BEAM COOLING, PAST, PRESENT AND FUTURE*

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Abstract

This review paper has the purpose to describe the history of creation of the cooling methods, the highlights of their application to experimental physics, present status of development and application of the methods, future projects with cooling methods use, trends in their development and some novel ideas appeared during recent years.

INTRODUCTION

The truism saying "the history does not teach anything" has no relation to physics. The longstanding history of cooling methods development is a fascinating "novel" of fighting with famous theorem formulated by Joseph Liouville in 1838: the theorem of phase space density conservation [1]. And very first significant step has been done by A. Kolomensky and A. Lebedev [2] more than one century later. They have described process of particle momentum spread decrease ("damping") in electron beam subjected to synchrotron radiation (SR) and have derived the formula for characteristic time of the process. The development of the SR damping theory was continued by K.W. Robinson who deduced the theorem on sum of decrements, the rule of decrements redistribution, etc. [3]. However, the synchrotron radiation is "a gift of nature" that does not work for heavy particles (SR intensity is inversely proportional to cube of particle mass for given particle energy value). Therefore we consider here "the cooling methods" which allow to reduce phase space volume of heavy particles beams, i. e. enhance the beam phase space density. Beginning with description of the first proposals and methods development in the past we consider present status of this activity and the methods applications and discuss novel ideas and projects under design intended for future.

PAST

First Proposals

The very first step in creation of a cooling method for heavy particles has been done by A. Kolomensky in 1965. He proposed [4] to use particle ionization losses in a medium. However, the nature turned out to be merciless to strongly interacting particles – the particle loss rate is higher of cooling rate by two orders of magnitude in relativistic energy range ($\varepsilon > m_p c^2$) where *ionization cooling* works. Nevertheless, it was a good start idea that has been reformulated later (see below, 1970). First really effective cooling method – *the electron cooling* – was developed at the same time by G. Budker [5]. Soon, together with A. Skrinsky, they proposed to apply this method to storage of antiprotons in an accelerator ring. In 1968 S. van der Meer has published the idea of *stochastic cooling* [6]. It is worth to quote his Nobel lecture [7]: "Such a system resembles Maxwell's demon, which is supposed to reduce the entropy of a gas by going through a very similar routine, violating the second law of thermodynamics in the process. It has been shown by Szilard that the measurement performed by the demon implies an entropy increase that compensates any reduction of entropy in the gas. Moreover, in practical stochastic cooling systems, the kicker action is far from reversible; such systems are therefore even less devilish than the demon itself." And two years later G. Budker and A. Skrinsky proposed to use ionization cooling method for cooling of muons which are devoid of strong interaction [8, 9]. This version of the method is known nowadays as "*muon cooling*".

*Work supported by RFBR grant 12-02-00072 a

First Experimental Proof

It has taken 8 years until first experiment on *electron cooling of protons* at NAP-M storage ring has been performed in INP, Novosibirsk. Simultaneously first approximation of the method theory has been developed (see details in [10]). One year later the first *stochastic cooling* has been demonstrated at ISR (CERN) [11].

Cooling Boom

After first advance of the middle of the 70th in experimental corroboration of two cooling methods a cooling "boom" seized many accelerator laboratories around the World. Twelve laboratories constructed cooler rings and performed experiments on study of cooling physics during the 80th and beginning of the 90th (Table 1).

In 1984 by initiative of H. Poth the first Workshop dedicated to electron cooling had been organized and performed in Karlsruhe Kernforschungszentrum. It is followed with biennial periodicity since then and until now.

1990-2012: The Productive Years

As result of following advance in cooling methods development many remarkable results have been achieved. First the creation of *laser cooling* should be pointed out. These studies were performed at TSR (1990) [12] and ASTRID (1991) [13] cooler storage rings. Extremely low ion longitudinal temperature, of the order of a few meV, has been obtained.

During these years both electron and stochastic cooling systems became routine tools at cooler storage rings. The BETACOOL code for cooling processes simulation was developed (JINR) [14] and experimentally tested at COSY, ESR, CELSIUS, S-LSR, LEAR,

ISBN 978-3-95450-140-3

Fermilab Recycler, and others (see Ref. [14] and References there).

