Abstract

We present here the relevant space charge issues for long-term beam storage. The impact on the choice of the working point and the prediction of the beam loss is discussed for the example of the SIS100. We present a first estimate on the effect of self consistency and discuss the equivalence of space charge, and electron clouds induced “quasi” incoherent effect.

INTRODUCTION

The increase of the beam intensity is an essential requirement for basic research of several new projects. Basic issues are beam quality control (control of the emittance increase) and beam loss. At GSI the SIS100 synchrotron [1] of the FAIR project is foreseen to deliver $U^{+28}$ at an intensity of $6 \times 10^{13}$ ions/s with $Q = 0.2$. This goal is reached by injecting 4 bunches from SIS18 in 2 different cycles. The maximum allowed beam loss is of 5% (1W/m hands-on maintenance). The beam loss control will be obtained as a trade-off between collimation system, magnet field quality, and resonance correction system. However, as the storage time in SIS100 is of one second ($\sim 2 \times 10^5$ turns), during the storage the bunch has time to experience the space charge repulsion, the lattice nonlinearities, and the synchrotron motion. The latter plays, jointly with the space charge, an essential role in determining beam loss. This complex beam dynamics has been addressed in some detail in [2].

SPACE CHARGE ISSUES

The space charge issues in a long term storage regime can be classified in two categories:

- space charge effect which occurs in static condition. This situation is typical of a static working point, which sits on a resonance and the beam evolution is purely affected by the nonlinear self-consistent behavior of the beam.

- space charge effect in presence of dynamic change of some parameters. In this case the dynamical change, for instance of the tunes, adds an extra complexity as resonance conditions are met dynamically and the self-consistent behavior of the beam is altered.

Space charge effect on Linear coupling

The linear coupling in presence of space charge has been studied in [3]. The study has been performed for static and dynamic conditions. Of particular interest is the study in which the tunes are changed dynamically performing a crossing of the linear coupling resonance. The interest in crossing the linear coupling is in the possibility to exchange beam emittances in a controlled way. The final goal is to develop a strategy to relax the space charge tuneshift constraint. In [3] it has been shown that an adiabatic crossing of the linear coupling from “below” the resonance produces a ”snowplow” effect where the stop-band changes dynamically while the crossing is performed. The final result is that on the linear coupling resonance the two emittances become equal, and in the $x - y$ plane the beam becomes upright (emittance equilibration).

Montague resonance

The 4th order potential created by the space charge is responsible for exciting the resonance $2Q_x + 2Q_y = 0$ [4]. This resonance is very dangerous as it is created directly by the beam even for a perfectly linear lattice. For this reason this resonance should be always avoided. The measurement and theory of the Montague resonance are found in [5, 6].

Space charge induced periodic crossing of a resonance

Here the space charge and the synchrotron motion are responsible for a periodic modulation of the tune. An example of this regime for the SIS18 is found by exciting a 3rd order resonance $3Q_x = 13$ via a single sextupole with $k_2 = 0.1$ m$^{-2}$ and taking $Q_{x0} = 4.35$, and $Q_{z0} = 10^{-3}$. The space charge tuneshift is $\Delta Q_{x,sc} = 0.1$. In Fig.1a the evolution of the single particle emittance $e_x$ of a test particle with initial coordinates $x = 1.5\sigma_x$, and $x' = y = y' = z' = 0$ and $z = 3\sigma_x$ is shown. The space charge forces are modeled by a frozen potential. Note the initial scattering of $e_x$, which stems from an incomplete trapping as the islands are non-adiabatically crossing the particle’s orbit. The scattering is responsible for a nonlinear diffusion of the particle trajectory (see in Fig. 1b the dense accumulation of orbits at small radii). When the diffusion has brought the particle to large amplitudes, the island crosses adiabatically the particle orbit with consequent particle trapping [7]. In Fig. 1a this is visible
in the large jumps of $\epsilon_x$. In Fig. 1b the path of the particle orbit in the Poincaré section is shown: note that the region explored by the test particle is very wide with respect to the rms beam size (the $x$ axis is in units of $\sigma_x$). When a full bunch is simulated, this region becomes populated by a halo (see by comparison purely space charge driven halo as in Ref. [8]). The shadowed region on the right represents an example of a forbidden region, which may arise from the presence of a mechanical aperture limitation in the ring. Due to the scattering/trapping of the invariant, the particle eventually reaches the forbidden area and gets lost. When the maximum amplitude is limited by the dynamic aperture, the beam loss mechanism is essentially the same, with the difference that the interception of the halo with the border of stability creates a chaotic region.

