Experiences with MPS related systems and foreseen improvements for LS1

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Abstract

This paper will focus on three instruments with implications for machine protection, namely: the abort gap monitor, the DIDT (current transformer) and the interlocked BPMs in IR6. For each of these instruments the current status will be presented, including existing performance and reliability issues as well as statistics and nature of failures observed during LHC RUN 1 (2010-2012). The plans for modifications and improvements during LS1 will also be presented highlighting the impact on performance and reliability alongside with the resources requirements to carry them out.

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 (DIDT) and the Abort Gap Monitor (AGM). 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 DIDT 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 DIDT is thus primarly used to protect from fast beam debunching (RF issues). The DIDT monitor is not yet connected to the beam dump interlock as it is still in development.

Finally the AGM 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 AGM is based on the detection of synchrotron light and is not yet connected to the beam dump system due to its limited reliability.

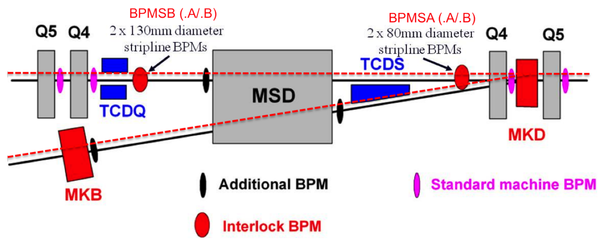

Figure 1: Layout of the beam dump channel.

INTERLOCKED BPMS IN IR6

The BPMs consist of shorted-strip-line pick-ups installed just after the Q4 quadrupole (BPMSA) and just before the TCDQ absorber (BPMSB). 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 design [1][2], 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 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 as explained in another presentation at this workshop [3]. It should be noted that the interlock is based on simple integration windows and not sliding integration windows and the interlock status is re-evaluated at the end of each integration cycle.

As for the other warm parts of the LHC, long coaxial cables are used to bring the electrode signals to the acquisition electronics (normalizer). As will be shown the long cables are at the origin of the main issue with this system. In fact, reflections at the normalizer side are totally re-reflected at the electrode side (short circuit) and can trigger false acquisitions if the amplitude of the reflection is above the detection threshold. The reflections are about 27 dB below the real signal meaning that the reflections from a nominal bunch (1.1 10^{11} protons) are stronger than the signal from a pilot beam (5 10^{9} protons). For this reason the detection threshold can be remotely switched, by the operators (and the LHC sequencer), between two hard wired values, one for low intensity beams like the pilots (*high sensitivity* mode) and one for high intensity beams (*low sensitivity* mode). The lower threshold allows pilot bunches to trigger the BPM acquisition while the higher threshold avoids that reflections from the nominal bunches trigger spurious acquisitions.

BPM interlock for the proton run

During the 2011 run the physics fills were often terminated by the BPM interlock when the weakest bunch approached $4\ 10^{10}$ protons; at this intensity level the position measurement became unreliable and produced unneeded beam dumps. In order to remove this limitation the attenuators installed on the strip-line signals have been reduced (shifting the curves in Fig. 2-top to the left). Due to errors in the documentation a few iterations were required to achieve the correct attenuation values. After this change the physics fills were no longer perturbed by the BPM interlock.

