LHC EMITTANCE MEASUREMENTS IN RUN 2

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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 its 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 wirescanners, the synchrotron radiation monitors, the beam gas vertex detector and the quadrupolar moment measurement from the beam position monitors will be presented alongside the assessment of the obtained performance. The new features implemented and the issues encountered in Run 2 will be highlighted.

INTRODUCTION

This papers reviews the implemented improvements, operational experience, and performance reach of the transverse beam size diagnostics in the LHC throughout Run 2. The major hardware and software changes since the Long Shutdown 1 (LS1) tackling the observed operational limitations and implementing improvements and new features are highlighted.

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 the synchrotron light telescopes and assessing the quality of the Beam Gas Vertexing detector and the beam position monitors quadrupolar moment measurements.

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). The current provided by the latter is proportional to the local density of the beam impacting the wire and is used to measure the beam density profile.

The LHC is equipped with 8 scanners: an operational and a spare WS per plane per beam. The acquisition chain allows for Bunch by Bunch measurement at all energies. However, the WS usage along the cycle is limited by a maximum circulating beam intensity (energy dependent threshold), either to avoid the wire breakage or the quench of the adjacent superconducting magnets due the shower of particles produced during the wire-beam interaction.

During Run 2, the reliability of the system and easing its maintainability was of top priority. At the control level, a new VME crate was installed alongside the main one that used to house the control system of the 8 scanners. 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, independent scans in both beams, it reduces the failure risks due to multiplexing. The CPUs were upgraded from PPC to Linux providing an increased processing power and reducing the probability of memory limitations, observed in the previous years.

Several studies targeted the improvement of the measurements quality [1]. On one hand, the main limitation of the system accuracy was found to be the saturation of the PMT and the uncertainties on the absolute scale of the potentiometer. On the other hand, the precision was also undermined by the noise introduced in the acquisition chain, both in the wire position and the PMT current readings.

To overcome these limitations, several hardware modifications and software signal conditioning techniques were adopted to enhance the overall performance of the system:

- the PMT analog signal transported from the tunnel to the service areas (more than 100 m of cables), where the integration and digitization take place, was studied in detail. The noise in the High Voltage supply and the one coupled to the long cables carrying the analog signal was studied by analyzing the empty scans spectra (without circulating beams). At first, a software implementation to counteract this effect was implemented with a background subtraction of an empty bucket within the abort gap region. This temporary cure was partially efficient, especially for low frequency noise, however it enhanced the high frequency noise introduced. A further improvement was obtained when a solution, at the hardware level, was adopted later in the run, that consisted in disabling the turn acquisition mode. Disconnecting this mode's cables in the tunnel installation broke important ground loops that undermined the signal quality. It is worth mentioning that this acquisition mode was never used operationally in the LHC and was conceived for internal sanity checks of the acquisition chain.

- the gains at the pre-amplifier level were modified (in the tunnel) improving further the grounding strategy and reducing greatly the residual low frequency noise.

- the profile distortion, when the PMT was operated in saturation (requested charge exceeds the stored charge in the PMT base) impacting directly the measurements accuracy, was mitigated via an offline characterization in the lab of the assembly "PMT + base". It allowed identifying precisely the photon flux level bringing the

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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 by the users: the choice of the neutral density filter to attenuate the photon number at the exit of the scintillators before reaching the PMT.

The attempts to checks systematics on the absolute scale of the WS, by comparing an imposed beam displacement with the profile centroid shift, 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 alternative technique to validate the absolute scale of the wire displacement during a scan was tested. 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 WS on beam 1 horizontal, 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 $1\,\mathrm{m\,s^{-1}}$. The agreement of the two techniques was very good: 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 the systematics introduced into the beam size estimation from the potentiometer scale are at the percent level.

