EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
ORGANISATION EUROPEENNE POUR LA RECHERCHE NUCLEAIRE

CERN - PS DIVISION

PS/ AR/ Note 94-14

POSSIBLE AAC STACKING RATE IMPROVEMENTS

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This work has been triggered by a seminar given at CERN on collider concepts for high energies where, for a Z^0 factory or a proton/antiproton collider, a luminosity of 10^{33} $cm^{-2}s^{-1}$ is required. Improvements of the antiproton production and cooling rate are reviewed and quantitatively estimated with the basic assumption that no drastic change would be made in the fundamental design.

Geneva, Switzerland
8 August 1994

1. INTRODUCTION

This work has been triggered by a seminar [1] given at CERN on collider concepts for high energies and luminosities, where a multibunching scheme for particle/antiparticle collisions in a single magnetic ring at energies beyond LHC has been presented. For a Z^0 factory or a proton/antiproton collider at very high energies, a luminosity of 10^{33} $cm^{-2}s^{-1}$ is required. All the realistic improvements of the $\bar{p}$ production involved in a higher production rate are reviewed. Production beams, targetry, collecting lenses, stochastic cooling have been examined, and the possible gains in $\bar{p}$ production are quantitatively estimated. Other promising items are also briefly outlined.

The CERN antiproton source (AAC) has been built for two main antiproton users: the $p\bar{p}$ collider and LEAR. A high $\bar{p}$-production rate was requested by the $Sp\bar{p}S$ collider to provide sufficient luminosities in the interaction regions. But, the $Sp\bar{p}S$ collider physics programme has come to an end, and since the beginning of 1992 the AAC has been operating in single-client mode. To supply the LEAR experiments with small quantities of antiprotons, relatively low $\bar{p}$-production rates are needed. For single-client runs, the peak performance in $\bar{p}$ production is decreased, except when special circumstances impose it, but the high reliability level has to be maintained. The consolidation of some machine elements was necessary, in particular in the target area where an important effort was made to keep the remote-handling vehicle operational and to reinforce the high-current magnetic horns foreseen to replace the 20 mm lithium lens actually in use.

If a higher production rate was now requested, it would be necessary to build new and expensive hardware spares to attain the same level of performance as for the $p\bar{p}$ collider physics. Better performance is excluded without a considerable effort in money and staff. In the following, all parts of the AAC complex are reviewed to determine the necessary improvements to guarantee sufficient reliability in case a higher $\bar{p}$-production rate would be needed and to prevent slow damaging in current operation.

2. PROTON BEAM INTENSITY AND EMITTANCES

To match the circumference of the AC machine, the production beam must be merged into one quarter of the PS prior to extraction.

Three different recombination schemes have been used in the past [2] which all profit from the upgrade of the PSB energy from 800 MeV to 1 GeV. The beam, longitudinally recombined by a rf dipole at 1 GeV in the Booster/PS transfer line and by rf merging at 3.5 GeV/c, followed by successive changes of harmonic numbers at 26 GeV/c, is now operated with an intensity of up to 1.7×10^{13} protons per cycle. It is limited by the transverse space charge at 1 GeV in the PS, although transient beam loading in the PS plays an important role. A good improvement has been obtained with the one-turn delay feedback around the PS rf amplifiers [19].

The $\bar{p}$-production beam could be improved by increasing the PSB energy from 1 GeV to 1.4 GeV needed for the LHC and by the experience gained for creating such a beam. The beam intensity could be increased to 2×10^{13} protons per cycle.

The transverse emittance is of great importance for the $\bar{p}$-production beam and the improvements are very useful if all the particles are inside the emittance of 2 to 3π mm·mrad. In the meantime the reduction of the bunch length (less than 30 ns) as well before the PS ejection would be very promising for the performance of the AAC. A shorter bunch length would make the AC cooling and accumulation processes easier. Studies would be necessary for achieving such performances. The improvement of the production beam intensity could give a factor of 1.3.

3. TARGET AND TARGET OPTICS OPTIMIZATION

For a more efficient antiproton production, targets made from dense metals have been studied [3, 4]. Some of the best candidates (iridium, rhenium, tungsten, tantalum, copper) can be used.

