EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

FP/mh CERN/PS/88-43 (AR)

# PERFORMANCE OF THE CERN ANTIPROTON ACCUMULATOR COMPLEX

B. Autin, G. Carron, F. Caspers, V. Chohan, C.D. Johnson, E. Jones,
H. Koziol, P. Krejcik, G. Le Dallic, M. Martini, S. Maury, C. Metzger,
F. Pedersen, L. Rinolfi, J.C. Schnuriger, T.R. Sherwood, C.S. Taylor,
L. Thorndahl, S. van der Meer, E.J.N. Wilson

## Abstract

Almost one year after the completion of the ACOL project, the operational performance of the CERN AAC (Antiproton Accumulator Complex), composed of target area, antiproton collector ring (AC), and antiproton accumulator ring (AA) is presented and compared with design goals. Machine studies identifying the present limitations are presented, as well as possible steps to be undertaken to push those limits further away.

Paper presented at the European Particle Accelerator Conference,
Rome, 7-11 June 1988

Geneva, Switzerland
June 1988

# *PERFORMANCE OF THE CERN ANTIPROTON ACCUMULATOR COMPLEX*

B. Autin, G. Carron, F. Caspers, V. Chohan, C.D. Johnson, E. Jones, H. Koziol, P. Krejcik,
G. Le Dallic, M. Martini, S. Maury, C. Metzger, F. Pedersen, L. Rinolfi, J.C. Schnuriger,
T.R. Sherwood, C.S. Taylor, L. Thorndahl, S. van der Meer, N. Walker, E.J.N. Wilson
European Laboratory for Particle Physics (CERN)
CH-1211 Geneva 23

## Abstract

Almost one year after the completion of the ACOL project[1,2], the operational performance of the CERN AAC (Antiproton Accumulator Complex), composed of target area, antiproton collector ring (AC), and antiproton accumulator ring (AA) is presented and compared with design goals. Machine studies identifying the present limitations are presented, as well as possible steps to be undertaken to push those limits further away.

## Introduction and Summary

The ACOL project design goal was to increase e CERN antiproton accumulation rate by a factor of 10 from $6 \cdot 10^9$ $\bar{p}$'s/h to $6 \cdot 10^{10}$ $\bar{p}$'s/h.

Presently $14.5 \cdot 10^9$ $\bar{p}$'s/hour (a factor of 2.4) has been achieved. The deficiencies which cause the remaining missing factor of about four are mostly understood and are being cured. A 40 to 60% increase in stacking rate will occur in the very near future. Progress on the remaining part of the missing factor is harder to predict, but we aim to reach the design performance sometime in 1989.

The main limitations to the accumulation rate are due to:

1) 26 GeV/c proton production beam intensity.

2) AC injection yield.

3) AC $\bar{p}$ RF debunching.

4) AC stochastic cooling rate (p, H, V).

5) AA injection orbit precooling rate (p, V).

In addition, a transverse coherent instability with an unexpected fast growth rate limits at present the maximum stack intensity to about $2.4 \cdot 10^{11}$ $\bar{p}$'s.

## 26 GeV/c proton production beam from the PS

Three types of production beam have or will be used depending on the recombination scheme used to squeeze the production beam to within one quarter of the PS circumference.

*Table 1 - Production Beams*

| Period | Intensity | Bunch Length | Booster Energy | Recombination |
|---|---|---|---|---|
| Nov/Dec 87 | $9 \cdot 10^{12}$ | 12 ns | 1 GeV | RF dipole, PSB/PS |
| Apr/May 88 | $6.5 \cdot 10^{12}$ | 12 ns | 800 MeV | none - one ring |
| Autumn 88 | $>10^{13}$ | <25 ns | 1 GeV | Garoby scheme |

The RF dipole recombination[3] of two PSB rings in the Booster-PS transfer line was used last year but was abandoned this spring due to the SPS fixed target programme, which requires four PSB rings, and only two were converted to 1 GeV so far. With 4 PSB rings to be converted to 1 GeV in June, this restriction will disappear, and we can return to the higher intensity.

