ELECTRON COOLING OF STORED IONS

Andreas Wolf
Kernforschungszentrum Karlsruhe, Institut für Kernphysik,

ABSTRACT
The experimental conditions of electron cooling in storage rings with magnetically confined electron beams are discussed. Particular attention is paid to 'fast' electron cooling, which will be important for low-energy ion storage rings. Measurements of cooling rates and of equilibrium ion beam temperatures are reviewed. A short report is given on the recent development work for electron cooling at the CERN Low-Energy Antiproton Ring (LEAR), and on related electron beam diagnostic experiments. Conclusions are drawn in view of electron cooling at future ion storage rings.

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1. INTRODUCTION

Since some years electron cooling [1] has been recognized as an important component of ion storage rings which are currently being designed or are under construction [2, 3]. The main advantage of electron cooling compared with the other confirmed phase-space cooling method for ions - stochastic cooling - is to provide particularly short cooling times also in dense, cold beams [4]. Since the original proposal by Budker, our knowledge of electron cooling of ion beams has been improved through the repeated interaction of theoretical predictions and experimental results [5, 6]. Regarding the basic process of collisional energy exchange between electron and ion beams, the present status of the theory has been reviewed by Sørensen [7].

In this paper we discuss aspects of the electron cooling hardware, in particular its influence on the efficiency of phase-space cooling. The emphasis is on problems that are interesting in view of the new ion storage rings. As the range of ion energies envisaged in the different projects extends over almost four decades (from 100 keV/amu to 600 MeV/amu), it seems important to consider the variation of the experimental conditions with the beam velocity. One of the main aspects in the discussion of experimental results obtained so far with stored proton beams (Section 3) is the evidence for 'fast' cooling [8, 9]. This originally unexpected effect, found in some of the electron cooling tests, provides a basis for optimistic predictions of the cooling performance at low energy.

After the initial cooling experiments, a first electron cooling device for routine operation was developed for the Low-Energy Antiproton Ring (LEAR) at CERN [10, 11]. The measured operating parameters of this device and the results from electron beam studies using non-de-
structive diagnostics are given in Section 4. The paper concludes with an outlook on further studies of electron cooling at the new ion storage rings.

2. THE ELECTRON BEAM DEVICE AND ITS IMPLICATIONS FOR THE COOLING PROCESS

2.1 Basic considerations

In the electron cooling set-up, the ion beam in the storage ring is overlapped on part of the ring circumference by a beam of electrons moving at a velocity matched to that of the circulating ions ($v_e = \beta c$). Only a single-pass electron beam will be considered here. This beam is generated in an electron gun, drifts along the cooling region, and terminates at a collector (Fig. 1).

From the principles of electron cooling [7] it is known that the rate of energy exchange is proportional to the electron density and to the length of the cooling section relative to the storage ring circumference. Furthermore, electron cooling is most efficient at the lowest possible velocity deviations between electrons and ions. In order to estimate the cooling efficiency and the minimal ion beam temperature which can be reached in thermal equilibrium, the effective electron temperature of electron cooling devices will be considered. This can be calculated from the velocity spread of the electrons close to the nominal ion orbit in the cooling device.

Both microscopic and macroscopic processes give rise to velocity deviations in the electron beam. The microscopic processes result in a thermal velocity distribution in the strict sense. The main contribution to thermal motion in the electron beam comes from the cathode; a much smaller influence is expected in a single-pass beam from colli-
sions of the electrons with the residual gas or with the stored ions. Interaction among the electrons themselves, redistributing the thermal energy in the electron beam between the degrees of freedom, deserves some attention (see Subsection 2.4).

Several macroscopic sources of velocity deviations in the electron beam will be discussed in the following. They are mainly related to the external fields applied for acceleration and transport of the electron beam, and to the electron space-charge field.

2.2 Magnetically confined, cooling electron beams

Clearly the requirements of a high electron density and, at the same time, small velocity deviations over a long straight beam section are contradictory. The beam transport method which seems to offer the best compromise between high current density and low velocity deviations [12] is to continuously focus and guide the electrons by means of a longitudinal magnetic field. The magnetic field must be coaxial with the accelerating field in the electron gun, and its strength is made high enough for the Lorentz force to far exceed the space-charge forces in the drifting beam. Using the plasma frequency $\omega_{pl}$ and the cyclotron frequency $\omega_c$ of the electrons in the beam rest frame, this condition can be expressed as

$$\frac{\omega_c}{\omega_{pl}} \gg 1.$$ (1)

In electron beam technology, the situation is known as 'immersed flow' [13]. Corresponding to their transverse energy, the electrons perform a helical motion with a radius of about 10 $\mu$m at the typical magnetic field strength of 0.05 T. The pitch of the helix,

$$\lambda_c = \frac{2\pi R c}{\omega_c}$$ (2)
with \( \gamma = 1/\sqrt{1 - \beta^2} \), usually amounts to some centimetres. By applying an adiabatic change of the field direction (radius of curvature \( \gg \lambda_e \)), the electrons are merged with the ion beam and bent out of it again in toroidal field sections at both ends of the cooling region (see Fig. 1).