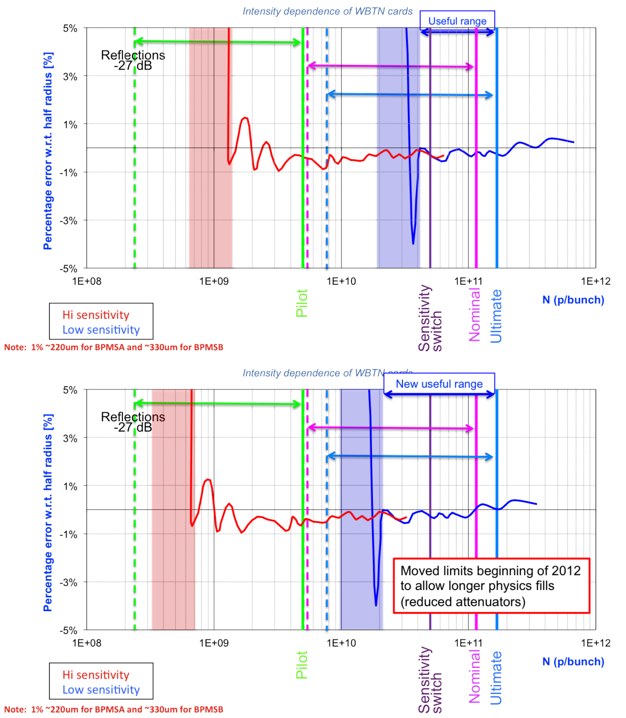

Figure 2: BPM error vs. bunch intensity for the two sensitivity modes. The left edge of the shaded areas corresponds to the detection threshold while the width represents the non-linear response region. The solid lines represent the intensity of specific bunch intensities, while the dashed lines represents the intensities of the reflected signals. The top plot shows the situation in 2011 while the bottom plot shows the situation at the beginning of 2012.

BPM interlock for the proton-lead run

With the change of attenuators a new problem was introduced; the overlap region between high sensitivity mode and low sensitivity mode fell now right around the intensity needed for the p-Pb run. In this configuration the nominal bunch signal sits just in the non-linear region in low sensitivity mode while in high sensitivity mode it is the reflection of the signal that sits in the non-linear region. This was discovered during p-Pb setup MDs at the end of 2012.

In order to correct this new problem the attenuators were changed again during the Christmas break as can be seen in Fig. 3 (only the high sensitivity mode is used in p-Pb runs).

Again the change solved one problem, but introduced a new one. The lower intensity limit of the BPMs after the change corresponded to about $4\ 10^{9}$ charges with the consequence that almost all p-Pb physics fill have been dumped by the BPM system. Seen that the BPM interlock fired after the luminosity had already decayed to modest values it was decided not to intervene again.

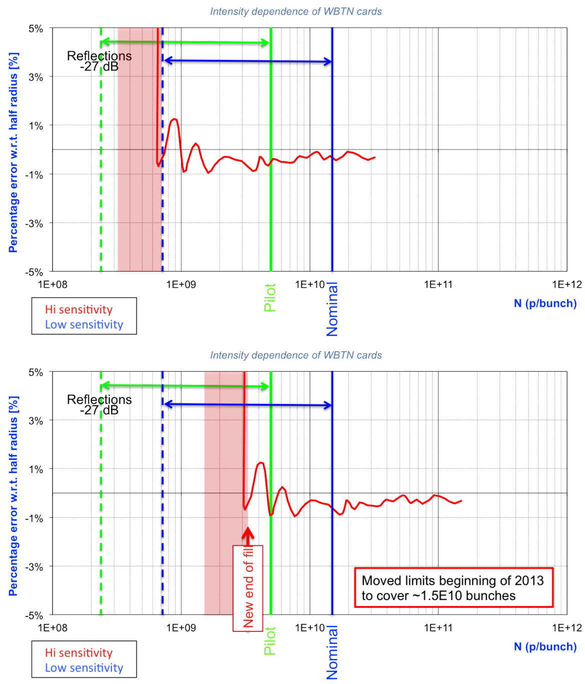

Figure 3: BPM error vs. bunch intensity during the p-Pb run. The top plot shows the situation at the end of the p-p run while the bottom plot shows the situation at the beginning of 2013.

Situation and outlook

The reflection/detection threshold problems have been aggravated by the fact that the software tools available for the analysis of a BPM induced dump event were not adequate. In fact only experts were able to find out what happened and verify if a dump was a spurious trigger due to reflection, weak bunch or real orbit excursion. Moreover every attenuators modification requires a lengthy validation process using beam scraping. During the 2012–2013 run there have been 158 dumps triggered by the BPM interlock. Of these dumps 1 was in SETUP mode, 120 in INJECTION, 3 in FLAT-TOP, 2 in RAMP, 3 in ADJUST and 29 in STABLE-BEAMS of which 22 during the p-Pb run. It has to be noted that the BPM interlock always acted as needed in presence of a real excessive orbit excursion.

In order to mitigate the spurious dumps, to simplify the threshold level changes and to make the system more user friendly, several actions are under study for LS1.

