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PRODUCTION OF MEV ANTIPROTONS

S. Baird, J. Bosser, M. Chanel, P. Lefèvre, R. Ley, D. Manglunki, S. Maury,
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INTRODUCTION

Antihydrogen production and spectroscopy is one of the key subjects for a possible future low-energy physics programme. The production of MeV antiprotons to be stored in Penning traps after the necessary post-deceleration or energy degradation is the determinant element which justifies considering the antihydrogen activity around the existing CERN low-energy antiproton facility.

The basic scheme using 105 MeV/c antiprotons, degraded at the trap entrance is now used by the experiment PS196 at LEAR for antiproton storage in a Penning trap. Recently beams at a momentum as low as 61 MeV/c have been extracted from LEAR. This is smaller than the design limit of 100 MeV/c. The limitations of these schemes will be analysed. The expected performances of a fast extraction of bunched beams at 105 and 61 MeV/c for multibatch filling of Penning traps will be indicated.

The fast extraction by kicking out a part of the coasting beam will also be considered. This is a conceptually simple scheme but it requires new hardware. We consider it as an option in case of difficulties with the electron cooling of bunched beams. The essential hardware for this operation is the electron cooling; its performance and foreseen developments will be presented.

A look at the alternative of replacing the present cascade (AC, AA, PS, LEAR) by a single dedicated machine will convince us that LEAR, associated to the present antiproton source, fits the demands of a future antihydrogen physics programme well. As the antiproton production at the PS drops very steeply for antiproton energies below 3 GeV, simpler schemes are not well suited to provide the desired fluxes.

1. LIMITATIONS TO STORED BEAM INTENSITY AT VERY LOW ENERGY IN LEAR.

In its original idea, LEAR was conceived to decelerate the antiprotons to 100 MeV/c [1]. The low-energy range has been extended down to 61.2 MeV/c (2 MeV kinetic energy) to facilitate the post deceleration to keV energies in a radio-frequency quadrupole, a cyclotron or a similar decelerating structure. In this low-energy domain, two conflicting effects limit the intensity in LEAR; on one hand the acceptance limitations require small emittances and therefore strong cooling, on the other hand the space-charge effects and other blow-up mechanisms tend to lead to large emittances. These effects are strongly energy- and intensity-dependent and it is increasingly difficult to find acceptable equilibrium at low energy and high intensity.

1.1 Definitions

For a quantitative description of the beam density limitations we recall some basic relations:

- The emittances are defined as surfaces in the phase planes, with beam size ($2\sigma_x$) and divergence ($2\sigma_{x'}$)given by twice the rms width of the projected distributions:

$$\varepsilon_x = \pi 2\sigma_x 2\sigma_{x'} = \pi \frac{(2\sigma_x)^2}{\beta_x}$$

$$\varepsilon_z = \pi 2\sigma_z 2\sigma_{z'} = \pi \frac{(2\sigma_z)^2}{\beta_z}$$

$$\varepsilon_\ell = \pi 2\sigma_p 2\sigma_s$$

  where β_x and β_z are the lattice parameters, $\sigma_p = \sigma(\Delta p/p)$ and σ_s are respectively the rms values of the distribution of the momentum and the longitudinal position inside the bunch.

- In an adiabatic process, for example deceleration without cooling, the normalised emittances are invariant:

$$\varepsilon_x^* = \beta\gamma\varepsilon_x$$

$$\varepsilon_z^* = \beta\gamma\varepsilon_z$$

$$\varepsilon_\ell^* = \pi 2\sigma_E 2\sigma_t = \frac{E_0}{c}\beta\gamma\varepsilon_\ell$$

  Here $\sigma_E = \sigma(\Delta E)$ and $\sigma_t = \sigma(\Delta t)$ are the rms values of the projected distribution of energy spread and position in the bunch, where the distance from the bunch centre is expressed by the time $\Delta t = \Delta s/\beta c$ rather than by the longitudinal position Δs, and $\beta = v/c$, $\gamma = E/E_0$, $\beta\gamma = cp/E_0$ are the relativistic parameters.

