# INJECTION PAINTING AND ASSOCIATED HW FOR 160 MeV PSB H$^-$

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## *Abstract*

Linac4 will replace the currently used Linac2 in the LHC injector chain. The motivation is to increase the proton flux availability for the CERN accelerator complex and eventually achieve the LHC ultimate luminosity goals. Linac4 will inject 160 MeV H$^-$ ions in to the four existing rings of the PS Booster (PSB). A new charge-exchange multi turn injection scheme will be put into operation and requires a substantial upgrade of the injection region. Four kicker magnets (KSW) will be used to accomplish transverse phase space painting in order to match the injected beams to the required emittances. This paper presents hardware issues and related beam dynamics studies for several painting schemes. Results of optimization studies of the injection process for different beam characteristic and scenarios are discussed.

## INTRODUCTION

The ultimate luminosity reach of the LHC foresees to increase the bunch intensity from $1.15\times10^{11}$ protons (p$^+$) to $1.7\times10^{11}$ p$^+$. One of the key intensity limitation is determined by the direct space charge effects at the PS Booster (PSB) for low energies. The replacement of the Linac2, currently injecting 50 MeV p$^+$ into the PSB, with Linac4 will allow to increase the injection energy to 160 MeV [1]. This will mitigate the space charge effects and permit to increase the beam intensity at the Booster. Moreover, the conventional multi turn injection, used with Linac2, will be substituted by a H$^-$ charge exchange injection system [2]. This consists of a horizontal closed orbit bump (chicane) and a thin carbon foil (stripping foil) converting hydrogen ions to protons by removing the electrons. The chicane is made up of four dipole magnets (BS), with 66 mrad deflection, which are located symmetrically around the stripping foil. A further attenuation of the space charge effects can be obtained controlling the distribution, in phase space, of the injected particles. The energy of the injected beam will be varied to fill the bucket with an equal density distribution (longitudinal painting) [3]. The H$^-$ charge exchange allows to inject more times in the same phase space volume. An additional closed orbit bump will be used to fill first the centre and then the outer area of the ellipse in the transverse phase space (transverse painting).

The PSB has to provide beam to several users with different requirements in terms of beam intensity and emittance. Decay time modulation of four kicker magnets (KSW), which are already installed in the PSB lattice, will allow to accomplish the transverse phase space painting to the required emittances [4].

## PSB USERS BEAM REQUIREMENTS

Particles are accelerated up to 1.4 GeV in the PSB and then they can be either directed to the Proton Synchrotron (PS) or directly to the isotope facility ISOLDE. The Booster has to provide the PS with beams having different emittances and intensities, in order to fulfill the requirements of several users. Six beam types are foreseen for the Large Hadron Collider (LHC), during nominal and ultimate operation. Beams with extremely different characteristics are then needed for a number of fixed target experiments (CNGS, East and North area targets), the Antiproton decelerator (AD) and neutron time-of-flight facility (nTOF).

Linac4 supplies $1\times10^{14}$ protons per pulse to the PSB, with a pulse length of 400 $\mu$s. Protons need roughly 1 $\mu$s to perform one turn in the Booster. Number of injection turns needed to fill the PSB rings, target intensities and emittances are summarized in Table 1 for the different users.

## INJECTION TRANSVERSE PAINTING

The beam will be injected in the PSB with an angle of 66 mrad with respect to the axis of the circulating beam. The strength of the BS chicane magnets (RBEND) will be maximum during injection, corresponding to a -45.9 mm orbit bump, and will decrease linearly after the injection. Edge focusing effects will occur at the pole faces and perturb the vertical betatron oscillations. This perturbation can be compensated either with additional trim quadrupoles (active) or by a pole face rotation of the BS (passive) [5]. The studies presented in this paper refer to the passive compensation case, and to a pole face rotation of 66 mrad (SBEND).

