SOURCES OF EMITTANCE GROWTH AT THE CERN PS BOOSTER TO PS TRANSFER

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Abstract

The CERN PS Booster (PSB) has four vertically stacked rings. After extraction from each ring, the bunches are recombined in two stages, comprising septum and kicker systems, such that the accumulated bunch train is injected through a single line into the PS. Bunches from the four rings go through a different number of vertical bends, which leads to differences in the betatron and dispersion functions due to edge focussing. The fast pulsed systems at PSB extraction, recombination and PS injection lead to systematic errors of delivery precision at the injection point. These error sources are quantified in terms of emittance growth and particle loss. Mitigations to reduce the overall emittance growth at the PSB to PS transfer within the LHC injectors upgrade are presented.

ERROR SOURCES AND STABILITY CALCULATION

For this study the error sources at the PSB to PS transfer have been divided into correctable and uncorrectable or dynamic errors. Correctable errors comprise magnet misalignments, magnet systematic errors such as different laminations or steel, and magnet random errors, e.g. different transfer function within a production series. Also long term drifts of the trajectory due to temperature and humidity are considered correctable.

Uncorrectable errors can be random, such as shot-to-shot stability, in particular in view of the pulse-to-pulse modulated energy levels (1.4 and 2.0 GeV) of the transfer, and systematic like power converter ripple and fast pulsed kicker waveforms. Initially, only correctable errors were assigned in the transfer line model and its correction feasibility verified. During this transfer, four lines are combined into one line within a relatively short distance compared to the vertical offset. Due to the important deflection angles there are strong error sources which have to be compensated by few instrumentation and correction elements. The study showed that failure of beam position monitors are detrimental to the correction capability, and it is required to include the extraction septum as correction knob into the automatic trajectory algorithm used in the control room.

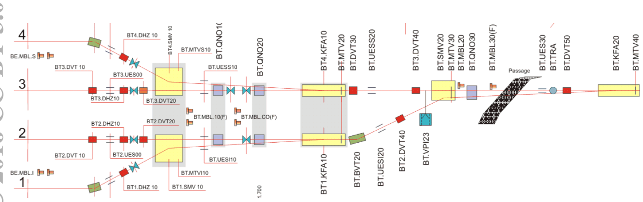

Figure 1: Layout of the PSB recombination [1].

After this verification the machine was assumed to be free of correctable errors and dynamic errors were assigned separately to identify the main contributors to delivery imprecision. The effect of these errors was evaluated firstly, by their impact on the beam envelope of the line and consequently losses and activation of material, secondly, by comparison of trajectory variations and beta beating with the forseen margins in the envelope calculation and thirdly, by calculation of emittance growth due to offsets in position and angle at PS injection.

Due to the different number of deflections seen by each bunch in the vertical recombination, Fig. 1, edge focussing from the vertical dipoles causes the optics to be different for each line [2]. This leads to an unavoidable emittance growth from betatron and dispersion mismatch at PS injection. The optics of the four lines can be perfectly matched to the PS injection optics for one of the four lines, but it is deliberately mismatched for all lines with the aim to minimize the overall emittance growth for all four lines. The optics for the transfer line coming from ring 4 is shown in Fig. 2.

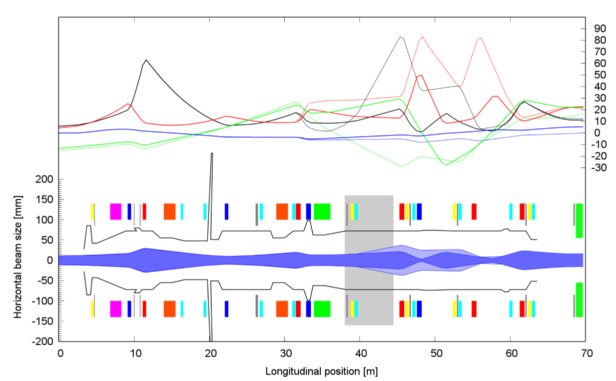

Figure 2: Present (thin) and new (thick) optics for the PSB to PS transfer in the top part. Horizontal betatron and dispersion functions are denoted in black and green, vertical betatron and dispersion functions in red and blue, respectively. In the bottom part the 3 σ horizontal LHC beam envelope is shown.

DYNAMIC ERRORS

Dynamic errors were applied separately to understand the sensitivity of steering mismatch to each error source at PS injection. The resulting steering mismatch per magnet is shown in Table 1. The radial offset of the mismatched circle in normalised phase space serves as a good measure of the resulting beam impact. Several of the magnets in this line will be rebuilt for the 2 GeV upgrade, most importantly the horizontal dipole BT.BHZ10 and the vertical dipoles BVT10 and BVT20. The dynamic error specification of these magnets

Table 1: Resulting Offset in Position and Angle at PS Injection from Each Error Source. The columns in bold denote the radial offset in normalised phase space in units of the unperturbed emittance (LHC).

