A BEAM QUALITY MONITOR FOR LHC BEAMS IN THE SPS

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Abstract

The SPS Beam Quality Monitor (BQM) system monitors the longitudinal parameters of the beam before extraction to the LHC to prevent losses and degradation of the LHC luminosity by the injection of low quality beams. It is implemented in two priority levels. At the highest level the SPS-LHC synchronization and global beam structure are verified. If the specifications are not met, the beam should be dumped in the SPS before extraction. On the second level, individual bunch position, length and stability are checked for beam quality assessment. Tolerances are adapted to the mode of operation and extraction to the LHC can also be inhibited. Beam parameters are accessed by acquiring bunch profiles with a longitudinal pick up and fast digital oscilloscope. The beam is monitored for instabilities during the acceleration cycle and thoroughly checked a few ms before extraction for a final decision on extraction interlock. Dedicated hardware and software components implementing fast algorithms are required. In this paper the fast algorithms are presented.

MOTIVATION

The BQM system [1] evaluates the quality of the beam just before extraction from the SPS to decide whether or not it can be injected into the LHC. First, the azimuthal beam position in the SPS ring will be verified to check the successful SPS-LHC synchronization. Unstable beam or bunches that are too long to fit into the 2.5 ns LHC buckets will create satellite bunches or uncaptured beam in the LHC, and this can stress or even harm LHC machine components such as collimators or superconducting magnets. Non-uniform intensity distribution along the batches can degrade LHC luminosity. To avoid these situations, the longitudinal beam structure and bunch parameters are verified in the SPS and beam that is out of specification should not be injected in the LHC but dumped beforehand, at the end of the SPS cycle.

Two levels of priority are distinguished in the BQM implementation. High priority is given to the verification of bunch and batch positions to help avoid excessive stress on LHC machine protection elements. Lower priority is given to beam quality in view of LHC performance optimization. The beam quality tolerances, which are not discussed in detail here, will be varied during commissioning and operation: looser criteria improve acceptance rate and thus LHC filling time; tighter margins improve beam uniformity and thus machine luminosity. At high beam intensity, beam quality criteria can fall into the high priority category.

The BQM consists mainly of an ADC and a processing unit. The ADC digitises a Wall Current Monitor signal (WCM) to obtain a longitudinal Bunch Profile (BP) that can be analysed by the processing unit so that the beam characteristics can be extracted. A user interface allows online changes to the parameter tolerances and the system output carries the decision whether to dump the beam or inject it in the LHC. This paper concentrates on the fast algorithms used for deriving the beam parameters and beam stability from the BPs.

PARAMETER LIST

The SPS accelerates the LHC beam from 26 GeV/c to 450 GeV/c. The nominal beam for LHC physics consists of two to four batches of 72 bunches (25-ns spaced), but other types of beam are also necessary, e.g. for setting up the machine (see Table 1). The safety beam, or pilot, is a single bunch of reduced intensity, which is still measurable by the LHC beam observation systems but which can be entirely lost at injection without quenching the LHC magnets. A beam with 75 ns spacing and the “43-bunch” beam are other examples of schemes foreseen during the early phases of LHC operation.

The BQM is programmed to handle all these possible schemes. A BP acquisition after the last injection (e.g. during the ramp) is scanned to find where the WCM signal exceeds a certain threshold, in which case the bucket is considered to be occupied by a bunch (“coarse” bunch position). The coarse bunch positions are compared to the expected batch structure (arrays stored for each possible beam scheme in the processing unit memory) to verify that no bunches are present in incorrect positions. The required batch structure is input to the system via the user interface. While bunches in incorrect positions in the ring can be harmful, missing bunches (e.g. due to missing PS Booster or PS batches) can possibly be tolerated at the expense of machine luminosity (low priority).

While the batch structure can be verified early on in the cycle, the bunch parameters for extraction, such as bunch length and fine position, have to be checked as late as

Table 1: LHC beams in the SPS (the number of bunches is per PS batch, the intensity is per bunch at extraction).

scheme	# batches	# bunches	# p/bunch
pilot bunch	1	1	5×10^9
nominal	2–4	72	1.15×10^{11}
75 ns	2–4	24	1.15×10^{11}
43-bunch	2–4	1	1.15×10^{11}
TOTEM	2–4	4	3×10^{10}

Table 2: Parameters to be checked with the BQM, typical values and acquisition time (acq. time) in the SPS cycle.

parameter	typical values	acq. time
bunch pos. (coarse)	bucket number	during ramp
bunch pos. (fine)	$\Delta_{\text{batch}} = \pm 0.1$ ns	before extr.
bunch length	1.4–1.7 ns	before extr.
peak amplitude	$\Delta_{\text{batch}} = 10\%$	before extr.

possible in the cycle, after SPS-LHC rephasing. In fact, beam stability has to be checked close enough to extraction for instabilities not to develop between the time of the measurement and the actual time of extraction. The time available for the evaluation is thus comparable to the synchrotron period T_s (~ 5 ms for $V_{200} = 7$ MV at the end of the Flat Top, FT). A list of the parameters, and typical values, to be checked with the BQM is given in Table 2.