In addition to the injection chicane, a horizontal painting bump is implemented. The height of the bump, at the beginning of the injection, depends on the beam and other injection parameters. The painting bump starts to decay already during injection to control the filling of the horizontal phase space. Vertical beam ellipse areas are partially filled without painting, letting the space charge forces reshuffle the particle distribution on successive turns. The following studies were performed to understand the effect of different KSW decay modulations on the beam emittance and to de-

Table 1: Target beam intensities (per ring) and rms normalized emittances are listed for the different PSB users. The number of turns needed for injecting the desired number of protons is also shown.

| **User** | **Description** | **Intensity per ring $[p^+]$** | **Emittance** | | **Injection turns** |
|---|---|---|---|---|---|
| | | | **H [mm mrad]** | **V[mm mrad]** | |
| LHC25 | 25 ns LHC beam | $3.25\times10^{12}$ | 2.5 | 2.5 | 20 |
| LHC50 | 50 ns LHC beam | $2.43\times10^{12}$ | 2.5 | 2.5 | 15 |
| LHC75 | 75 ns LHC beam | $< 2.43\times10^{12}$ | 2.5 | 2.5 | <15 |
| LHCPILOT | Early LHC pilot | $5\times10^{9}$ | 2.5 | 2.5 | 1 |
| LHCPROBE | Early LHC probe | $5\times10^{9}$<br>$2.3\times10^{10}$ | 2.5 | 2.5 | 1<br>1 |
| LHCINDIV | Individual bunch physics beam | $2.3\times10^{10}$<br>$1.35\times10^{11}$ | 2.5 | 2.5 | 1<br>1 |
| CNGS | CNGS target | $6.0\times10^{11}$<br>$8.0\times10^{12}$ | 10.0 | 8.0 | 4<br>49 |
| SFTPRO | North Area target | $6.0\times10^{12}$ | 8.0 | 6.0 | 37 |
| AD | AD target | $4.0\times10^{12}$ | 8.0 | 6.0 | 25 |
| TOF | nTOF beam | $9.0\times10^{12}$ | 10.0 | 10.0 | 55 |
| EASTA/B/C | East Area target | $1.0\times10^{11}$<br>$4.5\times10^{11}$ | 3.0 | 1.0 | 1<br>3 |
| NORMGPS<br>NORMHRS | ISOLDE GPS/HRS target | $1.0\times10^{13}$ | 15.0 | 9.0 | 62 |
| STAGISO | ISOLDE special target | $3.5\times10^{12}$ | 8.0 | 4.0 | 22 |

fine the optimum painting scheme for nominal 25 ns LHC and CNGS beams.

## ORBIT SIMULATIONS

Simulations were performed with the particle tracking code ORBIT [6] (Objective Ring Beam Injection and Tracking) using multiple processing. This program allows to simulate $H^-$ charge exchange, via stripping foil, and dynamics of beams with strong direct space charge forces. Apertures and acceleration were also included. A routine is implemented in ORBIT to simulate the painting bump using the thin lens formalism for the KSW. This approximation cannot be applied to the chicane magnets because edge focusing effects would be neglected. Initial 6D distributions of 500 000 macroparticles were generated using a Mathematica notebook, including the longitudinal painting. For the studies presented in the following, a particle distribution matched in dispersion (Dx = -1.4 m) and for a horizontal position of -35 mm and 0 offset was generated. The initial lattice, created with MAD8, stays unchanged during injection, while a new lattice has to be reloaded, at each turn, when the chicane fall starts. Theses studies were dedicated to injection painting, particles were tracked over 100 turns and a fixed lattice was used.

### *Effect of Stripping Foil on Emittance*

The stripping foil, needed for charge exchange injection, causes also a scattering which determines an emittance growth and, therefore, a beam quality degradation [7]. Simulations were carried out, for the nominal 25 ns LHC beam with and without the stripping foil (carbon, 300 $\mu$g/cm$^2$), to quantify this effect. Particles were tracked over 100 turns keeping the painting bump height fixed at -35 mm. In this way, the circulating beam was passing through the stripping foil at each turn. It was shown that, after injection, the foil caused a linear blowup of the emittance, that increased by a factor of 2 after 100 turns (see Fig. 1). Circulating beam must be moved away from the foil as fast as possible to limit this effect. Presently, the chicane fall time is slow (about 5 ms), and the painting bump has to be used for this purpose.

