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MULTI-TURN INJECTION OF 50 MEV PROTONS INTO THE CERN PROTON SYNCHROTRON BOOSTER

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Since 1978, Linac2 produces beams of 50 MeV protons with a current around 160 mA, which are injected into the CERN Proton Synchrotron Booster (PSB) with conventional multi-turn injection using a horizontal septum. It is planned to replace Linac2 during a future long stop with a new H- linac, Linac4, injecting at higher energy (160 MeV) and making use of the modern charge-exchange injection principle. Due to the age of Linac2 and to a delicate vacuum situation the risk of a serious Linac2 breakdown has to be considered. Therefore it is necessary to study if the PSB could produce beams useful for the LHC and other experiments injecting a Linac4 proton beam at 50 MeV with much lower average current compared to Linac2 and without the need for a long installation of the 160 MeV H- injection hardware. Benchmarking of the PSB injection model with the existing injection system with Linac2 using the ORBIT code has been done for a LHC-type beam and then the injection model was used to estimate the brightness for LHC-type beams that could potentially be reached in one PSB ring with the injection of a Linac4 proton beam at 50 MeV.

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INTRODUCTION

The Proton Synchrotron Booster located at CERN, Geneva, Switzerland, is currently boosting protons injected by Linac2 from 50 MeV to 1.4 GeV. It is the second accelerator of the LHC injector chain and consists of four superposed rings. Linac4 is a 160 MeV linac under construction aiming at boosting the performance of the CERN PSB with higher injection energy and replacing the present conventional multi-turn injection of 50 MeV protons with a septum by H^- charge exchange injection. General planning of the CERN complex foresees the connection Linac4 – PSB not before the end of the second LHC long run. In case of a serious breakdown of the presently used Linac2, which is ageing and showing weaknesses in terms of vacuum tightness, it is envisaged to inject 50 MeV proton beams with lower beam current and emittance from Linac4 as emergency scenario.

This work indicates the brightness that can be expected for a LHC beam (LHC-25ns) in the PSB after a multi-turn injection of 50 MeV protons from Linac4. The results are derived from simulations done with ORBIT. The reference parameters of the PSB injection with Linac2 are first used to test the model and then parameters of Linac4 are used as input of the simulation. An optimization of the injection process can be done to obtain an estimate of the highest reachable brightness for the LHC beam.

PSB MULTI-TURN INJECTION

During injection into the PSB, the beam is stacked in horizontal betatron phase-space using a closed orbit bump generated by four slow kickers to bring the stacked beam very close to the injection septum to minimize the transverse emittance of the resulting beam in the PSB. The incoming beam is deflected by the injection septum, which results in an injection with small position and angle errors. Subsequently the bump decreases and the beam moves to the reference closed orbit (see Fig. 1). The injection septum blade has a thickness of 1 mm and is 40 mm away from the closed central orbit.

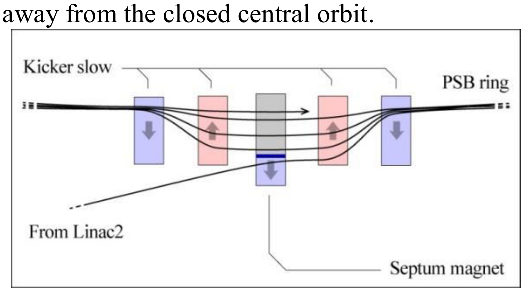

Figure 1: Multi-turn injection principle (after 4 turns).

During operation in order to produce all the required beam types, the following injection parameters can be optimized: the working point at injection, the injection timing and the horizontal and vertical positions and angles of the injected beam.

ORBIT CODE AND PSB MODEL

The ORBIT code (Objective Ring Beam Injection and Tracking) [1] was designed to track macro-particle coordinates through a set of accelerator elements and calculate space charge and other collective effects.

The model of the PSB lattice is composed of bending and quadrupole magnets imported with a special routine from MAD-8 [2] to ORBIT. The horizontal and vertical tune values are fixed in the MAD-8 model. The injection slow kickers are modelled in ORBIT with the ideal bump routine (linear decay of the bump). As ORBIT does not contain a septum module, a foil of thickness null as first element of the lattice and an aperture as last element of the lattice are used to simulate as realistically as possible the injection septum BI.SMH of the PSB [3]. The foil at the beginning of the lattice simulates the septum blade seen by the injected particles and the aperture at the end the septum blade seen by the circulating particles. The transverse space charge is modelled with the 2.5D FFT-PIC (Particle-In-Cell) modules without boundary condition(s). The FFT-PIC is a fast method to calculate transverse space charge, first by binning the macroparticles to a grid, then calculating the force distribution on the grid using a FFT method, and finally interpolating the force from the grid back to each macro-particle. Transverse space charge nodes are inserted after each transfer matrix included in the lattice file. The longitudinal space charge is modelled with one FFT node.

