CERN Summer Student Report

15 August 2025
nana.okropiridze@cern.ch

Longitudinal painting studies in the Proton Synchrotron Booster (PSB)

Author: Nana Okropiridze
Supervisors: Foteini Asvesta, Tirsi Prebibaj
CERN, CH-1211 Geneva, Switzerland

Keywords: Longitudinal painting, space charge, Xsuite, PSB

Abstract

For experiments involving high-intensity proton beams, optimising the injection process in the synchrotron is essential to minimise beam losses caused by space-charge effects. Several techniques have been developed to fill the longitudinal phase space of particle beams, thereby reducing the peak line-charge density and the associated space-charge tune spread. Among these, longitudinal painting is an elegant method that has been proposed and tested at the injection to the CERN Proton Synchrotron Booster (PSB) to produce high-intensity beams for downstream experiments. The aim of this project was to implement longitudinal painting in Xsuite simulations of the PSB injection process, perform simulations including space-charge effects to evaluate its impact on beam performance, and participate in Machine Development (MD) studies at the PSB. Experimental measurements were taken with and without longitudinal painting, and the results were compared to simulations to assess their agreement.

Contents

1 Introduction

1.1 Tune spreads and associated losses in circular accelerators

The betatron tune describes the number of transverse oscillations a particle, not following the central orbit (defined by the centres of all quadrupoles), performs during a complete revolution in an accelerator. To first order, it is determined by the strength of the quadrupole magnets [1]. Magnet imperfections, such as misalignments, fringe fields, and field errors, can perturb the betatron motion and drive resonances, which may ultimately lead to particle losses. Particles whose tunes satisfy the following resonance condition can be excited by these imperfections and eventually be lost [2]:

$$n_x Q_x + n_y Q_y = r,\ \{n_{x,y}, r\} \in \mathcal{Z} \tag{1}$$

The working point of an accelerator is usually chosen to avoid resonance conditions. However, several effects can shift particles away from the nominal working point, causing parts of the beam to acquire betatron tunes that satisfy a resonance condition.

1.1.1 Linear chromaticity

By analogy with chromatic aberrations in optics, particle accelerators introduce the concept of *linear chromaticity*, which quantifies the dependence of the focusing strength of quadrupoles on the particle momentum. Particles with different momenta experience different focusing, resulting in a shift of their tunes [3]. The corresponding tune shift is given by:

$$\Delta Q_{x,y} = Q'_{x,y} \frac{\Delta p}{p} \tag{2}$$

1.1.2 Direct space charge

In high-intensity beams, the Coulomb forces between charged particles generate self-fields that act like a defocusing quadrupole in both transverse planes. This leads to a negative tune shift in both horizontal and vertical planes. To first order, the effect can be expressed as [4]:

$$\Delta Q_{x,y} \propto \frac{\lambda}{\beta \gamma^2 \hat{\varepsilon}^n_{x,y}}. \tag{3}$$

Here, λ is the beam charge line density, $\hat{\varepsilon}^n_{x,y}$ are the normalised transverse emittances, and β and γ are the relativistic factors.

1.2 Methods to mitigate space charge effects in the PSB

1.2.1 Double-harmonic RF system

The shape of the RF voltage used to accelerate particles determines the longitudinal distribution of the beam. By superposing two sinusoidal voltages of the form

$$V_{RF} = V_1 \sin(\omega_{rev} t + \phi_1) + V_2 \sin(2\omega_{rev} t + \phi_2),$$

where the second voltage has twice the frequency of the first and is in counter-phase, the local voltage gradient at the bunch centre is reduced. This causes the bunch to spread along the longitudinal direction, thereby lowering the peak charge line density [5].
Figure 1 illustrates the effect of a double-harmonic RF system on the bucket shapes.

