INTERPLAY BETWEEN SPACE CHARGE AND INTRA-BEAM SCATTERING FOR THE CERN ION INJECTORS

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Abstract

The CERN ion injectors, SPS and LEIR, operate in a strong space charge and intra-beam scattering regime, which can lead to degradation of their beam performance. To optimize machine performance requires thus to study the interplay of these two effects in combined space charge and intrabeam scattering tracking simulations. In this respect, the kinetic theory approach of intra-beam scattering has been implemented in pyORBIT and benchmarked against analytical models. First results of combined space charge and intra-beam scattering simulations for SPS and LEIR are presented in this contribution. The simulation results are compared with observations from beam measurements.

INTRODUCTION

In the CERN ion injectors, such as the Low Energy Ion Ring (LEIR) and Super Proton Synchrotron (SPS), lattice imperfections can excite resonances and eventualy limit the machine performance. In addition, in this regime of low kinetic energies, incoherent effects like Intra-Beam Scattering (IBS) and Space Charge (SC) can be strong enough to further degrade the quality and the lifetime of the beam.

Each of these effects has been intensively studied in several regimes and accelerators. In particular, IBS plays an important role in ion and proton storage rings where the beam is stored for many hours [1–3]. Moreover, SC has been studied in many low-energy machines where the induced SC tune spread may result in particle losses and emittance increase in the vicinity of resonances [4–13].

The interplay between IBS and SC can further enhance particle diffusion in phase space, as was shown for the Compact LInear Collider Damping Rings (CLIC DRs) using a simplified IBS kick [14]. However, similar studies for the ion injectors that operate below transition are not trivial. In this regime, IBS can lead to emittance exchange which could not be simulated with the already implemented simplified kick in Ref. [14]. Therefore, a more general IBS kick was implemented based on the Kinetic Theory and Nagaitsev's formalism [15–17].

In this contribution, the general IBS kick based on the Kinetic Theory is benchmarked against analytical predictions and used for studying the interplay between SC and IBS in the CERN ion injectors LEIR and SPS. First comparisons between beam measurements and simulation results are also discussed.

COMBINED SIMULATIONS FOR SPS

The SPS is the last accelerator of the LHC ion injector chain and the second largest machine in CERN's accelerator complex, with a circumference of 7 km. Even though the SPS is a high-energy machine, in the case of heavy ions SC induces a considerable tune shift of $\Delta Q_{x,y} = (-0.2, -0.29)$ for the case of Pb ions at injection energy, making the beam susceptible to resonances.

In operational conditions, an emittance exchange between horizontal and vertical planes, followed by a large emittance blow up in both planes was observed along the acceleration cycle, as shown in Fig. 1 (lines with point markers). A simulation campaign performed in 2016 could not explain the observed behavior neither from standalone SC or IBS simulations, nor from the sum of them [18].

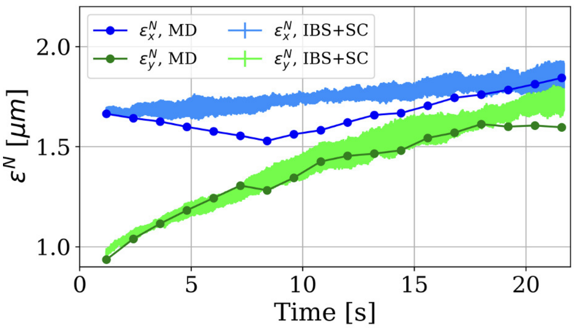

Figure 1: Evolution of the horizontal (blue) and vertical (green) emittance as observed in operation (dotted lines) and from combined SC and IBS simulations (solid line with errorbars) in PyORBIT (averaged over 3 different runs). The error bars correspond to the one standard deviation.

To this end, a simulation campaign was initiated to investigate the impact of the interplay of SC and IBS. The simulations were performed using the pyORBIT tracking code [19] with the "frozen" potential SC kick acting on the particles. The kicks are computed analytically using the Bassetti-Erskine formula [20], taking into account the local longitudinal density and the transverse beam sizes of a chosen distribution. In this case, the SC potential is re-evaluated every 1000 turns, based on the evolution of the tracked particles. A quadrupolar error is included in the ideal lattice, inducing a 5-10% beta-beating, similar to what is observed in the real machine in operational conditions.

