# 40 YEARS OF ELECTRON COOLING AT CERN

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*Abstract*

For nearly 40 years electron cooling has been used extensively on the storage rings of the CERN accelerator complex for the accumulation of ions or for the improvement of beam quality for precision experiments. Since the first cooling experiments on ICE (Initial Cooling Experiment) the coolers have evolved to incorporate the latest advances in electron cooling technology and many unique experiments have also been performed when the coolers are not used for everyday operation. The trapping of anti-hydrogen atoms and more recently lead-lead and proton-lead collisions in the LHC have been made possible thanks to cooling in the Antiproton Decelerator (AD) and cooling and accumulation of lead ions in the Low Energy Ion Ring (LEIR) respectively.

The next cooler to be built at CERN will be installed on ELENA (Extra Low ENergy Antiproton ring) and will operate at electron energies below 350 eV. Many challenges lie ahead in operating at such a low energy with minimum perturbation to the storage ring. The present AD cooler, which has already seen two re-incarnations, will also be replaced with a new state-of-the-art device operating at higher energies in order to improve the quality of the antiproton beam in this ring.

## INTRODUCTION

Electron cooling was proposed by G. Budker [1] in 1966 as a possible means to accumulate antiprotons and was successfully demonstrated in 1974 on the proton storage ring NAP-M in Novosibirsk [2]. At that time CERN decided to embark on a project to test electron cooling and another technique for phase space compression proposed by Simon van der Meer, stochastic cooling. The goal was to determine which of the two methods would be more appropriate for the cooling and accumulation of high-energy antiprotons which would subsequently be used in the SPS collider.

## THE ICE AGE

The Initial Cooling Experiment, ICE, was built at CERN between 1977 and 1979 using components from the g-2 storage ring previously used to measure the magnetic moment of the muon. The 74.38 m ring (Fig. 1) operated with protons in the momentum range 0.3 to 2.1 GeV/c and operated close to the transition energy.

The ICE electron cooler is shown in Fig. 2, and was composed of: a) a flat cathode electron gun producing and accelerating the electrons; b) a drift space, in the central part of which electrons and protons travel together; c) a collector where the electrons are decelerated and finally absorbed. The gun and collector are inclined at 36° (in the vertical plane) with respect to the horizontal central part of the drift region. A vacuum level compatible with the average ring vacuum level of $10^{-9}$ Torr was provided all along the electron and proton trajectories. The electrons were guided from the gun to the collector entrance in a longitudinal magnetic field.

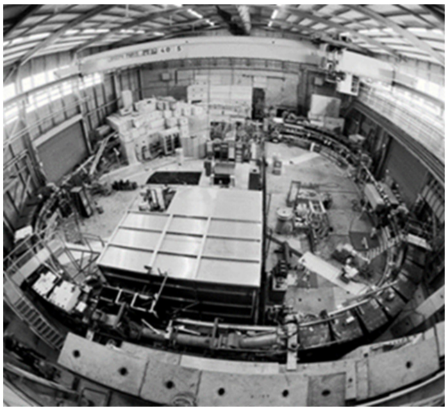

Figure 1: The Initial Cooling Experiment ring at CERN.

With the electron and proton beams well matched in velocity (to about 4 parts in 10 000) and direction (to about $5x10^{-4}$ rad) cooling was immediately observed. Within one second the proton beam stabilized with greatly reduced spreads in angle and energy.

A mean lifetime of about 140 minutes, corresponding to the calculated value for losses produced by single scattering on the rest gas, was observed for the cooled beam. Without cooling the measured lifetime was 2 minutes.

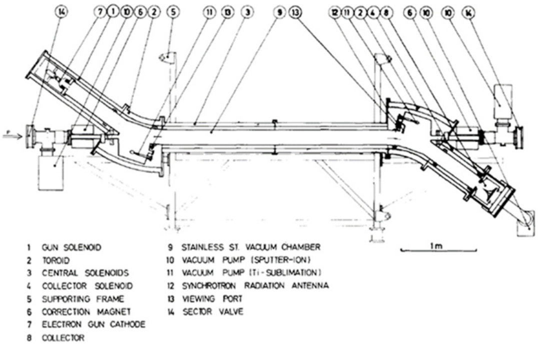

Figure 2: The ICE electron cooler.