The antiproton production density decreases when increasing the atomic number, Z, of the target material due to the higher probability of the antiproton reabsorption in the target nucleus. The geometry of the target is also a function of the focal length of the collector. If a collector with a long focal length, or more precisely small collection angles, is used (magnetic horn) a longer target with a low atomic number, like copper or nickel, can be used. If a collector with a large collection angle is used (lithium lenses), a short target is needed (i.e. short absorption length), which implies the use of high Z materials (iridium, tungsten, rhenium).

Designed to be used with the 36 mm lithium lens, the AAC target is a thin rod of iridium clad in copper and then embedded in graphite and water-cooled. It has proven to be very reliable without any noticeable performance degradation. No experimental optimisation has been felt necessary until now and no change decided. On several occasions, the short space between the target and the collecting lens has been an issue. Computations have shown that small changes could be made without losing its present reliability, which would give a relevant gain in $\bar{p}$ production. A very simple modification, which does not imply any change in design is to increase the length of the active part of the target with the same graphite and metallic box. This will improve the yield for small maximum collection angles.

Different target materials and geometries have also been studied [5], and $\bar{p}$ relative yields have been calculated by simulation for non-axisymmetric geometries (elliptic proton-beam cross sections, beam and lens offset, different β_H and β_V...). The calculations are made with the present iridium target (3 mm diameter and 55 mm length), with $\beta_0 = 1.5$ cm, with the betatron function of the $\bar{p}$ transfer line reflected backwards to the focus, and for an abscissa $Z_0 = 2$ cm of the focus (assuming that rms radii σ_{xp} and σ_{yp} are equal), the case $\sigma_{xp} = 0.75$ mm is taken as representative of the present situation in the target zone with a 20 mm lithium lens.

Calculations show that for a larger target radius there is no yield increase and no significant increase for a longer target. A slightly better yield is obtained with a radius reduced to 1.3 mm. However, the yield is higher for a reduced proton-beam size, of the order of 20% for σ_{xp} = 0.5 mm. These results show the predominant role of the proton beam radius σ_{xp}. Two pulsed quadrupoles are used to focus the production beam on the target. The gain can be obtained by increasing the strength and the aperture of this focusing system.

Calculations have been repeated with a target made of copper (or nickel whose properties are very similar). For a nominal proton beam size σ_{xp} = 0.75 mm on the optimised copper target (r = 1.5 mm, L = 90 mm), the yield can be increased by about 20% with small collection angles. But this also reduces the phase-space density and lowers the yield at high collection angles [11]. For a high production beam intensity of up to 2×10^{13} protons, the combined effects of the beam heating and shock waves can cause a rapid fatigue failure, in particular in the region of the end cap of the container traversed by the proton beam. During the tests in the old AA, steel containers have been pierced by the beam and underline the importance of the cooling.

Measurements made in the AA in 1983 with the magnetic horn pulsed at 170 kA and with different target materials show that copper gives more yield compared to tungsten or aluminium [6]. Here the yield is defined as the number of $\bar{p}$'s measured on the injection orbit of the AC ring per incident 26 GeV/c protons striking the production target. Later on, iridium embedded in graphite and water cooled has proven to be a reliable target without any noticeable performance degradation. If there is a request to increase the stacking rate with the new collector, any improvements or gain in yield is welcome. To find out the best material to obtain a high yield and a good reliability, tests of different targets with the optimisation of the optics could be envisaged.

4. COLLECTING LENSES

Antiprotons emerging from the target are focused and matched into the transport line with an acceptance of 200π mm·rad by a collector lens. Different collectors have been used in operation and their performances are shown in Fig. 1 [4]:

- a 20 mm diameter lithium lens pulsed with a 480 kA excitation current,
- a 34 mm diameter lithium lens pulsed at 1 MA,
- a 60 mm diameter magnetic horn pulsed at 400 kA,
- others have been used for tests:
    - a 36 mm lithium lens,
    - a plasma lens.

