PERFORMANCE OF THE CERN ANTIPROTON ACCUMULATOR COMPLEX

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Abstract

Almost one year after the completion of the ACOL project1,*, 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 the CERN antiproton accumulation rate by a factor of 10 from $6 \times 10^3 \text{ p's/h}$ to $6 \times 10^{10} \text{ p's/h}$. Presently, $14.5 \times 10^9 \text{ p's/h}$ (a factor of 2.41 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 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 $2.4 \times 10^{11} \text{ p's}$.

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

<table>
<thead>
<tr>
<th>Period</th>
<th>Intensity</th>
<th>Bunch Length</th>
<th>Booster Energy</th>
<th>Recombination</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nov/Dec 87</td>
<td>$9 \times 10^5$</td>
<td>12 ns</td>
<td>1 GeV</td>
<td>RF dipole, PDB/PS</td>
</tr>
<tr>
<td>Apr/May 88</td>
<td>$6.5 \times 10^5$</td>
<td>12 ns</td>
<td>800 MeV</td>
<td>none - one ring</td>
</tr>
<tr>
<td>Autumn 88</td>
<td>$&gt;10^5$</td>
<td>25 ns</td>
<td>1 GeV</td>
<td>Garoby scheme</td>
</tr>
</tbody>
</table>

The novel RF bunch merging scheme invented by R. Garoby4,5 progresses according to schedule. The beam loading compensation scheme6 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 transition7 has recently been successfully tested at intensities up to $10^{11}$.

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 target8,9 ($\Phi \times 55 \text{ mm}$) performs well so far. It has been used with two different collector lenses: a $\Phi 20 \text{ mm}$ lithium lens (420 kA peak) during November/December 1987, and a $\Phi 60 \text{ mm}$ 400 kA peak parabolic aluminium horn during April/May 1988. The measured and calculated10 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

<table>
<thead>
<tr>
<th>Collector Lens</th>
<th>Measured (p/p)</th>
<th>Calculated (p/p)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Phi 20 \text{ mm}$ Li-lens</td>
<td>200x200 x 200x200</td>
<td>n.a.</td>
</tr>
<tr>
<td>$\Phi 60 \text{ mm}$ Horn</td>
<td>220x220 x 200x200</td>
<td>5.7 x 10^{-6}</td>
</tr>
</tbody>
</table>

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.

Calculations10 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 $1.3 \text{ MA peak} \Phi 36 \text{ mm}$ 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 $1.5 \times 10^{13} \text{ protons per pulse}$ without any observable yield degradation or damage.

Antiproton Collection, Debunching and Cooling in AC

The AC ring11 has achieved and exceeded the design acceptance ($Ap=220 \mu$, $Av=200 \mu$, $Ap/p > 8\%$). Nevertheless, the expected depopulation of large betatron amplitudes by non-linear coupling11,12 is being tackled by sextupole presently being added in zero dispersion straight.
...preamplifiers, the electronic power is dominated by emittance blow-up is observed in any of the three planes. In spite of cold pick-up structures and preamplifiers, the electronic power is dominated by thermal noise power.

### Table 1: AAC Performance Summary

<table>
<thead>
<tr>
<th></th>
<th>Start-up Nov. 87</th>
<th>Best so far May 88</th>
<th>Estim. July 88</th>
<th>Design Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cycle time (s)</strong></td>
<td>4.0 ± 0.1</td>
<td>2.4 ± 0.1</td>
<td>4.0 ± 0.1</td>
<td>2.4 ± 0.1</td>
</tr>
<tr>
<td><strong>Rep. rate (cycles/hour)</strong></td>
<td>750</td>
<td>1500</td>
<td>750</td>
<td>1500</td>
</tr>
<tr>
<td><strong>Proton per cycle</strong></td>
<td>8.9 ± 10^12</td>
<td>6.5 ± 10^12</td>
<td>6.5 ± 10^12</td>
<td>6.5 ± 10^12</td>
</tr>
</tbody>
</table>

