ELECTRON COOLING EXPERIMENTS AT THE HEIDELBERG HEAVY ION STORAGE RING TSR

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Abstract

The electron beam in the TSR is used as an electron target and as a cooling device. The longitudinal friction force on heavy ions was measured using the electron cooler and induction accelerator of the TSR. Using the beam profile monitor transverse electron cooling was investigated for different ion species.

1 INTRODUCTION

The heavy ion storage ring TSR [1] installed at the Max-Planck Institut für Kernphysik is used for accelerator, atomic and molecular 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. With different stacking techniques - multi-turn injection and electron cooling stacking [2] high currents up to several mA of long living ion beams can be accumulated in the TSR in spite of weak currents delivered by the tandem.

The transverse temperature of the electron beam is of importance for recombination experiments at small relative velocities. Small transverse temperatures can be obtained by adiabatic expansion of the electron beam after acceleration [3]. The transverse temperature $T_\perp$ divided by the longitudinal magnetic field $B_\|$ of the electron cooler is an adiabatic invariant: $T_\perp/B_\|$ = const. The gun solenoid of the electron cooler is operated at magnetic fields up to 10 kG with a smooth transition to the next solenoid of about 0.4 kG resulting in an expansion factor of up to 25.

2 LONGITUDINAL ELECTRON COOLING

At the TSR longitudinal electron cooling is investigated with the aid of an induction accelerator (IndAcc)[4] applying a constant accelerating or decelerating force on the cooled ion beam. Within the linear regime of the cooling force the equilibrium between the IndAcc and electron cooling leads to a shift in the revolution frequency which together with the strength of the applied induced voltage allows to evaluate the electron cooling force. From these measurements the slope $dF_\|/dv_\|(v=0)$ can be calculated. An interaction length of 1.2m, over which at the TSR the angular matching between the beams is within a few 10^{-4} rad, has been used in the calculation.

Systematic measurements have been made using a $^{12}C^{6+}$ beam at an energy of 73.3 MeV and a $^{19}F^{6+}$ beam at an energy of 74.6 MeV. The magnetic field B_{cool} in the interaction section for those measurements was 418 Gauss.

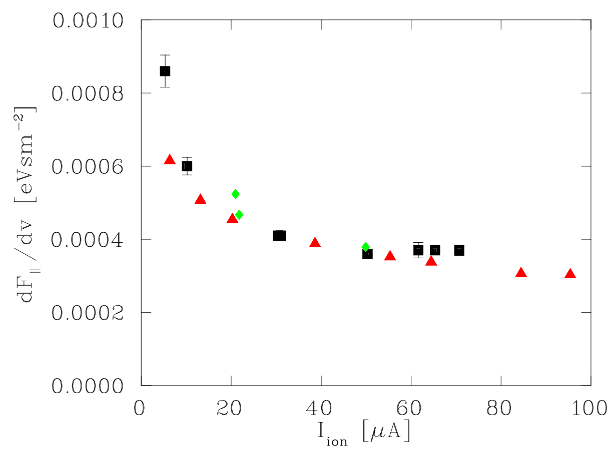

Figure 1: *The slope of the longitudinal cooling force as a function of the ion current of a $^{12}C^{6+}$ beam (E = 73.3 MeV)*

Figure 1 shows the slope of the longitudinal electron cooling force for different ion currents of the carbon beam. The slope clearly decreases with increasing ion current. One possible explanation may be: Higher ion intensities lead to increasing intra beam scattering and thereby the transverse velocity spread of the cooled ion beam increases with the ion current, which reduces the cooling force. Results from three different beam times are marked with different plotting symbols. The electron density for these experiments was $0.79 \cdot 10^7$ cm^{-3}.

Figure 2 shows the slope of the longitudinal cooling force as a function of the electron density. This experiment was done using the carbon beam at an intensity of 50 μA (squares) and 20 μA (circles) and the fluor beam at an intensity of 10 μA (triangles). To the measured data a power law $\propto n_e^\alpha$ was fitted, resulting in an exponent α between 0.6 and 0.7.

