ISBN: 978-3-95450-243-1 ISSN: 2226-0374 doi:10.18429/JACoW-COOL2021-P1008

ELECTRON COOLING USING A PULSED AND DITHERING BEAM FROM AN ELECTROSTATIC ELECTRON COOLER

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Abstract

In this paper we report results of an experimental study of a pulsed-beam electron cooler. We have found the effects of the electron bunch length and longitudinal ion focusing strength on the temporal evolution of the longitudinal and transverse ion beam profile and demonstrate the detrimental effect of timing jitter as predicted by the space-charge theory and simulations.

Our experiment has suggested the need of further investigations into specific aspects of bunched cooling such as synchro-betatron coupling and phase dithering effects of using a relative shorter electron bunch to cool a longer ion bunch.

INTRODUCTION

Electron cooling continues to be an invaluable technique to reduce and maintain the emittance in hadron storage rings, for example the US Electron-Ion Collider (EIC) and the Electron-Ion Collider in China (EICC) where stochastic cooling is inefficient in cooling the proton beam and radiative cooling is negligible. Extending the energy range of electron coolers beyond what is feasible with a conventional, electrostatic approach necessitates the use of RF fields for acceleration and, thus, a bunched electron beam. To experimentally investigate how the relative time structure of the two beams affects the cooling properties, we have set up a pulsed-beam cooling device by adding a synchronized pulsing circuit to the conventional electron source of the main Cooler Storage Ring (CSRm) cooler at Institute of Modern Physics (IMP) in China. The experiment conducted in December 2019, using both synchronized [1] and modulated synchronization of electron pulses to the ion beam bunches. This "Dithering" technique modulates the electron bunch arrival time relative the ion revolution frequency by using a shorter electron bunch to cool a longer ion bunch. It is sometimes called "longitudinal painting" in some references.

EXPERIMENT SETUP

Table 1 lists the experimental parameters for both pulsed beam and dithering beam cases. An electron cooler and an RF cavity are placed in the dispersion-free sections in the CSRm ring at Institute of Morden Physics (IMP). The active length of the electron cooler is 3.4 m. The RF voltage ramped from 0.6 to 2 kV in the frequency range of 0.25 to 1.7 MHz. Figure 1 illustrates arrival time Δt verses real time t with a triangle wave variation. The modulation hardware delays or advances the phase of the signal with respect to the reference signal V_{ref} by an amount of $asin(V_{mod}/V_{ref})$ with V_{mod} being the instantaneous value of the modulating voltage. The magnitude of phase change is determined by the reference voltage and was kept constant in the experiment at a value of about 600 ns peak-to-peak. This corresponds to approximately +/- 40° of phase with respect to the reference signal which occurs at 2 × 191.5 kHz. The modulation frequency was changing from 100 Hz to 1000 Hz during the experiment.

Table 1: Beam and Instrumentation Parameters

ion beam	
particle type	$^{86}Kr^{25+}$
beam current	< 100 μA
rest mass	930.5 MeV/nucleon
kinetic energy	5.0 MeV/nucleon
β	0.103
γ	1.005
revolution frequency f_{rev}	191.5 kHz
harmonic number h	2
RF voltage V_{RF}	0.6–2 kV
electron cooler	
acceleration voltage	2.7 kV
positive grid voltage	50 V
negative grid voltage	−551 V
peak current	30 mA
pulse length	> 100 ns

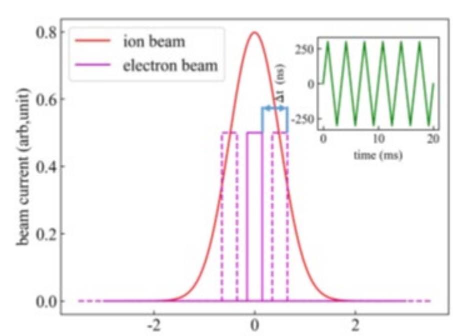

Figure 1: Experimental setup for the longitudinal phase modulation using a triangle waveform. The example here uses a 300 ns square electron pulse to cool an ion beam with a 0.5 μs rms bunch length. The modulation amplitude is 300 ns with frequency of 300 Hz.

