RESULTS FROM ELECTRON COOLING EXPERIMENTS AT LEAR

A. Wolf[1], P. Dittner[2], C. Habfast,[3], L. Hütten, H. Poth, W. Schwab, B. Seligmann, J. Stein[4], M. Wörtge
Kernforschungszentrum Karlsruhe, Institut für Kernphysik
Postfach 3640, D-7500 Karlsruhe 1, West Germany

S. Baird, J. Bosser, M. Chanel, M. Girardini, H. Haseroth, C.E. Hill, P. Lefèvre, R. Ley,
D. Manglunki, D. Möhl, G. Molinari, A. Poncet, G. Tranquille, J.-L. Vallet
PS Division
CERN
CH-1211 Genève 23, Switzerland

Abstract

Electron cooling experiments at the CERN Low-Energy Antiproton Ring (LEAR) have been performed with protons at 49, 21, and 10 MeV. The experimental procedure and results concerning the equilibrium beam properties and the beam stability are presented. The applied diagnostic methods include the detection of hydrogen atoms recombining in the cooler and the observation of collective longitudinal beam noise spectra distinctly different from usual Schottky spectra. The importance of magnetization effects for the cooling force is confirmed.

Introduction

Phase-space cooling in the Low-Energy Antiproton Ring LEAR at CERN is presently achieved by a stochastic cooling system working at discrete energies between 180 and 20 MeV in normal operation. The cooling times are on the order of minutes and antiproton beams with a relative momentum spread of about $\pm 1 \times 10^{-3}$ and emittances around 7 π mm mrad are obtained [1]. By introducing electron cooling at LEAR one expects the additional possibility of applying much faster phase-space cooling and reaching a higher phase-space density. The test runs of the electron cooler constitute the first experience with very cold, intense low-energy beams at this machine.

Strong phase-space compression, as achieved by electron cooling, offers new possibilities for experiments in nuclear, atomic, and elementary particle physics [2]. At LEAR [3], it opens up the way towards the efficient operation of an internal target at antiproton energies below 70 MeV [4] and other experiments which require a stored antiproton beam of low emittance [5, 6]. Furthermore, one can envisage to achieve efficient electron cooling also at very low energies, possibly down to 1 MeV, so that the deceleration of antiprotons in LEAR is facilitated. Finally, a higher phase-space density could be useful for experiments using extracted low-energy antiproton beams from LEAR [7, 8].

The electron cooling device, installed in LEAR in 1987, has been developed and built by a collaboration between CERN and Kernforschungszentrum Karlsruhe (KfK), partly based on experience and hardware from the CERN Initial Cooling Experiment (ICE) [9]. Details concerning the layout, parameters, and laboratory tests of the electron beam device have been presented elsewhere [10, 11]. First results of electron cooling experiments in November 1987 with protons at 49 and 21 MeV are presented elsewhere [12]. The present contribution mainly reports about the measurements of March 1988 at 49 and 10 MeV.

Instrumentation and Main Parameters

In the electron cooling experiments the standard (anti)proton-beam diagnostic equipment of LEAR is used, in particular the longitudinal and transverse Schottky noise pick-ups, the electrostatic position pick-ups for orbit measurements, and the beam current transformer. Additional diagnostic equipment is installed for analyzing the neutral hydrogen beam emerging from the electron cooler because of electron-proton recombination. The atoms leave the ring tangentially at the main bending dipole downstream of the cooler. A multiwire proportional chamber (MWPC) and plastic scintillation counters, set up closely behind a 50 μm stainless steel vacuum window, are used to measure profile and intensity of this hydrogen beam. Proton beam handling includes orbit correction, beam heating by noise voltages applied to longitudinal and transverse kickers, excitation of coherent transverse oscillations, and bunching by a radiofrequency (RF) cavity.

The basic parameters of LEAR and of the electron cooler during the test runs are listed in Table 1. The control of the electron cooler mainly consists of setting the acceleration voltage, and of fine tuning the electron beam direction in the overlap region with the proton beam.