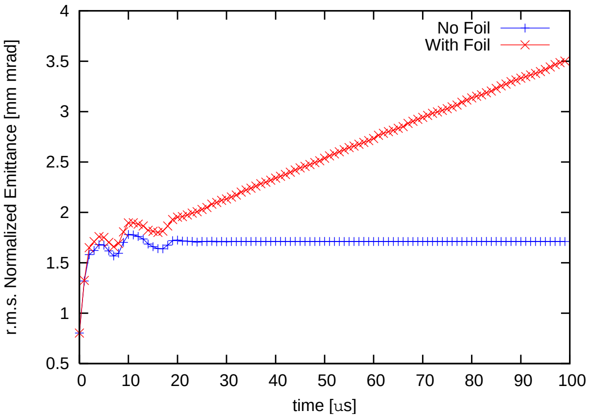

Figure 1: Effect of stripping foil on beam emittance for nominal 25 ns LHC beam. Particles were tracked over 100 turns and injection finished after 20 turns.

### *KSW Possible Waveforms*

Two different options, of possible waveforms for the painting magnets, were analyzed. The first option (see Fig. 2) foresees a slow linear decay of KSW current (dI/dt) until the end of the injection, and then a fast linear fall to 0, in order to move the beam away from the stripping foil. An initially faster exponential decay, followed by an almost constant slope fall, until the end of the injection, characterizes the second option (see Fig. 3). The last part of the waveform is identical in both cases (15 $\mu$s) and depends on the maximum KSW dI/dt. The second option would allow to better distribute particles in the horizontal phase space by reducing the charge density in the core of the bunch. This is beneficial, especially for high intensity beams, because it would reduce the instabilities induced by space charge effects.

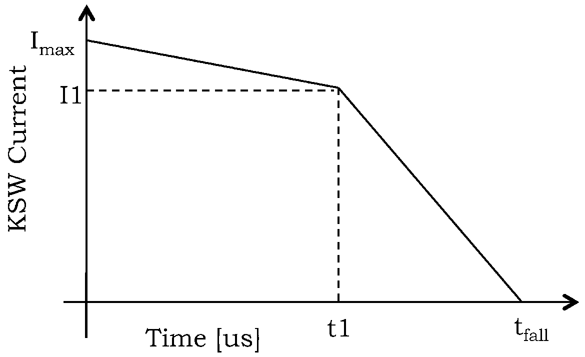

Figure 2: Decay of KSW painting magnets current as a function of time (Option 1). Injection ends at time t1 and the magnets are off at t$_{fall}$. I$_{max}$ gives current corresponding to a bump height, at the foil, of -35 mm.

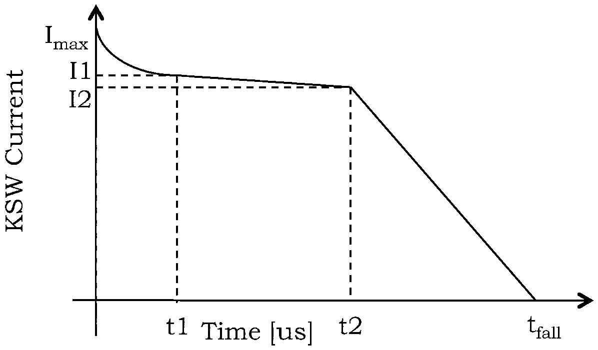

Figure 3: Decay of KSW painting magnets current as a function of time (Option 2). The exponential decay ends at time t1 and injection finishes at t2. The magnets are off at t$_{fall}$. I$_{max}$ gives current corresponding to a bump height, at the foil, of -35 mm.

