

LONGITUDINAL PAINTING SCHEMES FOR H⁻ CHARGE EXCHANGE INJECTION INTO THE PS2

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Abstract

Minimization of direct space charge tune shift at injection into the PS2 is important for the reduction of beam losses. A determining parameter for the tune shift is the bunching factor, defined as mean current over peak current for one RF period. Various longitudinal painting schemes for PS2 injection, all based on synchrotron motion, have been studied with respect to the resulting bunching factors.

INTRODUCTION

PS2 [1] is a synchrotron studied at present within the proposed upgrades of the LHC injector chain [2]. H⁻ with a kinetic energy of 4GeV will be provided by the Superconducting Proton Linac (SPL) [3] and injected with a charge exchange injection scheme.

At many accelerators [4] the injection lasts many periods of the synchrotron motion. Then one can make use of this motion smearing out the beam to obtain longitudinal painting without additional measures. This study aims at clarifying, whether if such a “passive” longitudinal injection painting scheme may be feasible for PS2, without “active” energy modulation as proposed [5] for the CERN PS Booster with Linac4 would have to be implemented.

After summarizing basic assumptions for modelling the SPL beam and PS2, three different schemes for longitudinal painting into the PS2 are proposed and simulation results presented.

BASIC ASSUMPTIONS

Amongst possible options for PS2, the generation of the highest intensity LHC type bunches with $4.2 \cdot 10^{11}$ protons per bunch, the option of a lattice with an imaginary gamma transition $\gamma_{tr} = 50$ i and a “40 MHz” principle RF system providing 1.2 MV at injection, yielding a harmonic number of $h = 180$ with the circumference $C_{PS2} = (3000/7) \pi$ m, have been chosen. This is a likely scenario with significant motion in longitudinal phase during injection and, thus, may allow for a “passive” painting scheme.

The SPL bunches will be delivered with a kinetic energy of 4 GeV, a fundamental RF frequency of $f_{SPL} = 352.2$ MHz, longitudinal rms (defined as $\epsilon_l = \pi \sigma_\tau \sigma_E$ for an upright ellipse) emittance of $\epsilon_l = 1.6 \cdot 10^{-6} \pi$ eVs and an rms length of $\sigma_\tau = 20.8$ ps [6] at the PS2 injection point. The energy spread considered as a free parameter, adjusted by an appropriate setting of a debuncher.

Properties of the SPL bunches have to be described, as sketched in Fig. 1, in terms of phase of the receiving PS2

synchrotron used by the program ESME [7]. The distance between consecutive bunches is given by $\varphi_{bb} = (f_{ps2}/f_{spl})360^\circ = 0.2234^\circ$, with $f_{ps2} \approx 218.607$ kHz denoting the PS2 revolution frequency. One PS2 circumference can be expressed by $(1/f_{ps2})360^\circ = 1611\varphi_{bb} + \varphi_T$ with $\varphi_T \approx 0.0250^\circ$. Thus, bunch positions are given by $\varphi_B = \varphi_{off} + n_B\varphi_{bb} - (n_T - 1)\varphi_T$ with φ_{off} a phase offset, n_B a bunch index and n_T the turn number. The rms bunch length in terms of PS2 phase is given by $\sigma_\varphi = \sigma_\tau f_{ps2} 360^\circ = 0.00162^\circ$. The longitudinal rms emittance converted to PS2 phase is given by $\epsilon_{l\varphi} = f_{ps2} \epsilon_l 360^\circ$. A PS2 bucket has a total length of $360^\circ/h = 2^\circ$ (extension $\pm 1^\circ$ around the center)

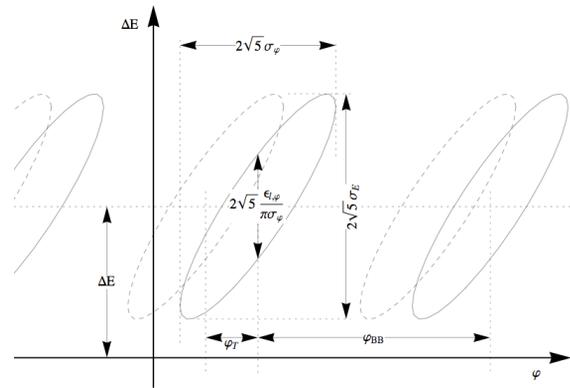


Figure 1: Potential SPL bunches at the PS2 injection. Bunches represented by dashed lines are injected one turn later than the ones described by solid curves. The ellipses denote the full beam for the elliptical density and, thus, parabolic profile assumed for the simulations presented.

