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NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

Electron cooling – the first 30 years and thereafter

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Abstract

A brief description of the development of the electron cooling method is given. The status of the theoretical methods and a summary of the methods used in experimental studies are presented. Current experiments using the electron cooling method and proposals for future experimental set-ups and facilities where electron cooling is applied are considered.

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Keywords: Storage ring; Electron beam; Ion; Binary collisions; Cooling force; Equilibrium state; Crystallization; Neutralization; Adiabatic expansion; Antihydrogen

1. "In the beginning was the word..."

The official life of the electron cooling method started in 1966, when G.I. Budker gave his talk at the "International Symposium sur les anneaux de collisions a electrons et positrons" in Saclay [1]. The general idea of electron cooling is to make use of the Coulomb interaction of a charged heavy particle beam with a comoving cold electron beam. The time which is necessary to reach thermoequilibrium in this "two-component plasma" is

$$\tau_{\text{plasma}} = \frac{3}{8\sqrt{2\pi}} \frac{mM}{Z^2 e^4 n_e L_C} \left(\frac{T_p}{M} + \frac{T_e}{m} \right)^{3/2} . \tag{1}$$

Here Ze, M and T_p are the charge, mass and temperature of the particles (ions), respectively, m, n_e and T_e are the mass, density and temperature of the electrons, respectively, and L_C is the Coulomb logarithm. The number coefficient is valid for a Maxwellian distribution of the velocities of both components.

When, at the beginning of the 60s, Budker began to think of electron cooling, he was very well aware of Coulomb interactions in a plasma, because his preceding inventions were related to plasma physics: the relativistic stabilized electron beam and the plasma trap, the so-called "corkotron" or "the mirror trap".

Another predecessor of electron cooling was the so-called ionization cooling: when the ionization energy losses of a particle penetrating a medium – let's say, a gaseous one – decelerate it. Unfortunately, application of ionization cooling is severely limited by a strong interaction between the particle and the atomic nuclei of the medium. The only exception is muons, and nowadays ionization cooling of muons is the goal of intense development (muon colliders!).

The grandeur of Budker's idea is defined by two remarkable points: to use free electrons, which permits one to avoid the undesirable strong interaction, and to move these electrons with a velocity close to that of the particles to be cooled, i.e. to apply an electron beam for particle cooling. In his first report Budker was discussing electron cooling of a proton beam to increase the luminosity of p–p colliding beams. For a proton energy of 500 MeV he estimated the cooling time to be 100 s. He accepted the suggestion of G. O'Neil to call the method "electron cooling". The idea looked very attractive, but nobody believed that it could be realized. Nevertheless, the story began. And now we have the three decades of electron cooling.

The First Decade of electron cooling (1966–1976), which started with Budker's report, was marked with a few significant events:

1966: The proposal of A. Skrinsky to use electron cooling for antiproton storing in proton–antiproton colliding beams schemes.

1967–1970: The elaboration of the first electron cooling device EPOKHA (a Russian abbreviation for Electron Beam for Cooling of Antiprotons) [2]. The main features of this apparatus (Fig. 1), an intense electron beam immersed in a longitudinal magnetic field and special electron gun optics permitting the formation of an intense electron beam with low angular spread and electron energy

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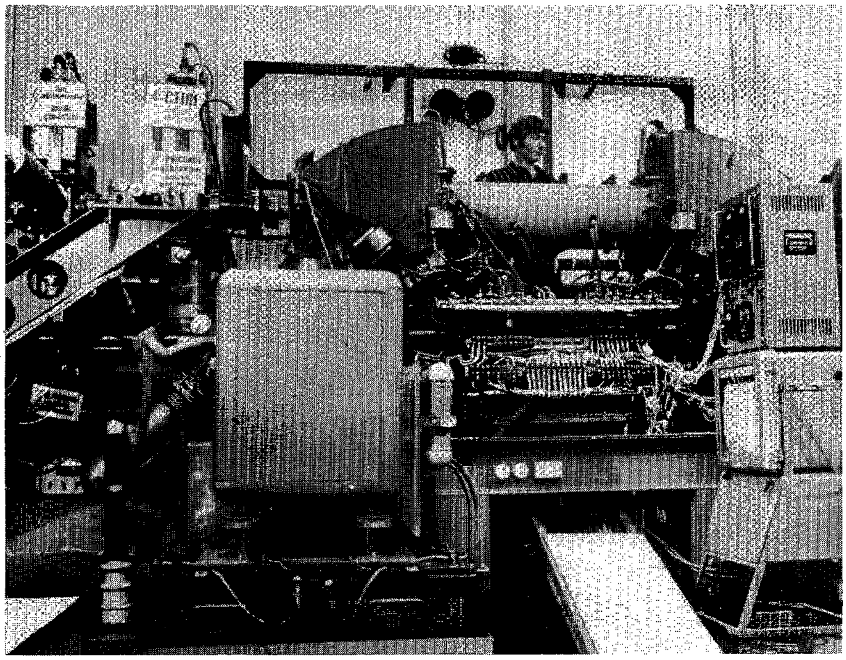


Fig. 1. The EPOKHA set-up.

recuperation (Budker's proposal), continue to be indispensable for any analogous system up to now.

