3D EMITTANCES TAILORING TECHNIQUES AND OPTIMIZATION WITH SPACE CHARGE FOR THE FUTURE CERN PS BOOSTER OPERATIONS WITH LINAC4

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Abstract

In the frame of the LIU (LHC Injectors Upgrade) project, the CERN PS Booster is going to be renovated to host a new H^- charge-exchange injection from the Linac4. One important feature of the new injection scheme is the possibility to tailor a wide range of 3D emittances for CERN's different users in an intensity span in the order of 5×10^9 to 1.6×10^{13} protons per PSB ring. This paper gives an overview of 3D multi-turn injection techniques, focusing on the future LHC beams, which aim at reaching high brightness, and on highest intensity beams (ISOLDE), where losses are the main concern. Complete RF capture simulations and transverse injection maps, including space charge effects, are presented and also intended to be used during the commissioning with Linac4.

INTRODUCTION

The CERN PS Booster (PSB) is the first synchrotron in the LHC protons accelerator chain. In the framework of the LIU project, a new H^- injection system of 160 MeV from Linac4, instead of the present 50 MeV proton injection from Linac2 [1], will be adopted. The main physical reason for this change is the large incoherent space charge (SC) tune spread that presently limits the brightness of the beams. Through Linac4, it will be possible to tailor the transverse and longitudinal emittances in the PSB ring aiming to fit the requirements of the high-luminosity future LHC beams [2].

The purpose of this paper is to recap the longitudinal and transverse injection schemes that will be adopted for the emittance tailoring. Two different beam typologies will be taken into account for the LHC and ISOLDE, a nuclear experiment facility requiring high intensity per pulse. PTC-Orbit [3] simulations of an injection map with horizontal and vertical offsets parametrization will be shown in the PSB SC dominated regime for the future High Luminosity LHC-type beam operations. The results in terms of emittance blow-up, brightness, and SC tune spreads will be presented, with particular emphasis to the emittance balancing mechanism induced by the linear coupling.

LONGITUDINAL INJECTION SCHEMES

Linac4 will provide to the PSB a train of microbunches at a repetition rate of 352.2 MHz (2.84 ns) with a transverse emittance of 0.4 mm·mrad in both planes [4]. The train of micro-bunches is chopped and (de-)bunched in the Linac4 in order to create the total bunch length and an energy spread that best fits the waiting double RF accelerating bucket in the PSB ring [5]. For the High Luminosity (HL) LHC operations (3.4×10^{12} p/b) a multi-turn injection scheme without modulation of the 160 MeV central injection energy is foreseen, in order to lower the number of injected turns per target intensity, minimize the number of hits on the stripping foil (to reduce scattering) and simplify the commissioning. For the ISOLDE beam (16×10^{12} p/b), instead, the baseline refers to the multi-turn injection scheme with energy modulation already proposed by Carli and Garoby [6]. For both schemes, the double RF voltages are put in anti-phase in order to minimize the peak line density and, thus, the transverse SC effects.

TRANSVERSE INJECTION SCHEMES

At injection in the PSB, the beam is displaced from the ring orbit towards the stripping foil through a horizontal chicane bump imposed by 4 magnets (BSWs), whose maximum amplitude is -45.9 mm (the negative sign indicates a displacement toward the outer part of the ring). On top of this, a set of 4 fast kickers (KSWs) is used to make the beamlets hit the foil and paint, turn-by-turn, the horizontal phase space. An example of the horizontal displacement functions for the HL-LHC beams (23 injection turns at 61% chopping factor and 40 mA unchopped from the Linac4) is shown in Fig. 1: the beam is injected always at -35 mm, to be added up to the previous -45.9 mm.

