Experimental Benchmarking of the Magnetized Friction Force

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Abstract.. High-energy electron cooling, presently considered as essential tool for several applications in high-energy and nuclear physics, requires accurate description of the friction force. A series of measurements were performed at CELSIUS with the goal to provide accurate data needed for the benchmarking of theories and simulations. Some results of accurate comparison of experimental data with the friction force formulas are presented.

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INTRODUCTION

High-energy magnetized electron cooling puts special demands on the accuracy of estimates of the cooling times [1]. For example, for parameters of the proposed RHIC cooler [2], the cooling time of Au ions at the energy of 100 GeV/u (γ=108) is of the order of 1000 s making a typical order of magnitude estimates not practical. The major goal of the present experiments was thus the accurate measurement of the magnetized friction force in order to provide the data needed for detailed benchmarking of theories and simulations. The other goal was to begin a detailed study of some features which are critical for proposed high-energy coolers [2], [3]. As part of a collaboration between BNL and European laboratories working on high-energy cooling for the RHIC-II [2] and FAIR projects [3], a variety of experiments were proposed in order to resolve the issues regarding the magnetized cooling force. The experiments, which were performed at CELSIUS [4] in December 2004 and March 2005, can be summarized as follows: 1) Accurate measurement of the longitudinal friction force for standard operational parameters of the cooler. 2) Cooling force measurements for different alignment angles between electron and ion beams. 3) Measurement of the time evolution of ion beam profiles as a result of simultaneous electron cooling and heating due to Intrabeam Scattering (IBS) before an equilibrium is reached. 4) Set-up the electron cooler to explore the friction force for various regimes of magnetization. 5) Study the effect of imperfections of solenoidal magnetic field lines. A detailed description of all the experiments performed can be found in Refs. [5, 6].

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MEASUREMENT APPROACH

For low relative velocities between ions and electrons the longitudinal magnetized friction force increases linearly with velocity, reaching its maximum near the longitudinal velocity spread of the electron beam. Here, we used a measurement technique that allows very precise measurements in the region of low relative velocities, including accurately finding the maximum of the force. In this range, the simplest way of measurement is the phase-shift method. It uses a bunched ion beam and is based on measuring the phase difference between the RF system and the ion beam, resulting from the competition of the weak RF voltage and the longitudinal friction force.

Typically, the relative velocity difference is introduced by changing the energy of the electron beam. However, changing the electron acceleration voltage is usually done with a rather large voltage step. On the other hand, since this method employs bunched beams, changing the energy of the ion beam by changing the frequency of the RF cavity is more accurate. In our experiments, changing the RF frequency by a few Hz resulted in a very fine step in relative velocity. A similar technique was used successfully before, for example at IUCF [7]. In experiments reported in this paper, the longitudinal friction force curves were measured for protons at the injection energy of 48 MeV. More details on the experimental setup and accuracy of the measurements can be found in [6].

FITTING EXPERIMENTAL CURVES

The measured force for the magnetic field in the cooling section of B=0.1T and the electron currents of 500, 250, 100 and 50 mA (with good alignment of proton and electron beams) is shown in Fig. 1:

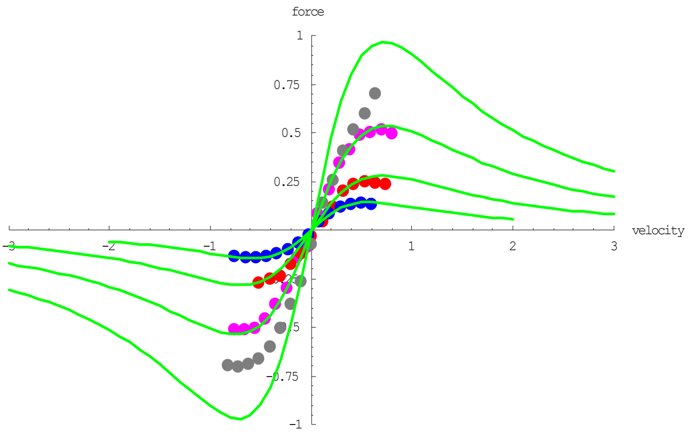

FIGURE 1. Longitudinal friction force in [eV/m] vs. velocity [10^4 m/s] for electron currents of 50 (blue, lowest set of data), 100 (red), 250 (pink), 500 mA (black, highest set of data) and magnetic field in cooling solenoid B=0.1T.

