

## TWO YEARS OF AD OPERATION: EXPERIENCE AND PROGRESS

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### Abstract

The antiproton decelerator (AD) has been running successfully for physics for the past two years. After the end of the commissioning period [1] that finished in 2000, the machine has gradually been improved. The main efforts were concentrated on increasing the beam intensity, reducing the cycle length and improving the machine stability. The intensity of the injected beam has been significantly increased due to a higher beam intensity from the PS complex and also due to increased transverse acceptances in the AD machine.

The beam losses during deceleration were reduced from 30-40 % down to a few percent, mainly due to improvements of the operation of the deceleration RF cavity. Altogether these improvements increased the intensity of the ejected beam by a factor of two.

Improvements of the electron cooling were followed by a reduction of emittances and cycle duration (about 15%). Progress in beam diagnostics now allows the monitoring of the machine performance during the whole cycle.

The stability of the machine at the ejection momentum 100 MeV/c remains a crucial point and the identification of the causes of fluctuations in the ejected beam parameters are now under investigation.

### 1 INTRODUCTION: HOW AD WORKS

The simplified low energy antiproton facility at CERN consists of just one ring, the Antiproton Decelerator [2], which produces a beam with a momentum of 100 MeV/c (kinetic energy 5.3 keV) that is shared by three experiments: ASACUSA, ATHENA and ATRAP.

Protons of 26 GeV/c are ejected from the PS and transferred to a target. There antiprotons are produced and transferred to the AD. After injection at 3.57 GeV/c (Fig.1) the beam is rotated by 90 degrees in longitudinal phase space, taking advantage of the short bunch length of about 25 ns. Then the beam is debunched, stochastically cooled, bunched again and decelerated down to 2 GeV/c. There it is stochastically cooled again, primarily to reduce the momentum spread to fit the requirements of the deceleration RF cavity. After the end of stochastic cooling the AD working point is moved from  $Q_x=5.385$ ,  $Q_y=5.37$  to  $Q_x=5.45$ ,  $Q_y=5.42$  taking advantage of the small emittances to cross the 5<sup>th</sup> order resonance  $5Q_x=27$ . The first working point provides maximum machine acceptance at injection momentum, while the second places the beam in the region of the tune diagram where more resonance free space is available. This is particularly important at low momenta.

The beam is then decelerated down to 300 MeV/c and

cooled by the electron beam from the e-cooler. After cooling, the beam is rebunched on harmonic number 3 (the deceleration RF cavity operates in the range 0.5 – 1.6 MHz) and decelerated to the ejection momentum of 100 MeV/c. Then the antiprotons are again cooled by the electron beam, rebunched on harmonic number 1 (this is necessary to extract all the particles in one bunch, for which the RF cavity resonant frequency is lowered to 174 kHz by means of a relay-switched capacitor), rotated by 90 degrees in longitudinal phase space (if experiments demand shorter beam, which is typically the case) and finally ejected.

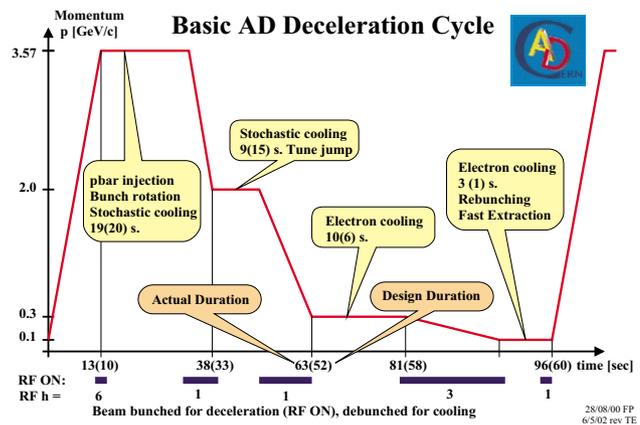


Fig.1. AD cycle.

### 2 BEAM DIAGNOSTICS

The beam measurements in AD are challenging due to the low beam intensity and momentum. Typically, a few  $10^7$  particles are decelerated to 100 MeV/c.

In addition to the tools available from the beginning of the machine commissioning (low noise closed orbit measurement system [3], low frequency (0.3-30 MHz) longitudinal Schottky PU to measure bunched beam intensity and momentum spread, transverse Schottky PU to measure tunes, scrapers to measure beam size and adjust electron cooler performance as well as to maximize machine acceptances at injection momentum) new beam instrumentation has been set up recently.

The new low frequency (5-7 MHz) transverse Schottky pickup is used for BTF tune measurements at flat tops and ramps [4]. Initial tests of the new Beam Ionisation Profile Monitors have been made with promising results [5]. This device allows the non-destructive monitoring of beam centres and emittances throughout the cycle (Fig.2).

