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ELECTRON COOLING EXPERIMENTS AT FERMILAB

R. Forster, T. Hardek, D. E. Johnson, W. Kells, V. Kerner, H. Lai, A. J. Lennox
F. Mills, Y. Miyahara, L. Oleksiuk, R. Peters, T. Rhoades, D. Young
Fermilab *
P. O. Box 500
Batavia, Ill. 60510

and

P. M. McIntyre
Fermilab/Texas A&M University
College Station, Texas 77843

SUMMARY

A 115 MeV proton beam has been successfully cooled in the Electron Cooling Ring at Fermilab. Initial experiments have measured the longitudinal drag force, transverse damping rate, and equilibrium beam size. The proton beam was cooled by a factor of ~50 in momentum spread in 5 sec, and by a factor of 3 in transverse size in 15 sec. Long term losses were consistent with single scattering from residual gas, with lifetime ~1000 sec. Using the measured electron beam temperature T_e = 0.8(2) eV, the observed cooling agrees well with expectations from cooling theory.

I. Introduction

The Electron Cooling Ring at Fermilab was constructed in order to study the electron cooling and accumulation of proton beams.[1] Electron cooling will be used at Fermilab to cool and accumulate antiprotons in the program (Tevatron I)[2] to make $\bar{p}p$ colliding beams at $\sqrt{s}$ = 2TeV. For this purpose it is essential 1) to extend the energy range of previous studies[3,4] to the energies (hundreds of MeV) relevant to $\bar{p}$ cooling; and 2) to study (for the first time) accumulation of many successive proton beams in the aperture of a storage ring. The present work represents the first step in this program.

The electron beam and cooling ring have each been described elsewhere.[5,6] Their parameters are summarized in Tables I, II. In Section II is a commentary on those features of their performance that are important for understanding the present cooling experiments. In Section III the cooling experiments are described, and results are presented. In Section IV, the longitudinal and transverse cooling data are interpreted using the theory of cooling developed by several authors.[7,8,9]

TABLE I
Electron Beam Parameters

Energy	62.4	keV
Current	2	A
Cooling length L	5	m
Beam Diameter	5	cm
Magnetic guide field	700	G
Voltage regulation	10	V

TABLE II
Cooling Ring Parameters

Energy	114	MeV
Circumference C	135	m
Number of protons	$\sim 5 \times 10^5$	
Tune ν_x	3.56	
Tune ν_y	5.56	
γ_t	3.6	
RF Harmonic	7	
RF Voltage	.015-3	kV
Proton emittance	$15\pi 10^{-6}$	m-rad
Cooling s.s. Parameters β_x	20	m
Cooling s.s. Parameters β_y	30	m
Cooling s.s. Parameters α_p	0.1	m
Mean pressure	5×10^{-9}	Torr

II. System Operation

Electron Beam

The electron beam was designed to produce a beam with energy 20-200 keV, current 1-20 ADC, and rest frame temperature ~.5 eV. For such a beam to be practical, the electrons must be decelerated nearly to rest before collection, so as to recover most of their energy. While commissioning and developing the electron beam, we discovered a novel mechanism for beam collection.[10] Under certain conditions, residual gas ions are stably trapped on equipotentials in the vacuum, and neutralize the electron space charge in the deceleration region. Thus we were able to decelerate a beam of several amps to an energy of ~1 kV, with losses $\Delta I/I \lesssim 5 \times 10^{-4}$. This mechanism was an important aid in achieving quiescent electron beam operation with T = 62 keV, I = 5A for the present experiments.

Cooling Ring

Once stable operation of the electron beam was achieved at T_e = 62 kV, the cooling group decided to proceed with cooling experiments at the corresponding proton energy, T_p = 114 MeV. Since the linac, transport line, and cooling ring were designed for operation at 200 MeV, considerable effort was required to retune those systems. The linac group succeeded in producing 114 MeV protons with good optical quality by turning off three of the 9 RF tanks, and rephasing the last tank. The injection line to the cooling ring was modified to increase its momentum acceptance. The cooling ring was retuned for operation at lower energy. Several working points were explored; a point slightly above 1/2-integral resonance was chosen because of its isolation from low-order non-linear resonances. The coupling due to the electron beam solenoid did not create problems.

