Beam instrumentation for machine protection

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Abstract

This paper will focus on three instruments with implications for machine protection, namely: the abort gap monitor, the fast beam current change monitor and the interlocked BPMs in IR6. For each of these instruments a brief description of the issues observed during run 1* will be given and the improvements done during the long shutdown (LS 1) presented, with particular focus on the performance and reliability aspects.

INTRODUCTION

In order to guarantee the safe functioning of the LHC it is important to monitor certain beam parameters with sufficient accuracy and reliability. In particular in this paper the focus will be set on three devices: the interlocked beam position monitors in IR6 (beam extraction), the fast beam current change monitor (FBCCM aka dI/dt) and the abort gap monitor (BSRA).

The interlocked BPMs in IR6 are used to avoid large orbit offsets at the beam extraction septum which could lead to the beam scraping the septum or the absorber (TCDS) that protects the septum in case the dump kicker (MKD) misfires. A schematic of the extraction channel is depicted in Fig. 1. The orbit reading of these special Beam Position Monitors (BPMs) is directly linked to the beam dump, meaning that both the measurement accuracy and the presence of measurement glitches are important, the later leading to undesired beam dumps and the consequent loss of physics time.

The FBCCM monitor is based on the fast current transformer and is used to detect fast AC (bunched) current changes which could arise from beam losses or debunching. In fact beam losses are already monitored by the beam loss monitors and indirectly also by the quench protection system. The FBCCM is thus primarily used to protect from fast beam debunching (RF issues).

Finally, the BSRA is used to monitor the population of particles in the 3 μs long abort gap. Particles that are present in the abort gap are swept over the machine elements at the moment the dump kickers fire. Hence, it is necessary to assure that the number of particles in the abort gap remains below a safe limit. The BSRA is based on the detection of synchrotron light and during run 1 it was not connected to the beam dump system due to its limited reliability.

During run 1 several issues affected the reliability of these devices [1]. Actions have been taken during LS 1 to address these problems.

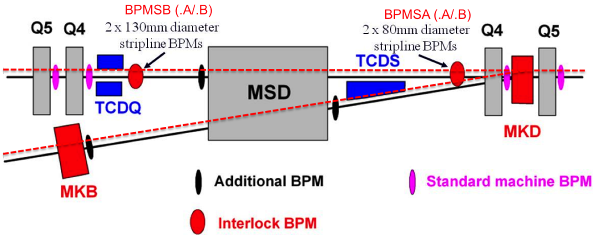

Figure 1: Layout of the beam dump channel.

INTERLOCKED BPMS IN IR6

The BPMs consist of strip-line pick-ups installed just after the Q4 quadrupole (originally named BPMSA and renamed to BPMSX after LS 1) and just before the TCDQ absorber (BPMSB, renamed to BPMSI after LS 1) [2]. Each monitor is doubled for redundancy and is referred to as system A or system B. The signal acquisition is based on the standard LHC normaliser design [3][4], but with a custom firmware adding the interlocking features. The whole interlock logic is made in hardware (and firmware) and is connected to a maskable input of the beam interlock controller (BIC).

The interlock logic requires that either 70 bunch readings out of the last 100 turns are out of limits (protecting against single bunches with large excursions) or that 250 readings in the last 10 turns are out of limits (protecting against fast orbit excursions). The limits are set at 3 mm [5].

The normaliser triggers a position acquisition every time a signal pulse larger than a given threshold is detected at its input (asynchronous acquisition). Unfortunately, if the pulse amplitude is close to the threshold the read position is quite inaccurate and can trigger the interlock. Moreover, the use of shorted strip-line detectors as pick-ups implies the presence of re-reflections in case of not perfect matching at the electronics end. In the initial design two remotely selectable detection thresholds had been included, one for the pilot bunch and one for the nominal bunches. In real operation, however, the intensity distribution of the bunches is far from uniform and it was impossible to find threshold levels accommodating all the possible signal amplitudes and the corresponding reflections.

The situation was further complicated by the need to use the same threshold values for both the proton and the heavy ion runs where the bunch intensities are quite different.

The software tools available to the operators to study the interlock events was insufficient, making it difficult to understand whether the interlock fired due to real beam oscillations or just the aforementioned quirks.

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[*] With run 1 we refer to the LHC running period 2009-2013.

