STUDIES ON TRANSVERSE PAINTING FOR H^- INJECTION INTO THE PSB

C. Bracco, C. Carli, T. Fowler, B. Goddard, G. Gräwer, J-B. Lallement,
M. Martini,W. Weterings, CERN, Geneva, Switzerland

Abstract

Linac4 will inject 160 MeV H^- ions into the CERN PS Booster (PSB). This will allow to reduce space charge effects and increase beam intensity but will require a substantial upgrade of the injection region. The PSB has to provide beam to several users with different requirements in terms of beam intensity and emittance. Four kicker magnets (KSW) will be used to accomplish painting in the horizontal phase space to match the injected beams to the required emittances. Multiple linear functions, with varying slopes for each user, have been defined for the KSW generators waveforms according to detailed beam dynamic studies for all target intensities and emittances. Preliminary studies have been carried out to evaluate how to obtain the required vertical emittance and the option of a transverse painting, also in the vertical plane, is explored.

INTRODUCTION

The substitution of Linac2 with Linac4, in CERN's injector chain, will allow to increase the injection energy into the PSB from 50 MeV to 160 MeV [1]. This will mitigate space charge effects and permit to increase the beam intensity at the Booster. A new multi-turn H^- charge-exchange injection system, consisting of a horizontal chicane (BS) and a thin carbon stripping foil, will be put in place [2].

A controlled distribution of the injected particles will provide further space charge attenuation. Energy modulation, from Linac4, will be used to fill the bucket with an equal density distribution [3]. Transverse painting will be performed in the horizontal plane, by means of four existing PSB kicker magnets (KSW), to uniformly fill the transverse phase space area.

The PSB has to provide beams with different emittance and intensity (LHC, CNGS, ISOLDE, nTOF, etc.). Tracking simulations of 500 000 macroparticles were performed with ORBIT (Objective Ring Beam Injection and Tracking [5]) to define the optimum KSW decay modulation for all the PSB users, according to their specific requirements. Initial 6D distributions were generated, including the longitudinal painting, using a Mathematica notebook. H^- charge exchange, foil scattering, space charge, acceleration and apertures were included in the simulations.

INJECTION PAINTING

Multi-turn H^- charge exchange allows to inject several times in the same phase space volume. The number of turns needed to fill the PSB depends on target intensity and Linac4 energy modulation. An intensity of 3.25×10^{12} protons is required for the LHC nominal beam. Linac4 should provide 0.6 ms pulses of up to 1×10^{14} protons; this would mean a 20 turns injection for the LHC beam (taking into account a PSB revolution time of 1 μs). In reality, mainly due to RF limitations, a minimum number of 40 turns is necessary to complete the longitudinal painting in the bucket. This corresponds to injecting 8.13×10^{10} protons per turn and this value was taken as the reference for the cases studied and presented in this paper.

Horizontal Plane

The beam will be injected in the PSB with an angle of 66 mrad and will be horizontally deflected, by the BS magnets, to be merged to the circulating beam. The chicane will stay constant during injection, giving a bump of -45.9 mm at the stripping foil, and will then linearly decay to zero in 5 ms. The KSW painting bump will be at its full amplitude (-35 mm) at the startup of the painting process and will decay, in a controlled way, until injection is accomplished. This will allow to fill first the centre and then the outer area of the transverse phase space and to move, as fast as possible, the circulating beam away from the foil in order to limit the emittance blowup induced by scattering processes.

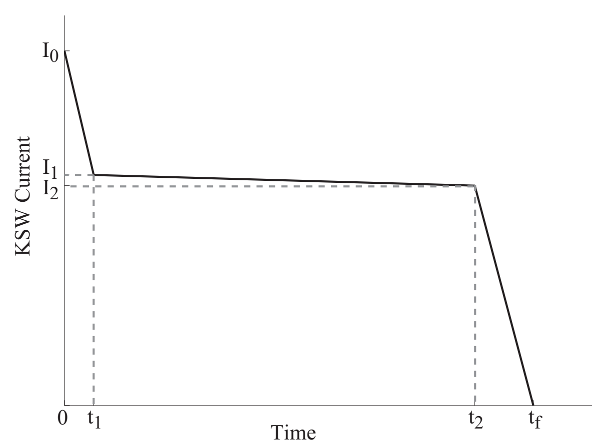

Figure 1: Decay of KSW current as a function of time. The first linear decay ends at time t_1 and injection finishes at t_2. I_0 indicates the current corresponding to a bump height of -35 mm at the foil.

A high flexibility in the KSW current decay is required in order to fulfill the needs of the different users [4]. A multiple-linear waveform was chosen for the KSW generators which is schematically shown in Fig. 1. An initially faster decay, over few turns (until t_1), is followed by an almost constant slope fall until the end of the injection (t_2). The last part (t_2-t_f) is used to move the beam away from the foil and depends on the maximum achievable dI/dt (15 μs). Such a waveform allows to distribute particles in the transverse space in a more uniform way with respect to a simple linear function; charge density in the core of the bunch is reduced and space charge effects are less severe. The current I_0 gives the -35 mm bumps and corresponds to a kick of -5.56 mrad (0.029 T) at the first and the last KSW (KSW16L1 and KSW2L1), and of -1.62 mrad (0.008 T) at the two central KSW (KSW16L4 and KSW1L4).

