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Electron cooling[☆]

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Abstract

The brief review of the most significant and interesting achievements in electron cooling method, which took place during last two years, is presented. The description of the electron cooling facilities—storage rings and traps being in operation or under development—is given. The applications of the electron cooling method are considered. The following modern fields of the method development are discussed: crystalline beam formation, expansion into middle and high energy electron cooling (the Fermilab Recycler Electron Cooler, the BNL cooler—recuperator, cooling with circulating electron beam, the GSI project), electron cooling in traps, antihydrogen generation, electron cooling of positrons (the LEPTA project).

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1. Introduction

The electron cooling method since its first presentation by Budker, the method inventor, in 1966 [1] has undergone a long and significant development. Demonstrated and studied in the first experiments in INP, Novosibirsk (1974, Figs. 1 and 2) [2], CERN (1980) [3] and Fermilab (1982) [4], the method became an efficient tool of the experimental studies in different fields of application. Nowadays 10 storage rings are in operation and two facilities under construction (Table 1). The projects of new accelerator facilities with electron cooling application in the middle and high-energy range are being developed (see Section 3). As before all the cooler storage rings operate presently in low ion energy range—below 700 MeV/amu. Remarkable results have been achieved at these rings due to effective electron cooling of all kinds of ions of the periodic table and antiprotons.

What was done with *electron cooling application*?

(1) *Particle physics*. Experiments with cooled and extracted slow antiprotons at LEAR (CERN) have brought a new knowledge in particle physics. Among them, as an example, one can point out the

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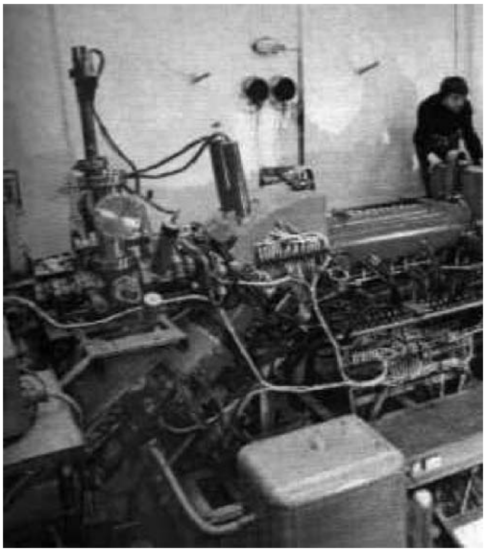

Fig. 1. The beginning of Electron Cooling Epoch: the first electron cooler EPOkhA at Budker INP, Novosibirsk (Rus. Abbreviation "Electron Beam to Cool Antiprotons).

Fig. 2. The team of experimentalists in the control room of the first cooler storage ring NAP-M: I. Meshkov, B. Sukhina, D. Pestrikov, V. Ponomarenko, V. Parkhomchuk, N. Dikansky (demonstrates proton beam profiles at injection, without and after electron cooling).

experimental discovery of so-called Okubo–Zweig–Iizuka rule violation, in $p\bar{p}$ interaction at low energy, which proved a complicated structure of nucleons [5].

Important results were achieved in particle physics of middle energy ("meson physics") with protons of 1–2 GeV energy interacting with a target at three storage rings—IUCF, COSY and CELSIUS. These experiments are in progress. One should note here the idea of superthin target application in a cooler ring, proposed in Ref. [6].

(2) *Nuclear physics*. Physics of radioactive nuclei and rare isotopes, studies of exotic nuclei states are carried out with cooled ion beams at ESR and SIS (GSI). High-precision measurements of isotope mass, with accuracy below $\Delta M/M \leqslant 10^{-6}$ were performed at ESR.

(3) *Atomic physics*. New stage of experiments in atomic and molecular physics became possible owing to electron coolers TSR, CryRing, ASTRID. The cooling electron beam is used in this rings as an electron target, which allows to study electron-ion interaction at pure vacuum conditions.

(4) *Antihydrogen generation*. First antihydrogen generation in-flight was performed at LEAR in 1996 [7]. Later commissioning of AD cooler ring at CERN made possible to set up two experiments with antihydrogen ("H"-bar) generation at rest—ATHENA and ATRAP. Both of them reported obtaining first H-bar atoms in 2003. Here *electron cooling in traps* is used as an efficient tool.

(5) *Beam physics*. Effect of a sudden reduction of an ion beam momentum spread during electron cooling discovered in NAP-M [8] was studied in details in ESR, SIS [9] and CryRing [10]. It was interpreted as a beam ordering ("crystallization") and recently, three-dimensional crystalline beams were obtained in traps and in small storage ring PALLAS [11].

