LONGITUDINAL BEAM QUALITY MONITORING

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Abstract

Reliable monitoring of the longitudinal beam quality is essential for a safe and efficient operation of any high intensity accelerator. The definition of beam quality criteria vary from one machine to the other, depending on the beam and machine parameters. In this paper, the most commonly used concepts of longitudinal beam quality monitoring are addressed with emphasis given on the applications in the circular accelerators at CERN.

INTRODUCTION

Monitoring of the longitudinal beam quality is one of the key ingredients in the operation of high intensity particle accelerators and an essential component to increase the beam performance. Moreover, it ensures the machine safety by quickly spotting any beam degradation (instability, losses) or hardware problem (RF cavities trips, errors in the phase of successive modules in Linacs, problems during RF manipulations, etc.) and therefore allows for an efficient correction in critical situations. Reliable longitudinal beam observations are especially crucial during machine commissioning and machine studies. In addition, in certain circumstances, the longitudinal beam parameters could be used as an input to optimize other beam manipulations.

The criteria defining the longitudinal beam quality vary from one machine to the other, depending on the particle type and on the beam pattern (single- or multi-bunch beams). Specific needs and problems of each machine determine what should be monitored (instabilities, distributions or long term evolution), and therefore they define the requirements in resolution and frequency of acquisitions.

The variety of the beam parameters for the different types of accelerators define the measurement approach, which in most cases, is focused on obtaining accurate and reliable longitudinal bunch profiles. Such profiles can be further analyzed to obtain the required bunch parameters (bunch shape, length, position, and emittance). A large spectrum of diagnostic techniques has been developed over the years to cope with the increased needs in time resolution (in the order of a few fs). They can be distinguished in direct measurements of the beam: wall-current monitors (WCM) pick-ups, RF zero-phasing, transverse deflecting cavities, beam shape monitors, etc or in those using the synchrotron radiation to reconstruct the bunch distribution: streak camera, coherent radiation, etc [1].

This paper will be focused on how longitudinal beam quality is monitored in the CERN accelerator complex, and in particular in the LHC and the SPS. The bunch lengths of interest are of the order of few ns, measured by WCMs with bandwidths of around 3 GHz together with fast-sampling oscilloscopes (up to 40 GS/s).

MONITORING OF SINGLE BUNCHES

Precise and accurate diagnostics with high resolution are needed to monitor the longitudinal quality of single bunches. The knowledge of bunch position and length are usually adequate to identify and characterize longitudinal instabilities during machine operation. However, higher resolution is often needed in order to resolve in more details the intrabunch motion and the longitudinal distribution (higher mode of instabilities, RF manipulations, luminosity calculations, etc.). In addition, the measurements should well cover at least a few synchrotron periods, which, depending on the accelerator, could be translated to an acquisition of a few thousands of turns. Figure 1 presents an acquisition of longitudinal bunch profiles at the moment of injection into the LHC. Measurements were done using a WCM [2] pick-up

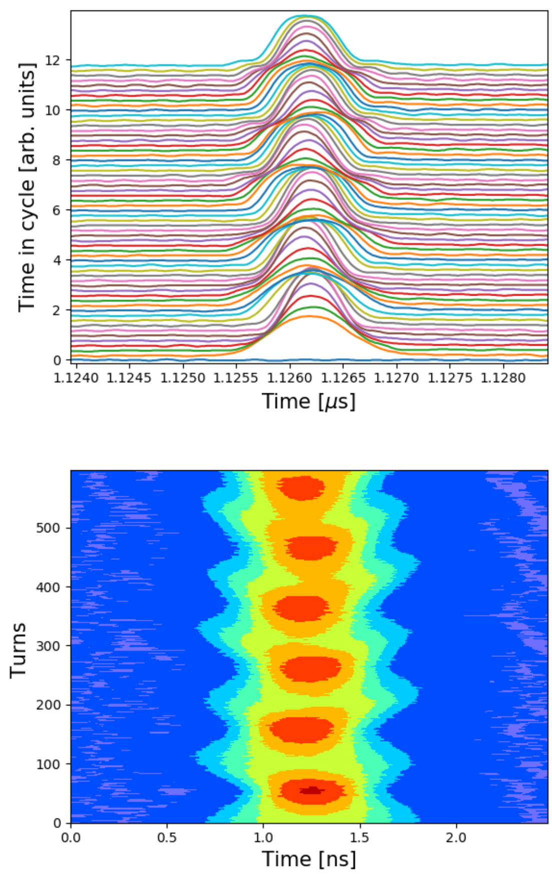


Figure 1: Two common illustrations of longitudinal bunch profile measurements at the LHC injection (V_{RF} = 6 MV). Top: "mountain range" plot. Bottom: "waterfall" plot. The quadrupole oscillations of the bunch are clearly visible, initiated by an RF voltage mismatch.

