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SPECIFICATIONS FOR A NEW ELECTRON COOLER OF THE ANTIPROTON DECELERATOR AT CERN

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Abstract

After more than 40 years of operation in different machines, the Antiproton Decelerator (AD) electron cooler (e-cooler) is expected to be replaced by a new one designed at CERN. This new design is primarily driven by the necessity to ensure the reliable operation of the CERN antimatter facility for the next decade and beyond. This will also be the occasion to overcome the known limitations of the present e-cooler, as well as to integrate the most promising recent technologies. In this paper, we review the present AD e-cooling performance and discuss the main effects that have an impact on that performance. We then outline the chosen parameters and the design choices based on studies and experience. Finally, a preliminary analysis of the expected performance of AD with the new e-cooler is presented.

INTRODUCTION

The purpose of AD is to collect antiprotons (pbars), cool and decelerate them from the injection momentum of 3.57 GeV/c to the extraction momentum of 100 MeV/c. Cooling is performed with stochastic cooling acting on two plateaus at 3.57 GeV/c and 2 GeV/c, and electron cooling acting on two plateaus at 300 MeV/c and 100 MeV/c before extraction to the Extra Low ENergy Antiproton (ELENA) ring. A typical cycle in AD is shown in Fig. 1. Recent experience shows that most shot-to-shot intensity fluctuations are visible after deceleration from 2 GeV/c. This might be due to poor performance of the stochastic cooling at 2 GeV/c, higher sensitivity to magnetic field perturbations at lower energy, the reproduciblity of systems such as e-cooling, or a combination of these effects. The main components of the present AD e-cooler were originally built for the Initial Cooling Experiment (ICE) in the 1970's, subsequently used for the Low Energy Antiproton Ring (LEAR), and finally reassembled in a shorter version for the AD. Major breakdowns of the electron collector during the 2018 run and the difficulties in finding spare parts, called for a review of the consolidation plans in 2019 [1]. On that occasion, the review panel recommended building a new e-cooler system to ensure reliable machine operation. This is also the occasion to improve the cooling performance, possibly getting closer to the initial AD design specifications [2], for which the cooling time was six seconds at 300 MeV/c and one second at 100 MeV/c.

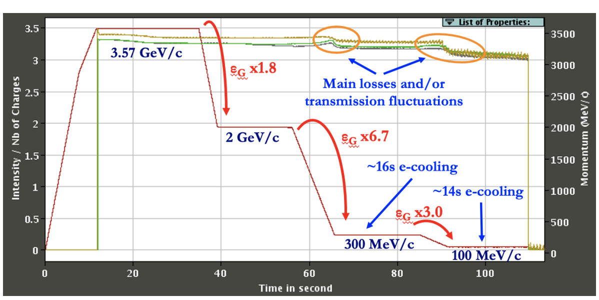

Figure 1: Typical AD cycle. The magnetic cycle is in red, while the black, green and gold traces show the intensity (in units of 10^7 charges) for three different shots.

The detailed specifications for the new e-cooler are provided in Ref. [3]. This paper summarises the main considerations that led to these specifications, shows the typical performance of the present e-cooler, and finally gives an estimate of the expected performance with the new e-cooler.

NEW E-COOLER SPECIFICATIONS

The typically accepted scaling law for the cooling time in the laboratory frame is given by Refs. [4–6]:

$$\tau \approx 4 \times 10^{12} [\mathrm{A\,s\,m^{-2}}] \frac{L_{\text{ring}}}{L_{\text{cooler}}} \frac{A}{q^2} \frac{r^2_{\text{e-beam}}}{I_{\text{e-beam}}} \beta^4 \gamma^5 \Theta^3, \quad (1)$$

$$\text{where: } \Theta \approx \sqrt{\epsilon_{x/y}/\beta_{x/y} + T/(m_e(\gamma\beta c)^2)}\,. \quad (2)$$

In practice, Eq. (1) gives only an indicative value for the expected cooling time, but it can be useful to highlight the main parameters affecting performance. Assuming that the geometric factors (L_{ring} and L_{cooler}, lengths of the ring and e-cooler active section, respectively), particle type (A, ion mass number and q, charge state, both equal to 1 for antiproton beams, and electron mass m_e), beam emittance ($\epsilon_{x/y}$) and beam relativistic factors (γ and β) are fixed, one can expect to reduce the cooling time by increasing the electron current ($I_{\text{e-beam}}$), reducing the beam radius ($r_{\text{e-beam}}$), reducing the electron temperature (T, in eV), or increasing the Twiss beta functions ($\beta_{x/y}$).

