EVOLUTION OF HIGH INTENSITY BEAMS IN THE CERN PS BOOSTER AFTER H- INJECTION AND PHASE SPACE PAINTING

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Abstract

With the LHC Injector Upgrade (LIU) project, the injection energy of PS Booster (PSB) – first circular accelerator in the LHC injector chain – will be raised from 50 MeV to 160 MeV and the present multiturn injection will be upgraded to H- injection with transverse and longitudinal painting. In the scope of this project, it is planned to double the beam intensities, profiting from the fact that the $\beta\gamma^2$ factor will be two times larger (0.35 at 50 MeV and 0.71 at 160 MeV), so the resulting tune spread driven by a direct space charge should remain similar. This paper describes the feasibility to double the intensity of high intensity and large emittance beams, looking into the evolution under space charge and taking into account losses constrains in the ring and in the extraction lines.

INTRODUCTION

The PSB, a low energy accelerator, is made of 4 rings stacked on top of each other, in order to reduce the space charge related effects. The beam is accelerated simultaneously in the 4 rings in about 500 ms and after the extraction is merged into one transfer line and passes to the ISOLDE experiment or it is injected into the Proton Synchrotron (PS). The PSB currently provides beam for CERN experiments in a range of intensities varying from 40e10 p+ to 800e10 p+ per ring and with transverse normalized emittances between 2 mm.mrad and 15 mm.mrad. In the frame of the LIU project, its injection energy will increase from 50 MeV to 160 MeV, which together with the new H- injection will allow to provide a higher intensity for the PSB users. The injection will involve a charge exchange process occurring at a carbon foil of 200 $\mu g/cm^2$ thickness [1]. Four kicker magnets BI.KSW will perform a transverse painting in the horizontal phase-space. In order to satisfy the broad needs of the CERN experiments, multiple painting functions have been studied independently for each user [2].

This paper studies the feasibility to double the intensity for the PS Booster highest intensity and emittance beam (800e13 p+, 15/10 mm.mrad in horizontal and vertical plane respectively), which is delivered to the ISOLDE facility. For this kind of beam, transverse losses are expected due to strong space-charge effects at lower injection energy, therefore special attention to the control of the beam loss should be drawn. It is planned to replace the existing aperture restriction, the Window Beam Scope (WBS), with a new one, suitable for the upgrade. At the current WBS location there is not enough room to accommodate a new, 130 mm instead of 40 mm thick absorber, therefore a new location was found approximately 2.5 m downstream. Moreover, due to the geometrical emittance reduction due to the higher energy, the aperture of the new absorber should be scaled down and optimized.

The long-term evolution of the high intensity beam is discussed for two cases. A first scenario assumes the PSB equipped with the WBS at its old position with scaled apertures to take into account the injection energy increase. Assuming 5 mm of expected closed orbit distortion, the current WBS aperture (50 mm vs 28.6 mm) scales to 38.18 mm and 22.4 mm respectively [3]. This scenario was used as a baseline to define a kicker painting waveform function. In the second scenario, the WBS is replaced by a new absorber, placed at the new location, 2.5 m downstream of the existing one. Its aperture scales with the PSB optics (as the square root of the beta functions) with respect to Scenario 1 and are equal to 29.94 mm vs 34.15 mm, thus it is expected to accommodate the same beam size in sigma units.

In the first part, we comment on 5 ms beam evolution, which is the time needed for the injection bump to decay. Then, the results of 20 ms beam evolution are presented. At the end, the effect of the vertical offset on the transverse emittances is discussed.

LIMITATIONS ON TRANSVERSE EMITTANCE

Studies have shown [4] that the main limitation imposed on the vertical emittance in the PSB ring comes from one of the recombination septa, which presents the lowest acceptance of all the elements. Therefore the baseline value of the vertical emittance was set to 6 mm.mrad in order to keep the same value of losses as today. These studies have been made assuming an extraction energy of 1.4 GeV for the high intensity beams, which is considered the “worst case” while the PSB is expected to accelerate beams up to 2 GeV. The 2 GeV extraction case has not been studied. Due to the geometric emittance reduction it would allow more beam acceptance but on the other hand the particles hitting the septum blade will do so at a higher energy.

To mitigate the effect of losses from the high intensity, large emittance beams, it is preferred to scrape the beam tails at and directly after injection, rather than to lose particles with increased kinetic energy. In order to reduce the activation level of the machine, the objective is to keep the beam loss below 5% of the total intensity during the first few ms of evolution.

