

SYSTEMATIC STUDIES OF TRANSVERSE EMITTANCE MEASUREMENTS ALONG THE CERN PS BOOSTER CYCLE

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Abstract

The CERN Proton Synchrotron Booster (PSB) will need to deliver two times the current brightness to the Large Hadron Collider (LHC) after the LHC Injectors Upgrade (LIU) [1] to meet the High-Luminosity-LHC beam requirements. Beam intensity and transverse emittance are the key parameters to increase brightness, the latter being more difficult to manipulate.

It is, therefore, crucial to monitor not only the emittance evolution between the different injectors but also along each acceleration cycle. To this end, detailed emittance measurements were carried out for the four rings of the PSB at various times in the cycle with different beam types. A thorough analysis of systematic error sources was conducted including multiple Coulomb scattering happening during profile measurements with wire scanners, where experimental and analytical treatments of the emittance blow-up were compared to FLUKA simulations. In order to properly account for the dispersive contribution, the full momentum spread profile was considered using a deconvolution method. We conclude with an assessment of this first comprehensive emittance evolution measurement along the PSB cycle.

INTRODUCTION

The PSB is the first accelerator in the injector chain of the LHC, composed of four superposed rings that have a common injection and extraction beamline. The PSB presently receives protons from the linear accelerator Linac2 at an energy of 50 MeV and accelerates them to 1.4 GeV. The injector chain will be upgraded between 2019 and 2021 to deliver two times the current beam brightness to the LHC [2]. The beam brightness is defined as [3]:

$$B_n = \frac{2I}{\pi^2 \epsilon_x \epsilon_y}, \quad (1)$$

where I is the beam intensity and $\epsilon_{x,y}$ is the normalized beam emittance in the horizontal/vertical plane. The beam intensity will be increased to double the beam brightness, but this will in turn amplify unwanted space charge effects. Space charge can cause emittance blow-up and has stronger implications at lower energies.

In order to be able to operate with an increased intensity for the same transverse emittances, the injection energy will be increased to 160 MeV with the connection of Linac4 so that the space charge tune spread remains roughly the same. On the other hand, the monitoring and control of the emittance is also key to achieve the desired beam brightness,

as can be seen from Eq. 1. Any source of emittance blow-up along the PSB cycle needs to be identified and mitigated to maintain a high brightness beam. The emittance $\epsilon_{x,y}$ can be calculated from a measurement of the beam size as

$$\epsilon_{x,y} = \left(\frac{\sigma_{x,y}^2}{\beta_{x,y}} - \frac{D_{x,y}^2 \delta^2}{\beta_{x,y}} \right) \beta_{rel} \gamma_{rel}, \quad (2)$$

where $\sigma_{x,y}$ is the beam size, $\beta_{x,y}$ the beta function, $D_{x,y}$ the dispersion function, δ the momentum spread, and β_{rel} and γ_{rel} the relativistic factors (Fig. 1).

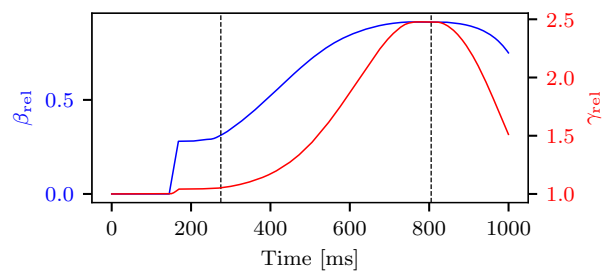


Figure 1: The relativistic factors β_{rel} and γ_{rel} along the PSB cycle. The dashed lines indicate injection and extraction times (at 275 ms and 805 ms, respectively).

The emittance values presented in this study are calculated with Eq. 2, where the beam profile and momentum spread were measured and the optics functions $\beta_{x,y}$ and $D_{x,y}$ were calculated with MAD-X (Methodological Accelerator Design) [4] by matching the measured tunes for each beam type and selected time in the operational cycle.

