Space charge induced losses in the CERN injector complex

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ABSTRACT: Space charge effects in high intensity and high brightness synchrotrons can lead to undesired beam emittance growth, beam halo formation and particle loss. A series of dedicated machine experiments has been performed over the past decade in order to study these effects in the particular regime of long-term beam storage as required for certain applications. This paper gives an overview of the present understanding of the underlying beam dynamics mechanisms, with particular emphasis on space charge induced losses and the experience gained at the CERN injector complex. The focus is on the space charge induced periodic resonance crossing, which has been identified as the main mechanism causing beam degradation for long storage times. Examples of space charge driven and error driven resonances are presented, including possible mitigation strategies. Furthermore, an outlook for possible future directions of studies is presented.

KEYWORDS: Accelerator modelling and simulations (multi-particle dynamics; single-particle dynamics); Beam dynamics; Beam Optics
1 Introduction

Space charge effects in high intensity and high brightness synchrotrons can lead to undesired beam emittance growth, beam halo formation and particle loss. Furthermore, some accelerator projects require long-term storage (up to several seconds) of high brightness bunches at injection energy in order to allow accumulating several injections from an upstream machine. This is the case for the Proton Synchrotron (PS) and the Super Proton Synchrotron (SPS) at CERN, which are part of the injector chain for the Large Hadron Collider (LHC). On the other hand, even if the beam is accelerated immediately after injection is completed, keeping emittance growth and space charge induced losses within acceptable limits can be challenging in low energy machines such as the Proton Synchrotron Booster (PSB) at CERN, which is the first synchrotron in the LHC injector chain.

In preparation for the High Luminosity LHC (HL-LHC) [1], the injector chain at CERN is presently being upgraded in the framework of the LHC Injectors Upgrade (LIU) project [2]. In simplified terms, the aim of the LIU project is to enable the injectors to deliver twice higher intensity at today’s transverse emittances, i.e. doubling the brightness compared to today’s performance, to match the requirements of the HL-LHC. For the various machines of the proton injector chain at CERN, table 1 shows an overview of the required storage times at the corresponding injection energy, the maximum vertical incoherent space charge tune shift $\Delta Q_{y,\text{max}}$, and the loss and emittance growth budgets. Although the LHC injector chain for ion beams will not be discussed in detail here, it should be mentioned that beam degradation due to space charge and intrabeam scattering are challenging in the Low Energy Ion Ring (LEIR) and in particular in the SPS, where beams with
large space charge tune shifts of up to $\Delta Q_y = -0.3$ need to be stored for up to 40 s on the injection plateau during accumulation. In this case the beam quality is subject to strong degradation, which has been taken into account for the projection of the LIU-ion target beam parameters [3].

### Table 1. Target parameters for proton beams after completion of the LIU project at CERN.

| Machine | $\Delta Q_y,_{\text{max}}$ | Storage time | Loss budget | Emittance growth budget |
|---------|-----------------|--------------|-------------|------------------------|
| PSB     | $-0.5$          | $< 1$ ms     | 5%          | 5%                     |
| PS      | $-0.31$         | 1.2 s        | 5%          | 5%                     |
| SPS     | $-0.21$         | 10.8 s       | 10%         | 10%                    |

2 Beam degradation due to periodic resonance crossing

Keeping the beam degradation within tight tolerances can be quite challenging in the presence of large space charge tune spreads. A detailed understanding of the underlying beam dynamics mechanisms is required. Therefore, a series of dedicated machine experiments have been performed over the past decade in collaboration between CERN and GSI in order to study the space charge dynamics in this regime.

2.1 One-dimensional resonances

The first systematic experimental study of long-term space charge effects in presence of non-linear resonances was performed at the CERN PS in 2002–2003, as reported in [4] and [5]. In this experiment, the fourth order horizontal resonance $4Q_x = 25$ was deliberately excited by a single octupole magnet. A bunched proton beam with a maximum horizontal (vertical) incoherent direct space charge tune shift of $-0.075$ ($-0.12$) was stored at injection energy for about 1 s and for different working points. Depending on how the space charge tune spread overlaps the resonance, two regimes of beam degradation can be clearly identified, as illustrated in figure 1. For bare machine working points only slightly above the resonance, beam loss dominates. At the same time a reduction of both the horizontal emittance as well as the bunch length are observed. For higher machine tunes, losses are reduced but a halo is formed in the horizontal plane leading to an enlarged emittance.

