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DEMONSTRATION OF ELECTRON COOLING USING A PULSED BEAM FROM AN ELECTROSTATIC ELECTRON COOLER*

M. W. Bruker, S. Benson, A. Hutton, K. Jordan, T. Powers, R. Rimmer, T. Satogata, A. Sy, H. Wang, S. Wang, H. Zhang, Y. Zhang, Jefferson Lab, USA
F. Ma[1], J. Li, X. M. Ma, L. J. Mao, X. P. Sha[1], M. T. Tang[1], J. C. Yang, X. D. Yang, H. Zhao[2], H. W. Zhao, Institute of Modern Physics, China
[1]also at University of Chinese Academy of Sciences, Beijing, China
[2]present address: Brookhaven National Lab, Upton, NY, USA

Abstract

Electron cooling continues to be an invaluable technique to reduce and maintain the emittance in hadron storage rings in cases where stochastic cooling is inefficient and radiative cooling is negligible. Extending the energy range of electron coolers beyond what is feasible with the 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 CSRm cooler at Institute of Modern Physics. We show the effect 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 theory and simulations. Compared to actual RF-based coolers, the simplicity and flexibility of our setup will facilitate further investigations of specific aspects of bunched cooling such as synchro-betatron coupling and phase dithering.

EXPERIMENTAL SETUP

The electron beam used for the cooling experiment is generated by the conventional magnetized electron cooler installed in the CSRm ring [1]. The details of the facility are described in [2].

By switching the grid voltage of the gun between two values using a solid-state switch synchronized with the ion ring RF as shown in Fig. 1, we can generate rectangular electron pulses while leaving the other properties of the cooler essentially unmodified. Knowing the time-of-flight difference between the BPMs, we can achieve a well-defined yet adjustable temporal overlap between electron and ion bunches. The beam parameters are listed in Table 1; a more detailed description of the setup can be found in [3].

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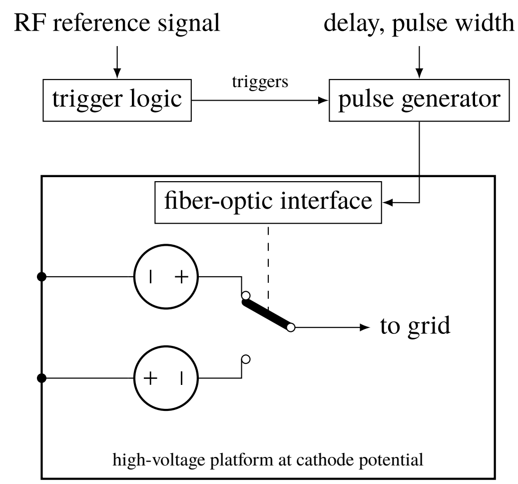

Figure 1: Schematic model of the electron pulse synchronization setup.

Table 1: Beam and Instrumentation Parameters

Ion Beam	
particle type	^{86}Kr^{25+}
beam current	$< 100\,\mu$A
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

BEAM DIAGNOSTICS

The longitudinal bunch shape and timing of the two beams can be measured independently using beam position monitors (BPMs) installed outside of the interaction straight. By summing the signals from opposite plates, we make the

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BPMs insensitive to the transverse beam position. The beam current signal is obtained by digitizing this sum and dividing it by the respective BPM transfer impedance in the frequency domain [3].

The first property of interest is the timing and current stability of the electron beam. Because the ion beam has no significant space charge, the electron beam can be considered unaffected by the interaction, so the electron beam signal can be diagnosed in isolation. The spread of the electron bunch length is shown in Fig. 2 for various bunch lengths used in our experiment. In the case of nominally 400 ns-long bunches, two different bunch lengths are generated randomly due to a hardware deficiency. Apart from that, the RMS bunch length jitter is generally below 2 ns. An example of the timing accuracy of the leading edge is shown in Fig. 3 for the case of nominally 500 ns-long bunches. The bunch charge is less stable in comparison as exemplified in Figs. 4 and 5, having an RMS spread of more than 1 %.

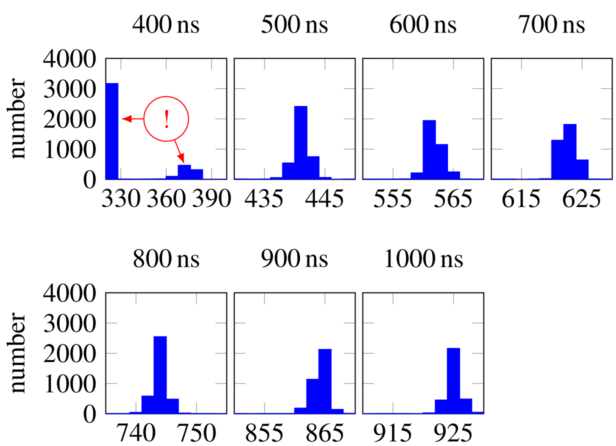

Figure 2: Histogram of observed electron bunch lengths (in ns), one plot per setting. Due to a deficiency of the circuit triggering the grid pulser, the central values of the distributions differ from the set point by varying amounts. In the 400 ns case, two different bunch lengths are created.

