STATUS OF THE LHC EMITTANCE DIAGNOSTICS

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Abstract

Measuring the beam transverse emittance is fundamental in every accelerator, in particular for the LHC, where its precise determination and preservation is essential to maximize the luminosity and thus the performance of the colliding beams. In this contribution, a review of the status of the synchrotron radiation monitors, the beam gas vertex detector and the wirescanners will be presented alongside the assessment of the obtained performance. The new features implemented and the issues encountered during 2017's operation will be highlighted. Additionally, the interventions and improvements planned for the coming winter shutdown will be discussed.

INTRODUCTION

During the Extended Year End Shutdown (EYETS) 2016/1017, several modifications to the LHC beam size instrumentation were done, some actions were to tackle the observed limitations in 2016 operation and some were improvements allowing the implementation of new features for these devices. In the following, the wire-scanners, the synchrotron radiation monitors and the beam gas vertex detector 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 YETS.

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 synchrotron light telescopes. Their working principle consists of a thin carbon wire moved across the beam at the speed of $1\,\mathrm{m\,s^{-1}}$; 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.

During EYETS 16/17, the WS underwent a consolidation aiming at improving the measurements quality and the system maintainability. At the control level, a new VME crate was added alongside the main VME crate that used to house the control system of the 8 scanners (4 operational and 4 spare systems). This duplication allowed to reduce the multiplexing levels, whereas the 4 scanners per beam are now controlled from one independent crate. Not only this allows performing simultaneous scans in both beams, it reduces the failure risks due to multiplexing. It is worth mentioning that a modification of the OP application is mandatory to allow scanning in parallel B1 and B2. In addition, the CPU were upgraded from PPC to Linux allowing an increased processing power and reduced probability of memory limitations, observed in the previous years.

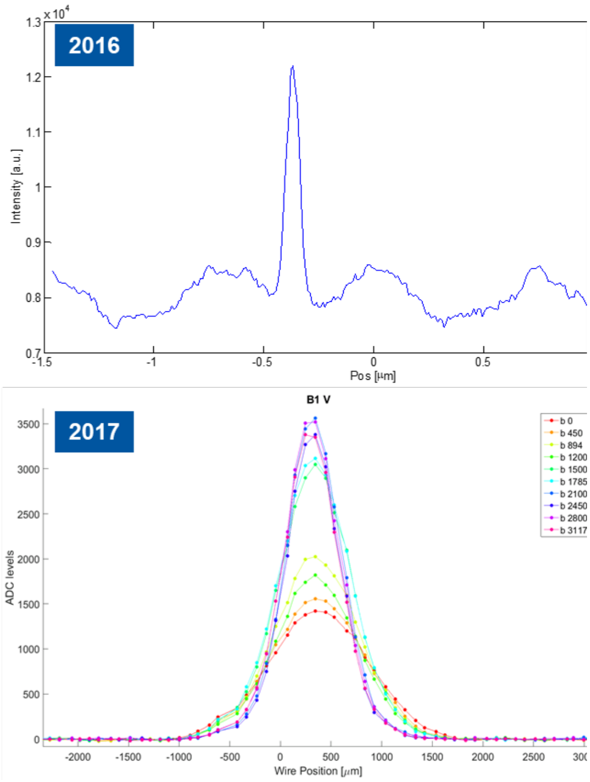

Figure 1: Beam profiles without post-processing as obtained at the end of the WS acquisition chain before the improvement of the SNR of the analog signal transported from the tunnel to US45 (2016) and after (2017).

A great care was dedicated to the analog signal of the PMT transported from the tunnel to the service areas (more than 100 m of cables) where the integration and digitization take place. Being a dominant source of the beam size precision degradation, improving the SNR of the analog signal is crucial to obtain reliable online measurements with the least post-processing. The intervention at the pre-amplifier level (in the tunnel) and the improved grounding strategy reduced greatly the residual low frequency noise, as can be seen in the profiles shown in Fig. 1.

