EXPERIMENTAL DEMONSTRATION OF ELECTRON COOLING WITH BUNCHED ELECTRON BEAM*

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Abstract

Electron cooling at high energy is presently considered for several ion colliders, in order to achieve high luminosities by enabling a significant reduction of emittance of hadron beams. Electron beam at cooling channel in a few to tens MeV can be accelerated by a RF/SRF linac, and thus using bunched electrons to cool bunched ions. To study such cooling process, the DC electron gun of EC35 cooler was modified by pulsing the grid voltage, by which a 0.07-3.5 us of electron bunch length with a repetition frequency of less than 250 kHz was obtained. The first experiment demonstrated cooling coasting and bunched ion beam by a bunched electron beam was carried out at the storage ring CSRm at IMP. A preliminary data analysis has indicated the bunch length shrinkage and the momentum spread reduction of bunched 12C+6 ion beam. A longitudinal grouping effect of coasting ion beam by the electron bunch has also observed. In this paper, we will present the experiment result and its preliminary comparison to the simulation modelling.

INTRODUCTION

Electron cooling, a well-established method proposed by Budker to improve the phase space densities of stored ion beams, was applied successfully in many proton, antiproton and ion storage rings [1]. The first electron cooling experiment was carried out at NAP-M (Novosibirsk) with protons at the energy of 68 MeV in 1974. After that, several electron cooling devices were built for low-energy proton and ion storage rings in twentieth century. The first relativistic electron cooling of 8.9 GeV/c antiprotons was demonstrated in 2005 at Fermi lab [2]. Later, a 2 MeV magnetized electron cooling device was installed in COSY at Juelich and a cooling of proton beam at the energy of 1.67 GeV/c was achieved [3]. Furthermore, various possibilities such as coherent electron cooling and micro-bunched electron cooling have been proposed for using the electron beam's instabilities to enhance cooling rate. A prototype based on ERL has been developing at BNL to demonstrate longitudinal cooling in coherent electron cooling mode [4]. All electron cooling systems which were in operation so far employed electron beam generated with an electrostatic electron gun in DC operating mode. Such conventional DC electrostatic accelerator is quite possible to provide electrons of kinetic energies of up to about 5-8 MeV. For even higher energies the most promising approach would appear to be the RF accelerator of electron beam in an energy-recovering linac system and thus using bunched electron beam for cooling [5]. Some efforts were devoted to explore various aspects of such bunched electron beam cooling but experimental studies of such cooling are still lacking.

The first experiment to demonstrate electron cooling by a bunched electron beam was carried out in the storage ring CSRm at IMP. The 35keV conventional magnetized DC electron cooler provides pulsed electron beam by a modification of its high voltage platform. The electron beam is generated by a thermionic cathode. The grid electrode situated near the cathode edge can produce the negative electric field at the cathode thereby suppressing the emission of electrons. The grid electrode was originally designed for providing hollow electron beam to avoid instabilities of over-cooling beams. By varying the potential of this electrode it is possible to obtain electron beam with variable transverse profile. In our case, a pulsed voltage is applied on it to switch on and off the electron beam fast. Modifications are also made on the connection between grid and anode in order to have good characteristics for time pulse shape. Figure 1 provides a pulsed electron beam measurement by the modified 35 keV electron cooler.
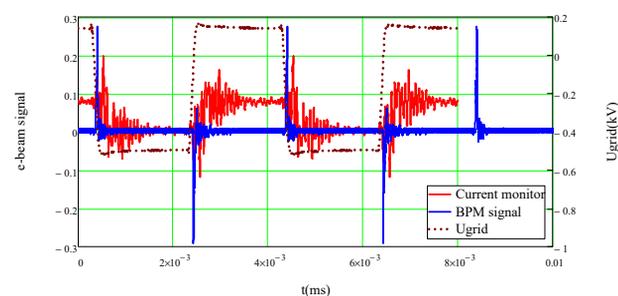

Figure 1: Modulated voltage on the grid electrode of the gun (dash line), pulsed electron beam current (red) and BPM signal generated by pulsed electron beam in the cooler.

In this experiment, a 7.0 MeV/u C^{6+} ions provided by the cyclotron SFC were injected and accumulated in CSRm. The electron cooling system and the RF station can be switched on respectively to study the pulsed electron cooling of coasting or bunched ion beam. The main parameters of experiment are listed in Table.1.

