Recent Developments at the TSR Heidelberg *

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Abstract

The heavy ion cooler storage ring in Heidelberg has been operated in the synchrotron mode. A $^{12}C^{6+}$ ion and a CD^+ molecular ion beam have been accelerated up to the rigidity limit of the ring of 1.5 Tm. At the electron cooler a new heated cathode has been installed and together with an adiabatic expansion of the electron beam considerably reduced transverse electron beam temperatures have been reached. Using the beam profile monitor transverse electron cooling was investigated for different ion species and indirect transverse cooling of a longitudinally laser-cooled ion beam could be demonstrated for the first time.

1 INTRODUCTION

The Test Storage Ring TSR [1] installed at the Max Planck Institut für Kernphysik is used for accelerator, atomic and nuclear physics experiments. The ring has a circumference of 55.4 m and a maximum rigidity of 1.5 Tm and can receive heavy ions up to iodine from a 12 MV tandem Van de Graaff and a normal conducting RF linac combination. Electron cooling is used to reduce the phase space of the stored beam and for the accumulation [2] of ions.

2 BEAM ACCELERATION

The magnet system of the heavy ion cooler storage ring TSR was designed for a beam rigidity in the range between 0.2-1.5 Tm. In order to change the energy of the stored ions a new resonator [3] was built and the control system of the TSR was modified and enhanced. With this new system one can now vary simultaneously the magnetic fields and the frequency of the resonator to accelerate or decelerate stored ions. It was possible to accelerate a stored $^{12}C^{6+}$ (E_0 = 73.3 MeV) beam, without phase feedback loop, by more than a factor of three in kinetic energy ($E_f \approx 240$ MeV- corresponding to an increase of the revolution frequency of 0.7707 MHz to 1.394 MHz) with particle losses of less than 10%. The maximum energy reached for $^{12}C^{6+}$ was about 300 MeV corresponding to a rigidity of 1.44 Tm. Deceleration of $^{12}C^{6+}$ ions was possible from 73.3 MeV to 19 MeV.

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Synchrotron acceleration was used to enable the research on dissociative recombination of CD^+ molecules with electrons. In the experiment a beam of 2.0 MeV CD^+ was supplied by a Van de Graaff accelerator using a standard Penning source and injected into the TSR. After injection the energy was ramped up from 2.0 MeV to 7.5 MeV by synchrotron acceleration, which allowed to increase the density of the velocity matched electron beam and which facilitated the detection of the neutral reaction products. The time required for ramping was 5 s. Up to $5 \cdot 10^7$ particles were stored in the TSR at an average vacuum of $1 \cdot 10^{-10}$ mbar with a beam lifetime of 4.5 s. After reaching the maximum energy, the bèam was merged with the electron beam of the cooler. Typical values for the electron current were 10 mA corresponding to an electron density of $5 \cdot 10^6 cm^{-3}$. It was possible to detect and resolve previosly unknown resonances [4].

3 ADIABATIC EXPANSION OF THE ELECTRON BEAM

The electron beam in the TSR is used as a beam cooling device and as an electron target. The transverse temperature of the electron beam is of particular importance for recombination experiments at small relative velovities. Small transverse temperatures can be obtained by adiabatic expansion of the electron beam after acceleration [5]. The transverse temperature $T_\perp$ divided by the longitudinal magnetic field $B_\parallel$ of the cooler is an adiabatic invariant:

$$\frac{T_\perp}{B_\parallel} = const,$$

which is preserved, if the change of magnetic field within a cyclotron wavelength $\lambda_c = \frac{2\pi m v_\parallel}{eB}$ is very small compared to the total field:

$$\xi = \frac{\lambda_c}{B}\left|\frac{dB}{dz}\right| = \frac{\sqrt{8mE_\parallel}\pi}{eB^2}\left|\frac{dB}{dz}\right| \ll 1,$$

where $E_\parallel$ is the electron energy and m the electron mass. In the cooler an adiabatic expansion of the magnetic field by a factor approximately 7 and a corresponding reduction of $T_\perp$ from 110meV (cathode temperature $\approx 1000\ ^\circ C$) to approximately 16 meV was realized with adiabaticity parameters ξ at a typical electron energy of $E_{\|} = 5$ keV of less than 0.09. The expansion was realized by replacing the old heated (2″) cathode by a smaller one with 0.75″ diameter, by adjusting the Pierce shield and by running the existing gun solenoid at a magnetic field up to 3 kG with a smooth transition to the next solenoid having typical field of about 0.4 kG.

