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TWO-DIMENSIONAL LONGITUDINAL PAINTING AT INJECTION INTO THE CERN PS BOOSTER

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Abstract

To inject highest beam intensities at the transfer from Linac4 into the four rings of the PS Booster (PSB) at CERN, protons must be accumulated during up to 148 turns in total. With the conventional, fixed chopping pattern this process results in an approximately rectangular distribution in the longitudinal phase space. As the bucket shape in the PSB does not correspond to this distribution, the process leads to longitudinal mismatch, contributing to emittance growth and reduced transmission. The field in the last accelerating cavity of Linac4 can be modulated, which leads to fine corrections of the extracted beam energy. At the same time, the chopping pattern can be varied. Combining both allows injecting a near uniform longitudinal distribution whose boundary corresponds to an iso-Hamiltonian contour of the RF bucket, hence significantly reducing mismatch. In an operational context, the longitudinal painting must be controlled in a way that allows easy intensity variation, and can even require different painting configurations for each of the four PSB rings. This contribution presents the first demonstration of longitudinal painting in the PSB, and its impact on beam performance.

INTRODUCTION

The Proton Synchrotron Booster (PSB) is the first synchrotron in the CERN proton accelerator complex, its injector is the H^- accelerator Linac4. To meet the requirements of the downstream accelerators and experimental facilities, the beam parameter space covers approximately three orders of magnitude in intensity (from 10^{10} to 10^{13} protons per bunch) and more than an order of magnitude in longitudinal emittance (from 0.1 eVs to 3 eVs). As part of performance optimisation following the implementation of the LHC Injectors Upgrade (LIU) project, efforts are ongoing to maximise the available intensity from the PSB [1, 2].

In accelerators with strong space charge, tailoring the longitudinal distribution to reduce the tune spread is standard practice, and can be achieved in multiple ways. Controlled longitudinal emittance blow-up is applied in the PSB to increase the emittance of LHC-type beams to 3 eVs before injecting to the PS, which allows an increase in beam brightness [3, 4]. In the CERN Low Energy Ion Ring (LEIR), the RF frequency is modulated during capture to intentionally increase the longitudinal emittance, allowing higher transmission [5]. An intentional energy offset at injection has been studied as a potential mechanism to increase transmission in the J-PARC RCS [6].

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The objective of longitudinal painting is to provide a well matched distribution from injection, avoiding filamentation and reducing space charge by maximising the longitudinal emittance. Conventional techniques, such as adiabatic capture or injecting a larger emittance are not applicable to the PSB, and using intentional mismatch to increase emittance would negatively affect performance.

Longitudinal painting is of most interest for high intensity beams. This is because the painting process requires a relatively long injection. The following section explains how painting is achieved, and what operational limits must be considered.

CONTROL OF LINAC BEAM IN TIME AND ENERGY

The PSB uses multi-turn charge-exchange injection of H^- ions accelerated by Linac4. The H^- is stripped at injection and protons are accumulated over up to 148 turns into each of the four PSB rings. The number of turns is defined by the maximum Linac4 pulse length and the time required to switch between PSB rings. Transverse painting during injection is applied to control and optimise the transverse emittance [7].

In standard operation, each injected turn is overlapped with the previous turns in longitudinal phase space. After filamentation, the beam will then fill some area in longitudinal phase space. Figure 1 shows a typical longitudinal separatrix at PSB injection in blue, in red is an iso-Hamiltonian contour containing 80% of the bucket area, the target contour to be filled after injection and filamentation. The key parameters related to longitudinal painting are also indicated.