When the electron beam was turned on, slow electrons accumulated in the cooling region, and caused large tune shifts of the proton beam. These slow electrons were ionized from the residual gas by the electron beam, and then trapped - transversely by the magnetic guide field and longitudinally by the accelerating potentials.[11] We were able to clear the slow electrons from the beam, using clearing electrodes provided for this purpose. No further tune problems were observed on the proton beam during cooling experiments.

III. Cooling Experiments

In each of the experiments described below, the electron beam was first tuned and aligned using cooling rate and equilibrium beam size as diagnostics; then a fresh proton beam (DC) was injected into the cooling ring, and cooling studies commenced.

Transverse Cooling

Transverse cooling was observed by recording the

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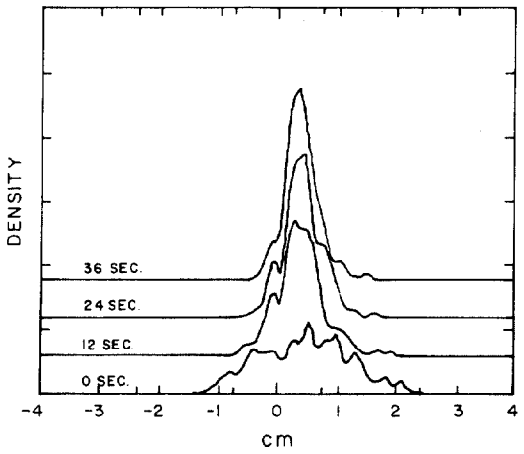

Figure 1. Vertical beam profiles at 12 sec intervals following injection.

vertical beam profile during cooling. The profile monitor[12] measured the (y,s) coordinates of ions formed in the residual gas. A typical set of profiles are shown in Figure 1. Each profile corresponds to an interval of ~1 sec. The injected beam is nearly flat; as cooling proceeds, the beam cools to an approximate Gaussian. The area under successive profiles remains approximately constant except for a small beam loss during cooling.

Data from several runs are summarized in Figure 2, which shows the r.m.s. beam size σ as a function of time. The exponential cooling time is τ = 15(2) sec and the equilibrium beam size is σ_y = 1.8(2) mm. Also shown are data for a run in which the beams were mis-aligned. The equilibrium beam size increases as expected. The electron beam temperature can be inferred from the measurement of σ_y:

$$T_{e\perp} \leq T_{p\perp} = M\langle v_y^2\rangle = M\left(\frac{\sigma_y}{\beta_y}\right)^2 \beta^2\gamma^2 c^2 \qquad (1)$$

This yields $T_{e\perp} \leq .9(1)$eV.

Longitudinal Cooling

The small-amplitude longitudinal drag force $F_{\parallel}$ was measured using a proton beam which was already cooled to equilibrium. The electron beam energy E_e is suddenly changed by an amount δE_e, and the response time δt of the proton distribution is measured. To observe the response of the proton distribution, a feeble RF bucket (h=7) is applied to the beam, with a frequency corresponding to the new energy $(M/m)(E_e + \delta E_e)$. As the beam approaches the new energy, it first bunches near the bucket separatrix, then begins filling the bucket. A coherent signal is detected at the RF frequency using a broadband toroid. This behavior can be seen in Figure 3, which plots the detected signal as a function of time after the energy step, for steps δE_e = 50, 100, 150 eV. The drag force $F_{\parallel}$ can be obtained for each step size:

$$F_{\parallel} = \frac{dp^*}{dt^*} = \frac{\delta E_p}{\beta c\,\delta t}\frac{C}{L} = \frac{M}{m}\frac{C}{L}\frac{\delta E_e}{\beta c\,\delta t} \qquad (2)$$

$F_{\parallel}$ is plotted in Figure 4, as a function of δE_e.