with a bandwidth of around 3 GHz connected to a Tektronix, DPO7254 oscilloscope with sampling rate of 40 GS/s. Two commonly used means to illustrate the acquired data are shown, the mountain range plot (top) and the waterfall plot (bottom). In both representation, one can clearly observe the quadrupole oscillations of the bunch, triggered by the mismatch of the RF voltage at LHC injection.

In addition to a clear illustration of the intra-bunch motion, the waterfall plots can be used to identify phase and energy errors at injection. This is illustrated in Fig. 2. In the left plot, the dipole oscillations are initiated by an energy error, since the bunch is injected in the bucket center (white vertical line). In the right plot, the oscillations are caused by a phase error, as an initial phase displacement with respect to the bucket center can be observed. Note that in both cases the impact on the bunch is similar.

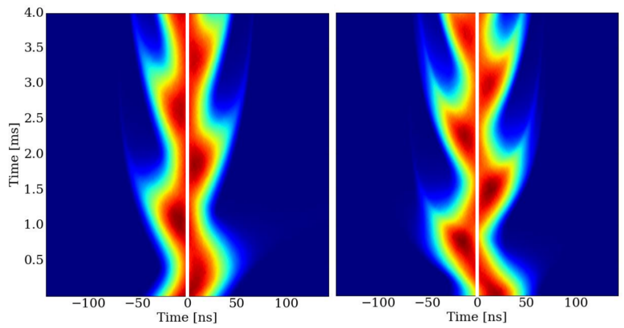


Figure 2: Waterfall plots presenting simulations of dipole oscillations of a bunch caused by energy (left) and phase (right) errors at injection. The white, vertical line indicates the bucket center [3].

The acquired bunch profiles can be fitted to obtain information on the bunch parameters (bunch position, peak, length and intensity). Different types of fits can be applied, depending on the specific bunch distribution (Gaussian, parabolic, etc). However, for an efficient monitoring of the beam quality during operation, faster algorithms (for example full-width-half-maximum of the bunch profile) are usually preferred in some cases, even at the expense of loosing accuracy.

The bunch parameters obtained after the fitting could be further analyzed to extract more information: quantify the injection errors, obtain the frequency of oscillation, the damping rate of a coherent motion or its growth rate (in case of instabilities), etc. Figure 3 depicts the bunch length oscillations due to the voltage mismatch at the LHC injection. By fitting these oscillations one can estimate the synchrotron frequency (actually $2f_s$) and the damping time of the quadrupole motion, which is used to detect possible issues with the RF voltage amplitude.

Furthermore, the 2-dimensional longitudinal phase-space distribution of the bunch can be reconstructed, based on measurements of the bunch profiles, by applying tomographic techniques. Apart from visualizing the longitudinal phase-space, longitudinal tomography provides information on the longitudinal emittance and the momentum spread of the

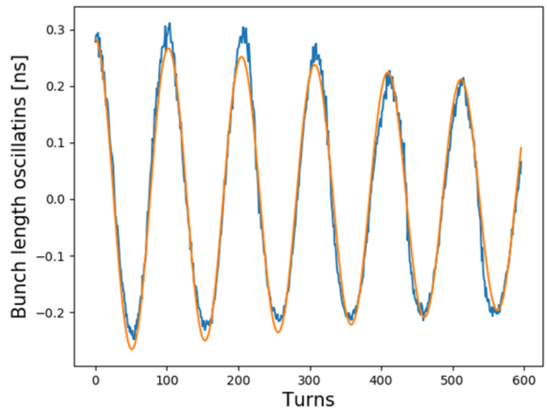


Figure 3: Bunch length oscillations at the LHC injection with V_{RF} = 6 MV. The synchrotron frequency f_s = 54.9 Hz and damping time of τ_d = 0.15 s were obtained after applying a sinusoidal fit (orange curve). The revolution period is T_{rev} = 88.9 μs.

bunch, with better precision than an analysis of bunch profile. In addition, it gives an accurate model of the particle distribution which is very important for analytical calculations and macro-particle simulations in view of beam instability studies.

