RECENT DEVELOPMENTS AT ION COOLER RINGS

D. Reistad, The Svedberg Laboratory, Uppsala, Sweden

Abstract

Three methods to cool stored ion beams have been achieved experimentally. These are electron, stochastic, and laser cooling. After an introduction, in which the relative merits and problems of these cooling methods is discussed on a principal level, we discuss some of the recent interesting developments at the ten existing cooler rings and briefly review several recently proposed and/or started projects.

1 INTRODUCTION

An ion cooler ring is an ion ring (storage ring or synchrotron), in which a "beam cooling" device is installed. Existing ion beam cooling devices are based upon *electron cooling* [1-3] *stochastic cooling* [4-6] or *laser cooling* [7-8].

1.1 Electron cooling

In *electron cooling* the stored beam is "mixed," over a fraction of the ring with a "cold" (i.e. mono-energetic and parallel) electron beam of the same velocity. The electron beam is created in an electron gun and electro-statically accelerated to the appropriate velocity. After the interaction region, the electron beam is decelerated to a potential close to that of the cathode, and collected in a collector. Ions experience friction against the electron beam, and are thus "cooled" both longitudinally and transverse at the same time. The cooling force and the cooling time can be estimated from a binary collision model. It turns out that quite different scaling relationships are valid depending upon whether the ion velocity (in the electron beam rest frame) is smaller or larger than the rms. electron velocity $\Delta_\perp$:

$$\tau_\perp \propto \beta\gamma^2 \left(kT_e\right)^{\frac{3}{2}} \text{ for } v_\perp < \Delta_\perp$$

$$\tau_\perp \propto \beta^4\gamma^5\varepsilon^{\frac{3}{2}} \text{ for } v_\perp > \Delta_\perp$$

where β and γ are the usual relativistic factors, $kT_e = m_e\Delta_\perp^2/2$ is the electron transverse "temperature," and $v_\perp = \beta\gamma c\sqrt{\varepsilon/\beta_C^*}$ is the transverse ion velocity, where β_C^* is the average value of the Courant Snyder beta function at the cooler. Electron cooling works best for beams that are not "too" hot to begin with, or, more precisely, for ion beams with transverse ion velocities which are smaller than the rms. velocity of the electrons. This condition is easy to fulfil at low energies but not always met at high energies, which is when is most essential in order to get reasonable cooling times.

1.2 Stochastic cooling

Stochastic cooling makes use of signals from a very high bandwidth pickup in order to control a kicker placed at a suitable distance downstream to the pickup, in order to kick the ions in the stored beam towards the centre of the phase space volume. The signal delay must match the time it takes for the "beam sample" to go from the pickup to the kicker.

The pickup and kicker can be transverse or longitudinal. For transverse cooling the kicker has to be placed an odd number of quarter betatron wavelengths downstream the pickup.

Longitudinal cooling can be achieved by placing the pickup at a place in the ring, where the dispersion is large, and let the transverse information translate into a longitudinal kick. This method is called "Palmer cooling." Another method to achieve longitudinal stochastic cooling is the notch-filter method [9]. With this method, the amplified pickup signal is passed through a filter, in which the phase shifts by 180° at all harmonics of the desired revolution frequency. Thus, "beam samples" that travels with the wanted revolution frequency are not affected, while those that are travelling too fast are decelerated and those that are too slow are accelerated.

For an ideal system without noise one would expect the cooling time to be given by $\tau = 2N/W$, where N is the number of stored ions to be cooled and W is the bandwidth of the system. In practice, the system is not ideal and there is noise, which slows cooling by up to an order of magnitude.

