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THE NEW GENERATION OF ANTIPROTON SOURCES

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ABSTRACT

The new projects ACOL and TEVATRON 1 and the conceptual studies of antiproton options for large hadron colliders are analyzed in terms of performances and complexity and compared to the Antiproton Accumulator.

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Introduction

Lepton colliders always consist of one ring in which electrons and positrons have head-on collisions. A similar situation where antiprotons hit protons frontally in a single ring emerged only recently. The reasons for the late appearance of proton-antiproton colliders are the scarcity of the antiprotons and the absence of a natural condensation of the phase space like the compensation of synchrotron radiation by repeated radio frequency fields. The invention of beam cooling techniques^{1,2)} was a major breakthrough in the control of antimatter. As the present workshop is devoted to very high energies, the discussion will be restricted to those antiproton sources which are based on stochastic cooling³⁾.

The only source in operation at the present time is the antiproton accumulator^{4,5)} (AA) at CERN, it delivers particles to the intersecting storage rings⁶⁾ (ISR), the low energy antiproton ring⁷⁾ (LEAR) and the supersynchrotron (SPS) used in a collider mode⁸⁾. By 1987, its stochastic cooling systems will be upgraded, it will be surrounded by a second ring, the antiproton collector^{9,10)} (ACOL) and the target zone will be improved. This new source will be used in conjunction with LEAR, SPS and may be a large hadron collider (LHC)¹¹⁾ in a more remote future. For brevity, the new CERN \bar{p} -source will be referred to as ACOL.

At Fermilab, the source consists of a set of two rings¹²⁾, the de-buncher and the accumulator, which supplies the Tevatron with antiprotons. The construction is well advanced. The very first collisions may be observed in September 1985 but the first two real physics runs are scheduled for September-December 1986 and May-August 1987.

In the context of the American Super Superconducting Collider (SSC) design, a special study was dedicated to an antiproton option at the University of Chicago in February 1984¹³⁾. Parameters were defined in order to achieve luminosities in excess of $10^{32} \text{ cm}^{-2}\text{s}^{-1}$ in the collider.

The principles of operation of AA, ACOL, TEVATRON I and SSC \bar{p} -option are described in Section 1; their parameters are compared in section 2.

Principles of Operation

A single ring hadron collider is particularly attractive when the antiproton source in a modest part of the whole complex in terms of capital investment. From this viewpoint, the purest example is the present CERN antiproton facility which consists of three machines : ISR, LEAR and SPS fed by a ring of 25 meter radius, the AA (Fig. 1). Let us recall its general principles of operation.

A primary proton beam of 26 GeV/c momentum impinges a copper rod which emits antiprotons in a relatively wide cone. The antiprotons are focused in a