PARAMETER EVALUATION

The standard analysis used to treat BPs in the SPS RF Machine Developments (MDs), consists of the use of a Gaussian fit for evaluation of bunch length (defined as $\tau_{\text{fit}} = 4\sigma_{\text{fit}}$) on a BP acquired at 10 GS/s and deconvolved by pick-up and cable transfer functions. The use of a fit in the offline analysis is motivated by its relative immunity to noise in the measurement. For the evaluation of beam parameters at extraction this analysis is too time consuming and simpler and faster algorithms have to be envisaged.

A full width half maximum (FWHM) algorithm for the estimation of bunch length, for example, is based on the search of a maximum and minimum of the signal in a certain interval (e.g. a bucket); the signal width is then the distance between the points situated halfway between the maximum and the minimum. In order to improve the precision of the estimate, interpolation is used between the two points before and after the half-maximum crossing. Moreover, the same two points can be used for estimating the bunch position, as the midpoint between the two. A FWHM algorithm is less immune to noise than a fit, but it is more general as it can also be applied when the bunches do not have a Gaussian shape (e.g. when the bunch shape was modified by instabilities or artificial blow-up).

A lower sampling rate gives fewer acquisition points and this would make data treatment faster and at the same time allow the use of cheaper, more readily available acquisition cards. However, due to the wider spacing between acquired points (for example 200 ps/S, at 5 GS/s, instead of 100 ps/S), the derivation of beam parameters from the BPs suffers some additional uncertainty when compared to the analysis on data acquired at a higher sampling rate. Figure 1 shows a comparison between bunch lengths calculated through a Gaussian fit on 10 GS/s deconvolved data and through a FWHM algorithm on the same data decimated to 5 GS/s (all data in this document are from LHC beam BPs acquired in SPS MDs in 2007, and include both stable and unstable beam [2]). There is good agreement between the two algorithms and despite the different sampling rates. The slope of the linear fit is 0.61, which is close to 0.59 that is the scaling factor between τ_{fit} and τ_{fwhm} for a Gaussian curve ($\tau_{\text{fwhm}} = \sqrt{(\ln 2)/2} \cdot \tau_{\text{fit}}$). The wider spread of the data around 1.5 ns is due to BPs which have a double-peaked profile, which is not well approximated by a Gaussian curve.

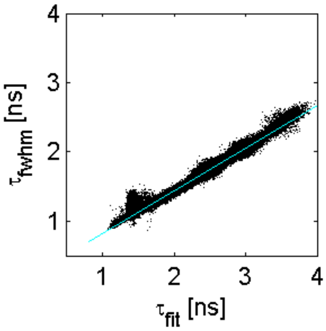

Figure 1: Bunch lengths from Gaussian fit to 10 GS/s data and from FWHM on 5 GS/s data, linear fit in cyan.

STABILITY ASSESSMENT

The use of the FWHM algorithm allows beam parameters to be checked, but multiple BPs are needed before extraction to evaluate beam stability. The amplitude of possible bunch oscillations can be estimated by acquiring the BPs at fractions of T_s to observe dipole or quadrupole oscillations.

Given a particular interval between the BP acquisitions (acq. period), a certain number of acquired BPs (number of acqs) will guarantee an estimation of a minimum percentage of the oscillation amplitude regardless of the phase at which the acquisitions start. This analysis is useful in deciding how to sample the beam in order to be able to estimate beam stability with reasonable accuracy. In Figure 2 the minimum detected percentage of oscillation amplitude is plotted for a dipole oscillation at $154\ \mathrm{T}_0 < \mathrm{T}_\mathrm{s} < 263\ \mathrm{T}_0$ (the interval corresponds to T_s calculated for $V_{200} = 7\,\mathrm{MV}$

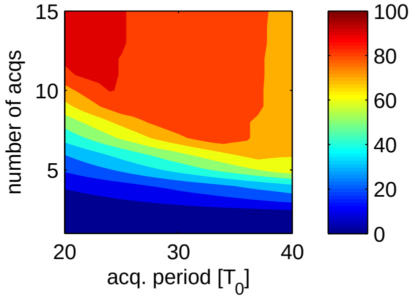

Figure 2: Minimum oscillation amplitude (in percentage) detected from few acquisitions spaced a certain period.

with or without $V_{800} = 500\,\mathrm{kV}$, and an uncertainty of 20%; $\mathrm{T}_0 = 23.1\ \mu\mathrm{s}$ the revolution period). A higher number of acquisitions at a higher acquisition rate allows up to 90% of the actual oscillation amplitude to be detected. A similar plot in the case of quadrupole oscillations reveals that 6–8 samples at 20–30 T_0 interval allow detection of more than 70% of oscillation amplitude.