Increasing $I_{\text{e-beam}}$ seems to be the most straightforward optimisation. However, a higher current increases the electron energy variation with the distance from the beam centre as a result of space-charge effects, which could be detrimental to cooling performance. For a uniform e^- transverse distribution, the expected variation of the energy as a function of the radius r is given by Ref. [7]:

$$\frac{\Delta E(r)}{E} \approx 1.2 \times 10^{-4} \frac{I_{\text{e-beam}}[\mathrm{A}]}{\beta^3} \left(\frac{r}{r_{\text{e-beam}}}\right)^2. \quad (3)$$

Taking as an example the present AD e-cooler at 100 MeV/c with $I_{\text{e-beam}} = 100$ mA, $\beta \approx 0.1$, $E \approx 3$ keV, and $r_{\text{e-beam}} =$

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25 mm, the energy excess at the edge of the electron beam is as high as 36 eV, to be compared with typical transverse and longitudinal electron temperatures of 100 meV and 1 meV, respectively. This effect is partially compensated by the natural or controlled accumulation of rest-gas ions trapped in the magnetic field of the e-cooler [8]; however, the recommendation of [9] is that “modern coolers should be designed to avoid natural neutralisation”, since neutralisation can lead to instabilities, as reported in [10]. Hence, care has to be taken in the vacuum chamber and magnetic field design to avoid trapping ions. Additionally, the high current can be difficult to generate at the cathode, transport without losses, and dump on the e-cooler collector without additional vacuum load. In this respect, the new AD e-cooler is being designed to double $I_{\text{e-beam}}$, but it is expected to start operation with today’s operational value of 2.4 A at 300 MeV/c, and to explore higher currents later.

Other possible optimisations are to increase the electron density by reducing the electron beam radius, or to reduce the electron temperatures. Both could be controlled by reducing the gun cathode radius (r_{cath}) and by implementing beam adiabatic expansion [5, 11] such that:

$$r_{\text{drift}} \approx r_{\text{cath}} \sqrt{B_{\text{cath}}/B_{\text{drift}}} \quad (4)$$

$$T_{\text{drift}} \approx T_{\text{cath}} B_{\text{drift}}/B_{\text{cath}} \ , \quad (5)$$

where B_{cath} and B_{drift} are the longitudinal magnetic field in the cathode and interaction region, respectively, while r_{drift} is the electron beam radius in the interaction region. However, the effective temperature in the cooling region is strongly affected by the gun optic design [5, 12], as well as by variations of the guiding magnetic field along the electron trajectory. Thus, for a given design the actual tuning space might be limited.

A typical requirement to avoid heating is that the change of magnetic field vector ($\mathbf{B}$) must occur over a distance much longer than the spiral length of the cyclotron motion (λ_c), which can be translated into the adiabatic condition [13]:

$$\frac{\lambda_c}{B} \left| \frac{\mathrm{d}\mathbf{B}}{\mathrm{d}z} \right| \ll 1. \quad (6)$$

For the present AD e-cooler at $p = 300$ MeV/c and $B = 600$ Gauss is $\lambda_c \approx 54$ mm, leading to:

$$|\mathrm{d}\mathbf{B}/\mathrm{d}z| \ll 11 \text{ [Gauss/mm]} \ , \quad (7)$$

which is taken into account in the magnetic system design for the new AD e-cooler.

