STATUS OF THE BEAM INSTRUMENTATION AT THE LHC

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Abstract

In this contribution, a review of the beam instrumentation status in the LHC 2016 Run is presented. The treated devices are the beam loss monitors based on diamond detectors, the beam position monitors, the wire-scanners, the beam gas vertex detector and the synchrotron radiation monitors. The new features implemented and the issues encountered during 2016's operation will be highlighted for each instrument. Additionally, the interventions and improvements planned for the coming winter shutdown will be discussed.

INTRODUCTION

During the Year End Shutdown (YETS) 2015/1016, several modifications to the LHC beam instrumentation were done, some actions were to tackle the observed limitations in 2015 operation and some were improvements allowing the implementation of new features for these devices. In the following, the beam loss monitors based on diamond detectors, the beam position monitors, the wire-scanners, the beam gas vertex detector and the synchrotron radiation monitors will be discussed. This contribution aims for highlighting the implemented changes, assessing the improvements and listing the remaining issues that will be tackled during the next Extended YETS (EYETS).

DIAMOND BEAM LOSS MONITORS

The existing Beam Loss Monitor (BLM) system using ionization chambers is not adequate to resolve losses with a time resolution below some 10 µs neither to measure very large transient losses, e.g. beam impacting on collimators. The diamond beam loss monitors (dBLM) are therefore complementarily used for beam loss diagnose in the *ns* range time resolution resolving single bunch level beam loss signal, with a dynamic range exceeding 4 orders of magnitude [1]. The diamond beam loss monitors consist of pCVD diamond detectors (10 mm x10 mm x10 mm) with gold electrodes on both sides operated with a bias voltage.

Presently, two readouts are available for these monitors, distributed around the ring as shown in Fig. 1. The first one, based on LeCroy oscilloscopes, is installed for the diamonds in the injection region and the beam dump lines. It offers an output in a “waveform" mode with $2 \cdot 10^5$ samples at 1 GHz. The second one, a commercial system “Rosy" from CIVIDEC, is FPGA-based for on-line, real-time, and dead-time-free data processing. It offers two readings:

- Waveform mode, a buffer of 10^9 samples at a sampling rate of $5 \cdot 10^9$ samples/s.
- Histogram mode, a buffer of $256 \cdot 10^6$ samples with 1.6 ns binning and 1.2 ns time jitter for loss measurements that are synchronized with the LHC revolution period and a beam-loss-based tune measurement for all circulating bunches in parallel.

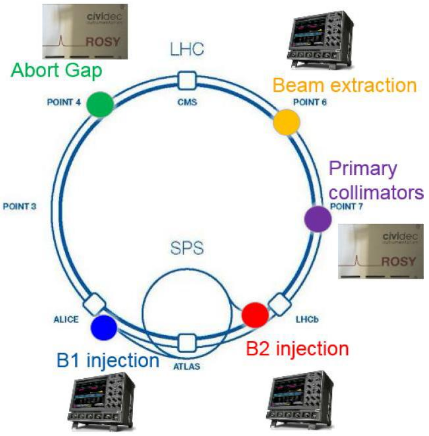

Figure 1: The distribution of dBLM along the LHC circumference, with their main use and their readout system.

On one hand, a FESA class developed in 2016 allows the acquisition of the Lecroy oscilloscopes data synchronized with injections and stores the loss data waveform in the Post-Mortem. On the other hand, expert tools developed in python allows configuring the device and storing the data on EOS servers. Also a GUI is available for offline viewing of these data.

Interesting studies took place during the year to probe the usability of the dBLMs, both during the LHC operation and in special MDs, from losses lasting only few turns up to steady state losses in collision. Alternatively to abort gap monitoring using synchrotron light, tests were carried out to verify the applicability of diamonds for monitoring such a low protons population [2]. Additionally, studies aiming to understand losses at the primary collimators in collisions were carried out. A possibility of using these data for fast UFO busting was also considered. However, the most interesting use of the dBLM, as shown in Fig. 2, was found for injection losses diagnostics where it is a key instrument in identifying the sources of the losses across the accelerators [3].

Therefore, integrating the diamonds in the control system easing the access and the use of the diamonds data is of big interest since it would improve the operation.

