MULTI-PARTICLE SIMULATIONS OF THE FUTURE CERN PSB INJECTION PROCESS WITH UPDATED LINAC4 BEAM PERFORMANCE

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Abstract

In the framework of the LHC Injectors Upgrade (LIU) project, the injection process in the CERN Proton Synchrotron Booster (PSB) will be renovated after the connection with the Linac4. A new H- charge exchange injection system using a stripping foil is foreseen to increase the brightness of the stored beams and to provide high flexibility in terms of emittance tailoring at 160 MeV. Realistic multi-particle simulations of the future injection processes for high brightness beams (i.e. for the LHC) and high intensity beams (i.e. for the ISOLDE experiment) are presented in this paper. The simulations are based on the present performance of Linac4 and include scattering induced by the foil, space charge effects and compensation of the lattice perturbation introduced by the bumpers of the injection chicane.

INTRODUCTION

The LHC injectors upgrade (LIU) project [1] at CERN aims at renovating the LHC injector chain in order to produce beams with twice the present brightness for the LHC. The PSB is the first synchrotron of the injector chain, it is constituted by four superimposed rings and has the important role of defining the beam brightness B for the LHC beams:

$$B = \frac{N}{0.5(\epsilon_{\mathrm{x,n}} + \epsilon_{\mathrm{y,n}})} \tag{1}$$

where N is the bunch intensity and $\epsilon_{x,y}$ is the normalised transverse emittance. The PSB will start operating in connection with the new Linac4 [2] in 2020 after the long shutdown 2 (LS2). Major upgrades will be the introduction of a conventional H- charge exchange multi-turn injection system with injection chicane and stripping foil and the injection energy will be increased to 160 MeV, which will increments the relativistic $\beta_{rel}\gamma_{rel}^2$ by a factor 2, thus allowing to double the brightness for the LHC beams. The LIU proton beam parameters are summarised in [3].

Linac4 started its commissioning phase in 2016 [4]. Between 2016 and 2017 about three months of operation was carried out to test the new injection system. Half of the injection chicane was mocked up and operated during the so-called “half-sector tests” [5]. During this time, different foils, which will be used to strip the injected H^- ions to the circulating H^+, were tested. The quality of these foils in terms of stripping efficiency, emittance blow-up and losses [6] induced by scattering is fundamental for the production of high brightness beams.

MAIN LINAC4 AND PSB BEAM PARAMETERS

The reliability run of Linac4 is on-going [7]. The quality of the Linac4 beams is a prerequisite to achieve the target intensities and brightness for all the PSB users. The range of intensities per bunch stored in the PSB spans between 10^9 and 10^{13} protons per bunch (ppb). The maximum number of injection turns in each PSB ring is defined by the maximum pulse length of the new beam injection (BI) distributor (DIS), which is located in the PSB beam injection line. This device allows injections over 150 PSB turns per ring and distributes the beam to the four superimposed rings of the PSB. The revolution period of the PSB ($T_{\mathrm{rev,PSB}}$) at 160 MeV is ~1 μs. The Linac4 beam parameters requested by the PSB are summarised in [8].

Current

The Linac4 current is fundamental to determine the maximum number of protons that can be collected in any of the four PSB rings. An interesting feature of Linac4 is the possibility to chop parts of the pulse with the chopper [9]. The chopper is used to fit the Linac4 bunchlet trains (1 every 2.8 ns) in the longitudinal phase space of the radio-frequency (RF) bucket of the PSB. The “chopping factor” (CF) is defined as the portion of beam average current in output from the chopping stage with respect to the average current at the entrance of the chopper, as shown in Fig. 1. Typical values of CF are around 0.6, but, in principle, any value between 0 and 1 is permitted.