1968: The idea of stochastic cooling of van der Meer (CERN) [3].

1970: The first project of proton–antiproton colliding beams (VAPP-NAP group, INP Novosibirsk [4]).

1972: The beginning of the NAP-M design (Fig. 2 and Table 1), a proton storage ring for electron cooling experiments [5].

1974: The first electron cooling of protons (the NAP-M group: G. Budker, N. Dikansky, I. Meshkov, V. Parkhomchuk, D. Pestrikov, A. Skrinsky and B. Sukhina) [6].

The first experiments brought the first puzzles: are a theoretical cooling time of 3.7 s and an experimental cooling time of 5 s in good agreement? At first the answer was "yes"! However, after an improvement of the stability of the high voltage power supply (better than 5×10^{-5}) and the quality of the longitudinal magnetic field (straightness of field lines better than 10^{-4} of an angular deviation) we achieved, in the experiments of 1975–76 [7], at the

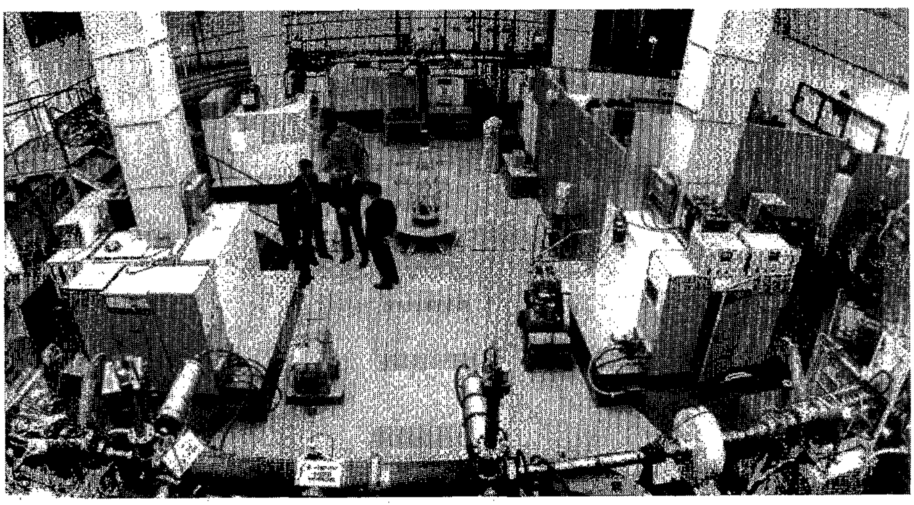


Fig. 2. The NAP-M storage ring.

Table 1
Typical parameters of the NAP-M experiment

Proton energy [MeV]	65
Electron energy [keV]	35.4
Electron beam current [A]	0.4
Electron beam diameter [cm]	1.0
Electron beam angular spread [mrad]	3.0
Storage ring perimeter [m]	47.2
Cooling section length [m]	1.0
Cooling time [s] expected	3.7
experimental (1974)	5.0

same experimental parameters a cooling time of 0.08 s, which is 50 times shorter than the theory predicted (!), and an angular spread of the cooled proton beam of 30 μrad, which is 2 times less. These results opened

The Second Decade of Electron Cooling (1976–1986).

1976–78: Observation and study of "fast" electron cooling [7,8].

1976–1978: The theory of electron cooling with a "flattened distribution" (V. Parkhomchuk) and "magnetized" electrons (Ya. Derbenev, A. Skrinsky) [9,10]).

1976: The Novosibirsk projects of proton–antiproton colliding beams for IHEP (Protvino), FNAL and CERN [11].

77–79: ICE (Initial Cooling Experiment) at CERN [12].

1979–82: Test ring experiment at FNAL [13].

1976: Schottky noise depression in a cooled proton beam in NAP-M – the orderliness of the cooled proton beam [14].

1976: The proposal of experiments with superthin internal targets in ion storage rings with electron cooling [15].

1979: Lamb shift measurements with hydrogen in-flight [16].

1978: The idea of antihydrogen and protonium generation [8].

1982: The first project of an antiproton storage ring with electron cooling for antihydrogen generation [17].

1984: The idea of a crystalline charged particle beam in a storage ring with electron cooling [18].

Some ideas were not realized at that time; however they defined the tendency of the development of the method and of applications. The main result of the second decade was the formulation of the electron cooling theory, understanding of the physics of the electron cooling process.

The Third Decade of Electron Cooling (1986–1996)

1986–1988: Single pass electron cooling experiment MOSOL [19,20].

1987: The first electron cooling of a proton beam in LEAR at CERN [21].

1988: The first electron cooling of an antiproton beam in LEAR at CERN [22].

