Commissioning of the ESR Electron Cooling Device

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Abstract

The ESR electron cooler [1] has come to a routine operation for experiments with stored heavy ions in the SIS/ESR-complex at GSI [2]. The ion species which have been cooled in the ESR storage ring range from $^{20}Ne^{10+}$ to $^{209}Bi^{82+}$ at typical energies between 100 and 300 MeV/u. Besides the use for beam cooling the electron cooler is also an essential component for accumulation of high intensity beams and for storage of radioactive beams as has been recently demonstrated.

The cooling experiments with highly charged ions confirm the expected limitations due to intrabeam scattering as well as the increase of particle losses by recombination of stored ions with cooling electrons. The dependence of ion beam equilibrium temperature on ion and electron beam intensity has been studied. At small ion beam intensity a momentum spread $\Delta p/p = 1 \cdot 10^{-6}$ and a beam emittance $\epsilon_{x,y} = 0.03\ \pi$ mm mrad has been observed.

1 INTRODUCTION

The ESR storage ring is equipped with an electron cooling system which is capable to reduce the phase space volume of the ion beam by several orders of magnitude. Typical beam parameters for heavy ion beams after acceleration in the synchrotron SIS are momentum spread $\Delta p/p \simeq 10^{-3}$ and transverse emittances $\epsilon_{x,y} \simeq 10\ \pi$ mm mrad, for radioactive nuclei produced in the fragment separator [3] the beam quality can be even worse. Due to rf stacking the longitudinal momentum spread can be increased to $\Delta p/p \simeq 10^{-2}$. Therefore an efficient cooling system is desired to prepare beams for precision experiments or for experiments making use of the ESR internal gas jet target [4]. The electron cooling system also offers the interesting option to use the intense electron beam as an electron target to study the interaction of highly charged ions with free electrons at adjustable relative velocity.

2 ELECTRON BEAM OPERATION

The electron cooling device has been operated very reliably during more than thousand hours of storage ring experiments without any serious failure. Although operation is satisfactory the full design parameters have not yet been achieved and limitations exist for the parameters of the electron cooler. The high voltage applied to the acceleration column has been raised to 210 kV. Although conditioning was sometimes painstaking due to crossed E-B fields in gun and collector section and the associated discharges, the present high voltage limitaton is caused by sparks in the air filled Faraday room.

The electron current has been raised up to 2 A with loss currents of less than 2 mA corresponding to a collection efficiency of 0.9990, for smaller electron currents the efficiency increases to 0.9998. The large dissipated power and the increase of the vacuum pressure from the 10^{-11} to the low 10^{-9} mb range impedes the long term operation of higher currents. The current limitation originates from the long collector entrance electrode which has to be set to a potential high enough to avoid reflection of the beam electrons due to the large space charge potential. As computer simulations have shown a reduction of the electrode length should improve the collection efficiency at high currents considerably.

The magnetic guiding field in cooling experiments is operated at $B_0 = 1.1$ kG which is presently the maximum field that can be corrected for the ion beam. However, installation of a more powerful power supply for the ion beam correction magnets will easily allow an increase to the design value $B_0 = 2$ kG.

3 COOLER ADJUSTMENTS

The standard ring tuning is performed with cooler magnets set to the desired value (typically $B_0 \approx 1$ kG) and with the correction magnets - compensation of longitudinal field component and correction of dipole component of the toroids - operated at values according to trajectory calculations. Fine adjustments have been performed once experimentally with a stored and cooled ion beam.

After setting of all correction elements for the electron beam to values that were determined in transmission experiments with electron beam, the acceleration voltage can be raised to the value that fullfills the requirement of equal velocity of ions and electrons. Then the various voltages in the collector region are applied and the electrons can be extracted by setting the gun anode to voltage. The current can be chosen independent on all other cooling parameters, only the collector voltages have to be scaled with the current according to empiric values for maximum collection efficiency.

The final goal of cooler adjustments is the achievement of a maximum cooling rate for a certain electron beam intensity. As the electron velocity also determines the ion velocity by dragging the ions to the same velocity the main problem is matching of the transverse degrees of freedom. The transverse position of the ion beam in the 5 cm diameter electron beam has been varied by parallel displacement of the ion beam but no significant effect on the quality of the cold ion beam has been observed. Nevertheless this remains to be studied in more detail especially with regard to the cooling rate.

The most important adjustment concerns the relative angle between electron and ion beam. Any misalignment introduces systematic transverse velocity components which reduce the cooling force. A coarse adjustment by aligning the ion beam parallel to the electron beam is included in the initial closed orbit correction. Fine adjustment is performed for each experiment by steering the electron beam in the cooling section. The applied correction field strength of the electron beam steerer coils corresponds to angles below 1 mrad. As a consequence cooling can always be observed immediately after switching on the cooler and fine adjustments are necessary to optimize cooling rate and ion beam equilibrium temperature only.