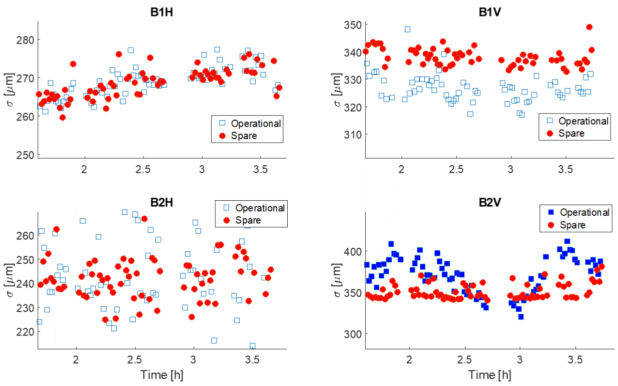

Figure 1: Beam size evolution of one bunch at top energy as seen by the operational and the spare WS in both beams and planes.

Towards the end of Run 2, an erratic behavior was observed on one of the operational scanners (B2V). The investigations that followed were a great opportunity to study the consistency on the measurement among all the 8 scanners: throughout the LHC cycle the beams were scanned with both the operational and spare scanners in all planes. Figure 1 shows the results of this consistency check. The agreement was found to be bounded to few percents when no HW issues were found. The miss-behaving scanner (B2V) is awaiting a tunnel intervention, at the start of the Long Shutdown 2 (LS2), to extract the wire and study the issue in depth.

Finally, LS2 will be a good opportunity to tackle the remaining reliability failures, dominated by software/firmware issues. An upgrade to FESA 3 is expected to take place alongside a renovation of the operational OP application. Since all the WS will be opened during LS2, due to the requested vacuum sectors changes, all the wires will be replaced and mechanical inspections are planned to investigate deeper the origin of the higher measurement spread on B2H. It is also worth mentioning the ongoing studies to replace a spare scanner with a prototype of a modified, more reliable, mechanics for a better scan control and an updated firmware. The detection system may also be upgraded on that scanner to the N-PMT version (LIU-like) featuring an automatic dynamic range selection.

QUADRUPOLAR MOMENT

There has been a rising interest in exploring the capabilities of existing beam position instrumentation for estimating transverse beam sizes in the LHC, probing the Quadrupolar moment measurements, especially during the energy Ramp [2].

The extraction of the second-order moment of the PU signals, containing information about the beam size, is in fact very challenging in the LHC mainly due to two limiting factors:

- the low quadrupolar sensitivity ($\sim 10^{-3} mm^{-2}$) since the quadrupolar moment constitutes only a very small part of the PU signal, which is dominated by the contributions of beam intensity and position. As a consequence, the quadrupolar signal can be easily lost due to imperfections in the measurement system such as electronic noise, asymmetries, or even due to mechanical uncertainties.
- the parasitic effect of beam position attached to the second-order moment in addition to the desirable beam size information. As a consequence, the beam size measurement may be dominated by the beam position if the beam is significantly displaced.

To examine the possible use of existing BPM technology for quadrupolar measurements several tests have been performed in LHC.

To ease the beam centering at the PU locations, mainly BPM systems embedded in the collimators and equipped with the high resolution Diode ORbit and OScillation (DOROS) electronics were used. The parasitic position signal has been therefore efficiently removed.

In fact during MD studies at the end of Run 2, it was successfully demonstrated that differential measurements of the quadrupolar momentum are achievable.

Moreover, with good differential measurements during the LHC energy ramp using selected circular button BPMs,

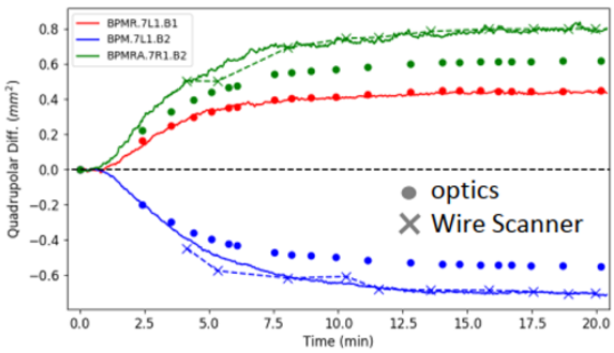

Figure 2: Differential of the quadrupolar moment as measured from three BPMs in the LHC during the energy Ramp compared with the computed one from the measured beam size (with WS) and the model beam size as predicted by the machine optics.

fixed to the beam pipe, at locations with small beam position change during the ramp, the quadrupolar evolution was obtained as shown in Fig. 2.

