DECELERATION OF ANTIPROTONS FOR PHYSICS EXPERIMENTS AT LOW ENERGY
(A LOW ENERGY ANTIPROTON FACTORY)

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1. Introduction

Experiments using low energy antiprotons at the CERN PS[1] and elsewhere[2] are limited by the rates and the momentum resolution obtainable in standard $\bar{p}$ beams (Table 1). The aim of this paper is to work out the relative merits of a small 4 to 0.1 GeV/c antiproton decelerator synchrotron - similar to the "shuttle ring"[3] proposed to speed up phase-space cooling of $\bar{p}$ beams for the SPS. We conclude that even without cooling a large factor in intensity of low energy beams could be gained. If in addition (as proposed by Rubbia[3] and first considerated in the present context by Skrinsky et al.[4]) deceleration is combined with cooling, another large improvement in beam density would result. This could open quite new possibilities of fixed target experiments with sharply collimated $\bar{p}$ beams. Furthermore one can hope for luminosities which make high precision $\bar{p}$-p and $\bar{p}$-A experiments[5] with stored beams possible.

2. Antiproton production at the PS

In order to compare a standard beam line and a decelerator, we estimate the $\bar{p}$ production by 23 GeV/c protons impinging on a lead target[6] (Fig. 1). As usual, the $\bar{p}$ rate is given per interacting proton. Here we normalize to a phase-space volume $v = |1\,\mathrm{msr}| \times [\pm 1\%(\Delta p/p)]$ since for this choice the rate accepted by a magnetic beam line, which has constant v independent of momentum, is directly proportional to the reading on the curve.

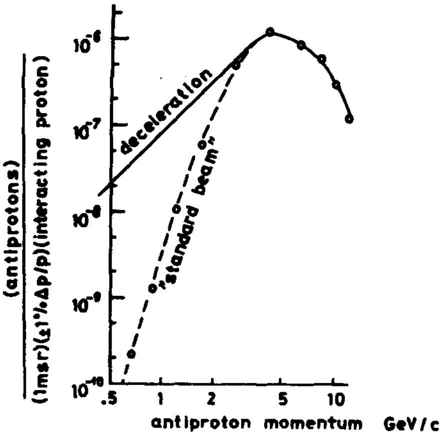

Fig. 1. Production of antiprotons at 0° on lead by 23 GeV/c protons[6]. The number of $\bar{p}$ per interacting proton is normalized to 1 msr solid angle and ±1% momentum bite. Below 4 GeV/c the curve is estimated by "kinematic reflection"[7]. The straight line shows the expected phase-space density of antiprotons ($v \propto p^2$) in a deceleration synchrotron (without bunch rotation or phase-space cooling).

The values above 4 GeV/c in Fig. 1 are measured[6]. Since, to our knowledge, there are no comparable low-energy measurements available, the corresponding branch of the curve is calculated assuming symmetry of the $\bar{p}$ production as in the nucleon-nucleon centre-of-mass system. This approximation, known as the "reflection" method[7], is exact for a hydrogen target.

In the standard beam (Table 1), the $\bar{p}$ are collected at an energy close to the working energy of the experiment. The expected yield is therefore given by the dashed line of Fig. 1. In order to get reasonable rates at low momentum one has to accept the largest possible phase-space volume. This results in well-known experimental problems : beam lines and spectrometers become bulky and expensive and targets have to be large in volume since one has to accept big beam cross-sections, big divergencies and large momentum spreads. The detector systems have to match the large targets in size and complexity. The poor $\bar{p}$ separation and the big target- and detector volumes can cause severe background problems. The lower the energy the more difficult it becomes to find a compromise between $\bar{p}$ intensity and beam quality.

In the decelerator, antiprotons are captured at high momentum where density and rate are optimal. During deceleration the horizontal and vertical beam emittances E_h, E_v and hence $\Delta\Omega \propto \sqrt{E_h E_v}$ increase as 1/p. The same is true for the relative momentum spread. Hence, ideally, the phase-space density N/v will decrease like $p^2/p^2_{injection}$. This is shown as the solid line in Fig. 1. Actually by RF gymnastics and/or by phase-space cooling, this loss of density can be reduced or overcome. However it is concluded from Fig. 1 that even without these techniques, the decelerator compares favorably at low momentum.