Actions on BPM interlock during LS 1

During LS 1 several actions have been carried out on the BPM interlock system, in particular the shorted strip-lines have been modified and now have proper 50 Ω terminations reducing the re-reflections (Fig. 3). For the same purpose absorptive low-pass filters, with a cut-off frequency of 100 MHz, have also been added at the pick-up output. The orbit and interlock functions have been separated and are now handled by two different acquisition boards. This action frees resources for the post-mortem data of the interlock function, allowing a history buffer of 3564 bunch slots over 294 turns. The FESA server will be adapted to this new structure and to the new firmware (also the ppc VME CPUs have been replaced with x86 modules). A GUI for the analysis of the BPM interlock post-mortem data is now under development in BI with the collaboration of OP. Figure 2 shows the main modifications to the BPM interlock system during LS 1.

All the BPM DAB acquisition cards are now installed inside thermal controlled racks since rather large temperature drifts perturbed run 1. However, this change is more important for the orbit system than for the BPM interlock.

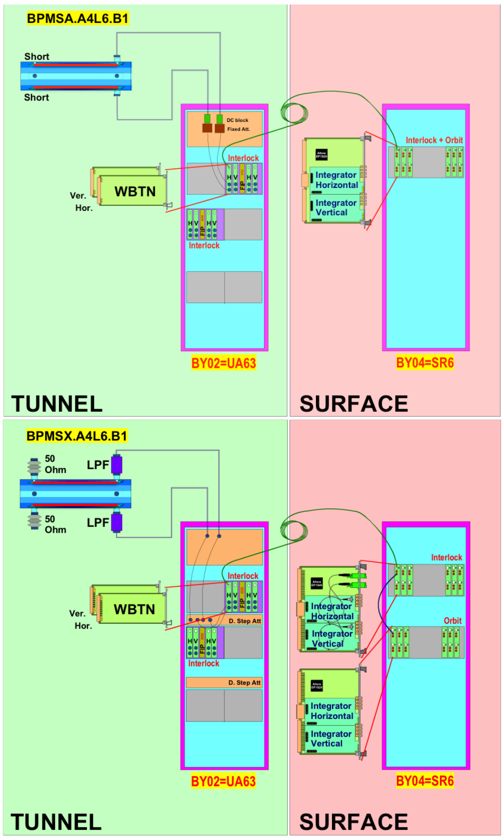

Figure 2: Changes made to the interlocked BPM system during LS 1. The top picture shows the situation during run 1 while the bottom picture shows the situation after LS 1.

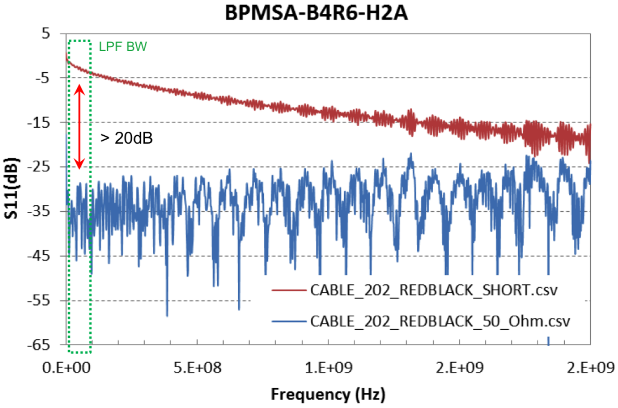

Figure 3: Reflection amplitudes for the shorted strip-lines (red curve) and for the 50 Ω terminated ones (blue curve). By matching the downstream ports of the strip-line and limiting the bandwidth to 100 MHz, reflections amplitudes (S11) are reduced by 20 dB.

BPM interlock after LS 1

The modifications of the pick-ups allow the extension of the operational range of the normaliser card for each sensitivity mode by about 10-15 dB as shown in Fig. 4. Nevertheless, since the pilot bunches are usually lost during the proton physics cycle, it is necessary to keep the two sensitivity modes and to set the detection threshold of the low sensitivity mode above the intensity of the pilots (values to be defined with OP and the machine protection team). This means that for the proton physics there will be little change compared to run 1. The main advantages will be in the post mortem analysis and in the heavy ion physics (like Pb-Pb and Pb-p) where the high sensitivity mode can now cover easily the required range.

