Observation of Magnetized Cooling in the IUCF Cooler

Timothy JP Ellison

The Indiana University Cyclotron Facility
2401 Milo Sampson Lane
Bloomington, IN 47405 USA

Abstract

Measurements of the longitudinal drag rate (R_D, the rate at which the electron beam can change the energy of the proton beam) for 45 MeV protons having longitudinal velocities relative to the electron beam, $v^*_{p\parallel}$, in the range from $1 \times 10^{-7} < v^*_{p\parallel}/c < 1 \times 10^{-2}$, are summarized along with measurements of the *effective longitudinal electron beam energy spread*, $\delta E_{e,spread}$, as function of electron beam current, I, and angular misalignment between the electron and proton beams, $\theta_{misalignment}$. It was found that $\delta E_{e,spread}$ increases approximately linearly with $\theta_{misalignment}$; this appears to be consequence of the combination of the electron beam space charge depression and the fact that the equilibrium proton beam size increases approximately linearly with $\theta_{misalignment}$. For well aligned beams, $\delta E_{e,spread}$ is consistent with electron beam intrabeam scattering, and in this regime, the normalized drag rate is enhanced considerably over the predictions of the nonmagnetized theory. These results are compared with measurements made at other laboratories.

I. INTRODUCTION

The initial measurements of the longitudinal drag rate [1] for the IUCF 270 keV electron cooling system were in close agreement with the nonmagnetized theory, although there was a larger than expected effective longitudinal electron beam energy spread, $\delta E_{e,spread}$. The nonmagnetized longitudinal drag rate as a function of the longitudinal proton velocity relative to the electron beam for a transversely cooled beam, $R_D\,(v^*_{p\parallel})$, can be simply expressed as:

$$R_D\left(v^*_{p\parallel}\right) = R_{D,\max}\left(\frac{\Delta_{e\perp}}{v^*_{p\parallel} + \Delta_{e\perp}}\right)^2 \qquad \left(v^*_{p\parallel} > \Delta_{e\parallel}\right) \qquad (a)$$

$$(1)$$

$$= R_{D,\max}\,\frac{\delta E_{e,error}}{\delta E_{e,spread}} \qquad \left(v^*_{p\parallel} < \Delta_{e\parallel}\right) \qquad (b)$$

where

$$R_{D,max} = \frac{4I\eta\left(r_e mc^2\right)^2}{e\gamma r_b^2\, kT_c}\,\Lambda_c \qquad (2)$$

where $\pm\,\Delta_{e\parallel} = \pm\,\beta c\ (\delta E_{e,spread}/2W)$ is the width of the electron beam longitudinal velocity spread corresponding to $\delta E_{e,spread}$; $\Delta_{e\perp}$ is $(kT_c/m)^{1/2}$ where k is the Boltzmann constant and m the electron mass; r_e is the classical electron radius; e the electron charge and γ the usual relativistic parameter. T_c, η, r_b, and Λ_c and W are defined in Table I. Since we will be discussing the *electron beam effective energy spread*, $\delta E_{e,spread}$, it is more illuminating to express the drag rate as a function of the *equivalent electron energy error* ($\delta E_{e,error} = 2W(v^*_{p\parallel}/\beta c)$), i.e. the drag rate experienced by a cooled proton if the electron beam energy were to be instantaneously stepped by $\delta E_{e,error}$.

The nonmagnetized model [Eqs. (2) and (1) using the parameters for the IUCF electron cooling system tabulated in Table I and I = 1 A] is shown along with early measurements [1] in Figure 1. The upper scale shows the drag rate as a function of $\delta E_{e,error}$.

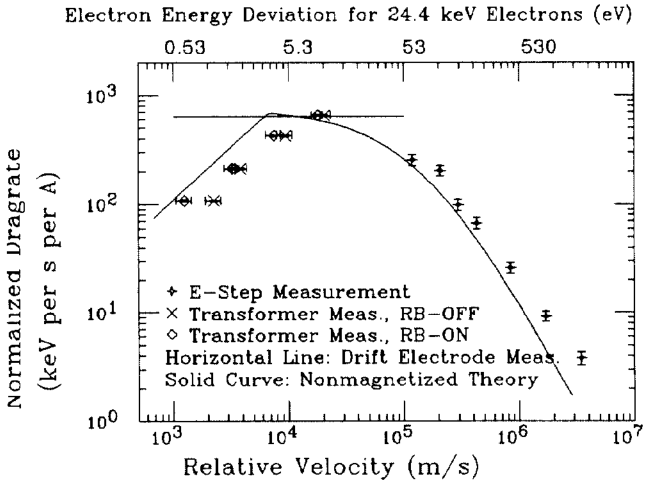

Figure 1. Measured normalized drag rate (R_D/I) in the IUCF Cooler.