- The bunching factor is defined as the ratio between the mean and the peak intensity:

$$B_f = \frac{\langle I \rangle}{\hat{I}} = \frac{\sqrt{2\pi}}{4}\frac{4\sigma_s}{2\pi R}h$$

($B_f = 1$ for coasting beams). $2\pi R$ is the machine circumference and h is the harmonic number.

1.2 Acceptance Limitations

In addition to the limitation given by the size of the vacuum chamber of the ring, there is a more severe physical acceptance limitation imposed by the aperture of the extraction channel: $\varepsilon_{x,z} < 9\pi$ mm·mrad, $2\sigma_p < 2 \times 10^{-3}$

A small emittance of the extracted beam is also desired to obtain small spot sizes on the degrader (to reduce non-linear and chromatic effects).

The dynamic acceptance of the machine - i.e. the largest beam size for which long-term stability exists - is smaller than the physical acceptance. This is due to multipole fields in the magnetic elements which cause unstable motion of particles having transverse oscillation amplitudes above a certain limit. These effects are amplified during the deceleration because of the impossibility at very low energy to have a perfect synchronisation between the rf and the magnetic field programmes with the consequence that the decelerated beam does not move in the centre of the vacuum chamber. This radial error causes excitation of non-linear transverse resonances. In addition field errors tend to become more significant at low energy.

1.3 Limitations Due to Intra-Beam Scattering (IBS)

Coulomb scattering between beam particles can convert energy from the common longitudinal motion into transverse and longitudinal energy spreads, thus leading to beam blow-up. An equilibrium is reached when the emittances are such that the growth time due to IBS is equal to the electron cooling time: $\tau_{IBS} = \tau_{EC}$. A computer program indicates for $N = 3 \times 10^9$, at cp = 61.2 MeV/c, equilibrium with $\varepsilon_x = 5\pi$ mm·mrad, $\varepsilon_z = 3\pi$ mm·mrad, $2\sigma_p = 5 \times 10^{-4}$ for cooling times of $\tau_{EC}^{\perp}$ = 10 s (transverse planes) and $\tau_{EC}^{\parallel}$ = 1 s (longitudinal plane). These cooling times correspond to the present performances of the LEAR electron cooler.

A crude approximation for the growth rate due to IBS is given by [2, 3]:

$$\tau_{IBS}^{-1} \approx \frac{c r_p^2}{\varepsilon_x \varepsilon_z \varepsilon_\ell} \frac{N}{m} \frac{1}{\beta^3 \gamma^4}$$

Here N is the total number of particles, m the number of bunches, c the velocity of light and r_p the classical proton radius. Using normalised emittances this can also be expressed as:

$$\tau_{IBS}^{-1} \cong \frac{N}{m \varepsilon_x^* \varepsilon_z^* \varepsilon_\ell^*} \frac{1}{\gamma}$$

One notes that the growth rate is independent of the bunching factor and - for constant normalised emittances - only weakly depends on energy ($\gamma = 1$ in the low-energy range). Thus the IBS will limit the emittance on flat-top during cooling when the normalised emittances decrease, but it will not change during deceleration where these emittances can only grow - or ideally stay constant.

1.4 Space-Charge Limitations

The space-charge detuning leads particles to cross resonances. This effect is quantified by the incoherent tune shift [4]:

$$\Delta Q_z = r_p \frac{N F_1 G}{\varepsilon_z\left(1+\sqrt{\varepsilon_x/\varepsilon_z}\right)} \frac{1}{\beta^2 \gamma^3} \frac{1}{B_f}$$

where F_1 is the effect of the beam image currents in the vacuum chamber ($F_1 \approx 1$ at low energy), and G is the transverse distribution factor: $G = 1$ for constant projected distribution (Laslett tune shift), $G = 2$ for a Gaussian distribution.

One notes that $\Delta Q_z \equiv N/\left(\beta \gamma^2 \varepsilon_z^* B_f\right)$ increases strongly during deceleration of the bunched beam. Experience suggests that the following Laslett tune shifts cannot be exceeded without considerable beam blow-up: $\Delta Q < 0.01$-0.015 in storage rings where the beam circulates for a very long time, and $\Delta Q < 0.3$-0.5 in synchrotrons where the beam is rapidly accelerated so that large tune shifts prevail for only a few milliseconds. At 61.2 MeV/c in LEAR, with the equilibrium conditions of (1.3), ΔQ_z (Laslett-coasting) = 0.05, to be compared with 0.01 accepted in the ISR (storage ring limit). During deceleration with $B_f = 0.5$ and Gaussian transverse distribution: ΔQ_z (bunched) = 0.2, which is already close to the accelerator limit.

