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EXPLORING SPACE CHARGE AND INTRA-BEAM SCATTERING EFFECTS IN THE CERN ION INJECTOR CHAIN

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Abstract

As of today, the LHC ion physics programme is mostly based on Pb ion collisions. For the future, the ALICE3 detector proposal requests significantly higher nucleon-nucleon luminosities, as compared to today's operation. This improved performance could be potentially achieved with ion species that are lighter than Pb. In this respect, the CERN Ion Injector chain (consisting of LINAC3, LEIR, PS and SPS) will need to provide significantly higher beam intensities with light ion beams as compared to Pb, whereas operational experience with such beams is limited. We present space charge and intra-beam scattering studies across the Ion Injector chain to identify the relative impact of these effects. This is the first step for identifying the ideal ion isotopes and charge states for maximised LHC luminosity production.

INTRODUCTION

The Large Hadron Collider (LHC) ion physics programme is mostly based on heavy-ion collisions using lead (Pb) ion beams [1]. The ion injector chain consists of the ion source, LINAC3, the Low-Energy Ion Ring (LEIR), the Proton Synchrotron (PS) and the Super Proton Synchrotron (SPS), as described in detail in [2]. The present CERN ion injector chain is shown in Fig. 1, with the path of Pb ions, their charge state and associated stripper foils highlighted.

Injector optimizations have been undertaken along the years for maximising the beam intensities within the LHC Injector Upgrade (LIU) project [2, 3]. Two alleged intensity limitations that remain are space charge (SC) and intra-beam scattering (IBS) effects [4]. SC and IBS have been studied extensively in the context of resonances [5–7] and to increase extracted bunch intensity from LEIR [9], but the combined impact of SC and IBS still remains as one of the main bottlenecks to higher bunch intensity injected into the LHC.

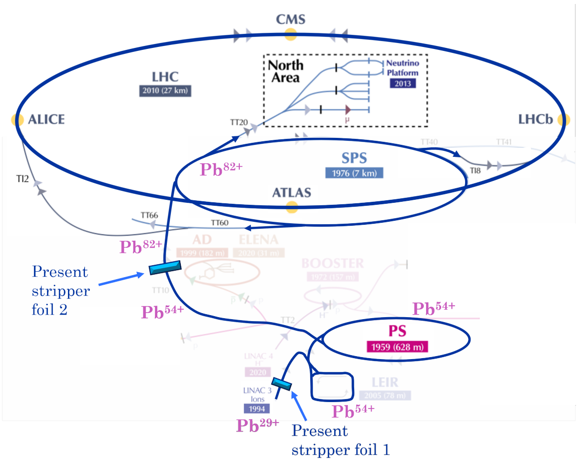

Figure 1: The CERN Ion Injector Chain [8].

These beam-degrading effects are important in the light of future CERN ion programmes, first to be tested with an upcoming short oxygen $^{16}O^{8+}$ pilot run for the LHC in 2024 [10]. Working Group 5 (WG5) of the HL/HE-LHC Workshop presented in 2018 a report to extend the LHC ion programme beyond Run 4 with ions lighter than Pb for higher beam intensities and nucleon-nucleon luminosities in the LHC [11], also highlighted by the 2022 Letter of Intent of the ALICE3 collaboration [12]. Also the NA61/SHINE experiment at the CERN North Area (NA) has requested ion species such as O, magnesium (Mg) and boron (B) beams [13], most of them untested in the CERN accelerator complex. In this article, we present a first mapping of the SC and IBS effects based on measured beam parameters throughout the Pb cycles in LEIR, PS and SPS.

SPACE CHARGE AND INTRA-BEAM SCATTERING

Space charge is a fundamental collective effect, referring to the Coulomb forces between charged particles in a high-intensity beam. This effect results in a non-linear defocusing force [14], introducing a tune spread of the beam particles. Space charge does not by itself cause beam losses, but can excite resonances far away from the set tune if the tune spread is large enough, or in combination with resonances excited by magnetic imperfections, leading to emittance growth and beam losses [15]. In this study, we calculate the maximum SC-induced tune shift $\Delta Q_{x,y}$ from the lattice integral in Eq. (18) in [14]. $\Delta Q_{x,y}$ is larger for smaller emittances, higher bunch intensities and lower energy.

