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Cooling Force Measurements at CELSIUS

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Abstract. The design of future high energy coolers relies heavily on extending the results of cooling force measurements into new regimes by using simulation codes. In order to carefully benchmark these codes we have accurately measured the longitudinal friction force in CELSIUS by recording the phase shift between the beam and the RF voltage while varying the RF frequency. Moreover, parameter dependencies on the electron current, solenoid magnetic field and magnetic field alignment were carried out.

Keywords: electron cooling, friction force.
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INTRODUCTION

Electron cooling friction force has several different descriptions [1, 2, 3], which predict different cooling force and are valid at different degrees of magnetization. In order to make predictions about the cooling times at future coolers it is important to know the cooling force accurately. This is especially important for high energy cooling projects such as the RHIC-project [4] where the cooling times could be of the order of 1000 s and a prediction on the order of magnitude is not sufficient. In this paper we present measurements of the longitudinal cooling force in CELSIUS using the phase shift between the beam and the rf voltage varying the rf frequency.

EXPERIMENTS

The cooling force has a linear dependence on the relative velocity of ions and electrons at low relative velocities. One way to measure the cooling force in this linear region is the so called phase-shift method. In this method the phase difference, $\Delta\phi$, between the bunched beam and the rf voltage is measured. The phase shift results from the competition between the cooler force and the force from the rf voltage. The friction force is then given by

$$F_{\parallel} = \frac{Ze\hat{U}_{RF}\sin(\Delta\phi)}{L_{cool}} \quad (1)$$

where Z is the charge of the ion, e is the elementary charge, $\Delta\phi$ is the phase shift and L_{cool} is the interaction length of the cooler.

The relative velocity between the ions and the electrons in the beam frame is given by

$$v_{\parallel}^{*}=\beta c\frac{\Delta p}{p}=\frac{\beta c}{\eta_p}\frac{\Delta f}{f}=\frac{C}{\eta_p}\cdot\Delta f, \qquad (2)$$

where C is the circumference, η_p the slip factor, f the rf frequency and Δf the frequency shift. The phase shift method has been employed earlier in different varieties at CELSIUS [5] and at other laboratories such as IUCF [6], TSR [7] and MSL [8].

Phase discriminator

A phase discriminator was used to measure the phase difference between the beam particles and the rf voltage. In the following this technique is described in more detail.

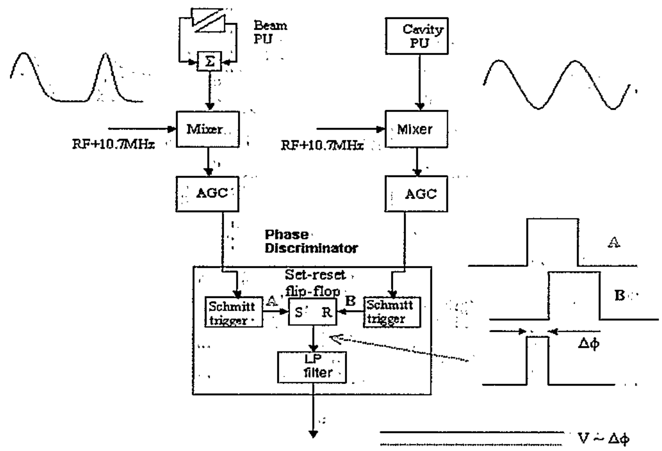


FIGURE 1. Schematic drawing of the principle of the phase discriminator.

In order to measure the phase difference between the rf cavity and the beam a phase discriminator was used as shown in Fig. 1. The signals from the beam pick-up and the cavity pick-up are sent to a phase discriminator after being up-converted to the carrier frequency (10.7 MHz) by a mixer and amplified to 10 dBm by an automatic gain control module. The phase discriminator converts the phase difference between signal (A) and (B) in Fig. 1 to a pulse length in a flip-flop. This pulse length is proportional to the phase difference, $\Delta\phi$, and is averaged in a low-pass filter to obtain an output voltage proportional to the phase difference. Since the low pass filter in the phase discriminator has a cut off frequency of 15 Hz, the output represents an average phase difference over about 20 ms. A digital Le Croy oscilloscope was used for further averaging of the signal over 2 s to get a good signal-to-noise ratio.

Measurement accuracy

The accuracy of the measurements from different sources are summarized in Tables 1 and 2. The uncertainty in determining $v_{\parallel}$ (Table 1) is relatively small and is dominated by the uncertainty in η_p, which is estimated from optics calculations. The uncertainty in $F_{\parallel}$ (Table 2) on the other hand, is larger and dominated by the uncertainty in the effective cooler length. The field of the toroids influence the effective solenoid length, giving a field region which is different from the nominal length. Another significant source to the uncertainty is the true value of the voltage in the rf cavity. The rf voltage was measured with two different techniques. One was voltage measurement with a probe in the cavity and the other measurement of the synchrotron frequency. It was concluded that the synchrotron method was the most accurate. The synchrotron frequency is given by $f_s = \sqrt{\eta_p e U_{RF} / 2\pi T \beta^2 \gamma} \cdot f_{RF}$, and the rf voltage can thus be determined by measuring the synchrotron frequency. The uncertainty of the measurement of the synchrotron frequency was ± 3 % and η_p is known by ± 0.5% giving an accuracy in U_{RF} of ± 7 %.