The evolution was found consistent with the behaviour expected by the optics model, according to the lattice parameters. In particular, the quadrupolar signal increase when $\beta_x < \beta_y$ since Q ($\sim {\sigma_x}^2 - {\sigma_y}^2$) is negative and the beam size shrinks due to abiabatic damping. In contrast, the opposite behaviour is expected when $\beta_x > \beta_y$. To validate even more the BPM measurements, comparative values as obtained using Wire Scanners measurements are depicted. As can be seen, the BPM measurements are in very good agreement with the Wire Scanners ones during most of the ramp evolution time.

These promising results could potentially allow measuring the emittance evolution during the Ramp.

On the other hand, absolute measurements at constant energy are dominated by large and systematic offsets. These can potentially come from small asymmetries between the four pick up electrodes. Studies will continue in exploring techniques to minimize these effects aiming at absolute measurement of the beam size.

BEAM GAS VERTEX DETECTOR

The LHC Beam Gas Vertex (BGV) demonstrator is a non-invasive transverse beam size monitor developed as part of the high luminosity upgrade of the LHC (HL-LHC). It allows for beam profile and position measurements to be made throughout the full LHC cycle, irrespective of beam energy. It uses two tracking stations to reconstruct inelastic beam-gas interactions to measure the transverse beam size in both the horizontal and vertical plane simultaneously. A dedicated gas chamber was installed to provide a uniform target for the beam to interact with, which included a thin exit window for the secondary particles to escape with minimal scattering. High-precision scintillating fibre (SciFi) detectors placed in two stations behind this exit window record the very forward collisions and enable high precision track reconstruction. A dedicated pattern recognition algorithm was developed using the correlation of the impact parameter (IP) of the recognised tracks to calculate the beam size, in alternative to the challenging vertexing for such a demonstrator [3]. 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 Run 2, 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. In EYETS 16/17 the triggering system was improved by adding the “L0 confirm” trigger level. Combined with an improved offline analysis for high precision track selection, the demonstrator provided interesting observations on the beam size, especially during the energy ramp where other diagnostics are missing. The correction algorithm needed to account for the detector geometry, acceptance, secondary tracks and noise is obtained via Monte Carlo simulations that characterize the full instrument.

The beam size comparison between BGV and BSRT over several energies showed a promising compatibility. 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. An example of a continuous measurement during a full LHC cycle can be found in Fig. 3, where an average beam emittance was obtained with integration times of 20 s.

Although the demonstrator fulfilled its goal, data usability is pending the assessment of the systematics, still to be investigated, comparing the measurements with the other transverse diagnostics. In LS2, a decision will be taken for the two new systems to be installed for HL-LHC.

BEAM SYNCHROTRON RADIATION MONITORS

The Beam Synchrotron Radiation monitors consists of an operational imaging system (BSRT) and two development systems, respectively the interferometer and the coronagraph. They all use the synchrotron light generated by the beam traversing a dedicated super-conducting undulator and a D3 type separation dipole located in IR4. This section covers the gained experience and the challenges faced in Run 2 [4].

Imaging system

The Beam Synchrotron Radiation Telescope (BSRT) images the beam synchrotron light by the mean of a Keplerian telescope installed in the tunnel in IR4. Due to the SR peculiar characteristics, the optical system results diffraction

