Provisional text
not revised by CERN
Translation Service

NUCLEAR PHYSICS INSTITUTE

SIBERIAN BRANCH OF USSR ACADEMY OF SCIENCE

PS/DL/Note 76-25
October 1976

Preprint N.P.I. 76-32

G.I. Budker, A.F. Buluchev, N.S. Dikansky
V.I. Kononov, V.I. Kydelainen, I.N. Meskov
V.V. Parkhomchuck D.V. Pestrikov, A.N. Skrinsky
B.N. Sukhina

NEW EXPERIMENTAL RESULTS OF ELECTRON COOLING

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

(Translated at CERN by O. Barbalat)

* * * * *

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 83 ms (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. An experiment of cooling a low energy proton beam (1.5 MeV) is 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 (Ref. 1-3) showed satisfactory agreement with the theoretical ideas developed in Ref. 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 an improvement of the vacuum conditions :

- Sublimation sorption pumps mounted inside the vacuum chamber of the quadrant magnet allowing to spread titanium on the whole length of the chamber.
- Baked up vacuum chamber in the electron beam injection section.
- Sorption pumps in the cooling section and in the "shoulder" installation where the electron beam and the collector are placed.
- Significant increase of pumping speed in the electron beam line and in the oily inlet of the joint of the cooling cathode gun which reduces the outgasing of its "hot" elements.

The diameter of the cathode was increased to 20 mm, the impregnated cathode was replaced by an oxidized one. As before the electrons were used to heat the cathode. In addition the introduction of blocking electrodes in the collector allowed to preserve the high efficiency of the recuperation ($\Delta I_e/I_e < 5.10^{-5}$; $U_{coll} = -2$ kV) by increasing to 40 mm the diameter of the outlet aperture.

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

In the middle of the cooling section a grid was installed to remove ions from the electron beam and a measuring plate to control the ion current and afterwards 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 7.10^{-9} Torr and an average vacuum in the storage ring of 5.10^{-10} Torr. The proton beam monitoring system was supplemented by a measurement of 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 very reliably performed by measuring the beam size of the neutral hydrogen atoms generated in the cooling section as a result of the radiative recombination of protons and electrons (Ref. 1-3). Hydrogen atoms removed through the vacuum chamber appendage show up by a nuclear scintillation. The size "represented" by the scintillation Q_N and the proton beam size a_p in the cooling section are related by the geometrical dimensions and the β-function. The result of the calculation of a_p from Q_N is given in Table 1 and named the diameter of the proton beam. It corresponds to an electron temperature in the particle system (Ref. 3-4) of $T_e = 0.23 \pm 0.07$ eV.

The flux of neutral hydrogen atoms amounted to 2.10^3/s with $I_e = 0.4$ mA and $I_p = 80$ μA. This recombination rate corresponds to an electron temperature in the particle system (Ref. 6) of

$$T_e = 0.24 \pm 0.06 \text{ eV}$$

(When estimating T_e by the recombination rate one obtains a non-symmetric electron distribution function : $T_{//} << T_e$ see below).

Table 1

Typical parameters of the experiment and results of proton cooling

Proton energy	65 MeV
Electron energy	35 MeV
Cathode diameter of the electron gun	20 mm
Electron current I_e	0.1 - 0.8 A
Proton current I_p	20 - 100 μA
Average vacuum	5.10^{-10} Torr
Equilibrium size (diameter) of the proton beam in the middle of the section	0.47 mm
Cooling time (I_e = 0.8 A) τ_e	83 ms
Proton life time in the cooling regime	more than 8 hours
Effective electron temperature	0.25 eV
Specific flux of neutral hydrogen atoms ($\frac{dN}{dt} / J_e J_p$)	$80A^{-1}$ μA^{-1} sec^{-1}

The longitudinal friction force $F_{//}$ is measured with the aid of the method used in Ref. 3. The rate of change of the mean radius of the proton orbit in the cooled beam after small ramdom variation of the electron energy is :

$$\frac{dr}{dt} = \frac{\psi R_o}{p_s} \eta F_{//} \qquad (1)$$

with

- p_s : the proton momentum
- ψR_o : orbit deformation for a unit deviation of the momentum from the equilibrium value
- η : fraction of orbit occupied by the electron beam.