1.3 Laser cooling

Laser cooling works only for a few particular ions. In order to be laser cooled, the ions must have a closed transition between two atomic energy levels (i.e. the population must be confined to these two levels). A laser beam of suitable frequency is placed parallel and/or antiparallel to the ion beam. Those ions that are in resonance with the laser beam absorb photons. Each absorbed photon transfers momentum $h\nu/c$ to the ion. This momentum transfer is in the direction of the laser beam propagation. When the ion spontaneously returns to the low energy level it again recoils with momentum $h\nu/c$, but now in a random direction. The average momentum transfer after many spontaneous emissions is negligible, because the angular distribution of the emission is symmetric. Thus there is a net radiation pressure force, directed along the laser

Table 1, Existing ion cooler rings

	$B\rho$ (Tm)	stochastic cooling	electron cooling	laser cooling	main purpose (accelerator physics programmes at all rings)	ref.
CRYRING (Stockholm)	1.4		0.2 – 13 kV		atomic and molecular physics	17-19
TSR (Heidelberg)	1.5		0.5 – 16 kV	13.3 MeV $^{7}\mathrm{Li}^{+}$ 7.3 MeV $^{9}\mathrm{Be}^{+}$	atomic and molecular physics	20-23
ASTRID (Århus)	1.9		0.01 – 2 kV	100 keV $^{7}\mathrm{Li}^{+}$ 100 keV $^{24}\mathrm{Mg}^{+}$	atomic and molecular physics	24
“Cooler” (Bloomington, IN)	3.6		20 – 300 kV		nuclear and accelerator physics	25-27
TARN II (Tokyo)	6.1	7 MeV/*c*	15 – 110 kV		accelerator and atomic physics	28-29
CELSIUS (Uppsala)	7.0		5 – 300 kV		nuclear physics	30-31
LEAR, LEIR (CERN)	7.0	2 – 1270 MeV/*c* antiprotons	1 – 30 kV		prepare beams of Pb^{54+} for LHC	32-33
ESR (Darmstadt)	10.0	at injection of radioactive ions $(0.7 \le \beta \le 0.75)$	2 – 240 kV		atomic, nuclear and accelerator physics	34-38
COSY (Jülich)	11.7	1 – 2.5 GeV protons	20 – 100 kV		nuclear physics	39-41
SIS (Darmstadt)	18.0		5 – 35 kV		nuclear physics, injector to ESR	42-44

beam, on resonant ions. The force depends on the velocity of the ion through the Doppler shift.

In order to achieve cooling there must exist a counter-force. This can be from another laser, from an induction accelerator, or from RF.

The first ion beam that was laser-cooled was metastable $^{7}\mathrm{Li}^{+*}$ [10, 11]. Presently, work on laser-cooling makes use of 7 MeV Be^{+} (MPI, Heidelberg) and 100 keV Mg^{+} (ISA Århus).

1.4 Comparison between the three cooling methods.

Electron cooling can cool ion beams to lower temperatures and higher phase space densities than stochastic cooling can. Laser cooling can cool ion beams to still much lower temperatures than electron cooling. An ultimate goal of laser cooling experiments is the attainment of crystallised beams. Shortcomings of laser cooling are the obvious limitation to few specific ions, which are not fully stripped, and that it works only indirectly in the transverse degrees of freedom.

To compare electron and stochastic cooling we observe that electron cooling works best when the beam energy is low while stochastic cooling times are independent of the energy. Electron cooling times on the other hand are independent of the number of stored particles whereas stochastic cooling times scales with the number of particles

Stochastic cooling works best with large emittances. The opposite is true for electron cooling.

Stochastic and electron cooling are therefore complementary. A good example is stochastic pre-cooling of fragments, which will be employed at the ESR in Darmstadt [38].

Only electron cooling can give short cooling times when the number of stored particles is very high. Therefore, electron cooling is now considered also for high energy applications [12-16].

2 THE EXISTING ION COOLER RINGS

Ten ion cooler rings exist at present. They are listed in order of increasing $B\rho$ in table 1. The newest addition to the list is the Heavy Ion Synchrotron SIS at GSI in Darmstadt, at which an electron cooler has very recently been commissioned [43-44]. This will be used for accumulation of ions and forms a part of the SIS intensity upgrade programme.