As can be seen in Fig. 1, the model assumes an $\delta E_{e,spread}$ of ± 3.6 eV, corresponding to the region where the drag rate increases linearly with $\delta E_{e,error}$ (i.e. $\delta E_{e,error} < \delta E_{e,spread}$). The width of the linear region for the *measured* drag rate, however, is consistent with a $\delta E_{e,spread}$ of about 10 eV; a value much larger than expected from the cathode potential regulation (± 1 V). There are a number of other mechanisms which can also cause a real or effective electron beam energy spread: longitudinal-longitudinal (∥-∥ IBS) and transverse-longitudinal (⊥-∥ IBS) intrabeam scattering [2], and effects arising from the electron beam space charge depression [3].

This work is supported by The National Science Foundation under Grant NSF PHY 90 15957.

Table I. Parameters of the IUCF 270 keV cooling system during measurements.

Parameter	Symbol	Value	Units
Cooling Region Length	L_c	2.2	m
Ring Circumference	C	87.8	m
L_c/C	η	0.025	
Coulomb Logarithm	Λ_c	10.7	
Electron Beam Radius	r_b	1.27	cm
Cathode Temperature	T_c	1300	K
E-Beam Kinetic Energy	W	24.3	keV

II. MEASUREMENTS OF THE EFFECTIVE ELECTRON BEAM ENERGY SPREAD

One can attempt to determine the predominant cause of $\delta E_{e,spread}$ by determining how it varies with I and $\theta_{misalignment}$: $\delta E_{e,spread}$ should vary as $I^{1/6}$ if primarily due to $\|$-$\|$ IBS, $I^{1/2}$ if primarily due to $\perp$-$\|$ IBS [2], and as I if primarily due to the electron beam space charge [3].

A. Effect of Electron Beam Current

The measured *normalized drag rate* (R_D/I) is shown in Figure 2 as a function of $\delta E_{e,error}$, for constant ring and electron cooling system settings and I = 0.1, 0.2, 0.4, and 0.8 A. Two features are readily apparent from these data: firstly, $\delta E_{e,spread}$ increases ≈ linearly with electron current pointing to the electron beam space charge as a predominant source. This can be seen from the width of the region over which the drag rate increases to its maximum value. Secondly, the $(R_D/I)_{\max}$ decreases with I.

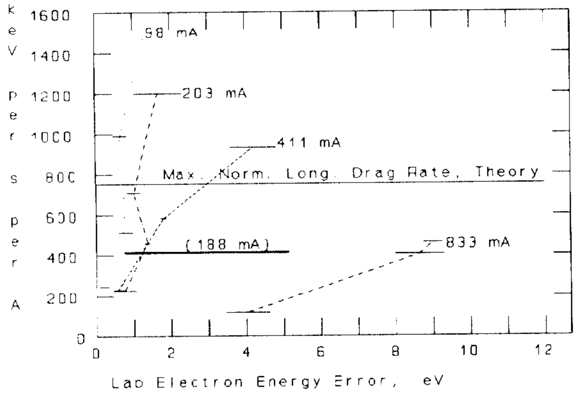

Figure 2. Normalized drag rate (R_D/I) vs. lab frame electron energy error for varying electron beam currents.

B. Effect of Electron/Proton Beam Alignment

An angular misalignment, $\theta_{misalignment}$, between the proton and electron beams in the cooling section causes the equilibrium proton beam emittance to increase substantially; for example, we have seen that a 0.37 mrad misalignment between the beams increases the equilibrium proton beam emittance from about 0.05π to 1π μm, such that the rms divergence approximately equals $\theta_{misalignment}$ [3,4]. Consequently one expects to observe $\delta E_{e,spread}$ to increase linearly with $\theta_{misalignment}$ due to the combination of the electron beam space charge and both the increase in proton beam size and transverse movement with respect to the equipotential electron beam axis:

$$\delta E_{e,spread} = \pm \frac{eIr\Delta r}{2\pi\epsilon_o \beta c r_b^2} \tag{3}$$

where

$$\Delta r = \theta_{misalignment} \cdot \left[\frac{L_c}{2}, \beta_{x,cooler} \right]_{\max}$$

