WHERE ARE WE AFTER 30 YEARS OF ELECTRON COOLING

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Abstract

During the 30 years that have past since the first technique for cooling of heavy-particle beams was proposed, electron coolers have been installed at a dozen storage rings. We briefly review the development of electron cooling during these years and describe the existing installations. Today's coolers are used both for preparing dense ion beams and as electron targets for studies of electron–ion recombination and similar processes, and an overview of these applications is given. Some recent results related to cooled beams are mentioned and we indicate a few directions for future developments.

1 INTRODUCTION

Electron cooling was proposed by Budker 30 years ago [1] as a means to increase the phase-space density of heavy-particle beams in storage rings. The main application considered initially was to increase the luminosity in proton–proton or proton–antiproton colliders.

Very briefly, an electron cooler uses an intense beam of cold electrons, guided from a gun to a collector by a magnetic field parallel to the beam. The electron beam is merged with the heavy-particle beam over a distance of typically one or a few metres, and, provided that the two beams have the same average velocity, heat is transferred from the hot heavy particles to the electrons through the Coulomb interaction between the particles. Longitudinal and transverse cooling times can vary from milliseconds to tens of seconds or more depending on particle species and energy. A thorough review of the subject is given in reference [2].

Electron cooling was first demonstrated in 1974 at the NAP-M ring in Novosibirsk [3]. The group in Novosibirsk laid the foundation to both the theoretical and experimental knowledge about the cooling process. This included the effect of the "flattened" electron-velocity distribution, i.e., the fact that the longitudinal energy spread of the electrons in the frame of reference moving with the electrons is much smaller than the transverse energy spread, the improvement found in the cooling efficiency due to the magnetic field in the cooler, which reduces the effective temperature of the electrons and changes the dynamics of the electron–ion collisions, etc. Studies of electron cooling were also performed using a 850-keV ion beam from an electrostatic accelerator in a single-pass setup, MOSOL. Here it was observed, for instance, that the magnetic field causes the interaction between ions and electrons to be stronger for negatively charged ions (H^-) than for positively charged ions (protons) [4].

The need to accumulate antiprotons for the $p\bar{p}$ colliders at CERN and Fermilab motivated the construction of two rings dedicated to cooling tests at the end of the 1970s: the Initial Cooling Experiment (ICE) at CERN and the Electron Cooling Experiment at Fermilab. The results from these rings essentially confirmed the results from Novosibirsk. At the same time it was realised, however, that stochastic cooling was better suited for the accumulation of antiprotons. Nevertheless, the development of electron cooling has continued through its implementation at a number of small ion storage rings during the last ten years. In most of these rings, the electron cooler is used not only for beam cooling or other beam manipulations, but also as an electron target for studies of recombination, ionisation, excitation, or de-excitation of the stored ions.

2 COOLERS IN OPERATION

There are nine electron coolers in operation today. Their principal design parameters are shown in Table 1. In addition, there is one cooler being built at GSI, to be used for accumulation of ions in the SIS ring.

In several of the smallest rings equipped with electron cooling (TSR in Heidelberg, TARN-II in Tokyo, ASTRID in Århus, and CRYRING in Stockholm), atomic and molecular physics is the dominating field of research. In these rings cooling and/or studies of the electron–ion interaction have been performed using a wide range of ions, both positive and negative, from molecular ions such as, for example, OH^+ at TSR, HeH^+ at TARN-II, H_2D^+ at CRYRING and C_2^- at ASTRID, via light atomic ions to heavy, highly charged ions like Pb^{54+} at CRYRING or Au^{51+} at TSR. For partially stripped ions with a low charge-to-mass ratio, the maximum velocity can be very low. Typical ion energies are $2 - 20$ MeV per nucleon, corresponding to approximately $1 - 10$ keV electron energy, but the CRYRING cooler has been used both for cooling, accumulation, and recombination at 160 eV electron energy, and in ASTRID ionisation has been studied down to 100 eV.

In many recombination experiments the emittance of the ion beam is important, and phase-space cooling has to be applied. Even more critical, however, is the quality of the electron beam, since, in particular for a cooled ion beam, the velocity spread of the electrons is higher than that of the ions. A crucial parameter is thus the temperature of the electrons which determines the energy resolution when the recombi-

	LEAR	IUCF	CELSIUS	ESR	COSY
Electron energy (keV)	30	270	300	320	100
Electron current (A)	3	4	2	10	4
Cathode diameter (mm)	50	25	20	50	25
Beam expansion factor	–	–	–	–	–
Magnetic field (T)	0.2	0.15	0.18	0.25	0.15
Cooling solenoid length (m)	1.5	2.8	2.5	2.5	2
Solenoid length/ring circumference (%)	1.9	3.2	3.1	2.3	1.1
Reference	[2, 5]	[6]	[7]	[8]	[9]