4.1 Lithium Lenses

A current is sent into the lithium lens [7] (which is a simple cylinder) to create the necessary field to focus the antiprotons in the bulk of the lithium. Due to the relatively slow diffusion of the fields from the outer surface towards the axis, the lens is only efficient after the peak current and, therefore, the effective current is only 80% of the peak value. The lithium is in a container and the optical efficiency is also dependent on the reabsorption and scattering of particles in the dense material of the window. The first 20 mm lithium lens developed for $\bar{p}$ production at CERN has shown a very good reliability. A 36 mm lithium lens has also been developed in collaboration with INP/Novosibirsk. Tested in the machine at 1.2 MA, it gave a higher yield than the 20 mm lithium lens by about 20% [8]. But during life tests in laboratory the stainless-steel container failed. A new 34 mm diameter lens with a stronger container has been made and operated at 1 MA. The water cooling was insufficient and the pulse current was limited at 1.0 MA to avoid pressure pulses due to partial melting of the lithium.

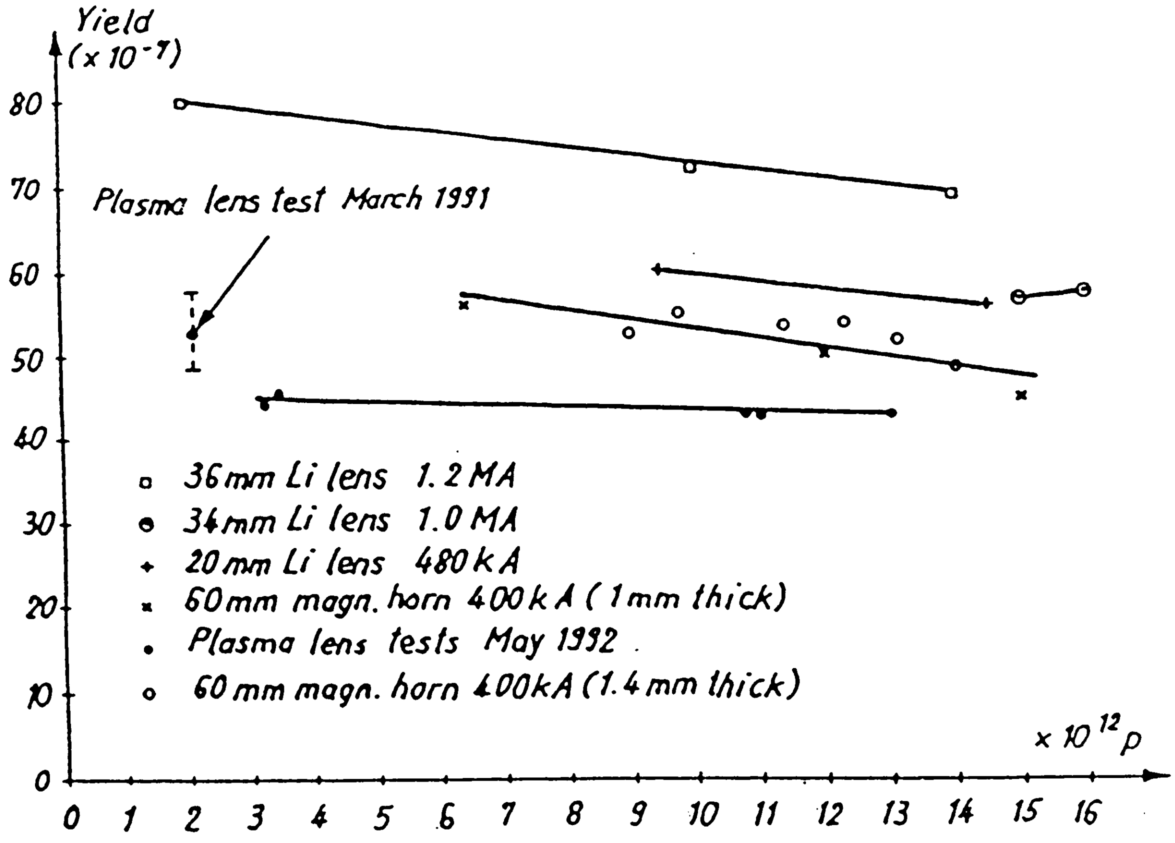

Fig. 1 - Yield vs. intensity for different collector lenses

4.2 Magnetic Horns

The magnetic horn is a simple tube of aluminium alloy designed to allow particles with different production angles to stay in the non-linear magnetic field long enough to get out parallel to the axis. Fields are used at their maximum values. The magnetic horns used in the AA were limited to 170 kA, but the biconical design [9] adopted in 1986 to build an alternative collecting lens for the ACOL project has a peak current of 400 kA. A first prototype tested in real conditions in 1988 and in the following years had a lifetime > 5 × 10^5 pulses. Other horns of similar design had insufficient lifetime. Thicker horns were built due to difficulties in finding sufficiently homogeneous aluminium alloy bars, and to mechanical stresses which had been underestimated in the first design [10]. These new horns, which proved to be reliable enough (5×10^5 pulses at 500 kA), became, and remain the main spare collecting lenses.

4.3 Plasma Lens

Initially, the plasma lens has been studied and developed as an alternative to the lithium lens to collect antiprotons. It was designed, built and tested in laboratory and in beam conditions at CERN [15, 16]. Due to the pinch effect, the current stands on the lens axis without any material support, then the fields outside and inside the plasma region can be used to focus the particles. Yields produced by the plasma lens were comparable to those of the magnetic horn. This experience was interesting but a lifetime test has not been done.

5. TARGETS AND COLLECTORS AT HIGHER CURRENTS

5.1 Lithium Lenses

The 36 mm and 34 mm lithium lenses have provided so far the highest current intensities and the highest recorded $\bar{p}$-production yields.