Additionally, to mitigate the profile distortion when the PMT was operated in saturation (requested charge exceeds the stored charge in the PMT base) that impacted directly the measurements accuracy, an offline characterization in the lab of the assembly “PMT + base” allowed to identify precisely

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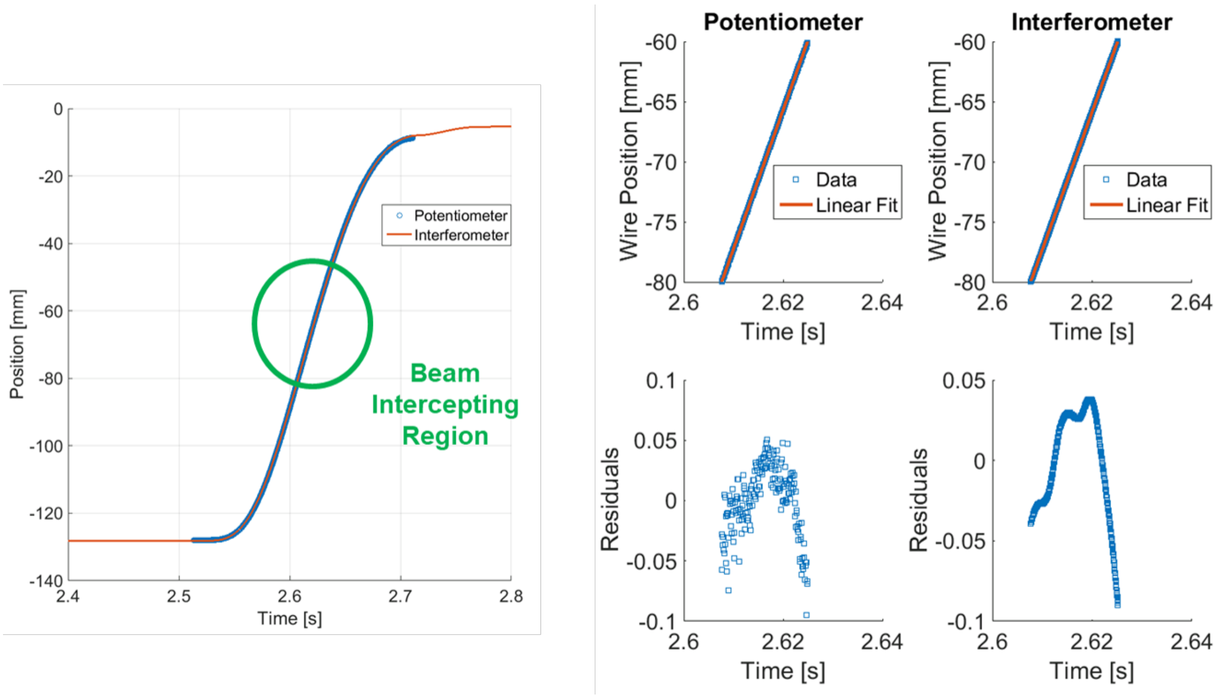

Figure 2: Left: Wire position as measured by the potentiometer and the optical interferometer during a scan at 1 m s^{-1}. Right: The slopes of the wire position at the beam interception region are computed and the residuals of the linear fits are shown for both measuring techniques.

the photon flux level bringing the tube to saturation. This was an important input to obtain a predefined set of high voltage settings for the scans, releasing the operator from this task and reducing the operational mistakes. Finally the scanners now are operated with a single setting to be inserted: the choice of the neutral density filter to attenuate the photon number at the exit of the scintillators before reaching the PMT.

Throughout the years, the attempts to checks systematics on the absolute scale of the WS, by comparing an imposed beam displacement with the profile movement, were limited by the accuracy of the beam position monitors (in the order of 5% for such large aperture BPMs). During one of the technical stops, an attempt to validate the absolute scale of the wire displacement during a scan was carried out. The aim was to study the accuracy of the provided wire position via the potentiometer. An external laser interferometer, used in collimator jaws displacement sensing (kindly offered by the EN-STI group), was installed in a spare wirescanner device on beam 1, on the metallic stub holding the wire. As it is moving solidly with it during a scan, the wire position seen by the potentiometer and the interferometer could be compared. It is worth mentioning that this measuring technique is successfully validated even for moving targets at 1 m s^{-1}. Figure 2, presents the agreement of the two techniques: the estimated speed differed by only 0.8%. This measurement, carried out on the spare scanner just for space constraints in the present tunnel installation, gives confidence that very small systematics are introduced into the beam size estimation from the potentiometer scale (at the percent level). The interferometery technique was however found more precise, featuring lower noise as can be seen from the fit residuals in Fig. 2.

As the beam brightness is further improved in the injectors, one of the issues facing the WS, especially in the horizontal plane where the optical function is reduced down to 180 m, the accuracy of the fits is compromised by the reduced number of points/sigma (1.2 points/sigma for 1 µm beams) combined with the present noise levels in the PMT signal and wire position readout. As this cannot be mitigated at the HW level by reducing the wire speed in a scan, studying eventual flexibility in the ATS optics to increase the beta function in IR4 could be the only chance to overcome this issue.

