ANTIPROTON DECELERATOR STATUS REPORT

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Abstract

The Antiproton Decelerator (AD) has been delivering 5.3 MeV antiprotons to the experiments for 10 years now. Beam cooling is essential for the AD operation. We review the AD machine and in particular the cooling performance. We give an overview of the present and future experiments and also the possible further deceleration of the beam from 5.3 MeV to 100 keV kinetic energy.

INTRODUCTION TO AD

The Antiproton Decelerator (AD) started regular operation [1] in 2000. The AD has been constructed from the parts of the AC machine in order to provide 5.3 MeV antiprotons for initially 3 experiments, ASACUSA, ATRAP and ALPHA. The experiments have the ultimate goal to produce antihydrogen in their trap and measure its properties with spectroscopy in order to verify CPT symmetry with a high precision. ASACUSA has been doing spectroscopy with antiprotonic helium. Later a fourth experiment ACE joined. They have been studying living tissue irradiation with antiprotons in order to investigate the possibility to use antiprotons for cancer therapy. AEgIS is a recently approved fifth experiment aiming to measure directly the effect of the Earth's gravity on antihydrogen. This will be the first experiment of this kind.

THE DECELERATION CYCLE

Antiprotons are produced by sending a 26 GeV/c proton beam onto a water cooled iridium target. Antiprotons on the downstream are focused by a magnetic horn to collect as many as possible. Then a dogleg shaped part of the injection line separates the antiprotons from the other types of particles. Four bunches are injected into the AD ring by a magnetic septum and a kicker. The momentum spread of the beam is large at injection, about a $\pm 3\%$. In order to decrease the dp/p to fit more beam inside the momentum acceptance of the stochastic cooling, which is around $\pm 1\%$, a bunch rotation is applied. After bunch rotation the dp/p is $\pm 1.3\%$. There are two bunch rotation cavities in the ring, each gives about 500 kV at harmonic 6. The cavities are ramped up already when the beam is injected and after a quarter of synchrotron turn they are turned off. The AD cycle has 4 flat parts, these are introduced in order to cool the beam. After injection and the bunch rotation, stochastic cooling is applied at 3.57 GeV/c. The second stochastic cooling process takes place at the 2 GeV/c plateau. The machine operates with two different tunes, one for higher energies and one for lower energies. The tune is changed after the second stochastic cooling. The beam is decelerated to 300 MeV/c where electron cooling is applied. After further deceleration to the final momentum, electron cooling is applied for a second time at 100 MeV/c. Figure 1 shows the AD cycle.

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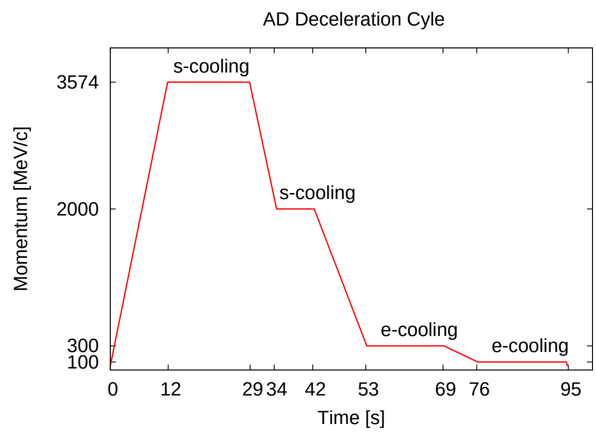

Figure 1: The AD deceleration cycle.

Table 1: AD Main Parameters

Circumference [m]	182
Prod. beam [protons/cycle]	1.3×10^{13}
Injected beam [pbars/cycle]	4×10^{7}
Momentum [GeV/c]	3.57-0.1
ϵ_{tr} $[\pi \times mm \times mrad]$	180-0.8
$\pm$dp/p	$3 \times 10^{-2} - 7 \times 10^{-5}$
Average vacuum [Torr]	4×10^{-10}
Cycle length [s]	96
Dec. efficiency [%]	85

OPERATIONAL PERFORMANCE

The AD operates non-stop during the entire run since 2004. Machine supervisors are working during the day and providing an on-call service outside working hours, including weekends. In the last two years AD suffered several major breakdowns. A consolidation budget and program has been approved in order to improve the reliability of the hardware and make the necessary maintenance and preventive actions. In 2008 the number of injected antiprotons has decreased by 30 %. Many things have been verified in order to find the cause of the lower injected intensity, like injection line optics and matching, production beam parameters, AD acceptances, bunch rotation settings. At the end of the shutdown we discovered a mechanical fault of the target positioning system. The positioning mechanism has been repaired and the injected intensity is back to the normal values during the 2009 run. New optics have been put into operation in the ejection line leading to smaller beam size and lower transfer losses. The Table 2 shows the yearly statistics of the AD.