	Tolerance ΔI/I	x rms mm	p_x rms µrad	R_x^2/ϵ_0 1×10^{-3}	y rms mm	p_y rms µrad	R_y^2/ϵ_0 1×10^{-3}
Random effects							
PSB orbit ± 0.15/0.10 mm (h/v)		0.04	4	**0.4**	0.04	2	**0.2**
BVT10	1×10^{-4}				0.08	1	**0.3**
SMV10	1×10^{-4}				0.13	1	**1**
QNO10	5×10^{-4}				0.11	1	**1**
QNO20	5×10^{-4}				0.03	1	**0.06**
KFA10	3×10^{-4}				0.02	1	**0.06**
SMV20	1×10^{-4}				0.01	4	**1**
KFA20	3×10^{-4}				0.01	0	**0.02**
BVT20	1×10^{-4}				0.05	3	**1**
BT.BHZ10	1×10^{-4}	0.07	0.02	**4**			
All random effects		**0.08**	**17**	**5.1**	**0.21**	**6**	**4.0**
Systematic effects							
KFA10	5×10^{-3}				0.39	15	**17**
KFA20	5×10^{-3}				0.22	8	**5**

were chosen in order to have a balance between the quadratically summed random errors in both planes. The specifications and results shown in Table 1 are relevant for LHC beams where the impact on the relative emittance growth due to steering mismatch is relatively large due to the small normalised rms emittance of 2 µm. Emittance growth is less important for fixed target large emittance beams as long as particle losses are well controlled. This distinction lead to a specification of different field homogeneities for the small emittance LHC beams and large emittance beams where a five-fold increase of the integrated field error was assumed. This increased error was translated into a steering error of 0.4 and 1.6 mm in the horizontal and vertical planes, respectively. This is comparable to the assumed orbit tolerance of 1.5 mm in the calculation of the beam envelope. The change of the beam size due to filamentation is negligible. Assuming 2 mm for alignment errors and 1.4 GeV beam energy, 3.3 σ in the horizontal and 4.1 σ beam size in the vertical plane can be injected into the PS. This has to be compared to the 3 σ target for the transfer of large emittance beams and is therefore acceptable.

SYSTEMATIC ERRORS

In order to estimate the emittance growth from systematic errors like kicker waveform ripple, a measured longitudinal bunch profile with 2 ns resolution from a PSB to PS transfer was folded with a measured kicker waveform. The emittance growth was calculated for each 2 ns slice of the bunch profile. For the effect of the emittance growth on the entire bunch the worst case of full filamentation without any damping was assumed. The particles from each 2 ns slice with the respective emittance growth were therefore re-distributed to calculate the overall growth per bunch.

The effect of the flattop ripple on the first injected batch of four bunches from the PSB is shown in Fig. 3 for the short-circuit mode proposal of the 2 GeV upgrade [3]. While the beam emittance is barely affected by the flattop ripple, there is a significant growth of bunch 1 and 2 from the post pulse ripple during the second batch injection. The expected emittance growth for the standard LHC beam for the different kicker waveforms is summarized in Table 2. In addition, two worst case scenarios were simulated. In one case the centre of one bunch was directly placed on the biggest ripple coming from the short-circuit reflection. In this case the emittance growth for the full bunch increased from 0.5% to 2.5%. For the second worst case scenario, a longitudinally

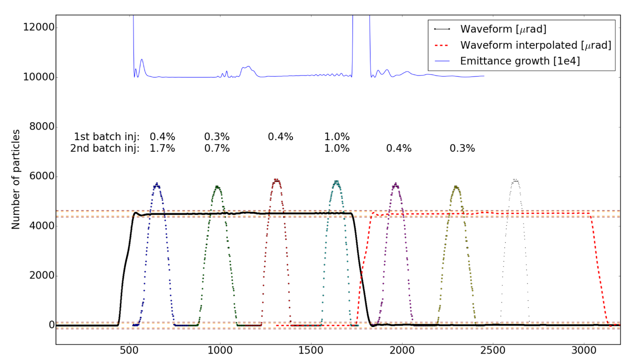

Figure 3: Calculated emittance growth due to kicker waveform ripple.