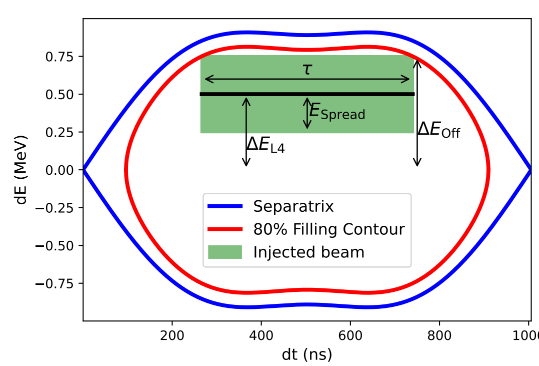

Figure 1: A typical longitudinal separatrix at PSB injection (blue) with the iso-Hamiltonian contour encircling 80% of the bucket area (red). The green box shows a beam injection with positive energy offset, representing an injected turn during longitudinal painting, with key parameters indicated.

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At a given energy relative to the synchronous particle, ΔE_{off}, the length of the target contour, τ, can be computed. If a pencil beam is injected with bunch length τ and energy offset ΔE_{off}, it will match the target contour and eventually filament to fill it. However, in practice the energy spread, E_{spread}, must also be considered. Therefore, the Linac4 energy offset, ΔE_{L4}, is given by

$$\begin{aligned} \Delta E_{\text{L4}} &= \Delta E_{\text{off}} - E_{\text{spread}} \; ; \Delta E_{\text{off}} > 0, \\ \Delta E_{\text{L4}} &= \Delta E_{\text{off}} + E_{\text{spread}} \; ; \Delta E_{\text{off}} < 0. \end{aligned} \tag{1}$$

The $\Delta E_{\text{off}} \pm E_{\text{spread}}$ distinction is due to the highest energy particles being considered when injecting to the top half of the bucket, versus the lowest energy particles when injecting to the bottom half of the bucket. Since the RF bucket is approximately reflexive symmetric about the reference energy ($dE = 0$ in Fig. 1), these are equivalent when $\Delta E_{\text{L4}} = 0$.

Figure 2 shows the Linac4 energy offset (solid purple line, left axis) and injected pulse length (dashed green line, right axis) for 3 swings injecting to the target in Fig. 1 with an energy spread of $E_{\text{spread}} = 250$ keV.

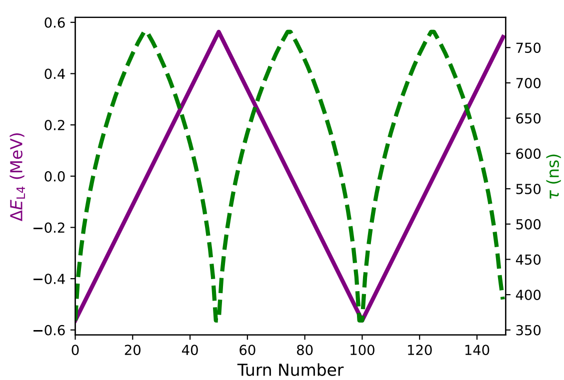

Figure 2: The energy offset, ΔE_{L4}, and injected length, τ, of the beam at each injected turn, the length varies to match the target contour in Fig. 1 at different energy offsets.

Finally, whilst synchrotron motion is slow, it will still influence the result of painting. Depending on the RF parameters, a synchrotron period lasts from 500 to 1000 turns, whilst injection lasts up to 148 turns. Therefore, synchrotron motion is fast enough that the first injected turn will undergo up to 1/3 of a synchrotron period by the time the last turn is injected. By painting with a larger number of energy swings, therefore passing over the target multiple times, the amount of synchrotron motion during each crossing of the bucket is kept to a minimum, which will result in a more uniform distribution.

IMPLEMENTATION

The length of each injected turn is set by the chopper, a transverse deflecting structure following the RFQ that diverts unwanted beam to a low energy dump [8]. The energy modulation and energy spread are provided by the final RF systems of Linac4. The last 13 cavities of Linac4 are π-mode structures (PIMS), the first 12 PIMS cavities accelerate and the final cavity defines the energy spread [9]. To produce the required energy offset, the field amplitude in the final pair of accelerating cavities (PIMS1112) is offset by ΔV relative to the amplitude setpoint. To maintain the required E_{spread}, the phase of the debuncher relative to the RF clock must then be offset by $\Delta\varphi$ due to the change in time-of-flight with beam energy. After some initial discrepancies between simulations and measurements were observed, the relationships between ΔV, ΔE_{L4} and $\Delta\varphi$ were measured to be

$$\begin{aligned} \Delta E_{\text{L4}} &= 1.7 \times \Delta V, \\ \Delta\varphi &= \Delta E_{\text{L4}} \times (15^{\circ}/100\ \text{MeV}). \end{aligned} \tag{2}$$

