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Electron Cooling and Accumulation of 200-MeV Protons at Fermilab.

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Summary

Experimental measurements have been made of the cooling of 200-MeV protons by an electron beam of 1 to 3 A and an energy of 110 keV. These experiments are an extention of earlier measurements on the cooling of 115-MeV protons and were performed in the Fermilab experimental proton storage ring. At 200 MeV the proton beam lifetime in the storage ring is extended from 10 to 4000 sec with electron cooling. The cooling times with an electron beam current of 1 A were approximately 2 sec for momentum and 5 to 10 sec for transverse cooling of the proton beam. For proton intensities of approximately 2×10^6 particles, the six-dimensional phase-space density of the proton beam was increased by a factor of 2×10^5. These results and data on equilibrium proton distributions and frictional forces are in reasonable agreement with the theoretical predictions. In addition, the accumulation of successive "hot" batches of protons into a cold core, i.e. stacking, has been demonstrated.

Introduction

Interest in increasing phase-space density of heavy particle beams has prompted an investigation of beam-cooling techniques.[1] At Fermilab, a cooled antiproton beam will be used for producing proton-antiproton collisions at center-of-mass energies of 2 TeV in the 1 km-radius superconducting storage ring.[2] The technique of electron cooling was first proposed by Budker[3] in 1966 and demonstrated by the Novosibirsk group[4] in 1974. A cool electron beam moving parallel to a hotter proton beam at the same average speed will increase the phase density of the proton beam by Coulomb interactions. In addition to the measurements by the Novosibirsk group, experimental verification of this technique has been demonstrated at CERN[5] using 46-MeV protons and at Fermilab[6] with 115-MeV protons. Recently the Fermilab electron cooling system has been used for cooling at a higher energy of 200 MeV and for the accumulation of protons at this energy.

Electron Cooling Ring and Diagnostics

The 200-MeV proton storage ring and the electron cooling system have been previously described.[7,8,9] The storage ring, shown schematically in Fig. 1, consists of 24 dipoles and 32 quadrupoles arranged in a racetrack configuration with two long straight sections. The momentum dispersion in the long straight sections were chosen to be zero for simultaneous cooling of different-momenta protons. The nominal operating parameters for the system at 200 MeV are given in Table I.

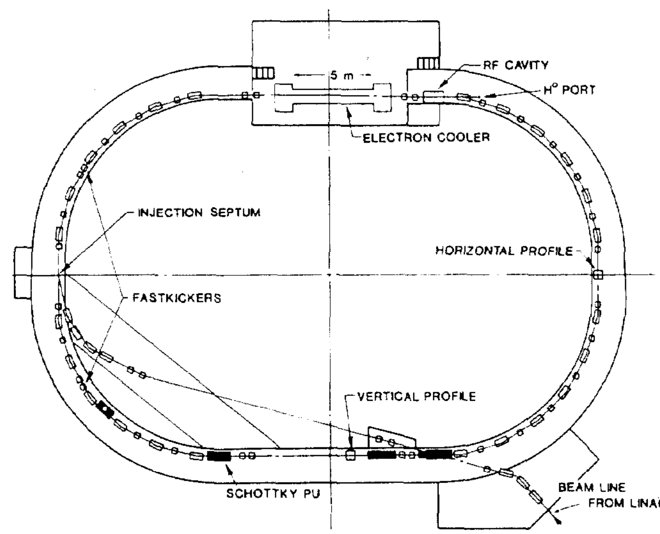

Fig. 1 Schematic view of the Fermilab 200-MeV experimental electron cooling ring. Bending magnets represented by open rectangles, quadrupoles by open squares.

