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STUDY OF THE TRANSVERSE EMITTANCE BLOW-UP ALONG THE PROTON SYNCHROTRON BOOSTER CYCLE DURING WIRE SCANNER OPERATION

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Abstract

Transverse emittance measurements with wire scanners have been extensively studied across the accelerator complex at CERN due to their important role in characterizing the beams and their complicated modelling. In recent years, this topic has been of particular interest for the LHC Injectors Upgrade (LIU) project, where a tight transverse emittance blow-up budget between the Proton Synchrotron Booster (PSB) and the Proton Synchrotron (PS) is imposed to ensure the required beam brightness for the High Luminosity LHC (HL-LHC). In order to maintain a high brightness beam, any source of emittance blow-up along the PSB cycle needs to be identified and mitigated. While wire scanners have been mostly used at extraction energy in the PSB, they can also operate along the energy cycle. The scattering of the protons with the wire increases considerably at lower energies, leading to an overestimation of the beam emittance. In this proceeding we present the most recent studies, focusing on precisely quantifying the blow-up created by the flying wire with measurements in an optimized set-up and compared to FLUKA simulations.

INTRODUCTION

The HL-LHC project aims at a tenfold increase in annual recorded luminosity, which will be achieved by reducing the beta function at the interaction points and increasing the beam brightness delivered by the injectors, among other strategies [1,2]. Peak luminosity and brightness are inversely proportional to the beam emittance, which ideally needs to be preserved during the acceleration process across injectors to ensure maximal luminosity at the LHC. In this context the identification of unexpected sources of emittance blow-up becomes an important part of the PSB operation, given that it is the first accelerator of the injector chain and it is where the brightness of the LHC beams is defined. Wire scanners are the only instrumentation available in the PSB rings that can be used to measure the beam emittance. They consist of a thin wire that crosses the beam during several turns, creating a shower of secondary particles that is later detected and transformed to a signal proportional to the number of particles intercepted by the wire. The elastic scattering of the protons at the wire is non negligible at low energies and (or) long lasting scans, such as at the PSB injection kinetic energy (50 MeV), and results in an emittance growth that biases the measurement. In order to be able to accurately predict the emittance blow-up caused by the measurement itself multi-turn FLUKA simulations were started in recent years [3]. This study presents the latest results concerning this effort, such as the successful reproduction of the observed asymmetric profiles, emittance measurements at two different wire speeds, and a discussion on the type of data analysis performed.

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EMITTANCE MEASUREMENTS AND REPRODUCTION WITH FLUKA

Measurement Set-Up

The operational Batch Compression Merging and Splitting (BCMS) beam type [4] for LHC in 2018 was used to carry out the emittance measurements in Ring 3, where the vertical shaving was removed. The tune was set to be constant along the cycle and the beta function was obtained from the optics model matched for that particular tune. These measurements were performed only in the vertical plane in order to remove systematic errors from the dispersive contribution [3]. The average speed of the different wire scans was obtained from the recorded and linearised wire position, which were found to be lower than the specified ones (8.8 m/s for the expected 10 m/s scans and 13 m/s for the expected 15 m/s scans).

Multi-Turn FLUKA Simulations

The Monte Carlo code FLUKA [5,6] was used to simulate the interaction of the proton beam with the wire. The simulated wire was a mono strand type, i.e. of cylindrical shape, with 33 μm of diameter and made of graphite with a density of 1.8 g/cm^3. Due to the thinness of the wire the scattering is very localized. To account for this, FLUKA's single scattering option was enabled in the simulations to replace the multiple Coulomb scattering approximation. Interactions with the wire are then integrated analytically without approximations, with corrections for nuclear and spin-relative effects. A wire scan takes place during several passages of the beam through the wire, so the recently developed multi-turn approach in FLUKA [3,7] was used.

Data Analysis Considerations

In order to test the accuracy of the fits to the beam profiles we took advantage of the fact that the position of all the particles in phase space are known in the FLUKA simulation. This allows to calculate the Root Mean Square (RMS) emittance statistically [8] and to compare it to a Gaussian fit. Figure 1

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shows two different calculations of normalised emittance performed on the same data set, obtained from a FLUKA simulation of the flying wire with a Gaussian distributed beam. We can see the large disagreement between methods at the beginning of the cycle, and how it reduces as the emittance blow-up decreases with time. This is due to the fact that at injection the beam profile is considerably deformed by the measurement itself (shown in the next section), losing its Gaussian properties. Both methods converge when the beam conserves its shape after the measurement. These results suggest that the sole Gaussian fit method is not adequate for low kinetic energies, below 400 MeV (cycle time = 500 ms).