In the quoted reference, similar measurements were obtained by use of data from the radial density distribution (vertical magnesium curtain). The dependence of $F_{//}$ on the difference between the average velocities of the protons and the electrons Δv_e (introduced by the energy difference) was confirmed by the appearance of a "flattening" in the electron velocity distribution (Ref. 3). The experimental value of $F_{//}(v_e)$ is in good agreement with the calculations (continuous curve on fig. 1) obtained for an electron velocity distribution in the particle system with the shape of a thin disk of dimensions :

$$\left.\begin{array}{lll}\text{"disk radius"} & \Delta v_{\perp} \sim \sqrt{T_e/m} & \\ \text{"disk thickness} & 2\Delta v_{//} \sim 2\sqrt{T_{//}/m} & \\ & T_{//} = \dfrac{T_k^2}{2\gamma^2\beta^2 mc^2} \approx \left.\dfrac{T_k^2}{4W}\right/_{\beta<<1} & \end{array}\right\} \quad (2)$$

with

$T_{//}$, T_e : longitudinal and transverse electron temperatures in the particle system

W, βc : kinetic energy and electron velocity in the laboratory system

T_k : effective cathode temperature introduced besides the real temperature of the thermo-emissive cathode T_k^0 to account for pulsing and source noise, stresses, training, etc. (Ref. 3).

$$T_k = T_k^0 + e\,\Delta U \qquad (3)$$

The expression for the friction force (Ref. 5)

$$\vec{F} = -\frac{4\pi e^4 L n_e}{m} \int d^3 v_e \; f(\vec{v}_e) \frac{(\vec{v}_p - \vec{v}_e)}{|\vec{v}_p - \vec{v}_e|^3} \qquad (4)$$

contains two independent parameters, the electron temperature, characterizing the distribution function $f(\vec{v}_e)$ and the product of the collision Coulomb logarithm L by the electron density n_e. Fitting by the least square method for

$$f(\vec{v}_e) = \delta(v_{/\!/})\begin{cases} 1/\pi(\Delta v_\perp)^2 , & v_\perp \leq \Delta v_\perp \\ 0 , & v_\perp > \Delta v_\perp \end{cases} \quad (5)$$

one obtains

$$T_e = 0.28 \pm 0.06 \text{ eV}$$
$$L_{/\!/} n_e = 2.2\ 10^9/\text{cm}^3$$

For $J_e = 0.3$ A/cm^2 , this gives $n_e = 2.10^8/\text{cm}^3$, $L_{/\!/} = 11$.

Measurements of $F_{/\!/}(\Delta v_e)$ were obtained in the same conditions of artificially increasing the "thickness of the disk"; for this the electron energy is modulated by a variable voltage of 30 V at the frequency of 500 Hz. The results (dotted curve on Fig. 1) show that the thickness of the disc grows indeed as

$$\Delta v_{/\!/} \sim \sqrt{T_{/\!/}/m} = \frac{e\,U_m}{m\beta c} \quad (6)$$

(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 <u>cooling time</u> τ_e (damping time of the proton betatron oscillations).

The utilised method is described in Ref. 2 and 3 : the proton beam was kicked by the inflector before the cooling, betatron oscillations were excited and the increase of the beam density with time by the action of the electron cooling was recorded (by means of the density measuring apparatus).

The cooling time was computed by an EBM* working on-line with the density measuring system. In the range of electron currents of 0.1 - 0.8 A the cooling time decreased proportionnaly to I_e^{-1} and was 83 ms for $I_e = 0.8$ A.

