HIGH INTENSITY BENCHMARKING STUDIES IN THE SIS18 SYNCHROTRON

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

Abstract

The prediction of beam loss for long term storage of a high intensity beam is a challenging task essential for the SIS100 design. On this ground an experimental campaign using a high intensity beam has been performed at GSI on the SIS18 synchrotron with the purpose of extending a previous benchmarking experiment made at the CERN-PS in the years 2002-2003. We report here the results of this experimental campaign and the benchmarking with the simulation predictions.

INTRODUCTION

The necessity to store high intensity bunches for many synchrotron oscillations has become of interest with the advent of projects as the FAIR project and for synchrotrons as the SIS100 [1]. The combined effect of space charge and synchrotron motion during the long term storage in presence of lattice nonlinearities creates a new challenge on beam dynamics. The key concept into this dynamics is in the tune modulation created by the synchrotron motion and the longitudinal bunch shape. This notion is possible because the longitudinal motion is much slower than the transverse one. The dynamics with the tune modulated becomes particularly interesting when the tune modulation pushes a bunch particle through a transverse resonance creating a periodic resonance crossing. This circumstance is almost certain when the incoherent space charge tune-shift reaches peak values as $\Delta Q_x > 0.25$. During resonance crossing a particle can be "trapped" into the resonance as was shown in Ref. [2] for the case of purely lattice driven resonance. However, the condition of complete trapping does not occur in an accelerator during standard operation because the crossing speed is relatively fast for fulfilling the trapping condition. When a particle is not trapped into a resonance, it is necessarily "scattered" [3, 4] and this is the dominant regime when a resonance is periodically crossed due to synchrotron motion. During the long term storage a repeated resonance crossing originates a multiple scattering into resonances and the bunched beam is subject to a long term diffusional regime [5]. The presence of space charge characterizes this regime creating an amplitude dependent detuning of "inverse" nature with respect to the lattice nonlinearity type. The resonance crossing is a subject already studied in Ref. [2], but only for resonances created by lattice nonlinear elements as sextupoles and octupoles. In Ref. [4] the possibility of space charge driven resonance crossing has been suggested. Later studies focused on beam loss and emittance growth for SIS100 scenario parameters. In 2002-2003 within a CERN-GSI collaboration, for the first time, the long term effect of a high intensity bunch was experimentally studied in the CERN-PS synchrotron. The results of that experiment were analyzed and presented in Ref. [6]. The experiment was performed by exciting a 4th order resonance with a controlled octupole, in an otherwise resonance free region in the tune space. A bunch was injected in the PS synchrotron with a bunch to bucket transfer from the PS booster to the PS and stored for 4.5×10^5 turns. The 4th order resonance was then excited, and by using a flying wire the time evolution was assessed by repeating the measurements while changing the trigger time. Several working points were studied in a scan and the main finding was that the beam loss is located immediately on the right of the resonance, and further right an emittance growth regime with a peak emittance growth of $\sim 45\%$ was found. These results could be interpreted into a frame of a theory of periodic resonance crossing induced by space charge and synchrotron motion. Following the CERN-PS experiment, an effort to simulate those measurements took place, whose results are reported in Ref. [7]. The simulations could not at first reproduce properly the beam loss found in the experiment. Only after further studies [8] it was found that the chromaticity plays an essential role into determining the beam loss stop-band. Simulations including the chromaticity in the PS synchrotron modeling brought the beam loss prediction closer to the observed value, but still 50% less than the measured value. In spite of the simulation of the CERN-PS experiment showing acceptable agreement, there was no further experimental confirmation of these high intensity effects. Moreover, the results of the CERN-PS experiment did not explore the nature of the underlying mechanisms creating beam loss or emittance growth, which the theory identified as the trapping/scattering space charge driven effects. To fill this gap in GSI in the years 2006-2008 an extensive experimental campaign took place on the SIS18 synchrotron to further study the long term effects in a high intensity bunch. The particular feature of the SIS18 have put some constraint on the choice of the lattice resonance used in these studies. The experimental investigation made extensive use of all diagnostic equipments available. For every beam "shot" transverse and longitudinal profiles were stored for further analysis. We present here the main findings of the GSI campaign and compare them with the CERN-PS results. The interest in these studies is mainly to benchmark the understanding and the code capability of

* g.franchetti@gsi.de

predicting beam loss and emittance increase in long term storage as is foreseen in the main scenario for the SIS100 synchrotron part of the FAIR project [1].

