LONG TERM SIMULATIONS OF THE SPACE CHARGE INDUCED BEAM LOSS EXPERIMENT IN THE SIS18

G. Franchetti*, O. Chorniy, I. Hofmann, W. Bayer, F. Becker, P. Forck, T. Giacomini, M. Kirk, T. Mohite, C. Omet, A. Parfenova, P. Schütt, GSI, Darmstadt, Germany

Abstract

In this proceeding we present the simulations of the experiment made in the SIS18 synchrotron on the effect of the space charge in a bunched beam stored for one second. The simulations attempt to reproduce 4 sequences of measurements with 4 different types of beams at different intensities using sextupole driven resonances. Our results confirm the conclusions from previous measurements at the CERN-PS using octupoles driven resonances. Some conclusion on the beam physics case are addressed.

INTRODUCTION

An extensive experimental campaign on space charge and resonances has taken place in 2006-2008 on the SIS18 synchrotron at GSI. The purpose of this study was to provide experimental data for code benchmarking and to investigate experimentally the basic beam loss and emittance increase mechanism acting on a beam during long term storage. The beam dynamics mechanism is believed to be trapping or scattering [1, 2, 3]. While these effects were subject of early investigations mainly as single particle effects, only recently it has been proposed that incoherent space charge can drive a periodic resonance crossing in a bunch [4]. In order to disentangle the effect of the synchrotron motion from that of the space charge, we have performed 4 separated set of measurements characterized by the presence or absence of high intensity as well as of the synchrotron motion. First results of these measurements were presented in HB2008 [5]. Here we present the full campaign and the associated simulation results. The details on the experimental campaign, the parameters characterizing the beam and a more detailed discussion on the simulations are documented in the extensive paper Ref. [6]. The necessity of consolidating the beam loss prediction is very important for the SIS100 synchrotron and its magnet field quality requirement [7, 8]. Uncontrolled beam loss is required to be within a 5% budget in order to mitigate a progressive vacuum degradation, dangerous for beam lifetime. Therefore the mechanism studied here plays an important role for the discussion on the nonlinear components in magnets, residual closed orbit distortion as well as in the resonance compensation strategy.

* g.franchetti@gsi.de

EXPERIMENTAL RESULTS AND SIMULATIONS

Low Intensity Coasting Beams

The experimental campaign consisted in measuring the time evolution of a well controlled bunched beam for several tunes taken in the neighborhood of the resonance $3Q_x = 13$. The beam used is composed of $^{40}\mathrm{A}^{18+}$ with KV emittances at injection of $\epsilon_x = 19$ mm-mrad, $\epsilon_y = 14$ mm-mrad. The injection energy is of 11.28 MeV/u. In order to be able observe a beam distribution broadening, a beam smaller than the SIS18 acceptances ($A_x \simeq 200$ mm-mrad, $A_y \simeq 50$ mm-mrad) was created. Transverse beam profiles are measured with the intra-beam profile monitor (IPM) [9], while the longitudinal profile is measured with a beam position monitor. The operational condition of the full campaign have been set so to compensate the natural chromaticity in order to study only the pure space charge driven effects. The third order resonance in this experiment is already excited by natural errors, which are not known by previous measurements. We have used data on beam loss in order to construct a model of the nonlinear lattice of SIS18. In Fig. 1a we show a tune scan of the beam response after 1 second storage, the curves show the emittance ratio and the beam survival. Around the third order resonance beam loss becomes substantial because of the reduction of the separatrix [10]. The pattern of beam loss and the beam loss stop band can be modeled when the resonance is driven by one localized sextupolar error, which we assume as the source of the resonant dynamics. By monitoring the beam loss a stop-band of $\Delta Q_x \simeq 0.12$ due to the 3rd order resonance $3Q_x = 13$ was found. The titled shape of the beam loss curve around the third order resonance is created by some extra detuning made by the chromatic correction sextupoles and other high oder nonlinearities. From the simplified model we find that the presence of only the chromatic correction sextupoles creates a too strong effect on the simulated tilting of the beam loss curve. Hence we have included and properly excited an octupolar error in the same location of the sextupolar error. The location of these two nonlinear components has been taken arbitrary as we do not posses more information on the machine nonlinearities and their location. However, with this model, we simulated the experiment with results shown in Fig. 1b. Note in both pictures Figs. 1a,b the error-bars, which are estimated as described in Ref. [6]. The large error-bars in Fig. 1a are the results of beam fluctuation typical of low intensity. The error-bars in Fig. 1b are originated by the