$$\epsilon / \epsilon_0 = 15$$

**Figure 1:** a) Single particle emittance evolution normalized to the initial emittance; b) Poincaré section of one particle.

### The role of the chromaticity

A detailed 2D modeling of the effect of a long-term storage of a high intensity bunch is reported in [9]. An important result is that the halo extension reaches large amplitudes when the bare tune approaches the resonance at $Q_{x\tau} = 13/3$ from above (in this example $Q_{x0} > Q_{x\tau}$ and $Q_{x0} \rightarrow Q_{x\tau}$). When the chromaticity is present (here natural chromaticity) the particle tune is altered by the coupling with the longitudinal plane. Let’s consider the particles in the bunch of given maximum off momentum $\delta p/p$. During the synchrotron oscillations an extra tune modulation is introduced by the chromaticity. If the bare tune is $Q_{x0}$, when a particle is in the center of the bunch ($z = x = 0$), the single particle tune is $Q_x = Q_{x0} \pm \Delta Q_{x,chr} = \Delta Q_{x,sc}$. The +/- sign is related to the loss/gain of momentum during the synchrotron oscillations, and $\Delta Q_{x,chr} = Q_{x0} \delta p/p$ represents the maximum tune variation due to the chromaticity for the particles with maximum off-momentum $\delta p/p$. The effective bare tune resulting from the inclusion of the chromaticity is $\tilde{Q}_x = Q_{x0} - \Delta Q_{x,chr}$. This quantity is affected by the longitudinal position of a particle and if $\tilde{Q}_x$ is below the resonance when $z = 0$, but $Q_x$ at maximum longitudinal particle amplitude is above the resonance, e.g. when $\Delta Q_{x,chr} = 0$, then there exists a longitudinal amplitude $z^\ast$ such that $\tilde{Q}_x$ is on the 3rd order resonance. The situation is then similar to the case without chromaticity but with the bare tune on the resonance. In this case the fixed points are brought to large amplitudes (infinity if the resonance strength approaches zero) as this distance is required to reduce the space charge detuning and keep the particle trapped.

This argument can be applied to all particles in the bunch that have effective "bare tune" $\tilde{Q}_x = Q_{x0} - \Delta Q_{x,chr}$ below the resonance, while $Q_{x0}$ is above the resonance. The number of those particles is a function of $Q_{x0} - Q_{x\tau}$. The overall effect is that the chromaticity leads to a beam loss stop-band as large as the maximum $\Delta Q_{x,chr}$.

### Simulation of the CERN-PS experiment

In the experimental campaigns undertaken at the CERN-PS these high intensity effects have been explored in well-controlled experimental conditions. The main parameters of the measurements are $\Delta Q_x = 0.075$, storage time of $4.5 \times 10^7$ turns. The rms momentum spread of the beam is $\Delta p/p = 1.5 \times 10^{-5}$ (for more information on the experiment see Ref. [2]). Figure 2 summarizes the experimental findings and the simulation results. The green curve shows the simulation results of the beam intensity after 1 second storage. The reproduction of the beam loss (16% maximum beam loss) is still below the measurement (maximum beam loss of 32%), but the role of the chromaticity is important: without it only 8% beam loss appears in the simulations. In these simulations the PS beam pipe (14/7 cm) has been assumed constant throughout the ring. Note also that in the emittance growth regime the simulated horizontal emittance is larger than the measured one. We explain this result in terms of beam loss, in fact in the experiment in the tune range $6.28 < Q_{x0} < 6.3$ beam loss is detected, which will reduce the measured emittance growth (especially close to $Q_{x0} = 6.28$). The still remaining discrepancy of 16% be-
between measured and simulated beam loss may stem also from the lack of self-consistency.

