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ON THE OPTIMUM DISPERSION OF A STORAGE RING FOR ELECTRON COOLING WITH HIGH SPACE CHARGE

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Abstract

With the intense electron beams used for cooling, matching of the ion and electron velocity over the largest possible fraction of the beam profile becomes important. In this situation, a finite dispersion from the ring in the cooling section can lead to an appreciable gain in the transverse cooling speed. Based on a simple model of the cooling force, an expression for the "optimum" dispersion as a function of the electron beam intensity, the momentum spread and other properties of the ion beam will be derived. This simple theory will be compared to measurements made on the Low Energy Ion Ring (LEIR) at CERN during 1997.

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On the Optimum Dispersion of a Storage Ring for Electron Cooling with High Space charge

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With the intense electron beams used for cooling, matching of the ion and electron velocity over the largest possible fraction of the beam profile becomes important. In this situation, a finite dispersion from the ring in the cooling section can lead to an appreciable gain in the transverse cooling speed. Based on a simple model of the cooling force, an expression for the "optimum" dispersion as a function of the electron beam intensity, the momentum spread and other properties of the ion beam will be derived. This simple theory will be compared to measurements made on the Low Energy Ion Ring (LEIR) at CERN during 1997.

1. Introduction

In any cooler storage ring, the lattice parameters β and D determine the size and angular spread of the ion beam at the electron cooler. The cooling rate, which is given by

$$\frac{1}{\tau} = 2.5\times10^{-13}\times\left(\frac{1}{R}\frac{q^2}{A}\frac{1}{\beta^4\gamma^5}\right)\times l_c\, j_e\,\frac{1}{\theta^3}$$

shows that electron cooling is most efficient for small angle differences between the two beams. One would thus imagine that a large value of β ($\theta^2 = \varepsilon/\beta$, θ = ion beam angle) would give the best cooling results.

On the other hand, a large β function also implies a large ion beam, and one expects a degradation in the transverse cooling force as the size of the ion beam becomes comparable to the electron beam dimension. This degradation is due to the space-charge effect, which complicates the electron-ion velocity matching over a large beam size and is also due to imperfect overlap when the ion beam is larger than the electron beam.

As a consequence one anticipates optimum conditions for intermediate values of β where the beam size is slightly smaller than the electron beam. The dependence of the cooling time on the lattice functions was explored experimentally using 50 MeV protons and was repeated with Pb ions when once injected intensity was increased through the multi-turn injection scheme [1].

2. Experimental set-up

To measure the relevant beam properties, all the machine diagnostics [2] were interfaced to a PC based data acquisition system. Throughout the experiments, the 'cooling down time' needed to reduce the horizontal emittance from 40 π mm mrad to 4 π mm mrad was determined and used for comparison. The 'cooling down time' was measured using Schottky signals. They also proved to be useful for measuring the ion beam intensity in the initial experiments, which were too low to be reliably measured with the beam current transformer. Beam ionisation profile monitors (BIPM) were used to complement the cooling down time measurements as well as to obtain absolute values of the beam emittance.

The electron beam used in these experiments was generated by a variable intensity electron gun developed in 1994 [3]. It consists of three electrodes, the Pierce electrode, the grid and the anode, and uses adiabatic optics to produce high intensity electron beams with low angular spread. The electron current is controlled through the voltage regulation of the grid electrode. Up to 0.5 A of electron current at an energy of 2.5 keV has been obtained using this gun but its operation at these high densities is problematic due to the formation of a Penning trap between the cathode and the grid electrode.

3. Results and discussion

In 1996 a series of measurements were made using 50 MeV protons for four different optical settings shown in Table 1 (machines 1,4,6 and 7). Cooling down times as a function of the horizontal beta function at the cooler were measured using the BIPM for proton intensities of $2\text{x}10^9$ particles and for an electron current of 1.2 A. The results are shown in Fig. 1 and one sees that the best cooling times were obtained with machines 1 and 7, whilst machines 4 and 6 gave very mediocre cooling times. It should be mentioned that in addition to the difference in horizontal beta function, machines 1 and 7 also have a non-zero value of the dispersion function at the cooler. From the measurements and the observations of the cooling process using the Schottky signals (Fig. 2), it seems clear that the effect of D is superimposed on the influence of β_h and may even be the dominant effect.

