NEW ADVANCES IN BEAM COOLING *

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Abstract

New developments in beam cooling since ICFA'2004 seminar are presented with concentration on trends in electron cooling, stochastic cooling, muon cooling and beam crystallization – the trends, which, as one can expect, will mark the future in the cooling methods applications.

INTRODUCTION

A variety of remarkable events in the field of beam cooling have occurred during last two years:

- The first demonstration of electron cooling at intermediate energy (8 GeV antiprotons) in the FERMILAB recycler [1].
- The commissioning of low energy ion cooler LEIR at CERN (5 MeV/amu Pb^{54+}) [2].
- The commissioning of two state-of-the-art low energy electron coolers (LANZHOU) built in Novosibirsk [3].
- The commissioning of the storage ring LEPTA aimed for "electron cooling all around" (at JINR Dubna) [4].
- The commissioning of a special dispersion-free ring for cooling beam ordering experiments (at Kyoto University) [5].
- The approval of the international Muon Ionisation Cooling Experiment MICE (at Rutherford Appleton Laboratory) [6].

In addition there has been considerable advancement both in the understanding and the scope of beam cooling:

- An international effort has lead to a big step forwards in the conception, modelling, benchmarking and hardware design for various medium and high-energy (both stochastic and electron) coolers (e.g. for RHIC, FAIR, TEVATRON…) [7, 8].
- New proposals have emerged for the use of cooled beams (e.g. very small aperture machines for medical and particle physics applications) [9].
- There has been great progress concerning the conditions for and the potential use of ordered (crystalline) beams.

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TRENDS IN ELECTRON COOLING

Medium and high energy

All proposals (FERMILAB, RHIC, FAIR …) are based on a very long interaction region (15–20 m). To sustain low temperature, the electrons are accelerated in a linear device all the way from the cathode to the interaction energy. They make a single traversal of the cooling region and are then decelerated to recuperate their energy. Thus the arrangement is similar to low emittance linacs with energy recovery as proposed e.g. for advanced synchrotron light sources.

Different schemes of acceleration/deceleration have been proposed using either electrostatic (continuous beam) or RF (bunched beam) acceleration. The FERMILAB scheme ([1]) uses a pelletron high voltage device to generate the 4.3 MeV electrostatic acceleration potential. The BNL proposal for RHIC ([10]) is based on a linac with electron bunches matching the RHIC bunch structure. The Novosibirsk proposal [11] for FAIR uses a proton or H^{-} beam from a cyclotron to charge up a high voltage platform. A question of particular importance is the magnetisation of the electron beam. This can increase the cooling speed, ideally without augmenting, in the case of heavy ions, the electron-ion recombination rate.

Obviously the generation of a strong magnetic field along the orbit in a high voltage device is a challenge. In fact the FERMILAB device goes without strong magnetisation whereas in the FAIR proposal it is an essential ingredient. The Novosibirsk team proposes to solve the problem using isolated multiple coils fed by individual generators on high voltage ([11]). The technology will be tested in a new cooler at COSY ([12])

The basis of non-magnetized medium energy cooling has been demonstrated by the pioneering work at FERMILAB. In the future we will see much work directed towards magnetized electron cooling at medium and high energy.

Low-energy

The design for low energy (2–200 keV electron energy) has only relatively little changed, evolving from the pioneering Novosibirsk concept in the early 1970s. After the construction and the use of more than a dozen of coolers all over the world, the latest generation (LEIR [2], Lanzhou [3]) has the following new features:

- Very precise magnetic field with a great number of trim coils (to allow fast cooling).
- "Hollow" e-beam (to avoid "overcooling" in center and also to reduce ion-electron recombination).

- Electrostatic bends (to reduce trapping of secondary particles).
- Magnetic expansion (to adjust beam size).
- Magnetisation of an e-beam of a relatively high transverse "temperature" (to decouple "temperature" for cooling from "temperature" for ion-electron recombination).
- High perveance together with elaborate measures to stabilize the beams (to reach fast cooling). As an example: a beam of 1 A at 25 keV (45 MeV proton energy) was stably reached at COSY, in August 2005 ([13]).