where r is the average offset between the electron and proton beams, $\beta_{x,cooler}$ the beta function in the cooling region, βc the proton beam velocity, L_c the length of the cooling region, and ϵ_0 the permittivity of free space. Assuming (Eq. 1b) that the drag rate increases linearly in the region $\delta E_{e,error} < \delta E_{spread}$, one would expect to observe $\delta E_{e,error}$ to increase linearly with the product of I and $\theta_{misalignment}$ for a fixed value of R_D/I. The apparent linear increase in $\delta E_{e,error}$ with I is observed in Figure 2. In Figure 3 one observes an approximately linear increase in $\delta E_{e,error}$ with $\theta_{misalignment}$ for fixed I (0.188 A) and R_D (78 keV/s). The model (solid line) assumes r = 3.3 mm. These tests should be repeated with known values of r.

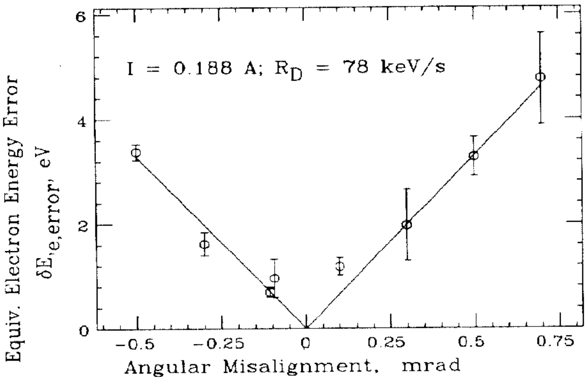

Figure 3. Measured $\delta E_{e,error}$ as a function a angular alignment between the electron and proton beam with a fixed normalize drag rate.

The author believes that the sensitivity of the equilibrium emittance and δE_{spread} to small changes in the $\theta_{misalignment}$ provides a measurement of the straightness of the field lines in the main solenoid.

III. OPTIMIZATION OF COOLING AND OBSERVATION OF MAGNETIZED EFFECTS

The cooling was optimized by using the measurement of $\delta E_{e,spread}$ as a function of $\theta_{misalignment}$ as a diagnostic to minimize $\theta_{misalignment}$. Using a 0.208 A electron beam, the

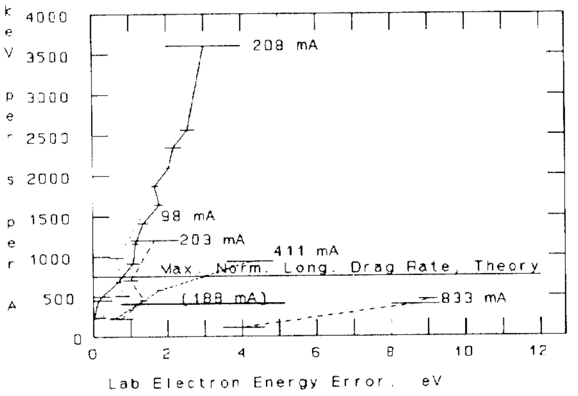

Figure 4. (R_D/I) vs. $\delta E_{e,error}$. The solid curve (0.208 A) is data after minimizing $\delta E_{e,spread}$.

maximum measured longitudinal drag rate increased to a value about 5 times higher than the predictions of the nonmagnetized theory (Figure 4). The effective $\delta E_{e,spread}$, however, was not reduced below about 2 - 3 eV, a value which appears to be consistent with $\parallel$-$\parallel$ and $\perp$-$\parallel$ IBS.

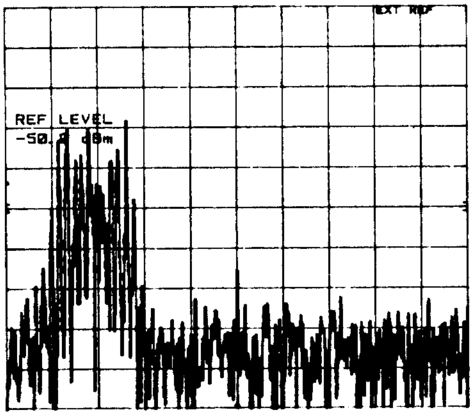

Figure 5. 45 MeV proton beam $\parallel$ Schottky signal. (CF 54.7 MHz; RBW = VBW = 300 Hz; 5 dB/div; 2 kHz (0.1 s)/div.

