# Recent Developments in Small Cooling Rings

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*Abstract*

The small Cooling rings constructed and commissioned in the last few years are now used routinely as important tools in several areas of physics. An extremely wide range of charged particles are accelerated, stored and cooled, and used in atomic and nuclear physics experiments. Most experiments are performed on the circulating beam in the ring. The ions used are atomic or molecular, stable or unstable, polarized or unpolarized, positive or negative and the charge states range from singly ionized to bare heavy nuclei. Electron, stochastic and laser cooling are used to improve the beam quality. Recent developments and trends at the different operating facilities will be described.

## 1. INTRODUCTION

Around 25 years ago, electron and stochastic cooling were invented by Budker and van der Meer, respectively. Electron cooling was first studied in NAP-M and stochastic cooling in the ISR. The first ideas for realistic applications of beam cooling was for antiproton accumulation. Hence two test rings were built, ICE at CERN and ECE at Fermilab, with the aim of studying beam cooling. The subsequent development of the antiproton facilities at CERN and Fermilab is well-known, but by far the most important fore-runner for the small cooler rings of today was LEAR, which has now been in operation for more than a decade. Here it was demonstrated that all the advanced techniques needed to operate a storage ring/synchrotron can be accomplished in a small facility. Stochastic, and more recently, electron cooling was demonstrated on an operational basis. This led several laboratories to design and build cooler rings for their own applications, and it is these ion cooler rings we see operational today.

The latest beam cooling technique, laser cooling, has been used in electromagnetic traps for a long time, with a large impact on atomic physics. This cooling mechanism, which at least in principle is much more powerfull than electron cooling and stochastic cooling, is now being investigated in storage rings. Laser cooling is, however, far from being as universal as the other cooling methods, and it will presumably only have impact on specialized areas. For a very recent review of the state of the art of cooling in rings, we refer to [1].

From the start, there was naturally a scepticism/conservatism about the versatility of such storage rings/synchrotrons, but experience has shown the universality of these devices. Today exotic ion species, some of which were even unknown at the time when the storage rings were designed, have been stored and used in experiments.

The advantages of using a cooler ring/synchrotron instead of another type of accelerator are many, and we mention here only a few relevant for the following discussions:
1) The <u>long storage/interaction time</u> allows a) lifetime measurements, b) active or passive deexcitation of e.g. molecular ions before measurements, c) coherent interactions.
2) <u>Cooling</u> of the injected ion beams can in particular for rare species, e.g. reaction products, lead to intense beams with very small emittance and momentum spread. Also the multiple Coulomb scattering and energy loss from internal targets can be compensated by cooling.
3) The <u>flexibility</u> allows easy changes of energy, ion mass, ion charge and polarity.
4) The <u>colinear geometry</u> in an electron cooler setup is ideal for the study of the ion-electron interaction at low relative energies, i.e. electron recombination and detachment.

Most of the experiments made at the small cooling rings are performed in the ring itself, and less often on external beamlines. Hence the rings are an integral part of the experiments, and in describing the recent developments in the small cooling rings, we will naturally have to go into some detail of the physics being performed.

We will not attempt here a complete review of all the existing ion storage rings. Only a brief description of some recent developments at all the operating rings will be given, and we refer to the review given at the last EPAC [2], to the specific laboratory annual reports and to contributions to this conference for more details. We also note , that there are also plans for new cooler rings in e.g. Italy, Russia and USA.

In the following some selected topics from the developments at the ion storage rings in the last couple of years will be described in more detail. This choice will clearly be somewhat subjective and maybe biassed towards the small rings, and the areas selected do not neccessarily reflect the most important ones.

## 2. OPERATING COOLER RINGS

The operating cooler rings are listed in table 1 in order of increasing energy or rigidity. The rings are designed for very different physics purposes, the smaller ones mainly for atomic physics and the larger ones more for nuclear and elementary particle physics.

All rings have a UHV system operating in the $10^{-10}$-$10^{-12}$ mBar region, and they are all also used as synchrotrons for acceleration or deceleration. All the rings have an electron cooling device, which at the smaller rings are as important as an electron target as a cooling device. Stochastic cooling are used/planned at LEAR, ESR, TARN II and COSY. Internal targets are/has been used for nuclear/particle physics in TSR, LEAR, ESR, IUCF, CELSIUS and COSY.

Recently the neccessity of transverse profile monitors for studying, and optimizing, electron cooling has become apparent. Profile monitors using restgas ionization have been developed at CRYRING [3], TSR [4] and TARN II [5]. At CELSIUS a magnesium jet profile monitor have been installed [6]. Also position-sensitive detectors placed after short straight section are used for this purpose.