For optimization of cooling the observation of ions which have captured an electron in the cooling section is very helpful. Their spatial distribution represents the ion beam emittance and the total rate increases with the inverse square root of the transverse electron temperature. Therefore minimum beam size and maximum count rate of charge changed ions indicate optimized cooler performance and it has been found that in this case the longitudinal cooling force also has its maximum. In contrast to this the longitudinal momentum spread under optimized cooling conditions shows a small local maximum which can be reduced by up to a factor of two by misalignment of the electron beam with a relative angle of typically 0.5 mrad. The improvement of the longitudinal ion beam quality at the expense of the transverse emittance and vice versa seems to indicate that the equilibrium is a delicate balance between cooling and intrabeam scattering which transfers heat from the transverse to the longitudinal degree of freedom. The increase of intrabeam scattering for a transversely dense ion beam exceeds the increase of longitudinal cooling rate and causes an increase of momentum spread under optimum cooling conditions.

4 EQUILIBRIUM BEAM PROPERTIES

The properties of the ion beam have been studied with various ions in the equilibrium between electron cooling and inevitable heating mainly caused by intrabeam scattering. In these measurements the momentum spread of the ion beam was determined from Schottky scans of the distribution of the revolution frequencies of the ions while the horizontal and vertical emittances were deduced from the spatial distribution of ions which had captured an electron in the cooling section and were detected in a position sensitive wire chamber [5].

The ESR electron cooler design allows the independent choice of electron beam energy and intensity with a temperature of the electron beam that varies only weakly with intensity.

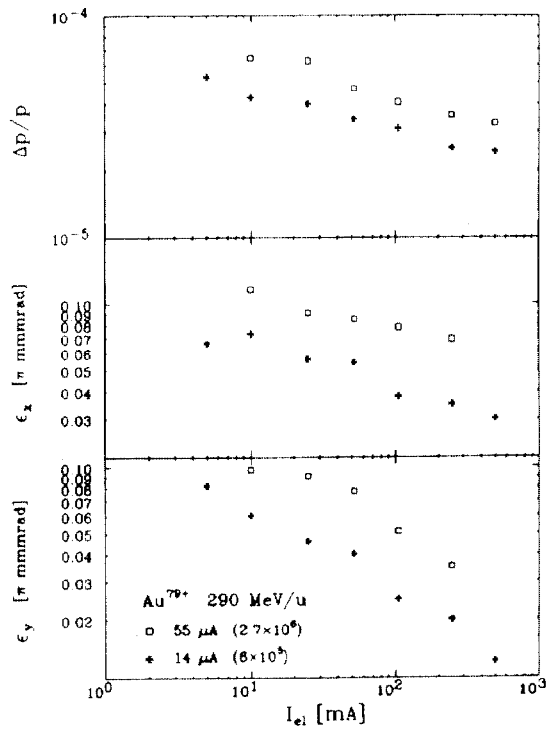

Figure 1: Momentum spread and emittances of a cooled $^{197}Au^{79+}$ 290 Mev/u beam as a function of the electron current for two ion beam intensities.

The ion beam properties were studied with $^{197}Au^{79+}$ 290 MeV/u for electron currents ranging from 5 to 500 mA ($n_{el} \simeq 1 \cdot 10^5$ to $1 \cdot 10^7$ cm^{-3}). The dependence of the ion beam momentum spread and emittance on electron beam intensity (fig. 1) is weak and even an electron current of 5 mA suffices to preserve a good beam quality.

Computer simulations of the intrabeam scattering rate for these experimental values confirm a nearly linear increase of the heating rate and consequently the cooling rate with electron beam current [6]. Small deviations for the highest currents may indicate an increased transverse electron temperature. Since intrabeam scattering is the dominant heating mechanism, the equilibrium properties also depend on the ion beam intensity. The heating rate increases with particle number and for fixed cooling rate an increase of momentum spread and emittance is observed. This was studied with a $^{129}Xe^{54+}$ 250 MeV/u beam. Different particle numbers were stored and cooled at three electron currents (fig. 2). The equilibrium momentum spread and emittances show a clear dependence on the stored ion current. The momentum spread increases for larger particle numbers with a $N^{1/3}$ dependence whereas the transverse emittances indicate an increase with $N^{1/2}$. The weaker transverse cooling force component is likely to cause the difference in longitudinal and transverse ion beam equilibrium temperature.

