DISPERSIVE ELECTRON COOLING AT THE HEIDELBERG HEAVY ION STORAGE RING TSR

M. Beutelspacher, M. Grieser, D. Schwalm, A. Wolf, MPI für Kernphysik, Heidelberg, Germany
K. Noda, NIRS, Chiba, Japan

Abstract

At low electron-ion relative velocities the cooling rates due to the electron cooling force differ by a factor of 4 - 8 [1]. By dispersive electron cooling, it is possible to transfer longitudinal cooling rate into horizontal cooling rate. In this scheme, a horizontal gradient in the longitudinal cooling force leads to a cooling or heating rate due to dispersive coupling. This gradient can be achieved by displacing the electron beam with respect to the ion beam, exploiting the parabolic velocity profile of the electrons because of the space charge. Operating the TSR with a somehow higher dispersion D_S = 1.63 m in the interaction region, longitudinal cooling force and transverse cooling rates for low electron-ion relative velocities were measured in agreement with a simple model, taking into account the electron density and dispersion.

1 PRINCIPLE OF DISPERSIVE ELECTRON COOLING

The principle of dispersive cooling is shown in figure 1. A change in the longitudinal momentum of a stored ion $\Delta p_{\|}$ leads to a horizontal displacement of the closed orbit due to dispersion:

$$\Delta x = x_D = D_S \cdot \frac{\Delta p_{\|}}{p_0} \tag{1}$$

p_0 is the longitudinal momentum of the ion in the laboratory frame, the proportionality factor D_S is called the dispersion. A positive change $\Delta p_{\|}$, which is transfered to the ion ring outward reduces the betatron amplitude and therefore damps the betatron oscillation. A positive momentum change experienced ring inward excites the horizontal oscillation. Assuming a horizontal gradient of the longitudinal cooling force a net effect of this process arises [2]:

$$\frac{1}{\epsilon_x}\frac{d\epsilon_x}{dt} = -\frac{D_S}{p_0}\eta_c \frac{dF_{\|}}{dx} \tag{2}$$

ϵ_x is the horizontal emittance, p_0 the average longitudinal momentum of the ion beam in the laboratory frame and η_c = 1.2m/55.4m is the fraction between the interaction length and the circumference of the TSR. A horizontal gradient of the longitudinal cooling force is achieved by displacing the electron beam with respect to the ion beam because of the parabolic velocity profile of the electrons due to the space charge, as shown in figure 2:

$$\langle v_e(r)\rangle = v_0 + \alpha_D r^2 \tag{3}$$

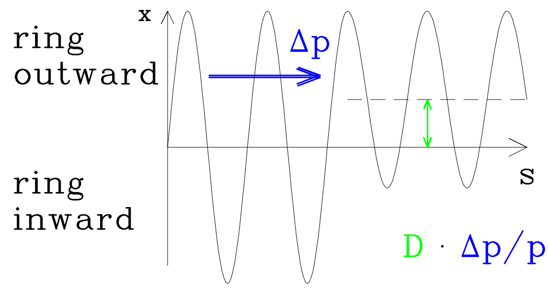

Figure 1: Principle of dispersive cooling. A positive change in the longitudinal momentum $\Delta p_{\|}$, transfered to the ion ring outward, shifts the closed orbit towards the outer part of the ring and therefore damps the horizontal betatron oscillation.

v_0 is the velocity on the axis of the beam in the laboratory frame, n_e is the electron density, m_e the electron mass and $\alpha_D = e^2 n_e/(4\epsilon_0 m_e v_0)$. Ions, which find themselves closer to the outer part of the ring (on the “right” side respectively, compare figure 2) interact with faster electrons and are accelerated. Ions, which are closer towards the inner part of the ring, interact with slower electrons and are therefore decelerated. By this means a horizontal gradient of the longitudinal cooling force arises $dF_{\|}/dx \approx \alpha_{\|} \cdot 2\alpha_D x$, where $\alpha_{\|}$ is the longitudinal friction coefficient $\alpha_{\|} = -dF_{\|}/dv_{\|}|_{v_{\|}=0}$.