Moreover, the interlocking logic of the scanners based on intensity and energy thresholds needs to be revisited as the plugged numbers refer to emittances of ~2.3 µm.

Finally, the system reliability is still one of the challenges facing OP; in few occasions in 2017 the WS were unavailable and shortly blocking operation. Additional diagnostics were put in place to diagnose the CPU crashes origin, the FESA class (still FESA 2) failures and the incomplete wire movements. As the error messages to the user from the OP application remain cryptic, a clear procedure on how OP should behave still needs to be defined.

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

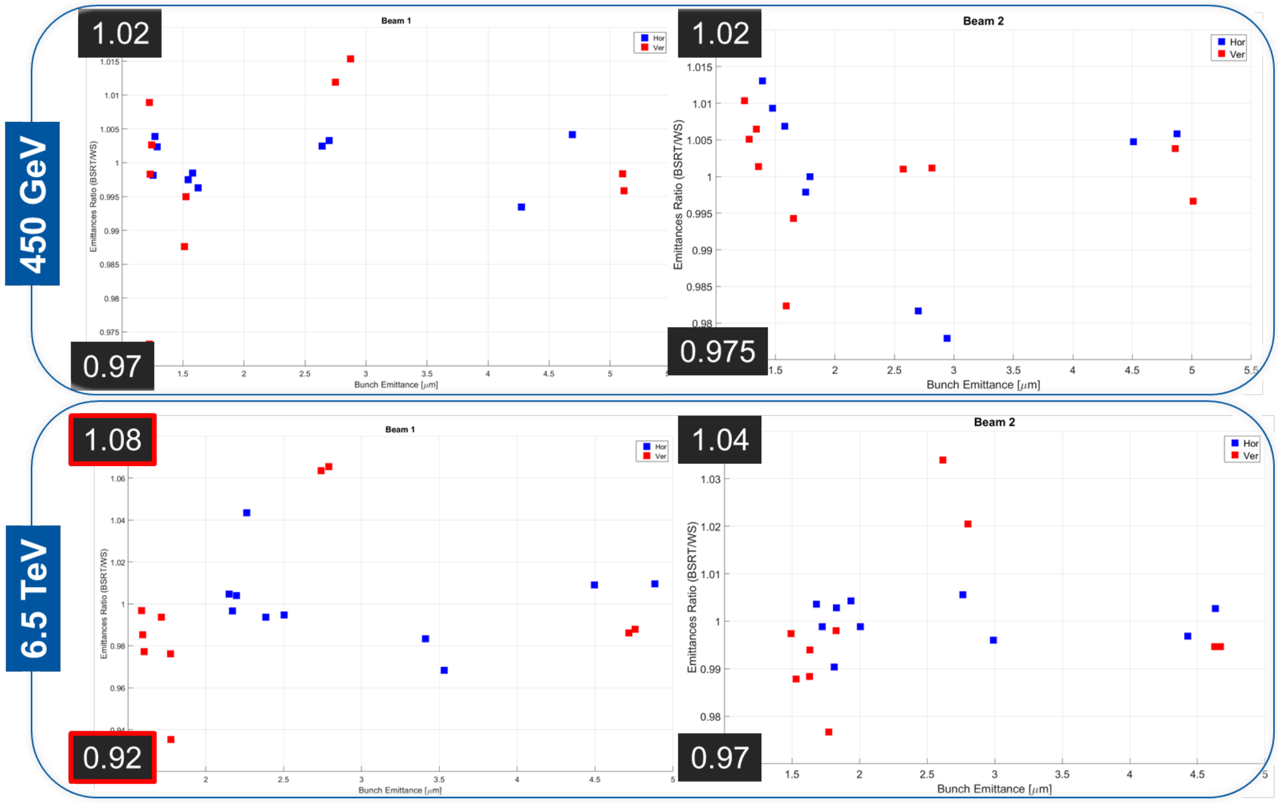

Figure 3: Beam size comparison as measured by BGV and BSRT. On the left the average beam size is shown in function of energy, whereas on the right, a zoomed plot at the energy of 6.5 TeV is shown for 3 different fills.

type dipole located in IR4. This section will cover the upgrades of the SR imaging system during EYETS 16/17, the issues faced during the 2017 operation will also be discussed.

The present year was the first year where digital cameras and the new generation of Image Intensifiers (I.I) were used in operation in the LHC BSRT. Not only it featured faster frame acquisition rate (w.r.t the BTV cards used for analog cameras frame grabbing) but also an increased images SNR. The full ring scan time was greatly reduced to almost 1 minute. In fact, as a single measurement per bunch is enough, the BSRT was operated at the measurement rate of 30 bunches/s. At the HW level, also a target was installed in the tunnel to verify the reproducibility of the optical component alignment on the optical bench. The system was found to be stable along the full year.