Table 1: Main Parameters of Experiment

Parameter	Unit	value
Ions		$^{12}C^{6+}$
Ion energy	MeV/u	7.0
Revolutions period	Us	4.4
Particle number		10^8
Initial bunch length	ns	700 or DC
Electron energy	keV	3.8
e-beam avg. current	mA	<50
e-beam pulse width	ns	70 - 3500
e-beam radius	cm	2.5

COASTING ION BEAM COOLING

A pulsed electron beam was used to cool the coasting (DC) ion beam stored in CSRm firstly. The ions C^{4+} provided by the cyclotron was injected with a stripper, then we switched on the pulsed electron beam 1 or 2 seconds after then injection. Immediately we found the stored particles were lost, as shown in Figure 2.
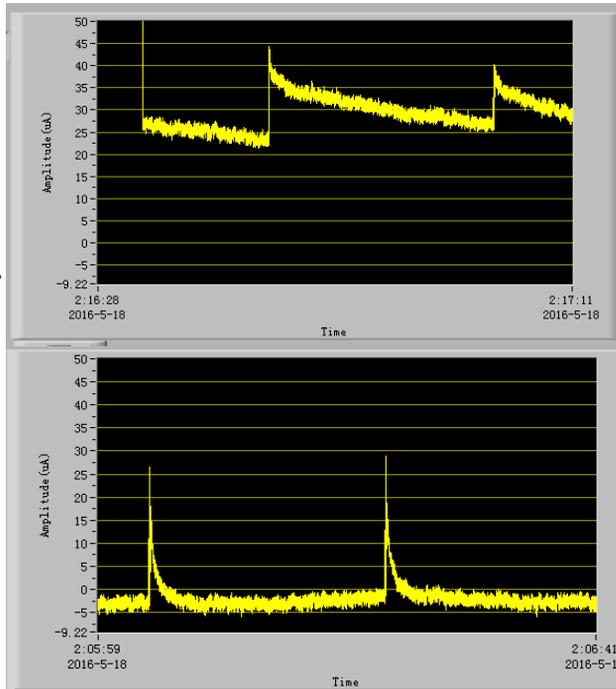

Figure 2: The DCCT signals of stored beam without (above) and with (below) pulsed electron beam.

By a scanning of the frequency of electron pulse, a dependence of beam lifetime on pulsed frequency was observed, as shown in Figure 3. The stored ions were stable only at synchronization point, for example, the frequency of pulsed electron beam is integer or half integer of the ion beam revolution period. It is easy to explain if a space charge field at the edge of pulsed electron beam was considered. Because of a density change, an opposite electric field was produced at rise/fall edge of electron pulse:

$$E_z(z) = -\frac{g}{4\pi\varepsilon_0 \beta c\gamma^2}\frac{dI_e(z)}{dz} \qquad (1)$$

It is similar to a RF bucket around the electron beam. If there was no synchronization, ions can be kicked out by this RF voltage quickly, as shown in Figure 4.
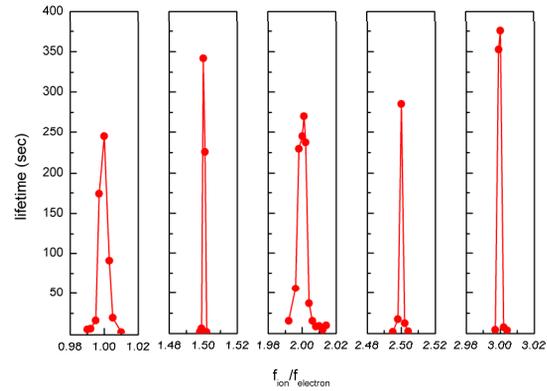

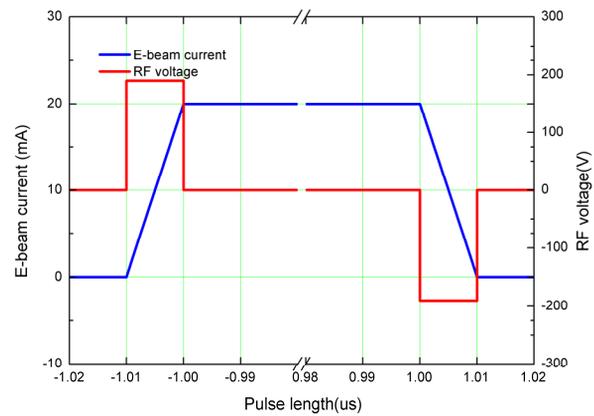Figure 3: The dependence of lifetime on a synchronization between ion and electron pulses.

Figure 4: RF bucket with amplitude of 150V can be created by an electron pulse, the peak current is 50mA and the rise/fall time is 10ns.