Table 1: Main parameters of LEAR and the electron cooler

Proton energy	49.4	21.0	9.89	MeV
Proton momentum (p)	309	200	137	MeV/c
Revolution frequency (f)	1.192	0.795	0.550	MHz
$(\Delta f/f)/(\Delta p/p) = \eta$	0.95	1.00	1.02	
Horizontal betatron tune (Q_x)		2.305		
Vertical betatron tune (Q_z)		2.730		
Lattice functions at cooler:				
Horizontal beta		1.9		m
Vertical beta		5.3		m
Dispersion		3.6		m
Electron acceleration voltage	27.7	11.8	5.50	keV
Electron current	2.6	0.7	0.23	A
Electron beam radius		2.54		cm

Vacuum Conditions

The electron cooler has been designed for presenting a minimal load to the LEAR vacuum system. The vacuum has been monitored carefully during the March test run at the operating energies of 10 MeV and 49 MeV, comparing to a reference situation before turning on the cooler (vacuum gauge readings between 3×10^{-12} and 1×10^{-11} Torr with a residual gas composition of 90% H_2). At 10 MeV, no pressure rise was seen on any of the vacuum gauges distributed over the ring. During continuous operation at 49 MeV, a pressure rise of 4×10^{-11} Torr was seen on only one gauge, situated about 1 m downstream of the cooler. A residual gas analysis performed close to the cooler in LEAR and in an earlier laboratory test [11] indicates that the gas released by the cooler is mainly CO. The average nitrogen equivalent pressure in LEAR, relevant for Coulomb scattering on the residual gas, is hence estimated to 2×10^{-12} Torr during 49 MeV operation and to less than 1×10^{-12} Torr at 10 MeV and lower energies. For comparison, the nitrogen equivalent pressure amounted to about 0.5×10^{-12} Torr before the run.

Initial Cooling

Electron cooling of the proton beam is observed immediately in the longitudinal Schottky noise spectrum. A series of such spectra recorded after the proton injection (Fig. 1) shows the reduction of the proton beam momentum spread from 6×10^{-3} (full width at base) to a value below the resolution of the spectral analyzer (less than 3×10^{-4}) within a time of 3 to 5 s. The time needed to cool the beam down depends on the fine tuning of the electron velocity. The proton beam average momentum can be moved to any value within the capture range of electron cooling by adjusting the electron acceleration voltage. The interpretation of the longitudinal noise spectrum of the cooled beam needs a careful analysis, as will be discussed below.

Equilibrium Beam Properties at 49 MeV

Transverse Diagnostics: Neutral Hydrogen Beam

Fast hydrogen atoms are observed at a count rate of typically some 10^3 s^{-1} as soon as the 49 MeV proton beam has been cooled down. With the measured electron and proton beam currents, a recombination coefficient $\alpha = (2.0 \pm 0.1) \times 10^{-12}$ s^{-1}cm^3 is deduced from the count rate. Assuming radiative recombination of electrons and protons [13] and an electron velocity distribution with vanishing longitudinal velocity spread,

---
[1] now at Heidelberg University
[2] Visitor from Oak Ridge National Laboratory
[3] now at DESY, Hamburg
[4] Visitor from KFA Jülich

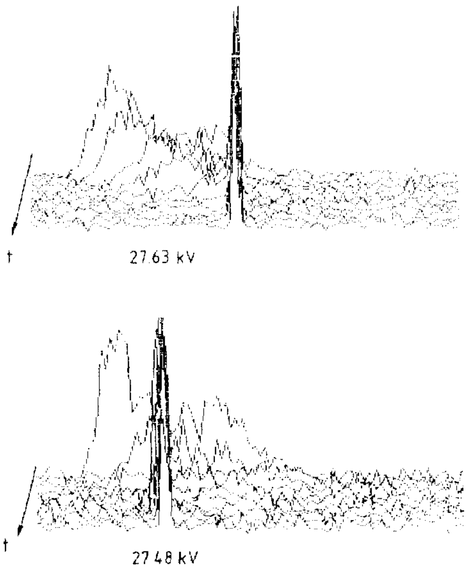

Fig. 1: Beam noise spectra observed on a longitudinal pick-up electrode during cooling down the proton beam injected from the Linac at 49 MeV. The time interval between scans is 1 s. Values of the electron acceleration voltage are given. The initial shape of the momentum distribution corresponds to the Linac beam in the LEAR acceptance.