1988: The beginning of the era of 9 cooler rings: LEAR, IUCF, TSR, CELSIUS, TARN-II, ESR, CRYRING, ASTRID, COSY [23–25]. One can acknowledge as doubtless achievements of this period:

- Antiproton beam forming for antiproton physics experiments at LEAR;
- Electron cooling of "all the elements" of the periodic table (TSR, CELSIUS, TARN-II, ESR, CRYRING);
- Electron cooling of multicharged and fully stripped ions (ESR);
- High precision measurement of isotope masses (ESR);
- New stage of experimental atomic physics: the studies of radiative and dielectronic recombination, deep shells of atomic structure and others (TSR, ASTRID, ESR, CRYRING);
- Laser cooling aided by e-cooling (ASTRID, TSR).

2. The status of electron cooling physics

What did we learn and what do we know now about the physics of electron cooling?

First of all, the specificity of the electron beam used in coolers should be mentioned. When an electron beam is generated with an electron gun, immersed in a longitudinal magnetic field, the beam characteristics have two specific features: the so called "flattened distribution" of electrons over velocities and "magnetization" of electrons, if the magnetic field is as strong as is necessary (see formula (5) below). The "flatness" of the electron velocity distribution appears due to acceleration in an electrostatic field: the electron longitudinal velocity spread decreases due to the acceleration and increases at the same time as a result of the "relaxation" of the electron random distribution in space. This relaxation is produced by the Coulomb interaction between electrons (see Ref. [24] for details). The transverse temperature does not change significantly during acceleration (or changes slightly due to gun optics aberrations). Finally one gets the formulae:

$$T_\perp \equiv m\Delta_\perp^2 = T_{\text{Cathode}} + T_{\text{Optics}},$$
$$T_\parallel = m\Delta_\parallel = \frac{T^2_{\text{Cathode}}}{\beta^2\gamma^2 mc^2} + e^2 n_e^{1/3}. \tag{2}$$

Here $\Delta_\perp$ and $\Delta_\parallel$ are the components of the electron velocity spread, β is the ratio of the ion velocity to the speed of light c, $\gamma = (1-\beta^2)^{-1/2}$, and n_e is the electron density in electron rest frame. In a typical case (E_e = 50 keV, $n_e = 5\times 10^7\ \text{cm}^{-3}$, $T_{\text{Cathode}} \sim T_{\text{Optics}} \sim 0.1$ eV) we have $T_\perp \sim 0.2$ eV, $T_\parallel \sim 0.1$ μeV + 50 μeV.

Describing the binary collisions in magnetized plasma, one can point out three types of collisions (Fig. 3) between a particle (P) and an electron (e) in a magnetic field: fast (1), multiple (2) and "magnetized" (3). In case (1) the interaction is not influenced by the magnetic field, because the collision time is much shorter than the Larmor revolu-

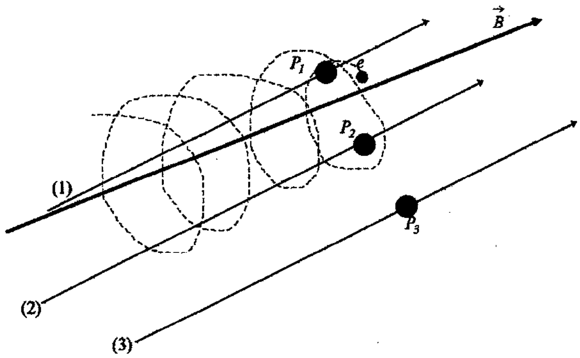


Fig. 3. Three kinds of collisions between an electron (e) and a particle (P) in a magnetized electron beam: fast (1), multiple (2) and "magnetized" (3).

tion period of the electron. In case (2) the particle meets (collides) a few times with the same electron due to electron Larmor rotation. This magnifies the friction force by a factor N equal to the number of such collisions. In case (3) the electron looks for a particle like a Larmor circle, which can move only along some magnetic field line. The magnetized collisions play a significant role if the average radius of the Larmor circles, which is equal to

$$\rho_\perp = m\Delta_\perp c/eB\,, \tag{3}$$

is smaller than the radius of the Debye shielding sphere

$$R_{\text{shielding}} = \max\{R_{\text{Debye}}, R_Z\}\,,$$

$$R_{\text{Debye}} = \sqrt{\frac{T_\parallel}{4\pi n_e e^2}}\,, \tag{4}$$

$$R_Z = \left(\frac{3Z}{n_e}\right)^{1/3}.$$

When $R_{\text{shielding}} > \rho_\perp$, a number of "Larmor circles" exists inside the shielding sphere and the ion can undergo magnetized collisions. Otherwise, no electrons inside the sphere look like "little Larmor circles". In the case of usable parameter magnitudes one has $R_{\text{Debye}} > R_Z$; then the magnetization condition can always be obtained if $\rho_\perp < R_Z$, or