Electron cooling development initiated a creation of another cooling method—the laser cooling. An ion beam circulating in a storage ring and cooled preliminary with an electron beam can reach a significantly lower temperature when the laser cooling is applied—TSR, ASTRID, ESR.

(6) *First experience "electron cooled" ions application in cancer therapy*. The most significant new application of electron cooling is being developed at NIRS (Chiba, Japan) for medical diagnostics in cancer therapy. The beam of $^{12}C^{6+}$ ions, accelerated and cooled in the HIMAC (Heavy Ion Medicine Accelerator [12]), is extracted and will be directed to a patient or used for basic research.

Table 1
Electron cooler storage ring

Ring	Laboratory country	Years of operation	Particles	Maximum energy (MeV/u)	Circumference (m)	Electron cooler	
						Length (m)	Energy (keV)
NAP-M	Budker INP USSR	1974–1984	p	1.5–85	47	1.0	0.8–46
ICE	CERN Switzerland	1979–1980	p	46	74	1.5	26
Test ring	Fermilab USA	1980–1982	p	200	111	2.0	111
LEAR (LEIR)	CERN Switzerland	From 1988	p	64	78.6	1.0	35
MOSOL (single pass cooling)	Budker INP USSR	1986–1988	p, H^-	0.85	Length 3 m	2.4	0.470
IUCF COOLER	Bloomington USA	From 1988	$A \leqslant 7$	500	86.8	2.8	10–270
TSR	Heidelberg Germany	From 1988	$A \leqslant 127$	30	55.4	1.5	3–20
TARN-II	Tokyo Japan	1989–	$A \leqslant 20$	100	77.8	1.5	$\leqslant 130$
ASTRID	Aarhus Denmark	Since 1993	Light ions	50	40		27
ESR	Darmstadt Germany	Since 1990	$A \leqslant 238$	30–560	108.4	2.5	10–320
CELSIUS	Uppsala Sweden	Since 1989	$A \leqslant 40$	340 (1360)	81.8	2.5	10–300
CRYRING	Stockholm Sweden	Since 1992	$A \leqslant 238$	0.3–24	51.6	1.1	2–20
COSY	Jülich Germany	Since 1993	p	40–2500	184	2	100
HIMAC	Chiba Japan	Since 1993	He, C, Ne, Si, Ar	800	131.88	1	30
SIS	Darmstadt Germany	Since 1998	$A \leqslant 238$	2.0	216	3.35	35
AD	CERN Switzerland	Since 1998	antiprotons	2.76 GeV–5.31 MeV	169.56	2	50–150

(7) *Recent achievements*. Electron cooling method experiences an intense development nowadays. New ideas in theory, experimental technologies and applications appear continuously. A short review presented below gives a description of most significant achievements.

A few facilities are under construction now. The first of them is The Heavy Ion (HIRFL-CSR) complex in The Institute of Modern Physics (Lanzhou, China). That is two rings facilitiy similar to the K4–K1O project at JINR [13], which was elaborated in the 90th, but abandoned due to lack of funding. The HIRFL-CSR project is under realization. Both rings are being manufactured in Lanzhou, two electron coolers are constructed in Budker INP collaborating with IMP. First of them is transported to Lanzhou, assembled and tested (Fig. 3).

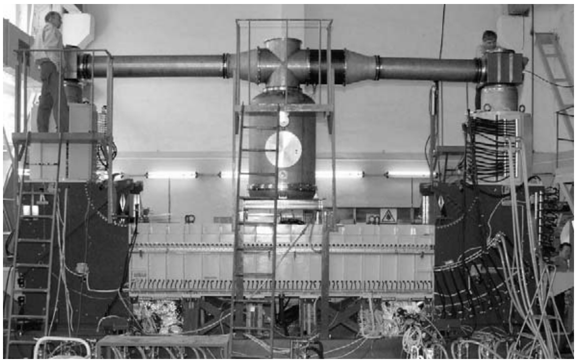

Fig 3. Test of the HIRFL-CSR electron cooling system in Lanzhou (fabricated in Budker INP, Novosibirsk).

The Low-Energy Antiproton Ring (LEAR) was used very successfully in the 80th, as mentioned above, will be transformed in an ion storage ring LEIR for storing and preliminary acceleration of lead ions for injection into cascade of CERN accelerators—PSB, PS, SPS and finally in LHC. This project is under realization now [14]. Particularly, new electron cooler will be manufactured and commissioned by the team from Budker INP.