the measured recombination coefficient indicates a transverse electron temperature of (0.24 ± 0.03) eV [12]. The presence of an isotropic velocity distribution is excluded by the experimental result since, with this assumption, one would calculate an electron temperature below the cathode temperature of 0.12 eV.

The width of the neutral hydrogen beam profile yields the divergence of the cooled proton beam. In the March run, the profiles were observed by a MWPC with a resolution of 1 mm. They represent an average over 1 s according to the integration time of the MWPC. The standard deviations of the profiles, observed at beam intensities up to 3×10^9 stored protons, indicate rms proton angles of $\theta_x = 0.4$ mrad and $\theta_z = 0.3$ mrad. for the horizontal (x) and vertical (z) direction. The corresponding beam emittances (defined for 90% of the beam particles and calculated from the lattice function values at the cooler) are $E_x = 1.3\ \pi$ mm mrad and $E_z = 1.8\ \pi$ mm mrad. For the rms beam size in horizontal (vertical) direction one obtains 0.8 mm (1.5 mm). The transverse proton beam temperature of 12 to 16 eV, obtained from the divergence, is much higher than expected for a thermal equilibrium with the electron beam. Variations of the widths, correlated to the instabilities discussed below, were seen in the hydrogen profiles.

Longitudinal Diagnostics: Collective Beam Noise

Scanned with a high spectral resolution, the longitudinal Schottky spectrum of a cooled proton beam reveals the shape shown in Fig. 2. The peak splitting increases with the stored proton current which is measured by the current transformer. When the acceleration voltage of the electron cooler is modulated strongly (up to ±5 kV at 4 kHz) the spectrum becomes wider, the splitting disappears and, for a constant proton current, the integrated intensity of the Schottky spectrum increases by a big factor (≈ 5). These observations indicate that the Schottky noise is suppressed and its spectrum deformed below a critical momentum spread. This behaviour is in fact expected [14] owing to the electromagnetic interaction among the protons. For a cold intense beam, the spectral density of the charge fluctuations is concentrated in sidebands of the revolution frequency, whose position is determined by the characteristic frequency of the collective proton motion. Collective longitudinal beam noise has been observed previously in electron cooling experiments at Novosibirsk [15], where mainly the integrated intensity has been analyzed. With the results obtained at LEAR, the spectral shape of the noise can also be investigated in detail.

Spectra at varying proton current have been fitted by theoretical curves, taking into account the collective effects [14]. From the fit parameters, the momentum spread has been determined. As a function of the proton current, measured independently, the results are plotted in Fig. 3. The relative momentum spread around 1.4×10^{-5} (FWHM) derived at less than 3×10^8 stored protons corresponds to a longitudinal temperature