The change in energy also affects the time-of-flight from Linac4 to the PSB, and since the distance is significantly greater than between PIMS1112 and the debuncher the absolute change is much more significant. However, because the PSB RF period is 994 kHz, compared to 352.2 MHz in Linac4, the relative effect is much smaller. Nonetheless, it has been measued as $\Delta t = -11.6$ ns/MeV, where Δt is the change of arrival time relative to the PSB RF bucket.

Figure 3 summarises the flow of information when computing the settings for longitudinal painting. The input parameters are shown at the top, with the required functions to control the hardware at the bottom. The PSB RF configuration and target filling factor define the target iso-Hamiltonian contour. The target contour is then combined with the required number of injected turns, number of energy swings and (connection not shown) E_{spread} to define $\Delta E_{\text{L4}}(t)$. From $\Delta E_{\text{L4}}(t)$, the functions for $\Delta V(t)$ and $\Delta\varphi(t)$ are computed. Lastly, comparing $\Delta E_{\text{L4}}(t) \pm E_{\text{spread}}$ with the target contour allows $\tau(\text{turn})$ to be computed, which is then converted to a bitmask, where each bit equates to one Linac4 RF bucket, for use in the chopper. At high level, the calculation and control of the required parameters is done with a custom Python library, for which a graphical interface developed with the Inspector tool is available [10].

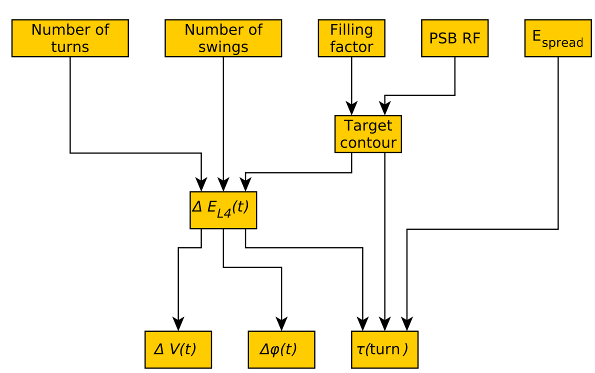

Figure 3: A depiction of how the input parameters are used to compute the longitudinal painting functions. The connection between E_{spread} and ΔE_{L4} is not shown as the impact is small, the effect is to slightly reduce the required offset.

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Operational Limits

It is not possible to paint entirely arbitrary patterns due to the capabilities of the chopper and the Linac4 RF systems. The maximum allowed energy swing is determined by the peak amplitude of PIMS1112. During longitudinal painting studies in 2023, the setpoint of this system was 4.25 MV per cavity. The maximum field amplitude was 5.8 MV, therefore up to 1.55 MV was available for longitudinal painting. However, as small changes in configuration can be expected with time (changes in setpoint, parameter drift), a limit of 1 MV is used to ensure an adequate operational margin.

As well as the maximum of the energy swing, there is also a limit on the gradient. In this case, $d\Delta\varphi/dt$ in the debuncher cavity is the limit, specifically due to the power required to simultaneously compensate for beam loading and modulate the RF phase. A maximum of 5 °/μs is imposed, however keeping below this limit generally provides better stability of the cavity field.

Lastly, the chopper must be considered. The hardware imposes a limit on how quickly the pattern can repeat and how long it must remain in the chopper on (beam off) and chopper off (beam on) states, these limits are illustrated in Fig. 4.

