STATUS AND PERFORMANCE OF THE IUCF 270 keV ELECTRON COOLING SYSTEM

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SUMMARY

The IUCF 270 keV electron cooling system has demonstrated collection efficiencies of 100% (+0/-2 ppm (parts per million)) operating with a 2 A electron beam (0.4 A/cm^2). In addition, a very complete set of longitudinal drag rate measurements have been completed. These measurements span rest frame electron-proton velocity differences of over three orders of magnitude, and include the region where the average longitudinal electron-proton velocity difference is less than the electron beam longitudinal velocity spread (a region which has not previously been measured). No obvious Schottky signal suppression (evidence of beam crystallization) has been observed for low intensity cooled proton beams, though many interesting collective phenomena have been observed for high intensity cooled proton beams.

INTRODUCTION

The IUCF electron cooling system has now been in operation for about 1 year. The cooling system design[1] and first cooling experiments[2] have been described elsewhere. During this period the system has been tested over much of its design range, operating with electron beam currents up to 2 A and energies up to 250 keV (the energy required for cooling 459 MeV protons). The system has also been used for trouble-free cooling of 44 MeV $^3He^{++}$ beams, as well as proton beams ranging in energy from 45 to 287 MeV (apparently the highest energy electron cooling to date).

This paper summarizes some of the measurements made with the electron cooling system. In the first section below, we discuss the electron collector system, and describe a simple technique we have demonstrated which provides essentially perfect collection efficiencies. In section II we summarize a number of longitudinal drag rate measurements made with 45 MeV proton beams, and compare these measurements with the simple nonmagnetized theory. In the final section, we note a few of the collective beam effects observed, and comment on our search for Schottky signal suppression (evidence for beam "crystallization") at low proton beam currents.

I. ELECTRON COLLECTION SYSTEM

The electron cooling system nominally operates with collection efficiencies of ≥ 99.99%. We have, however, demonstrated a technique[3] enabling the system to operate with collection efficiencies of 100% +0/-2 ppm. The system is quite simple: an electric field normal to the magnetic guide field is used to give the electron beam an (**E** × **B**) drift to compensate for the centripetal (**R** × **B**) drift which occurs in the toroids. In the past, electron cooling systems have used magnetic dipole fields to correct for the beam drift which occurs in the toroids. However, the (**R** × **B**) drift velocity points in the same direction regardless of the electron direction of travel, whereas the transverse magnetic dipole fields (which essentially "tilt" the longitudinal solenoidal field lines) provides a transverse component to the electron velocity which is dependent upon the electron direction of travel. This causes any beam reflected from the collector to become offset with respect to the primary beam by four times the drift which occurs within a single toroid, as shown in Fig. 1a, where there are dipoles fields in the gun and collector solenoids. An (**E** × **B**) drift, though, is similar to the (**R** × **B**) drift in that its direction is independent of the electron direction of travel, as shown in Fig. 1b, where an (**E** × **B**) drift in the main solenoid is used to compensate for the centripetal drift. In this case, any electrons which escape the collector oscillate to the gun and then back to the collector where they are given another chance to be collected. This technique should thus allow nearly *any* collector to operate with essentially perfect collection efficiencies.

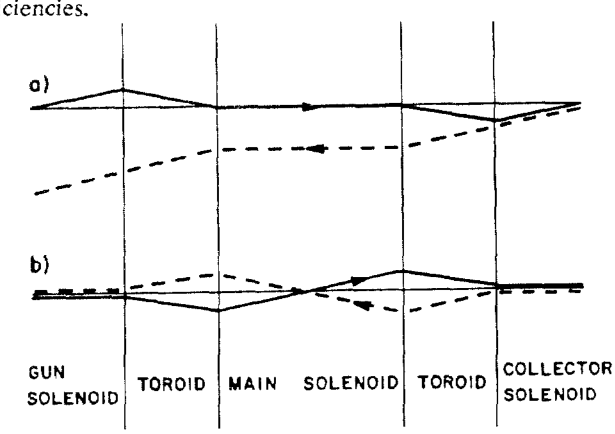

Figure 1. The solid lines represent the trajectory of the primary electron beam; the dashed line the trajectory of beam reflected from the electron collector. See text for explanation.

II. LONGITUDINAL DRAG RATE MEASUREMENTS

The longitudinal drag rate, R_D, (the rate at which the electron beam can change the energy of the proton beam) has been measured in three different ways. Below each method is briefly described, and then the data is compared with the simple nonmagnetized theory of electron cooling.