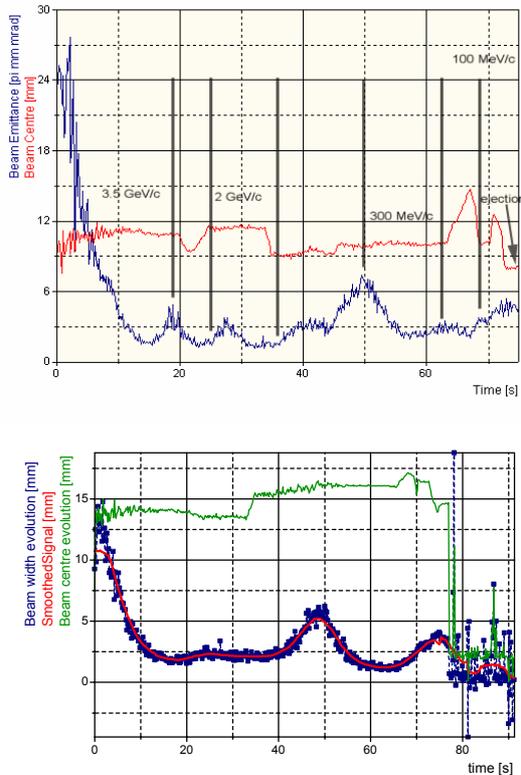


Fig.2. Beam horizontal and vertical widths and centres during the cycle as seen with beam ionisation profile monitor.

### 3 PROGRESS IN MACHINE PERFORMANCE

#### 3.1 Increase of the beam intensity

A significant part of the AD development programme has been concentrated on increasing the intensity of the injected beam and minimizing the beam losses during the cycle.

The intensity of the proton production beam from the PS was increased from  $1.1 \times 10^{13}$  to  $1.5 \times 10^{13}$ , and at the same time precautions were taken to avoid the blow up of the horizontal emittance at PS injection. Vertical machine acceptance was increased from  $180 \pi \cdot \text{mm.mrad}$  to  $200 \pi \cdot \text{mm.mrad}$  due to better alignment of several AD magnetic elements as well as position pickups. This was followed by better orbit correction. The horizontal machine acceptance was also improved from  $165 \pi \cdot \text{mm.mrad}$  to  $180 \pi \cdot \text{mm.mrad}$ , but this is still smaller than the design value of  $200 \pi \cdot \text{mm.mrad}$ .

The losses during the AD cycle were carefully analysed with intensity measurements based on the longitudinal Schottky pickups [6]. Most of the losses occurred during the ramps between injection energy and 2 GeV/c and between 2 GeV/c and 300 MeV/c due to a 50 Hz (150 Hz, 250 Hz) related voltage modulation. By improving the signal transmission of the analogue RF programme to the deceleration cavity, the problem was solved.

Losses during the ramp from 300 MeV/c to 100 MeV/c were eliminated by improving electron cooling at 300 MeV/c and implementing a more sophisticated linear coupling compensation scheme. During the commissioning, the linear coupling compensation was done by two compensating solenoids connected in series with the main solenoid of the electron cooler and by two skew quadrupoles connected to a common power supply. The following winter shutdown (year 2000), the two compensating solenoids and the two skew quadrupoles were equipped with individual power supplies. This allowed, along with suppression of the difference resonance  $Q_x - Q_y = 0$  (by minimization of the distance between normal modes) to reduce significantly the stop band for the sum resonance  $Q_x + Q_y = 11$  (the operational optics is known by orbit response measurements [7]). After that the space available in the tune diagram, which provides the best beam lifetime at 100 MeV/c, was significantly increased.

At present the deceleration efficiency in routine machine operation is around 95% with a peak value of 100%.

Summing up the contribution from all sources, the routine intensity of the ejected beam is now about  $3 \times 10^7$  antiprotons, which is 50% more than in 2001.

#### 3.2 Reduction of the cycle length

The recent progress in the electron cooling performance (see Table 1 and Fig.3) allowed a reduction in cooling time at 300 MeV/c from 15 s to 10.2 s and at 100 MeV/c from 11.6 s to 3.2 s. The total AD cycle length was reduced by one PS supercycle duration and is now 96.4 s (i.e. less than 7 PS supercycles of 14.4 s duration or 6 supercycles of 16.8 s duration).

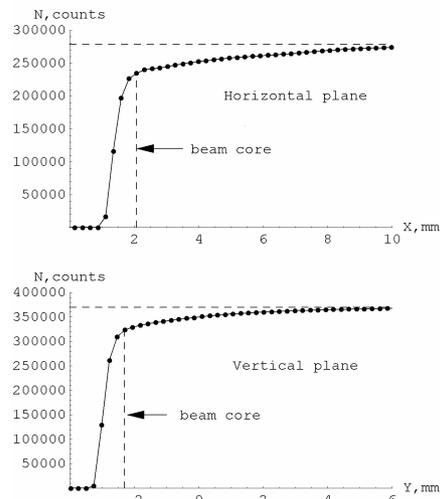


Fig.3. Beam emittance measurements with scraper. The coordinates are the scraper position and the number of counts on a scintillator. The beam core (containing 85% of particles) is shown by a vertical dashed line.