ANALYTICAL CORRECTIONS TO EMITTANCE MEASUREMENTS

Emittance Growth due to Wire Scans

The beam size can be derived from beam profile measurements carried out with a wire scanner. A wire scanner consists of a thin wire that crosses the beam during several turns, creating a shower of secondary particles that is detected with a scintillator coupled to a photomultiplier. For each wire position during a scan, the photomultiplier signal is proportional to the number of particles intercepting the wire, which allows to reconstruct the beam profile [5]. The measurement result can be biased by the interaction of the particles with the wire.

The charged particles traversing the wire suffer repeated elastic interactions due to the electrostatic forces of the wire atoms. Depending on the wire characteristics and the energy

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of the particles the interaction will result in single, plural, or multiple Coulomb scattering. This translates into a net deflection from the particle's direction that results in an artificially wider beam profile, leading to an overestimation of the emittance that needs to be compensated. Such an effect was studied in detail for the Super Proton Synchrotron (SPS) [6, 7], where the emittance blow-up was estimated analytically using Molière's theory for small angle deflections. In this approximation the scattering distribution is fitted to a Gaussian [8]:

$$\sigma_\theta = \frac{13.6}{p\beta_{\text{rel}}} \sqrt{\frac{X}{X_0}} \left[1 + 0.088 \log_{10} \left(\frac{X}{X_0} \right) \right], \quad (3)$$

where p is the particle momentum, β_{rel} is the relativistic velocity factor, X is the thickness of the scatterer and X_0 its radiation length. The constants 13.6 and 0.088 are called Highland constants and were recalculated in [8] via Monte Carlo simulations to optimize the result for all atomic numbers. This approximation is accurate to 11% for $10^{-3} < X/X_0 < 100$ for particles with $\beta_{\text{rel}} = 1$.

The emittance growth caused by an angular kick θ , such as the net deflecting angle in multiple Coulomb scattering, can be calculated from the induced change in the action J of the particle [9, Chapter 2.III.9], given by

$$\Delta\epsilon = \langle \Delta J \rangle = \frac{1}{2} \beta \langle \theta^2 \rangle = \frac{1}{2} \beta \theta_{\text{RMS}}^2, \quad (4)$$

where θ_{RMS}^2 is the root mean square of the angle, which in this case is also equal to the square of the standard deviation σ_θ^2 .

Combining Eqs. 2 and 3, we can calculate the emittance growth caused by one passage of the beam through the wire. However one measurement takes hundreds of passages, depending on the wire speed and the revolution frequency. This can be taken into account by adding a probability factor for the interaction with the wire during a scan $n = X f_{\text{rev}} / v_{\text{wire}}$, where f_{rev} is the revolution frequency and v_{wire} the speed of the wire. The cylindrical geometry of the wire also needs to be taken into account since not all the particles will traverse the same wire thickness. The average traversed thickness is $X = \pi d / 4$, where d is the wire diameter. Equations 3 and 2 paired with the probability factor n and average traversed thickness have been used in [6, 7] to estimate the emittance growth caused by the wire scans in the SPS. The same approach was used in flying wire simulations in the PSB [10]. In this study we will use the same analytical treatment and compare it to emittance measurements at different energies along the cycle.

Deconvolution of the Measured Beam Profile

In the horizontal plane, the beam profile measured with the wire scanner is a convolution of the betatronic and dispersive contributions. In order to calculate the betatronic emittance and use it as a beam quality indicator for comparison with other accelerators the dispersive part needs to be removed from the measured profile. It is common to

do this by simply considering the root mean square value of the momentum spread δ . However, this approximation might not be sufficient if the momentum profile follows a non-Gaussian distribution as in the PSB. The LIU beam brightness requirements set tight limits on the precision and accuracy of the measurement of emittance, which is why efforts are being put into testing more accurate methods such as doing the full deconvolution of the measured beam profile [11]. This method is used in this study to calculate the betatronic emittance (see Fig. 2).