Table 1 : Some low energy $\bar{p}$ beams

Beam	CERN k_4	 k_{18}	 m_{14}	Brookhaven C2,4
Target	Beryllium (internal)	Beryllium (internal)	Beryllium (internal)	Iridium (external)
Production angle (mrad)	260	300	360	180
Proton Energy (GeV)	19.2	23	23	28
Protons on target	10^{11}	7×10^{11}	6×10^{11}	10^{12}
Solid angle (msr)	0.50	3.3	6.4	2.65
Momentum bite (±%)	1	1.5	1.8	1
$\bar{p}$ flux per burst				
at : 1.2 GeV/c	220			
1.0 GeV/c	64			
0.9 GeV/c		1800	6000	
0.8 GeV/c	16			
0.75 GeV/c				7500
0.7 GeV/c	6.8			
0.6 GeV/c	1.8			

3. Some features of the decelerator

The decelerator tailormade to our purpose is a, say, 4 to 0.1 GeV/c synchrotron with characteristics similar to the $\bar{p}$ rings which have been proposed for the ISR[9] or the SPS[3] : large acceptance; powerful RF system for debunching (bunch rotation) and deceleration; possibly stochastic precooling and postcooling by electrons (as suggested by Rubbia[3]).

Clearly the "shuttle ring"/3/ proposed as part of a dense antiproton source for the CERN SPS can be used for our purpose if extraction into an experimental area is incorporated. Some typical parameters (from ref. 3) are given in Table 2. Note that this ring can deliver $\sim$ 2-5 x 10^7 $\bar{p}$ per PS pulse (10^{13} protons) at all energies between 3.5 and 0.4 GeV/c. Although the density decreases during the deceleration procedure, the number of antiprotons remains constant because the acceptance of the ring is much larger than the acceptance of the injection system.

As a second example we assume that the experimental cooling ring (ICE) now under construction at CERN is converted into a $\bar{p}$ decelerator at some later stage. This implies the installation of a conversion target in the beam line, the addition of RF and ejection equipment to the ICE ring as well as "pulsed" operation

Table 2

Examples of a decelerator

Machine	"Primitive Machine"		Optimized Machine	
	"ICE"	"upgraded ICE"	"shuttle ring"	"lower energy shuttle"
Radius (m)	12	12	25	25
Momentum(GeV/c)	2.1-0.3	3.2-0.1	3.5-0.45	3.5-0.1
Injected beam*): p/p	± 3 °/oo		± 30 °/oo	
E_h (mrad. mm)	12π		28π	
E_v (mrad. mm)	30π		28π	
$\Delta p/p$ after bunch rotation	± 1 °/oo		± 6°/oo	
Acceptance inside ring:				
$\Delta p/p$	± 3 °/oo		± 40 °/oo	
E_h (mrad. mm)	80π		230π	
E_v (mrad. mm)	45π		230π	
Conversion $\bar{p}/p$ *) **)	0.7×10^{-7}	1.5×10^{-7}	25×10^{-7}	
Solid angle accepted*) (msterad)	1.3		2	
No. of protons/pulse used	2×10^{12} (1 bunch)	10^{13}? (5 bunches)	10^{13} (5 bunches)	
No. of $\bar{p}$/pulse at:				
3 GeV/c	-	1.5×10^{6}	2.5×10^{7}	
2 "	1.5×10^{5}	"	"	
1 "	1.3×10^{5}	1.1×10^{6}	"	
0.45	6×10^{4}	3.5×10^{5}	"	
0.3 "	3.5×10^{4}	1.5×10^{5}	-	1.1×10^{7}
0.1 "	-	1.6×10^{4}	-	1.2×10^{6}
Transition energy γ_{tr}	0.97		4.5	
RF voltage for bunch rotation U(kV)	20	250	1000	

*) Maximum values, smaller beams injected for deceleration to lowest energies.

**) *6 cm tungsten target, efficiency $\eta = 0.3$, quadrupole matching.*

of the magnets (cycle of 10-30 seconds because the magnets are not laminated). Injecting the $\bar{p}$ produced from one PS bunch (with 2×10^{12} p) the expected yield is $\approx 1.5 \times 10^5$ $\bar{p}$/pulse for momenta between 2.1 and 1 GeV/c, decreasing to $\approx 3 \times 10^4$ $\bar{p}$ at 0.3 MeV/c.

The RF system needed for bunch rotation and deceleration is relatively modest and in fact a considerable gain in $\bar{p}$ yield seems possible with a more powerful (250 kV) RF system together with a very fast kicker which permits injection of 5 bunches.

The two cases considered suffice to illustrate that even without cooling an optimized decelerator might deliver a clean beam (free of pions and other background particles) of 10^7 $\bar{p}$/pulse down to 0.3 GeV/c (10^6 $\bar{p}$/pulse at 0.1 GeV/c) and a rather "primitive" machine seems capable of, say, 10^5 $\bar{p}$/pulse at 0.3 GeV/c or 10^4 at 0.1 GeV/c. Clearly this would open new possibilities for many of the experiments[1,2]. A difficulty in the decelerator is beam control (low intensity!)