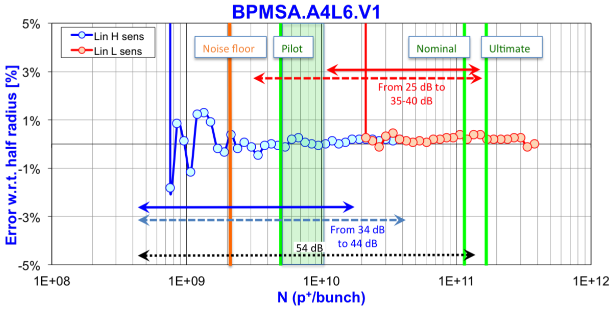

Figure 4: Position error vs. signal amplitude for the post LS 1 situation. The red curve shows the low sensitivity response, while the blue curve shows the high sensitivity case.

BPMs and scrubbing dublets

The electron cloud phenomena, caused by secondary electrons released from the beam pipe surface, may induce instabilities in the closely spaced proton bunches and constitute an excessive thermal load for the cryogenic system. Beam scrubbing is an effective way of reducing the secondary emission coefficient of the beam pipe surface and thus reducing the e-cloud effect. Unfortunately, the effectiveness of the scrubbing decreases as the secondary emission yields decreases, meaning that it takes a very long time before the emission coefficient is reduced below the e-cloud threshold. The effectiveness of the scrubbing can be increased by reducing the bunch spacing. This is one of the reasons why in run 1 the scrubbing was done with 25 ns beams and the subsequent physics with 50 ns bunch spacing. Although the emission coefficient obtained after scrubbing was not below the threshold for 25 ns operation, it was for 50 ns. After LS 1, running at 50 ns will have negative implications due to the large pile-up in the experiment. In order to efficiently scrub the LHC for 25 ns operation, it has been proposed to use the so called *doublets*, i.e. sequences of bunches with 5 and 20 ns spacing. This is obtained by capturing trains of 25 ns bunches across two RF buckets in the SPS [6]. In order to use this new scrubbing scheme it is important that the various LHC devices can cope with the doublets beam. In particular it is important that the orbit and BPM interlock systems can give reliable information. Computer simulations and laboratory tests have been performed to study the response of the BPM system to the doublets pattern. Figure 5 shows the results of these simulations. For the arc BPMs the largest error is 0.4 mm and stays below 0.2 mm for high intensity bunches, while for the interlocked BPMs the error can be as large as 1 mm, reduced to 0.5 mm for high intensity bunches. In both cases the error shows a maximum exactly at 5 ns spacing which is the spacing of the doublets. Nevertheless, if these values are confirmed with beam it should not prevent from scrubbing the LHC with doublets.

FBCCM

The fast current change monitor is a device that detects rapid changes of the bunch currents. The system, as already mentioned, is based on the current measurements provided by the fast beam current transformers (FBCT aka BCTFR). Figure 6 shows the schematics of the FBCCM signal processing.

The signal from the FBCT is first digitised, then a narrow-band band-pass-filter (FIR) and an IQ-demodulator are used to extract only the 40 MHz component of the signal. The variations over time of each 25 ns bin are computed using six different integration windows (running sums) corresponding to: 1, 4, 16, 64, 256 and 1024 turns and compared with energy dependent threshold values.

If any of the computed delta is above the corresponding threshold, the interlock output is fired pulling the BIC channel (initially masked during the commissioning phase). The thresholds are stored in a lookup table which is addressed using the beam energy from the LHC timing telegram (MTG).

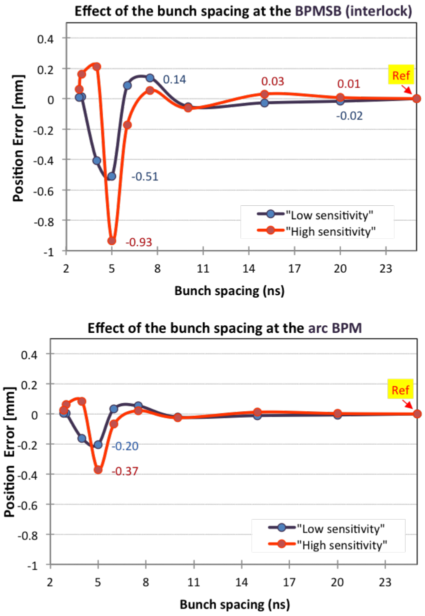

Figure 5: Measurement error as function of the *doublets* bunch spacing. The top plot refers to the strip-lines of the interlocked BPMs, while the bottom plot refers to the arc button BPMs.

