STUDIES OF TRANSVERSE ELECTRON COOLING

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Abstract

We have used a transverse instability that can be excited in an electron-cooled ion beam in order to produce beams with well-defined emittances. These beams have been cooled and the transverse cooling times have been studied as functions of the emittance. Ions of different charge states (D^+, F^{6+} and Pb^{54+}) have been used for the measurements to investigate the charge-state dependence of the cooling time. Comparisons are also made with numerical simulations of the cooling process.

1 INTRODUCTION

Electron cooling is a technique for reducing the emittance of stored ion beams that works best for beams of small emittances. More precisely, typical quantities like emittances, beam diameters, etc., shrink approximately exponentially with time if the velocity spread of the ion beam is small compared to that of the electron beam (and intrabeam scattering is neglected). At higher velocity spreads, the decrease is slower than in the exponential regime. To know the cooling rate as a function of the emittance of the ion beam is important for applications of electron cooling, and in this paper this emittance-dependent rate is discussed.

A method to achieve an ion beam with a transverse profile of a particular kind, namely a hollow beam where all particles perform betatron oscillations with the same amplitude, is introduced. This method allows us to measure the cooling rate as a function of the betatron amplitude of the ions. Since, in principle, any transverse beam profile can be constructed by superimposing these “elementary beams” with definite betatron amplitudes, the measurements make it possible to predict how the cooling will proceed for a beam with an arbitrary profile.

2 HOLLOW BEAMS

In electron cooling, the energy spread of the ion beam is given to electrons having the same speed as the ions and moving parallel to them. If the ion and electron beams are not perfectly aligned, cooling still occurs, but is less efficient. When the alignment reaches a certain threshold value, however, a qualitatively different situation is obtained and the ions start to perform betatron oscillations with large amplitudes.

This is caused by the non-linear force that the ions experience when they move through the electron beam of the cooler. The force has a maximum at a certain relative velocity, and the threshold for the appearance of betatron oscillations is located where the transverse velocity component of the misaligned electron beam is equal to the velocity of the force maximum.

This transition from stable particle motion, described by a stable fixed point in phase space, to oscillating motion corresponding to a circular attractor, or limit cycle, is known as a Hopf bifurcation [1]. It has been studied earlier both for longitudinal [2] and transverse [3] motion, and is also discussed in [4]. A simple analysis can be made based on the amount of energy a ion gains or loses during one oscillation period through the interaction with the cooler electrons. If we assume that the relative motion is purely transverse, we have

$$\Delta E = \int_0^{2\pi} \mathbf{F}_\perp(\mathbf{v}_\perp) \cdot \mathbf{v}_\perp \mathrm{d}\theta,$$

where ΔE is the energy gain, $\mathbf{F}_\perp(\mathbf{v}_\perp)$ is the transverse cooling force, $\mathbf{v}_\perp$ is the relative velocity between ions and electrons, and the integral is taken over one betatron period. The cooling force has to be calculated according to some suitable model (we use that described in [5] where the force is antiparallel to the relative velocity), and the velocity can be written as $\mathbf{v}_\perp = v_\perp \mathbf{e}_\perp$, $v_\perp = \hat{v}_\perp \cos\theta$. We also introduce the transverse electron velocity $\delta v_\perp$ due to the misalignment of the electron beam. It is then clear that, for a given $\delta v_\perp$, the steady-state oscillation amplitude is obtained for the $\hat{v}_\perp$ that satisfies

$$\int_0^{2\pi} F_\perp(\hat{v}_\perp \cos\theta - \delta v_\perp) \cos\theta \, \mathrm{d}\theta = 0,$$

corresponding to neither loss nor gain of energy. For other values of $\hat{v}_\perp$ the oscillations grow or shrink depending on

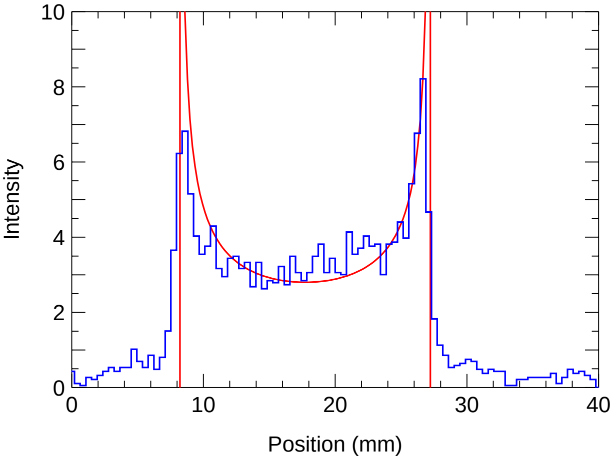

Figure 1: Vertical profile of Pb^{54+} beam with a superimposed projection of a circle in phase space.