	TSR	TARN-II	ASTRID	CRYRING
Electron energy (keV)	20	110	2	20
Electron current (A)	3	4	0.2	3
Cathode diameter (mm)	51	14	10	40
Beam expansion factor	7	14	$6 - 20$	10, 20
Magnetic field at electron gun (T)	0.3	0.5	0.27	0.3
Cooling solenoid length (m)	1.5	1.5	1	1.1
Solenoid length/ring circumference (%)	2.7	1.9	2.5	2.1
Reference	[10, 11]	[12]	[13]	[14]

Table 1: Design parameters for electron coolers in operation today.

nation cross section is measured as a function of the relative energy between ions and electrons and also the count rate or the signal-to-noise ratio. Normally, the transverse electron temperature, at least at low electron energies, is equal to the temperature of the cathode that the electrons are emitted from (around 900°C, corresponding to a thermal energy spread of 100 meV). The longitudinal energy spread is in the order of 0.1 meV due to the acceleration of the electrons, limited not by the cathode temperature but by the relaxation between the potential and the kinetic energy in the electron beam. The introduction of the adiabatic electron-beam expansion, first at CRYRING [15, 16], then also at TSR, TARN-II, and ASTRID, has made it possible to reduce the transverse temperature considerably. Using a high magnetic field at the electron gun, a lower field in the rest of the cooler, and a transition between the two fields that is adiabatic with respect to the cyclotron motion of the electrons, the transverse temperature becomes reduced by the same factor as the field is reduced. Expansion factors between 7 and 20 have been used, giving the electrons transverse energy spreads in the range $5-15$ meV. As the beam expansion has been implemented, electron guns that are smaller but have essentially unchanged perveances have usually been installed, so that the electron density in the region where the electrons and ions interact is the same with beam expansion as it was before. The beam expansion has resulted in a much improved energy resolution in many recombination experiments and represents a significant step in the evolution of electron cooling during recent years.

At the larger of the small ion storage rings (LEAR at CERN, the IUCF Cooler in Bloomington, CELSIUS in Uppsala, ESR in Darmstadt, and COSY in Jülich), where nuclear or particle physics dominates, the electron coolers are used more for cooling and beam manipulations than as electron targets. (The cooler at the ESR is an exception in this respect, since it to a large extent is used for atomic physics, although at higher energies than at the four smaller rings). Here the development has been directed toward higher electron energies (at CELSIUS electron cooling has been used for protons up to 500 MeV), higher charge states (up to U^{92+} at ESR), and more intense electron beams (experiments with a neutralised electron beam have been performed at LEAR [17]). Also, beam physics has been a field of detailed investigations. An example is the studies of cooling of bunched beams at the IUCF Cooler [18, 19]. Further, the recent results from ESR showing an abrupt reduction in momentum spread in low-intensity beams of highly charged ions [20] are most interesting. Some of these topics are discussed in more detail below.

3 STUDIES OF ELECTRON COOLING

When cooling is applied to a circulating ion beam, the aim, generally speaking, is to reduce the beam emittance as much as possible in a time that is as short as possible. It is therefore important to be able to measure the efficiency of the cooling process and to study the properties of the electron beam, and a number of methods have been developed for this purpose. One quantity, related to the cooling time, that can be used to diagnose the cooling process is the drag force that an ion experiences when it passes through the electron beam. The drag force, or at least its longitudinal component (the component along the direction of motion of the electron beam), has been measured as a function of the velocity of the ion relative to the electrons using several different techniques.

Fig. 1 shows a compilation of drag-force measurements from all storage rings that use or have used electron cooling and also from the single-pass setup MOSOL in Novosibirsk. The points represent a selection of the "best" values reported for singly charged light ions (protons or deuterons in most cases). For ESR, data for Ne^{10+} divided by 100 were used, causing somewhat low values compared to the others since the drag force does not quite scale with q^2 (see below). The scatter of the data points reflects a wide range of measurement conditions, and a detailed comparison between the results from the different installations is not meaningful. It is clear, however, that the early cooling experiments show somewhat low values due to a relatively high electron temperature, while the most recent measurements at CRYRING and TSR with expanded electron beams show the highest forces. The values for the low relative velocities depend on the longitudinal electron temperature and thus on the electron-beam density used for the measurements, but they are also sensitive to the influence that the magnetic field has on the electron–ion interaction. As an illustration, theoretical drag forces for two different transverse temperatures, but without magnetic-field effects taken into account, are also shown in the figure. The curves were calculated using the model of binary collisions between ions and electrons with a transverse electron-energy spread of 10 and 100 meV (upper and lower curve, respectively) and a longitudinal spread of 0.1 meV.