### *LHC Beam*

ORBIT Tracking simulations have been performed, for the nominal LHC beam, to compare the effect of the two solutions proposed for the KSW waveforms. The LHC beam is injected over 20 turns and it has a relatively low intensity (see Table 1). A target r.m.s. normalized emittance, of 2.5 mm mrad (see Fig. 4), has been used to tune the parameters defining the KSW decay. For the linear decay case, 1.8% of the tracked particles were lost after 100 turns, while a slightly smaller fraction (1.5%) was lost for the exponential case. Final charge density, in the horizontal phase space after 100 turns, is shown in Fig. 5. No big differences can be seen between the two variants. The particle distribution is peaked in both cases but, due to the low intensity, this should not determine a major limitation. The initial exponential decay might anyhow be preferable since it allows to reduce the effect of emittance increase, induced by the stripping foil over the first turns.

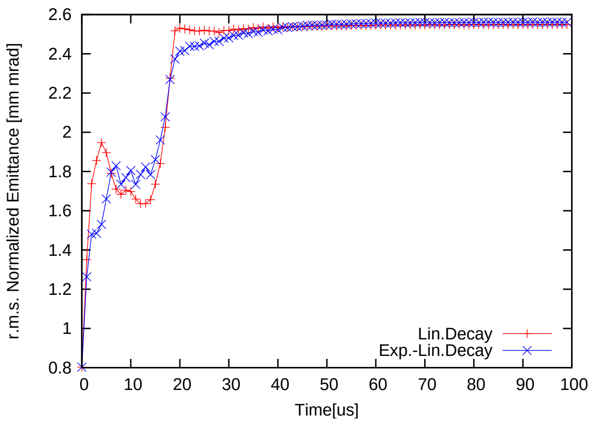

Figure 4: LHC beam normalized emittance is plotted, as a function of time, for linear KSW decay (option 1, red curve) and exponential-linear decay (option 2, blue curve).

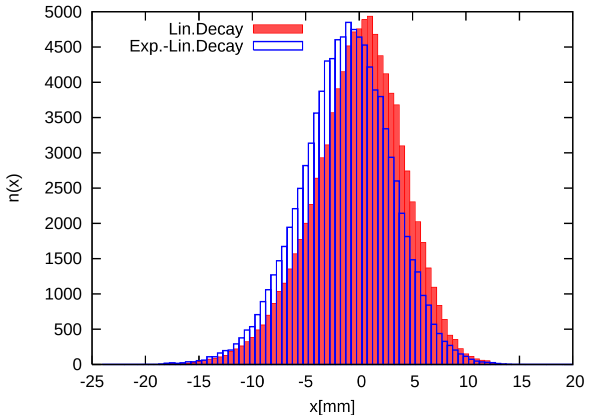

Figure 5: LHC beam charge density, in horizontal phase space, is presented for linear KSW decay (option 1, red curve) and exponential-linear decay (option 2, blue curve).

### *CNGS Beam*

Analogous simulations have been carried out for the CNGS high intensity beam ($8\times10^{12}$ $p^{+}$ see Table 1). In this case, injection takes place over 49 turns and an emittance of 10 mm mrad was used as target (see Fig. 6). The number of particles which are lost at the machine aperture is slightly higher for exponential waveform (1.9% with respect to 1.6% of the linear case). Anyway, for the high intensity beams, the exponential decay of the painting magnets gives a significant improvement (see Fig. 7). The linear waveform generates, in fact, a peaked particle distribution, while the exponential solution reduces the core density providing a more uniform spread of the particle in the horizontal phase space.

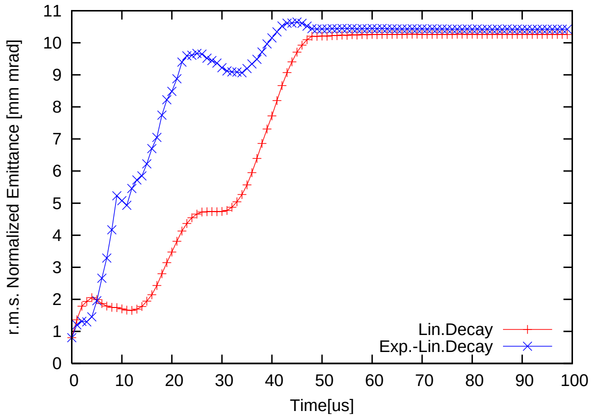

Figure 6: CNGS beam normalized emittance is plotted, as a function of time, for linear KSW decay (option 1, red curve) and exponential-linear decay (option 2, blue curve).

