COMMISSIONING OF THE ELECTRON COOLING DEVICE IN THE HEAVY ION SYNCHROTRON SIS

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Abstract

An electron cooling device has been installed and commissioned in the heavy ion synchrotron SIS. The ion beam is cooled and accumulated at the injection energy. The intensity of the synchrotron pulses can be increased by up to one order of magnitude in accumulation periods of less than 10 s. The beam emittances at injection energy result from an equilibrium between the cooling rate and the heating rate by intrabeam scattering. Beam losses for the cooled beams during acceleration, fast extraction and beam transfer have not been detected. Intensity limitations during accumulation are caused by charge changing processes or instabilities in the dense ion beam.

1 INTRODUCTION

The heavy ion synchrotron SIS [1] is capable to accelerate all species of heavy ions to maximum energies between 1 and 2 GeV/u corresponding to a maximum magnetic rigidity Bρ = 18 Tm. The ions are injected from the UNILAC linear accelerator at a fixed energy of 11.4 MeV/u [2]. By horizontal multiturn injection the injected beam with horizontal and vertical emittances $\epsilon_{x,y} \simeq 5\ \pi$ mm mrad and a momentum spread $\delta p/p \simeq 1 \times 10^{-3}$ is accumulated with a typical gain factor 15-20 resulting in a horizontal emittance $\epsilon_x \simeq 150\ \pi$ mm mrad. For light ions (A $\leq$ 20) the synchrotron can be filled nearly up to the space charge limit. For heavier ions, however, the intensity of the injected beams is limited by the ion sources and the low energy section of the linear accelerator.

In the framework of a high intensity upgrade program [3] an electron cooling system has been supplemented to the synchrotron for an additional gain factor by cooler assisted fast accumulation at the injection energy [4]. Short transverse cooling times shall allow fast repeated multiturn injection into the outer part of the horizontal ring acceptance, whilst the inner part is reserved for the cooled accumulated ion beam. Even considering the reduced emittance of the cooled beam and the corresponding tune shift a significant intensity increase can be expected.

2 INSTALLATION OF THE ELECTRON COOLING SYSTEM IN SIS

The parameters of the new electron cooling system were specified according to the requirement of fast beam accumulation with cooling times on the order of 0.1 s [4]. The electron cooling system was designed in a collaboration between GSI and BINP, Novosibirsk. The components which were delivered partially by BINP (magnets, gun, collector) and by industrial suppliers were inspected and assembled at GSI during the spring and summer of 1997. Tests with electron beam in a test position outside the ring tunnel proved that nearly all specifications were met or even exceeded [5].

After the electron beam test operation the complete system was hooked to a crane, moved to the synchrotron and lowered through the concrete ceiling into the ring tunnel. Inside the ring tunnel it was moved to its location in front of the so-called reinjection section where it was positioned with an accuracy of better than 1 mm to the axis of the straight section. The vacuum system was kept sealed during all these operations and only for the final connection to the ring vacuum system it was vented for a few hours. After bakeout of the vacuum system in the ring position a final system inspection with electron beam operation proved full functioning in accordance with the previous test outside the ring tunnel.

3 FIRST BEAM COOLING

For the initial cooling and accumulation studies the electron cooling system was operated in a pure dc mode, i.e. the values for magnetic field, electron energy and electron current were constant during the whole SIS acceleration cycle. The electron beam could be switched off by a fast high voltage switch acting on the anode voltage. This was used to stop the electron beam after accumulation just before the adiabatic increase of the rf amplitude and the ramping of the frequency in order to avoid interferences between cooling and rf system. But also with permanent electron beam no adverse effects on the acceleration process were observed.

The magnetic field strength in the cooling section was kept constant at $B = 0.06$ T which is the field level optimized to give the best field quality in the interaction region between electron and ion beam [5]. The correction elements for compensation of the horizontal kicks on the ion beam introduced by the toroids were set to the calculated values. Due to imperfections of the kick compensation and maybe also coupling between horizontal and vertical ion motion by the solenoidal field the multiturn injection efficiency was about 60 % of its value without cooler magnets.

After adjustment of the electron energy to the injection energy of a Zn^{28+} ion beam used in the first experiments cooling could immediately be observed by Schottky noise analysis as a reduction of the momentum spread .

Beam diagnostics to monitor the cooling process in the transverse degree of freedom were not available during the first commissioning experiments. Nevertheless the existence of transverse cooling was examined when the bumper amplitude was reduced to allow beam accumulation. The multiturn injection was repeated at the injection level with a repetition rate of a few Hertz. After minor tuning of the electron energy the accumulation started and could be observed with the standard slow current transformer as an increase of the ion current (Fig. 1).