After a fixed-frequency experiment with Δt=0 during which there was almost no beam loss for Krypton bunch

* This work was supported jointly by U.S. DOE Contract No. DE-AC05-06OR23177 and the National Natural Science Foundation of China, No. 11575264. This experiment was also supported by the International Partnership Program of Chinese Academy of Sciences, Grant No. 113462KYSB20170051,
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cooling, the modulation was applied. A beam diagnostic measurement cycle was set in 50 s. Initially, the ions were injected by the SFC and accumulated into CSRm in multi-turn injection with the help of DC cooling. A coasting beam of 10^8 particles was obtained after a 10 s accumulation. After additional DC cooling of 2 s, the DC electron beam was turned off. Then the beam emittance and momentum spread blew up within 3 s due to intra-beam scattering (IBS) heating. The RF system was then turned on to adiabatically form 2 bunches. The capture time was 2.5 s. The modulated electron bunches were then turned on for ion bunch cooling. The longitudinal ion beam profile was measured with a beam position monitor [2] (BPM) and the transverse beam size was measured by an ionization profile monitor [3] (IPM). In addition, a DC beam Current Transformer monitor (DCCT) and a spectrum analyser (SA) connected to a Schottky pickup [4] were used to record the beam current and to observe the process from injection to the end of cooling [1].

INITIAL DATA ANALYSIS

It was clearly observed that the ion beam bunch length was reduced and the peak current was increased by the modulated electron bunches indicating some cooling. However, the beam loss was severe. As shown in Fig. 2, the beam loss increases monotonically as a function of the modulation frequency. Figure 3 shows the cooling processes for a different electron bunch length with the same modulation frequency. The cooling rate is higher for a longer electron pulse and the ion beam loss is reduced.

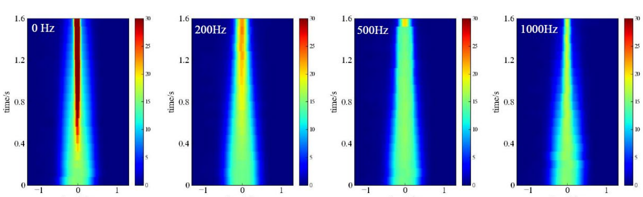

Figure 2: Evolution of longitudinal beam profile of bunched ion beam from bottom to top during the cooling process measured at different modulation frequencies for the 300 ns electron bunch length. Colour code indicates the bunch peak current with a maximum of 30 mA.

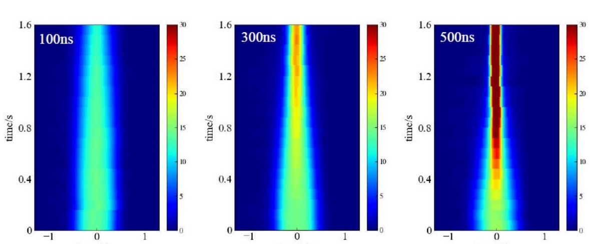

Figure 3: Same process as Fig. 2 for a different electron pulse length for a fixed 200 Hz modulation frequency.

Another measure is to calculate integrated charge on the BPM. So normalized to initial total charge, the percentage of particle loss can be calculated as shown in Fig. 4, the higher modulation frequency, the larger jittering time in synchronization, and the more beam loss. Calculated jittering time is about 2.7 ns at 100 Hz modulation frequency.

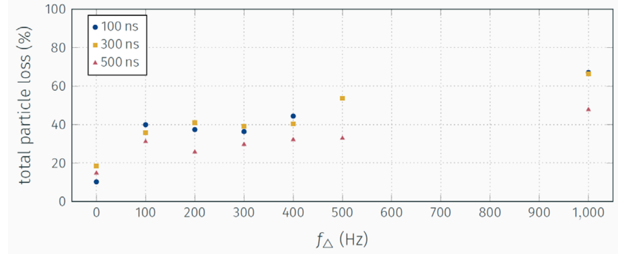

Figure 4: Measured Kr beam loss from the BPM signal as function of modulation frequency.

