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EXPERIMENTAL DEMONSTRATION OF ION BEAM COOLING WITH PULSED ELECTRON BEAM*

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Abstract

The DC electron gun of EC35 cooler at the storage ring CSRm, IMP was modified by pulsing its grid voltage to produce electron pulses in 0.07-3.5 µs length, with a repetition frequency of less than 250 kHz, and to synchronize with the ion revolution frequency. The first two experiments have clearly demonstrated the cooling of a RF focused ion bunches by the pulsed electron beam of similar or shorter pulse width. The momentum spread of cooled ion bunch has been reduced from ~2×10^{-3} to ~6×10^{-4} within 0.5 second. The simulation models developed so far agree with the measurement results qualitatively as an evidence of cooling. A longitudinal grouping effect of the coasting ion beam being cooled by the pulsed electron beam has been also observed [1]. In this paper, we will present examples on the bunched electron cooling data after carefully analysing the ion BPM and its Schottky signals.

INTRODUCTION

Cooling ion beams at high energy is presently considered for an electron-ion collider at JLab [2], in order to achieve high luminosities by enabling a significant reduction of the emittance of hadron beams. An electron beam in a cooling channel at 20-55 MeV will be accelerated by an ERL linac, thus using bunched electrons to cool bunched ions. To study such a cooling process using an existing ion accelerator complex, the CSR at IMP was chosen to do such an experiment with a small modification to its original DC electron gun.

The 1st experiment was done in May 2016. The pulsed beam electron was formed by a high voltage (HV) pulser as shown in Fig. 1. Pulsed beam cooling was first observed with the data recorded at different injection fills. The 2nd experiment was carried out in April 2017 with an improved synchronization, variable delays, triggering control and the beam instrumentation for taking data in the same injection fill, so the cooling process was more clearly observed and recorded. All experiments were done at injected $^{12}C^{+6}$ energy of 7MeV/u with the help of DC cooling to accumulate the ion intensity in the coasting beam, then the DC cooling was switched off to capture the long ion bunch with a RF voltage. The cooling time was measured after switching on the HV pulser with variable RF voltages, electron pulse lengths and currents.

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EXPERIMENT SETUPS

In addition to the modification of SC35 cooler for electron pulsing, the original beam diagnostic devices of DCCT, electron BPM and ion BPM (upstream of the SC35 cooler) were used. The RF cavity voltage was readout and its event signal was used to trigger the PLC of the HV pulser. A Labview program was developed specially for the subsystem synchronization, delay variation and triggering the recording frames of LeCroy scope for the BPMs. The original EPICS/Labview programs were used for recording the data of a CCD camera of the ionization profile monitor, DCCT and the (RF) Schottky signal from the spectrum analyser connected to the ion BPM.

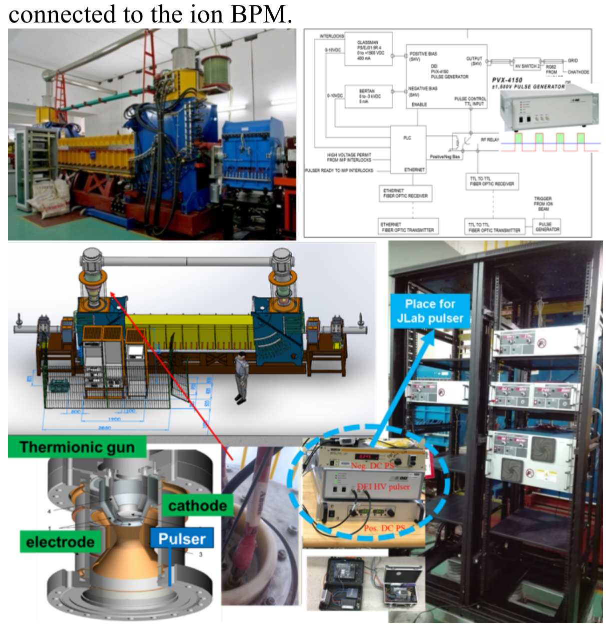

Figure 1: SC35 cooler looking from inside of CSRm ring downstream of ion beam (top left) with upgrade of all DC power supplies installed on the local control racks (middle, right) and the HV pulser connected to the grid electrode of original DC gun (bottom left) to switch the electron current with a fiber-optical control circuit (top right).