All of the existing cooler rings are well represented at this conference. It is not necessary to here repeat information anyway given more accurately in other papers at the same conference. We will instead discuss a few topics of common interest at the ion cooler rings.

3 EXPANDED ELECTRON BEAMS AND ELECTRON COOLING FORCE MEASUREMENTS

The first electron coolers were built with a constant magnetic field strength over full length of the electron beam, with the exception of a slight decrease of the field in the collector, which is made to expand the electron beam in order to distribute the thermal load.

In this arrangement, the transverse temperature of the electrons becomes (at best) equal to the cathode temperature, about 0.1 eV. The longitudinal temperature is strongly reduced by the acceleration of the electrons (this comes from the simple fact that *energy* and not *velocity* is added to the electrons during the acceleration). Non-relativistically, and neglecting intra-beam scattering among the electrons, the longitudinal temperature would become $\left(kT_{\text{cathode}}\right)^2 / 4E_{\text{e}}$ (In reality, the longitudinal electron temperature becomes determined by high voltage supply ripple and by intra-beam scattering among the electrons, but is still much less than the transverse electron temperature).

The transverse electron temperature can be reduced by the same factor as the cross section of the electron beam is increased by adiabatically decreasing the magnetic field along the path of the electrons, between the electron gun and the electron cooling interaction region [45].

$$\frac{kT_{\perp}}{B_{\parallel}} \approx \text{const.}$$

Such an expansion of the electron beam has been introduced in most of the low-energy electron coolers, including the recently commissioned one at SIS. The expansion factors are variable, up to 8 (at SIS), 20 (ASTRID), 25 (TSR), and 100 (CRYRING and TARN II).

Atomic physics measurements on dielectronic recombination cross sections performed at most of these rings have confirmed that indeed, the electron temperature becomes as low as the cathode temperature (100 meV) divided by the expansion factor, in the case of CRYRING and TARN II approximately 1 meV.

Four different methods have been developed to measure the longitudinal electron cooling drag force at different laboratories.

In the *voltage-step method* the output of the electron cooler high-voltage power supply is quickly changed after that the ion beam has been cooled. One observes how fast the ion beam adjusts its velocity to match that of the electron beam.

$$F_{\parallel} = \frac{p}{\eta} \frac{df/dt}{f}$$

This method does not require any special equipment, and has been done at all rings. It works only well, however, when the relative velocity between the ions and the electrons is rather large $\left(>10^4 \text{ m/s}\right)$. The drag force maximum is just about at $v = 10^4 \text{ m/s}$, so there is a lot of interest in measuring the drag force at this and lower relative velocities. Therefore, several other methods have been developed as briefly outlined below.

A simple method, which also does not require any special equipment and has been done at all rings, can be used for measuring the electron cooling drag force on bunched beams. This method can be used just about up to the force maximum [46]. The cooling force is deduced from the observed phase shift of the beam, which occurs due to the electron cooling drag force,

$$F_{\parallel} = qe\hat{U}_{\text{RF}} \sin \Delta\phi_{\text{S}} .$$

A very elegant method, which was originally developed at LEAR [47] and has been further developed at GSI [48] and used also at the TSR and CRYRING is based upon heating the beam with calibrated noise at the same time as it is cooled. Using some mathematics involving the Fokker-Planck equation, one can deduce the cooling force as a function of v from a measured beam velocity distribution function $\rho(v)$, which is obtained from a Schottky noise measurement or a Beam Transfer Function (BTF) measurement. One obtains

$$F_{\parallel}(v) = D \frac{\partial\rho/dv}{\rho(v)}$$

where D is the diffusion constant.

Another method, which also is useful for measuring the drag force for small relative velocities was employed for the first time at the Indiana Cooler [49]. This method is based on creating a counter-force to the electron cooling drag force by means of the same principle as that of the betatron accelerator. Such “Induction Accelerators” have been installed also at TSR and recently also at TARN II [28]. The cooling force vs. relative velocity is determined from the observed velocity shift of the ion beam under the balance between the electron cooler drag force and the external force from the induction accelerator,

$$F_{\parallel} = \frac{qe}{2\pi R} \frac{d\Phi}{dt} .$$

Several of these methods have been used at the ESR and the TSR to systematically evaluate the influence of various parameters, including the ion charge, upon the electron cooling force [20, 48].