Electron guns which generate beams with low transverse energy in a magnetic guiding field are described in the literature [14, 15]. Computer programs for electron trajectory calculations, which also take into account space-charge, are a valuable help in the designing of such guns [16, 17]. The motion of the electrons in the plane perpendicular to the magnetic field lines can be regarded as harmonic oscillations driven by transverse forces. Even under the influence of substantial transverse fields, the transverse energy may be kept low if the time dependence of the fields seen by the moving electrons is made resonant or adiabatic with respect to the cyclotron motion. With careful design and alignment this offers the possibility to reduce the transverse electron energy to the value given by the starting conditions at the cathode. At least in the following estimates, where a precise value of the transverse energy is not required, one can therefore assume that the transverse electron velocities in the cooling section have a thermal distribution determined by the cathode temperature (\( \approx 1300 \) K for thermo-ionic cathodes, corresponding to \( 0.1 \) eV of thermal energy per degree of freedom).

For a part of the collision processes between electrons and ions, the influence of the transverse electron motion on the energy exchange is strongly suppressed by the presence of the magnetic field [7]. This is the case for those collisions in which the interaction of the particles is adiabatic with respect to the electron cyclotron motion. The fraction of adiabatic collisions is important once the magnetic field
satisfies the confinement condition, Eq. (1). [In fact, the number of such collisions is approximately proportional to \( \ln(\omega_c/\omega_p) \).] Hence, in a magnetically confined beam, ions frequently interact with magnetized electrons whose effective temperature results only from the velocity spread of the guiding centres associated with the cyclotron motion.

This 'freezing' of transverse electron motion in the magnetic guiding field is the origin of the 'fast' electron cooling effect. Since the longitudinal velocity spread in the electron beam rest frame is reduced by the acceleration, the effective temperature of the magnetized electrons can be orders of magnitude lower than the cathode temperature. Numerical values of the effective temperature, which determine the possibilities and limits of 'fast' electron cooling, will be considered in Subsection 2.4.

Inside an ion storage ring the electron cooler with its magnetically confined electron beam can be regarded as a self-contained unit which has only little influence on the ion optics, provided the guiding field for the electrons is not too strong and does not occupy a large fraction of the storage ring. Effects which can be corrected by adjusting other ring elements are the orbit bump in the toroid magnets and the focusing or defocusing (depending on the sign of charge of the ions) by electron beam space-charge. The solenoid field leads to a coupling of horizontal and vertical ion motion, and may require additional corrections especially when the nuclear polarization of stored ions is to be maintained during cooling. Storage rings in which the ion beam is accompanied by a cooling electron beam over almost the whole circumference, and in which the cooling device strongly influences the ion optics, are considered for antiproton accumulation [18].
2.3 Electron beam space-charge

2.3.1 Achievable currents

The basic parameter which describes the space-charge influence in
the electron beam [13] is the 'perveance'

$$P = \frac{I}{U^{3/2}},$$

(3)

where $I$ is the beam current and $U$ the potential with respect to the ca-
thode fixed by the condition of velocity matching. (Let us recall that
the electron beam energy is roughly a factor of 2000 lower than the ion
energy per amu.) At the cathode, the space-charge itself limits the
emission so that the electron current is proportional to power $3/2$ of
the acceleration voltage; the geometry of an electron gun and the re-
lative potentials on its electrodes define the perveance of the produced
electron beam. The perveance can only be chosen below an upper limit
at which beams become unstable. Without space-charge compensation by
positive ions, the limiting perveance is of order $10^{-5}$ A/V$^{3/2}$. There-
fore, electron currents available for beam cooling can reach several A
above 50 MeV/amu but, for example, only some $10^{-2}$ A at 1 MeV/amu. On
the other hand, assuming a constant perveance, the influence of space-
charge on the geometry of electron trajectories is independent of the
beam velocity, at least in non-relativistic approximation ($\gamma \approx 1$).

The high-current electron beams for cooling at higher energies can
be made available, with relatively small power dissipation in the cool-
ing device, by decelerating the electrons before they reach the collec-
tor surface (Fig. 2). Depending on the collector geometry, the rela-
tive current loss by electrons re-emitted from the collector can be
minimized to $\Delta I/I \approx 10^{-1}$ to $10^{-4}$. The required positive bias $U_{co}$ of
the collector versus the cathode depends on the beam current according
to the 'collector perveance' [19], as described by Eq. (3) with $U = U_{co}$. Since the perveance of the collector can be much higher than that of the drifting beam, the collector voltage $U_{co}$ has to be only a small fraction of the acceleration voltage.

Deceleration in the collector may become dispensable at low energies [20] where high currents are already excluded by space-charge. On the other hand, the power dissipation in the cooling device, even with deceleration at the collector, represents a serious limit to available electron currents above some 100 keV electron energy.

2.3.2 Systematic velocity deviations

An electron beam confined by a magnetic field is essentially uniform along its direction of propagation. In the radial direction, however, the electric potential and hence the electron energy increase towards the outside of the beam because of the space-charge. For calculating the space-charge field it seems most reasonable to start from the assumption of a radially constant current density; with any velocity variation across the beam, the charge density itself will depend, at least slightly, on the radial position.