Below we shall mention a few of the highlights from the last couple of years and describe a few of the specialities.

### *2.1 CRYRING*

CRYRING is one of the rings mainly devoted to atomic physics, and until today most of the operating time has been devoted to electron recombination studies of ions and molecules [7]. Preceeding recombination measurements are naturally electron cooling, which amongst other places has been demonstrated at CRYRING for molecules.

At CRYRING the spectacular results of using a transversely very cold electron beam was first demonstrated, see [8,9,10] and below.

Also highly charged ions, $Ar^{13+}$, has been stored and cooled in CRYRING. These ions are produced in a cryogenic EBIS ion source, CRYSIS, and considerable progress has recently been made with this ion source, leading to e.g. the production of up to $2 \cdot 10^7$ charges per pulse of $Xe^{52+}$.

Accumulation of ions at the rather low energy of 0.3 MeV/u has also been made alternating transverse cooling and subsequent injections of new pulses.

### *2.2 TSR*

The experimental developments at TSR features among other things electron recombination studies (also laser-stimulated) and laser cooling [11]. For recombination, the emphasis has also recently been on molecules [12]. The polarisation of protons by a polarised hydrogen gas target has been studied, as a feasibility study for a spin filter for antiprotons [13].

A high-current injector is currently being built, in order to produce high-intensity $Li^+$ and $Be^+$ beams for laser cooling, but later also ions from an ECR ion source are intended for this injector. This new injector will decouple the TSR from the tandem and linear post-accelerator, and in particular facilitate operation with ions and molecules of low charge states.

### *2.3 ASTRID*

In ASTRID, the flexibility of storage rings/synchrotrons has maybe been demonstrated to the most extreme. Here the same storage ring is used both as a cooler/storage ring for ions and as a 580-MeV synchrotron-radiation source. The success of the electron operation is documented by fig. 1, which shows the electron current for a typical fill. Around 200 mA is accumulated at 100 MeV and accelerated to 580 MeV with almost no losses, where the beam is stored with a current lifetime product of more than 1000 mA hours. The lifetime is at high currents determined by the Touschek effect, that is intrabeam scattering outside the acceptance of the ring.

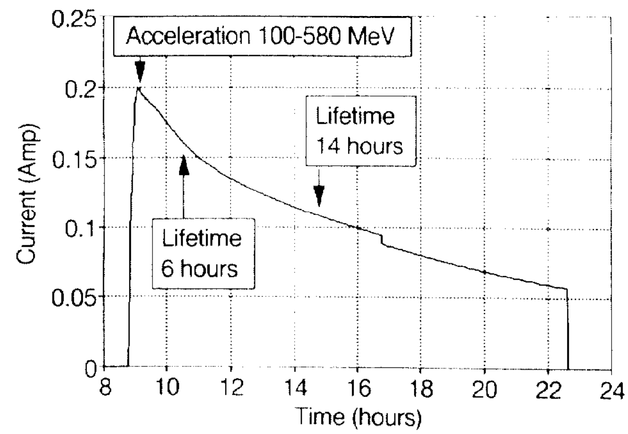


Figure 1. Electron current in ASTRID.

For the ions, the versatility is accentuated by the storage (and acceleration) of ions ranging in mass from 1 amu for protons up to 840 amu for the buckminsterfullerenes ($C_{60}$ and $C_{70}$). Also many negative ions produced either directly in an ion source, or through charge exchange, have been used in e.g. lifetime measurements (see below) or electron-detachment studies. Another research project starting is photodetachment of negative ions using the easily variable energy of the ions to tune a fixed-frequency (in the laboratory system) laser in the ion rest system.

### *2.4 IUCF COOLER*

Many nuclear/intermediate energy physics experiments have been made at the IUCF cooler ring, also with polarized beams, on internal targets. This was the first ring to operationally use electron cooling to produce high-quality, that means small emittance and energy spread, beams for nuclear research. Many accelerator-physics experiments have been made at IUCF, where a small-emittance bunch, obtained by electron cooling, simulate single-particle motion [14]. Both transverse and longitudinal motion have been studied both in and near the chaotic regions. Also space-charge dominated beams have been investigated in the cooler synchrotron [15]. Finally we mention the extensive use of polarized beams, and the demonstration/investigations of siberian snakes.

### *2.5 TARN II*

Although TARN was originally built for accelerator studies, it has recently been used extensively for recombination studies using the electron cooler device as an electron target [16].