Two beam transformers, L4L.BCT3113 and L4L.BCT4013, located at the entrance and the exit of the chopper respectively, can be used to measure the input and output currents. In the ideal case of a perfectly flat Linac4 pulse, the peak current at the entrance I_{peak} of the chopper corresponds also to the average current $I_{\mathrm{avg}} = I_{\mathrm{peak}}$, calculated along one $T_{\mathrm{rev,PSB}}$. After the chopping stage, the average current is reduced by CF to $I_{\mathrm{avg}} = \mathrm{CF} \times I_{\mathrm{peak}}$.

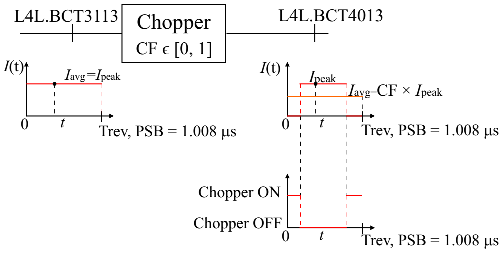

Figure 1: A sketch of the Linac4 current before and after the chopping.

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The intensity N per PSB turn can be expressed as:

$$\begin{aligned}\frac{N}{\text{PSB turn}} &= \int_0^{T_{\text{rev, PSB}}} I(t)dt \times \frac{1}{\text{proton charge}} = \\ &= (\text{CF} \times I_{\text{peak}} \times T_{\text{rev, PSB}}) \times \frac{1}{1.6 \cdot 10^{-19}} \text{ [ppb/turn]}\end{aligned} \quad (2)$$

As an example, parameters for the production of a single bunch for the LIU Standard LHC beams production ($N_{\text{target}} = 3.42 \times 10^{12}$ ppb), assuming the desired $I_{\text{peak}} = 40 \cdot 10^{-3}$ A and CF=0.61 [8, 10], are shown:

$$\begin{aligned}\frac{N}{\text{PSB turn}} &= (0.61 \times 40 \cdot 10^{-3} \times 1.008 \cdot 10^{-6}) \\ &\times \frac{1}{1.6 \cdot 10^{-19}} = 1.512 \cdot 10^{11} \text{ ppb/turn}\end{aligned} \quad (3)$$

This leads to the number of turns needed to reach the target intensity:

$$\text{Nr. of PSB turns} = \frac{N_{\text{target}}}{\frac{N}{\text{PSB turn}}} = \frac{3.42 \cdot 10^{12}}{1.512 \cdot 10^{11}} \approx 23 \quad (4)$$

Presently, a peak current of $I_{\text{peak}} = 20$ mA could be achieved at the entrance of the chopper, thus the same bunch intensity would be produced in 45 turns (neglecting losses in the PSB). It is clear that, given the allowed 150 injection turns injection per ring, the Linac4 current becomes a limiting parameter for the maximum intensity of high intensity users (e.g. ISOLDE).

Moreover, in the case of non-flat pulses, as presented in Fig. 2, the jitter around the average value would affect the actual intensity reach for a given N_{target}. For this reason it is important to have a stable average current at the chopper entrance. The stability requirements [8] are of maximum jitter ±5% for high intensity beams (600 µs pulse length) and ±2% for LHC beams (160 µs pulse length) in the assumption that the transmission from the chopper to the PSB is unaltered. Present realistic pulse shapes at the exit of the ion source fulfil the specifications in the assumption that the pulse arrives unaltered to the entrance of the chopper.

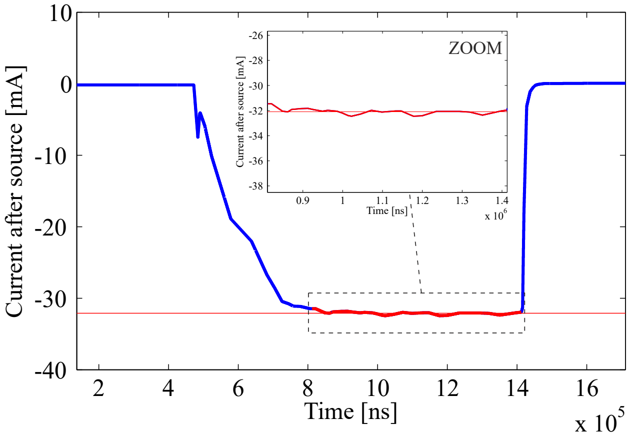

Figure 2: A measured H⁻ Linac4 current profile at the exit of the ion source. The red line lasts 600 µs (~600 PSB turns, i.e. 4×150 turns per PSB ring). The measured jitter around the average current is ~2%.