The novel RF bunch merging scheme invented by R. Garoby[4,5] progresses according to schedule. The beam loading compensation scheme[6] for the PS 9.5 MHz cavities, which is necessary for the bunch merging scheme at high intensity was installed early this year and successfully commissioned in March. The initial merging of pairs of bunches at 3.5 GeV/c followed by acceleration at h = 10 through transition[7] has recently been successfully tested at intensities up to $10^{13}$.

This scheme has a potential capability of doubling the intensity on the target with a modest increase in bunch length.

## Antiproton Production

The water cooled high density iridium target[8,9] (Ø 3 x 55 mm) performs well so far. It has been used with two different collector lenses: a Ø 20 mm lithium lens (420 kA peak) during November/December 1987, and a Ø 60 mm 400 kA peak parabolic aluminium horn during April/May 1988. The measured and calculated[8,10] $\bar{p}$ yields are shown in Table 2. The lithium lens will be reinstalled early June to make a direct yield comparison with the horn into the full acceptance.

*Table 2 - Antiproton yield into AC*

| | $A_H x A_V$ (mm.mrad) | Measured ($\bar{p}$/p) | Calculated ($\bar{p}$/p) |
|---|---|---|---|
| Ø 20 mm Li-lens 420 kA peak | 200πx200π | n.a. | $7.6 \cdot 10^{-6}$ |
| | 200πxx50π | $4.1 \cdot 10^{-6}$ | n.a. |
| | 150πx150π | $3.9 \cdot 10^{-6}$ | $6.6 \cdot 10^{-6}$ |
| | 75πx 75π | $2.4 \cdot 10^{-6}$ | n.a. |
| Ø 60 mm Horn 400 kA peak | 220πx200π | $5.7 \cdot 10^{-6}$ | $7.2 \cdot 10^{-6}$ |
| | 200πx200π | $5.3 \cdot 10^{-6}$ | $7.0 \cdot 10^{-6}$ |
| | 150πx150π | $4.1 \cdot 10^{-6}$ | $5.4 \cdot 10^{-6}$ |
| | 75πx 75π | $2.4 \cdot 10^{-6}$ | n.a. |

It appears from Table 2 that the measured yield is down by about a factor 1.5 from the expected yield for yet unknown reasons.

Calculations[10] show that with a high density passive target, optimum matching into the AC acceptance requires collection of even larger angles than obtainable at present. This could be achieved by a 1.3 MA peak Ø 36 mm lithium lens which is being developed by CERN in collaboration with INP (Novosibirsk) and scheduled for installation in the beam in 1989. A 50% yield improvement is expected.

To obtain an early indication of possible thermal shock and radiation damage, an iridium target was irradiated by up to $1.6 \cdot 10^{13}$ protons per pulse without any observable yield degradation or damage.

## Antiproton Collection, Debunching and Cooling in AC

The AC ring[11] has achieved and exceeded the design acceptance ($A_H$=220π, $A_V$=200π, $\Delta p/p > 6\%$). Nevertheless, the expected depopulation of large betatron amplitudes by non-linear coupling[11,12] is being tackled by sextupoles presently being added in zero dispersion straights.

