THE EFFECT OF BEAM VELOCITY DISTRIBUTION ON ELECTRON-COOLING AT ELENA*

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Abstract

ELENA is a novel storage ring at CERN, designed to deliver low energy, high quality antiprotons to antimatter experiments. The electron cooler is a key component of this decelerator, which counters the beam blow-up as the antiproton energy is reduced from 5.3 MeV to 100 keV. Typical numerical approximations on electron cooling processes assume that the density distribution of electrons in analytical form and the velocity distribution space to be Maxwellian. However, it is useful to have an accurate description of the cooling process based on realistic distribution of electrons. In this contribution, BETACOOL simulations of the ELENA antiproton beam phase space evolution were performed using uniform, Gaussian and "hollow beam" electron velocity distribution. The results are compared with simulations considering a custom electron beam distribution obtained with G4Beamline. The program was used to simulate the interaction of an initially Gaussian electron beam with the magnetic field measured inside the electron cooler interaction chamber. The resulting beam lifetime and equilibrium parameters are then compared with measurements.

INTRODUCTION

The Extra Low ENergy Antiproton storage ring (ELENA) [1] is a 30.4 m synchrotron at CERN designed to provide low energy, high quality antiprotons to the experiments of the Antimatter Factory (AF). ELENA will improve the capture efficiency by decelerating the antiprotons from the Antiproton Decelerator (AD) (which currently provides beam to the AF) at kinetic energy 5.3 MeV (momentum 100 MeV/c) down to 100 keV (momentum 13.7 MeV/c), with a beam population of ~ 107 antiprotons.

ELECTRON COOLING

Electron cooling is central to the success of the ELENA project, since it reduces or eliminates the emittance blowup caused by the deceleration process. Additionally, at low energies, collective effects such as intra-beam scattering (IBS) and rest gas scattering become significant contributors to emittance growth. Very small emittances are needed to achieve further deceleration and to improve extraction to trap efficiency for the experiments. ELENA aims to increase the number of antiprotons trapped in the experiments by a factor of 100 [2]. The antiprotons are decelerated in two stages allowing for two energy plateaus where electron cooling is applied. For this study we focus on the second cooling plateau, right before extraction.

Electron cooling is an effective technique to reduce the 6D phase space volume of a circulating beam of heavy particles [3] such as protons, antiprotons and ions in a storage ring [4]. The working principle is the following: a charged particle beam and a cold electron beam (constantly renewed) are overlaid in a small section of the machine. Whilst moving at small relative velocities they interact by means of electromagnetic forces. In the rest frame of the electrons the ions are seen as passing through the electron gas with a variety of velocities. The ions transfer their energy to the electrons through elastic Coulomb scattering resulting in a cooling effect. The general expression of the force of an ion inside an electron beam with velocity distribution function $f(\nu_e)$ is:

$$\vec{F} = -\frac{4\pi n_e e^4 Z^2 L_C}{m_e} \int \frac{\vec{V}-\vec{\nu_e}}{|\vec{V}-\vec{\nu_e}|} f(\nu_e) d^3\nu_e, \qquad (1)$$

where e and $m_e$are the electron charge and mass, V and ν_e are the ion and electron velocities, respectively. L_C is the Coulomb logarithm:

$$L_C = \ln\left(\frac{\rho_{max}}{\rho_{min}}\right), \qquad (2)$$

where ρ_{max} and ρ_{min} are the maximum and minimum impact parameters respectively. In the presence of a strong magnetic field the electrons are confined along the lines of constant magnetic flux, like beads on a wire and the integrand in Eq. (1) is modified. The field is considered strong when the radius of the electron gyration is much smaller than the maximum impact parameter:

$$\rho_\perp = \frac{c m_e \Delta_\perp}{eB} \ll \rho_{max}, \qquad (3)$$

with $\Delta_\perp$ being the electron Root Mean Square (rms) velocity spread in the transverse direction. In the framework of the binary collision model the transverse and longitudinal components of the cooling force for strong magnetisation can be approximated by the formulae [5]:

$$F_\parallel = -\frac{4\pi n_e e^4 Z^2 L_M}{m_e} \int \frac{V_\perp^2 (V_\parallel - \nu_e)}{\left(V_\perp^2 + (V_\parallel - \nu_e)^2\right)^{5/2}} f(\nu_\parallel) d\nu_\parallel, \qquad (4)$$

$$F_\perp = -\frac{2\pi n_e e^4 Z^2 L_M}{m_e} \int \frac{V_\perp \left(V_\perp^2 - 2(V_\parallel - \nu_e)^2\right)}{\left(V_\perp^2 + (V_\parallel - \nu_e)^2\right)^{5/2}} f(\nu_\parallel) d\nu_\parallel, \qquad (5)$$

where the Coulomb logarithm is evaluated as $L_M = ln\left(\frac{\rho_{max}}{\rho_\perp}\right)$, and assuming that the transverse electron motion is completely suppressed by the magnetic field.