After the present YETS, since no change to the infrastructure is foreseen, the bunch-by-bunch losses waveforms acquired for every injection with the LeCroys scopes will be available through FESA to the Injection Quality Check

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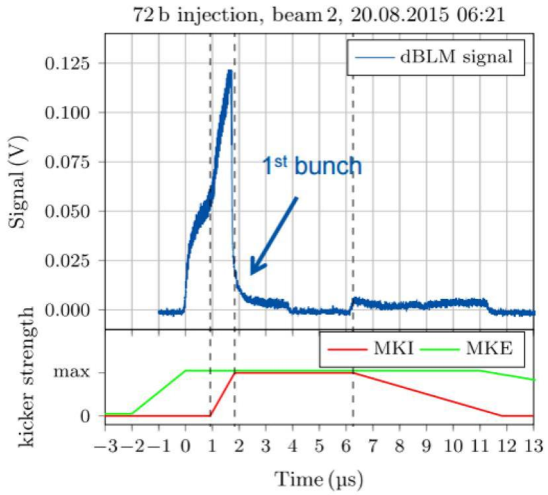

Figure 2: A typical dBLM loss signal in the injection region and its synchronization with SPS extraction kickers and LHC injection kickers rise time.

(IQC). It is worth mentioning that some operational experience will be required needed to set the thresholds for the diamonds losses.

Finally, a plan of standardizing the dBLMs readout is ongoing, where VME FMC Carrier (VFC) card based acquisition will be adopted. It will allow for a fast sampling (∼600 MSPS) of the diamond signal and will replace both the Lecroy oscilloscopes and the Rosy boxes since also the histogramming will be integrated at the firmware level. A final review of the specification is taking place now and a final test system is foreseen to be installed in the laboratory, in the SPS (BA1) and in the LHC (in parallel to the existing readout) to validate the full chain performance. Profiting of the synergy with the recent fBCT readout development (based on the same VFC card), only few changes are expected to adapt the existing FESA class for the dBLMs. Once the validation of the system is completed, the deployment of the new electronics for all the diamonds systems in the LHC is supposed to be relatively easy and transparent.

BEAM POSITION MONITORS

The LHC beam position system consists of more than 2000 measurement channels distributed along the LHC underground tunnel. The electronic readout of the pick-up signals is based on Wide Band Time Normalisers (WBTN) capable of processing the analogue signals from the pick-up at 40MHz. The WBTN principle encodes the position information for each passing bunch into a pulse width modulation, sent via optical fibers to the acquisition electronics on surface. This readout chain can provide several different parallel orbit modes:

- the default mode, “Asynchronous orbit", where each incoming bunch data from a particular BPM enters a moving average filter (implemented as an exponential response IIR filter). The time constant of this filter can be configured and therefore it provides the average beam position over some chosen time. This mode is used in the orbit feedback.
- the “Synchronous orbit" (to be used mainly in the directional strip-line monitors) allows certain bunches to be masked (i.e. not taken into consideration) for calculation of the orbit. Here the average position of selected bunches are averaged over a set number of turns. This mode is needed to operate with asymmetric beam intensities (as in the case of proton and lead collisions).
- the “Capture" acquisition mode, provides the orbit of individually selected bunches turn by turn position over a configurable number of turns. This mode is needed for the dedicated optics measurement Runs and for the injection quality checks.

In YETS 2015/2016 and during operation this year, a new firmware was deployed, addressing several issues to enhance the BPMs performance improving the system stability and maintainability. A solution for the observed conflict between the two “Asynchronous orbit" and “Capture" acquisition modes was implemented and the synchronization handling was optimized to improve the "Capture" data reliability. Additionally, the new firmware allowed a higher accuracy (more bits) averaging in the “Orbit" mode improving the position’s resolution. Finally, the “Synchronous Orbit" acquisition mode was also enabled permitting its use during the proton-lead physics Run. The FESA class was accordingly adapted to cope with the new firmware.

In conclusion, despite its size and complexity, the system performed well during the 2016 Run; nevertheless some issues were uncovered during operation:

- Non optimal LSA settings and bunch selection (presence of colliding encounters) prohibited the usage of the “Synchronous Orbit" during the ions Run; this issue was solved by establishing the good settings to use.
- Spurious orbit reading, called “Dancing BPMs", was sporadically observed. This issue in the electronics seems to be solved by replacing some acquisition cards; new diagnostics were put in place to study it further.
- Problems in the “Capture" acquisition mode:
    - Some were diagnosed to the absence of the beam synchronous triggers, where the reboot of the BST was enough to solve the issue. Since this affects several systems, new diagnostics were put in place to monitor the triggers for additional investigations. The latter will allow to probe the “De-phasing" effect that is still not fully understood.