*Table 3 - AAC Performance Summary*

| | | Start-up Nov. 87 | Best so far May 88 | | Estim. July 88 | Design Goal |
|---|---|---|---|---|---|---|
| | Cycle time (s) | 4.8 s | 2.4 s | 4.8 s | 4.8 s | 2.4 s |
| | Rep. rate (cycles/hour) | 750 | 1500 | 750 | 750 | 1500 |
| | Proton per cycle | $8.9 \cdot 10^{12}$ | $6.5 \cdot 10^{12}$ | $6.5 \cdot 10^{12}$ | $9 \cdot 10^{12}$ | $>10^{13}$ |
| After inj. & deb. in AC | Injection yield ($\bar{p}/p$) | $4.1 \cdot 10^{-6}$ | $5.7 \cdot 10^{-6}$ | $5.7 \cdot 10^{-6}$ | $6.3 \cdot 10^{-6}$ | $10^{-5}$ |
| | $\bar{p}$'s in AC ($\Delta p/p=5.3\%$) | $3.6 \cdot 10^{7}$ | $3.7 \cdot 10^{7}$ | $3.7 \cdot 10^{7}$ | $5.7 \cdot 10^{7}$ | $10^{8}$ |
| | $\bar{p}$'s in AC ($\Delta p/p=1.5\%$) | $2.7 \cdot 10^{7}$ | $2.9 \cdot 10^{7}$ | $2.9 \cdot 10^{7}$ | | $9.5 \cdot 10^{7}$ |
| | RF deb. efficiency | 75% | 78% | 78% | 78% | 95% |
| After cooling in AC | $\bar{p}$'s surviving ($\Delta p/p=5.3\%$) | $3.0 \cdot 10^{7}$ | $2.8 \cdot 10^{7}$ | $3.3 \cdot 10^{7}$ | | |
| | $\bar{p}$'s surviving (4 eVs) | $2.8 \cdot 10^{7}$ | $1.3 \cdot 10^{7}$ | $2.5 \cdot 10^{7}$ | | |
| | $E_H$ (mm.mrad, 95%) | 28π | 27π | 13π | | 25π |
| | $E_V$ (mm.mrad, 95%) | 28π | 34π | 18π | | 25π |
| | RF & cooling eff. (4 eVs) | 78% | 35% | 68% | 68% | |
| After transfer to AA | $\bar{p}$'s injected (4 eVS) | $1.8 \cdot 10^{7}$ | $1.05 \cdot 10^{7}$ | $2.6 \cdot 10^{7}$ | | |
| | $E_H$ (mm.mrad, 95%) | n.a. | 19π | 12π | | |
| | $E_V$ (mm.mrad, 95%) | n.a. | 22π | 17π | | |
| | Transfer eff. AC/AA | 64% | 79% | 100% | 100% | |
| After precooling in AA | $\bar{p}$'s in AA (1 eVs) | $1.4 \cdot 10^{7}$ | $0.56 \cdot 10^{7}$ | $2.15 \cdot 10^{7}$ | | |
| | $E_H$ (mm.mrad, 95%) | n.a. | 18π | 13π | | |
| | $E_V$ (mm.mrad, 95%) | n.a. | 20π | 12π | | |
| | Transfer to tail (1 eVs) | $1.2 \cdot 10^{7}$ | $0.23 \cdot 10^{7}$ | $1.65 \cdot 10^{7}$ | | |
| | Transfer to tail (4 eVs) | $1.5 \cdot 10^{7}$ | $0.56 \cdot 10^{7}$ | $2.2 \cdot 10^{7}$ | | |
| | Precool. & transfer eff. | 67% | 22% | 64% | 64% | |
| In AA stack core | Stacked per cycle | $1.2 \cdot 10^{7}$ | $0.4 \cdot 10^{7}$ | $1.92 \cdot 10^{7}$ | $2.95 \cdot 10^{7}$ | $4 \cdot 10^{7}$ |
| | Acc. yield ($\bar{p}/p$) | $13.5 \cdot 10^{-7}$ | $6.8 \cdot 10^{-7}$ | $29 \cdot 10^{-7}$ | $33 \cdot 10^{-7}$ | $40 \cdot 10^{-7}$ |
| | Stacking rate ($\bar{p}$/h) | $9 \cdot 10^{9}$ | $6.0 \cdot 10^{9}$ | $14.4 \cdot 10^{9}$ | $22 \cdot 10^{9}$ | $60 \cdot 10^{9}$ |

The pbars are debunched by a 1.5 $MV_p$, 9.5 MHz RF system, which uses bunch rotation for one quarter of a synchrotron period followed by a matched isoadiabatic debunching. At present only the bunch rotation is operational, which causes dilution in longitudinal phase space: only ~75% of the particles are within the nominal $\Delta p/p$ of 1.5% while an ideal dilution-free transformation of a 12 ns bunch should give 100% within a $\Delta p/p$ of 0.7%.