1.5 Coulomb scattering on the residual gas

This effect increases strongly at low energy: the emittance growth rate (small angle scattering) is given by [5]:

$$\frac{d\varepsilon_{x,z}}{dt} \approx \frac{0.61\, R P_{MS}}{Q_{x,z} \beta^3 \gamma^2} \quad [\pi \text{ rad·m/s}],\ R \text{ in meters and } P_{MS} \text{ in Torr.}$$

The mean pressure P_{MS} (2×10^{-12} Torr) in LEAR is low enough to give a small multiple scattering effect in the presence of electron cooling. Nevertheless, a good vacuum is a necessity at very low energies because large angle scattering, which increases in a similar way for low-beam energy, will then lead to a beam lifetime limit which cannot be improved by cooling.

1.6 Instabilities

To avoid coherent beam instabilities (transverse and longitudinal), one requires low impedances, as seen by the beam. The coherent transverse instabilities are counteracted by a feedback system. This "damper" is an essential tool to conserve the dense LEAR beam.

In the longitudinal plane, short circuits on the gaps of the rf cavities, which otherwise present a large impedance, are needed to keep the coasting beam stable.

Machine experiments are still necessary to study the behaviour of bunched beams in the presence of strong electron cooling. Care has been taken in the design of LEAR to keep the impedances of the beam environment small and to work below transition energy where beam stability conditions (including IBS) are more favourable [6]. Work is going on to identify and reduce parasitic coupling impedances.

2. INTENSITY LIMITATIONS

2.1 Present Limitations

Taking into account the limiting factors listed in Ref. [4], we can estimate the intensity limits as a function of beam momentum and emittance (Table 1) and compare them with the values reached in operation (Table 2).

Table 1

Maximum permissible intensity for two extreme sets of equilibrium emittances
Theoretical limits.

cp	MeV	200		105		61.3	
T	MeV	21.1		5.9		2	
ε_x	π mm·mrad	10	2	10	2	10	2
ε_z	π mm·mrad	10	2	10	2	10	2
$2\sigma_p$	10^{-3}	1	0.5	1	0.5	1	0.5
$\tau_{IBS} = \tau_{EC}$	s	360	36	200	20	100	10
$\hat{N}$ debunched	10^9	40	8	10	2	3.5	0.7
$\hat{N}$ bunched ($B_f = 0.3$, $\Delta Q_{sc} = 0.02$)	10^9	12	2.4	3	0.7	1	0.2

Table 2 - Maximum coasting beam intensity on three different flat tops, operational conditions

cp	MeV	200	105	61.3
ε_x	π mm·mrad	<5	5	<10
ε_z	π mm·mrad	<5	5	<10
$2\sigma_p$	10^{-3}	0.5	<1	1
$\tau_{EC}^{\perp}$	s	10	10	10
$\tau_{EC}^{\parallel}$	s	1-3	1-3	1-3
$\hat{N}$ debunched	10^9	9	3	1

The intensity presently reached on 105 or 61.3 MeV/c flat tops is independent of the intensity of the cooled beam before the deceleration and a great part of the losses occur during the deceleration. This indicates that the limits are given by the space-charge forces of the bunched beam associated with the dynamic acceptance limitations [4].

The present intensity of coasting beams is only a factor 2 from the theoretical limit. To gain the missing factor, two series of improvements have to be worked out:

- improvement of the deceleration process and resonance compensation to increase the dynamic acceptance.
- reduction of the density effects by the programming of a more flexible electron cooling (new gun) so both too small and too large equilibrium emittances can be avoided

2.2 Multibatch Extraction Scheme

Already in recent runs the decelerated intensity was large enough to reach the limits for the bunched beam. The operation in a multibunch, fast extraction mode can be envisaged provided that the necessary machine studies and tests demonstrate that this mode is operable; in particular that strong electron cooling permits us to keep the bunched beam on the extraction flat top stable for a sufficiently long time (1-2 minutes) to perform several fast extractions.