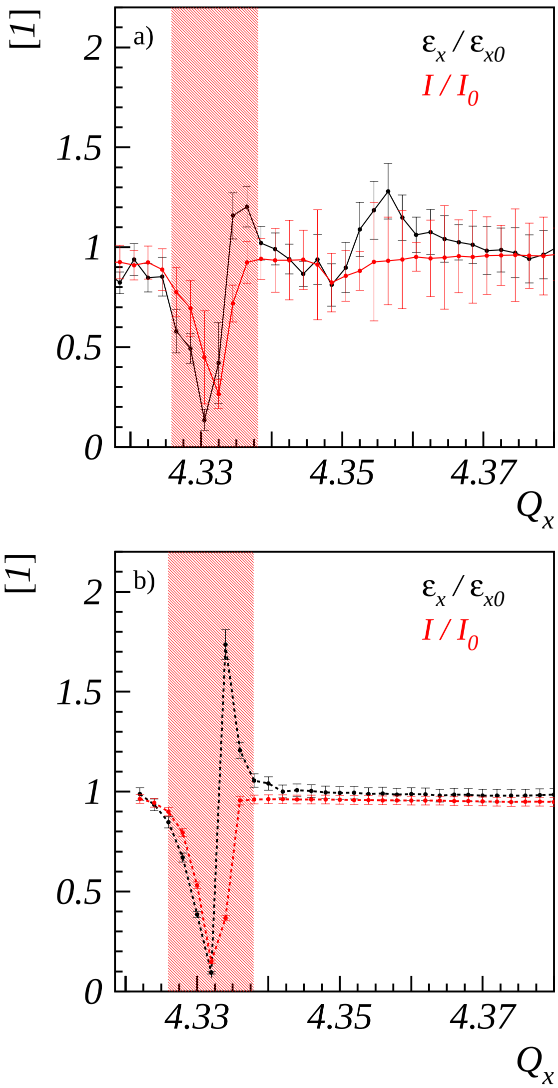

Figure 1: Emittance growth and beam survival after 1 second storage. In picture a) the experimental results are shown as function of working points around the third order resonance. In picture b) are shown the corresponding simulations. These results are obtained for the low intensity coasting beam.

limited number of macro-particles used in the simulations (2000 macroparticles, see in Ref. [6]). In spite of the coarse modeling, we obtain a decent reproduction of the measurements. Note that the emittance growth at $Q_x \simeq 4.36$ is not found in the simulation as result of the incomplete modeling of the nonlinearities, which we have been set only to reproduce the third order resonance $3Q_x = 13$ beam loss.

High Intensity Coasting Beams

After the measurement of the low intensity coasting beam we increased the intensity and again investigated the beam response. The experimental procedure to rise the intensity was made via changing the beam current from the UNILAC avoiding so to affect the beam size. We should mention here that the Linac-Synchrotron injection scheme based on the "multi-turn injection" is affected by the change of the horizontal tune Q_x. On our range of tunes explored, the variation of the beam intensity is found $\sim \pm 15\%$. The experimental results are shown in Fig. 2a and the correspondent simulations in Fig. 2b. We note that the minimum of the beam survival shifts on the left because of the effect of the space charge. We estimate the peak incoherent tune-shift as $\Delta Q_{x/y} = -0.025/-0.03$. These measurements show that the high intensity diminishes the beam loss, the same result is found in the simulations. For this particular resonance this is due to the detuning of the space charge, which brings particles out of the resonance when the bare tune is set on the resonance. In this measurement the region of emittance growth is a little larger with respect to Fig. 1b. A detailed analysis of the position

