ISBN: 978-3-95450-184-7   doi:10.18429/JACoW-IPAC2018-THPAF015

BEAM TRACKING STUDIES OF ELECTRON COOLING IN ELENA*

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Abstract

The Extra Low ENergy Antiproton storage ring (ELENA), which is currently being commissioned at CERN, will further decelerate antiprotons extracted from the Antiproton Decelerator (AD) from 5.3 MeV to energies as low as 100 keV. It will provide high quality beams for the antimatter experiments located within the AD hall. At such low energies, it is important to correctly evaluate the long term beam stability. To provide a consistent explanation of the different physical phenomena affecting the beam, tracking simulations have been performed and the results will be presented in this contribution. These include electron cooling and various scattering effects under realistic conditions. The effects of several imperfections in the electron cooling process will also be discussed. In addition, analytical approximations of the temporal variation of emittance under these conditions will be presented, and compared with numerical simulation results.

INTRODUCTION

ELENA is a low energy storage ring designed to increase the efficiency of the antimatter experiments at CERN [1], its final layout is represented in Fig 1.

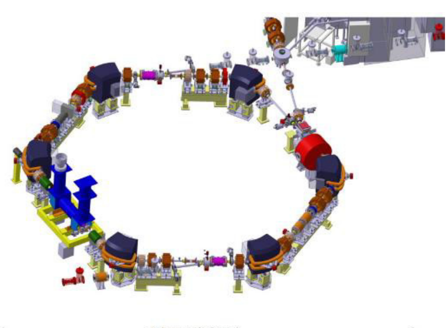

Figure 1: Sketch of the ELENA ring layout with its main components.

Currently under final commissioning phases, ELENA will accept antiprotons from the Antiproton Decelerator (AD) [2] and employ the use of an electron cooler [3]. At these lower energies, fewer antiprotons will be lost to degrader foils at the end of the deceleration process and as a result the anti-hydrogen experiments will receive higher intensity beams, considerably increasing the number of trapped antiprotons.

In the past few months the ELENA ring has been equipped with an extremely compact electron cooler.

* Work supported by European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 721559.
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ELECTRON COOLING

Electron cooling is a method of increasing the phase-space density of 'hot' heavy charged particles, ions or antiprotons, through Coulomb interactions with a 'cold' electron beam, co-propagating with the same average speed in a small section of a ring. The method was proposed by G. Budker in 1967 [4], successfully tested in 1974 with low-energy protons [5], and later implemented at a many storage rings [6-8].

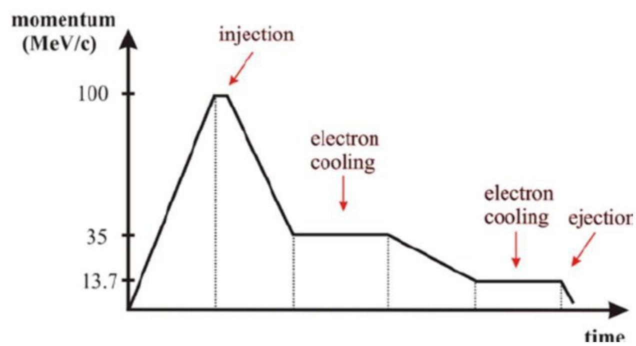

Figure 2: ELENA cycle.

Electron cooling is extremely important in ELENA since it reduces or eliminates the emittance blow-up caused by the deceleration process of the antiproton beam. Very small emittances are needed to achieve further deceleration and ease extraction to the trap experiments. The ELENA cycle (Fig. 2) comprises two cooling plateaux, one at 35 MeV/c of 8 seconds and another at 13.7 MeV/c for just 2 seconds (Table 1).

Table 1: ELENA Electron Cooler Parameters

Beam momentum	35-13.7 MeV/c
Velocity factor, $\beta = v/c$	0.037–0.015
Electron beam energy	355–55 eV
Electron current, I_e	5–2 mA
Electron beam density, n_e	1.38–1.41 10^{12} m^{-3}
Magnetic field in the gun, B_{gun}	1000 G
Magnetic field in the drift, B_{drift}	100 G
Expansion factor	10
Cathode radius	8 mm
Electron beam radius, r_b	25 mm
Betatron functions, $\beta_{x,y}$	2.103, 2.186
Horizontal dispersion, D_x	1.498 m
Flange-to-flange length	1.93 m
Solenoid length	1 m
Effective length (good field region)	0.7 m
Electron beam transverse temperature, $k_B T_{e\perp}$	0.01 eV
Electron beam longitudinal temperature, $k_B T_{e\parallel}$	0.001 eV

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Friction Force

An antiproton moving in a free electron gas with a velocity distribution experiences a friction force [9], which in a model of binary collisions can be written as:

$$\vec{F}(\vec{u}) = -\frac{4\pi e^4 n_e}{(4\pi\epsilon_0)^2 m_e} \int L_C(\vec{u}) f(\vec{v_e}) \frac{\vec{u}}{u^3} d^3\vec{v_e} \ , \qquad (1)$$

where e, n_e and m_e are the electron charge, density and mass respectively, L_C is the Coulomb logarithm defined as the logarithm of the ratio of the maximum and minimum impact parameter, $f(\vec{v_e})$ is the electron velocity distribution and $\vec{u} = \vec{v_e} - \vec{v_i}$ is the relative ion velocity.

