RUN 2 OVERVIEW OF THE LHC BEAM INSTRUMENTATION

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Abstract

This papers reviews the implemented improvements, operational experience, and performance reach of the major LHC Beam Instrumentation systems, excluding transverse beam profile diagnostics, throughout the LHC Run 2. The major hardware and software changes since the Long Shutdown 1 (LS1) are highlighted and the main actions addressing the remaining open issues during the Long Shutdown 2 (LS2) are listed. An outlook for the post-LS2 commissioning is provided based on the experience gained during the Run 2 commissioning period.

BEAM POSITION MONITORS

Orbit Measurement system

The beam orbit in the LHC is measured using 1070 Beam Position Monitors (BPM) making it the largest such an installation in the world [1]. The system provides beam orbit data at 25 Hz with a resolution of a few micrometres. The long-term reproducibility of the measurements, shown in Fig. 1 is in the order of 50 µm which is a combination of the stability of the BPM system itself, ground motion and other similar effects.
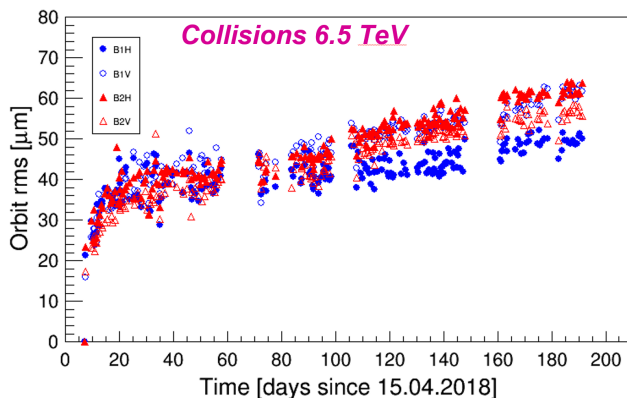

Figure 1: Stability of the LHC beam orbit measurements in 2018.

The LHC orbit measurement system is based on Wide-Band Time Normalisers (WBTN) [2] installed in the LHC tunnel. The WBTN cards are connected through long optical fibres to analogue integrator cards installed on the surface. Even though such a system architecture proved to be well adapted for the LHC, the system has revealed a few important limitations over its operation.

Primarily, the measurements need to be corrected for the injected bunch pattern [3]. This has been achieved by calibration carried out before each LHC fill. However, the residual error due to the bunch pattern dependence is in the order of 50 µm.

The analogue integrators are also very sensitive to ambient temperature changes [4]. This limitation has been mitigated by installation of thermalised racks maintaining the integrators' temperature within ±0.2 °C. Nevertheless, the remaining beam position measurement error is at the level of 50 µm.

Throughout the Run 2, the LHC orbit measurement system saw a number of improvements. The so-called "dancing" BPM issue of channels providing spurious readings was identified to originate in wrong positions of hardware switches on the electronic cards which were corrected. Moreover, a "synchronous orbit" measurement mode was introduced to cope with bunches of very different intensities during proton-ion fills of the LHC. Also the firmware saw multiple changes fixing discovered bugs and providing more stability and maintainability of the code. Lastly, a testbed was developed to allow validating changes introduced to the system before beam commissioning.

During LS2, there are no major activities foreseen on the LHC orbit measurement system with the large consolidation project foreseen not before LS3.

Beam Position Interlock

The beam position interlock consists of 8 dedicated BPMs installed in LHC IR6. The system provides real-time bunch-by-bunch positions and is designed to be fail-safe.

The existing system is based on the same electronics as the orbit measurement system and, therefore, it faces the same constrains. Moreover, due to the interlock specificity, there are two additional important limitations of the system.

Firstly, the measurement sensitivity must be chosen according to the existing beam conditions. In some cases, when the intensity of a pilot bunch is relatively high, this might lead to spurious readings and result in a false beam dump.

Secondly, the existing system is incompatible with a doublet operation whereby there are two bunchlets spaced by 5 ns within a single 25 ns bunch slot.