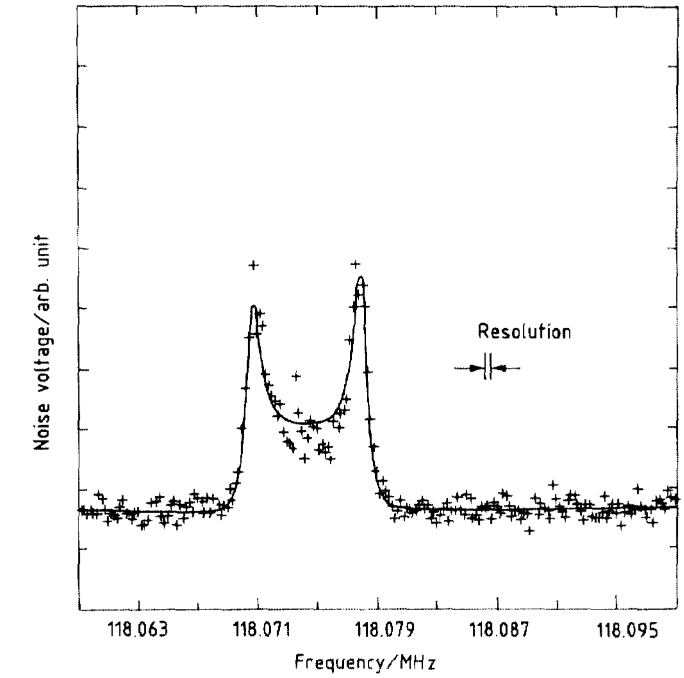

Fig. 2: Longitudinal beam noise spectrum of 2×10^9 stored protons at 49 MeV. Momentum spread for the fitted curve: 2×10^{-5} FWHM.

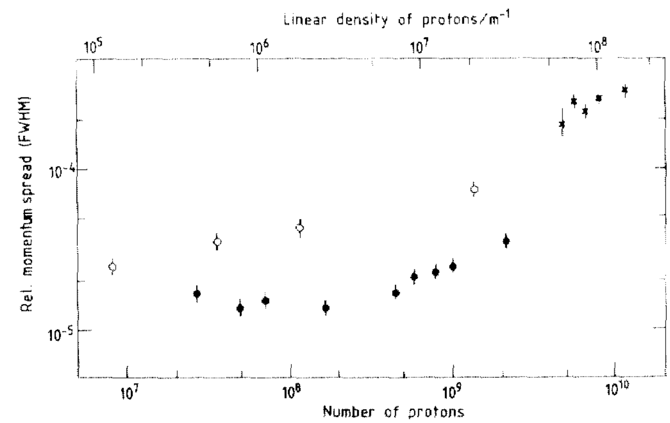

Fig. 3: Equilibrium momentum spread as a function of the longitudinal density of stored protons and their total number (for unbunched beams). Full (open) circles are results for unbunched beams at 49 MeV (10 MeV) obtained from collective beam noise spectra. Crosses are results for a 49 MeV bunched beam.

of only about 0.003 eV. Like in the experiments at Novosibirsk [15], this result lies much below the *transverse* temperatures of both the electron and the proton beam.

Proton Beam Stability

Cooled beams of up to 3×10^9 protons were stored in LEAR with an e-folding lifetime between 1 and 3 h. At more than 10^9 stored protons, the beam lifetime depends on the proton momentum spread and on the chromaticity $\Delta Q/\Delta p$ adjusted in LEAR. When the chromaticity is suppressed using sextupole corrections, lifetimes of only some minutes are observed at a low momentum spread. By increasing the relative momentum spread of the proton beam to more than 7×10^{-4} (FWHM) with the help of noise (applied to a longitudinal kicker while electron cooling is active) or by adjusting a finite chromaticity in LEAR (≈ 0.5 in both transverse directions), the lifetime is increased to more than 1 h.

Periodic blow-ups – apparently due to a coherent horizontal instability of the coasting beam – were clearly observed in the March run. While the transverse noise spectra and the hydrogen beam profile were observed, the beam emittance was seen to blow up rapidly (within < 1 ms) from an equilibrium value to 10 to 20 π mm mrad (10^9 stored protons, 49 MeV). Since electron cooling was continuously active, the low equilibrium emittance was reached again very shortly afterwards ($\approx$ 100 ms). The magnitude and the repetition rate of this instability (typically 4 to 30 min^{-1}) depend on the chromaticity, on the longitudinal and transverse equilibrium emittance, and on the beam intensity. The periodic emittance blow-up is also observed in situations where the beam lifetime is long. Further work is needed to explain the origin of this instability which in some respects resembles the *hiccups* observed [16] in the CERN Antiproton Accumulator. Since the instability might be caused by electrons of the residual gas, trapped by the proton beam, it is of interest to study the effect of clearing electrodes and to find out if it also appears in cold antiproton beams.