Transverse Emittance

The impact of a different starting emittance for the high brightness beams was analysed to evaluate the influence on the final emittance of the accumulated beams in the PSB. Due to the lower current, the updated transverse emittances of the Linac4 microbunches are also reduced to $\epsilon_{x,y,1\sigma} \approx$ 0.3 µm [7], with respect to the values that were used in 2016 [10], i.e. $\epsilon_{x,y,1\sigma} \approx 0.4$ µm.

TRACKING SIMULATIONS

Results of tracking simulations are shown in this paper for the LHC, where high brightness is desired, and for the high intensity ISOLDE beams [11], where many turns of injection and reduced losses (<2% after injection) are needed. The simulations include the multi-turn injection process, transverse and longitudinal space charge, minimisation of the beta-beating induced by the injection chicane fall, injection in accelerating bucket in double RF with 8 kV$_{\text{h=1}}$ + 6 kV$_{\text{h=2}}$ in antiphase and $\dot{B}\rho = 10\frac{Tm}{s}$, where h is the harmonic number. The transverse tune is the optimised one for LHC [10], i.e. (Q_x, Q_y)=(4.43, 4.60).

LIU LHC Standard Simulations

The brightness curves (intensity vs. average normalised transverse emittances) for the LIU LHC Standard ($N = 3.42 \times 10^{12}$ ppb) beams have been simulated for the previous beam parameters [8, 10]. The injection process consists of threading a pencil beam from Linac4 with a given offset with respect to the closed orbit, determined by the "slow" (BSW) and the "fast" (KSW) bump magnets at -80.9 mm at the stripping foil location. A sketch of the new injection system is shown in Fig. 3

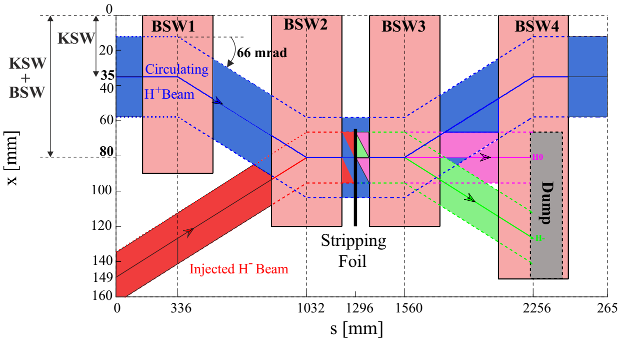

Figure 3: View from top of the future injection "chicane" for the H⁻ injection scheme, defined by the BSW magnets. The beginning of the process with the foil hits by the injected H⁻ beam (red), which is stripped into the circulating H⁺ proton beam (blue). The unstripped H⁻ (light green) and the H⁰ (magenta) hit a beam dump inside the BSW4 and are lost [12].

The emittance after tracking for 10 ms was in both planes ~1.2 µm, i.e. 30% less than the LIU LHC limit $\epsilon_{x,y,n}$ = 1.7 µm, for horizontal and vertical injection offsets up to 3 mm [10]. Figure 4 shows the final emittances for different injection offsets.

