PS/AR Note 95-17
30.06.1995

SIMPLIFIED ANTIPROTON SCHEMES FOR ANTIHYDROGEN PRODUCTION IN TRAPS

S. Maury and D. Möhl

1. INTRODUCTION

In view of a possible future antihydrogen programme, simplified schemes for the production of MeV antiprotons have been studied and were presented at the antihydrogen workshop in Munich, July 1992 [1]. In this note, we update these studies taking two main developments into account that occurred during and after the workshop: The momentum favoured for transfer to the traps for antihydrogen production is now 100 MeV/c (i.e. about 5 MeV kinetic), instead of 60 MeV/c (~2 MeV) as assumed in [1]. Secondly, the proposal to use LEAR as heavy ion accumulation ring is now part of the LHC design proposal [2]. Hence we concentrate upon schemes compatible with these new boundary conditions .

Let us briefly recall the present scenario of providing low-energy antiprotons. It involves four machines (AC, AA, PS and LEAR) to collect, cool and decelerate $\bar{p}$'s in the following sequence:

1) Antiprotons, produced by 26 GeV/c protons impinging on the production target, are collected and precooled at 3.5 GeV/c in the AC.

2) They are then transferred to the AA where they are accumulated and further cooled.

3) Batches of a few 10^9 are unstacked from the AA and ejected to the PS at regular intervals (of typically one half to several hours).

4) These batches are decelerated in the PS from 3.5 to 0.6 GeV/c.

5) They are then transferred to LEAR where cooling (at 3 or 4 intermediate momenta) and deceleration alternate to bring the full flux to low energy. With electron cooling, typical emittances at 100 MeV/c are 1π mm mrad and $dp/p = 5 \times 10^{-4}$ for batches of 10^9.

It is clear that a simplification of this scheme (which was designed as an annex to the antiproton source for the Sp$\bar{p}$s) would be desirable. The fluxes, however, which can be obtained with more simple schemes, have to be estimated carefully to establish their feasibility for an antihydrogen factory.

2. SCALING RELATIONS AND ASSUMPTIONS

To scale the yield into a given acceptance we use the differential conversion rate

$$r = \frac{dN_{\bar{p}}}{(dp/p)d\Omega N_p}$$

This factor depends strongly upon the momentum of both the protons and the antiprotons (i.e. the momentum at which the antiprotons are collected). The rate curve reproduced in Fig.1 (taken from the first proposal of LEAR [3]) assumes 26 GeV/c primary protons. This is the highest momentum that the PS can safely produce. To work out the yield, we multiply the differential conversion rate by the "acceptance factor"