Both of the above issues are being addressed by a new beam position interlock system currently under development [5]. The new solution will be based on modern digital signal processing, will operate without gain-switching within an LHC fill, and it will be compatible with a doublet operation. The position measurement resolution goal is set to be below 200 µm. A vertical slice test of the new system is planed for the LHC Run 3.

DOROS System

The Diode Orbit and Oscilation system (DOROS) is a set of alternative acquisition electronics for BPMs [6]. It was originally designed for the BPMs embedded in the LHC collimators, but it is currently installed also on 40 standard LHC BPMs distributed around the tunnel.

In general, the DOROS system showed excellent performance during the LHC Run 2 and it was routinely used for establishing collisions in the LHC experiments. The main remaining limitation of the system are the residual nonlinearities with beam intensity variations, as shown in Fig. 2. These result in systematic errors up to 30 μm.
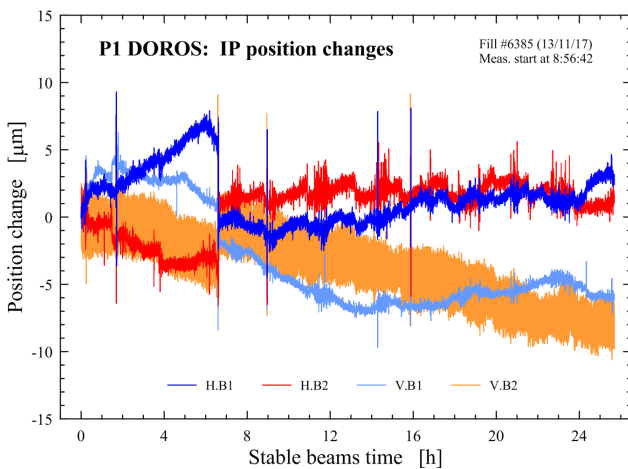

Figure 2: DOROS beam position readings jumps at system gain adjustment.

Throughout the Run 2 the DOROS system also experienced two hardware faults which are believed to be linked to radiation. The sensitive component has been identified and its 100 times more radiation-tolerant replacement has been found. The replacement campaign will take place during the LS2.

Also during the LS2, it is planned to introduce some new functionalities to the system. The data publishing rate will be made compatible with the LHC orbit feedback for a possible future addition to the feedback. Moreover, real-time orbit spectra will be made available for the Q2s in IP1.

BEAM LOSS MONITORS

Main System

There are around 4000 ionisation chamber Beam Loss Monitors (BLM) installed in the LHC as the main beam loss monitoring system. This large, distributed and interlocked system showed generally good performance during the LHC Run 2. There are no know protection critical issues.

The availability of the system has been constantly improving reaching its best in 2018. This is due to diligent fault analysis by the BLM team, as well as preventive interventions carried out in LS1.

Throughout the Run 2, there have been some developments done on the BLM system. It implemented data logging into NXCALS. Historical data migration from CALS is currently ongoing. 700 new processing modules for a future upgraded acquisition system are presently in production to allow a vertical slice test to take place during the Run 3. Together with the EN/SMM group, the BLM team has been developing an irradiation source to be installed on the Train Inspection Monorail (TIM) for checking the functionality of the system without beam as shown in Fig. 3.

Figure 3: Irradiation source installed on the TIM for BLM validation.

During the LS2 approximately 40 % of the BLM channels need to be removed and reinstalled due to DISMAC and other related tunnel activities. Therefore, the system will require a full check-out and an irradiation test campaign to validate the system before beam commissioning in the Run 3.

The Run 3 commissioning will consist of 11 hardware and 3 system tests documented in the appropriate EDMS documents. Also, software migrated to FESA3 and upgraded firmware will need to be thoroughly validated.

Diamond Monitors

The LHC diamond BLMs were developed during the LHC Run 2 to provide bunch-by-bunch loss measurements [8]. They are installed in 10 locations around the LHC tunnel: injection lines, extraction lines, and in the betatron cleaning region.

During early commissioning the system used commercial ROSY boxes for signal acquisition. In 2018, the acquisition chain was replaced with a standardised BI equipment which allowed a much better integration into CERN's controls environment.

