A benchmarking experiment in SIS18 for dynamic aperture induced beam loss

G. Franchetti, B. Franczak, and P. Schütt

GSI Darmstadt, D-64291 Darmstadt, Germany

May 10, 2004

1 Introduction

For SIS18 standard operation as well for the choice of new working points it is important to carry out a systematic investigation of the lattice nonlinear resonances. The previous knowledge of intrinsic measured lattice nonlinear components can be integrated into a computer code and beam loss can be predicted. However beam loss prediction is critic [1, 2, 3, 4] and a benchmark against experiment is the only way to establish how good the modeling of the SIS18 nonlinear lattice is (here it is assumed that the modeling of the nonlinear dynamics is correct). This kind of benchmark will provide the insight and experience for simulating dynamic aperture induced beam loss in the future ring SIS100 [5].

1.1 Beam loss induced by lattice nonlinearities

It is well known that the trajectory of a particle is completely determined by its initial coordinates. In a linear ring the motion is always stable: particle amplitude oscillation is always confined. All the particle initial conditions will always produce confined trajectories. The situation changes dramatically when nonlinear components are present in the ring : not all the initial conditions will produce stable motion. Unstable motion will lead to the particles eventually hitting the walls of the vacuum chamber. A motion unstable will make the particle be extracted from the ring. The domain of stable conditions is a volume in the 4D phase space (non necessarily connected). Once a beam is injected all particles whose initial coordinates are not in the stable domain will be eventually lost. However particles which are "far" from the stable area are lost quickly, whereas a particle in the vicinity of the border of the stable area takes longer to be lost.

1.2 Dynamic aperture and resonances

When nonlinearities are present they create a stability domain who's extent is called the dynamic aperture. This domain of stability is however strongly affected by the machine working point. In the perturbative theory nonlinearities are the driving terms for possible resonant behavior of a single particle. The resonance condition is identified by the relation $n_x q_x + n_y q_y = N$. However: when the particle amplitude becomes large, the conditions under which the perturbative theory applies are violated. Consequently single particle resonances predicted by perturbative theory "cannot" a priori be transported to the level of dynamic aperture. Nevertheless we call here a local reduction of the dynamic aperture, a "resonance".

1.3 Beam loss crossing a resonance

When the lattice tune is on a resonance, the dynamic aperture shrinks. If a beam is injected in a lattice with tunes away from a resonance beam loss won't occur. If then tunes are dynamically changed during beam storage so as to cross a resonance, during the crossing the part of the phase space which was stable becomes then unstable. Particles which find themselves to be far out of the stability domain will be lost. However, this process is also affected by the speed of crossing. If the crossing is very slow, all the particles that will be found out of the stability domain will be lost. In this case the crossing will "scrape off" the beam to the size of the dynamic aperture. When the crossing is performed fast, the particles which are found in the stochastic region will not have enough time to diffuse into highly nonlinear regions. Therefore while the crossing proceeds their amplitudes will remain limited long enough to allow them to be swallowed again into the stable area. The fast crossing will cause less beam loss.

2 The experiment

With these basic ideas an experiment in the SIS18 has been performed using $^{40}Ar^{10+}$ at 11.39 MeV/u. The measurements have been made the evening of 10/3/2004.

2.1 Beam loss in the high intensity tunespread

In Fig. 1a) we show the measured beam intensity while crossing the line in the working point diagram from $(4.23, 3.6) \to (4.05, 3.15)$. Here we write (q_x, q_y) for denoting the horizontal and vertical tune. This tune scan is practically