$$d\Omega \, . \, dp/p \sim \sqrt{A_v A_h} \; \Delta p/p$$

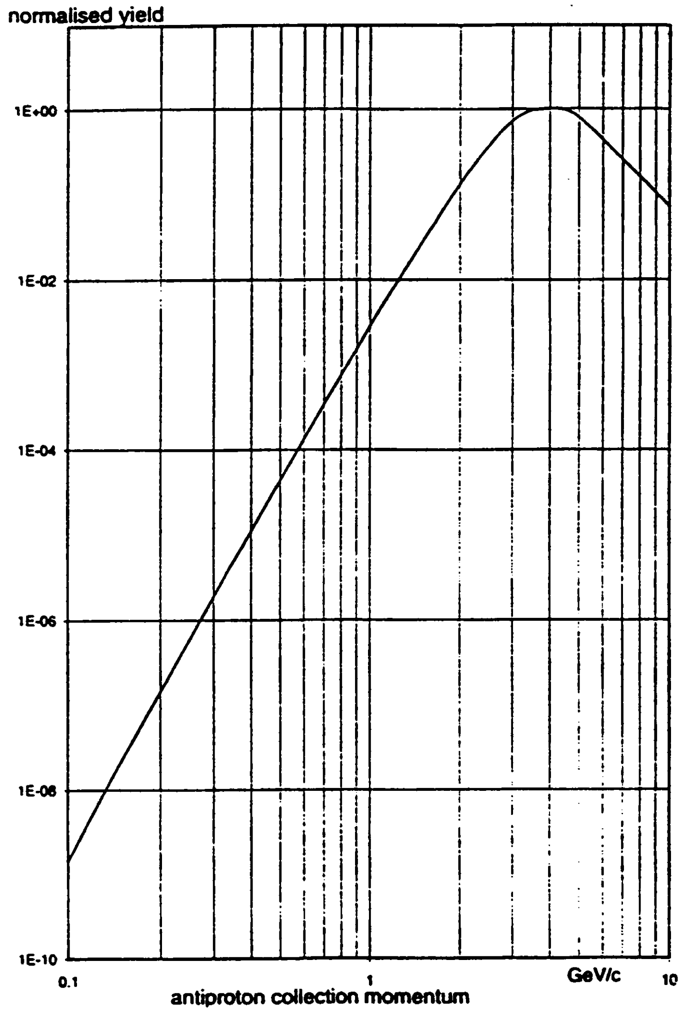

Fig. 1 : The normalised yield versus the antiproton collection momentum. For momenta below 0.6 GeV/c the curve is obtained by extrapolation of the curve published in [3].

We use the measured yield into the AC acceptance ($A_v = A_h = 200\pi$ mm·mr, $\Delta p/p = 30 \times 10^{-3}$) at 3.5 GeV/c with a production beam of 1.5×10^{13} protons/pulse, namely 5×10^{7} antiprotons/pulse, as "normalisation factor". This permits us a scaling that is accurate over a large range of collection momentum and acceptances.

For most of the schemes to be discussed below, we assume that *no stacking* of antiprotons is required. Instead we take the antiprotons produced from one PS-pulse and "transport" them to 100 MeV/c. This considerably simplifies the scenario since no accumulator ring is needed. The low-energy antiproton intensity *per second* is then (in principle) the same as with stacking. The intensity *per pulse* however is smaller (by the number of production cycles contained in the batch extracted in the accumulation schemes). This smaller intensity may be problematic both for the instrumentation in the "decelerator machine" and for the traps.

We now use the elements discussed above to make performance estimates of different schemes.

SCHEME 1 : Low-Energy Antiprotons Directly from the Target

The easiest arrangement that comes to mind would be to take the antiprotons at low energy from the production target and inject them (after further energy degradation) directly into the trap. However, one concludes from fig.1 that the production cross section drops by more than a factor of 10^8 as one goes from 3.5 GeV/c collection momentum to 100 MeV/c. Therefore even if the trap had as large an acceptance as the AC, we would expect only 1 antiproton (approximately) every 10th pulse. It is probable that some factor could be gained by degrading from a higher momentum. In addition, the length of the antiproton pulse that can be trapped is given by the length of the "catching trap" and there may be room for some debunching and the concurrent gain in momentum acceptance. But even then, the flux of antiprotons is too low by many orders of magnitude to be useful for antihydrogen production.

We note in passing that the antiproton pulse from the target fills the acceptance of the antiproton channel "in one go" so that any sort of multiturn or multi-batch injection is not efficient unless one can device fast cooling.

Table 1: Number of antiprotons per pulse produced from 1.5×10^{13} protons, collected in different scenarios.

Machine	AC	AA	LEAR
production beam momentum (GeV/c)	26	26	12-26
$\bar{p}$ collection momentum (GeV/c)	3.5	3.5	2.0
cross-section (sr. GeV/c)$^{-1}$	1.2 x 10^{-2}	1.2 x 10^{-2}	1.5 x 10^{-3}
A_h (π mm·mrad)	200	85	100
A_v (π mm·mrad)	200	85	40
$\Delta p/p$ (10^{-3})	60	15	10
$\left[\left(\sqrt{A_h A_v}\right)(\Delta p/p)\right] \Big/ \left(\sqrt{A_h A_v}\,\frac{\Delta p}{p}\right)_{AC}$	1.0	0.1	0.03
$N_{\bar{p}}$ / pulse injected	5×10^7	5×10^6	2×10^5

