NEW RESULTS OF RESEARCH ON ELECTRON COOLING


Novosibirsk 1976

Presented to the All Union High Energy Accelerator Conference
Moscow, October 1976

Translated at CERN by O. Barbalat
(Original: Russian)
Not revised by the Translation Service

(CERN Trans. 77-01)

Geneva
January 1977
ABSTRACT

Electron cooling experiments performed after the improvement of the NAP-M installation are described.

Measurements showed that the betatron oscillation damping time is inversely proportional to the electron current and for a current of 0.8 A it amounts to 3 msec (with a proton energy of 65 MeV). The possible causes of this unexpectedly small damping time are discussed. Results of cooling experiments on a bunched proton beam are given. Experiments of cooling a low-energy proton beam (1.5 MeV) are briefly described.
The first cycle of electron cooling studies was concluded at the Institute of Nuclear Physics of the Siberian Branch of the USSR Academy of Sciences in May 1975. The basic results obtained at that time (Refs. 1-3) showed satisfactory agreement with the theoretical ideas developed in Refs. 4 and 5. In January 1976, the experimental apparatus had been modernized and the next step in the study began.

The upgrading of the NAP-M storage ring was mainly directed towards improving the vacuum conditions:

- Sublimation sorption pumps were mounted inside the vacuum chamber of the quadrant magnet so that titanium could be sputtered over the whole length of the chamber.

- A pre-heating vacuum chamber was incorporated in the electron beam injection system.

- Sorption pumps were installed in the cooling section and in the "shoulder" installation where the electron gun and the collector are placed.

- The pumping speed in the electron gun was significantly increased and oil cooling of the cathode assembly of the gun was introduced, which reduced the outgassing of its "hot" elements.

The diameter of the cathode was increased to 20 mm, and for this reason the impregnated cathode was replaced by an oxidized one. As before, the electrons were used to heat the cathode. The incorporation of an additional blocking electrode in the collector made it possible to preserve the high efficiency of the recuperation \( \Delta I_e/I_e < 5 \times 10^{-5}; U_{\text{coll}} = -2 \text{ kV} \) when increasing to 40 mm the diameter of the inlet aperture.

The extremities of the cooling section were equipped with two pick-up stations to measure the position of the centre of the bunched proton beam and of the modulated electron beams with an accuracy better than 0.5 mm.

In the middle of the cooling section, grids were installed to remove ions from the electron beam, and measuring plates to control the ion current and consequently the vacuum in the interaction section.

For electron currents of 400 mA, the saturation ion current was 20 nA which corresponds to a vacuum in the interaction section of \( 7 \times 10^{-9} \) Torr and an average vacuum in the storage ring of about \( 5 \times 10^{-10} \) Torr. The proton beam monitoring system was supplemented by a system for measuring the radial density distribution of the proton beam (magnesium curtain method, Ref. 3).
Typical parameters of the experiments are given in Table 1.

Determination of the proton beam dimension was most reliably performed by measuring the size of the beam of neutral hydrogen atoms generated in the cooling section as a result of the radiative recombination of protons and electrons (Refs. 1-3). Hydrogen atoms removed through the vacuum chamber appendage were recorded by a nuclear photographic emulsion. The size of the "image" on the photographic emulsion $Q_N$ and the proton beam size $a_p$ in the cooling section are unambiguously related by the geometrical dimensions and the $\beta$-function of the storage ring. The calculation of $a_p$ from $Q_N$ provides the diameter of the proton beam given in Table 1. It corresponds to an electron temperature in the particle system (Refs. 3-4) of $T_e = 0.23 \pm 0.07$ eV.

The flux of neutral hydrogen atoms amounted to $2 \times 10^3$/sec with $I_e = 0.4$ mA and $I_p = 80$ $\mu$A. This recombination rate corresponds to an electron temperature in the particle system (Ref. 6) of $T_e = 0.24 \pm 0.06$ eV.

(When estimating $T_e$ by the recombination rate, account is taken of the symmetric electron distribution: $T_\parallel < T_e$ see below.)

Table 1

<table>
<thead>
<tr>
<th>Typical parameters of the experiment and results of proton cooling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton energy</td>
</tr>
<tr>
<td>Electron energy</td>
</tr>
<tr>
<td>Diameter of cathode of electron gun</td>
</tr>
<tr>
<td>Electron current $I_e$</td>
</tr>
<tr>
<td>Proton current $I_p$</td>
</tr>
<tr>
<td>Average vacuum</td>
</tr>
<tr>
<td>Equilibrium size (diameter) of the proton beam in the middle of the section</td>
</tr>
<tr>
<td>Cooling time ($I_e = 0.8$ A) $\tau_e$</td>
</tr>
<tr>
<td>Proton life-time in the cooling mode</td>
</tr>
<tr>
<td>Effective electron temperature</td>
</tr>
<tr>
<td>Specific flux of neutral hydrogen atoms $[(dN/dt)/J_e J_p]$</td>
</tr>
</tbody>
</table>
The longitudinal friction force $F_\parallel$ was measured by the method used in Ref. 3, on the basis of the rate of change in the mean radius of the proton orbit $R_0$ in the cooled beam after small erratic variation of the electron energy:

$$\frac{dr}{dt} = \frac{\Psi R_0}{P_s} \eta F_\parallel,$$

(1)

where

$p_s$ : the proton momentum

$\Psi R_0$ : orbit deformation for a unit deviation of the momentum from the equilibrium value

$\eta$ : fraction of orbit occupied by the electron beam.