The maximum collected solid angle being proportional to the current when the beam goes through the lens, the argument for higher current in the 20 mm lithium lens is obvious but introduces many technical difficulties due to the higher mechanical stress and amount of heat to be removed after each pulse. The drift space between the target and the lithium lens is an important parameter. In order to collect antiprotons with a higher angle, this drift should be shortened by reducing the physical length of the collector and the current in the lens should be increased. In this case, the target could be placed closer to the collector and more antiprotons are collected. The gain in yield would be of about 10% compared to the standard lithium lens. To obtain higher yields, a current increase of the lithium lenses is necessary to focus particles with larger angles [11].

It is interesting to consider possible improvements of the 34 mm lithium lens to achieve a reliable lifetime [12]:

- A first proposal would be to connect "hydraulically" to the active lithium volume a buffer volume, capable of absorbing and reducing the pressure surges from the lens which are transmitted through the viscous lithium into the buffer.
- A second proposal would be to increase the metal temperature to the liquid state which, providing a shorter current pulse, would yield the same amount of heat as for the solid state, but would better transmit the pressure surge to the buffer.
- A third proposal would be to keep circulating in a loop the metal in liquid phase from the lens to a water-cooled heat exchanger.

In these cases, the shock impedance matching throughout lithium has to be considered.

An important laboratory work would have to be done to get a good reliability at current intensities ≥1.3 MA which would provide a gain in field of about 30% compared to the standard 34 mm lithium lens.

In Table 1 the performances of the collecting angles, the existing (Fig, 1) and possible future collectors are compared to the 400 kA magnetic horn performances [13, 14] (yield = 46×10^{-7} $\bar{p}/p$, $I_p = 1.5 \times 10^{13}$) with the present iridium target. The 400 kA magnetic horn and the 20 mm lithium lens [20] have a similar collecting angle but the lower number of antiprotons is explained by a mismatch between the magnetic horn and the injection line. The design of the line has been done with a 36 mm lithium lens and then it was not possible to get a good matching with a magnetic horn. This was not the case with the 20 mm lithium lens.

Table 1 - Performances of the collecting angles, the existing and possible future collectors

Collectors	$N\bar{p}$ (10^7)	Factor	Collecting angle (mrad)
400 kA magnetic horn*	6.90	1.0	82
500 kA magnetic horn	7.93	1.15	92
20 mm Li lens (480 kA)*	8.00	1.16	80
34 mm Li lens (1 MA)*	8.40	1.22	95
36 mm Li lens (1.2 MA)	10.07	1.46	105
Liquid Li lens (1.3 MA)	11.17	1.62	118

* Collectors used in operation

5.2 500 kA Magnetic Horn

The maximum collecting angle in a biconical horn being proportional to $\sqrt{I}$, the solid angle of collected particles is therefore proportional to the peak current, and depending on the thickness of the horn the gain in yield is proportional to the current increase. A study of 500 kA horns has shown that a maximum gain of 15 % can be expected after replacement of 400 kA horn. The performance could be improved when the design of the horn is finalised after laboratory tests.