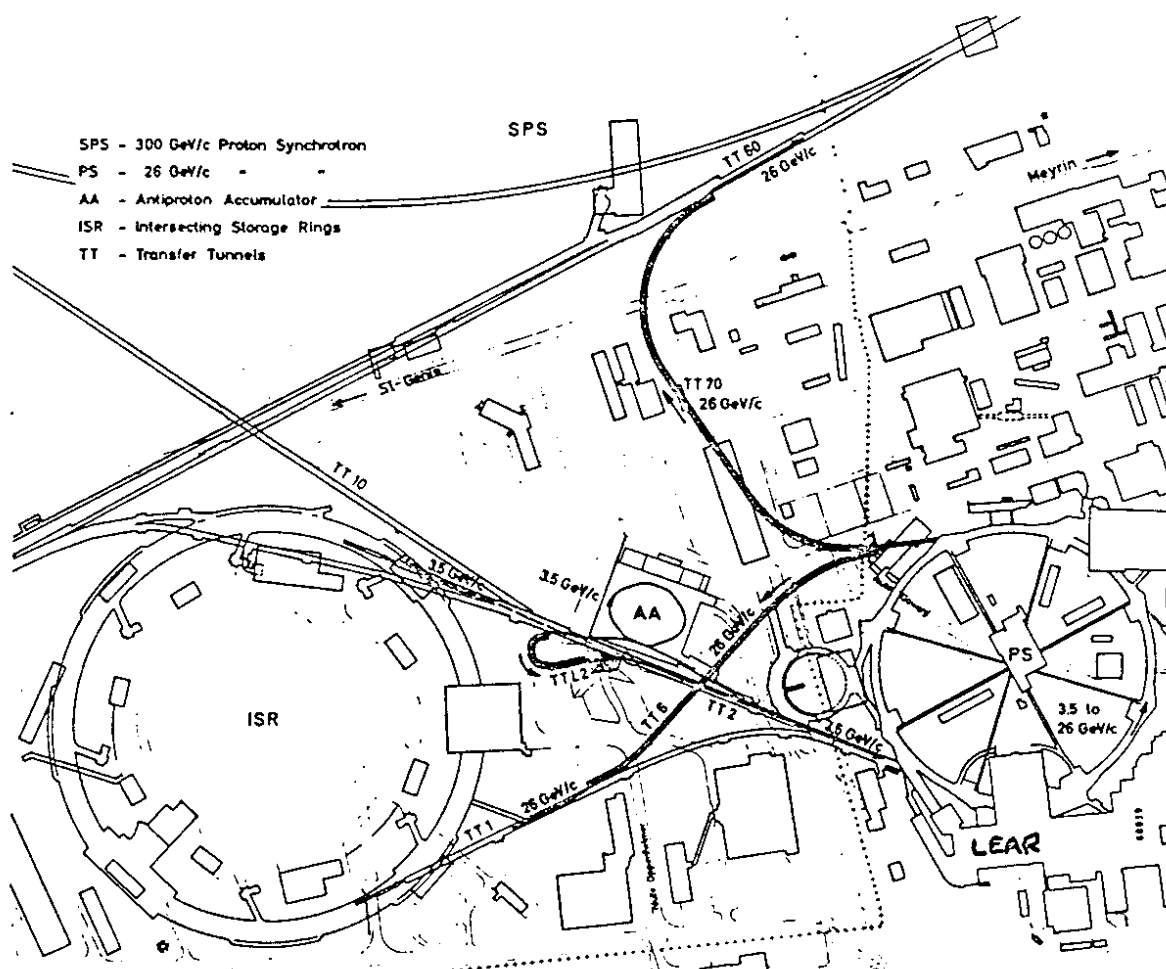


Fig. 1: CERN Antiproton Complex

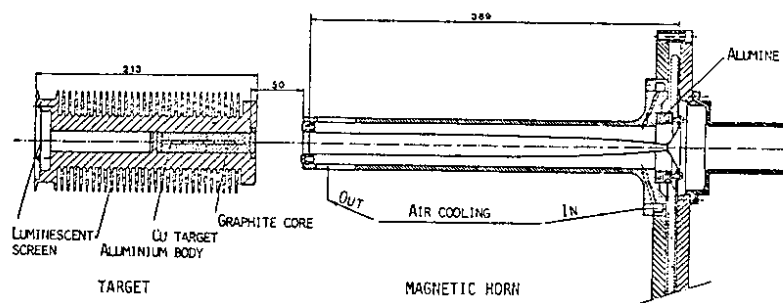


Fig. 2: Target and magnetic horn in the AA target station

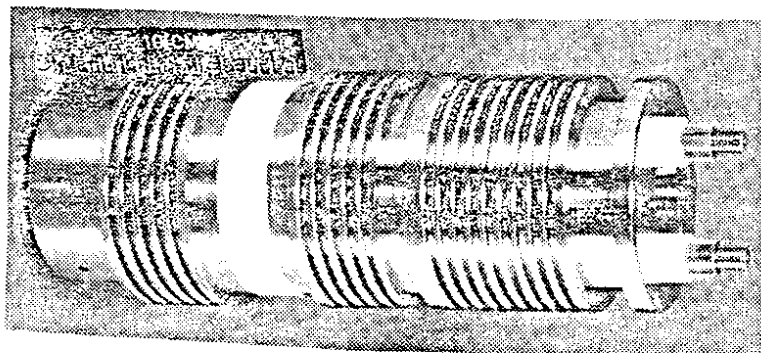


Fig. 3: Pulsed target

magnetic horn, a device widely used in neutrino physics (Fig. 2). It is tried to improve the production of antiprotons by pulsing an intense current¹⁴ (>100 kA) which re-distributes the particles in the transverse phase space at the end of the target (Fig. 3). In addition, wider production angles will be focused in lithium^{15,16} or plasma lenses¹⁷⁻²⁰ (Figs. 4 and 5). After the primary focusing, the beam is transported in an alternating gradient channel, injected into the outer part of the accumulator and cooled by a factor 10 in momentum. It is