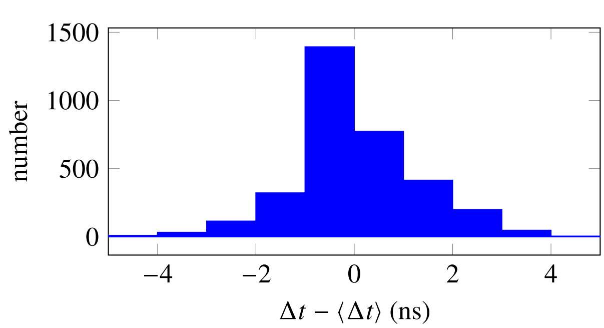

Figure 3: Distribution of the pairwise difference Δt of electron bunch arrival times (measured at the leading edge). $\langle \Delta t \rangle = 1/(hf_{\mathrm{rev}}) = 2.611\,\mu\mathrm{s}$, nominal bunch length 500 ns. The RMS jitter in this example is 1.3 ns, which, being close to the sampling interval of the digitizer, should be considered an upper bound rather than an accurate measurement.

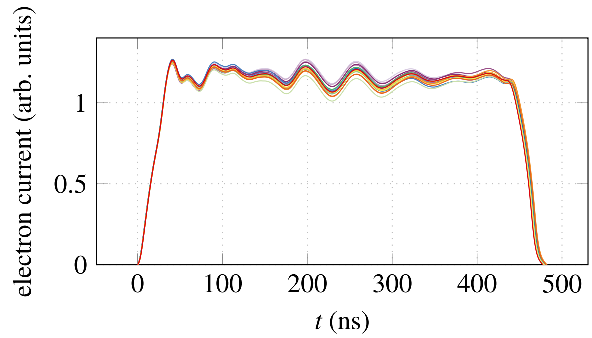

Figure 4: Variation of the longitudinal electron bunch shape as obtained from the BPM (nominally 500 ns) over the course of a single experiment, i.e. 1.6 s. For the sake of comparison, the waveforms are aligned at the left edge. While the profile is essentially rectangular, the plateau contains some parasitic ringing with a characteristic shape and random variations, which may result from the switching process.

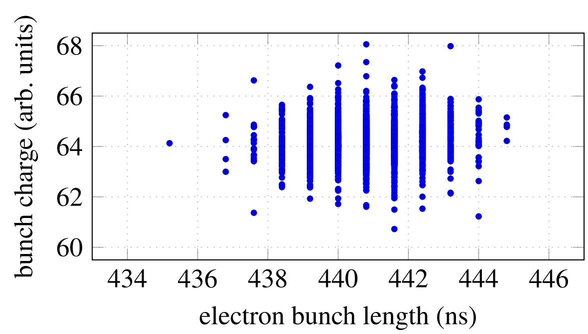

Figure 5: Distribution of the electron bunch charge obtained by integrating the filtered and transformed BPM signal between the bunch edges. The randomness of the bunch charge is uncorrelated with that of the bunch length. In this example, the RMS spread of the bunch charge is 1.3 %, while that of the bunch length is only 0.3 %. The temporal granularity is not real; it is caused by the finite sampling frequency of the digitizer.

ION BUNCH EVOLUTION

The longitudinal cooling process can be observed by measuring the ion current signal using the respective BPM and the transverse profile using an ionization profile monitor installed in the ring. While the resulting bunch profile is not necessarily Gaussian, giving rise to ambiguity as to how the cooling rate ought to be defined, the evolution of the measured profile is largely compatible with simulations and free of major surprises. Figure 6 shows the relative decrease in bunch charge and RMS bunch length throughout the cooling process at an exemplary RF voltage of 1 kV. More detailed results pertaining to cooling rates can be found in [3].

The most interesting feature of this data set is the observation that the interaction with the cooling beam deteriorates the ion beam life time. It has been theoretically explained that random fluctuations of the electron current, the bunch length, or the timing will cause the ion emittance to grow

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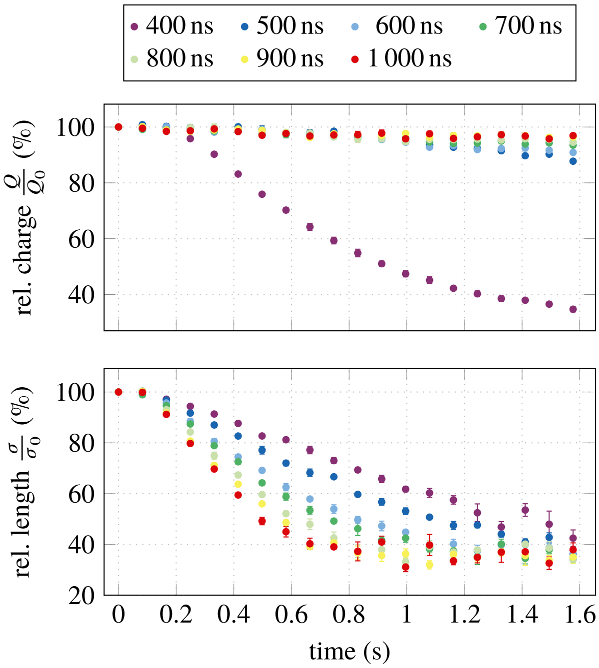

