

# LONGITUDINAL INJECTION SCHEMES FOR THE CERN PS BOOSTER AT 160 MeV INCLUDING SPACE CHARGE EFFECTS

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## Abstract

In the frame of the LHC Injectors Upgrade project, the CERN PS Booster will be equipped with a H<sup>-</sup> injection system at 160 MeV to tailor the initial transverse and longitudinal profiles. We are here reviewing the different multi-turn longitudinal injection schemes, from the beam dynamics point of view, taking into account the needs of the large variety of the PSB users, spanning in intensity from 5e9 to about 1.6e13 protons per bunch. The baseline of the longitudinal injection has always been the longitudinal stacking with central energy modulation: this scheme has the advantage of filling uniformly the RF bucket and mitigate transverse space charge, but it requires at least 40 turns of injection. A simpler injection protocol without energy modulation is here analyzed in detail to find the optimum initial conditions in terms of bucket filling and reduction of transverse and longitudinal space charge effects, with the advantage of minimizing the number of turns for the LHC beams. Simulations with space charge of the longitudinal injection process from different Linac4 trains are presented to fix possible longitudinal injection scenarios during the future commissioning and operation with Linac4.

## INTRODUCTION

The transverse space charge in the CERN PS Booster (PSB) is one of the main bottle-necks for the machine beam dynamics. In the framework of the CERN LHC Injectors Upgrade project (LIU) project, the machine will be equipped with a new H<sup>-</sup> charge-exchange injection at 160 MeV, substituting the present 50 MeV proton multiturn injection. The Linac4 chopper will give the opportunity to tailor the longitudinal beam profiles in a way to minimize the space charge effects in terms of losses and longitudinal/transverse emittances. The PSB has to produce large variety of beams and we here consider the production of the 2 most important ones: the high intensity and large emittance beam for ISOLDE experiment and the LHC high brightness beam [1]. For ISOLDE we will inject 100 turns [2] and use the baseline scheme proposed already by C. Carli and R. Garoby [3]: in this way the energy modulation in the Linac4 requires at least 40 turns to complete this longitudinal painting scheme.

This is the reason why for the standard LHC beams ( $I=29.55e11$  p.), 20 turns injection [4], for which it is important to minimize the number of foil hits and blow-up due to the scattering at the screen, we consider no energy modulation. The main concern of this solution is the inho-

mogeneities and beating of the bunch shape, leading to a dense core and less populated tails [3]. However this regulation becomes more practical in control room during the commissioning of the machine.

Several simulations have been run through the ESME [5] and PyOrbit [6] codes with Linac4 realistic bunches to evaluate the parameters of possible initial unmodulated injections in a double RF accelerating bucket for the first 10 ms after injection: it is possible, in simulation, to vary the bunch length (in reality with the chopper) and/or the energy spread  $\Delta E$  (in reality with the debuncher) of the injected beams. The choice of using PyOrbit for pure longitudinal studies goes in the direction of using the code as baseline for 6D tracking including transverse-longitudinal space charge effects. Finally PyOrbit and BlonD [7] have been compared to estimate the contribution of space charge effects for the unmodulated injection scheme, after an initial benchmark between the two codes.

## LONGITUDINAL PAINTING SCHEME WITH ENERGY MODULATION

A longitudinal painting scheme with energy modulation has been selected as preferred one for high intensity beams, because it makes possible a uniform population of the initial accelerating RF bucket and, therefore, a reduction of the line density [protons/m] and an increase of the bunching factor, which are favorable conditions for reduced transverse space charge effects. This scheme aims at filling the 80% of the double RF accelerating bucket through a series of small energy spread (0.1 MeV) beams which are injected at different central energy. The central energy is modulated in time in a triangular way between  $\pm 1$  MeV. Figure 1 shows the bucket at the end of the filling, before the full filamentation phase. As said, this method requires at least 40 turns to be completed.

## THE UNMODULATED INJECTION

The longitudinal machine settings for the simulations are shown in Table 1. Figure 2 shows the three initial tested values of energy spread from Linac4: 113 keV, 336 keV and 592 keV rms. Figure 3 shows that the solution at 336 keV (halfway) is preferable, as it minimizes the peak line density due to the rotation in the longitudinal phase space of the mismatched beam, with respect to the 113 keV case (Fig. 4). Figure 5 represents the peak line density evolution turn-by-turn for the two cases.

On the other side, at 592 keV rms, the beam has a very large energy spread (over the acceptance). In this case, to

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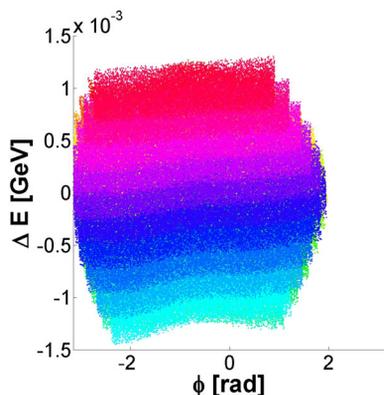


Figure 1: Longitudinal painting scheme with energy modulation. The different color bands are the beams which are injected turn-by-turn at different central energy.

minimize the mismatch, the bunch length should be smaller, but this leads to a reduction of the chopping factor and an increase of the number of turns in the multi-turn injection. For this reason, this solution has been dismissed.

