Report on Operation of Antiproton Decelerator

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Abstract. The Antiproton Decelerator (AD) at CERN operates for physics since 1999. The 3.5 GeV/c antiprotons produced in the target by a 26 GeV/c proton beam coming from CERN PS. Since the experiments need a low energy antiprotons, beam is decelerated in the AD down to an extraction momentum of 100 MeV/c. Due to significant emittance blow up during deceleration, as well as tight requirements from experiments on extracted beam sizes, efficient compression of beam phase space is indispensable. Two cooling systems, stochastic and electron are used in AD. The progress in machine performance is reviewed, along with plans for the future. Special emphasis is given to the proposed new extra low energy antiproton ring (ELENA) for deceleration of antiproton beam further down to an energy of 100 keV (momentum 13.7 MeV/c), which would allow much higher antiproton capture rate with significantly higher beam density.

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INTRODUCTION

The Antiproton Decelerator (AD) operates routinely for physics program since 1999. The 100 MeV/c antiprotons are delivered in single bunch or multi-bunch mode to one of the three experiments: ASACUSA, ATHENA, ATRAP. From 2003 the ACE experiment receives 300 MeV/c antiprotons in single bunch ejection.

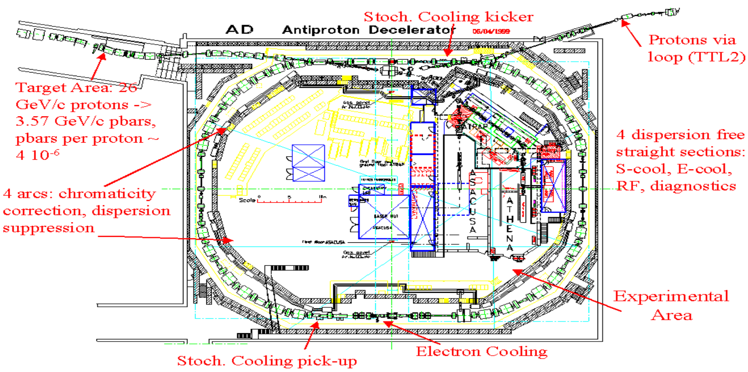

FIGURE 1. AD Hall layout.

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The machine performance was gradually improved after the start of operation. The essential contribution to the progress in performance, along with experience comes from the use of new diagnostics. The important parts of routine machine operation are machine development (MD) sessions, where new hardware and software can be tested, or particular aspects of beam physics in AD (like electron cooling) is a subject of study. In addition, MD's are used for machine performance maintenance, which could suffer due to various reasons.

BASIC AD CYCLE

Antiprotons are produced in a target with 26 GeV/c proton beam from CERN PS, then collected and transferred to the AD ring. After injection at 3.57 GeV/c, antiprotons are rotated 90 degrees in the longitudinal phase space, taking advantage of the large AD momentum acceptance and short bunch length of about 25 ns. Then beam is stochastically cooled and decelerated down to 2 GeV/c. Stochastic cooling is repeated again, mainly to reduce a momentum spread to fit requirements of the deceleration RF cavity.

The beam is then decelerated down to 300 MeV/c and cooled down by the electron beam from the electron cooler. After cooling, the beam is decelerated to the ejection momentum of 100 MeV/c (kinetic energy 5.3 MeV). Then the antiprotons are cooled again by the electron beam, rotated 90 degrees in the longitudinal phase space (if experiments demand shorter beam, which is typically the case) and ejected.

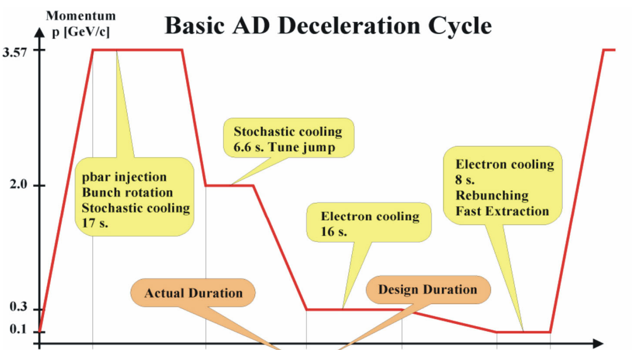

FIGURE 2. Basic AD cycle.