The 50 MeV proton beams from Linac2 and Linac4 are assumed to have a Gaussian distribution in transverse phase-space and a uniform distribution in longitudinal phase-space. At the injection point for Linac2 and Linac4, the horizontal beam size of the incoming beam is set to half of the PSB β_h [4], while the vertical beam size is matched to the PSB β_v and the waist positions $\beta'_h = \beta'_v$ are set to zero [5]. These parameters were optimized with simulations described in [4] and [5].

LINAC2 SIMULATIONS

The model has to be able to reproduce a LHC-25 beam with similar emittance and injection efficiency to that provided by the actual ring 3 of the PSB. The reference parameters of the PSB injection and of the Linac2 proton beam are listed in Table 1. The injection timing and the horizontal and vertical positions and angles of the injected beam are optimized to reach maximum intensity within the required emittance. The injection timing is defined by the delay between the moment when the injection kicker pulses at its maximum and the moment when the beam is injected.

Table 1: Reference Parameters of the Linac2 Beam and of the PSB Injection

Parameter	**Symbol**	**Value**
Linac2 normalized rms beam emittance	$\varepsilon^*_h = \varepsilon^*_v$	1.2 π mm mrad
Linac2 beam current		155 mA
Bump Collapse Time	TIKS	50 µs

In the real case for a LHC-25 beam, 2 turns are injected and the injection working point is Q_h=4.42 and Q_v=4.49. The normalized transverse rms emittances are $\varepsilon^*_h \approx 1.90\ \pi$ mm mrad and $\varepsilon^*_v \approx 1.75\ \pi$ mm mrad, respectively, and the injection efficiency is around 57% with an intensity of 1.85×10^{12} right after injection before small losses occur due to the capture process.

The simulations are carried out over 100 turns after the start of injection ending before the capture. The bump decay is completed after around 20 turns, with 100000 macroparticles injected per turn. The most optimized simulation shows an injection efficiency of 61%, with an intensity of 1.98×10^{12} protons and $\varepsilon^*_h \approx 1.88\ \pi$ mm mrad and $\varepsilon^*_v \approx 1.70\ \pi$ mm mrad. The simulations indicate an rms emittance blow-up of less than 4% during the first 10000 turns (~ 16 ms).

These results deduced from the PSB model match well the reality for the LHC-25 beam; however it has to be mentioned that there are still open questions for other beam types.

LINAC4 SIMULATIONS

The PSB model is then used to run simulations injecting a Linac4 50 MeV proton beam. The Linac4 50 MeV proton beam is expected to have a horizontal and vertical normalized rms emittance of 0.4 π mm mrad with a nominal current of 40 mA and a maximal average current of 50 mA. The current limit in Linac4 comes from the power available to compensate beam loading in the first tank of the DTL. The simulations are run for the nominal and for the maximal current and are optimized to produce a beam with the highest achievable intensity within the emittance of the LHC-25 beam currently produced by the PSB. The injection bump collapse time, the injection timing, the number of injected turns and the horizontal and vertical positions and angles of the injected beam are the parameters to tune. The injection working point is the same as for the Linac2 case. The simulations are carried out over 100 turns after injection with 50000 macroparticles injected per turn.

For both Linac4 currents, the simulations show optimum results with an injection of 9 turns and a bump collapse time of 90 µs (see Table 2). The injection efficiency is in the order of 45%, compared to 61% for Linac2.

Table 2: Optimum Results for the Simulation of a 50 MeV Proton Beam Injected from Linac4 into the PSB After 100 Turns

Injection Parameters and Resulting beam	**L4 current 40 mA**	**L4 current 50 mA**
Injection Timing [µs]	38.5	40
Initial horizontal offset [mm]	-43	-43
Initial vertical offset [mm]	1	1
Beam Intensity	1.68×10^{12}	2.19×10^{12}
Normalized rms emittance horizontal [π mm mrad]	1.87	1.81
Normalized rms emittance vertical [π mm mrad]	1.78	1.91

Simulations for the optimum cases indicate an emittance blow-up of around 2% for the 40 mA and of around 4% for the 50 mA cases during the first 10000 turns.

RESULTS

We introduce the brightness scaling as the ratio of the brightness obtained for the optimized case with Linac4 to the brightness obtained for the optimized case with Linac2.

Our simulations show that it is possible to reach 83% of today's LHC-25 beam brightness injecting a 40 mA Linac4 proton beam, while injecting a 50 mA Linac4 proton beam, 106% of today's LHC-25 beam brightness could be achieved. These results are slightly beyond expectation [6].