The electron cooling systems employed at low-energy rings are typically based on an electron beam immersed in the longitudinal magnetic field of a solenoid (magnetised electron beam) [10].

In the presence of a finite-strength magnetic field the binary collisions analytical approach has complications. It does not provide a closed form solution anymore, because the relative motion and the centre of mass motion are coupled. Even if a variety of theoretical models for the friction force has been developed, the available expressions make various approximations, and the discrepancy between theory and experiments can be large. In this study, to avoid limitations of the models, the Parkhomchuk semi-empirical formula was used [11]:

$$\vec{F}(\vec{u}) = -\vec{u}\frac{4e^4 n_e}{m_e}\frac{L_M}{\left(u^2+\Delta^2_{e,eff}\right)^{3/2}} , \qquad (2)$$

where $\Delta_{e,eff}$ is the effective electron velocity spread taking into account variations of the magnetic field line position in the transverse direction.

The logarithm is here defined as:

$$L_M = \ln\left(\frac{\rho_{max}+\rho_{min}+\rho_\perp}{\rho_{min}+\rho_\perp}\right) , \qquad (3)$$

where ρ_{max} and ρ_{min} are the maximum and minimum impact parameters respectively and $\rho_\perp = m_e c\Delta_{e,\perp}/(\mathrm{eB})$. For ELENA we can approximate $L_M \cong 10$. The expression (2) has been successfully benchmarked with measurements [12] and its accuracy is sufficiently good to estimate the e-cooler performance. Among others, Eq. (2) is implemented in the BETACOOL [13] code, which will be described in the following section.

BEAM DYNAMICS SIMULATIONS

An investigation of the ion beam dynamic evolution was performed using multi-particle simulations with the BETACOOL program [14]. The general goal of the program is to simulate long-term processes such as IBS, various types of cooling, rest-gas scattering, internal target, beam losses, etc. In this algorithm, the ion beam is represented as an array of modelling particles. Heating and cooling processes involved in the simulations led to variations of the ion distribution function in six-dimensional phase space. The code BETACOOL has been benchmarked with measurements in the past, giving a good agreement [10, 15, 16].

Electron Cooler Imperfections

In this study different possible imperfections of the cooling section of the storage ring were considered. For example, a common defect of the machinery is the presence of a misalignment between the circulating ion beam and the electron beam. It could be a horizontal or transversal displacement or a tilting angle. In all of the cases, simulations were run with different values of shifts.

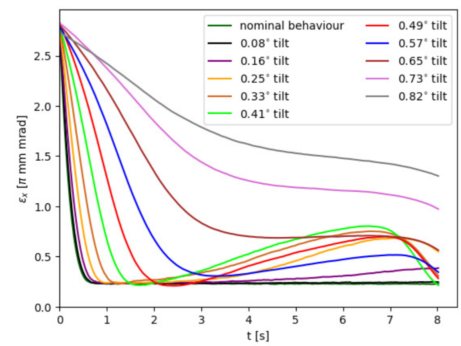

Figure 3: Horizontal emittance in presence of different tilt angles on the transversal plane.

The effect of the presence of a tilt angle between electron beam and the circulating particles is that part of the electron longitudinal velocity is experienced by the ions as transverse velocity spread. This increases the effective electron temperature that the ions are subjected to and the efficiency of the cooler is hence reduced. The long term emittance evolution depicted in Fig. 3 shows the reduced effect of the cooling section as the shift between the upstream extremities of electron and ion beams gets larger.

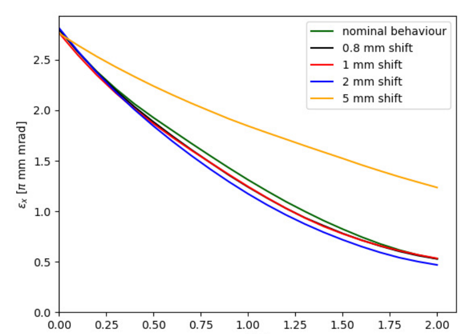

Figure 4: Horizontal emittance with parallel vertical displacement.

Figure 4 shows the effect of a parallel vertical displacement of the electron cooler in respect of the antiproton beam longitudinal axis. For small shifts the cooling rate is improved. This effect can be explained by observing that the displacement of the electron beam produces a horizontal gradient in the longitudinal cooling force because of the

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parabolic velocity profile of the electrons due to the space charge [17].

Electron Velocity Distributions

The simulation software BETACOOL contains algorithms that allow us to take into account local properties of electron distribution as well as calculate friction force for an arbitrary velocity distribution. In the program, the following models of the electron beam are realized:

- uniform cylinder;
- cylinder with round (or elliptical) cross-section with Gaussian distribution in transverse plane (Gaussian cylinder);
- hollow beam;
- parabolic.

