TRANSVERSE COOLING TIMES AND COOLED BEAM PROFILES AT CELSIUS

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Abstract

The CELSIUS storage ring is equipped with a magnesium-jet beam profile monitor built at INP, Novosibirsk. The monitor has been used to measure transverse cooling times by fitting the profiles to a theoretical curve which also takes intra-beam scattering into account.

1 EQUIPMENT AND PRINCIPLE

How the magnesium-jet method [1] can be used to determine cooling rate and its dependence on various parameters is thoroughly described by Budker et al. [2]. A magnesium-jet beam profile monitor was installed on the injection straight section of CELSIUS [3] and is now in routine operation. There are two main modes of operation: In the beam profile measurement mode, a 0.5 mm wide magnesium-vapour jet is swept across the ion beam. Magnesium atoms are ionized and electrons are recorded with a photo-multiplier tube as a function of jet position. At the present location of the monitor the dispersion is small and the β is large. Therefore the beam size is dominated by the transverse emittance, rather than by the momentum spread.

In the other mode the magnesium-jet is stationary at the centre of the profile and the PM-tube current is proportional to the density of the ion beam within the jet. This mode of operation has been used in the present work for cooling time determinations of coasting beams. The PM-tube current can be sampled with a maximum rate of 2 kHz. The obtained values are displayed immediately after a measurement series on the screen of a control PC and also written to a file for later investigation.

Controlled beam heating is achieved by firing a transverse pulse kicker on an already well cooled ion beam. The beam is excited both in the horizontal and vertical planes since the kicker is inclined 45 deg. The collective betatron oscillations induced by the kicker are expected to damp out quickly so that the beam profiles will be Gaussian. The advantage of using the kicker is that the beam is not heated longitudinally.

2 DETERMINATION OF COOLING TIME

The transverse cooling time is usually defined as the time it takes to damp betatron oscillation amplitudes by a factor e. This assumes exponential damping which is equivalent to an exponential growth of ion density. However, intrabeam scattering of the ion beam and other types of diffusion put a limit on the density. Therefore, exponential damping can only take place in the beginning of the cooling process.

When the ions have smaller velocity spread than the electrons, the cooling force is linear with respect to the ion velocity. This is valid for betatron amplitudes smaller than

$$\hat{x} \approx \sqrt{\frac{2kT_e}{m_e c^2}} \frac{\sqrt{\beta_m^* \beta_c^*}}{\beta\gamma}$$

at the position of the beam profile monitor. $kT_e \approx 0.11$ eV is the temperature of the electrons in the particle rest frame, β_m^* and β_c^* are the beta functions at the monitor and cooler respectively. At the injection energy for $^{20}\mathrm{Ne}^{10+}$ and $^{17}\mathrm{O}^{8+}$, 17 MeV/u, the cooling force is linear for betatron amplitudes smaller than 33 mm.

By solving the Fokker-Planck equation an expression for horizontal ion velocity spread, σ_{v_x}, is obtained as [4]

$$\sigma_{v_x}^2 = \sigma_{v_{x0}}^2 e^{-2t/\tau} + \sigma_{v_{x\infty}}^2 \tag{1}$$

where $\sigma_{v_{x0}}$ and $\sigma_{v_{x\infty}}$ are constants and τ is the transverse cooling time.

The differential equation to eq. (1) is

$$\frac{d}{dt}\sigma_{v_x}^2 = -\frac{2}{\tau}\sigma_{v_x}^2 + \Lambda \tag{2}$$

where Λ is a constant growth term. This is adequate, for instance, in the case of scattering against rest gas or an internal gas target. If intra-beam scattering dominates the diffusion the growth term is proportional to the beam density, $\rho_x \rho_y \rho_z$ and inversely proportional to the square of the ion velocity spread σ_v^2 [5]. In our case, with a coasting beam, ρ_z is constant. Hence eq. (2) can be replaced by

$$\frac{d}{dt}\sigma_{v_x}^2 = -\frac{2}{\tau}\sigma_{v_x}^2 + \Lambda\frac{\rho_x \rho_y}{\sigma_v^2} \tag{3}$$

Since the ion beam is assumed to have a Gaussian density distribution, $\rho_{x,y}$ is inversely proportional to the beam rms. width $\sigma_{x,y}$. Also, betatron oscillations in the ring relates beam width and velocity spread through

$$\sigma_{x,y} = \frac{\beta_{x,y}^*}{\beta\gamma c}\sigma_{v_{x,y}} \tag{4}$$

Considering these relations and the fact that the longitudinal magnetic field in the cooler couples the two transverse planes, eq. (3) is rewritten again

$$\frac{d}{dt}\sigma_{v_\perp}^2 = -\frac{2}{\tau}\sigma_{v_\perp}^2 + \frac{\Lambda}{\sigma_{v_\perp}^4} \tag{5}$$

Table 1: Summary of measurements and calculations.