The IBS effect was included in the simulation model based on the Kinetic Theory and is applied with a similar form to

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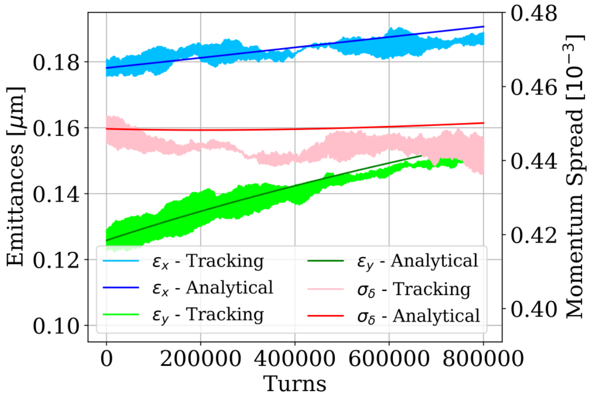

Figure 2: Comparison of the momentum spread (red), the horizontal (blue) and vertical (green) emittances, between analytical IBS predictions (dark colors) and tracking IBS simulations (light colors).

the Langevin equation:

$$\Delta p_u = -K_u p_u \sigma_s \sqrt{\pi}\rho_s(z)\Delta t + r\sigma_{p_u}\sqrt{2C_u\sigma_s\sqrt{\pi}\rho_s(z)\Delta t}, \tag{1}$$

where r is a Gaussian random number with zero mean and unit standard deviation, σ_{p_u} the standard deviation of the momentum p_u in plane u, σ_s the bunch length, ρ_s the longitudinal line density and K_u, C_u are functions of the friction and diffusion coefficients, respectively, for each plane. These coefficients are evaluated using the Nagaitsev's method [15]. Every turn, each particle receives a change of its momenta depending on the beam parameters and the particle's longitudinal position. The emittance evolution resulting from this kick was successfully benchmarked with analytical calculations using the Nagaitsev formalism [15], as shown in Fig. 2. A very good agreement is observed in the evolution of both horizontal and vertical emittances as well as momentum spread.

Using this setup, a combined simulation with SC and IBS was performed. Figure 1 shows the evolution of the normalized horizontal (blue) and vertical (green) emittances in time, as observed from the measurements (lines with point markers) and as predicted by the combined simulations (solid line). For the first time, a very good agreement could be achieved in both planes, demonstrating the importance of the interplay between the two effects in this case. In the vertical plane the agreement is truly excellent while, in the horizontal plane some minor discrepancy is observed in the trend of the evolution. It has to be noted that in these simulations the experimentally observed particle losses and bunch length evolution were not considered. Further simulations and measurements are planned in order to take all the effects self-consistently into account to further improve this benchmarking.

SPACE CHARGE AND INTRA-BEAM SCATTERING STUDIES IN LEIR

LEIR is the second accelerator of the CERN ions injectors chain. A coasting beam is injected from the upstream LINAC3. The beam is captured and ramped-up in energy to be injected to the Proton Synchrotron. The main machine parameters of LEIR are summarized in Table 1.

Table 1: LEIR Parameters

Ring Parameters	
Circumference [m]	78.54
Pb^{54+} rest energy [GeV]	193.7
Injection Kinetic energy [GeV/u]	0.0042
Gamma transition, γ_{tr}	2.8384
Harmonic number, h	2
RF voltage [MV]	0.0011
Momentum compaction factor	0.1241

In the past, low intensity studies showed that the vertical emittance evolution could not be explained only by IBS [21]. In order to understand the source of this discrepancy in the vertical plane, a simulation campaign with combined IBS and SC tracking simulations was initiated, to investigate the impact of the interplay between the two effects, especially in the vicinity of excited resonances.

In LEIR, due to its low lattice periodicity (2-fold) and due to random magnetic errors, various resonances are observed to be excited, including the $3Q_y = 8$ and the coupling $Q_x + 2Q_y = 7$ resonances [21]. Due to the high complexity of the machine, a low-intensity (one injection) set of measurements was chosen to benchmark the simulations that will follow. In this set of measurements, the available skew sextupole correctors were used to compensate the $3Q_y$ resonance, while all the other resonances remain uncorrected.

Table 2: Beam Parameters for the LEIR

Beam Parameters	
Total number of charges, N_c	$1.74{\times}10^{10}$
Normalized horizontal emittance, ε_x [μm]	0.162
Normalized vertical emittance, ε_y [μm]	0.189
Bunch length, σ_s[m]	4.5

Space Charge and IBS Studies

A tune scan similar to the experimental campaign described below was performed in simulations using pyORBIT with the "frozen" potential SC kick and the ideal LEIR lattice, i.e. without any machine imperfections. The horizontal tune was set to $Q_x = 1.82$ in all cases, while the vertical tune was varied. Results will be presented in terms of final over initial values ratio, where the initial values are measured 675 ms after the start of the magnetic cycle, while the final ones are measured 1600 ms after the start of the magnetic cycle whose duration is 3600 ms.

