EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH

CERN/PS 90-34 (AR)
June 1990

ANTIPROTON ACCUMULATOR COMPLEX (AAC) PERFORMANCE

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CERN, 1211-Geneva-23, Switzerland

ABSTRACT

Antiprotons are produced in the target area, debunched and stochastically cooled in the Antiproton Collector (AC) and then transferred to the Antiproton Accumulator (AA) for final cooling and accumulation into a stack from which bunches are extracted and transferred to the different users. During Sp$\bar{p}$S runs, the performance of the AAC is of crucial importance for the collider luminosity. The stacking rate evolved from 1.2×10^{10} $\bar{p}$/h in early 1988 to 5.8×10^{10} $\bar{p}$/h in May 1989. A maximum stack intensity of 1.31×10^{12} $\bar{p}$ has been obtained. This is comparable to or exceeds the ACOL project design performance. The problems encountered and the countermeasures taken are presented. During periods of production for LEAR only, the excellent AAC performance permits intermittent $\bar{p}$ production, which results in lower operating cost and a reduced power consumption.

Paper presented at the European Particle Accelerator Conference, EPAC 90

Nice, France, 11-16 June 1990

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CERN, PS Division, CH-1211 Geneva 23

†died the 2nd March 1990

Abstract

Antiprotons are produced in the target area, debunched and stochastically cooled in the Antiproton Collector (AC) and then transferred to the Antiproton Accumulator (AA) for final cooling and accumulation into a stack from which bunches are extracted and transferred to the different users. During Sp$\bar{p}$S runs, the performance of the AAC is of crucial importance for the collider luminosity. The stacking rate evolved from 1.2×10^{10} $\bar{p}$/h in early 1988 to 5.8×10^{10} $\bar{p}$/h in May 1989. A maximum stack intensity of 1.31×10^{12} $\bar{p}$ has been obtained. This is comparable to or exceeds the ACOL project design performance. The problems encountered and the countermeasures taken are presented. During periods of production for LEAR only, the excellent AAC performance permits intermittent $\bar{p}$ production, which results in lower operating cost and a reduced power consumption.

Introduction

The ACOL project [1,2,3] design goal was a tenfold increase of the antiproton accumulation rate from 6×10^9 $\bar{p}$/h to 6×10^{10} $\bar{p}$/h, while accumulating into stacks up to 10^{12} $\bar{p}$ with acceptable transverse emittances. This performance was more or less obtained in May 1989, less than two years after turn-on following the end of the ACOL project. Improvements were made to all factors which contribute to the stacking rate:

- 26 GeV/c production beam intensity.
- AC injection yield.
- AC $\bar{p}$ debunching.
- AC stochastic cooling rate (p, H, V).
- AA injection orbit precooling rate (p, V).
- Reliability.

The stochastic cooling rates influence both stacking efficiency and maximum repetition rate. In addition stack intensity limitations due to coherent and incoherent instabilities caused by accumulated ions were identified and cured. Intrabeam scattering is also a limiting factor.

26 GeV/c Proton Production Beam

Due to the circumference of the AC ring, the PS production beam must be merged into one quarter of the PS circumference prior to extraction. Since the end of the ACOL project, three different recombination schemes have been used:

Table I - Different production beams

Period	Intensity	Bunch Length	PSB Rings	Recombination
11/87-10/88	1.0×10^{13}	12 ns	2	RF Dipole[4] PSB/PS
10/88-09/89	1.5×10^{13}	30 ns	2	PS RF merging [5,6,7]
09/89-12/89	1.7×10^{13}	30 ns	4	PS RF merging+RF Dipole

All three schemes profit from the upgrade of the PSB energy from 800 MeV to 1 GeV [8].

The first scheme is limited by transverse space charge at 1 GeV in the PS; the second one (which fills 1/2 the PS ring at 1 GeV) in the PSB at 50 MeV, while the third scheme again is limited at 1 GeV in the PS although transient beam loading in the PS plays an important role; soon to be improved by a one-turn delay feedback [9,10] around the PS RF amplifiers.