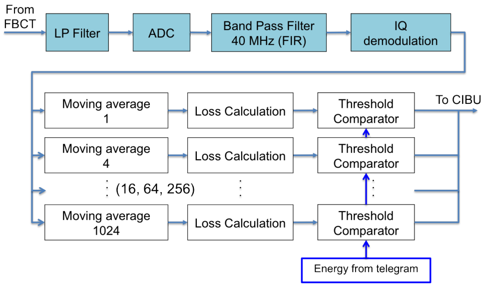

Figure 6: Schematic diagram of the signal processing inside the FBCCM monitor.

The system is contained in a box to which the bunch clock, the Master Timing Generator (MTG) and the FBCT signals are fed. The control of the parameters and the readout of the data takes place over a TCP connection (ethernet).

FBCCM modifications during LS 1

Two similar firmware implementations of the FBCCM have been tested during run 1. One of the two designs has been retained without significant modifications. The electronics cards on the other hand have been consolidated with the replacement of development boards by custom made boards. The FBCCM boxes have also been split with only one channel per box in the new version in order to eliminate the observed crosstalk. The hardware modifications have also reduced the noise, mainly by better separating the analogue and digital parts. A picture of the new FBCCM box can be observed in Fig. 7.

Figure 7: Picture of the operational FBCCM electronics box.

Another limitation of the FBCCM observed in 2011 was the position dependency of the fast beam current transformers. This issue resulted in orbit oscillations mistakenly identified as fast current variations. This problem has also been studied during LS 1 and two possible solutions have been identified: a CERN developed wall current monitor (BCTW) and a CERN/BERGOZ integrating transformer (BCTI). Both solutions can potentially solve the issue and will be tested in parallel after LS 1.

FBCCM after LS 1

Six FBCCM acquisition boxes have been produced. Four will be installed in LHC and two kept in the lab for tests and spare. Of the four installed devices, two will be the operational devices (one per beam, identified as systems A) with stable hardware and firmware and will be connected to the LHC FBCT monitors. The other two (systems B) will be used for debugging and development and will be connected to the alternative fast current monitors under development, the BCTW and the FBCTI respectively. Similarly, for the fast current transformers the run 1 devices will remain the operational devices (system A), while the BCTW and FBCTI will be used on system B for development. The FBTCI will be installed on beam 1, while the BCTW on beam 2. The devices are installed in a way that allows switching between FBCTI and BCTW without breaking vacuum.

A FESA class and the relative expert GUI have been produced, while the post mortem analysis tool is still being worked on in collaboration with OP.

As already mentioned, the FBCCMs will be connected to the beam interlock system (BIS), but the relative BIC channels will be initially masked allowing the collection of trigger statistics. After the commissioning and validation phase the mask will be removed and the FBCCM will become part of the machine protection system.

Some beam time will be needed for the commissioning of the FBCCM, mainly for repeating and validating the tests performed in the lab, requiring controlled losses, beam scraping etc. Most of the debugging and setting up can be carried out in parallel with the normal operation of LHC. The possibility of carrying out realistic beam simulations in the lab is also under investigation.

ABORT GAP MONITOR

The abort gap monitor is based on an MCP-gated-photomultiplier-tube measuring the intensity of synchrotron light (SL) emitted by the beam during the abort gap [8]. The abort gap itself is a 3 μs long gap in the longitudinal distribution of the particles in LHC that has to be kept ”empty” in order to allow the safe firing of the extraction kickers. Any particle inside the abort gap is, due to the rising edge of the dump kicker, only partially deflected and will be lost somewhere around the ring instead of being sent to the dump. If the number of these particles is too high damage can be caused to the accelerator components or to the experiments.

The initial specifications of the instrument did not demand high grade reliability since the device was foreseen only as a monitor not connected to the beam dump system. Only an alarm had to be generated for the control room operators, if the level of particles in the gap exceeds a certain threshold.

The abort gap population is published and logged at 1 Hz. The measurement accuracy depends on the SL intensity and thus on the beam energy ($I_{\rm SL} \propto E^4$). For protons the sensitivity is better than 10% of the quench level for all energies (fulfilling the specifications). For lead ions, however, the specifications can only be fulfilled above 1.5 TeV, since the amount of light at lower energies is too low and a new undulator would be needed to improve on this [9]. If properly calibrated the accuracy of this monitor is much better than the 50% requested in the specifications.