---

* Electronic Computing Machine

The obtained results show a substantially better than expected agreement (Ref. 4-5) for 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 using the interaction of gas with the beam. The result of photographic densitometry (Helium atmosphere, pressure 3.10^{-5} Torr, current 0.4 A) are given on Fig. 2. It shows the dependence of the flux of neutral hydrogen atoms and of the cooling time on the position of the protons inside the electron beam. All three curves have a strongly pronounced maximum for widths which coincides remarkably. The current density reached the value $J_e = 0.3$ A/cm^2 for a total beam of 0.4 A (0.13 A/cm^2 in the cooling location).

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

Estimates of the electron temperature given above yield results 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 parameters contained in the equation for T_e (Ref. 4-5) - the collision Coulomb logarithm for the transverse momentum transfer from electrons to protons - would lead to accept a value with an order of magnitude of 200 which is clearly untenable. Measurement of the dependence of the damping time with the "disk thickness" in the experiments with energy modulation of the electrons gave an unexpected sharp dependence of τ_e with $v_{//}$ (eq. 6). One finds that τ_e increases twice for an increase of only 2.10^{-3} eV (Fig. 3).

With a growth of the amplitude of the modulation and correspondingly of $\Delta v_{//}$ and $T_{//}$ the value of τ_e approaches the calculated value τ_M obtained by using eq. 4 for the force and the "flattening" in the distribution $f(v_e)$. This is in all appearance indicative of the very great complexity of the character displayed by the friction force in the beam with "transmagnetic" electrons and when the longitudinal spread in particle velocity is very small ($\Delta v_{/\!/} / v_{\perp} \leq 10^{-3}$ (2)).

Experimental acceleration of protons by electrons described in Ref. 1, was repeated. One succeeded in increasing the proton energy from 65 MeV to 85 MeV in a time of the order of 200 s 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 s 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 oscillation beforehand the cooling of the beam done immediately after the inflector kick occurred much more rapidly (with a characteristic time smaller than the 0.015 s resolving time of the density measuring device) damping the oscillations to an intermediate amplitude value then more slowly, with the characteristic time τ_e , down to the equilibrium value. With the increase of the proton and electron currents, the value of the intermediate amplitude (for a constant initial amplitude) decreases. So for $I_e = 400$ mA, $I_p = 50$ μA, the intermediate amplitude is 1/3 of the initial value, equal to 3 mm and the time τ_e is 0.17 s.

In this range the observation of instability of the proton beam in the cooling regime should evidently occur. For $I_p \geq 60$ μA , $I_e \geq 200$ mA , and a characteristic time in the order of 50 ms, a self-produced bunching of the beam occurs and vanishes together with an increase of the beam size. The instability disappeared by reducing the proton intensity below 40 μA.

The application of electron cooling for heavy particles of low energy (order of the MeV) presents a special interest (Ref. 2-3). In that case, however, one can show that principally the cathode temperature does not allow to obtain a sufficiently "cold" electron beam.

$$\frac{\Delta v_\perp}{\beta c} \approx \sqrt{\frac{T_R}{2W}} \sim 10^{-2} \qquad (7)$$

An experiment of cooling low energy proton in the NAP-M installation was tried with the following parameters :

W_p = 1.4 MeV (injection energy)
W_e = 760 eV, I_e = 4 mA.

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

REFERENCES

1. G. Budker et al., Proc. 4th All Union Acc. Conf., Vol. 2, p.309 (1975).
2. G . Budker et al., IEEE-Trans Nucl. Sci. NS-22, P.2093 (1975).
3. G. Budker et al., submitted to Particle Accel., Preprint 76-33.
4. G. Budker, Atomnaya Energia 22, 346 (1967).
5. Derbenew and Skrinsky, Kinetics of Electron Cooling, submitted to Particle Accel., Preprint No. 225.
6. I. MacDaniel, Collision Processes in Ionized Gases - "MIR" (1967).
7. VAPP-NAP Group Report, 8th Int. Part. Accel. Conf., p.72, (CERN 1971).