MUSES project at RIKEN has undergone significant changes during last two years. Nevertheless, electron cooling systems remain among key elements of the facility [15].

In the frame of the TEVATRON luminosity upgrade program one plans to use electron cooling for 9 GeV antiprotons at the RECYCLER ring.

The system was constructed and is testing now [16].

2. Low-energy electron cooling

2.1. Cooling of high intensity beams

Very important understanding of intensity limitation nature of a cooled beam was obtained during recent years. Experimental studies of proton beam injection and storage with electron cooling in COSY [17] demonstrated two-stages mechanism of particle loss:

(1) fast losses directly after injection,
(2) slow losses in the cooled proton beam caused by a coherent instability with transformation of horizontal oscillations into vertical ones.

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The fast initial losses are supposed to be a result of an influence of the electron beam field nonlinearity. Another explanation is related with plasma oscillations in the ion and electron beams, which lead to noise of big amplitude reducing the ion lifetime. Similar phenomenon—so called "electron heating—was observed for the first time at CELSIUS cooler ring [18].

The second stage of the loss takes place when coherent oscillations appear in the cooled ion beam. Recently, the transformation of horizontal coherent oscillations into the vertical ones leading to particle losses was discovered at HIMAC [12]. Comprehensive explanation of these effects was not done yet and they have to be studied in more details.

2.2. From the beam ordering to crystalline beams

New wave of the interest to a beam ordering in storage rings is connected with a problem of achievement large luminosity of the electron—radioactive ions collisions. Low intensity of the radioactive ion beams from a fragment separator in combination with a short life-time of the nuclei leads to pure intensity of the beam stored inside a ring—of the order of 10^5–10^6 particles. At usual transverse dimensions of the beam of such intensity is not enough to provide measurements of the charge distribution inside the nuclei. Experiments at ESR demonstrated that the ion beam ordering leads to dramatic decrease of the ion beam radius—down to a few microns. In principle the decrease of the ion beam size allows to decrease electron beam radius in the collision point and as a result to increase the luminosity by a few orders of magnitude. To achieve this goal one needs to increase intensity of the ordered state of the ion beam in the ring by about three orders of magnitude in comparison with modern level. Theoretical study of the beam ordering [19–23] as well as experiments with bunched ordered beams performed at ESR [9,24] and CryRing [10] gave very promising results. For experimental investigation of the luminosity limitation in the electron—ordered ion beam collisions one can use the TARN II ring, which has relevant parameters for this goal [15].

Independently on the possibility of its application for nuclear physics experiments an ordered state of ion beams in a storage ring is very interesting object of investigation. In last years the first two- and three-dimensional ion crystals were obtained at small storage ring called PALLAS (the ring radius is about 20 cm and ion energy is only a few eV) [25]. To obtain 2D and 3D crystals is one of the goals of new project of storage ring (S-LRS project) under development in Kyoto University [26].

2.3. Progress in theory and numerical simulations

Expansion of the electron cooling method outside the usual range of the cooling system parameters stimulates new efforts in the theory of the cooling process. It is related first of all to new projects as Recycler cooling system, electron cooling for RHIC, new GSI project for cooling of antiprotons and electron cooling of positrons at LEPTA ring, which is under construction in JINR. Wide range of magnetic field value proposed to be used in the cooling section (from 50 G for Recycler cooling system up to about 2 T for RHIC one) indicates that magnetization effect on electron cooling rate still remains "a field to be cultivated". New model of magnetized binary collisions was developed by theory group of Erlangen University in collaboration with CERN [27], analytical study and numerical simulation of electron cooling of positrons were continued in the frame of LEPTA project [28].

Some progress in understanding of the beam ordering mechanism is related with new criterions of one- and two-dimensional ion beam crystal formation in storage rings derived on the base on the model of ion binary collision [20,21].

For numerical simulation of the cooling process new computer codes were developed during last years. The code MOCAC (created by ITEP group [29]) based on Monte Carlo simulation of electron cooling, intrabeam scattering, interaction with internal target and so on was used for the beam dynamics investigations in the TWAC storage ring in ITEP, storage rings of MUSES and GSI projects. For simulation of the electron cooling process in RHIC cooling system the SIMCOOL code was created in Budker INP. JINR cooling group in collaboration with ITEP, RIKEN, GSI and BNL performed new development of the BETACOOL code [30]. One of the goals of this development is numerical simulation of the ion beam crystalline state formation in storage rings [20,21].

