

# HIGH-INTENSITY AND HIGH-DENSITY CHARGE-EXCHANGE INJECTION STUDIES INTO THE CERN PS BOOSTER AT INTERMEDIATE ENERGIES

M. Martini, CERN, Geneva, Switzerland, C.R. Prior, Rutherford Appleton Laboratory, Oxford, UK

## Abstract

For the high brilliance LHC ultimate beam and the high intensity CNGS beam, single batch injections into the CERN Proton Synchrotron (PS) will be used to increase the overall machine intensity compared with the present double batch injections. Charge-exchange injection into the PS Booster with a new linac at intermediate energies is thus examined. A key parameter to consider is the energy dependence of beam incoherent tune shifts at injection. Increasing the linac energy from the present 50 MeV to 160 MeV should yield a safer tune shift. For each PS Booster ring, a charge-exchange injection scheme is envisaged inside a proper straight section, redesigned with new bends to make a local bump and using the existing fast bump magnets for horizontal phase-space painting. Accsim simulations for charge-exchange injection at 160 MeV have been investigated for both LHC and CNGS beams. After optimizing the parameters that are used for the space charge tracking routines, the results of the simulations agree well with expectations, signifying that the LHC ultimate and CNGS beams may be provided with single PS Booster batches within the required emittances. For assessment, simulation of injection at 50 MeV for the current LHC beam has been performed, yielding a fairly good agreement with measured performance. Concurrently, similar charge-exchange injection simulations have been carried out using an alternative programme developed at the Rutherford Appleton Laboratory.

## INTRODUCTION

The CERN PS Complex of accelerators will have to deliver beams for the LHC, CNGS and ISOLDE of higher brightness or intensity than presently achieved. Single batch injections into the CERN Proton Synchrotron (PS) are thus foreseen to increase the whole machine intensity compared with the present double batch injections, avoiding in addition the current long injection plateau in the PS machine. A beneficiary of this improvement will be the ISOLDE facility. Indeed, in the medium term the ISOLDE community demands an overall intensity upgrade of about a factor five [1].

A key limiting parameter for the proton beam intensity increase is the high incoherent space charge tune shift in the present PSB 50 MeV injection. The energy dependence of beam incoherent tune shifts being inversely proportional to the factor  $\beta\gamma^2$ , increasing the linac kinetic energy from 50 MeV to 160 MeV should decrease the tune shifts by about a factor two allowing approximately doubling the PSB beam intensity. With a new linac injector, called Linac4, upgraded both in

particle intensity and output energy, the particle type will be changed from proton to  $H^-$  to permit phase painting for better beam distribution and minimised space charge effects of the beam (Table 1). To implement the  $H^-$  injection scheme, the layout of the injection region of the PSB will have to be redesigned installing new bends for local bump and using the existing fast bumpers for painting during the injection process.

Simulations using the Accsim code [2] for the 160 MeV  $H^-$  injection and accumulation in the PSB have been investigated for both LHC ultimate and CNGS beams. Once the parameters used for the space charge tracking routines have been carefully adjusted, simulation results confirm the expected gain in intensity while keeping the beam emittances under control. Simulation of the present 50 MeV PSB injection for the LHC beam, requiring double batch injections into the PS, has been done for comparison. Achieved results are in good agreement with actual beam performance. In the meantime,  $H^-$  injection and accumulation simulations in the PSB by means of an alternative programme developed at the Rutherford Appleton Laboratory are in progress for cross-checking.

Table1: Intensity and emittance figures of the LHC ultimate and CNGS beams.