Antiproton Production

The production beam is focused on the target with 2 pulsed quadrupoles. A high density target [11,12] made of iridium (Ø 3 × 55 mm) embedded in graphite and enclosed in a sealed, water cooled, titanium container performs well. Despite the higher intensities of the primary proton beam, no yield degradation due to target damage has been observed, although an irradiated target assembly cut open [13,14] showed that the iridium is damaged by the thermal shock, but sufficiently contained to maintain initial yield. Antiprotons emerging from the target are focused and matched into the injection transport line by a collector lens.

A lithium lens of 20 mm diameter, pulsed at 480 kA, was the principal collector lens used operationally and yielded 62×10^{-7} $\bar{p}$/p on the AC injection orbit after various optimizations.

A 60 mm diameter parabolic aluminium horn operating at 400 kA peak has provided trouble free operation during several operational periods. It is simpler and cheaper to build and operate, but at 400 kA its yield is about 10% lower than the Ø 20 mm Li-lens. Lack of suitable test area outside the target area has until recently prevented the exploring of high currents.

The above-mentioned yields agree with calculations [15] except for an unexplained factor of 1.5. These calculations also indicated that an even better yield could be obtained by using a 36 mm diameter Li-lens pulsed at 1.3 MA, thereby collecting $\bar{p}$'s emerging at large angles. A collaboration with INP (Novosibirsk, USSR) was launched early in 1988, and in spring 1989 a 36 mm diameter Li-lens (originally designed for 800 kA), a coaxial pulse transformer (designed for 1.5 MA), and an associated pulser was ready for test. A flange failure during testing at 1.1 MA forced us to postpone beam tests until July 1989. These tests were encouraging with a 20% $\bar{p}$ yield improvement for the nominal production beam and a 40% improvement with lower intensity primary beam (with lower emittance).

During subsequent life test in the laboratory, the stainless steel container failed after half a million pulses at 1.1 MA. New 34 mm diameter lenses [16] with stronger containers are being made, and should be tested and ready for the Sp$\bar{p}$S collider run this autumn.

Antiproton Collection and Debunching

The AC ring [17] has achieved and exceeded the design acceptance ($A_H = 220\pi$, $A_V = 210\pi$,$\Delta p/p > 6\%$). The observed depopulation of large betatron amplitudes, was expected to be partly due to non-linear coupling, as already observed in the old AA [18]. Sextupoles were added in 1988 in zero dispersion straight-sections to reduce this coupling [29]. Although these sextupoles were successful in reducing this coupling, no measurable increase in $\bar{p}$ yield was obtained since the natural depopulation of large amplitudes in the 200 π.mm.mrad AC is much more pronounced than in the 100π mm.mrad AA.

The 5 antiproton bunches are injected into 5 buckets of a 6th harmonic RF system [19]. After one quarter synchrotron period (1.2 MV, 9.5 MHz) rotation in longitudinal phase plane, the voltage is quickly reduced to match the initially mismatched bunch, and finally reduced adiabatically.

The debunching performance is expressed as the percentage of antiprotons found within a 1.5% momentum spread after debunching, relative to the total number injected in the full momentum spread of 6%. It progressed from 75% early in 1988, to 87% in 1990. Progress is due to the addition of an isoadiabatic interval (1988), closed loop control of voltage and phase (1989), and improved setting-up procedures (1990).

Stochastic Cooling

The novel 1-3 GHz AC stochastic cooling system [20,21] in which moving pick-up and kicker electrodes accompany the beam as it shrinks, was very soon identified as a critical item in achieving design performance, even using a 4.8 s cycle instead of a 2.4 s cycle as originally planned.

In spite of cold pick-up structures and preamplifiers, the available power (~10 kW) limits the gain to values below optimum during most of the cycle. Several improvements were introduced during 1988 and 1989:

- Added cryogenic cooling of pick-up combiner boards.
- Periodic filters for betatron systems to increase signal to noise ratio.
- Two-stage momentum cooling filters.
- Dynamic phase correction as function of pick-up and kicker positions.
- More band III power (2.4-3.0 GHz).
- Better optimized pick-up and kicker movements versus time.