For both ion species the longitudinal cooling force was measured for different expansion factors. Figure 3 shows the slope of the longitudinal cooling force as a function of the expansion factor. The experiments were performed at a constant electron density of $0.79 \cdot 10^7$ cm^{-3}. The different plotting symbols for the carbon beam (squares and circles) result from two different beam times. The dashed

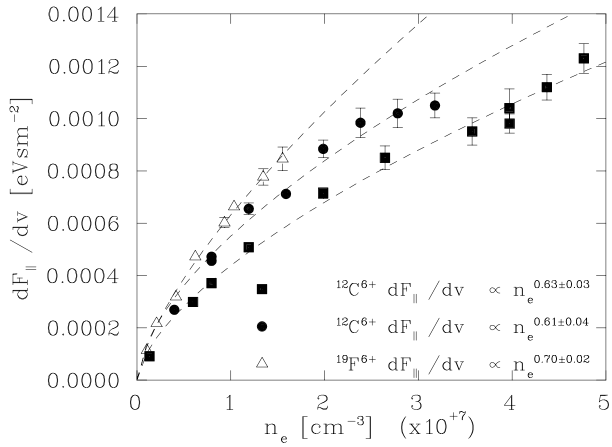

Figure 2: *The slope of the longitudinal cooling force as a function of the electron density*

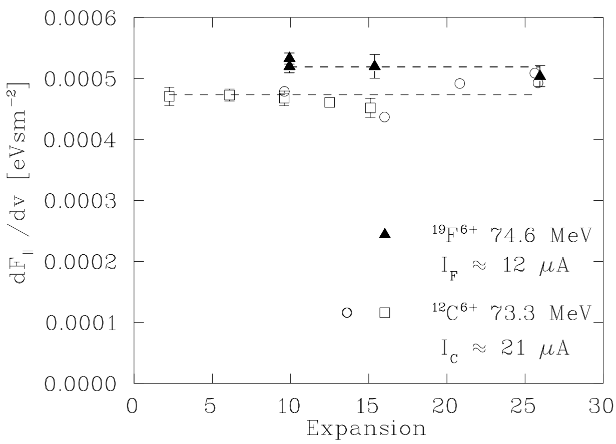

Figure 3: *The slope of the longitudinal cooling force as a function of the expansion factor*

lines are constant functions fitted to the measured data indicating that the transverse temperature of the electron beam has no influence on the longitudinal friction force.

3 TRANSVERSE ELECTRON COOLING TIMES FOR SMALL INITIAL BEAM DIAMETER

If the initial beam diameter of the ion beam is small enough, betatron oscillations are damped exponentially. In this case the slope of the cooling force $\alpha_y = dF_y/dv_y(v_y = 0)$ can be calculated from the time constant τ and the ion mass m_i: $\alpha_y = 2/\eta_c \cdot\ m_i/\tau_y$, the index y represents the two transverse degrees of freedom, η_c = 1.2/55.4 is the ratio between interaction length in the cooler and the circumference of the ring. The factor 2 results from betatron oscillation. Ion beams with small initial profiles are produced using following method: After injection the ion beam is cooled down to equilibrium,

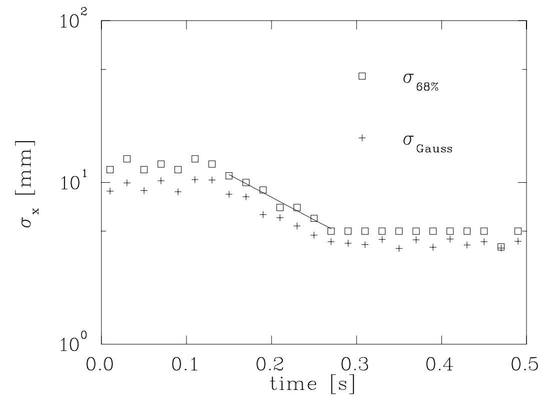

Figure 4: *Measured horizontal beam width σ_x during electron cooling*

then electron cooling is switched off and RF-noise is applied to the horizontal or vertical kicker for 1 or 2 seconds in order to blow up the ion beam. Immediatly after switching off the RF-noise electron cooling is switched on again and the time development of the beam profiles are recorded with the beam profile monitor. An example of such a cooling time measurement at an electron density of $n_e = 0.79 \cdot 10^7 cm^{-3}$ is shown in figure 4. The half beam width containing 68% of the particles is marked with $\sigma_{68\%}$,

