EXPANDING THE CERN ION INJECTOR CHAIN CAPABILITIES: NEW BEAM DYNAMICS SIMULATION TOOLS FOR FUTURE ION SPECIES

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Abstract

The present ion physics program in the CERN accelerator complex is mainly based on lead ($^{208}Pb^{82+}$) ion beams. Lighter ions have been considered both by the ALICE3 detector upgrade proposal at the Large Hadron Collider (LHC) — as a potential way to achieve higher integrated nucleon-nucleon luminosity compared to the present Pb beams — and also by the Super Proton Synchrotron (SPS) fixed-target experiment NA61/SHINE. However, there is little or no operational experience at CERN with ions species lighter than Pb. This calls for beam-brightness and intensity limitations studies to assess the performance capabilities of the CERN ion injector chain, which consists of LINAC3, the Low-Energy Ion Ring (LEIR), the Proton Synchrotron (PS) and the SPS. This paper presents tracking simulation results for the SPS, compared against recent Pb beam emittance and beam loss measurements at the long injection plateau. The simulation models include limiting beam dynamics effects such as space charge and intra-beam scattering (IBS), whose impact on the future ion injector chain performance is discussed. Beam dynamics simulation results for the planned $^{16}O^{8+}$ pilot physics run are also presented.

INTRODUCTION

The LHC ion physics programme is mostly based on heavy-ion collisions using $^{208}Pb^{82+}$ ion beams [1–3]. There are proposals to extend operations with ions lighter than Pb, as a way to achieve higher beam intensities and nucleon-nucleon luminosities in the LHC [4], also highlighted by the ALICE3 collaboration [5]. In addition, a Letter of Intent has been submitted for an SPS fixed target experiment (NA60+) with $^{208}Pb^{82+}$ [6] while the NA61/SHINE experiment has requested ion species such as oxygen (O), magnesium (Mg) and boron (B) [7] . Most lighter ion species are untested in the CERN ion injector chain [8]. The ion injector chain performance for Pb beams has been optimized over the years within the LHC Injector Upgrade (LIU) project [8, 9]. However, remaining intensity limitations are believed to originate from space charge (SC) and intra-beam scattering (IBS) effects [10, 11], and potentially also from tune modulations due to SPS power converter ripples [12]. In this paper, we focus on beam dynamics simulation studies of space charge and IBS at the SPS injection plateau, where the strongest beam degradations are observed. The simulation results are discussed in the context of recent Pb beam measurements, as a step to provide accurate performance estimates of future ion species, in particular for the upcoming 2025 LHC oxygen $^{16}O^{8+}$ pilot run [13, 14].

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SPS ION BEAM MEASUREMENTS

In 2023, measurements with $^{208}Pb^{82+}$ beams were carried out at the SPS injection plateau, which, for LHC beams, lasts for about 45 seconds with 14 injections from the PS. The study focused on the four bunches of the first injection. Wire scanners were used for transverse emittance measurements, and the high-bandwidth ("fast") beam current transformer (FBCT) for individual bunch intensity. Losses of bunch intensity N_b (ions per bunch) of about 20% and a blow-up of the normalized emittances $\varepsilon^n_{x,y}$ by up to a factor 2.5 were observed, as shown in Fig. 1. The long SPS injection segment is the most challenging part in the whole ion injector chain, effectively limiting the beam quality for the LHC. The measured trends are qualitatively similar to measurements from the 2017 Injector MD days [15], but now observing a higher increase of ε^n_y after changing the nominal vertical tune from $Q_y = 26.25$ to $Q_y = 26.19$, as this was found to increase transmission by about 5%. Figure 2 shows a

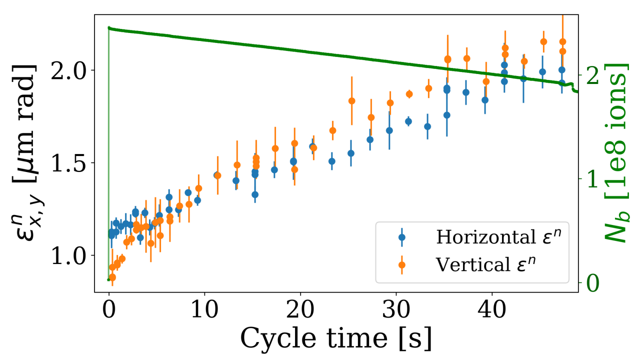

Figure 1: Measured $\varepsilon^n_{x,y}$ and N_b at SPS injection for Pb.