The transverse electron temperature of the electron beam could be measured with laser induced recombination [6]. In this experiment the induced recombination rate of the ions with an electron beam as a function of laser photon energy was measured and a transverse electron temperature of 17 ± 2 meV could be deduced. Measuring the width of dielectronic recombination resonances of $^{80}Se^{23+}$ (E=350 MeV) at low relative energies between ions and electrons, a transverse electron temperatur of 19 ± 5 meV was determined. Figure 1 shows the measured recombination rate coefficient as a function of relative energy between ions and electron. The solid curve is a fit to the data resulting in temperatures given in the insert.

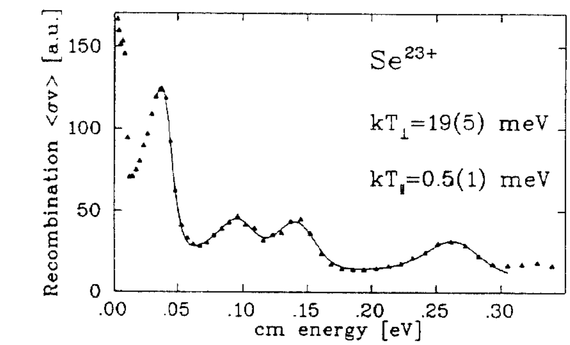

Figure 1: *Dielectronic recombination rates for $^{80}Se^{23+}$ ions.*

4 INDIRECT TRANSVERSE LASER COOLING

One of the main topics of the experimental program at the TSR is the study of cold, dense ion beams. Indirect transverse cooling expected as a result of longitudinal laser cooling in connection with intrabeam scattering (IBS) could now be observed for the first time [7] . The experiment was performed with 10^7 $^9Be^+$ ions stored at an energy of 7.3 MeV with a storage lifetime of 25 s. In order to precool the ion beam, having initial temperatures of $T_{\|} \approx 4000$ K and $T_{\perp} \approx 10^6$ K, it is first merged with the cold electron beam in the electron cooler. Electron cooling reaches equilibrium after about 7 s and leads to temperatures of $T_{\|} \approx 300$ K and $T_{\perp} \approx 4000$ K. The transverse temperatures are derived from the transverse beam sizes, measured with a beam profile monitor [9]; at $T_{\perp} \approx 4000$ K the average beam diameter is about 0.5 mm. After switching off the electron cooling longitudinal laser cooling is performed. In Figure 2 the transverse temperature evolution of an ion beam is shown. After the electron cooling is switched off the ion beam starts to heat up due to intra beam-scattering if no further cooling is applied. But when longitudinal laser cooling started 2 s later, the transverse temperature reduces again to an equilibrium value of 2500 K. The longitudinal beam temperature at the beginning of laser cooling first drops to ≈ 5 K and then heats up to an equilibrium value of 15 K.

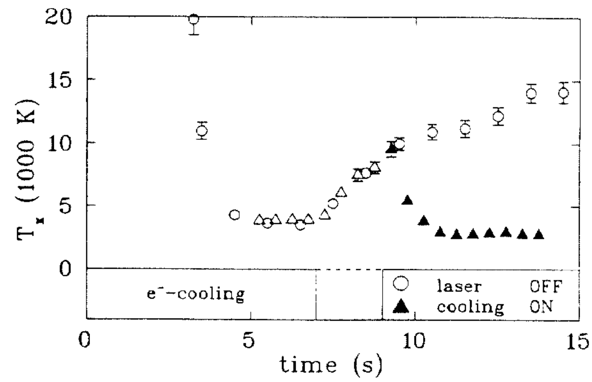

Figure 2: *Evolution of the horizontal beam temperature observed with and without longitudinal laser cooling after electron precooling.*

5 TRANSVERSE ELECTRON COOLING

Using the method of beam accumulation by stacking with electron cooling intensities can be enhanced by factors of several thousand as compared to a single turn injection. For this stacking method the total intensity multiplication factor N is given by [2]:

$$N = n_r \cdot M_{eff} \cdot T$$

where n_r is the repetition rate, M_{eff} the effective intensity multiplication factor of a multiturn injection and T is the beam life time. As the repetition rate n_r for the multiturn injection depends on the time T_{cool} necessary for cooling the ion beam ($n_r = 1/T_{cool}$) systematic measurements of cooling times were carried out with $^{12}C^{6+}$ and $^{32}S^{16+}$ (E=11.4 MeV/u) ion beams using the adiabatic expanded electron beam. In the experiments the horizontal phase space was filled by multiturn injection resulting in a horizontal beam diameter at the position of the beam profile monitor of 40.4 mm (fig. 3) and an acceptance of approximate 110 πmmmrad. At the position of the electron cooler the Twiss parameters have the following values: $\beta_x = 3.0m$, $\beta_y = 0.7m$ and $D_x = 0.35m$. The beam profile of the $^{12}C^{6+}$ ions after cooling (also shown in fig. 3) displays a 1 mm beam with extending to ± 8 mm. In the following the cooling time T_{cool} is defined as the time necessary to cool 80% of the particles outside the region of the cooled beam (marked in fig. 3) into the marked region. For $^{12}C^{6+}$ with E/A=11.4 MeV/u a cooling time of 1.02±0.02 s at an electron density of $n_e = 0.32 \cdot 10^8 cm^{-3}$