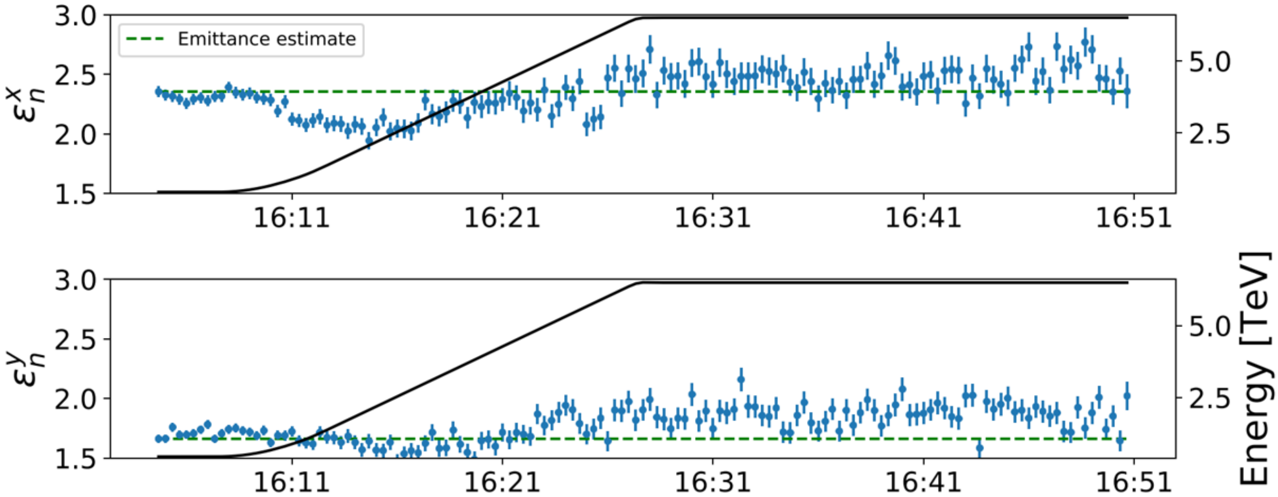

Figure 3: Average beam size measured by the BGV along a full LHC cycle with protons in 2018.

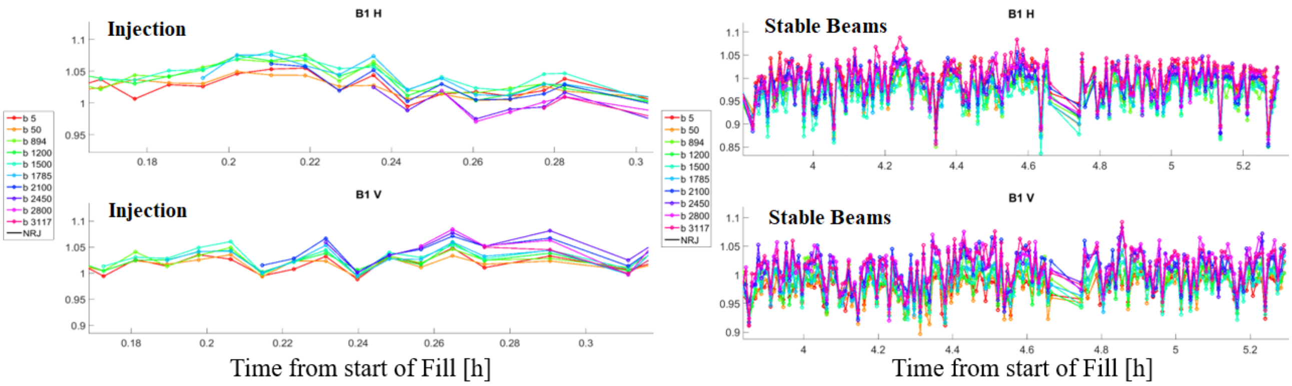

Figure 4: Ratio of emittances computed from beam size measured by WS and BSRT for emittances ranging from 1.5 µm to 4.5 µm for Beam 1 after 2 months from the last calibration run. Both injection and top energy comparisons are shown

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limited and its parameters (magnification and resolution) can only be determined using the real beam as source. This implies that the only way to measure the absolute beam size with the BSRT is to cross calibrate it with another system providing the absolute beam emittance, in our case the WS.