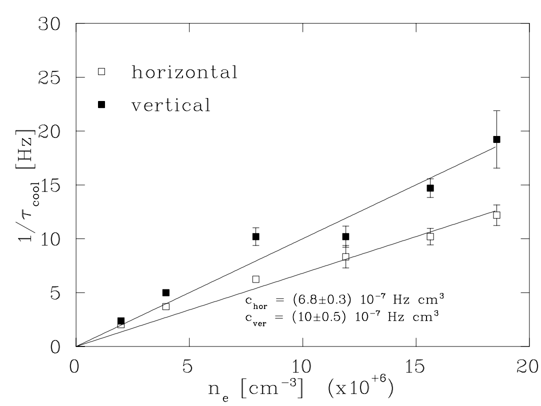

Figure 5: *Measured horizontal and vertical cooling rates as a function of electron density*

the standard deviation σ_{Gauss} of a gaussian fit is also shown. The cooling time τ was determined by an exponential fit $\sigma_{68\%} \sim e^{-\frac{t}{\tau}}$, the fit gives a cooling time τ of 156 $\pm$ 11 ms. The dependence of the cooling rate $1/\tau$ on the density of the electron beam is shown in figure 5. The magnetic field B_{cool} was 418 G and the expansion factor was 9.6. To the transverse cooling rates linear functions are fitted $1/\tau_y = c_y \cdot n_e$, resulting in $c_{hor} = (6.8 \pm 0.3)\ 10^{-7}\mathrm{s}^{-1}\mathrm{cm}^3$ and $c_{ver} = (10 \pm 0.5)\ 10^{-7}\mathrm{s}^{-1}\ \mathrm{cm}^3$.

The slope of the longitudinal and the transverse cooling force can now be compared. A transverse cooling rate of about 8 s^{-1} for an electron density of 0.79 10^7 cm^{-3} results in a slope of the transverse cooling force of about $\alpha_\perp \approx$

$1 \cdot 10^{-4}$ eVs/m^2.

The slope of the longitudinal cooling force at this density is $\alpha_\parallel \approx 5 \cdot 10^{-4}$ eVs/m^2, which is about a factor 5 bigger than the transverse one.

4 TRANSVERSE ELECTRON COOLING TIMES FOR LARGE INITIAL BEAM DIAMETER

Injected ion beams have high transverse velocities according to a beam diameter of typically 20 mm (as shown by figure 6). The beam diameter is defined as the width containing 68% of the particles. Due to the large beam diameter the ions interact with a non linear force in the cooler. An example of a cooling time measurement is given in fig. 6. The profile of a $^{12}C^{6+}$ (6.1 MeV/u) ion beam having an initial diameter of $d_i = 19.8$mm is cooled to an equilibrium diameter of $d_f = 1.1$mm within 2 seconds. Defining the particles within the region between $-3d_f$ and $+3d_f$ marked in fig. 6 as cooled, the cooling time T_{cool} is defined as the time it takes to cool 80% of the particles outside the cooled region into the marked region. In order to examine the dependence on mass (A) and charge (Z), cooling times were measured for $^{12}C^{6+}$ and $^{32}S^{16+}$, having the same velocity of $\beta = 0.16$ and beam profile after multi-turn injection and using a constant electron density of $n_e = 0.28 \cdot 10^8 cm^{-3}$. The cooling time measured are $T_{cool,C} = 1.26 \pm 0.02$ s and $T_{cool,S} = 0.5 \pm 0.03$ s. Assuming a Z^2/A dependence the