2.4. Electron cooling technique development

New technical ideas aiming to improve efficiency of electron cooling system proposed at Bad Honnef cooling conference were realized and tested in the HIRFL-CSR cooling system constructed in Budker INP [31]. Among them:

- formation in the electron gun the hollow electron beam in order to avoid overcooling the ion beam and related instabilities,
- usage of electrostatic compensation of the electron beam centrifugal drift inside toroids in order to improve recuperation efficiency,
- special design of electron collector of a very high efficiency.

At TSR was constructed and installed at the ring a new device—electron target for atomic physics experiments—realizing old idea of adiabatic acceleration of the electron beam [32]. In combination with cryogenic photocathode of the electron gun it permits to achieve electron beam at extremely low temperature in the particle rest frame [33].

3. Expansion into middle and high-energy electron cooling

After cancellation of the PETRA cooling system project the expansion of the electron cooling method into the middle energy range is related with four projects under development now.

Fermilab Recycler Electron Cooler, BNL cooler-recuperator, HESR electron cooling system of GSI project and electron cooling system for COSY at maximum ion beam energy. Creation of the cooling system in Fermilab is in the final stage [16], the other projects are in the design study.

The GSI project of an international accelerator facility of the next generation [34] presumes electron cooling of heavy ions in NESR (New Experimental Storage Ring) at ion energy of about 800 MeV/amu and electron cooling of antiprotons in HESR (High-Energy Storage Ring) and both cooling systems will be designed and constructed in cooperation with Budker INP.

Maximum energy of the electron beam in the existing projects (about 50 MeV) is required for electron cooling of gold ions in RHIC (BNL). For this aim bunched electron beam accelerated by RF linac and injected into solenoid of the cooling section can be used. After passage through the cooling section the electron beam energy is recuperated in the same linac [35].

One of the possibilities to realize electron cooling of proton and deuteron beam in COSY at maximum energy is related to idea of cooling with circulating electron beam. The feasibility of the method will be checked in the frame of the LEPTA project [28]. One of the LEPTA project goals is to investigate electron (or positron) beam dynamics in the ring with focusing by longitudinal magnetic field. On the other hand realization of this project can open the way to antihydrogen generation in flight. Presently, the LEPTA ring is constructed in JINR and its general elements are under the test using modeling electron beam.

4. Electron cooling in traps, antihydrogen generation

Electron (and positron) cooling of antiprotons in Penning traps is one of the key processes permitting to achieve first production of cold antihydrogen atoms in last year in CERN [36]. In contradiction to electron cooling in storage rings an electron cooling in traps has a few peculiarities:

- electron cloud has a reversed flattened distribution of electron velocities (longitudinal velocity spread is substantially larger than transverse one),
- cooling of antiprotons is caused by interaction with electrons, which are cooled by synchrotron radiation in magnetic field,
- positron cooling of antiprotons requires trapping in the same place inside trap the particles with opposite sign of electric charges.

Experimental as well as theoretical investigations of this process are necessary for preparation of the first experiments with trapped atoms (see details in Ref. [37]). Successful antihydrogen generation in traps excites new interest to its generation in-flight, which permits to provide complementary setting up of physical experiments.

5. Conclusions

(1) Electron cooling became nowadays an efficient tool of low-energy heavy particle (ions, antiprotons) beams formation in storage rings.
(2) Particle beam physics is enriched significantly with development of electron cooling method and its application to formation of intense and dense heavy particle beams.
(3) Expansion both into the range of middle and high particle energy and, into the range of extremely low energy (cooling in traps) allows to construct new facilities which have many applications in particle and nuclear physics.