In Fig.1, we also plot the curves with fitted $\Delta_{e,eff}$ based on the empiric formula introduced by Parkhomchuk [8]

$$\vec{F} = -\vec{v}\frac{4Z^2e^4n_eL_M}{m}\frac{1}{\left(v^2+\Delta^2_{e,eff}\right)^{3/2}}, \text{ with } L_M = \ln\left(\frac{\rho_{\max}+\rho_{\min}+\langle\rho_L\rangle}{\rho_{\min}+\langle\rho_L\rangle}\right) \quad (1)$$

where v is the velocity of ion, Z is the ion charge, n_e is the electron density, e and m is charge and mass of electron, $\Delta_{e,eff}$ is an effective longitudinal velocity spread of electrons, and L_M is the Coulomb logarithm of the magnetized collisions.

For small currents of electron beam the major contribution to the effective velocity comes from the solenoid imperfections. One can see that for the electron currents of 50 (blue; lower curve), 100 (red), and 250 (pink) mA the curves based on Eq. (1) go nicely through the experimental data. The resulting effective velocity $\Delta_{e,eff}$ in these cases is about $0.75*10^4$ m/s.

For a high electron current (500 mA), the experimental data is significantly lower than the corresponding curve if the effective velocity (based only on the magnetic imperfections) comparable to the low currents is used. However, for high electron currents one needs to take into account the space-charge effect of the electron beam which results in the drift of the electrons in the crossed fields (the electric and magnetic fields of the electron beam and longitudinal magnetic field of the cooler). At a given radius r within the electron beam of uniform density distribution, the drift of the electron velocity is given by the expression:

$$v_d = \frac{2I}{B\beta\gamma^2}\frac{r}{a^2}, \quad (2)$$

where I is the current of electron beam, B is the strength of the magnetic field in the cooling section, β and γ are the relativistic parameters, and a is the radius of the electron beam.

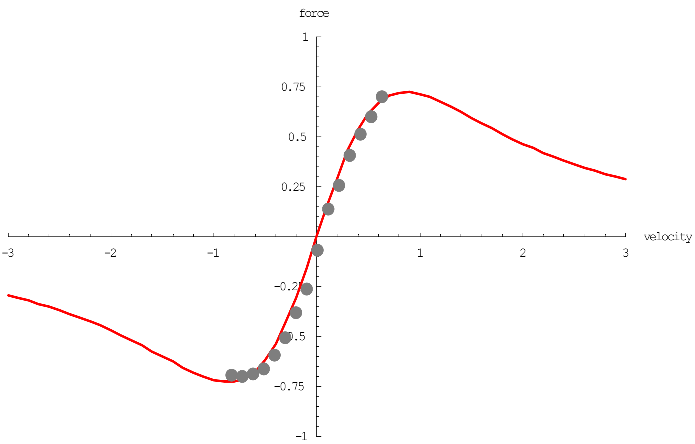

FIGURE 2. Measured friction force (points) in [eV/m] vs. velocity [10^4 m/s] for an electron current of 500 mA (B=0.1T) and the curve based on Eq. (1) with additional contribution to the effective velocity from the space charge of the electron beam.

For the set of data with 500 mA (B=0.1T) and measured parameters of the proton distribution the resulting drift velocity is around $0.7*10^4$ m/s (calculated at an rms radius of the proton beam). We can take this into account by adding an extra term to the effective velocity. This results in the solid curve shown in Fig.2 that is based on Eq. (1) and goes through the experimental data even for high electron beam currents.