Measurements have also been done at CRYRING [18], TSR [20], and TARN II [28] to evaluate the effect of the expansion of the electron beam upon the longitudinal drag force. At CRYRING and TARN II a significant increase in the maximum of the drag force is observed after a first expansion of the electron beam by a factor of 10, but a second expansion of another factor 10 has not significantly changed the drag force. At TSR on the other hand, recent measurements indicate no influence of the electron temperature on the drag force at all [20].

4 DISPERSIVE COOLING

To achieve crystallised beams, three-dimensional cooling is required. As mentioned above, a short-coming of laser cooling is that it only works directly longitudinally. Effective three-dimensional cooling can be observed, and explained by intra-beam scattering [21-22]. Since a goal for laser cooling is however to achieve crystallised beams, for which intra-beam scattering is predicted to vanish, other ways to achieve transverse cooling have to be found. Recently, a way to exploit dispersive coupling to achieve transverse laser cooling has been shown to work at the TSR [23].

Tests made at LEIR show that dispersion at the electron cooling straight section seems to be essential also for electron cooling [32] of Pb^{54+}. In this case, one probably takes advantage of the strong longitudinal cooling force to enhance the horizontal cooling.

5 BEAM DIAGNOSTICS

All rings make extensive use of Schottky noise diagnostics. This is especially impressive at the ESR, where the Schottky noise monitor is capable of detecting even single circulating ions. At the ESR, this has been exploited together with the large momentum acceptance of this machine to make precise mass measurements on many ions with previously unknown masses [38].

Another spectacular achievement using the sensitive Schottky noise diagnostics at the ESR is the observation of "ordering" (sudden disappearance of intra-beam scattering when the number of stored ions has decreased to a few thousand) [36] in electron-cooled ion beams. This observation has now been extended to the transverse planes. The measurements have been done with scrapers.

All rings have some sort of non-destructive beam profile monitor. CRYRING, TSR, ESR, LEIR and TARN II have rest gas ionisation monitors which employ microchannel plates to detect ions and/or electrons created by ionisation of the rest gas by the beam. At the ESR this monitor has been placed in a dipole magnet, and coincidence between the ion and the electron is required, this gives a back-ground free measurement [48]. CELSIUS has a "magnesium-jet" beam profile monitor, based on a beam profile monitor which was used at NAP-M in Novosibirsk [50]. ASTRID has a beam profile monitor, which exploits the fluorescence of the laser cooled beam. A high-resolution, low-noise, cryogenically cooled CCD camera is used to image either the vertical or the horizontal beam profiles.

ASTRID also exploits the fluorescence of the laser-cooled beam to measure the velocity distribution of the beam. A device, called PAT (Post-Acceleration Tube) consists of a cylindrical tube which can be placed on a DC potential. This changes the ion's local velocity and thereby the Doppler-shifted resonant frequency of the optical transition. Recording the fluorescence intensity (via a photo-multiplier looking through a hole in the PAT) while scanning the voltage allows measurement of the ion velocity distribution.

A group at the TSR is developing a beam profile monitor based on a caesium magneto-optical trap [51]. A 50 µm cloud of about 10^4 caesium atoms will be moved horizontally and vertically across the ion beam. The rate of ionised caesium atoms will be observed as the cloud position is varied.

All proton and deuteron cooler rings make use of ions which have become neutralised by picking up an electron in the electron cooler for profile measurements. At the ESR an elaborate system has been built to make use of down-charged and also up-charged (in an internal target) heavy ions for profile measurements. This is possible thanks to the large momentum acceptance of the ESR. Moveable detector pockets allow the insertion of different detectors such as wire-chambers to measure the profile or to do other measurements on those ions. Staff at the ESR have also developed a slow extraction system, which extracts down-charged ions from the electron cooler [35].