$$B > \left(\frac{n_e}{3Z}\right)^{1/3} \frac{m\Delta_\perp c}{e}\,. \tag{5}$$

Summarizing all the possible cases of collisions between an ion and electrons, one can write down the formulae for the electron cooling friction force. These formulae consist of three parts. Each one describes one of the three specific cases of interaction: high (H), $V > \Delta_\perp$; low (L), $\Delta_\perp > V > \Delta_\parallel$; and superlow (S), $V < \Delta_\parallel$ ion velocity. Correspondingly, there are three groups of Coulomb logarithms, and every group, in its turn, contains three terms, describing the fast (F), multiple (A: "adiabatic") and magnetized (M) collisions. Thus, the complete formulae look rather complicated (see details in Ref. [24]):

$$F_\perp = -\frac{2\pi n_e Z^2 e^4}{m} V_\perp \times \begin{cases} \dfrac{1}{V^3}\left(2L_{\text{FH}} + \dfrac{V_\perp^2 - 2V_\parallel^2}{V^2} L_{\text{MH}}\right), & \text{H} \\ \dfrac{2}{\Delta_\perp^3}(L_{\text{FL}} + N_{\text{L}} L_{\text{AL}}) + \dfrac{V_\perp^2 - 2V_\parallel^2}{V^2}\dfrac{L_{\text{ML}}}{V^3} & \text{L} \\ \dfrac{2}{\Delta_\perp^3}(L_{\text{FS}} + N_{\text{S}} L_{\text{AS}}) + \dfrac{L_{\text{MS}}}{\Delta_\parallel^3}, & \text{S} \end{cases}$$

$$F_\parallel = -\frac{2\pi n_e Z^2 e^4}{m} V_\parallel \times \begin{cases} \dfrac{1}{V^3}\left(2L_{\text{FH}} + \dfrac{3V_\perp^2}{V^2} L_{\text{MH}} + 2\right), & \text{H} \\ \dfrac{2}{\Delta_\perp^2 V_\parallel}(L_{\text{FL}} + N_{\text{L}} L_{\text{AL}}) + \left(\dfrac{3V_\perp^2}{V^2} L_{\text{ML}} + 2\right)\dfrac{1}{V^3}, & \text{L} \\ \dfrac{2}{\Delta_\perp^2 \Delta_\parallel}(L_{\text{FS}} + N_{\text{S}} L_{\text{AS}}) + \dfrac{L_{\text{MS}}}{\Delta_\parallel^3}, & \text{S} \end{cases} \tag{6}$$

where all the parameters, including the force components, are taken in the particle rest frame, n_e is the electron density, Ze is the particle (ion) charge, m is the electron mass, $V_\perp$ and $V_\parallel$ are the ion velocity components, $N_{\text{L}} = [\Delta_\perp/\pi V]$, $N_{\text{S}} = [\Delta_\perp/\pi\Delta_\parallel]$, the symbol [ ] denotes the integral part of the magnitude in brackets, and $V = (V_\perp^2 + V_\parallel^2)^{1/2}$. The Coulomb logarithms are described by the expression:

$$L_{\text{FH}} = \ln\frac{mV^3}{Ze^2\omega_{\text{B}}} = L_{\text{FL}}\,,$$

$$L_{\text{MH}} = \ln\frac{V\omega_{\text{B}}}{2\Delta_\perp\omega_e}\,,$$

$$L_{\text{AL}} = \ln\frac{2\Delta_\perp}{V}\,,$$

$$L_{\text{ML}} = \ln\frac{\max\left\{\dfrac{V}{\omega_e}, \left(\dfrac{3Z}{n_e}\right)^{1/3}\right\}}{2\rho_\perp}\,,$$

$$L_{\text{FS}} = \ln\frac{m\Delta_\parallel\Delta_\perp^2}{Ze^2\omega_{\text{B}}}\,,$$

$$L_{\text{AS}} = \ln\frac{2\Delta_\perp}{\Delta_\parallel}\,,$$

$$L_{\text{MS}} = \ln\left(\frac{1}{2\rho_\perp}\left(\frac{3Z}{n_e}\right)^{1/3}\right). \tag{7}$$

Here $\omega_{\text{B}} = eB/mc$ and $\omega_e = \sqrt{4\pi n_e e^2/m}$ are the electron cyclotron and plasma frequencies, respectively.

Any analytical calculations using these formulae are relatively cumbersome, and the most efficient way is to use computer simulations. For rough estimations one usually uses the approximate formula for the cooling time: the time which is necessary to cool down an ion with initial angular and/or momentum shift. In the laboratory reference frame this formula can be written as follows:

$$\tau_{\text{cool}} \approx \frac{\beta^4\gamma^2}{6\pi c r_p L_C} \frac{mc^3}{\eta e J} \frac{A}{Z^2} [\gamma^2(\Theta_x^2 + \Theta_z^2) + \Theta_s^2]^{3/2} . \quad (8)$$

Here r_p is the classical proton radius, $L_C \sim 10$ is the Coulomb logarithm (by an order of magnitude), e and m are the electron charge and mass, respectively, η is the ratio of the cooling section length to the ion ring circumference, J is the density of the cooling electron beam, A and Ze are the atomic weight and charge of the ion respectively (we also note that $mc^3/e = 17$ kA), and $\Theta_\alpha = \Delta p_\alpha / p$ are the components of the ion momentum shift.

