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MEASUREMENTS AND SIMULATIONS OF THE E-COOLING PERFORMANCE IN ELENA

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Abstract

Understanding and optimizing the electron cooling performance is essential to ensure high-brightness antiproton beams at the Extra Low Energy Antiproton (ELENA) ring at CERN. This paper presents measurements and simulations of the electron cooling performance in ELENA. The simulations are obtained using the Parkhomchuk model for electron cooling, which was recently implemented in the Xsuite simulation framework. The studies focus on the impact of electron-/ion-beam trajectory overlap on cooling performance.

INTRODUCTION

ELENA is part of the anti-matter factory at CERN, and its role is to provide low-energy antiprotons for various experiments. Examples of the studies for which these antiprotons are used can be found in Refs. [1–4].

ELENA receives antiprotons with a kinetic energy of 5.3 MeV from the Anti-proton Decelerator (AD) and further decelerates them down to 100 keV. There are two cooling plateaus in ELENA, one at 653 keV and one at 100 keV. The first cooling plateau is to minimize losses during deceleration, the second is to improve the quality of the extracted beams. These studies will focus on the cooling at the 100 keV plateau, which is the most relevant for defining the beam parameters as seen by the experiments. Since the AD cycle length is of the order of 110 s, the repetition rate of antiproton beams is impractical for systematic measurements relying on multiple shot acquisitions, as described in this paper. Therefore, the studies presented in this paper will not use antiprotons from the AD, but the H^- beam from the local ELENA ion source [5]. The H^- cycle length in ELENA is about 15 s, and electron cooling performance is expected to be comparable between the H^- and the antiprotons.

This study is the continuation of an effort to characterize electron cooling performance in ELENA [6] and to benchmark simulation tools being developed [7]. Information about electron cooling can be found in Refs. [8, 9].

METHOD AND PARAMETERS

A dedicated ELENA cycle was set up for the purpose of these studies: about 4×10^7 H^- are injected in ELENA on a 3 s-long 100 keV plateau, where they are left to debunch. The electron cooler is started 5 ms after injection. After a given delay, the coasting beam is extracted, and the beam size is measured in a Secondary Emission Monitor (SEM) in one of ELENA's transfer lines. The time evolution of the beam size acts as the main metric for assessing the cooling effect. This is done by measuring the extracted beam size for various cooling times. Using coasting beams allows for minimizing heating effects such as intra-beam scattering (IBS) and space charge (SC). The drawback of this approach is that the extraction induces a horizontal swipe of the ion beam during the rise and fall time of the extraction kicker. However, this is of the order of 100 ns, which is significantly shorter than the length of the coasting beam of 7 μs, which is the revolution period of the machine. Hence, it is assumed that the incorrectly extracted beam head and tail have a negligible contribution to the reconstructed transverse beam size. Additionally, each measurement is fully destructive; hence assessing the time evolution of the emittance requires measuring many consecutive shots to compensate for the unavailability of a fast beam profile monitor in ELENA.

Simulation Model

The simulations in this paper use the Xsuite framework, a beam-tracking code actively developed at CERN with multipurpose physics in mind [10]. The electron cooling module of Xsuite is based on the Parkhomchuk model [11, 12] and takes into account the space charge within the electron beam, as described in Ref. [9]. The Parkhomchuk model in Xsuite has been successfully benchmarked against that of Betacool [7]. The Parkhomchuk electron cooler in Xsuite applies a kick to the circulating beam based on the following equation

$$\vec{F} = -\frac{4Z^2 e^4 n_e \vec{V}}{m_e \left(\vec{V}^2 + V_{\mathrm{eff}}^2\right)^{3/2}} \ln \frac{\rho_{\mathrm{max}} + \rho_{\mathrm{L}} + \rho_{\mathrm{min}}}{\rho_{\mathrm{L}} + \rho_{\mathrm{min}}}, \quad (1)$$

where Z is the charge of the circulating particle, e is the elementary charge, n_e is the electron density, V is the velocity difference between the circulating beam and the electrons, m_e is the electron mass, V_{eff} is the effective Larmor motion of the electrons in the magnetic field, ρ_{max} and ρ_{min} are the maximum and minimum impact parameters, and ρ_{L} is Larmor radius of the electrons. This kick is computed separately in all three planes: horizontal, vertical, and longitudinal. For example, the horizontal kick F_x is computed using the horizontal velocity difference V_x between a circulating particle and the electrons, and likewise for the vertical and longitudinal planes. However, the total velocity difference V between a circulating particle and the electrons involves all three planes and is given by $V^2 = V_x^2 + V_y^2 + V_z^2$.

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The simulation's cooling rate was assessed by monitoring the emittance and energy spread for a coasting beam while tracking in a linearized representation of ELENA (linear transport matrix approach).Table 1 summarizes the relevant electron cooler parameters assumed for the simulations along with the Twiss parameters at the e-cooler and the SEM and beam parameters. Electron current and magnetic field values are estimated based on the operational current in the power supplies. The initial beam emittances are estimated from the measured beam profiles, neglecting the dispersion's contribution at the SEM. The other parameters are based on design [13–15], models [16], and previous studies [6].