The calibration runs were scheduled during the intensity ramp up fills at the machine startup and after the technical stops. It consist of a dedicated cycle with 10 bunches of different emittances and a couple of hours dedicated for flying the wires and optimizing the BSRT optical system. In average, three calibration runs took place per year during Run 2.

The system has been operational since 2015 and has improved over the years, especially with the new calibration technique, independent of the beam position monitors scaling errors coupled to the adoption of low noise digital cameras and a new generation of image intensifiers. The latter, not only 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. All this was possible following the improvements of the control system, implemented in the FESA server, that handles the automatic steering and settings management for a continuous operation.

The BSRT imaging system was reliably used in operation 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 to investigate the quality of the BSRT beam size measurement.

The accuracy of the absolute emittance provided by the system was found to be at the level of 20%, from the comparison with OP scans and estimations from the experiments instantaneous luminosity, while the relative accuracy (bunch by bunch) was estimated to be of the order of few %. However, contrarily to the measurements at constant energy (injection or Flat Top), the error during the energy ramp is much larger and results unusable for the moment due to the complexity of the light source (its longitudinal extension, spectrum and intensity dependence on the energy) and the high spread in the scan to scan wire scanner measurements.

In 2018, and over few months, the repeatability of the system was remarkably good, as shown in Fig. 4, where at a distance of 2 months from the last calibration, the agreement between the emittances seen by the WS and BSRT along the full LHC cycle was better than 10%. The system reliability suffered however from several limitations, as observed in Run 2, that can be summarized in the following:

Figure 5: The damages caused by the SR to the BSRT system: the image intensifier ageing, the etching of the viewport material and the coating deterioration of the NUV band-pass filter.

- **Image Intensifiers**: the major contributor to the BSRT accuracy degradation with time. The visible effect was a sensitivity reduction where exposed to the SR, deforming the sensor's response. The issue was investigated by the manufacturer identifying the photo-cathode to be the dominating component in the ageing. As the impact on the beam size determination was considerable, several mitigation strategies were implemented:

  – compensating the sensitivity non-uniformity at the SW level,

  – avoid operating in the damaged area of the sensor,

  – spot painting via motorization the camera on both transverse axes to continuously move to spread equally the photo-cathode wearing out.

  As a consequence, the integration time needed to be increased as well as the MCP gain with a direct implication on the maximum frame rate reachable with the digital cameras: increasing by an order of magnitude the needed time to scan the full ring compared to the maximum data flux the CPU can handle.

  Early in the run, small issues were also identified and solved: the coupling of external noise to the long cables carrying the analog gain signal of the MCP compromised the reliability of the I.I. requiring often manual resets.Additionally, the speed of the MCP Gain change, was found relatively slow and limited to ~ 5Hz therefore not suitable for a feedback on a bunch by bunch basis. The gain changes throughout the cycle was therefore implemented based on a feed-forward (w.r.t. energy). As a consequence, pilot bunches were visible only following an expert intervention, till it was further automated in 2018.

- **Optical components**: visual inspections during the technical stops showed viewports (vacuum exit window) and band-pass color filters being “marked” by the SR. The light distribution seems engraved in the fused silica of the viewport through an etching mechanism and printed on the coating of the filter as if "burnt" by SR density. Investigations of the etching mechanism are not conclusive yet, however according to the experts, Hydrofluoric acid (requiring fluorine atoms, NUV light and Oxygen) or derivatives could be the culprit, therefore all the Magnesium Fluoride mirror coating needs to be replaced. As for the filters, shuffling the the optical bench setup, moving the filters away from SR focusing plane to reduce the power density has cured the issue and the replaced filters showed no new damage.

- **Calibration reproducibility**: The calibration technique relies on the hypothesis of a Gaussian beam transverse distribution and a Gaussian optical point spread function (PSF). 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 caused by the extended source (D3) at Flat Top. 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%. Additionally, 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.

All of the aforementioned challenges hindered the accuracy and stability the system in Run 2 and will be tackled during LS2.

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 overcome optical resolution limitations and 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.