Figure 6: Evolution of the statistical properties of the longitudinal ion bunch profile as a function of time, averaged over five identical experimental runs per setting. Each color corresponds to one setting of the electron bunch length. The cooling beam is switched on at $t = 0.1$ s. $V_{\mathrm{RF}} = 1$ kV.

due to their effect on the betatron tune shift brought about by space-charge focusing [4]. In our case, the beams are non-relativistic and the space-charge forces correspondingly large, causing not only emittance degradation in an average sense but also a random spontaneous loss of ions due to transverse aperture limitations.

In the case of our nominally 400 ns-long bunches, Fig. 6 shows a reduction of the ion beam lifetime to about 1 s. This surprising effect is caused by the pronounced bunch length spread with this particular setting (see Fig. 2). The result is compatible with simulations as shown in the next section.

It is also evident that everything else being equal, shortening the electron bunch length tends to exacerbate the heating, presumably because the relative contribution of timing jitter gets larger. However, the bunch charge jitter also contributes, which is more difficult to quantify because whether or not the ringing shown in Fig. 4 is a real property of the beam has not been investigated so far.

TRACKING WITH SPACE CHARGE AND JITTER

As a consistency check, we performed a 6-d tracking simulation of a randomly generated ion ensemble through the CSRm lattice, including the space-charge forces from the electron bunches modeled as macrocharges on a 3-d grid. Figure 7 shows the ion phase spaces after 50000 revolutions ($\approx$ 0.26 s) in the case of perfectly constant electron beam parameters on the one hand and bunch length jitter distributed according to the measured 400 ns case on the other hand. Significant heating is observed in the latter case. Quantifying the resulting beam loss involves making an assumption about the transverse aperture as a function of the ring coordinate. To get a sense of the order of magnitude, we naively assume the beam pipe to have a constant radius of 50 mm, which, when checking for collisions after each optical element of the ring, gives a particle loss of 38 % at $t = 0.5$ s, not far from the result shown in Fig. 6.

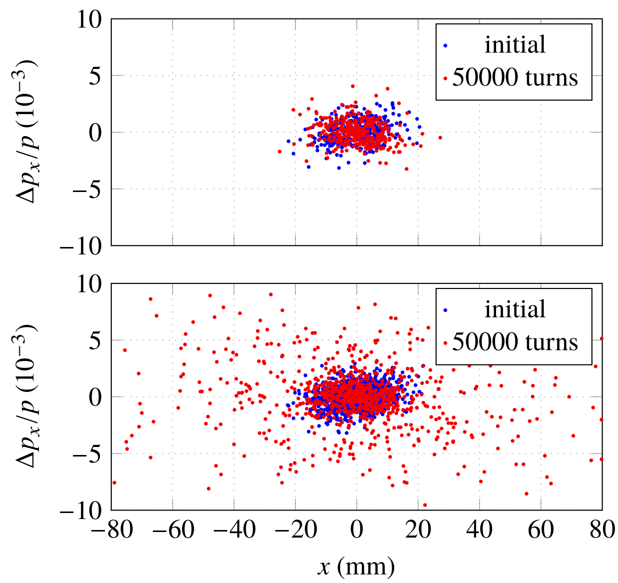

Figure 7: Comparison of the transverse phase space of the simulated ion ensemble after tracking with constant electron bunch parameters (top) and bunch length jitter as measured in the 400 ns experiment (bottom).

CONCLUSION

Adding synchronized pulsing capabilities to an existing electron cooler provides a convenient way to investigate specific aspects of beam physics related to bunched-beam electron cooling, such as timing requirements. While the cooling process itself works as expected, space charge proves to be an unexpectedly dangerous problem in the case of even slightly unstable parameters, which the simplicity and scale of our setup enable relatively easy theoretical access to. Although space-charge issues will not be as pronounced in high-energy cooling devices, further research may be necessary to fully understand them.

REFERENCES

[1] V. Bocharov *et al.*, "HIRFL-CSR electron cooler commissioning", *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 532, no. 1, pp. 144–149, 2004. doi:10.1016/j.nima.2004.06.041

[2] J. Xia *et al.*, "The heavy ion cooler-storage-ring project (HIRFL-CSR) at Lanzhou", *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 488, no. 1, pp. 11–25, 2002. doi:10.1016/S0168-9002(02)00475-8

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[3] M. W. Bruker *et al.*, “Demonstration of electron cooling using a pulsed beam from an electrostatic electron cooler”, *Phys. Rev. Accel. Beams*, vol. 24, p. 012801, Jan. 2021. doi:10.1103/PhysRevAccelBeams.24.012801

[4] G. Wang, “Ion Emittance Growth Due to Focusing Modulation from Slipping Electron Bunch”, Brookhaven National Laboratory, Upton, USA, Rep. C-A/AP/536, 2015.