5.3 Conducting Target

A further improvement to the target production rate is obtained by passing a pulsed current through the target at the beam passage time. Antiprotons, which are produced along the target, are then focused, thus reducing the effective target length.

The conducting target was tested in the AA in 1983 [17]. Two types of pulsed-current targets were tested in the laboratory. Both survived many thousands of pulses without beam but only a few thousands pulses in the production beam. Pre-heated before current pulsing, the lifetime under beam was improved. However, evidence accumulated that it is difficult to maintain its high-current integrity for longer than one or two weeks [18].

The study and tests of the conducting targets could be worth starting again. The 1983 design is described in Ref. [3] and could be used as a starting point for future developments. With target current pulses between 70 and 150 kA, $\bar{p}$ yields 50% higher than those of passive targets were measured, but their lifetimes were very short. The use of new techniques could increase the lifetime of such targets by minimising stresses produced by the beam and pulsed current at high operating temperatures. The pulsed-current targets [3] must withstand the magnetic pinch and the electrical heating in addition to the beam heating. The main technological problem is to find a target system which will support high currents, shocks and radiation levels for a useful lifetime of at least 10^6 beam pulses. The use of liquid targets (e.g. with liquid metal in a closed circuit or in a pre-pressurised cylinder) could also be envisaged, but, in this case, the shock impedance matching throughout the target has to be seriously considered. Effectively, initial prototypes have been built with soft, low melting metals, like iridium and tin, but due to lack of manpower and funds, they have never been tested. The AAC target area is equipped for high-radiation operation and a new technique to replace the conducting target could be envisaged with, for instance, a revolving set-up.

The improvement due to the conducting target could give a factor of 1.5.

6. STOCHASTIC COOLING UPGRADING OPTIONS FOR THE AAC

Upgrading the number of antiprotons from the target the AAC cooling systems have to be improved to profit from the increased yield. Several options are possible and will be discussed in the following.

6.1 AAC Cooling Systems (Medium Improvement Programme)

6.1.1 AAC Cooling Systems

The AAC cooling systems have been pushed rather far in their optimisation. The temperature of the movable pick-up-kicker structures is around 20-30 °K with termination resistors at about 20 °K. Small improvements are possible all along the electronic chain, but the main improvement is the complete exchange of the actual loop couplers with printed circuit versions, which might increase the sensitivity by a factor up to 1.5.

On the kicker side a significant increase in power would not be permitted by the admissible power load of the kicker structures. Other improvements could be made at the beginning of the cooling cycle where power limitation for the transverse cooling may be valid. In principle, the kicker structures could also be replaced by a printed version, but this would be more delicate as for the pick-up case, due to thermal dissipation problems.

More improvements can be envisaged with the amelioration of the AC longitudinal cooling notch filters, by using optical fibre technologies or BAW (bulk acoustic wave) elements. With a better average notch depth and precision, smaller final Δp/p values may be obtained provided there are no other limitations like the impedance of the AC ring.

During the AC cooling process, longitudinal emittances Δp/p are reduced by a factor 9 and transverse ε with 95% of the beam nearly from 160π to ~5π mm·rad (factor 32). In order to work all the time at the optimal gain (apart from power limitations at the beginning) variable attenuators which do not introduce a significant phase change in all 9 AC systems would be useful.

6.2.2 AA Cooling Systems

6.2.2.1. Pre-cooling. The pre-cooling pick-up (PU) could be realised as a printed circuit version at the cryogenic or normal temperature. This would improve the signal/noise ratio which is, however, already rather good. The printed version of the PU and kicker structures would have possibly a slightly higher coupling impedance (also valid for a printed kicker).

Cryogenic terminations are another way to improve on the noise temperature of the pick-up, in particular without rebuilding the interior of the PU tank.

Here also better notch filters are helpful, and a variable gain may be considered.