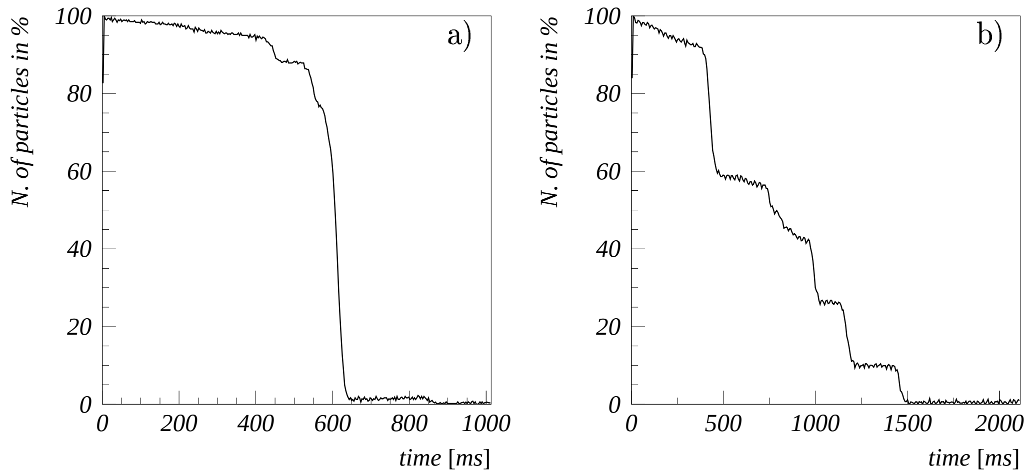

Figure 1: a) beam intensity for the crossing $(4.23, 3.6) \to (4.05, 3.15)$; b) beam intensity for the crossing $(4.1, 3.15) \to (4.23, 3.6)$.

made over the space charge induced tunespread foreseen for the high intensity working point [6]. The measured data are characterized by an initial time offset of about 300 ms: before it the machine tunes do not change. Note that the beam is completely lost after $\sim$ 600 ms. This instant corresponds to the tune $q_x = 4.2, q_y = 3.51$. Since the beam has been completely scraped by the resonance induced instability, there is no beam left in order to detect beam loss induced by resonances which may exist below $2q_y = 7$. In order to detect these resonances we performed the inverse crossing $(4.1, 3.15) \to$

(4.23, 3.6). Note the initially slightly rightwards shifted horizontal tune in order to eliminate the otherwise detected beam loss at injection. The beam intensity of this measurement versus time is shown in Fig. 1b): note the step-structure in the measured beam loss. The beam is completely lost by about 1500 ms. At this time correspond the tunes of $q_x = 4.2, q_y = 3.49$. We infer consequently that the beam loss at 600 ms in Fig. 1a) and at 1500 ms in Fig. 1b) is caused by the half integer resonance $2q_y = 7$. In spite of this accordance among the two cases for the total loss of the beam at $q_y = 3.5$ we did not prove the existence of a resonance **"line"** at $2q_y = 7$. Moreover all the beam loss steps detected in Fig. 1b) remain unidentified.

2.2 Systematic resonance crossing

In order to prove that beam loss follows a resonance pattern characterized by the general relation $n_x q_x + n_y q_y = N$ we repeated the previous crossing and beam intensity measurements keeping unchanged the slope of the crossing line, but shifting it horizontally. A sketch of these measurements is shown in Fig. 2a). In red are shown the tune scan performed. In Fig. 2b) we show all these beam intensity measurements in a waterfall-like picture. The top curve in Fig. 2b) is relative to the first crossing in the left of Fig. 2a). The second curve is arbitrarily shifted down by 15 units and so on following the same order. In green color in Fig. 2 is plot the crossing and beam loss discussed in Sect. 2.1. In all these curves the initial time offset of 300 ms has been removed. Note that all these crossings are parallel, so when beam loss is due to a horizontal resonance line the corresponding beam loss should appear at the same time for all these intensity curves. This is actually the case for the beam loss measured at t=1200 ms. Fig. 2b) shows actually that the resonance line $2q_y = 7$ exits. We can also see that beam loss moves when considering the curves from top to bottom. This suggests that beam loss are actually following a tilted resonance line: when the line is with positive slope (difference resonance) it is expected to see that the correspondent beam loss moves towards the right (going from top to bottom). The inverse is true for a sum resonance. A first inspection of Fig. 2b) reveals two difference and one sum. Other beam losses do not reveal a clear pattern.