The diamond BLMs were the fist BI system to use NXCALS for data archiving. As of the end of the Run 2, the system recorded around 200 days of bunch-by-bunch data, an example of which can be seen in Fig. 4.

Throughout the LHC Run 2, the diamond BLMs proved to be very valuable for LHC operations team. The system features an on-board UFO trigger and was used for scraping studies. Moreover, the diamond BLMs were one of the key instruments for analysis of the 10 Hz beam oscillation observed in 2018.
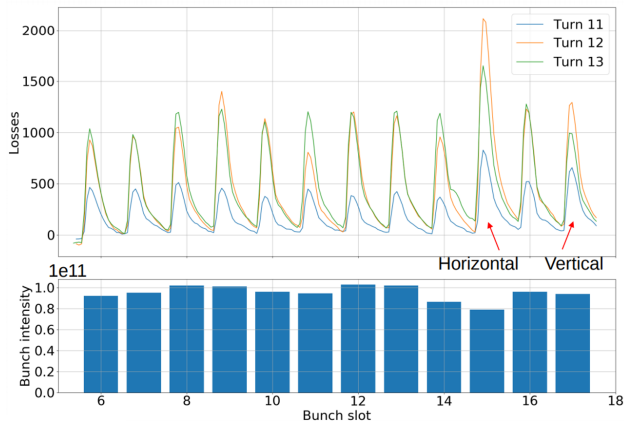
Figure 4: Bunch-by-bunch loss measurements provided by the diamond BLMs.

BEAM CURRENT TRANSFORMERS

Beam Intensity Measurements

The total beam intensity in the LHC is measured by four DC Current Transformers (DCCT) [9] with a resolution of 10^9 particles. In general, the DCCTs are a very stable system requiring a minimal amount of troubleshooting during the LHC operation. Nevertheless, during the LHC Run 2, there have been some developments done to the DCCTs.

Firstly, the acquisition electronics was upgraded to use 24-bit analogue-to-digital converters which allowed the system to operate with a single sensitivity setting compared to the four original sensitivity ranges [10]. This, in turn, simplified preparation of the Van der Meer scans not longer requiring a DCCT expert to manually block the measurement range for the scan duration.

Secondly, based on the experience gained on similar systems in the LHC injectors, the DCCT noise level was reduced by approximately 50 %.

Finally, both software and firmware were upgraded to fix minor bugs and provide more stability to the system.

During the LS2 the vacuum sector where the DCCTs are installed will be baked-out. During this procedure, the DCCTs will need to be protected as the bake-out temperature is far beyond the damage limit of the monitors. There are no other DCCT related interventions planned in the LS2.

Bunch Intensity Measurements

The original LHC bunch intensity measurement system [11] underwent major modifications during the Run 2 due to its limited performance caused by an unwanted sensitivity to the transverse beam position as shown in Fig. 5. The beam pick-ups were replaced by CERN-developed Wall Current Transformers [12]. The original acquisition electronics based on analogue integrators were also upgraded to a digital system [13].

One of the operationally beneficial features brought by the new acquisition electronics is removing the need to manually phase the system with the beam timing. For the old imple-

mentation, this procedure needed to be performed regularly as improper phase setting could lead to measurement errors up to 50 %.

Currently, work is ongoing to develop an absolute calibration system for the bunch intensity measurements. Tests of this system are planned during the LHC Run 3.
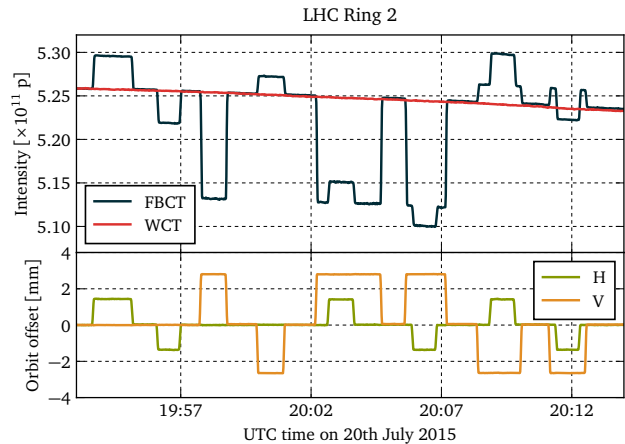

Figure 5: Beam position sensitivity of the FBCT (old system) and WCT (new system).