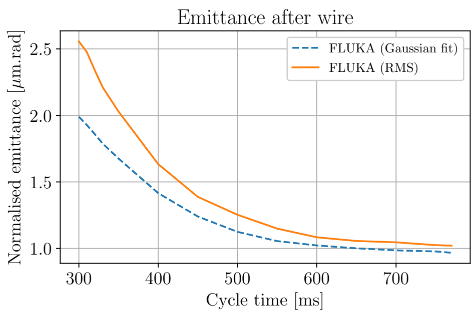

Figure 1: Normalised Emittance Calculated from the Simulated Particle Distribution, Observed After the Wire Scan.

Reproduction of Asymmetric Profiles

Previous studies [9] showed that the main contribution to the asymmetry of the beam profiles measured with the wire scanner comes from the Coulomb scattering of the beam particles at the wire during the measurement, while other effects such as space charge are negligible in comparison. FLUKA simulations showed that, in fact, the profile asymmetry observed experimentally is reproduced by only considering contributions from scattering, as shown in Fig. 2. Wire scanner measurements are done in time (here translated to position in the horizontal axis), which means that the emittance blow-up will grow as the scan advances (from left to right in Fig. 2) and the particles interact with the wire. A clear asymmetry is seen as a result of this, particularly for lower energies where wide angle scattering is more prevalent. We can also observe from this figure that the measured beam presents non-Gaussian tails, while the FLUKA simulation was done assuming a Gaussian distribution matched to the optics at the wire. Since tails contribute to the beam emittance, an accurate modeling of the observed beam profile will be included in future simulations.

Emittance Measurements

Figure 3 shows the normalised emittance calculated from wire scanner measurements along the acceleration cycle for two different wire speeds compared to the FLUKA simulations. Only measurements with similar intensities were kept for analysis since in the PSB the beam emittance increases linearly with the injected intensity due to the multi-turn injection system, and the injected intensity can fluctuate with every shot (~ 5 %). The average intensity for the measurements at 8.8 m/s was $46 \pm 1 \times 10^{10}$ protons and $42 \pm 1 \times 10^{10}$ protons for the ones at 13 m/s.

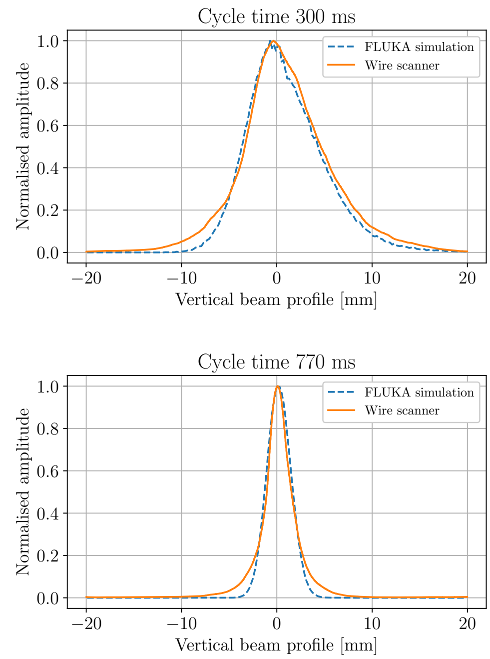

Figure 2: Beam profiles measured with the wire scanner and simulated with FLUKA after the injection (top) and at extraction (bottom) kinetic energies (61.2 MeV and 1.4 GeV).

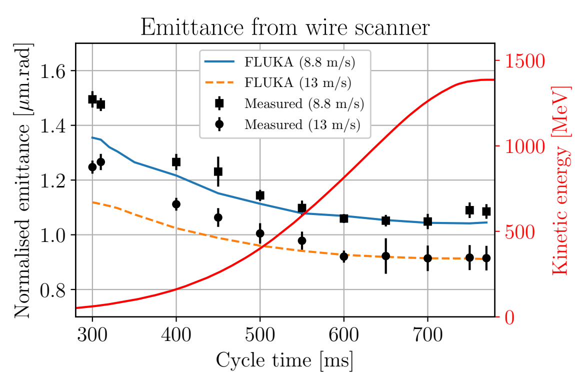

Figure 3: Normalised vertical emittance calculated from a Gaussian fit to the beam profile (measured and simulated) along the PSB acceleration cycle, which is shown in red.