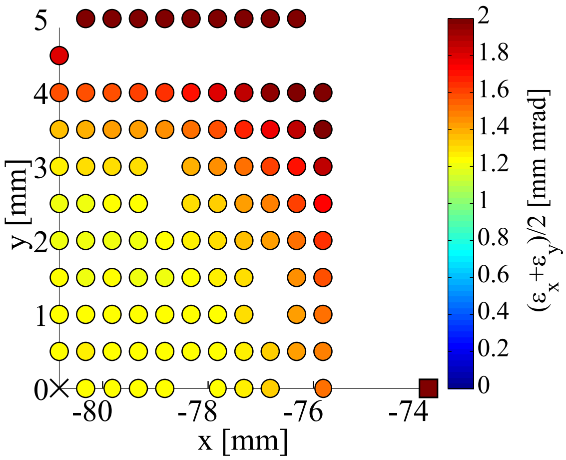

Figure 4: The final emittances 10 ms after injection for $I_{\text{peak}} = 40$ mA and $\epsilon_{x,y,n,0} = 0.4$ µm and different transverse offsets [10].

No space charge - emittance growth due to foil scattering Tracking without space charge was carried out to assess the impact of the new starting emittances on the final blow-up due to the scattering of the foil. The foil has 200 µg/cm^3 thickness. Injections up to 90 turns, which would theoretically correspond to I_{peak}=10 mA, were performed by injecting "on-axis", i.e. on the closed orbit (x,y)=(-80.9,0) and starting from different transverse emittances (see Fig. 5). The maximum emittance growth after 45 turns was around 66%, which is lower than the LHC Standard emittance limit.

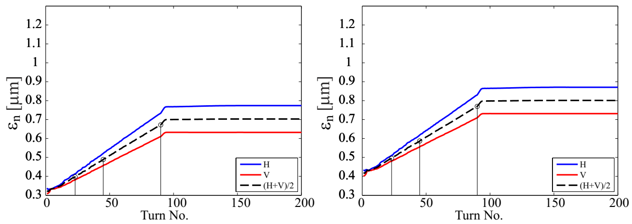

Figure 5: Emittance growth due only to foil scattering and starting from different transverse emittances.

"On-axis" injection - with space charge "On-axis" simulations were carried out considering 45 turns injection and $\epsilon_{x,y,n,0} = 0.3$ µm. Tracking with mismatched optics between Linac4 and PSB was also performed. In particular, at the foil, $\beta_{x,y}$ were increased by 20%, $\alpha_{x,y}$ were increased from 0 to 0.4 rad, D_x was increased by 20%, the angular offsets x' and y' from 0 to 0.4 mrad [8]. The emittance evolution for the mismatched case is shown in Fig. 6.

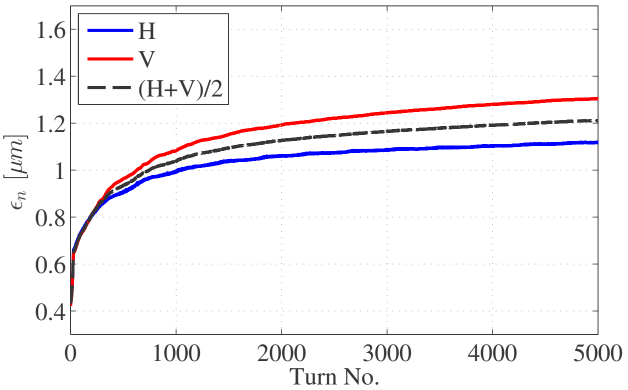

Figure 6: "On-axis" injection: horizontal (H), vertical (V) and (H+V)/2 emittance evolutions for the case with mismatched initial distributions and updated parameters, i.e. I_{peak}=20 mA and $\epsilon_{x,y,1\sigma} \approx 0.3$ µm.

A comparison with the matched optics with updated and past parameters is shown in Fig. 7. The final emittance is in all cases $\epsilon_{x,y,n}$ ~1.2 µm after 5000 turns, very similar to the one that one would obtain by injecting for 23 turns, i.e. considering $I_{\text{peak}} = 40$ mA, and starting from $\epsilon_{x,y,n,0} = 0.4$ µm. This confirms that, for the "on-axis" injection, the emittance blow-up is dominated by space charge and that the new initial emittance and number of injected turns have a small impact.

