ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-MOPTS100

TRANSVERSE EMITTANCE MEASUREMENT IN THE CERN PROTON SYNCHROTRON IN VIEW OF BEAM PRODUCTION FOR THE HIGH-LUMINOSITY LHC*

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Abstract

In the framework of the LHC Injectors Upgrade project the improvements required to achieve the parameters of the future beams for the High-Luminosity LHC are being studied and implemented. In order to deliver high brightness beams, control over the beam intensity and emittance is fundamental. Therefore, a highly accurate and reliable transverse emittance measurement is essential. Presently at the CERN Proton Synchrotron, the only operationally available emittance monitors not impacting the facility beam production are the flying wire scanners used to measure the circulating beam profile. The wire scanners will be replaced with a new generation in the next two years and a prototype is already installed. The prototype has been commissioned with beams featuring a wide range of intensities and emittances. This paper evaluates the performance of the prototype with respect to the present system via beam-based measurements. The transverse emittance measurement is discussed, considering the different potential error contributions to the measurement, such as knowledge of the machine optics and the dispersive contribution to the beam size.

INTRODUCTION

The High Luminosity LHC (HL-LHC) [1] requires beam parameters that are beyond the present CERN injector chain production capabilities. In order to cope with this requirement, the present LHC injector chain is undergoing a substantial upgrade in the framework of the LHC Injectors Upgrade (LIU) project [2]. These upgrades will reshape drastically the lower energy part of the acceleration chain, with the goal of doubling the beam brightness. The achieved and target beam parameters are reported in Table 1. The intensity N will be doubled and the normalised transverse emittances $\epsilon_{x,y}$ retained at the present values. The brightness increase will be realised by increasing the injection energy to the Proton Synchrotron (PS), from 1.4 to 2 GeV, whilst increasing the longitudinal emittance ϵ_z and consequently the momentum spread $\delta p/p_0$ in order to limit the Laslett maximum space charge tune shift $\Delta Q_{x,y}$.

In order to deliver the required high beam brightness, a very tight transverse emittance blow up budget of only 5% will be tolerated from the PS Booster (PSB) extraction to the PS extraction [2]. Consequently, a very precise and accurate measurement of the transverse emittance becomes essential along the whole accelerator complex. This is particularly challenging in the horizontal plane, where the beam profile is modified due to the dispersion and the momentum spread. The increased momentum spread after the upgrade will worsen this effect. A number of studies have been conducted in the PS [3, 4] and in the PSB [5, 6] in the past years. Recently, a transverse emittance blow up in the transfer between the PSB and the PS has been measured and investigated [7]. This can be partially attributed to the existing dispersion mismatch at PS injection due to the design of the existing transfer line, which will be modified as part of the LIU project upgrade [8]. In this perspective, a reliable transverse emittance measurement is essential in both accelerators.

In the PS, the transverse emittance can be monitored by means of the wire scanner (WS) system [9] without disrupting the normal operation of the machine. Presently, three horizontal scanners (one of which is a prototype of the new generation [10]) and two vertical scanners are installed. The machine is also equipped with three Secondary Emission Monitors (SEMs) grids to sample the first few tens of turns of the injected beam [11] and scintillating screens in the extraction septa used mostly for steering [12].

The LHC physics programme is carried out using two different beam production schemes: the 'standard' 25 ns spacing scheme and the Bunch Compression Merging Splitting (BCMS) scheme. These constitute the two baseline beams that are foreseen to be used after LIU completion. The BCMS scheme was primarily used during the physics runs as it allows for a higher luminosity in the LHC with respect to the traditional scheme [13]. For this reason, this work concentrates on BCMS beams.

LIU WIRE SCANNER SYSTEM

A new generation of rotational beam wire scanners has been developed as part of the LIU project. They will replace all the current generation wire scanners [14] by the restart of the accelerator complex in 2020. The limited resolution of the wire position reading, mechanical vibrations, limited resolution of the secondary acquisition system and aging of the components constitute the main limitations of the present WS system. During the 2018 run, a prototype of the new generation wire scanner has been extensively tested in the PS and some of the results are presented here.

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Table 1: LIU Beam Parameters at the Proton Synchrotron Injection [15], Achieved and Target. The achieved parameters for the BCMS beam have been updated according to the latest results, summarised in [16].

