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The CERN Low-Energy Antiproton Programme: the Synchrotrons

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Abstract

When ideas for the SPS proton–antiproton collider firmed up, it was realized that the abundant production of antiprotons offered a further unique possibility: deceleration and cooling would provide low-energy antiproton beams of unprecedented intensity and purity. A proposal was made to add a small facility for experiments with cooled antiproton beams in the energy range of 5 to 1200 MeV. This was to become the Low-Energy Antiproton Ring, LEAR. Originally thought to only exist parasitically on the antiproton production for the SPS Collider, the project took on an ever-growing importance and, owing to its great successes, has even outlived the SPS Collider. It continues to this day in the simplified form of the Antiproton Decelerator, AD. Our paper describes the accelerator aspects of this venture.

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Introduction

Stimulated by the ideas for the SPS $p\bar{p}$ Collider, Kilian et al. [1] realized in 1976 that cooling and deceleration of antiprotons would provide beams of unprecedented intensity and purity for low-energy physics. This led to the proposal to add to the antiproton project a small facility [2] for experiments with cooled $\bar{p}$ -beams in the energy range of 5–1200 MeV. The proposal received enthusiastic support and, in 1980, the Low-Energy Antiproton Ring (LEAR) [3] was launched.

Already in 1979 it had been decided to use also the existing Intersecting Storage Rings (ISR) for colliding beam and internal target experiments with antiprotons from the Antiproton Accumulator (AA) [4]. Thus with LEAR, ISR and SPS, the $\bar{p}$ -programme would cover c.m.-energies from almost rest to 540 GeV. Here, we include the ISR in the low-energy programme, while the SPS collider as the high-energy part is described elsewhere [5].

The ISR was first to store antiprotons (April 1981), before the SPS (July 1981), and the very last run of the ISR (June 1984), before being shut down definitely, was also with antiprotons. LEAR was built in the old PS South Hall, which also served as its experimental area, and antiprotons were first delivered to users in June 1983. After the end of the SPS collider programme in 1991, LEAR remained the only user of the Antiproton Collector (AC) and the AA. Its unique but complex and costly operation continued until November 1996. In 1997, the AA was dismantled and the AC converted into the Antiproton Decelerator (AD) [6], a simplified all-in-one ring, for low-energy $\bar{p}$ -operation. Since 1999, 100 MeV/c antiprotons are again available to three (since 2003: four) experiments installed in the same hall as the AD ring. LEAR was used for some more time to test ion cooling [7]. In 2006 it will begin a new career as a Low-Energy Ion accumulation Ring (LEIR) for the LHC [8].

In the following we give a brief description of the accelerator aspects of the low-energy $\bar{p}$ -programme. Readers interested in more detail are referred to Refs. [4, 9, 10] for the ISR, Refs. [2, 3, 11] for LEAR, and Refs. [6, 12] for the AD.

2. The Intersecting Storage Rings

The ISR facility was included in CERN's antiproton programme, as there was much promise for interesting physics with proton–antiproton collisions in its energy range of up to 62 GeV c.m. An early scheme had foreseen the transport from the AA of antiprotons at their production momentum, 3.5 GeV/c. This was dropped in favour of transfer at momenta up to 26 GeV/c, since post-acceleration of the antiprotons in the PS had been chosen for the SPS collider. For the ISR it brought the possibility to stack several antiproton shots, about 1 per day, for greater luminosity.

A major item was a new transfer line from the PS to the ISR (TT6, Fig. 1). So as not to lose any of the precious shots, this line was fitted with new, highly sensitive and reliable single-shot beam diagnostics together with precise steering elements. In the rings, magnetic modifications were necessary at the intersection points because the magnets of the experiments affected protons and antiprotons differently. Beam diagnostics, RF control and injection oscillation damping were adapted to cope with the low intensities (at most 6×10^{11} $\bar{p}$ per

shot), far below the usual proton intensities (10^{13}). Very importantly, there was stochastic cooling for both protons and antiprotons. A superconducting low-beta insertion was in the offing anyway and a welcome asset for high $p\bar{p}$ luminosity.

Fig. 1. General layout of CERN's accelerator complex in 1983.
Newly built antiproton lines are drawn thicker.

In April 1981, a first $610 \mu\text{A}$ antiproton beam collided with an 830 mA proton beam, producing a luminosity of $1.1 \times 10^{25} \text{ cm}^{-2}\text{s}^{-1}$. From then on, many technical and operational improvements led to ever-increasing performance, with a luminosity of several $10^{28} \text{ cm}^{-2}\text{s}^{-1}$ at the end of the ISR collider operation in December 1983. Centre-of-mass energies ranged from 30 GeV to a maximum of 62 GeV, reached by means of phase-displacement acceleration. The record antiproton intensity was 13.82 mA , and the corresponding record luminosity $4.5 \times 10^{28} \text{ cm}^{-2}\text{s}^{-1}$ [10, 13].