The relative importance of the space-charge potential is expressed by the parameter

$$\alpha = \sqrt{\frac{2\varepsilon^2}{(\varepsilon + 1)}} \frac{P}{4\pi \varepsilon_0 \sqrt{(2e/m)}}.$$  \hspace{1cm} (4)

The reference perveance in the second brackets, calculated from the charge $e$ and the mass $m$ of the electrons, has a numerical value of $6.60 \times 10^{-2}$ A/V$^{3/2}$. Using the space-charge parameter $\alpha$, the radial variation of the electric potential $\phi(r)$ in the beam of radius $R$ can be represented by the series [21]

$$\phi(r)/U_0 = 1 + \alpha(r/R)^2 - \frac{1}{2} \alpha^2 (r/R)^4 + \ldots.$$ \hspace{1cm} (5)
By definition, the perveance $P$ is calculated from the potential $U_0$ on the beam axis. The term of first order in $\alpha$ describes the potential of a uniformly charged cylindrical rod. At any finite value of $\alpha$ the series provides a possibility to determine deviations from the first-order potential which is frequently used in estimates.

In order to avoid excessive potential variations, electron cooling devices are generally operated at $\alpha < 0.1$, i.e. $P < 6 \, \mu A / V^{3/2}$. It is then possible, with at most 10% inaccuracy, to neglect higher-order terms in Eq. (5). In this approximation, the relative deviation of longitudinal velocities across the beam is

$$\left( \frac{\Delta v_\parallel / v_\parallel}{v_\parallel} \right)_r = \left[ \gamma (\gamma + 1) \right]^{-1} \frac{\alpha r^2 / R^2}{v_\parallel} \approx \frac{1}{2} \frac{\alpha r^2 / R^2}{v_\parallel} . \quad (6)$$

At the surface of the beam, the velocity deviation is about $5 \times 10^{-3}$ for the typical perveance $P = 0.6 \, \mu A / V^{3/2}$.

Associated with the space-charge potential is a radial electric field increasing linearly with the radial position. Directed perpendicularly to the magnetic field and to the beam velocity, this electric field leads to a rotational $E \times B$ drift motion around the centre of the electron beam. To lowest order, the transverse velocity relative to the beam velocity $v_\parallel$ is given as a function of radial position by

$$\left( \frac{v_\perp / v_\parallel}{v_\parallel} \right)_r = \left[ \gamma (\gamma + 1) \right]^{-1} \frac{\alpha \lambda_c r / (\pi R^2)}{v_\parallel} \approx \frac{\alpha \lambda_c r / (2\pi R^2)}{v_\parallel} ; \quad (7)$$

it decreases as the magnetic field increases. The relative error of this expression is of order $(\omega / \omega_c)^2$. The confinement condition given in Eq. (1) implies that the angular velocity of the drift motion is small compared to $\omega_c$. The helical pitch $\lambda_c$, being an invariant like the perveance $P$, has been chosen to describe the strength of the magnetic field. This expresses the influence of the magnetic field on the electron trajectories independently of the beam velocity. Basically,
the electron cooling device can be operated at constant $\lambda_c$ so that lower magnetic fields are required at lower beam energies, which reduces the influence of the electron cooler on the ion optics of the storage ring.

2.3.3 Space-charge influence on the cooling process

As a consequence of electron beam space-charge, the velocity of an ion in the electron rest frame depends not only on its trajectory angles and momentum deviation but also on its position with respect to the electron beam axis. This tends to reduce the cooling rate in situations where the cooling force decreases with the increase of ion rest-frame velocities, in particular during cooling down towards an equilibrium state. The increase of rest-frame velocities, and the corresponding reduction of cooling rates due to space-charge, will be particularly pronounced if the lattice functions $\beta_x$, $\beta_z$ and the dispersion $D$ assume large values at the cooling device. In particular, we shall consider the transverse velocities described by Eq. (7) ($E \times B$ rotational drift), which increase linearly with the radial position and dominate over the longitudinal deviations for relatively cold ion beams close to the electron beam axis. The relative velocity deviations of the electrons over the ion beam of size

$$\langle x \rangle = \langle x' \rangle \beta_x$$

(8)

can be kept smaller than its divergence $\langle x' \rangle$ provided [see Eq. (7)]

$$\lambda_c < 2\pi R^2/(\alpha \beta_x^3) .$$

(9)

This requires a magnetic field strength increasing linearly with $\beta_x$.

Taking typical values ($\beta_x = 6 \text{ m, } \alpha = 10^{-2}$), we obtain $\lambda_c < 2R$. In order to keep the influence of the solenoid on the ion optics low, it
seems reasonable to make the field strength just as high as necessary to suppress the influence of the $E \times B$ drift on the cooling efficiency.

For the longitudinal velocity deviations [Eq. (6)], a similar comparison with the ion velocity spread can be made. Assuming a hot ion beam which extends over the whole electron beam cross-section, one finds that the influence of the space-charge velocity profile on the cooling efficiency is suppressed if none of the lattice-function values exceeds $2R/a \approx 5 \text{ m for } a = 10^{-2}$.