**IMPACT OF SPACE CHARGE IN SIS100**

The issues discussed here should be taken into account for the choice of the SIS100 working point. In Fig. 3 we summarize all these constraints. The choice of the working point \( Q_x = 18.84, Q_y = 18.73 \) is made by taking into account the effect of the Montague stop-band rescaled from the CERN-PS measurements [5]. Also a distance from the integer resonances \( Q_x = 19, Q_y = 19 \) is necessary in order to avoid resistive wall instability problems [10]. The position of the working point right below the Montague stop-band keeps the working point far enough from the half integer resonance \( 2Q_x = 37 \) so that the tune spread does not overlap it. However the effect of the 3rd and 4th order resonances on a long-term storage of a high intensity bunch needs to be evaluated. The modeling of the SIS100 includes the following aperture limiting devices [11]:

- Charge catchers present in each doublet after a dipole;
- Period 1, injection: magnetic septum at injection, Kicker modules;
- Period 2, transfer to SIS300: 2 kickers;
- Period 6, extraction: electrostatic septum, Lambertson septum, magnetic septa.

In the lattice with these insertions the magnet nonlinearities have been modeled by assigning to each dipole and each quadrupole the nonlinear components measured in Ref. [12].

A first consequence of the nonlinear lattice is a reduction of the accepted beam phase space due to the nonlinear motion. The aperture (linear acceptance) shrinks from \( A_x = 97.5 \text{ mm-mrad}, A_y = 39 \text{ mm-mrad}, \) to \( A_x = 78 \text{ mm-mrad}, A_y = 31.2 \text{ mm-mrad} \) for a waterbag beam over \( 10^4 \) turns. Note that for this evaluation we kept the emittance ratio \( \epsilon_x/\epsilon_y \) constant at 2.5.

We make then a preliminary study on the effect of the beam distribution on beam loss. In this study we always keep the maximum tunespread unchanged for each example, to \( \Delta Q_x \sim -0.14, \Delta Q_y \sim -0.25 \), to be able to find an indication of the role of the beam tails. We consider first a bunched beam with transverse waterbag distribution with edge emittance of \( \epsilon_x = 78 \text{ mm-mrad}, \epsilon_y = 31 \text{ mm-mrad} \) as for the previously found acceptance. We remove then the effects due to nonlinear motion created by the lattice nonlinear errors. The rms bunch length has been taken 27 m so that with \( 1.5 \times 10^{11} \) particles the space charge tuneshift is \( \Delta Q_x \sim -0.14, \Delta Q_y \sim -0.25 \). A simulation over \( 10^6 \) turns with a space charge frozen model shows a beam loss of 23% (see Fig. 4). Clearly this amount of beam loss is unacceptable for \( U^{+28} \) because of vacuum-degradation processes related with beam loss-induced gas desorption [13].

This result for the waterbag distribution applied to a large beam scraped at the edge of the acceptance is therefore not an option for the SIS100. Alternatively we considered a transverse Gaussian bunched beam whose emittances are \( \epsilon_x = 35(2\sigma) \text{ mm-mrad}, \epsilon_y = 14(2\sigma) \text{ mm-mrad} \) with rms bunch length of 27 m. The rms beam size is smaller, but tails are not scraped. In order to compare with the previous beam loss, we keep the same space charge tuneshift by lowering the number of particles to \( 0.75 \times 10^{11} \) particles per bunch. The factor 2 in particle density compensates the emittance reduction. We find here a beam loss of 4.5% (Fig. 4).

By taking instead a waterbag transverse beam with edge emittances \( \epsilon_x = 35(2\sigma) \text{ mm-mrad}, \epsilon_y = 14(2\sigma) \text{ mm-} \)
mrad, rms bunch length of 27 m, and with space charge tunespread $\Delta Q_x \sim -0.14$, $\Delta Q_y \sim -0.25$ no beam loss is found. This result stems from the characteristic truncation of a waterbag distribution: the particles are found till the edge of the beam which is at $2\sigma$, whereas for Gaussian beams the particle distribution between 2 and $3\sigma$ has larger amplitudes, where trapping phenomena are more efficient and lead to beam loss faster than for the case of the waterbag. Hence the difference in the result.