SCHEME 2: LEAR Alone

1) LEAR in Hall 193

This scheme, which is not fully compatible with the "boundary conditions" discussed above, is included for comparison here. The antiproton collection momentum would be at 2

GeV/c, the highest possible with LEAR. We lose a factor 8 on the production cross section but the momentum of the production beam can be reduced to 12 GeV/c instead of 26 GeV/c without loss of yield [1]. Another factor of 30 is lost because the acceptances of LEAR are smaller than those of the AC (see Table 1), thus 2×10^5 $\bar{p}$ can be injected into LEAR. Taking a deceleration efficiency from 2 GeV/c down to 100 MeV/c of 50%, 10^5 can be ejected at 100 MeV/c. The time needed for cooling and deceleration to 100 MeV/c and fast extraction would be about 1 minute before a new pulse is injected. At the injection energy, and probably at another "flat top" at about 1 GeV/c, stochastic cooling is used. Two intermediate "flat tops" at lower momentum are taken for electron cooling before final electron cooling at 100 MeV/c. The emittances at 100 MeV/c can be as low as 1π mm·mrad and $\Delta p/p = 5 \times 10^{-4}$, so the phase space density $N/(E_h E_v)(\Delta p/p)$ is many orders of magnitude higher than in the previous scheme.

One could think of LEAR being moved into building 193 (the building of the AC and AA which are obsolete in this scheme). The target area is the present one, except that the collection and the injection line should be rematched to the new momentum.

Building 193 is large enough to cover the Penning trap experiments. This scheme is attractive because the PS is then only for the antiproton production.

The lead-ion accumulation in LEAR is incompatible with this scheme.

2) LEAR in its present location

If LEAR stays in the South Hall, a new target area and a production beam line have to be built. Even in this location, the lead ion accumulation and the $\bar{p}$-deceleration are not easily compatible.

SCHEME 3: AC and LEAR

In this scenario, the antiproton collection momentum is at 3.5 GeV/c in the AC (as it is today) and the number of antiprotons collected is 5×10^7, a factor of 250 larger than with LEAR only. The antiproton beam is cooled with the present stochastic cooling systems and then two options are open :

1) LEAR in Hall 193:

The deceleration to 2 GeV/c is done in the AC. The injection energy is below the transition energy thus crossing of transition is avoided. During deceleration, the η parameter increases from +0.018 to +0.135. This large η makes a "rearrangement" of the stochastic cooling system necessary. The overlapping of the Schottky sidebands takes place from 2.5 GHz onwards. With a $\beta(= v/c)$ change of 7% the present cooling systems can be used, except the band III which extends up to 3 GHz.

The beam is injected into LEAR at 2 GeV/c. The LEAR machine is re-installed in building 193. Taking into account the deceleration efficiency in the AC (90%), the transfer to LEAR (90%), and the deceleration efficiency down to 100 MeV/c (50%), 2×10^7 $\bar{p}$/pulse are available for Penning traps. About one pulse per minute can be expected.

After having filled the traps, physics can be done for hours or days and during this period all the AC machine can be put into economy mode or switched off.

This scheme is incompatible with the lead ion accumulation in LEAR.

2) LEAR in its present location:

The AC is used at 3.5 GeV/c for collecting and cooling of the antiprotons. The transfer is done from the AC to the PS by modifying the present AA ejection line by adding 1 or 2 bending magnets. This ejection requires closer study. After the deceleration in the PS down to 600 MeV/c, the beam is ejected to LEAR. Finally, the beam is decelerated to 100 MeV/c prior to being extracted towards the traps.

Taking into account the transfer efficiency from AC to LEAR (85%), deceleration from 600 MeV/c to 100 MeV/c (50%), 2×10^7 $\bar{p}$/pulse remain for antihydrogen production. The same comment can be made as before: when the AC is not used it will be put into economy mode.

This site is compatible with the Pb-ion stacking but the necessary modifications of LEAR make this dual function difficult. The PS, in this scheme, is also needed for $\bar{p}$ transfers.