SIMULATIONS OF BEAM LOSS

To understand this beam loss mechanism, two independent tracking simulation codes have been developed at IMP [5] and JLab [6]. The CSRm beam transport matrices are obtained from MAD-X deck. Both codes include analytical models of magnetized electron friction force cooling, intra-beam scattering, the space charge kicks from the electron beam edges in the cooler, and ion synchrotron motion. They are all are similar to the BETACOOL and JSPEC codes [7-9].

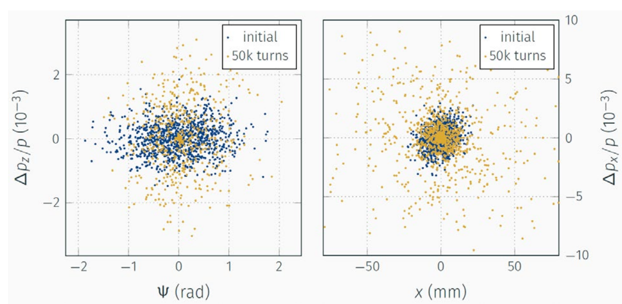

Figure 5: JLab tracking simulation indicates the longitudinal and horizontal emittance coupling and growth after 50000 turns. The model assumes 1/3 of bunches randomly kicked with an edge shift in Δt = 50 ns, and an ensemble of 1000 ions with the initial emittance.

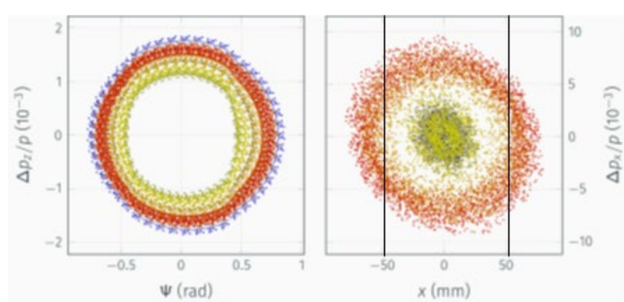

Figure 6: Phase space of single ion tracking with same conditions as Fig. 5. The ions can be lost on the ±50 mm beam pipe aperture.

A large space-charge tune shift (Eq. (1) from [10]) at low energy can cause emittance growth (heating) and then further beam loss due to a synchro-betatron coupling resonance. The emittance growth time in our experiment for a

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typical 20 ns arrival jitter is ~0.34-0.66 s due to the very low β^2 and γ^3. We have estimated a fluctuation of 1% of rms peak current at 30 mA in our experiment for a typical 20 ns arrival jitter is ~0.34-0.66 s. Emittance growth cannot be easily avoided at k=0, dc like, 30 mA in synchro-betatron resonance with such a large space charge tune shift.

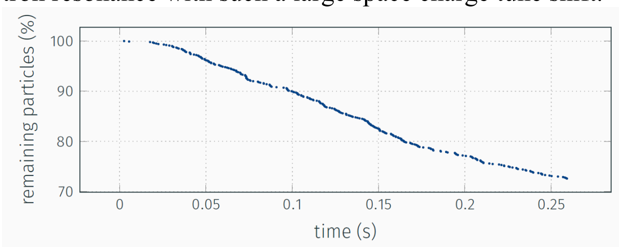


Figure 7: Beam aperture loss during the dithering cooling process by the tracking simulation in Fig. 6.

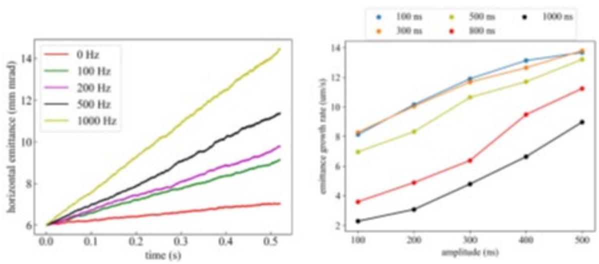
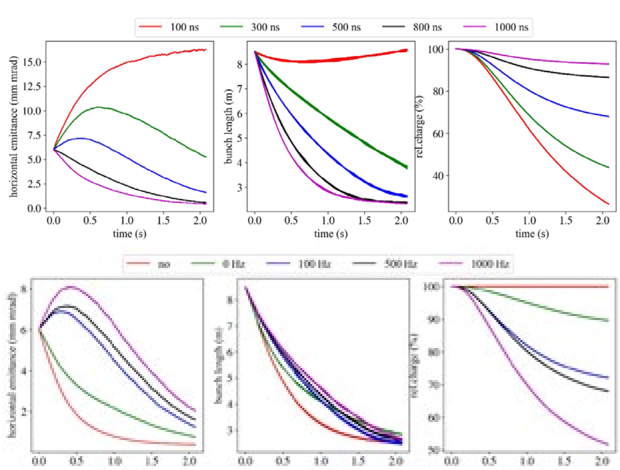