Gaussian bunch shape was assumed and blown up to the maximum specified bunch length. In this case bunches 2 and 3 are not affected as expected. Bunch 1 and 4 show an increased emittance growth of 2 - 3 %. Measurements in the PS were performed with the injection kicker to benchmark the analytical calculation (Fig. 4). The measurement setup had to be continuously improved since the transverse profile of the small emittance LHC beams is difficult to quantify in the machine. The final setup used a cycle with two basic

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Table 2: Emittance Growth in % from Present Terminated System and Upgrade Kicker Waveforms in Field (B) and Current (I)

	Flattop ripple	Rise/fall edges	Post pulse ripple
Upgrade, B	0.4	1.0	1.7
Terminated system, I	0.1	1.7	7.7
Upgrade, simulated I	0.3	1.3	1.3

periods (BP) where in the first BP the beam was nominally injected and ramped up to extraction energy. In the second BP the timing trigger of the second batch injection was used to coherently kick the circulating beam and measure with wire scans the transverse profile before and after the kick. With this method any dependencies on shot-to-shot intensity, trajectory and emittance variations coming from the PSB were eliminated. However, a few percent of inaccuracy comes from the wire scanner measurement itself, due to systematically affecting the profile by the scan. Another inaccuracy is given by the big contribution of up to 50% from dispersion to the measured profile and therefore the need to measure accurately the momentum spread of the beam. A set of measurements with different kick strengths was taken, down to the minimum voltage which could be applied on the generators. Another reduction of the kick compared to the injection case comes from performing the measurement at extraction flattop. For smaller kicks applied the profiles

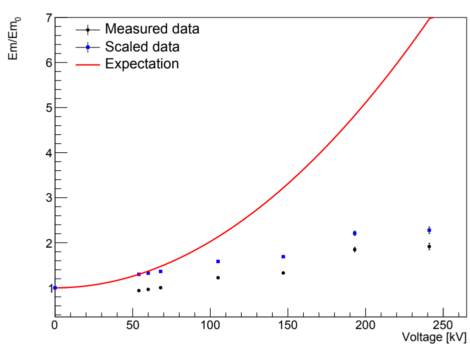

Figure 4: Measured emittance growth from PS injection kicker deflections on extraction flattop. In red the analytical expectation of emittance growth for the applied kicks.

can be reasonable fitted with a Gaussian distribution, in case of bigger kicks the beam tails get strongly populated. In these cases a Breit-Wigner function was used for fitting. The variation between scanning the wire in and out amounts to about 4% in the horizontal and 0.5% in the vertical plane. The analytical calculations are a worst case scenario and therefor an upper boundary for the emittance growth to be expected. For the profiles not showing too strong tail population, the measured data shows about 40% less blow-up than the analytic calculation.

EMITTANCE GROWTH

The effect of optics mismatch due to different edge focussing in each line and due to steering error was translated into emittance growth at PS injection according to the analytic calculation. The results for the present situation (LHC beam emittance assumed) and the upgraded optics for LHC and high intensity (HI) beams is shown in Table 3. Presently the horizontal dispersion cannot be matched and therefore an additional quadrupole was added in the line to remove this mismatch. However, the spread in vertical dispersion due to edge focussing in the recombination part causes a bigger relative emittance growth than the horizontal dispersion mismatch. This spread cannot be fully overcome, but reduced to a minimum for all four lines. Also the spread in the betatron functions for the upgrade has been reduced to a minimum which leads to an overall reduced emittance growth for LHC beams with respect to the present situation. The large emittance HI beams have been optimised for minimum beam envelopes at the aperture bottlenecks rather than emittance conservation. Energy errors, geometrical mismatch and coupling are negligible in this transfer.

Table 3: Emittance Growth at PS Injection Due to Different Error Sources in the PSB to PS Transfer

Mismatch	Emittance growth [%, hor/vert]		
	Pres. LHC	Upgr. LHC	Upgr. HI
Steering	0.3/1.5	0.3/1.5	0.1/0.5
Betatron	4.6/6.8	1.3/0.0	2.0/0.0
Dispersion	4.4/8.8	0.2/2.4	0.0/5.3
Total	**6.3/11.2**	**1.3/2.8**	**2.0/5.3**

CONCLUSIONS

The most important error sources at the PSB to PS transfer have been quantified in terms of emittance growth at PS injection. Unavoidable optics mismatch due to different edge focussing per line in the recombination part has shown to be the most important cause of emittance growth. To mitigate this effect, the spread in betatron and dispersion function between the four lines has been minimised. The sensitivity of emittance growth due to random dynamic errors of magnets was studied and used to specify dynamic errors of magnets to be built for the 2 GeV upgrade. Systematic errors from kicker waveforms have been studied for upgrade models by folding longitudinal bunch profiles and kicker waveforms in order to get a weighted effect of emittance growth from kicker field ripple. Measurements with beam show that the theoretical estimates for emittance growth are conservative and can currently not be reproduced in the machine. The theoretical estimates allow distinguishing the importance of rise and fall time with respect to flattop and post pulse ripple of kicker systems.

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