In this mode the beam is bunched to a harmonic number (h) which provides enough distance between bunches for the rise and fall of the extraction kicker (100 ns) and with sufficient bunch length (rf voltage) to have a good filling of the trap.

The length of the extracted pulse is an important parameter. Table 3 shows possible parameters for two pulse lengths: 500 ns (long trap) and 200 ns (present situation). Two cases are considered in Table 3 for the equilibrium emittances resulting from IBS and cooling. They correspond to stronger or weaker electron cooling. The same maximum acceptable space-charge effect is assumed in both cases on the extraction flat top.

Table 3 - Multiple fast extraction intensities available at 105 and 61.3 MeV/c

cp	MeV	105		61.3	
Bunch length	ns	200	500	200	500
Number of bunches	*h*	4	2	8	4
Bunching factor B_f		0.2	0.3	0.3	0.3
Ntotal[1] decelerated-debunched	10^9	1.1 to 2.2	1.4 to 2.8	0.4 - 0.9	0.5 - 1.1
N ejected/bunch[2]	10^8	2.2 to 4.4	5 to 11	0.5 to 0.9	1.1 to 2.2
Cycle duration[3]		~5'	~4' 30"	~7'	~6'
$\hat{N}$ ejected/hour	10^{10}	1 to 2	1.5 to 3	0.3 to 0.6	0.5 to 0.9
NAA/hour[4] taken from AAC	10^{10}	2.3 to 4.6	3 to 6	1 to 2	1.2 to 2.4

The extraction uses the existing machine set up and can be tested now and enhanced with the improvement of the electron cooling (variable current gun) foreseen for next year (see par. 3).

2.3 Alternative extraction scheme

In case of difficulties of the previous scheme one can think of fast extraction by kicking out a piece of a coasting beam. For this purpose a new electrostatic septum has to be built with a rise and fall time of 10 ns, small compared to the filling length of the trap, and with a flat top adjustable between 200 and 500 ns. A slice of coasting beam is repeatedly extracted. To keep the extracted intensity per pulse constant, an rf voltage is applied on harmonic 1 prior to extraction to bunch the required intensity. In this way ten batches can be extracted with an overall efficiency estimated at 50%. This scheme has the advantage of keeping the space charge effect at its coasting beam value, but losses due to kicker rise and fall are unavoidable.

1) Two cases of equilibrium emittances: strong cooling: $\varepsilon_h = \varepsilon_v = 5\pi$ mm·mrad; softer cooling: $\varepsilon_h = \varepsilon_v = 10\pi$ mm·mrad.

2) Extraction efficiency assumed around 80%.

3) LEAR synchronised on 14.4 seconds PS super cycle, the cooling between two batches in Penning trap being of the order of 10 seconds.

4) Efficiency of transfer and deceleration ~60% at 105 MeV/c and ~50% at 61.3 MeV/c.

2.4 Antiproton production

The present production limit is 1.2×10^{10} antiprotons per hour per production cycle of 4.8 seconds, thus permitting to use every other of the 2.4 seconds PS cycles at maximum. The repetition rate is limited by the AC stochastic cooling. The present target system associated with a magnetic horn will be able to insure a production of 10^7 antiprotons/second, using three production cycles during a 14.4 seconds PS super cycle. Such a scheme is compatible with most of the expected PS operations.

Nevertheless, for some busy periods where the PS has to serve several users, including frequent transfers from AAC to LEAR, one might be obliged to accept two production cycles per 14.4 seconds, thus limiting the production to $2.4 \times 10^{10}\,\bar{p}$/hour. We assume this rate is still compatible with the requirements of the low energy users, provided good deceleration and extraction efficiencies can be reached (overall 25%-50% from AA to end of beam line).

3. DEVELOPMENTS OF THE ELECTRON COOLING DEVICE

The LEAR electron cooling device is now used routinely for low-energy antiproton operations. It has undergone a number of major upgrades, the two most important being the conversion of the control system to a workstation based system similar to that of LEAR and the construction of a new electron beam collector for the efficient recuperation of the high intensity electron beam, 2.5 A at 28 keV.