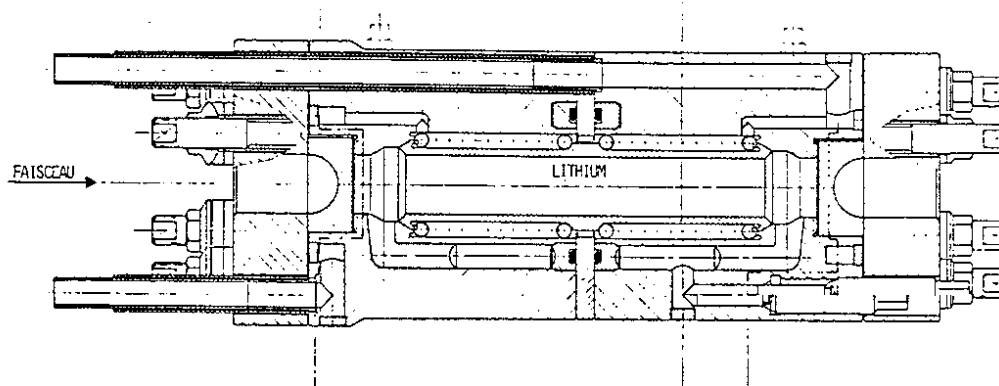


Fig. 4: Cross-section of a lithium lens

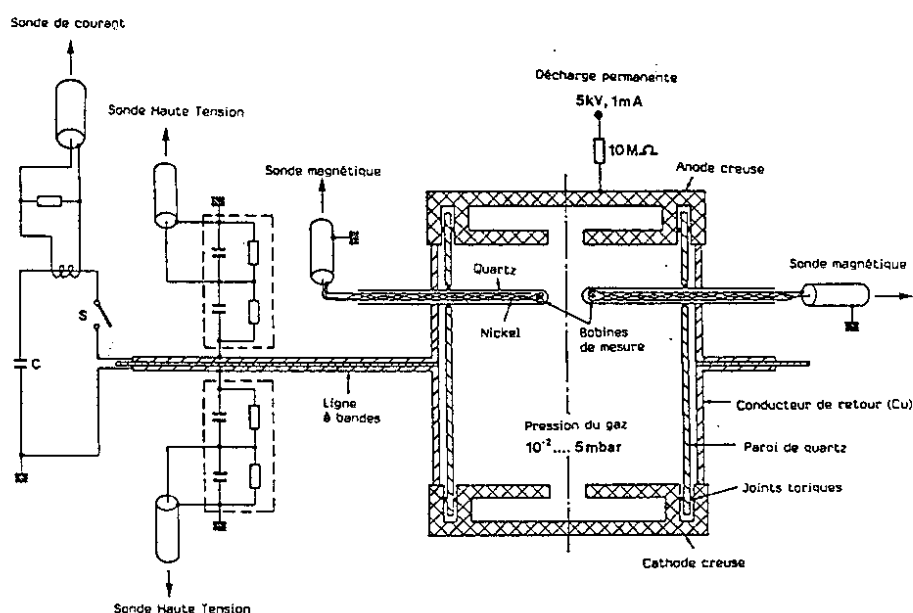


Fig. 5: Plasma lens and diagnostic equipment

then decelerated near the central orbit where it merges the previously injected particles and migrates slowly towards the high density part, the core, of the accumulator. In the core, the beam is further cooled transversely and once the desired intensity and beam size have been reached, three bunches are extracted, one at a time, sent to the synchrotron for acceleration to 26 GeV/c and injected into the collider where a proton beam has been disposed beforehand. The two beams are then accelerated together to their final momentum (315 GeV/c) and collisions can be observed. Needless to say that the procedure of antiproton transfer is very carefully monitored and that in many ways, it resembles a rocket launching.

The scenario is basically the same in all antiproton sources. The variants are in the degree of sophistication of the source. To increase the acceptance, a collector ring is added around the accumulator (Figs. 6 and 7): two operations are performed in it : de-bunching and pre-cooling to condition the beam for the further accumulation. De-bunching is a coherent operation which respects