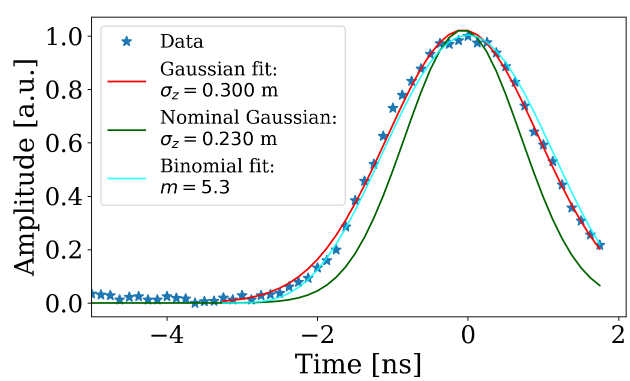

Figure 2: Measured BSM longitudinal profile of Pb at PS extraction, with new Gaussian/binomial fits and previous nominal Gaussian bunch length $\sigma_z = 0.23$ m.

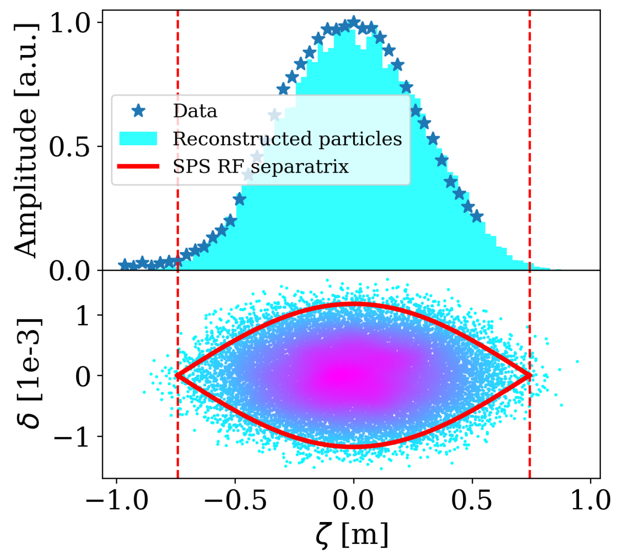

Figure 3: Reconstructed longitudinal Pb particle coordinates with binomial parameter $m = 5.3$ from data in Fig. 2 (top), and projection in longitudinal phase space (bottom).

measured longitudinal profile for nominal Pb beams, using available data from the Bunch Shape Monitor (BSM) at PS extraction, with a Gaussian fit (red) and a binomial fit (cyan), whose profile density function comes from Table 2 of [16]. The measured profile was cut in order to discard artificial ringing in the measurement caused by the limited bandwidth of the cables on the longitudinal pick-up. In contrast, previous space charge and IBS studies assumed Gaussian profiles with RMS bunch lengths $\sigma_z = 0.23$ m [17], which correspond to the beam after capture in the SPS.

Figure 3 shows the reconstructed longitudinal phase space over the longitudinal position coordinate $\zeta = s - \beta_0 ct$ (centered at the SPS RF bucket) of 20 000 macroparticles, using the measured profile at PS extraction from Fig. 2. About 8% of the generated particles lie outside the SPS RF bucket and will get lost in the first few turns, before the slow IBS-/space charge-driven losses commence. For the initial particle distribution in simulations of binomial beams, we only consider particles inside the RF bucket. Previous experimental Pb ion studies in SPS also found — using the wall-current monitor with higher longitudinal resolution than the FBCT — that about 2% of the injected particles are not captured, and an additional 5% of the particles spill out of the RF bucket in the course of the long SPS injection segment [18].

LEAD BEAM DYNAMICS IN THE SPS

The main question addressed in this study is to which extent tracking simulations of space charge and IBS can explain the observed emittance growth and beam losses in Fig. 1, with as realistic beam parameters as possible. For this purpose, the Python package `fma_ions` [19] was developed as a numerical analysis toolkit for ions in the CERN ion injector chain to study the effects of space charge, IBS and tune ripple, using `xsuite` [20] for the particle tracking. A total of 1080 space charge elements are installed around the SPS lattice to provide kicks from the "frozen" potential, calculated from the Bassetti-Erskine formula [21]. The IBS model used by `fma_ions` is based on the kinetic formalism [22], implemented in the prototype Python package `xibs` [23, 24], which applies kicks to the particles at every turn in the tracking. Tracking simulations of two million turns (corresponding to about 45 s) at the SPS injection plateau are conducted for two cases: 1) a beam with a Gaussian particle distribution in all three planes, with the previously assumed bunch length $\sigma_z = 0.23$ m [17], and 2) transversely Gaussian but longitudinally binomial beam as measured at PS extraction in Fig. 2. Space charge, magnet errors and IBS effects are added in various combinations. All cases except the ideal lattice include magnet imperfections, with a typical vertical 10% β-beat emulated through a single defocusing quadrupole (QD) error — similar to the procedure in [17] — and non-linear magnet errors from [25]. Table 1 displays the SPS Pb beam parameters used in the simulations at SPS injection, after the initial losses of particles outside the SPS RF bucket are removed for case (2).