Table 1: First Generation of Cooler Storage Rings

	Facility (Lab)	Operation years
1	NAP-M (Storage Ring for Antiprotons – Model, Budker INP)	1974-1984
2	ICE (Initial Cooling Experiment, CERN)	1979-1980
3	Test Ring (Fermilab)	1980-1982
4	MOSOL (MOdel of SOLenoid, BINP)	1986-1988
5	LEAR (Low Energy Antiproton Ring, CERN)	1988-1996
6	IUCF Cooler (Indiana Univ. Cyclotron Facility)	1988-2002
7	TSR (Test Storage Ring, MPI, Heideberg)	1988 =>
8	TARN-II (Test Accumulation Ring for Numatron, Tokyo Univ.)	1985-2000
9	ASTRID (Aarhus STorage RIng in Denmark, Aarhus Univ.)	1989-2005
10	CELSIUS (Cooling with ELectrons and Storing of Ions from Uppsala Synchrocyclotron, Uppsala Univ.)	1989-2005
11	ESR (Experimental Storage Ring, GSI)	1990 =>
12	CRYRING (CRYebis connected to a small synchrotron RING, MSL, Stockholm Univ.)	1992-2009
13	COSY (COoler-SYnchrotron, FZJ)	1992 =>

Several cooling facilities have been constructed and commissioned:

- SIS-18 (1998, Schwere Ionen Synchrotron, GSI), its electron cooler was constructed at BINP,
- HIMAC (2000, Heavy Ion Medical Accelerator in Chiba, Japan),
- AD (2000, Antiproton Decelerator, CERN),
- S-LSR (2005, Small Laser Equipped Storage Ring, Kyoto Univ.) – commissioning with electron cooling,
- HIRFL (2008, Heavy Ion Research Facility at Lanzhou, IMP Lanzhou); two electron coolers have been constructed at BINP),
- In 2001 the International Muon Ionization Cooling Experiment (MICE) was started at RAL (Great Britain) and Fermilab,
- Significant advance in electron cooling method expansion into high energy range has occurred in 2005 with commissioning of "The Pelletron", HV electron cooler of 4.3MeV electron energy and 1 A electron current at Fermilab [15],
- In 2006 with the bounds of LHC project (CERN), the Low Energy Ion Ring (LEIR) was commissioned with Electron cooling of Pb ions, electron cooler has been constructed at BINP.

And very recent event: in March 2013-3D Laser cooling has been performed at S-LSR (Table 2 below).

HIGHLIGHTS OF COOLING APPLICATION

Particle Physics

Most remarkable physics result was obtained in 1984 at SuperAntiproton-Proton Synchrotron-collider (SP-barPS, CERN) in experiment on search of $W^{\pm}$ and Z^0 bozons. The collider was operated with antiprotons provided by Antiproton Generation Complex based on *stochastic cooling* application and included Antiproton Accumulator (AA) (constructed around 1978). Owing to this technology collider had sufficient luminosity. The experiment resulted in the discovery of "nobel level".

Another significant achievement in particle physics occurred owing to construction of *electron cooler* "Pelletron" mentioned above. Its application to antiproton storage in Recycler ring allowed to reach in Run IIA the luminosity of proton-antiproton collider "Tevatron" (2x900 GeV) of $L_{max} = 4\cdot10^{32}$ $cm^{-2}\times s^{-1}$ and provide during 2001-2011 the integrated luminosity of 11.87103 1/fb ≈ $1.19\cdot10^{39}$ cm^{-2}. That led to "observation" of the Higgs boson of 126 GeV at 3σ CL (as announced 2 July 2012 at Fermilab seminar).

The next physics result to be pointed out is H-bar Generation in ALPHA Trap (CERN). Application of *stochastic and electron cooling* in AD ring allowed to store and decelerate sufficient number of antiprotons for 3 experiments – ALPHA, ASACUSA & ATRAP. The first of them Antihydrogen Laser PHysics Apparatus (ALPHA) succeeded in November 2010 first to capture and store 38 antihydrogen atoms for about 170 ms. Then, 26 April 2011 309 antihydrogen atoms were trapped and kept, some for as long as 1000 seconds. It really clears the way to experiments with antimatter (antiatoms).

Nuclear Physics

Electron cooling application at ESR (GSI) allowed to develop, beginning since 1996, the high precision Schottky mass spectroscopy. During this period 194000 Schottky peaks for different nuclei peaks have been identified, 500 different nuclei have been measured and about 200 of them of unknown mass. Mass measurement accuracy is of $2\cdot10^{-7}$. Later high precision Time-Resolved Schottky Mass Spectroscopy (TR SMS) was developed at GSI. This method is a perfect tool to study nuclei decays in-flight. Another example of electron cooling unique

ISBN 978-3-95450-140-3

application in nuclear physics studies is measurement of half-life of bare nuclei in-flight inside the cooler ring developed at ESR as well.