To measure the cooled beam diameters or angular divergences, three methods were used; neutral beam profiles, beam scrapers, and a horizontal beam profile monitor. For the measurement of the equilibrium momentum spread, a longitudinal pickup sensitive to Schottky noise was used to monitor the variation in particle density and frequency spread.

The measurement of the transverse dimensions gave r.m.s. horizontal and vertical widths of 2.6 mm and 2.5 mm respectively, corresponding to angular divergences of

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-MOZGBF3

$\theta_h$(r.m.s. ) = 2.3 × $10^{-4}$ and $\theta_v$(r.m.s. ) = 2.3 × $10^{-4}$. The lowest momentum spread recorded was $\delta p = 4 \times 10^{-5}$ (fwhm) for a beam intensity of 8 × $10^6$ protons (Fig. 3). Further measurements of cooling times, drag rates and frictional forces as a function of the cooler parameters were also performed during the two years of operation [3].

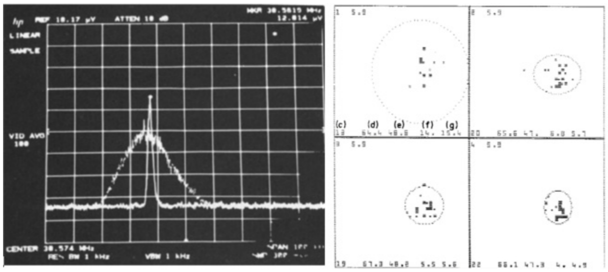

Figure 3: (left) Frequency spectrum of Schottky noise at the beginning and end of the cooling process. (right) Cross-sections of neutral atom beam as seen by a two-dimensional Multi Wire Proportional Chamber.

## LEAR AND LEIR

Even though stochastic cooling was retained for the Antiproton Accumulator project, the request by physicists for a program with low energy antiprotons gave a new lease of life to the ICE electron cooler [4].

To complement the stochastic cooling system and improve the duty cycle of the Low Energy Antiproton Ring (LEAR), the original ICE cooler went through several modifications between 1981 and 1986 for it to be integrated in LEAR [5].

Operation in LEAR required a static vacuum level less than $10^{-11}$ Torr which meant that the cooler needed a major upgrade of its vacuum system. Higher pumping speeds and a careful choice of materials were needed if any significant reduction in the vacuum level was to be obtained. The complete vacuum envelope was re-designed and built using high quality AISI 316LN stainless steel and bakeable at 300˚C. The use of NEG (non-evaporable getter) strips developed for the LEP project provided the increase in pumping speed and three such modules were initially installed on the cooler.

By the autumn of 1987 the cooler was ready to cool its first beam. The first cooling tests were made on a 50 MeV proton beam injected directly from the Linac 1 and the initial results confirmed all expectations from this device. Many of the cooling performance measurements that were made on ICE were redone in LEAR using proton beams with a wide range of intensities [6].

After protons, the attention turned to antiprotons and the use of electron cooling for improving the duty cycle of the LEAR deceleration. Normally 15 minutes were required to obtain a "cold" beam at 100 MeV/c, the lowest momentum in LEAR. With electron cooling this duration was decreased to 5 minutes as cooling was only needed for 10 seconds on each of the intermediate plateaus. The necessary hardware modifications needed to render the cooler operation as reliable and effective as possible included the replacement of the collector with one having a better collection efficiency (>99.99%), a new control system to synchronise the cooler power supplies with the LEAR magnetic cycle, and the implementation of a transverse feedback system (or "damper") needed to counteract the coherent instabilities observed with such dense particle beams. Another important modification to the cooler was the development, with CAPT in Lipetsk, of a variable current electron gun [7] allowing the online control of the electron beam intensity by varying the voltage difference between the cathode and the "grid" electrode. This new gun was of the adiabatic type designed to operate in a relatively low magnetic field, a prerequisite for its integration in LEAR.