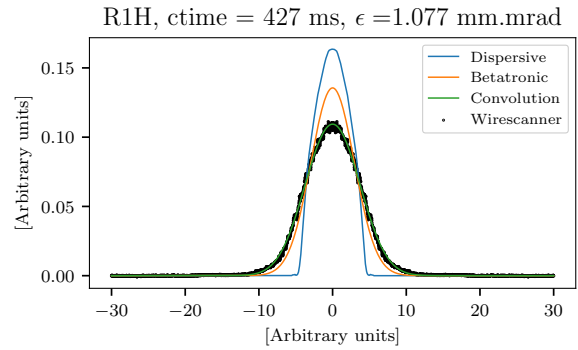


Figure 2: Usage of the deconvolution algorithm presented in [11], where the betatronic part is calculated by deconvoluting the measured beam profile from the measured dispersive contribution. The measurement was done in ring 1 horizontal at a cycle time of 427 ms.

EMITTANCE MEASUREMENTS

Measurements were carried out on the BCMS (Bunch Compression; Merging and Splitting), LHC25, and LHC50 beam types, but only the results for the BCMS beam are presented in this paper. The BCMS beam has a nominal intensity of 8.5×10^{11} protons and transverse emittances smaller than $1.2 \mu\text{m}\cdot\text{rad}$ at extraction. The beam profile was measured with the wire scanner and the energy profile for deconvolution with the tomoscope [12]. Additionally, the beam profile was also measured with a SEM (Secondary Emission Monitor) grid system. Three SEM grids are located in the PSB Beam Measurement line for an independent emittance measurement, which is a single pass location in the extraction line. By measuring the beam profile before and after a wire scan was performed in the ring we can extract the relative emittance blow-up caused by the flying wire and compare it to the analytical corrections.

The emittance measurements are presented in Fig. 3 for ring 1, where the dispersive contribution was removed with the deconvolution method in the horizontal plane and the error bars represent one standard deviation. The calculated emittance blow-up due to the flying wire and measured with the SEM grids was subtracted from the measured betatronic emittance ('Experimental compensation'). The wire diameter used in the analytical treatment is $d = 24.9 \mu\text{m}$ ($X = 19.6 \mu\text{m}$) and the radiation length of carbon $X_0 = 18.9 \text{ cm}$. The wire speeds used are an average of the recorded speeds

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at the time of the measurement of 14.1 m/s in the horizontal plane and 13.9 m/s in the vertical plane.

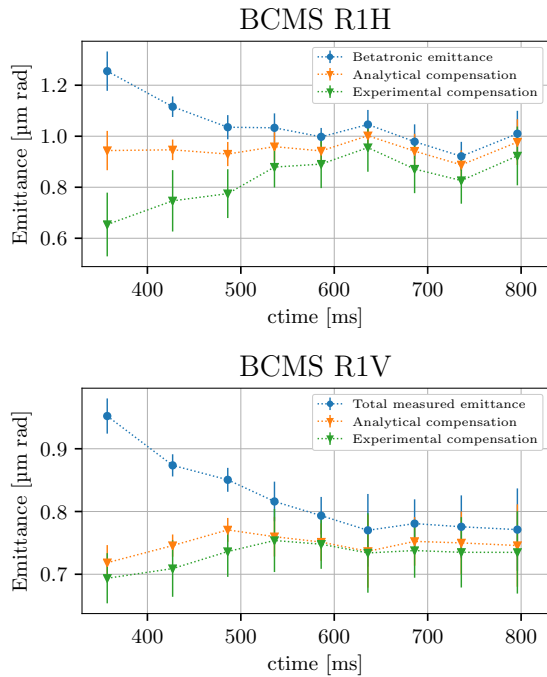


Figure 3: Emittance measurements in the horizontal (top) and vertical (bottom) planes in ring 1 for a BCMS-type beam with analytical and experimental corrections.