The transverse temperature of the electrons tends to average out for magnetised beams, and the straightness of the magnetic field in the cooling section, coupled with the longitudinal electron temperature, becomes the dominant effective temperature that defines the cooling time. Therefore, magnetic field imperfections should be smaller than the transverse velocity associated with the transverse [7] as well as longitudinal [14] electron temperatures along the interaction region:

$$c\gamma\beta B_\perp/B_\parallel \ll \sqrt{T_{e\parallel}/m_e} < \sqrt{T_{e\perp}/m_e} \quad (8)$$

i.e. assuming a longitudinal temperature $k_B T_{e\parallel} \approx 1$ meV and for $\beta\gamma \approx 0.3$, then one would need $\mathrm{rms}(B_\perp/B_\parallel) \ll 1.5 \times 10^{-4}$. This requirement is compatible with the value typically required for $\mathrm{rms}(B_\perp/B_\parallel) \lesssim 1 \times 10^{-5}$ in other e-cooler devices, e.g. [15–19], as well as values obtained in similar recent e-coolers [20], and in reach with the measurement capabilities developed for LEIR [21]. It will be thus pursued for the new AD e-cooler, as this could lead to the biggest improvement in cooling time, as the present e-cooler has a magnetic field quality of the order of 10^{-3}.

Table 1: Main parameters of the present e-cooler compared to the latest design [3]. Some of the main geometrical and layout parameters are assumed to remain unchanged.

	Present	**New Design**
Drift length [m]	~ 1.5	~ 1.5
Drift field [G]	600	~ 600
Cooling length [m]	~ 1	≥ 1
$r_{\text{e-beam}}$ [mm]	25	≥ 25
$\max(B_\perp/B_\parallel)$	10^{-3}	10^{-4}
$\mathrm{rms}(B_\perp/B_\parallel)$	n.a.	$< 10^{-4}$
Gun field [G]	600	2400
Gun P [µP]	0.58	2.6
Cathode radius [mm]	25	12.5
e^- beam $T_\perp$ [meV]	—	$\lesssim 100$
e^- beam $T_\parallel$ [meV]	—	$\lesssim 1$
e^- beam $\Delta E/E_0$	—	$\sim 10^{-5}$
e^- beam I_0 [A]	< 2.4	2.4 (< 4.8)
e^- beam $\Delta I/I_0$	—	$\sim 10^{-4}$
e^- start/stop time [s]	—	< 1
H_2 eq. pressure [mbar]$^+$	$< 10^{-10}$	$< 10^{-10}$
Availability during physics	—	99%

The initial emittance of the circulating beam could be reduced by starting e-cooling at higher momentum in the AD cycle. On the other hand, the cooling time scales unfavourably with $\beta^4\gamma^5$. Still, for increased flexibility, and possibly reliability, the new AD e-cooler is being designed to be able to run up to 500 MeV/c, which corresponds to an electron energy of 68 keV. This has to be seen as an ultimate target, while the baseline is to start at 300 MeV/c as today.

These considerations, together with the additional ones detailed in [3], lead to the specifications summarised in Table 1, listed together with the present e-cooler parameters.

PRESENT AND EXPECTED PERFORMANCE

The most challenging regime for the e-cooling performance is the one at the highest beam momenta which, in the present AD cycle (Fig. 1), is 300 MeV/c. The beam arrives at this momentum with about a factor seven larger

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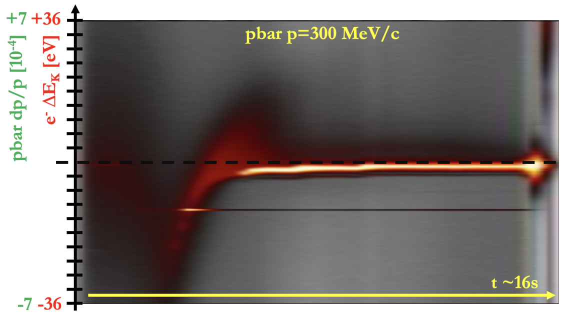

Figure 2: Variation in time of the longitudinal Schottky signal in scales of pbar dp/p and equivalent electron kinetic energy variation at the 300 MeV/c plateau.