Very low-energy

The ELENA and FLAIR [14] proposals of post-deceleration/cooling rings after the AD and the FAIR–RESR [15] respectively require efficient cooling of antiprotons with an energy as low as 100 keV ($v/c \approx 1.5{\cdot}10^{-2}$). The FLAIR project [14] calls for cooling also of ions with very low velocity. In addition cooling rings (using electrostatic bending and focusing) for molecules with v/c in the few percent range have been constructed or are being planned [16, 17, 18]. Cooling at such low velocities (with electron beams of energy as low as ~50 eV) poses new problems.

One challenge is the ultra low temperature (in the order of a few meV) required. Solutions proposed rely on a "cold" photo cathode [19]. However at present these are capable to deliver only a relatively low current. Magnetisation (to have low effective transverse temperature) is another perhaps additional way. But then, at the low energy, the magnetic field presents a strong perturbation of the ring's optics. Expansion can lower the transverse temperature but it also reduces the current density. In summary: there is a conspiracy of conflicting requirements.

There are other problems specific to the ultra low energy of both the ion and the cooling beam: instabilities, space-charge, intra-beam and gas scattering… to mention only a few. On the positive side: the energy contained in the cooling beam is low so that recovery is probably not required.

Intense research and probably new ideas are required to arrive at a good design of the very low-energy coolers.

STOCHASTIC COOLING

There is advance concerning high energy stochastic cooling in order to extend the luminosity in heavy ion colliders.

Bunched beam "Schottky noise" studies at RHIC are well progressing [20]. The coherent component of the signal at 4–8 GHz is much less violent than the effects observed some time ago in the $Sp\overline{p}S$ and the TEVATRON. Although special measures are necessary, the situation seems manageable for cooling of e.g. gold beams to extend the luminosity lifetime. The power problem can be solved by using an array of high Q (~1000) cavities stagger tuned over the band (4–8 GHz).

Ideas to combine high-energy electron (core) cooling with stochastic (halo) cooling, developed already for low energy at LEAR are being discussed for the High energy Experimental Storage Ring (HESR) planned at GSI Darmstadt [21].

STABILITY OF COOLED BEAMS

Electron cooling

An ion beam in an electron cooler storage ring can suffer from unwanted influences of the cooling beam and from other storage ring coupling impedances. Effects observed include [22]:

- nonlinear lens ("beam-beam") effects of the electron beam leading to ion loss or diffusion (LEAR);
- ion loss at injection (COSY) – so called "fast loss" – when the ion beam is larger than the electron beam size (probably similar to the "beam-beam effect");
- instability development in a well cooled high intensity ion beam due to interaction with the electron beam "electron heating" (CELSIUS, COSY, HIMAC), probably similar or identical to the "beam-beam" effect;
- "three-body" instability when secondary ions are trapped in the e-beam (LEAR, HIMAC, COSY);
- strong interaction of a well cooled ion beam with parasitic elements in the ring (LEAR, COSY).

A test of the ion beam stability with the novel hollow e-beam coolers is an important issue. There are two "hints" on very promising results of hollow beam application to electron cooling.

First of them is an experiment performed at Fermilab electron cooler [1, 23]: when electron beam in the cooling section was shifted in vertical direction by, approximately 2 mm (Fig. 1), the antiproton stack intensity increased by several times. This fact can be interpreted as decrease of cooling power in the area near antiproton beam axis that allowed to avoid "overcooling" – that reduces, correspondingly, the antiproton beam density and helps to avoid, by this measure, "the electron heating".

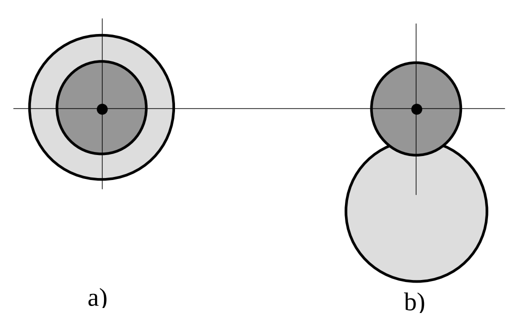

Figure 1: Cross-section of electron (light grey) and antiproton (dark grey) beams of Fermilab electron cooler: a) "standard" position, b) the shifted electron beam.