Because of space-charge, the longitudinal electron velocity is also influenced by the dimensions and the shape of the surrounding beam pipe. This can contribute to the effective electron temperature, as one easily estimates for a cylindrical tube in which the electron beam is centred. The on-axis potential $U_o$ is then related to the acceleration voltage $U_{ca}$ (the negative cathode voltage in the case of a grounded beam pipe) by

$$q = \frac{U_{ca}}{U_o} = 1 + \alpha [1 + 2 \ln(a/R)] . \quad (10)$$

A change $\Delta a$ in the tube radius $a$ leads to a longitudinal velocity variation

$$(\Delta v_l/v_o)_a \approx \frac{1}{2} \Delta q \approx 2\alpha \Delta a/a , \quad (11)$$

so that the longitudinal velocity is no longer uniform along the beam. With typical parameters ($a = 70 \text{ mm, } \alpha = 10^{-2}$), a change in radius of only $1 \text{ mm}$ has the same effect as changing the acceleration voltage by $3 \times 10^{-4}$. This suggests that, along the cooling region, the distance between the electron beam and the surrounding tube should not vary by more than $1 \text{ mm}$ if one wants to keep systematic variations of the longitudinal velocity below $10^{-4}$ on the axis.
2.4 Effective electron temperatures

The effective rest-frame velocity spread of the electrons, due to different sources, will now be discussed as a function of the ion beam energy (Fig. 3). Resuming the discussion started in Subsection 2.2, the effective temperature seen by ions during electron cooling in a magnetic field is basically determined by the longitudinal temperature in the electron beam rest frame. However, it can be increased by fluctuations of external fields which lead to additional longitudinal or transverse velocity spread in the motion of the guiding centres of the magnetized electrons relative to the ions. Such fluctuations can occur in space, i.e. along the ion beam in the cooler, or in time. The usual sources of longitudinal velocity spread are the acceleration voltage noise or an irregular electrostatic boundary around the electron beam. A transverse velocity spread in the motion of the guiding centres relative to the ions can, in particular, be caused by slow variations of the magnetic field direction along the cooling section.

The longitudinal velocity spread obtained after acceleration to the beam velocity \( v_b \), disregarding any relaxation processes within the electron beam, can be calculated from the energy spread of the electrons at the cathode. This yields the lowest possible longitudinal electron temperature

\[
\frac{1}{4}(kT_e) = \frac{1}{4}(eU_0(\gamma + 1)),
\]

which is shown in Fig. 3 and assumes values far below 1 K (see right-hand scale). The increase of longitudinal thermal velocities caused by interactions between the electrons is shown by the dashed curve, representing an estimate of the 'longitudinal-transverse relaxation' [22] for a constant-perveance beam of 0.6 \( \mu \text{A/V}^{3/2} \). (Other relaxation mecha-
nisms can be suppressed by applying a sufficiently strong magnetic guiding field, see Ref. [22].) An upper limit for the longitudinal rest-frame temperature determined experimentally (see Subsection 4.2) is also shown in Fig. 3.

In order to include the rest-frame velocities due to externally generated fluctuations of the average electron velocity, it seems reasonable to assume constant relative velocity deviations $\Delta v/v$ in the laboratory frame, given by the mechanical and electrical imperfections of the cooling device. The rest-frame velocity spread associated with these deviations increases with the beam energy, as shown by the curves for two values of $\Delta v/v$ in Fig. 3. At relativistic beam energies, longitudinal and transverse velocity deviations lead to different rest-frame velocities, as indicated by the two branches of these curves at high energy.

Having specified the effective electron temperature of magnetized electrons, one can identify the range of ion rest-frame velocities in which 'fast' cooling can be observed. As long as the ion velocity spread is larger than the transverse velocity spread resulting from the cathode temperature $T_e$, no difference in cooling rates will be observed because of the fast-cooling effect. Hence, the upper limit of the fast-cooling regime is situated at ion rest-frame velocities equal to the transverse electron velocity spread. From this limit, the fast-cooling regime extends down to ion velocities equal to the effective velocity spread of the magnetized electrons, as indicated by the shaded area in Fig. 3. If there are no other heating processes acting on the ion beam, even lower ion rest-frame velocities can be reached. Beyond the lower limit of the fast-cooling regime, the ion rest-frame motion is then damped exponentially until an equilibrium between the ion temperature and the effective electron temperature is reached.
3. RESULTS OF ELECTRON COOLING EXPERIMENTS: FAST COOLING

Electron cooling was tested at three proton storage rings between 1974 and 1981: in the NAP-M ring at the Institute of Nuclear Physics in Novosibirsk [23], at the CERN Initial Cooling Experiment (ICE) [24], and in the USA at the FNAL Cooler Ring [25]. The efficiency of the transverse and the longitudinal cooling was investigated in all the experiments. The results have been reviewed in previous publications [26, 27]. Here we will discuss mainly the indications for 'fast' cooling in relation to the expected effective temperatures of cooling electron beams. Characteristic differences between the experiments become evident if one considers the proton beam energy and the range of rest-frame velocities at which cooling rates were determined. Correspondingly the experiments are represented by vertical bars or by points in Fig. 3, where the proton rest-frame velocities can be located with respect to the fast-cooling regime. It is clearly seen that the experimental parameters at the NAP-M storage ring were particularly well suited to observe fast cooling. The comparison with the other experiments explains why fast-cooling effects could be clearly seen and systematically investigated only at the NAP-M installation. At ICE, the lowest proton rest-frame velocities at which coolings rates were measured were close to the thermal transverse electron velocity. At FNAL, the variations of the magnetic-field direction along the cooling region amounted to almost 1 mrad ($\Delta v/v \approx 10^{-3}$). This value can be deduced from the effective temperature due such variations, for which 0.12 eV at 200 MeV proton energy are quoted in Ref. [25].
3.1 Transverse cooling

The method used at NAP-M to determine the cooling decrement $\lambda$ of betatron oscillations was based on measuring the density of fast particles in the centre of the proton beam as a function of time [23]. The spatial resolution of 0.5 mm in this measurement allowed the NAP-M group to determine cooling rates at beam divergences above $\approx 5 \times 10^{-4}$. Details concerning the experimental conditions during the fast-cooling tests at NAP-M can be found in Ref. [8].