Table I. Parameters of the electron cooling ring and electron beam during cooling experiments

PARAMETER	VALUE	UNITS
Proton Energy	200	MeV
Revolution Period	0.798	μsec
RF Harmonic Number	6	
Effective Ring Radius	21.56	m
Bend Field	4.29	kG
Nominal betatron frequencies		
vertical, ν_v	5.57	
horizontal, ν_h	3.57	
Transverse Ring Acceptance		
horizontal, ε_H	40π	mm-mrad
vertical, ε_v	$20\ \pi$	mm-mrad
Longitudinal Ring Acceptance, $\Delta p/p$	±1%	
Beta functions in electron s.s.,		
β_v	40	m
β_H	25	m
Electron Cathode Potential, Vo	-111	kV
Electron Current, I_e	1-3	A
Electron Interaction Length	5	m
Electron Beam Radius	2.5	cm
Solenoid Guide Field, B_z	0.93	kG
Cooling Region Vacuum (at I_e=2 amp)	1×10^{-8}	Torr
Mean Ring Vacuum, I_e=0	1×10^{-10}	Torr
$\eta = 1/\gamma_t^2 - 1/\gamma^2 =$	0.60	

*Operated by Universities Research Association Inc., under contract with the U.S. Department of Energy.

The electron system produces a cold (1 eV transverse, 8×10^{-5} eV longitudinal) 0 to 6 A electron beam at 114 keV for cooling protons at 200 MeV. The electron cooling system is shown in Fig. 2. The electron beam is magnetically confined throughout the system by a 0.93 kG solenoidal field. Steering dipoles are located throughout the system. The 5 1-m solenoids in the interaction region were aligned to produce an effective transverse temperature of 0.12 eV. For optimum cooling, an alignment to within a few hundred microradians between the electron and proton beams was necessary.

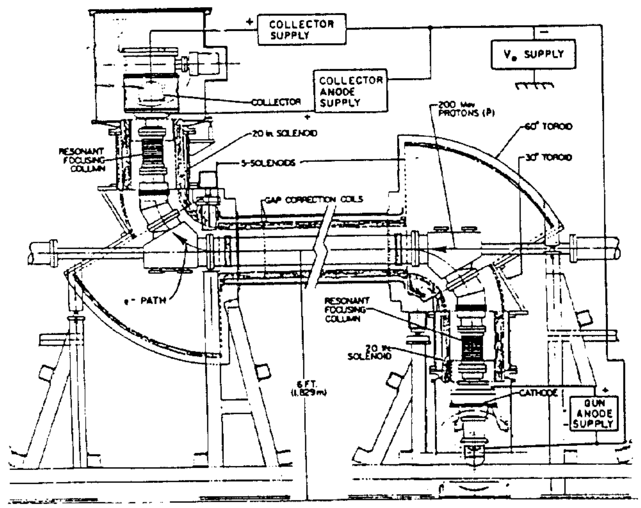

Fig. 2 Vertical cross section of Electron Cooling System.

A Pierce design is used for the electron gun which has an area convergence ratio of six. This causes an adiabatic increase in the electron transverse temperature from 0.12 eV to 1 eV. The collector is immersed in a magnetic field. The collector anode acts as a positive-ion trap and a suppressor for electrons backscattered from the collector. Collection inefficiencies (I_{loss}/I_{beam}) were a few parts in 10^4 at 114 kV and less than one part in 10^4 at cathode potentials of 50 kV.[10] Position electrodes located at the downstream end of the 5-m interaction region were used to measure the electron and proton beam positions. The position electrodes were also useful for adjusting the drift electrodes (segmented electrodes which surround the electron beam path to clear the beam of ions) by minimizing rf signals from the plasmas.

The cooling ring diagnostics were developed to operate with a very low intensity proton beam of 2×10^6 particles per pulse, 0.4uA. To observe the proton-beam momentum spread and intensity during cooling measurements, a slow-wave helical Schottky pickup[11] was used. Non-destructive profile monitors[12] were used to measure the proton beam size and position by position-sensitive counting of ions formed from collisions between the proton beam and residual gas in the vacuum chamber.

The rf system, besides being used for momentum stacking and accumulation, was a useful diagnostic for initially tuning the cooling system by cooling the proton beam into a bucket. RF harmonics of approximately equal height were observed up to 500 MHz due to the resultant very short bunch lengths of the electron-cooled proton beam. The rf was not used during cooling experiments because of heating effects caused by small mismatches between the rf frequency and the electron beam cathode potential.

