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ASSESSING THE PERFORMANCE OF THE NEW BEAM WIRE SCANNERS FOR THE CERN LHC INJECTORS

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Abstract

Reliably measuring the transverse beam profile in the LHC injector chain is essential for the operation of the CERN accelerator complex. This report aims to assess the reliability, stability, and reproducibility of a new generation of beam wire scanners developed at CERN in the framework of the LHC Injectors Upgrade (LIU). The study includes data from over 60000 scans performed in 2021 and 2022, with a particular focus on reproducibility, investigation of optimal operational settings to ensure a large dynamic range, and evaluation of absolute accuracy through comparison with other instruments present in the injectors.

INTRODUCTION

The LHC Injectors Upgrade (LIU) [1] program started in 2010 with the purpose of improving the beam performance throughout the injector chain, in order to satisfy the specifications required by the High Luminosity LHC (HL-LHC) project, and was completed in 2021. In parallel to the improvement of the beam parameters, it was necessary to design various pieces of beam diagnostics instrumentation for the injectors: the LINAC4, the Proton Synchrotron Booster (PSB), the Proton Synchrotron (PS), and Super Proton Synchrotron (SPS). Following several years of design and testing of prototypes during the LHC Run2 (2015-2018) [2–6], the new beam instrumentation suite was installed during the second LHC Long Shutdown (LS2) in 2019 and 2020, while commissioning with beam started in 2021. This paper focuses on the description of the new LIU beam wire scanner (LIU BWS) design, giving a general overview followed by a more detailed evaluation of the performance at their particular location in each of LHC injectors involved: PSB, PS, and SPS.

THE LIU BEAM WIRE SCANNER

A BWS is an instrument designed to measure the transverse beam profile [7]. A thin wire passes through the beam producing a shower of secondary particles that are measured with a detection system. The rate of secondary particles is correlated with the position of the wire, allowing for the reconstruction of the 1-dimensional transverse profile of the beam, usually measured in the horizontal or vertical plane. Figure 1 shows a schematic of the LIU BWS working principle and architecture.

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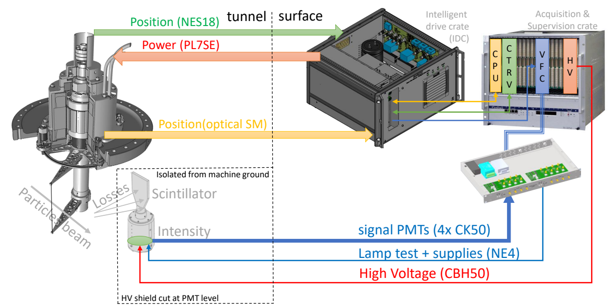

Figure 1: Schematic of the LIU BWS working principle and architecture [8]. The kinematic unit (the movable part of the scanner) and the detector measuring the secondary showers are placed in the accelerator's tunnel. These items are shown on the left side of the schematic. On the right side, we have the stand-alone control unit and the VME acquisition system, which are located in the service area on the surface. The CTRV is a CERN VME Timing Receiver board, while the VFC is the VME FMC Carrier board. The cables connecting tunnel and surface electronics are quite long, in some cases up to 150 m.

Upgrade Motivations

The design of a new LIU BWS was necessary in order to adequately measure the transverse profile of the new high intensity and brightness beams required by the HL-LHC project. The limitations of the present, old BWS are thoroughly discussed in previous works [9, 10] and here we briefly discuss some of the main shortcomings. The old wire scanners in the LHC injectors were either rotational (PSB, PS, SPS) or linear (SPS). The linear scanners in the SPS had strong limitations on beam intensity due to their low speed (1 m/s), leading to possible wire sublimation. For the rotational scanners the precision on the position of the wire was never better than 100 µm and was significantly degraded by electronic noise on the potentiometer reading, mechanical play, and vibrations [11]. From the operational point of view, the old wire scanners also required the operator to define the optimal working point for each measurement, which consisted of setting the detection parameters, i.e. the photo-multiplier tube (PMT) bias voltage and attenuation filter, before a beam profile could be measured. This often resulted in lengthy sessions of measurements. For the LIU BWS it was decided to design a unique standardised system, both, in terms of hardware and software, to satisfy the specifications of each of the LHC injectors. The LIU BWS is rotational, can be operated without need of selecting an op-

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timal working point, and features higher speeds of the wire, up to 20 m/s in the PSB and 24 m/s in the PS and SPS. The LIU BWS is designed to improve reliability and availability, and in some cases increase the accuracy of the beam profile measurement.