The friction force with the numerical factor given in Eq. (1) agrees well when directly compared to the experimental data. However, pre-cooled proton beam, with which the friction force measurements are made, has some finite values of an rms emittance and momentum spread. To provide an accurate comparison with the experimental data one also needs to measure an rms distribution of the proton beam during the measurement of the cooling force. The single-particle friction force formula should be then averaged over the proton distribution:

$$\langle F\rangle = C\frac{4\pi Z^2 e^4 n_e}{m\sqrt{2\pi}\Delta_\perp{}^2\Delta_\parallel}\int_0^\infty\int_{-\infty}^\infty \frac{v_\parallel \cdot L_M(v_\perp, v_\parallel, v_{eff})}{(v_\perp{}^2 + v_\parallel{}^2 + v_{eff}{}^2)^{3/2}}\exp\left(-\frac{v_\perp{}^2}{2\Delta_\perp{}^2} - \frac{(v_\parallel - v_0)^2}{2\Delta_\parallel{}^2}\right) v_\perp dv_\parallel dv_\perp \qquad (3)$$

where $\Delta_\perp$ and $\Delta_\parallel$ are measured rms velocities of the proton distribution, and the integrals are performed over the transverse and longitudinal velocities of the protons. In our experiments, an rms distribution of the proton beam was carefully measured for each set of the experimental curves.

In principle, there could be different approaches to a fitting procedure based on such averaging. The first one assumes that the numerical coefficient C in the expression for the single-particle force is known (for example, C=1/π as in Eq. (1) or $1/(2\pi)^{1/2}$ as in Ref. [9] for low relative velocities), while v_{eff} is a fitting parameter. In our experiments, the measured rms velocity spread of the proton beam was rather large so that fitted v_{eff}, as a result of such averaging, became very small (v_{eff}=0.1-0.2*10^4 m/s is needed for the case shown in Fig. 3). For such low effective velocity, the single-particle friction force would have a maximum around this small value having a non-linear decrease of the force for larger velocities. As a result, significant large-amplitude oscillations for the relative velocities corresponding to the non-linear part of the force are expected [7]. However, we did not see such oscillations for the velocities in this range. In fact, we measured the maximum of the friction force by carefully recording the onset of such large-amplitude oscillations but at significantly larger velocities.

The second approach is to take v_{eff} as a known parameter based on recorded oscillations of the longitudinal profile and measured maximum of the friction force. The fitting parameter is then an unknown numerical coefficient C. In such an approach, for our parameters and the region of low relative velocities discussed here, we find some enhancement for the numerical coefficient C compared to the factor 1/π or $1/(2\pi)^{1/2}$. However, the uncertainty of the numerical factor C found by such a procedure is rather large due to significant error bars in the measurements of the proton distribution as well as the values of the effective velocity which is found from the measured distribution but needs to be used in the single-particle expression. Rather than quoting some empiric values for the coefficient C at this point, we plan to determine numerical factors for the friction force expressions using numerical studies with the VORPAL code, by studying the velocities of ion which make various angles with respect to the magnetic field lines [10]. By accurately comparing with the formulae and experimental data, we should be able to have an estimate of the numeric coefficients for the magnetized friction force with a reasonably good accuracy.

A detailed study of the friction force both for the low and high relative velocities is presently in progress [11]. A systematic benchmarking of each of the performed experiments will be reported elsewhere.

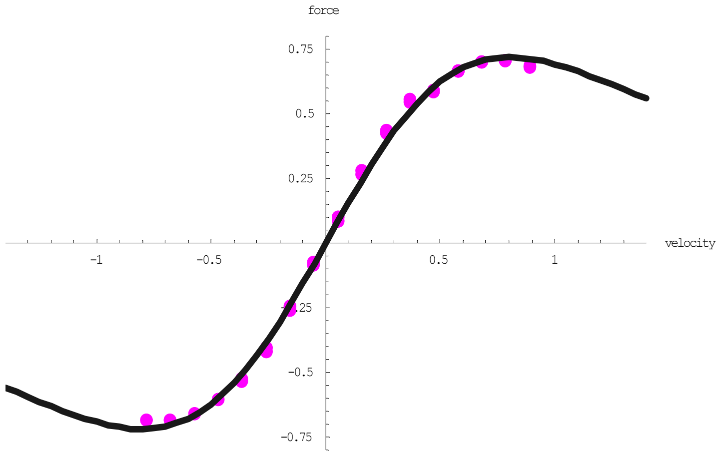

FIGURE 3. Longitudinal friction force in [eV/m] vs. velocity [10^4 m/s] for electron current of 300 mA (B=0.12T) and the force averaged according to the Eq. (3).

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