The equilibrium momentum spread was measured for bunched and unbunched beams. For unbunched beams, the Schottky scan technique was applied at h = 452. The observed FWHM was 17(3) kHz, corresponding to $\frac{\delta p}{p} = \eta\frac{\delta f}{f}$ = 3.8(6) x 10^{-5}.

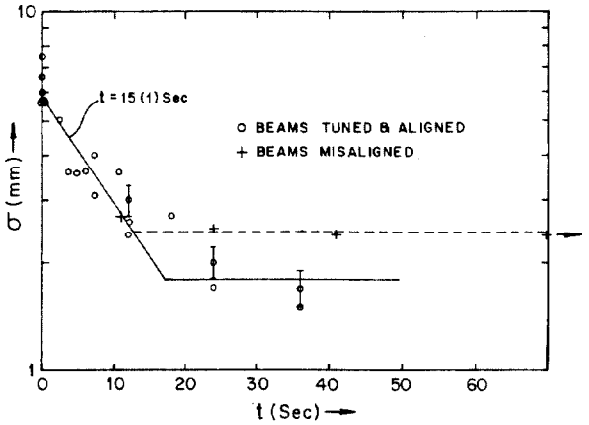

Figure 2. Compilation of vertical cooling data, showing exponential cooling time and equilibrium endpoint.

For bunched beams, the spectrum shown in Figure 5 is obtained with an RF voltage of 40 V. The envelope of harmonic peaks approximates a dependence $\frac{\sin H\phi}{H\phi}$. That is the dominant dependence in the Fourier transform of either a square or truncated cosine waveform, so one may obtain the phase width of the bunches from the extinction point (H = 25): $\phi = 14°$. This corresponds to a momentum spread $\frac{\delta p}{p} \sim 3 \times 10^{-5}$, with a roughly square distribution.

The dominant source of equilibrium momentum spread is the voltage regulation of the electron beam, $\delta E_e \sim 10$V, corresponding to $\frac{\delta p}{p} \sim 8 \times 10^{-5}$. This is consistent with the measured equilibrium.

IV. Results and Conclusions

We have measured the transverse temperature of the electron beam, and the longitudinal drag force for small amplitudes. For cooling by a flattened electron distribution with transverse temperative $T_{\perp} = \frac{1}{2} m \beta_{\perp}^2 c^2$, one obtains[8] a small amplitude drag force

$$F_{\parallel} = -\frac{8\pi n_e r_e^2 m c^2}{\beta_{\perp}^2}\mathcal{L} \qquad (3)$$

where $\mathcal{L}$ is the Coulomb logarithm for the (magnetized) interaction. The drag force for finite amplitudes is diminished from this value by correction for the aspect ratio $\beta_{e\nu}/\beta_{e\perp}$ and by diffusion for finite amplitude. Extrapolating the data of Figure 4 to zero amplitude, $F_{\parallel}$ = 1.8(2) x 10^{-4} eV/cm. Together with the result $\beta_{e\perp}$ = 1.8(2) x 10^{-3}, this yields a measurement of the Coulomb logarithm: $\mathcal{L}$ = 14(2). (4)

For transverse cooling, one obtains[8] a damping time

$$\tau = \frac{1}{2\pi^{3/2}}\beta_{\perp}^3\frac{M}{m}\gamma(n_e r_e^2 c\,\mathcal{L})^{-1}\frac{C}{L} \qquad (5)$$

Using the observed damping time τ = 15(2) sec, the Coulomb logarithm can again be determined:

$$\mathcal{L} = 19(4) \qquad (6)$$

The Coulomb logarithm for free scattering is $\mathcal{L} = \log(\rho_{max}/\rho_{min})$, where

$$\rho_{max} = \beta_{\perp}/\sqrt{8\pi n_e r_e} = .11 \text{ cm}$$

is the Debye length, and

$$\rho_{min} = 2r_e/\beta_{\perp}^2 = 1.7 \times 10^{-7}\text{cm}$$

is the backscatter limit. This yields $\mathcal{L}$ = 13 for free scattering. In a magnetic field, the proton has