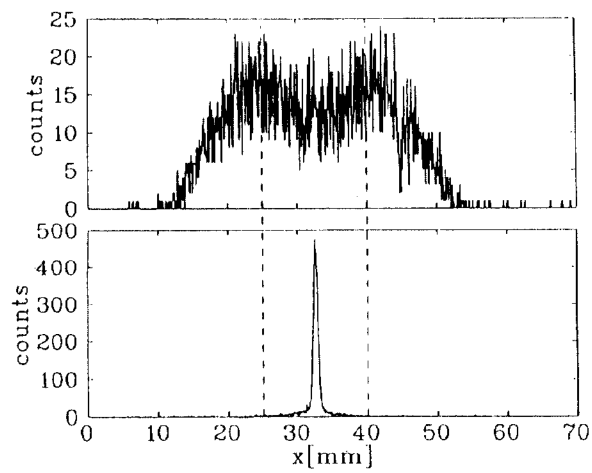

Figure 3: *Measured beam profile for $^{12}C^{6+}$ ions after multiturn injection (top) and after electron cooling for 1.5 s cooling (bottom).*

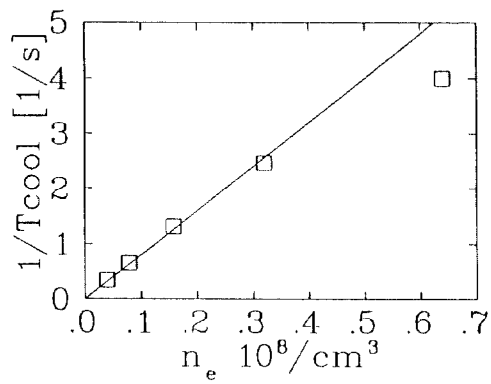

Figure 4: *Measured inverse cooling time for $^{32}S^{16+}$ (E=11.4 MeV/u) as a function of electron density.*

was measured. To examine the dependence on the mass (A) and charge (Z) transverse cooling was also measured with $^{32}S^{16+}$ having the same velocity and beam profile after the multiturn injection. In this case a cooling time of 0.39 ± 0.1 s was obtained. Assuming a Z^2/A dependence the ratio of the cooling times should be $\frac{T_{cool,c}}{T_{cool,s}} = 2.66$. The experimental value is 2.62 ± 0.1 in good agreement with this value. Figure 4 shows the measured inverse cooling time for $^{32}S^{16+}$ as a function of the electron density n_e. Up to a density of $0.3 \cdot 10^{10} cm^{-3}$ $1/T_{ecool}$ is proportional to n_e. Increasing of the electron density further leads to a deviation of the linear behavior, which can be explained by the increasing space charge parabola of the electron beam. For ions with $\beta = 0.156$ (E/A=11.4 MeV/u, $n_e \leq 0.3 \cdot 10^{10} cm^{-3}$) $1/T_{cool}$ is given by $1/T_{cool} = k \cdot n_e \frac{Z^2}{A}$, where $k \approx 10^{-8} cm^3/s$. As the cooling time decreases with decreasing ion velocity β, $1/T_{cool}$ can be estimated by

$$\frac{1}{T_{cool}} \geq k \cdot n_e \frac{Z^2}{A}$$

for $\beta \leq 0.15$.

Transverse cooling was also examined for different diameters of the electron beam. In this experiment the electron beam size was changed using different expansion factors but keeping the electron density constant by $n_e \approx 0.3 \cdot 10^8 cm^{-3}$. This experiment was carried out with a $^{32}S^{16+}$ (11.4 MeV/u) ion beam having in the electron cooling section a horizontal diameter of 4 cm after multiturn injection. With electron cooling the equilibrium was reached after about 0.5 s if an electron beam diameter of 5 cm was used, only when decreasing the diameter of the electron beam below the ion beam size the cooling times were increased; for an electron beam diameter of about 2 cm the cooling time increased to about 1 s.

6 ACKNOWLEDGMENT

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