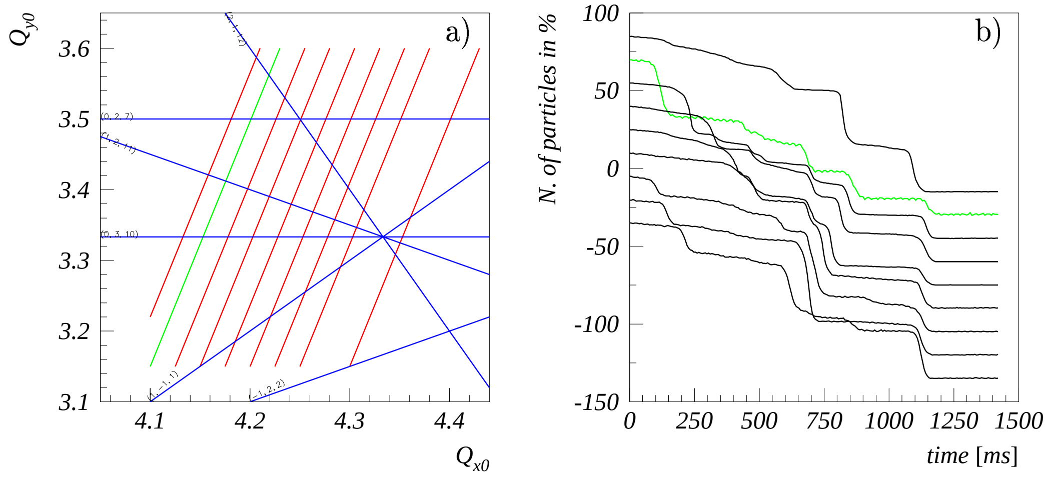

Figure 2: a) sketch of the tune line measurements; b) waterfall picture of all the beam intensity measured for the crossing described in a). In green color is plot the crossing and beam loss discussed in Sect. 2.1.

2.3 Resonances in the tune diagram

An improved picture of the SIS18 resonance web is obtained associating to the beam loss the tunes when the loss occurs. We use the following method: we compute the numerical derivative of the TRAFO data so that a beam loss appears as large negative peak. Then taking into account the initial measurement delay with respect to the tune ramp and the end time of the tune ramp, by using linear interpolation we associate the tunes where the spike in the derivative appears (beam loss). In order to automate this procedure we give a threshold for determining whether a spike is imputable to a real loss or is just a fluctuation: we consider a spike to be from a real loss when its value is beyond 1.5 the variance of all the derivatives obtained for that crossing. The collection of all the tunes in which beam loss occurs is shown in Fig. 3. This picture shows a clear pattern of resonance lines. Here it has to be mentioned that in previous measurements [7] the systematic error in tuning SIS18 with SISMODI has been established. These systematic errors are reported in Table 1. We see that the measured third order line $3q_y = 10$ appears consistently shifted upwards according to Table 1. The

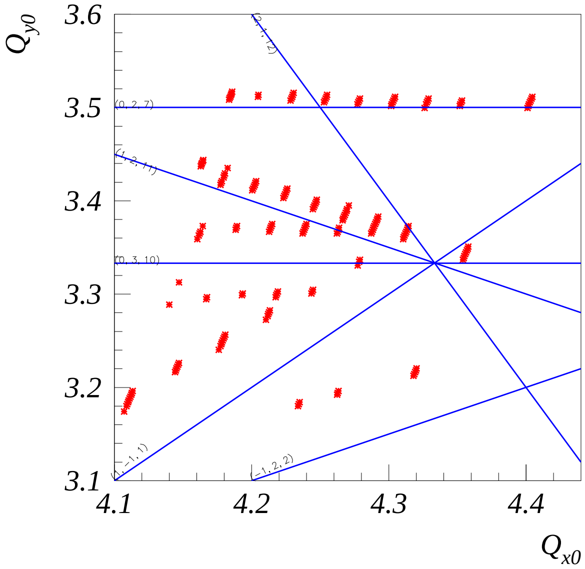

Figure 3: Measured resonance web in SIS18. The marks correspond to beam loss in during a resonance crossing.

same happens for the half integer resonance $2q_y = 7$. We conclude from Fig. 3 that 6 resonance lines are detected. Three of them are identified as $2q_y = 7, q_x + 2q_y = 11$, and $3q_y = 10$. The other 3 lines are distinctly visible but there is not enough data for their identification. It is also interesting to note that the systematic resonance $2q_x + q_y = 12$ was not detected. This maybe be attributed to a small beam (already eroded by previously crossed resonances). The detection of this resonance require a crossing scan where the initial vertical working point is shifted above $q_x + 2q_y = 11$.

