Electron Cooling of Heavy Ions at GSI

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Abstract

Electron cooling of heavy ions has been studied at the storage ring ESR over the whole range of ions up to bare uranium. Systematic measurements of the ion beam temperature evidence a dependence on the particle number which proves an equilibrum between cooling and heating by intrabeam scattering. Measurements of the longitudinal intrabeam scattering rate and of the the longitudinal cooling force provide with information about the longitudinal cooling times. Small deviations of the longitudinal cooling time from the theoretically predicted A/Z^2 -dependence are found.

1 INTRODUCTION

The ESR storage ring at GSI [1] is part of an accelerator complex [2] which can deliver ion species over the entire range of masses and after acceleration in the heavy ion synchrotron SIS can produce bare ions up to uranium. These ions having emittances $\epsilon_{x,y} \simeq 10 \ \pi mmmrad$ and a momentum spread $\Delta p/p \simeq 10^{-3}$ are injected into the storage ring ESR and can be cooled by the electron cooling system to a phase space density which is typically by 5 to 6 orders of magnitude larger than that of the uncooled beam after injection. This implicates the possibility to accumulate particles in the storage ring. Multiplication factors in excess of 100 are routinely achieved by a combination of rf stacking and cooling resulting in a maximum ion current of 7 mA. The beam lifetime of the cooled heavy ion beams under ultra high vacuum conditions is limited by radiative electron capture [3]. Therefore a high efficiency of the cooling system is desirable in order to reduce the ion beam losses by operation of the electron cooler at low electron currents. The achievable multiplication factors by cooled beam accumulation are also affected as for highly charged ions they are determined by a balance between the injection rate and the capture loss rate.

2 ELECTRON COOLER PARAMETERS

The large range of ion masses and charges as well as the possibility to decelerate the ions in the ESR require a large flexibility of the electron cooling sytem. A system was designed which allows independent choice of electron energy, electron current and magnetic guiding field [4]. For simplicity of operation the magnetic field in the present experiments was chosen in the range $B_o = 0.7 - 1.1 \ kG$. The lowest electron beam energy for cooling was 50 keV, the highest energy was 165 keV, since the maximum energy is presently limited by high voltage breakdown in the air filled Faraday room at approximately 190 kV. Reconstruction of the causing components is under way. No significant dependence of the cooling efficiency on the energy and magnetic field in this regime has been observed.

The electron current determines the cooling power which is directly proportional to it. The maximum electron current for continuous cooler operation was 1 A since for higher currents unreliable operation is caused by electron beam instabilities most likely due to discharges. For experiments with highly charged ions operation with high electron currents is undesirable in most applications as the beam lifetimes drops to a few minutes. To achieve fast cooling during injection of hot ion beams or to extract the stored ion beam by the electron capture process higher currents might be requisite. Reconstruction of the drift tubes which surround the electron beam on its way from the gun to the collector and modifications of the gun and collector geometry are expected to improve the high current performance. In the low current regime efficient cooling with currents of a few mA was observed, even a current of 1 mA was found to be sufficient to stabilize the ion beam against heating from scattering in the residual gas. Therefore in experiments with continuous electron cooling storage times on the order of days are feasible.

For optimized cooling a fine adjustment of the angle between electron and ion beam is necessary. Minimum transverse emittances of the ion beam indicate the optimum situation, although in this case the longitudinal momentum spread is not minimum necessarily. An increased heating by intrabeam scattering from the strongly compressed transverse to the longitudinal degree of freedom explains this contradiction.

3 EQUILIBRIUM BETWEEN COOLING AND INTRABEAM SCATTERING

In the static operational mode of storage and cooling at constant energy the ion beams are cooled to equilibrium temperatures which are determined by a balance between all heating sources and the cooling power of the electron cooling system. As the ESR is operated under ultrahigh vacuum conditions $(p \le 10^{-10}mb)$ scattering in the residual gas is negligible. For cooled ion beams of high phase space density the main heating process is intrabeam scattering.

This has been proven by systematic measurements of the longitudinal momentum spread and the transverse emittances as a function of the number of stored ions. The momentum spread was measured by Schottky noise or BTF analysis. Position sensitive wire chambers detecting ions after recombination with electrons in the cooling section provided a non-destructive method to measure beam profiles using the down charged ions which are spatially separated in dispersive sections of the storage ring [5].



Figure 1: Momentum spread and emittances of a cooled Au^{79+} 280 Mev/u beam as a function of the number of stored particles.

The equilibrium beam properties of a beam of bare gold ions at 280 MeV/u cooled by a 200 mA electron beam are shown in Fig. 1. The temperatures - longitudinal and transverse as well - increase with the number of stored ions N. The longitudinal momentum spread shows a N^{1/3}-dependence, whereas horizontal and vertical ion beam emittances grow with N^{2/3}. This is in good agreement with previous results for the equilibrium momentum spread of a xenon beam, but in small disagreement for the transverse degree of freedom which was increasing with N^{1/2} [3]. Considering that particularly the transverse degrees of freedom are sensitive to small alignment errors of the electron beam this effect may be accountable for the discrepancy.

During many experiments with cooled heavy ions the dependence of the momentum spread on the ion beam intensity was monitored parasitically by Schottky noise analysis (Fig. 2). Due to the experimental requirements the cooling electron currents vary, but all measurements show the $N^{1/3}$ -increase of the momentum spread with the number of stored ions, only for very small particle numbers the dependence seems to approach $N^{1/2}$. The separation of the light ions from the heavier ones is likely to be caused by some complication in the analysis of the Schottky noise. Due to the high phase space density the light ions show collective beam behaviour which aggravates the interpretation of the spectrum. Schottky noise analysis in this case can result in a momentum spread which deviates from that obtained by BTF analysis by up to a factor of two. The Schottky noise analysis results in systematically lower values for the momentum spread, but proves the $N^{1/3}$ -dependence.



