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BEAM LIFE TIME AND STABILITY STUDIES FOR ELENA*

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Abstract

The Extremely Low ENergy Antiproton ring (ELENA) is a small synchrotron equipped with an electron cooler, which shall be constructed at CERN to decelerate antiprotons to energies as low as 100 keV. At such low energies it is very important to carefully take contributions from electron cooling and heating effects (e.g. on the residual gas) into account. Detailed investigations into the ion kinetics under consideration of effects from electron cooling and scattering on the residual gas have been carried out using the BETACOOL code. In this contribution a consistent explanation of the different physical effects acting on the beam in ELENA is given. Beam life time, equilibrium momentum spread and emittance are all estimated based on numerical simulations.

INTRODUCTION

The Extra Low ENergy Antiproton ring (ELENA) is a new facility to be constructed at CERN to provide with lower energy, higher quality and more abundant antiproton beams to all the experiments working at the Antiproton Decelerator (AD), thus enabling the production of larger quantities of antihydrogen. ELENA shall further decelerate the antiprotons injected from the AD at kinetic energy 5.3 MeV (momentum 100 MeV/c) to 100 keV (momentum 13.7 MeV/c), with a beam population of $\sim 10^7$ cooled antiprotons. The ELENA facility will use electron cooling to counteract the emittance blow-up caused by the deceleration process. The ELENA design and its different components are described in [1]. The optics configuration of the ELENA ring is shown in Fig. 1 with tunes $Q_x = 2.3$ and $Q_y = 1.3$. In this paper this lattice structure has been used for the simulations.

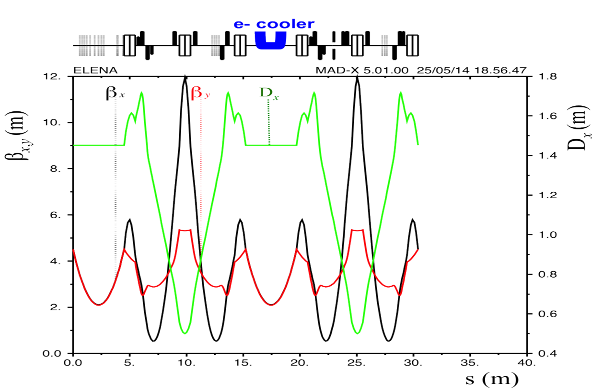

Figure 1: ELENA ring optics. The position of the electron cooler is indicated.

A particular challenge for low energy storage rings is the question of achievable beam life time and stability. Therefore, in this paper, by means of simulations, we have started to investigate different effects that can degrade the beam stability and life time, e.g. rest gas and Intra-Beam Scattering (IBS). Here, we have mainly focused on the residual gas effects.

ION KINETICS AND LONG-TERM BEAM DYNAMICS

In ultralow energy storage rings the beam life time is limited by effects such as beam-gas interactions and IBS. As we have mentioned before, the electron cooling will reduce the emittance blow-up caused by the deceleration process and those additional heating sources (beam-gas scattering and IBS).

In order to investigate the long-term beam dynamics in ELENA, we have performed multiparticle simulations based on the model beam algorithm of the code BETACOOL [2]. This code allows to calculate the evolution of beam distributions under the action of cooling forces (in this case electron cooling) and different scattering effects, and has been successfully benchmarked against experimental data in different rings, see [3] and references therein. Concretely, we have investigated the rest gas effects at the two beam momentum plateaus of the ELENA cycle where electron cooling is applied: first, at $p = 35$ MeV/c and second, at $p = 13.7$ MeV/c. Also the effects during the bunching operation just before extraction have been studied.

In the BETACOOL simulations we have taken into account the following processes: IBS, rest gas and electron cooling. IBS effects have been computed using the Martini model [4]. The rest gas effects include nuclear interactions and scattering on rest gas molecules able to lead to beam loss and emittance blow-up. It is worth mentioning that in the case of ELENA the dominating residual gas process is not multiple scattering, but single scattering.

For the simulations we have assumed a beam intensity of 2.5×10^7 antiprotons. Furthermore, the optical configuration of Fig. 1 has been used as an input in the BETACOOL simulations (the IBS Martini model uses these optic functions for calculations).

Rest Gas Effects at 35 MeV/c

For the case of electron cooling of a coasting beam of antiprotons at 35 MeV/c momentum , the growth rates ($1/\tau_x$, $1/\tau_y$ and $1/\tau_z$) due to the scattering of antiprotons on the residual gas have been computed and compared with those of the IBS and electron cooling. Here $\tau_{x,y,z}$ denotes the emittance life time in the horizontal, vertical and longitudinal direction, respectively.