At TARN II a superconducting SQUID has been developed for ultra-sensitive measurements of the stored beam current [29]. This has a measuring range from 1 nA to more than 1 µA. At CRYRING, an integrating current transformer from Bergoz has been installed and works well with sensitivity of the order of several nA.

6 IUCF

NSF funding for cyclotron operation at IUCF will end in October 1998 [52]. At that time, the cyclotrons will be retrofit to operate routinely at 210 MeV and be used for proton therapy and other commercial purposes.

At the same time the newly built Cooler Injector Synchrotron CIS [27] and the Indiana Cooler will continue to be funded for nuclear physics at least until 2001.

7 NEW PROJECTS

7.1 MUSES

The project of radioactive ion beam factory at RIKEN was authorised by the Japanese government in 1997 and the construction of a large superconducting cyclotron was started in 1998. Following this cyclotron construction period, the construction of MUSES [53] will be started. This consists of an Accumulator Cooler Ring (ACR), a Booster Synchrotron Ring (BSR) with an injector electron linac and Double Storage Rings (DSR) with $B\rho$ up to 14.6 Tm. The DSRs will be used for experiments including ion-ion merging and collisions, electron-ion collisions and collisions of ions with *x*-rays from an undulator.

Stochastic cooling is foreseen in the ACR and electron cooling is considered for both DSR rings.

7.2 HIRFL-CSR

Another major project for physics with radioactive and other heavy ion beams is proposed at the Institute of Modern Physics in Lanzhou, China [54]. This is the HIRFL-CSR, consisting of two rings with electron cooling, CSRm (10.6 Tm) and CSRe (6.4 Tm). Heavy-ion beams from the HIRFL will be accumulated, cooled and accelerated in CSRm, then extracted to produce radioactive ion beams or highly charged heavy ions, which will be used in CSRe for internal target experiments.

7.3 National Institute of Radiological Sciences

At the National Institute of Radiological Sciences (NIRS) in Chiba, Japan, exist plans for several projects which include electron cooling [55].

One of these projects is for radiation therapy of patients with positron emitters [56]. This allows the delivered dose distribution in the patient to be measured with positron emission tomography (PET). An electron cooler has been constructed, and will be installed in the lower of the two HIMAC rings. It will be used for electron cooling stacking at 6 MeV/*u* of ^{12}C and ^{20}Ne beams, which will be used to create the positron emitting ^{10}C and ^{19}Ne beams by projectile fragmentation.

In a second proposed (not yet funded) stage of the project, accumulation of the primary beam will instead be done in the upper ring, and the presently built electron cooler will be moved there. Another electron cooler, at 400 MeV/*u*, will be placed in the lower ring and be used to accumulate the positron-emitting ions.

A small cooler ring called S-Ring has been designed [57]. It is intended for bio-chemical studies with short beam pulses and for atomic and molecular physics.

8 CONCLUSIONS

There is a great and quite varied activity at the ten existing ion cooler rings, including the very recently commissioned SIS electron cooler. There are several new projects, all in Asia. The new electron coolers at Chiba will employ electron cooling for totally new applications (sophisticated radiation therapy, bio-chemistry and more). We should expect to hear good news from >10 ion cooler rings at future PACs, EPACs, and APACs.