OPERATION

In 2005 the CERN Accelerator Complex was not running, except for the ISOLDE Facility. During the previous year 2004 the total time for physics was substantially increased due to continuation of machine operation on weekends in autumn. The MD time was reduced due to limited manpower available, which contributed as well to increased time for physics. Unfortunately, of 3090 hours scheduled for physics the real time with beam was only 2194 hours (71%).

Two major problems were responsible for this reduction. The PS ejection septum leak happened twice, taking 1 week for replacement with spare unit, and 3 weeks next time to repair spare and install.

Excessive outgassing in the collector region of AD electron cooler was a reason for disassembly, inspection, replacement of all suspect equipment, bakeout, hence stops of machine for 2 weeks.

TABLE 1. Operational statistics.

Run time (h)	2000	2001	2002	2003	2004
Total	3600	3050	2800	2800	3400
Physics	1550	2250	2100	2300	3090
MD	2050	800	700	500	310
Uptime	86%	89%	90%	90%	71%

PROGRESS IN MACHINE PERFORMANCE

Beam Intensity Improvement

The beam intensity is gradually improving with years, with peak numbers shown in Fig.3. This progress is based mainly on higher intensity of a production beam. The optimization of machine acceptances at injection energy also had a positive effect.

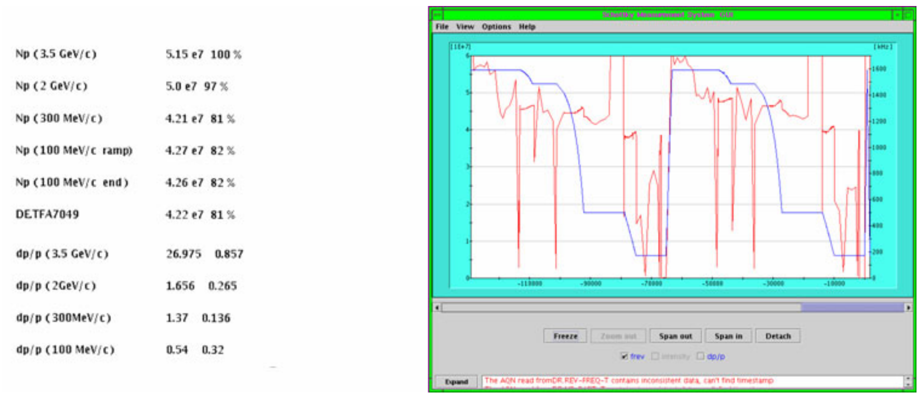

FIGURE 3. Schottky based intensity monitoring during AD cycle.

Ejected Beam Emittances Improvement

Beam bunch rotation before ejection makes it shorter (about 90 ns compared with 220 ns design value), which is appreciated by experiments. During beam bunching the longitudinal emittance grows significantly due to noise of the low level RF system.

This degradation was overcome by extending electron cooling for the time of beam bunching (see Fig.4, left). Unfortunately, this caused beam profile degradation: filamentation into 2 (sometimes even 3) parts and creation of extended tails (Fig. 5, left).

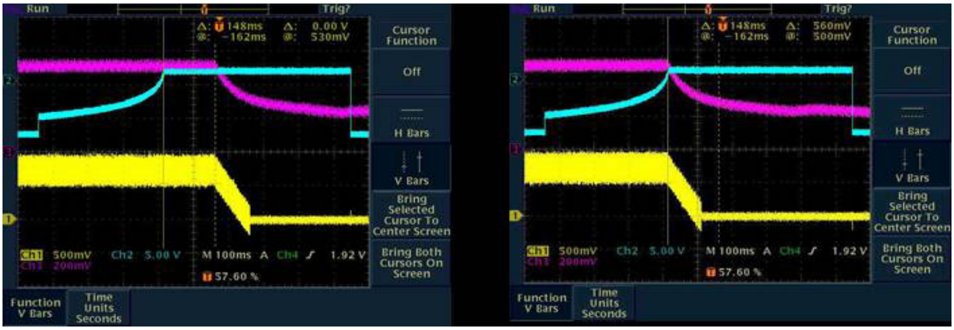

FIGURE 4. Voltage programming during the end of electron cooling and beam bunching. Left figure shows the curves before adjustment, and right figure after adjustment. Two curves on the top of each figure show voltage on the cooler cathode (constant, then decreasing) and voltage in RF cavity (increasing, then constant).

Careful adjustment of two voltage programs (RF cavity and cathode of cooler, Fig.4 on the right) in time with respect each other provided significantly improved transverse emittances (Fig.5, right) while keeping short bunch length of about 110 ns.