Intra-beam scattering is a stochastic process of small-angle multiple Coulomb scattering of charged particles in a beam that leads to momentum exchange between the planes and emittance growth. The IBS emittance growth rates $1/T_{\mathrm{IBS},\,u}$ ($u = x, y, z$) depend mainly on the machine optics, the bunch intensity N_b, the geometric emittance ϵ_u, bunch length σ_z and the beam energy. Higher N_b and smaller ϵ_u generally lead to stronger growth rates. The first IBS theory for accelerators was presented by Piwinski in 1974 [16], then generalised by Bjorken and Mtingwa (BM) for strong-focusing lattices in 1983 [17]. In 2005, Nagaitsev presented a faster numerical evaluation of the BM elliptic integrals [18], which we use to estimate $T^{-1}_{\mathrm{IBS},\,u}$ numerically.

In order to calculate $\Delta Q_{x,y}$ and $T^{-1}_{\mathrm{IBS},\,u}$, we measure beam parameters across typical Pb cycles in LEIR, PS and SPS: bunch intensity N_b, relativistic gamma factor γ and bunch

Table 1: Assumed $\varepsilon^n_{x,y}$ and $(\Delta p/p)_{\text{inj}}$ [19]

	LEIR	PS	SPS
ε^n_x [µm rad]	0.4	0.8	1.3
ε^n_y [µm rad]	0.4	0.5	0.9
$(\Delta p/p)_{\text{inj}}$ [10^{-3}]	1.18	0.63	1

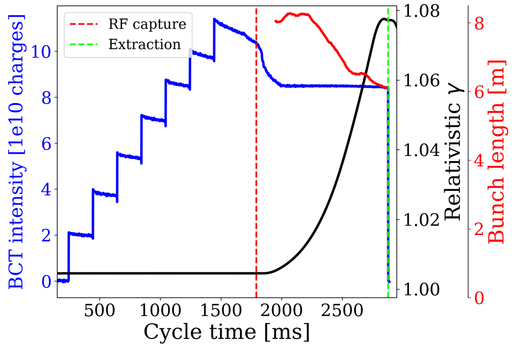

Figure 2: BCT total intensity, γ and σ_z during the LEIR nominal Pb cycle of 7 injections.

length σ_z. We assume constant values of the normalized emittance $\varepsilon^n_{x,y,z}$ and scale the momentum spread $\Delta p/p$ from reference values at injection [19] to evaluate of SC and IBS effects along the whole cycle in a given machine (neglecting emittance blow-up along ramp), shown in Table 1. The numerical calculations are done with a python package called Injector Model, available at [20], whose IBS module is based on a recent Nagaitsev formalism benchmarking study [21].

SPACE CHARGE AND IBS EFFECTS IN LEIR

The LEIR nominal Pb cycle's N_b and σ_z evolution, evaluated using a moving average (MA) for smoothing the experimental data, are presented in Fig. 2. The total beam intensity is measured with a Beam Current Transformer (BCT) and the relativistic γ is calculated from the measured magnetic dipole field B and the magnetic rigidity. The bunching factor (BF) is calculated from longitudinal tomoscope profiles, used to estimate the second-harmonic RMS bunch length.

The space-charge detuning $\Delta Q_{x,y}$ is displayed in Fig. 3 for the part of the cycle where the beam is bunched, i.e. from the start of radio-frequency capture to the flat top. As expected, initial stronger detuning is observed that decreases as the energy ramps up. The IBS growth rates $T^{-1}_{\text{IBS},\,u}$, shown in Fig. 4, are particularly strong in the horizontal planes but then decrease over the energy ramp.

SPACE CHARGE AND IBS EFFECTS IN PS

A typical Pb ion cycle in the PS is shown in Fig. 5, with two ramps and an intermediate plateau starting at 380 ms, where radio-frequency manipulations splits the two bunches into four and reduces the bunch intensity by a factor two.

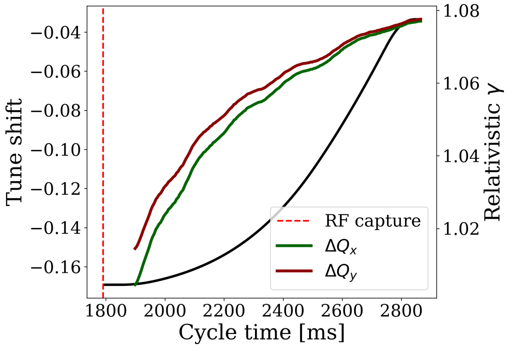

Figure 3: Space charge tune shift $\Delta Q_{x,y}$ during a LEIR nominal Pb cycle, with γ in black.