The experimental results [8, 9] have been summarized [9] by the following expression, which is valid in the fast-cooling regime:

$$\lambda(\langle V \rangle) = \langle V \rangle^{-1} (d\langle V \rangle/dt) = n_e \eta_L \langle V \rangle^{-2} \langle v_\perp \rangle^{-1} \langle \langle V \rangle < \langle v_\perp \rangle \rangle . \quad (13)$$

In this formula, $n_e$ is the rest-frame electron density, $\eta_L$ the ratio of the length of the cooling region to the ring circumference, $\langle V \rangle$ the r.m.s. ion rest-frame velocity (a function of time $t$), and $\langle v_\perp \rangle$ the transverse electron velocity spread. Theoretical results which reproduce this scaling of the cooling rate in the fast-cooling regime have been obtained by Sørensen and Bonderup [28].

In practice, approximately equal cooling times have been obtained at 1.5 MeV and at 45 MeV for proton beams of comparable geometrical emittance, although at 1.5 MeV the electron density was lower by a factor of 30. In Eq. (13) the decrease of $n_e \propto \beta^2$ for constant pereance (see Subsection 2.3) cancels against the decrease of $\langle V \rangle$, which itself depends linearly on $\beta$ for constant beam divergence. Cooling times that stay constant independently of the ion beam energy can be expected down to 100 keV/amu where, as seen from Fig. 3, sufficiently low longitudinal electron temperatures should still be available with a standard electron beam device.
The absolute values of the cooling rates measured in the three experiments at comparable rest-frame velocities are in reasonable agreement [26, 27]. An experimentally confirmed reference value which is useful for estimates is

\[ \lambda \approx 1 \text{s}^{-1} \times \left( \frac{n_e}{10^8 \text{cm}^{-3}} \right) \left( \frac{\eta_\pi}{0.02} \right) \]  

at \( \langle V \rangle = 10^7 \text{ cm/s} \). For the cooling rates at higher velocity spread much less experimental data are available. Theoretically, it seems well justified to continue the scaling at the upper end of the fast cooling regime using the standard formula [5]

\[ \lambda = n_e \eta_\pi \langle V \rangle^{-3} \quad (\langle V \rangle > \langle v_\pi \rangle) . \]  

(15)

The interpretation of experimental results with hot ion beams is complicated by the systematic velocity differences due to space-charge in the electron beam.

Within the fast-cooling regime, the value of the cooling rate given in Eq. (14) implies that the cooling time for ion beams at any energy with divergences of \( \approx 1 \text{ mrad} \) is of the order of 1 s, using an electron beam with a perveance of \( \approx 0.6 \mu \text{A/V}^{3/2} \).

3.2 Longitudinal cooling

3.2.1 The friction force

Measurements of the longitudinal friction force were performed with a coasting proton beam by detuning the electron beam energy and recording the subsequent change of the stored-ion energy \( E_i \). The dependence of the friction force \( F_n \) on the longitudinal rest-frame velocities \( V_n \) in the fast-cooling regime found at NAP-M were summarized [9] as

\[ \frac{dE_i}{dt} = v_\pi F_n \approx n_e \eta_\pi V_n^{-1} \langle v_\pi \rangle^{-1} \quad (V_n < \langle v_\pi \rangle) . \]  

(16)
Again, the theory of Sørensen and Bonderup [28] reproduces this scaling. The absolute values of the energy-loss rates obtained in the three electron cooling experiments differ by about one order of magnitude [26, 27]. The highest energy-loss rate obtained for a velocity difference \( V_n = 10^7 \text{cm/s} \), both at NAP-M and ICE, can be given as

\[
\frac{dE_i}{dt} = 0.2 \ \text{MeV/s} \times \beta \left( n_e / 10^8 \text{cm}^{-3} \right) \left( \eta_L / 0.02 \right) .
\]  

(17)

In the fast-cooling regime, the rate of energy change was

\[
\frac{dE_i}{dt} \approx 10^{-3} E_i \ \text{s}^{-1}
\]

(18)

at all beam energies, with a relative velocity detuning of \( V_n / (\beta c) \approx 10^{-3} \), and a perveance of 0.6 \( \mu \text{A/V}^{3/2} \).

3.2.2 Equilibrium momentum spread

The electron cooling experiments showed that under equilibrium conditions the longitudinal temperatures of the proton beam were much lower than the transverse temperatures. Indeed, the ion beam velocity distribution was 'flattened' similarly to that of the electrons. To some extent this can be understood from the fact that beam-heating processes such as residual gas scattering and the effect of magnetic field noise in the storage ring act mainly on the transverse ion velocity components. However, a strong exchange of thermal energy between the degrees of freedom is expected in a stored beam owing to intrabeam scattering. Since intrabeam scattering is expected to depend sensitively on the stored ion current, the variation of the equilibrium momentum spread with the number of stored protons has been investigated systematically at NAP-M and ICE [29, 24].