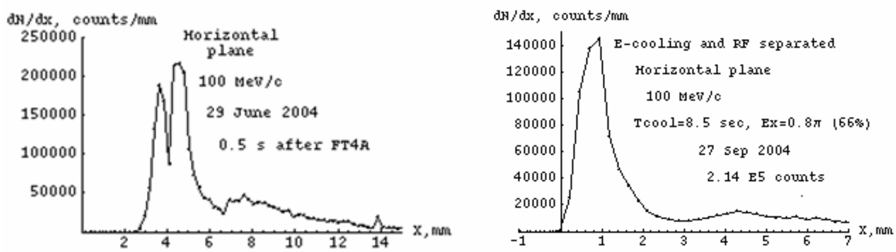

FIGURE 5. Horizontal beam profile measured with scraper before (left) and after (right) adjustment of the voltage programming for cooler cathode and RF cavity.

Reduction of Longitudinal Emittance

Implementation of "tomoscope"-like diagnostics allowed to trace evolution of the longitudinal beam emittance[1]. Particularly, it was found that with reduced voltage from 3kV to 0.5kV on ramp 300MeV/c->100 MeV/c the longitudinal beam emittance at the end of deceleration is reduced by a factor 2. The smaller bucket height causes a larger synchrotron frequency spread which follows by damping of emittance blow up.

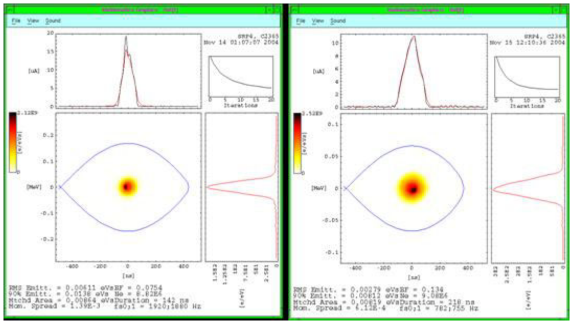

FIGURE 6. Beam inside of RF bucket for different voltage used for beam bunching and deceleration.

MACHINE PERFORMANCE LIMITATIONS

Intensity Limitations

The injection beam intensity is limited by a production beam and by machine acceptance (mainly longitudinal). The longitudinal space charge effect in CERN PS during complicated RF bunch gymnastics puts constraints both on intensity and bunch length of a production beam. Transverse acceptance of AD is optimized, and the longitudinal acceptance of stochastic cooling system is slightly smaller compared with the longitudinal beam emittance after bunch rotation.

The deceleration efficiency which is now about 80% could be increased a bit in the case of implementation of beam diagnostics (tunes and orbit measurements) on ramp. Certain progress might also be expected with more sophisticated correction of the eddy current effects.

Another way to increase intensity (by about 25%) could be achieved with 5 bunch production beam (now 4), which is acceptable for AD with bunch rotation cavities operating at 6^{th} harmonic, but needs certain modifications in CERN PS.

Stacking in the longitudinal phase space could provide about 50% antiprotons/sec gain. This scheme requires modifications in PS RF system and set up in AD.

Cycle Length Limitations

Ramp speed is limited due to eddy current effects. Fast eddy currents in a vacuum chamber of bending magnets (time constant about 2.8 msec) provoke the orbit excursion up to 11mm at the end of the ramp 2 GeV/c->300 MeV/c (most critical point). This can't be compensated. Slow eddy currents in the end plates of a bending magnets cause the orbit excursion up to 45 mm at the same point, but they are partly compensated by special programming of the magnetic field cycle. Yet more sophisticated compensation taking into account differences between the wide and the narrow magnets used in AD is possible and could contribute to machine performance.

Duration of plateaus is defined by the time needed for cooling. Stochastic cooling is well optimized. Electron cooling is slower than expected, probably due to drifting orbit. This drift is caused by slow decay of eddy currents in end plates; it is partly compensated, yet not perfectly.

The cooling performances in AD are summarized in Table below.

TABLE 2. AD cooling performances.