Table 1: Main parameters relevant for this work

Parameter	**Value**
ELENA e-cooler 100 keV parameters	
e^- kinetic energy E_k (keV)	0.054
Relativistic β	0.014
e^- beam current I (mA)	0.34
Cooler length L (m)	1
Transverse e^- temperature $T_\perp$ (meV)	100
Longitudinal e^- temperature $T_\perp$ (meV)	1
Drift solenoid field B (T)	0.0097
Expansion solenoid field B (T)	0.0292
Drift $B_\perp/B_\parallel$	1×10^{-3}
e^- beam radius (mm)	14
ELENA Optics parameters at e-cooler	
Beta functions β_x/β_y (m)	1.7/2.7
Dispersion D_x/D_y (m)	1/0
Machine tunes Q_x/Q_y	2.36 / 1.39
H^- beam parameters	
Geometrical emittances ϵ_x/ϵ_y (µm)	2.5 / 2.5
Root-mean-square dp/p	1×10^{-3}
Twiss parameters at SEM	
Beta functions β_x/β_y (m)	7.6 / 1.3
Dispersion D_x (m)	0.2

COOLING RATES

The simulations and measurements presented here will explore the impact of horizontal and vertical angles between the ion and electron beam inside the electron cooler on the time evolution of transverse emittances. The angle of the H^- beam was varied with a dedicated knob using four orbit correctors around the ELENA e^- cooler, while the trajectory of the e− beam is assumed to be unperturbed. To make a fair comparison between simulations and measurements, it is crucial to find the optimal cooler settings with respect to these parameters, which, from simulation, are expected to correspond to perfect alignment between ions and electrons. The procedure to find the optimum was to extract the beam 715 ms after the start of cooling and measuring the final emittance for a range of H^- beam angles. Figure 1 shows an example of the dataset used for such an optimization, together with the expected simulation values. This optimization procedure adjusted the operational settings by ≈ 0.5 mrad in both planes, an example of which can be seen by the dashed red lines in Fig. 1. The measurements in the plot are shifted so that the angular difference is taken with respect to the angle of maximum cooling. With the ELENA electron cooler optimization in place, it was possible to compare the measurements and simulations: a parametric sweep of overlap angles in the horizontal and vertical plane was performed in measurements and simulations, and the transverse emittances were logged as a function of time. In the case of the measurements, the emittance was computed based on the beam profiles at the SEM and the Twiss parameters at the SEM specified in Table 1.

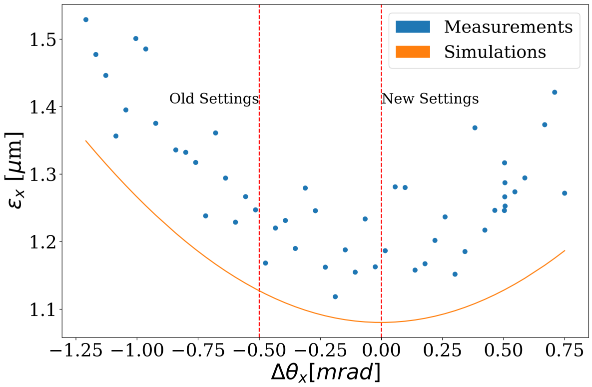
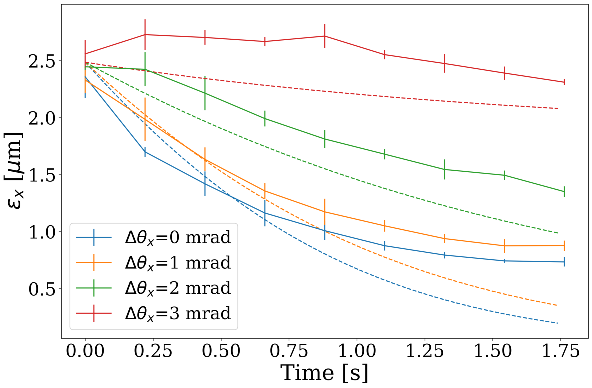
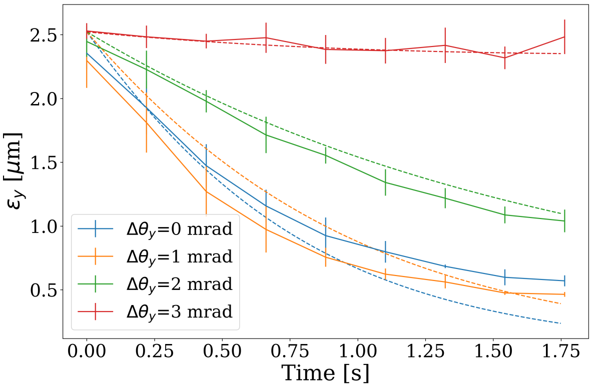


Figure 1: Measured (blue) and Simulated (orange) horizontal emittance after 715 ms of cooling as a function of the angle between ion and electron beams. In simulations and measurements, the angular difference is taken with respect to the angle with maximum cooling. Each point represents a single measurement.