THE EXPERIMENT

The study of the high intensity effects on a resonance requires the excitation of a controlled resonance and the preparation of a high quality beam, together with the analysis of the transverse and longitudinal profile with time. Transverse profiles are measured with the intra-beam profile monitor (IPM) [9], while the longitudinal profile is measured with a beam position monitor. An experimental campaign on SIS18 performed in 2004 (see Ref. [10]) provided the resonance diagram shown in Fig. 1 by scanning tunes across the tune plane and measuring beam loss (see scale for relative loss, no loss blue). Several 2nd and 3rd order resonances are excited by machine errors. The

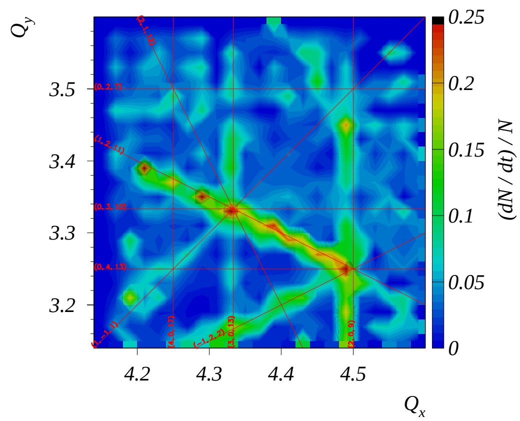

Figure 1: SIS18 measured beam loss as function of tunes.

synchrotron is equipped with only sextupoles for chromatic corrections and in order to perform a study of the interplay of space charge with lattice resonances, we select a natural resonance which is not too strong and allows sufficient free space for space charge tune-shift. The resonance for the slow extraction is a good candidate. In fact, in the SIS18 a system of 12 sextupoles is used to control the chromaticity and simultaneously the strength of the 3rd order resonance $3Q_x = 13$, which is routinely used for slow extraction. In the experimental campaign an ion beam of $^{40}A^{18+}$ was used. The beam emittances measured at the exit of the UNILAC are $\epsilon_x = 6.58$ mm-mrad, $\epsilon_y = 3.49$ mm-mrad, for a beam intensity of $I_U = 0.8$ mA. The injection energy in the SIS18 is 11.35 MeV/u. For the purpose of observing a high intensity driven beam blow-up, a beam smaller than the SIS18 acceptances ($A_x \simeq 200$ mm-mrad, $A_y \simeq 50$ mm-mrad) was created. This was reached by injecting beam in SIS18 for 10 μs, which for a revolution time of 4.6 μs, corresponds to 2.13 turns for a total of 2.1×10^9 ions in SIS18. However, because of the efficiency of the multi-turn injection, the number of particles stored in the SIS18 did not exceed 1.5×10^9. After injection the beam is stored for $\simeq 1$ second at injection energy, equivalent to $\sim 2 \times 10^5$ turns, and then accelerated for extraction. During storage the beam emittances are retrieved from the beam profiles measured with IPM [9]. By using the beta functions at the position of the IPM, $\beta_x = 6.28$ m, $\beta_y = 7.8$ m, and the measured beam distribution, the transverse rms emittances can be calculated. The possibility of creating beams of equal size at several intensities is important for proof of principle measurements. In order to keep the same initial profile at injection in SIS18, the intensity was changed directly via the UNILAC. However, the Linac-Synchrotron injection scheme based on the "multi-turn injection" is affected by the change of the horizontal tune Q_x. This drawback cannot be avoided, and makes a difference with respect to the CERN-PS experiment, were the bunch to bucket transfer kept the intensity virtually independent from the machine tunes.

GSI-SIS18 RESULTS AND COMPARISON WITH CERN-PS RESULTS

As the resonances measured in Fig. 1 were obtained without including the sextupoles for chromatic correction, the effective stop-band in this experiment resulted from the combined effect of natural errors and sextupoles. In order to assess the strength of this resonance, a tune scan was performed by using a coasting beam at low intensity. 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. These results were used to tune the nonlinear model of the SIS18. 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 $B_F = 0.37$ and $(\delta p/p)_{rms} = 1.3\times10^{-3}$, is stored for 0.9 seconds, then adiabatically de-bunched in 100 ms (before a final bunching with acceleration and extraction). Under this operational scheme we explored the beam response as a function of Q_x. 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. 2a we show the experimental finding. We find as in the CERN-PS experiment (Fig. 2c solid lines) that a region of beam loss (red curve) is located on the right side of the resonance. In absence of beam loss ($Q_x \sim 4.3425$) an emittance growth is observed (Fig. 2a black curve): this result is consistent with trapping/scattering regimes discussed in [8]. The red stripe marks the position of the beam loss stop-band measured with the low intensity coasting beam. The green curve shows the relative bunch length measured with a Gaussian fit, which becomes shorter closer to the maximum beam loss at $Q_x = 4.3365$. In Fig. 2b is shown the simulation of the measurements presented in Fig. 2a. Note that beam loss is reproduced with acceptable accuracy. The peak of beam loss is located on the left side of the low intensity stop-band. Note that out 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. 2a was already observed in the CERN-PS experiment [8], 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 [8]. In absence of beam loss ($Q_x \sim 4.3425$) an emittance growth without bunch shrinking is observed (Fig. 2a 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 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.