FEEDBACK SYSTEMS

The beam-based feedback system in the LHC is one of the most complex systems at CERN. It handles over 2000 measurement inputs and controls over 1200 magnets as well as the RF frequency used to generate the accelerating field [14]. Despite its scale and complexity, the system is very stable and caused no major issues during the Run 2.

The system consists of two functional elements: the controller (running the control algorithm) and the service unit (handling all activities related to monitoring, logging and proxying of the controller's settings).

The system has seen major changes since its inception. During the LS1 the service unit was ported to FESA for standardisation. The controller was documented with logging and triggering tasks being improved. During the LHC Run 2 a testbed was developed to allow performing dryn runs before commissioning. Moreover, the same testbed makes it possible to investigate any issues arising during operation in a test environment independent of the operational system.

The feedback system will see a major upgrade during the LS2. The controller will be re-engineered and ported to FESA for standardisation. To improve the post-LS2 start-up, a pre-commissioning test campaign is planned using the developed testbed. Nevertheless, the system will require a full revalidation with beam at the beginning of the LHC Run 3.

TUNE MEASUREMENTS

Tune measurements in the LHC are provided by the CERN-developed BBQ system based on Direct Diode De-

tection scheme [15]. The system is very stable and no major issues have been observed since the LS1.

There were some new functionalities introduced to the system during the LHC Run 2. Firstly, a trigger monitoring the BBQ signal growth rate was added for instability diagnostics. Moreover, firmware was implemented to simplify measuring the Beam Transfer Function (BTF).

There are some remaining limitations of the BBQ. The system is incompatible with the transverse damper operation. This has been mitigated by development of the gated BBQ which measures only the bunches not affected by the damper. Additionally, the system suffers from multiples of 50 Hz visible on the beam spectrum, as seen in Fig. 6. Occasionally, these lines overshadow the real tune signal leading the a wrong reading by the BBQ. A study into the origin of these lines is currently ongoing.
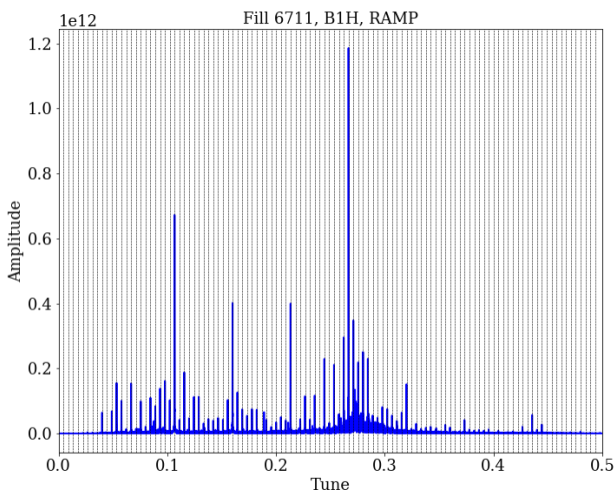

Figure 6: Multiples of 50 Hz visible on the BBQ measurements.

SCHOTTKY DIAGNOSTICS

The LHC Schottky system is capable of measuring tune, chromaticity and momentum spread in a non-invasive way [16]. It is, however, a semi-expert system requiring a considerable amount of fine tuning for non-standard beams. Nevertheless, in some cases it is a turn-key system providing operationally useful measurements without expert tuning, as shown in Fig. 7 for an ion beam before and after the energy ramp.

The system was overhauled during the LHC Run 2. It now features state-of-the-art analogue RF front-end. Also, chromaticity and tune measurements are logged online and are available for the operation team on fixed screens.