Figure 8: IMP tracking simulations of emittance growth rates. Modulation amplitude is 300 ns. Left: Effects of modulation frequency, pulse length is 500 ns; Right: Effects of electron pulse length, the modulation frequency is 500 Hz.

Further analysis and simulation models need to be studied to explore the third Q_z tune spread in 6D phase space with the RF focusing, the e-pulse edge kicking and their coupling effects to the transverse emittance. A preliminary simulation indicated, as in Fig.10, that the transverse tunes get spread out when the e-beam current increases, crossing several resonance lines. However, for a higher energy cooler like the Low Energy RIC electron Cooling (LEReC), the space charge tune shift has been reduced by 104 times. The synchro-betatron coupling can tolerate up to k=4_{th} order resonances [10].



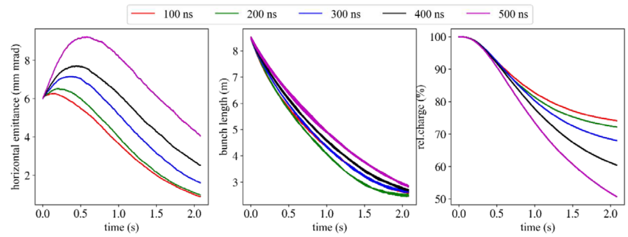


Figure 9: Ion beam emittance grown rate during the cooling process. Top: for different electron pulse lengths with 500 Hz mod. freq. and 300 ns mod. amp.; Middle: for different modulation frequencies with 300 ns mod. amp. and 500 ns e-pulse length; Bottom: for different mod. amp. with 500 Hz mod. freq. and 500 ns e-pulse length. From left to right are the emittance, bunch length and beam loss. verses cooling time respectively.

More precise triggering control of the HV pulsing system and an improved beam diagnostic system are needed at CSRs, IMP. Experiments at higher energy like at the CSRe, IMP will be useful for a further scaling law study of future EIC Strong Hadron Cooling (SHC) machine including the simulation support to understand those data.

$$\Delta\nu_{\text{peak},x/y} = \frac{N_e r_0 L_{\text{cool}}}{(2\pi)^2 Q_{x/y} f_{\text{rev}} \sqrt{2\pi}\sigma_e \gamma^3 \beta^2 a_e^2} \tag{1}$$

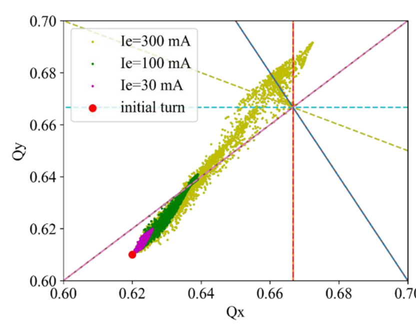


Figure 10: The transverse turn spread of the CSRm ring with the space charge effect from the electron beam. The e-pule length is 500 ns with different peak currents.

CONCLUSION

Pulsed electron bunches generated in a DC cooler to cool a RF focused krypton bunches in experiments at CSRm, IMP, have demonstrated cooling. However a dithering experiment has indicated a larger ion beam loss. Simulations and analytical calculations have indicated that space-charge kicks at random points in the synchrotron motion cause a large resonance coupling, leading to transverse emittance growth and then beam loss. Such large space-charge tune shift is dominated at low energy cooling in this experiment. Further studies for the RF based on higher energy cooler need to be done. Much slower dithering within a longer IBS lifetime of higher energy proton storage ring like EIC could potentially save electron linac cost like an Energy Recovery Linac (ERL) for the alternative solution to the proton cooling.

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