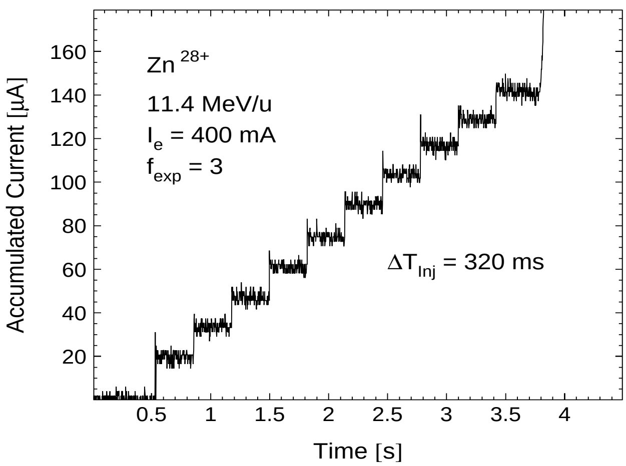

Figure 1: Ion current growth during cooler assisted beam accumulation. The Zn^{28+} beam was cooled at the injection energy 11.4 MeV/u with a 400 mA electron beam expanded by a factor of 3.

By further tuning of the electron energy which determines the ion energy after cooling and of the rf frequency the accumulated ion beam could be accelerated without losses during rebunching. The reduced longitudinal beam emittance relieves the requirement of large rf amplitudes during rebunching and thus allowed loss-free acceleration.

4 BEAM ACCUMULATION

For the increase of the average ion beam intensity provided by the synchrotron the speed of the accumulation process is crucial. Therefore the accumulation rate was studied as a function of cooler and ring parameters. The electron current and the magnetic expansion factor which allows a variation of the beam diameter in the cooling section directly affect the electron density and consequently the cooling rate. Fig. 2 shows the accumulation rate for Bi^{67+} versus the electron current for three different expansion factors. Currents higher than 1.0 A could not be applied for beam accumulation. The higher space charge of the electron beam excites a transverse drift motion in the crossed longitudinal magnetic and radial electric field which increases proportional with the electron beam space charge. In addition an increase of the space charge potential in the electron beam also results in a variation of the electron energy which grows quadratically with the radial position inside the electron beam. Both effects result in a higher relative velocity between ions and electrons which can push ions with larger emittances out of the ring acceptance. For electron currents below 0.4 A the accumulation rate increases roughly proportional to the electron density. An electron current around 0.6 A gives the minimum time for beam accumulation and the highest intensity gain.

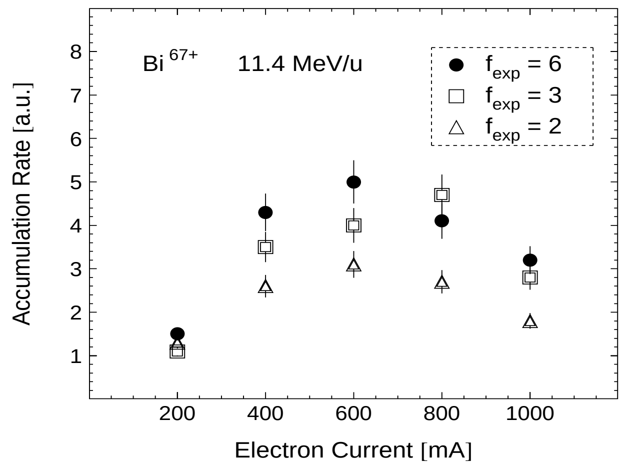

Figure 2: Accumulation rate for a Bi^{67+} beam as a function of the electron current for three expansion factors.

After optimization of injection and cooling parameters the maximum intensity gain factors amounted for Kr^{34+} to 2 s^{-1} and for Bi^{67+} to nearly 4 s^{-1} compared to a single multiturn injection. This reflects approximately the q^2/A-dependence of the cooling rate which determines the accumulation rate. The measured accumulation rates allow an increase of the intensity in a synchrotron pulse by one order of magnitude in a few seconds.

5 BEAM QUALITY

Beam accumulation with cooling does not only provide higher beam intensity, but also beams of higher phase space density. The beam emittance is reduced in full six-dimensional phase space. This is obvious from the accumulation technique. The bumper amplitude range which is used to fill the synchrotron acceptance during repeated multiturn injection is 20 mm compared to a value of 30 mm in the standard mode. This corresponds to a horizontal emittance significantly below 10 π mm mrad for the cooled ion beam opposed to an emittance of 150 π mm · mrad which is filled during the standard multiturn injection.