References

[1] G.I. Budker, Proceedings of the International Symposium On Electron and Positron Storage rings, Saclay, 1966, p. II-I-I; Sov. Atom. Energy. (in Russain), 22 (1967) 346.
[2] V.V. Anashin, G.I. Budker, N.S. Dikansky, et al., Proceedings of the Fourth All-Union Conference on Charged Particle Accelerators, Vol. 2, Nauka, Moscow, 1975, pp. 308 (in Russian).
[3] M. Bell, J. Chaney, H. Herr, et al., Nucl. Instr. and Meth. 190 (1981) 237.
[4] T. Ellison, W. Kells, V. Kerner, et al., IEEE Trans. Nucl. Sci. NS-30 (1983) 2370.
[5] V.P. Nomokonov, M.G. Sapozhnikov, Part. Nuclei 34 (2003) 184.
[6] G.I. Budker, N.S. Dikansky, I.N. Meshkov, V.V. Parkhomchuk, D. Pestrikov, S. Popov, A.N. Skrinsky, Proceedings of the Tenth International Conference on Accelerators of High-Energy Charged Particles, Vol. 2, 1978 p. 141 (in Russian).
[7] G. Baur, G. Boero, W. Oelert, et al., Phys. Lett. B 368 (1996) 251.
[8] E.N. Dementiev, N.S. Dikansky, A.C. Medvedko, et al., Preprint 79–70, Institute of Nuclear Physics, Novosibirsk, 1979, Particles (in Russian);
E.N. Dementiev, N.S. Dikansky, A.C. Medvedko, et al., Preprint 79–42, CERN/PS/AA, Geneva (1979).
[9] M. Steck, et al., Phys. Rev. Lett. 77 (1996) 3803.
[10] H. Danared, A. Kallberg, K.G. Rensfelt, A. Simonsson, Observation of ordered ion beams in CRYRING, Proceeding of PAC'2001.
[11] U. Schramm, T. Schats, D. Habs, in: J.L. Duggan (Ed.), Proceedings of the Conference on Application of Accelerators in Research and Industry, AIP Conf. Proc., p. 576 (to be published); Nucl. Instr. and Meth., these proceedings.
[12] K. Noda, Nucl. Instr. and Meth., these proceedings.
[13] G.M. Ter-Akopian, K4–K10 project. TREBLe: two ring exotic beam laboratory, CERN 94-03, 1994, p. 422.
[14] M. Chanel, Nucl. Instr. and Meth., these proceedings.
[15] T. Katayama, Nucl. Instr. and Meth., these proceedings.
[16] S. Nagaitsev, Nucl. Instr. and Meth., these proceedings.
[17] D. Prasuhn, Nucl. Instr. and Meth., these proceedings.
[18] D. Reistad, Measurements of electron cooling and electron heating at CELSIUS, CERN 94-03, 1994, p. 164;
D. Reistad, Nucl. Instr. and Meth., these proceedings.
[19] H. Okamoto, Nucl. Instr. and Meth., These Proceedings.
[20] T. Katayama, I. Meshkov, D. Moehl, A. Sidorin, A. Smirnov, E, Syresin, H. Tsutsui, Nucl. Instr. and Meth., these proceedings.
[21] T. Katayama, I. Meshkov, D. Moehl, A. Sidorin, A. Smirnov, E, Syresin, H. Tsutsui, Nucl. Instr. and Meth., these proceedings.
[22] R.W. Hasse, Nucl. Instr. and Meth., these proceedings.
[23] T. Katayama, D. Moehl, Nucl. Instr. and Meth., these proceedings.
[24] M. Steck, K. Beckert, P. Beller, B. Franzke, F. Nolden, Nucl. Instr. and Meth., these proceedings.
[25] U. Schramm, Nucl. Instr. and Meth., these proceedings.
[26] A. Noda, Nucl. Instr. and Meth., these proceedings.

[27] B. Mollers, C. Toepffer, M. Walter, G. Zwicknagel, C. Carli, Nucl. Instr. and Meth., these proceedings.

[28] V. Antropov, E. Boltushkin, A. Ivanov, et al., Nucl. Instr. and Meth., these proceedings.

[29] P. Zenkevich, Nucl. Instr. and Meth., these proceedings.

[30] G. Trubnikov, et. al., Simulation of electron cooling process in storage rings using BETACOOL program, Proceedings of the Internatonal Workshop on Beam Cooling and Related Topics, Bad Honnef, May 13–18, 2001.

[31] A.V. Bubley, V.V. Parkhomchuk, V.B. Reva, Nucl. Instr. and Meth., these proceedings.

[32] N.S. Dikansky, V.V. Kokoulin, V.A. Labedev, et al., Maximum possibilities of electron cooling, preprint Budker INP 88–61, Novosibirsk, 1988.

[33] F. Sprenger, Nucl. Instr. and Meth., these proceedings.

[34] B. Franzke, K. Beckert, A. Dolinskii, et al., Nucl. Instr. and Meth., these proceedings.

[35] I. Ben-Zvi, J. Brennan, A. Burrill, Nucl. Instr. and Meth., these proceedings.

[36] M. Fujiwara, Nucl. Instr. and Meth., these proceedings.

[37] L.I. Menshikov, R. Landua, Rus. Usp. Fiz. Nauk 173 (2003) 233; English translation: Phys. Uspekhi 46 (3) (2003) 233.