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ELECTRON COOLING SIMULATION BENCHMARKING

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Abstract

Electron coolers are commonly used in storage rings to reduce the phase space volume of heavy particles such as protons, antiprotons and ions. Their effect depends on the Coulomb interactions between the circulating beam and the cold electrons at small relative velocities. The cooling process can be modelled through different approaches and the behaviour of the cooling force, can be described by various formulas, which include different parameters. The aim of the present study is to compare the accuracy of the cooling simulations performed by two distinct beam-tracking codes: Betacool and RF-Track. Being based on different models and formulas, the two simulation tools require different parameters in order to realistically describe electron cooling. In this contribution, the impact of these parameters is discussed, and simulation predictions are compared with experimental data from LEIR (Low Energy Ion Ring) at CERN and ESR (Experimentier-Speicher-Ring) at GSI. Furthermore, the friction force is calculated for the new antimatter storage ring ELENA (Extra Low Energy Antiproton) at CERN.

INTRODUCTION

Electron cooling is an effective technique to reduce the phase space volume of a circulating beam of heavy particles [1] such as protons, antiprotons and ions in a storage ring [2-4]. The working principle is basically the following: a charged particle beam and an electron beam are overlaid in a small section of the machine and whilst moving at small relative velocities interact by means of electromagnetic forces. However, the simplicity of the concept is side by side with the complexity of the related physics. The phenomena involved fall into the realms of charged particle beam dynamics and plasma physics.

The resulting cooling force can be derived through two different approaches: dielectric theory and the binary collision model [5]. Unfortunately, neither of them can provide a closed form solution in case of a finite-strength magnetic solenoidal field. In order to be able to predict the parameter of the circulating beam after interacting with the electron cooler, it is then necessary to make approximations or to perform numerical evaluations.

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To take into account the finite value of the solenoidal magnetic field, a semi-empirical expression of the cooling force was proposed by Parkhomchuk [6].

An alternative approach is to use the analytical formula directly and carry out a numerical evaluation as opted by Nersisyan in his study of the stopping force [7]. In this contribution, simulation results using these two different approaches are compared in the context of the following facilities: LEIR and ELENA at CERN, and ESR at GSI.

SIMULATION CODES

Simulations of the cooling force in an experiment are important to determine the physical conditions in which the cooling process takes place and hence to optimise the parameters of the cooling system. Several tracking codes have been developed to simulate beam dynamics under different conditions. Betacool [8] and RF-Track [9] are two of them, both designed to simulate cooling processes. In this contribution, both codes are compared and contrasted against one another and measured data of the cooling force from existing electron coolers.

Betacool

The code has been developed since 1994 at JINR (Joint Institute of Nuclear Research, Dubna, Russia) electron cooling group and benchmarked against many experiments [10, 11]. The program represents the ion beam as an array of model particles which undergo a transformation of coordinates when interacting with the cooler. The cooling processes involved in the simulation lead to changes in the particle momentum components, which are calculated using a linear matrix for random phase advance. The cooling force can be chosen from a library of formulas or user written. For the purpose of this study the formula applied by Betacool simulations is the semi-empirical Parkhomchuk formula:

$$\vec{F} = -\vec{V}\frac{4Z^2e^4N_eL_p}{m_e}\frac{1}{\left(V^2+\Delta_{eff}^2\right)^{3/2}}, \quad (1)$$

where V is the relative ion-electron velocity, L_P is the Coulomb logarithm, N_e is the electron density per squared meter, m_e is the electron mass and Δ_{eff} is the longitudinal effective velocity spread of the electrons. Betacool uses an effective temperature $T_{eff} = m_e\Delta_{eff}^2$ as an input parameter that can be chosen to fit experimental data. Moreover, the electron beam can be described by different

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models (uniform cylinder, Gaussian cylinder, hollow, parabolic). In this paper, a uniform cylindrical distribution of the electrons is considered in the cooler.