Contrarily to imaging, at a given slit separation it provides just the beam width while to obtain the beam profile a scan of slits separation is needed.

This technique was implemented in the LHC, for the first time in a proton machine: In 2015, a prototype was installed on the B1 optical table, side by side to the imaging system.

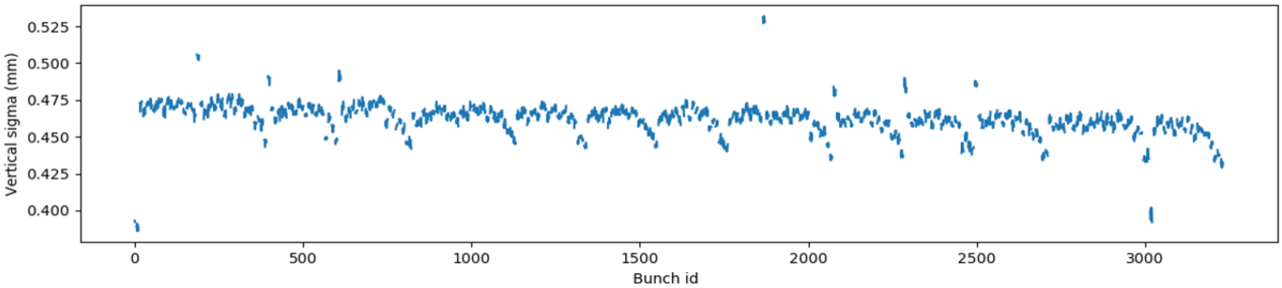

Figure 6: Precise Bunch by bunch vertical beam size measurements by the interferometer for lead ions at Flat Top in 2018.

The experience gained in some MDs allowed finalizing the interferometer setup and its installation in June 2016. A comprehensive set of measurements followed to qualify the interferometer comparing its results to the standard imaging system at both the injection energy and 6.5 TeV. The studies showed a good agreement at injection energy, while a discrepancy in the order of 30-40% between the two systems at top energy was found.

In 2018, the system was fully refurbished with a simplified version of the slits, allowing for precisely characterizing the quality of the measurements. Towards the end of the run, especially during the lead physics period, systematic studies to study agreement with WS took place. Although the precision of the measured beam size was remarkably good as seen in Fig. 6, the studies pointed out very important observations such as the dependence of the complex coherence factor on the slits position and not only on the beam size and slit separation. The observed discrepancy with respect to the WS was different for varying energies, as the SR imprint was changing. These results may imply the need of cross calibrating the interferometer w.r.t to the WS as well.

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, taking place in Run 2, consists of installing of a demonstrator on the B2 optical table side by side to the imaging system aiming at measuring 2D halo image with 10^{-3} to 10^{-4} contrast with respect to the beam core [5]. It profits from a collaboration with KEK who provided the special optics used previously in the Photon Factory coronagraph. Phase II follows, during LS2, with a custom optical system development, optimized for the LHC. The aim will be to probe contrast exceeding 10^{-5} in In Run 3.

In 2016 the synchrotron light coronagraph, was installed on Beam 2 and its working principal was demonstrated at 450 GeV. In a controlled experiment, 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. 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.

Later in 2017, the experiment was repeated at top energy and the contrast reach of the system was also quantified to be $4 - 6 \cdot 10^{-4}$, as shown in Fig. 7. The sensitivity to halo variation was found 10 times worse in horizontal than in vertical: $2 \cdot 10^{10}$ (horizontal) and $2 \cdot 10^{9}$ (vertical). Since then a big effort in modelling the system behavior for a realistic SR source is ongoing to understand this asymmetry and solutions are being implemented to push the performance further, such as a better angular selection of the light source.