Numerical calculations of the formulae (6) and (7) demonstrate very clearly the influence of the magnetization on the magnitude of the cooling force (Fig. 4): the magnitude of the friction force increases with increasing magnetic field and the maximum of its transverse component shifts from $V = \Delta_\perp$ (curve 1) to $V = \Delta_\parallel$ (curves 2–4).

Up to now the most precise experimental studies are performed for the longitudinal component of the friction force (see references in Ref. [24]). It is measured for all the ions of the periodic table of elements (Fig. 5). In general, good agreement between the theoretical description and experimental values of the force are observed in the region of the high and low ion velocities. At superlow velocities the results of different experiments seem to correspond to different values of the electron velocity spread $\Delta_\parallel$. This is fairly realistic, especially in the case of early experiments, like ICE CERN. Nevertheless, the behaviour of $F_\parallel$ in this region is an open question. Particularly, even the normalization of the experimental results, used here, is not completely correct [26], because the maximum of the friction force is proportional to $n_e^{2/3}$ (see Refs. [20,24]):

$$F_{\max} = -2\pi Z^2 e^2 n_e^{2/3} . \quad (9)$$

Also the proportionality of $F_{\max}$ to Z^2 seems doubtful [26].

The binary collision approximation is not the only possible approach in electron cooling theory. There also exists the "dielectric approximation", well developed in plasma physics. Its application to electron cooling gave up to now some contradictory results. So, the authors of Ref. [27] claimed a significant discrepancy between dielectric theory and the binary collision approach. This statement seems to be doubtful, because analysis of others (see Ref. [20]) showed good agreement between both approaches and, moreover, the data used in Ref. [27] for the binary collision approximation look incorrect [28].

There is also some effort to use computer simulations of the collisions and the cooling process, the so called "molecular dynamics" simulations [29]. These studies are limited yet by computer possibilities and a comparison of the obtained results with experiment is very difficult.

The equilibrium state of the ion beam cooled by a magnetized electron beam is defined by the electron longitudinal temperature $T_\parallel$:

$$T_{\text{ion}} = T_\parallel , \quad \text{or} \quad \sqrt{\langle V^2 \rangle} = \sqrt{\frac{m}{M}} \Delta_\parallel . \quad (10)$$

This value is very small; therefore even at low intensity of the ion beam the effects of the beam space charge and intrabeam scattering begin to play a significant role when the beam is well cooled. Particularly, a very interesting phenomenon observed in different experiments is the appearance of so called "space charge waves", well known in physics of intense particle beams (see details in Ref. [24]).

The dependence of the momentum spread of a cooled beam has a very specific character (Fig. 6): at certain conditions the momentum spread drops to a very low value and remains constant with a decrease of the ion beam intensity.

For the first time such a "disappearance" of the beam momentum spread was observed in experiments on NAP-M [14], where the suppression of the Schottky noise of the cooled proton beam up to a very low level was registered. Then the assumption of some orderliness of the cooled beam was declared and soon the idea of the crystalline beam was proposed [18]. The main criterion of beam crystallization (orderliness) is a decrease of the particular

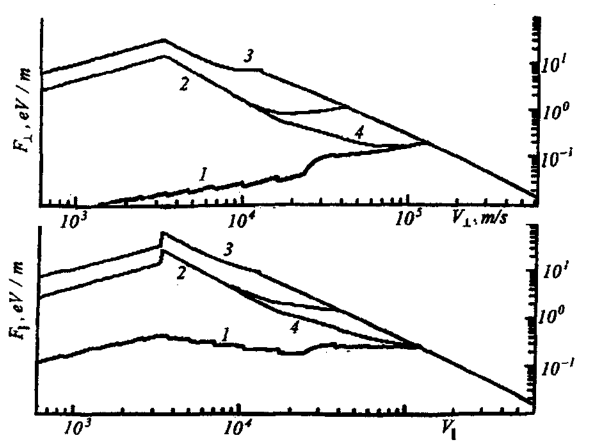
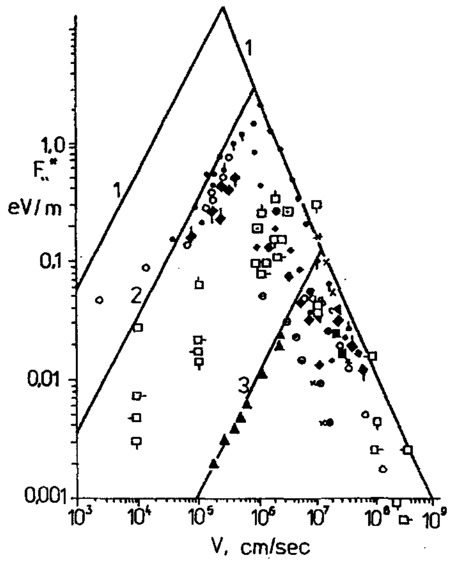