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BETACOOL

BETACOOL is a simulation software developed at the Joint Institute of Nuclear Research (JINR, Dubna, Russia) to simulate the long term beam dynamics of a circulating beam under different heating and cooling effects. Within the ‘Model Beam` algorithm [6] it is possible to simulate the beam evolution. The circulating beam is represented as an array of model particles and the so called “kicks” from active effects are calculated (coordinates and angles of every model particle are changed correspondingly) at each time step. Evolution of the particle momentum components is described in terms of the Langevin equation [7]. Each heating or cooling effect is characterised by friction and diffusion components. The friction leads to regular momentum variation, the diffusion is simulated using a random number generator.

Electron Beam Distribution

A few axisymmetric analytical distribution models for a coasting electron beam are available in BETACOOL: uniform cylinder, Gaussian cylinder, “hollow” beam and electron beam with parabolic density distribution [5], as shown in Fig. 1.

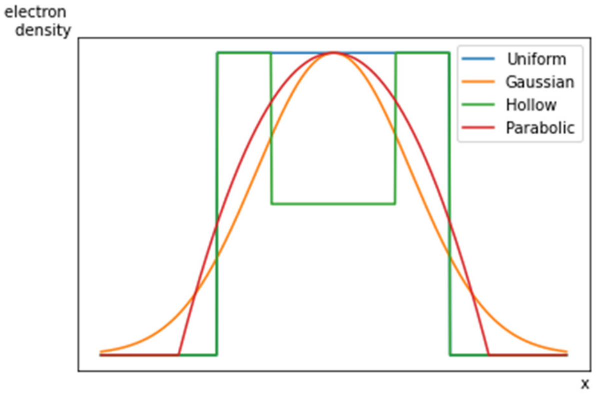

Figure 1: Representation of the different electron beam distribution models available in BETACOOL.

The cooler model takes into account variations of the electron beam position and angular deviation along the cooling section (that can be caused, for example, by magnetic field errors in the coils of the cooler).

Figure 2 shows simulation results obtained with BETACOOL, comparing emittance evolution with the different available models. The final achievable emittance can vary significantly depending on the electron beam distribution. The ELENA electron cooler however is equipped with a cathode that provides a beam with an approximately constant density over most of its surface. It is not possible to perform direct measurements of the electron beam profile inside of the electron cooler. As we can see a clear dependence of the emittance evolution on the electron beam distribution, we need to understand the true shape of the distribution. As no measurements are available, we have attempted to determine the distribution using measurements of the magnetic fields and the assumption that the cathode produces elections uniformly.

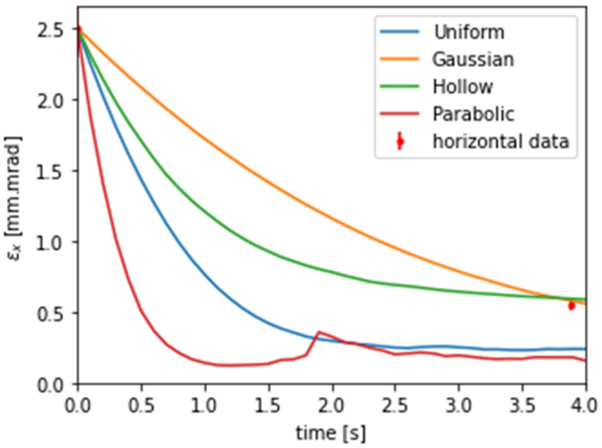

Figure 2: BETACOOL simulations of horizontal emittance evolution for the second cooling plateau (100 keV) in ELENA with different electron beam geometry models.

Magnetic Field Map

Before it was installed at CERN, measurements of the magnetic field inside the ELENA electron cooler assembly were performed [8]. The field map contains the three components (B_x, B_y, B_z) of the magnetic field along the interaction chamber and adjacent beam pipes over a total length of 360 cm. The map was then used to create a model in G4Beamline [9], where a Gaussian electron beam generated at the extremity of the cooler drift was tracked through the magnetic field map. Virtual detectors were placed along the drift to record the electron beam evolution across the 70 cm of the good field region.

Figure 3 shows the electron beam profiles, at the beginning and at the end of the drift. It is evident a shift of the centre of the Gaussian distribution compared to the initial profile, measuring $\Delta\mu = -0.8$ mm. This shift must be accounted for in the simulations of the beam evolution in BETACOOL.