We investigated how different electron density distributions affect the cooling rate. Simulations to compare the emittance evolution in case of different electron distribution shapes are plotted in Fig. 5. For each distribution the program calculates the electron density taking into account the real value of the electron peak current ($I_e = 2$ mA).

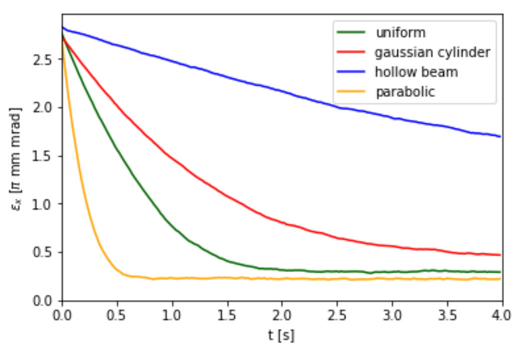

Figure 5: Plot of the horizontal emittance evolution for the different electron beam models provided in BETACOOL.

Figure 6 shows the behaviour of the longitudinal component of the approximated friction force for a Gaussian cylinder and a uniform distribution of the electron density. We can see that for low velocities the two different distributions lead to different intensities of cooling.

Measurements of the actual electron distribution are planned, in order to build a realistic model of the electron beam. In the meanwhile a study of the effect of the different distributions on the friction force acting on the circulating ion beam is currently being carried on.

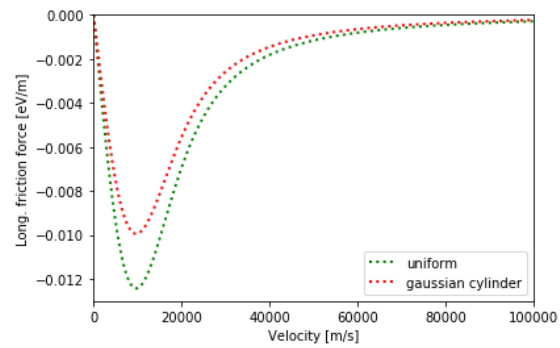

Figure 6: Longitudinal component of the approximated longitudinal friction force as a function of the antiproton velocity for different electron distributions.

SUMMARY AND OUTLOOK

A detailed study on the effect of imperfections and realistic models of the electron cooler is being developed.

Next steps are to analytically predict the cooling rate and the evolution of the emittance under different conditions. The simulated results along with the theoretical expectations will be then compared with the measurements from the real machine, in order to better understand the predominant effects acting on the cooling process.

Furthermore, a study aiming to simulate the magnetic field produced by the electron cooler coils is currently in progress.

ACKNOWLEDGMENT

Special thanks to our CERN collegues, in particular to Gerard Tranquille for inspiring discussions

REFERENCES

[1] T. Eriksson, ELENA – From installation to commissioning, Proceedings of IPAC2017, WEPVA034, Copenhagen, Denmark.
[2] http://home.web.cern.ch/about/accelerators/antiproton-decelerator
[3] G. Tranquille, The ELENA electron cooler, Proceeding of IPAC2016, TUPMR00, Busan, Korea.
[4] G. Budker, Sov. Atomic Energy, vol. 22, p. 346, 1967.
[5] G. I. Budker et al., IEEE Trans. Nucl. Sci., Vols. NS-22, p. 2093, 1975.
[6] S. Nagaitsev, Fermilab 4.3 MeV electron cooler, JINST, vol. 10, 2015.
[7] H. Danared, Studies of electron cooling with a highly expanded electron beam, Nucl. Instrum. Methods Phys. Res. A 441 (2000) 123-133.
[8] L. Hermansson, D. Reistad, Electron cooling at CELSIUS, Nucl. Instrum. Methods Phys. Res. A 441 (2000) 140-144.
[9] A. Shemyakin and L. Prost, The recycler electron cooler, [1306.3175] [FERMILAB-FN-0956-AD].
[10] A. Sidorin , Electron cooling simulations for arbitrary distribution of electrons, Proceedings of COOL2007, THAP01Bad Kreuznach, Germany.

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[11] V.V. Parkhomchuk, New insights in the theory of electron cooling, Nucl. Instrum. Methods Phys. Res. A 441 (2000) 9.

[12] A.V. Fedotov, et al., Experimental studies of magnetized friction force, Phys. Rev. E 73 (2006) 066503.

[13] A. Lavrentev, I. Meshkov "The computation of electron cooling process in a storage ring", preprint JINR E9-96-347, 1996.

[14] A. Sidorin, BETACOOL program for simulation of beam dynamics in storage rings, Nucl. Instrum. Methods Phys. Res. A 558 (2006) 325.

[15] A. Sidorin, Simulation of pellet target experiments with BETACOOL, Proceedings of RuPAC 2008, Zvenigorod, Russia.

[16] V. Gostishchev, Code benchmarking studies with the ESR internal target, GSI-ACCELERATORS-06.

[17] M. Beutelspacher, Dispersive electron cooling experiments at the heavy ion storage ring TSR, Nucl. Instrum. Methods Phys. Res. A 512 (2003) 459-469.