Fig. 4. Dependence of the cooling force on the ion velocity in the particle rest frame calculated for different values of the magnetic field and the electron temperature: the ion $^2D^+$ at energy 20 MeV/amu, electron density 0.8×10^8 cm^{-3}, $T_\perp$ [meV] = 100 (1, 4), 10 (2), 1 (3), $B = 0.3$ kG (1, 2, 3) and 1 kG (4). (a) The transverse force, when $V_\parallel = 0$; (b) the longitudinal force, when $V_\perp = 0$.



Symbol	Setup	Particles	Energy (MeV/nucleon)
	NAP-M	protons	65
●	MOSOL	protons	0.85
▲	ICE	protons	47
○	IUCF	protons	45
	LEAR	protons	49
+	TARN	protons	20
	CELSIUS	protons	180
⊙	CELSIUS	deuterons	783
	CELSIUS	O^{6+}	296
	TSR	deutrons	12
	TSR	Li^{3+}	12
	TSR	C^{6+}	12
	TSR	O^{5+}	12
	TSR	S^{16+}	12
•	CRYRING	deutrons	12.2
	ESR	C^{6+}	250
	ESR	Ti^{22+}	250
	ESR	Xe^{54+}	250
	ESR	U^{92+}	250

Fig. 5. Results of measurements of the longitudinal friction force $F^* = F_\parallel / Z^2 n_e^*$, where n_e^* is the reduced ion density in the particle rest frame and η is the ratio of the cooling section length to the ring circumference. The solid lines are calculations for various values of $\Delta_\parallel$ (cm/s): 3.4×10^5(1), 1×10^6 (2), 1×10^7(3).

temperature to a value lower than the interparticle potential energy:

$$T_{\text{particle}} < U_{\max} \approx \frac{z^2 e^2}{l}, \tag{11}$$

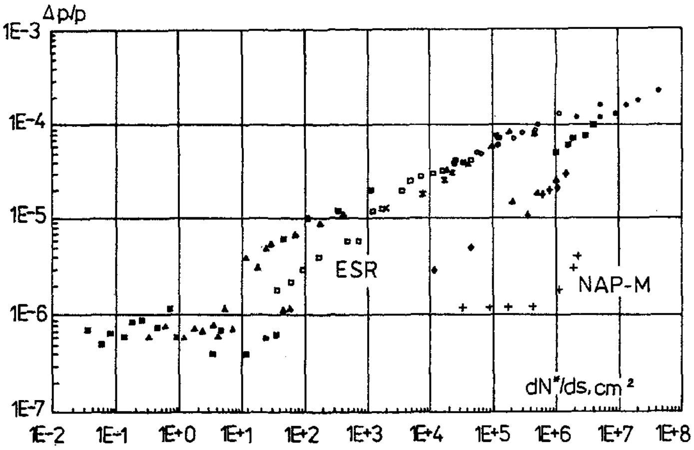
where l is the minimal distance between particles in the cooled ion beam (in the particle rest frame!) [18,28]:

$$l \approx \min\{l_\parallel, a_\perp\}, \quad l_\parallel = \frac{C/\gamma}{N}, \tag{12}$$

where N is the number of particles in the beam, C is the ring circumference, and $a_\perp$ is the transverse size of the beam (the maximum impact parameter in interparticle collisions). When condition (12) is satisfied, i.e. when the beam is cooled up to a low enough temperature, it gets the form of a chain: the ions do not pass one another. We can also formulate the conditions for the chain structure formation, introducing the Γ-parameter, which is usually used in solid physics to characterize the system orderliness:

$$\Gamma_{\parallel,\perp} \equiv \frac{z^2 e^2}{T_{\text{particle}} l} > 1. \tag{13}$$

The effect obtained on NAP-M was not confirmed by experiments on another storage rings during a long time. only recently a similar behavior of cooled beams of



Symbol	Ion	*E, MeV/u*	Symbol	Ion	*E, MeV/u*
+	protons	65	o	$^{129}Xe^{54+}$	250
✱	$^{209}Bi^{82+}$	230	□	$^{197}Au^{79+}$	290
□	$^{20}Ne^{10+}$	250	Δ	$^{84}Kr^{36+}$	150
Δ	$^{40}Ar^{16+}$	250	◆	$^{20}Ne^{10+}$	150
•	$^{12}C^{6+}$	5.3	o	$^{238}U^{92+}$	330
■	$^{197}Au^{79+}$	370	▲	$^{59}Ni^{26+}$	205

Fig. 6. Dependence of the ion momentum spread on the reduced linear density of the cooled beam:

$$\frac{dN^*}{ds}=\frac{Z^2}{A}\frac{N}{\eta_\omega\beta^2\gamma C^*},$$

$$C^*=\begin{cases} C-\text{coasting beam}, \\ l_{\text{bunch}}-\text{bunched beam}. \end{cases}$$

NAP-M – protons, ESR – ions.