A comparison of the momentum spread for different ions

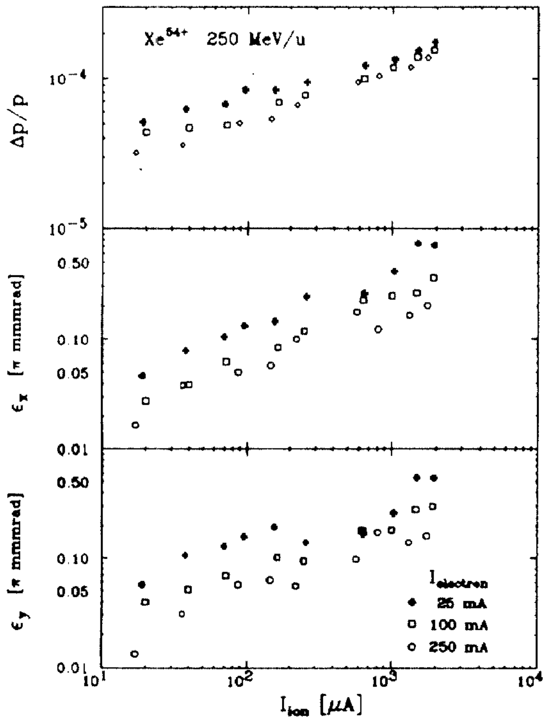

Figure 2: Dependence of ion beam ($^{129}Xe^{54+}$ 250 MeV/u) momentum spread and emittances as a function of stored ion current (particle number N). Emittances increase with $N^{1/2}$ and momentum spread shows a $N^{1/3}$-dependence.

which have been stored and cooled in the ESR is complicated by the fact that the electron currents varied (normally the higher charged ions were cooled with smaller electron currents because of the higher electron capture loss rate) and by the sensitivity of the ion beam temperature on the adjustment of cooling which is performed for each experiment seperately. For constant particle number the lower charged ions can be cooled to significantly smaller momentum spread which is also due to the smaller intrabeam scattering rate. A minimum momentum spread of $\Delta p/p = 10^{-6}$ has been observed for small ($N \leq 10^4$) particle number [7].

5 BEAM ACCUMULATON

Ion currents up to 6 mA have been accumulated in the ESR by a combination of rf stacking and electron cooling. With currents of typically some tens of μA which can be kicker injected and stored in the ESR currents of a few mA were obtained by deceleration with the rf cavity and cooling at the stack energy. Fast pulsing of the high voltage power supply also allows precooling on the injection orbit before deceleration to the stack orbit. Since electron cooling reduces the phase space volume and keeps the ions at the electron velocity this injection-deceleration scheme can be repeated up to the intensity limit of the storage ring which is either determined by beam instabilities or by loss due to radiative electron capture in the cooling section. This accumulation scheme is also feasible for the storage of radioactive nuclei with lifetimes long compared to the cooling time. First experiments have confirmed that electron cooling allows high resolution experiments with radioactive reaction products injected from the fragment separator. Electron cooling provides the possibility to separate ions of equal magnetic rigidity in the Schottky spectrum because of their different nuclear binding energy [8].

6 ELECTRON CAPTURE LOSS RATES

The ion loss rate due to radiative electron capture increases proportional to the density of electrons and to the square of the ion charge according to the recombination coefficient [9]

$$\alpha = \frac{1.92 \cdot 10^{-13} Z^2}{\sqrt{kT}} \left(\ln \frac{5.66 Z}{\sqrt{kT}} + 0.196 \left(\frac{kT}{Z^2} \right)^{1/3} \right) \left[\frac{cm^3}{s} \right]$$

The cooling experiments confirm this scaling for a transverse electron temperature $kT \simeq 0.3$ - 0.4 eV. Losses can be observed either by the signal of a current transformer detecting the stored ion current or by direct observation of the ions that have captured an electron in the cooling section and their detection after spatial separation in the dipole magnet after the cooler straight section. The high loss rate for highly charged ions imposes maximum electron currents depending on the experimental requirements concerning the beam quality. According to the results of equilibrium beam parameters beam lifetimes on the order of hours can be achieved for highly charged ions with electron currents of a few mA which are sufficient to obtain beam quality $\Delta p/p \leq 10^{-4}$ and $\epsilon_{x,y} \leq 1$ π mm mrad.

7 REFERENCES

[1] N. Angert et al., The 320 keV ESR-Electron Cooler, Proc. of the 2nd Europ. Part. Acc. Conf., Nice 1990, pp. 1374-1376

[2] K. Blasche et al., Status of the SIS/ESR-Facility at GSI-Darmstadt, Part. Acc., 1990, Vol. 32, pp. 83-90

[3] G. Münzenberg et al., Proc. of the First Int. Conf. on Radioactive Nuclear Beams, World Scientific, Singapore, p. 91

[4] A. Gruber et al., Internal Gas-Jet Target for the ESR at GSI, Nucl. Instr. Meth. in Phys. Res. A282 (1989) 87-93

[5] F. Bosch, First Experiments at the Darmstadt Storage Ring ESR, 5th Int. Symp. on Radiation Physics, Dubrovnik, Croatia, 1991, to appear in Nucl. Instr. and Meth. B

[6] I. Hofmann and M. Steck, Interpretation of Measured Cooling Equilibria by Intrabeam Scattering, GSI Scientific Report 1991, Darmstadt, GSI Report 92-1

[7] B. Franzke et al., this conference

[8] H. Geissel et al., First Storage and Cooling of Secondary Heavy-Ion Beams at Relativistic Energies, to appear in Phys. Rev. Lett.

[9] H. F. Beyer, D. Liesen and O. Guzman, On the Total Recombination Between Cooling Electrons and Heavy Ions, Part. Acc., 1989, Vol. 24, pp. 163-175