We can observe that the formula fits the experimental data in the vertical plane, while it underestimates the emittance blow-up in the horizontal plane. Looking at only the measured and calculated emittance blow-up shown in Fig. 4, we can see that in this particular case the analytical prediction follows the trend of the data despite being a thin wire scattering low energy particles ($X/X_0 = 1 \times 10^{-4}$ and $\beta_{rel} = [0.34 - 0.91]$ in the PSB). The error bars represent one standard deviation, showing good agreement between the data and the analytical formula. Nevertheless, a shift in values is observed for the horizontal plane. The source of this discrepancy is currently not understood, but it could be related to the systematic difference observed between emittance measurements taken with the wire scanner and the SEM grid at the PSB [13].

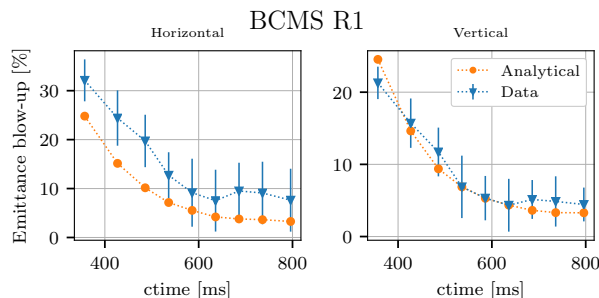


Figure 4: Calculated and measured emittance blow-up with the SEM grids due to the flying wire for ring 1.

PREDICTING THE EMITTANCE BLOW-UP WITH FLUKA

The wires used at CERN have diameters on the order of tens of microns, which means that a small variation in the wire thickness due to fabrication variations or usage can change the Coulomb scattering angle distribution considerably. Simulations were carried out in order to assess the impact of the wire characteristics on the analytical compensation of the emittance blow-up caused during a wire scan. The Monte Carlo code FLUKA [14, 15] is frequently used at CERN for various applications involving particle interactions with matter.

In the present study, FLUKA was used to simulate the interaction of beam particles with the wire scanner. Single Coulomb scattering was requested for the beam transport in the wire. Despite of the increase of computational time associated, this treatment is more accurate than the standard Multiple Coulomb scattering model described in [16]. Additionally, the multi-turn approach in FLUKA presented in [17] was used for the PSB wire scanners in order to simulate the beam particle tracking in the accelerator using a simplified model.

The simulation was done for ring 1 vertical and the results are shown in Fig. 5. We can observe that a variation in size of a few microns can change the estimation of the emittance blow-up by a few percent. We can see that the best fit to the data corresponds to an effective wire diameter of 16 μm , which diverges from the equivalent diameter $X = 19.5 \mu\text{m}$ used in the calculations. This could be due to the fact that the wire used for this measurement is multi thread, which constitutes a more complex geometry than a cylindrical, mono strand wire.

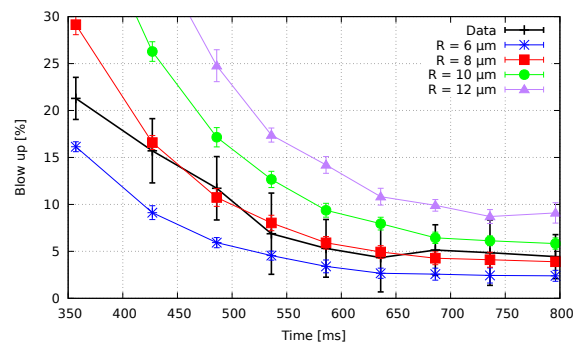


Figure 5: Sensitivity study to the wire size carried out with FLUKA for ring 1 vertical.

Additional simulations were done concerning the sensitivity to wire speed and wire density, which were found to have a lower impact on the final results.

CONCLUSIONS AND OUTLOOK

Emittance measurements show no unexpected sources of blow-up along the acceleration cycle in ring 1. The analytical prediction of the emittance blow-up caused by multiple

Coulomb scattering on the flying wire reveal a clear dependency on the wire size. Considering the transverse emittance blow-up budget of only 5% after LIU it becomes apparent that a very precise knowledge of the beam instrumentation used is essential, especially at the PSB injection energy.

ACKNOWLEDGMENTS

The authors would like to thank G. Sterbini, A. Guerrero, and the CPS operators for their valuable help!

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