ELECTRON COOLING OF ION BEAMS WITH LARGE MOMENTUM SPREAD

H. Fadil, Y. Iwashita, A. Noda, T. Shirai, ICR, Kyoto, Japan
M. Muramatsu, K. Noda, NIRS, Chiba, Japan
T. Furukawa, Chiba University, Chiba, Japan
S. Shibuya, SHI, Tokyo, Japan
M. Beutelspacher, M. Grieser, MPI-K, Heidelberg, Germany

Abstract

A novel scheme for a fast electron cooling of ion beams with large momentum spread has been studied and investigated experimentally. Efficient longitudinal cooling was achieved using an induction accelerator (IndAcc) sweep of the stored ion beam. A constant voltage from the IndAcc is applied to accelerate the beam toward the equilibrium point of the cooling force. Experimental studies of this scheme were performed at TSR. A carbon ion beam $^{12}C^{6+}$ of total energy 73.3MeV was shifted by $\delta p/p = 1$ with respect to the momentum of the electron beam, and the cooling times were measured. A reduction of the cooling time from 2.8sec without IndAcc to 0.6sec with application of 0.4V, was observed. Further experiments, to estimate the maximum IndAcc voltage that can be applied without causing beam loss, were performed at HIMAC.

1 INTRODUCTION

The recent successful application of heavy ion beams to the treatment of tumor cells [1], has prompted an increased interest in the development and construction of compact accelerator systems, dedicated to cancer therapy [2]. The LSR project has been initiated at Kyoto university as a response to this need. LSR is a new generation compact cooler ring currently under construction at ICR Kyoto, for use as an injector of carbon ions for a pulsed synchrotron with ultra-high magnetic field [3]. The ring will cool carbon ions produced from laser induced plasma[4], then inject them into the synchrotron. In the present work we propose a new scheme for fast electron cooling that can reduce the momentum spread $\delta p/p$ of laser produced carbon ions from 1% to 0.1%.

2 PRINCIPLE

Electron cooling is a method for reducing the phase space volume of a beam, that is based on energy transfer between the ions and a cold external electron beam[5]. A simple binary collision model of this process[6] yields a cooling force

$$F(\vec{v_i}) = -\frac{4\pi n_e Z^2 e^4}{(4\pi\varepsilon_0)^2 m_e} \int L_C(u) f(\vec{v_e}) \frac{\vec{u}}{\mid u \mid^3} d^3 v_e \qquad (1)$$

where, $\vec{u} = \vec{v_i} - \vec{v_e}$ is the ion-electron velocity difference, $L_C(u)$ is the Coulomb logarithm, n_e is the electron density and $f(\vec{v_e})$ is the normalized velocity distribution of the electron beam. Asymptotically, the force scales as $F \sim v_i^{-2}$ for $v_i \gg \sigma_e$, where σ_e is the electron longitudinal velocity spread. Therefore for our current purpose a conventional electron cooling scheme is not suitable. However, we believe a fast cooling can be achieved if we apply an external force to assist the electron cooling force in high relative velocity range. We propose utilizing an induction accelerator to rapidly push the ions toward the stable point of the cooling force, as shown in figure 1. The induction accelerator is a device similar to a voltage transformer, which is capable of applying a constant voltage on the stored beam, by varying the excitation current in the primary winding. If we apply an IndAcc voltage of the same sign as the cooling force, we will be able to reduce the cooling time.

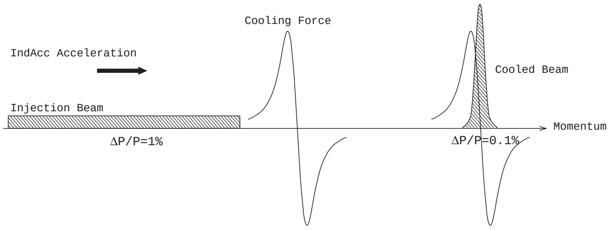

Figure 1: Principle of the induction accelerator sweep scheme; fast cooling is possible with IndAcc acceleration and capture by electron beam

3 EXPERIMENTS

The IndAcc sweep scheme was tested experimentally at TSR of MPI Heidelberg, as well as at HIMAC of NIRS. The results of these experiments are presented.