Momentum	Parameters	design	2004
3.57 GeV/c	Stochastic cooling time, sec	20	17
	h/v emittances (2σ), π mm mrad	5	3
	momentum spread (4σ), 10^{-3}	1	1
2.0 GeV/c	Stochastic cooling time, sec	15	6.6
	h/v emittances (2σ), π mm mrad	5	3
	momentum spread (4σ), 10^{-3}	0.3	0.15
0.3 GeV/c	Electron cooling time, sec	6	13.8
	h/v emittances (2σ), π mm mrad	2 / 2	2 / 4
	momentum spread (4σ), 10^{-3}	1	0.1
0.1 GeV/c	Electron cooling time, sec	1	8.4
	h/v emittances (2σ), π mm mrad	1	1 (core)
	momentum spread (4σ), 10^{-3}	0.1	0.1

EXTRA LOW ENERGY ANTIPROTON RING (ELENA)

Motivation

The ejected antiprotons from AD have a kinetic energy of 5.3 MeV, while a few keV energy is required to trap them. Two experiments (ATHENA and ATRAP) use the degrading foil to slow antiprotons down. The drawback of this procedure is significant transverse and longitudinal emittance blow up and beam losses in the foil. The efficiency of capture in this case falls down to 10^{-4}.

The ASACUSA experiment uses Radio Frequency Quadrupole Decelerator for post deceleration of antiprotons down to a few tens of kV. Beam transmission is about 25% in this case and emittance blow up is not far from expected ~1/βγ is observed. After the RFQD thin foil still has to be used to slow beam down.

A significant improvement could be achieved with extra decelerating ring with electron cooling.

Layout

A compact machine with circumference of about 25m is proposed for deceleration of the 5.3 MeV beam delivered by AD down to a kinetic energy of 100 keV. The lattice consists of 4 bending magnets and 8 quadrupoles, grouped in 4 families. One of the long straight sections is used for the electron cooler, and the other for the injection and ejection of the beam. (Fig.7). Special attention has to be paid to a beam diagnostics which is challenging at such a low intensity and energy.

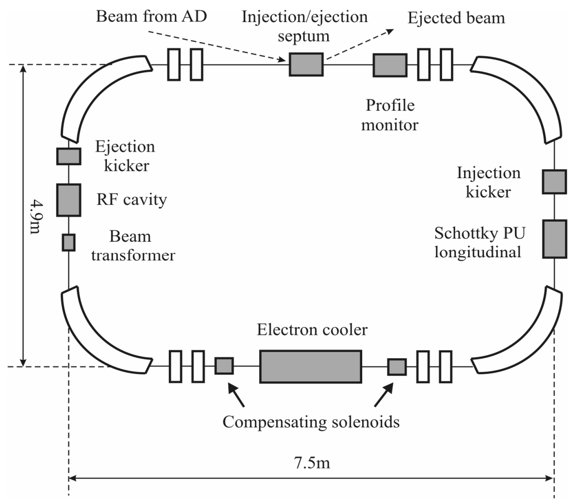

FIGURE 7. ELENA layout.

Electron Cooler and Its Effect on Machine Optics

The cooler is the key element in the machine. Cooling must be fast enough to maintain small beam emittances and counteract IBS and gas scattering at low energies. Careful cooler design has to be done to provide low transverse temperatures of the electron beam at very low energies. With 1m cooling length, integrated correctors, and 90° bend to minimize space it fits properly in one of the straight sections. The vacuum chamber in cooler is assumed to be coated with NEG's.

The simulations done with BETACOOL code [2] showed that about 150 Gs to 200 Gs magnetic field in cooler solenoid needed to make the cooling working fast. At low energy of 100 keV this field (together with fields of compensating solenoids) produces huge tune shifts, and special efforts have to be done to keep optics reasonable. This tune shift scales inversely with energy and is small at injection. During deceleration to low energies it goes up, hence optics has to be flexible to make the necessary adjustments. The tune shift due to the electron beam is noticeable as well (about 0.016) and has to be taken into account also. The parameters of the cooler are given in Table 3.

TABLE 3. Parameters of electron cooler for ELENA.

Cooling length, m	1
Voltage, V	490 / 54
Electron beam current, mA	55 / 2
Beam temperature, eV (transverse / longitudinal)	0.1 / 0.001
Beam radius, cm	2.5
Perveance, μP	5
Magnetic field, Gs	200
Full cooling time at 100 keV, s	2

Other Challenges in ELENA

The beam intensity limitation comes from incoherent tune shift caused by space charge. Based on experience in AD, CERN PS and Booster, a conservative estimate of 0.010 was chosen. This value puts strong limitation to the beam parameters at extraction energy of 100 keV. To relax them, longer extracted bunches of 300 ns have been accepted. Another option is to extract beam from ELENA in several batches. Unfortunately, experiments need about 20s between consecutive batches, and this is difficult to fit in due to lifetime limitation at low energy.