Figure 2: Dependence of ion beam momentum spread as a function of the number of stored ions. Electron currents and ion beam energies are indicated.

The observed equilibrium beam temperatures can be well founded in the framework of the intrabeam scattering theory giving indirect evidence of the prevalence of this heating mechanism for cooled heavy ion beams [6]. This was also confirmed by variation of the electron current and the good agreement between experimental and theoretical cooling rates.

4 LONGITUDINAL INTRABEAM SCATTERING RATES

The heating effect by intrabeam scattering was directly observed by a measurement of the longitudinal beam distribution after stopping cooling instantaneously. The energy of the electron beam can be detuned by stepping of the accelerating voltage ($\Delta V = 5 \ kV$) within milliseconds to an energy which causes a momentary interruption of the cooling action. The high voltage step was used as a trigger signal to start a fast Fourier analyzer (minimum sweep time 8 ms) with a variable delay after the trigger signal. In Fig. 3 the momentum spread of a 0.9 mA Dy^{66+} beam at 290 MeV/u which was cooled by an electron beam of $I_{el} = 500 \ mA$ is shown as a function of the delay time between the high voltage step and the start of the analyzer sweep. The time derivative of the momentum spread growth reflects the instantaneous heating rate.



Figure 3: Momentum spread of an intense Dy^{66+} beam at 290 MeV/u as a function of the time between interruption of cooling and start of the spectrum analyzer sweep.

From the initial value of the growth rate the longitudinal cooling rate of the electron beam in equilibrium can be concluded which results in a cooling time $\tau = 17 ms$ (normalized to $n_{el}^* = 1 \cdot 10^6 cm^{-3}$ and a relative cooler length $\eta_c = 0.0185$). Similar measurements with less intense beams of Au^{76+} , Pb^{82+} and U^{91+} resulted in cooling times $\tau = 5 - 8 ms$. As the difference in the A/Z^2 -ratio in these measurements is almost negligible the difference may be explained by a dependence of the cooling time on the intensity and phase space density of the ion beam. Measurements with simultaneous observation of the transverse degree of freedom will give more detailed information of the transverse heating rate and of the Z- and A-dependence of the cooling time.

5 LONGITUDINAL COOLING FORCE AND COOLING TIME

The measurement of the longitudinal cooling force can be separated into two regimes. For large relative velocities $(v^* > 10^4 m/s)$ the cooling force descends and can be easily measured by fast stepping of the accelerating voltage of the electron beam. The action of the detuned electron energy can be consequently monitored by fast Fourier analysis of the motion of the ion beam towards the velocity that is determined by the electron velocity. In contrast to this the cooling force at small relative velocities $(v^* \leq 10^4 m/s)$ is expected to increase directly proportional to the relative velocity up to a certain maximum. This linear increase of the cooling force corresponds to a constant cooling time which is on the order of milliseconds and therefore not accessible by the high voltage stepping method. Therefore the approach to heat the ion beam simultaneously with rf noise and to determine the cooling force from the particle distribution was applied [7].

The results of both methods for Ne^{10+} and Bi^{82+} ions

are displayed in Fig. 4 with the straight line indicating the smoothed cooling force curve from the heating method and the discrete data points originating from the high voltage step method. For easiness of comparison the results are normalized to an electron density $n_e^* = 1 \cdot 10^6 cm^{-3}$ proving a strong increase of the cooling force with the ion charge.



Figure 4: Cooling force as a function of the longitudinal relative velocity for Ne^{10+} at 150 MeV/u and Bi^{82+} at 230 MeV/u normalized to $n_e^* = 1 \cdot 10^6 cm^{-3}$. Data points were determined by high voltage stepping, straight lines are smoothed data from measurements of the particle distribution with heating by rf noise.

From these cooling force measurements a cooling time $\tau_c = 2.4 ms$ for Ne^{10+} and $\tau_c = 0.9 ms$ for Bi^{82+} (normalized to $n_c^* = 1 \cdot 10^6 cm^{-3}$) was derived for the linear part of the cooling force. The improvement for the heavier ion however is a factor of 2.5 smaller than expected from the Z^2 -scaling of the cooling force. Further studies under well controlled conditions are necessary to prove whether this is a deviation from the standard theory as predicted for highly charged ions or whether it is related to differences in the transverse beam size caused by small misalignments between electron and ion beam.

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7 REFERENCES

- B. Franzke, Nucl. Instr. Meth. B24/25 (1987) 18
 B. Franzke et al., these proceedings
- [2] K. Blasche et al., Part. Acc., 1990, Vol. 32, pp. 83-90
- [3] M. Steck et al., Proc. of the 3rd Europ. Part. Acc. Conf., Berlin 1992, pp. 827-829
- [4] N. Angert et al., Proc. of the 2nd Europ. Part. Acc. Conf., Nice 1990, pp. 1374-1376
- [5] F. Bosch, Nucl. Instr. Meth. A314 (1992) 269-276
- [6] I. Hofmann et al. Proc. of the 3rd Europ Part. Acc. Conf., Berlin 1992, pp. 783-785
- [7] H. Poth et al., Nucl. Instr. Meth. A287 (1990) 328-332