SCHEME 4 : AC Only

The present target area and the AC in its present location are used. The beam is injected at 3.5 GeV/c. After the bunch rotation, the antiprotons are cooled with band 1 only (0.8 GHz to 1.6 GHz) in order to get 5 π mm·mrad in the transverse planes and 0.18% for the final $\Delta p/p$. Then the beam is decelerated in several steps with more cooling before 100 MeV/c is achieved. The first flat top can be at 600 MeV/c where the transverse emittance is 30π mm·mrad and the $\Delta p/p = 1.1\%$.

The AC machine parameters on the central orbit at 3.5 GeV/c, 600 MeV/c and 100 MeV/c are listed in Table 2. A cooling time of about 60s is necessary to achieve 5π mm·mrad and 0.2% in the transverse plane and $\Delta p/p$ with a modest cooling system at about 150 MHz bandwidth (Table 3).

An electron cooling system would be installed in the AC for further cooling at 300 and 100 MeV/c.

Table 2 : AC machine parameters at 3.5 GeV/c, 600 MeV/c and 100 MeV/c

p (MeV/c)	3500	600	100
γ	3.9385	1.1870	1.006
β	0.9672	0.5387	0.106
f_{rev} (kHz)	1589.451	885.32	174.157
$B\rho$	11.923	2.001	0.3336
η	0.01867	0.664	0.943

Table 3 : AC cooling time at 3.5 GeV/c and 600 MeV/c

p (MeV/c)	initial $\varepsilon_{H,V}$ (π mm.mrad)	initial $\Delta p/p$ (%)	W (MHz)	Cooling time (s)
3500	200	1.5	1000	10
600	30	1.1	120	60

The flat top (600 MeV/c) used for stochastic cooling is chosen in such a way to copy or recuperate the unused hardware from the LEAR machine. During deceleration, the rf can be at various harmonics. The AA rf cavity could be used for this purpose. At low energies, a second new rf system is perhaps needed. Electron cooling is used to achieve 1π mm·mrad in the transverse plane at a $\Delta p/p$ smaller than 5×10^{-4} at 100 MeV/c suitable for the Penning trap experiments.

New experimental areas can be built inside the hall of building 193 with concrete blocks in such a way that people can stay inside the experimental areas during the $\bar{p}$-shot production.

At 3.5 GeV/c, the AC vacuum pressure is 5×10^{-9} T and the lifetime is 61 h. At low energies and in particular at 100 MeV/c, the beam lifetime will be very short. An improvement of the AC vacuum can be made because a bakeout at low temperature (150°C) has already been foreseen during the AC construction. Part of the bakeout hardware could be recuperated from the AA.

In the AC, 5×10^{7} $\bar{p}$ are injected at 3.5 GeV/c and with a deceleration efficiency of 25%, 1.2×10^{7} are available at low energy.

To provide further details, more studies will be necessary. At at first sight, however, this scheme looks attractive, compatible with all boundary conditions and capable of delivering fairly high intensities per pulse and per second.

SCHEME 5 : AA Only

The AA energy is above the transition energy so, during the deceleration, we have the disadvantage of crossing this energy unless a new optical setting with transition above the injection energy can be found. The AA is not equipped with fast cooling systems. Almost all of these systems need to be rebuilt.

Another disadvantage is that the dipoles, in particular BSTs are in the saturation and the deceleration will not be a linear scale. Assuming 4×10^{6} are injected at 3.5 GeV/c and with a deceleration efficiency of 25%, 1×10^{6} are available for antiproton physics.