The emittance of fast extracted beams after repeated multiturn injection is shown in Fig. 3 as a function of the number of Bi ions which were accelerated to 100 MeV/u. The beam size of the cooled beam in horizontal direction is reduced by a factor of 8 compared to the standard multiturn injection, the vertical reduction factor is about 4. The emittance after electron cooling usually depends on the ion

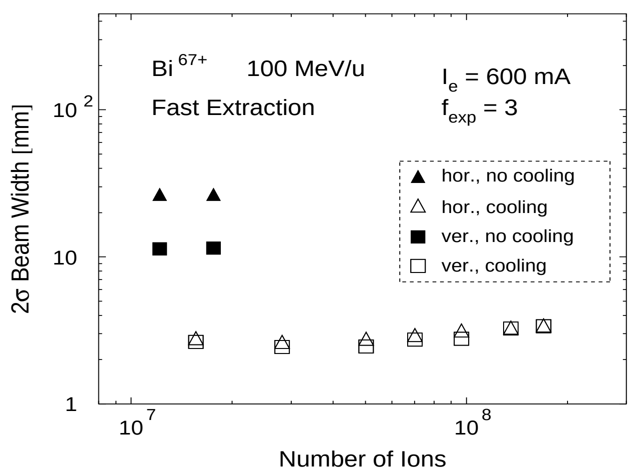

Figure 3: Horizontal and vertical beam size of the fast extracted ion beam (Bi^{67+} at 100 MeV/u) without and with cooling at the injection energy.

beam intensity as the cooling is counteracted by intrabeam scattering in the dense ion beam. For slow beam extraction at a third order resonance no reduction of the horizontal beam size and a smaller reduction (by a factor of 2) for the vertical beam size have been observed.

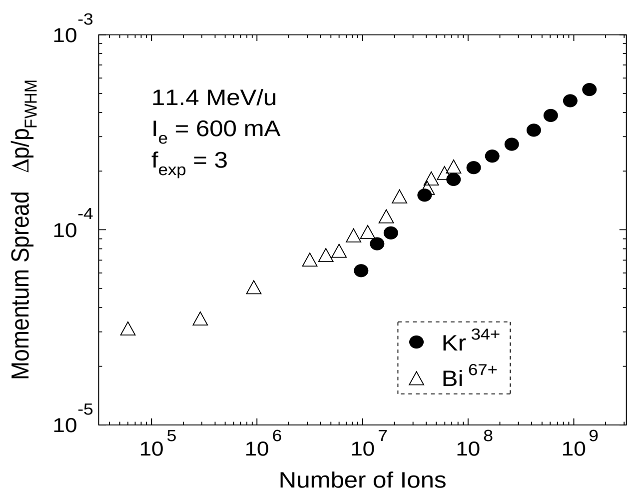

Figure 4: Momentum spread of the accumulated cooled ion beam at the injection energy 11.4 MeV/u. The electron beam of 600 mA was expanded by a factor of 3.

The influence of intrabeam scattering is also evident from Schottky noise measurements of the longitudinal momentum spread of the cooled coasting ion beam at injection energy just after accumulation. The dependence of the momentum spread is shown in Fig. 4 as a function of the number of accumulated ions. The Kr and Bi ions were cooled with an electron current of 0.6 A applying magnetic expansion by a factor of 3 (electron density $n_e = 6 \times 10^7$ cm^{-3}). The momentum spread growth can be described by a $N^{0.37}$-dependence on the ion number N.

6 LIMITATIONS TO THE ION BEAM INTENSITY

Two typical situations for beam accumulation and its limitations at maximum intensity were studied. For the lighter Kr^{34+} ion the standard multiturn injection delivers a few times 10^8 ions. The lifetime of Kr^{34+} with respect to interaction with the residual gas and to recombination with electrons in the cooler is on the order of minutes. Thus the intensity can be increased up to the limit by instabilities due to the interaction with ring impedances. For a 0.6 A electron beam and an expansion factor of 3 a maximum intensity of 7 $\times 10^9$ ions was achieved. This intensity was limited by transverse instabilities indicated by fast growth of transverse Schottky side bands of the coasting beam during accumulation. Both increase and reduction of the electron current resulted in lower values for the accumulated beam intensity.

The case of a typical highly charged heavy ion was investigated with a Bi^{67+} beam. This ion can be injected with a maximum intensity of a few times 10^7 ions per multiturn injection. The lifetime at injection energy in the residual gas is around 30 s. Due to the complicated electronic configuration (16 bound electrons) the lifetime is determined by recombination processes in the electron beam and therefore depends on the electron beam intensity. For an expansion factor of 3 ($kT_\perp \simeq 0.035$ eV) the lifetime normalized to an electron density $n_e = 1 \times 10^7$ cm^{-3} is about 40 s. The situation for neighboring charge states is nearly identical, no significant change with the electronic configuration has been found. Therefore the maximum accumulated intensity which amounted to 7×10^8 ions in one pulse is limited by the ratio of beam lifetime and injection repetition period which is determined by the cooling time. As both quantities are inversely proportional to the electron density a maximum gain factor of about 30 has been found independent of the electron current.

7 REFERENCES

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