In these studies the momentum spread was measured by analysing the Schottky noise spectrum of the stored beam [30]. Fluctuations in the
ion density around the ring induce signals at the revolution frequency \( f \) and its higher harmonics in a beam current pick-up device. If the circulating ions are uncorrelated the width of these Schottky noise bands is given by the spread of the particle revolution frequencies, and the signal amplitude is proportional to \( \sqrt{N} \) (where \( N \) is the number of stored ions). The machine constant

\[
\eta = \frac{\Delta f/f}{\Delta p/p}
\]  

relates the revolution frequency spread \( \Delta f \) to the momentum spread \( \Delta p \).

Values for the equilibrium momentum spread have been evaluated at ICE from the spectral width of the Schottky noise. The results are plotted in the upper part of Fig. 4 as a function of the number of stored protons. The equilibrium momentum spread determined in the FNAL experiment by the same method was \( 1 \times 10^{-5} \) at \( 2 \times 10^6 \) stored protons [25].

In the experiments at NAP-M it was observed that electron cooling leads to such low momentum spreads that the Schottky spectrum changes its appearance qualitatively. In a theoretical analysis motivated by the experimental findings, Parkhomchuk and Pestrikov [31] investigated the noise spectrum in the case where the assumption of uncorrelated ions is no longer valid. For a given momentum spread, a critical number of particles \( N_{cr} \) is reached when the interaction energy of an ion with other beam particles becomes equal to its thermal energy:

\[
N_{cr} = \frac{\eta n}{(\text{Im} Z_n)} \cdot C(\Delta p)^2/[p(Ze)^2].
\]  

Here, \( C \) is the ring circumference, \( p \) the ion momentum, \( Ze \) the ion charge, and \( Z_n \) the longitudinal coupling impedance [32] relating the longitudinal (fluctuating) electric field to the beam current (fluctuations) at the \( n \)th harmonic of the revolution frequency. In the interesting frequency range (\( \approx 10^7 \) Hz), \( Z_n \) is capacitive and \( |Z_n/n| \) is
roughly of the order of the free-space impedance \((\sqrt{\mu_0/\varepsilon_0} \approx 0.4 \, \text{k}\Omega)\) [32]. Parkhomchuk and Pestrikov found that below the critical momentum spread, at which \(N_{cr} = N\), the noise amplitude becomes proportional to \(\sqrt{N_{cr}}\) and hence to \(\Delta p\). On the other hand, at a constant momentum spread below the critical value, it is predicted that the spectral density of beam noise no longer increases with the number of particles.

Accordingly, the momentum-spread values found at NAP-M and plotted in the lower part of Fig. 4 were derived [29] from the amplitude of the noise signal, and not from its width as in the other experiments. Equation (20) has been inverted for plotting the critical momentum spread discussed above as a function of the beam current in Fig. 4. With the actual machine parameters, different lines result for the experiments NAP-M and ICE. Similarly, the relation between momentum spread and longitudinal ion temperature, which has been used to construct the right-hand scale, is different for the two machines, as the longitudinal effective mass

\[
M_{\text{eff}} = p/(\eta C_f) \tag{21}
\]

enters here:

\[
T' = (\Delta p)^2/M_{\text{eff}} = \eta C_f p (\Delta p/p)^2 \tag{22}
\]

It can be seen that the momentum spread measured at ICE always remains above the critical value.

For less than \(3 \times 10^7\) stored protons the equilibrium momentum spread observed at NAP-M is no longer determined by intrabeam scattering, which otherwise causes its increase with \(N\). Instead, a constant value of the longitudinal temperature is observed which has the order of magnitude of possible effective electron temperatures (see Fig. 3). Hence, thermal equilibrium with the electron beam only can be assumed.
The observation that intrabeam scattering no longer influences the momentum spread in very cold ion beams has been explained theoretically by the influence of focusing fields on the collisions between the ions, which can become adiabatic with respect to the betatron motion [33]. Furthermore, the experimental results inspired considerations regarding ordering phenomena and crystallization in stored, electron-cooled ion beams [33, 34]. The observed behaviour of the noise signal by itself provides some indication of an increase of order in the beam, caused by the interaction between the stored protons.

The influence of the interaction between the particles on the noise amplitude depends [35] on the sign of $\eta/(\text{Im } Z_n)$. More specifically, above the transition energy ($\eta < 0$), a strong increase of the density fluctuations in the beam is predicted if the particle number approaches $N_{cr}$ (with the capacitive coupling impedance expected in the frequency range considered). This might explain the self-bunching of low-intensity proton beams observed [27] during electron cooling above the transition energy at ICE.

4. ELECTRON COOLING AT LEAR

4.1 Project status

The electron cooling project at the CERN Low-Energy Antiproton Ring (LEAR) was initiated following the ICE activity by a collaboration between CERN and the Kernforschungszentrum Karlsruhe [36]. The aim is to provide highly efficient phase-space cooling for antiprotons at energies below 70 MeV, which is desirable for efficient operation of internal targets at these energies [37]. In particular, the low-energy antinucleon-nucleon scattering has to be studied in very thin targets, in order to avoid multiple scattering of the incoming antiprotons. Intro-
ducing such targets in a storage ring and making use of the recirculation of the antiprotons, the event rate is increased strongly. Moreover, spatial and energy resolution are improved because of the high quality of the cooled, internal beam. Also for normal operation of the storage ring, one can envisage benefits from electron cooling complementing the stochastic cooling system of LEAR. The lower end of the energy range of LEAR operation with electron cooling will presumably be determined by the vacuum conditions, to which much attention was paid during the development work on the electron cooler. The prospect of, for the first time, implementing electron cooling in the routine operation of a storage ring, and the perspective of improving the electron-cooling technique and of extending the range of its applications \[38, 39\] had a considerable impact on this project.