In 1984, operation continued for a few months with one ring only, colliding antiprotons at momenta between 3.5 and 6.5 GeV/c with a hydrogen jet target for the charmonium experiment R704. In these runs, stochastic cooling was used for the first time to compensate beam heating on an internal target. This novel technique was subsequently practiced at LEAR and many ion cooling rings [14] with stochastic or electron cooling.

3. LEAR

3.1. The magnet lattice

LEAR (Figs. 2 and 3) is almost square in shape with a circumference of 78 m ($\frac{1}{4}$ of the PS). Its four-period lattice with compact 90° bending magnets and eight quadrupole doublets provides four long straight sections, each of 8 m free length. These served for the installation of large equipment, in particular the electron-cooler and the internal gas jet target

experiments. Eight short straight sections, each 1 m long, accommodate less bulky equipment. The C-type magnets are open to the outside of the ring. This simplified injection, ejection, and the design of “exit lines” for neutral states formed in flight in the straight sections ($\bar{H}_0$, antineutrons, $\bar{p}p$ -bound states). The exit lines greatly eased the detection of antihydrogen atoms formed by $\bar{p}$ interaction with an internal gas target [15].

Fig. 2 - Layout of LEAR in the PS South Hall, with injection lines (test-protons and H^+ from the linac, antiprotons from the PS), and the lines transporting ejected antiprotons towards the experiments (status of 1984).

Fig. 3 - LEAR in the PS South Hall (1990). Clockwise from the bending magnet in the foreground, the 4 long straight sections (SS) house: electron cooling (SS3); RF cavities (SS4); injection and ejection (SS1); the internal gas jet target experiment JETSET (SS2). The detector of JETSET is partially dismantled. A web of coaxial transmission lines for stochastic cooling spans across the ring.

A particularity of the optics was the very strong focusing: a phase advance of $\sim 250^\circ$ /period yielded an “imaginary transition energy” (*decrease* of orbit length C with momentum, i.e. $(dC/C)/(dp/p) \equiv \alpha_p = \gamma_{tr}^{-2} < 0$). This leads to a large dispersion of the revolution frequencies $(df/f)/(dp/p) \equiv \eta = \gamma^{-2} - \gamma_{tr}^{-2}$, beneficial for cooling to small momentum spreads and for control of instabilities. Other important features were the ultra-high vacuum, 10^{-12} Torr, for sufficient beam lifetime at low energy and, described below, beam cooling and ultra-slow extraction.

3.2. The operating scheme

A single bunch, of usually a few 10^9 antiprotons, was skimmed off the AA stack at intervals ranging from 15 min to several hours. The average consumption, 10^6 $\bar{p}$ /s, was only 10% of the maximum accumulation rate of the AA. The bunch was decelerated in the PS to 609 MeV/c and transferred to LEAR, where it could either be decelerated to as low as 100 MeV/c (5.3 MeV kinetic energy), or accelerated, up to nominally 2000 MeV/c (1270 MeV).

In the “beam stretcher mode”, used for most of the experiments, ultra-slow extraction provided a continuous spill until the next fill. In the “internal target” mode for the JETSET experiment, a beam with an initial intensity of as much as 5×10^{10} $\bar{p}$ was kept circulating for many hours, even days, until most particles had been consumed by interaction with the gas jet target. For trap experiments one or several bunches were extracted by a fast kicker.

3.3. Cooling

Stochastic cooling of all three emittances was optimized for several strategic momenta: 609 (injection), 300, 200 and 100 MeV/c on the low-energy cycle, and 1000, 1500 and 1940 MeV/c on a high-energy cycle. Cooling compensated the adiabatic emittance growth during deceleration and counteracted various heating mechanisms, such as multiple Coulomb scattering, notably on the internal targets of the JETSET experiment. Final cooling was applied at the momentum at which the beam was delivered to the users, to provide a highly monochromatic and small-sized beam.

A complex cooling system with a great number of different pickups and kickers and containing a plethora of switchable delays was necessary to permit cooling at all momenta. For sufficient signal level, the pickup arrays had to be long. As much as possible they were installed inside the vacuum chamber in the bending magnets where space was “cheap”. An ever-growing web of coaxial lines was spun across the ring for the transmission of the signals from pickups to kickers. Diagonal paths were necessary for cooling at high energy to catch up with the particle velocity $\beta = v/c \approx 1$. For low energy, shorter paths were possible and favourable, to avoid de-synchronization between off-momentum particles and their correction signal (“unwanted mixing”).