A. Measurement techniques

1. Magnetic induction

Using a very large transformer (≈ 0.6 V·s capacity) a constant emf is applied across an insulator in the beam vacuum chamber. If the product of emf and the proton charge and revolution frequency (power per proton) is less than the maximum drag rate provided by the electron cooling system, the proton beam will change energy until the electron cooling system drag rate becomes equal to the power given to a particle by the transformer. This allows measurement of the longitudinal drag rate for ion beams with velocities very close to the average electron velocity, and gives a measurement of the longitudinal electron beam velocity spread. Data from measurements using this technique are plotted in Fig. 2 (O's) for ± 4 V cathode potential 60 Hz ripple, and (X's) for less than ± 0.3 V ripple (data taken using a ripple bucking system).

During these tests it was observed that the high energy tail developed by the beam during the accelerating portion of the transformer cycle was much more prominent than the low energy tail developed during the decelerating portion of the cycle. In addition, it was found that, for emf's which change the beam energy at a rate very close to the maximum longitudinal drag rate, beam loss occurs mostly in the acceleration portion of the cycle. This leads us to believe that the longitudinal drag force is slightly nonsymmetrical.

From the measurements with the ripple bucker on, we see an effective lab frame longitudinal electron beam energy spread of about ± 2 eV (FWHM), corresponding the a rest frame longitudinal energy spread of 4.4×10^{-5} eV, or a longitudinal temperature of less than 1 K. As has been pointed out[4] by R.E. Pollock (IUCF), this energy spread is on the same order as the potential energy of the electron magnetic moment in the 0.116 T magnetic field, raising the interesting question of whether the electron beam can become spin polarized.

2. Drift electrode voltage modulation

In this series of measurements, a triangular waveform voltage, V, was applied to the drift electrodes located inside the main cooling solenoid, thus modulating the electron beam energy with the same waveform. Providing that $e(M/m)(dV/dt)$ is less than the maximum longitudinal drag rate, where m and M are the electron and proton masses, the proton beam will be able to track the electron beam velocity modulation. The proton beam velocity modulation was monitored by measuring the stored coasting proton beam Schottky signal frequency modulation. Either the frequency or amplitude of the voltage modulation was increased until the electron beam energy slew rate exceeded $(m/M)R_{D,max}$, giving us a value for the maximum longitudinal drag rate. This value is depicted in Fig. 2 as the dashed line.

3. HVPS energy step

This measurement technique was used to measure the drag rate for very large velocity differences between the electron and proton beams. The electron beam energy was stepped by an amount ranging from about 200 to 2000 eV, and the proton beam energy rate of change was measured by monitoring the coasting proton beam Schottky signal rate of change in frequency. These measurements are displayed in Fig. 2 with "+" symbols.

B. Comparison with theory

The solid curve in Fig. 2 is the simple nonmagnetized theoretical longitudinal drag rate[5] for a transversely-cooled 45 MeV proton beam. The data and theory are normalized to an electron current density of 0.2 A/cm^2, and for the electron cooling region length equal to the circumference of the storage ring. The electron beam transverse velocity distribution is assumed to be a Maxwellian distribution due to a cathode temperature of 0.11 eV/k (1000 °C), where k is Boltzmann's constant. The electron beam longitudinal velocity spread is assumed to be a uniform distribution, the width of which is determined by the ± 4 V cathode potential ripple. The coulomb log is taken to be a constant, 10.7; the minimum impact parameter ($\sim v^{-2}$) being the classical value for the maximum possible momentum transfer, and the maximum impact parameter ($\sim v$) is the Debeye shielding length. In both cases, we have taken v to be the rms electron velocity due to the cathode temperature. The electron beam energy is 24.3 keV.

The agreement between the theory and experimental data is quite impressive. Most of the disagreement at high longitudinal velocity differences can be accounted for by the fact that the theory assumes the Coulomb logarithm to be a constant, whereas it actually increases as $3\ln(v_{\parallel}/v_{e\perp,rms})$, where $v_{\parallel}$ is the rest frame velocity difference between the proton and electron beams, and $v_{e\perp,rms}$ is the rms electron transverse velocity due to the cathode temperature.

The disagreement at low longitudinal rest frame proton beam velocities is due to our very approximate model for the electron beam longitudinal velocity distribution. In reality, this velocity distribution is due to a combination of cathode potential ripple, effects due to the electron beam space charge depression, and due to electron beam intrabeam scattering. All these effects are controllable, with the exception of the electron beam intrabeam scattering[6], which places a lower limit on the electron beam longitudinal velocity distribution. We suspect that the residual energy spread found with the ripple bucker on is due to electron beam intrabeam scattering, and in the near future we will perform tests where all other effects are negligible to test this theory.

This is the first time the longitudinal friction force has been measured for such small rest frame longitudinal velocity differences, and this is a matter of much interest to us: if this longitudinal energy spread can be reduced by an order of magnitude, then the longitudinal cooling rate for already-cooled beams would also be increased by an order of magnitude.