Proton Beam Lifetime

Typical proton-beam lifetimes with the electron cooling system magnets off were 60 to 100 seconds. However, with 1 A of electron beam in the cooling system, detuned in energy so that there was no cooling effect, proton beam lifetimes were 5 to 10 seconds. If the electron beam was tuned in energy for cooling, proton beam lifetimes of over 4000 seconds were obtained. This lifetime was close to the lifetime estimated for single-scattering loss.

Longitudinal Cooling Rates and Equilibrium

The initial momentum spread of the injected beam was 3×10^{-3} ($\Delta p/p$, FWHM). An equilibrium momentum spread of 1×10^{-5} was reached after 4 seconds of cooling with 1 A of electron beam. A Schottky-harmonic frequency spectrum was a direct measurement of the momentum spread ($\Delta p/p = \eta^{-1}\ \Delta f/f$) since beam current was below the critical current at which coherent distortions of the Schottky signal would occur. The equilibrium momentum spread was determined by the 2V-360Hz and 5V-15Hz (peak-peak) ripple of the electron-beam cathode potential. The cathode supply also had slower 10-15V fluctuations which the proton beam's narrow momentum spread would coherently track, $\Delta f = e\ \Delta V f \eta/\beta^2 E$. The longitudinal cooling rate was in good agreement with the measured friction force.

Transverse Cooling Rates and Equilibrium

The transverse emittances were reduced by a factor of 25, depending upon the initial emittances, to $0.4\pi \times 10^{-6}$ m in less than 20 seconds. The equilibrium transverse emittances were determined by the electron beam transverse temperature and the beta functions in the cooling region. Much lower transverse emittances would have been possible by lowering the electron beam temperature by eliminating the converging gun geometry and by lowering the beta functions in the cooling region. The converging cathode design was chosen to allow the possibility of operating with extremely high (28 A) beam currents. The beta functions were chosen to match the initial velocity spread of the proton and electron beams to maximize the cooling rates. The initial and final velocity distributions of the proton-beam in the cooling region are shown in Fig. 3, together with the electron beam velocity distribution.

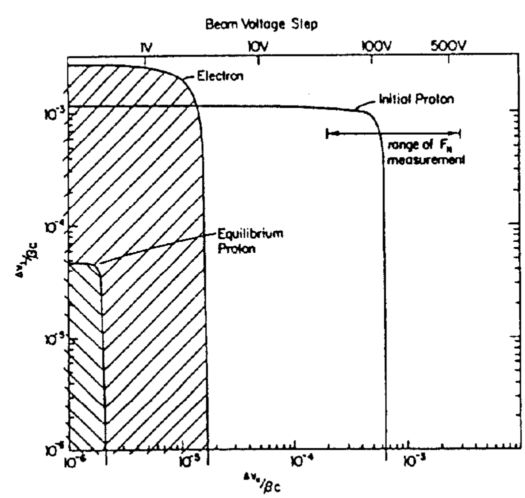

Fig. 3 Envelopes of initial and equilibrium velocity distributions.

Fig. 4 shows data on transverse cooling rates from the 200- and 114-MeV experiments. The 114-MeV experiments show evidence of a misalignment between the proton and electron beams, or a "hot" electron beam. The minimum observed proton transverse temperature for a 1-2A electron beam current was 0.6 eV. We observed no change in the proton transverse equilibrium as the proton-electron beam alignment was varied by $(M_p / M_e)^{1/2}$ times the betatron angle for a cooled proton beam.