First of all, filters providing 50 Ω impedance both on the input and output ports will be installed right at the electrodes connector. This will avoid the total reflection at the electrode side and thus reduce the overall amplitude of the reflections, extending the usable range of the high sensitivity mode. Theoretically, if reflections could be completely removed, a single sensitivity mode could cover the whole operational range ($1\ 10^9$–$3\ 10^{11}$ protons or about 50 dB). In reality it will be impossible to achieve this result, the exact extent of the improvement can only be quantified by measurements on the real system.

Another measure being investigated is the replacement of the two fixed threshold levels by a programmable DAC. This will have the same effect of changing the attenuators, but can be done remotely via a dedicated control parameter. This modification requires an adequate handling of the threshold values (like the BLM thresholds.)

The normalizer card will also be improved trying to reduce the position error in the non-linear region near the threshold value.

On the software side an effort will be made to improve the diagnostics and event analysis. This will require some changes at the firmware level and possibly also a change in the hardware if the memory present on the acquisition cards proves not to be sufficient. OP should also be involved in this process since a new GUI may be needed. Certainly the diagnostics and analysis tools will be less important after LS1 if the improvements of the system reduce the number of spurious triggers.

DIDT

The fast current change (i.e. dI/dt) monitor (DIDT) 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 4 shows the schematics of the DIDT signal processing.

The signal from the FBCT is first digitized, 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 of the 40 MHz component are then 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 values is above the threshold, the interlock output is fired pulling the corresponding BIC channel (currently not connected). The thresholds are looked up in a table using the energy values distributed on the LHC timing telegram (MTG).

The system is contained in a box (Fig. 5) to which the bunch clock, the Master Timing Generator (MTG) and the FBCT signals are fed. The control of the parameters and the read-out of the data takes place over a TCP connection (ethernet) as can be seen in Fig. 6.

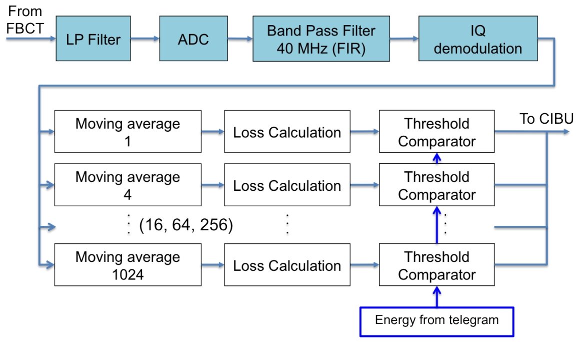

Figure 4: Schematic diagram of the signal processing inside the DIDT monitor.

Two different implementations have been tested in 2011. The two systems shared the same hardware design, but differed in the FPGA firmware. One system was based on a CERN developed firmware while the other came from a private company based on the Fast Magnet current Change Monitor (FMCM).

The CERN version was able to monitor the signals for both beams (GUI for online monitoring available and data logged in the database) while the other system was only available for one beam (no online monitoring available and data logged only locally on a PC). This allowed to test and compare the two implementations showing equivalent results.

The noise floor (i.e. the threshold below which the spurious triggers become relevant) is of about $2\ 10^{10}$ protons, but because of losses at injection the lowest *usable* limit is 0.3% of the full machine ($7\ 10^{11}$ protons). The injection losses will be masked by the data processing in the next version of the firmware and then the limit will be dominated by the performance of the FBCT, in particular by the position sensitivity of the FBCT. For the CERN system a small cross talk between beams of the order of 30–40 dB was also observed.

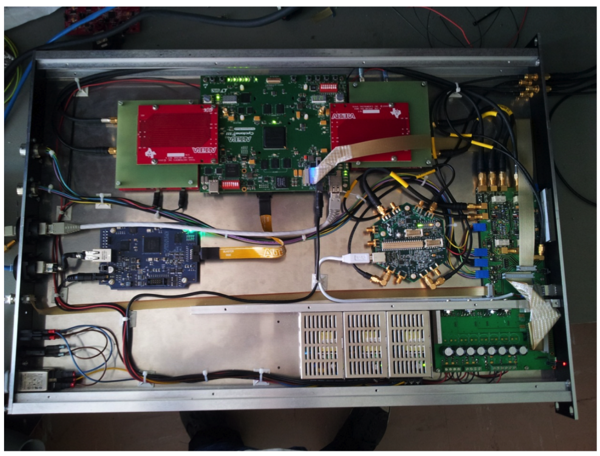

Figure 5: Picture of the prototype DIDT monitor.