The topics directly related to accelerator physics studied at TARN II is slow beam extraction, stochastic and electron cooling and rf-acceleration. Recently the vacuum system has been upgraded resulting in a pressure around $10^{-11}$ mBar.

Table 1: Operating small cooling rings

| Name<br>Institute<br>Location<br>Country | CRYRING<br>MSI<br>Stockholm<br>Sweden | TSR<br>MPI<br>Heidelberg<br>Germany | ASTRID<br>ISA<br>Århus<br>Denmark | COOLER<br>IUCF<br>Bloomington<br>USA | TARN II<br>INS<br>Tokyo<br>Japan | CELSIUS<br>TSL<br>Uppsala<br>Sweden | LEAR<br>CERN<br>Geneva<br>Switzerland | ESR<br>GSI<br>Darmstadt<br>Germany | COSY<br>KfA<br>Jülich<br>Germany |
|---|---|---|---|---|---|---|---|---|---|
| $C$[m] | 48.6 | 55 | 40 | 82.1 | 77.8 | 81.8 | 76.6 | 108.4 | 184 |
| $B\rho$[Tm] | 1.4 | 1.5 | 1.93 | 3.6 | 6.1 | 6.25 | 6.6 | 10 | 11.7 |
| $T_{max}$[T] | 1.1 | 1.3 | 1.6 | 1.6 | 1.5 | 0.89 | 1.6 | 1.6 | 1.7 |
| Injector | CRYEB-IS+RFQ | Tandem +LINAC RFQ+ LINAC | Isotope Separator | cyclotron K=220 | cyclotron K=70 | sy.cycl. K=180 | LINAC | Unilac+ SIS18 | cyclotron K=45 |
| Injection energy | 0.3 MeV/u | 0.5-15 MeV/u | 200 keV | 55-220 MeV/u | 10-68 MeV/u | 45-190 MeV/c | 4.2-180 MeV/c | 50-830 MeV/u | 11-45 MeV/u |
| A | 2-208 | 2-130 | 1-166 | 1-20 | 1-14 | 1-16 | 1,16,208 | 20-238 | 1-20(40) |
| Z | 1-13 | 1- | -1,1,2 | 0.5-1·A | 1-7 | 0.5-1·A | 1,1,6,53 | 0.4-0.5·A | 0.5-1·A |
| Electron cooling | 0.2-13 kV | 0.5-16 kV | 0.5-3 kV | 20-300 kV | 15-110 kV | 20-300 kV | 1-30 kV | 2-300 kV | 20-100 kV |
| Stoch. cooling | - | - | - | - | 7 MeV/c | - | 2-1270 MeV/c | 500 MeV/c | 0.8-2.5 GeV |
| Reference | 3,7,8,9,10 | 4,11,12,13,20 | 21,24,25,26,27 | 14,15 | 5,16 | 6,17 | 18 | 29 | 19 |

### *2.6 CELSIUS*

CELSIUS is operated with internal cluster-jet, hydrogen pellet and fibre targets. The main experimental program is studies of meson production near threshold. For heavy ions, accumulation of ions is needed using the electron cooler.

The "electron heating" phenomenon [17], which under some circumstances leads to an increase and not a decrease in beam emittance and which has also been observed at other cooler rings, are now at least partly explained as originating from high-order resonances, excited by the non-linear fields from the electron beam.

### *2.7 LEAR*

LEAR has now been used with antiprotons for more than ten years. Today electron cooling are used at the lower energies (2-50 MeV/c) instead of the much slower stochastic cooling.

For commissioning purposes, protons and $H^-$ have been used instead of the more "expensive" antiprotons. Also $O^{6+}$ has been studied on one occation.

LEAR is now being studied as a heavy-ion accumulator for the LHC [18]. In order to produce the dense bunches needed for the LHC, accumulation and cooling (electron-) is needed in LEAR. The ions to be tested are $Pb^{53+}$, where many multi-turn injections are needed to accumulate the $10^9$ ions needed for the LHC. Also other ions might advantageously be accumulated in LEAR before further acceleration in the CERN accelerators. For this purpose, and for the general improvement, the LEAR electron cooler is still being optimized, e.g. e-beam neutralisation is being studied.

### *2.8 ESR*

One of the advantages of the ESR is it's complex and versatile injector complex, consisting of the UNILAC and the SIS synchrotron, which, evt. in combination with the fragment separator, allows injection of a very broad range of ion masses and charge states. This means that fully stripped ions are available up to the heaviest elements, and also exotic nuclei far from stability.