Particle	T MeV/u	I_e mA	τ s	τ_{theory} s
$^{17}O^{8+}$	16.6	100	0.28	0.28
$^{20}Ne^{10+}$	17.3	100	0.26 ± 0.04	0.22
p	200	250	3.7 ± 0.4	1.4

The solution to eq.(5) is

$$\sigma_{v_\perp}^6 = \sigma_{v_{\perp 0}}^6 e^{-6t/\tau} + \sigma_{v_{\perp\infty}}^6 \tag{6}$$

to be compared with eq. (1).

Provided that the beam loss is zero during the cooling process, $\sigma_{x,y}$ can be obtained as a function of time and the cooling time can be determined by fitting the profile peak amplitude to a function

$$\frac{1}{\hat{\rho}^6} = \frac{1}{\hat{\rho}_\infty^6} + \frac{1}{\hat{\rho}_0^6} e^{-6t/\tau} \tag{7}$$

Cooling simulations have been made using a computer code [6] which takes IBS into account. The results from the simulations can be fitted, by eq. (7), which is visualized in fig. 1. The determined cooling times are in accordance with the values that are used as programme input.

The cooling time in the rest frame of the electrons can be related to the cooling force and transverse ion velocity as

$$\tau = -2m_i \left(\frac{\partial F_\perp}{\partial v_\perp} \right)^{-1}$$

The factor 2 is due to the effect of betatron oscillations. In the laboratory frame the cooling time is given by [7]

$$\tau = \frac{1}{\sqrt{2\pi}} \frac{C}{l_0} \frac{\gamma m_i}{m_e} \left(\frac{kT_e}{m_e c^2} \right)^{3/2} \left(\frac{r_0}{Zr_e} \right)^2 \frac{\beta\gamma e}{L_C I_e} \tag{8}$$

where I_e is the electron current. $r_0 = 10$ mm, $l_0 = 2.5$ m and $C = 81.8$ m are the electron beam radius, cooler length and ring circumference respectively. L_C, the Coulomb logarithm varies between 9 and 11 in our cases.

3 MEASUREMENTS AND RESULTS

In table 1, cooling times determined from different runs of oxygen, neon and protons are given. They are averages over several measurements except in the case of oxygen. The error is one standard deviation and the theoretical values are calculated from eq. (8).

In fig. 2 the response of the beam to the pulse kicker is shown. The different levels of the two curves are due to different ion currents. The spread is mainly due to a 50 Hz ripple on top of the signal. It can be seen that the amplitude changes of the beam profiles can be fitted by eq. (7).

The results from these measurements agree well with the theoretical expression (8) even though the model of the cooling force is very simple. The estimated proton cooling times are somewhat longer than the predictions due to instabilities caused by too high beam currents.

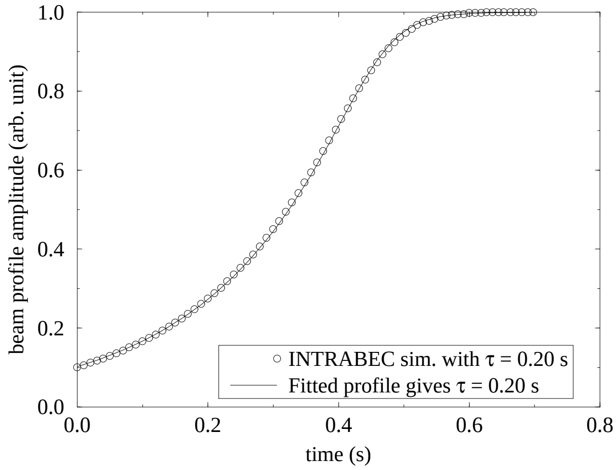

Figure 1: A computer simulation of electron cooling of $^{20}Ne^{10+}$ in CELSIUS fitted by eq. (7).

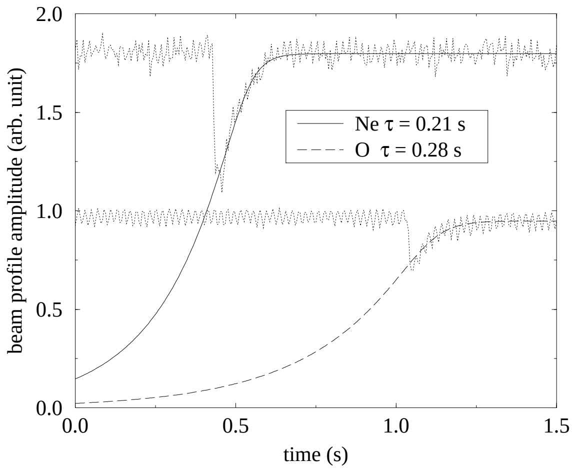

Figure 2: Measurements of $^{20}Ne^{10+}$ and $^{17}O^{8+}$ at injection energy together with theoretical fits.

4 REFERENCES

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