The technical development was partly based on hardware taken over from ICE. Whereas the electron gun, the magnet, and the collector were modified \[21, 40\], the vacuum system was completely rebuilt \[41\]. The vacuum system design was determined by the need for a pressure of the order of \(10^{-12}\) Torr on the one hand, and rather high gas loads due to the operation of the electron cooler on the other. Table I gives the typical operating parameters obtained since the end of 1985 as a result of the electron beam improvements, and summarizes the results of vacuum tests carried out prior to installation in LEAR. The status of the project is presented in detail elsewhere \[11\].

The installation of the electron cooling device in LEAR was accomplished at the end of July 1987, when it was connected to the vacuum system of the ring at a pressure of about \(3 \times 10^{-12}\) Torr. Operation of the electron cooler is being initiated at the time of writing, and first cooling tests are scheduled for October 1987.
4.2 Electron beam diagnostics

Two non-destructive electron beam diagnostic methods were tried out at the LEAR electron cooler in the period before its installation. They yielded information about the velocity distribution in the rest frame of the electron beam. The results are relevant for estimating the cooling performance and also for possible experiments with the electron beam, by which electron-ion interaction in the beam rest frame would be investigated. The two methods are complementary in the sense that each one is mainly sensitive to either the transverse or longitudinal rest-frame velocities.

4.2.1 Microwave diagnostic of the transverse beam temperature

The microwave radiation power emitted by the electrons during their cyclotron motion in the magnetic guiding field is proportional to their transverse energy. A measurement of the microwave power level in the cooling region can therefore provide information about the average transverse energy of the electrons present in this volume [24]. In the laboratory frame one expects [42] the radiation in a band extending from \(\gamma(1 - \beta) f_c\) to \(\gamma(1 + \beta) f_c\), where \(f_c = 1\, \text{GHz}\) is the electron cyclotron frequency in the beam rest frame. The expected spectral power density averaged over this band is about as high as the spectral power density of resistive noise at room temperature. Even at this low level the emitted radiation, picked up by a small inductive loop at the beam pipe, can be detected with modern low-noise preamplifiers. The signal is spectrally analysed after amplification. The spectrum will be influenced by the metallic beam pipe which modifies the HF field, acting as a cavity or waveguide. For the interpretation of the measured microwave power it is essential to calibrate the sensitivity of the detection circuit and to understand the coupling of the emitted power to the installed antenna.
Microwave spectra from a cooling electron beam were measured at ICE at a low resolution in frequency; the integrated noise power was used to derive a transverse energy of about 1 eV [24]. The microwave spectra recorded at the LEAR electron cooler [43] have a much improved resolution and show the radiation from the electrons concentrated in narrow peaks (Fig. 5a). These peaks are obviously related to standing waves in the drift tube, caused by reflection at the two ends where the vacuum envelope opens up to form the toroid vacuum chambers. A concise theory, explaining the microwave spectrum observable from fast, spiralling electrons distributed over an extended volume in a cavity-like environment, is not available. However, the spectra have been interpreted quantitatively by a simplified model in which cavity modes are identified, and which includes the coupling of spiralling electrons to these modes [43]. At fixed electron energy and magnetic field the transverse temperature extracted from the spectra showed (see Fig. 5a) a linear dependence on the number of electrons returning from the collector (loss current). In spite of the low loss current, these electrons are likely to make a large contribution to the microwave signal since their transverse energy is much higher than that of the primary beam electrons. Extrapolating to zero loss current, a transverse energy of (0.5 ± 0.2) eV is obtained.

4.2.2 Thomson-scattering diagnostic of longitudinal velocities

To enable a non-destructive measurement of longitudinal electron velocities, it has been suggested to analyse the Doppler shift of laser light Thomson-scattered from the electron beam [44]. This method has now been demonstrated at the LEAR electron cooler [45, 46]. In spite of the extremely low scattering cross-section, back-scattered photons can be separated from background by the large wavelength-shifting fac-
tor (≈ 2 for 26 keV electrons). Using a pulsed, tuneable dye laser and a narrow-band, fixed-wavelength filter in the optical path of the back-scattered photons, wavelength scans were performed which represent the energy distribution of the electrons at a particular radial position in the beam. The displacement of the observed transition maximum with changing acceleration voltage provides a clear signature of the Thomson-scattering signal. The energy spread derived from the signal width indicates a longitudinal temperature below 10 K. This allows one to place an upper limit on the influence of temperature relaxation (see Fig. 3) and confirms the fast-cooling capabilities of the electron beam. An analysis of the signal position enabled an absolute measurement of the electron velocity to be made, and showed that the compensation of electron space-charge by ions trapped in the beam cannot exceed a few per cent.

Using a cooled ion beam in a storage ring and a laser beam, Doppler-shift measurements at higher signal rates can be envisaged, inducing radiative electron-ion recombination in the cooling electron beam with the laser and detecting the recombined atomic systems [38]. Analysing the wavelength dependence [39] of the stimulated-recombination rate, it is also possible to derive the ratio of the longitudinal and the transverse temperature and the shape of the transverse energy distribution.