Table 1: Systematic errors setting the tune with SISMODI [7]

q_x	q_y	Δq_x	Δq_y
4.2	3.4	-0.010	-0.03
4.2	3.1	-0.015	-0.01
4.15	3.3	-0.015	-0.035

2.4 A proof of principle

We also checked the effect of the speed of crossing on the beam loss. We considered the crossing $(4.125, 3.150) \to (4.255, 3.6)$. The crossing through these two working points has been performed with two different velocities. In Fig. 4 we plot these results. In black is plotted the crossing in 1578 ms, in red the crossing was performed in 5354 ms. It is visible that resonance induced beam loss appears at reasonably equal instants in the two curves. As expected the slower crossing allows more time for the beam to be eroded by the unstable phase space. Consequently the red curve is always below the black.

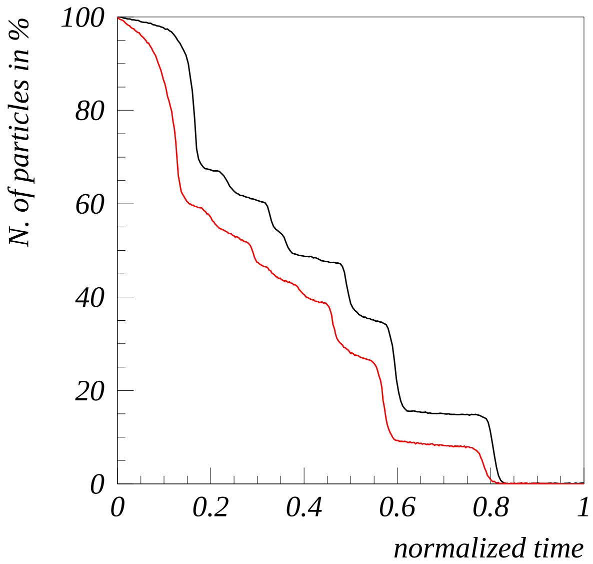

Figure 4: Beam loss versus speed of crossing. Black curve: crossing in 1578 ms; red in 5354 ms.

3 Conclusion and Outlook

With this experiment we have established an efficient measurement technique which allows a systematic exploration of the SIS18 resonance web. Three resonances have been recognized, and other three have to be identified. The relative simplicity of the technique allows a quest for SIS18 resonances. The tune scan from $q_x \simeq 4, q_y \simeq 3$ to the foreseen high intensity working point $q_x = 4.23, q_y = 3.6$ showed the existence of 6 resonances. It is therefore foreseeable that the issues concerning the interplay of space charge and lattice nonlinearities [8] will become relevant.

References

[1] J. P. Koutchouk, 2 (1999), iEEE Particle Accelerator Conference (PAC 99), New York, NY, 29 Mar - 2 Apr 1999.

[2] W. Fischer, M. Giovannozzi, and F. Schmidt, Phys. Rev. E **55**, 3507 (1997).

[3] F. Zimmermann, Part. Accel. **49**, 67 (1995).

[4] A. Chao *et al.*, Phys. Rev. Lett. **61**, 2752 (1988).

[5] C. D. R. http://www.gsi.de/GSI Future/cdr/.

[6] R. Baer *et al.*, 499 (1998), 6th European Particle Accelerator Conference (EPAC 98), Stockholm, Sweden, 22-26 Jun 1998.

[7] K. Blasche, private Communication.

[8] G. Franchetti *et al.*, Phys. Rev. ST Accel. Beams **6**, 124201 (2003).