Apart from being the first cooler to be used routinely for accelerator operations, the apparatus was also the first to demonstrate the cooling and stacking of ions. In 1989 a machine experiment was devoted to studies on $O^{6+}$ and $O^{8+}$ ions coming from the Linac 1. An increase by a factor of 20 in intensity was achieved by applying electron cooling during the longitudinal stacking process.

Many other experiments investigating the influence of the machine lattice parameters on cooling performance [8] and attempts to neutralise the electron beam space-charge [9] were also performed during the nine years of operation on LEAR.

The experience gained with the upgraded ICE cooler on LEAR provided the stepping stones for the design of a new state-of-the-art cooler for the I-LHC project (ions for LHC) [10]. This was the first of a new generation of coolers incorporating the latest developments in electron cooling technology (adiabatic expansion, electrostatic bend, variable density electron beam, high perveance, "pancake" solenoid structure) for the cooling and accumulation of heavy ion beams (Fig. 4). The cooler was built in collaboration with BINP in Novosibirsk and was commissioned at the end of 2005 [11]. It is routinely used to provide high brightness Pb ion beams for the LHC or fixed-target experiments in the SPS. LEIR uses a multi-turn injection in all three planes and the injected beam has a transverse emittance of about 2.5 µm and a momentum spread of 4 × $10^{-3}$. After cooling, the beam emittance is reduced by a factor of 10 and the longitudinal momentum is a few $10^{-4}$.

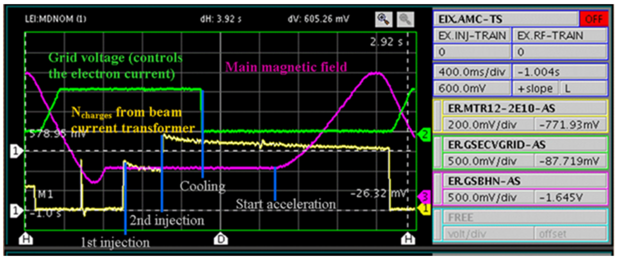

Figure 4: A standard 3.6s LEIR cycle during which 2 LINAC pulses are cooled-stacked in 800ms at an energy of 4.2 MeV/n. After bunching the Pb ions are accelerated to 72 MeV/n for extraction and transfer to the PS.

The high perveance gun provides an intense electron beam to decrease the cooling time. However, increasing the electron density induces an increase of the recombination rate (capture by the ion of an electron from the cooler), which is detrimental to the ion beam lifetime. To combat the increase in electron-ion recombination, the electron gun has a "control electrode" used to vary the density distribution of the electron beam. The beam profile is adjusted in such a way that the density at the centre, where the cold stack sits, is smaller and thus the recombination rate is reduced [12]. At larger radii, the density is large and allows efficient cooling of the injected beam executing large betatron oscillations.

Extensive studies have been made to determine the influence of the cooler parameters (electron beam intensity, density distribution, size) on the lifetime and maximum accumulated current of the ions have been reported in [13].

## DECELERATING ANTIPROTONS

After the completion of the LEAR physics programme in 1996 a simplified scheme for the provision of antiprotons of a few MeV was implemented at CERN [14]. This new facility called AD for Antiproton Decelerator, uses a modified AC (Antiproton Collector) in which stochastic cooling is applied at 3.5 GeV/c and 2 GeV/c, and electron cooling at the lower momenta of 300 MeV/c and 100 MeV/c. The LEAR electron cooler was moved to the AD in 1998 and had to be mounted in a U-shape because of the difference in height compared to LEAR (Fig. 5).