The consequences of the trapping/scattering theory for high intensity beams, here corroborated by two distinct experiments on different synchrotrons, are of relevance for applications. For example, a proper shaping of the longitudinal bunch distribution via an adequate RF scheme may be used to mitigate the damaging effect of the diffusional regime arising during long term storage. The benchmarking of this consequence is part of another experimental campaign still in progress in GSI.

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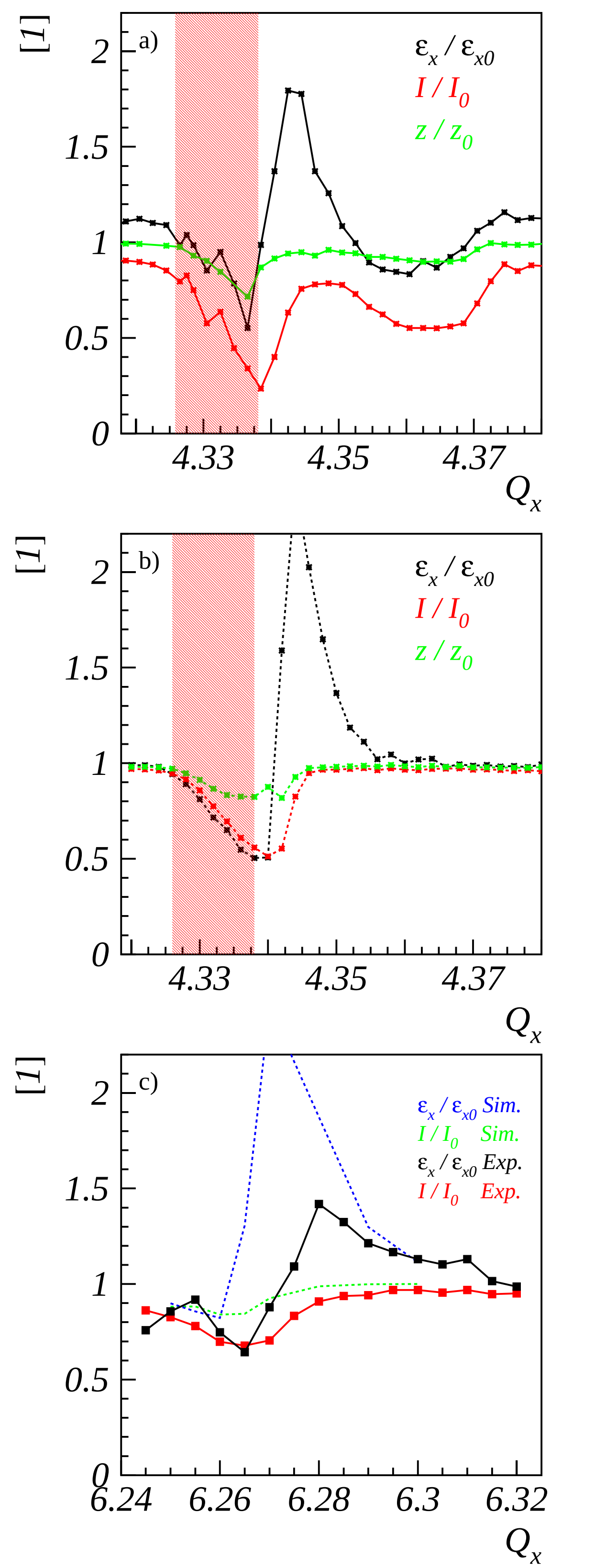

Figure 2: a) Transverse-longitudinal beam response to the long term storage as function of working points around the third order resonance; b) Simulation of picture a). c) Result of CERN-PS measurements, and in dashed lines simulation result on modeling (case where chromaticity is included).