Diode orbit and oscillation system

The Diode ORbit and OScillation System (DOROS) system was designed for measuring beam orbits in the BPMs embedded in the LHC collimators jaws [4]. Compared to standard WBTN electronics, orbit measurements are characterized by a higher signal to noise ratio. In fact, submicrometre orbit resolution (~0.1 µm) and micrometre stability was achieved with relatively simple and robust hardware, despite the relatively low signal amplitudes available from the small button electrodes of the collimator BPMs [5]. Based on a peak detection scheme, DOROS measurements should not be sensitive to any fluctuations of the signals temporal shape, however no bunch by bunch information is derived. The system is now operationally used for automatic positioning of the collimator jaws and for the continuous monitoring of the beam position at the collimator locations. Further developments involving the generation of beam interlocks from collimator BPMs are ongoing.

Even though DOROS was optimised for position resolution and absolute accuracy for centred beams in the collimators, the same system was also installed on some 20 LHC BPMs located around the LHC interaction regions for comparison with the standard LHC BPM system. It was found that the residual non-linearity of the orbit diode detectors causes systematic orbit errors at the level of tens of micrometres, as shown in Fig. 3.

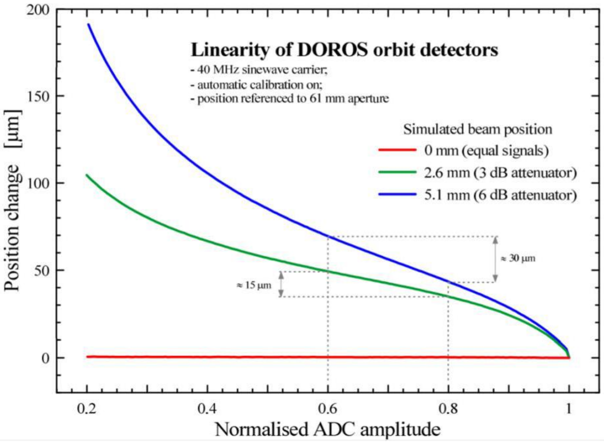

Figure 3: Position change caused by the nonlinearity of the compensated diode detectors (laboratory) [5].

The effect dominated the fill to fill reproducibility where the lack of adequate control of the system parameters enhanced the non-linearity observed when the gains are adjusted to accommodate to the amplitude drop caused by the beam intensity decay.

The relative change in signal amplitude with respect to the dynamics of the ADC induces fake orbit drifts and is clearly enhanced by the beam offset to the BPM centre, or when the beam intensity varies.

The effect is under investigations and is reproduced and quantified in the laboratory where extensive studies are currently carried out to linearize the detector characteristics.

Additionally, the DOROS system can also be used for observing beam spectra and deriving beam parameters from driven beam oscillations [6]. The beam spectra in the frequency range from DC to ~100 Hz can be analyzed using DOROS orbit data while the range from 0.5 to 5 kHz can be covered with the dedicated oscillation data channel. Since it provides high resolution measurements over many turns, better than an order of magnitude improvement in the beam spectra noise floor was observed compared to WBTN. Moreover, one of the applications of DOROS oscillation data is for local coupling measurement, which has been demonstrated with very small beam excitation. Recently, an improvement of the acquisition synchronization of the “capture“ mode in FESA with the ADT excitation allowed minimizing also the excitation time to what is just needed to measure the coupling. In the future, it is also planned to use DOROS for beta-beating measurements using the synchronous detection implemented in the DOROS FPGAs.

WIRE SCANNERS

Wire scanners (WS) are the reference instruments for transverse beam size and emittance measurements in the LHC. They are also used for calibrating other devices, such as the BSRT. Their working principle consists of a thin carbon wire moved across the beam at the speed of 1 m s^{-1}; the radiation produced by the interaction of the protons with the wire is observed by means of downstream scintillators coupled to Photo Multiplier Tubes (PMT). This charge deposition is proportional to the local density of the beam and is used to measure the beam density profile [7].