ORBIT simulations were performed to define the optimum KSW decay functions for all the PSB users. A particle distribution matched in dispersion (D_x = -1.3 m), with a horizontal position of -35 mm and 0 offset was used. Results of these studies are summarised in Table 1 where the parameters characterizing the functions for the different users are presented.

Table 1: Parameters characterizing the KSW waveforms for the different PSB users are presented. I_1 and I_2 give the percentage of KSW current with respect to I_0. The last column shows the offset needed to match the required r.m.s. emittance in the vertical phase space.

User	I_1 [%]	I_2 [%]	t_1 [μs]	t_2 [μs]	t_f [μs]	V. off. [mm]
LHC25	90	89	10	40	55	3.5
CNGS	70	69	25	98	113	7
SFTPRO	74	73	20	74	89	6
AD	72	71	20	50	65	6.5
nTOF	71	70	25	110	125	8
NORM	64	63	24	124	139	7.5
STAGISO	70	69	20	44	59	5

Injection process duration varies between a minimum of 40 turns (LHC) to a maximum of 124 turns (NORM). This would require a pulse length of the distributor magnets longer than the actual maximum design value (100 μs [6]). Magnet current intensity changes between 10% I_0 and 35% I_0 over 10-25 μs and then by 1% I_0 over 15-85 μs. Ideally, each KSW magnet will be powered independently from the others in order to make the system more flexible.

The evolution of horizontal r.m.s. emittance in time, as obtained with the defined painting functions, is shown in Fig. 2; target emittances are also shown as reference. A $\pm$1% current fluctuation with respect to the values in Table 1 means an emittance change of about $\pm$0.5 μm. For all the cases analysed, less than 1% particles were lost at the end of the injection process.

Preliminary studies have been performed using a beam unmatched in dispersion (D_x = 0) for LHC and CNGS; this option would require slightly less aperture and a smaller foil. A change of a few percent in I_1 and I_2, with respect to values presented in Table 1, had to be applied in order to match the target emittance: 95%-94% for LHC, 72%-71% for CNGS, that is still compatible with the hardware requirements presented above.

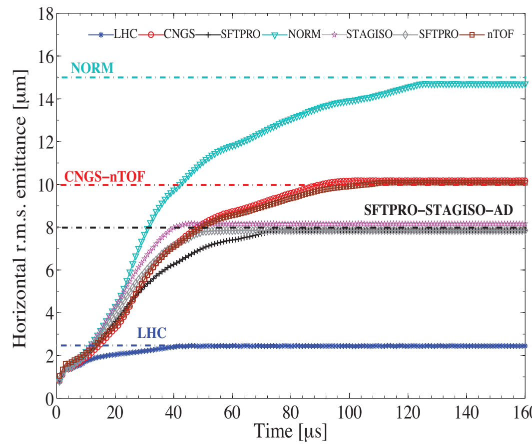

Figure 2: Horizontal emittance, during transverse phase space painting, is shown in comparison to the target values (dashed lines) for the different PSB users.

Vertical Plane

No painting in the vertical plane is foreseen at present. Desired emittances are obtained injecting the beam with a vertical offset, by means of the last steering magnets of Linac4, and letting the space charge forces reshuffle the particles distribution on successive turns. A deliberate optical mismatch at injection is also possible. The last column in Table 1 contains the offsets applied; Fig. 3 shows the r.m.s. emittance growth in time for the different beams.

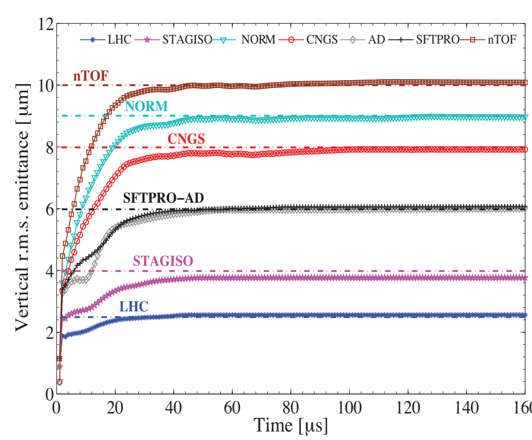

Figure 3: Vertical emittance, during transverse phase space painting, is shown in comparison to the target values (dashed lines) for the different PSB users.