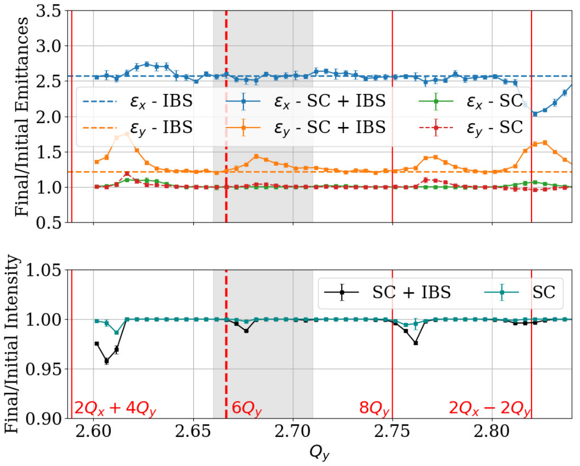

Figure 3: SC simulations versus combined SC and IBS simulations comparison of the final over initial values of the horizontal (green and blue, respectively) and vertical (red, orange) emittances (top) and intensity (bottom).

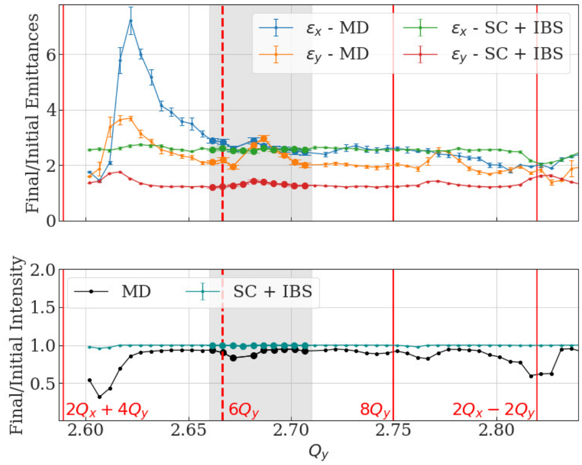

Figure 4: Measurements versus combined SC and IBS simulations comparison of the final over initial values of the horizontal (blue and green, respectively) and vertical (orange, red) emittances (top) and intensity (bottom).

Even in the case of the ideal lattice, the nonlinear SC potential can drive systematic resonances of even order. In the case of LEIR, SC simulations shown with light colors in Fig. 3, revealed four SC driven resonances: the coupling resonance $2Q_x + 4Q_y = 14$, the $6Q_y = 16$, the $8Q_y = 22$ and the $2Q_x - 2Q_y = -2$ resonance [22,23]. In these studies focus will be given in the working points around the $6Q_y$ resonance, indicated by the red shadowed area in the plots.

A similar vertical tune scan was performed including both SC and IBS, to study the interplay between the two. The results are summarized in Fig. 3 and compared to the case where only SC or only IBS is taken into account. The interplay of the two effects clearly enhances the beam response to the resonances, resulting in larger emittance blow-up and increased particle losses.

Comparison with Measurements

A first attempt was made to benchmark the experimental observations with combined SC and IBS simulations, as shown in Fig. 4. In the real machine, additional resonances can be excited due to magnetic errors and misalignments. In the measurements, the skew sextupolar components that excite the lower order $3Q_y = 8$ resonance have been corrected as much as as possible. Thus, the only resonance that is expected to have similar behavior between simulations and measurements is the SC driven resonance $6Q_y = 16$ at the same tune. In the absence of excited resonances, the horizontal plane is dominated by IBS, while, in the vertical plane an extra emittance blow-up, which cannot be explained by the interplay of the two effects, is observed for all working points. Furthermore, even though the simulation and experimental conditions for the $6Q_y$ resonance are expected to be equivalent, a stronger response of the beam to this resonance is observed in the experimental data. This could be an indication of a residual effect from the $3Q_y = 8$ resonance stemming from an imperfect compensation. In a similar way, a stronger response of the beam to the rest of the resonances is also observed, which is not surprising as no compensation was applied to these resonances in the experiment.

Further investigations are ongoing to identify the exact resonance conditions for a more accurate benchmarking between simulations and measurements.

CONCLUSIONS AND FUTURE PLANS

In this contribution, the interplay between SC and IBS, in the context of the LEIR and SPS accelerators for Pb ion beams, was addressed. For the SPS, simulations were performed in the presence of a quadrupolar error. The simulation results could explain for the first time the experimental observations from 2016, revealing the importance of the interplay between SC and IBS effects. Further simulations and measurements are planned in order to take all the effects self-consistently into account to further improve this benchmarking. For the case of LEIR, standalone SC and IBS simulations as well as combined simulations were performed, using the ideal lattice (i.e. without machine imperfections). In LEIR, several SC driven resonances are excited due to the low lattice periodicity. The combined simulations showed a clear enhancement of the particles' response to the resonances, leading to larger emittance blow-up and increased particle losses. A first attempt was made to compare the simulations with experimental data. Comparing to measurements in which the $3Q_y = 8$ resonance is compensated, revealed that the interplay of IBS and SC is not enough to explain the generally larger vertical emittance blow-up observed in the machine. A better modelling needs to be developed to include the same resonance components for both measurements and simulations. Future studies will also include non-Gaussian longitudinal profiles.

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