Table 2: AD Run Time by Year

Year	2003	2004	2006	2007	2008
Total [h]	2800	3400	2352	3800	3338
Physics [h]	2300	3090	2185	3760	3142
Md [h]	500	310	167	40	62
Uptime (%)	90	71	69	78	86

STOCHASTIC COOLING

The hardware for the stochastic cooling is recovered from the AC machine, but only the 0.9-1.6 GHz (nominal) band is kept due to space limitations. There are two stages of stochastic cooling in the cycle, the first at injection and a second at 2 GeV/c. Due to the two distinct momenta there are two separate signal paths for each plane. For longitudinal cooling the notch filter method is used. In order to increase the signal to noise ratio the transverse separation of the pickups is decreased during the cooling process. There is a kicker movement system too, but it is not used. Programmable gain invariant delays are used to optimize phase. Programmable static and dynamic phase invariant attenuators are used to optimize gain. These are controlled by function generators and the gain is decreased during the cooling. The performance figures are summarized in Table 3. Apart from recent problems with the pickup movement the stability of the stochastic cooling system is excellent since many years.

Table 3: Stochastic Cooling Performance

Momentum [GeV/c]	3.57	2.0
Duration [s]	17	7
$\epsilon_x/\epsilon_y[\pi \times mm \times mrad]$	5/5	3/3
dp/p	10^{-3}	10^{-4}

ELECTRON COOLING

The electron cooler was taken from the dismantled LEAR machine and with some modification was installed in the AD ring. The main parameters of the cooler are summarized in Table 4. The performance figures can be found in Table 5. Due to the very low momentum spread at 100 MeV/c even a small noise on the RF system can cause a significant increase of the longitudinal emittance during the capture process. In order to compensate this effect there is an overlap between the start of the capture and the end of the electron cooling. A longer overlap leads to shorter bunches, but with a higher percentage of the beam in the tails of the distribution. Another problem is the time jitter of the ejected bunch when the overlap is too big. In the last years electron cooling works well and the drag force has a significant effect on the RF system, disturbing the synchronization loop and causing about a 40 ns time jitter. Some attention is needed to find the correct setting. A typical beam profile is shown on Figure 2. The reason for the tail formation it not well understood. In many years during the AD operation the stability of the orbit was a major issue. Sudden jumps occurred, making difficult to keep electron cooling performance on the optimum. The source of the orbit jumps was identified as a faulty magnet coil. Since the coil has been replaced during the 2007 run the electron cooling performance is far more stable.

Table 4: Parameters of the Electron Cooler

Cooling length [m]	1.5
Electron beam energy [keV]	2.8-35
Electron beam current [A]	0.1-2.5
Field in solenoid [Gs]	590
Electron beam radius [cm]	2.5

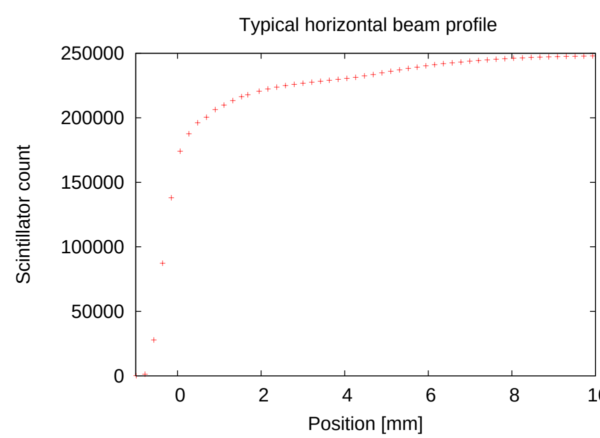

Figure 2: A typical horizontal beam profile obtained by the scraper at 100 MeV/c. The $\beta_h = 5m$ at the scraper position, ϵ_h = 0.5 π mm mrad with 80 % of the beam inside and with a long tail of the distribution.

FURTHER DECELERATION OF THE BEAM

The experiments can trap antiprotons with kinetic energy less than 10 keV. ALPHA and ATRAP use degrader foils to slow down antiprotons to this range. The foil method

Table 5: Performance of the Electron Cooler

Mom. [MeV/c]	300	100
Cooling time [s]	16	15
$\epsilon_x/\epsilon_y[\pi \times mm \times mrad]$	3/3	0.8/0.5
dp/p	10^{-4}	$< 7 \times 10^{-5}$

is very inefficient, 99.9 % of the beam is lost and the remaining part suffers a big emittance blow up due to the scattering on the foils. ASACUSA uses an RFQD with an adjustable output energy in the range of 10-100 keV. They also use a very thin degrader foil in order to isolate the trap vacuum from the rest of the system. With the RFQD about 25 % of the beam is decelerated and about 4% is kept in the trap.