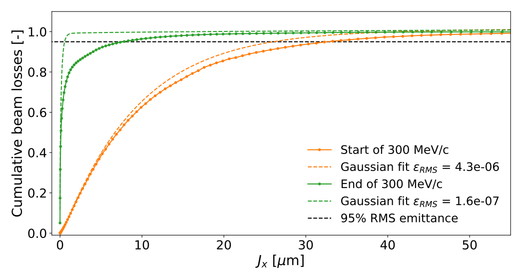

Figure 3: Normalised cumulative beam losses as a function of horizontal action measured by means of scrapers at the beginning (orange) and end (green) of the 300 MeV/c plateau. Raw data (solid) and Gaussian fit (dashed) curves are shown.

emittance from to the adiabatic emittance increase due to deceleration from 2 GeV/c. The longitudinal characteristics of the present AD e-cooler at this plateau can be extracted from the longitudinal Schottky signal (Fig. 2). The Schottky signal reveals a drift of several Volts on the electron energy during the first part of the plateau. This is due to the e-cooler High Voltage (HV) power supply which takes time before settling to the desired voltage (about 27 keV here). For this reason, the specifications in Table 1 call for a start/stop of the electron beam (within a few Volts) of better than 1 s. Other features visible in Fig. 2 are a constant frequency excitation (straight line) coming from the residual voltage in the RF system while the beam is coasting, and the RF recapture at the end of the plateau.

The evolution of the horizontal beam profile was assessed in recent scraper measurements (Fig. 3). The main purpose of AD is to decelerate at least 95% of the pbars. The cumulative beam losses shown in Fig. 3 can therefore be used to determine the beam edge in terms of beam action, that one is interested in keeping. It is noted that the cumulative losses follow well a Gaussian beam profile before cooling, while non-Gaussian tails are present after cooling.

The performance of the present and new e-cooler is simulated using Xsuite [22], a new simulation tool being developed at CERN that will include electron- and laser-cooling, as well as other effects such as space charge and intra-beam scattering. Figure 4 shows preliminary results of cooling rates at 300 MeV/c, for the Twiss functions at the e-cooler and the estimated transverse and longitudinal beam properties before/after cooling extracted from Figs. 2 and 3, as summarized in Table 2. In this preliminary simulation, a single pbar starting on the edge of the horizontal beam distribution (J_x = 35 μm, J_y = 0 μm, and $\delta p/p$ = 0) is tracked in a simplified ring with optics parameters as in Table 2 and with e-cooling modelled using the Parkhomchuk model [23]. The simulation shows the impact of the magnetic field quality for the present and new e-cooler design. No heating effects (e.g. intra-beam scattering or space charge) are included. Electron temperatures and current are in all cases as in Table 1. It is noted that the cooling performance of an ideal cooler with a perfect magnetic field is very close to the one simulated for the target parameters of the new AD e-cooler, while degrading the magnetic field quality by one order of magnitude (i.e. close to the parameters of the present e-cooler), the cooling times are drastically increased, as expected from the condition in Eq. (8).

Table 2: Optics Parameters for the AD Ring and E-Cooler, and 95% Beam Envelope Before/after Cooling as Measured in AD at 300 MeV/c

Q_x/Q_y	5.44/5.42
β_x/β_y [m]	10/4
D_x [m]	0.12
Before/after ϵ [μm]†	35/5
Before/after $\sigma_p/p^\dagger$	1e-3/1e-4

† Beam envelope values equivalent to $6\epsilon_{\rm rms}$ and $2\sigma_p/p$.

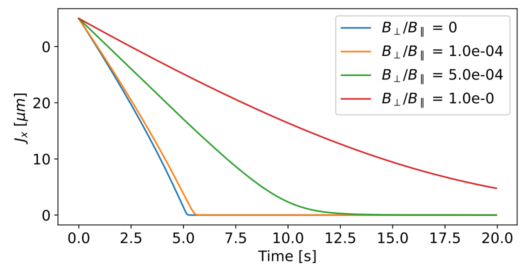

Figure 4: Simulated time evolution of horizontal action representing the 95% horizontal beam envelope for different magnetic field qualities: perfect magnetic field (blue), $B_\perp/B_\parallel = 10^{-4}$ (orange), 5×10^{-4} (green), and 10^{-3} (red).

CONCLUSION

The functional specifications for the new AD e-cooler have been provided in Table 1. The main goal for the new e-cooler design will be to improve reliability and spare part availability. However, it will also provide the opportunity to improve the magnetic field quality and the electron beam control by implementing adiabatic beam expansion, which will hopefully lead to better cooling performance. The options to increase the electron current by a factor of two and to reach an equivalent pbar momentum of 500 MeV has been retained as the ultimate scenario, and could allow different operational schemes of AD to be explored, which could further reduce the overall cycle length.

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