From 1987, electron cooling complemented stochastic cooling. The electron cooler, which had served until 1979 in the Initial Cooling Experiment (ICE) was resuscitated and upgraded for service in LEAR at momenta between 300 and 100 MeV/c. This device has even survived LEAR and now operates in the AD.

The combination of both cooling methods in LEAR lead to very high quality beams at low energy with emittances as low as space-charge and instabilities permitted, typically $10^9 \bar{p}$ with $E_{rms} \approx 1 \pi$ mm mrad and $\Delta p/p \approx 10^{-4}$. Elaborate stabilization systems were needed to hold beam instabilities in check.

3.4. Ultra-slow extraction

In the stretcher mode, a spill as constant as possible of some $10^6 \bar{p}/s$ was required by the users. The filling sequence was determined by the smallest intensity that the PS was able to handle. The limit was pushed down to $10^9 \bar{p}$, some 4 orders of magnitude below its usual value for protons. Even so, the spill length had to be at least 15 min, a formidable challenge, as so far extraction times of only a few seconds had been achieved. It meant beam stretching (“extraction time/revolution time”) by 9 orders of magnitude with, on average, less than one particle extracted per turn. A novel ultra-slow extraction technique was devised for this purpose. It is based on (yet another!) idea by van der Meer [\[16\]](#), which was brought to maturity by Cappi and Hardt [\[17\]](#).

Conventional slow extraction uses a programmed tune change, driving the beam towards a resonance, which eats into the tune distribution of the beam. The time structure of the spill is very sensitive to all sorts of tune ripple and exhibits spikes and holes (detrimental to the experiments) when the sweep is slow.

Ultra-slow (“stochastic”) extraction uses RF noise to diffuse the particles within an appropriate range of $\Delta p/p$, thereby producing a very-low-density tail on the momentum distribution. The chromaticity, $dQ/(dp/p)$, adjusted with sextupole lenses, leads to a corresponding tail in the Q -distribution and the extraction resonance is placed at a Q -value inside that tail. This largely reduces the influence of Q -ripple, as the density near the resonance is low and particles perform a random walk around it. The spill rate is controlled by the level of the noise transporting particles from the stack into the tail.

This concept worked admirably and permitted smooth 15-min spills in the first runs in 1983. Very soon, 1-h spills became common. At the end of the LEAR era, the number of transfers per day was minimized by taking from the AA batches of the highest intensity compatible with safe operation for the experiments. Figure 4 illustrates a 10-h spill; the record spill length was 14 h.

Fig. 4 - A typical spill in ultra-slow extraction, lasting 10 h. The beam is shared by two experiments (a “splitter magnet” divides the extracted beam). Each point on the curves represents the rate recorded by the experiment, averaged over 10 s. The brief interruption in the counting rate of OBELIX was for recalibration.

3.5. Performance

During the 14 years of operation, the number of antiprotons consumed by LEAR increased from a few 10^{11} to 2.6×10^{13} per year (Fig. 5). The step in 1987/1988 is due to the advent of the AC. Another step occurred in 1991/1992 when LEAR became the only client of the AC/AA. The total number of antiprotons supplied was around 1.5×10^{14} (0.24 nano-gram).

Fig. 5 - LEAR operation statistics from 1983 to 1996. Number of antiprotons injected (bars) and number of spills delivered (small squares).

The number of scheduled hours increased from 283 in 1983 to an impressive 5450 in the final year, 1996. The number of spills delivered to the users was usually 90%, and always more than 85%, of those scheduled.

4. The Antiproton Decelerator

4.1. The AD ring

By 1994 it had become evident that one could not afford for much longer the complex and costly operation for low-energy antiprotons (involving PS, AC, AA, again PS, and LEAR). The desire of the users' community to continue the highly interesting physics with low-energy antiprotons initiated a search for a substitute facility, which would satisfy at least part of the programme, such as the production of anti-hydrogen.

Studies [18, 6] resulted in the following scheme: the target area would remain as it was; the AA would be removed; the AC would be modified to be ramped from the injection momentum of 3.5 GeV/c down to 100 MeV/c; only fast ejection of antiprotons in a single bunch of about 10^7 $\bar{p}$ every minute would be provided.

Compared to LEAR one had to accept a large decrease (~ 10) in antiproton flux and the lack of ultra-slow extraction, but the number of machines involved was reduced from 5 to 2 and the operational burden greatly relieved.