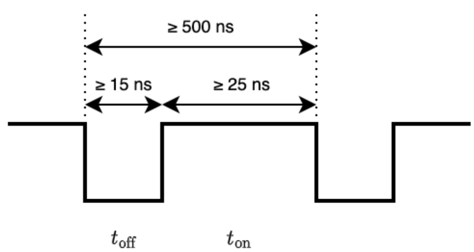

Figure 4: The lower bounds of the chopper on/off (beam off/on) states and the pattern repetition period.

MEASUREMENTS

Figure 5 shows the measured injected distribution with three different values of ΔE_{L4} that would have the τ required to match the given target contour reconstructed with longitudinal phase space tomography [11, 12].

The highest intensity beams produced in the PSB are for the ISOLDE experimental facility, which makes this style of beam ideal for testing longitudinal painting. For these beams, the space charge tune spread early in the cycle can exceed $|\Delta Q_{x,y}| = 0.5$ and the resulting interaction with resonances is one of the main limiting factors on beam transmission. Therefore, when modifying a cycle to use longitudinal painting, an increase in transmission at high intensity will indicate a reduction in the effects of space charge.

Figure 6 shows the transmission versus injected intensity with the standard injection (blue squares) versus the longitudinally painted injection (red circles). For intensities around 1×10^{13} ppb, the transmission is approximately 98% with both standard and painted injection. As the intensity is increased, the benefit of longitudinal painting appears.

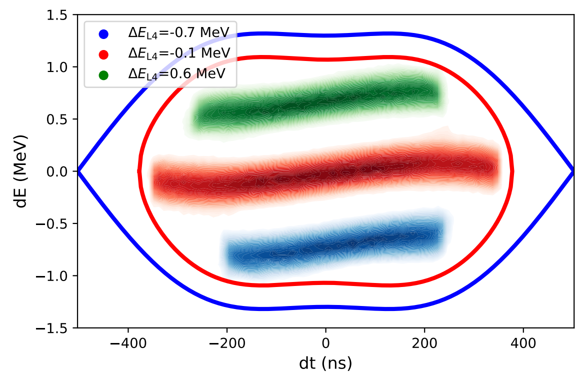

Figure 5: The phase space distributions at injection for three different ΔE_{L4} values, each distribution is a single injected turn designed to match the target contour at a particular ΔE_{off}.

At highest injected intensities, the transmission with the standard injection scheme drops below 90%, wherease with longitudinal painting it remains about 95%. The increase in transmission suggests that the beam has spent less time overlapping damaging resonances, and therefore that the space charge effects have been reduced.

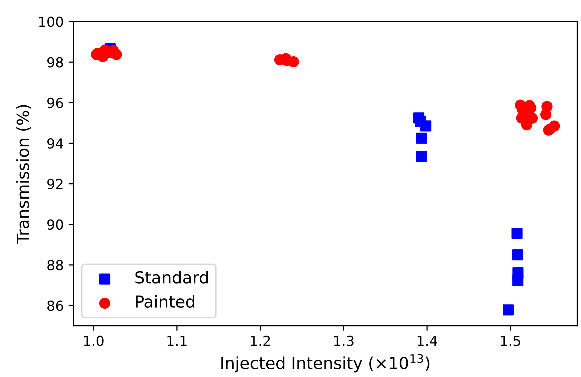

Figure 6: Extracted vs injected intensity for standard (blue squares) and longitudinally painted (red circles) injections.

CONCLUSION

Two-dimensional longitudinal painting has been demonstrated in the PSB for the first time, with very promising results. Modulating the energy and chopping factor of the injected beam during multi-turn injection allows a well matched longitudunal distribution to be produced. Compared to standard injection, longitudinal painting produces a more uniform distribution, which undergoes less filamentation. As a result, transmission at highest intensities, in the range of 1.5×10^{13} ppb, is significantly better with longitudinal painting, which is indicative of a reduction in transverse space charge effects. This improvement motivates further studies of the benefits of longitudinal painting for both high intensity and high brightness beam types.

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