Atomic Physics

It is enough to present here one but remarkable example of unique experiment setting up in atomic physics that has been performed at cooler storage ring. Such an experiment at ESR (1996) had a purpose of high precision measurement of U^{91+} 1S Lamb shift. The theory gave value of 463.4 ± 1 eV, and the experiment has given 459.8 ± 4.6 eV [16]. Such QED related studies will be continued at FAIR.

Particle Beam Physics

Crystalline beams One of most bright phenomena discovered in particle beam physics and related to cooling method is undoubtedly crystalline beam state. The story began with an experiment at NAP-M in 1979 when V. Parkhomchuk and team have observed a suppression of Schottky noise of proton beam as its momentum spread reduces under *electron cooling* (Fig.1) [17].

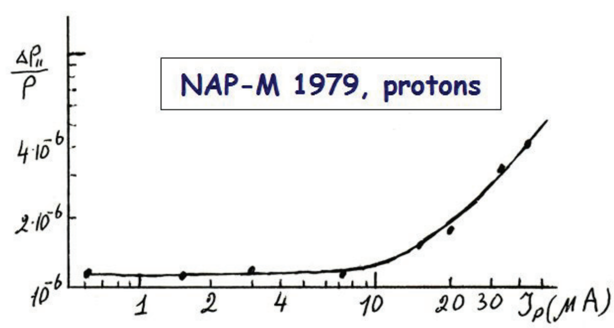

Figure 1: Proton beam momentum spread vs beam current under electron cooling in NAP-M cooler-ring [17].

In 1984 V. Parkhomchuk has formulated the concept of crystalline beam [18]. In succeeding years it was followed by an outburst of theoretical studies (A. Sessler, J. Wei, J.P. Schiffer, R. Hasse and others).

In 1996 a qualitative leap happened in experimental studies of electron cooling of particle beams when M. Steck with colleagues observed a sudden and abrupt decrease of ion momentum spread during gradual reduction of particle number in the beam (Fig. 2) [19]. The experiments at ESR were continued and led to conclusion that "very cool" ion beam takes the form of one dimensional string where ions, like beads on a thread, do not pass each other, i. e. state of the *beam ordering* is formed. Later such a beam phase transition into ordered state has been observed at CRYRING as well [20].

All these experiments has been performed with ion beam*. The question remained: why phase transition in proton beam was not observed in NAP-M experiment. An attempt to study this problem was made at COSY (2005) [22]. However, the phase transition was not obtained. It was explained by magnetic field ripples level in the ring magnets. One year later similar experiment at S-LSR has brought a success (Fig. 3) [23]. It turned out also that a particle beam under electron cooling undergoes the phase transition if dependence of particle momentum spread on the beam particle number N_p does fit to the function N_p^{α} with $\alpha = 0.3 \pm 0.3$ (see Fig. 2, 3). In NAP-M experiment (Fig. 1) $\alpha = 0.98$, at COSY $\alpha = 0.33$. Such a peculiarity was demonstrated with numerical simulation based on BETACOOL code developed by A. Smirnov (Fig. 4) [24]. His simulations confirmed also ordering criterion introduced by one of the authors (I. M.) of [24]:

$$\Gamma_2 = \frac{Z^2 e^2}{T_{\parallel} \sigma_{\perp}} > \pi \, . \qquad (1)$$

Here Ze is particle charge, $T_{\parallel}$ − particle longitudinal temperature (in particle Rest Frame), $\sigma_{\perp}$ − the beam transverse size. Before ordering criteria of a particle beam were formulated by several authors. None of them fits – experimental data properly. Peculiar dependence of momentum spread on N_p appears at equilibrium between cooling force and intrabeam scattering in the beam.