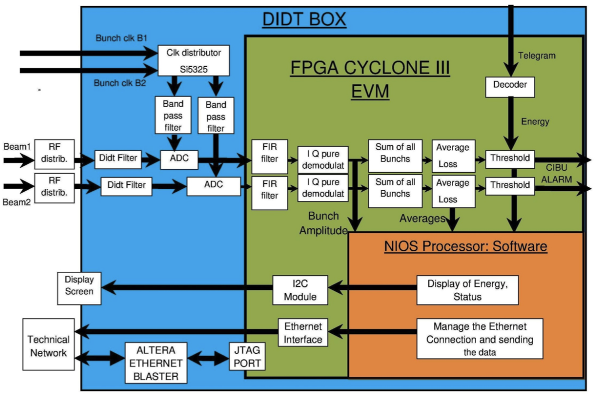

Figure 6: Layout of the DIDT monitor.

Plans for LS1

At the moment the DIDT electronics consists of a box containing several off-the-shelf boards. It is foreseen to design a new single PCB board that integrates all the different functions. This will allow the proper separation of analog and digital signals and reduce the electronic noise of the analog processing part, which is mainly caused by crosstalk from the digital part.

In order to eliminate the cross talk between beams each box will only be used to process the signals of one beam. In total six new boxes will be produced during LS1, two for B1, two for B2 and two spares, therefore each beam should be equipped with two redundant DIDT monitors for the start-up. For each beam, one DIDT will be connected to the existing FBCT and one to a new BCT.

The FBCTs themselves will be improved during LS1 with the aim of reducing the dependency on the beam position. At the moment this is considered the main limitation of the new DIDT monitors. Two different solutions are being investigated: BERGOZ ICT [4] and CERN inductive pick-up. The two monitors will be tested in the lab once ready and the one giving the best results will be deployed on system B (system A remains unchanged).

New software for the control and acquisition will also be developed during LS1. It is foreseen to have the complete and operational systems ready for the startup.

ABORT GAP MONITOR

The Abort Gap Monitor (AGM aka BSRA) is based on an MCP-gated-photomultiplier-tube measuring the intensity of synchrotron light (SL) emitted by the beam during the abort gap [5]. 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 a high reliability since the device was foreseen as a monitor, and not to be connected to the beam dump interlock. Only an alarm had to be generated for the control room operators if the level of particles in the gap surpasses a certain threshold. The AGM is part of the synchrotron light telescope and there are a few compatibility issues that reduce its reliability.

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 ($I_{SL} \propto E^4$). 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 [6]. The relative error of this monitor is below 50% which is adequate to its use.

Reliability of the AGM

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 and the stability of the HV generator, the aging of the photocathode of the PMT and finally electromagnetic noise in the signal.

The Beam Synchrotron Radiation Telescope (BSRT) consists of a rather complex optics system in order to measure the transverse beam size precisely. This complexity has an impact on reliability by itself, even more considering that the BSRT is still under development with frequent and constant modifications in order to improve the resolution (which is still insufficient). In 2012 the BSRT has been simplified considerably by replacing a complex focusing mirror setup with achromatic lenses. The positive effects of these changes have been visible also on the reliability. The layout of the two versions of the BSRT is shown in Fig. 7.

Another appreciable step forward was the identification of an important problem of the BSRT. It was discovered in 2012 that the synchrotron light extraction mirrors (in vacuum near the beam) were overheating up to the point of damage. The heating induced deformations in the extraction mirrors with consequent loss of optical resolution and instabilities in the pointing of the mirror.

Furthermore, a non optimized software package was also contributing to the loss of reliability. The present software has few automatic adjustments and requires frequent interventions by experts, and is not always intuitive. In many occasions human errors during the calibration procedure or in the programming of the acquisition parameters caused down times of the AGM.

Finally, some still unexplained jumps of the distributed turn clock occurring after a technical stop caused the AGM to publish wrong values.

Changes in the BSRT telescope layout

As already mentioned, during 2012 the BSRT telescopes were heavily modified. This was done in an attempt to simplify the system, increase the stability and hopefully improve the optical resolution as a consequence (sensitivity to vibrations). The change consisted in moving from a reflective imaging system (reflector) to a refracting imaging system (refractor).