The physics is mainly devoted to nuclear physics, but several atomic physics experiments have also been performed, e.g. atomic structure and recombination experiments of almost bare heavy nuclei, where the $Z^2$ scaling of the atomic levels shifts the transitions to very high energies.

### *2.9 COSY*

COSY was the last of the rings to come into operation, but it is now operationally delievering protons, resonantly extracted, for experiments. Also the electron cooler has been commissioned and experiments on internal targets are being prepared [19].

## 3. Electron Cooling

Although electron cooling has been known for more than a quarter of a century, it is only in the last few years where its strength has been exploited fully. Electron cooling is being used/studied at several rings for accumulation of intense beams, and it is used routinely in connection with internal target experiments.

In the last couple of years, the electron beam has been utilized at the small rings as an electron target, for a study of the ion-electron interaction, and in particular electron capture and electron detachment. By varying the electron energy the cross sections can be studied from the meV to the keV region. Although such experiments were performed before the cooler rings came into operation, the electron-cooler geometry is far superior to the previous setups. Furthermore, the long storage times allows the internal degrees of freedom of molecules to deexcite, either passively [20] or actively [21], before the measurement.

The resolution of such experiments is set by the temperature of the electron beam. As is well-known, the longitudinal temperature is very small owing to the large acceleration of the beam, whereas the transverse temperature is set by the temperature of the cathode, i.e. around a tenth of an eV. Recently [8,9,10], it was realized that adiabatic expansion of an electron beam in a decreasing magnetic field leads to a reduction in the transverse temperature corresponding to the reduction in the magnetic field. This effect has apparently been known for a long time, but was first realized at CRYRING, where the corresponding increase in the cooling force and the improvement in resolution of dielectronic recombination measurements of around a factor of ten was demonstrated.

This method of reducing the transverse temperature is much simpler than what has otherwise been proposed, e.g. photo emission from cold cathodes using lasers. The principle has already been adopted at TSR and ASTRID. By using solenoids with a very strong magnetic field (superconducting) one can envisage reductions in temperatures of up to two orders of magnitude. The impact of this effect will at least in the small rings be very large on recombination/detachment experiments, and maybe to a smaller extent on the cooling, which in many cases is less important.

## 4. Laser Cooling

Laser cooling has been used for a long time in electromagnetic traps, but its potential in storage rings has only been studied in the last few years. Let us here dwell a little on the cooling effect and summarize the state of art for laser cooling.

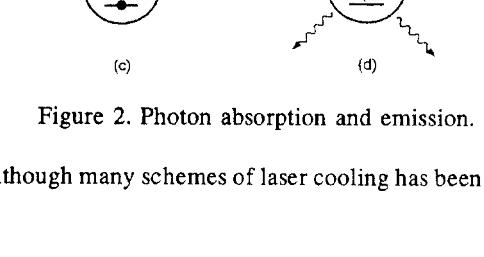


Figure 2. Photon absorption and emission.

Although many schemes of laser cooling has been realized in traps, let us here confine ourselves with the socalled spontaneous force. This origin of this cooling force is schematically presented in fig. 2. A laser with a narrow bandwidth is superimposed on an ion beam in a straight section in a storage ring. The ions are required to have an electronic structure with only two levels, a lower and an upper level, and no branching to other levels. If the ion velocity is such, that the Doppler shifted wavelength of the laser corresponds to the energy difference between the two levels of the ion, a photon may be absorbed (a-b). The ion will subsequently deexcite by photon emission (d). Since this emission process is isotropic and since the laser photons all have the same direction, the ion will on the average in each such absorption/emission proces have gained the momentum of the photon (c). This leads to a repulsive cooling force away from the resonant velocity. This force has always the same sign and no so-called stable point exists, that means a velocity where the force is zero and has a negative slope. To create a stable point one can either use an induction accelerator, as realized at TSR, to create an additional constant negative force, or use a second laser, as realized at TSR and ASTRID, to create a cooling force of opposite sign. Hence the co-propagating and counter-propagating lasers should be slightly detuned in the ion rest frame. The cooling will then consist of narrowing this capture range of the ions, and the momentum spread will be directly determined by the frequency difference of the two lasers.

Obviously the scenario that has been described only leads to longitudinal cooling, but transverse cooling can in principle be arranged by laser beams perpendicular to the ion beam, although at the expense of a very large reduction in overlap and cooling force. A scheme of coupling the transverse and longitudinal degrees of freedom for a bunched beam has recently been proposed [22].