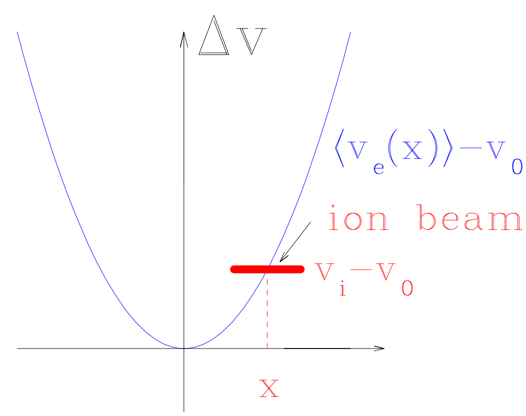

Figure 2: Parabolic velocity profile of the electrons due to the space charge. By displacing the electron beam with respect to the ion beam, a horizontal gradient of the longitudinal cooling force arises.

2 EXPERIMENTAL PROCEDURE

In order to study dispersive electron cooling, the electron beam is horizontally displaced with respect to the ion beam. A horizontal (vertical) displacement X (Y) of the electron beam leads to a higher ion beam velocity and therefore to an additional displacement x_D due to dispersion ($X > 0$ should mean displacing the electron beam towards the inner part of the ring). The change in the revolution frequency is given by:

$$\frac{\Delta f}{f_0} = \eta \frac{\Delta p_{\|}}{p_0} \tag{4}$$

$\eta = 0.89$ for the standard mode of the TSR. Using equations (1), (3) and (4) ,the change in the revolution frequency due to a horizontal (X) or a vertical displacement (Y) is then given by:

$$\Delta f(X) = \eta \frac{f_0}{D_S} \cdot \left\{ C - X - \sqrt{C^2 - 2CX} \right\} \tag{5}$$

$$\Delta f(Y) = \eta \frac{f_0}{D_S} \cdot \left\{ C - \sqrt{C^2 - Y^2} \right\} \tag{6}$$

$C = v_0/(2\alpha_D D_S)$. As $C \gg X$ and $C \gg Y$, developping the roots in (5) and (6) yields:

$$\Delta f(X) \approx \eta f_0 \frac{\alpha_D}{v_0} X^2 \cdot (1 + \frac{X}{C}) \tag{7}$$

$$\Delta f(Y) \approx \eta f_0 \frac{\alpha_D}{v_0} Y^2 \cdot (1 - \frac{1}{4}\frac{Y^2}{C^2}) \tag{8}$$

The electron beam is displaced in the horizontal direction by using the steerer S2X. The bit values are proportional to the displacement:

$$X = c_X \cdot S2X[bits] + d_X \tag{9}$$

Therefore it is possible to calibrate the displacement by recording the revolution frequency as function of the steerer strength. The measurements were performed using a $^{12}C^{6+}$ beam at an energy of 73.3 MeV. The parameters for the electron cooler setup were chosen as the following: $n_e = 8.0 \cdot 10^6$ cm^{-3}, B_{cool} =418 Gauss, 9.6 times expanded electron beam. The revolution frequency as function of a horizontal displacement is shown in figure 3. A function according to (5) is drawn as solid curve, yielding $c_X = -1.29 \cdot 10^{-2}\ mm/bit$ as fit parameter.

A parabolic function is drawn as dashed curve only taking into account the space charge of the electron beam and neglecting the additional displacement x_D.

The revolution frequency as function of a vertical displacement Y also allows the calibration of the displacment and shows no significant deviation from a parabola, as expected.

Starting from well aligned and centered beams the collective rotation of the electron beam due to space charge and the longitudinal magnetic guiding field has to be taken into account. Displacing the electron beam horizontally