Hardware Upgrades Overview

The LIU BWS features carbon wires with a 30 µm diameter. The kinematic unit has moving parts only in vacuum and uses magnetic and optical means to transfer power and signals to the outside. A solid rotor resolver and an optical encoder are used to measure the position of the shaft. The rotor resolver is used for trajectory control [12], while the optical encoder is used to precisely infer the fork and wire position during a scan [13]. The encoder was calibrated using a laser and exploiting the reflective and anti-reflective slits (40 µm pitch) engraved on the optical disc mounted on the shaft. The calibration allows to compensate for the uncertainties of the wire trajectory that are caused by the large acceleration to which the carbon wire is subjected [14]. The secondary shower is measured using one plastic scintillator (BC-408) coupled to four PMTs (Hamamatsu R9880U) and a related data acquisition system (DAQ). Neutral density filters of different optical density are used in front of each PMT to provide four different levels of attenuation. This scheme enables to cover the large dynamic range of signals coming from the secondary showers, with beams varying in energy (from 160 MeV to 450 GeV) and intensities (from about 10×10^{10} ppb to about 500×10^{10} ppb) across the LHC injectors [10]. Finally, the four output signals are digitized simultaneously by fast FMC ADCs with a sampling rate of 500 MS/s, which is sufficient to measure the profile of each bunch in the beam.

BWS PERFORMANCE ASSESSMENT

The first prototype LIU BWS was validated in 2017 and 2018 in all the injectors [15], and seventeen BWSs with the final design were installed during LS2. These are eight units in the PSB, five units in the PS, and four units in the SPS. The commissioning of the BWSs in the LHC injectors started in 2021, following the restart of the PSB in December 2020. The new BWSs have been extensively used in 2021 and 2022 to setup, tune, and characterize the new LIU beams, resulting in tens of thousand of scans, as shown in Figure 2. The only system failure reported in 2021 was a broken wire, due to an issue with carbon wire copper coating (used to facilitate the wire fixation), which was already known since the first LS2 tests.

Measurement Examples and Working Point Studies

Figure 3 shows an example LIU BWS beam profile measurement in the horizontal plane of a LHC25 beam in the PSB. Each measurement results in four estimations of the beam size, corresponding to the four PMTs with different attenuation. The best estimation of the beam size can be obtained by properly changing the high voltage and using

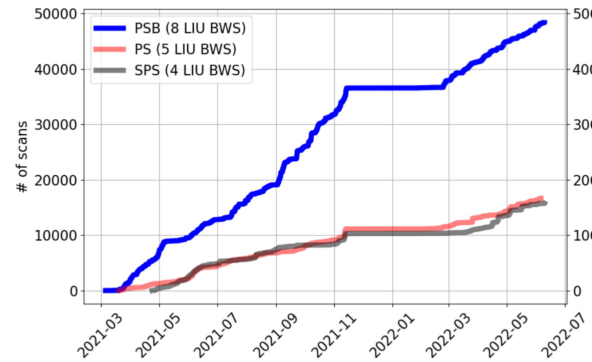

Figure 2: LIU BWS usage in 2021 and early 2022.

the appropriate PMT channel, with PMT channels with different attenuation agreeing within 3% in terms of beam size. The bias voltage for the PMTs must be chosen to ensure the signal is above the noise level, but at the same time does not saturate the digitizers or cause the PMTs to operate outside their linear regime. Both these effects may lead to an overestimation of the beam size. Currently, three high voltage bias levels can be selected by the operator to cope with the different beam types operated in the LHC injectors. Once the optimal high voltage has been selected, the BWS system has an algorithm to automatically select the best PMT read-out.

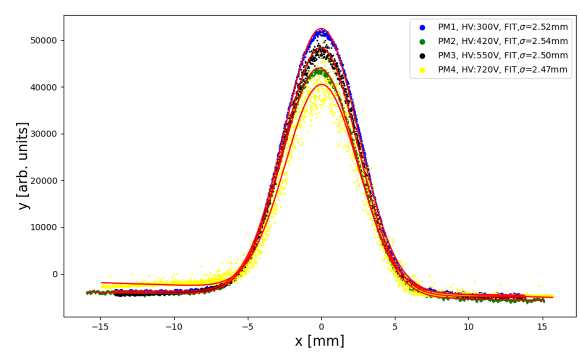

Figure 3: PSB horizontal profile of a LHC25 beam as measured by one of the LIU BWS.

Figure 4 shows one of the studies, performed to evaluate the selection of the optimal high voltage working point for the acquisition of a beam profile, in this case measuring the horizontal size of a LHCINDIV beam in the PSB. The high voltage was increased from 300 V to 1000 V in steps of 25 V and each time three scans were performed for statistical reasons. To select the best PMT for each measurement, we can either choose the one whose Gaussian fit to the beam profile corresponds to the minimum relative residual per point calculated as $\frac{1}{n}\sum_{i=1}^{n}\frac{|y-y_{fit}|}{y}$ where n is the number of points considered, or the one provided by the system's algorithm based on the ADC saturation detection. The upper plot of Figure 4 shows both histograms of beam sizes selected using either of these criteria. Both selections provide an average sigma of 2.21 mm, but the set of beam

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sizes selected by the algorithm has a lower relative standard deviation (STD). The same study has been performed for other PSB beams with similar results. That proves that the algorithm is working properly and it is able to automatically provide the optimal PMT for each measurement. The lower plot of Figure 4 shows all the beam sizes obtained during the same high voltage scan, with each PMT plotted with a different color. Noticeable, each PMT provides a stable measurement, about 2.21 mm, within a certain range (indicated by vertical magenta lines), but it is degraded outside this range due to noise (lower voltages) or saturation (higher voltages). Similar studies have been performed at the PS and SPS.