The second "hint" came from LEIR electron cooler. When it has been commissioned this year, it demonstrated an efficient stacking and cooling of Pb^{54+} ions at variable electron density distribution across the electron beam. So, when the density distribution was changed in such a way that distribution function became flat near the beam axis or even reduced ("quasihollow" beam), the stack intensity increased, by two times approximately. This fact can be explained also as a decrease of "overcooling" and avoiding of "electron heating" [23]. The first experiments on lead ion stacking gave good results close to the project requirements (Table 1) [2].

Table 1: Status of LEIR

Parameter	Project	Achieved
Ions	Pb^{54+}	
Ion number/ stacking time	$9{\cdot}10^8$/3.6 s (2009)	$1.5{\cdot}10^9$/6 s
	$2.5{\cdot}10^8$/2.4 s (April 2008)	
Emittance, μm	0.7	~ 0.7
Electron Cooler		
Current, mA	600 (design)	400 ⇒ 150 (used)

Nevertheless, the question of nonlinear density influence at large ion amplitudes remains. One has to mention here an effect, which agrees very well with the second assumption: if proton beam in COSY is accelerated up to 130 MeV (after single injection at 45 MeV) and proton beam size becomes smaller of electron one, the fast loss of protons is not observed when electron beam is turned ON [24].

Another problem – a "transition energy problem" – arises for the new high-energy coolers. Longitudinal stability is most critical above transition energy due to the "negative mass effect". Up to now, all electron-cooling rings have operated naturally below transition, whereas the new high-energy coolers have to work above transition. A recent experiment at the ESR (Darmstadt) tuned to $\gamma > \gamma_{tr}$ showed, that e-cooling is possible in this regime but with larger equilibrium spread than below γ_{tr}. In the old Initial Cooling Experiment at CERN, e-cooling above transition was not at all achieved. It will be important, to determine the density limits in the high-energy cooling rings.

Instability antidotes, electron cooling

The beam environment in the cooling ring has to be carefully controlled. Moreover a rather wideband feed back system has proven efficient and necessary to damp coherent instability (LEAR, COSY [22], S-LSR [5]). But it does not cure incoherent effects [22]. Therefore more detailed studies of the ion beam stability with the new hollow e-beam coolers, systems of clearing of secondary ions trapped in cooling electron beam, studies of ion beam behaviour at "large" and "small" amplitudes will be important issues!

The experience with feedback application for a coherent instability damping obtained recently at S-LSR has shown a very strong requirement to the feedback system parameters: its timing (delay of the feedback signal) has to be tuned with the precision of a few nanoseconds [5]. The system in S-LSR ring operates on 31st harmonics of revolution frequency (51.5 MHz).

Stability of stochastically cooled beams

The stability of the stochastically cooled beam in the presence of the usual coupling impedances is basically the same as for any cooling ring that produces dense beams (reduced Landau damping). In addition to this, the stochastic cooling system itself acts as a large "beam coupling impedance".

Beam stability is especially critical in accumulator rings of antiprotons or rare ions, where large stacks (10^{11}–10^{12} particles) have to co-exist with small injected batches (~10^8 particles).

Fast cooling and stacking of the injected batch in the presence of the stack requires partial aperture pick-ups and large separation (at the PU-s) of injection and stack orbits by momentum spread and dispersion. Non-dispersive separation by momentum spread (frequency) alone is insufficient if one wants to stack a big number of batches. The classical solution (CERN and FNAL) of a large dispersion ring is expensive and cumbersome. Therefore a revisit of the stacking problem is indicated (see [26]).