During development sessions in 2008 a novel deceleration technique using the longitudinal drag force of the electron cooler was attempted. The idea is to ramp the AD magnetic field and the electron cooler energy synchronously such that the circulating antiprotons are continuously cooled as their energy changes. Due to limitations in the control of the AD cycle, a very modest first test was made decelerating 3.5×10^7 antiprotons from 46.5 MeV to 43.4 MeV in 56 seconds whilst keeping the transverse emittances below 1 [π mm mrad] during the whole deceleration. Additional measurements to measure the drag force at 5.3 MeV (100 MeV/c) were also performed in order to estimate the time needed to decelerate the beam below this energy.

This year experiments to go below 5.3 MeV have been made with the beam successfully decelerated to 4.8 MeV (95.37 MeV/c) in 33 seconds as expected from the measurements made in 2008. 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 the progression of the experiments. The aim of future studies will be to optimize the deceleration of the beam to an energy of 4 MeV (87 MeV/c) and to measure the beam parameters during the ramp.

Another idea is to cool the beam at 100 MeV/c in a barrier bucket and obtain a much smaller longitudinal emittance than coasting beam cooling can provide. This is possible in the AD because the intensity is very low and even though the beam is confined longitudinally by a factor 20 the IBS and space charge effects remain acceptable. In the current scheme a coasting beam is cooled, captured into a single bunch, then a bunch rotation is applied and the beam is ejected. When the RFQD is used the 202 MHz bunch structure needed for deceleration is created by a buncher cavity 6 meters in front of the RFQD in the ejection line. This type of bunching limits the the deceleration efficiency to 50 % at best, in practice about 25 % is decelerated. The proposal is to cool the beam in a barrier bucket and capture it with 202 MHz already in the machine. This requires the installation of two 202 MHz cavities into the AD ring. This way there is no loss due to the buncher cavity and a factor

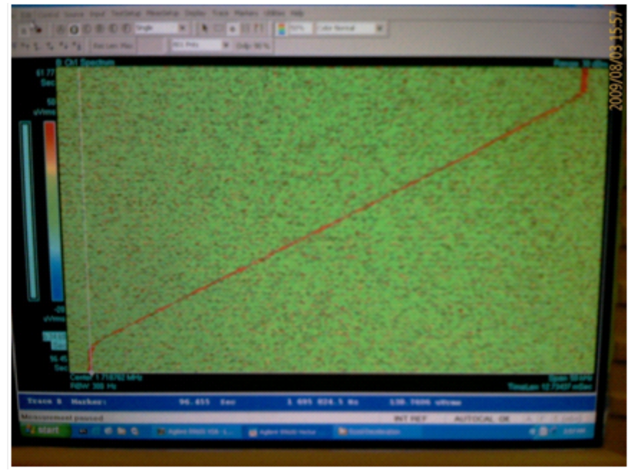

Figure 3: Beam deceleration using the the electron cooling drag force.

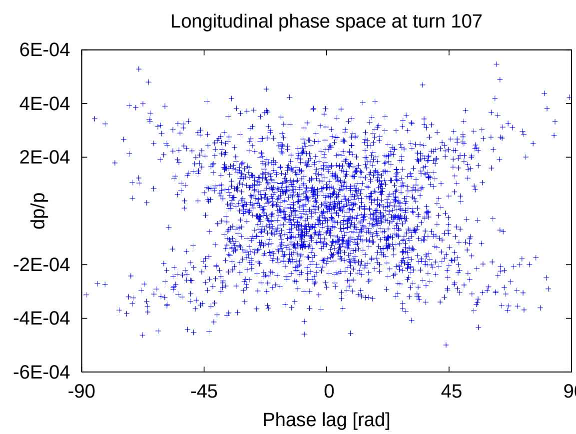

Figure 4: Longitudinal phase space plot at the end of the capture process with 202 MHz, with a 300 ns long barrier bucket. A starting dp/p =7 $\times$ 10^{-5} was assumed. This is a simulation result including longitudinal space charge forces.