Firstly, we can observe that despite having a higher average intensity, the emittance for the measurements at 13 m/s is lower than the ones for 8.8 m/s. Such a behavior was already observed in [10], where measurements at higher speeds yielded thinner profiles despite measuring at similar intensities. This can be due to a difference in calibration among wire speeds. The initial normalised beam emittances considered in the FLUKA simulation were ε_{H0}=1.208 μm·rad in the horizontal plane, ε_{V0}=0.96 μm·rad for the 8.8 m/s case, and ε_{V0}=0.83 μm·rad for the 13 m/s case, in the vertical plane. We can also observe from Fig. 3 that simulation

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Table 1: Predicted Emittance Blow-up at the Wire Scanner by FLUKA

Cycle time [ms]	Energy [MeV]	f_{rev} [MHz]	[10^{-2} μm.rad]		[%]	
			8.8 [m/s]	13 [m/s]	8.8 [m/s]	13 [m/s]
300	61.2	0.66	39.5	28.9	41.1	34.8
310	67.3	0.69	38.8	28.2	40.4	34.0
400	161.3	1.0	34.4	26.7	35.8	32.2
450	258.3	1.18	25.7	19.4	26.7	23.4
500	400.0	1.36	15.3	13.0	16.0	15.7
550	591.0	1.51	11.9	11.1	12.3	13.4
600	814.6	1.61	10.9	9.7	11.3	11.6
650	1052.3	1.68	9.4	8.9	9.8	10.7
700	1261.9	1.73	8.4	8.4	8.7	10.1
750	1378.0	1.74	8.2	8.3	8.5	10.0
770	1386.7	1.75	8.5	8.1	8.9	9.8

and measurement agree better at higher energies. The particle scattering at the beginning of the PSB energy cycle is very sensitive to the wire parameters such as radius and density, as well as to the wire speed and initial emittance [3]. The presence of tails in the experimental data might also contribute to this disagreement. On the other hand, larger scattering angles lead to immediate beam loss, as shown in Fig. 4. The source of these large angles is likely due to the strong interaction scattering, as the Coulomb threshold for protons with carbon-12 is ≈ 3.6 MeV [11].

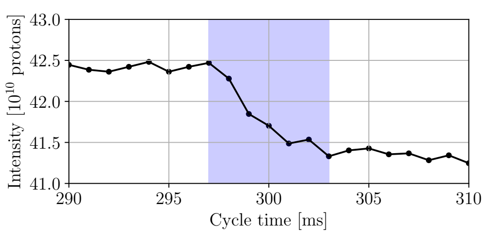

Figure 4: Beam intensity during a wire scan at 8.8 m/s, where the duration of the scan is marked in blue.

Prediction of Emittance Blow-Up with FLUKA

The emittance blow-up caused by the flying wire not only depends on the beam energy and duration of the scan (given by the revolution frequency and wire speed), but also on the wire characteristics, initial beam emittance, and beam distribution. It is therefore difficult to provide universal emittance blow-up values for the PSB energy cycle, but Table 1 can serve as reference for the values that can be expected in a BCMS cycle. We can see that scans at lower speeds create more emittance blow-up at the beginning of the cycle, and that this difference is flattened at higher energies and revolution frequencies. Below a kinetic energy of 400 MeV, the fit is considered unreliable due to the amount of asymmetric deformation of the profile. The emittance blow-up values predicted by FLUKA can be subtracted from the experimental data to obtain what should be the unperturbed emittance. Figure 5 shows how the measured normalised emittance would look like after the emittance measurement blow-up removal. We can observe that the emittances are fairly constant along the cycle. The increase of the emittance visible in the last two points of the 8.8 m/s measurements has been identified as the effect of the radial steering changes done for extraction synchronisation with the downstream PS. We can conclude that no sources of emittance blow-up were present during these measurements, and that this method has sufficient precision to be used for this purpose.

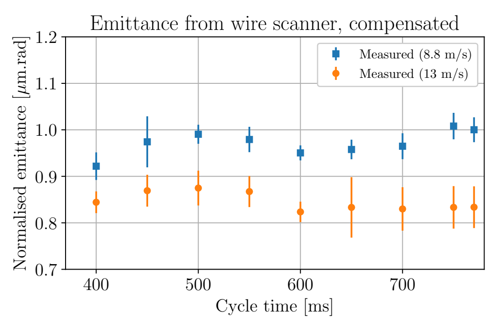

Figure 5: Normalised vertical emittance measured with the wire scanner along the PSB cycle without blow-up.

CONCLUSIONS AND OUTLOOK

The multi-turn FLUKA code has proven to be a flexible tool that can deliver quick and accurate predictions on the emittance blow-up by the wire passage, reproducing the most characteristic features that were observed experimentally. Through these studies we could show emittance preservation during the PSB acceleration cycle within the errors when subtracting emittance blow-up effects due to the measurement itself. With a better knowledge of the wire's parameters and a good reproduction of the observed beam distribution the accuracy of the simulations will be improved in future studies. We also studied the importance of the fitting methods used to treat the data and their limitations when the emittance blow-up is large. The largest discrepancies have been observed at the beginning of the energy cycle at 50 MeV, which will be diminished at the new injection energy of 160 MeV [1]. Additionally, the installation of a second set of new wire scanners [12] will offer the opportunity to compare independent emittance measurements to the FLUKA simulations.

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