IMPROVED PERFORMANCE OF THE GSI HEAVY ION ACCELERATOR COMPLEX WITH COOLED SYNCHROTRON BEAMS

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Abstract

Electron cooling at the injection energy of the heavy ion synchrotron SIS results in beam pulses of higher intensity and exceptional quality. The beam parameters after cooling have been measured and verify a reduction of the phase space volume by more than three orders of magnitude. Beam transfer of the cooled ion beam is much easier because of the reduced emittance. The time required to fill the storage ring ESR with highly charged ions has been reduced from minutes to seconds.

1 INTRODUCTION

An electron cooling system has recently been installed in the heavy ion synchrotron SIS [1]. It has been designed for fast accumulation of high intensity beams of highly charged ions at the injection energy [2]. The successful commissioning of the cooling device and the optimization of the accumulation procedure facilitate to increase the number of ions in a synchrotron pulse by more than one order of magnitude [3]. Even in view of the additional time required for the accumulation process a significant increase of the average beam intensity has been achieved, which will also be useful to provide beams of rare isotopes with increased intensity.

Although the accumulation process requires mainly an emittance reduction in the horizontal phase space plane, electron cooling provides a reduction of the 6-dimensional phase space volume. This has a beneficial effect on the general performance of the synchrotron and allows to deliver beams of unprecedented quality.

2 PROPERTIES OF THE COOLED HEAVY ION BEAM

The heavy ion beam after accumulation with cooling has lost any memory of its properties immediately after injection. The properties of the accumulated beam are determined by cooling and counteracting heating processes. Momentum spread and emittances are significantly reduced compared to the injected beam. The momentum spread of the coasting beam for moderate beam intensity can be directly determined from the width of the frequency distribution by Schottky noise analysis. Measurements for three ion species (Fig. 1) for identical electron beam parameters ($n_e = 5.5 \times 10^7 \mathrm{cm}^{-3}$) show an increase of the momentum spread with the particle number N proportional to $N^{0.37}$. For larger particle numbers the determination of the momentum spread is doubtful due to collective effects in the noise signal. At small particle numbers the measured frequency spread is determined by the stability of power supplies or changes of the bending field caused by long lasting eddy current effects as the ring magnetic field is ramped to the injection level just before injection and accumulation.

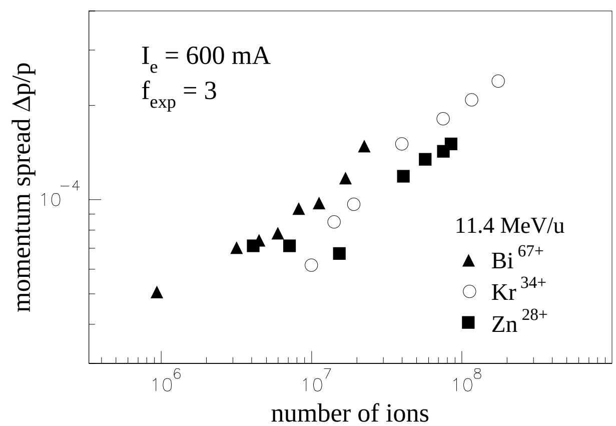

Figure 1: Momentum spread of cooled heavy ion beams at the SIS injection energy.

The transverse emittance of the circulating ion beam could not be measured directly so far for lack of appropriate non-destructive diagnostics. An indirect determination of the horizontal beam emittance was obtained by variation of the bumper amplitude which is applied during multiturn injection. The minimum amplitude which does not result in beam accumulation indicates that beam injection starts in the center of the acceptance. Thus even the cooled circulating beam hits the electrostatic septum and is lost during the subsequent multiturn injection. The accumulation process starts when the bumper amplitude is further reduced.

By variation of the bumper amplitude in small steps (1 mm typically) it was confirmed that for increasing spacing between electrostatic septum and the outermost displacement of the closed orbit during injection an increasing number of ions can be accumulated. The emittance of the cooled beam grows with the number of accumulated ions. The ion beam intensity saturates when the injected current balances the beam loss in the tails of the cooled circulating beam during the closed orbit bump towards the septum. Assuming a Gaussian distribution of the horizontal emittance of the cooled beam the emittance can be evaluated from the

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saturation current and the injected current. The horizontal beam emittance determined from this analysis increases almost linearly with the ion beam intensity (Fig. 2).

