Electron Cooling of Ion Beams with Wide Momentum Spread.

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Abstract

We propose a new scheme of an electron cooling for an ion beam with wide momentum spread. A constant voltage is applied by an induction accelerator (IndAcc) in order to shift the ion beam toward the sensitive region of the electron cooling force. The cooling time of an ion beam (73.3MeV C^{6+}) with momentum shift of $\Delta P/P=1\%$ was measured at TSR. The cooling time was 2.5sec without IndAcc and 0.6sec with applied IndAcc voltage of 0.4Volt.

1 INTRODUCTION

High-energy heavy ions can be produced by a high power short pulse laser[1,2]. Such beams have an exponentially decaying energy spectrum. Beams with this property are unsuitable for injection into synchrotrons without further decreasing their momentum spread. A phase rotation in the longitudinal phase space using an RF cavity can reduce the momentum spread to $\Delta P/P = 1\%$[3]. We propose to further cool this beam to $\Delta P/P = 0.1\%$ using an electron cooling and an induction accelerator.

For a hot beam ($\Delta P/P=1\%$), a conventional electron cooling takes a long time[4]. Most of this time is spent in bringing the beam toward the active region of the cooling force. Actually, the cooling force decreases fairly rapidly

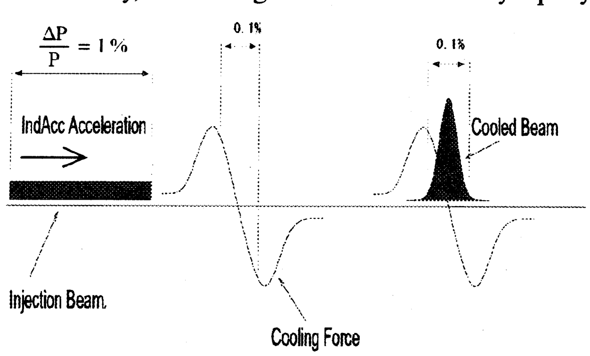

Fig. 1. Principle of the IndAcc sweep scheme.

outside a rather narrow region ($\Delta P/P=0.1\%$) centred around the velocity of the electron beam. We believe we can reduce the time and thus shrink the overall cooling time by applying an additional external force to the beam, accelerating the ions towards the active region of the cooling force [Fig.1]. An induction accelerator is the most suitable source as such an external force. It can apply constant acceleration on the ion beam for a preset period of time.

To test the feasibility of such a scheme, we have performed an experiment at TSR in MPI Heidelberg [Fig.2][5]. We have measured the cooling force for high relative velocities, as well as the cooling time of a carbon beam (73.3 MeV C^{6+}).

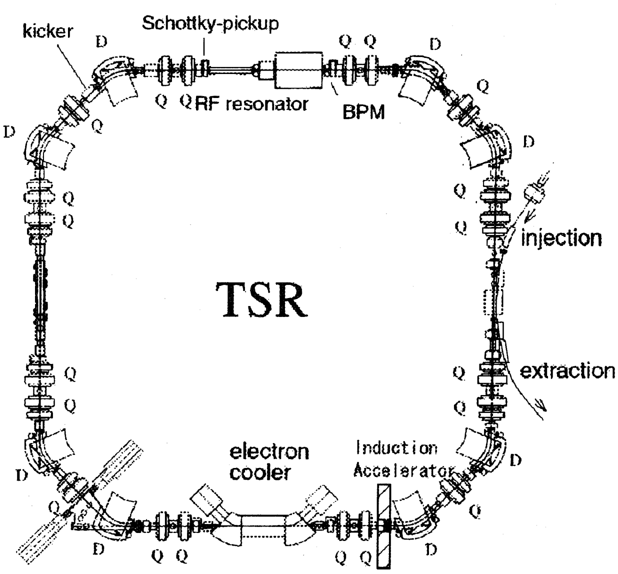

Fig. 2. Schematic layout of the Heidelberg heavy-ion Test Storage Ring, TSR.

2 COOLING FORCE MEASUREMENT

The cooling time depends on the total force acting on the beam, i.e the sum of the cooling force and the IndAcc force. To make numerical estimates of the cooling time, it is necessary to measure the cooling force.