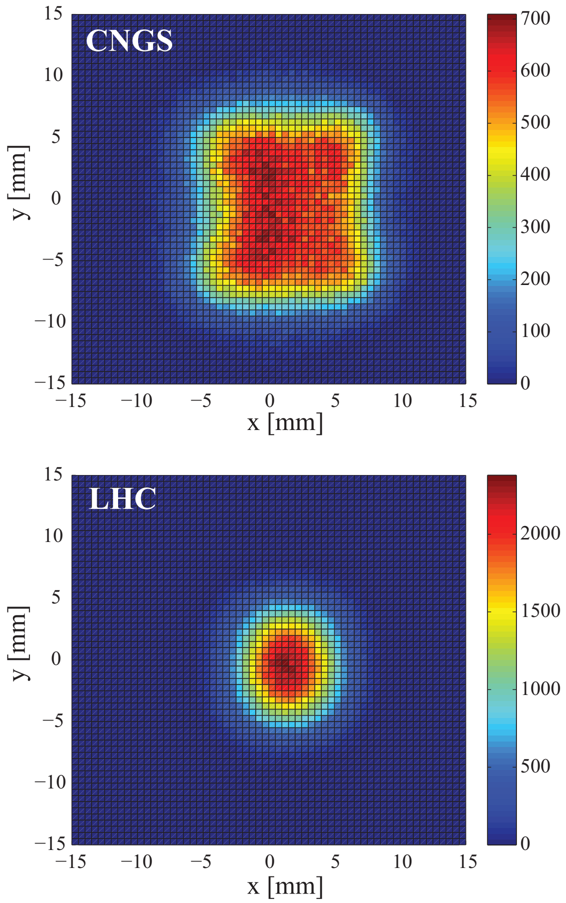

Figure 4: Charge density in x-y space is presented for CNGS (top) and LHC (bottom) beams at the end of transverse painting.

Horizontal painting and vertical offset allows to get a uniform particle distribution in the x-y plane for high intensity beams (e.g. CNGS: 8×10^{12} p^+, see top of Fig. 4). A less uniform distribution could be obtained for the high brightness LHC beam, as shown in Fig. 4 (bottom). Further studies are needed to look into the option of LHC beams with higher intensities and smaller emittances. The possibility of diluting injection over a period longer than 40 turns or using an initial offset should be considered.

Table 2: Vertical kicker parameters needed to have a 10 mm bump at the stripping foil. The first three magnets are currently installed in the PSB while the last one has been virtually added in the MADX lattice file.

	Kick [mrad]	Length [mm]	B [mT]
BR1DVT.16L1	2.53	403	1.94
BR1DVT.2L4	1.73	403	1.32
BR1DVT.3L4	-1.17	403	0.90
BR1DVT.2L1	2.33	403	1.78

The option of a vertical painting has been explored. Four kicker magnets are needed to generate a closed orbit bump and control the beam divergence at the foil. Three existing vertical kickers (BR1DVT.16L1, BR1DVT.2L4 and BR1DVT.3L4) could be used and a supplementary kicker could be installed in a free drift 3 m downstream of KSW.2L1 (BR1DVT.2L1). Preliminary MADX calculations confirmed that a closed bump of 10 mm could be obtained with these magnets (see parameters in Table 2); further studies need to be carried out to define a painting scheme analogous to the one used in the horizontal plane. A deliberate optical mismatch also needs to be investigated.

CONCLUSIONS

A new injection system into PSB will be implemented to reduce space charge and increase beam intensity. Four kicker magnets, presently installed in the Booster, will be used to perform beam painting in the horizontal phase space and to quickly move the beam away from the stripping foil after injection. Detailed ORBIT simulations have been performed to define the optimum painting scheme. A multiple linear waveform, with an initially faster decay, has been defined for each PSB user. Such a waveform will allow to reach the target emittances and uniformly fill the transverse space reducing space charge effects in the high intensity beams. Further studies to optimize high intensity and small emittance LHC beams are foreseen. High flexibility in the KSW current decay, with $\pm1\%$ tolerance, is required; independent powering of the magnets is preferable. The hardware specifications defined proved to be compatible with injection of beams matched and unmatched in dispersion. A vertical offset, provided by Linac4 steering magnets, permits to match the emittance requirements of the different users. The possibility of performing painting also in the vertical plane, if needed, seems feasible with the installation of a supplementary vertical kicker close to the injection region.

REFERENCES

[1] L. Arnaudon et al., "Linac4 Technical Design Report", CERN-sLHC-Project-Note-0020, CERN, Geneva, Switzerland, 2010.

[2] M. Aiba et al. , " Layout Considerations for the PSB H^- injection system", sLHC Project Note 0004, CERN, Geneva, Switzerland, 2009.

[3] M.Aiba et al., " Evolution Beam Parameters During Injection and Storage of the High Brightnesses Beams Envisaged for the Linac4 Injection into the CERN PS Booster", Proceedings of Hadron Beam 2008, Nashville, Tennessee, USA, 2008.

[4] C. Bracco et al., " Injection Painting and Associated HW for 160 MeV PSB H^- injection", Proceedings of HB2010, Morschach, Switzerland, 2010.

[5] J.D. Galambos et.al, "ORBIT User Manual version 1.10", 1999.

[6] W. Weterings et al., " 160 MeV H^- Injection into the CERN PSB", Proceedings of PAC07, Albuquerque, New Mexico, USA, 2007.