Guided by these observations with protons, the cooling time results were checked with lead ions (Fig. 3) where it was found that machine 7 was by far the best suited machine, in terms of optical parameters at the cooler, for fast cooling. obtained with only 350 mA of electron current.

machine	*1*	*4*	*6*	*7*	*97*
β_h (m)	1.9	9.5	0.65	4.8	5.0
β_v (m)	6.4	10.5	5.5	5.0	5.0
D (m)	3.6	9.9	0.0	5.0	0.0

Table 1: Lattice functions at the cooler for the different machine optical settings.

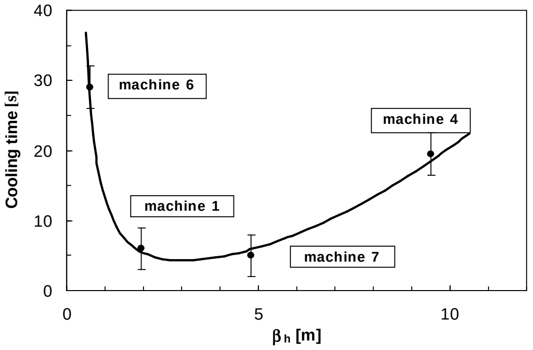

Figure 1. Plot of the cooling down time for 50 MeV protons as a function of the horizontal beta function in the cooler.

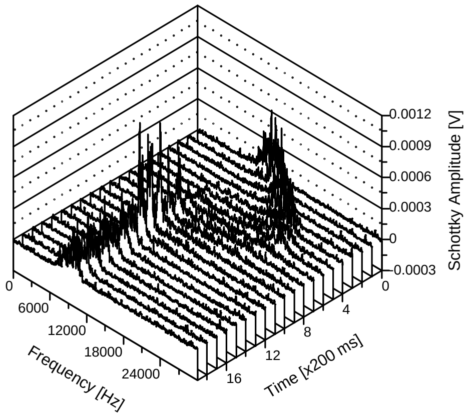

Figure 2. Longitudinal Schottky signal observed after a single injection of Pb^{54+} ions. One clearly sees the influence of the ions having large amplitude betatron oscillations which causes an initial acceleration in the longitudinal plane and eventually leads to beam loss if the amplitude is larger than the electron beam dimension.

To test the influence of dispersion on the cooling down time, a series of measurements were performed with protons using machine 97. This lattice was optimised for multi-turn injection and therefore did not give the best cooling times. However, being a very flexible lattice, it was possible to modify the dispersion at the cooler without changing the optical settings elsewhere.

Cooling down times were measured as a function of the offset in position between the electron beam and the protons. The results are shown in Fig. 4 and it is quite clear that the dispersion plays a major role in horizontal cooling. The fastest cooling times were obtained with settings having a non-zero dispersion at the cooler. However with dispersion, the cooling is no longer symmetric and, depending on the sign of the dispersion, is faster either to the interior of the machine (-ve dispersion) or to the exterior (+ve dispersion). In the case where the dispersion is zero, a perfectly symmetric distribution of the cooling down time around the optimum was found, with a loss of a factor of two in the cooling down times.

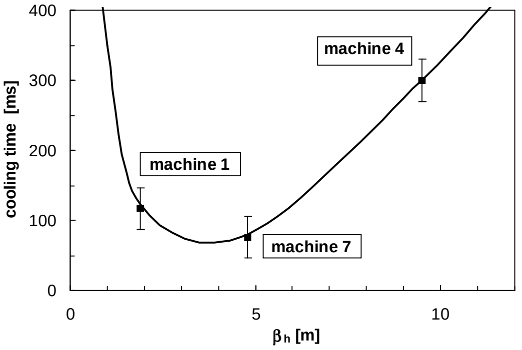

Figure 3. Cooling down time for Pb^{54+} ions at 4.2 MeV/u as a function of horizontal beta function in the cooler.

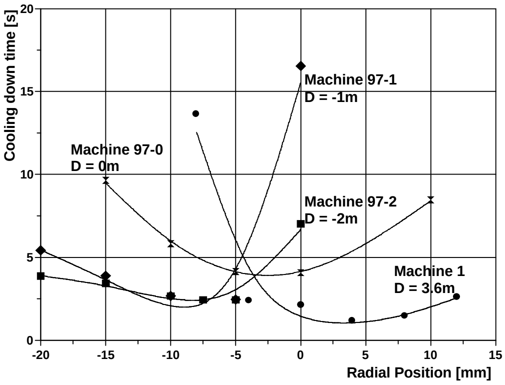

Figure 4. Cooling down times for 50 MeV protons as a function of the horizontal offset between proton and electron beam for machine 1 and machines 97-0, 97-1 and 97-2.