The noise in the PMT signal acquisition chain was investigated by studying the spectrum of 100 scans with no beam in machine. Originating from the High Voltage supply or coupled to the analog signal in long cables, this noise was suppressed using the background subtraction technique. It consists of picking a bucket in the abort gap as a noise reference and subtracting it from the bunch profile in the filled buckets; it was unfortunately found that this treatment could enhances the noise at higher frequencies and contribute to the worsening of the WS precision. In 2016, investigations to mitigate this disturbance to the PMT signal took place and a cure was found at the hardware level, by disconnecting the "turn" acquisition mode cables in the tunnel installation, breaking important ground loops that undermined the signal quality. It is worth mentioning that this acquisition mode is not in use in the LHC operation and was conceived for internal sanity checks of the acquisition chain of the instrument. The obtained benefit was more visible on B1. The studies will continue to identify the dominating sources for the residual noise on B2 as shown in Fig. 4.

Figure 5 shows the contribution of the uncertainty on determining both the shower intensity (via the PMT) and the wire position on the emittance measurement accuracy for the horizontal plane of LHC beam 2.

In fact, once the noise coupling to the PMT signal is mitigated, errors on the absolute scale of the wire movement translates directly into an error on the measured beam size [8]. Therefore, a parallel method to validate the WS potentiometer measurements is being developed: the integra-

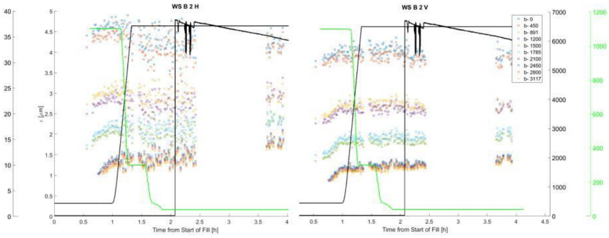

Figure 4: Beam 2, bunch by bunch, normalized emittance during a BSRT cross-calibration fill with 10 circulating bunches.

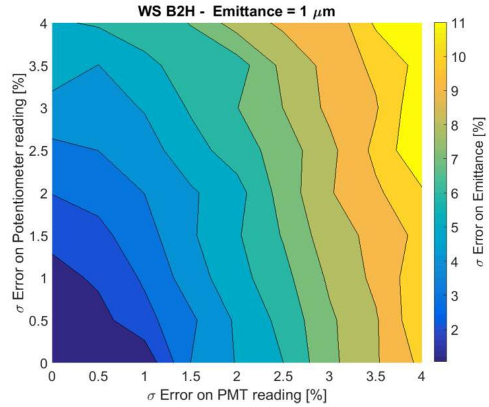

Figure 5: Emittance measurement accuracy as a function of errors on potentiometer and PMT readings for LHC beam 2.

tion of a laser interferometer onto the movable fork shaft is planned for in-situ measurements of the wire position during a scan. The laser interferometry yields a very high accuracy in relative movement measurement and is routinely used in some of the LHC collimators for a precise measurement of the jaws. Tests are planned to take place in this EYETS and the results will shade the light on eventual systematics dominating the beam size measurement.

BEAM GAS VERTEX DETECTOR

The Beam Gas Vertex (BGV) detector is a beam profile monitor being developed as part of the high luminosity LHC upgrade.

Its working principle consists of reconstructing the beam-gas interaction vertexes, where the charged particles produced in inelastic beam-gas interactions are measured with high-precision tracking detectors, to obtain the 2D beam transverse distribution.

The BGV allows for non-invasive beam profile and position measurements to be made throughout the full LHC cycle, irrespective of beam energy or luminosity. The detector has been designed to estimate the individual bunch transverse width with a precision of about 5% in approximately 5 minutes of integrated beam time, however the installed demonstrator aims at measuring the average transverse beam profile with a precision of about 10% in approximately 5 minutes of integrated beam time [9].

The full installation was completed in 2016 on B2, and the detector was fully commissioned. First data and beam profile measurements show that the complete detector and data acquisition system (SciFi detector planes, trigger, readout, CPU farm, control and DAQ software) are operating as expected. The dead channels were found to be less than 1% of the total. The detector was successfully operated with a neon gas injection adjusted such as to provide an adequate trigger rate, without disturbing the beam. A pressure of approximately 6.10^{-8} mbar in the interaction volume was used during data-taking campaigns in 2016 under various beam conditions in parallel to operation and in dedicated MDs.