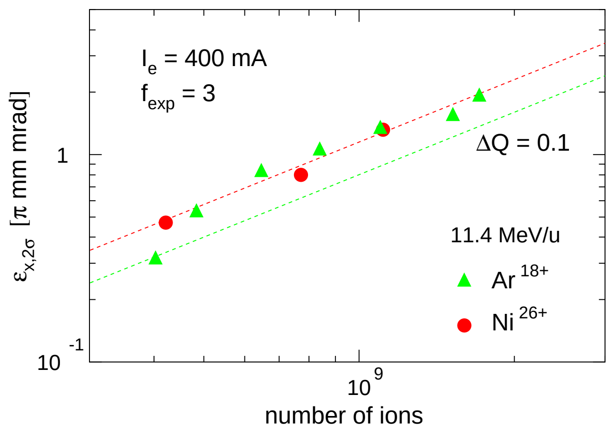

Figure 2: Horizontal emittance of the cooled beam evaluated from the saturation current in the synchrotron when the bumper amplitude was varied.

Usually the emittance of electron cooled highly charged ions is determined by an equilibrium between cooling and heating by intrabeam scattering. This equilibrium emittance however is expected to grow weaker than linearly with beam intensity [4]. Therefore the measured emittances might indicate an additional heating process. The dashed lines in Fig. 2 represent the emittance ϵ corresponding to a tune shift $\Delta Q = 0.1$ according to

$$\Delta Q = \frac{r_p}{2\pi\beta^2\gamma^3}\frac{q^2}{A}\frac{N}{\epsilon} \qquad (1)$$

for Ni^{26+} and Ar^{18+}, respectively. This tune shift is estimated for a coasting beam without any geometrical factor larger than unity and therefore represents the best case. Heating from betatron resonances might contribute to the observed equilibrium beam emittances. Moreover, imperfections in the closed orbit bumps can pretend an increased beam emittance, particularly for small particle numbers with correspondingly lower emittances. This means that the actual beam emittance is even smaller than estimated and resonance heating is stronger.

The beam quality after accumulation is dependent on the number of ions, but, in general, the cooled beams exhibit considerably better quality. The momentum spread of cooled beams is up to one order of magnitude reduced, compared to $\Delta p/p \simeq 1 \times 10^{-3}$ injected from the linac. The horizontal emittance which amounts to $\epsilon_x \simeq 150\,\pi$ mm mrad after multiturn injection is reduced by more than two orders of magnitude. The vertical emittance is $\epsilon_x \simeq 5 - 10\ \pi$ mm mrad without cooling. For electron cooled ion beams the vertical emittance is usually of similar value as the horizontal. Consequently the phase space volume is, dependent on the ion beam intensity, compressed by 3–6 orders of magnitude.

3 ACCELERATION AND BEAM EXTRACTION

During beam accumulation at the injection energy the rf amplitude is set to zero and only a few milliseconds before the acceleration starts the rf amplitude is raised adiabatically to 9 kV. If the electron velocity which determines the ion velocity is well matched (better than 10^{-3}) to the initial rf frequency (h=4) the capture into the buckets and subsequent acceleration can be performed without measurable particle losses. Due to the large bucket height it is not necessary to switch off the electron beam during rf capture and acceleration.

The accelerated ion beam can be extracted either by a slow resonant extraction or by fast kicker extraction. The parameters of the cooled beam have also been measured after acceleration. For a measurement of the momentum spread after acceleration the rf amplitude was decreased to zero adiabatically. Surprisingly measurements for a Zn^{28+} beam accelerated to 500 MeV/u showed a momentum spread $\Delta p/p \simeq 3 \times 10^{-4}$ independent of the beam intensity. The absence of the expected adiabatic shrinkage after acceleration indicates a mismatch of the ramps for frequency and magnetic field or the presence of unwanted noise or phase jumps on the rf system.

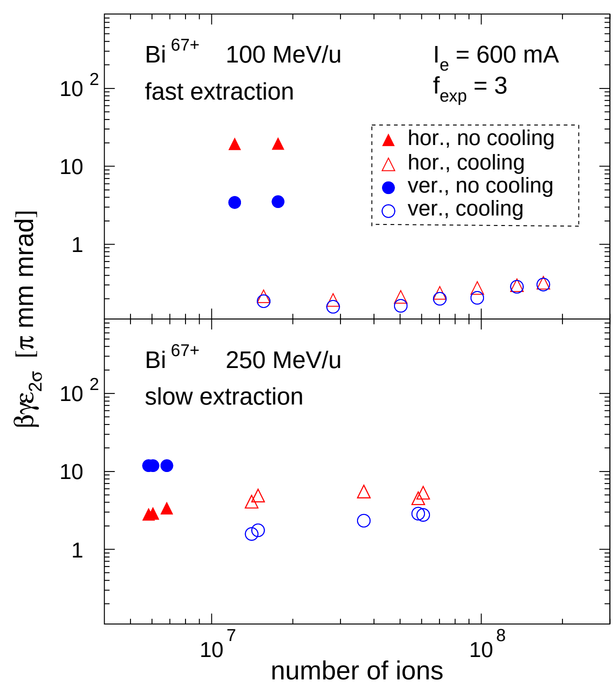

Figure 3: Normalized beam emittance measured with profile grids after extraction from the synchrotron.