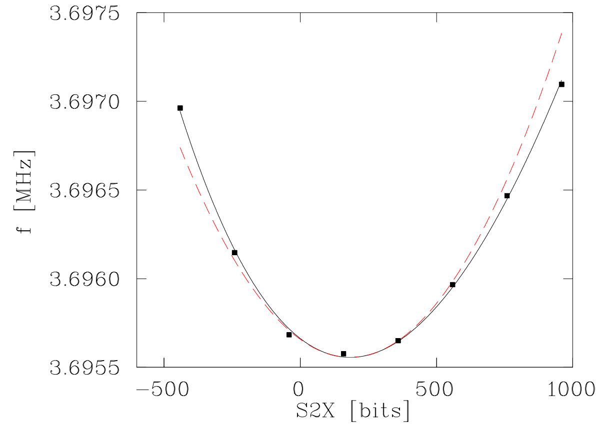

Figure 3: Sixth harmonic of the revolution frequency as function of the applied steerer strength for a horizontal displacement. The solid curve is a function according to (5), yielding $c_X = -1.29 \cdot 10^{-2}\ mm/bit$ as fit parameter. The dashed curve is a parabola only taking into account the space charge of the electron beam and neglecting dispersion.

(vertically) acquires reoptimizing the vertical (horizontal) angle of the electron beam.

Rotating the standard lattice of the TSR about an angle of 90° in the horizontal plane, a value of D_S = 1.63 m is achieved in the cooling region, compared to D_S = 0.3 m for the standard mode.

3 COOLING FORCES AND COOLING RATES

For low relative electron-ion velocities the longitudinal cooling force is measured directly with the aid of an induction accelerator [3]. From this measurement the longitudinal friction coefficient $\alpha_{\|} = -dF_{\|}/dv_{\|}|_{v_{\|}=0}$ is evaluated.

Studying the cooling process of ion beams having small initial diameters, i.e. low transverse velocities in the cooling region, with the aid of the beam profile monitor [4], it is possible to measure the transverse cooling rates $1/\tau_{x,y}$, which are related to the transverse friction coefficients $\alpha_{x,y} = m_i/\eta_c \cdot 2/\tau_{x,y}$ [1]. m_i is the ion mass and the factor 2 results from betatron oscillations.

Displacing the electron beam in the vertical direction, the longitudinal friction coefficient and the transverse cooling rates are found to be independent of the vertical displacement, as expected, since there is dispersion only for the horizontal degree of freedom. They amount to $\alpha_{\|} = 6.57 \cdot 10^{-4}\ eVs/m^2$ and $1/\tau_x = 23 \cdot 1/s$, $1/\tau_z = 25 \cdot 1/s$.

A different situation occurs, displacing the electron beam horizontally. The longitudinal cooling force on an ion moving with $v_{i\|}$ in the laboratory frame is given within the linear regime of the force by:

$$F_{\|}(v_{i\|}; x) = -\alpha_{\|}(v_{i\|} - \langle v_e(x + \Delta x_D)\rangle) \tag{10}$$

$x = X + x_D$ denotes the horizontal distance between the closed orbit of the ion and the center of the electron beam, Δx_D is the additional horizontal displacment due to dispersion $\Delta x_D = D_s v_\parallel / \langle v_e(x) \rangle$; $v_\parallel = v_{i\parallel} - \langle v_e(x) \rangle$. Neglecting terms of the order of $\Delta {x_D}^2$ one finds:

$$F_\parallel(v_\parallel; x) = -{\alpha_\parallel}^*(x) \cdot v_\parallel \tag{11}$$

with

$${\alpha_\parallel}^*(x) = \alpha_\parallel \cdot (1 - 2\frac{\alpha_D D_S}{v_0(x)} \cdot x) \tag{12}$$

$v_0(x)$ denotes the velocity, where the electron cooling force vanishes, $v_0(x) = \langle v_e(x) \rangle$.

The measured longitudinal friction coefficients are shown in figure 4 as squares. A dashed curve is drawn according to (12), for $\alpha_\parallel$ the mean value of $6.6 \cdot 10^{-4}$ eVs/m^2 for the two measurements at $x = 0$ is taken. The experimental data are in good agreement with (12).