The observed rate of events matches expectations and the distribution of the z-coordinates at which the impact parameter is minimized, displayed in Fig. 6, shows that the measurements are well inside the limits of the gas target and are correlated with the expected gas pressure profile [10].

The measurements were crucial to assess the system performance, understand the limitations and plan the next steps. In fact, for the Run in 2017, an upgrade of the triggering mechanism is planned, where an additional hardware trigger (L0 confirm) is planned to be installed during the EYETS to improve the cross-talk between the two beams. Moreover, further refinement of the vertexing algorithm along with better event selection through improved triggering will be required to reduce this rather large statistical error and allow a full comparison with other LHC profile measurement devices. The offline analysis for high precision track and vertex reconstruction is planned to be incorporated in the CPU farm for real-time measurement.

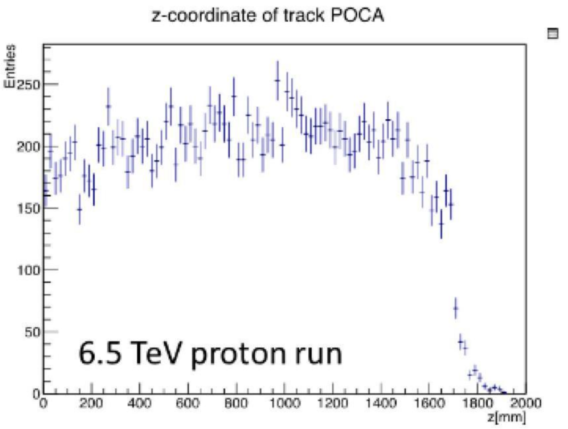

Figure 6: The distribution of Beam-gas interactions Point Of Closest Approach (POCA) along the beam passage (z-distribution) at 6.5 TeV.

In conclusion, the BGV operating parameters are now being optimized and the reconstruction algorithms developed to produce accurate and fast reconstruction on a CPU farm in order to provide real time beam profile measurements to the LHC operators and to the logging databases are being put in place.

SYNCHROTRON LIGHT MONITOR

The Beam Synchrotron Radiation Telescope (BSRT) monitors image the synchrotron light generated by the beam traversing a dedicated super-conducting undulator and a D3 type dipole located in IR4. This section will cover the upgrades of the SR imaging system and new observations on the cross-calibration technique with the WS [11]. Additionally, the SR interferometer and coronagraph, installed on B1 and B2 respectively, will be discussed.

SR Imaging

The BSRT imaging system was reliably used in operation throughout 2016 for bunch-by-bunch beam size measurements. It has been crucial for several studies (beam-beam, instabilities and EC studies) and often crosschecks with independent emittance measurements, such as the luminosity scans, were carried out and confirmed the accuracy of the BSRT beam size measurement, found to be at the level of 10% as shown in Fig. 7. The BSRT cross-calibration to the wire-scanners took place in the intensity ramp up fills (where the first stable beam fill of 3 colliding bunches was replaced with a 10 colliding bunches fill). This allowed parasitic three calibration Runs this year:in April, August and October. August calibration was not successful and resulted in an underestimation of the beam emittance. Investigations are still ongoing to understand the results, however important hints on the dependence of the BSRT calibration on machine conditions, optics and beam modes are observed. In fact, Fig. 8 shows the variation in the calibration factors whether beams were colliding or not in IP1 and IP5. The successive calibration (in October) was made such as no optical elements were moved in the system, hence the calibration factors found could be applied backwards to correct the measurements between calibration 2 and calibration 3, and no data loss is expected. Investigations are also in place to identify the source of the big spread in the beam size measurement observed on BSRT B1 and check whether it is correlated with beam behavior such as orbit drifts or oscillations.

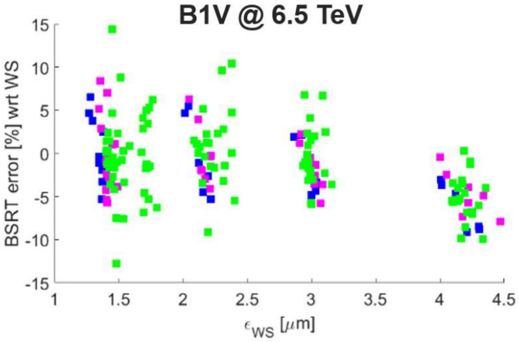

Figure 7: Discrepancy between the vertical emittance measured via WS and BSRT for LHC beam 1 at 6.5 TeV in function of the absolute normalized emittance.