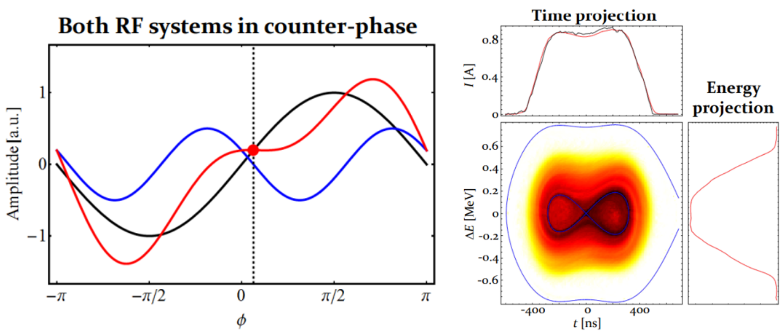


Figure 1: Effect of a double-harmonic RF system on the shape of iso-Hamiltonian curves in longitudinal phase space [5].

1.2.2 Longitudinal painting

Beams delivered from Linac4 to the PSB are rectangular in time and approximately parabolic in energy. By using longitudinal painting during turn-by-turn injection, it is possible to closely match the target iso-Hamiltonian contour in the longitudinal phase space. At each turn, the injected beam is characterised by its bunch length (τ), its energy offset (ΔE_{L4}) from the reference energy, and its energy spread (E_{spread}). By superposing different rectangular distributions in a controlled injection scheme, the target contour in longitudinal phase space can be filled, resulting in an almost rectangular charge line density (see Fig. 2) [6], [7].

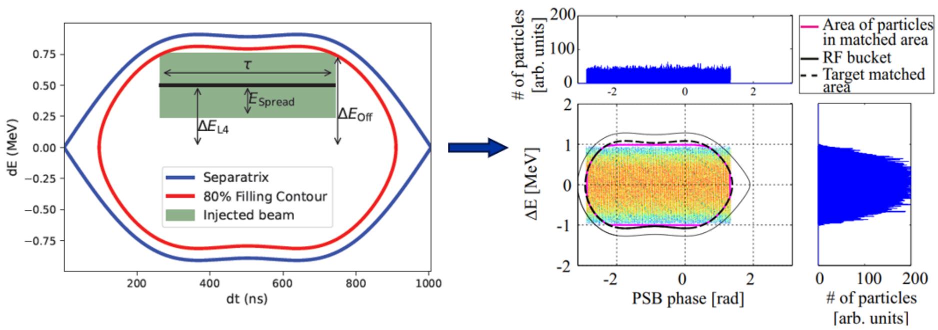


Figure 2: Illustration of longitudinal painting in the PSB and its effect on the longitudinal phase-space distribution [6], [7].

2 Implementation of Longitudinal Painting in Xsuite

2.1 Generation of Particle Distribution for Longitudinal Painting

The longitudinal and transverse coordinates of each generated particle are sampled from different distributions:

- **Longitudinal coorinates**

  Longitudinal coordinates are sampled from a square distribution modulated by a Joho parameter $m = 1.5$:

  $$d(z,m) = \left(1 - [\text{clip}(z,0,1)]^2\right)^{m-\frac{1}{2}}$$

  For each injection turn, the longitudinal coordinates of the particles are generated in the following steps:

  1) Parameters defining z_{min}, z_{max}, E_{spread}, and ΔE_{L4} are read from a CSV file.
  2) Trial z and dE coordinates are generated, where

     $$z \sim \text{uniform}(z_{\text{min}}, z_{\text{max}})$$
     $$dE = vE_{\text{spread}},\ v \sim \text{uniform}(-1,1)$$

  3) A selection rule is applied to retain only the particles satisfying:

     $$w \sim \text{uniform}(-1,1),\ w < d(|v|,m)$$

  4) The energy offset ΔE_{L4} is added to obtain the final energy coordinate:

     $$E_f = dE + \Delta E_{\text{L4}}$$

- **Transverse coorinates**

  The transverse coordinates are read out and randomly assigned to the newly generated particles from a text file containing the measured particle distribution at the PSB injection foil.