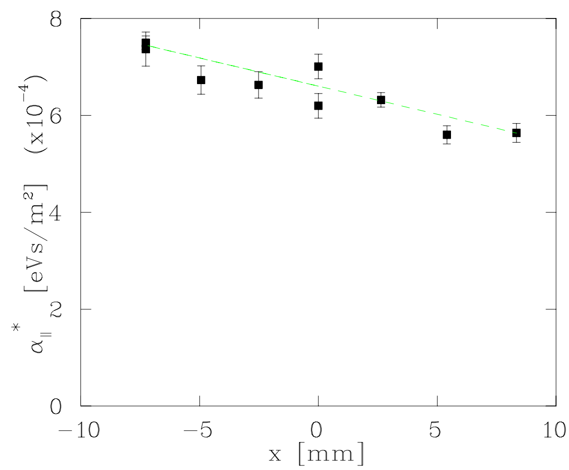

Figure 4: Measured longitudinal friction coefficient as function of x (filled squares). A function according to (12) is drawn as dashed curve, $\alpha_\parallel$ being chosen as the mean value of the two measurements with $x = 0$.

The transverse cooling rates as function of x are shown in figure 5. The vertical rates are found to be independent of x, amounting to $1/\tau_y = 23.5 \cdot$ 1/s (dashed line). The horizontal cooling rates are drawn as squares. They increase for positive x and decrease for negative x. Taking into account, that the cooling rate is related to the rms beam width σ, equation (2) is rewritten:

$$1/\tau_{x,disp} = \eta_c \frac{\alpha_D D_S}{p_0} \alpha_\parallel \cdot x \tag{13}$$

The gradient $dF_\parallel/dx$ has been approximated by $dF_\parallel/dx = d/dx[-{\alpha_\parallel}^*(x)\ (v_{i\parallel} - \langle v_e(x) \rangle)] \approx \alpha_\parallel \cdot d/dx \langle v_e(x) \rangle = \alpha_\parallel \cdot 2\alpha_D x$.

A function $1/\tau_x = 1/\tau_x(x = 0) + 1/\tau_{x,disp}$ is drawn as solid line, describing the horizontal cooling rates very well. The offset $1/\tau_x(x = 0)$ was fitted to the data, amounting to $1/\tau_x(x = 0) = 22\cdot$ 1/s and $1/\tau_{x,disp}$ was calculated according to the experimental values with (13).

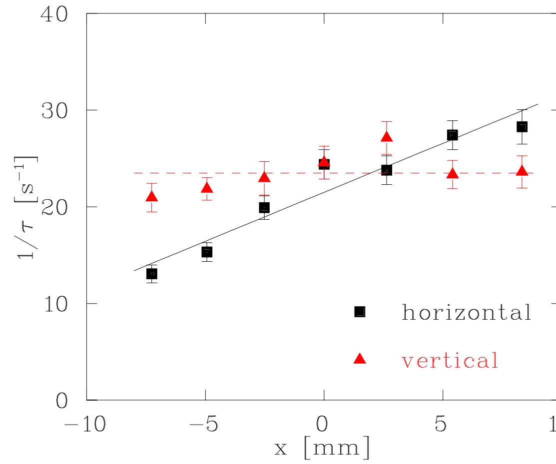

Figure 5: Transverse cooling rates as function of x. To the vertical rates a constant function is fitted (dashed line), to the horizontal rates a function $1/\tau_x(x = 0) + 1/\tau_{x,disp}$ is drawn (solid line). The fitted offset amounts to $1/\tau_x(x = 0) = 22\cdot$ 1/s and $1/\tau_{x,disp}$ according to (13).

4 SUM OF THE FRICTION COEFFICIENTS

Using (12) and (13) the sum of the friction coefficients can be evaluated analytically. Using $\alpha_x(x) = 2m_i/\eta_c(1/\tau_x(x = 0) + 1/\tau_{x,disp})$ and $\alpha_y(x) = \alpha_y = 2m_i/\eta_c \cdot 1/\tau_y$ one finds:

$$\sum_i \alpha_i(x) = \alpha_\parallel + \alpha_x(x = 0) + \alpha_y = const \tag{14}$$

The sum of the friction coefficients is constant, independent of x. Therefore, in the regime of low relative velocities, it is possible to transfer longitudinal cooling rate into horizontal rate. As the transverse friction coefficients are a factor of 2-4 smaller than the longitudinal one (for ions with charge states Z=1 to Z=8) [1], by dispersive electron cooling it should be possible to create a horizontal cooling rate which can be compared to the longitudinal one.

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