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SIMULATIONS OF THE CERN PS BOOSTER PERFORMANCE WITH 160 MEV H- INJECTION FROM LINAC4

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The ultimate luminosity (2.3 x 10^{34} cm^{-2} s^{-1}) in the LHC can only be reached or even exceeded if a major upgrade of the CERN proton injector complex takes place. The first identified bottleneck towards higher brightness beams is the 50 MeV proton injection of Linac2 into the PS booster (PSB). Doubling the intensity in the PSB can be achieved with a new linac (Linac4), which increases the injection energy to 160 MeV. Linac4 will provide H^- ions and use charge-exchange injection into the PSB instead of using the present multi-turn injection. We present the current status of simulations with ACCSIM, ORBIT, and ESME for all three planes. We use different initial distributions, compare the results of ACCSIM and ORBIT and highlight their differences.

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The ultimate luminosity (2.3×10^{34} cm^{-2} s^{-1}) in the LHC can only be reached or even exceeded if a major upgrade of the CERN proton injector complex takes place. The first identified bottleneck towards higher brightness beams is the 50 MeV proton injection of Linac2 into the PS booster (PSB). Doubling the intensity in the PSB can be achieved with a new linac (Linac4), which increases the injection energy to 160 MeV. Linac4 will provide H^- ions and use charge-exchange injection into the PSB instead of the present multi-turn injection. We present the current status of simulations with ACCSIM, ORBIT, and ESME for all three planes. We use different initial distributions, compare the results of ACCSIM and ORBIT and highlight their differences.

INTRODUCTION

The simulation of the PSB performance presents a unique challenge even to well established simulation codes like ACCSIM [1] and ORBIT [2]. After the H^- injection [3], four bunches are accelerated in four stacked rings (one bunch per ring) from 160 to 1400 MeV within ≈ 0.5 s, using h=1 and a 2^{nd} harmonic cavity to flatten the longitudinal bunch profile. The injected bunch trains are longitudinally tailored to the length of the RF bucket by means of a low-energy beam chopper in Linac4 [3]. Since the bunches are injected at the space-charge limit, we have to consider high space-charge forces for long bunches over several 10^5 turns, which is clearly beyond todays simulation capabilities.

The ultimate goal of this study is to show that Linac4 will enable the CERN proton injector chain to reach the following performances (see Table 1): i) nominal LHC intensity with single-batch injection (instead of double-batch) from the PSB into the CERN proton synchrotron (PS), ii) ultimate LHC intensity using double-batch injection (impossible with the present Linac2), iii) to double the beam intensity delivered to CNGS, and iv) to double the beam intensity available to ISOLDE.

TRANSVERSE DYNAMICS

Since a realistic simulation of the full acceleration cycle contains too many uncertainties and is too time consuming we start with a simple case and increase gradually the complexity of the simulations.

Table 1: Beam intensities to be delivered by the PSB.

Beam	intensity per ring [10^{12} part.]	tr. emittances r.m.s., norm. (H/V) [μm]
LHC nominal†	3.25	2.5/2.5
LHC ultimate‡	2.55	2.5/2.5
CNGS	12.5	11.5/4.6
ISOLDE	16.0	12.0/7.0

† single batch, ‡ double batch

Beam Evolution at 50 and 160 MeV

At present a 50 MeV coasting beam is injected during a few turns and then bunched non-adiabatically. With Linac4 a chopped beam will be directly painted into the PSB buckets at 160 MeV, which should yield an improved longitudinal capture and reduce inhomogeneities and the beating of the longitudinal bunch shape. When increasing the injection energy from 50 to 160 MeV one expects to double the number of particles accelerated within the same emittances (scaled according to the reduction of space-charge forces, which is proportional to $1/\beta\gamma^2$). To test this basic assumption we investigate the behaviour of H^+ bunches with 0.625×10^{13} particles at 50 MeV and 1.3×10^{13} particles at 160 MeV. With a working point of 4.28/5.47 (H/V) and the CNGS beam parameters (Table 1) we obtain for both simulations identical tune shifts of -0.45/-0.83 (H/V). As expected, the resulting emittance evolution (using ACCSIM) is almost identical as shown in Fig. 1. The slight difference between the simulations is probably due to the different number of turn needed to complete 10 ms: 6 k for the 50 MeV case and 10 k for the 160 MeV case.

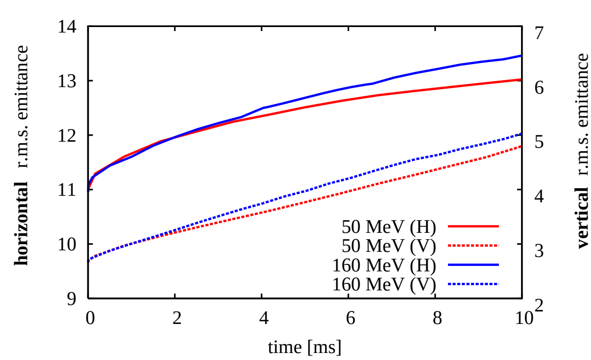

Figure 1: Normalised r.m.s. emittance evolution (in π mm mrad) for injection of the CNGS beam on a 50/160 MeV plateau, using 0.625/1.3 $\times$ 10^{13} particles (ACCSIM, not taking into account chromatic effects).

