SIS Operation at High Beam Intensities

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Abstract

The heavy ion synchrotron SIS at GSI was designed for operation at the space charge limit e.g. with $2 \cdot 10^{11}$ Ne^{10+} ions and $4 \cdot 10^{10}$ U^{73+} ions at an injection energy of 11.5 MeV/u. Machine operation with neon ions close to this limit and relevant measurements are discussed. The layout of a correction coil system for the control of machine resonances is presented. For machine operation with high intensity beams in combination with electron cooling the installation of feedback systems for the suppression of coherent instabilities is addressed.

1 INTRODUCTION

The heavy ion synchrotron SIS was designed for operation at the space charge limit, i.e. for the acceleration of $2 \cdot 10^{11}$ Ne^{10+} ions and $4 \cdot 10^{10}$ U^{73+} or $2 \cdot 10^{11}$ U^{28+} ions at an injection energy of 11.5 MeV/u. At present, the UNILAC injector linac can provide an injection current of about $3mA$ for neon and $20\mu A$ for uranium ions. With neon ions the high intensity operation of the SIS could be tested during the last two years, while for uranium and all other heavy ions the beam intensities were restricted to about $1 \cdot 10^8$ heavy ions per machine cycle. In the first half year of 1999 the old Wideröe part of the UNILAC with a total acceleration voltage of 34MV will be replaced by a new RFQ/IH - linac with 84MV, which will boost the beam currents for heavy ion beams to about 2mA for SIS injection. Thus it will be possible to approach the SIS space charge limit also for heavy ions [1].

Meanwhile a low energy electron cooler has been installed in the SIS [2]. In May 1998 first tests of the new cooler have shown that even with the present low injection currents the beam intensities can be raised e.g. to about $1 \cdot 10^9$ Bi^{67+} -ions per SIS cycle by repetition of 50 multiturn injections with about 100ms electron beam cooling after each injection (Fig. 1). This new SIS operation scheme proved especially useful for the transfer of heavy ion beams to the experimental storage ring ESR, which now can be filled with one single SIS pulse. It could be shown that with beam currents of about $10mA$ in the SIS the limit is reached, where coherent transverse beam instabilities gradually appear, while without electron cooling high intensity neon beams of about 40mA at injection and 120mA at high energy did not cause coherent instabilities.

2 HIGH INTENSITY NEON BEAMS

Usually beam intensities in synchrotron operation are restricted by the incoherent vertical tune shift during the RF

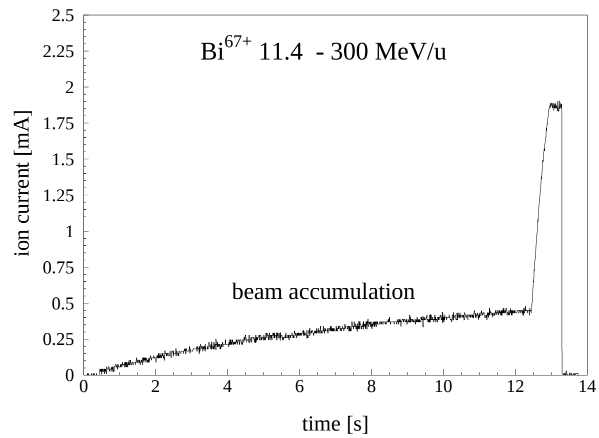

Figure 1: Beam accumulation by repeated multiturn injection with intermediate electron cooling.

capture process. This tune shift, which is given by

$$\Delta Q_v = N \, \frac{q^2}{A} \, \frac{1}{\beta^2 \gamma^3} \, \frac{g}{B_f} \, \frac{r_p}{\epsilon_v + \sqrt{\epsilon_h \epsilon_v}}$$

can be as high as $\Delta Q_v = -0.6$ in high intensity proton machines. At the SIS the low injection energy of $11.5\mathrm{MeV/u}$ and the factor q^2/A reduce the maximum number of ions, e.g. by a factor 25 for neon ions compared to protons at $50\mathrm{MeV}$ injection energy. Table 1 shows the incoherent tune shifts in the SIS with two different data sets for the transverse beam emittances in ($\pi\mathrm{mm} \cdot \mathrm{mrad}$), in the first column the design values and in the second the actual values for SIS operation.