To provide reasonable lifetime ultra high vacuum of $3\ 10^{-12}$ Torr is assumed. This will limit beam emittance blow up due to residual gas scattering to 0.5 π mm mrad/s.

Another lifetime limitation comes from intra beam scattering. Due to its dependence on bunch length it is much more severe for bunched beam (deceleration and extraction). With beam parameters at 100 keV after cooling (N_b=1.5 10^7, $\varepsilon_{x,y}=1\pi$ mm mrad and $\Delta p/p=10^{-4}$, bunch length 1.3m) emittances go up as high as $\varepsilon_{x,y}$=2.4 / 0.96 π mm mrad and $\Delta p/p$=6.4 10^{-4} during 0.5 sec approximately needed for beam bunching and extraction (calculations made with BETACOOL code). Taking this into account, RF programming for beam bunching and before extraction has to have significant margins.

Main parameters of ELENA are summarized in Table 4. To have 1.3 10^7 antiprotons in extracted beam, at least 40% efficiency for beam transfer from AD to ELENA and its further deceleration is needed.

TABLE 4. ELENA main parameters.

Energy, MeV	5.3 – 0.1
Circumference, m	22.6
Working point at 100 keV	1.45 / 1.43
Emittances at 100 keV, π mm mrad	5 / 5
Intensity limitation by space charge for 1 bunch	1.3 10^7
Average antiproton flux (one bunch), 1/sec	1.5 10^5
Maximal incoherent tune shift	0.10
Bunch length at 100 keV, m / ns	1.3 / 300
Required vacuum for $\Delta\varepsilon=0.5\pi$ mm mrad/s,Torr	3 10^{-12}
Beam emittances after 0.5s blow up by IBS ($\varepsilon^i_{x,y}=1\pi$ mm mrad, $\Delta p/p$=1 10^{-4}), s	2.4 / 0.96 / 6.4 10^{-4}

ELENA Allocation in AD Hall

Only small rearrangements have to be done to locate the ELENA ring in the AD Hall (Fig.8). Certain rearrangement of shielding and barracks is needed. ELENA injection line has to be designed and prepared as well. The beam delivery from ELENA to experiments requires the use of electrostatic elements in the transfer lines, which is different to the present case in AD.

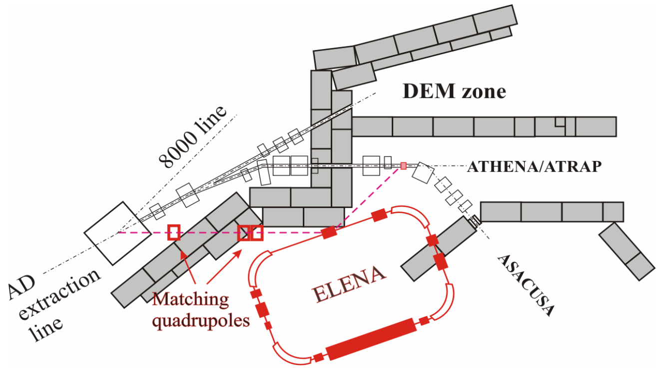

FIGURE 8. ELENA layout in AD Hall.

CONCLUSIONS

Since 2000 AD performance is gradually improving and now 3 10^7 antiprotons in shot are delivered to experiments every 85 seconds. The deceleration efficiency now is as high as 80% due to well working stochastic and electron cooling systems. The beam emittances at ejection are about 1 π mm mrad in both planes and momentum spread after bunch rotation is about 10^{-3}.

To make antiproton capture in trap more efficient, small ring for decelerating antiprotons further down to 100 keV is proposed. This would increase the efficiency of trapping at least one order of magnitude or more.

REFERENCES

1. S. Hancock, e.a. . Tomographic Measurements of Longitudinal Phase Space Density, CERN-PS-99-002-OP.
2. I.N.Meshkov e.a. Simulation of electron cooling process in storage rings using BETACOOL program, in: Proceedings of Beam Cooling and Related Topics, Bad Honnef, Germany, 2001.
3. Charlton e.a. Extra Low ENergy Antiproton ring between the present Antiproton Decelerator and experiments in AD/CERN. CERN-SPSC-2005-029/I-233.