A factor 2 improvement in $\Delta p/p$ is expected when the full RF cycle comes into operation some time in 1988.

The novel 1-3 GHz AC stochastic cooling system[13,14,15] in which the pick-up and kicker electrodes accompany the beam as it shrinks, cools the beam simultaneously in all three planes: horizontal, vertical and momentum. The design goal of compressing the phase space density of $10^8$ $\bar{p}$'s by a factor 500 in 2.4 s has not yet been reached, although it has been exceeded in 4.8 s. This shortcoming has so far made it advantageous to operate the AAC at 4.8 s cycle time, where the overall efficiencies are good, (see Table 2). About half of the injected $\bar{p}$'s finish up in the core in spite of the poor debunching efficiency.

All pbar momentum distributions and efficiencies are measured by longitudinal Schottky scans analysed by fast, real time FFT spectral analysis, averaging and integration. Transverse emittances are destructively measured by scrapers and scintillation counters[16].

In spite of cold pick-up structures and preamplifiers, the electronic power is dominated by thermal noise power.

The available power limits the gain to values far below optimum gain. Less than a quarter of the installed power of almost 10 kW was foreseen to be used for momentum cooling but, with the higher initial $\Delta p/p$ almost half of the installed power is spent on momentum cooling (which is still not fast enough), thus leaving less power available for the betatron cooling.

In spite of expected improvements to the debunching process, it is expected that the AC stochastic cooling systems will remain one of the bottlenecks for AAC performance at full repetition rate. Several additional improvements to the cooling gain may be needed such as:

1) lower temperature of pick-up combiner boards,
2) periodic notch filters to improve the betatron Schottky signal to thermal noise ratio,
3) two-stage momentum cooling filters,
4) dynamic phase correction as function of pick-up and kicker positions,
5) more power.

## AC to AA Transfer

The cooled pbars (4 eVs by 25π by 25π, nominal) are adiabatically bunched in the AC prior to transfer to a matched bucket in the AA where they are adiabatically debunched. The RF buckets are capable of transferring efficiently at least twice that area, but the bottleneck is rather the momentum acceptance of the AA precooling system. With the 4.8 s cycle transverse emittances are below the AA acceptance ($A_H x A_V$=23π x 25π, design 25πx25π), and the transfer is efficient and no significant emittance blow-up is observed in any of the three planes.

With collimated proton test beams with almost constant phase space density a small transverse blow-up of 15 to 25% is observed indicating a slight mismatch.

### AA Stochastic Precooling[14]

The momentum precooling at the AA injection orbit works well with the 4.8 s cycle where the initial momentum spread is well within the nominal 0.21% in $\Delta p/p$ (= 4 eVs). About 80% of the pbars within the 4 eVs are within 1 eVs after 4.8 s.

The vertical precooling system becomes unstable in the presence of an intense stack. In spite of ferrite traps between kicker and pick-up to stop waveguide propagation in the vacuum chamber, propagating TE modes launched by the kicker couple to longitudinal modes of the core which travel past the ferrite traps, excite other propagating TE modes in the chamber near the pick-up and thus close the unstable loop. Ferrite damping material will be installed near both pick-up and kickers in June, and will probably eliminate this problem.

The vertical precooling is essential to reduce the vertical emittance below the nominal $16\pi$ acceptance (presently $12\pi$ due to a known obstacle) in the stack tail and core region. The lack of vertical precooling is therefore especially harmful for the fast cycle, where the precooling and transfer efficiency into 1 eVs at the tail drops from 64% to 22% due to the larger initial vertical emittance.

Also the momentum cooling efficiency drops drastically due to a combination of larger initial $\Delta p/p$ and shorter cooling time.