For the transverse beam emittance a considerable improvement with cooled beam could be demonstrated. Beam profiles have been measured for Bi^{67+} after extraction (Fig. 3). Using the calculated β-functions at the profile grid the normalized emittances have been calculated. Even with ten times higher beam intensity the horizontal emittance of the cooled beam after fast extraction is reduced by more than a factor 50 and the vertical emittance by more than a factor of 20. The values for the cooled beams are upper limits only as the measurement was limited by the resolution of the profile grid .

After slow extraction the normalized horizontal emittance is similar with and without cooling and amounts to about 3-4 π mm mrad. The normalized vertical emittance of the cooled beam is 2-3 π mm mrad compared to 12 π mm mrad without cooling. The emittance after slow extraction is spoiled by resonance heating and in the horizontal phase plane determined by the extraction channel. The main advantage for slow extraction is the increased intensity in a synchrotron pulse.

4 TRANSFER OF COOLED BEAMS TO THE STORAGE RING ESR

The high quality and intensity of the cooled synchrotron beams have considerably improved the conditions for filling of the storage ring ESR [1]. The small emittance allows beam transfer after fast extraction without significant losses. Even the additional increase of the beam emittance and the momentum spread after passage of a stripper which provides bare or few electron ions for storage in the ESR does not lead to additional beam losses.

Recently the possibility has been established to merge after acceleration the four synchrotron bunches which are generated for acceleration into one bunch by adiabatic debunching and rebunching at the first harmonic of the revolution frequency [5]. This single bunch is short enough to inject the whole contents of the synchrotron in one transfer to the ESR. The high intensity synchrotron bunch will also be advantageous for the production of radioactive nuclei in the fragment separator FRS from which $B\rho$ selected isotopes can be transferred to the storage ring ESR.

An additional option in the operation of the GSI accelerator complex is the reinjection of maximum charge state ions from the storage ring to the synchrotron. As the heaviest ions are not completely stripped at the usual injection energy (11.4 MeV/u) higher energies can be reached after stripping between the synchrotron and the storage ring and reinjection into the synchrotron with post-acceleration to the maximum energy for the bare charge state.

For the operation of such a reinjection cycle cooling and accumulation at the injection energy of the synchrotron could be favorably used. The time for accumulation (5 s) is short compared to the total cycle time (30 s) which allows to increase the average intensity available in the experimental area by nearly the gain factor for the accumulation process. The current transformer signal in synchrotron and storage ring for this reinjection mode demonstrate the high efficiency of beam transfer with cooled beam (Fig. 4). The reduction of the particle number after injection into the storage ring is caused by stripping to the bare charge state at the relatively low energy of 310 MeV/u. Before installation of the SIS electron cooling system the bare ions had to be accumulated in the ESR over several minutes. This time consuming stacking procedure in the ESR has been abandoned and only a 12 s period is required to cool the bare ions with the ESR electron cooling system. Finally the bare gold ions are reinjected into the synchrotron, accelerated to the top energy of 1.5 GeV/u and extracted over a variable time interval.

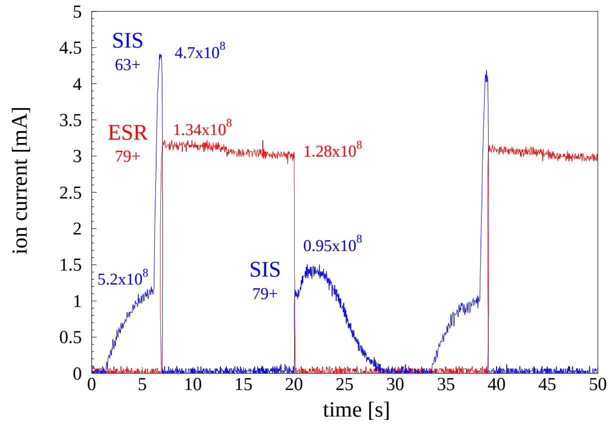

Figure 4: Ion current in the synchrotron SIS and in the storage ring ESR during operation in the reinjection mode. The Au^{63+}ions were accumulated over 5 s in the SIS, accelerated to 310 MeV/u and fast extracted to the ESR after rebunching with h=1. Stripping between SIS and ESR produced Au^{79+} ions which were cooled in the ESR over 12 s, reinjected into the SIS, further accelerated to 1.5 GeV/u and finally slowly extracted over 5 s.

5 REFERENCES

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