Three BSRT cross-calibrations to the wire-scanners were requested in 2017. The first took place during the beam commissioning period in June, followed by another in August and a last one in October. The calibration technique relies on the hypothesis of a gaussian beam transverse distribution and a gaussian optical point spread function. With the decreasing emittance injected from the SPS, reaching as low as 1 μm, the validity of such calibration process needed to be verified, seen the non gaussianity of the PSF due to incoherent depth of field of the system casused by the extended source (D3). The experimental data obtained in the first calibration, proved that the accuracy for the small emittance at top energy was worse as expected, however limited to ±8% as shown in Fig. 4.

The main limitation of the system, found at the early stage of operation, was the ageing of the I.I. The visible effect was a sensitivity reduction where exposed to the SR, deforming the sensor's response, as shown in Fig. 3. As the impact on the beam size determination was considerable, the mitigation strategies were to compensate the non-uniformity at the SW level, to avoid operating in the damaged area of the sensor and to steer the light spot to a new working point. The integration time needed to be increased as well as the MCP gain to wear less the I.I. with a direct implication on the maximum frame rate reachable with the digital cameras. The issue is being investigated by Hamamatsu to identify the dominating component in the ageing: photocathode, MCP or phosphor.

An attempt of calibrating the BSRT to the WS during the Ramp took place during the second calibration Run. Automatic scans were acquired at regular intervals (∼ 1min) all along the ramp. As no available measured optics are available throughout the Ramp at the location of the profile monitors, the Injection optics were assumed up to 2 TeV and the collision ones from 2 TeV to top energy. Reliable calibration factors could be found only from E >3 TeV with slightly worse accuracy compared to FlatTop.

The BSRT operation faced several issues in 2017:

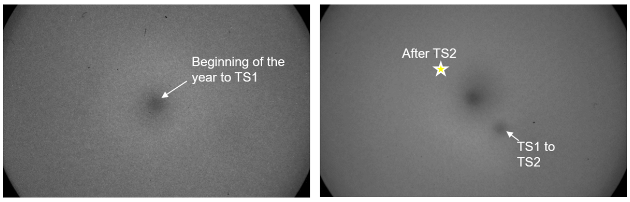

Figure 4: Beam size comparison as measured by BGV and BSRT. On the left the average beam size is shown in function of energy, whereas on the right, a zoomed plot at the energy of 6.5 TeV is shown for 3 different fills.

- **Image Intensifiers**, the major contributor to the BSRT accuracy degradation with time. The ageing increased by an order of magnitude the needed time to scan the full ring compared to the maximum data flux the CPU can handle. Moreover, several resets of the intensifier units were needed (often on B2); one of the causes is suspected to be the coupling of external noise to the analog gain signal of the MCP.

- **MCP Gain**, was found relatively slow ~ 5Hz therefore not suitable for a feedback on a bunch by bunch basis. The gain changes throughout the cycle are therefore implemented based on a feedforward (w.r.t. energy). As a consequence, pilot bunches are visible only following an expert intervention, till it is further automated for 2018 run.

- **Viewports**, following a visual inspection at the end of the run, the B1 viewport was found "marked" by the SR. The light distribution seems engraved in the fused silica, as shown in Fig. 5. Opening the vacuum on B1 may be needed to replace the window and analyse the deposit closely.

- **Calibration reproducibility**, several observations in 2017 (thanks to the new ADT activity monitor) showed a correlation between the estimated beam size from BSRT (sum of 200 2D images integrated over 200 LHC turns) and the bunch oscillation. High frequency beam displacements would translate in an apparent emittance blowup representing a limitation if taking place during the calibration fills.

The experience accumulated in 2017 shaped the upgrades and the new changes proposed for the 2018 run. To mitigate properly the ageing of the I.I without perturbing the properties of optical system when continuously steering the SR spot, the camera itself will be motorized on both transverse axes and will continuously move to spread equally the wearing out of the photocathode reducing its impact. Additionally, a review of the lens setup on the optical bench will take place to allow sending the unfocused SR directly to the camera to be used to measure remotely the sensor non uniformity. The new lenses setup should also avoid having continuously for every ramp move back and forth the focusing lenses reducing the probability of losing steps on the stepper motor. Moreover, to ease the data mining and emittances retrieval, it is planned for 2018 to log bunch emittances and average emittance evolution throughout the fill.