3.1 Cooling time measurement at TSR

The purpose of the current scheme is the efficient cooling of an ion beam with wide momentum spread. However, at TSR the injection beam has a rather small momentum spread. Therefore the experiment was performed using cool beams shifted in momentum by 1% with respect to the electron momentum. The time necessary for the electron beam to recapture the ions, is an approximation of the cooling time of hot ion beam with 1% momentum spread. Cooling times were measured for a carbon beam $^{12}C^{6+}$ of energy 73.3MeV and an electron beam density $n_e = 2.4 \times 10^7 cm^{-3}$. The injected beam is shifted in momentum to $\delta p/p = 1\%$ with respect to the electrons and the time evolution of the Schottky noise signal of the beam is measured. Such a measurement without application of IndAcc voltage is shown in figure 2. The ion beam is positioned initially to the left, and is captured by the electron beam located to the right. The IndAcc voltage is then applied and the same measurement is performed. The dependence of the cooling time on the applied IndAcc voltage is shown in figure 3. Numerical quadrature of the equation of motion of the ions under the action of the IndAcc and the electron cooling force is computed (curves in fig. 3) and fitted to the data points. The cooling time is defined as the time necessary to achieve zero ion-electron relative velocity. We observe that the cooling time is decreased substantially from 2.8 sec without IndAcc sweep, to 0.6 sec with application of IndAcc voltage $U_{ind} = 0.4V$. This scheme is capable of achieving fast cooling times for ion beams with large momentum spreads.

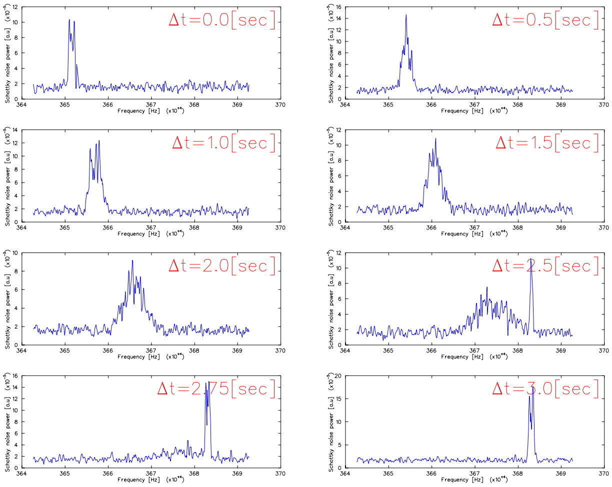

Figure 2: Time evolution of a $^{12}C^{6+}$73.3MeV ion beam under the action of the cooling force for electron density $n_e = 2.4 \times 10^7 cm^{-3}$ and no IndAcc voltage ($U_{ind} = 0V$). After 3 seconds the ion beam is completely captured.

3.2 *Maximum IndAcc voltage measurement at HIMAC*

Applying the IndAcc voltage has the effect of shifting the stable point of the electron cooling force. At TSR a maximum IndAcc voltage of 0.4V was applied, and the stable point was always preserved for the electron density used in the experiment. However applying a higher voltage can cause the loss of the stable point, and therefore loss of the ion beam. The dependence of the maximum IndAcc voltage on the electron density was investigated at HIMAC (Heavy Ion Medical Accelerator in Chiba). For this purpose, a new IndAcc was constructed and installed, which can produce a maximum voltage of 4V for a pusle width of 84ms. Argon ions $^{40}Ar^{18+}$ of total energy $240MeV$ were cooled by the electron beam, and the IndAcc voltage was applied. The loss of the stable point, should be observed as a shift in the Schottky noise signal of the beam taken at different time instants, as the beam is accelerated by the IndAcc. The result of this measurement for electron densities $n_e = 0.7 \times 10^7 cm^{-3}$ and $n_e = 1.0 \times 10^7 cm^{-3}$, is shown in figure 4. We observe that for $n_e = 0.7 \times 10^7 cm^{-3}$, beam capture is lost for an IndAcc voltage higher than $U_{ind} = 0.7V$. For $n_e = 1.0 \times 10^7 cm^{-3}$ the maximum IndAcc voltage is $1.0V$. This result can be compared to the data taken at TSR by scaling the appropriate parameters. As seen in equation 1, the cooling force has a linear and square dependence on the electron density and the ion charge re-