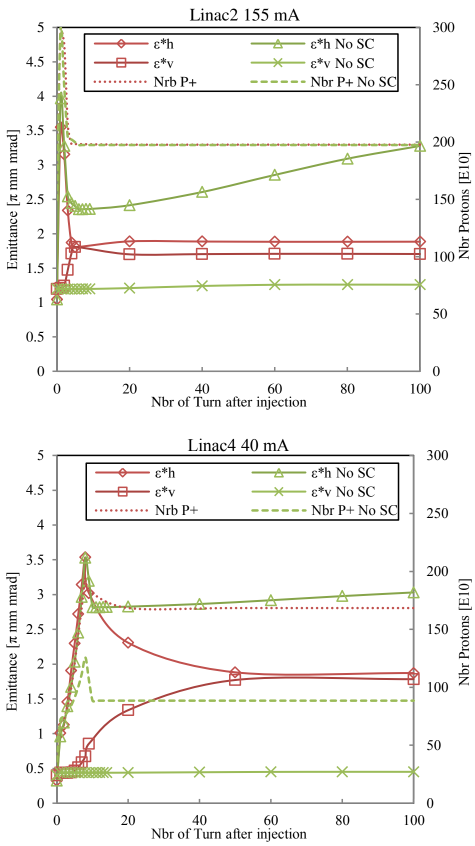

Figure 2: Horizontal and vertical normalized rms emittance (ε^*_h, ε^*_v) and number of protons as a function of number of turns after injection for optimized LHC-25 simulations with and without space charge with a Linac2 (top) and Linac4 40 mA beam(bottom).

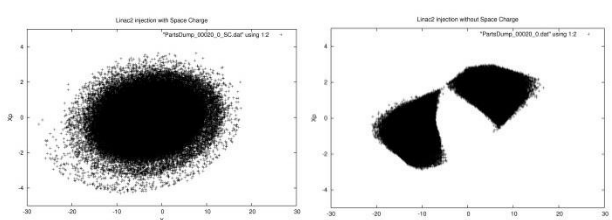

Figure 3: Horizontal phase-space profile of the resulting beam 20 turns after injection for 2 turns injected (Linac2) with space charge (left) and without space charge (right).

Figure 2 shows the results of the optimized simulations for Linac2 and Linac4 injection with and without space charge. In all the cases beam intensity and horizontal emittance increase during subsequent injection turn, i.e. 2 turns for Linac2 and 9 turns for Linac4. Once the injection is finished, beam intensity and horizontal emittance decrease due to horizontal losses at the septum blade. As the horizontal tune is 4.42, each beamlet interacts again with the blade ~2 turns after its injection inducing large horizontal losses. As the injection bump decays, the particles move away from the septum blade and the beam intensity stabilizes.

Space charge introduces a defocusing effect, which is dependent on the particle position inside the bunch and on the bunch distribution itself. It can be seen as an extra rotation in phase-space around the bunch centre and in the opposite direction than the betatron motion. If space charge is present, particles in the injected beamlets will have different tunes depending on their position inside the bunch. This mechanism explains for Linac2 and Linac4 cases with space charge the decrease of the horizontal emittance over few tens of turns after the end of injection, as the mixing of the beamlets and smoothing of the distribution is made possible by space charge. For the cases without space charge, the beamlets do not mix (see Fig. 3 right) and the horizontal emittance increases due to filamentation after injection until it reaches equilibrium (after a few 100 turns). For the Linac4 case the highest resulting beam intensity is reached for the space charge case. As explained before, with space charge the rotation of the particles with the strongest detuning close to the centre of the bunch will be slowed down and eventually they will not interact with the septum because, when they would be in the critical position, the painting bump would have already fallen enough to carry them away from the septum blade. The space charge mechanism is therefore helping in reducing the amount of losses with Linac4 and in producing beam with smaller horizontal emittance in case of Linac2.

CONCLUSION

The model of the PSB gives coherent results for the production of a LHC-25 beam with the present multi-turn injection of a Linac2 50 MeV proton beam. Comparing simulation results of the multi-turn injection with a Linac2 beam and with a Linac4 50 MeV proton beam with nominal average current, i.e. 40 mA, indicates that only 83% of today's brightness of the LHC-25 beams could be reached in the PSB. However assuming 50 mA for the average current of the Linac4 proton beam, i.e. its maximum deliverable current due to klystron power limitations, today's brightness for the LHC-25 type beams could be reached in the PSB. In conclusion Linac4 with a 50 MeV proton beam with 50 mA beam current could be used as backup solution in case of major failure of Linac2, at least to provide usable production beams for the LHC.

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