Several operational modes have been foreseen for use on the deceleration cycle, but it is the so-called "pulsed-mode" which has been adopted. In this mode the accelerating voltages, applied to the cathode and the anodes, and the solenoid current are put on for 10 s on the 309, 200 and 105 MeV/c flat-tops of the normal LEAR cycle. At 61.2 MeV/c the cooler remains on during the extraction process in order to maintain a good beam lifetime. The voltages of the collector and the repeller as well as the coils at the entrance and the exit of the collector remain at fixed values throughout the cycle, whilst the currents of the correction coils are ramped, following the LEAR magnetic cycle. In this way the field of the solenoid does not perturb the beam during the actual deceleration.

Using electron cooling in this manner, the overall duty cycle of the machine is significantly improved along with an increase in the beam lifetime (especially at lower energies) and a substantial reduction of the transverse and longitudinal emittances is obtained. When the cooler is properly optimised (well aligned electron and antiproton beams, electron beam energy set correctly, etc.), transverse emittances are usually under 2π mm·mrad with a momentum spread $2\sigma_p = 2.5 \times 10^{-4}$. The cooling times also depend very much on whether or not the beams are well aligned and are typically of the order of a few seconds for complete cooling in all three planes.

During the cooling process the beam density increases very rapidly and once it reaches a given threshold it will become unstable and perform coherent betatron oscillations. The feedback system developed to counteract these coherent transverse instabilities consists of a pickup system used for the detection of the instability and a kicker system placed at an odd number of quarter betatron oscillation wavelengths away from the pickup. The observed signal is then linearly amplified, delayed and applied to the kicker. The bandwidth of the system is determined by the number of modes to be corrected and the gain by the growth rate of the instability. In our case a band from 70 kHz to 70 MHz is necessary in order to cover the first 20 modes of the whole energy spectrum of LEAR. To maintain damping during energy ramping a closed-orbit suppressor (COS) has also been developed. This is needed for the suppression of the strong coherent signal observed when a bunched beam is not properly centred in the pickup.

For the near future we are developing, in collaboration with INP-Novosibirsk and CAPT-Lipetsk, a new variable intensity electron gun. This will open up the possibility of having an electron cooling "à la carte" where the beam characteristics and the cooling times could be modified by simply varying the electron beam intensity. The performance of the cooler will be improved as the new gun is designed to operate with electron currents of up to 3 A even at the lower energies, which is not possible with the present gun.

4. A DEDICATED FACILITY

The present scheme of providing low-energy antiprotons involves the following steps:

- 26 GeV protons from the PS are ejected onto the conversion target;
- antiprotons are collected and precooled in the AC ring at 3.5 GeV/c (near the production maximum);
- they are then transferred to the AA where stacks up to 10^{12} $\bar{p}$ are accumulated;
- batches of 10^9 to 10^{10} antiprotons are skimmed off from the AA at regular time intervals (15 min to several hours);
- these batches are decelerated in the PS from 3.5 to 0.6 GeV/c;
- they are then transferred to LEAR where they are re-cooled and decelerated to low momenta.

The question has been raised as to the efficiency of a much simpler scheme dedicated to the low-energy use only. In principle, an "all-in-one" scheme could then be used where $\bar{p}$ collection and deceleration are done in one single ring. Two extreme cases to be discussed below take either LEAR itself for $\bar{p}$ collection and deceleration, or an "AA-type", 3.5 GeV/c, ring with very large acceptance.

To compare the rates available at low energy we have to look at the scaling of conversion cross section with $\bar{p}$ energy and $\bar{p}$ yield with the acceptance of the collector ring accumulation rate. Some values of the normalised production cross section are compiled in Table 4 which exhibits the well-known, very fast drop-off for energies below the optimum $\bar{p}$ momentum. To compare the yield into given transverse (A_h, A_v) and longitudinal (Δp) acceptances we use:

$$\frac{N_{\bar{p}}}{N_p} \propto \sqrt{A_h A_v}\,\Delta p$$

Table 4

Scaling of conversion cross section.
Differential production cross section $\sigma = (d^2N_{\bar{p}}/d\Omega dp)/N_p$ (Ref. [7])