Table 1: SIS Incoherent tune-shifts for Ne^{10+}-ions

N	number of stored ions	$2 \cdot 10^{11}$	$1 \cdot 10^{11}$
B_f	bunching factor	0.40	0.40
g	form factor	1.4	1.4
ϵ_h	hor. beam emittance	200	200
ϵ_v	vert. beam emittance	50	25
ΔQ_v	vertical Q-shift	0.46	0.36

At present the Unilac with the high intensity Chordis ion source and the Wideröe injector linac can provide for Ne^{10+}-ions beam currents of about 3mA for injection into the SIS. Fig. 2 shows multi-turn injection in high current operation. A total beam current of 35mA or $\mathrm{N_i} = 1 \cdot 10^{11}$ neon ions was accumulated during 22 turn injection of a 2.2mA UNILAC pulse current. Beam losses were about 20% as expected theoretically for the beam emittance of

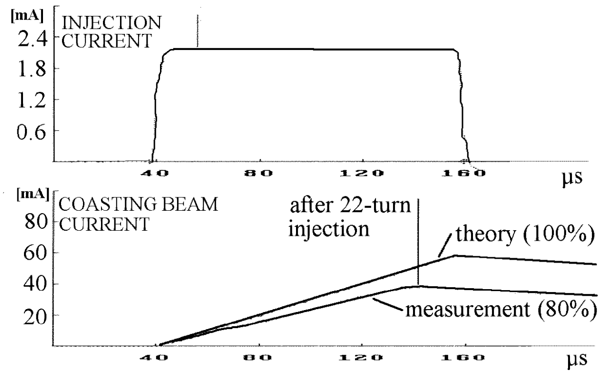

Figure 2: Multi-turn injection of $1 \cdot 10^{11} \mathrm{Ne}^{10+}$-ions

$\epsilon_{\mathrm{x}} = 4\pi\mathrm{mm} \cdot \mathrm{mrad}$ with the shadow effect of the electrostatic septum.

The incoherent tune-shifts were determined experimentally by the excitation of quadrupolar oscillations on the coasting beam in a time interval of 500ms after injection. Fig. 3 shows the results, which are in reasonable agreement with the calculated tune-shifts [3]. The measured vertical tune-shift for the coasting beam of $\Delta\mathrm{Q_v} = 0.1$ should lead to a tune-shift of about $\Delta\mathrm{Q_v} = 0.25 - 0.3$ in the RF capture process. It could be shown that the usual working point for SIS operation at $\mathrm{Q_h} = 4.3$ and $\mathrm{Q_v} = 3.27$, which was chosen with respect to resonance extraction at $\mathrm{Q_h} = 4\frac{1}{3}$, is not suitable for high current operation. For beam intensities beyond $5 \cdot 10^{10}$ neon ions per pulse the beam losses during RF capture strongly increased. Hence, it was not possible to capture and accelerate more than $4 - 5 \cdot 10^{10}$ neon ions per pulse. In order to simulate

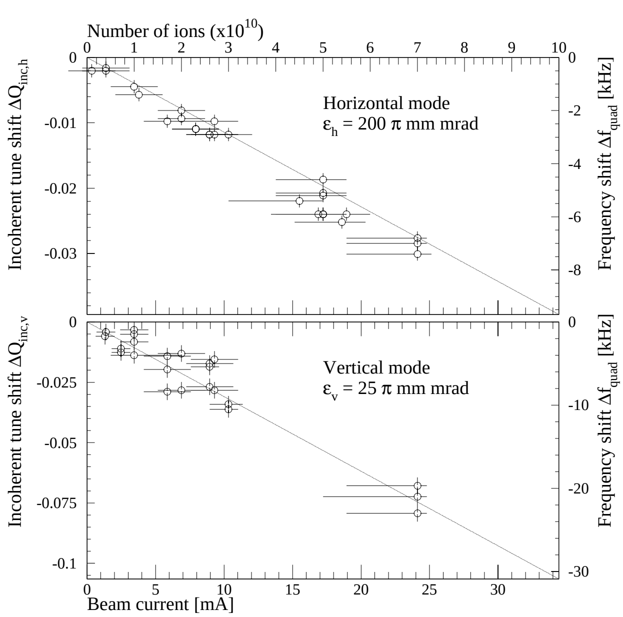

Figure 3: Incoherent tune-shift for the coasting Ne^{10+} beam at $11.4\mathrm{MeV/u}$.