INJECTION WITH ENERGY OFFSET AND SINGLE HARMONIC RF

In the simplest scheme studied, a beam with an energy offset of -7.6 MeV and a 3.6 MeV rms energy spread is injected into a 1.2 MV single harmonic RF bucket. The beam is chopped such that only bunches within 0.5° are injected yielding a chopping factor of 0.5. After 163 turns, the required intensity is accumulated.

Results of ESME simulations without space charge effects, with initial coordinates of the macro-particles generated with mathematica, are plotted in Fig 2. The injected beam does not match the curved shape of the bucket: bunches far from the center of the bucket are close to the separatrix, whereas bunches close to the center stay far. This is responsible for the pronounced tails of the profile and the small bunching factors.

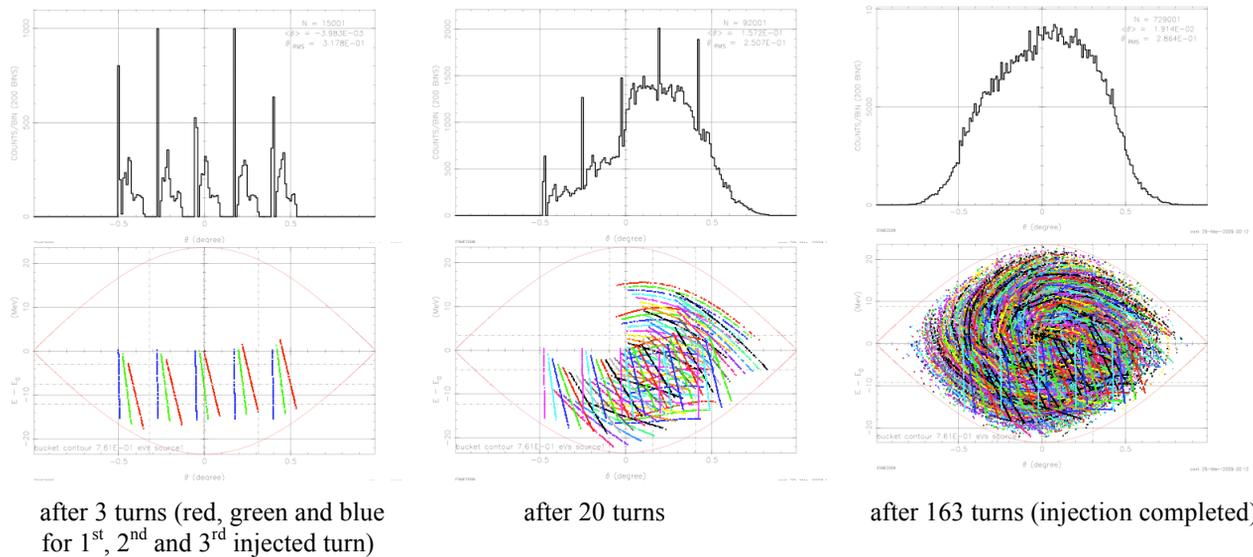


Figure 2: Phase space, generated by an ESME run, during injection with an energy offset into a single harmonic bucket.