Figure 5: Beam size comparison as measured by BGV and BSRT. On the left the average beam size is shown in function of energy, whereas on the right, a zoomed plot at the energy of 6.5 TeV is shown for 3 different fills.

Finally, all these measures to improve the system reliability will be complemented with a more regular calibration fills, at the rate of once per month, as endorsed by the LHC machine committee.

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 [4]. 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. On several occasions in 2017, the detector was parasitically operated with local Neon gas injection at 10^{-8}mbar and was commissioned along the full LHC cycle. Dedicated data-taking campaigns were scheduled mainly in machine development periods and the BSRT calibrations under various beam conditions. Compared to the previous year, the changes in EYETS 16/17 improved the triggering system by adding the "L0 confirm" trigger level. Combined with an improved offline analysis for high precision track selection and vertex reconstruction, the demonstrator provided interesting observations on the beam size, especially during the

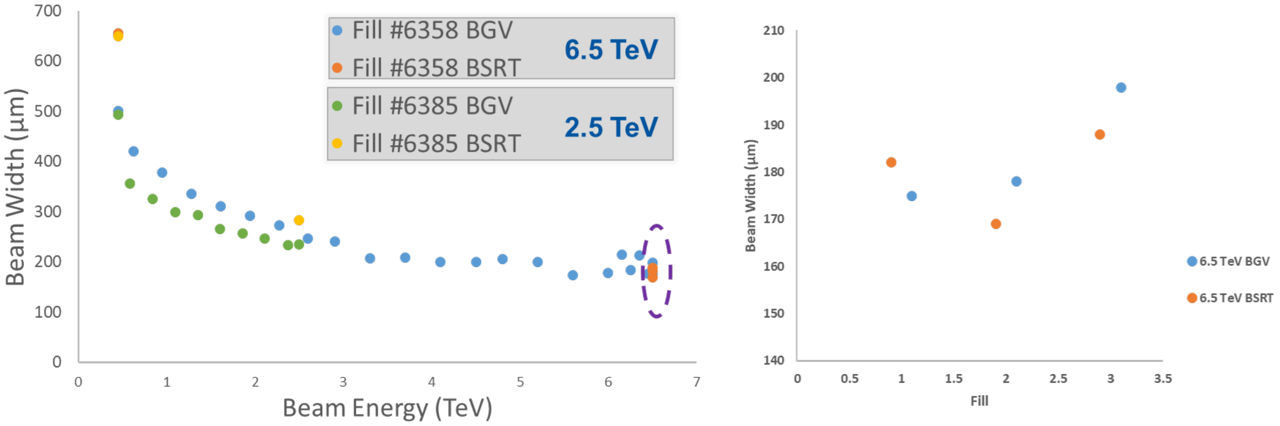

Figure 6: Beam size comparison as measured by BGV and BSRT. On the left the average beam size is shown in function of energy, whereas on the right, a zoomed plot at the energy of 6.5 TeV is shown for 3 different fills.

energy ramp where other diagnostics are missing. Figure 6, shows the beam size comparison between BGV and BSRT over several energies. The compatibility is promising, however the systematics are still to be investigated. It is worth mentioning that the beam size reconstruction is done using the track correlation algorithm instead of vertexing, and is computed with an underlying hypothesis of round beams. In terms of measurement precision, the collected experimental data confirmed the scaling of the statistical errors with the square root of the number of tracks used in the beam size determination. With integration times in the order of 20 minutes per single bunch, a precision better of 5% on the beam size is achieved. The coming year of operation will be dedicated to study the BGV agreement with other emittance diagnostics. The systematics introduced in the BGV measurements will be deeply investigated. Regular runs of data taking should take place continuously with a permanent gas injection to allow comparison with other measurements over longer timescales. In order to benchmark the simulations of the system, several MD periods will be requested to investigate the BGV behaviour in special beam conditions as bumps in IR4.

CONCLUSIONS

This paper summarized the challenges the LHC beam profile monitors faced in 2017's operation and highlighted the major changes they will undergo in the coming YETS. For the wire scanners, used mainly for the BSRT calibration, the accuracy and precision enhancement were presented. For the synchrotron radiation monitor, the successful shift to digital cameras was discussed, however the accuracy was compromised by the ageing of the image intensifiers. For the beam gas vertex detector, the parasitic data obtained throughout the year were very promising and compatible with the other emittance diagnostic systems. For the 2018's run, the focus for all the aforementioned diagnostics will be on the system's reliability enhancement for a smooth operation.

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