Reliability of the BSRA

The main source of error is the stability of the various calibration factors. These factors are influenced by: the alignment of the optical elements in the telescope, the attenuation of light in the different components, the gain-voltage curve of the PMT, the stability of the HV generator, the ageing of the photocathode of the PMT and finally the electromagnetic noise in the signal.

The BSRA is part of the synchrotron light telescope and there are a few compatibility issues that reduce its reliability. The Beam Synchrotron Radiation Telescope (BSRT) consists of a rather complex optics system in order to measure the transverse beam size precisely and is still in constant evolution. In 2012 an RF heating problem on the extraction mirrors has been discovered. This problem has become very serious with the increase of the beam intensity during the run, requiring the replacement of the damaged in-vacuum mirrors. The mirror heating problem has been carefully addressed during LS 1 with extensive RF computer simulations, test bench measurement and mechanical redesign. A completely new extraction mirror layout has been developed and installed. According to the simulations and the test bench measurements no heating issues are expected after LS 1, it has however to be noticed that the confidence level of the RF simulations is not very high, due to, among other reasons, the difficulty of simulating the thin multilayer reflecting coating of the mirrors.

The optical system of the BSRT has been completely redesigned during LS 1 in order to move the working point to lower wavelengths as compared to run 1. This modification is necessary to cope with the higher beam energy and the resulting smaller beam size. In the redesign particular care has been given to the abort gap and longitudinal density monitors (BSRL, better known as LDM) integration, reducing the interferences between the different systems to the minimum.

BSRA after LS 1

Concerning the BSRA, the most important change during LS 1 is represented by the redesign of the BSRT extraction mirror and of the optical telescope setup. Another important action has been the review of all the calibration and verification procedures of the BSRA. A document describing these actions and the way these should be implemented in the FESA server, with particular emphasis on the reliability aspect, has been produced and will constitute the base for a refurbishing of the software layer [10]. The new FESA server will include several automated calibration and self-test procedures as well as a dedicated interlock property. It is foreseen to trigger self checks from the LHC sequencer and verify the health of the system at the start of every cycle. The interlock property will be used by the SIS to trigger the cleaning of the abort gap or to trigger the beam dump. Figure 8 shows the logic that will be implemented in the interlock property.

Another action during LS 1 has been the redesign of the electronic acquisition chain of the BSRA. The fast linear amplifier and the DAB integrator will be replaced by a custom integrating amplifier and a 100 MHz ADC FMC module. This change should allow a reduction of the noise level and thus an increase in sensitivity of the BSRA. The new electronics will probably not be deployed for the LHC startup as it looks difficult to completely validate the hardware and the software in time.

CONCLUSIONS

The limitations observed during run 1 and the actions taken during LS 1 for the interlocked BPMs in IR6, the FBCCM monitor, and the abort gap monitor have been presented together with the expected performances after LS 1.

The BPMs should not be a performance limit after LS 1. The detection threshold level of the low sensitivity mode has to be defined together by BI and OP.

A full set of FBCCM monitors will be available after LS 1. The prototypes gave encouraging results. Some debugging and fine tuning will be needed during the commissioning phase requiring dedicated beam time.

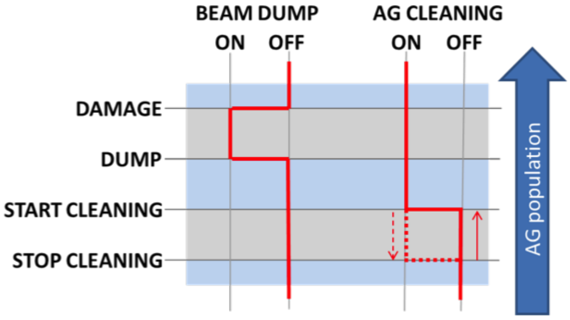

Figure 8: Abort gap cleaning and beam dump logic implemented in the BSRA FESA server. The four thresholds will be defined by the machine protection team.

The reliability of the BSRA will be improved as well as the sensitivity. The system will include self-diagnostic and calibration procedures and will be connected to the SIS for triggering the abort gap cleaning and eventually the beam dump if needed.

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