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. Ma1, J. Li, X. M. Ma, L. J. Mao, X. P. Sha1, M. T. Tang1, J. C. Yang, X. D. Yang, H. Zhao2, H. W. Zhao, Institute of Modern Physics, China
1also at University of Chinese Academy of Sciences, Beijing, China
2present 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].

Table 1: Beam and Instrumentation Parameters

| Ion Beam | Electron Cooler |
|----------|-----------------|
| particle type | 86Kr25+ |
| beam current | < 100 µA |
| rest mass | 930.5 MeV/nucleon |
| kinetic energy | 5.0 MeV/nucleon |
| 𝛽 | 0.103 |
| γ | 1.005 |
| revolution frequency frev | 191.5 kHz |
| harmonic number h | 2 |
| RF voltage VRF | 0.6–2 kV |
| 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
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 %.

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.

**ION BUNCH EVOLUTION**

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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.

**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**

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