6.2.2.2. Stack Tail. As discussed above, the stack-tail PU and kicker structures could also be replaced by a printed version. Replacing the terminations of the stack-tail PU by cryogenic loads would lead to a slight improvement of cooling speed.

6.2.2.3. AA Core Systems

a) ***Transverse AA core systems.*** The basic difficulty of the transverse AA core cooling is that all systems depend on the performance of the 2-8 GHz PU consisting of 4 Faltin-type slot couplers. There are severe microwave mode problems linked to this structure, particularly in the vertical plane. A possible cure of the problem would be to remove the 2-8 PU structure and to try to improve the microwave mode performance by adding absorbing ferrite. A new 2-8 AA PU properly built with a printed version and carefully tested in laboratory would certainly be a better approach.

Another problem of the transverse system is strong common mode signals. Readjustments of the vertical position and aperture of this PU during the Spring 1994 start-up have already led to a significant improvement in cooling performance of this system. A possible further cure of the symptom is to add notch filters in order to reduce the strong revolution harmonics, in particular for the vertical system.

Cryogenic termination for this PU would not help unless 4 very symmetric preamplifiers are installed in front of the signal combining network, which finally delivers the horizontal and vertical signals.

b) ***Longitudinal AA core systems.*** The 2-4 GHz longitudinal core system works rather satisfactorily. The 2-4 GHz TWT amplifier could be replaced by a solid state version for better reliability and easier maintenance. Amongst other changes this would require new phase correctors.

All these improvements on the AC and AA cooling systems would allow us to cool and accumulate in the AA a flux of antiprotons of about 1.1×10^8 every 4.8 s.

6.2 AAC Cooling Systems (Large Improvement Programme)

If one really wants to go beyond to 1.1×10^8 $\bar{p}$/cycle, the following options can be taken into account: to double or to triple the stacking rate we would need to double or to triple the bandwidth of the cooling systems in the AC. This would require a careful evaluation of the space available in the sectors of the machine usable for stochastic cooling pick-ups and kickers. Assuming no extra section being available, one may consider building new tanks with printed pick-up and kicker structures which are supposed to be shorter by a factor 1.5 for the same sensitivity as the existing structures and covering the same frequency bands. The liberated space could be occupied by a cooling band 4 and/or 5. So far, we have AC cooling bands 1 to 3, i.e. 0.9-1.65 GHz, 1.65-2.4 GHz and 2.3-3.2 GHz. The cooling bands 4 and 5 may possibly extend up to 6 GHz. It must be noted that for the present η of the AC, these cooling bands 4 or 5 could not be used from the beginning of the cycle where $\Delta p/p$ and thus $\Delta f/f$ is too large because of excessive mixing at these high frequencies.

The same argument applies also for upgrading precooling and stack-tail systems in the AA. Technologically, printed structures up to about 7 GHz appear to be feasible in the AC machine and for the pre-cooling and stack-tail systems in the AA machine, but a large number of technical problems linked to this bandwidth extension are expected. These include microwave mode propagation and leakage in the AC and AA vacuum chamber, expensive power amplifiers and fast transmission lines across the ring with low loss and dispersion for this frequency range.

As an option one may consider using a variable η during the cooling cycle in the AC, thus a smaller value than used presently at injection and increasing η during the cycle. This should have a positive effect on all cooling systems in the AC such as increasing the mixing towards the end of the cycle and reducing the relative effect of errors in the notch filters. A detailed study is needed.

Taking into account that the number of antiprotons is increased compared to the present situation, the 4.8 s cycle is preferable to the 2.4 s cycle. The stacking efficiency is always higher when there is more time for cooling. The second reason is operational because it needs only half the PS cycles.

7. DISCUSSION

As already discussed, all improvements of the AC cooling system (medium improvement programme) and the use of a 4.8 s cycle, a stacking rate of about 1.1 × 10^8 $\bar{p}$/cycle may be achieved. This is equivalent to a stacking rate of 7.4 × 10^{10} $\bar{p}$/h. So, the improvement factor cannot be higher than a factor of 1.6 compared to the 400 kA magnetic horn performance. To go beyond this stacking rate, new cooling systems have to be installed, as described (large improvement programme).