2.2 Implementation of Particle Injection and Tracking with Longitudinal Painting in Xsuite

The implementation procedure consists of three main stages:

1) Particle generation:
   - A varying number of particles is generated for each turn, using the method described above, to uniformly fill the longitudinal phase space.
   - The generated particles are stored in a DataFrame, which includes an additional column specifying the turn number at which each particle will be injected.
   - DataFrames for all turns are concatenated into a single DataFrame and saved as a CSV file.

2) Particle injection:
   - At each turn, the CSV file is filtered for the corresponding injection number.
   - A new particle object is created from the filtered DataFrame using an Xsuite built-in function.
   - These newly generated particles are added to the existing particle object associated with the PSB lattice.

3) Tracking:
   - An Xsuite built-in function is used to track the particle distribution turn-by-turn.
   - The transverse emittances and beam intensity are computed and stored after each turn.

Parameters used for simulations

- Beam parameters:

  Table 1 lists the beam parameters used for injection and tracking.

N_{b}	$N_{\mathrm{macroparticles}}$	F_{chopping}	$N_{\mathrm{injections}}$	N_{turns}
9.5e12	5e5	0.63	97	25000

Table 1: Beam parameters used for simulations: N_{b} is the bunch intensity, $N_{\mathrm{macroparticles}}$ is the number of macroparticles used for injection, F_{chopping} is the chopping factor, $N_{\mathrm{injections}}$ is the number of turns over which macroparticles are injected, and N_{turns} is the total number of tracking turns.

- Machine parameters:

  The injection chicane, tune ramp, and injection foil scattering were included in accordance with the operational parameters used during the longitudinal MD studies. The cavity voltage and transverse painting settings may not have fully matched the real operational values. Table 2 shows the kicker magnet (KSW) parameters used for transverse painting in the simulations.

X_BUMP	KBIKSW1L4	KBIKSW2L1	KBIKSW16L1	KBIKSW16L4
-3.5e-02	5.1720959073e-03	1.3941261670e-02	1.6031186470e-02	3.7937180185e-03

Table 2: Kicker magnet (KSW) parameters for transverse painting: X_BUMP represents the horizontal bump amplitude, and the other four parameters represent the strengths of the four kicker magnets.

3 Results from experiments and simulation

3.1 Results from longitudinal MD studies on 6 August 2025

For the longitudinal painting Machine Development (MD) studies at the PSB, both unmodulated and modulated beams were injected at two different chopping settings and at varying beam intensities. In the case of an unmodulated beam, the *chopping factor*, defined as the fraction of the linac pulse transmitted during each turn, was kept constant throughout the injection. For longitudinal painting, the effective chopping factor varied between turns in order to produce different bunch lengths. In this context, the term *bucket filling factor* is used instead.

For longitudinal painting, three different *bucket-crossing* settings were tested. Here, bucket crossing refers to the number of sweeps in the energy offset between the boundaries of the iso-Hamiltonian contour. For example, a value of 3 corresponds to an up–down–up sequence.

Figure 3 shows the measured normalised transverse emittances for different painting settings and injected beam intensities.