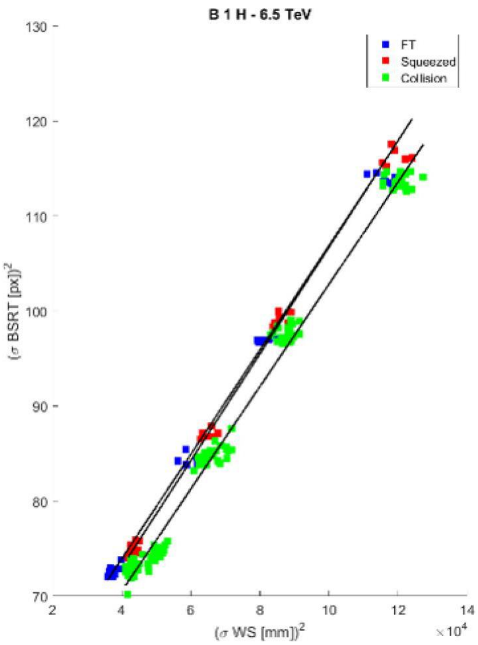

Figure 8: Correlation of uncorrected BSRT beam widths with beam size measured via WS in function of the beam mode at Flat Top.

At the software level, the BSRT FESA class was ported to FESA 3 and allows now on-demand logging of bunch by bunch profiles. It is worth mentioning that both the abort gap monitor and the Longitudinal Density Monitor (LDM) were in good shape all over year and were essential during Van Der Meer luminosity calibrations Run.

In YETS, in the framework of the BSRT consolidation, digital “Basler" cameras and new “Hamamastu" intensifiers will replace the analog intensified “Proxitronic" cameras and the FESA class will be adapted accordingly to increase the acquisition rate to ~200 frames per second (>50 bunches per second). Additionally, a big intervention is planned on the BSRT hardware where all optics will be removed to replace the optical table mounting to allow the extracting the optical table from the shielding enclave to ease maintenance.

SR Interferometer

As the SR parameters approach the diffraction limit, direct imaging for beam size measurement is highly challenging and very sensitive to the cross-calibration techniques. SR Interferometry is the best alternative to measure the small beam size with visible SR. It consists of determining the size of a spatially incoherent (or partially coherent) source by probing the spatial distribution of the degree of coherence after propagation, with a theoretically achievable resolution of a few microns.

This technique was therefore implemented in the LHC, for the first time in a proton machine [12]: In 2015, a prototype was installed on the B1 optical table, side by side to the imaging system. The experience gained in some MDs allowed finalizing the interferometer setup and its installation in June 2016.

It features a new slit assembly that allows the measurement of the horizontal and the vertical beam sizes with the possibility to change the slit width, separation, height and center remotely. The system can also be operated as a 2D interferometer by inserting at the same time the horizontal and the vertical slits. The light polarizer used in 2015 (seen to introduce additional focusing with strong astigmatism) was replaced with a high quality precision linear polarizer constructed by laminating a polymer polarizing film between two high-precision glass substrates (flatness better than $\lambda/6$). In 2016, a comprehensive set of measurements were performed to qualify the interferometer comparing its results to the standard imaging system at both the injection energy and 6.5 TeV. A deep analysis of all systematics was carried out, studying the SR wave front distortion, its dependence on the wavelength, the polarization, on the double slit center and height, and the detector properties such as exposure gain and linearity.

A good agreement was observed at injection energy, while a scaling factor of about 1.3 is yet to be understood between the two systems at top energy. Nevertheless interferometry was able to provide coherent relative bunch size measurements at 6.5 TeV. Moreover, the feasibility of 2D interferometric measurements has also been demonstrated. During the YETS, the alignment of the interferometer is to be improved to allow parallel measurements without compromising the quality of the imaging system. This would allow in 2017 Run, to accumulate statistics to cross-calibrate the measurements to the WS at top energy and check stability of the system, validating its accuracy and precision.

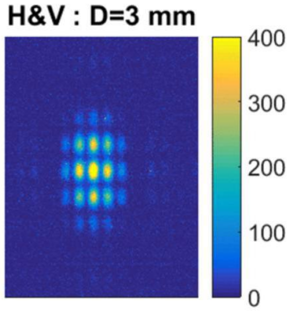

Figure 9: 2D Interferograms recorded for simultaneously inserted slits in the H and V plane.