Table 1: SPS Pb beam parameters.

Ions per bunch N_b	2.46×10^8
RMS bunch length σ_z (Gaussian)	0.23 m
RMS bunch length σ_z (binomial)	0.285 m
ε^n_x, ε^n_y (μm)	1.1, 0.9
Q_x, Q_y	26.3, 26.19

The $^{208}Pb^{82+}$ tracking simulations for the SPS injection plateau used 10 000 macroparticles, recording normalized emittance $\varepsilon^n_{x,y}$ and bunch intensity N_b evolution over time

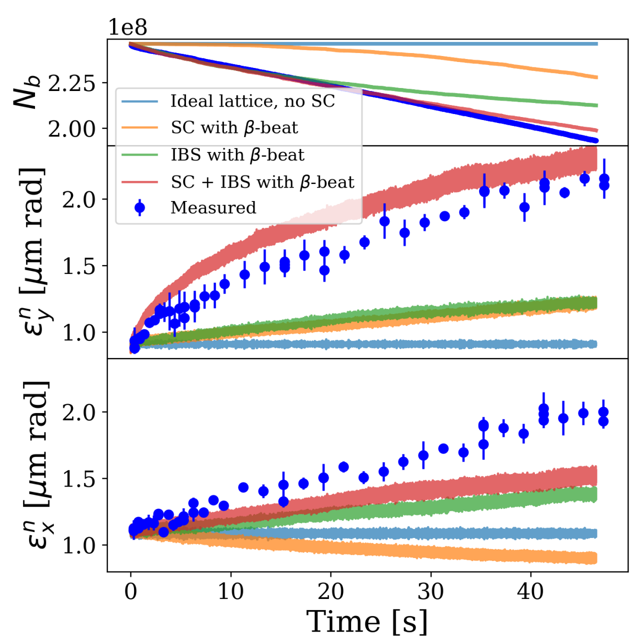

Figure 4: Simulated $\varepsilon^n_{x,y}$ and N_b at SPS injection, with fully Gaussian Pb beams, combined with various effects.

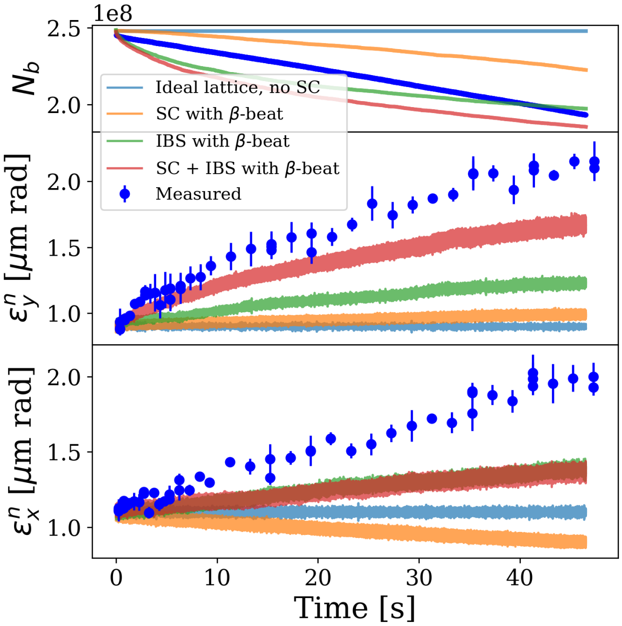

Figure 5: Simulated $\varepsilon^n_{x,y}$ and N_b at SPS injection, with transversely Gaussian and longitudinally binomial Pb beam.