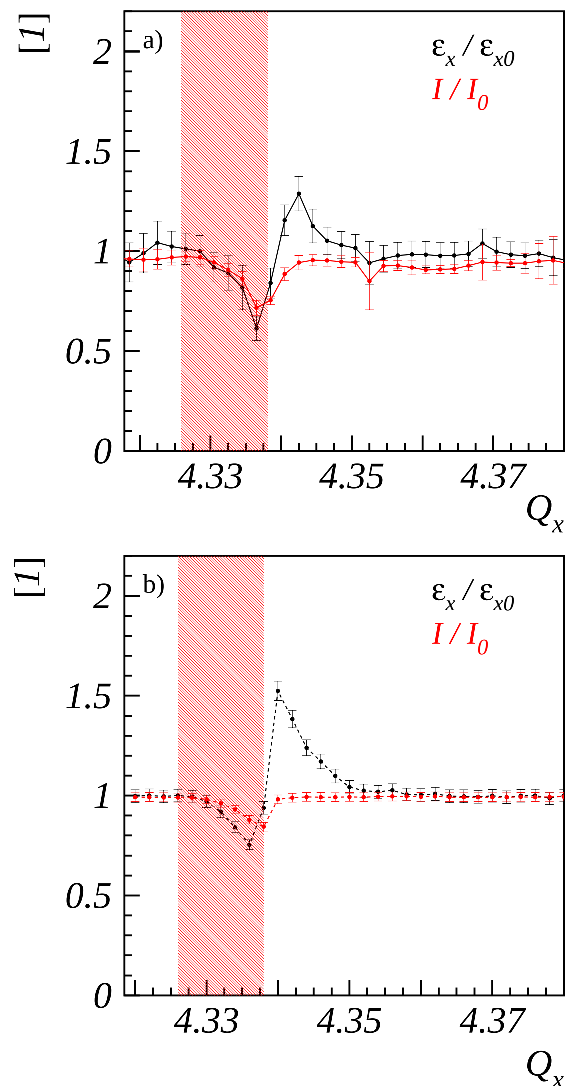

Figure 2: The pictures shown here are the correspondent of Fig. 1a,b but now for a high intensity coasting beam. The peak tune-shift is $\Delta Q_{x/y} = -0.025/-0.03$.

of the transverse third order islands reveals that their outer position is controlled by space charge and the machine bare tune: The islands at $Q_x = 4.34$ are located at the outer position, but still touching the tail of the beam, hence the large emittance increase. At the tune $Q_x = 4.35$ the location of the islands is completely inside the beam, hence the emittance growth practically disappears.

Low Intensity Bunched Beam

The longitudinal focusing necessarily creates an oscillation of the longitudinal particle momentum. After injection the beam is left to coast for 100 ms as prior to being bunched in 10 ms with a final RF voltage of 4 kV. This bunch, characterized by a bunching factor $B_F \simeq 0.335$ and $(\delta p/p)_{rms} = 1.3 \times 10^{-3}$, is stored for 0.9 seconds, then adiabatically de-bunched in 100 ms (before a final bunching with acceleration and extraction). In ideal conditions, the single particle off-momentum should not play any role once the machine has chromaticity compensated. Only the dispersion affects the beam sizes according to the bunch length and RF voltage. We proceeded with our systematics by repeating the tune scan as made for the other two types of beam. The results and simulations are shown in Fig. 3a,b. In these measurements we also included the monitoring of the longitudinal distribution and in Fig. 3a this is shown with the rms bunch length (green curve). The results show that no relevant effect occurs to the beam loss and emittance ratio. A slight enlargement of the beam loss stop band takes place, and the maximum beam loss decreases. Some effect on the bunch length is detected in a form of shortening. Our simulations retrieve a similar effect, the maximum beam loss are mitigated, while on the left of the stop band an emittance growth, consistent with our modeling (Fig. 1b) is still found. The main finding of this measurement is that some residual chromaticity mildly affect the beam loss stop-band, and also that the chromaticity does not enlarge significantly the beam size.