THE THEORY AND SIMULATION

Future projects – RHIC, FAIR, ELENA, FLAIR… – do need efficient tools for numerical simulation of the beam dynamics in the cooler ring. A significant progress was achieved in the development of the BETACOOL code [7] and its benchmarking ([8]). The code can be used to simulate a great variety of different processes in a beam circulating in a storage ring with a given lattice: electron cooling with an intense electron beam (space charge effects), intra-beam and residual gas scattering, the influence of an internal target etc. Simulation of electron cooling process with BETACOOL is based actually on three different approaches:

- analytic formulae obtained by Ya. Derbenev and A. Skrinsky and developed later by I. Meshkov into form suitable for concrete calculations (so called "DSM formulae") [26];
- approximate formula derived by V. Parkhomchuk and co-authors by fitting of early electron cooling experiment results at NAP-M (see [7], [8] and References in there);
- "direct" calculation of binary collisions of an ion with cooling electrons – the approach, which is under development by the groups from Tech-X, Colorado, USA – the VORPAL code[8], and Erlangen University, Germany[27].

The first and second approaches give, in a rather good agreement, a value of friction (cooling) force in the range of "large" ion velocities V_i (in particle rest frame):

$$V_i > \begin{cases} \Delta_\perp, & \textit{nonmagnetized electron beam,} \\ \Delta_\|, & \textit{magnetized electron beam.} \end{cases}$$

Here $\Delta_\perp, \Delta_\|$ are the rms values of electron velocity spreads – transverse and longitudinal ones, respectively. However, maximum value of the friction force

$$F_{max} = \begin{cases} F(V_i = \Delta_\perp), & \textit{nonmagnetized electron beam,} \\ F(V_i = \Delta_\|), & \textit{magnetized electron beam,} \end{cases}$$

is significantly larger for the first approach. Similar difference takes place in the range of small ion velocities

$$V_i < \begin{cases} \Delta_\perp, & \textit{nonmagnetized electron beam,} \\ \Delta_\|, & \textit{magnetized electron beam.} \end{cases}$$

As recent analysis has shown, the insertion of the direct calculation into BETACOOL gives intermediate result and allows agree both first approaches.

Recently the BETACOOL code was extended for the simulation of stochastic cooling [21] and its application to laser cooling is in progress.

MUON COOLING

The international scoping study

A lot of development towards a neutrino factory and the muon beam cooling required for it has been going on recently [6, 28, 29].

An international scoping study of a Neutrino Factory and Super-Beam Facility was launched in spring 2005. In the "Executive summary" [30] it is stated that "….… The principal objective [of the scoping study] … will be to lay …foundations for a …conceptual design study of the facility. The … study has been prepared … by the international community …: the ECFA/BENE network in Europe, the Japanese NuFact-J collaboration, the US Muon Collider and Neutrino Factory Collaboration and the UK Neutrino Factory Collaboration. …Rutherford Appleton Laboratory will be the "host laboratory" for the study…Highlights of this programme include the international Muon Ionisation Cooling Experiment (MICE)… which has been approved at the Rutherford Appleton Laboratory (RAL) …It will begin taking data in 2007 with beam from ISIS (RAL)".

The MICE experiment

The MICE Collaboration [6, 31] includes more than 40 institutions from Belgium, Italy, Japan, Netherlands, Russia, Switzerland, UK, US (spanning 17 hours in time zones): (Louvaine, Bari, Frascati, Genoa, Legnaro, Milano, Napoli, Padova, Roma, Trieste, KEK, Osaka, NIKHEF, BINP, CERN, Geneva University, PSI, Brunel, Daresbury, Edinburgh, Glasgow, Imperial, Liverpool, Oxford, RAL, Sheffield, ANL, BNL, Chicago, Fairfield, Fermilab, IIT, Iowa, Jlab, NIU, UCLA, LBNL, Mississippi, Riverside, UIUC).

The experiment

- aims to show that it's possible to design, engineer and build a section of the ionization cooling channel capable of giving the desired performance for a Neutrino Factory;
- plans to place this section in a muon beam investigating the limits and practicality of ionization cooling.