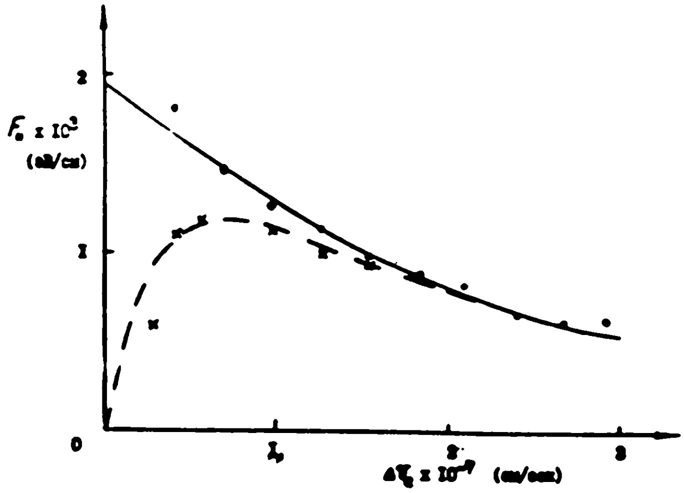

Fig. 1 : Relation between the friction force and the difference in average velocity of the protons and electrons Δv_e due to random change in electron energy. The dotted curve corresponds to experiments with an energy modulated electron beam.

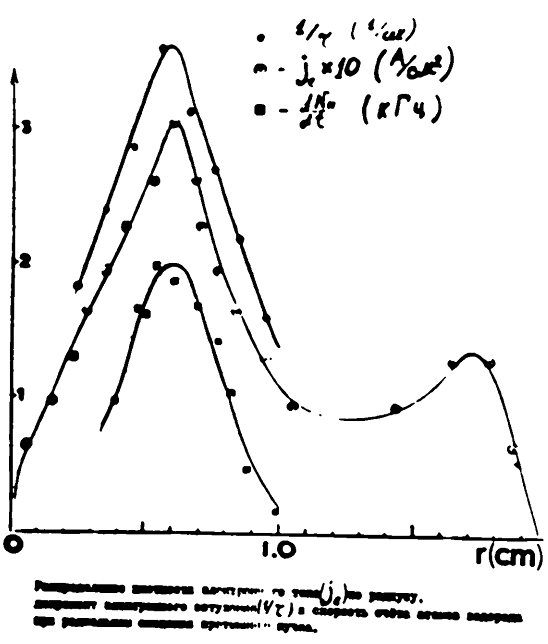

Fig. 2 : Comparison of measurement results of the radial electron density distribution J_e with the cooling time τ_e and the neutral hydrogen atom current dN/dt as a function of the position of the protons inside the electron beam.

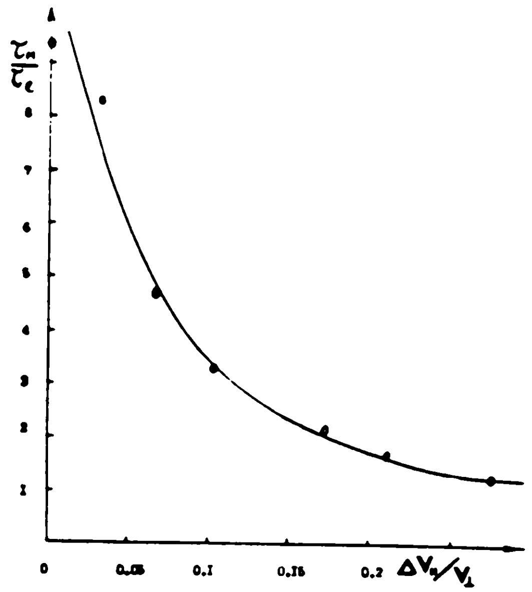

Fig. 3 : Ratio of the calculated cooling time τ_M with the experimental value as a function of the spread in longitudinal velocities $\Delta v_{\parallel}$ (in units of the transverse velocity $\Delta v_{\perp}$).