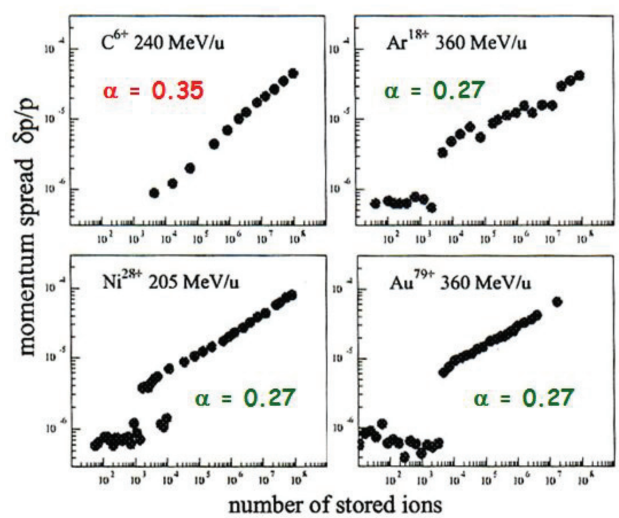

Figure 2: Ion momentum spread vs ion number under electron cooling in ESR [19].

Further progress in crystalline beam problem is related to 3D laser cooling that promises to form 3D crystalline beam.

Antiproton electron cooling was first accomplished at LEAR at the end of 1988 – beginning of 1989 (Fig. 5). Since that time "era" of antiproton generation and cooling by electrons began at CERN and lasts to present days.

* We do not consider here 3D crystallization of particle "cloud" in traps, like it was done in PALLAS [21].

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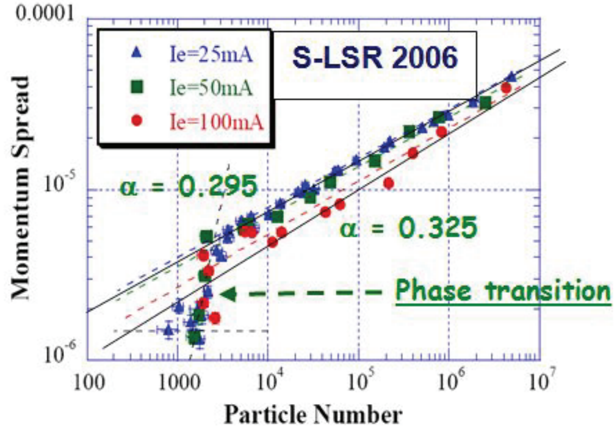

Figure 3: Proton momentum spread vs proton number under electron cooling in S-LSR [23].

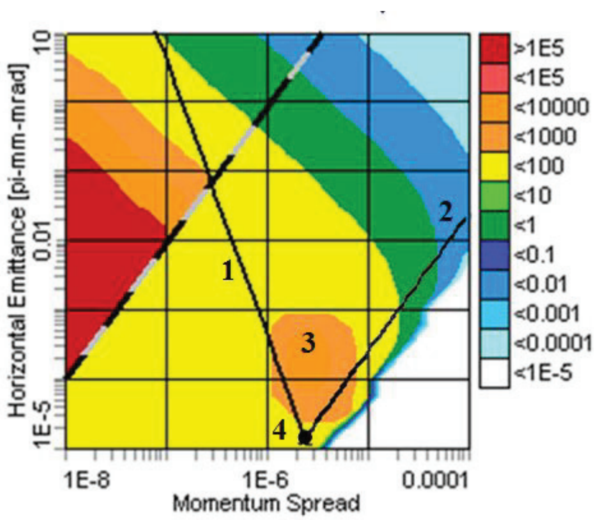

Figure 4: "3D" Dependence of IBS longitudinal heating rates (in colours) vs horiяontal emittance and momentum spread of proton beam (S-LSR, 7 MeV, N_p = 10^3); 1 – criterion (1) line; 2 – proton cooling "trajectory"; 3 – anomalous island of IBS heating of longitudinal momentum component; 4 – ordering point where the lines 1 and 2 meet.

Stability of intense cooled beams is obviously a problem of practical interest. An excitation of instability of a proton beam in presence of electron one has been observed first at CELSIUS (1993) and later at COSY (2001) and HIMAC (2003). The instability had coherent character, was accompanied with horizontal-vertical coupling and damped with an efficient feed-back system (see details in [25]). Developing this problem V. Parkhomchuk derived a criterion for coherent instability threshold. He used an original transfer matrix approach [26]. Until now the criterion was not tested properly in experiments and the problem requires further investigation.