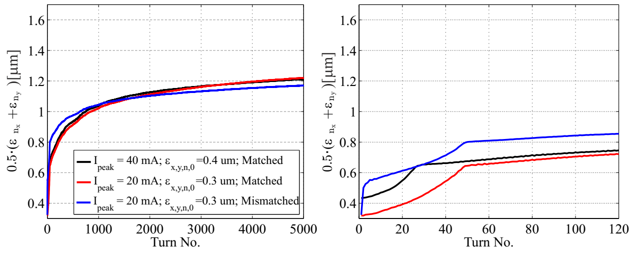

Figure 7: Average Emittance growth for "on-axis" injection during first 5000 (left) and 120 turns (right) for matched and mismatched optics.

"Off-axis" injection - with space charge An injection offset of (Δx, Δy)=(2, 2) mm was considered for the "off-axis" injection. Such an offset was chosen in order to stay inside the $\epsilon_{x,y,n}$ ~1.2 µm region of Fig. 4 and still have 1 mm margin for the transverse intra-bunch deflection of the beam incoming from Linac4 [8]. Simulations in Fig. 8 show that, by exceeding the proposed offset, the average emittance quickly exceeds the LIU LHC limit.

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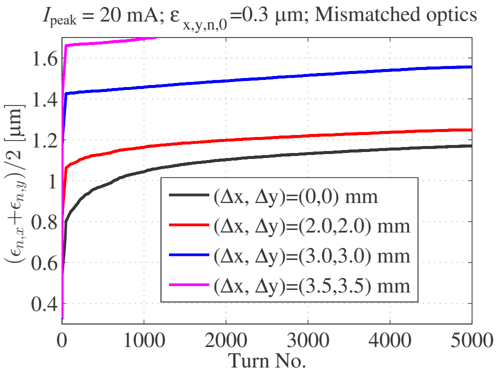

Figure 8: Average transverse emittances for different injection offsets.

Simulations with the same Linac4 current, emittance and optics match/mismatch conditions as for the "on-axis" case are shown in Fig. 9. Figure 10 shows that a 6% increase is visible in the average final emittance for the case with the optics mismatch.

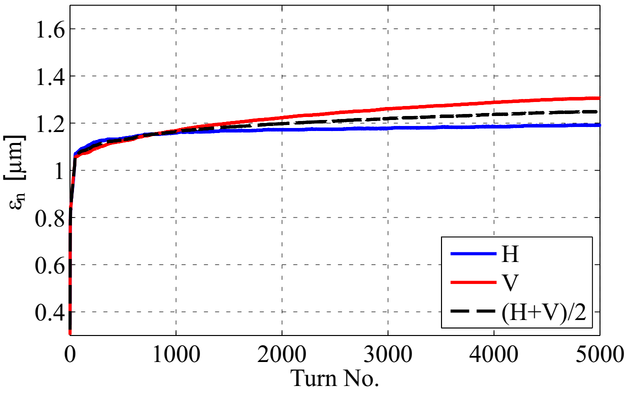

Figure 9: "Off-axis" injection: horizontal (H), vertical (V) and (H+V)/2 emittance evolutions for the case with mismatched initial distributions and updated parameters.

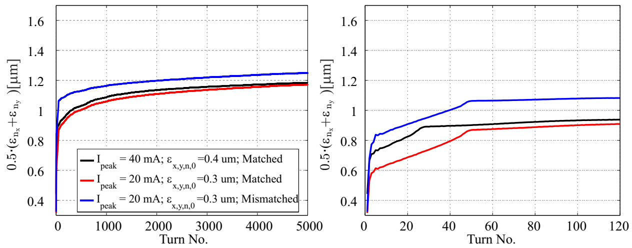

Figure 10: Average Emittance growth for "off-axis" injection during first 5000 (left) and 120 turns (right) for matched and mismatched optics.

The initial emittance has a small impact on the final emittance also in this case (<2% difference), as shown in Fig. 11.