Longitudinal bunch tomography was originally developed at CERN [4], in order to investigate the longitudinal emittance evolution during the complex RF manipulations (bunch splitting, merging, rotation, etc.). It is now a well-established operational tool, necessary at certain times in the cycle (beam injection, extraction, RF manipulations) and has been extensively used in all machines of the CERN PS Complex. Figure 4 presents an example of the phase-space distribution of a bunch injected to the LHC with a large energy error (top figure), reconstructed by tomography. After filamentation and due to special issues with the phase-loop, a hole in the center of the longitudinal phase-space appeared (bottom figure), which was preserved until the beginning of the ramp (~30 minutes later).

Long term evolution

For most of the accelerators it is essential to monitor the longitudinal beam quality during the entire cycle. Since the cycle duration varies from a few seconds to many hours (LHC case), the frequency of the acquisitions has to be adapted. In this case, the evolution of beam parameters (bunch lengths and positions) is monitored, providing an overview of the beam stability, as well as the possibility to identify instability thresholds. An example of the bunch length evolution in an SPS proton cycle is shown in Fig. 5, where depending on the bunch intensity, different types of instabilities can be observed: a slow instability which manifests with slow emittance blow-up during the ramp (green trace) and a fast instability indicated by an abrupt emittance blow-up (red trace) [5].

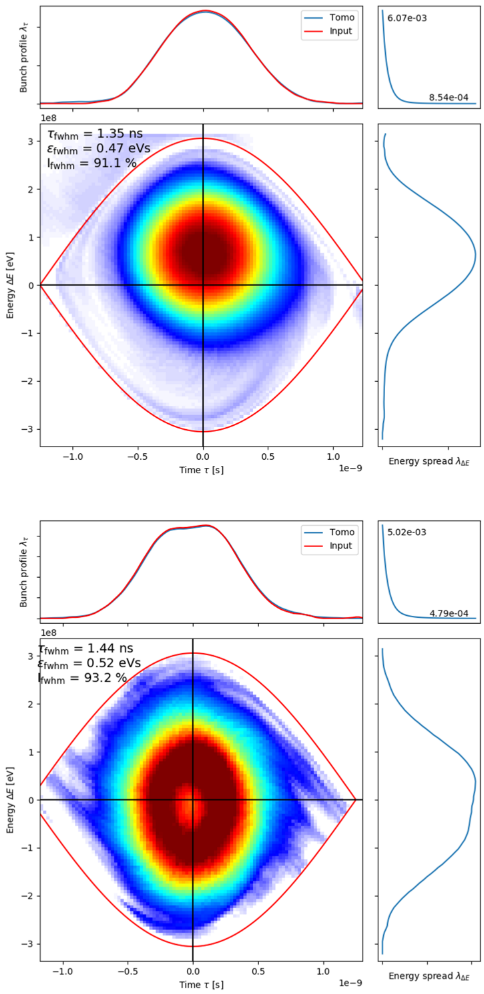


Figure 4: Tomographic reconstruction of a bunch in the LHC. Top: at the moment of injection. Bottom: 30 minutes later. A hole in the center of the longitudinal phase-space is generated due to the large energy error, and survived until the beginning of the ramp.

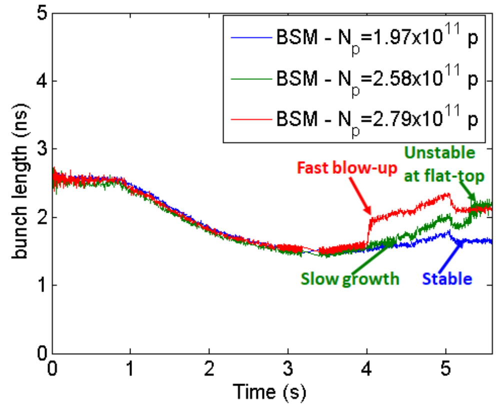


Figure 5: Bunch length evolution at the SPS in double harmonic operation (bunch shortening mode) for different intensities. Blue trace: stable bunch. Green trace: slow instability manifests with slow emittance blow-up during the ramp. Red trace: fast instability indicated by a sudden increase of the bunch length (microwave instability) [5].