In this study, similar measurements were obtained by use of a detector of the radial density distribution (vertical magnesium curtain). The dependence of $F_\parallel$ on the difference between the average velocities of the protons and the electrons $\Delta v_e$ (introduced by the jump in energy) confirmed views of a "flattening" in the electron velocity distribution (Ref. 3). The experimental values of $F_\parallel(v_e)$ are in good agreement with calculations (the continuous curve in Fig. 1) obtained for an electron velocity distribution in a particle system having the shape of a thin disc measuring:

\[
\begin{align*}
\text{disc radius} & \quad \Delta v_\perp \sim \sqrt{\frac{T_e}{m}} \\
\text{disc thickness} & \quad 2\Delta v_\parallel \sim 2\sqrt{\frac{T_\parallel}{m}} \\
T_\parallel &= \frac{T_k^2}{2\gamma^2 \beta^2 mc^2} \approx \frac{T_k^2}{\beta < 1} \approx \frac{4W}{\beta < 1}
\end{align*}
\]

(2)

Here

$T_\parallel, T_e$ : longitudinal and transverse electron temperatures in the particle system

$W, \beta c$ : kinetic energy and velocity of the electrons in the laboratory system

$T_k$ : effective cathode temperature including, in addition to the real temperature of the thermo-emissive cathode $T_{k0}$, the pulses and noise from the voltage source, training, etc. (Ref. 3):
\[ T_k = T_k^0 + e \Delta U. \] (3)

The expression for the friction force (Ref. 5)
\[ \mathbf{F} = -\frac{4\pi e^4 \eta_e}{m} \int d^3 \mathbf{v}_e f(\mathbf{v}_e) \frac{(\mathbf{v}_p - \mathbf{v}_e)}{|\mathbf{v}_p - \mathbf{v}_e|^3} \] (4)
contains two independent parameters: the electron temperature, characterizing the distribution function \( f(\mathbf{v}_e) \); and the product of the collision Coulomb logarithm \( L \) by the electron density \( n_e \). Fitting by the least square method for
\[ f(\mathbf{v}_e) = \delta(v_{\|}) \begin{cases} 1/\pi(\Delta v_{\perp})^2, & v_{\perp} \leq \Delta v_{\perp} \\ 0, & v_{\perp} > \Delta v_{\perp} \end{cases} \] (5)
one obtains
\[ T_e = 0.28 \pm 0.06 \text{ eV} \]
\[ L_n n_e = 2.2 \times 10^9 / \text{cm}^3. \]

For \( J_e = 0.3 \text{ A/cm}^2 \), this gives \( n_e = 2 \times 10^8 / \text{cm}^3 \), \( L_n = 11 \).

Measurements of \( F_{||}(\Delta v_{||}) \) were obtained in the same conditions of artificially increasing the "thickness of the disc"; for this, the electron energy was modulated by an a.c. voltage of 30 V at a frequency of 500 Hz. The results (the dotted curve in Fig. 1) show that the thickness of the disc does in fact increase to
\[ \Delta v_{||} \propto \sqrt{\tau_{||}/m} = \frac{e U_m}{m \beta c} \] (6)
[equation (2)]. Here \( e \) and \( m \) are the charge and mass of the electron.

The most interesting experimental results were obtained by the measurement of the cooling time \( \tau_e \) (damping time of the proton betatron oscillations).

The method utilized was that described in Refs. 2 and 3: by kicking a pre-cooled proton beam with an inflector, betatron oscillations were excited, and the increase in the beam density with time due to the action of the electron cooling was recorded (by means of a density measuring apparatus).
The cooling time was computed by a computer working on-line with the density measuring system. In the range of electron currents of 0.1-0.8 A the cooling time decreased proportionally to $I_e^{-1}$ and was 83 msec for $I_e = 0.8$ A.

The results obtained proved to be much better than those expected according to Refs. 4 and 5 for an electron beam with an average current density in the order of 0.1-0.2 A/cm$^2$. Therefore measurements of the current density distribution in the electron beam were conducted by making the gas glow under the effect of the beam. The results of density measurement of the photographs (helium atmosphere, pressure $3 \times 10^{-5}$ Torr, current 0.4 A) are given in Fig. 2. The latter shows the dependence of the flux of neutral hydrogen atoms and of the cooling time on the position of the proton beam inside the electron beam. All three curves have a strongly pronounced maximum and widths which approximately coincide. The current density reached a value $J_e = 0.3$ A/cm$^2$ for a total current of 0.4 A (instead of the expected value of 0.13 A/cm$^2$).