**After inj. & deb. in AC**

| **Injection yield (P/p)** | 4.1 ± 10^6       | 5.7 ± 10^6         | 5.7 ± 10^6     | 10^5        |
| **P's in AC (A/p=5.3%)**  | 3.6 ± 10^7       | 3.7 ± 10^7         | 3.7 ± 10^7     | 10^8        |
| **P's in AC (A/p=1.5%)**  | 2.3 ± 10^7       | 2.9 ± 10^7         | 2.9 ± 10^7     | 9.5 ± 10^7  |
| **RF deb. efficiency**    | 75%              | 78%                | 78%            | 95%         |

**After cooling in AC**

| **P's surviving (A/p=5.3%)** | 3.0 ± 10^7       | 2.8 ± 10^7         | 3.3 ± 10^7     | 25%         |
| **Eq (mm.mrad, 95%)**        | 28%              | 27%                | 13%            | 25%         |
| **Ey (mm.mrad, 95%)**        | 28%              | 34%                | 18%            |            |
| **RF & cooling eff. (4 eVs)** | 78%              | 35%                | 68%            |            |

**After transfer to AA**

| **P's injected (4 eVs)**    | 1.8 ± 10^7       | 1.05 ± 10^7        | 2.6 ± 10^7     | 100%        |
| **Eq (mm.mrad, 95%)**       | n.a.             | 19%                | 17%            |            |
| **Ey (mm.mrad, 95%)**       | n.a.             | 22%                | 17%            |            |
| **Transfer eff. AA/AA**     | 64%              | 79%                | 100%           |            |

**After precolling in AA**

| **P's in AA (1 eVs)**       | 1.4 ± 10^7       | 0.56 ± 10^7        | 2.15 ± 10^7    |            |
| **Eq (mm.mrad, 95%)**       | n.a.             | 16%                | 13%            |            |
| **Ey (mm.mrad, 95%)**       | n.a.             | 20%                | 12%            |            |
| **Transfer to tail (1 eVs)** | 1.2 ± 10^7       | 0.23 ± 10^7        | 1.65 ± 10^7    |            |
| **Transfer to tail (4 eVs)**| 1.5 ± 10^7       | 0.56 ± 10^7        | 2.2 ± 10^7     |            |
| **Precool. & transfer eff.**| 67%              | 22%                | 64%            |            |

**In AA stack core**

| **Stacked per cycle**       | 1.2 ± 10^7       | 0.4 ± 10^7         | 1.9 ± 10^7     | 4 ± 10^7   |
| **Acc. yield (P/p)**        | 13.5 ± 10^10     | 6.8 ± 10^7         | 29.8 ± 10^7    | 4 ± 10^7   |
| **Stacking rate (P/h)**     | 9 ± 10^9         | 6.0 ± 10^9         | 14.4 ± 10^9    | 2 ± 10^9   |

The cooled pbars (4 eVs by 25x by 25x, 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 precolling system. With the 4.8 s cycle transverse emittances are below the AA acceptance (Ap<sub>Ay</sub>=23x25x, design 25x25x), and the transfer is efficient and no significant emittance blow-up is observed in any of the three planes.

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 Ap<sub>p</sub> of 1.5% while an ideal dilution-free transformation of a 12 ns bunch should give 100% within a Ap<sub>p</sub> of 0.7%.

A factor 2 improvement in Ap<sub>p</sub> is expected when the full RF cycle comes into operation some time in 1988.

The novel 1-3 GHz AC stochastic cooling system 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<sup>8</sup> p's by a factor 2000 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 p's finish up in the core in spite of the poor debunching efficiency.
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**

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 90% 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% acceptance (presently 12% 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**

For the highest pbar flux encountered so far this system performs well and efficiently. Some modification of the pick-up shape was necessary to reduce the coupling to the core to improve stability. The 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**

Performs well with stack intensities below a few $10^{11}$. Core emittances are below 16% vertically and 25% horizontally, but higher proton stack intensities with associated exotic sources of beam heating 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 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**