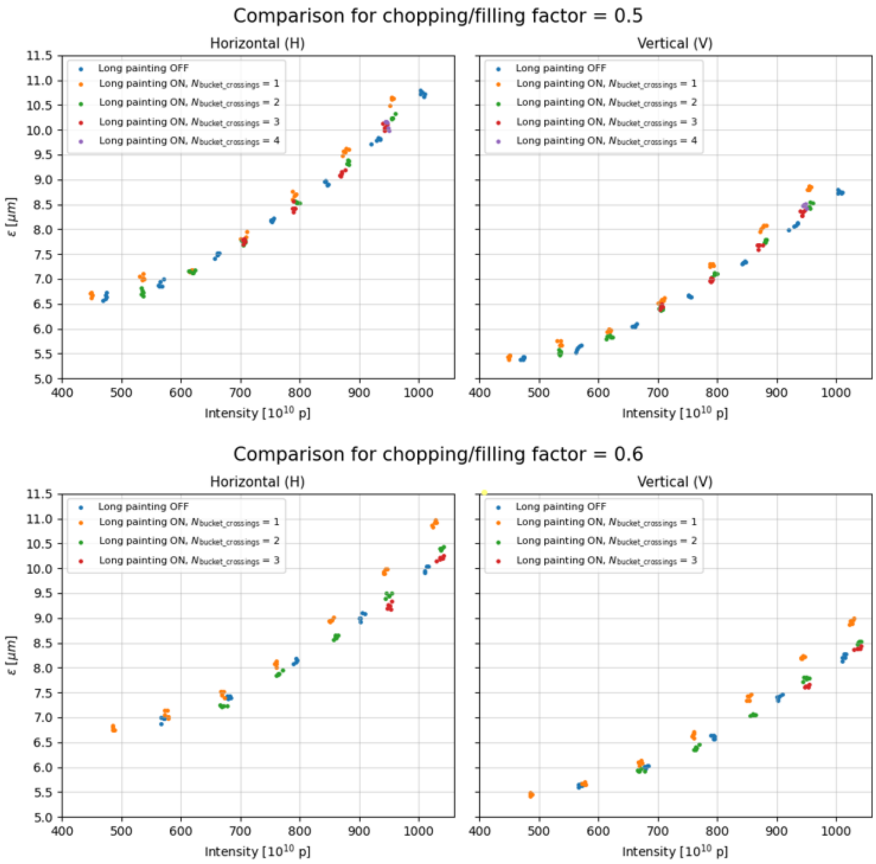


Figure 3: Measured normalised transverse emittances for different painting settings and injected beam intensities

Figure 4 shows the evolution of the beam intensity from injection to extraction. The calculated beam losses after 25 000 turns are approximately 1% for each painting setting.

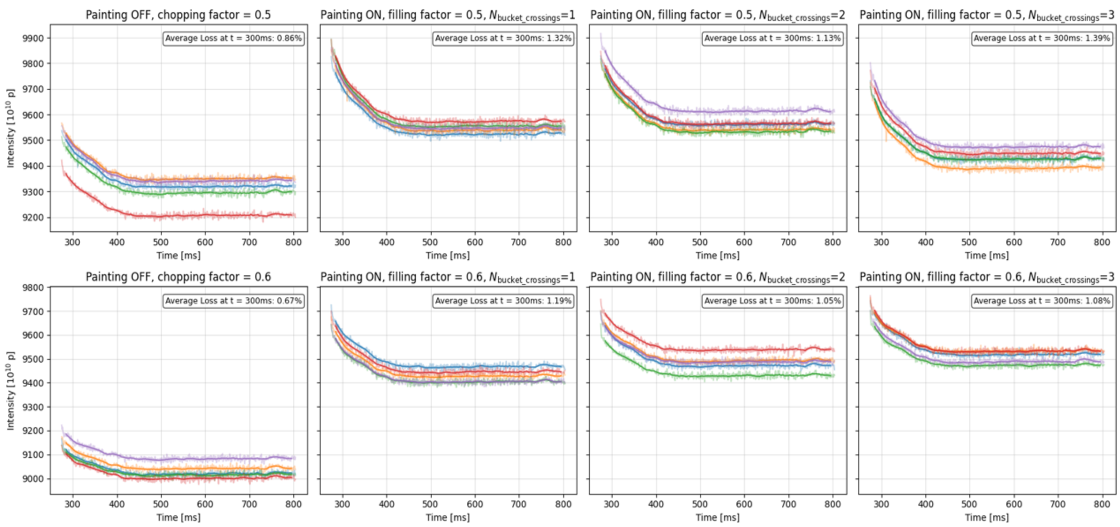


Figure 4: Beam intensity curves for the tested painting settings at $\sim (9.2 - 10) \times 10^{10}$ p injected intensities

Brightness

Using the measured intensities and emittances, the beam brightness was calculated as [2]:

$$B = \frac{N_b}{0.5\,(\varepsilon_x + \varepsilon_y)}. \tag{4}$$

Figure 5 presents the calculated brightness for injected intensities of $\sim (9.2 - 10) \times 10^{10}$ p at different chopping or filling factors.