The first of these improvements was the most expensive and complex, but also the most effective. By lowering the temperature from 100 °K to 30 °K the thermal noise was reduced by 4 dB, and acceptable transverse emittances and efficiency were obtained after 2.4 s. But also the 4.8 s cycle was improved (Table II):

Table II - AC stochastic cooling performance

Date	4.8 s		2.4 s	
	$E_{H,V}$	ε (4 eVs)	$E_{H,V}$	ε (4 eVs)
May 88	~15π	68%	30π	35%
May 89	4π	92%	13π	70%

Improvements were also needed for the AA precooling system (p, V):

- Second band added : 1.6-2.4 GHz. (Initially only 0.8-1.6 GHz).
- Lower noise preamplifiers.
- Damping of propagating TE modes by ferrite materiel (coupling via longitudinal modes of stack)

Nevertheless, the precooling and stack tail systems are not sufficiently fast to digest the $\bar{p}$ with adequate efficiency for the 2.4 s cycle, while the precooling and stack tail systems do not limit the efficiency with a 4.8 s cycle.

As for the AC, the AA precooling gain is limited to below optimum by thermal noise and available power. The cheapest way to obtain sufficient gain and speed would be to add cryogenic cooling of the AA precooling pick-ups. Even so, barely 10% could be gained in overall daily production rate since the number of production cycles per hour available from the PS using 2.4 s cycles only increase by a factor typically 1.5 to 1.7, and not 2, due to other users (LEAR, SPS, fixed target, East Hall, LEP). For this reason (and others such as budget, manpower, future of Sp$\bar{p}$S Collider), the cryogenic pick-ups in AA were abandoned and therefore also 2.4 s operation.

The AA stack core 4-8 GHz transverse cooling [22] system initially suffered from difficulties in obtaining a good BTF (Beam Transfer Function) due to hardware coupling and poor common mode rejection, but after these problems were cured, equalizers were made to improve phase and bandwidth. But even after improvements of the 2-4 GHz stack core momentum system, the stack momentum width (due to intrabeam scattering) at intensities above a few 10^{11} particles is too wide to exploit the highest frequencies (above 6 GHz) of the transverse system due to too high an η value [(Δf/f)/(Δp/p)].

This leads to heating of the low and high momentum edges of the stack, and increased loss rate which eventually consumes a large fraction of the stacking rate. For this reason, the transverse core bandwidth has been extended towards lower frequencies by adding 2-4 GHz transverse cooling of the core, and, recently a proton stack of 1.67×10^{12} has been obtained with acceptable loss rate. Also the stack core momentum system (2-4 GHz) has been improved by adding a 1-2 GHz system.

Stack Intensity

In 1988 stack intensity was initially limited to about 3×10^{11} $\bar{p}$ due to a coherent transverse ion-$\bar{p}$ quadrupolar instability [23,24]. This instability disappeared after improving the electrostatic clearing and choosing a tune close to 2.25 in both planes. Nevertheless, residual ions caused high loss rates above 6×10^{11} due to excitation of high order non-linear resonances. This was improved dramatically when the residual ion neutralization was further reduced by transverse shaking. The record stack intensity of 1.3×10^{12} $\bar{p}$ was obtained with less than 40% stacking efficiency probably due to the limitation mentioned above in the core 4-8 GHz system. After adding the 1-2 GHz and 2-4 GHz systems recently stacking efficiencies above 70 % has been obtained with more than 10^{12} $\bar{p}$ in the stack.

Diagnostics

These improvements would not be possible without powerful diagnostic tools and controls software [25]; for example:

- Transverse and longitudinal Schottky scans (tunes vs. frequency, emittances vs. frequency, emittances vs. time, etc.).
- Real time $\bar{p}$ efficiencies and momentum distribution by FFT spectral analysis of Schottky signals [26].
- Transverse and longitudinal coherent injection oscillations [27] for almost all injections (including correction matrices):
  - p via loop to AA (L, H, V)
  - p via loop to AC (L H, V)
  - $\bar{p}$ from target to AC (H, V) (resonant PU) (μ^-, e^-)
  - $\bar{p}$ from AC to AA (L, H, V) (resonant PU)
  - p direct to AC (L, H, V)
  - p direct to AA (L, H, V)
- Transverse quadrupolar coherent injection oscillations [28] from AC to AA, and from PS to AA (check and correct the mismatch).
- Clearing current monitoring.
- Software to localize acceptance limitations.
- Software to measure acceptances.
- Software to measure $\bar{p}$ emittances in AC and AA by scintillators and scrapers.