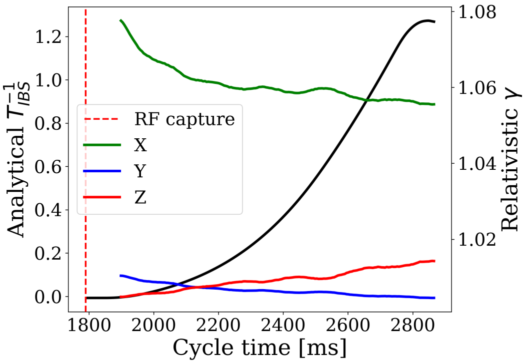

Figure 4: IBS growth rates $T^{-1}_{\text{IBS},\,u}$ in the PS cycle.

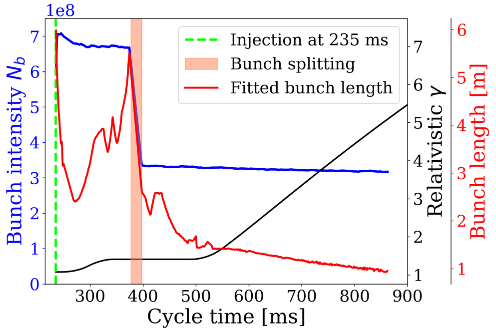

Figure 5: RMS bunch length σ_z, intensity per bunch N_b and γ during the nominal PS Pb cycle.

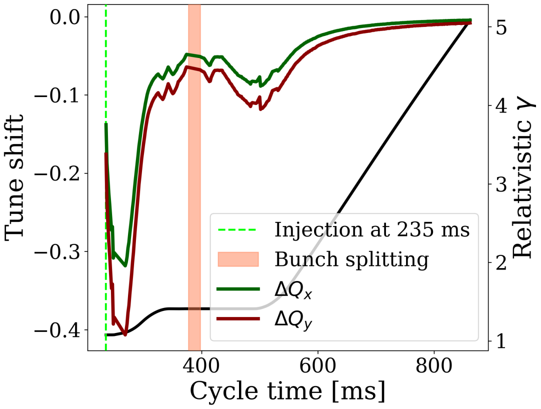

Figure 6: Space charge tune shift $\Delta Q_{x,y}$ during a nominal Pb cycle, with relativistic γ in black.

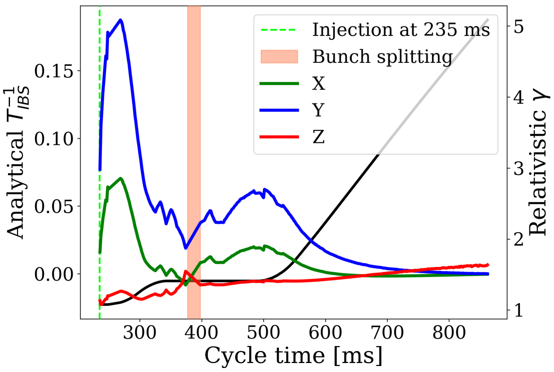

Figure 7: IBS growth rates estimates $T^{-1}_{\mathrm{IBS},\,u}$ in the PS cycle.

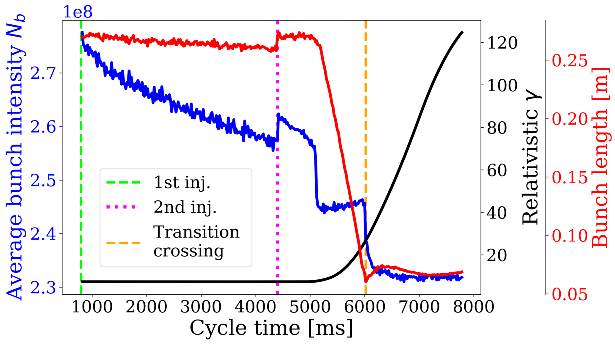

Figure 8: σ_z, N_b and γ for a SPS Pb cycle.

The bunch length σ_z is estimated from Gaussian fits of longitudinal profiles [22].