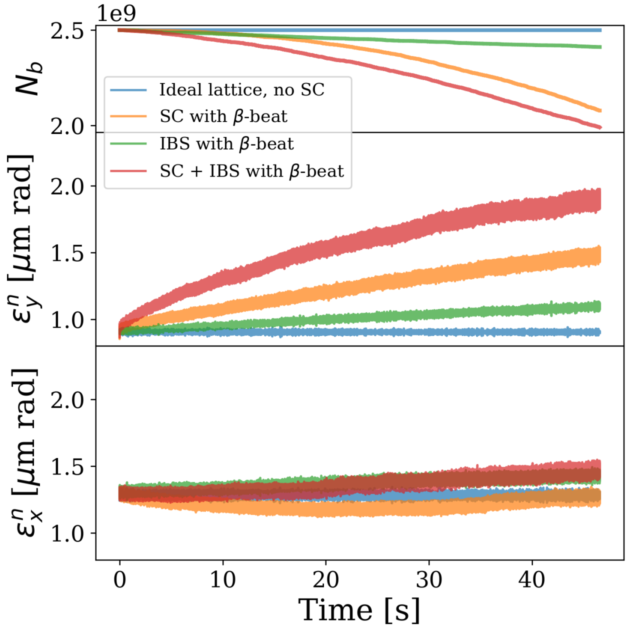

Figure 6: Simulated Gaussian $^{16}O^{8+}$ beams at SPS injection.

for the two cases: case (1) in Fig. 4 and case (2) in Fig. 5, compared with measurements from Fig. 1. As expected, the ideal lattice without magnet errors and collective effects gives a flat emittance evolution and no beam losses. The combination of SC and IBS leads to largest emittance growth for Gaussian Pb beams in Fig. 4; combining β-beat, non-linear magnet errors, space charge and IBS effects generates emittance growth almost in line with vertical measurements and 60% of horizontal measurements. Losses occur to a higher extent for binomial beams in Fig. 5 than the Gaussian beams, although the emittance growth is not as strong. It should be noted that the losses in the simulations are almost entirely due to particles spilling out of the RF bucket. In the case of SC only, this is unexpected. First investigations indicate that this loss out of the RF bucket is caused by a non-symplectic implementation of the frozen space charge model, which becomes evident in the case of the fast synchrotron motion of the Pb ions at SPS injection. Work is planned to improve the space charge model.

OXYGEN BEAM DYNAMICS IN THE SPS

Tracking simulations with Gaussian $^{16}O^{8+}$ beams were also performed, with beam parameters from Table 1 but using $\varepsilon^n_x = 1.3$ μm rad and $N_b = 25 \times 10^8$ as mentioned in [17, 26] (including PS bunch splitting). These parameters lead to a maximum incoherent space charge tune shift of $\Delta Q_{x,y} = (-0.19, -0.28)$. The corresponding space charge tune shifts for Pb beams in Fig. 4 are $\Delta Q_{x,y} = (-0.16, -0.21)$. Due to this larger tune spread for O with respect to Pb, the original vertical tune $Q_y = 26.25$ was used for $^{16}O^{8+}$. Figure 6 highlights four cases to investigate the underlying beam dynamics. For $^{16}O^{8+}$, IBS alone is weaker than for Pb beams in Fig. 4, but the interplay of space charge and IBS still leads to significant vertical emittance growth. It is worth noting that the O pilot beams are foreseen to be accelerated almost immediately after injection, but measurements of O beam emittance evolution at the SPS injection plateau would provide valuable ion tracking simulation benchmarking. Similar to the lead ion beams, the predominantly longitudinal losses seem to be caused by the non-symplectic implementation of the space charge model and have to be studied further.

OUTLOOK AND CONCLUSIONS

Significant losses and transverse emittance growth are observed for $^{208}Pb^{82+}$ beams on the long SPS injection plateau, which effectively limits the beam performance of the CERN ion injector chain. Both ALICE3 and NA61/SHINE are interested in lighter ion species, which are however mostly untested in the CERN ion injector chain. This paper presents SPS tracking simulation models including magnet errors, space charge and IBS, for the SPS injection plateau which were compared against measurements of transverse emittances and bunch intensity. In simulations, the combination of space charge and IBS seems to be the main contributor to beam degradation. The longitudinal losses out of the RF bucket in the simulations seem to originate from a non-symplectic implementation of the frozen space charge model, which have to be addressed in future studies. Overall, compared to Pb, the $^{16}O^{8+}$ beams are much less affected by IBS. Until the $^{16}O^{8+}$ beams are available in the SPS, space charge effects can also be studied with high-brightness proton beams with similar space charge tune shift. Planned future studies include better assessment of the β-beating in the machine, as this is an important ingredient resulting in emittance growth due to SC in the simulations.

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