CONSIDERATIONS FOR THE HIGH INTENSITY WORKING POINT OF THE SIS100*

G. Franchetti†, O. Boine-Frankenheim, I. Hofmann, V. Kornilov, P. Spiller, J. Stadlmann
GSI, Darmstadt, Germany

Abstract

In the FAIR project the SIS100 synchrotron is foreseen to store a high-intensity beam of a size occupying a large fraction of the beam pipe. The challenging beam loss control requires a careful account of the beam loss mechanisms and how to avoid/compensate them: single particle resonances, space charge effects and beam and vacuum instabilities are the main issues of concern. We discuss the status of work leading to the present choice of the SIS100 working points.

THE SIS100 SYNCHROTRON

In the FAIR project [1] the SIS100 synchrotron [2] is composed of six super-periods made by 14 doublet focusing DF structures and by 28 dipoles. The sc dipole magnets of Nuklotron type have apertures of 130 mm x 65 mm. The length of the ring is 1083.6, five times the SIS18 circumference, and the maximum magnetic rigidity is $B\rho = 100$ Tm. In Fig. 1 is shown the layout of the existing facility and the SIS100 in the new facility. In the research program foreseen in FAIR, SIS100 has to deliver a primary beam of 6×10^{11} U^{+28} ions per cycle at energies from 400 to 2700 MeV/u. This intensity is reached for a short cycle time of 1.6 s. This requires a vacuum quality in the XHV range with a base pressure of $P = 10^{-12}$ mbar, since the large ionization cross section of U^{+28} makes the interaction of the ion beam with residual gas atoms a critical issue. Experience with the SIS18 has shown that during high intensity operation ion desorption processes lead to significant vacuum degradation and limitation of beam lifetime. Beam loss control therefore becomes a primary issue. In the present scenario the SIS100 has the RF harmonic $h = 10$. After four transfers of two bunches from SIS18 (operating with $h = 2$), eight buckets of SIS100 will be filled and two will remain empty. The nominal intensity at transfer rigidity of 18 Tm is 7.5×10^{10} ions per bunch, with transverse emittances (at 2σ deviation) of $\epsilon_{x/y} = 35/14$ mm-mrad. The first bunch injected into the SIS100 will be stored for 1 second while, the transverse tuneshift is $\Delta Q_y = -0.3$ for maximum intensity. Such an operating mode requires a careful account of the high intensity related effects and cures, where possible.

Figure 1: FAIR project and SIS100.

BEAM LOSS SOURCES

Nonlinear dynamics effects

These effects are induced by the lattice nonlinearities and are substantially single particle effect. Their contribution is determined by estimating the long term dynamic aperture. However, for SIS100 the beam is filling a large fraction of the beam pipe so that the "nonlinear acceptance" becomes a critical issue. The SIS100 working points must be chosen sufficiently away from single particle resonances.

Space charge and nonlinear dynamics effects

In order to explore the interplay of lattice nonlinearties with space charge, a campaign of experiments was started in 2002 at the CERN-Proton Synchrotron (PS) in a CERN-GSI collaborative effort for benchmarking our theoretical model versus an experiment with enforced beam loss. By exciting an external 4th order resonance it was found that a bunched beam of emittances $\epsilon_{x/y} = 25/10$ mm-mrad (normalized at 2σ) and a tuneshift $\Delta Q_y = 0.075$ reduces its intensity by 32% during 1 second storage when the bare tunes are 0.015 off the resonance [3]. The beam loss is attributed to the combined effect of beam space charge and synchrotron motion, which creates a periodic migration of islands in the transverse phase space. Particles trapped into islands are brought to the dynamic aperture and are eventually lost [4]. These simulation studies, which did not include the effect of chromaticity, predicted a beam loss of 8%. The effect of the chromaticity was added in [5]: there it was shown that chromaticity enhances the amplitude of the fixed points to particularly large values and leads to beam loss in the range of tunes between the resonance and the depressed tune via chromaticity. An estimate of the number of particles, which are candidates to be trapped and eventually get lost, is given by the formula tested in [4], $\Delta N/N = (Q_{x0} - Q_{x,res})/\Delta Q_x$. The beam loss prediction including the natural chromaticity for the CERN-PS experiment has thus increased to 16%.

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† g.franchetti@gsi.de

Transverse collective effects

Transverse collective instabilities can lead to losses and seriously limit the operation of the SIS 100 synchrotron. Different types of instabilities define specific (partly conflicting) requirements on tune values and especially fractional tune choice. As an example we consider here one of the candidates of concern for the SIS100, the resistive-wall instability. Fig. 2 presents the frequency and the growth time for the unstable slow wave excited by the resistive-wall impedance as estimated for a tentative SIS 100 beam.