		N (10^{11} p)	$\epsilon_{n,x,y}$ (μm)	E (GeV)	ϵ_z (eVs/b)	Δt (ns)	$\delta p/p_0$ (10^{-3})	$\Delta Q_{x,y}$
Present	Standard	16.84	2.25	1.4	1.2	180	0.9	(0.25, 0.30)
	BCMS	7.5	1.0	1.4	0.85	145	0.9	(0.24, 0.34)
Target	Standard	32.50	1.80	2.0	3.0	205	1.5	(0.18, 0.30)
	BCMS	16.25	1.43	2.0	1.48	135	1.1	(0.20, 0.31)

The new WS features an improved mechanical design to cope with the increasing request of speed and reproducibility. It is based on a rotational architecture, with a frameless motor, where all mobile parts are located in vacuum on a shared shaft [10]. Two metallic 3D-printed forks hold the wire assuring the necessary mechanical rigidity [17]. The wire position acquisition system is separated by the motion part and realised by means of an optical reflective disk that is read by a high accuracy optical encoder [18]. A multi photomultiplier system is used to detect with a high dynamic range the shower of secondaries generated by the wire-beam interaction, eliminating the need for optical filters [19].

During the 2018 run a significant amount of beam time was allocated to study the new WS prototype performance compared to the present system. The tests spanned all the intensity and emittance range available in the PS, concentrating mostly at injection energy. The prototype WS was operated at 10 m/s, while the old system operated at 15 m/s. Once made operational, the new WS system will operate at 20 m/s.

A number of test protocols were devised, e.g. the beam is scanned using both the WS systems within a delay of tens of ms to allow the beam filamentation. Then the WS scanning first is switched, normally every shot or after a batch of 20 scans. More complicated scanning patterns were also adopted, to assess the independence of the measurements from possible machine drifts. Another case is the brightness curve measurement shown in Fig. 1, where the emittance is measured shot by shot while the beam current is varied randomly. In that case a precision of 0.8% and 1.17% has been measured with the old and the prototype of the new system, respectively. Considering all the tests carried out, the instrument performed always better than 2% precision including the fluctuations of the beam itself. In view of this experience, a WS precision of 1.5% is assumed in this work. The accuracy of the system is assessed in the lab where the wire scanner is calibrated using a dedicated test bench. Additional information about the process can be found in [10].

TRANSVERSE EMITTANCE MEASUREMENT

The beam transverse normalised emittance is usually calculated by mean of the well-known formula

$$\epsilon_{n,x} = \left(\sigma^2 - D_x^2\delta_{\mathrm{RMS}}^2\right)\frac{\beta_r\gamma_r}{\beta_x} \quad (1)$$

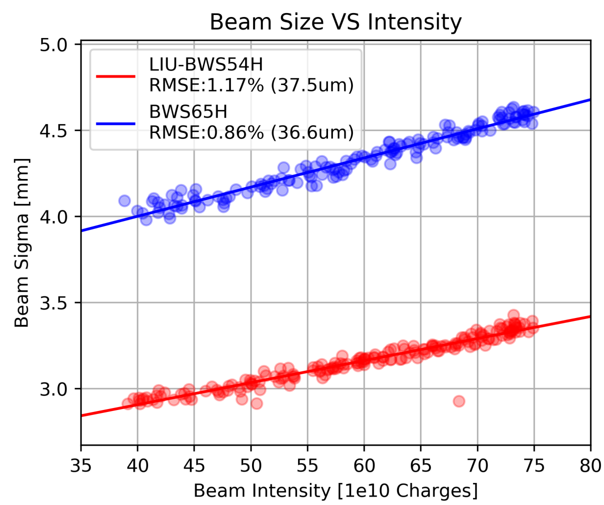

Figure 1: Brightness curve measurement using the new WS system (LIU-BWS54H) and the old one (BWS65H). Note that the optic functions are different at the two apparatus locations (see Table 2).

where σ is the standard deviation of the beam profile fitted with a Gaussian function, β_x and D_x the betatron and dispersion functions, δ is the momentum spread, and β_r and γ_r the relativistic parameters. This formula holds on the assumption that both the beam transverse and longitudinal profile are Gaussian. All the parameters are measured and the precisions of the single measurements are taken into account. Assuming the various sources of error as independent, the emittance measurement precision is given by linear error propagation as

$$\sigma_{\epsilon_{n,x}} = \beta_r\gamma_r\left[\left(\frac{2\sigma}{\beta}\sigma_\sigma\right)^2 + \left(\frac{2D\delta}{\beta}\right)^2\left(\delta^2\sigma_D^2 + D^2\sigma_\delta^2\right) + \left(\frac{\sigma^2 - D^2\delta^2}{\beta^2}\sigma_\beta\right)^2\right]^{\frac{1}{2}} \quad (2)$$

where the relativistic parameters are considered free of error. The implication of the beam longitudinal non-Gaussian profile are discussed in [20].