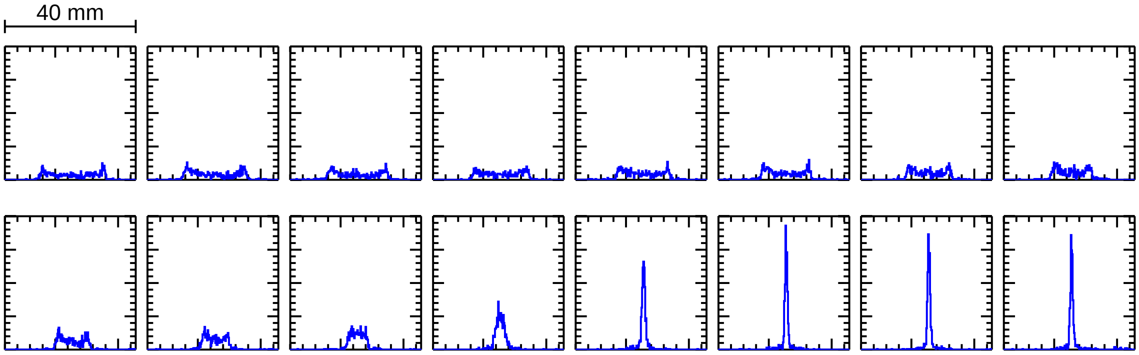

Figure 2: Vertical profiles of an F^{6+} beam during successive 61-ms intervals, starting 61 ms before the electron beam is realigned with the ion beam and cooling begins.

the sign of the integral. The above analysis is only approximate since it does not include, e.g., the influence of the electron-beam space charge on the ion motion. Simulations discussed below show that this influence is stronger in the horizontal plane than in the vertical due to the dispersion in the ring.

Since the density of ions is quite small in the wide beam that the oscillations give rise to, intra-beam scattering is small, and all ions move on a thin ellipse in the horizontal or vertical phase space, depending on in which plane the misalignment is made. (If the electron beam is misaligned in both planes, and coupling between the planes can be neglected, the ions will of course perform independent oscillations in the two planes.) In fig. 1 is shown the vertical profile [6] of a Pb^{54+} beam obtained at CRYRING. Superimposed on the measured profile is the projection of a thin circle in the vertical phase space. Clearly, within the resolution of the profile monitor, all ions indeed seem to have the same betatron amplitude.

3 COOLING

3.1 *Experiments*

When a hollow beam of this kind is cooled, one would expect that all ions cool at the same rate. We have tested this by first creating the hollow beam through a misalignment of the electron beam, achieved by exciting dipole coils inside the central solenoid of the electron cooler. Then, after a time interval an order of magnitude longer than a typical cooling time during which the hollow beam develops, the dipole coils are reset to the aligned condition, and the cooling process can be followed.

Fig. 2 shows a set of beam profiles obtained in this way. The first frame shows the vertical profile of an F^{6+} beam while the electron beam is misaligned by 2.6 mrad, and the following frames are taken during successive 61-ms intervals starting just after the realignment. The electron current was 80 mA, and the electron beam was (like in all measurements presented in this paper) misaligned and reset simultaneously and by equal amounts in both planes.

One can see that the profile indeed has the same shape throughout most of the cooling process, and that one easily can obtain the cooling rate as a function of the betatron amplitude.

Similar measurements were made also with beams of deuterons and Pb^{54+} ions. Both horizontal and vertical profiles were measured except for the lead ions where the horizontal profile monitor was out of order. All results are summarized in fig. 3, where the results are normalized to an electron current of 100 mA (i.e., an electron density of 1.7×10^{13} m^{-3}), while the real current varied between 70 and 110 mA. Also, they are normalized to $q/A = 1$, where q is the charge state of the ion and A the mass number, assuming that the cooling time is inversely proportional to $q^{1.7}/A$. Finally, the initial misalignment of the electron beam was smaller for the F^{6+} ions than for the other two, and the fluorine points are therefore shifted to the right in order to make them coincide better with the other points.