Figure 6 shows that the SC tune shift $\Delta Q_{x,y}$ is largest after injection in the early part of the first ramp, where the bunches become very short. The IBS growth rates $T^{-1}_{\mathrm{IBS},\,u}$ shown in Fig. 7 follow similar trends as the SC tune shift: they are largest in the first ramp, with a second smaller peak after the bunch splitting. The highest growth rate occurs in the vertical plane.

SPACE CHARGE AND IBS EFFECTS IN SPS

Figure 8 shows an SPS Pb cycle with two injections, occurring at 800 and 4400 ms, with four bunches each. The bunch intensity N_b is measured with high-bandwidth (“fast”) BCT, and σ_z with a wall current monitor.

The space charge tune shifts for the SPS shown in Fig. 9 indicate smaller values compared to peak values in the PS. However the beam has to be stored at injection energy for up to 45 s in the operational cycle for LHC filling. Furthermore, the intensity is expected to be slightly higher in operational conditions and thus the tune shift will be actually slightly higher.

The IBS growth rates $T^{-1}_{\mathrm{IBS},\,x,\,y}$ for the SPS shown in Fig. 10 are 10-20 times smaller than PS peak values. $T^{-1}_{\mathrm{IBS},\,y}$ decreases quickly during the ramp, but $T^{-1}_{\mathrm{IBS},\,x}$ increases again after transition. The longitudinal plane experiences an increased growth rate during the ramp, which is probably due to decreased $\Delta p/p$ during acceleration. During the SPS flat bottom duration of 4.2 s in this cycle, assuming constant $T^{-1}_{\mathrm{IBS},\,y} = 0.011$ and $T^{-1}_{\mathrm{IBS},\,x} = 0.005$ from Fig. 10 implies an IBS-driven emittance growth of about 10% vertically and about 4% horizontally. Much higher emittance growth values are expected for the nominal long cycle. The beam quality degradation due to IBS and SC on the long injection plateau of the SPS will therefore be the focus of future studies of the injector performance limitations.

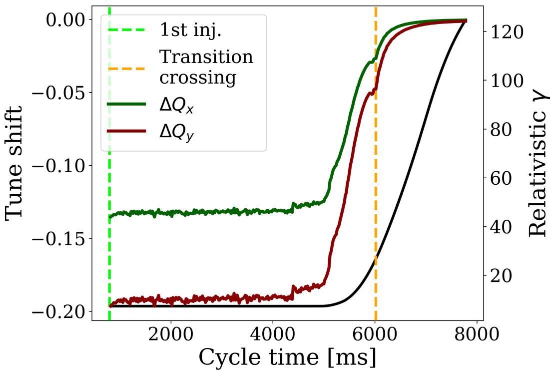

Figure 9: $\Delta Q_{x,y}$ during the SPS Pb cycle, with γ in black.

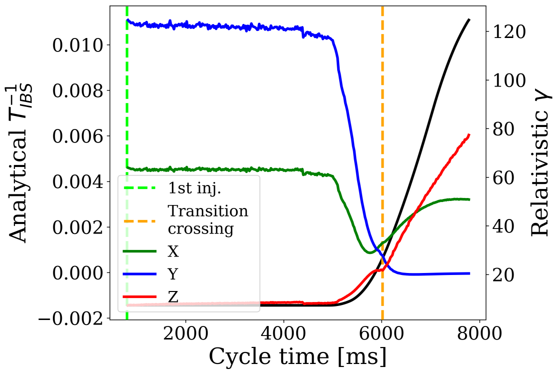

Figure 10: Analytical IBS $T^{-1}_{\mathrm{IBS},\,u}$ during the SPS cycle.

OUTLOOK AND CONCLUSIONS

Space charge and IBS constitute two of the most important limitations to achieve higher ion bunch intensities in the CERN ion injectors. In this paper, we estimate SC tune shifts and IBS emittance growth rates from measured Pb ion beam parameters. These estimates provide a first important milestone to develop a model predicting performance limitations for various ions beams. The next crucial step is to study the interplay of these two effects, to compare estimates with measured emittance evolutions, to observe their combined impact on potential future ion candidates. The scheduled oxygen pilot run in 2024 will allow for further benchmarking of our Injector Model to identify ion performance limitations across the CERN injectors.

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