The present bandwidth of the AA precooling systems is 0.8 to 1.6 GHz; a second band (1.6 to 2.4 GHz) is being installed and will be commissioned before the end of June. This will certainly improve efficiencies, especially for the fast cycle.

### AA Stack Tail Stochastic Cooling[14]

For the highest pbar flux encountered so far this system performs well and efficiently. Some modification of the pick-up shape was necessary to duce the coupling to the core to improve stability. e somewhat wider stack required a reduction in bandwidth to avoid overlap, so only the first band (0.8-1.6 GHz) is installed.

Careful attention to kicker symmetry of the stack tail momentum kicker has paid off: no significant transverse heating has been observed, at least for the power levels needed so far.

### AA Stack Core Cooling[17]

Performs well with stack intensities below a few $10^{11}$. Core emittances are below $1\pi$ vertically and $2\pi$ horizontally, but higher antiproton stack intensities with associated exotic sources of beam heating[18] will expose the core systems to a more demanding task. Proton cooling tests at the maximum stack design intensity of $10^{12}$ particles have not yet been done due to an unexpectedly violent transverse coherent instability for intensities above $2 \cdot 10^{11}$.

### Intensity Related Instabilities

Coherent horizontal instabilities occur for cool proton and antiproton stacks above about $10^{11}$ with the damper[19] off, and about $2 \cdot 10^{11}$ with the damper on. In spite of increased damper gain the instabilities remain, although the losses associated with them have disappeared. Since very similar behaviour is observed for both proton and antiproton stacks, neutralisation phenomena can be excluded.

The instabilities are thought to be caused by larger transverse coupling impedances due to major changes of the AA ring components, combined with less Landau damping due to a cooler beam. Further studies with intense, cool proton stacks are being pursued with high priority.

### Acknowledgements

The successful completion of the ACOL project on schedule, followed by a commissioning period of only 4½ months before pbars were produced for physics would not be possible without the enthusiasm and dedication demonstrated by all ACOL team members.

### References

[1] E.J. Wilson (Editor), CERN 83-10 (1983).

[2] E. Jones, "The CERN p$\bar{p}$ Facility", this conference.

[3] G. Nassibian and K. Schindl, IEEE Trans. on Nucl. Sci., Vol. NS-32, No 5, p. 2760 (1985).

[4] R. Garoby, CERN PS/RF/Note 83-15 (1983).

[5] R. Garoby, IEEE Trans. on Nucl. Sci., Vol. NS-32, No. 5, p. 2332 (1985).

[6] B.J. Evans et al., Proc. of the 1987 IEEE Particle Acc. Conf., Washington 1987, p. 1925 (1987)

[7] R. Garoby, private communication.

[8] C.D. Johnson et al., Proc. of the 1987 IEEE Particle Acc. Conf., Washington 1987, p.1749 (1987).

[9] C.D. Johnson, CERN PS/87-95 (AA).

[10] N. Walker, private communication.

[11] B. Autin et al., "The CERN Antiproton Collector Ring", this conference.

[12] P. Krejcik, "Nonlinear Beam Behaviour in the CERN Antiproton Collector", this conference.

[13] B. Autin, CERN/PS AA/82-20.

[14] B. Autin et al., Proc. of the 1987 IEEE Particles Acc. Conf., Washington 1987, p. 1549 (1987).

[15] B. Autin et al., Alta Frequenza, Vol. LVI, N10 (1987), p. 381.

[16] V. Chohan et al.,.IEEE Trans. on Nucl. Sc., Vol. NS-32, No. 5, p. 2231 (1987).

[17] J. Bosser et al., "Design and Performance of the AAC Stack Core Cooling System", this conference.

[18] E. Jones et al., IEEE Trans. on Nucl. Sci.,Vol. NS-32, No. 5, p. 2218 (1985).

[19] F. Pedersen et al., IEEE Trans. on Nucl. Sci., Vol. NS-30, p. 2343 (1983).