$^{197}Au^{79+}$ and $^{59}Ni^{28+}$ ions was observed on ESR at GSI [30]. Examining the data of both experiments one can distinguish three critical points (numbers 1, 2, 3 in Fig. 6) where the Γ-parameter in larger than 1 (Table 2).

The beam orderliness observed experimentally encourages the following studies to be more sophisticated.

3. Development of the electron cooling method

Enhancement of the electron cooling efficiency always remains the principal problem of the method. One can point out a few directions of such a development.

1) Creation of a new generation of electron guns, which permit one to generate high perveance electron beams with small angular spread. For instance, the three electrode gun for the LEAR electron cooler has a maximal perveance of $5\ \mu A/V^{3/2}$ [31].

2) Formation of intense electron beams with neutralized space charge. This allows one to achieve a very low electron velocity spread. The stable current of a neutralized electron beam is limited by the so called beam-drift instability:

$$I_{\text{neutralised}}\le\frac{\beta^2 cB}{kL}. \tag{14}$$

Here L is the beam length and $1<k<8$ is the numerical coefficient, the value of which depends on the beam length, electron energy, electron collection efficiency,

Table 2
The parameters of the ordered beams in NAP-M and ESR experiments

Storage ring	NAP-M	ESR	ESR
Point N	1	2	3
Particles	p	$^{197}Au^{79+}$	$^{59}Ni^{28+}$
E, MeV/u	65	370	205
$\Delta p/p$	1.2×10^{-6}	4×10^{-7}	6×10^{-7}
$T_\parallel$, meV	0.17	14	6.5
ε, π mm mrad	2×10^{-3}	$\sim1\times10^{-3}$	
$a_\perp$, mm	0.1	~0.1	
Number of particles	2×10^{7}	1×10^{3}	700
$l_\parallel$, mm	2.3×10^{-3}	150	180
$\Gamma_\parallel$	3.7	4.3×10^{-3}	1×10^{-3}
$\Gamma_\perp$	0.08	6.4	1.7
Orderliness	yes	yes	yes

vacuum conditions and magnetic field B. Some active methods of instability suppression permit one to reach $k=2$ in high vacuum (for details see Ref. [32] and references therein).

3) The idea of a decrease of the electron angular spread (transverse temperature) by beam expansion in a decreasing magnetic field was proposed and tested fairly long ago [33,34], and recently an enhancement of the longitudinal cooling force by about 10 times due to electron beam expansion was demonstrated and measured in CRYRING experiments [35]. Nowadays there are a few proposals to use this method.

Actually, to increase the cooling efficiency, one should increase the magnetic field in the gun area B_{gun}, and keep the magnetic field B_{cool} and electron density in the cooling section constant. It follows from adiabatic invariance conservation, that in this case the electron Larmor circle radius decreases with increasing B_{gun}:

$$(\rho_\perp)_{cool}=\frac{1}{e}\sqrt{\frac{T_c mc^2}{B_{gun}B_{cool}}}. \tag{15}$$

Otherwise, when one keeps B_{gun} and $(n_e)_{cool}$ constant and decreases B_{cool}, the magnetization becomes worse (see Formulae (3) and (5)). Fig. 3 presents the results of the cooling force calculation for the parameters of the CRYRING experiment. One can conclude from this picture that an expansion (compression in the gun area!) of the cooling electron beam can improve the magnetization of the electrons and, as result, magnify the cooling force, but only in the region of low ion velocities, near the force maximum, and it practically has no effect in the region of high ion velocities. Therefore, compression does not decrease the cooling time of an ion beam with a large emittance and/or a large momentum spread. Computer simulations of the electron cooling process confirm this conclusion: the cooling time decreases with electron temperature only if the beam emittance is small enough. For a large emittance the cooling time practically does not depend on T_e. Nevertheless, the adiabatic expansion is profitable when one deals with a preliminary cooled ion beam. Then the cooling force enhancement helps to keep the beam parameters the same in experiments with an internal target, colliding beams, crystalline beams and so on. Another application is atomic physics experiments when the electron beam is used as an electron target with a variable electron temperature.

4) The intention to apply electron cooling to the medium energy range, at an electron energy of the order of a few MeV, looks very attractive. A corresponding study is being carried out for several years at FNAL [36].

4. Electron cooling today and thereafter

The various applications of the electron electron cooling method in experimental physics are now bringing remarkable results. One can point out different fields where this method is applied and where further applications and developments are expected.

4.1. High energy physics

Electron cooling invested originally for high energy physics development, continues to bear fruit in this field. The existing facilities are:
- LEAR CERN – storing and cooling of antiprotons, antiproton physics (closed for antiprotons in December 1996);
- IUCF Bloomington – intermediate energy physics with cooled and polarized proton beams;
- COSY jülich KFA, CELSIUS Uppsala University – high energy physics with the use of cooled proton and ion beams.