SCHEME 6: Deceleration in a Synchrotron

Here we assume that the antiprotons are decelerated from the production maximum (~3.5 GeV/c) to the lowest possible energy in the PS. The limit is probably 300 MeV/c (50 MeV kinetic), but we shall assume 100 MeV/c for the purpose of comparison. No cooling is used prior to or during deceleration. The emittances then grow (at least) adiabatically and the acceptances are determined by the ejection channel and/or the synchrotron at 100 MeV/c. We estimate these acceptances to be $A_h = 100\pi$ mm·mrad, $A_v = 25\pi$ mm·mrad, $\Delta p/p = 5 \times 10^{-3}$. Scaled adiabatically, these accceptances at 3.5 GeV/c are 2.8π mm·mrad, 0.7π mm·mrad, and 0.14×10^{-3}, but we assume optimistically that a factor of 5 in momentum acceptance can be gained by bunch rotation at 3.5 GeV/c. We then obtain a yield of about 8×10^3 antiprotons per pulse at 100 MeV/c with the large emittances specified above and a pulse length of 5 µs corresponding to 1/4 of the PS circumference and $\beta = v/c = 0.1$. Only a fraction of this could be digested by the catching trap. Intermediate storage of the antiprotons at 3.5 GeV/c is necessary to "switch" the PS from production at 26 GeV/c to deceleration unless one can use another machine (e.g. SPS with some gain since the production cross section at higher energy is somewhat higher) for production. It turns out that in any case the phase space density without cooling is much too low.

3. CONCLUSION

Table 4 outlines the advantages and disadvantages of the proposed schemes. The schemes without phase-space cooling (schemes 1 and 6) do not seem feasible. Perhaps the most cost-effective scheme would be to move LEAR to building 193, if 5×10^4 $\bar{p}$/pulse with emittances of smaller than 1π and $\Delta p/p$ smaller than 5×10^{-4} are suitable for the Penning trap experiments. In this option, the possibility of lead ion accumulation in LEAR is lost.

Alternatively, the AC machine alone could be used as an antiproton source for the future antihydrogen programme. The present target area and the AC could stay in place. The machine needs a certain amount of modification mainly the addition of electron cooling but then fluxes as high as 10^7 $\bar{p}$/pulse could be hoped for. This scheme looks specially attractive to us.

REFERENCES

[1] S. Baird, J. Bosser, M. Chanel, P. Lefèvre, R. Ley, D. Manglunki, S. Maury, D. Möhl and G. Tranquille, *Production of MeV Antiprotons*, CERN PS/93-06 and *Proceedings of the Anti-Hydrogen Workshop*, Munich, Germany, 1992, (J. Eades, ed.), *Hyper-Fine Interactions, Vol.76, 1993, p.61.*

[2] LHC Study Group, *The Large Hadron Collider Accelerator Project*, CERN/AC/93-03.

[3] U. Gastaldi, K. Kilian and D. Möhl, *Deceleration of Antiprotons for Physics Experiments at Low Energy (A Low-Energy Antiproton Factory), Proceedings of 10th International Conference on High-Energy Accelerators*, Protvino, 1977.

TABLE 4

Option	Advantages	Disadvantages	Intensity available at 100 MeV/c	
			per pulse	per second
Lear - Scheme 2, 1 (in building 193)	- Target area conserved - Ony 1 machine involved for $\bar{p}$ - Traps in building 193 - Physics independent of the PS	- $\bar{p}$ collection to be redone - Moving Lear - Incompatible with Pb-ion	10^5	2×10^3
Lear - Scheme 2, 2 (in the South Hall)	- LEAR in its present location - Physics independent of the PS	- Rebuild target area - New production beam	10^5	2×10^3
AC and Lear - Scheme 3, 1 (both in building 193)	- Physics independent of the PS - No change $\bar{p}$ production	- 2 machines involved - Deceleration in AC to 2 GeV/c	2×10^7	4×10^5
AC and Lear - Scheme 3, 2 (present situation)	- No changes necessary	- 3 machines involved - Modify AA ejection line - PS also used for $\bar{p}$-transfer	2×10^7	4×10^5
AC - Scheme 4 (building 193)	- Physics independent of the PS - No change $\bar{p}$ production	- Deceleration in AC to 100 MeV/c - Low-energy cooling needed	1.2×10^7	2.5×10^5
AA - Scheme 5 (building 193)	- Physics independent of the PS - No change $\bar{p}$ production - Stacking possible	- Transition energy crossing - Dipoles in saturation - Deceleration in AA to 100 MeV/c - Low-energy cooling needed	1×10^6	2×10^4