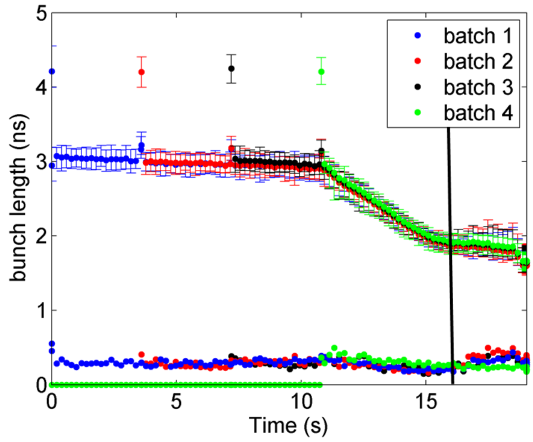


Figure 6: Average bunch length evolution along a nominal LHC proton cycle in the SPS. Different colours correspond to different batches of 72 bunches. The dots on the bottom show the bunch length spread within each batch. The black solid line corresponds to the onset of the instability.

MONITORING OF MULTI-BUNCH BEAMS

Similar type of plots, of the bunch parameters evolution along the cycle, can be generated to visualize the longitudinal beam quality in the case of multi-bunched beams. However, for the sake of simplicity, the average value of the bunch parameters can be plotted. The spread of the bunch parameters within the batch (rms or min-max values), which is related to the stability of the beam can be also shown in the same plot. An example of the average bunch length evolution of a nominal SPS proton cycle used for filling the LHC is shown in Fig. 6. One can see that all 4 PS batches, with 72 bunches each, become unstable at a certain moment in the cycle. The onset of instability is indicated by the black, vertical line and can be identified by the increase of the spread in the bunch lengths within the batches (shown as error bar and also with the points in the bottom of the plot).

It is clear that the increased number of bunches makes the need of faster data analysis algorithms during machine operation even more essential. Further reduction of the acquisition rate is necessary and possibly the time resolution needs to be reduced as well, in order to keep the amount of data in a reasonable range. Nevertheless, once the onset of an instability is identified the acquisition can be adjusted in order to resolve in more details the intra-bunch motion, at relevant moments during the cycle. An example of dipole and quadrupole oscillations of a 72-bunch batch, obtained from bunch profile measurements at the SPS extraction (last point in Fig. 6), is shown in Fig. 7. The large amplitudes of both dipole and quadrupole oscillations mean that the bunches are very unstable and that this beam should be prevented from transfer to the LHC.

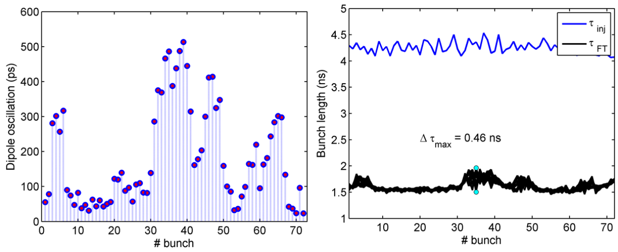


Figure 7: Example of dipole (left) and quadrupole (right) oscillations of a 72-bunch batch, obtained from bunch profile measurements at the SPS extraction. The large oscillation amplitudes (around 500 ps peak to peak) of many bunches indicate that this beam is very unstable.

THE BEAM QUALITY MONITOR AT CERN

The importance of monitoring the longitudinal beam quality led to the implementation of the dedicated Beam Quality Monitor (BQM) [6, 7] essential for the daily operation of the SPS and LHC. The BQM measures longitudinal bunch profiles using a WCM pick-up, and monitors the longitudinal beam parameters (beam pattern, bunch lengths, bunch positions, and intensities) on a cycle-by-cycle basis. Fast algorithms for online analysis of the data have been developed and used. In particular, the bunch length is calculated using the Full-Width-Half-Maximum (FWHM) algorithm in order to save time. The FWHM of each bunch is quickly measured from the acquired beam profiles and from that the standard deviation σ of the bunch is obtained assuming a Gaussian distribution. The bunch length is then defined as $\tau = 4\sigma$.