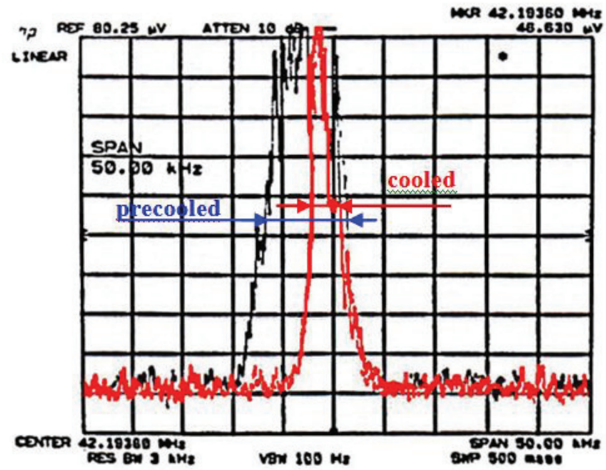

Figure 5: First Electron Cooling of Antiprotons in LEAR (CERN), $\Delta p/p = 6\cdot10^{-5}$, December 14, 1988.

Laser cooling method being under development since 1990 is an outstanding achievement of particle beam physics that allows to form ultracold particle beams. That necessary for formation of ordered and 3D crystalline beams. The first one can find application to formation of ion-ion colliders with the beams of rare and/or short-lived isotopes [24].

Minimum equilibrium temperature magnitudes reached with cooling are shown in Table 2.

Table 2: Minimum Particle Temperature in Cooled Beams

Cooling method	Particles/ Ring	Energy	$T_{\parallel}$, K	$T_{\perp}$, K	Reference
Electron cooling	$^{40}Ar^{18+}$ / ESR	360 MeV/u	10	2000	[19]
	protons / S-LSR	7 MeV	1.9	11	[23]
Laser cooling	$^{9}Be^{+}$ /TSR	7.3 MeV	$5\cdot10^{-3}$	–	[27]
	$^{24}Mg^{+}$/ S-LSR	40 keV	0.4	7.0 (hor.)/ 2.1 (ver.)	[28, 29]

PRESENT

We have now 9 cooler storage rings operated in the Laboratories around the World (commissioning year is shown in brackets): TSR (MPI, Heidelberg, 1988), ESR (GSI, 1990), COSY (FZJ, 1992), SIS-18 (GSI, 1998), HIMAC (Chiba-Inage, 2000), AD (CERN, 2000), LEIR (CERN, 2006), S-LSR (Kyoto Univ., 2005), CSRm & CSRe (HIRFL, IMP, Lanzhou, 2008). All they cover a wide range of physics problems and applications which are being studied or used at these facilities: particle, nuclear and atomic/molecular physics, antimatter physics,

ISBN 978-3-95450-140-3

particle beam physics and formation of beams as intermediate accelerators of accelerator facilities, accelerator technology and (even!) cancer therapy.

Among considerable number of projects with cooling application under development at least 6 reached the stage of technical design, prototype and construction and elements fabrication. Those are NICA (JINR, Dubna), FAIR (Darmstadt), MICE (RAL/Fermilab), Bunched beam Stochastic Cooling (RHIC, BNL), Low Energy Particle Toroidal Accumulator (LEPTA, JINR), Cryogenic Storage Ring (CSR, MPI, Heidelberg). Two first of them need for operation medium energy electron coolers. The working prototype of such machines is electron cooler of 2 MeV electron energy constructed in Budker INP (Novosibirsk) and being under commissioning at COSY presently. MICE experiment is of great interest not only for muon collider – a project of rather far future – but also for today's projects of muon neutrino fabrics.

One can point out also 4 projects which are for the present moment in the stage of conceptual design ("paperwork"):

- ELENA (CERN, approved), aimed for antihydrogen physics.
- Medium Energy Electron-Ion Collider (MEIC, JLab) with both DC electron cooler of 1.5 MeV electron energy and of 50 MeV one based on electron recuperator linac (ERL).
- Electron-Ion Collider (eRHIC, BNL), both aimed for particle physics with polarized electron beams.
- Coherent electron cooling (BNL/JLab) – further development of electron cooling with numerous possible applications.

CONCLUSION

The By now cooling methods have been developed for cooling by synchrotron radiation (SRC), electrons (EC), high frequency stochastic signal (stochastic cooling, SC), laser radiation (laser cooling, LC), cooling of muons by ionization in medium (muon cooling, MC). These methods allow to cool particle beams of electrons (SRC), protons and antiprotons (EC, SC), ions (EC, SC, LC), muons (MC). The particle energy range covered by different cooling methods stretches from 100 keV/u (ions) up to 8 GeV (p-bars).

The ideas and proposals stated recently (e. g., like coherent electron cooling, ERL-cooler, etc.) do show that development of cooling methods is in active state and did not reach yet its apogee.

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ISBN 978-3-95450-140-3