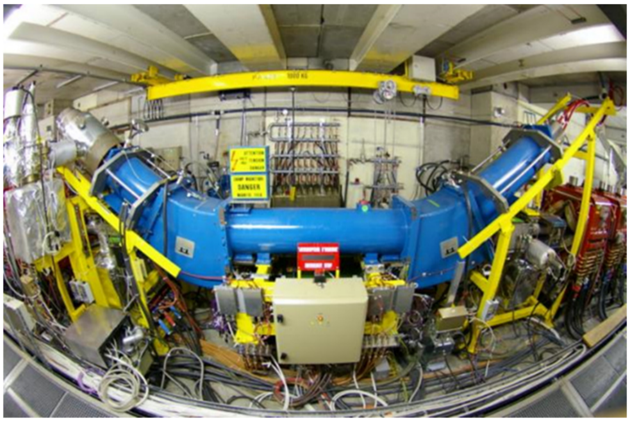

Figure 5: The AD cooler system.

A novel deceleration technique using electron cooling was attempted at the AD where the cooler and the main magnetic field of the AD are ramped simultaneously to a lower energy plateau. In so doing the antiproton beam is kept cold throughout the deceleration process avoiding the adiabatic blow-up that all beams experience when their energy is reduced [15]. The first tests were very modest decelerating $3.5 \times 10^7$ antiprotons from 46.5 MeV to 43.4 MeV whilst keeping the transverse emittances below 1 $\pi$ mm mrad during the whole deceleration process. Experiments to go below 5.3 MeV were later made with the beam successfully decelerated to 4.8 MeV (95.37 MeV/c) in 33 seconds. The control of the closed orbit, and more specifically the alignment of the antiproton beam with the electrons, proved to be more delicate than expected and hindered progress.

## ELENA AND THE FUTURE

Deceleration of antiprotons in the AD goes a long way towards the needs of the experimenters, but the 5.3 MeV energy of the extracted beam is still far above what the experiments, accumulating antiprotons in stationary traps, require. The further deceleration in a degrader foil, used by a number of the AD experiments, is accompanied by a big loss of intensity.

ELENA is a 30 m circumference ring for cooling and further deceleration of the 5.3 MeV antiprotons delivered by the AD down to 100 keV [16]. By deceleration using a ring equipped with beam cooling, an important increase in phase-space density and a high experiment injection efficiency can be obtained, resulting in an increased number of trapped antiprotons. With the construction of the ELENA ring, the AD experiments expect improvements of up to two orders of magnitude.

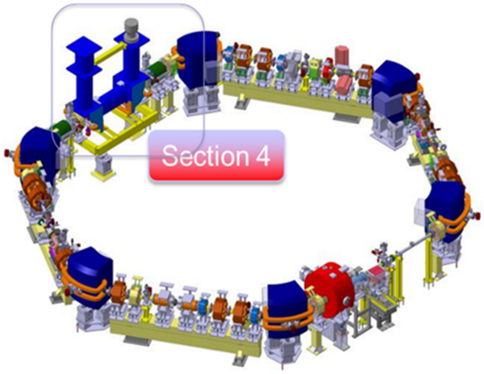

Figure. 6: The ELENA ring with the position of the electron cooler in straight section 4.

The electron cooler is now installed in section 4 of the ELENA ring (Fig. 6) and the rest of this section accommodates the orbit correctors and compensation solenoids of the cooler.

For fast and efficient cooling special attention must be paid to the design of the electron gun and the quality of the magnetic field guiding the electrons from the gun to the collector [17]. Another big challenge is the generation of a cold and stable electron beam at an energy of just 55 eV in order to cool the 100 keV antiprotons.

## CONCLUSION

Electron cooling has played a pivotal role in the success of the low energy physics program at CERN for nearly 40 years. The first electron cooler has seen two re-incarnations and is still used today to provide cold antiproton beams to the AD experiments. The heavy ion program for the LHC and the fixed target experiments would not be possible without the LEIR electron cooler which accumulates and cools a variety of ions and is central in the whole injection chain. The future looks bright for electron cooling at CERN with a new low energy cooler being commissioned on ELENA and a new cooler foreseen for the AD such that the original ICE cooler can finally retire after so many years of excellent performance.

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