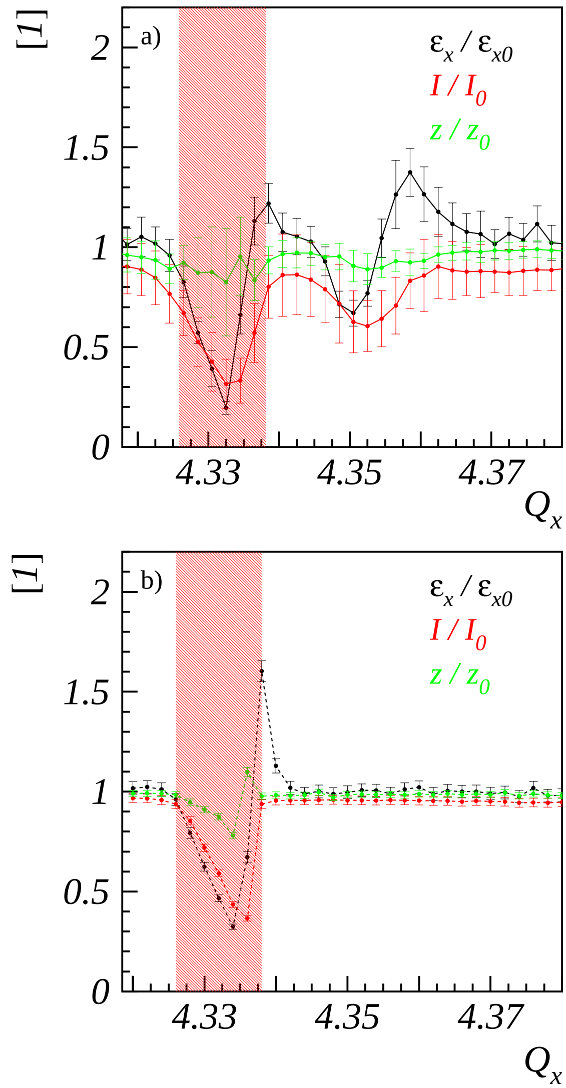

Figure 3: Low intensity bunched beam. a) measurements, b) simulations. We plot in both pictures also the change in bunch length (green curve).

High Intensity Bunched Beam

The average peak space charge tune-shift directly measured from the IPM data yields $\Delta Q_x \simeq -0.04$, and $\Delta Q_y \simeq -0.06$. In Fig. 4a we show the experimental finding. We find as in the CERN-PS experiment (Fig. 4c solid lines) that a region of beam loss (red curve) is located on the right side of the resonance [4]. In absence of beam loss ($Q_x \sim 4.3425$) an emittance growth is observed (Fig. 4a black curve): This result is consistent with trapping/scattering regimes discussed in Ref. [11]. The green curve shows the relative bunch length, which becomes shorter close to the maximum beam loss at $Q_x = 4.3365$. In Fig. 4b is shown the simulation of the measurements presented in Fig. 4a. Note that beam loss is reproduced with acceptable accuracy, but differs by a factor of 2 at $Q_x = 4.3365$. The peak of beam loss is located on the left side of the low intensity stop-band. Note that above the resonance, in absence of beam loss, both measurement and simulation exhibit maximum of emittance increase. On the other side of the single particle stop-band at $Q_x = 4.375$ no bunch shortening or beam loss is observed. The correlation beam loss / bunch shrinkage shown in Fig. 4a was already observed in the CERN-PS experiment [11], but only for a few bunch profiles. Here it is confirmed for the full storage time and it is consistent with the interpretation that particles with large synchrotron amplitude are lost because they are trapped/scattered into the stable islands [11]. In absence of beam loss ($Q_x \sim 4.3425$) an emittance growth without bunch shrinking is observed (Fig. 4a black and green curves).