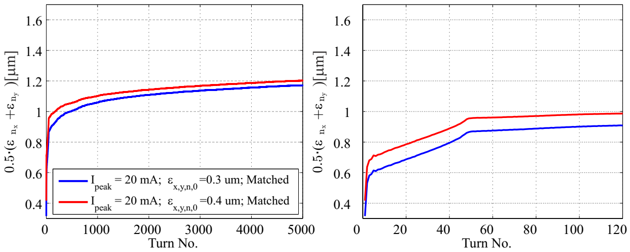

Figure 11: Average emittance growth for "off-axis" injection during first 5000 (left) and 120 turns (right) for different initial emittance and matched optics.

ISOLDE Beams Simulations

Simulations for the present ISOLDE bunches were performed by considering $N_{\text{target}} = 1 \times 10^{13}$ ppb. The longitudinal painting technique will be adopted in this case. Following the optimisation in [13], in order to paint a longitudinal matched area of 1.5 eVs, 124 turns are needed with an energy spread of 120 keV from the Linac4 de-buncher and an energy swing amplitude of ±0.8 MeV from the Linac4 PIMS cavities [14] as shown in Fig. 12.

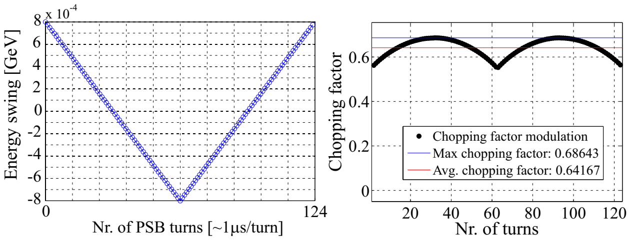

Figure 12: Energy swing (left) and chopping factor (right) patterns for $N_{\text{target}} = 1 \times 10^{13}$ ppb in 124 turns.

As one can see, for this particular longitudinal painting choice with CF_{avg}=0.64, I_{peak}=20 mA leaves only 20% of margin to reach the target intensity in 150 turns. For this reason the reduction of the current pulse jitter and the losses in the PSB during injection become critical.

In the transverse plane, the ISOLDE beams require horizontal painting at injection through the modulation in time of the current of the KSW magnets, which contribute to the initial offset with -35 mm to be added to the -46 mm of the slower BSW magnets. The vertical emittance is determined by a fixed injection offset of 6 mm in this case. Once determined the longitudinal painting pattern, the KSW modulation function [15] has to be adapted to the number of injection turns needed to reach N_{target} and the target horizontal emittance. A possible KSW offset modulation function is shown in Fig. 13.

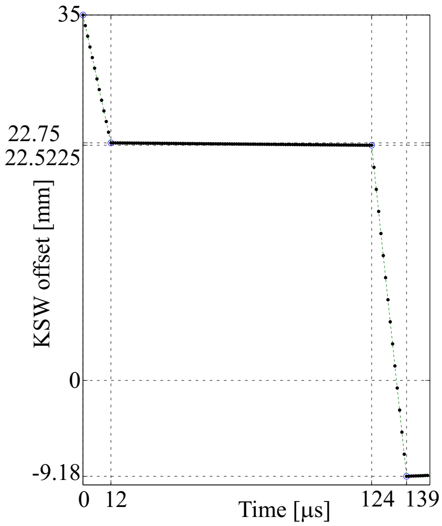

Figure 13: KSW offset modulation for 124 turns injection.

Two new beam absorbers, a fixed and a moving mask, will be added during the Long Shutdown 2 (LS2) [16]. Tracking simulations were performed taking into account the most restrictive aperture bottleneck introduced by the new beam absorbers. The emittance and intensity evolutions are shown in Fig. 14.