In the stacking rate calculation, a stacking efficiency of 90% is assumed with 750 cycles per hour, which is equivalent to a cycling of 4.8 s. A stacking efficiency is defined as the number of antiprotons put into the AA stack per antiprotons injected into the AC.

Known and expected performances of the collectors are given in Table 2 with the present configuration and with the improved production beam intensity.

Table 2 - Stacking rate with the present situation
and with the improved production beam intensity

Collectors	N$\bar{p}$ (10^7)	SR (10^{10} $\bar{p}$/h)	Prod. beam intensity (×13)(10^{10} $\bar{p}$/h)
400 kA magnetic horn*	6.90	4.60	6.0
500 kA magnetic horn	7.93	5.30	6.9
20 mm Li lens (480 kA)*	8.00	5.40	7.0
34 mm Li lens (1 MA)*	8.40	5.67	7.4
36 mm Li lens (1.2 MA)	10.07	6.70	8.8
Liquid Li lens (1.3 MA)	11.17	7.37	9.6

* Collectors used in operation

The gain from the proton beam intensity and the quality improvement are of great importance for the $\bar{p}$ production. This gain of intensity of 30% together with a reduction of the proton beam radius would lead to another improvement factor. To analyse the behavior of the target in a high proton beam intensity up to 2 × 10^{13}, limited tests were done in 1987 in 20-bunch mode. It remains to be demonstrated that the target can withstand higher beam densities in operation. The technical difficulties of increasing the production beam intensity in smaller transverse emittances could contribute to the deterioration of the previous improvement factor and provide a gain below the multiplication factor of intensity. It is worthwhile to point out that the efforts already made to improve the PS beam for LHC are welcome and may play an important role for the antiproton production in the next years.

In the case that a collector with a small collection angle would be used, a longer target could be designed with a lower Z. The stacking rate could be increased by another factor of 1.2 for the 400 kA magnetic horn but by a lower factor (~1.15) for the 500 kA magnetic horn because the gain from lower Z decreases when the collection angle is increased.

Table 3 - Stacking rate increase with a longer target

Collectors	SR (10^{10} $\bar{p}$/h)
400 kA magnetic horn	7.2
500 kA magnetic horn	7.9

The conducting target is far from being operational and would therefore need a development programme. The improvement factor of 1.5 obtained during tests in the old AA with this kind of target was achieved for much smaller primary beam intensities and only for short periods of time. Technological studies and tests could start if there were a need for a large increase of the stacking rate. The possible stacking rate is shown in Table 4.

Table 4 - Stacking rate increase with a conducting target

Collectors	SR (10^{10} $\bar{p}$/h)
400 kA magnetic horn	10.9
500 kA magnetic horn	11.9
20 mm Li lens (480 kA)	10.5
34 mm Li lens (1 MA)	11.1
36 mm Li lens (1.2 MA)	13.2
Liquid Li lens (1.3 MA)	14.3

The best choice depends largely on the stacking rate needed to achieve a high luminosity. The liquid lithium lens performance in addition to the new stochastic cooling improvements give a stacking rate of 7.4 × 10^{10} $\bar{p}$/h. This value can be increased by a factor of 1.3 because of the improvement of the production beam intensity which gives a stacking rate of 9.6 × 10^{10} $\bar{p}$/h (with a conducting target, the stacking rate could be increased up to 14.3 × 10^{10} $\bar{p}$/h).

9. CONCLUSIONS

With the improvements of the antiproton production and collection, in addition to the Medium Improvement Programme of the stochastic cooling systems, the global improvement factor cannot exceed 1.6. A new stochastic cooling system with an increased bandwidth could give a global improvement factor of 2.1. The improvement of the cooling has to go hand in hand with an upgrading of the $\bar{p}$-production with advanced technology. A conducting target together with a large lithium lens could probably give not more than a factor of 3.1 compared to the 400 kA magnetic horn. It is obvious that studies and tests would be needed, and due to the lack of the personnel involved in the design, development and construction, a collaboration and co-operation contracts with other laboratories and universities could be envisaged.

ACKNOWLEDGEMENTS

The authors would like to thank C.D. Johnson, D. Möhl, F. Pedersen, P. Sievers, and L. Thorndahl for helpful discussion and valuable comments.

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