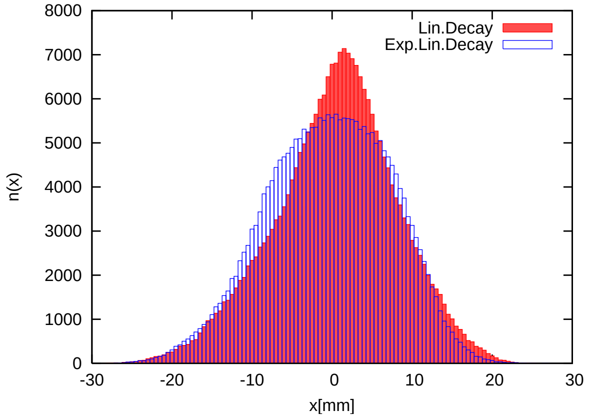

Figure 7: CNGS beam charge density, in horizontal phase space, is presented for linear KSW decay (option 1, red curve) and exponential-linear decay (option 2, blue curve).

## KSW MAGNETS

The exponential solution, for KSW waveform, proved to be the most promising, in particular, for high intensity beams. In Table 2, the parameters used to characterize the exponential decay (Option 2, see Fig. 3 ) are presented for the simulated cases. KSW magnets can provide a maximum bump, at the stripping foil, of -55 mm. This bump corresponds to a kick of 8.74 mrad (0.045 T) at the first and last KSW (KSWP16L1 and KSWP16L4), and of 2.55 mrad (0.013 T) at the second and third KSW (KSWP1L4 and KSWP2L1). Current decay of the painting magnet varies in time and for different PSB users beams. Functions have to be defined for each user requiring a high flexibility of the KSW. Detailed studies have still to been performed for all the remaining intensities and target emittances presented in Table 1. It is reasonable to estimate, according to the results obtained, an initial exponential fall corresponding to a $\Delta$I between 0% $I_{max}$ and 50% $I_{max}$ over 1-20 $\mu$s, followed by a constant slope fall over 5-100 $\mu$s ($\Delta$I = 2% - 100% $I_{max}$). A hardware limit sets the maximum achievable dI/dt to 15% $I_{max}$. This has an influence on the exponential fall time constant and on the final fast fall, that is expected to vary between 5 $\mu$s and 15 $\mu$s ($\Delta$I = 0% - 70% $I_{max}$). New power supplies deign and switches for slope changes are needed. Moreover, the most convenient way for powering the magnets (in series, in parallel or independently) is under investigation.

Table 2: Waveform parameters used to characterize the exponential decay of the KSW magnets (Option 2).

| | **LHC Beam** | **CNGS Beam** |
|---|---|---|
| I1 | 94% $I_{max}$ | 71% $I_{max}$ |
| I2 | 92% $I_{max}$ | 70% $I_{max}$ |
| t1 | 7 $\mu$s | 10 $\mu$s |
| t2 | 20 $\mu$s | 49 $\mu$s |
| $t_{fall}$ | 35 $\mu$s | 64 $\mu$s |

## CONCLUSIONS

A $H^-$ charge exchange injection system, at 160 MeV, will be implemented into PSB to reduce space charge effects and increase beam intensity. Kicker magnets, presently installed in the Booster, will be used to perform beam painting in the horizontal phase space and to fast move the beam away from the scattering foil after injection. Two different options have been analyzed for decay modulation of KSW magnets. Orbit simulations, for nominal LHC and CNGS beam, have been performed to investigate the optimum painting forms. Preliminary results showed that an initial exponential decay is preferable. This reduces the emittance increase induced by the stripping foil over the first injection turns and, for high intensity beams, limits the charge density in the core of the bunch. Same studies have to be extended to all other beam types, and functions have to be defined for each user. Time and current ranges have been estimated and imply a high flexibility of the KSW. Studies have to be carried out to evaluate how to obtain the required vertical emittance and the effect of injection offsets, dispersion and betatron mismatch.

## REFERENCES

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