2-3 in intensity can be gained. The longitudinal emittance of the beam is much lower in this case, because the large increase in momentum spread due to the h=1 bunching in the current scheme is not present. Due to the longitudinal space charge forces the beam can not be compressed enough to fit inside the ± 10 degree phase acceptance of the RFQD [2], therefore the buncher cavity is still needed to give a further longitudinal focusing, however it doesn't throw away a large part of the beam in this case. Figure 4 shows the longitudinal phase space plot at the end of the capture, Table 6 shows the ratio of the beam inside a given phase extent. If the RFQD can be modified to have a larger phase acceptance, maybe at the expense of an increased length then it would be possible to drop the buncher cavity and obtain a beam at 100 keV with with a much smaller momentum spread. This possibility needs further investigation. At the expense of installing two cavities in

Table 6: Percentage of the Beam Inside a Given Phase Extent

Phase [±deg]	25	30	35	40	45
Portion inside	61%	70%	78%	83%	87%

the AD ring the intensity can be multiplied by a factor 2-3 for ASACUSA. A preliminary test has been done with bunched beam cooling at 100 MeV/c with $V_{rf} = 500$V, h=3 to test this idea. These preliminary results are very promising. The tail structure similar to the profile shown on Figure 2 was observed. The bunch length was determined by the longitudinal space charge force and found to be dependent on the intensity. At lower intensity the transverse profile was better, the ratio of the beam in the tail of the distribution was smaller. This could indicate that an intensity dependent effect like IBS or tune shift due to space charge plays a role in the formation of the tail. The barrier bucket cooling can be tested with the existing equipment in the AD ring, the test is under preparation. A proposal [3] based on the idea described above will be published soon by the author.

EXTRA LOW ENERGY ANTIPROTON RING (ELENA)

The Motivation

ELENA is a compact ring [4] for further deceleration and cooling of 5.3 MeV pbars delivered by the CERN Antiproton Decelerator. The ultimate goal of ELENA is to increase the number of antiprotons in traps of AD experiments significantly. By using a ring equipped with beam cooling, high deceleration efficiency and important increases in phase-space density can be obtained, resulting in an increased number of trapped antiprotons. The low energy limit for this machine is 100 keV. It was chosen as a compromise between requirements from experiments of ultra low energy beam and constraints given by space charge limitations in machine and cooler, requirements to vacuum of few 10^{-12} Torr and others. For the ATRAP and ALPHA experiments, improvements of 2 orders of magnitude can be expected. ASACUSA on the other hand presently uses first an RFQD for deceleration to 100 keV, and then additionally an ultra-thin degrader (1 micron thick) for deceleration to 5 keV. Here, a 10-fold increase can be expected thanks to reduced transverse and longitudinal emittances.

Location of ELENA

With a circumference of about 26m, ELENA can be located in the AD hall where assembly and commissioning would not disturb current AD operation too much. AD experimental areas could be kept as they are now, but much lower beam energies require new transfer line elements (electrostatic) and diagnostics. Some reshuffle of AD Experimental Area has to be done to prepare the space for

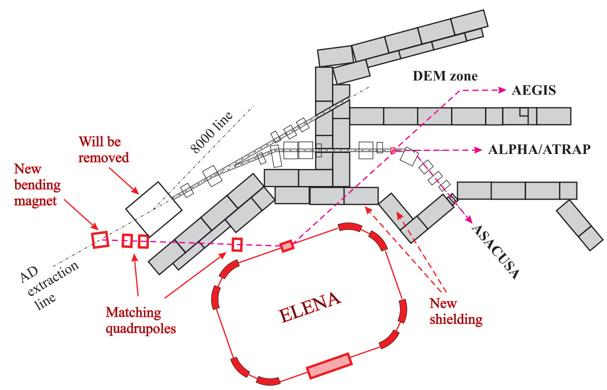

Figure 5: ELENA ring location in AD Experimental Area.

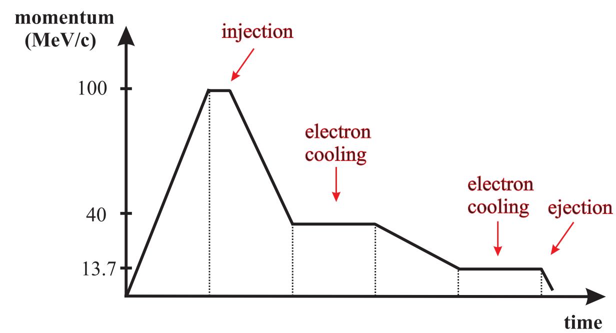

Figure 6: Schematic view of ELENA cycle.

ELENA, as well as modifications in shielding. The precise positioning of a new ring in AD Hall is dictated by optimal conditions for injection and for extraction [5] into existing experimental areas.