Bunched Proton Beam Cooling

By electron cooling of a bunched proton beam at LEAR, very short bunch lengths down to 2 m (FWHM) are obtained at RF peak voltages below 1 kV. The momentum spread of the cooled bunches can be calculated from the bunch length and the RF amplitude. The results are included in Fig. 3, and shown as a function of the coasting beam intensity (number of stored protons) that would produce the linear charge density inside the bunches. It can be seen that the bunched beam momentum spread is considerably higher than expected from an extrapolation of the coasting beam results. The hiccups described above were less violent in a bunched beam.

Cooling at Lower Energies

Electron Cooling of a Decelerated Beam

A particular advantage of electron cooling is its potential to provide efficient phase-space cooling in the entire low-energy operating range of LEAR. In order to use this possibility, the electron cooler must be well integrated in the LEAR control system, mainly for synchronizing the magnetic field of the cooler with the required correction fields in LEAR. Some experience has been gained in this respect by trying out proton deceleration to 21 MeV and subsequent electron cooling. During the injection and deceleration cycle, the cooler was operated at a very low magnetic field and a 1 keV, 7 mA electron beam. After deceleration, the solenoid field of the cooler, the electron energy, and the correction magnets in LEAR were changed manually in a few steps until velocity matching was reached and cooling was observed. In the short time available for these tests, it could only be verified qualitatively that the cooling times and the equilibrium beam properties were similar to those observed at 49 MeV. A big fraction of the injected beam was lost during the manipulations before cooling started. Improvements to the LEAR control system are in progress, which will allow the cooler and the required correction fields to be turned on smoothly at any LEAR energy, thus avoiding such losses.

Cooling Tests at 10 MeV

For low-energy cooling tests at a fixed energy, 10 MeV protons were injected directly from Linac I into LEAR. Constant corrections to the cooler magnetic fields were applied as for the 49 MeV runs. At 10 MeV, up to 10^9 protons were cooled down and stored for many minutes. The cooled beam again generates collective longitudinal noise spectra from the shape of which the relative momentum spread was determined as described above. The results as a function of beam intensity are included in Fig. 3. The transverse emittances, given for 90% limits and determined from the hydrogen beam profile, are E_x = 13 π mm mrad and E_z = 18 π mm mrad. Hiccups leading to higher emittances were again observed for intensities above a few 10^8 stored protons.

Magnetic Cooling Force Measurement

At the low proton beam energy of 10 MeV, small longitudinal velocity differences between electrons and protons down to 5% of the transverse electron velocity spread can be applied under well controlled conditions. This offers the possibility to measure the friction force on the protons in the electron beam at small relative velocities, where the magnetic field in the cooler is expected to enhance this force [17]. The friction force is determined by observing the time dependence of the average revolution frequency of the cold beam in the longitudinal noise spectrum and by changing the electron beam energies in small steps of 5 to 100 eV. At low relative velocities, a friction force is measured which is 3 times higher than