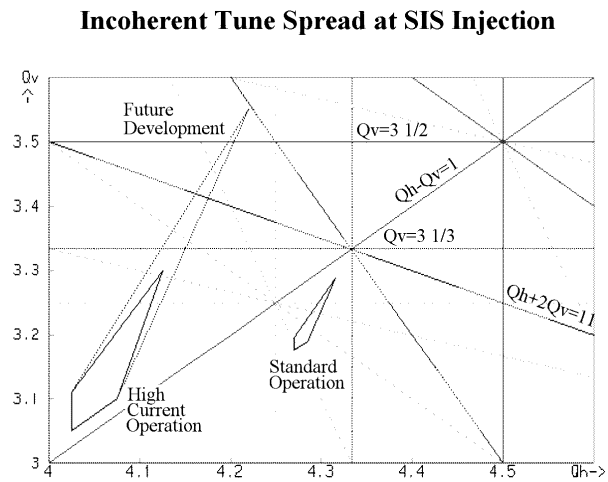

Figure 4: Resonance chart

the incoherent tune-shift during RF capture the Q-setting of the machine was deliberately shifted for a low current beam along an analogue line as indicated in Fig. 4 The observation of the coasting beam current clearly showed the effect of the forth order resonance lines, which cross at $\mathrm{Q_h} = 4.25, \mathrm{Q_v} = 3.25$ (Fig. 5). As a consequence a new working point at $\mathrm{Q_h} = 4.16, \mathrm{Q_v} = 3.31$ was tested, which is situated in the tune-diagram comparable to the PSB working point [4]. Here we succeeded immediately to accelerate $8 \cdot 10^{10}$ neon ions out of $1 \cdot 10^{11}$ injected ions. The corresponding ion currents are 36mA at injection and 110mA on the extraction flat-top. Coherent instabilities were not observed at these intensities. So far higher injection currents of about 3.5mA for multi-turn injection of $2 \cdot 10^{11}$ neon ions were not yet available. The measured tune-shift indicates anyhow that the present intensity limit for RF-capture and acceleration is about $1 \cdot 10^{11}$ neon ions per pulse.

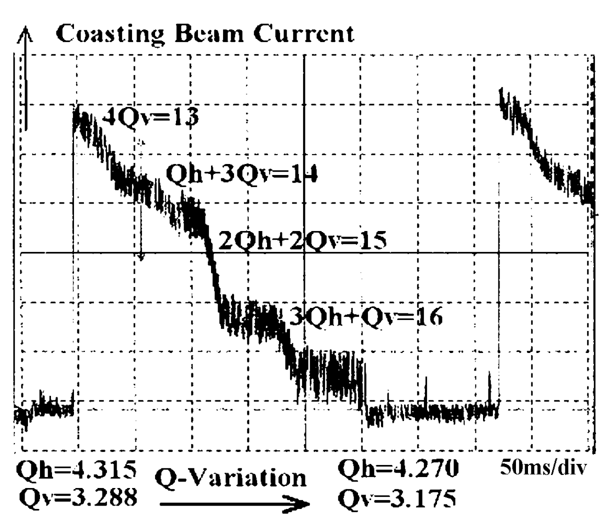

Figure 5: Beam losses at 4^{th}-order resonances

3 SIS IMPROVEMENT PROGRAM

SIS operation at high intensities shall be further improved by the installation of new equipment:

- A set of correction coils will be installed for machine operation at an incoherent tune-shift of $\Delta Q_v = -0.6$, i.e. at the design beam intensities of about $2 \cdot 10^{11}$ Ne^{10+}-ions and $4 \cdot 10^{10}$ U^{73+} or $2 \cdot 10^{11}$ U^{28+}-ions per pulse.

- New feedback systems for the compensation of coherent transverse and longitudinal instabilities are being studied, especially for operation with cooled ion beams. A design report will be prepared during the next months.