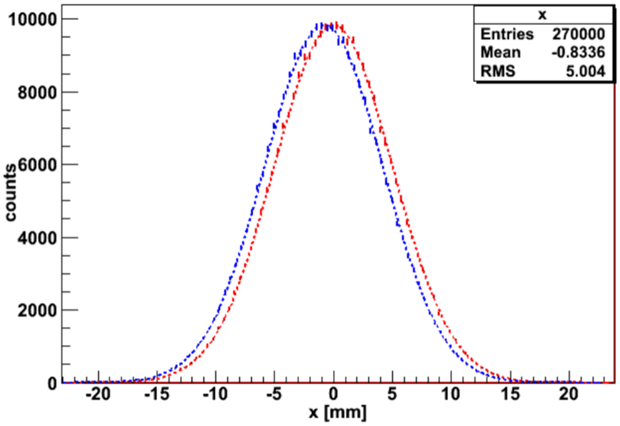

Figure 3: Simulated electron beam profile obtained from virtual detectors at the beginning (red) and at the end of the cooling drift (blue). The simulation was performed in G4Beamline, with a Gaussian electron beam moving inside the magnetic field.

ELECTRON BEAM MISALIGNMENT

In BETACOOL different procedures exist to include the displacement of the electron beam position in transverse and longitudinal planes, the distance between electron and ion bunches, solenoid errors and so on [10]. We used the Gaussian cylinder electron distribution model and, to account for the observed electron beam shift, we included in the BETACOOL beam dynamics simulations the presence of solenoid errors, i.e. coils transverse dislocation in respect of the solenoid central axis. The corresponding field inhomogeneities cause a misalignment between the electron and antiproton beam orbits, altering the relative velocity. In fact, the circulating beam experiences a higher effective electron temperature because part of the longitudinal velocity is now experienced as an additional transverse velocity. Finally, the longitudinal and transverse degrees of freedom of the electron beam are mixed, which may lead to less effective cooling. Figure 4 shows the ELENA emittance evolution for the second cooling plateau simulated with BETACOOL including a horizontal solenoid error of 0.8 mm.

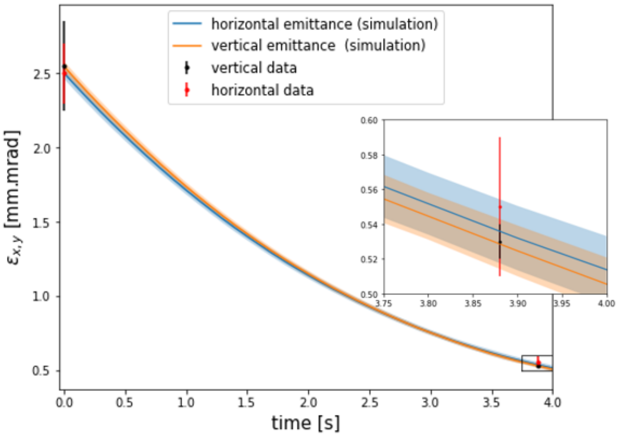

Figure 4: Antiproton beam emittance evolution simulations for the second cooling plateau. The BETACOOL simulation included a 0.8 mm horizontal solenoid error. The simulated final emittances are compared with data from the scraper.

We compared the simulated emittances with data taken with the ELENA scraping system during commissioning [11, 12]. Table 1 summarises the measurements. The simulated emittances show very good agreement with the data. Unfortunately, scraper measurements provide only initial and final emittance values limiting the insight to the beam evolution during cooling. The validation of the simulated final emittances by the data is nonetheless significant and confirms the legitimacy of our assumptions. The solenoid error included in the model and the Gaussian cylinder distribution for the electrons reasonably well represents the actual electron beam behaviour.

Table 1: ELENA Scraper Emittance Measurements for the Second Cooling Plateau

$\varepsilon_{x,\mathrm{init}}$	2.50 ± 0.2 mm·mrad	$\varepsilon_{x,\mathrm{fin}}$	0.55 ± 0.04 mm·mrad
$\varepsilon_{y,\mathrm{init}}$	2.55 ± 0.2 mm·mrad	$\varepsilon_{y,\mathrm{fin}}$	0.53 ± 0.01 mm·mrad

CONCLUSIONS

We considered the impact of electron beam velocity distribution on the cooling force and looked at possible considerations for the case of the ELENA electron cooler. In the magnetic field measurements of the cooler assembly, we noted a tilt in the longitudinal component of the field. The motion of a Gaussian distributed electron beam interacting with the field was simulated using G4Beamlineand the beam profiles obtained at the end of the cooling drift show a net shift of the centre of the electron distribution. We found very good agreement from the scraper and the BETACOOL simulations when including solenoid errors in the model. To better characterise the antiproton beam behaviour, measurements of the emittance for intermediate time steps are required to compare with the simulations. Additionally, experiments introducing controlled variations of the electron/antiproton relative position, for example using orbit bumps could provide accurate information about the misalignments inside of the electron cooler and improve the accuracy of the simulation model.

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