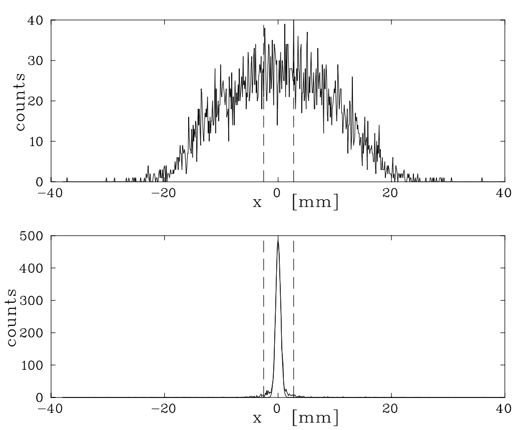

Figure 6: *Measured beam profile in the horizontal plane for $^{12}C^{6+}$ ions after multi-turn injection (top) and after 2 seconds of electron cooling (bottom).*

ratio of the cooling times should be $T_{cool,C}/T_{cool,S} = 2.67$. The experimental value is 2.5 ± 0.2 in agreement with the theoretical value.

In order to investigate the velocity dependence of the cooling time, measurements with different ion species were performed at velocities ranging from $\beta = 0.03$ to $\beta = 0.16$. The ion and molecule species used for those measurements were HeH^+, $^{18}O^{2+}$,$^{28}Si^{2+}$, $^{14}N^{3+}$, $^{12}C^{6+}$,$^{35}Cl^{6+}$, $^{32}S^{16+}$, $^{80}Se^{23+}$. The electron densities were in the range between $0.1 - 3 \cdot 10^7 cm^3$. The magnetic field B_{cool} was 218 G and the expansion factor was 7.7. The initial beam diameters at the position of the beam profile monitor were 22.3 ± 7.6 mm. Figure 7 shows the measured inverse cooling time $1/T_{cool}$ normalized to Z^2/A and an electron density of $10^8 cm^{-3}$ plotted against the ion velocity $\beta = v/c$. Each symbol represents a different ion species. The inverse cooling time can be described by $1/T_{cool} \approx k_2 \cdot n_e \frac{Z^2}{A}\frac{1}{\beta^2}$

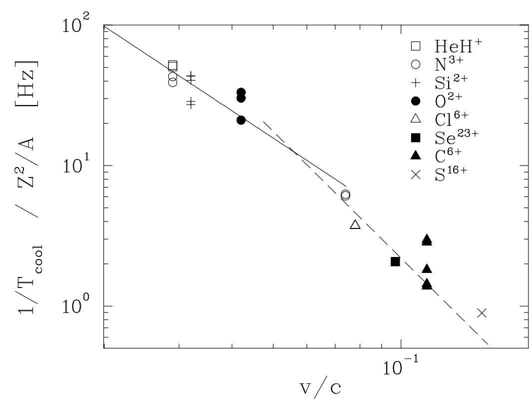

Figure 7: *Normalized inverse cooling time as a function of ion velocity. The inverse cooling times are normalized to Z^2/A and an electron density $n_e = 10^8 cm^{-3}$*

with $k_2 = 3.9 \cdot 10^{-2}\ s^{-1}/10^8 cm^3$. The function $k_2 \cdot n_e \frac{Z^2}{A}\frac{1}{\beta^2}$ is drawn as a solid line in fig. 7 in the velocity region $0.025 \leq \frac{v}{c} \leq 0.07$. In the velocity range $0.07 < \frac{v}{c} \leq 0.16$ $1/T_{cool}$ can be described by $k_3 \cdot n_e \frac{Z^2}{A}\frac{1}{\beta^3}$, where $k_3 = 2.2 \cdot 10^{-3} s^{-1}/10^8 cm^3$ shown in fig. 7 as a dashed line. This empirical formula gives a reasonable estimate for the inverse cooling time $1/T_{cool}$. For $^{12}C^{6+}$ at an energy of 73.3 MeV and an electron density of $n_e = 0.79 \cdot 10^7 cm^{-3}$ the above formula gives a cooling time of $T_{cool} \approx 3s$ for large initial diameter. The cooling of this beam starting with a small initial diameter lead to a time constant $\tau \approx 160$ ms.

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