The emittance evolution of the 160 MeV case was confirmed with ORBIT for a case with a simplified physics model using an averaged longitudinal line density. Both codes show increased emittance growth once chromatic effects are taken into account.

Beam Evolution at Different Energies

At present there are no collimators used in the PSB, since most of the beam loss is either due to aperture limitations at the injection point or due to the non-adiabatic capture process. In both cases particles are lost at low energy and produce little radiation. For operation with Linac4 the injection and capture losses should be minimal due to the employment of H^- injection and the use of the beam chopper which should avoid capture losses altogether. This means that losses created by space-charge induced emittance growth is expected to be the main source of machine activation. Being at high energy these losses must be localised by the use of collimators and one important design criterion for these devices is their maximum interception energy. For this purpose we study a pessimistic case (no 2nd harmonic) of the behaviour of the nominal LHC beam (see Table 1) at various energy plateaus (160, 400, and 600 MeV) with ACCSIM (including chromatic effects). The transverse distribution has a parabolic profile. Figure 2 shows that the rate of emittance increase over 15000 turns is reduced to insignificant values at higher energies and the simulations suggest that there will be no significant beam loss above 500 MeV.

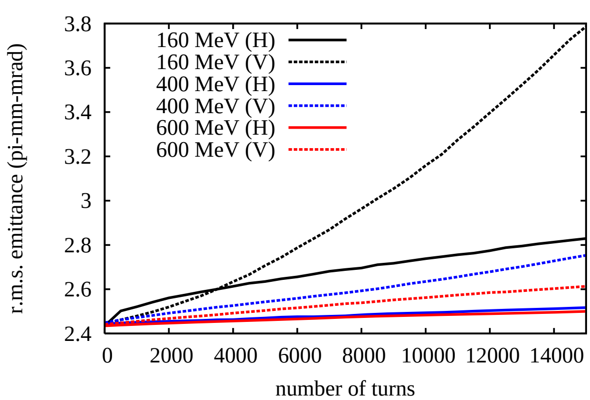

Figure 2: Normalised r.m.s. emittance evolution of the nominal LHC beam injected on energy plateaus of 160, 400, and 600 MeV.

Simulations with Different Distributions

Considerable effort is made to define a suitable set of simulation parameters for ORBIT (number of macro-particles, space-charge grid, distribution, etc). When comparing simulation results with ACCSIM we noticed in all ORBIT simulations a sudden transverse r.m.s. emittance increase in the vertical plane after approximately one thousand turns, which is not observed with ACCSIM. When changing the distribution type from parabolic to Gaussian this sudden blow-up takes place in the first few hundred turns and continues as a larger, continuous blow-up as shown in Fig. 3. It should be noted that an increase in the number of macro-particles in the simulation results in a shift of the turn number at which the blow-up for parabolic distributions (in ORBIT) starts. An increase from 10^5 (as in Fig. 3) to 2×10^5 shifts the onset of the instability from $\approx$ 1000 turns to $\approx$ 1700 turns. In the horizontal plane the results of both codes agree well and do not exhibit any instable behaviour. We believe that the sudden r.m.s. emittance growth is triggered by a numerical linear instability driven by the initial waterbag-like distribution, similar to the one driven by the KV distribution as documented in [5]. For future simulations we will explore the use of different profiles, which should neither be too pessimistic (as the Gaussian distribution) nor too artificial (as the parabolic profile).

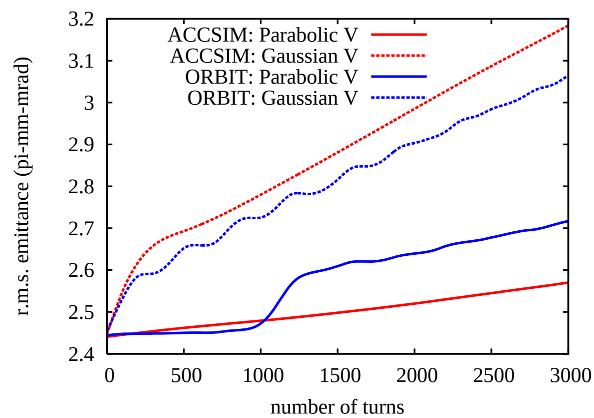

Figure 3: Normalised r.m.s. emittance evolution of the nom. LHC beam injected at 160 MeV using a parabolic and Gaussian transverse distribution (vertical plane).

LONGITUDINAL PAINTING

The low-energy beam chopper allows parts of the linac bunch train to be removed, meaning that the present injection of a coasting beam using a rather non-adiabatic capture can be replaced by an injection with longitudinal painting.