	PSB intensity	PS intensity 1.4 GeV	PS emittances $\beta\gamma \sigma^2/\beta_x$
LHC ultimate single Linac4 160 MeV	$3.25 \times 10^{12}$ per ring	$1.3 \times 10^{13}$ 6 bunches	2.5 $\mu\text{m}$ (H) 2.5 $\mu\text{m}$ (V)
LHC ultimate double Linac2 50 MeV	$1.63 \times 10^{12}$ per ring	$1.3 \times 10^{13}$ 6 bunches	2.5 $\mu\text{m}$ (H) 2.5 $\mu\text{m}$ (V)
CNGS single Linac4 160 MeV	$1.25 \times 10^{13}$ per ring	$5.0 \times 10^{13}$ 8 bunches	11.5 $\mu\text{m}$ (H) 4.6 $\mu\text{m}^{(1)}$ (V)

<sup>(1)</sup> Maximum beam emittances at injection imposed by the PS acceptance ( $A_{H,V}=60/20 \mu\text{m}$ ) to limit the losses at 1%. Permitting a 5% beam loss would increase the PS emittance limit to 20.7 and 7.6  $\mu\text{m}$ .

## PSB $H^-$ INJECTION SCHEME

### Injection layout

The charge-exchange injection scheme retained in this study is the improved scenario already conceived in [3] and sketched in Fig. 1.

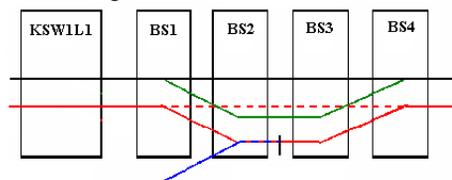


Figure 1: Geometry of the proposed PSB  $H^-$  injection in the long straight section 1L1. All angles are equal to the slope of the incoming  $H^-$  beam (66 mrad). The global central orbit bump ( $\sim 6$  cm) is provided by the short bump ( $\sim 3$  cm) and the programmed long bump ( $\sim 3$  cm).

For each of the four PSB rings, the H<sup>-</sup> injection takes place in a 2.5 m straight section, to be redesigned with four new dipole magnets (BS's) providing a short range closed orbit bump around the stripping foil and the existing four "kicker slow" (KSWs) to make a programmed long range bump for horizontal phase plane painting. A combination of short and long bumps displaces the central proton beam orbit so that it merges with the incoming H<sup>-</sup> beam.

*Longitudinal capture*

The longitudinal capture of the incoming linac beam into the PSB has to be studied before carrying out transverse phase plane simulations. Assume the 160 MeV Linac4 as PSB injector, delivering a 30 mA linac beam current after a 75% chopping factor. The capture has been optimised using an iso-adiabatic bunching process [4], raising the RF voltage from 0.6 kV at injection to 8 kV in 2.6 ms. Performance of the capture and acceleration have been checked with the Long1D simulation code [5]. Tracking results are displayed in Fig. 2.

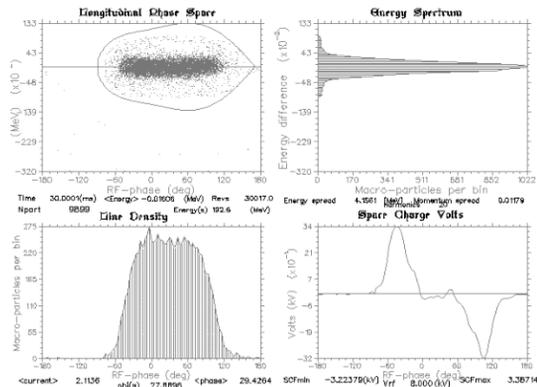


Figure 2: Long1D tracking over 30017 PSB turns (30 ms): Scatter-plot of particles in the longitudinal phase-plane, energy spectrum, line density and space charge voltage. ~1% beam loss.

*Phase-plane painting strategy*

The beam emittances required for LHC and CNGS are painted by the 0.22 μm output linac normalised rms beam emittance. Beams are gradually injected through the stripping foil from the centre of horizontal stored beam ellipses to the outside by way of a controlled shift of the closed orbit via the programmed long orbit bump, filling progressively the ellipse areas. Vertical beam ellipse areas are partly filled without painting (packed within a ring area), letting the space charge forces reshuffle the particle distribution on successive turns. No longitudinal painting is done because the linac bunch parameters are too large with respect to the PSB bucket. With the Linac4, the whole H<sup>-</sup> injection process is achieved within 17 and 66 PSB turns, respectively for the LHC and CNGS (single batch operation) beams. Suitable working points of 4.28 horizontal and 5.47 vertical have been settled to prevent excessive emittance blow-up shortly after injection.