The fast recording data of sampling rate of 1/ns in 1 ms data length, with 150 ms apart of 15 data sets per cooling cycle were recorded on both ion BPM and electron BPM from the LeCroy scope 640ZI and the spectrum data from a slower sampling rate of 1/20.5µs, 801 data points per sweep on the Tektronics RSA6100 were used for the cooling data post analysis.

Due to the IGBTs switching power of 150W limitation, the HV pulser's grid voltage was clamped to

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220V, the maximum peak electron pulse current would be limited to 72mA, large enough for the pulsed beam cooling at low energy. The maximum pulse repetition rate would be 571 kHz. To be more conservative for the hardware protection and easier for the comparison of cooled and uncooled beams, only one of two ion bunches in the ring (h=2) was overlapped by an electron pulse. We then had used the pulse rate being the same as the ion revolution frequency.

EXPERIMENT PARAMETERS

Table 1 lists the experiment parameters we have used in 2016-2017 and proposed parameters toward higher ion energies at the CSRe ring in 2018-2019. The same parameters are also used in the simulations for the modelling benchmarks.

Table 1: Recent and Proposed Cooling Experiment Parameters and also for the Simulation Benchmarks

ION RING	CSRm	CSRe		
specieses	12C6+	12C6+	12C6+	
bunch charge				
charge per nucleon	0.5	0.5	0.5	
bunch length (σ)	20	2	2	m
kinetic energy per nucleon	7.0	18.0	400.0	MeV
total Energy per nucleon	945.3	956.3000	1338.3000	MeV
beta	0.121	0.193	0.713	
gamma	1.007	1.019	1.426	
gamma transition	5.168	2.629	2.629	
phase slip factor	0.948	0.818	0.347	
revolution time	4.427	2.784	0.754	us
revolution frequency	225.907	359.134	1326.098	kHz
Harmonic Number	2	1	1	
bucket height - eSC	1.687E-07	3.182E-07	5.672E-07	
Vrf	1200	600	600	V
RF frequency	451.814	359.134	1326.098	kHz
bucket height - Vrf	1.773E-06	3.017E-06	1.446E-05	
energy spread ratio: eSC/Vrf	0.095	0.105	0.039	
Schottky Pickup	**CSRm**	**CSRe**		
	± 0.25MHz	±1MHz	±1MHz	
resonance frequency	6.77721	244.57	244.57	MHz
harmonic number	30	680	184	
Electron Cooler	**SC35**	**SC300**		
kinetic energy	3.81	9.80	217.84	keV
beta	0.121	0.193	0.713	
gamma	1.007	1.019	1.426	
electron pulse edge width	25	25	25	ns
electron pulse edge width	0.035	0.056	0.208	rad
dI/dt	2.64	2.64	2.64	mA/ns
Cooling section length	3.4	3.4	3.4	m
Electron kick δE per turn	0.306	0.118	0.004	keV
max peak current	3	3	3	A
max magnetic field	0.15	0.15	0.15	T
cathode radius	1.25	1.25	1.25	cm
E beam radius at cooler section	1.25-2.5	1.25-4.0	1.25-4.0	cm

ION BPM DATA ANALYSIS

The differential voltage of bunched ion current induced from the shoe-box type BPM located at 12.07m downstream of gun-side electron BPM was taken and the up and down plate voltages were summed up by a RF combiner and amplified by a 50Ω input impedance, ~60dB gain MITEQ AU-1647 preamp. The sum signal from the electron BPM was also directly fed into the same LeCroy scope without a preamp. In the first try, after the 1st integrations of both signals, the pulse shapes of ion bunch could be delayed by 332.8ns and overlapped to the co-moving electron bunches. However, there is an artificial dip after each cooled ion bunch which greatly affects the 2nd pulse shape integration value used to get the correct bunch charge information. After investigations of circuit modelling and the experiment, we have found there is a push-pull effect on the DC power supply to the low input impedance of preamp when a high pulse current drives it. To correct this data deficiency, we have developed an equivalent circuit to simulate the current draining property, so a transfer function FFT between time and frequency domains can be used to correct this frequency dependent defect. After this correction, the normal ion pulse shape as function of cooling time can be plotted as in Fig. 2. For each cooling process, 15 temporal equally spaced sampling data sets were taken, each data set covers 1ms with 1ns sample spacing. Within 1ms of the sampling time, we clearly observed the synchrotron motions in both RF focused bunches. Within 1.75 seconds, using 15 recorded data sets, the cooled bunch indicates a cooling time of ~0.5 seconds. After 2nd integrations of each 15 curves, although the relative charge varies from each of the sampled 15 data sets, the total charge of uncooled bunch is still more than the total charge of cooled bunch except at the multiples of synchrotron period. However integrated charge within the electron pulse width is nearly a constant. More data analysis and higher data quality with shorter electron pulses are needed to show whether the bunched cooling process only increases the charge density within the pulsed electron length.