REFERENCES

[1] H. Poth, Physics Reports, 196 (1990) 135.
[2] I.N. Meshkov, Nucl. Instr. and Meth. in Phys. Res. A 391 (1997) 1.
[3] J. Bosser, CERN 95-06, 673.
[4] F. Caspers, Proc. 31st Workshop of the INFN Eloisatron Project, Crystalline Beams and Related Issues, Erice, Italy, 12-21 November 1995, 111.
[5] D. Möhl, Nucl. Instr. and Meth. in Phys. Res. A 391 (1997) 164.
[6] D. Möhl, CERN 95-06, 587.
[7] R. Grimm et al., CERN 94-03, 39.
[8] E. Bonderup, CERN 95-06, 731.
[9] G. Carron, L. Thorndahl, CERN/ISR-RF/78-12.
[10] S. Schröder et al., Phys. Rev. Letters 64 (1990) 2901.
[11] J.S. Hangst et al., Phys. Rev. Letters 67 (1991) 1238.
[12] T.J.P. Ellison, Nucl. Instr. and Meth. in Phys. Res. A 364 (1995) 27.
[13] M. Gentner et al., these proc. MOP54C.
[14] P. Wesolowski et al., these proc. THP36G.
[15] S. Nagaitsev et al., these proc. THP08C.
[16] S.O. Sidorin et al., these proc. THP06J.
[17] A. Källberg, these proc. WEP11E.
[18] H.T. Schmidt et al., these proc. WEP07E.
[19] H. Danared et al., these proc. THP25F.
[20] M. Grieser et al., these proc. WEP14F.
[21] H.-J. Miesner et al., Phys. Rev. Lett. 77 (1996) 623.
[22] H.-J. Miesner et al., Nucl. Instr. and Meth. in Phys. Res. A 383 (1996) 634.
[23] I. Lauer et al., *Transverse laser cooling of a fast stored ion beam through dispersive coupling,* to be published.
[24] S.P. Møller, J.S. Nielsen, these proc. WEP05F.
[25] R.E. Pollock et al., Phys. Rev. E 55 (1997) 7606.
[26] B. v. Przewoski et al., Rev. Sci. Instr. 67 (1996) 165.
[27] G.P.A. Berg, D.L. Friesel, these proc. WEP01F.
[28] T. Tanabe et al., these proc. THP13F.
[29] T. Tanabe et al., these proc. WEP20F.
[30] L. Hermansson et al., these proc. WEP05E.
[31] C. Ekström, these proc. WEP06E.
[32] G. Tranquille et al., these proc. THP09B.
[33] M. Chanel et al., these proc. WEOA01A.
[34] M. Hausmann et al., these proc. WEP03A.
[35] T. Winkler et al., these proc. WEP06A.
[36] M. Steck et al., these proc. THP42G.
[37] F. Nolden et al., these proc. THP39G
[38] B. Franzke et al., these proc. WEOA02A.
[39] D. Prasuhn et al., these proc. WEP11F.
[40] A. Schnase et al.,, these proc. WEP12F.
[41] H. Stockhorst et al., these proc. WEP13F.
[42] K. Blasche et al., these proc. WEP01A.
[43] M. Steck et al., these proc. WEP05A.
[44] L. Groening et al., these proc. THP38G.
[45] H. Danared, Nucl. Instr. and Meth. in Phys. Res. A 335 (1993) 397.
[46] D.D Caussyn et al., Phys. Rev. Lett. 73 (1994) 2696.
[47] H. Poth et al., Nucl. Instr. and Meth. in Phys. Res. A287 (1990) 328.
[48] T. Winkler, *Untersuchungen zur Elektronenkühlung hochgeladener schwerer Ionen,* thesis, Naturwissenschaftlich-Mathematischen Gesamtfakultät der Ruprecht-Karls-Universität, Heidelberg 1996.
[49] T.J.P. Ellison, *Electron Cooling,* thesis, Department of Physics, Indiana University, Bloomington, IN, 1990.
[50] G.I. Budker et al., Particle Accelerators 7 (1976) 197.
[51] V. Luger et al., Max-Planck-Institut für Kernphysik, Heidelberg, Jahresbericht 1996, page 154.
[52] D.L. Friesel, private communication.
[53] T. Katayama, these proc. WEP22F.
[54] J.W. Xia et al., Proc. First Asian Particle Accelerator Conference, APAC'98, Tsukuba, Japan, 23-27 March, 1998.
[55] K. Noda, private communication.
[56] M. Kanazawa et al., these proc. WEP12C.
[57] K. Ohtomo et al., these proc. WEP34C.