Machine Cycle

Due to the small emittance of a beam ejected from AD, beam in ELENA can be decelerated down to intermediate energy without cooling at injection energy. This makes design of electron cooler much easier. After the last cooling at 13.7 MeV/c, the beam is ejected

Ring Configuration and Machine Parameters

Two long straight sections are suited for electron cooler and for injection/ejection septa, see Figure 7. Two short straight sections will be used for injection/ejection kickers, diagnostics, RF and other equipment. The lattice includes 8 bending magnets and 8 quadrupoles. Quadrupoles will be built as multipoles which include in some of them skew quadrupolar and sextupolar components, in other horizontal and vertical steering elements. The main intensity limitation in ELENA is due to incoherent tune shift caused by space charge. It is negligible during deceleration and cooling of coasting beam. To deliver short bunch of 1.3 m to trap of experiment the bunch rotation in the longitudinal phase space is applied. At the end of this process the bunch is short and space charge effects have to be taken into ac-

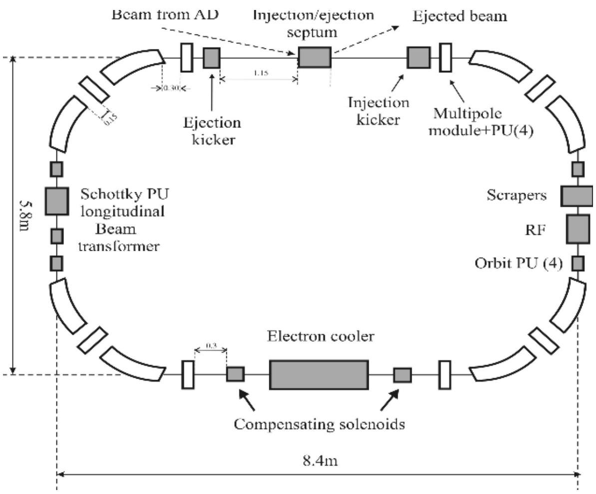

Figure 7: ELENA ring layout.

count. For the conservative value of tune shift ΔQ = 0.1 and beam emittances $\epsilon_{x,y}$=3 π mm mrad in ELENA intensity in one bunch is limited to 0.65×10^7 pbars. Therefore it is proposed to bunch the beam after cooling at 13.7 MeV/c at harmonic h = 4, thus increasing the maximum number of pbars available at least up to 2.6×10^7. Each of 4 experiments with trap (including AEgIS) will receive a quarter of total amount of pbars. Fast switching electrostatic magnet placed in a common part of extraction line allows to extract all 4 bunches during one turn. The main machine parameters are given in Table 7:

Table 7: ELENA Basic Parameters

Momentum range, MeV/c	100 - 13.7
Energy range, MeV	5.3 - 0.1
Circumference, m	26.062
Intensity of injected beam	3×10^7
Intensity of ejected beam	2.5×10^7
Number of extracted bunches	4
Em. at 100 keV, π.mm.mrad, [95%]	3 / 3
dp/p after cooling, [95%]	10^{-4}
Bunch length at 100 keV, m / ns	1.3/300
Required vacuum, Torr	3×10^{-12}

The ELENA Electron Cooler

For fast and efficient cooling special attention must be paid to the design of the electron gun and the quality of the longitudinal magnetic field guiding the electrons from the gun to the collector [6]. The electron gun has to be designed in a way to produce a cold ($T_\perp < 0.1$ eV, $T_\| < 1$ meV) and relatively intense electron beam ($n_e \approx 3 \times 10^{12} [cm^{-3}]$). The gun is immersed in a longitudinal field of 700 Gs which is adiabatically reduced to maximum field of 200 Gs in the transition between the gun solenoid and the toroid. Due to this, transverse temperature is reduced as well during beam adiabatic expansion. The main characteristics of the proposed device are summarized in Table 8.

Table 8: ELENA Electron Cooler Parameters

Cooling length [m]	1
Beam cooled at momentum [MeV/c]	35 and 13.7
Electron beam energy [V]	355 and 54
Electron beam current [mA]	15 and 2
Magnetic field in solenoid [Gs]	200
Electron beam radius [cm]	2.5

CONCLUSION

The AD is continuing to provide good quality beam to the physics community. Intensities are well above 3×10^7 pbars per shot since the repair of the target positioning system, with a repetition rate around 96 seconds. Deceleration efficiency is above 80 %. Ejected beam emittances are below 1 π mm mrad. The AD experiments have been producing interesting physics and pursuing their ultimate goal, the antihydrogen spectroscopy. The AEgIS experiment has been approved and will measure the strength of gravity on antimatter. The direction for improvements is to decelerate the beam to lower energy and increase the number of antiprotons in the traps by a large factor, even orders of magnitude.

ACKNOWLEDGMENTS

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