analysis where more waveforms should be averaged to improve the signal to noise ratio. The speed of the bus data transfer between ADC and CPU limits the number of waveforms that can be transferred to the CPU in the tight timing limits at the flat top (the current transfer of 8 waveforms takes 12-13 ms, which is about half the total time available). Dedicated hardware has been recently bought and is being installed, it should allow to overcome part of these limitations: a more powerful CPU and crate, an 8 GS/s ADC with extended memory and a fibre optic link.

CONCLUSIONS

The SPS BQM has been in operation since autumn 2009 in checking a number of longitudinal beam parameters and characteristics. It quickly became an indispensable tool during LHC filling, so much that it was questioned whether it should be made somewhat redundant. It is also used for diagnostics by RF experts, and minor modifications were quickly put in place to cope with new requirements. Algorithms were used and developed to perform the data analysis coping with tight timing constraints: a FWHM evaluation for the bunch length, waveform subtraction for stability analysis. For the detection of satellite bunches an acquisition averaging with baseline compensation and reconstruction of bucket edges was devised. The current system performance is limited by the hardware and new components were purchased to be deployed in the next few months (recent CPU, fibre optic link, 8 GS/s ADC). A positive impact on the measurement performance is expected.

The success of the system is proven by the fact that a similar tool for online monitoring of longitudinal beam parameters is now in use also in the LHC [5], and another one is planned for the PS. In the longer term similar SPS interlocks based on transverse measurements are also desirable.

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