TABLE 1. Parameter values and estimation of accuracy for $v_{||}$, Eq. (2).

Parameter	Value	Estimated accuracy	Comment
C	81.76	± 0.1 %	Exact orbit unknown in the arcs
η_p	0.783	± 0.5 %	From optics
Δ_f	Varied around 1129.0 kHz	± 0.01 %	Determined by accuracy in the frequency generator.
$v_{\|\|}$		± 0.5 %	Total estimated accuracy.

TABLE 2. Parameter values and estimation of accuracy for $F_{||}$, Eq. (1).

Parameter	Value	Estimated accuracy	Comment
U_{RF}	10.2	± 7 %	From synchrotron frequency measurements;
$\Delta\phi$	25.0 mV / 1° @ 50 Ω	± 1 %	Read as a voltage from phase discriminator. From input of a known phase difference to the discriminator
L_C	2.50 m	± 10 %	Effective cooler length. Influenced by the toroidal field.
$F_{\|\|}$		± 12 %	Total estimated accuracy.

High voltage ripple

The ripple of the high voltage power supply is a potential source to the longitudinal electron velocity spread. The ripple of the CELSIUS cooler has dominating contributions at 50 and 300 Hz while the typical cooling time is of the order of 1 s. The ripple is measured to be < 3 V rms at 26 kV voltage, thus a relative ripple $\Delta U/U < 1.1 \cdot 10^{-4}$. This ripple corresponds to a longitudinal electron velocity spread rms in the beam frame of $v^*_{\Delta U} = \beta c \dfrac{\gamma}{\gamma+1} \cdot \dfrac{\Delta U}{U} = 5.5 \cdot 10^3$ m/s.

Measurement conditions

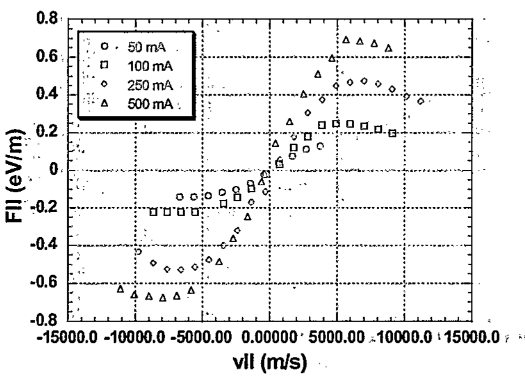
The experiments were performed using the phase-shift method described above. The experimental conditions can be summarized as follows.

The measurements were done with protons at the injection energy, 48 MeV, which corresponds to a cooler voltage of 26 kV. Since the phase shift method was used, the measurements were performed with a bunched beam, however using a rather low rf voltage around 10 $\hat{V}$. The phase shift was measured with a phase discriminator with integration time of 2 s to get a good signal-to-noise ratio. Changing the rf frequency instead of cooler voltage allowed us to make measurements in fine steps in relative velocity (1 Hz of 1129 kHz). The typical measurement step was 10 Hz.

We recorded transverse profiles with the magnesium-jet monitor as well as longitudinal bunch profiles. The longitudinal profiles have a distinct parabolic shape, which indicates that the beams are space charge dominated and have considerably smaller momentum spread than could be directly inferred from the bunch length [9].

RESULTS

In the following examples of results of longitudinal cooling force measurements are presented. The measurements were of different kinds: 1) Measurements for standard operational parameters of the cooler. 2) Measurements for different alignment angles between the electron and proton beams. 3) Measurements to study the influence of the non-straightness of the longitudinal magnetic field lines. 4) Measurements at different settings of the electron cooler to explore the friction force at various regimes of magnetization. In this report only the measurement data is presented and the detailed comparison with theoretical models will be presented elsewhere [10],[11].



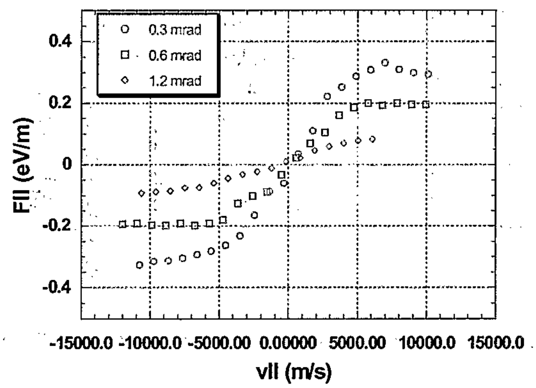


FIGURE 2. (Left) Longitudinal cooling force at standard cooler settings, B = 0.1 T and 48 MeV protons, for electron currents 50, 100, 250 and 500 mA. (Right) Longitudinal cooling force at different misalignment angles horizontally between the proton and the electron beams of 0.3, 0.6 and 1.2 mrad.