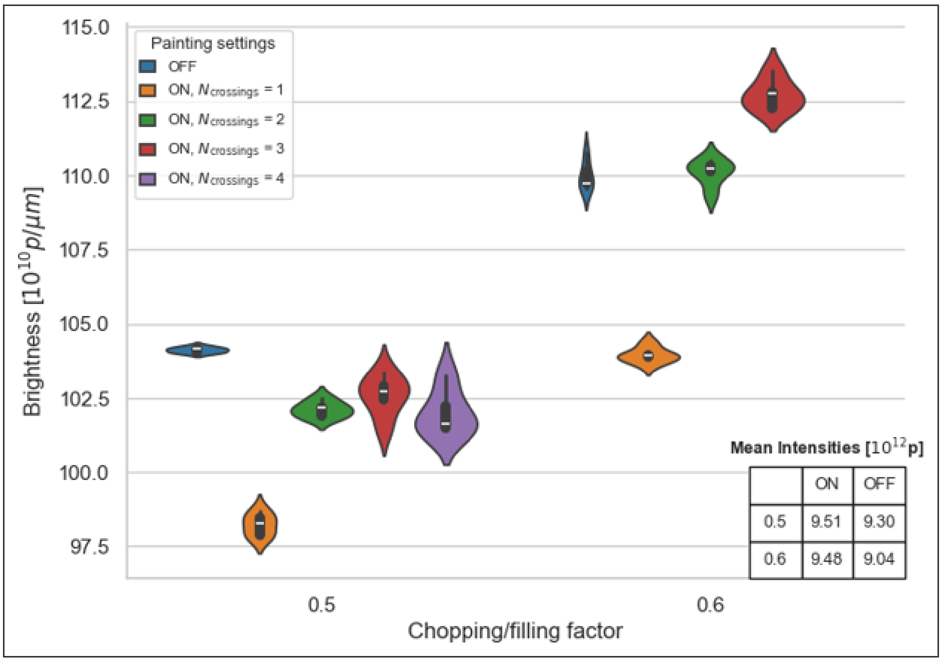


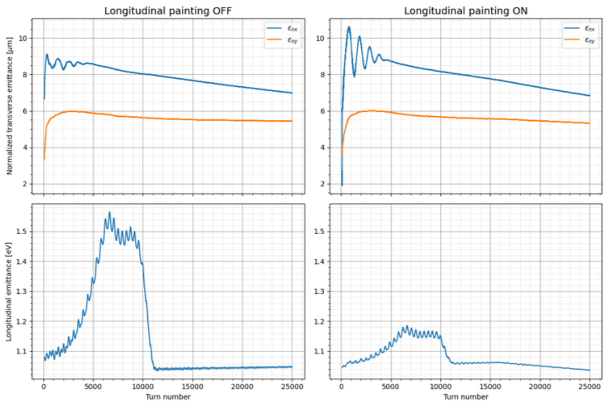
Figure 5: Calculated brightness for different painting settings at $\sim (9.2 - 10) \times 10^{10}$ p injected intensities

An increasing number of sweeps shows a clear trend toward improved beam brightness. However, within the range of injected intensities considered here, there is no substantial improvement in brightness—except for the case of a 0.6 filling factor with three sweeps, which shows a marginal enhancement. It should be noted that this particular setting also exhibits higher losses compared to the others. Higher intensities and/or filling factors may yield more pronounced benefits, but this will require further investigation in future studies.