Table 2 shows the results of the tracking at 336 keV rms energy spread without longitudinal space charge. One should note that for low target emittances the simulated min-max total bunch length is not much affected by the initial beam length: this is due to the bucket structure. A suitable solution is 47% chopping factor with initial bunch length of 474 ns. Considering 50 mA from the source, 10 turns are needed to obtain an injected intensity of  $14.77 \times 10^{11}$  protons (LHC BCMS) and, consequentially, 20 turns for a standard LHC beam ( $I=29.55e11$  p.).

Fixed the initial bunch length (47% chopping factor), a  $\Delta E$  tuning can be done to achieve the required performances in terms of total bunch length ( $<700$  ns for max 80% bucket filling) and total longitudinal emittance ( $<1.4$  eVs for max 80% bucket filling).

Table 1: A Summary of the Longitudinal Machine Settings for Simulations. \* For peaks balancing [3]

Linac4	Energy spreads [keV rms]	113, 336, 592
	Repetition rate [MHz]	352.2
PSB	Harmonic number	1+2
	$V(h1) - V(h2)$ [kV]	8, 6
	Relative phase between the cavities* [deg]	206
	Acceleration rate at injection $\dot{B}\rho$ [Tm/s]	10

After this analysis [8], a good tuning could be 47% chopping factor at 403 keV rms, reaching 600 ns total bunch length (at C285) and 1.4 eVs total emittance.

## LONGITUDINAL SPACE CHARGE EFFECT

The train of Linac4 bunches injected at every turn has a uniform profile in phase and a waterbag-like profile in

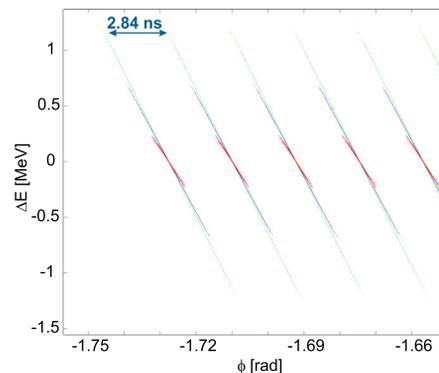


Figure 2: Linac4 bunches at injection in the PSB spaced by 2.84 ns. Red - 113 keV rms. Blue - 336 keV rms. Green - 592 keV rms.

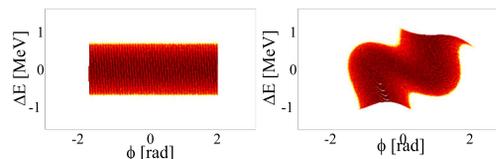


Figure 3: The initial (left) phase space and after 143 turns (right) for the initial 336 keV rms cases - ESME simulations.

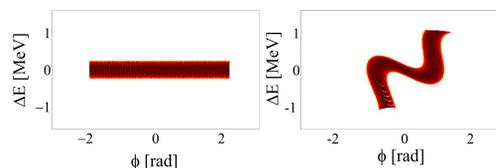


Figure 4: The initial (left) phase space and after 143 turns (right) for the initial 113 keV rms case - ESME simulations.

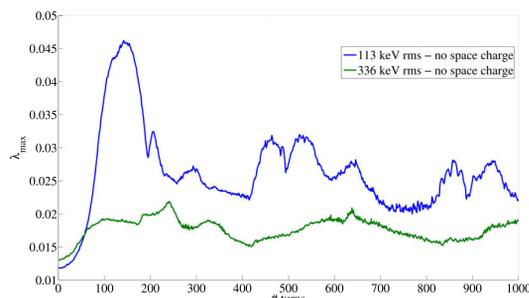


Figure 5: The normalised peak line density vs. turns for the 113 keV and 336 keV rms case - ESME simulations.

energy spread over 336 keV rms. This may lead to important longitudinal space charge effects at the edges of the bunch, as they depend on the derivative of the line density. Below transition the effect of the longitudinal space charge is defocusing, i.e. the bunch length increases: this effect gets very important for very long bunches which approach the unstable region close to the outer separatrix.