During recent years, cooling of highly charged ions has been studied at several rings. At the ESR, drag-force measurements have been performed for ions in a range of charge states between C^{6+} and U^{92+} [27]. One might expect that the drag force is proportional to the ion charge q squared since the Rutherford cross section for scattering between

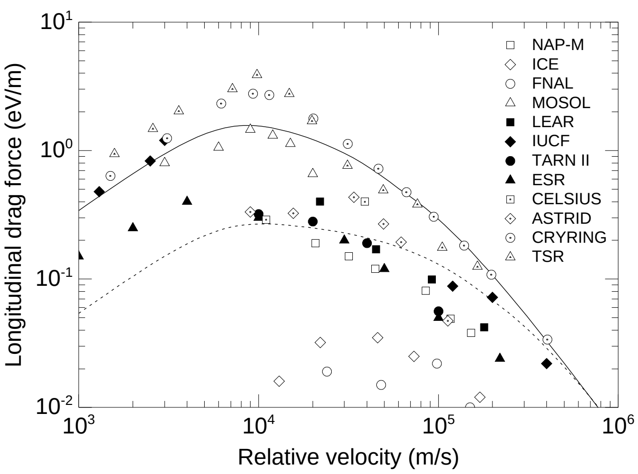

Figure 1: Results of drag-force measurements (points) normalised to singly charged ions and an electron density of 10^{14} m^{-3} [21, 22, 23, 4, 24, 6, 12, 25, 26, 13, 11]. Curves represent theoretical calculations, cf. text.

ions and electrons is proportional to q^2. For highly charged ions, however, non-linear effects in the ion–electron plasma become important, leading to a drag force that scales with a power of q that is smaller than 2. The data from ESR show that the exponent varies between 1.6 and 2.0 depending on the relative ion velocity. These results are in qualitative agreement with molecular-dynamics calculations of the stopping power in strongly coupled electron plasmas [28].

Highly charged ions not only have high cooling rates, but also high recombination rates. The theory of radiative recombination predicts a rate that, like the cooling rate, is approximately proportional to the charge of the ion squared. Since the cooling time is much shorter than the recombination time for singly charged ions, the same should thus hold for highly charged ions. However, measurements of the recombination rate have given results that are higher than one would expect from theory (see, e.g., [29]). The effect is clearly noticeable for bare ions but can be very large for ions that are only partially stripped. This was seen, for instance, at LEAR, where measurements of lifetimes and cooling times of lead ions in charge states around 53 were performed, motivated by the need for dense heavy-ion beams in the future Large Hadron Collider. It was found [30] that the lifetime of Pb^{53+} ions was about 25 times shorter than predicted by the theory for radiative recombination. The same ion has also been studied at CRYRING, where a recombination rate coefficient that was another factor of 12 higher than the one obtained at LEAR was observed. It is conceivable that the higher rate at CRYRING is caused by the lower transverse electron temperature due to the beam expansion. In the case of ions that are not fully stripped, dielectronic recombination can most probably explain at least part of the enhancement of the rate, but a good understanding of the effect is still lacking.

A topic intimately related to electron cooling is the study of cooled ion beams. Already at the NAP-M ring it was observed and explained how cold beams with high phase-space densities develop collective excitations in the form of density waves, and how these waves distort the Schottky spectra of such beams, giving them a characteristic double-peak structure [31].

At NAP-M it was also observed that the Schottky power was independent of the particle number at low beam intensities [32]. This was interpreted as an ordering of the beam particles, or a crystallisation. The observations caused a great deal of speculation about the structure of ordered ion beams, and much effort has been put into calculations and molecular-dynamics simulations of ordered beams. Such beams would have very low emittances and could thus have many applications. The calculations have yielded information on possible crystal structures [33] and also about criteria that ring lattices have to fulfil in order to allow crystals to survive once they have been created [34]. On the other hand, it has not been clear how the crystal would be able to form in the first place since very strong cooling is needed to overcome the intrabeam scattering in a dense, condensing beam and the heating in the bends and the focussing elements of the ring. Consequently, the results from the ESR [20], showing a sharp reduction in momentum spread for low-intensity beams of highly charged ions, are very interesting.

During the usual exponential decay of the beam, the corresponding decay of the Schottky power could be seen until less than 100 particles were left in the ring. As the beam intensity dropped below a certain limit—typically a few thousand particles—the width of the Schottky spectrum suddenly shrank to a very low value. This value was consistent with the momentum spread caused by the ripple on the dipole magnetic field. Clearly, this transition has to be the manifestation of an ordered state, where the positions of the beam particles are locked with respect to each other. However, this phenomenon is quantitatively quite different from the NAP-M case, where the beam consisted of protons, and the number of stored particles was several orders of magnitude higher.