Once the BPs are acquired, the complexity of the algorithm has to be kept to the minimum in order to have a fast evaluation and decision on the beam stability. For this reason, it is foreseen to perform a detailed analysis (e.g. FWHM) of the first acquired frame only. Later frames are only compared to the first by direct subtraction to give information on beam stability.

Figure 3 shows two examples of subtraction analysis on real BPs. In (a1), eight BPs of a stable bunch acquired at a 27 T_0 spacing are shown, while the bunch in (b1) shows non-rigid dipole oscillation. In (a2–3) and (b2–3) the results of subtracting the BPs are shown: plots in the middle row (a2 and b2) are obtained by subtracting the first acquired BP from those following ($\Delta_1^{(i)} = \mathrm{BP_i} - \mathrm{BP_1}$, $i = 2\ldots8$), while in the bottom row (a3 and b3) the plots are obtained by subtracting frames that are one frame apart or three frames apart ($\Delta_2^{(i)} = \mathrm{BP_i} - \mathrm{BP_{i-2}}$, $i = 3\ldots8$ and $\Delta_4^{(i)} = \mathrm{BP_i} - \mathrm{BP_{i-4}}$, $i = 5\ldots8$). Plots in the bottom row detect higher deviations because they compare frames that are at roughly opposed phase in the oscillation. Compared to the study in the middle row, more comparisons between frames are required, making the analysis more computationally intensive, and assumptions are made on the period of oscillation, making the method less general.

The estimation derived from subtracted BPs (with the Δ_4 method) is compared in Figure 4 with the variation in bunch position derived from the Gaussian fit analysis. The two approaches have good agreement, apart from a few bunches for which the fit position shows little variation while the subtracted BP method shows oscillation amplitudes up to 90% of bunch peak amplitude. These bunches show non-rigid dipole oscillation and are not well approximated by a Gaussian curve. An example is the bunch in Figure 3 (b1). For comparison, bunches (a) and (b) in Figure 3 give a variation of bunch position from fit of 11 ps and 23 ps respectively, while the maximum oscillation calculated with the Δ_4 analysis is 6% and 80% respectively.

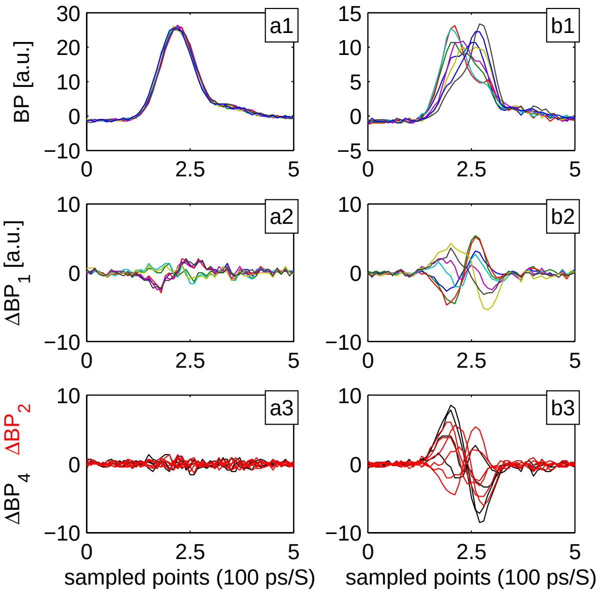

Figure 3: BPs at FT (a1, b1) and subtracted BPs (a2, b2, a3, b3). Stable bunch (a); non-rigid dipole oscillation (b).

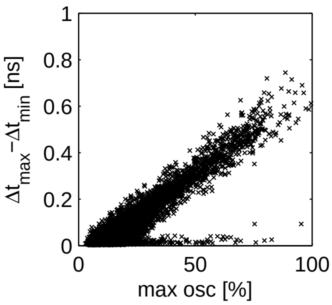

Figure 4: Comparison between maximum deviation in bunch position from fit analysis ($\Delta \mathrm{t_{max}} - \Delta \mathrm{t_{min}}$) and maximum deviation as percentage of bunch peak amplitude from Δ_4 BP subtraction (max osc).

CONCLUSIONS AND FUTURE PLANS

The SPS BQM is a system to assess longitudinal beam parameters prior to extraction to LHC to help avoid injection of beam which would be out of specifications. A fast assessment of beam parameters like bunch length and position as late as possible in the SPS cycle is needed, and fast algorithms are studied. A FWHM algorithm is used to derive bunch length and position from the BP. Beam stability is assessed by subtracting BPs acquired at proper intervals to detect oscillations in bunch position and length (also for BPs that are not Gaussian). An estimation of satellite bunches remains to be added to the checks.

The whole system is now being implemented in a VME crate, using an Acqiris ADC card to acquire and sample the signal, and a CPCI processing unit for the data analysis.

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