The exponent of 1.7 in the charge-state dependence of the cooling time was chosen in order to make the data points for the different ions in fig. 3 to fall on top of each other as well as possible. This value is only approximate,

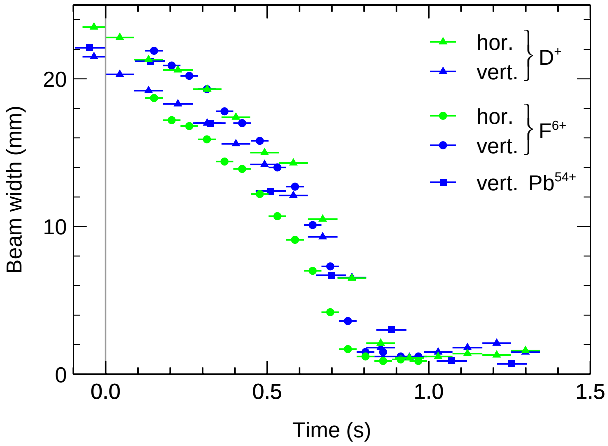

Figure 3: Full beam width (distance between peaks or, if only one peak, FWHM) as a function time. The horizontal lines through the points represent gate intevals.

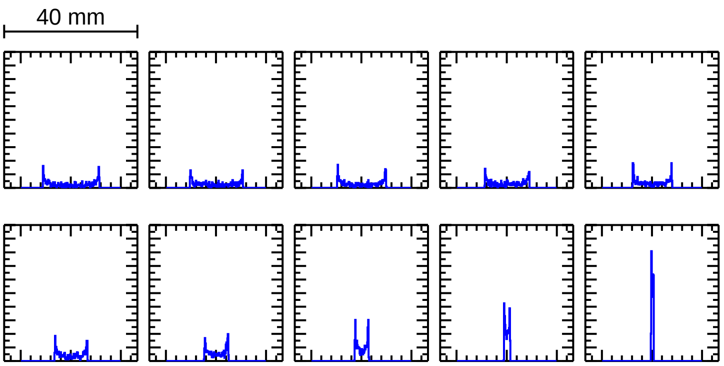

Figure 4: Simulated vertical profiles of an F^{6+} beam after successive 36-ms intervals, starting when the electron beam is realigned with the ion beam and cooling begins.

since the betatron tunes, the centering and the alignment of the electron and ion beams, or other such factors that may influence the cooling times may have been slightly different between the runs with the different ions. The measurements were performed, however, at the same beam energy of 4.2 MeV per nucleon and with the machine set up according to the same procedure. A deviation of the exponent from the value of 2 that one would expect from the simplest theories for the electron–ion interaction (such as a pure two-body Coulomb interaction) has been described earlier for longitudinal cooling [7, 8] and has also been discussed theoretically [9].

3.2 Simulations

We have tried to reproduce the amplitude of the induced betatron oscillations and the cooling times using a simple tracking program. It takes into account basic features of the machine and the cooler such as beta functions, dispersion, a three-dimensional cooling force, the space charge of the electron beam and the alignment and relative positions between ion and electron beams, but not intrabeam scattering.

Fig. 4 shows a simulated cooling sequence corresponding to the measurement of fig. 2. The first frame shows the profile with the electron beam misaligned by 2.6 mrad, and the following frames show the profile 36, 72, 108 ms, etc., after the beams were realigned. The time scale is somewhat different compared with the experimental results; in the simulations the cooling force was assumed to be proportional to q^2/A. Otherwise, the main difference to the experiment is due to the absence of intrabeam scattering and a better spatial resolution.

In fig. 5, the results of the experiment and the simulations are compared directly. The time scale for the simulations was here changed by using the experimentally obtained $q^{1.7}/A$ dependence of the cooling force instead of q^2/A. The simulation results depend on a number of ring and cooler parameters such as beta functions, dispersion, relative positions between ions and electrons, the transverse magnetic field generated by the coils that produce the misalignment, and, perhaps most importantly, the cooling force. For the cooling force we have used the binary-collision model defined in [5] with a transverse temperature of 3 meV, which has been found earlier to agree quite well with experimental data [4]. Apart from that choice and the q dependence, no fitting parameters were used to obtain the relatively good agreement experiment and simulations.

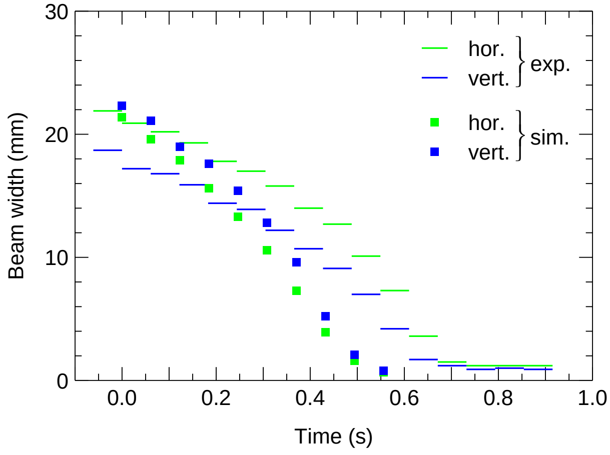

Figure 5: Full width of F^{6+} beam as a function time.

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