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EVOLUTION FOR HIGH INTENSITY BEAMS DURING THE CHICANE FALL AND NEXT 15 MS

The intensity and emittance evolution have been studied during the first 5 ms, which is the time needed to collapse the injection chicane magnets [5]. A multiturn injection process lasting 100 turns (~100 µs) for a beam intensity of 1600e10 p+ is simulated, assuming the horizontal painting waveform defined in [1] together with an injection vertical offset of 8 mm. The working point in the simulations has been set to $Q_x = 4.28$ and $Q_y = 4.55$. Beam tracking has been made using combined PTC [6] and pyORBIT [7] codes, containing space charge calculations and particle-matter interaction modules. As a first step, a perfectly aligned lattice has been assumed with acceleration included into the model and the edge effect and eddy current at the chicane magnets, together with the compensation for the half-integer resonance.

At the end of injection, the high intensity beam reached the emittance of 13.72 mm.mrad and 6.07 mm.mrad. At the end of the chicane fall time, the obtained values are 13.74 mm.mrad and 6.06 mm.mrad in horizontal and vertical plane respectively, while keeping the beam loss around 4.5% level in Scenario 1. For Scenario 2, the beam reached similar emittances of 13.72 mm.mrad and 6.05 mm.mrad with a beam loss level of 4.8%. We observed almost no emittance blow up, due to a very efficient collimation by the absorbers. For comparison, we considered also the simple PSB aperture model made only of the main magnets: quadrupoles and dipoles equipped with scrapers and without the dedicated local aperture restriction of the WBS. In this case, the final emittances reached values of 13.88 mm.mrad and 6.36 mm.mrad with a beam loss level of less than 2.5%. These are mostly longitudinal losses, due to foil scattering and transverse losses coming from scraping the tails of the un-collimated beam at the dipoles scrapers. The comparison between Scenarios 1 and 2, containing an absorber and a 3rd scenario with no absorber is shown in Figure 1. The final horizontal emittance value is the same for the case with and without absorber, meaning that the considered aperture restrictions do not limit the beam in the horizontal plane.

The beam loss level during the chicane fall in Scenario 1 and 2 is smaller than 5%, therefore fulfil the requirements presented in the previous paragraph. Figure 2 shows the different loss patterns for the three scenarios. Since the horizontal acceptance is large, the vertical plane is the main source of the beam loss. In presence of the absorber, losses are localized at the position of the WBS, at about 70 m in the machine, while for the case without absorber, they are spread around the accelerator at the scrapers protecting the main dipoles.

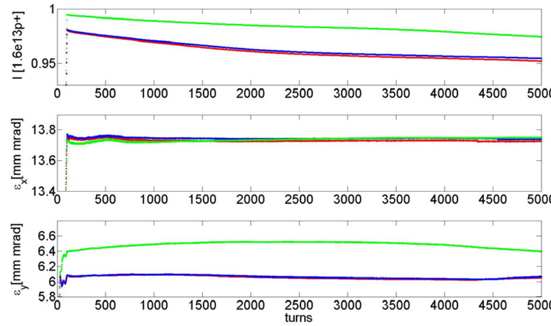

Figure 1: Plots of intensity (top), horizontal normalized emittance (middle) and vertical normalized emittance (bottom) for the first 5 ms of the beam evolution in: Scenario 1 (blue line), Scenario 2 (red line) and PSB lattice without the aperture restrictions (green line). 1 turn lasts ~1µs.

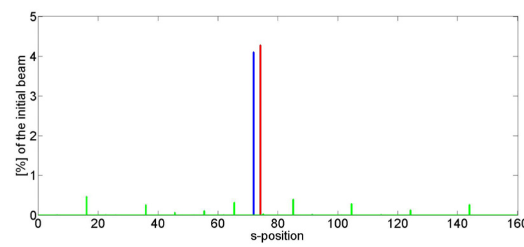

Figure 2: Expected loss pattern for different scenarios. Scenario 1 in blue, Scenario 2 in red. Loss pattern for the lattice without an absorber in green.

Studies of further evolution of the beam showed that the beam loss continues after the chicane collapses, and after 20 ms exceed 10% of the initial beam. This effect is due to the strong space charge interactions, which lead to emittance growth followed by losses at the aperture restrictions. In order to avoid this phenomenon, the jaws of the absorbers could be further open. However increasing the absorber acceptance will translate into growth of the vertical beam emittance and the constraint imposed by the PSB recombination septum will not be fulfilled. For that reason we tried to shape the beam vertical emittance by adjusting with the injection offset.

IMPACT OF THE VERTICAL OFFSET AT THE INJECTION ON THE FINAL EMITTANCE VALUES

The dependency between the vertical offset at injection and the obtained emittance values at the end of the chicane fall has been studied. In this case, we assumed a lattice without aperture restrictions to let the beam freely evolve without imposing aperture constraints on the emittances. The vertical offset of the injected beam was varied in a range between -10 mm to +10 mm, while keeping the same longitudinal and horizontal painting scheme. Figure 3 shows the impact of the vertical offset at

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injection on the values of the emittances after 5 ms. The effect is symmetric with respect to y = 0 mm. This study shows that the two transverse planes are coupled and that the vertical offset has an impact on the final emittances in both vertical and horizontal plane. In particular, this is valid for small vertical offsets. The same effect was observed for a lattice with aperture restrictions and is consistent with the finding of [8], which focused more on the LHC beam.