Clearly, laser cooling is far from universal, and it only works for ions dominated by a two-level structure, where the energy difference should be within reach of tunable lasers. Furthermore the lifetime of the upper level should be short, in order to produce a strong cooling force. This leaves very few ions well-suited for laser-cooling, e.g. $Li^{+*}$, $Be^{+}$ and $Mg^{+}$.

Although the momentum of a single photon is small, a large cooling force is possible owing to the high photon intensity in a laser beam. The final temperature is set by the recoil from a single photon, if no other heating processes are present, and can be as low as 0.01 eV.

For laser-cooling of a lithium beam energy spreads below $10^{-6}$ have been obtained for dilute beams [23,24]. Lithium is however not very attractive since the cooling is performed from a metastable state, which is long-lived but weakly populated.

At TSR laser cooling, combined with electron cooling, has been investigated in detail for Beryllium [11].

At ASTRID, the favourite candidate has recently been Magnesium, which, however, required the development of frequency doubling of a dye laser beam, since the transition is in the ultraviolet region. Using two lasers, cold beams have been obtained [25]. Also bunched beam cooling has been demonstrated with only one laser [26]. The synchrotron motion induced by an rf-cavity combined with the cooling force from one laser leads to an effective cooling, as qualitatively demonstrated by fig. 3, where the narrowing of the velocity profile is shown.

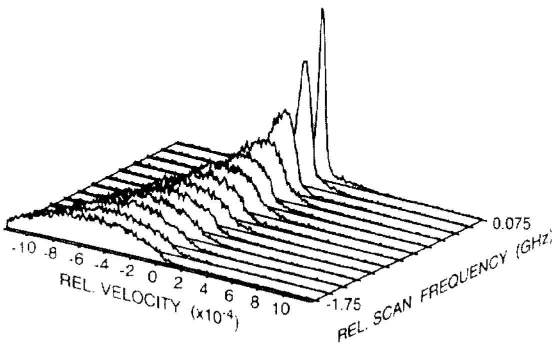


Figure 3. Bunched beam laser cooling.

Let us finally mention, that the laser itself provides a very useful diagnostic tool. By observing the flourescent light, as a weak laser is scanned through the velocity profile, this velocity profile can be measured to high accuracy.

## 5. LIFETIME STUDIES

A very simple exploitation of a storage ring, is to use it for lifetime measurements.

At ASTRID, this has been concentrated on negative ions, where several fundamental systems have been investigated. Recently, the existence of unexpected longlived state of $CO^{++}$ has been demonstrated [27]. In fig. 4 the yield of C or O as detected after a straight section, and which reflects the circulating intensity, shows lifetime components in the ms and second range. Enriched $^{13}C^{16}O^{++}$ was used, in order to avoid contamination from e.g. $^{14}N^{+}$ and $^{14}N_2^{++}$.

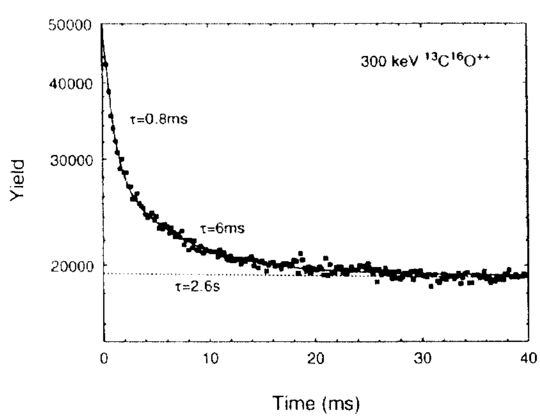


Figure 4. Decay of a $CO^{++}$ beam.

At TSR, the lifetime of a specific metastable state, only populated by 20 % of the $C^{4+}$ beam, was measured [28]. By detuning the electron energy to a dielectronic recombination resonance specific for this state, the lifetime could be measured by monitoring the dielectronic recombination rate.

At ESR the nuclear lifetime of beta-decaying (to a bound electronic state) nucleus has been measured [29]. The bare nucleus $^{163}Dy^{66+}$ can decay into $^{163}Ho^{66+}$. The Holmium ions are detected by stripping in a gas jet to bare $^{163}Ho^{67+}$ ions. This, and other beautiful experiments performed at ESR, rely on the simultaneous storage of several charge states in the large momontum acceptance ring ESR.

## 6. CONCLUSIONS

Although the small cooling rings have only been in operation for around 5 years now, the investments have started to pay off, and many techniques and developments have been made. There is, however, much still to come, as the potential of this type of accelerators becomes apparent to the experimental physicists.

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