The beam degradation observed in the PS experiment was explained by trapping and scattering of particle trajectories during the periodic resonance crossing induced by space charge in a bunched beam, as anticipated by a simplified simulation model in 2002 [6]. This picture was refined in the following years [5, 7, 8], but the main factors to explain the observed behavior are the detuning effect mostly due to space charge (and only to a small extent from the octupole), the octupole driving the resonance, and the synchrotron motion resulting in the modulation of the space charge detuning and thus the periodic resonance crossing. This mechanism can lead to losses when individual particles are transported to betatron amplitudes that exceed the acceptance of the machine.

This mechanism was confirmed in a complementary systematic measurement campaign performed at the GSI SIS18 in 2007, where the horizontal third order resonance $3Q_x = 13$ was studied for both coasting and bunched beams with different beam intensities and space charge tune spreads [9]. The strong emittance growth was only observed for the high intensity bunched beam...
Observation of Octupole Driven Resonance Phenomena with Space Charge at the CERN Proton Synchrotron

E. ... of loss-free core-emittance blow-up
Regime where continuous loss occurs ★ Due to longitudinal motion

Introduction

Linear and nonlinear properties of the lattice [12], following a method previously applied in the SPS [13]. The observations of the combined effect of space charge and nonlinear resonance on beam loss and simulation codes. The observations of the combined effect of space charge and nonlinear resonance on beam loss and simulation codes.

Figure 1. Measured relative horizontal emittance and beam intensity as a function of the working point close to a one-dimensional resonance as observed in the PS experiment with a bunched beam performed in 2002-2003 (left). Illustration of the two regimes as described in the text (right). Figures taken from [5]. Copyright CERN, reused with permission.

but not for the coasting beam with the same space charge tune shift, since there is no periodic resonance crossing for a coasting beam.

2.2 Two-dimensional sum resonances

While the studies reported above concentrated on one-dimensional non-linear resonances, an experiment in 2012 at the CERN PS was dedicated to studying the beam behaviour close to the third order coupled sum resonance \( Q_x + 2Q_y = 19 \), which was deliberately excited by a sextupole magnet [10]. The beam was stored for about 1 s. Also in this experiment the loss-dominated and the emittance growth-dominated regimes were observed depending on the working point. However, the halo formation measured with wire scanners was observed to be very asymmetric between the horizontal and vertical planes. In particular, the beam developed much larger tails in the vertical plane. Figure 2 provides an overview of these results. Note that the completely different shape of the beam profiles in the vertical and horizontal planes observed in the measurements was reproduced quite accurately in particle tracking simulations using the frozen space charge implementations in MADX [11–13] and in MICROMAP [7, 14].

This observation could not be explained by a naive extension of the one-dimensional model developed earlier, since the particle trajectory on the coupled resonance follows resonant tori in phase space rather than fixed points. These resonant tori, in this context referred to as “fixed lines” [15–17], have a peculiar shape in the 4 dimensional phase space of horizontal and vertical coordinates. In the case of the \( Q_x + 2Q_y \) resonance, the projection of the single particle trajectory in the physical \( x-y \) space has a larger excursion in the vertical plane and, depending on the phase advance from the driving sextupole to the observation point, follows either a figure-of-eight or a C-shape. This explains the larger vertical halo observed in this experiment at the PS.

It should be mentioned that an experimental campaign was performed at the CERN SPS to study the fixed lines on the \( Q_x + 2Q_y \) resonance in the “zero” space charge limit [18]. Furthermore,
a general theory of space charge dynamics in the presence of non-linear coupled sum resonance of arbitrary order has been published [19].

3 Half integer resonance at the CERN PSB

As first synchrotron of the proton accelerator chain at CERN, the PSB has up to now received proton beams with 50 MeV kinetic energy from Linac2 which were injected through multi-turn betatron stacking for up to 13 turns. The coasting beam was adiabatically captured into a double harmonic RF bucket resulting in a few percent losses inherent to the capture process. For LHC type beams, which are of relatively low intensity compared to other beams produced by the PSB, the main performance criterion is the beam brightness given by the ratio of intensity over transverse emittance $\varepsilon$. LHC beams are produced at the brightness limit imposed by the space charge detuning and the blow-up due to resonances at the integer tunes. Hence, for a given longitudinal emittance and a given working point the transverse emittances increase proportionally to the beam intensity such that the same space charge tune spread is reached. To maximise the beam brightness, LHC beams are produced with high fractional tunes (i.e. far away from integer tunes) just below the half integer resonances at injection (typically at $Q_x, Q_y = 4.40, 4.45$). During the ramp, the working point is gradually moved to lower fractional tunes towards the extraction working point as the space charge tune spread reduces with energy. The resulting beams usually have transverse beam profiles close to a Gaussian distribution, which is important for the luminosity production in the LHC. In comparison to that, the optimization of high intensity beams produced in the PSB for other physics users such as fixed target experiments has resulted in a slightly different operational working point. In fact, it was found that minimum losses for these high intensity beams can be achieved when injected with vertical tunes slightly above the half integer resonance (typically with $Q_x, Q_y = 4.28, 4.55$), provided that the beta-beating is compensated efficiently using the available quadrupole correctors of the PSB.