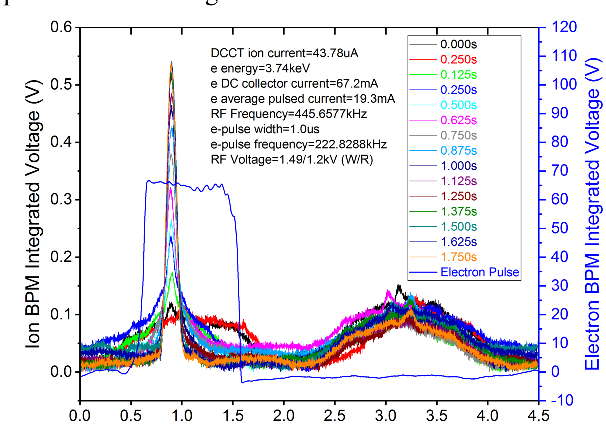

Figure 2: Ion pulse shape change as function of pulsed electron cooling time starting from the t=0 at pulser on.

SCHOTTKY SIGNAL DATA ANALYSIS

Initial Schottky signal analysis from the same ion BPM, corresponding to the same event of Fig. 2, at the m=30 harmonic of revolution frequency has been found to be very useful for the calculation of ion bunch momentum spread [3]. The Schottky signal intensity proportional to the $J_u(ma)$ Bessel function only has a significant magnitude for μ<ma. The synchrotron side-

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band therefore only extends up to the coasting beam frequency spread. So the spectrum tapering structure in Fig. 3 represents the cooling rate of the cooled bunch momentum. The spacing of peaks corresponds to the bunch synchrotron frequency. $\Delta f = m f_0 \eta \Delta p/p$, where m=30, revolution f_0=222.83 kHz, slippage factor η=-0.9487. We can then roughly calculate that $\Delta p/p$ has been reduced from ~2×10^{-3} to 6×10^{-4} with a cooling rate of ~0.5 s.

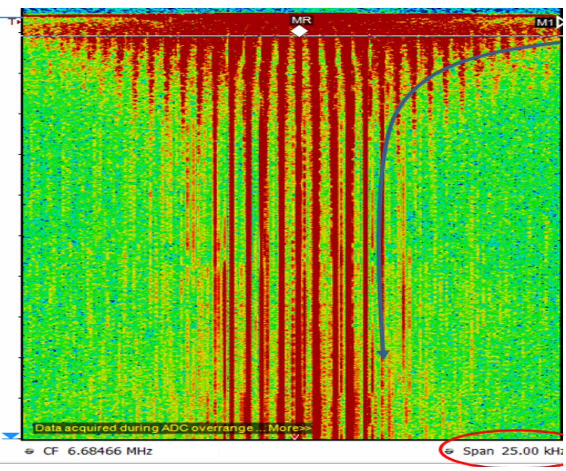

Figure 3: Schottky signal spectrum recorded from ion BPM with time T-trigger to T-equilibrant from up to down with a colour map of red in high intensity.

INITIAL DATA PROCESS ANALYSIS

The bunch length σ_{bunch} can be fitted from the ion BPM voltage by the Fokker-Plank equation, in which the equivalent capacitance and resistance of BPM are considered. In Fig.4, one data point is fitted to one of 15 data files and its current is read from its DCCT readout. It can be seen that the bunch length is decreasing during cooling and the equilibrium state is achieved after about 1s. The pulse width (>0.5 us) is always longer than the ion bunch length so the cooling times are much closer.