5. ELECTRON COOLING AT THE NEW ION STORAGE RINGS

The new projects involving electron-cooled storage rings will offer many possibilities to study the process of phase-space cooling and the cold ion beams themselves. To conclude this paper, let us summarize some of the interesting topics which could be assessed in experiments. Most of them would explore fields in which very few or no experimental results are available at present.
In the rings working at energies below 50 MeV/amu the 'fast' electron cooling effect is expected to be observable very clearly. Hence, the results from the NAP-M project will be verified and probably complemented by further studies of the limits of fast cooling. Since the dimensions of the ion beam are expected to become very small, the ion beam diagnostics may have to be improved for such investigations. There still are many uncertainties on the behaviour of the cold, dense ion beams one intends to produce using electron cooling. This concerns especially the interaction between the ions by collisions (intrabeam scattering) and by collective fields (instabilities, onset of ordering). Such processes might cause problems in reaching the desired beam quality, but also present an interesting field for basic research.

In a storage ring, ions other than protons have never been cooled by electrons. In particular, the dependance of the cooling rate on the charge and the mass M of the ions will have to be investigated. Deviations from the first-order scaling with \((Ze)^2/M\) would reveal details of the collisional energy exchange, such as the applicable impact parameter range, or the influence of the internal structure of the ions. Differences in the cooling of positive and negative ions are suggested by recent theoretical [47] and experimental [48] studies.

Since the interaction between the stored particles will be much stronger with highly charged ions, the limits on the beam density are expected to be more severe but, on the other hand, interesting phenomena such as ordering mechanisms should be favoured. Even with protons, electron cooling has not been tested with more than \(10^9\) stored particles, although many projects are aiming at much higher numbers of stored ions. In particular, the ion density in cold beams may far exceed the electron density in the cooling beam.
The technological problems of the electron cooling devices will be very different at both ends of the energy range. At very low energies the thermal motion at the cathode or interactions among the electrons will require particular attention [22, 49]. At the opposite end of the range, reliable operation of electron coolers with acceleration voltages up to 300 kV is still a challenge. In all cases the vacuum system requires special consideration either, at high energies, because of the high dissipated power or, at low energies, because of the required very low pressures. Also in the future, electron cooling of stored ions will need substantial technical effort which, however, will be rewarded by new, interesting experimental possibilities.

Acknowledgements

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Table I
Parameters of the LEAR electron cooler

<table>
<thead>
<tr>
<th>Basic parameters</th>
<th></th>
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<tr>
<td>Antiproton energy range</td>
<td>&lt; 5 - 70 MeV</td>
</tr>
<tr>
<td>Electron energy range</td>
<td>&lt; 3 - 40 keV</td>
</tr>
<tr>
<td>Electron beam radius</td>
<td>2.54 cm</td>
</tr>
<tr>
<td>Cooling region length</td>
<td>1.5 m (= 0.02 of LEAR circumference)</td>
</tr>
<tr>
<td>Perveance</td>
<td>&lt; 0.53 µA/V^{1/2}</td>
</tr>
<tr>
<td>Pitch of cyclotron motion</td>
<td>7.6 cm (at full perveance)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Typical (proved) parameters of operation</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron energy</td>
<td>26 keV (max. 40 keV)</td>
</tr>
<tr>
<td>Electron current</td>
<td>2.2 A (max. 3.3 A)</td>
</tr>
<tr>
<td>Relative current loss</td>
<td>3 × 10^{-3} (min. 1 × 10^{-2})</td>
</tr>
<tr>
<td>Pressure in cooler (beam on)</td>
<td>1 × 10^{-12} Torr</td>
</tr>
<tr>
<td>Precision of magnetic field direction</td>
<td>±2 × 10^{-4} rad</td>
</tr>
<tr>
<td>Electron energy fluctuations</td>
<td>±3 × 10^{-5}</td>
</tr>
</tbody>
</table>
FIGURE CAPTIONS

Figure 1: Schematic drawing of the electron cooling set-up and of the electron motion in the magnetic guiding field.

Figure 2: Electric circuit of the electron cooling device with energy recovery at the collector.

Figure 3: Diagram showing rest-frame velocities relevant for the electron-ion interaction as a function of ion beam energy. The effective electron velocity spread as discussed in the text is shown by lines. The bars indicate the working points for measurements of electron cooling rates. The shaded area shows the fast-cooling regime assuming Δv/v = 10⁻². An upper limit of the longitudinal temperature as measured at the LEAR electron cooler is also shown (T₁,exp).

Figure 4: Equilibrium proton momentum spread and corresponding beam temperature as measured in the electron cooling experiments NAP-M and ICE. The critical longitudinal temperatures, shown for both storage rings, correspond to the critical momentum spread calculated from Eq. (20) using Ncr = N. Ring parameters: β = 0.35, η = 0.1, C = 47 m (NAP-M); β = 0.3, η = 0.32, C = 78 m (ICE). Since the free-space impedance is used for |Im Zn/n|, the lines give only approximate values of the critical longitudinal temperature.
Figure 5: Microwave diagnostics at the LEAR electron cooler [43]:

(a) Microwave spectrum at 26 keV, 2.2 A, 0.046 T. The cyclotron frequency $\nu_0$ (including the transverse Doppler shift) and the TE$_{11}$ cutoff frequency of the beam pipe (radius 70 mm) are indicated.

(b) Transverse electron energy derived from microwave spectra as a function of the loss current at the collector. The different point styles represent different methods to vary the loss current.
Fig. 1
Fig. 2
Fig. 5