AAC Performance

After all these improvements the stacking rate at medium stack intensities was increased by a factor of 10 with respect to that of the old AA.

We show in Table III the peak performance and the operational values, compared with the design values. The daily stacking rate is an average during stacking periods, and takes into account the fluctuations of PSB, PS and AAC machines.

Table III - AAC Performance

		1988	1989	
	DESIGN	OPERATION	OPERATION	PEAK
Production beam (ppp)	1.0×10^{13}	1.35×10^{13}	1.45×10^{13}	
Repetition period	2.4s(1500/h)	4.8s(750/h)	4.8s(750/h)	
Yield ($\bar{p}$/p)	10.0×10^{-6}	5.7×10^{-6}	5.4×10^{-6}	5.8×10^{-6}
$\bar{p}$ injected in AC	10.0×10^{7}	7.7×10^{7}	7.7×10^{7}	8.3×10^{7}
$\bar{p}$ after bunch rot.	9.0×10^{7}	5.6×10^{7}	6.2×10^{7}	6.8×10^{7}
$\bar{p}$ after AC cooling		5.7×10^{7}	7.2×10^{7}	7.6×10^{7}
$\bar{p}$ after transf. to AA		5.4×10^{7}	6.3×10^{7}	7.0×10^{7}
H emit. after AC cool.		10 π	4 π	
V emit. after AC cool.		10 π	4 π	
$\bar{p}$ after AA precool.		5.3×10^{7} (4eVs)	7.5×10^{7}	7.9×10^{7}
		3.8×10^{7} (1eVs)	6.2×10^{7}	6.2×10^{7}
$\bar{p}$/pulse	5.0×10^{7}	4.9×10^{7}	7.0×10^{7}	7.7×10^{7}
Stacking rate (10^{10}/h)	7.5	3.6	5.3	5.8
Daily production (10^{11})	10	6.0	8.5	11.5
Daily stack.rate(10^{10}/h)		3.3	4.4	5.16
Stack intensity max.	1×10^{12}	0.85×10^{12}	1.03×10^{12}	1.3×10^{12}
Transverse emittances	1-2 π	2-3 π	2-3 π	
Total efficiency	50 %	63 %	91 %	93 %

We also show in Fig. 1 the evolution of the AAC stacking rate versus years.

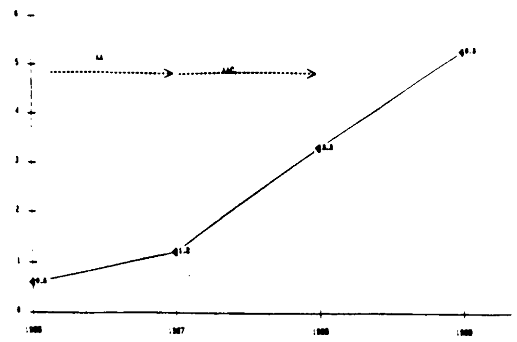

Fig. 1 - Stacking rate (10^{10} $\bar{p}$/h)

Summary

The good AAC performance and reliability enable one to stack typically 9×10^{11} $\bar{p}$/every day. On several occasions, more than 10^{12} $\bar{p}$ were obtained in operation during the Sp$\bar{p}$S period. During the 2 last periods of 1989, all the $\bar{p}$'s produced were dedicated to LEAR. During runs for LEAR physics a lower $\bar{p}$ flux is needed.The excellent AAC performance permits intermittent $\bar{p}$ production, i.e. 5×10^{11} $\bar{p}$ are accumulated in the AA, then the accumulation is stopped, the injection line power supply currents are reduced to 10% of their operational values, the AC ring switched off for saving power, and finally just the $\bar{p}$ transfers are operational.This mode is called Economy Mode, but the $\bar{p}$ accumulation is tested every day during 15 minutes.

During the last run of 1989, AAC was in this mode for 77% of the time. This represents a saving of 4650 MWh.

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