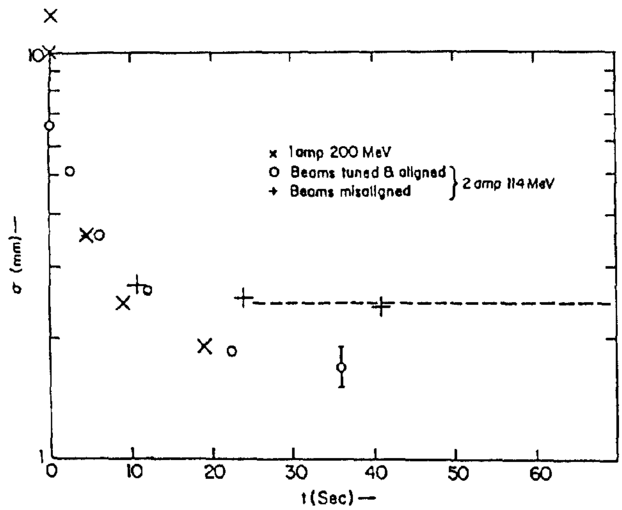

Fig. 4 Vertical proton-beam profile width as a function of time after injection.

Friction (Drag) Force Measurements

Friction force measurements were performed by stepping the electron beam energy and then monitoring the proton beam energy as it is "dragged" to its new equilibrium energy. Measurements were made for electron beam energy steps of 50 to 500 eV. The proton beam energy was monitored by viewing the real-time Schottky frequencies. The data is displayed in Fig. 5 and are scaled with respect to the electron density, the electron temperature, and γ to allow comparison with the results from other measurements. The un-magnetized theory predicts friction forces in good agreement with our data for a (typical) Coulomb log of 9.5.

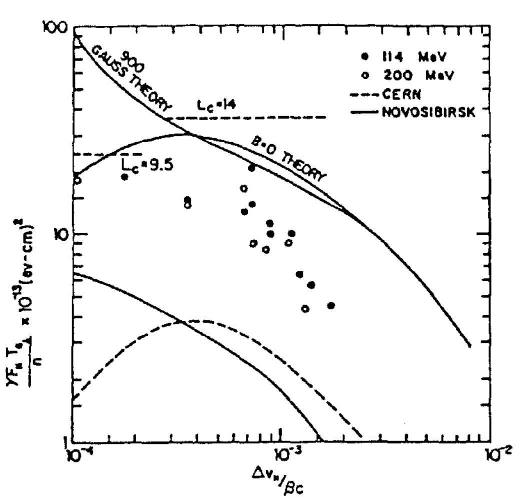

Fig. 5 Normalized longitudainal drag force in the rest frame.

Stacking Studies

The electron cooling ring was designed to allow injection of fresh (hot) beam without perturbing the cold stack at a higher energy, by using a pair of synchronous orbit kickers. The chromaticity was corrected to allow operation over a 2% momentum separation between the orbits. Several different accumulation schemes were attempted. Figure 6 shows the intensity of the stack during accumulation. In this scheme fresh protons were rf captured and accelerated to the stacking orbit, where they phase displaced the cooled stack. An intensity increase in the stack by a factor of 12 is shown and saturation is evident. The saturation apparently results from the anomalously low lifetime of the stack protons when they are phase displaced, thus momentarily not being cooled. Ways to circumvent this problem by continuously electron cooling the stack during accumulation are possible, but the measurements have not been completed.

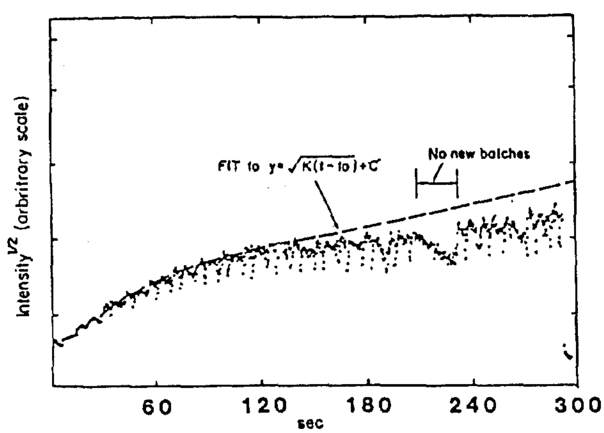

Fig. 6 Accumulation for beam injected every 5 sec.

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