The projects are:
- LEAR CERN – storing and cooling of multicharged ions for ion–ion colliding beams in LHC;
- AD (Antiproton Decelerator) CERN – a new stage in

antiproton physics – a machine proposed to replace the existing LEAR;
- Recycler at FNAL – medium energy electron cooling for storing of antiprotons and enhancement of the luminosity of the Tevatron collider;
- GSI – ion–ion and electron–ion colliding beams in the energy range of several GeV/u.

4.2. Nuclear physics

Application of cooled ion beams permits experiments in nuclear physics to be performed under conditions unavailable before. Among them are the following:
- Generation and storing of "exotic" nuclei: radioactive ion beams, short-lived isotopes and isomers and nuclei in excited states;
- Studies of nuclear physics in collision of a cooled circulating beam with an internal target;
- High precision measurements of the lifetime of radioactive nuclides;
- High precision measurements of isotope masses.

It is worth mentioning, that the isotope mass resolution in a cooled ion beam is equal to [24]

$$\frac{\Delta M}{M} = -\gamma_{tr}^2 \frac{\Delta\omega_s}{\omega_s} + (\gamma_{tr}^2 - \gamma^2)\frac{\delta\nu}{\nu} + \frac{\delta B}{B}, \qquad (16)$$

where $\delta\omega_s$ is the ion revolution frequency spread, $\delta\nu$ is the ion longitudinal velocity spread, and δB is the level of pulsation of the storage ring magnetic field. The best resolution achieved in experiments (GSI), is of the order of 10^{-6} [30,37].

The existing facilities are:
- ESR GSI, TSR MPI Heidelberg, CELSIUS Uppsala, CRYRING Stockholm University.

The projects are:
- K4-K10 JINR Dubna [25], HIRFL IMP Lanzhou [38] – cooled ion beams interacting with internal targets;
- MUSES RIKEN [39] – ion–ion and electron–ion colliders in the energy range up to 800 MeV/u ions and 2.5 GeV electrons;
- GSI – electron–ion collider, 300 MeV/u ions, 500 MeV electrons, counter- or copropagating electron–ion beams [40].

4.3. Atomic physics

Experimental studies with cooled ion beams have a big advantage – the parameters of the experiment can be well controlled and finely regulated. One can point out two main directions of such studies:
- the use of the cooling electron beam as an electron target;
- laser spectroscopy with superhigh resolution (including laser cooling and related problems).

The experiments being performed or planned are:
- recombination, excitation–radiation processes in ions, including highly stripped ions, where transitions between deep internal shells (states) are involved.

The existing facilities are:
- TSR MPI Heidelberg, ASTRID Aarhus University, ESR GSI, CELSIUS Uppsala University, CRYRING Stockholm.

The projects are:
- new sets of experiments on all existing facilities.

4.4. Crystalline beam physics

This problem is under intense theoretical examination presently, and computer simulation methods are widely and efficiently exploited. There are still many unclear points in the understanding of the reliability of the idea, such as, for instance, the crystalline beam structure stability, particularly when the beam is transferred from a straight section into a bending magnet. Many questions are answered already and the progress in theoretical analysis is significant. Nevertheless, the "last word" is for experiment. And a corresponding proposal of the experiment exists – a project of INFN (Legnaro, Italy) of a dedicated storage ring for ion beam crystallization [41].

4.5. Antihydrogen and positronium beams generation; tests of the CPT theorem and QED

The first generation of antihydrogen atoms in antiproton–nuclei collisions in LEAR at CERN [42] encouraged an activation of an antihydrogen generator elaboration. Since the first publication [8] the idea has undergone a large evolution (see Refs. [17,43]) and recent proposals permit one to estimate it as a realistic one (see details in Ref. [44]). The proposed scheme permits one to generate intense and directed fluxes of antihydrogen and orthopositronium. The essential point of the proposal is the use of electron cooling to cool both the antiprotons and the positrons. The possible high precision experiments with antihydrogen and positronium in-flight are of profound interest for tests of fundamental physics theories – the CPT-theorem and quantum electrodynamics [45].

5. Conclusion

The electron cooling exerted in fact a revolutionary influence on the mentality of physicists – it worked as a "gun trigger" in the development of the many cooling methods we have developed and are developing today:
- stochastic cooling (permitted the creation of the first proton–antiproton collider!),

– laser cooling in storage rings,
– ionization, or "muon cooling" (future muon colliders).

A few advanced cooling methods are being discussed now, such as stochastic cooling in optical diapason [46], coherent electron cooling [47], expansion of electron cooling in the range of intermediate energies [36] and others. The proposals for electron–ion colliders, where the application of cooling methods is a key point, look very promising. Celebrating the 30th anniversary of electron cooling one can say that cooling methods and their technique are under intense development and enrich possibilities of new experiments in physics.

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