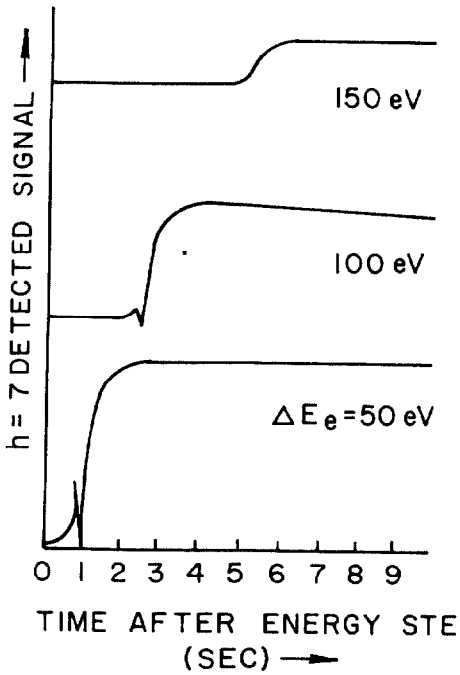

Figure 3. Longitudinal drag force measurement. At t=0 (dashed line), electron energy is stepped by an amount δE. After a time δt, the beam is cooled to the new energy and is RF captured.

quasi-free interactions only for impact parameters less than the gyroradius

$$\rho_L = \beta_\perp c/\omega_e = 4.4 \times 10^{-3}\,cm$$

The Coulomb logarithm is reduced to $\mathcal{L}_m = \log \rho_L/\rho_{min} = 10$.

The longitudinal and transverse cooling results appear to overestimate the expected Coulomb logarithm. The most likely explanation is that the actual electron temperature is somewhat lower than the upper limit obtained from the end-point proton temperature measurement.

V. Future Plans

During the coming year we plan to study electron cooling at 200 MeV energy, with electron beam currents up to 10 A. The cooling ring is being equipped with new injection kickers to facilitate momentum stacking. The process of coalescing two beams will be a major topic of study.

We are examining the possibility[13] of improving the performance of the $\bar{p}$ source design by increasing the energy of electron cooling to T_e = 1.5 GeV. The advances in elctron beam collection[8] made to date make the design of the required electron beam (750 kV, 10 A) quite feasible.

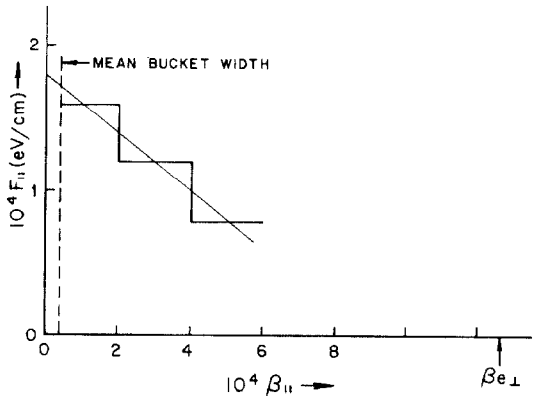

Figure 4. Longitudinal drag force F for three values of $\beta_\parallel = \delta E_e/p_e$. The RF bucket width is shown.

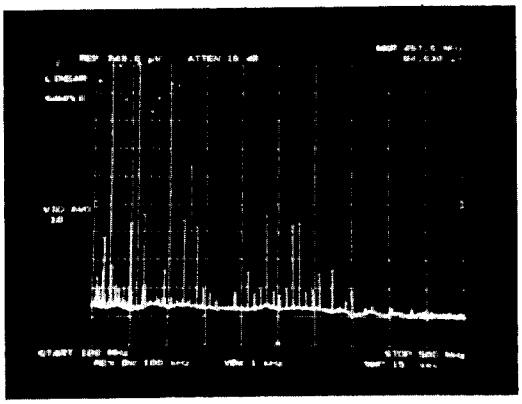

Figure 5. RF spectrum of the cold proton beam, bunched by a weak RF bucket: V_{RF} = 40V, h = 7.

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