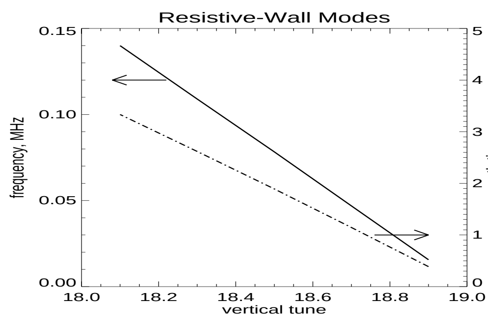

Figure 2: Frequency (full line) and growth times (chain line) for the resistive wall instability for SIS100 conditions.

Due to the long bunches planned for SIS 100, the coasting beam limit appears a reasonable, but still conservative stability assessment. The resulting recommendation is the choice of as small as possible a fractional vertical tune. An important SIS100-specific aspect for curing this instability is that effective Landau damping requires both, momentum spread and nonlinear oscillations in the betatron motion [6]. Demanding particle tracking simulations are still necessary to investigate accurately the nonlinear damping effects. Also, other instability mechanisms (transverse coupled-bunch etc.) must be considered for the final tune choice proposal. Finally, other sources of transverse impedances as kickers collimators, etc. are being taken into account.

SIS100 MODELLING

The nonlinear SIS100 lattice [2] is modeled via the systematic errors from sc dipoles and quadrupoles. The multipoles b_n, a_n of the multipolar expansion are retrieved by integrating the magnetic field over a reference circle of radius R. We use the multipolar components obtained from measurements on Nuclotron magnets performed in JINR [7]. For 96 nuclotron magnets the integrated magnetic field has been measured at 10 excitation currents from 640 A to 6380 A. In Table 1 we report the multipolar components for dipoles and quadrupoles at lowest excitation current. In the center of each quadrupole and dipole we apply a nonlinear kick consistent with the integrated multipole strength. In the bends the effect of 10 mm sagitta is accounted through a proper coordinate shift at the location of the bend nonlinearities.

Table 1: a) Systematic and standard deviations of multipoles for dipoles, R = 25 mm. b) Quadrupole systematic multipoles, R = 40 mm. All values are in units of 10^{-4} and for I = 640 A.

a)

N	b_n	Δb_n	a_n	Δa_n
1	10^4	0.08	-2.66	16.0
2	0.029	0.42	-0.051	1.08
3	-4.4	0.65	-0.24	0.4
4	-0.03	0.19	0.001	0.37
5	0.094	0.17	0.1	0.16

b)

N	b_n	a_n
1	9.00	10.75
2	6815.8	0.00
3	1.26	-3.41
4	0.68	-0.82
5	0.67	0.28
6	-13.05	2.78
10	4.98	-2.12

SIS100 WORKING POINTS

The fine-tuning of the SIS100 working points has been undertaken using DA calculations for the 3 different scenarios of SIS100 operations defined in Ref. [8]. The DA is defined here as the radius (in normalized coordinates) of the largest circle inscribed inside the domain of stable initial conditions. For the sake of computer time we are only calculating the short-term DA using 10^3 turns. As customary we express the DA in terms of the beam σ, which is defined at injection energy by our reference rms emittance of 12.5 mm mrad (in horizontal plane) at 12 Tm.

Working point for Bunch Compression and Normal Operations (WP1)

We propose the working point $Q_x = 18.84, Q_y = 18.73$ (WP1), see Fig. 3 (left). This working point is chosen at a "safe" distance from the diagonal to avoid the Montague resonance (for details see Ref. [11]). We assume that the

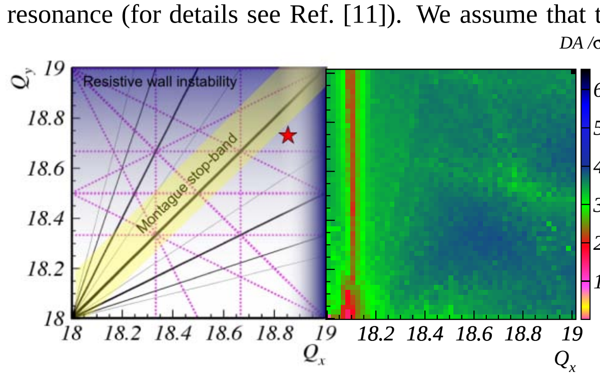

Figure 3: Left: Schematic of tune diagram, with red star marking the proposed working point (WP1). Right: scan of DA at 1000 turns over same tune area.