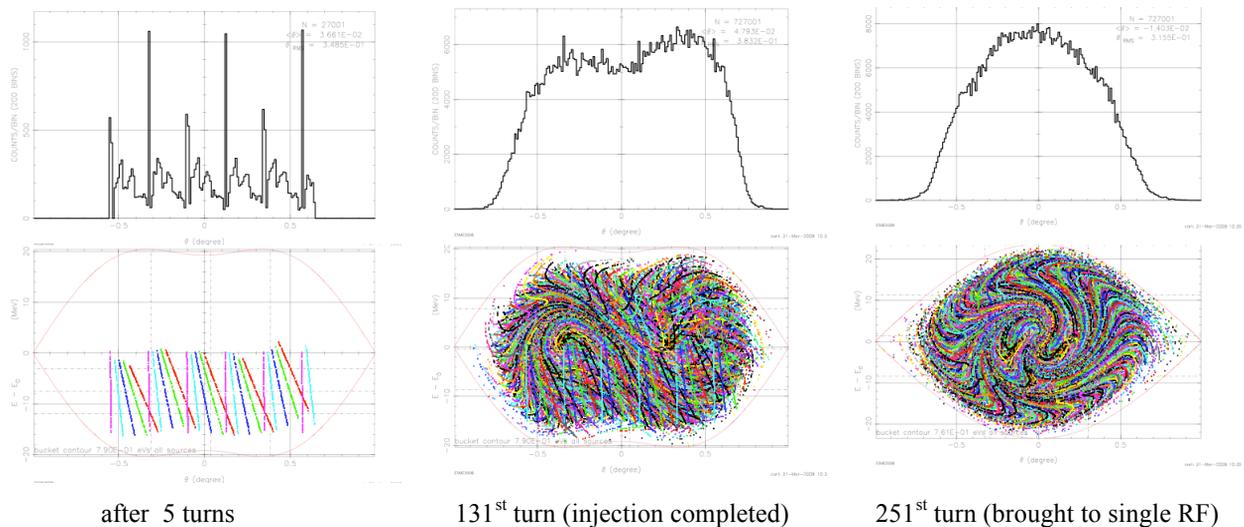


Figure 3: Phase space plots from an ESME run for the injection with energy offset into a double harmonic bucket.

An even lower chopping factor would improve the bunching factor, but lead to very long injection durations.

INJECTION WITH ENERGY OFFSET INTO A DOUBLE HARMONIC BUCKET

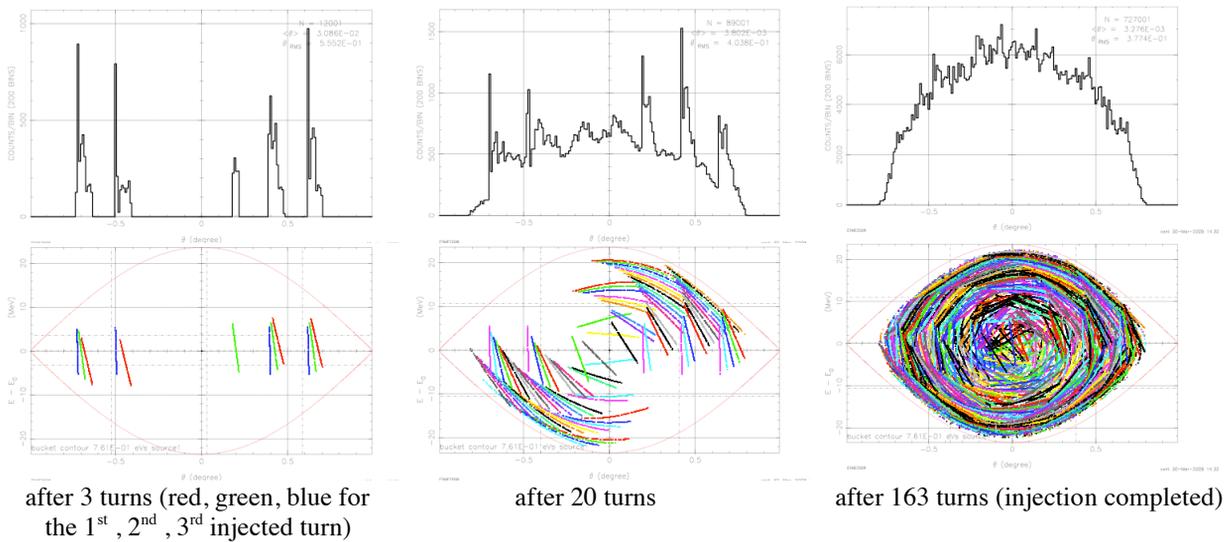
The matching between the arriving beam and a single harmonic bucket is improved by adding a second harmonic RF component with opposite phase flattening the bucket. The scheme presented here aims primarily at improving the injection (although keeping the second harmonic RF for acceleration would further improve) with possibly a fixed frequency low duty cycle cavity. In the simulations presented, both the first and second harmonic RF system provide 0.8 MV during injection. After completion of the injection, the second harmonic RF component is ramped down to zero, while the main system is brought to nominal voltage of 1.2 MV. The better matching is used to increase both the chopping