MICE is accepted as an official (UK) project at RAL. Funding for the beamline/infrastructure and the tracker come from RAL. Important hardware and study contributions come from US (MUCOOL collaboration);

The MICE collaboration has been very successful in getting contributions from many different funding agencies! Great progress has also been made in modelling ionization cooling and emittance measurement.

First beam is expected April 1, 2007.

Basically the muon-cooling channel consists of linear accelerator sections interlaced with liquid hydrogen absorbers. This channel has to be fairly long and is expensive. Hence the interest in "ring coolers" [32], where cooling is done over many revolutions and *muon cooling rings* should/will attract more study!

BEAM ORDERING

The experimental observation in the 1970s of Schottky noise suppression in a cooled proton beam by V. Parkhomchuk et al. inspired a lot of enthusiasm on "crystal beams".

The excitement continues but was somewhat damped in the 1990s when it became clear (due to the work of A. Sessler, G. Wei, H. Okamoto, A. Ruggiero and many others) that 3D crystallisation is subject to a set of tough conditions that cannot be met in existing storage rings.

The observation of 1D ordering by M. Steck and co-workers at GSI in 1996 and its theoretical explanation by the "two-particle model" of R. Hasse – has led to a new boom of interest in beam crystallization in storage rings .

The proposal to use a 1D chain in an ion-electron collider presents a first attractive particle physics application showing the potential of ordered beams.

Concerning 1D ion ordering observed at GSI and (later) also at CRYRING one should mention the problem of proton beam ordering. Recent experiments at COSY demonstrated a saturation of the Schottky noise signal at a level of $\Delta p/p \sim 2\cdot 10^{-6}$, but a "phase transition jump" (like at NAP-M in Novosibirsk) was not observed [7, 24]. This is to be confronted with molecular dynamics simulation [7] which explains the COSY but not the NAP-M results.

The understanding of the optics and the cooling required for beam ordering is progressing due to the work of an "international network of enthusiasts" (including A. Sessler, J. Wei, H. Okamoto, T. Katayama, A. Noda, R. Hasse, A. Sidorin, A. Smirnov and the present author).

The idea of a dispersionless ring [5, 33] (to avoid "shear" and, related to it "tapered cooling") removes a big tumbling stone from the road to 3D ordered beams.

Beam ordering experiments

The RF quadrupole ring PALLAS [34] has shown possibilities and limits of 3D crystal beams at very low energy ($v/c \approx 10^{-5}$). "Shearing forces" in the bends were identified as one major obstacle to 2D and 3D crystals at higher beam energy.

A new ring S–LSR (conceived by a collaboration of the ICR, Kyoto University and the Japanese Institute of Radiological Sciences) with electrostatic and magnetic bends has been commissioned recently [5]. It can run in a "dispersion free" mode where shear forces are (to first order) absent. For this the bending fields have to satisfy the condition:

$$\left(1+1/\gamma^2\right)\cdot E_r = -v \cdot B_z$$

S–LSR can work dispersion free with Mg^+ ions up to $v/c \approx 2\cdot 10^{-3}$ ($E \approx 1.5$ KeV/nucleon). At higher energy the bending voltage (~ twice the voltage for pure electrostatic bending, see equation above) gets excessive.

S-LSR type rings with mixed electric and magnetic bending, when tuned to have zero linear dispersion have large transition energy, $\gamma_{tr} \Rightarrow \infty$. For high energy one can think of a purely magnetic lattice with $\gamma_{tr} = \infty$ where the dispersion is negative in part of the magnets and $\gamma_{tr}^{-2} = (1/C)\cdot \int D/\rho \, ds = 0$. Is such an "on average shear-less ring" well suited for crystallisation?

One concludes that a lot of fascinating experimental and theoretical work is going on towards crystal beams in general and at higher energy in special.

CONCLUSION

There is a surprising diversity of new and very exiting developments in the – by now mature – field of beam cooling. The selection of them presented here is unavoidably incomplete and biased. We apologize for that.

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