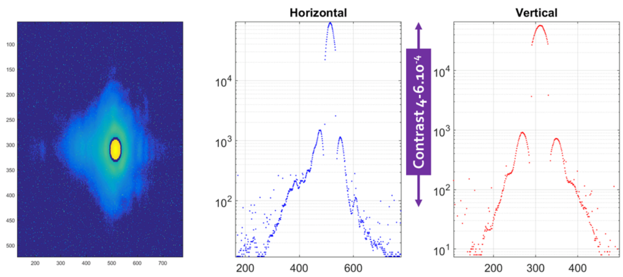

Figure 7: High dynamic range profiles obtained via the coronagraph at top energy, reaching a contrast of $4 - 6 \cdot 10^{-4}$.

EMITTANCE CALCULATION

The crosscheck between all the aforementioned techniques for beam size measurement can take place only with an accurate knowledge of the beam normalized emittance $\varepsilon_{n_{x,y}}$, expressed in Eq. 1:

$$\varepsilon_{n_{x,y}} = \frac{\gamma \cdot \beta_r}{\beta_{x,y}} \left[{\sigma_{x,y}}^2 - \left(D_{x,y} \cdot \frac{\delta P}{P} \right)^2 \right] \tag{1}$$

where γ and β_r are the relativistic parameters, $D_{x,y}$ and $\beta_{x,y}$ are the optical functions, $\sigma_{x,y}$ and $\frac{\delta P}{P}$ are respectively the beam size and the momentum spread.

For small beam emittances ($< 1\mu m$), significant errors could be introduced by neglecting the dispersive contribution to the beam size. Figure 8 quantifies this discrepancy introduced when computing for the various optics along the cycle with the nominal settings of the correction bumps, part of the operational LHC cycle, the dispersion function D for a given typical momentum spread. A maximum deviation of the beam emittance up to 12% could be observed at the start of the Squeeze beam process and is reduced to few units when the correction of the spurious dispersion of the crossing angles is fully introduced.

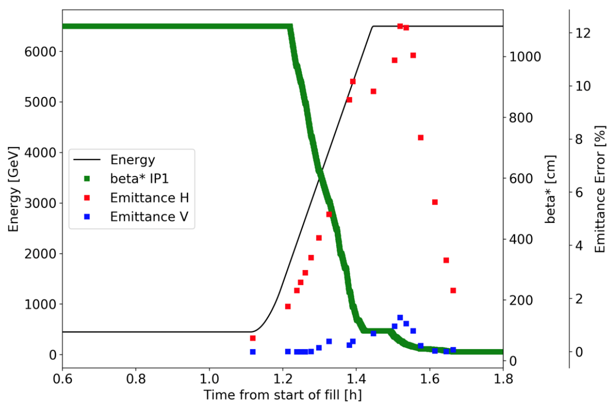

Figure 8: Evolution of the error committed when computing the beam emittance from the measured beam size from the WS, not accounting for the spurious dispersion along the nominal LHC cycle in 2018 .

It is also worth mentioning that accounting for the optics functions deviation w.r.t the model ones, as measured during the special runs by the OMC team, a systematic offset is still observed between the emittances computed from the beam size measured in IR4 (with both WS and BSRT) and the the emittances computed from the convoluted beam size inferred from the experiments luminosity in IP1/5. In the range of operational emittance (~2.5 μm), as shown in Fig. 9, the disagreement amounts to 10-15% in both planes.

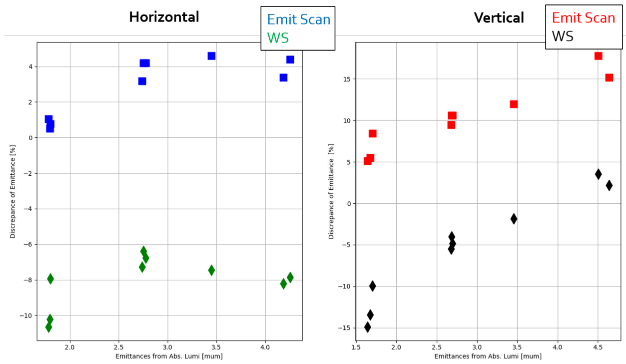

Figure 9: Discrepancy between the emittance obtained from the convoluted beam size measured via WS and the one estimated from the luminosity from both absolute luminosity of both experiments and the emittance scans.

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