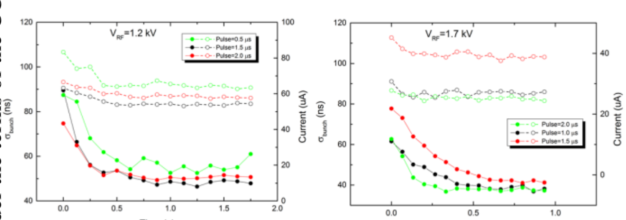

Figure 4: Ion bunch length (solid circle) and beam current (open circle) vs. cooling time under different electron pulse lengths. The RF voltage is 1.2 kV at left plot and 1.7kV at right plot.

We also calculated the integrated bunch charge but without a transfer function correction. As shown in Fig. 4, the total cooled charge is proportional to the DC beam current disregarding the RF voltage, indicating the RF potential well is much higher than the electron bunch edges as shown in Fig. 7 (right).

SIMULATION MODELINGS

Independent 1D simulations have been carried out both at JLab and IMP with the aims of adding dynamics of betatron and synchrotron motions to the 3D cooling codes developed from the BetaCool and benchmarking them to our experimental data. The Figs. 6 and 7 show one of tracking results in the longitudinal phase space.

CONCLUSION

Initial data analysis of our first two experiments indicates clearly that the pulsed electron has cooled initial RF focused ion bunch into a shorter length by at least a factor of ~2 within the electron pulse length. The momentum reduction factor is ~3.3. The experiment data qualitatively agrees with the cooling simulations but needs further calibration of beam diagnostic devices in next experiment. A future experiment at higher energies at CSRe ring at IMP has been proposed and funded by the DOE in US and the CAS in China.

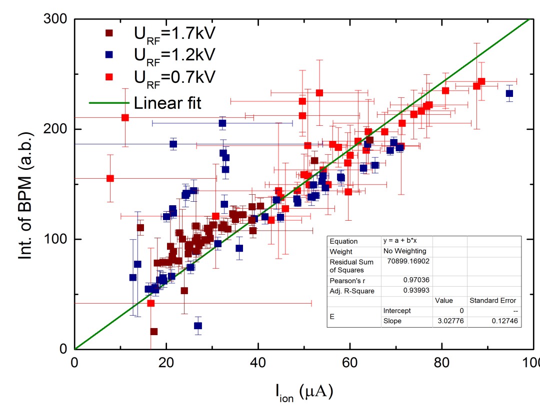

Figure 5: Integration charge of each cooled ion BPM bunch signal vs. the DCCT measured value in the ring.

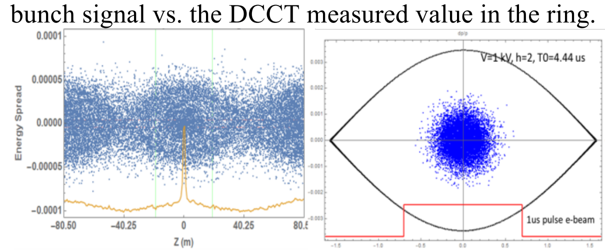

Figure 6: Independent developed 1D cooling programs: including multi-particle tracking, friction cooling force, betatron (with CSRm ring lattice) and synchrotron motions, Martini IBS model and longitudinal space charge effect.

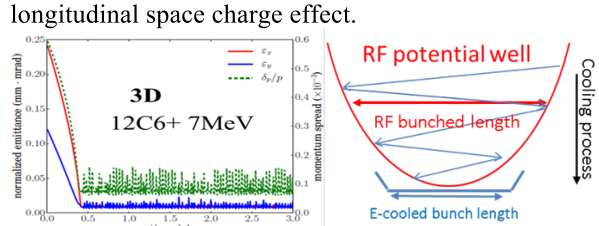

Figure 7: Modified BetaCool code predicted experiment cooling rate (left) and the RF-electron potential well model (right) for further improvement of the 3D coding on the RF focusing aided and bunched electron cooling.

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REFERENCES

[1] L.J Mao et al., "Experimental demonstration of electron cooling with bunched electron beam", *Proc. of COOL' 17*, Bonn, Germany , paper TUP1.

[2] S. Benson et al., "Development of a bunched beam electron cooler for the Jefferson Lab electron-ion collider", *Proc. Of IPAC' 18*, paper MOPMK015.

[3] D. Boussard, "Schottky noise and beam transfer function diagnostics", *CERN Accel. School 1985:0416*, CERN-SPS/86-11.