Two options were initially foreseen in the baseline [7, 8]. The first one is the so-called "on-axis": the beam is injected exactly at the closed orbit location in the horizontal and vertical plane. For this option, the emittance blow-up is totally dominated by SC. The second option foresees a "transverse painting": the beamlets, injected always at the same location, paint the horizontal phase space, and thus tailor the horizontal emittance, through a modulation of the KSWs. A vertical offset (~ 3 mm) is used to enlarge the vertical emittance. This option also suffers from SC, even if the emittance blow-up is mainly controlled by the painting process. Simulations for these two options show that, for the HL-LHC beams, where high brightness is desired, it is possible to reach a minimum average emittance of 1.2 mm·mrad, giving a 30% margin with respect to (w.r.t.) the LIU requirements [2].

Injection Offset Scheme for the Future HL-LHC Beams

A third injection option is going to be used for the LHC beams, where high brightness is desired. It is possible, in

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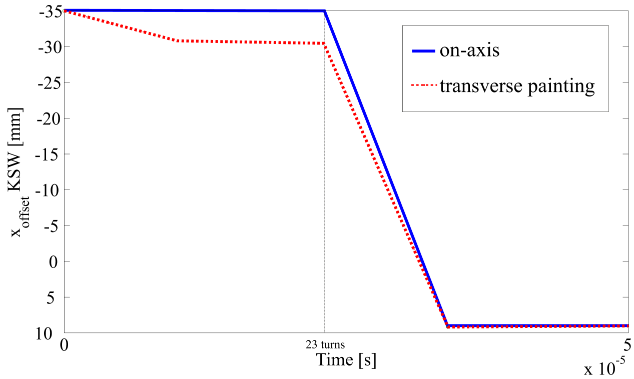

Figure 1: The KSW offsets decay for the "on-axis" (dashed red line) and "transverse painting" (solid blue line) options.

fact, to paint the phase space through a fixed transverse offset, keeping the KSWs at fixed strength as in the "on-axis" solution. Simulations have been done to predict the beam blow-up varying the initial offset of the beam from the closed orbit at x=-80.9 mm. Simulations including SC (at 3.42×10^{12} p/b), displacing the injection point every 0.5 mm over an offset matrix, have been done. The range has been set from 0 to +5 mm distance from the closed orbit in the horizontal and vertical directions. The results in terms of average emittance are shown in color-code in Fig. 2 left. These show that the 1.2 mm·mrad emittance can be preserved within a tolerance of 3.5 mm and 3 mm offsets, in the horizontal and vertical planes, respectively (yellow dots). Round beams are foreseeable in this range (green dots in Fig. 2 right). The simulations showed also that the profile should stay Gaussian-like due to the presence of SC [5]. A numerical analysis of the maximum SC tune shifts has

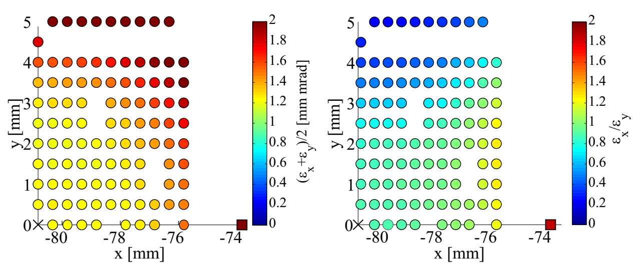

Figure 2: Half-sum (left) and ratio (right) of the normalized emittances after 10 ms tracking. The black cross at $(x, y) = (-80.9, 0)$ represents the closed orbit value at injection.

been performed. The maximum tune shift, occurring for the "on-axis" solution, is around (-0.6, -0.7). Figure 3 shows that the values never significantly overcome the coupling line, even for high horizontal and small vertical offsets, where one would expect a prevalently vertical tune spread. This is the case of the point with injection at (x, y)=(-73.9, 0), shown with a square marker. The coupling line can be excited by either tilts in the magnets or by space-charge itself [9, 10].