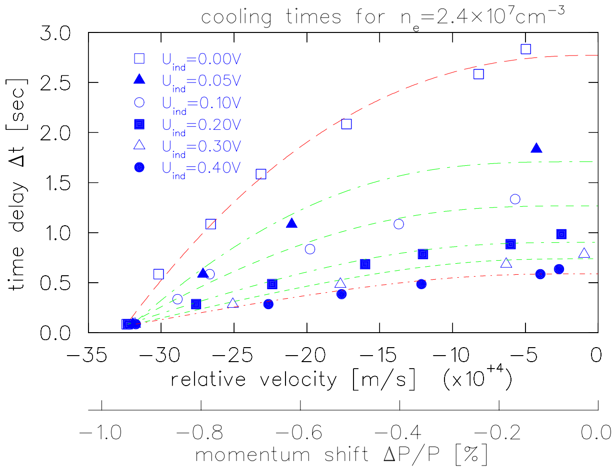

Figure 3: Dependence of the cooling time on the IndAcc voltage; reduction from 2.8sec without IndAcc voltage to 0.6sec with 0.4V is observed.

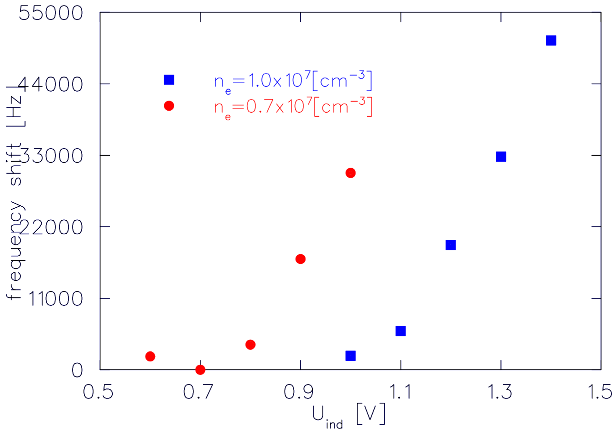

Figure 4: Frequency shift of the measured spectra as a function of the applied IndAcc voltage. Scaling of the cooling force from TSR data shows that these limit correspond to the maximum of the cooling force.

spectively. However, is was found empirically at TSR that the force has a $Z^{1.3}$ dependence on the ion charge[7]. The maximum of cooling force measured at TSR is $10eV/m$ for $n_e = 2.4 \times 10^7 cm^{-3}$. Scaling this value to ${}^{40}Ar^{18+}$ gives a maximum force of $12eV/m$ for $n_e = 0.7 \times 10^7 cm^{-3}$ and $17eV/m$ for $n_e = 1.0 \times 10^7 cm^{-3}$. We assume that in order to preserve a stable point, the maximum IndAcc force must be below the maximum of the cooling force,

$$U_{ind} \le \frac{F_{ecool} L}{Ze} \qquad (2)$$

where L is the length of the electron cooler. For HIMAC $L = 1m$. The above equation gives for $n_e = 0.7 \times 10^7 cm^{-3}$ a maximum voltage of $0.67V$ and for $n_e = 1.0 \times 10^7 cm^{-3}$ $0.97V$. These values are in quite good agreement with the measured values. We conclude that the maximum IndAcc voltage is limited only by the maximum of the cooling force.