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For the BETACOOL simulations of the first cooling process, the initial emittances at 95% of the antiproton distribution were $\epsilon_{x,y} = 8\,\pi$ mm·mrad and the momentum spread $\Delta p/p = 0.002$. For an optimum setting of the electron cooler the following parameters have been considered: an electron current of 5 mA and an electron temperature of 10 meV (110 K) [1].

Table 1 summarises the equilibrium parameters after the first cooling process and compares the growth rates assuming a vacuum pressure of 3×10^{-12} Torr (nominal) at room temperature. For the case of the rest gas effect the heating rates are in good order of magnitude agreement with recent analytical estimates presented in [5].

Table 1: Equilibrium Parameters in ELENA for Beam Momentum $p = 35$ MeV/c

Parameter	Value
Emittance (95%) ϵ_x, ϵ_y [π mm·mrad]	0.2, 0.09
Momentum spread $\Delta p/p$	0.0002
Electron cooling rates (x, y, z) [s^{-1}]	-4.09, -4.09, -7.86
Rest Gas heating rates (x, y, z) [$\times 10^{-3}$ s^{-1}]	1.2, 1.2, 0.016
IBS heating rates (x, y, z) [$\times 10^{-4}$ s^{-1}]	1.7, 0.55, 0.24

The evolution of the transverse emittances (95%) over 10 s of cooling is depicted in Fig. 2 for different values of vacuum pressure. The corresponding momentum spread evolution is shown in Fig. 3. For pressures $> 2 \times 10^{-10}$ Torr the heating process due to rest gas dominates over cooling and the emittances experience an important increase.

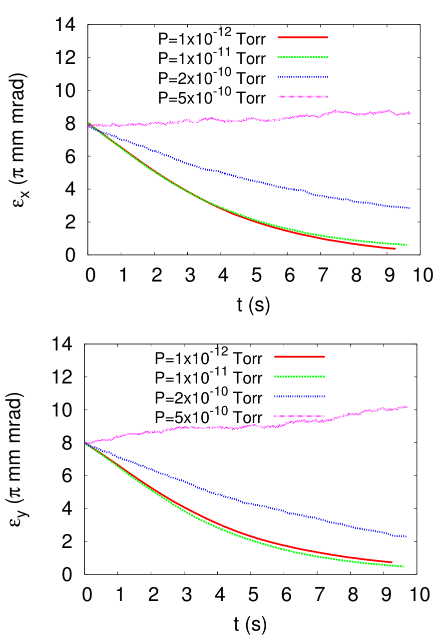

Figure 2: Evolution of the transverse emittances over the first cooling for different levels of vacuum pressure in the beam pipe.

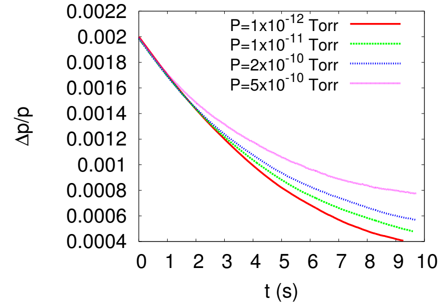

Figure 3: Evolution of the r.m.s. momentum spread over the first cooling for different levels of vacuum pressure in the beam pipe.

Rest Gas Effects at 13.7 MeV/c

In a similar way, we have also studied the residual gas effects for the second cooling process in the ELENA cycle for a coasting beam of antiprotons at $p = 13.7$ MeV/c. In this case, for the simulations we have considered the following initial parameters of the antiproton beam: $\epsilon_{x,y} = 2.5\,\pi$ mm·mrad and $\Delta p/p = 0.0005$. For the electron cooling the following input parameters have been used: 2 mA electron current and 10 meV (110 K) temperature. The BETACOOL results of the equilibrium parameters are summarised in Table 2.

Table 2: Equilibrium Parameters in ELENA for Beam Momentum $p = 13.7$ MeV/c

Parameter	Value
Emittance (95%) ϵ_x, ϵ_y [π mm·mrad]	0.25, 0.14
Momentum spread $\Delta p/p$	0.00023
Electron cooling rates (x, y, z) [s^{-1}]	-33.12, -33.12, -64.2
Rest Gas heating rates (x, y, z) [s^{-1}]	0.056, 0.057, 0.0043
IBS heating rates (x, y, z) [s^{-1}]	0.033, 0.001, 0.12

Fig. 4 shows the evolution of the transverse emittances (95%) over 2.4 s of cooling for different values of vacuum pressure. The corresponding momentum spread evolution is shown in Fig. 5. For pressures $> 2 \times 10^{-10}$ Torr one can observe a dramatic blow-up of the transverse emittances and momentum spread. Figure 6 illustrates the residual gas effect in the transverse beam profiles. Gas pressures higher than 1×10^{-11} Torr lead to a significant increase of the beam size, with long tails which will translate into halo formation and particle losses if such a halo exceeds the machine acceptance ($A_{x,y} = 70\,\pi$ mm·mrad).