The electron cooling process is most easily described, using a binary collision model[6,7]. In this model, the slowing down of the ion is due to momentum transfer during electron-ion collisions. The cooling force can then be calculated in the rest frame of the electrons as,

$$F_e = -4\pi Z^2 e^2 c^2 r_e n_e \int L_C(u) f(v_e) \frac{u}{|u|^3} d^3 v_e \qquad (1)$$

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where, Ze is the ion charge, c the speed of light, n_e is the electron density, r_e is the classical electron radius, L_C is the Coulomb logarithm, $f(v_e)$ is the electron velocity distribution and u is the ion velocity in the frame co-moving with electrons. The cooling force has a linear dependence on the electron density, and for very high relative velocities it can be approximated by an inverse square of the relative velocity.

The cooling force has been measured in the high relative velocities range for an electron current of Ie=90mA, using the induction accelerator at TSR[8]. A constant voltage was applied to the beam in the opposite direction to the cooling force, and the time evolution of the Schottky signal of the beam was measured. The total force applied to the beam, F_{tot}, is

$$F_{tot} = F_{ecool} + F_{ind} = \frac{L}{C} F_e - \frac{ZeU_{ind}}{C} \qquad (2)$$

where, Uind is the IndAcc voltage, L is the cooler section length and C is the ring circumference. The sign of the total force depends on the value of the IndAcc voltage. The cooling force can be computed from the IndAcc voltage for which the total force vanishes. The measured cooling force is plotted as a function of the relative momentum in Fig. 3, and the data is fitted to the relation,

$$F_e' = a\left(\frac{\Delta P}{P}\right)^{-b} \qquad (3)$$

where a, b are parameters. The fitted results give $a=6\times10^{-4}$ eV/m and b=1.3. This fitting is used to compute the cooling time for various electron currents.

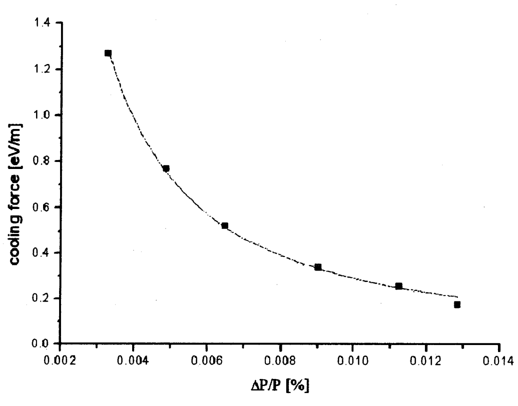

Fig. 3. Measured cooling force for Ie=90mA.

3 COOLING TIME MEASUREMENT

3.1 Method

The cooling time was measured by the following method,

1. The ion beam is injected and cooled at point A, where the electron beam is initially located.
2. The electron beam is shifted to point B by changing the cathode potential of the electron cooler. The ion beam is then moved to this new position.
3. The electron beam is then shifted back to its original position A, at time t=0.
4. After a time Δt, the Schottky signal of the beam is measured, yielding the time evolution of the ion beam under the effect of the cooling force and the IndAcc force.

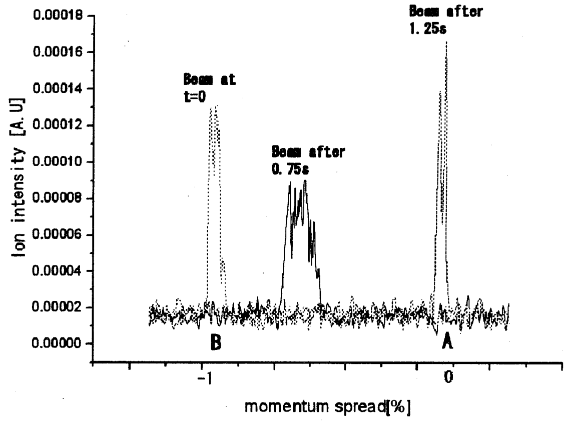

Fig. 4. Measured Schottky spectra for Ie=90mA and Uind=0.1V.

The cooling time is defined as the time it takes the beam to move from point B to point A. One example is shown in Fig. 4, for electron current Ie=90mA and IndAcc voltage Uind=0.1V.

3.2 Computed cooling time

Since the cooling force is proportional to the electron density, by equation (3), we can compute the cooling time for various electron currents. Figure 5 shows the cooling times computed for electron currents of 90mA, 150mA and 223mA.