4 SIMULATION OF ELECTRON COOLING PROCESS FOR LSR

A single particle tracking computer code has been developed in order to simulate the cooling process for LSR, and to optimize the LSR lattice for hot ion beam cooling[8]. The calculation is based on an approximation of the cooling force for non-magnetic flattened distribution of the electrons [9]. The horizontal and vertical betatron vectors are computed using the transfer matrix. The effect of the electron beam space charge is also included. The main parameters used in the computation are shown in table 1. The tracked particle is assumed to have initial phase space coordinates as

Table 1: Main parameters used in the electron cooling simulation

ion beam	${}^{12}C^{6+}$,$2MeV/u$
Circumference	20.1 [m]
Tunes	$(1.58, 1.16)$
emittances	$(50\pi, 20\pi)$ [mm.mrad]
β-functions at E-cooler	$(2.0, 3.1)$ [m]
Dispersion at E-cooler	1.55 [m]
E-cooler length	0.5 [m]
electron current	50 [mA]
electron beam radius	2.5 [mm]

$$\begin{pmatrix} z \\ \theta_z \end{pmatrix} = \begin{pmatrix} 0 \\ \sqrt{\epsilon_z/(\pi\beta_z)} \end{pmatrix}, \delta p/p = 0.01 \qquad (3)$$

where z is either the horizontal or vertical coordinates. This test particle was tracked under the action of both electron cooling and constant IndAcc voltage. The results are shown in figure 5. A longitudinal cooling time of $0.4sec$ sec is achieved with IndAcc voltage of $0.5V$. We observe that the reduction of the cooling time becomes less important as we apply higher voltages, and application of a voltage larger than $0.5V$ does not appreciably reduce the cooling time.

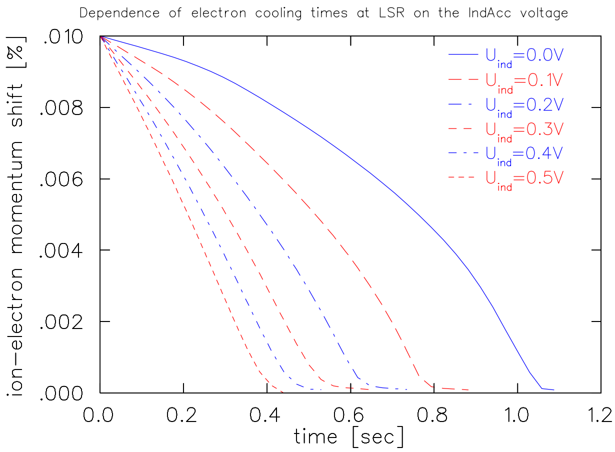

Figure 5: Result of computer simulation of electron cooling process for LSR. A cooling time of 0.4 sec can be achieved by applying an IndAcc voltage of $0.5V$

5 CONCLUSION

The IndAcc sweep scheme rests on the use of an induction accelerator to accelerate the hot ion beam toward the equilibrium point of the cooling force. Experimental tests of this scheme were performed at TSR and HIMAC. Applying this scheme yielded an important reduction of the cooling time from 2.8 sec to 0.6 sec. Also we have found that the maximum IndAcc voltage is limited only by the maximum of the cooling force. For LSR, computer simulation showed that fast longitudinal cooling can be achieved. However, if the emmittances of laser produced ions are very large the transverse cooling time can become the dominant factor, and further study for such a case is necessary.

6 REFERENCES

[1] M. Kanazawa et al., Proc. ’99 PAC, New York, p.600-602.

[2] A. Noda et al. these proceedings.

[3] K. Endo et al., Proc. EPAC2000, Vienna, pp.2515-17.

[4] E.L Clark et al., Phys. Rev. Lett. 85, 1654 (2000).

[5] G. I. Budker, Proc. Int. Symposium on Electron and Positron Storage Rings, Saclay, 1966 (Presses Universitaires de France, Paris, 1967), p. II-1-1

[6] YA.S. Derbenev and A.N. Skrinsky, Part. Acc. 8 (1977), pp. 1-20

[7] M. Beutelspacher, doctoral thesis, Univ Heidelberg, 2000(Report MPI H-V18 2000)

[8] T. Shirai et al., these proceedings.

[9] J. Bosser, CAS, Oxford, CERN/95-06, Vol. 2, September(1985)