The role of the SPS BQM is of great importance since it ensures the beam quality at extraction in order to meet the LHC requirements (bunch lengths, intensities, etc.). The system, among other very important tasks, is specified to verify the stability of the beam (dipole and quadrupole oscillations) before extraction. In case any of its specified checks fails, the BQM removes the beam permit, preventing the beam from extracted into the LHC. A screenshot of the SPS BQM graphical user interface is shown in Fig. 8.

Similarly, the LHC BQM provides information on the longitudinal beam parameters (bunch length, position, intensity, beam pattern, etc.) along the cycle. A screenshot of the LHC BQM graphical user interface is shown in Fig. 9, where the average bunch length evolution of the two beams is shown. One can clearly observe a slow bunch lengthening during flat bottom due to RF noise and intra-beam scattering effects [10]. The irregular behaviour of the bunches during the ramp (green region in the plot of Fig. 9) is caused by the controlled longitudinal emittance blow-up, which is applied during the ramp and is essential to avoid longitudinal instabilities [8]. During that process, the average bunch length measurement from the BQM is actually used as an input to the feedback for the emittance blow-up, ensuring a specific value of the bunch length at top energy ($\tau \sim$1.2 ns).

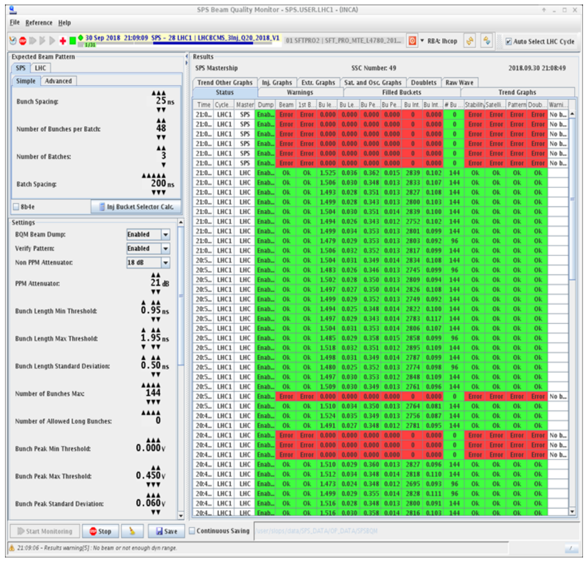


Figure 8: Screenshot of the SPS BQM graphical user interface (by F. Follin). On the left, the settings can be changed. On the right, each line shows the analysis results for a cycle: all checks green allow extraction, any check not passed (red) prevents extraction.

Figure 9: Screenshot of LHC BQM graphical user interface (by F. Follin), indicating the number of bunches circulating in each ring and the average bunch length evolution: bunch lengthening at injection energy and controlled longitudinal emittance blow-up during the ramp.

In the LHC, due to the long cycle, the acquisitions are done at 1 Hz, which means that it is not possible to resolve the intra-bunch motion (timescale of a few tens of synchrotron oscillations periods). However, the BQM still provides an overview of the beam stability, as well as the possibility to identify the onset of instability, since the average, minimum and maximum values of all circulating bunches are measured. An example of an instability which occurred in Beam 2 during operation is presented in Fig. 10. Due to technical problems, the controlled longitudinal emittance blow-up was not applied for this beam. This can be seen as a continuous reduction of the average bunch length during the ramp (marked by the two vertical dotted lines). As a result the instability threshold was reached and many bunches became unstable, which is indicated by the large bunch length spread.

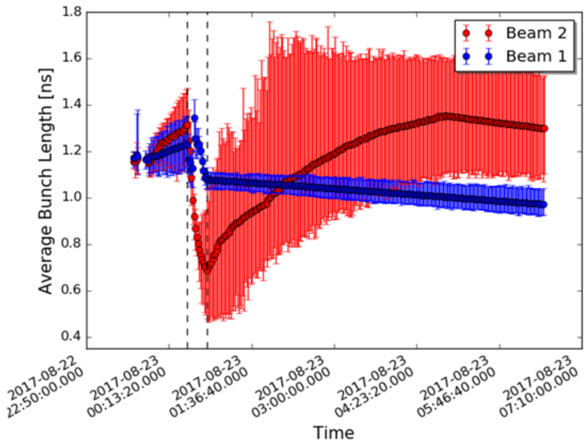


Figure 10: Example of the average bunch length evolution during a nominal LHC cycle. Continuous reduction of the average bunch length of Beam 2 during the ramp (marked by the two vertical dotted lines), since controlled longitudinal emittance blow-up was not applied. The instability threshold was reached and many bunches became unstable, indicated by the large bunch length spread.