Simulations of H<sup>-</sup> injection and acceleration have been done with Accsim, using the hybrid fast multipole method for space charge tracking. The parameters, field solver

grid size and the number of applied angular kicks, representing space charge force integral, were adjusted to be adequate to the PSB lattice.

**SIMULATION OUTCOME AT 160 MeV**

*H<sup>-</sup> injection and accumulation: LHC ultimate*

Fig. 3 sketches the LHC ultimate stored and injected horizontal beam ellipses for the 160 MeV injection into the PSB. The maximum long bump amplitude is 33 mm. Tracking runs of 60000 macroparticles have been made using elliptical transverse beam densities and uniform (phase), Gaussian (energy) longitudinal beam densities.

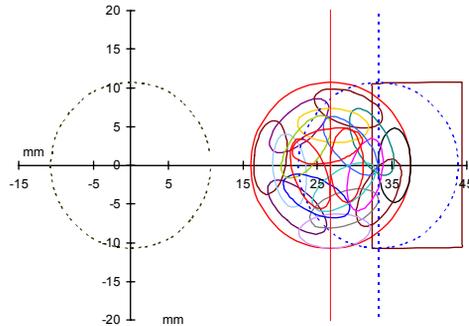


Figure 3: LHC ultimate beam (single batch mode), horizontal normalised phase-plane (no space charge): The 3 circles (right to left) show the stored beam ellipse contours on 1<sup>st</sup> injected turn (maximum long-bump amplitude), 17<sup>th</sup> (last) turn and at zero long-bump amplitude. Ellipses sketch the painting over a few turns. The rectangle depicts the foil (carbon 100 μg/cm<sup>2</sup>).

Accsim scatter plots in the presence of space charge 6 ms after completion of the injection process into the PSB are displayed in Fig. 4. The predicted average number of foil traversals per particle does not exceed 5.

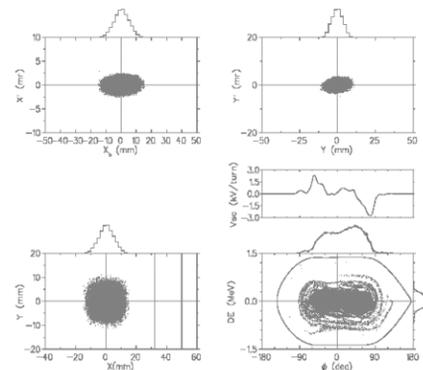


Figure 4: LHC Accsim tracking over 6000 PSB turn (~6 ms): Scatter-plot of particles in transverse (top), longitudinal (bottom right) phase-planes and real space (bottom left) and longitudinal space charge voltage (middle right). No beam loss.

Fig. 5 plots the time evolution of LHC ultimate (single batch mode) normalised beam emittances and direct space charge tune shifts derived from the simulations. Within the 6 ms tracking both emittance curves stay below the 2.5 μm constraint value, though the vertical emittance should exceed the 2.5 μm on longer run. For comparison, simulation of the standard 50 MeV PSB injection for the

present well studied and tested LHC ultimate beam (double batch mode) has been performed, yielding similar vertical emittance behaviour.

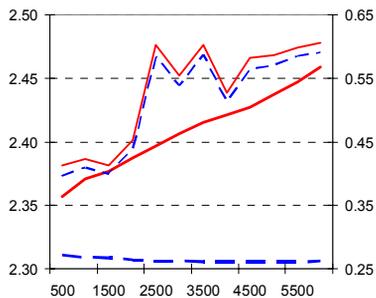


Figure 5: LHC ultimate normalised transverse emittances [ $\mu\text{m}$ ] (left scale) (continuous, dotted thick lines: vertical, horizontal) and tune shifts ( $-\Delta Q$ ) (right scale) (continuous, dotted thin lines: vertical, horizontal) in PSB versus turns (1 turn  $\sim 1\mu\text{s}$ ).