The influence of the dispersion on the cooling down time can be explained by reference to Fig. 5, which shows the longitudinal velocity profile vs. horizontal position for both electrons and ions. For the ions, the working line is given by the dispersion function D as

$$\frac{\Delta v}{v}=\frac{1}{\gamma^2}\frac{\Delta p}{p}=\frac{1}{D\gamma^2}x$$

The shaded area around this line has its width given by the betatron oscillation and its height by the momentum bite of the ion beam, whereas the electrons have a parabolic velocity distribution given by their space-charge. The cooling force increases when the relative velocity between the electrons and ions decreases. In fact in a simple binary collision model, the friction force on an ion at position *x* is proportional to $\{v_i(x)-v_e(x)\}/\{v_i(x)-v_e(x)\}^3$. For zero dispersion, this difference in velocity is on average relatively large. With a finite value of dispersion, the difference can be much smaller, but for large *x*, beyond the second intersection of the dispersion with the parabola, becomes negative and the ions will then experience heating. Thus one expects fastest cooling for a value of dispersion such that the ion working line matches the inside of the electron parabola. In this matching some margin has to be given for the betatron motion.

It is clear from this qualitative picture that the optimum *D* value depends on the electron current, the ion momentum bite and on the betatron oscillation width to be handled. Neglecting the betatron oscillation and accommodating for the ion momentum spread in the way sketched in figure 5b, the optimum dispersion is obtained as

$$D\approx\sqrt{\frac{1}{30\Omega}\frac{\gamma+1}{\gamma}\frac{\beta U a_e^2}{I_e(\Delta p/p)}}$$

For the parameters used for stacking ($\Delta p/p=10^{-2}$, stack + ramp + instantaneous spread), the above equation yields *D*=1.6 m, but to leave room for betatron oscillations a smaller value (*D*=0.5 to 1 m) should be chosen. For the results summarised in Fig. 3 the initial momentum spread was smaller ($\Delta p/p=1.5\text{x}10^{-3}$), and the equation suggests a somewhat larger dispersion. (*D*=4 m). Finally, for the measurements with protons shown in Fig. 1, the optimum predicted dispersion is *D*=6 m.

4. Conclusions

It has been shown that the transverse cooling time is influenced by the lattice parameters of the ring and that the value of the dispersion function in the electron cooling device can greatly enhance the horizontal cooling. By using a simple model of the cooling force one can derive an expression for estimating the optimum value of dispersion in the cooler which, after a slight correction to accommodate the betatron oscillation, agrees quite well with the observations made during machine studies on the LEAR/LEIR machine. A simple computer code is now being developed that determines the optimum lattice parameters in the cooler for the future LEIR machine [4], which will be needed to accumulate and cool Pb ions for the LHC.

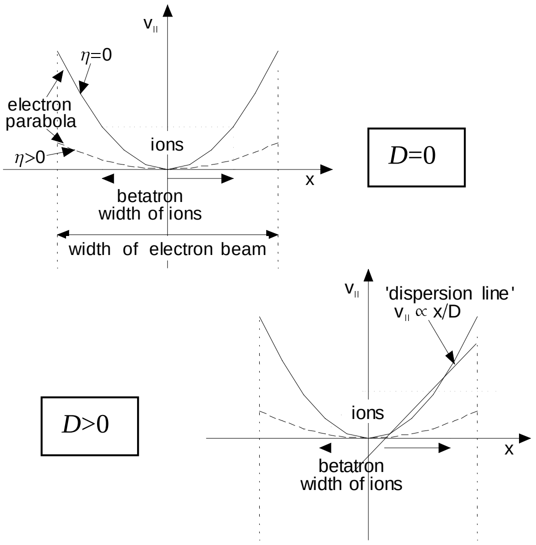

Figure 5. Velocity vs. horizontal position of the electron and ion beams with and without a horizontal offset between the two beams. Owing to space charge, the electron profile is a parabola, whereas the velocity of the ions varies linearly, with slope 1/*D*. Because of their betatron oscillation, ions occupy the shaded area around the dispersion line.

5. References

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