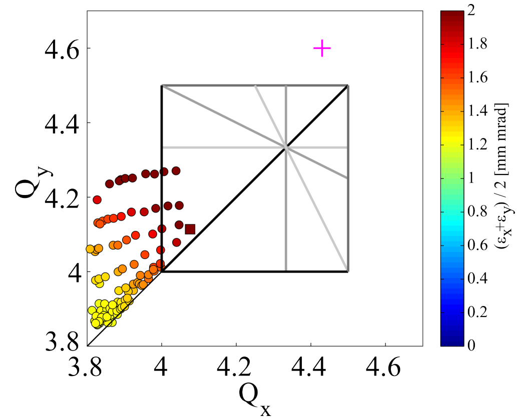

Figure 3: Maximum SC tune shifts after 10 ms tracking for the simulations of Fig. 4. The magenta cross is the bare tune (4.43, 4.60). Solid lines in grey scale are the most dangerous resonance lines.

Figure 4 shows that the coupling has an effect already during the multiturn injection process, i.e. within the first 23 turns, and manifests itself as a transfer of emittance from the horizontal to the vertical plane in a loss-less regime.

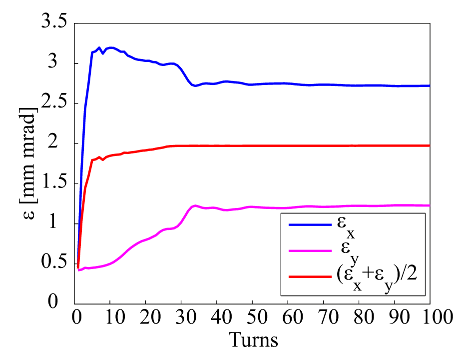

Figure 4: Normalized emittances evolution vs time for the first 100 turns of tracking.

Measurements in the Present Machine

Measurements have been performed in the present machine in order to evaluate the effect of the coupling, keeping constant the number of injected turns (three). The horizontal injection tune has been varied, while keeping the vertical one fixed at $Q_y = 4.54$. Transverse emittances and intensity measurements have been taken at the extraction energy of 1.4 GeV, in order to guarantee a better reliability of the wire-scanner measurements. The measurements have then been scaled down to 50 MeV (present injection energy) for the SC tune shifts estimations. Figure 5 shows the results: the maximum tune shifts are disposed around the coupling line, thus giving a positive indication that the maximum SC tune shift is also limited by this resonance, as shown by the previous simulations.

High Intensity Beams

The ISOLDE beams will be injected through transverse painting [7, 8], lasting around 100 turns.

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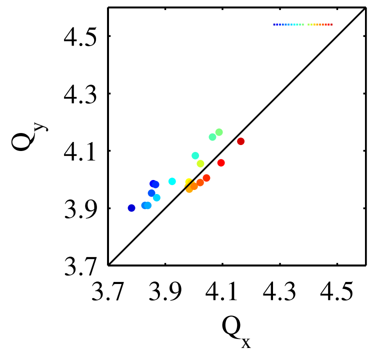

Figure 5: Maximum SC tune shifts (circles) at 50 MeV in the present machine varying the injection tune (points in color-code on top-right). The black line is the coupling line.

The vertical offset for the transverse painting scheme has been scanned in PyOrbit simulations [11]. An effect from the coupling line, totally similar to the one previously shown for the LHC beams, has been observed, with transfer of emittance from the horizontal to the vertical plane. Figure 6 shows that the maximum tune shift induced by SC is sitting on the coupling line for small values of vertical offset.