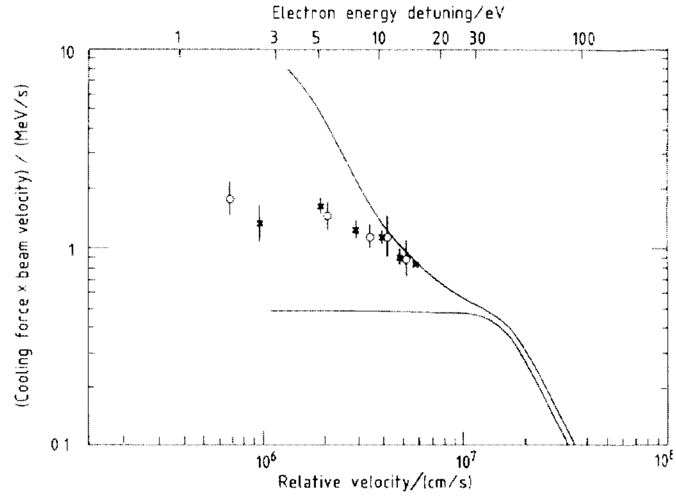

Fig. 4: Results of longitudinal cooling force measurements at 10 MeV, and theoretical cooling forces without (lower curve) and with magnetization (upper curve).

expected without magnetic field effects (Fig. 4). At an energy detuning below 10 eV, the experimental result lies below the theoretical 'magnetized' friction force, possibly because of the transverse proton beam divergence present during the experiment. The importance of magnetic-field effects for electron cooling at low energies is clearly demonstrated by this measurement.

Conclusion

The electron cooling tests with protons at LEAR have shown that fast phase-space cooling can be achieved over a wide energy range, according to the expectations, and that stored beams with a very low momentum spread and with small emittances are obtained. Unusual collective longitudinal noise spectra of these cold beams are observed and have been analyzed in order to determine the momentum spread. Some 10^9 protons can be stored in LEAR with continuous electron cooling in the present configuration. A transverse instability (hiccup) is observed, which can be influenced by changing the momentum spread of the beam or the chromaticity, and which requires further investigations with proton and antiproton beams. The results of these tests represent an important step towards use of electron cooling at LEAR.

References

[1] P. Lefèvre, in *Proc. 4th LEAR Workshop*, Villars-sur-Ollon, 1987 (Chur: Harwood Academic Publ., 1988), pp. 19 – 29.

[2] G.I. Budker and A.N. Skrinsky, *Sov. Phys. Usp.*, vol. 21, pp. 277 – 296, 1978.

[3] L. Hütten *et al.*, *Proc. Workshop on Physics at LEAR with Low Energy Cooled Antiprotons*, Erice, 1982 (New York: Plenum, 1984), pp. 605 – 618.

[4] E. Steffens *et al.*, in *Proc. 3rd LEAR Workshop*, Tignes, 1985 (Gif-sur-Yvette: Ed. Frontières, 1985), pp. 245 – 252.

[5] U. Gastaldi and D. Möhl, in same Proc. as ref. [3], pp. 649 – 657.

[6] R.S. Conti *et al.*, in same Proc. as ref. [1], pp. 643 – 646.

[7] M. de Saint Simon *et al.*, in same Proc. as ref. [1], pp. 633 – 636.

[8] G. Torelli, in same Proc. as ref. [1], pp. 629 – 632.

[9] M. Bell *et al.*, *Nucl. Instr. Meth.* vol. 190, pp. 237 – 288, 1981.

[10] H. Poth *et al.*, in same Proc. as ref. [1], pp. 121 – 130.

[11] C. Habfast *et al.*, "The LEAR electron cooler: recent improvements and tests," *Physica Scripta*, 1988 (in print).

[12] H. Poth *et al.*, "First results of electron cooling experiments at LEAR," in preparation for *Z. Phys. A*.

[13] M. Bell and J.S. Bell, *Part. Acc.*, vol. 12, pp. 49 – 52, 1982.

[14] V.V. Parkhomchuk and D.V. Pestrikov, *Sov. Phys. Tech. Phys.*, vol. 25, pp. 818 – 822, 1980.

[15] E.N. Dement'ev, *et al.*, *Sov. Phys. Tech. Phys.*, vol. 25, pp. 1001 – 1004 , 1980.

[16] E. Jones *et al.*, *IEEE Trans. Nucl. Sci.*, vol. NS – 32, pp. 2218 – 2220 , 1985.

[17] Ya.S. Derbenev and A.N. Skrinsky, *Part. Acc.*, vol. 8, pp. 235 – 243, 1978.