In Fig. 2 are shown results from cooling force measurements at standard cooler settings at electron currents of 50, 100, 250 and 500 mA. The proton current was rather low, 40 μA, in order to reduce IBS.

In another set of experiments we measured the dependence on the cooing force on the alignment angle between the proton and the electron beam in both vertical and horizontal directions. The purpose was to increase the relative velocity in a controlled way. In Fig. 2, right panel, are shown measurements for 0.3, 0.6 and 1.2 mrad misalignment angle horizontally. For calibration, both beam position monitors and an H^0 monitor was used. The H^0 monitor [12] is a silicon-strip detector situated 9 m from the cooler; a tilt angle of 1 mrad thus corresponds to a movement at the H^0 detector of 9 mm. The resolution of the H^0 detector is 1 mm, giving a resolution of about 0.1 mrad for the tilt angle.

In a third experiment the effects of the errors of the longitudinal solenoid field was investigated. The solenoid of the CELSIUS cooler is equipped with correction coils for correction of the solenoid field errors. Measurements of the magnetic field error in the CELSIUS cooler have been reported earlier [13] to be $\theta_e = 1$ mrad rms before corrections and $\theta_e = 0.2$ mrad rms after corrections. The measurements were carried out without corrections applied (DTCOR off) and with corrections applied (DTCOR on), see Fig. 3. It is clear that the cooling force is significantly reduced with a larger magnetic field error. The data can be used in comparisons with simulations of field errors [14].

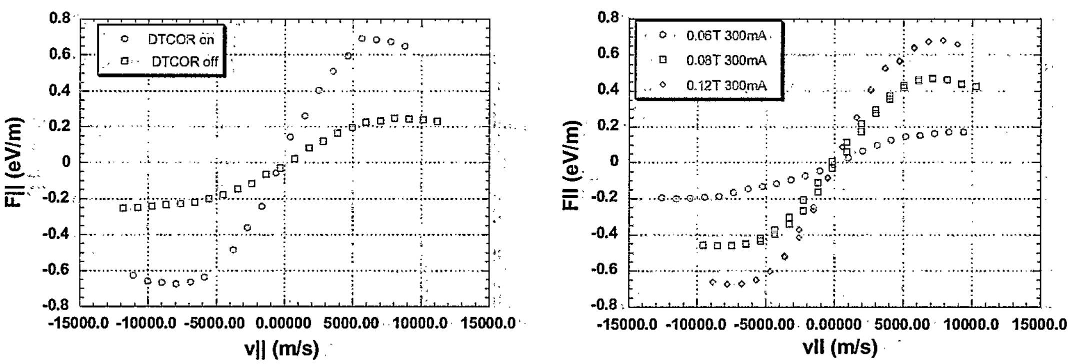


FIGURE 3. (Left) Longitudinal cooling force at different errors of the magnetic field in the cooling section. DTCOR on corresponds to an error of 0.2 mrad rms and DTCOR off corresponds to an error of 1 mrad rms. (Right) Longitudinal cooling force for different magnetic field 0.06, 0.08 and 0.12 T. The electron current was 300 mA.

We also compared the friction force for different magnetic fields as shown in Fig. 3 right panel. The idea here was to compare the cooling force at different degree of magnetization. Similar measurements were carried out for a number of different combinations of magnetic fields and electron currents.

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REFERENCES

1. Y. S. Derbenev and A. N. Skrinsky, Part. Acc. **8** 235 (1978).
2. I. N. Meshkov Phys. Part. Nucl. **25** 631 (1994).
3. V.V. Parkhomchuk, Nucl. Instr. Meth. A 441, 70 (2000).
4. RHIC E-cooler, http://www.agsrhichome.bnl.gov/eCool
5. Y.-N. Rao et al. Proc. of Workshop on Beam Cooling and Related Topics, Bad Honnef, 2001.
6. D.D. Caussyn et al. Phys. Rev. E, **51**, 4947 (1995).
7. M. Beutelspacher et al. Nucl. Instr. Meth. A **441**, 110 (2000).
8. H. Danared, Nucl. Instr. Meth. A **391**, 24 (1997).
9. S. Nagaitsev et al., 1993 Proc. of Workshop on Beam Cooling and Related Topics, Montreux, Switzerland, 1993; CERN 94-03, 405.
10. A.V. Fedotov et al. These Proceedings.
11. A.V. Fedotov et al. "Experiments towards high-energy cooling", submitted for publication (2005).
12. T. Bergmark et al. Nucl. Instr. Meth. A **441**, 70 (2000).
13. M. Sedlaček et al. "Design and construction of the Celsius electron cooler", 1993 Proc. of Workshop on Beam Cooling and Related Topics, Montreux, Switzerland, 1993, CERN 94-03, 235.
14. D. L. Bruhwiler et al. Proceedings of PAC 2005, 4206.