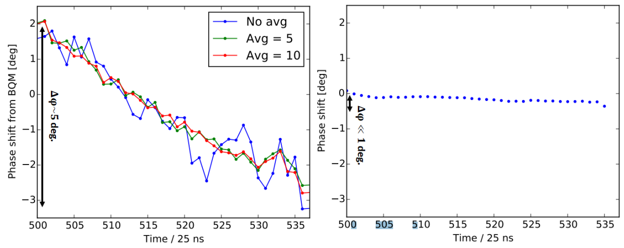
OBSERVATION OF BUNCH PHASES

Dipole oscillations of the bunches can be also monitored in the LHC by direct measurements of the bunch phase, using a beam phase-module, similar to the one used in the phase-loop [9]. This system determines the bunch position as the difference between the beam phase, measured from the WCM pick-up, and the RF voltage phase. Therefore, the effect of beam loading is excluded. This is not the case when bunch positions are obtained from the measured bunch profiles by the BQM, where the phase shift due to transient beam loading is also included and it is larger than the phase shift due to other effects of interest (resistive impedance and e-cloud). On the contrary, using the phase-module a relative accuracy of 0.01 degrees can be achieved in the bunch by bunch phase measurements (see Fig. 11).

Thanks to this accuracy, a diagnostic tool was implemented in the LHC (Fig. 12), in order to monitor the e-cloud activity during regular operation, as well as during the scrubbing runs that take place in the beginning of each year.

CONCLUSION

Longitudinal beam quality monitoring is one of the main key components for a safe, reliable and efficient operation of particle accelerators. What needs to be monitored depends strongly on the requirements, issues and beam parameters of the specific machine. For the CERN accelerator complex an accurate knowledge of the bunch profile, which is generally measured with high bandwidth WCMs, is crucial both in day-by-day operation and during the various machine studies. Single- and multi-bunch analysis of the beam signal and the longitudinal parameters obtained, can be used to quickly identify instabilities or hardware problems and therefore increase the efficiency of the corrective actions. Other means to monitor the longitudinal beam quality, such as the peak-detected Schottky spectrum [11] (incoherent and coherent bunch motion) and the Beam Synchrotron Light Monitor Longitudinal [12] (satellite bunches and beam losses), also very important both in operation and machine studies were beyond the scope of this summary.



(a) From BQM (b) From phase module

Figure 11: Bunch-by-bunch phase shift computed from bunch positions measured by the BQM (left) and by the phase-module (right). The larger phase shifts in BQM (a) are due to beam loading. In both cases the one-turn feedback is off [9].

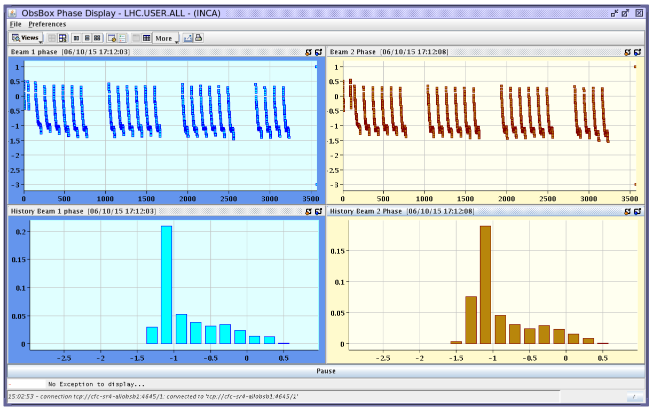


Figure 12: Screenshot of the graphical user interface (by G. H. Hemelsoet) of the bunch-by-bunch phase measurement with the phase-module. Clear e-cloud signatures along the bunch trains can be observed at the top plots, both for Beam 1 (left) and Beam 2 (right).

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