factor to the nominal SPL value 0.63 and the bunching factor. The duration of the injection is reduced to 131 turns. Simulation results in Fig. 3 show that the tails are indeed reduced and bunching factor is increased.

BUCKET CENTER DEPOPULATION WITH A COMPLEX CHOPPING SCHEME

In the scheme for injection into a 1.2 MV single harmonic bucket described in this section, the density at the bucket center is reduced by removing some bunches with a chopper operating at a higher frequency to:

- Tailor the phase space with lower density at the bucket center by adjusting the boundaries for chopping turn-by-turn.
- Reduce inhomogeneities caused by an injection lasting only a few synchrotron periods. With the two fold symmetry introduced with the scheme, bunches overlap already after half of a synchrotron period.



after 3 turns (red, green, blue for the 1st, 2nd, 3rd injected turn) after 20 turns after 163 turns (injection completed)

Figure 5: Phase space plots during injection with a complex chopping scheme to depopulate the phase space center.

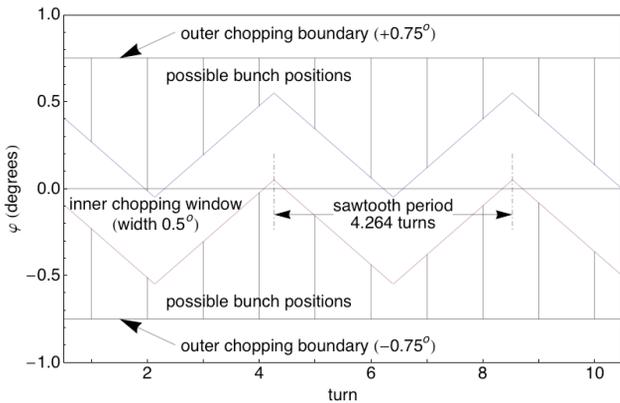


Figure 4: Outer and inner (varying with turn number) chopping boundaries to depopulate the bunch center.

As sketched in Fig. 4, SPL bunches outside a window ($\pm 0.75^\circ$ for the simulation presented) or within a central moving chopping window (extreme extensions from -0.55° to $+0.05^\circ$ and -0.05° to $+0.55^\circ$ for the example presented) are removed by the chopper. The chopping factor has not been reduced below 0.5 to avoid a further increase of the injection.

SUMMARY AND OUTLOOK

Simulations presented here show that “passive” longitudinal painting without energy modulation, but making use of the synchrotron motion are within reach for PS2. The scheme with the highest potential is based on a complex chopping scheme requiring a chopper with faster response than the one planned now.

In general, the margin between bunches obtained with painting and the bucket boundary is marginal for all simulations presented. This is a direct consequence of the attempt to achieve simultaneously a reasonable chopping factor (0.5 somewhat arbitrarily assumed minimum) and a profile without pronounced peak and tails.

Before choosing an injection scheme for PS2, the following questions should be investigated:

- Feasibility of a high frequency chopper for the complex chopping scheme, requiring sometimes to let just one single bunch pass.
- Minimum acceptable chopping factor: In case of the SPL version envisaged for PS2, the mean current is limited by power available for klystrons and, thus, beam loading, but higher beam currents (nominal 65 mA nominal for Linac4) may be possible for beam dynamics and the source and compensate a smaller chopping factor.
- Are the envisaged energy spreads of the SPL bunches feasible by appropriate settings of the debuncher cavity?

Longitudinal painting requires that the duration of the injection is sufficient. For low intensity beams, one could obtain efficient “passive” longitudinal painting by artificially reducing the chopping factor not injection beam at every passage of a bunch at the injection point, but injecting only e.g. every second turn.

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