The design value for the AD cycle is 60 s. Limiting factors for further cycle length reduction are as follows.

- Electron cooling is still slower than expected. While at 100 MeV/c it is 3.2 s (and it is hard to reduce it further due to slow eddy current effects), at 300 MeV/c it could be optimised further. The limitation comes from the lack of strength in the dipoles that adjust the antiproton orbit w.r.t. electron orbit. This can be solved by implementing another scheme of orbit manipulation inside the electron cooler, where combined dipoles (marked HV on Fig.4) are exchanged with the vertical dipoles, taking advantage of the bigger phase advance between kicks in the horizontal plane, hence significantly reducing the required strength of the dipole for a given local orbit bump.
- Cycle programming and timing system limitations.
- Maximum dB/dt is lower than foreseen. The cycle ramps are longer than expected (22 s total instead of 8 s) mainly due to the slow eddy current effects. AC magnets that are used now in AD were designed for machine operation at fixed energy.

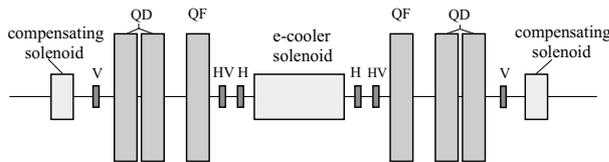


Fig.4. The schematic view of the AD electron cooling insertion

At present it seems possible to reduce the AD cycle length by one PS supercycle duration. This would be achieved by a further reduction of the electron cooling time at 300 MeV/c and by some modifications to the timing system. A small reduction of the stochastic cooling time could also be considered. The ramps will be studied carefully and shortened if possible using the recently available tune measurement system, which can measure tunes during the ramps [8]. A reduction of the AD cycle length will increase the number of antiprotons per second delivered to experiments and provide a basis for the reduction in accumulation time in the traps. In addition, it will reduce the time required for transfer line adjustments, because at present only destructive measurements are available for beam position measurements.

	End 2001	Design
Momentum [MeV/c]	100	100
Intensity [pbars per pulse]	$3 \times 10^7$	$1.2 \times 10^7$
Deceleration efficiency [%]	95	25
Cycle repetition time [s]	100	60
Horizontal emittance [85%, $\pi$ m mrad]	0.3	1

Vertical emittance [85%, $\pi$ mm mrad]	0.3	1
$\delta p/p$ (debunched)	$1 \times 10^{-4}$	$1 \times 10^{-4}$
$\delta p/p$ (bunched)	$2 \times 10^{-3}$	$1 \times 10^{-3}$
Minimum bunch length [ns]	220	200

Table 1. Extracted beam parameters.

## 4 CONCLUSION

After one and a half years of running for physics, the AD routinely delivers about  $3 \times 10^7$  particles in one bunch with a repetition rate of about 100 seconds to the experiments. The number of antiprotons per second is approximately 1.5 times larger than the design value. The deceleration efficiency is close to 100%. Electron cooling at 300 MeV/c needs to be improved further. The reduction in cycle length is expected to be accomplished without major problems and will provide about 15% gain in beam intensity per second. Special attention will be paid to machine stability at ejection energy, which is the most crucial point.

## 5 REFERENCES

- [1] S.Maury et al. Commissioning and First Operation of the Antiproton Decelerator (AD). Proc. PAC2001, Chicago, Illinois, USA, June 18-22 2001, p 580.
- [2] S. Baird et. al. Design Study of the Antiproton Decelerator, CERN/PS 96-43 (AR).
- [3] M.LeGras, L.Soby, D.J.Williams, The closed orbit system for the AD, Proc. DIPAC 1999, Chester, UK.
- [4] S.Maury and F.Pedersen, AD machine and areas, Proc. PS Days Evian 2001.
- [5] G.Tranquille et al., private communication.
- [6] M.E. Angoletta et al, The new Digital Receiver based system for Antiproton beam diagnostics, Proc. PAC 2001, Chicago, Illinois, USA, June 18-22 2001, p.2371.
- [7] P.Belochitskii et al. Optics for the antiproton decelerator at CERN, Proc. PAC 2001, Chicago, Illinois, USA, June 18-22 2001, p.2563.
- [8] O.Marqversen et al. Real Time Tune Measurements on the CERN Antiproton Decelerator, Proc. DIPAC 2001, Grenoble, France.