Nevertheless, a difference of roughly an order of magnitude remains with the results of previous work (Refs. 2-3) ($\tau_e = 5$ sec with $J_e = 0.13$ A/cm$^2$).

The above estimates of the electron temperature yield results which are in good agreement. Difficulties arise when attempting to compare the experimental values of the cooling time with the theoretical value which corresponds to a temperature $T_e = 0.25$ eV. The only free parameter contained in the equation for $T_e$ (Refs. 4-5) -- the collision Coulomb logarithm for the transverse momentum transfer from protons to electrons -- should be taken to be of an order of magnitude of 200, which is clearly untenable. Measurement of the dependence of the damping time on the "disc thickness" in the experiments with energy modulation of the electrons gave an unexpectedly sharp dependence of $\tau_e$ on $v_\parallel$ [Eq. (6)]. It was found that $\tau_e$ increases twofold for an increase in $T_\parallel$ to only $2 \times 10^{-3}$ eV (Fig. 3).

With a growth of the modulation amplitude and correspondingly of $\Delta v_\parallel$ and $T_\parallel$, the value of $\tau_e$ approaches the calculated value $\tau_M$ obtained for the force [Eq. (4)] and the "flattening" of the distribution $f(v_e)$. This is in all appearance indicative of the more complex behaviour of the friction force in a beam with "transmagnetic" electrons and particles with very small longitudinal velocity spread [$\Delta v_\parallel / v_\perp \leq 10^{-3}$ (2)].
The experimental acceleration of protons by electrons described in Ref. 1, was repeated. The proton energy was successfully increased from 65 MeV to 85 MeV in a time of the order of 200 sec without appreciable particle loss.

Cooling of a bunched proton beam showed a bunch compression to an equilibrium size $\Delta \ell = 5$ m (the perimeter of NAP-M is 47 m). The measurement of the cooling time in that case gave 0.5 sec with $I_e = 0.4$ A. More detailed studies were not carried out.

In the experiments, effects having clearly a collective character were detected. When exciting betatron oscillations in the protons of a pre-cooled beam, there occurred, immediately after the inflector kick, a rapid damping of the oscillations (with a characteristic time smaller than the 0.015 sec resolving time of the density measuring device) to an intermediate amplitude value, followed by slower damping, with a characteristic time $\tau_e$, down to the equilibrium value. With the increase in the proton and electron currents, the value of the intermediate amplitude (for a constant initial amplitude) decreased. Thus, when $I_e = 400$ mA, $I_p = 50$ $\mu$A, the intermediate amplitude was 1/3 of the initial value of 3 mm and the time $\tau_e$ was 0.17 sec.

To this range of phenomena we should, it would seem, ascribe the observed proton beam instability in the cooling mode: when $I_p > 60$ $\mu$A, $I_e > 200$ mA, and with a characteristic time of the order of 50 msec, the spontaneous bunching of the beam occurred and vanished accompanied by an increase in its transverse dimension. The instability disappeared when the proton intensity was reduced to 40 $\mu$A.

Electron cooling of heavy particles of low energy (order of the MeV) presents a special interest for various applications (Refs. 2-3). In that case, however, it may happen that because of the cathode temperature it is basically impossible to obtain a sufficiently "cold" electron beam:

$$\frac{\Delta v_\perp}{c} \approx \sqrt{\frac{T_e}{2W}} \approx 10^{-2}.$$  \hspace{1cm} (7)

Test experiments on the cooling of low-energy protons were carried out in the NAP-M installation with the following parameters:
\[ W_p = 1.4 \text{ MeV (injection energy)} \]
\[ W_e = 760 \text{ eV, } I_e = 4 \text{ mA}. \]

All the basic electron cooling effects appeared: reduction of the transverse proton beam size, resonant increase of its life-time and entrainment of the protons by electrons when the energy of the latter was varied.

* * *

REFERENCES


6) I. MacDaniel, Collision Processes in Ionized Gases - "MIR" (1967).

Fig. 1 Relation between the longitudinal friction force and the difference in average velocity of the protons and electrons $\Delta v_{\parallel}$ due to erratic change in electron energy. The continuous curve corresponds to the calculated values; .... = experimental values xxx = experimental values with electron energy modulation.

Fig. 2 Comparison of measurement results of the radial electron density distribution $J_{e}$ and the cooling time $t_{e}$ and the neutral hydrogen atom current $dN/dt$ as a function of the position of the proton beam inside the beam of electrons.

Fig. 3 Ratio of the calculated value $(T_{m})$ to the experimental value $(T_{e})$ of the cooling time as a function of the spread in longitudinal velocities $\Delta v_{\parallel}$ (in units of the transverse velocity $\Delta v_{\perp}$).