Optics Measurements

Both the betatron and the dispersion functions were measured during the 2018 run. The betatron function has been

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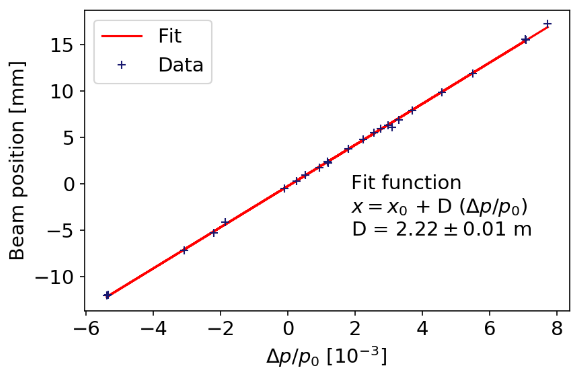

Figure 2: A dispersion measurement realised using the prototype wirescanner.

measured with high precision using a novel method, presented in this conference [21]. After exciting the beam oscillation by means of a kicker or an AC dipole, this technique makes use of turn-by-turn phase measurements together with the machine optics model in order to measure the beta function at the beam position monitor (BPM) locations. It is also independent from the BPM calibrations. The beta function value is then propagated to the neighbouring elements by mean of the optics model. This is convenient in the PS case, where a BPM is installed in close proximity to each wire scanner.

The horizontal dispersion is measured introducing a beam energy offset in the machine and sampling the response of the beam position. In the PS this is realised by change of the RF frequency. Both the BPMs and the WS can be used to sample the beam position change. The introduction of the new WS increased the beam position determination precision from ≈70 µm to ≈10 µm benefiting from the optical encoding system. These values have been measured on a dedicated calibration bench [22]. The WS are used to measure the dispersion, as the precision is superior to the BPM system, capable of a precision between 80 and 150 µm on the BCMS-type beams [23]. Figure 2 shows a typical dispersion measurement using the wire scanner.

The results of the optics measurements are presented in Table 2. The vertical dispersion is assumed to be negligible in the machine.

Table 2: Optic Functions Values at Horizontal and Vertical Wire Scanner Locations

Device	β_x [m]	D_x [m]
LIU WS	12.70 ± 0.08	2.22 ± 0.01
BWS65	22.3 ± 0.4	3.200 ± 0.008
Device	β_y [m]	D_y [m]
BWS85	11.53 ± 0.11	-

Momentum Spread

The longitudinal phase space is reconstructed by tomography [24, 25] over a user-defined number of turns. This allows to project the momentum spread profile and calculate δ_{RMS} to input in Equation 1.

At the moment the phase space tomography system is being rebuilt and upgraded. So the accuracy and precision evaluation of the system goes beyond the scope of this paper. It is immediate from Equation 2 that after LIU, the increased value of δ will worsen the emittance measurement precision.

The emittance is evaluated using the parameters in Table 1, assuming a precision of the δ_{RMS} of 2%, and that the precision of the WS remains constant in the face of a change in beam size up to half a mm. For BCMS beams it increases from 6.7% to 8.2% after the upgrade in the WS at the position of the old system, and from 6% to 7.1% for the new WS used in the tests. In the case of the standard beam production scheme, the increase is from 4.8% to 9.7% and from 4.2% to 8.6%, respectively.

CONCLUSIONS

The emittance measurement for high brightness beams in the PS has been discussed including the possible sources of error under the assumption of Gaussian beams.

In the vertical plane, the dispersion is a factor 10^2 smaller than in the horizontal plane and a factor 10^3 smaller than the betatron function. For this reason it can be neglected and the direct measurement of the betatron emittance from the beam profile is possible. This facilitates the emittance calculation, making possible to measure emittance with a precision better than 3.5%.

Conversely, in the horizontal plane there are no zones free of dispersion in the PS. This means that the effect of the dispersive component is always relevant, and it will worsen after the upgrade due to the momentum spread increase. Under the assumption of Gaussian beams, an emittance measurement precision of $\approx 7-8\%$ is expected depending on the position of the wire scanner in the ring for the BCMS beam production scheme. More dramatic is the scenario for the standard beam production scheme, that sees the error on the emittance measurement almost doubled, due to the larger momentum spread.

These results will be validated at the restart of the accelerator, when all the new wirescanners will be installed and the tomoscope upgraded. Future work will include the study of the effect of the betatron and dispersive beam profile convolution, applied to the beams after the upgrade. The studies of the systematic differences between the different accelerators of the LHC injection chain and the various wirescanners installed in the PS will also continue at the restart of the accelerator complex.

ACKNOWLEDGEMENT

We would like to thank the CERN PS & PSB operation teams for their invaluable help. A special thanks for the support and the useful discussions goes to S. Albright, F. Antoniou, H. Damerau, A. Lasheen, A. Oeftiger, A. Santamaria Garcia, J. Belleman, and the colleagues from the Beam Instrumentation and Beam Transfer teams.

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-MOPTS100

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