During the cooling process with a synchronized electron pulse, an ion beam BPM signal was observed clearly and the amplitude increased step by step, as shown in Figure 5. It means ions were not only cooled into a small momentum spread, but also captured in a small longitudinal space, and cannot escape from the bucket, while the momentum is smaller than bucket amplitude. The width of ion beam pulse is the same as electron pulse, an integration of BPM signal also shown us the ion bunch length is equal to the electron pulse, which was called "grouping" effect, as shown in Figure 6. In addition, the linear density decreases from the beginning to the end of ion pulse. By considering of electron momentum spread caused by the longitudinal potential in different transverse position, a simulation result shown a same behaviour, but the details is still not very clear.
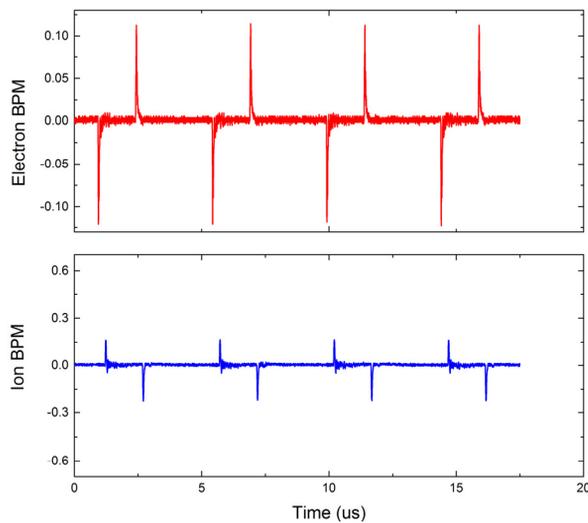
Figure 5: The BPM signal was observed clearly, even without RF system. The width is the same as electron pulse.
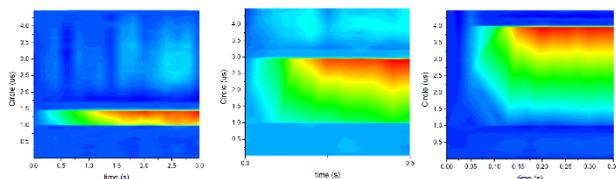

Figure 6: The BPM signal was observed clearly, even without RF system. The width is the same as electron pulse.

BUNCHED ION BEAM COOLING

Cooling of bunched ion beam by pulsed electron beam was done due to study the cooling time depends on the parameters of electron beam, such as frequency, peak current, and pulse width. A sinusoidal RF voltage is applied. The RF voltage fixed to 1.0kV at 2 times of revolution frequency (454 kHz) is used to capture ions to the buckets, therefore there are two ion bunches in the ring. But because of limitation of pulse generator, electron pulse with repletion frequency less than 250 kHz can be obtained, which means only one ion bunch can be cooled in the ring, as shown in Figure 7.
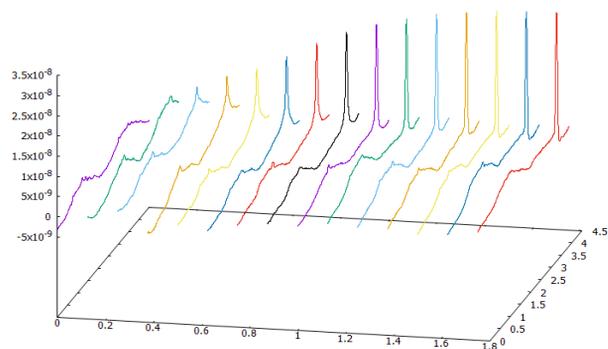

Figure 7: The ion bunch was cooled by pulsed electron beam. There are two ion bunches in the ring but only one was cooled by pulsed electron beam.

By changing of electron pulse parameters, such as width, peak current, a cooling process was studied. A preliminary data analysis shown some different, especially the cooling time of particles in tail depends on the width of electron pulse, as shown in Figure 8. More details should be studied according to further data analysis.
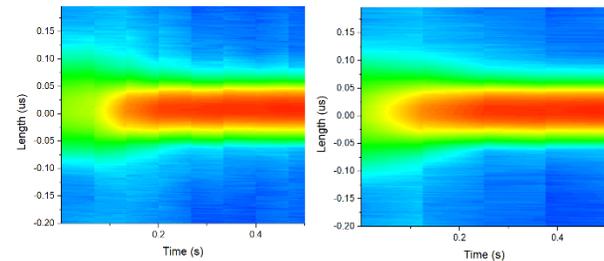

Figure 8: Preliminary data shows a difference of cooling process by different electron pulse width (2.5 µs left and 1.0 µs right).

CONCLUSION

Cooling process of coasting and bunched ion beam by pulsed electron beam was studied at CSR storage ring. Cooling of coasting ion beam shows a grouping effect, which means particles are not only cooled to equilibrium, but also captured by electron pulse, finally a width equal to electron pulse was obtained. Cooling of bunched ion beam was done to study the cooling time dependence, a preliminary data analysis only shown some difference with vary parameters, details should be studied further.

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