Rest Gas Effects During Bunching

In this section the effect of the residual gas during the bunching process of antiprotons prior ejection is studied. Since previous studies [1] have indicated that it may be necessary to apply cooling during bunching to achieve the required extraction requirements, in these simulations we have also applied electron cooling. Table 3 shows the equilibrium parameters for this case after 0.4 s of electron cooling.

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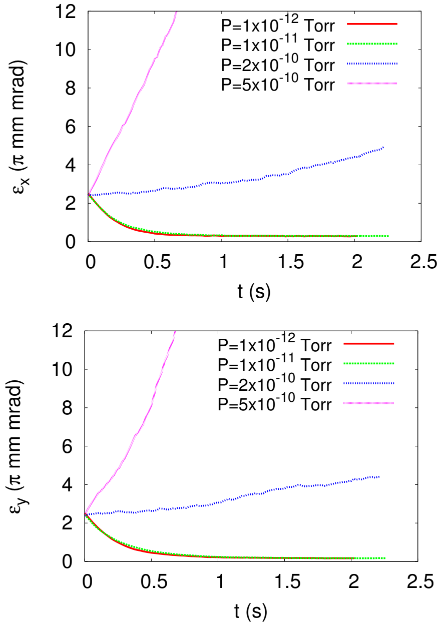

Figure 4: Evolution of the transverse emittances over the second cooling for different levels of vacuum pressure in the beam pipe.

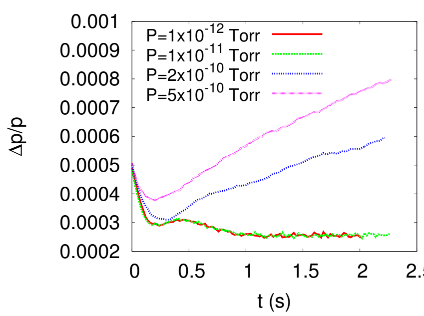

Figure 5: Evolution of the r.m.s. momentum spread over the second cooling for different levels of vacuum pressure in the beam pipe.

For the bunching process we have also studied the emittance and momentum evolution for different scenarios of gas pressure. In this case, the variation of gas pressure seems not to affect the momentum spread. However, increasing the pressure up to $\sim 1 \times 10^{-10}$ Torr translates into a significant increase of the transverse beam emittances to values higher than 1 π mm·mrad, see Fig. 7.

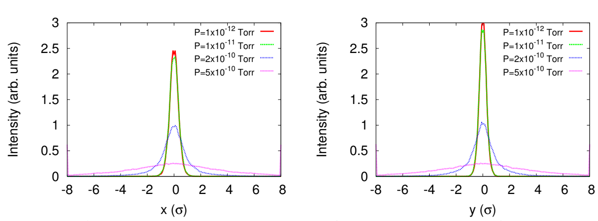

Figure 6: Transverse beam profile at the end of the second cooling for different vacuum pressures.

Table 3: Equilibrium Parameters in ELENA for the Bunching Process

Parameter	Value
Emittance (95%) ϵ_x, ϵ_y [π mm·mrad]	0.56, 0.33
Momentum spread $\Delta p/p$	0.0003
Electron cooling rates (x, y, z) [s^{-1}]	-18.9, -18.9, -18.9
Rest Gas heating rates (x, y, z) [s^{-1}]	0.48, 0.7, 0.017
IBS heating rates (x, y, z) [s^{-1}]	0.84, 0.84, 0.84

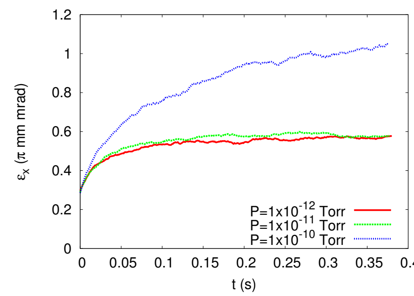

Figure 7: Evolution of the horizontal emittance during the bunching process prior to extraction with cooling for different levels of vacuum pressure in the beam pipe.

CONCLUSIONS AND OUTLOOK

We have started a detailed investigation into the different cooling and heating effects which determine the beam life time and stability of the ELENA antiproton beam. Preliminary BETACOOL simulation results of equilibrium parameters and growth rates have been shown. Concretely, in this paper we have put special emphasis on the study of the residual gas impact on the beam stability. Preliminary BETACOOL results are in good agreement (in order of magnitude) with recent analytical estimates of heating rates due to rest gas [5]. This investigation is in progress and a detailed comparison of analytical and simulation results will be presented in future publications.

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