RF-Track

The approach used to develop RF-Track is different; the cooling force formula is based on Nersisyan treatment in which the integrals are solved numerically using a Monte Carlo technique and tabulated in appropriate 2D meshes (to be interpolated linearly at run time). In this case the cooling force formula is described in Eq. (2).

$$\vec{F} = -\frac{4\pi N_e K^2}{\mu}\left\{\iiint \left[L_F \frac{\vec{V}}{V^3}\right] f(\vec{v}_e) d\vec{v}_e + \int \left[L_M \frac{V_\perp^2}{V^5}\left(\vec{V}_\parallel + \frac{\vec{V}_\perp}{2}\left(1 - \frac{V_\parallel^2}{V_\perp^2}\right)\right)\right] f(v_{e\parallel}) dv_{e\parallel}\right\} \quad , \qquad (2)$$

whereby K is the coupling constant of the Coulomb interaction, μ is the reduced mass expressed in MeV, and are Coulomb logarithms, V represents the relative velocity of ions and electrons, is the transverse component of the velocity of the ions in the presence of a magnetic field, is the relative longitudinal velocity in the presence of magnetic field and is the electron velocity distribution.

In the program, the ion beam is represented as an ensemble of macro particles in 6D phase space in order to provide an accurate tracking and capturing non-linearities. The electron beam is represented as a fluid (plasma) on a 3D cartesian mesh that enables to consider arbitrary electron densities and velocity distributions. The evolution of the electrons is performed following the Euler equation of fluid dynamics.

BENCHMARKING RESULTS

LEIR

The Low Energy Ion Ring [12] at CERN is part of the accelerator complex that provides LHC with short dense bunches of lead ions. In this case, the cooling force has been calculated as the ratio of the momentum variation over time with increasing electron velocities.

An evaluation of the effect of the Parkhomchuk empirical parameter has been done in order to find the correspondent value to be tuned with the parameters requested by RF-Track and the Nersisyan formula. A scan over various values of the free parameter was performed setting the other variables of the simulations on the values corresponding to the LEIR electron cooler specifications. The variation of results in both, a horizontal and vertical shift of the peak of the force, strongly affecting the predicted performance of the machine (Fig. 1 a).

The other simulation tool, RF-Track, does not require such an empirical parameter. The formula implemented in the code to calculate the cooling force depends on the electron thermal velocity spread (longitudinal and transversal), having a temperature $T_e = m_e\Delta_e^2$. Since also Δ_{eff} is related to the thermal motion of the electrons, it is interesting to observe how tuning the two temperatures in RF-Track (Fig. 1 b) it is possible to replicate the scan in Betacool.

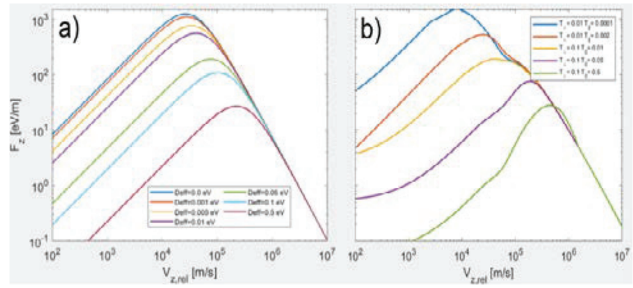

Figure 1: Scan of the LEIR Cooling Force under varying simulation parameters: a) with Betacool b) with RF-Track.

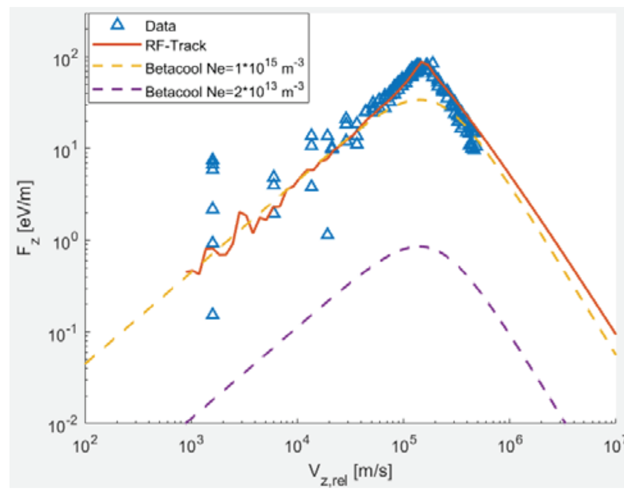

Figure 2: The longitudinal cooling force acting on Pb ions in LEIR electron cooler.