To evaluate space charge contributions, a benchmark has been performed between PyOrbit and BlonD with space charge detuning analytical formulas [9], starting with the simple case of a single harmonic not accelerating bucket. An

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Table 2: The 336 keV RMS Case with Different Chopping Factors (Without Longitudinal Space Charge). \*80% of the total acceptance, \*\*100% of the total acceptance

100% matched area [eVs]	Total injected bunch length [ns] (nr. of Linac4 bunches)	Max total bunch length [ns] ( $\pm 16$ ns) after 1000 turns	Total bunch length [ns] ( $\pm 15$ ns) @ C285 (175 MeV) - trev=974 ns	Linac4 current per pulse per ring [mA] / chopping factor	No. Of charges per pulse per ring / turns to achieve 14.77e11 p.
1	398 (139)	587	570	19.6 / 39%	1.24e11 / 11.8
1.1	442 (155)	595	570	21.8 / 44%	1.38e11 / 10.7
<b>1.2</b>	<b>474 (166)</b>	<b>605</b>	<b>590</b>	<b>23.4 / 47%</b>	<b>1.48e11 / 10</b>
1.3*	501 (176)	620	595	24.8 / 49%	1.56e11 / 9.5
1.7**	637 (223)	738	710	31.4 / 63%	1.99e11 / 7.4

example of the benchmark output is shown in Fig. 6: starting from a 150 ns (0.46 rad) parabolic bunch matched without space charge, the synchrotron frequency decreases and the bunch length increases due to the longitudinal space charge effects. The effective impedance  $Z/n$ , imaginary because only due to space charge, is 795.8 $\Omega$ . The results show good agreement between the codes and with analytical estimates.

Space charge simulations have then been performed also for the realistic injection scenario.

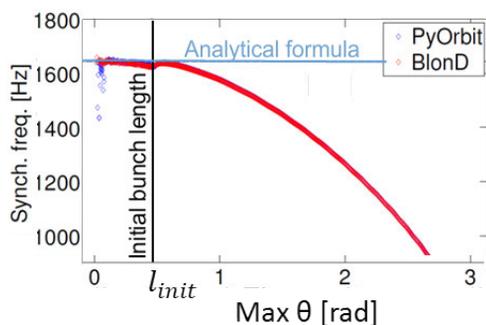


Figure 6: The synchrotron frequency benchmark between PyOrbit and Blond at Intensity=2.955e10 p.

Figures 7 and 8 show the results with 47% chopping factor at 403 keV rms with the two codes and intensity=29.55e11 p.. The intensity has been taken all in a single shot, even if, in reality, it will be injected over 20 turns. In both codes, an initial 16% overshoot in peak line density is foreseen during the initial filamentation time, which lasts ~3 ms, while in the long term the peak line density increases by less than 10% with respect to the initial one. The bunch lengthening effect, computed with a foot-tangent algorithm, is more evident with Blond w.r.t. PyOrbit (Fig. 8, bottom, +4%). The foot-tangent method takes into account the maximum and minimum derivative tangent lines of the low-pass filtered bunch profile and then derives the bunch length as the difference between the intersection points of these two lines with the profile baseline.

## CONCLUSIONS

Two possible longitudinal injection schemes are foreseen from the Linac4 to the CERN PSB in the LIU beams sce-

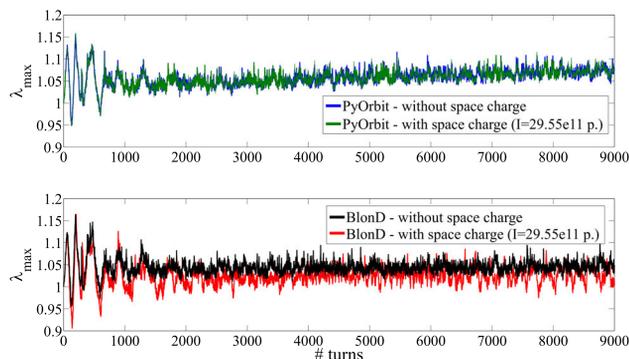


Figure 7: The peak line density in PyOrbit (top) and Blond (bottom).

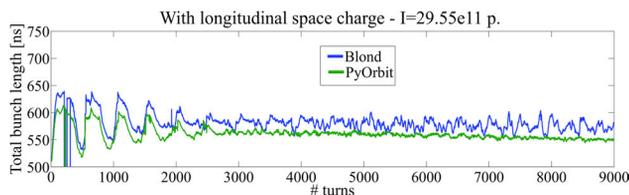


Figure 8: The total bunch length with space charge (I=29.55e11 p.).

nario: with energy modulation for high intensity beams and w/o for the LHC- type beams. This paper focuses on the unmodulated injection option. At first, single particle trackings with ESME and PyOrbit have been performed to evaluate the best option in terms of energy spread and bunch lengths for chopped beams giving an option of 474ns and  $\Delta E=403$  keV rms to obtain a longitudinal emittance lower than 1.4 eV-s and stay inside 80% of the total acceptance. Afterwards, the inclusion of longitudinal space charge has been performed in two different codes (PyOrbit and Blond), which have been previously benchmarked in terms of longitudinal space charge evaluation. Further simulations are foreseen to evaluate the effects of the multi-turn injection and comparison with the energy modulation scheme for high intensity beams. Studies are also planned to benchmark the codes with the present measured capture process.

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