Figure 5 is a Schottky signal spectrum obtained while operating with this high drag rate. The sharp spikes occurring each 1/60th s in sweep time are characteristic of a pure tone being frequency-modulated by a 60 Hz triangle waveform with a deviation of ± 3.1 kHz. My interpretation of this signal spectrum is that the proton beam energy is being coherently modulated by:

$$\pm\ 2.9\ \text{keV}\ [\ =\ \pm\ \tfrac{1}{2}\beta^2\gamma M_p c^2 \eta^{-1}(3.1\ \text{kHz}/54.6\ \text{MHz})]$$

The normalized drag rate necessary for this is about 3500 keV/s-A, consistent with measurements shown in Figure 4.

IV. MAGNETIZED COOLING

These high drag rates are consistent with the theories of cooling with a magnetic field[5]. In this regime, cooled protons experience adiabatic collisions (taking place over a time period long compared to the electron gyroperiod) with the electron Larmor circles. Since the cooling solenoid magnetic field straightness in on the order of 0.3 mrad (rms) (about 7 times smaller than the intrinsic angular divergence of the electron beam due to the 0.12 eV cathode temperature) the electrons appear about 50 times "colder"; however, the coulomb logarithm for such adiabatic collisions is about 10 times smaller, yielding an ≈ 500% increase in the drag rate (see Eq. 2). In Figure 6 the measured *scaled* drag rate ($\gamma R_D/\eta j_e$, where $\eta = L_c/C$ and j_e is the electron current density) is shown along with data from other laboratories as well models showing the contribution to the drag rate from the "fast" (nonmagnetized model) and "adiabatic" (magnetized model) collisions.

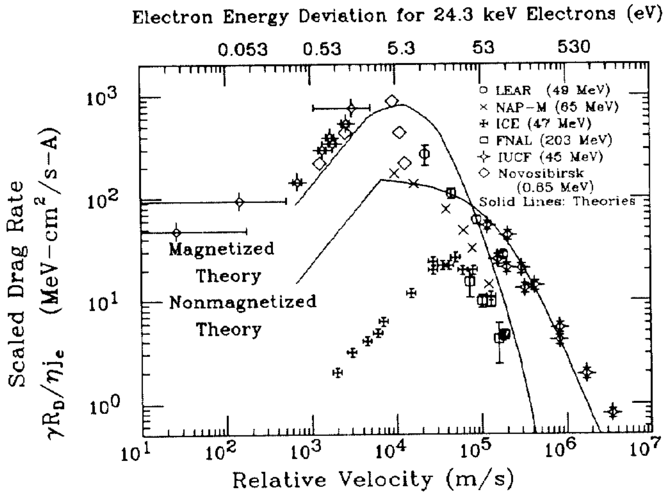

Figure 6. Scaled drag rates from IUCF and other laboratories along with magnetized and nonmagnetized model.

Acknowledgements

These measurements would not have been possible without the help of a myriad of IUCF personnel, especially M. Ball, B. Brown, J. Collins, V. Derenchuk, D. Friesel, B. Pollock, and T. Sloan. I also owe thanks to L. Lebedev (I.N.P., Novosibirsk) for explaining to me, in an intuitive manner, the basics of electron beam intrabeam scattering.

References

[1] Timothy JP Ellison, Dennis L. Friesel, and Robert J. Brown, "Status and performance of the IUCF 270 keV electron cooling system", *Proc. 1989 IEEE P. A. C., Acc. Eng. and Tech.*, (Chicago, IL, 20-23 March 1989).

[2] N.S. Dikansky, V.I. Kudelainen, V.A. lebedev, I.N. Meshkov, V.V.Parkhomchuk, A.A. Sery, A.N. Skrinsky, B.N. Sukhina, "Ultimate possibilities of electron cooling", preprint 88-61 (I.N.P., Novosibirsk, 1988).

[3] T. Ellison, "Electron Cooling" (Ph.D. Thesis, Indiana University, 1990).

[4] M. Ball, D. Caussyn, J. Collins, D. Duplantis, V. Derenchuk, G. East, T. Ellison, D. Friesel, B. Hamilton, B. Jones, M.G. Minty, S.Y. Lee, and T. Sloan, "Beam property measurements in the IUCF Cooler", these proceedings

[5] Ya. S. Derbenev and A.N. Skrinsky, "The effect of an accompanying magnetic field on electron cooling, *Part. Accelerators*, **8**, 235-243 (1978).