- The existing RF accelerating cavities will be modified by the installation of amplifier feedback systems, which reduce the effective longitudinal impedance of the tuned cavities below the present value of $3\mathrm{k}\Omega$. In addition, new RF cavities with a total voltage of about 200kV shall be installed for bunch compression [5].

The layout of a system of correction coils for SIS high intensity operation with $\Delta \mathrm{Q_v} \geq 0.5$ was studied. It is planned to compensate the half-integer resonance $2\mathrm{Q_v} = 7$ and the third-order resonances $\mathrm{Q_h} + 2\mathrm{Q_v} = 11$ and $3\mathrm{Q_v} = 10$ in order to prepare the synchrotron for operation at a working point $\mathrm{Q_h} = 4.23, \mathrm{Q_h} = 3.60$ (see Fig. 4). In addition, adequate control of the difference resonance $\mathrm{Q_h} - \mathrm{Q_v} = 1$ shall be used to enlarge the vertical beam emittance during RF capture and to limit the incoherent vertical Q-shift.

For the second-order resonances the beam envelopes were derived from the transfer-matrix for a single turn. This matrix, which includes both the effects of a random error distribution and the compensation by correction coils, can be used to determine analytically the strengths of the correction quadrupoles.

The half-integer resonance $2\mathrm{Q_v} = 7$ is driven by gradient errors of the 36 main quadrupoles in the ring. Two pairs of correction quadrupoles in a symmetrical FFDD configuration suffice for a perfect correction of any set of quadrupole errors. The investigation of different random sets with the maximum relative error δg in units of $1 \cdot 10^{-4}$ yielded the following relation between the strength of the correction quadrupoles $x_{nq}(m^{-1}) = (g_{nq}L)/(B\rho)$ and the maximum error:

$$x_{nq}(m^{-1}) = (0.0015 - 0.005)\sqrt{\delta g}$$

It is proposed to foresee correction of this resonance in the energy range from $11.5MeV/u$ up to about $25MeV/u$, which means for the acceleration of U^{28+}-ions a magnetic rigidity of $\mathrm{B}\rho = 6\mathrm{Tm}$.

The difference resonance $\mathrm{Q_h} - \mathrm{Q_v} = 1$ is driven by tilt errors of the main quadrupoles, which induce coupling between the horizontal and vertical motion. The theoretical studies based on the four-dimensional transfer matrix have shown, that on the resonance an oscillatory exchange of the horizontal and vertical emittance occurs. The period T_{sq} of this oscillation depends on the set of tilt errors. The resulting period in terms of the revolution time T_r depends on the maximum tilt angle α_t (in units of 0.0005):

$$T_{sq}/T_r = (200 - 1000) \cdot (1/\alpha_t)$$

The theoretical studies show that a precise compensation of the coupling requires four pairs of symmetrically arranged skew quadrupoles. The normalized strength x_{sq} of the skew quadrupoles is given by:

$$x_{sq}(m^{-1}) = (0.003 - 0.012) \cdot \sqrt{\alpha_t}$$

. In addition to resonance compensation the skew quadrupoles can be also used for control of the vertical beam emittance and hence the vertical tune-shift in the RF capture process.

The third-order resonances were studied by particle tracking. The resonance $\mathrm{Q_h} + 2\mathrm{Q_v} = 11$ is driven mainly by the sextupole terms of the 24 dipole magnets, which were measured as $k_{ns}(m^{-2}) = 0.01$ at the injection field of 0.2T. For a compensation of this resonance two of the existing six correction sextupoles can be used. The required normalized sextupole strength is about

$$x_{ns}(m^{-2}) = (0.01 - 0.02)$$

The resonance $3\mathrm{Q_v} = 10$ is driven by skew sextupole terms that are introduced by the vertical steerer magnets with a strength of $k_{ss}(m^{-2}) = 0.005$ for 10% steerer magnet excitation. Usually just four or five of the twelve steerer magnets are used with less than 10% excitation. It could be shown experimentally that even in this case losses are observed for a slow crossing of the resonance within about 100ms. The numerical studies show that two correction skew sextupoles with the normalized strength

$$x_{ss}(m^{-2}) = (0.003 - 0.01)$$

are adequate for the compensation of this resonance even with 10% steerer magnet excitation .

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