4. Deceleration and cooling

Stochastic cooling[10] prior to deceleration can "compress" the $\bar{p}$ phase-space such that the low energy beam still fits into the aperture. This eliminates the p^2 loss (Fig. 1) in density (intensity), and ideally all $\bar{p}$ that can be captured into the aperture at high energy can be decelerated. The characteristics of a momentum and emittance cooling system designed according to the criteria of ref.10 are given in Table 3. One notes that at intensities up to 10^7 $\bar{p}$/pulse, cooling times in the range of 2 to 20 s are within the realm of possibility.

Table 3

Stochastic cooling prior to deceleration*)

Circumference/2π of ring R = 12 m, cooling at p = 3 GeV/c. Momentum and horizontal emittance cooling by : 10 pairs of pick-up electrodes, 10 accelerating gaps (50 Ω each), 10 amplifiers (500 MHz bandwidth, 60 W RF power, 250 nA rms noise current each). Vertical emittance cooling by : 10 pairs of pick-up electrodes, 10 pairs of deflector plates, 10 amplifiers (500 MHz bandwidth, 60 W RF power, 250 nA rms noise current each).

Number of particles assumed	$N_{\bar{p}}$		10^7	
Momentum spread	$\Delta p/p$(°/oo)		1	5
Gain parameter (fraction of error corrected per passage) g		Momentum & E_h cooling	0.005	0.001
		E_v cooling	0.0025	0.0025
Cooling time (lower limit)	τ (sec)	Momentum	2	10
		E_h cooling	4	20
		E_v cooling	15	15

*) The amplifier system assumed is much more powerful than the one to be used in the ICE where cooling will take several minutes.

Once the beam has been decelerated, electron cooling[11] which is very efficient at low energy and which is less sensitive to the number of $\bar{p}$ seems then the "natural" ingredient to collimate the low energy beam (size $<$ 10 mm, $\Delta p/p$ $< 10^{-3}$). These dense and clean beams would resolve all the problems of the standard beam discussed above. In addition, new types of experiments become feasible[4] for instance scattering of stored $\bar{p}$ beams on an internal jet target, colliding $\bar{p}$-p experiments[5] or experiments with "overlapping" $\bar{p}$ and p beams[5] at low energy which might prove to be a very powerful tool to investigate antiprotonic atoms.

As an example, Table 4 gives some parameters of a system of "overlapping storage rings" which consists of an antiproton and a separate proton ring. In the "overlapping mode"[5], the two beams travel parallel in the intersection region. This set-up should provide for a precision study of the $\bar{p}$-p system at low energies by investigating e.g. resonances near the threshold, emission and resonance spectra of the $\bar{p}$-p atom, quasinuclear bound states and annihilation from known initial states.

5. Conclusion

Deceleration and/or cooling open new and exciting possibilities for antiprotons physics at low energy. Deceleration alone could largely improve the conditions of experiments which are presently under way. Addition of cooling would make a new class of experiments feasible. The "shuttle ring - freezer ring" system proposed as $\bar{p}$ source for the SPS could be used for our purpose if extraction into an experimental area is incorporated. Alternatively a relatively simple decelerator ring with characteristics similar to the experimental cooling ring ICE or some

Table 4

A 0.3 GeV/c $\bar{p}$-p overlapping storage ring system (some tentative parameters)

Radius, R = 5 m, (each ring)
Lattice functions in interaction point: $\beta_v \approx \beta_h = 1$ m, $\alpha_p = 3.5$ m

Proton parameters;

Number $N_p = 2\times10^{12}$
Emittances: $E_h \approx E_v = 100\pi$ mrad. mm, $\Delta p/p = \pm 2^{o}/oo$
Beam size (2σ) in interaction point: $a_p = \pm 10$ mm

Antiproton parameters:

Number $N_{\bar{p}} = 10^{11}$
Emittances: $E_h \approx E_v < 50\pi$ mrad.mm, $\Delta p/p < 2^{o}/oo$
Beam size (2σ) in interaction point: $a_{\bar{p}} < 5$ mm
Length of overlapping region: ± 0.50 m

Luminosity (unbunched): $2\times10^{28} \frac{\Delta v'}{c}$ cm^{-2}sec^{-1}
Typical velocity spread (2σ) in c.m. system: $\frac{\Delta v'}{c} \approx 3\times10^{-3}$

other 4 GeV/c synchrotron to which stochastic and electron cooling is added could serve low energy $\bar{p}$ physics.

Both cooling techniques have been tried experimentally, however extrapolations made in this paper extend over several orders of magnitude. In addition, beam control at the expected intensity of the decelerator will be difficult.

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