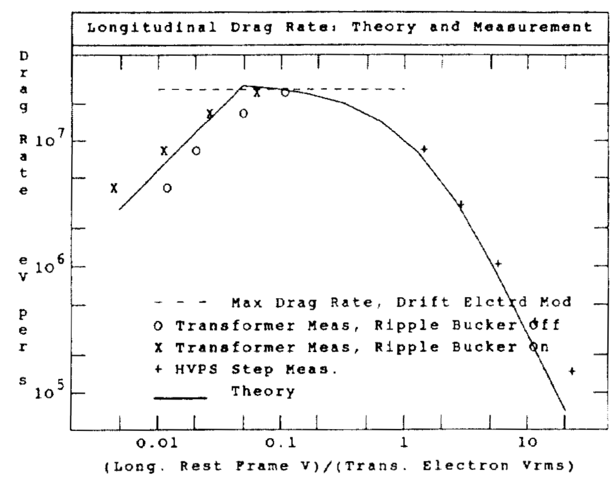

Figure 2. Longitudinal drag rate and theory. The drag rate is plotted as a function of the ratio of the proton longitudinal velocity in the electron beam rest frame divided by the electron rms transverse velocity. See text for detailed explanation.

III. COLLECTIVE BEAM EFFECTS

Figure 3 shows a set of Schottky signal spectra from a 45 MeV cooled proton beam for proton beam currents (from the bottom) of 0.1, 1, 10 and 100 μA. The beam current for the uppermost trace is unknown. Such behavior, predicted by Chattopadhyay[7] and previously observed at the LEAR ring[8], is due to self-bunching of the extremely low momentum spread beam. At high beam currents we observe coherent signals from the beam; the releative amplitude at various harmonics depends upon the rf cavity tuning. By deliberately tuning the rf cavity to maximize the beam self bunching, a coherent time structure can be veiwed in the time domain on a oscilloscope displaying the signal from a wideband longitudinal pickup.

We have also observed another very interesting phenomenon: at very high proton beam currents (≥ 300 μA), we have seen large coherent signals in the Schottky signal spectra from coasting beams at the upper horizontal sideband (but not the lower). Such a signal could be produced if the beam transverse and longitudinal motions were coherently related (i.e., if the beam were self bunched, and if the betatron motion of bunches 90° out of phase longitudinally were also 90° out of phase, the signal pickup would provide the proper mixing to produce such a signal).

We have measured the Schottky signal power as a function of time and observed a nearly perfect exponential decay of power over time as the beam intensity falls from about 20 to 0.5 μA, which is consistent with no Schottky signal suppression (beam "crystallization") at low intensities.

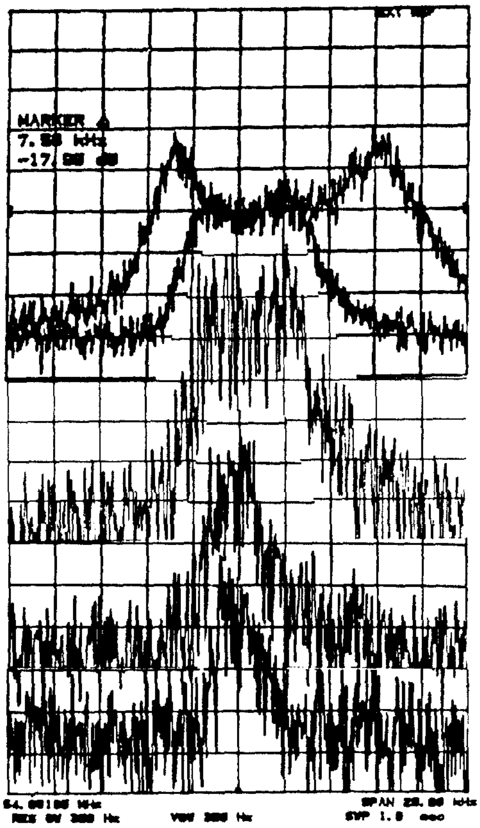

Figure 3. Longitudinal Schottky signal spectra from coasting 45 MeV proton beams with intensities of (from the bottom) 0.1, 1, 10, and 100 μA. The beam intensity for the uppermost trace is unknown. (CF 54.681 MHz (h = 53), 2 kHz/div, 5 db/div).

IV. CONCLUSION

The IUCF electron cooling system has worked very reliably since first commissioned about one year ago. The measured longitudinal drag rate is consistent with an effective transverse electron beam temperature equal to that of the cathode and is in near perfect agreement with the nonmagnetized theory of electron cooling. We are now investigating the source of the electron beam longitudinal velocity spread, which cannot be accounted for by the cathode potential ripple. Interesting collective phenomena are observed at high intensities, and thus far, no obvious Schottky signal suppression for low intensity beams has been observed.

ACKNOWLEDGEMENTS

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