Apart from the magnetic aspects, it was the adiabatic increase of beam emittance during deceleration that posed the greatest challenge. The beam had to be cooled, not only right after injection, but also on intermediate plateaus. As in LEAR, this was necessary to prevent the emittance from becoming too large. The AC stochastic cooling system [19] was therefore adapted for additional use at 2 GeV/c. Electron cooling had to supplement it at lower energies.

A typical cycle used in 2003 [20] is shown in Fig. 6. Upon injection, the antiprotons fill the acceptances. Bunch rotation reduces the momentum spread and lengthens bunches, whereupon stochastic cooling in all 3 phase spaces reduces the transverse emittances and the momentum spread. This now permits deceleration to 2.0 GeV/c, where further stochastic cooling is applied, allowing the next deceleration to 300 MeV/c. Now electron cooling is called upon before the last deceleration to 100 MeV/c and final electron cooling to very small emittances (Table 1). The beam is then rebunched and rotated, whilst cooling continues, to provide a bunch of only 90–200 ns length as required by the trap experiments, still with a $\Delta p/p$ of a few 10^{-4} . In this way, some 10^7 antiprotons are provided to the experiments every 1.5 min.

Fig. 6 – A typical AD cycle. The horizontal scale shows the times achieved operationally in 2003; design values are in brackets.

Table 1 - AD performance

Characteristic	Design	Operational in 2003
Acceptance H, V (π mm mrad)	200, 200	200, 180
Acceptance $\Delta p/p$ (%)	± 3	± 3.2
Number of $\bar{p}$ injected	5×10^7	5×10^7
Time for stochastic cooling at 3.5 GeV/c (s)	20	17
at 2.0 GeV/c (s)	15	6.6
Time for electron cooling at 300 MeV/c (s)	6	13.8
at 100 MeV/c (s)	1	8.4
Emittances (2σ), H, V at 100 MeV/c after cooling (π mm mrad)	1.1	$\leq 1, \leq 1$
Momentum spread $\Delta p/p$ (4σ) at 100 MeV/c after cooling after rebunching ($h=1$) and bunch rotation	1×10^{-4} —	1×10^{-4} $8 \times 10^{-4} - 4 \times 10^{-4}$
Bunch length (4σ) at 100 MeV/c (ns)	200–500	90–200
Number of $\bar{p}$ ejected	1.2×10^7	3.0×10^7
Total cycle time (s)	60	85
Average flux extracted ($\bar{p}/s$)	2×10^5	3.5×10^{-5}

The length of the cycle is determined by the rate at which the AC magnets, conceived for constant field, can be ramped and by the length of the plateaus for cooling. The large range of $B_{\max}/B_{\min} = 35$ and the low field at 100 MeV/c ($B_{\min} \approx 430$ G) required a major upgrade of the complex magnetic system [21]. The low intensity of the antiprotons posed a challenge to diagnostics and beam control, all the more because the orbit had to be carefully monitored and adjusted in a machine that had not been built to be ramped.

The conversion of the AC into the AD was completed in 1998 and tests were made with protons. In November 1999, the first 100 MeV/c antiprotons were sent to the ASACUSA experiment. In 2000 operation started in earnest, with beams given to all three experiments (ASACUSA, ATHENA, ATRAP).

4.2. The Radio-Frequency Quadrupole (RFQ) post-decelerator

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 trap-experiments require. The further deceleration in a degrader foil, still in use for two of the AD experiments, is accompanied by loss of intensity and dilution in density. This led to the idea to use an RFQ “the wrong way round” for post-deceleration [22]. Combining the RFQ with the electrostatic deceleration at its output leads to final energies in a range of 10–100 keV. The electrostatic deceleration is obtained by applying a d.c. voltage (up to 90 kV) on the inner electrodes (“vaness”) in addition to the RF-field. The proposal for the RFQ decelerator was made in 1998. In 2000, construction was completed and the device shipped to the University of Aarhus, Denmark, where protons of sufficiently low energy were available for tests. In 2001, the RFQ was installed in the AD-Hall and put in service for the ASACUSA experiment.

5. Conclusions

The low-energy antiproton programme had been conceived as an “adjunct” to the SPS collider, at little extra cost and consuming only a small fraction of the antiprotons production. But the results obtained with LEAR soon made it an important and very visible part of CERN's activities. The interest was such that LEAR continued for 5 years beyond the end of the collider. The AD then took over, and holds promise to deliver important physics contributions for several more years to come.