SR Coronagraph

The coronagraph is a spatial telescope used to observe the sun corona by creating an artificial eclipse. The concept of this apparatus consists of blocking the glare of the sun central image allowing to observe its corona. An observation of the beam halo at the LHC using a coronagraph is planned in two phases. Phase I, following the installation of a demonstrator on the B2 optical table side by side to the imaging system, aims at measuring halo with 10^3 to 10^4 contrast with respect to the beam core [13].

Parasitic studies took place in 2016 to check the system alignment and validate the optical configuration. Additionally, a dedicated experiment was scheduled in MD time and aimed at demonstrating the coronagraph working principle, its background and the achievable contrast.

The MD took place at injection energy and the beam halo was successfully measured for the first time with a coronagraph [14]. In fact, an artificial increase of protons population in the halo region was achieved via a controlled transverse emittance blow-up using the transverse damper. A direct correlation of light increase in the imaging plane of the coronagraph with the emittance growth was observed. Successively, the gap of the primary collimators in IP7 was reduced in both planes respectively, shaving the halo population to probe any light variation in the coronagraph images as shown in Fig. 10. A linear relation between the intensity lost as measured by the fast beam current transformers and the SR light lost in the halo region was obtained. A contrast of $2 \cdot 10^{-3}$ was reached. It is worth mentioning that for lake of time in the MD only one "core block" with a fixed was used, therefore the reached contrast (that depends on the block diameter) is not to be taken as the limit of the actual coronagraph demonstrator. Finally, parallel to operation, some observations took place with the coronagraph at 6.5 TeV. A parasitic light was observed close to the blocked beam core (at the 10^{-3} level to the latter). Its origin is not clear, however it is being investigated and a full realignment of the system is planned to take place in YETS in order to rule out the possibility of it being an internal reflection in the system. In 2017, dedicated MD time will be requested to assess whether the present configuration will allow a beam halo measurement at flattop and will an invaluable input to steer the final design of the coronagraph for HL-LHC.

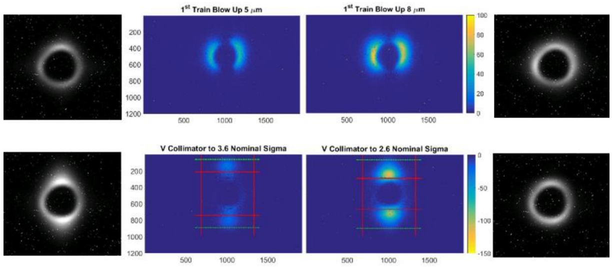

Figure 10: Measurement of an artificially created beam halo via emittance blowup with the ADT (upper images) and scraped beam halo via collimators closing (lower images).

CONCLUSIONS

This paper summarized the challenges some of the LHC beam instrumentation faced in 2016's operation and highlights the major changes they will undergo in the coming EYETS. Several studies targeted the use of dBLMs for new loss scenario studies, mostly for injection losses diagnostic.

It was observed that the exploitation of such data is valuable and efforts in standardizing the readout systems for these devices will continue aiming to integrate the data in the control system. Additionally, the changes in the firmware of the WBTN readout of the BPMs was highlighted along with the benefits of using the synchronous orbit in operation with ions. The new features implemented at the software level to improve the "phase-in" procedure were also discussed. The accuracy of the beam orbit processed with the DOROS electronics was also presented and the strategy to tackle the systematics with a better control of the system's parameter at the FESA level was shown. The improvements in the triggering of the oscillation channel in FESA was also mentioned and could allow potentially online coupling measurements. Moreover the encouraging BGV recent studies allowed verifying the integrity of the system and plan the trigger upgrade during YETS for an improved online beam size reconstruction in 2017's Run. Slight modification in the WS hardware to reduce the noise on the PMT readings were presented and the foreseen studies to verify the accuracy of the wire position readings to tackle the challenges of small beam size measurement were also highlighted. Finally the status of the synchrotron radiation monitors was discussed: the plan to upgrade the imaging system to digital cameras for faster acquisitions was shown; the successful beam halo measurements at injection with the coronagraph were presented and the interferometer studies in 2016 were summarized.

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