The physics of cooled bunched beams has been a subject of study particularly at the IUCF Cooler. Investigations of the bunch length of a cooled beam as a function of particle number and rf amplitude showed that the length can be explained by a simple theory based on the equilibrium between the rf field in the acceleration cavity and the space charge of the bunch. The longitudinal dynamics of this bunch is similar to that of a single particle [18]. It was also observed that, when the rf frequency was shifted from the revolution frequency of the ions (as determined by the electron cooler), the bunch started to perform phase oscillations with respect to the rf. The frequency shift where the oscillations set in depends on the drag force in the cooler and can be used for a determination of the relative ion velocity at which the drag force has its maximum [19].

4 APPLICATIONS

As already indicated, the amount of applications of electron cooling and cooled beams is large and steadily growing, and here it is not possible to mention more than a few. A common use of cooling is for the accumulation of ions. By cooling while injecting new pulses into the ring, stacking can be performed either in the transverse or the longitudinal phase space or both, and the number of particles that can be stored in the ring can exceed the contents of an injector pulse by several orders of magnitude. Such stacking can be essential for highly charged or polarised ions where the intensity from the injector often is low. Other applications of cooling as such is to increase the beam lifetime and prevent emittance blow-up when internal targets (e.g., gas targets) are used, or to allow a deceleration of the beam without getting too large an emittance.

The small transverse extension and small momentum spread of a cooled beam is important for many types of experiments in nuclear physics. A small momentum spread can improve the energy resolution in cross section measurements, a small beam size allows a better separation of reaction products, etc.

In atomic and molecular physics, the use of storage rings with electron cooling has had a profound impact on many fields of research (see, e.g., [35] for a recent review). Compared to traditional single-pass experiments, studies of recombination, excitation, or other processes using stored ions and cooler electrons benefit not only from the intensity gain one can achieve through different stacking methods. The phase-space cooling of the ions together with an internal cooling of the ions (relaxation of excited electronic, vibrational, or rotational states obtained by just keeping the ions stored for a while) that sometimes is very important makes it possible to define the initial state of the ions very accurately. Also the electron continuum is well defined—the electron density and the overlap with the ion beam are accurately known, and the electron temperature can be determined from independent experiments. Finally, one can mention that the (relatively) high ion energies in storage rings make many recombination measurements almost free of background. Yet, ions with energies of tens of MeV or more can easily be used to study reactions at centre-of-mass energies below one meV.

5 OUTLOOK

Electron cooling is developing both toward higher energies and toward improved performance at low energies.

At low-energy storage rings, the need for a low electron temperature when the coolers act as electron targets can be met by using adiabatic beam expansion, which, as already mentioned, has given transverse energy spreads down to $5-15$ meV. At CRYRING, a superconducting gun solenoid with a field strength of up to 5 T will be installed in the near future. This will allow a beam expansion with a factor of 100 and transverse electron-energy spreads down to 1 meV and will create possibilities for still higher energy resolution in recombination experiments at low relative energies. A similar project is under way at TARN-II [36].

Another way to reduce the electron temperature is to use cold photo-cathodes as electron emitters [37, 38]. These do not give as high currents as conventional thermionic cathodes, but could be used in dedicated electron targets, installed as complements to electron coolers in storage rings. Such targets are being built or planned at several laboratories. These targets could in addition possibly use guns with adiabatic acceleration (i.e., adiabatic with respect to the plasma period of the electrons) as a means to reduce also the longitudinal electron temperature, at least at low currents.

A completely different kind of electron cooler is being studied at Fermilab [39]. The aim of this project is to build a cooler for 8 GeV antiprotons, requiring electrons of 4.3 MeV kinetic energy. The cooling system would use a 5 MeV Pelletron accelerator and the preliminary design includes a 66 m long cooling section. At these energies, there is no need to have a constant magnetic field along the electron beam. Instead, periodic focussing with a number of quadrupole or solenoid magnets would be used. A return line brings the electron beam back to the high-voltage terminal, where a very high collection efficiency is needed in order to keep the power dissipation manageable. A cooling system of this kind would be more efficient than stochastic cooling for reaching low emittances with intense antiproton beams. In fact, it would also be the first time that electron cooling would be used for the purpose originally suggested by Budker—to increase the luminosity in proton–antiproton colliders.

We have shown, however, that during the 30 years that have passed since the first beam-cooling technique was proposed, electron cooling has found a large number of other applications in several branches of physics. It is used routinely at a growing number of accelerators and storage rings and it is still developing.

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