fractional tune should not be closer to the next higher integer than 0.15 to avoid the resistive wall instability. Subject to further calculations provisions have to be made to correct some of the 3rd and 5th order resonances crossed by the tune spread. Note that Fig. 3 (right) shows that the (idealized) DA can be as large as 3.5σ. No particular resonances appear excited, besides the one at $Q_x = 18$ (which appears at 18.1 due to the linear components in dipoles). The effect of random errors (Table 1) for the DA at 3.3σ is to create a distribution of DA's centered at 2.6σ with a spread of +/- 0.2σ. This result suggests that random components may excite resonances not visible in Fig. 3 (left), which might have an enhanced impact on beam loss in presence of high intensity beams. At 2700 MeV/u (100 Tm), where the field nonlinearity is larger, the DA is now 6σ. The normalization is obtained by using the adiabatically reduced beam emittance at 100 Tm. The change of quality of the magnetic field is now responsible for the appearance of more resonances than in Fig. 3 (left). In fact a distribution of DA for random errors shrinks the DA from a safe 6σ to 2-3σ. This stems from the excitation of the resonance $9Q_x = 168$.

Working point for slow extraction

The working point required for the slow extraction scenario (WP2) is chosen at $Q_x = 17.32, Q_y = 17.3$ (see Fig. 4, left) away from the cluster of 4th order resonances. At the end of the ramp a fast tune ramp can bring the working point close to the 3rd order resonance for slow extraction. The cluster of 4th order resonances can be an issue for tune shifts of $\Delta Q_y = -0.2$ at injection even though simulations indicates that no severe problems are encountered, if only systematic errors are included. A scheme for avoiding the 4th order cluster at injection might be taking as initial working point $Q_x = 17.425, Q_y = 17.35$. This working point is kept at a distance from the diagonal of 0.075. In Fig. 4 (right) we show the DA scan over the tune

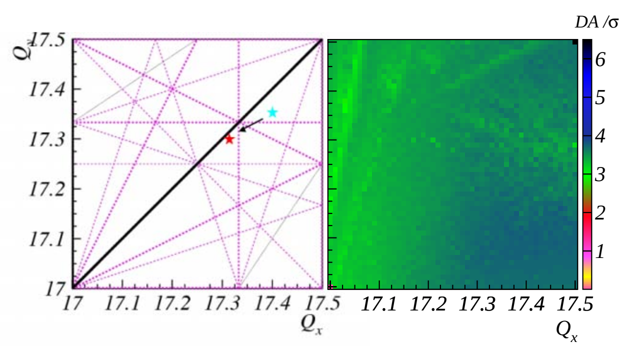

Figure 4: Left: WP2 before acceleration (blue star) and for slow extraction (red star).Right: Scan of DA at 1000 turns for I=640 A.

diagram of Fig. 4 (left). Note that in this calculation the effect of chromatic correction sextupoles is not included. The effect of random errors for the working point WP2 makes the DA shrink from 3.2σ to $2\sigma \pm 0.6\sigma$. This result shows that in the most pessimistic case the DA evaluated at 1000 turns can be expected to be as small as 1.4σ. This requires cures by sorting of magnets and by suitable compensation schemes. In the high energy scenario at 100 Tm the DA remains relatively large (5.5σ) such that the effect of random errors still keeps it at an acceptable value: for the working point WP2 at 100 Tm the DA shrinks to $3.8\sigma \pm 0.8\sigma$. The impact of the 3rd order resonance needed for resonant slow extraction on nonlinear dynamics with space charge is not evaluated here and further studies are mandatory.

Working point for proton operation

For the proton operation the working point (WP3) $Q_x = 21.85, Q_y = 21.79$ is chosen. This working point is also kept as optional for heavy ion operation. Results are shown in Fig. 5. For the proposed working point WP3 we obtain

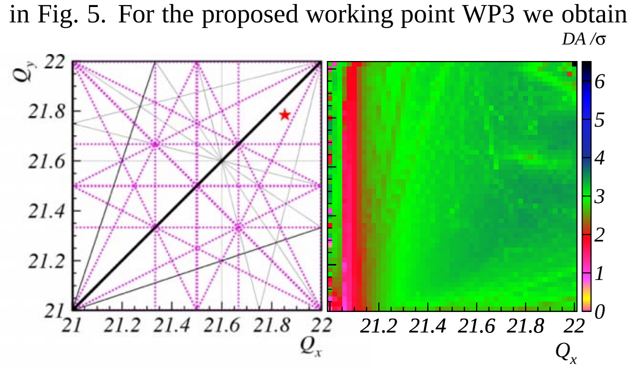

Figure 5: Working point WP3 (left). On the right, scan of DA at 1000 turns for I=640 A.

a reduced DA of 3.4σ without random errors. The effect of the random errors leads to a DA of $2.9\sigma \pm 0.3\sigma$.

OUTLOOK

The present study shows that the adopted field errors already lead to serious limitations in the available aperture. A more complete evaluation of the impact on beam loss due to high intensity effects and all sources of nonlinearities and errors will be carried out next for all three working points in order to decide on further fine-tuning of working points and on the requirements for compensation of nonlinearities.

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