This study shows that the role of the tail of the distribution, which is relevant for the collimation system, becomes more complex in presence of space charge induced trapping phenomena.

It should be added that these calculations do not include other effects such as the interaction of trapped particles with beam pipes and aperture restrictions (aperture restrictions are treated as perfect absorbers). In fact, particle dynamics in presence of trapping phenomena leads to slow amplitude growth. The evaluation of the impact of effects as $dE/dx$ and multiple scattering for particles crossing with small angle limiting devices is therefore necessary.

**ESTIMATES OF THE IMPACT OF SELF-CONSISTENCY**

The assumption of using a frozen bunch distribution plays an important role in the beam loss prediction. The inconsistency of the frozen model is evident when beam loss reaches, for instance, 20-30% of the initial intensity at once. Less obvious is the impact of beam loss as dynamical process on the trapping of particles. In order to show the relevance of the self-consistency in the long-term prediction we made a simulation in which we used a constant focusing model of the CERN-PS ring. We reproduced similar conditions as in the experiment. The space charge modeling is taken analytic from an axi-symmetric bunched beam as the 4th resonance acts mainly on the horizontal plane. In Fig. 5 the green dots show the results of the beam loss when the simulation is pushed to $2 \times 10^6$ turns: the chromaticity is included, but the distribution is kept frozen. Note that the maximum beam loss reaches $\sim 21\%$ (in $2 \times 10^6$ turns). The black curve is instead obtained by adding in an artificial way the effect of beam loss on the space charge through the permeance $K$ (the chromaticity remains included), which is then reduced according to the beam loss. Note that the beam loss of the black curve in Fig. 5 is over $4.5 \times 10^5$ turns and near $Q_x = 6.25$ is larger than the experimental findings. This stems from the modeling of the self-consistency. This example shows how relevant the effect of the self-consistency on the beam loss is: combined together with the chromaticity it enhances considerably the beam loss for a very long storage (see Fig. 5 black and green curves). For understanding the shape of the beam loss in Fig. 5 we first attempt to characterize Fig. 2 (for the frozen model). For this purpose we define the parameter $\mathcal{R} = (Q_x - \Delta Q_x)/\Delta Q_x$, which specifies the distance of the resonance rescaled with respect to the tuneshift. The parameter $\mathcal{R}$ may be thought to be a rescaling factor in $Q_x - \Delta Q_x$ in Fig. 2 according to the space charge tunespread of the beam considered. In the frozen model the asymptotic beam loss is mainly depending on $\mathcal{R}$. The bunch space charge tune-spread plays a role mainly in determining the time-scale in which the asymptotic loss is reached. Therefore in a self consistent simulation, while beam loss occurs, the ratio $\mathcal{R} = (Q_x - \Delta Q_x)/\Delta Q_x$ increases. The upper limit reachable is $\mathcal{R} \leq 1$. In fact when $\mathcal{R} > 1$ the tune-spread does not overlap anymore with the resonance, therefore as $\mathcal{R}$ approaches unity beam loss will stop. The integrated effect on beam loss of the change of $\mathcal{R}$ is difficult to assess. In fact, if the change of $\mathcal{R}$, due to beam loss, is too fast then there is not enough time for...
the beam loss associated with each $R$ to buildup: this is shown in Fig. 5 in the range $6.26 < Q_{x0} < 6.28$. There the ”self-consistent” beam loss (black curve) exhibits less beam loss than the measurements (red curve). Vice-versa the maximum loss occurs for $Q_{x0}$ close to the resonance. In this case the asymptotic beam loss is small, consequently $R$ will change value very slowly and there is time for the beam loss associated with each $R$ to accumulate. This is visible in Fig. 5 where for $Q_{x0}$ close to the resonance the maximum beam loss of 45% is found (black curve). The asymmetry of the beam loss vs. $Q_{x0}$ stems from this effects.