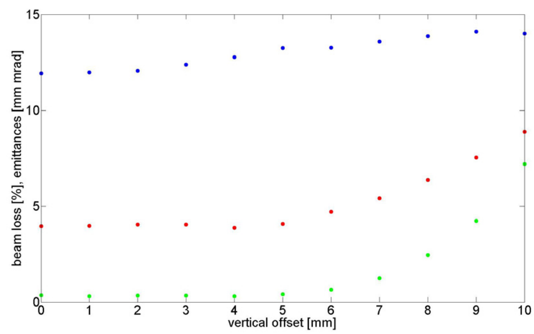

Figure 3: Dependency of the beam characteristic after 5 ms with respect to the vertical injection offset. Beam loss [%] is plotted in green, horizontal emittance [mm.mrad] in blue and vertical [mm.mrad] emittance in red.

Taking into account the limits of the final vertical emittance (6 mm.mrad) together with the maximum beam loss during the chicane fall (5%) and trying to provide a beam size as large as possible in order to avoid large emittance blow-up due to space charge, the range of interest in vertical offsets can be narrowed to 5 mm to 8 mm. This will result in expected beam emittances of 13 to 14 mm.mrad in the horizontal plane and 4 to 6 mm.mrad in the vertical plane, while accommodating 1600e10 p+.

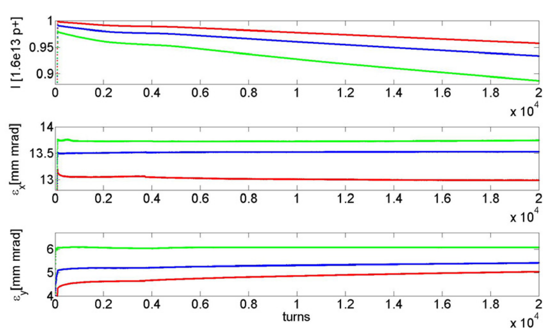

Figure 4: Intensity and (normalized) emittance evolution for Scenario 2, with a vertical offset of 6 mm (in red), 7 mm (in blue), 8 mm (in green). 1 turn lasts ~1μs.

Longer tracking studies have been performed for an offset of 6 mm and 7 mm. In case of y = 6 mm, the final value of the vertical emittance after 20 ms reached 5.05 mm.mrad with a loss level of 3.9%. However, we observed that beam suffers from an emittance blow up in the vertical plane (Figure 4). For the scenario with y = 7 mm, the vertical beam emittance reached the value of 5.44 mm.mrad while slightly exceeding the acceptable loss level of 5%. In both cases, the horizontal emittance stays between 13 mm.mrad and 14 mm.mrad. The beam profile evolution for the case with y =7 mm is presented in Figure 5. Further detailed studies are foreseen to check the long term stability of the both scenarios.

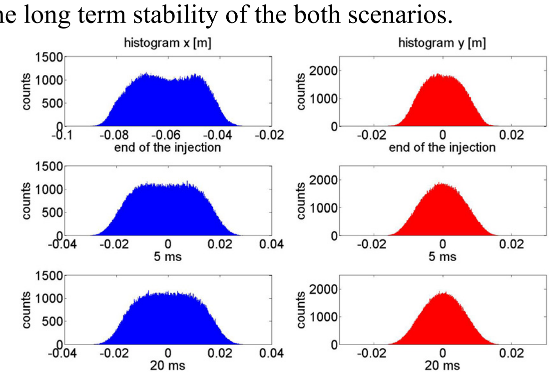

Figure 5: Horizontal (left) and vertical (right) beam transverse distribution at the end of the injection process (~100 μs), after 5 ms and 20 ms for the case with 7 mm offset.

CONCLUSIONS

In this paper we have presented the results of simulations of injection, and the first turns with 1600E10 protons per ring, in order to assess the emittance and losses for the high intensity ISOLDE beam in the PSB, taking into account the imposed constraints of the vertical maximum emittance of 6 mm.mrad, and of the beam loss at low energy of less than 5% of the total intensity. Long term simulations showed that in order to fulfil these constraints, we should modify the baseline scenario of 8 mm vertical injection offset and then we can optimize the PS Booster aperture restriction.

Studies proved that the vertical offset of the injected beamlets has an impact on both horizontal and vertical emittance and on the resulting beam loss, and it is one of the parameters defining the final characteristics of the high intensity beams. The range of most likely vertical offsets at injection was determined to be to 5 mm to 8 mm. Scenarios with 6 mm and 7 mm vertical offset ware tested and gave promising results. As a next step, long term tracking studies should be performed in order to determine the maximum beam intensity and beam emittances that PS Booster can provide for its users.

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