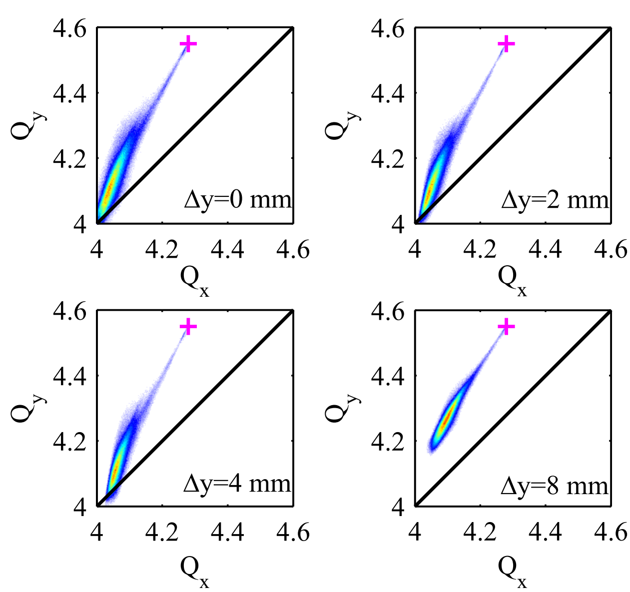

Figure 6: Tune spread simulations after 10 ms for the ISOLDE beams and different vertical injection offsets. The color-code is the particle density (blue, low density - red, high density). The solid black line is the coupling line. The magenta cross is the injection bare tune.

"Fixed Lines" With Space Charge

Particles in the SC necktie which are narrowly bounded around the coupling line perform a motion with a well defined pattern in the 4D phase space. These trajectories, known as "fixed lines" in the single particle motion [12], have been simulated for the first time in a SC dominated regime [5] with a self-consistent SC code. Figure 7 shows as illustration the motion of a selected particle of the previous LHC beams simulations. The particle, whose tune averaged over one synchrotron period [5] is sitting on the coupling line, has a turn-by-turn phase advance which is narrowly oscillating around it (see Fig. 7 left). The motion in the phase space is affected by the coupling and follows a toroidal trajectory ("fixed line") in the (x, y, x') phase space (see Fig. 7 right).

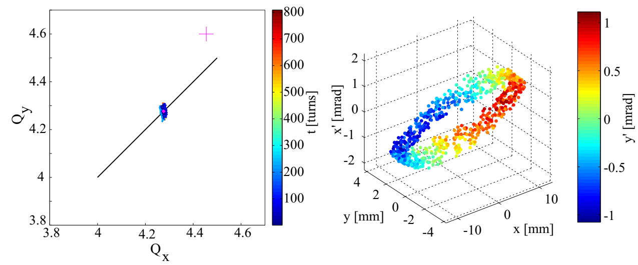

Figure 7: Left - the particle turn-by-turn tune evolution in one synchrotron period (in color-code). Right - the corresponding simulated "fixed line" in presence of SC and coupling: 4D Poincaré map of the (x, y, x') phase space. The color-code is the y' coordinate.

CONCLUSIONS

The PSB is going to be upgraded with a new H$^-$ 160 MeV injection energy system, replacing the present 50 MeV proton one. Different injection schemes, leading to different emittance tailoring techniques, will be adopted for the different users. Two of them, the LHC and ISOLDE, have been analyzed in this paper.

In the longitudinal plane, a modulation of the injection energy is used to paint the longitudinal phase space of the ISOLDE beams. The central energy modulation is not foreseen for the LHC beams.

Two main injection schemes, "on-axis" and with "transverse painting", are foreseen in the transverse plane. Simulations have been carried out in order to predict the future beam characteristics. For the LHC a new scheme consisting of introducing a fixed injection offset w.r.t. the closed orbit has been proposed. This option is simpler than the baseline transverse painting scheme with the KSW and matches the HL-LHC parameters in terms of brightness. Parametric offset simulations showed that the goal of 1.2 mm·mrad emittances for 3.42×10^{12} p/b can be reached with an offset in both planes of ~3 mm around the closed orbit, defining also the tolerances w.r.t. injection offset errors. These simulations have shown the contribution of the coupling line, which induces an emittances balancing process and represents a limit for the particles maximum SC tune shift. Measurements on the present machine have given positive indication for this effect.

Simulations for ISOLDE beams, presented in detail in [11], showed the same coupling effect w.r.t. the variation of the vertical offset.

Particles sitting on the coupling line showed a 4D phase space behavior typical of "fixed lines": this concept has been extended for the first time to the SC dominated regime for the future LHC beams simulations.

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