**FIRST EXPERIMENTAL EVIDENCE OF ELECTRON CLOUD INDUCED RESONANT PHENOMENA?**

It is well known that when a proton bunch passes through an electron cloud, a pinch of the electrons takes place [14, 15, 16, 17]. In a recent study it has been pointed out that the pinched electron cloud plays the same role as the space charge does for the trapping phenomena [18]. The pinched electrons produce an inverse space charge force responsible for a positive detuning. In addition, the density of the pinched electrons $\rho_{ec}$ is strongly correlated to the position $z$ along the bunch. The $e$-density is characterized by a first peak at 1/4 of oscillation of the electrons in the linear portion of the beam potential, other peaks follow at each 1/2 wavelength with superimposed a gradual increase of the $e$-density from the head to the tail of the bunch, due to the arrival of electrons form larger amplitudes, performing non-linear oscillations [18]. This correlation $z$ vs. $\rho_{ec}$ is kept at every bunch passage through the cloud, and together with the synchrotron motion is responsible for an “electron cloud induced tune modulation”. The type of dynamics for the protons is then similar to a space charge induced tune modulation: when the EC ‘detuning’ crosses a resonance, a periodic crossing occurs and a slow emittance increase is possible. As found for the space charge, when halo particles are lost, a bunch shortening may be expected [9]. In Fig. 6 we show the experimental evidences of this effect. Fig. 6a shows the correlation of bunch length reduction versus beam loss obtained in the CERN-PS experiment with large space charge. [19]. In Fig. 6b we show the equivalent measurement obtained at the CERN-SPS in the presence of an electron cloud. The colored curves refer to different bunches along the bunch train. The colored traces represent the amplitude-length correlations of 7 different bunches sampled along a batch of 72 bunches (as indexed by the key in the upper left corner of the plot). The SPS data were acquired in August 2003 during a coast run lasting about 20 minutes. It is clear that the bunch lifetime degrades along the train, since the trailing bunches exhibit a worse lifetime and shorten more quickly than bunches in the head of the batch. This fact can be considered as a signature of a detrimental effect which is felt differently by bunches at different positions along the bunch train, and affects more the bunches in the tail. The electron cloud builds up and reaches saturation after about 10-20 bunches. The amplitude-length correlations of most of the bunches seem to be the same as they all lie on quasi parallel curves, but the trailing bunches eventually lose more and more. The slopes which appear to differ from the other are those of the first (steeper) and the last bunch (smoother). This can be related to the different bunch positions along the batch or to the different initial bunch lengths with comparable intensities. Electron cloud incoherent emittance blow up could be certainly a good candidate to explain this observation. However, further data analysis on SPS coast runs is still ongoing. The important finding is that both experimental curves (Figs. 6a,b) show qualitatively a similar pattern: the shorter the bunch becomes, the larger is the beam loss. Further experimental and theoretical investigation are needed in order to show that this interpretation is correct.

**Figure 6**: a) Correlation beam intensity vs. bunch shortening in the PS experiment; b) The same correlation for 5 different bunches in a train of 72 bunches in the SPS.
CONCLUSION/OUTLOOK

In this work we discussed the relevant space charge issues for SIS100. We reviewed the present status of the understanding of the space charge induced trapping phenomena. The results of these studies and the tools developed have been applied to the choice of the SIS100 working point. The impact of the high intensity on beam loss have been estimated, with particular reference to the type of beam distribution assumed. All these results are, however, affected by the lack of self-consistency, which has been shown to play an important role in determining long-term beam loss. Finally, a comparison between experimental measurements of space charge and electron cloud induced effects has been presented. This evidence of similarity is not yet conclusive, but seems to support the theoretical basis here discussed. Further experimental and theoretical studies are needed to provide data for code benchmarking, and validate the theoretical understanding. We add that at GSI an experiment (S317) on the long term effect for a high intensity beam is presently being performed and the measurements obtained will help benchmarking the code prediction and understanding of this complex dynamics.

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REFERENCES