DISCUSSION/OUTLOOK

In this experiment we have studied the interplay between the high intensity of a bunched beam and the presence of

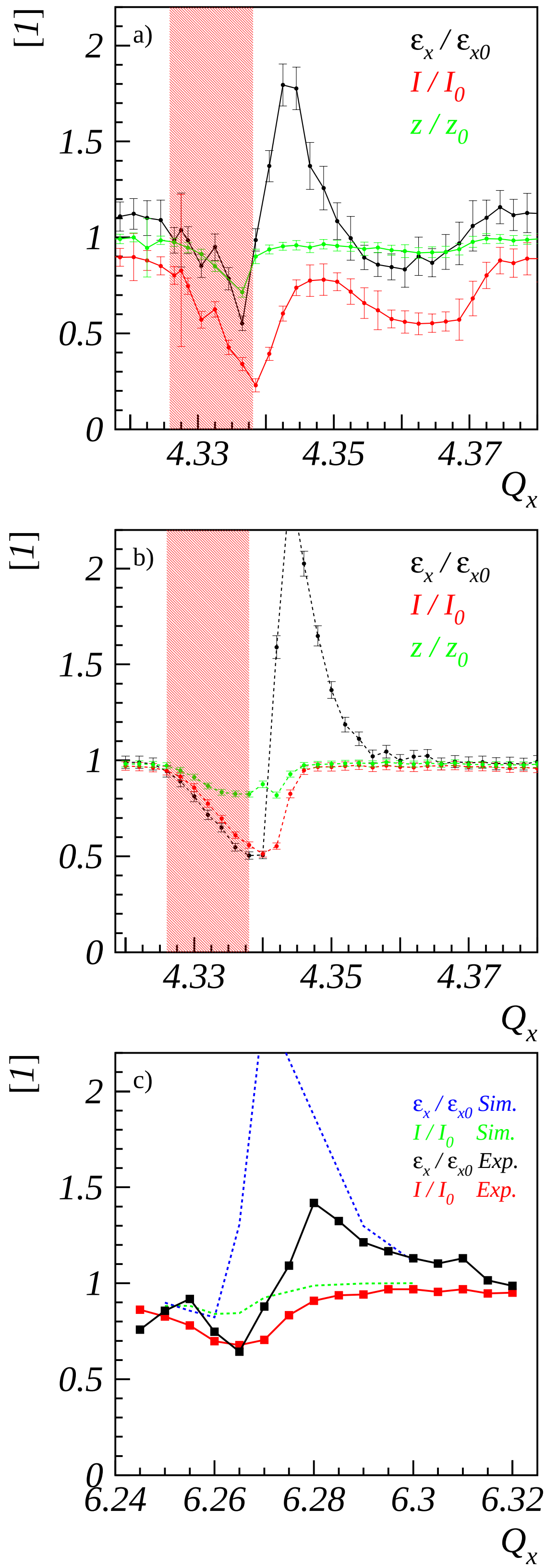

Figure 4: High intensity bunched beam. a) Transverse-longitudinal beam response to the long term storage as function of working points around the third order resonance; b) Simulation of picture a); c) Result of CERN-PS measurements, and in dashed lines simulation result on modeling (case where chromaticity is included).

the 3rd order resonance.

The nonlinear dynamics is in this case different from that one of the CERN-PS experiment. The octupole induced 4th order resonance is always stable, even for very weak space charge, which is not the case for a sextupole resonance for which at low intensity the three stable fixed points can be found at very large amplitudes. Nonetheless we retrieve similar features of emittance growth and beam loss in both cases. In spite of the different resonances, space charge tune-shift, beam emittances and storage time, our retrieving of similar patterns in the beam response allows us to interpret on a solid base that in both experiments the underlying beam physics is the same. Clearly in both experiments the lack of complete knowledge of the experimental conditions is still a source of the differences found with the simulations.

Our work also allows to conclude on an experimental basis that only the simultaneous presence of high intensity and synchrotron motion and a resonance (Fig. 4a) is responsible of the long term emittance growth and beam loss. All other cases (Fig. 1a, Fig. 2a, Fig. 3a) do not exhibit the same beam pattern. The simulations of the measurements for the 4 types of bunches provides good agreement considering the complexity of the beam dynamics under study. While the emittance growth prediction is relatively close to the measured data, the beam loss shows a gap between simulations and experiment which can be up to a factor of 2 for cases of maximum beam loss.

These differences might be partly due to self consistency effects, but further theoretical/numerical studies are necessary to support this interpretation.

We thank the support of O. Boine-Frankenheim, P. Spiller, and all the S317 collaboration.

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