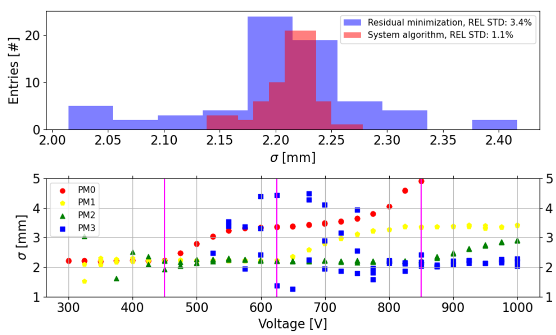

Figure 4: Top: comparison between residual minimization and algorithm methods to select optimal PMT. Bottom: voltage scan with vertical lines indicating optimal ranges for each PMT.

Figure 5 shows an example of LIU BWS measurement in the SPS for beams of type LHC25, with bunches separated by 25 ns. The upper plot shows the vertical profiles for each bunch in a batch of 72 bunches, and the lower plot the corresponding emittances. The emittance growth at the end of the batch is physical and it a result of electron cloud effects.

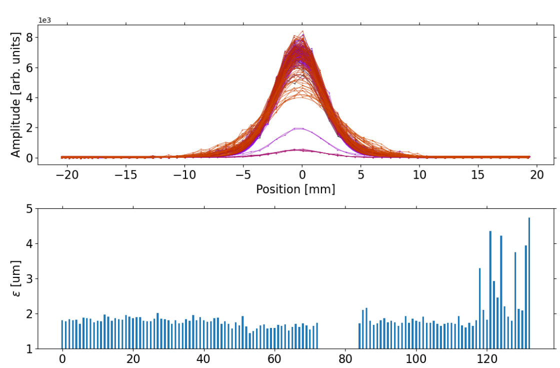

Figure 5: Top: SPS profiles of bunches separated by 25ns. Bottom: corresponding bunch-by-bunch emittances.

Preliminary Uncertainty Assessment

Since the LEGACY rotational BWSs were maintained in the PSB, we can directly compare them with the LIU BWSs. Figure 6 shows a comparison for the vertical emittance of different beams obtained with 30 measurements for each beam. We compare vertical emittances to minimize uncertainties arising from dispersion functions and momentum spread. The comparison indicates good agreement, demonstrating that the measurements provided by the LIU system are consistent. Mixing measurements from both systems and calculating the average RMS provides an upper limit estimation of the systematic uncertainty of 4%. The average statistical uncertainty is about 3% for the LEGACY system and 2% for the LIU system, and it was estimated from the RMS of the beams size distributions. Preliminary upper limit statistical uncertainty estimations on the beam size are 3% and 5% for the PS and SPS LIU BWSs, respectively.

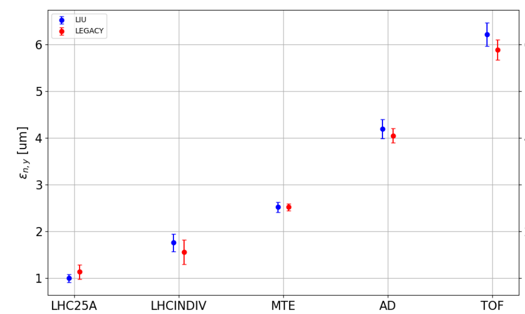

Figure 6: Comparison between LEGACY and LIU BWSs in the PSB for different beam types.

CONCLUSION AND OUTLOOK

The successful beam commissioning of the new LIU BWSs in the LHC injectors was presented, which demonstrated reliable and precise measurements with improved availability compared to the old BWSs. The next steps of the LIU BWS commissioning are the comparison between BWS and BGI in the PS, measurements at the SPS flat-top energy with reduced rotational speed, and further analysis where the uncertainty on the beam size measurement will have to be necessary decoupled from the bunch-by-bunch and shot-by-shot beam jitters, in order to provide a complete assessment of the LIU BWS absolute accuracy and resolution. Two new prototypes BWS have been designed for the LHC, in the context of an electro-mechanical consolidation, to cope with previous recurring operational system failures. The LHC prototypes are linear - in contrast with the rotational BWS installed in the LHC injectors in the context of the LIU upgrade - and mechanical modifications and new electronics have been designed. These prototypes will need to be extensively commissioned in expert mode, benefiting from the previous experience with the commissioning of the rotational BWS for the LHC injectors.

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