The principle harmonic is h=1 with a voltage of 8 kV. A second harmonic RF component is added for bunch flattening (6 kV is assumed to yield a good bunching factor). Moreover, it is assumed that injection takes place on a moderate ramp in order to keep the beam only for a short period at low energy with strong direct space-charge effects. This approach results in little, but not negligible motion in longitudinal phase-space during injection. Thus, longitudinal painting cannot be obtained free of synchrotron motion, but requires active energy modulation of the Linac4 beam. The shape of the waiting bucket is plotted in Fig. 4.

An active longitudinal injection painting scheme based on a well controlled modulation of the Linac4 output energy is proposed. During the first ten turns or so, the mean Linac4 output energy decreases from a positive offset of about 1.1 MeV to a negative offset of about -1.1 MeV as indicated in Fig. 4. The r.m.s. energy spread is 120 keV.

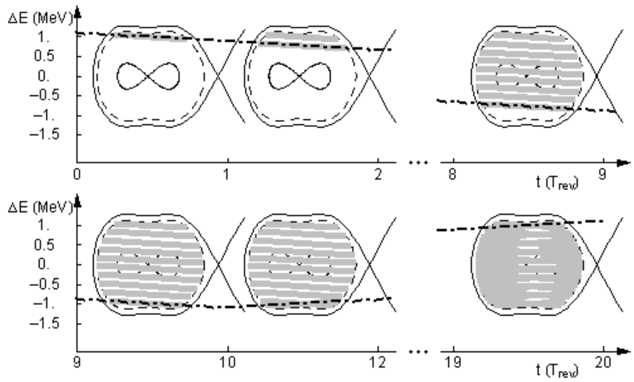

Figure 4: Principle of the proposed longitudinal injection painting scheme.

All bunches arriving outside a contour (plotted as dashed line in Fig. 4) in longitudinal phase-space ($\approx 20\%$ of the total acceptance) are removed by the chopper. During the next ten turns, the Linac4 output energy is raised again and the bucket is filled a second time. The maximum chopping factor in Linac4, defined as the percentage of un-chopped bunches is 62.2%. A average pulse current of ≈ 40 mA is needed to inject 3.25×10^{12} protons per ring, needed for nominal LHC operation, i.e. 20 turns lasting 20.16 μs in total. Higher intensities can be achieved by injecting during several energy modulation periods and/or increasing the period of the energy modulation.

ESME simulations have been carried out for injection of a nominal LHC beam during one energy modulation period corresponding to 20 turns and for a high-intensity beam injected during five energy modulation periods lasting in total 100 turns. A large number (10^6) of macro particles have been used and the parameters for computation of the longitudinal direct space-charge forces have been adjusted carefully. Thus, the direct space-charge forces could be modelled with an appropriate spatial resolution and without unphysical blow-up due to insufficient statistics. The direct space-charge forces have a significant impact on the high-intensity case mainly by reducing the bucket height. This has been compensated by reducing the energy modulation amplitude from 1.1 MeV to 0.95 MeV. The resulting distributions after about 3 ms are plotted in Fig. 5. Bunching factors, defined as ratio between the mean beam current and peak current obtained are around 0.60 (slightly higher for the LHC beam and slightly lower for the high intensity case). This bunching factor is about 10% higher than the one obtained in a simulation assuming the injection of a large energy spread beam into a waiting bucket. Assuming fixed transverse emittances, the expected gain in maximum accumulated intensity, that can be obtained with the proposed painting scheme is about 10%.

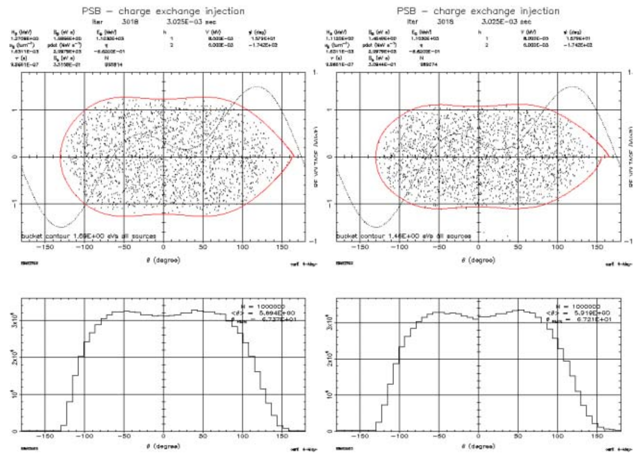

Figure 5: Long. phase-space 3 ms after injection: (left) nom. LHC beam, (right)very high intensity beam (right).

CONCLUSIONS AND OUTLOOK

While we are confident that an increase of the injection energy from 50 to 160 MeV will double the maximum intensity in the PSB it is far from trivial to make meaningful simulations on the emittance evolution and losses during the acceleration. So far, almost all cases show significant blow-up in the vertical plane, accompanied by a strong halo development. To protect the machine lattice, collimators should be installed that can intercept beam up to an energy of ≈ 500 MeV. Apart from further studies on suitable simulation conditions, different working points need to be explored to reduce the observed vertical blow-up. The next step will be a realistic modelling of the injection process together with the use of a 2nd harmonic cavity

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