From the outset, the low-energy antiproton programme presented a major challenge to the accelerator community. LEAR was an unconventional enterprise, conceptually and technically. The success of the AA and LEAR has made popular the novel extraction and cooling techniques, and set the example for a dozen ion cooling rings (“king LEAR's daughters”) built in Europe and the USA [14].

Another resounding success was the conversion of the constant energy AC into the ramped AD with its intricate system of stochastic and electron cooling, and diagnostics working with as few as 10^7 particles. With LEAR and AD, CERN has added to its tradition of building accelerators at low cost through innovation and re-use of existing equipment.

References

- [1] K. Kilian, U. Gastaldi, D. Möhl, Deceleration of antiprotons for physics experiments with low energy antiprotons, in: Proceedings of the Xth International Conference on High-Energy Accelerators, Protvino, Serpukhov, USSR, 1977.
- [2] P. Lefevre, D. Möhl, G. Plass, The CERN Low Energy Antiproton Ring (LEAR) project, in: Proceedings of the XI International Conference on High-Energy Accelerators, CERN, 1980, p. 819.
- [3] LEAR design study team, Design of a facility for experiments with low energy antiprotons, CERN Int. Report PS/DL 80-7, 1980.
- [4] P. Bryant, Antiprotons in the CERN Intersecting Storage Rings, in: P. Bryant, S. Newman (Eds.), Proceedings of CERN Acc. School, 1983, Antiprotons for Colliding Beam Facilities, CERN Report CERN 84-15, 1984, p. 509.
- [5] H. Koziol, D. Möhl, The CERN Antiproton Collider programme: accelerators and accumulation rings, to be published in Physics Reports; preprint CERN-AB-2004-097 ADM, 2004.
- [6] S. Maury (Ed.), Design study of the Antiproton Decelerator: AD, CERN Int. Report PS 96-43 (AR), 1996.
- [7] J. Bosser et al., Experimental investigation of electron cooling and stacking of lead ions in a Low Energy Accumulation Ring, Part. Accel. 63 (1999), p. 171.
- [8] K. Schindl, Ion injector issues, in: Proceedings of the LHC Project Workshop, Chamonix, 2004, Chamonix XIII, p. 64.
- [9] C.W. Fabjan, Antiprotons in the CERN Intersecting Storage Rings: status and prospects, CERN Int. Report EP/82-113, 1982.
- [10] M. Jacob, K. Johnsen, A review of accelerator and particle physics at the CERN Intersecting Storage Rings, CERN Report, CERN 84-13, 1984.
- [11] M. Chanel, LEAR performance, in: R. Landua (Ed.), Proceedings of the LEAR Symposium, CERN, May 15th 1998, to be published; preprint: CERN Int. Report-PS 99-40 (CA), 1999.
- [12] P. Belochitskii et al., Two years of AD operation: experience and progress, in: Proceedings of the Eighth European Particle Accelerator Conference, EPAC 2002, Paris, 2002, p. 317.
- [13] CERN, CERN Annual Reports 1981–1984.
- [14] B. Franzke, Review of heavy ion storage rings, in: Proceedings of the Third European Particle Accelerator Conference, EPAC '92, Berlin, 1992, p. 367.
- [15] G. Baur et al., Production of antihydrogen, Phys. Lett. B 368 (1996), p. 251.
- [16] S. van der Meer, Stochastic extraction, a low ripple version of resonant extraction, CERN Int. Report PS/AA 78-06, 1978.
- [17] R. Cappi, W. Hardt, Ultra slow extraction with good duty factor, in: Proceedings of the XI International Conference on High-Energy Accelerators, CERN, 1980, p. 335.
- [18] S. Maury, D. Möhl, Simplified antiproton schemes for anti-hydrogen production in traps, CERN Int. Note PS/AR/Note 95-17, 1995.
- [19] C. Carli, F. Caspers, Stochastic cooling at the CERN Antiproton Decelerator, in: Proceedings of the Seventh European Particle Accelerator Conference, EPAC 2000, Vienna, 2000, p. 2220, preprint: CERN Int. Report PS/2000-024(AE), 2000.
- [20] T. Eriksson, private communication, 2004.

- [21] F.V. Völker, et al. Power converters of the main dipole and quadrupole magnet strings of the Antiproton Decelerator at CERN, in: Proceedings of the Seventh European Particle Accelerator Conference, EPAC 2000, Vienna, 2000, p. 2220.
- [22] J. Bossert, et al. Feasibility study of a decelerating Radio-Frequency Quadrupole system for the Antiproton Decelerator AD, CERN Int. Note PS/HP Note 97-36, 1997.