As can be observed in Fig.2 in order to obtain a simulated force with Betacool (dotted lines) that agrees with the data (triangles) and RF-Track simulation results (orange line) is necessary to include a factor of 100. This could be accounted for by the underestimation of L_P due to the very low value of the magnetic field (B= 0.07 T). Further analysis to verify this hypothesis will be performed.

ESR

Measurements of the cooling force have extensively been performed in the past on other storage rings equipped with electron coolers. One of them is the ESR [13], which is part of the GSI accelerator complex, where different kinds of heavy ions are cooled by magnetised electrons. In this experiment, fully stripped Xenon ions circulate in the ring. The cooling force is extracted by averaging the forces over the ion distribution in the beam. Two different methods have been used to determine the force. At low ion velocities the cooling force is extracted from the equilibrium between cooling and longitudinal heating with RF noise. At high relative velocities between

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the rest frames of the beams the cooling force is deduced from the momentum drift of the ion beam after a rapid change of the electron energy. Details of these methods are given in [14, 15]. Figure 3 plots the measured data (triangles) along with the simulated forces obtained from Betacool (dotted yellow line) and RF-Track (orange line). Parkhomchuk expression appears to better imitate the behaviour of the real cooling force but diverges for high relative velocities.

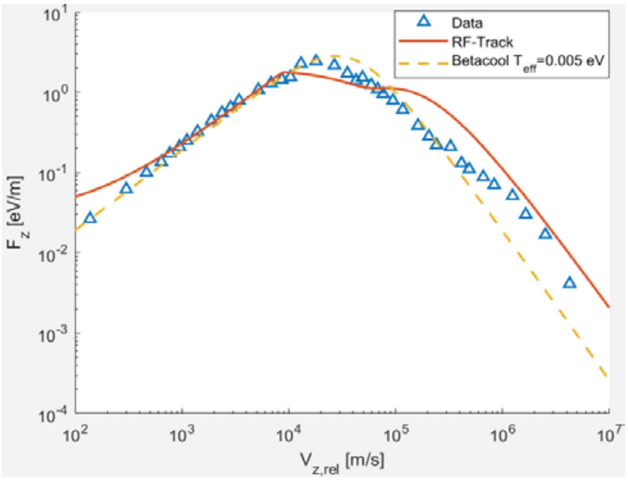

Figure 3: The longitudinal cooling force acting on Xe54+ ions in the ESR ring

ELENA

Last year the antimatter factory at CERN has been upgraded with the commissioning of the Extra Low ENergy Antiproton storage ring [16]. This facility is equipped with an electron cooler, which operates at extremely low energies reducing the emittance of the antiproton beam, thus increasing the trapping efficiency of the antimatter experiments. With the aim of having a well defined framework for the performance of this novel machine, simulations of the expected force have been computed as seen in Fig. 4. A good agreement is obtained between both codes.

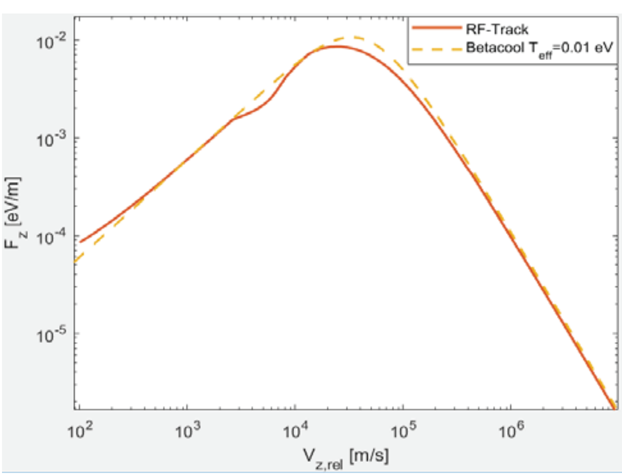

Figure 4: The longitudinal cooling force for the antiproton beam in ELENA.

OUTLOOK

Two beam dynamics simulation codes applying different models for the cooling force have been used to model the interaction of different ions and antiprotons within electron coolers operating at distinct conditions for different storage rings. A general good agreement is achieved between the two codes. However, for the case of the LEIR electron cooler there are some discrepancies, which require further investigations. A comprehensive understanding of the friction force models will allow more realistic predictions in the case of new facilities. Eventually, ELENA cooling performance simulations will be compared with experimental data after the CERN Large Shutdown 2.

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