### H injection and accumulation: CNGS

The CNGS horizontal beam ellipses for the 160 MeV injection into the PSB and the Accsim scatter plots with space charge 9 ms after injection are shown in Figs. 6-7. The maximum long bump amplitude is 35 mm.

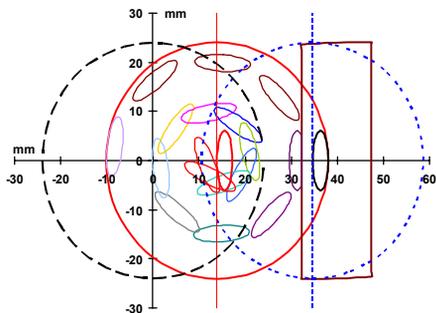


Figure 6: CNGS, horizontal normalised phase-plane (no space charge): The circles show the stored beam ellipse contours on 1<sup>st</sup> injected turn, 66<sup>th</sup> (last) turn and at zero long-bump amplitude.

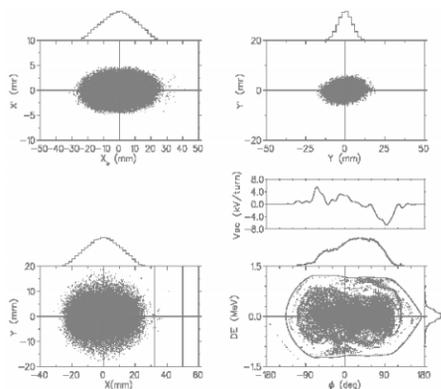


Figure 7: CNGS Accsim tracking on 9000 PSB turn ( $\sim 9$  ms).

The time evolution of CNGS normalised beam emittances and direct space charge tune shifts obtained from Accsim simulations are plotted in Fig. 8. The horizontal and vertical emittances are kept within the 11.5 and 4.6  $\mu\text{m}$  requirement during the 9 ms tracking. However, the vertical emittance may exceed the 4.5  $\mu\text{m}$

threshold on longer simulation time. This constrained value is imposed by the 20  $\mu\text{m}$  vertical PS acceptance to keep the beam loss at PS injection within 1%. Allowing for a 5% beam loss in its place, would increase the vertical emittance limit to 7.6  $\mu\text{m}$ .

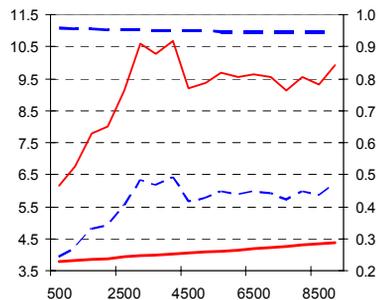


Figure 8: CNGS normalised transverse emittances [ $\mu\text{m}$ ] (left scale) (continuous, dotted thick lines: vertical, horizontal) and tune shifts (right scale) (continuous, dotted thin lines: vertical, horizontal) in PSB versus turns.

With the chosen vertical tune of 5.47 and the large computed vertical space charge tune shift ( $\sim -0.9$ ), a sizeable fraction of the beam should overlie the 5-integer resonance. Contrary to expectations and observations in analogous PSB situations, neither emittance increase nor major beam loss is reveal by the simulations. A possible explanation is that the incoherent space charge tune shift quoted in Accsim is the zero amplitude tune shift which may affect only a minor fraction of the particles.

## CONCLUSION AND OUTLOOK

Results of the LHC ultimate and CNGS high intensity beam simulations of 160 MeV charge-exchange injection and acceleration in the PSB match noticeably the expectations thanks to the higher injection energy. Hence, it follows that both LHC ultimate and CNGS beams can be shaped with quite good confidence by means of single PSB batches in the bounds of the transverse emittance requirements.

## ACKNOWLEDGEMENTS

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