As the vertical half integer resonance at $2Q_y = 9$ is one of the main drivers for losses in the PSB for high intensity beams, a dedicated benchmarking experiment was performed at injection...
energy [20]. The beam loss evolution over about 200 ms was studied on a constant energy plateau for a working point slightly above $Q_x = 4.5$ without half integer resonance correction. To reproduce the observed losses in PIC simulations, a very accurate machine model of the linear errors had to be developed using beam-based measurements. In the end, even the evolution of the longitudinal bunch profile measured in the experiment was in very good agreement with the simulations. Figure 3 shows a summary of the experiment and the simulation results.

![Figure 3](image)

**Figure 3.** Evolution of beam intensity in measurements and in various simulation configurations (left), with (A) simulation without errors but with space charge (B) simulation with errors but no space charge (C) simulation with only quadrupolar field errors (matching to $Q_y = 4.53$) and space charge (D) simulation with space charge and quadrupolar field and misalignment errors (E) simulation with only quadrupolar field errors (matching to $Q_y = 4.525$) and space charge. Comparison of the longitudinal profile evolution as observed in measurements (middle) and in simulations (right). Figures taken from [20].

As mentioned above, the PSB was already operating at the space charge induced brightness limit. In order to reach the target of doubling the beam brightness for LHC type beams, the injection energy of the PSB will thus be raised from 50 MeV to 160 MeV as part of the LIU project. Instead of the proton beams from Linac2, the PSB will receive H$^-$ beams from the new Linac4. The operation close to the half integer resonance will be particularly challenging due to the focusing errors induced by the new chicane dipoles required for the H$^-$ injection. The commissioning of the dedicated beta-beating correction scheme will thus be a crucial step in the commissioning of the upgraded machine.

### 4 Space charge driven resonances at the CERN PS

The production scheme for LHC beams in the PS requires two injections from the PSB, where the first batch has to be stored at injection energy for 1.2 s, i.e. for more than 1000 synchrotron periods. The operational optimization of the working point to minimize losses and emittance growth on the flat bottom has resulted in a working point of about $Q_x, Q_y = 6.21, 6.24$. In this case, the PS is operated at the brightness limit imposed by space charge. In particular, for working points closer to the integer tunes, emittance growth is observed at the end of the flat bottom. On the other hand, losses are observed for working points further away from the integer tunes in particular for working points with $Q_y \geq 6.25$.

A series of studies have been performed in the course of the LIU project in order to study possibilities for increasing the beam brightness and for characterising the losses encountered for
Figure 4. Losses as a function of the working point when storing the beam for 1.2 s at the PS injection plateau as observed in measurements (left) compared to particle tracking simulations (right) for a high brightness beam (top) and a medium brightness beam with same transverse emittances but lower beam intensity (bottom). Figures taken from [22].

higher tunes. Figure 4 shows the result of detailed static tune scans in which the beam was stored for 1.2 s at the PS injection plateau in both measurements (left) and corresponding simulations (right) using a frozen space charge model in which the space charge kicks are evaluated through an analytic expression [21]. Losses due to various resonances can be clearly identified as discussed in detail in [22]. Comparing a high brightness beam (top graphs) with a medium brightness beam (bottom graphs) shows increased losses caused by a resonance at $Q_y = 6.25$, which has been identified as the 8th order resonance $8Q_y = 50$ excited by the periodic modulation of the space charge potential due to the strong 50th harmonic of the PS lattice. Similarly, there is another 8th order resonance excited by the space charge potential at $2Q_x + 6Q_y = 50$. Both resonances lead to larger losses with the high brightness beam compared to the medium brightness beam. This result is reproduced also by the simulation model including only space charge as non-linear fields, which confirms that these are space charge driven resonances. Losses due to other resonances observed in the measurements are not seen in this simulation model and thus are caused by other non-linearities of the machine presently not known and thus not included in the model.

It becomes clear from figure 4 that working points above $Q_y = 6.25$ are not suited for operation of high brightness beams due to enhanced losses on the injection plateau. Thus, the LIU target
of doubling the beam brightness cannot be achieved by optimising the machine working point. Instead, the only option is to increase the injection energy in the PS by accelerating the beam to 2 GeV instead of 1.4 GeV kinetic energy in the PSB as part of the LIU project, with which a similar space charge tune spread as in present operation will be achieved for twice higher beam brightness.