The comparison between the measurements and simulations for the vertical angle is shown in Fig. 2b and for the horizontal angle in Fig. 2a. The simulations always underestimate the horizontal emittance compared to the measurements because the measurements didn't account for the dispersion and the momentum spread at the SEM. Aside, from the emittance difference due to dispersion, the results show a remarkable agreement between measurements and simulations. Firstly, both simulations and measurements show that there is no cooling for a large angular offset, such as the 3 mrad case. Good agreement is also observed for smaller angular offset, confirming that cooling performance becomes insensitive below approximately 1 mrad as already seen in Fig. 1. The measurements plateau after approximately 1 s. This could be due to heating effects, such as IBS, SC, or the effect of the actual temperature of the electrons. The simulations do not include these heating mechanisms, so the cooling process would continue until the beam reaches zero emittance. Future studies will focus on which of these heating effects acts as the bottleneck for the cooling process in ELENA. The horizontal scan from Fig. 2a also demon-



(a) Horizontal plane.



(b) Vertical plane.

Figure 2: Time evolution of the horizontal (a) and vertical (b) geometrical emittances for a series of set horizontal or vertical angles between ions and electrons. Dashed lines indicate simulation results and solid lines indicate measurements. The error bars indicate the standard deviation of 5 acquisitions for each setting. The angle in the other plane is fixed at zero.

strates a reasonable match between the measurements and simulations.

Coupling of Horizontal and Vertical Cooling

It is also interesting to see how the cooling in the horizontal and vertical planes affect one another. Figure 3 shows the effect of the horizontal angle on the vertical emittance. Both in simulation and measurement a degradation of cooling performance on one plane is expected whenever an angular offset is introduced in the other plane. Such a dependency is expected in simulation based on the Parkhomchuk model described in Eq. (1). To elaborate, the total velocity difference V^2 appears in the denominator of Eq. (1). Therefore, the cooling force F is considerably reduced in all planes whenever there is any angular (or energy) offset between the two beams. Even though both the simulation and measurement results from Fig. 3 show this coupling between the horizontal cooling and angle and the vertical emittance decay, the magnitude of the degradation is more pronounced in measurements than in simulations. In particular, for large horizontal angular offsets, the measurements show that the vertical cooling is completely stopped, while only minor degradation is predicted in simulations. One reason for this difference could be cross-talk between the horizontal and vertical planes when changing the H$^-$ orbit. Preliminary measurements have indicated that a large horizontal angular offset also introduces a sizeable difference in the vertical orbit of the H$^-$. This cross-talk could explain the greater coupling between the horizontal and vertical planes in the measurements compared to the coupling in the simulations and will need to be confirmed in future studies.

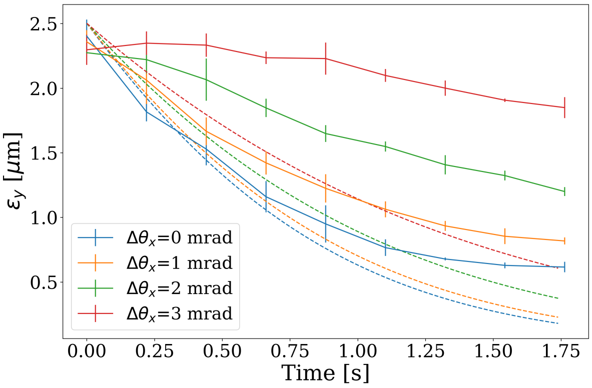


Figure 3: Time evolution of the vertical geometrical emittance for different for a range of horizontal angular offsets. Dashed lines indicate simulation results and solid lines indicate measurements.

CONCLUSION

The effect of the angular offsets between electrons and H$^-$ in the ELENA electron cooler on the transverse cooling performance was studied. This was measured by monitoring the beam size as a function of the duration of cooling for a series of angular offsets in the horizontal and vertical planes. Measurements were compared to the Parkhomchuk model implemented in Xsuite. Both simulations and measurements show good agreement. In particular, this study demonstrates the predictive power of the simulation tools in determining the tolerated angular offsets below which the cooling performance saturates. The measurements also show that the cooling process stops at a horizontal emittance of $\epsilon_x = 0.75\,\mu\text{m}$ and a vertical emittance of $\epsilon_y = 0.60\,\mu\text{m}$, which is expected to be due to heating effects such as IBS or SC which are yet to be included in the simulations. Lastly, the coupling between the cooling in the horizontal and vertical planes was studied, by examining the effect of the horizontal angle between the electron beam and the H$^-$ beam on the vertical emittance reduction and vice versa. In both planes, the simulations underestimated the degree of coupling, which will be the subject of future studies.

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