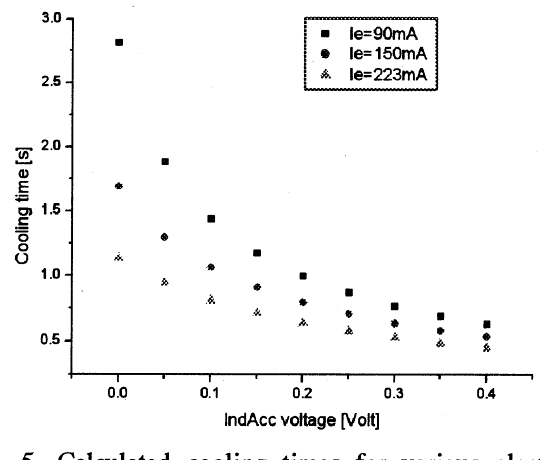

Fig. 5. Calculated cooling times for various electron currents.

The results of the calculation show a reduction of the cooling time when the IndAcc is used. Also, this reduction is more substantial for a low electron current than for a high current. For higher currents, the cooling force is stronger and the contribution of the IndAcc is smaller. Also, when IndAcc voltage is high enough, the dependence of the cooling time on the electron current becomes weaker. Thus, this IndAcc cooling scheme can be used to reduce the cooling time, especially in the case of a not so powerful electron cooler.

3.3 Results

The results of the cooling time measurement for electron current Ie=90mA are shown in figure 6. The cooling time without IndAcc sweep is about 2.5sec, and the cooling time with the IndAcc sweep of 0.4V is about 0.6sec. This reduction in cooling time is due to the induction accelerator.

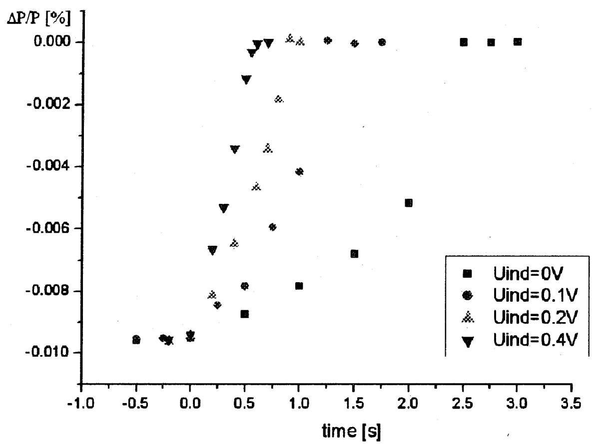

Fig. 6. Measured cooling times for various IndAcc voltages.

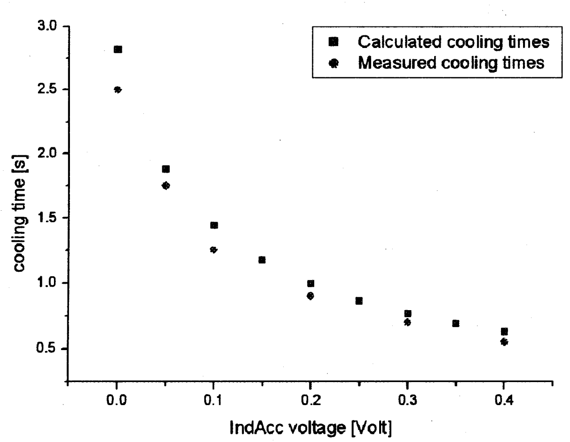

Fig. 7. Measured and computed cooling times for Ie=90mA as function of the IndAcc voltage.

The measured cooling time as well as the computed time for electron current of Ie=90mA are shown in Fig. 7. The measured values agree with the calculated values to within an error of about 15%. The maximum applicable voltage with the induction accelerator at TSR is about Uind=0.4V. It's possible to reduce the cooling time further, with a more powerful IndAcc. Using equation (3), an IndAcc voltage of Uind=3.2V can yield a cooling time of 0.1sec. An IndAcc with a maximum voltage of 4V has been constructed and tested at HIMAC in NIRS [9].

4 CONCLUSION

The cooling time of a hot ion beam can be reduced using this scheme. This reduction will be more important for a low electron current. For example, this scheme can be used as part of the cooling system in the small cooler ring planned in ICR[10][11]. This ring will cool C^{6+} (2MeV/u) beams produced from laser induced plasma. Compared to TSR, assuming the same perveance and electron beam size, this low ion beam energy implies a lower electron current for cooling. Thus an IndAcc can be used to compensate for this lower electron current, and achieve short cooling time. A voltage of Uind=0.6V is enough to achieve a cooling time of 0.1sec.

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