5 Impact of tune ripple at the CERN SPS

The LHC beam production scheme for proton beams requires multiple injections from the PS into the SPS in order to maximise the number of bunches in the LHC. Usually up to four injections are accumulated so that the first batch has to be stored for around 11 s on the SPS injection plateau at 26 GeV. In routine operation, the LHC beams usually had maximum space charge tune shifts of around $\Delta Q_y = -0.12$. The relatively high tune shift results from the short bunch length and the large circumference of the SPS. Up to now, space charge effects have not been limiting the performance of LHC beams in the SPS. With the LIU upgrades in the pre-injectors, the beam brightness will be doubled so that space charge tune shifts of up to $\Delta Q_y = -0.21$ will be reached.

Previous experiments with special high brightness multibunch beams with intermediate intensity indicated that such parameters should be sustainable in the SPS, without exceeding the tight budgets of 10% losses and emittance growth [2]. It remains to be demonstrated that similar performance can be achieved with the high beam intensity of the LIU target parameters. In addition, more recent studies at the SPS indicate that the tune modulation induced by power converter ripple can play an important role in the beam degradation during the long storage in presence of space charge [23]. Figure 5 shows the relative emittance growth and transmission for different working points in the SPS close to the third order resonance at $Q_x = 20.33$, which had been deliberately excited using a single sextupole. The experimental results (top graph) were obtained with a single bunch beam in order to exclude any multi-bunch effects, and the beam was stored on the SPS injection plateau for about 3 s. Tracking simulations of the same beam conditions using a frozen model are far from the experimental observations (middle graph), as there is hardly any emittance growth or beam loss close to the resonance. Only when the measured tune ripple induced by the power converters for the main quadrupoles of the SPS is taken into account (bottom graph), the simulations agree much better with the experimental data. Detailed studies on this subject are ongoing.

6 Mitigation of beam degradation due to magnet error driven resonances

In view of pushing the accelerator performance further, an important aspect to be addressed is the mitigation of the space charge induced beam degradation. On the one hand, individual non-linear resonances excited by magnetic errors can be compensated in case appropriate corrector magnets are available in the machine (at the expense of possibly further exciting other resonances or reducing the dynamic aperture). Typically two independent correctors with adequate phase advance are needed in order to control the resonance driving term in the complex plane. This has been tested in the PS for third order normal and skew resonances, see for example [24, 25] and in the PSB for the half integer resonance and third order resonances at 160 MeV [26]. It is clear that the PSB operation after the installation of the H− charge exchange injection with its injection chicane will require careful compensation of the half integer resonance in order to achieve optimal operational performance.
Figure 5. Relative emittance growth and intensity as a function of the measured horizontal machine tune in measurements (top), in simulations (middle) and in simulations including the tune ripple induced by power converters in the SPS (bottom).

7 Future directions of studies

The main mechanism for beam degradation of high brightness bunches in the long-term storage regime has been attributed to periodic resonance crossing. Future study efforts could focus on identifying and better understanding the interplay with other collective effects or beam dynamics.
mechanisms, such as tune modulation induced by power converter ripple, intrabeam scattering (especially for ions), electron-cloud, indirect space charge and impedance. All these effects are encountered and sometimes are entangled in some operational conditions in the CERN injectors.

A good example is the SPS. Reaching the LIU target beam parameters requires injecting 25 ns beams with unprecedented intensity and beam brightness. In the past, coherent (instabilities and fast losses) and incoherent (slow emittance growth and losses) electron cloud effects were observed in the SPS already with the nominal intensity. Over the years, this effect was slowly reduced by beam induced scrubbing. In recent machine studies with high intensity beams (not yet LIU intensity) a strong incoherent emittance growth was observed when storing the beam for about 20 s at injection energy. However, a clear improvement of the beam quality could already be observed after running the machine in this scrubbing configuration for two days [27]. Nevertheless, some residual electron-cloud might always be present in future operation and the interplay with space charge effects could become important.

Another important aspect to study is the interplay between space charge and intrabeam scattering for ion beams. To reach the LIU ion target parameters [3], the Pb-ion beam has to be stored for more than 40 s on the SPS injection plateau for accumulation of several batches from the PS. The space charge tune shift at SPS injection reaches up to $\Delta Q_y = -0.3$. In addition to the large space charge tune shift, intrabeam scattering is also contributing to emittance growth [28] and the interplay of these two effects need to be understood.

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