The disadvantage is that chromatic aberration are introduced, this effect was however studied and turned out not to be important because the BSRT operates using narrow band filters. With this modification the optical delay line at the entrance of the telescope, which has always been difficult to align and operate, could be removed. The optical delay line was needed to adjust the focus of the imaging system from the undulator to the dipole, task now accomplished by moving a lens. The two mentioned synchrotron radiation sources are about three meters apart.

With the present design there is no moving component before the AGM apart from the steering mirror (which is needed by the AGM as well).

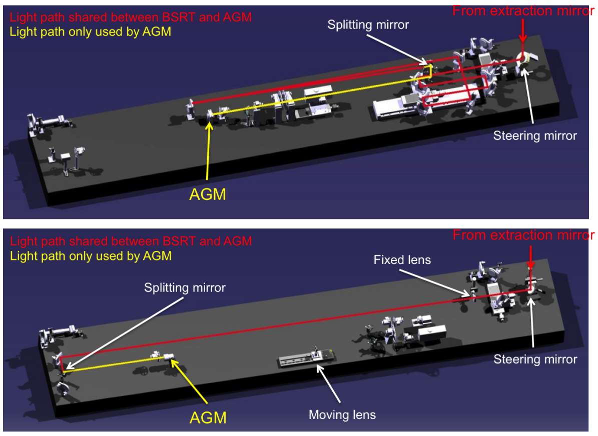

Figure 7: Old BSRT layout (top) and new (bottom). The red lines indicate the light path in common between BSRT and AGM while the yellow lines indicate the optical lines private to the AGM.

Plans for LS1

The main task for LS1 is to solve the problem of the heating mirrors. Several options are under investigation and a new solution should be ready for implementation soon. This task involves several people from different groups in different departments (BI, ABP, RF, VSC, MME and MEF) as the RF heating, optical properties, vacuum properties and mechanical constraints have to be considered at the same time. We will also take the opportunity to consolidate the installation as many changes were made in the short technical stops with no time for the polishing details.

The other big change will come from software improvements. We will try to reduce to a minimum the need for external interventions by adding automated calibration features, watch dogs, self tests, proper recovery from unexpected situations, and management of the alarms.

AGM after LS1

There will be no noticeable change in sensitivity as this is dominated by the light source and no change is foreseen here. The AGM hardware, excluding the part in common with the BSRT, will receive very little modifications, apart from a minor consolidation of the installation, as the AGM hardware has never been the cause for the problems.

Nevertheless we expect a substantial system stability improvement by: reducing the possibility of loosing the beam spot on the BSRT, obtaining more stable calibration factors/curves, and by introducing much more intelligence in the software controlling the acquisition, rising alarms when needed, but only when needed. To this extent a specification document is being written and will be circulated for comments among all the stakeholders before starting the ”coding” work.

CONCLUSIONS

The present status and limitations of the interlocked BPMs in IR6, the DIDT monitor, and the abort gap monitor have been presented together with the measures being taken by the BI group to improve the systems.

The BPMs should not be a performance limit after LS1. For this it is important that BI, OP and MPP work together and validate the proposed changes.

A full set of DIDT monitors will be available after LS1. The prototypes gave encouraging results, probably some debugging and fine tuning will be required going for the final systems.

The reliability of the AGM will be improved and although there will be no changes in performances, the system should become much more reliable and in particular self-diagnosing.

REFERENCES

[1] E. Calvo et al, “The LHC Orbit and Trajectory System”, DIPAC 03, Mainz, Germany, 2003.

[2] D. Cocq, “The Wide Band Normaliser: a New Circuit to Measure Transverse Bunch Position in Accelerators and Colliders”, Nucl. Instrum. Methods Phys. Res. A 416, 1998, 1.

[3] B. Goddard, ”LBDS protection,” these proceedings.

[4] `http://www.bergoz.com/index.php?option=com_content&view=article&id=56&Itemid=471`

[5] S. Bart Pedersen et al., “First Operation of the Abort Gap Monitors for LHC,” IPAC’10, Kyoto, May 2010, WEPEB072.

[6] A. S. Fisher, “Expected Performance of the LHC Synchrotron-Light Telescope (BSRT) and Abort-Gap Monitor (BSRA),” CERN-LHC-Performance-Note-014, Geneva, March 2010.