Proton momentum GeV/c	Optimum $\bar{p}$ momentum GeV/c	Corresponding cross section $(sr.GeV/c)^{-1}$	Cross section at 2 GeV/c $(sr.GeV/c)^{-1}$	Cross section at 0.6 GeV/c $(sr.GeV/c)^{-1}$
30	5	1.5×10^{-2}	1.5×10^{-3}	1.0×10^{-6}
26	3.5	1.2×10^{-2}	1.5×10^{-3}	1.0×10^{-6}
12	2	1.5×10^{-3}	1.5×10^{-3}	1.0×10^{-6}

Remarks:
- Going from 3.5 to 2 GeV/c antiproton collection energy one loses about a factor of 8 in conversion cross section; going to 0.6 GeV/c one loses 10^4 !
- If collection is to be at 2 GeV/c one may as well use only 12 GeV/c instead of 26 GeV/c primary protons.

Based on this simplified scaling, Table 5 gives acceptances and relative yields for four scenarios: the present scheme (ACOL), the AA only and LEAR at its maximum (2 GeV) or its present injection momentum. One observes that the "AA only" loses a factor of 10 (this is exactly the ACOL/AA improvement), LEAR loses already a factor of 30 to 100 merely due to the smaller acceptances. To scale the duty cycle, we estimate that

- a dedicated ring would need about 50 s for cooling/deceleration to 100 or 60 MeV/c and fast extraction, before a new pulse can be accepted. With slow extraction the loss in accumulation time would be even larger since no antiprotons can be stored during extraction.
- ACOL can accept beam from the PS once every 4.8 s.

Thus, due to the smaller duty cycle, the one-ring scheme loses (at least) another factor of 10 in the rate of low-energy antiprotons.

In Table 6, these factors are taken together to scale the fluxes to be expected in different variants of the simplified scheme. One notes that even in the most favourable one-ring scheme ("D-AA") two orders of magnitude are lost in the flux ($\bar{p}$/s) and three to four in the intensity per pulse. With a "LEAR-only" scheme the loss is even more dramatic. A scheme using AA plus LEAR might give acceptable rates but instead it is probably advisable to run the existing ACOL scheme in an economy mode with fewer production cycles.

Table 5

Scaling with acceptances assuming that the yield scales with the transverse and the momentum acceptances of the corrector ring as $N_{\bar{p}}/N_p \propto \sqrt{A_h A_v}\ \Delta p$

		ACOL	AA	D-LEAR
P	GeV/c	3.5	3.5	2 (0.6)
A_h	π mm·mrad	200	85	100
A_v	π mm·mrad	200	85	40
$\Delta p/p$	10^{-3}	30	7.5	5
Δp	MeV/c	105	26	10 (3)
$\sqrt{A_h A_v}\ \Delta p$	MeV/c	1*	0.1	0.03 (0.01)

Remark: Due to the smaller acceptances a "LEAR-type" collector/decelerator loses a factor of about 30 to 100 compared to ACOL

Table 6 - Yields at 60 MeV/c taking all factors together

	ACOL + LEAR (3 rings)	AA + LEAR (2 rings)	D-AA[1] (1 ring)	D-LEAR 2 GeV/c (1 ring)	D-LEAR 0.6 GeV/c (1 ring)
Limits for $\bar{p}$ collection					
$\bar{p}$/pulse accepted	5×10^7	5×10^6	5×10^6	2×10^5	5×10^2
Time between pulses [s]	4.8	4.8	50	50	50
Limits at 60 MeV/c					
$\bar{p}$/pulse circulating	3×10^9	3×10^9	5×10^5	2×10^4	20
	Beam intensity limit		Production limit		
$\bar{p}$/s extracted[2,3]	10^6	10^5	10^4	4×10^2	0.4 (!)
	Production limit				

1) Collection and deceleration in a 3.5 - 0.06 GeV/c ring with AA acceptances

2) 10% overall efficiency from collection to 0.06 GeV/c extraction

3) Fast extraction

CONCLUSION

LEAR is not far from the theoretical intensity limitations at ultra-low energies. After installation of the proposed improvement, the machine will be ready for multibatch filling of Penning trap dedicated to anti-hydrogen production. An essential part of this improvement programme concerns the new design of the electron cooler, which is well under way.

The solution of using a dedicated machine to replace AC, AA, PS and LEAR would lead to a loss of several orders of magnitude in the available intensities.

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