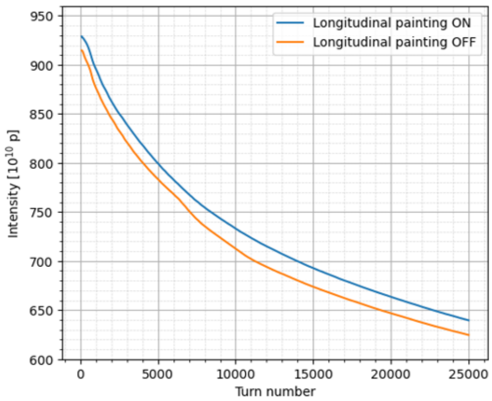
3.2 Results from simulations

To enable a direct comparison with the MD results, the simulation setup reproduced the main beam parameters from the experiment, including the injected intensities and chopping factors, as well as machine parameters like injection chicane, transverse painting settings, tune ramp, and injection foil scattering. The tracking was performed in Xsuite with space-charge effects enabled.

Figure 6 shows the calculated longitudinal and normalised transverse emittances, as well as the beam intensity evolution, for different painting settings in simulations with 5×10^{10} injected macroparticles. This corresponds to a bunch intensity of 9.5×10^{12} p, with space-charge effects included.



(a) Calculated longitudinal and normalised transverse emittances for different painting settings



(b) CCalculated intensities for different painting settings

Figure 6: Simulation results for the first 25 000 turns after injection for 5×10^{10} injected macroparticles representing a 9.5×10^{12} p bunch, including space-charge effects

The simulations show good agreement with the measurements in terms of normalised emittances. However, the simulated intensity losses are significantly larger ($\sim 30\%$ for both painting settings) than the measured $\sim 1\%$ losses, indicating that certain simulation parameters require further optimisation. Despite this discrepancy in absolute values, the relative trend, similar losses for both painting settings, matches the experimental observations.

4 Conclusion

Longitudinal painting has been successfully implemented in Xsuite and can now be used to predict the evolution of injected beam parameters with good precision. The MD studies and simulations indicate that, at the tested intensities, longitudinal painting does not provide a significant advantage over unmodulated beam injection in terms of particle losses and emittances when low chopping factors are used. However, at higher chopping settings, beams injected with longitudinal painting exhibited higher brightness. This suggests that at even higher chopping factors and intensities, longitudinal painting could outperform unmodulated injection, offering high-brightness beams for downstream experiments such as ISOLDE at CERN.

References

[1] Rhodri Jones. arxiv: Measuring tune, chromaticity and coupling. Technical report, 2020.

[2] Tirsi Prebibaj. *Optimization of the high brightness beam performance of the CERN PSB with H-injection*. PhD thesis, Frankfurt U., 2023.

[3] S Guiducci. Chromaticity. 1994.

[4] Kevin Shing Bruce Li. Collective Effects II. Presentation at CERN Accelerator School: Introduction to Accelerator Physics, October 2023. Retrieved from https://indico.cern.ch/event/1226773/contributions/5161246/.

[5] Heiko Damerau. Introduction to Non-Linear Longitudinal Beam Dynamics. Presentation at CERN Accelerator School: Introduction to Accelerator Physics, October 2023. Retrieved from https://indico.cern.ch/event/1226773/contributions/5161247/.

[6] Simon Albright, Rolf Wegner, Piotr Skowroński, Chiara Bracco, Bartosz Przemyslaw Bielawski, and Foteini Asvesta. Jacow: Two-dimensional longitudinal painting at injection into the cern ps booster. *JACoW HB*, 2023:563–566, 2024.

[7] Vincenzo Forte, Simon Albright, Maria Elena Angoletta, Philippe Baudrenghien, Elena Benedetto, Alfred Blas, Chiara Bracco, Christian Carli, Alan Findlay, Roland Garoby, et al. The psb operational scenario with longitudinal painting injection in the post-liu era. *Proc. IPAC*, 17, 2017.