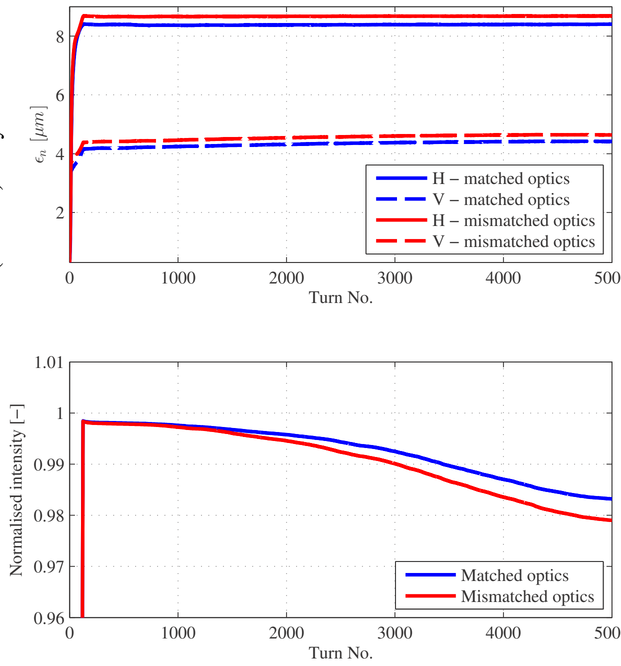

Figure 14: Results of tracking studies for an ISOLDE beam at $N_{\mathrm{target}} = 1 \times 10^{13}$ ppb.

The integrated losses are in the order of 2%, mainly localised at the location of the movable absorbers, as shown in Fig. 15. Only a small amount of losses (few permille) are concentrated close to the injection region, probably induced by the scattering process with the foil. The horizontal losses (~3‰) are mainly constituted by similar amount of particles, which are not captured in the RF bucket during the longitudinal painting process. Such losses are localised mainly at the location of the masks and partially around the machine, where the horizontal aperture is +57 mm.

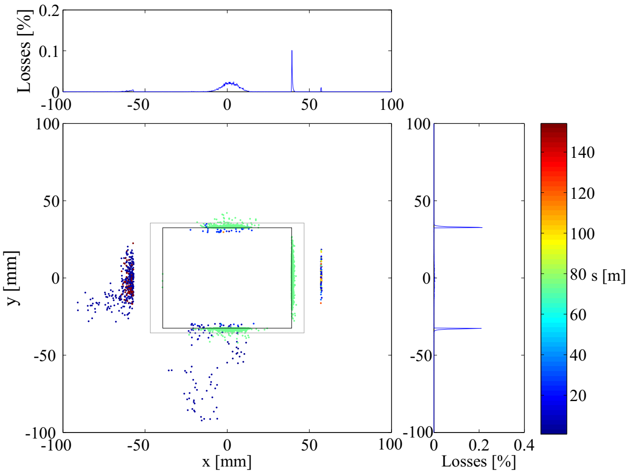

Figure 15: Loss distribution during the full tracking with PSB longitudinal position (s) in color-code. The rectangles represent the minimum aperture of the two new masks (movable - black, fixed - grey). The masks are located at around s=75 m (green markers).

CONCLUSIONS

The recent performance of the Linac4 corresponds to I_{peak}=20 mA before chopping and a transverse normalised emittance $\epsilon_{x,y,n}$ = 0.3 µm. New simulations for the PSB injection process of the LIU LHC Standard beams were performed with these latest parameters. Space charge, optics mismatch, scattering foil and beta-beating compensation due to the lattice perturbation introduced by the injection bump were included in the tracking studies. The results showed a negligible impact with respect to the target performance with Linac4 I_{peak}=40 mA and emittance $\epsilon_{x,y,n}$ = 0.4 µm, if other requested Linac4 parameters are inside the defined range [8].

Simulations for high intensity beams (ISOLDE) showed that, with the present current, the PSB should be able to produce bunches of 1×10^{13} ppb in 124 turns, which might vary depending on the choice of longitudinal painting parameters. If one considers a maximum of 150 turns injection per ring, this leaves only 20% to other sources of errors, like pulse flatness and losses inside the ring.

Future studies will include the study of LIU LHC BCMS beams and the modelisation and tracking of realistic fringe fields for the chicane magnets.

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