There are no major changes planned to the Schottky system in the LS2. Some research is ongoing on benchmarking the measurements provided by the LHC Schottky system against other measurement methods. Moreover, methods are being developed for better processing of the Schottky spectra. Algorithms based on these methods might be im-
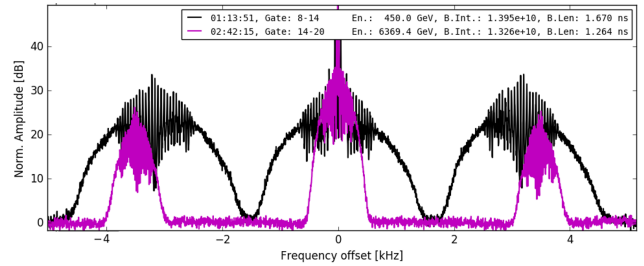

Figure 7: Schottky spectra with an ion beam before and after energy ramp.

plemented into the LHC Schottky system during the LHC Run 3.

BEAM INSTABILITY DIAGNOSTICS

Throughout the LHC Run 2, instability diagnostics proved to be crucial for optimising the machine operation [17].

The head-tail monitor was used extensively for intra-bunch position measurements. Since 2016, it has been triggered via the LHC Instability Trigger (LIST) from the BBQ growth rate trigger. Moreover, since 2017 the head-tail monitor has been also triggered at beam-dump for 16L2 diagnostics.

The head-tail acquisition electronics were upgraded in YETS17/18. The used 8-bit oscilloscopes were replaced by a 10-bit alternative providing a higher resolution, lower noise level and much longer available acquisition time.

Currently, the Multi-Band Instability Monitor (MIM) is under development for improved instability diagnostics. This system is designed to provide real-time data by taking comparative measurements of different parts of the beam spectrum. Based on promising first results, a full deployment of this system is planned during the LS2.

BI AVAILABILITY

Availability in 2018

During 2018 proton physics LHC operation, the BI installations were in fault for 26.3 h [18]. Out of this, 22 h were classified as "root cause" reflecting the effective impact on the LHC operation. These values account for approximately 2.2 % of time the LHC was in fault in 2018.

Most of BI faults in 2018 were one-off failures requiring a long expert intervention, e.g. a BTV screen getting stuck inside the beam-line accounting for 4.7 h of machine downtime.

All BI faults from 2018 were analysed using the Accelerator Fault Tracking system [19]. Steps such as preventive maintenance have been taken to further improve BI availability in the future.

Availability During Run 2

As summarised in Tab. 1, the BI availability has been improving until 2018 when a few long one-off faults happened. Notably, the BLM availability has been steadily improving

throughout Run 2 reaching its best performance in 2018. Among other factors, this is an effect of the preventive actions taken by the BLM team during LS1.

Table 1: Normalised days of operation in fault per BI system over the Run 2

System	2015	2016	2017	2018
BPM	0.083	0.028	0.004	0.030
Interlocked BPM	0.023	0.001	0.000	0.000
BLM	0.248	0.154	0.136	0.080
BCT	0.032	0.012	0.001	0.000
BBQ	0.002	0.000	0.000	0.020
Controls	-	-	-	0.010
Other	0.008	0.001	0.005	0.070
Sum	0.396	0.196	0.146	0.210

CONCLUSIONS

All the major LHC BI systems are fully operational. They are used daily by the LHC operations team and are available for expert use during Machine Development periods. Currently, there are no known major outstanding or blocking issues identified. The availability of the BI systems is constantly improving and the AFT tool is used for fault analysis.

Most of the LHC BI systems experienced some performance improvement during the LHC Run 2 with all non-interlocked systems having been upgraded. For the majority of the BI systems, the LS2 period will be dedicated to maintenance activities. Major upgrades are planned in terms of software and upgrade, especially for the feedback system. Moreover, the BI systems must be aligned with the changes done to the controls infrastructure during LS2.

The risk of blocking issues during the LHC Run 3 beam commissioning period is being mitigated by development and usage of custom built testbeds for pre-commissioning system validation. Nevertheless, some dedicated BI commissioning time is expected to be needed in the beginning of Run 3 to fully validate the operation of all LHC BI systems.

ACKNOWLEDGEMENTS

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