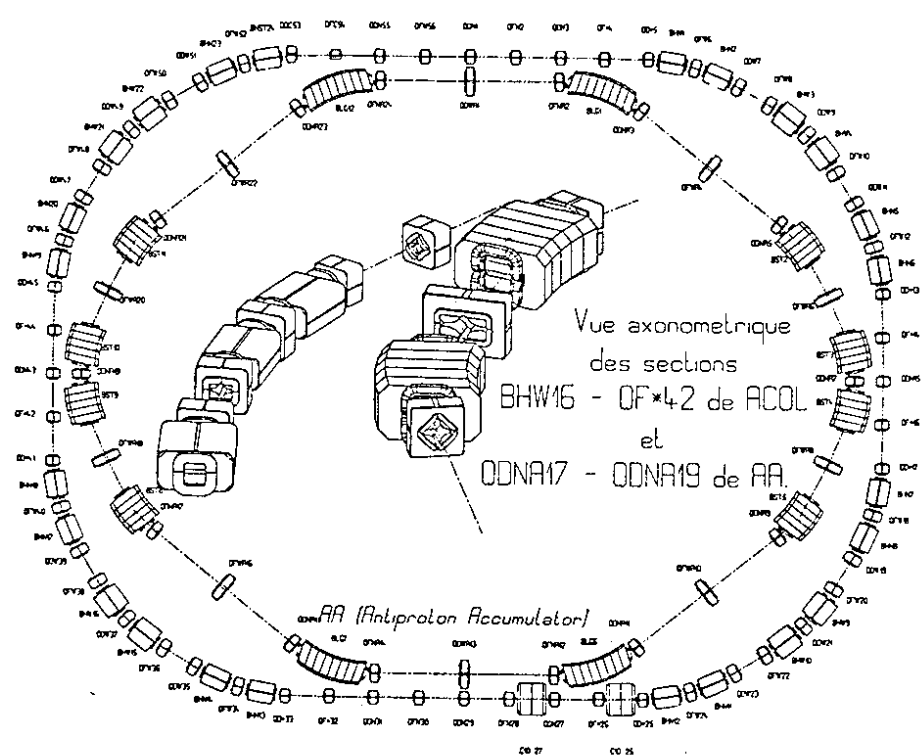


Fig. 6: CERN Antiproton Collector

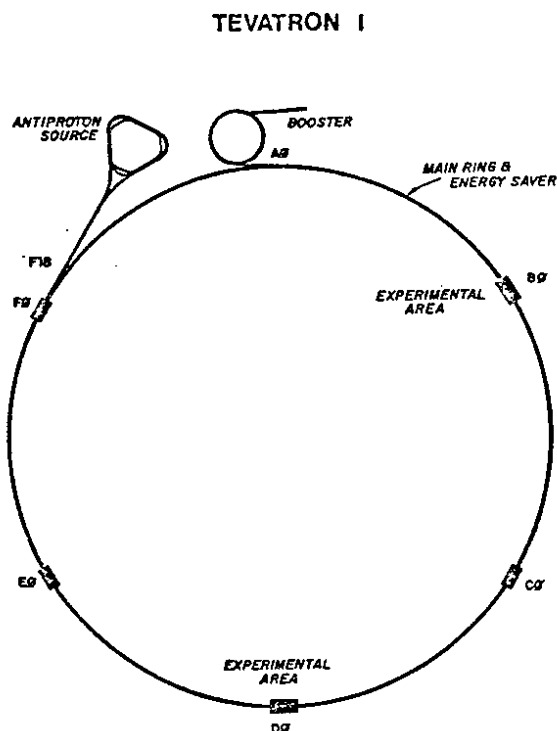


Fig. 7a: General layout of Fermilab Antiproton complex

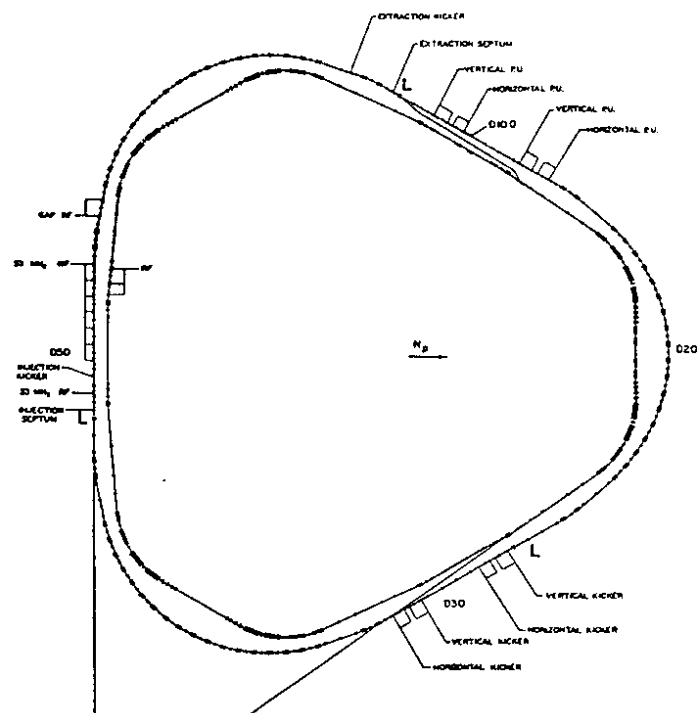


Fig. 7b: The debuncher (outer ring) and the accumulator (inner ring)

Liouville's theorem and trades momentum spread against time length, in practice, short bunches are elongated until the beam is continuous so that its spectral density, the number of particles per energy bin, is increased. The spectral density is indeed a basic input parameter to the stochastic accumulation and must

be as high as possible. De-bunching is a fast process which takes place in a few turns, the rest of the duty cycle is used to cool the beam transversely and longitudinally.

A second trend in the development of antiproton sources consists of using a high energy primary proton beam to produce antiprotons in a narrow cone and thus augment the initial phase space density. As the production is maximum near the centre of mass energy, the working energy of the source is raised and so is its circumference. The Fermilab set of rings exceeds half the ISR in length.

Last, the source turnover must be as fast as possible and the temptation is great to cascade rings in order to lengthen the precooling time yet staying in the duty cycle fixed by the proton synchrotron. In the case of the SSC \bar{p} -option (Fig. 8), this possibility was contemplated because the duty cycle is reduced to one second. Clearly one must resist the temptation and, carefully, the report mentions that all the stages of beam manipulation take place on special "orbits" and not in "rings" understanding that the magnet lattice must comply to the greatest number of beam dynamics constraints. An interesting feature of the SSC \bar{p} -option is the decoupling of the accumulation and storage functions; in this manner, the interference between the high level core signal and the low level signal of the freshly injected beam is greatly reduced in the accumulator and the 1 TeV injector is efficiently used as a holding ring to store 10^{14} antiprotons.

Performances

In order to satisfy the collider requirements, an antiproton source has to provide a given number of particles of specified phase space density in as short a time as possible.

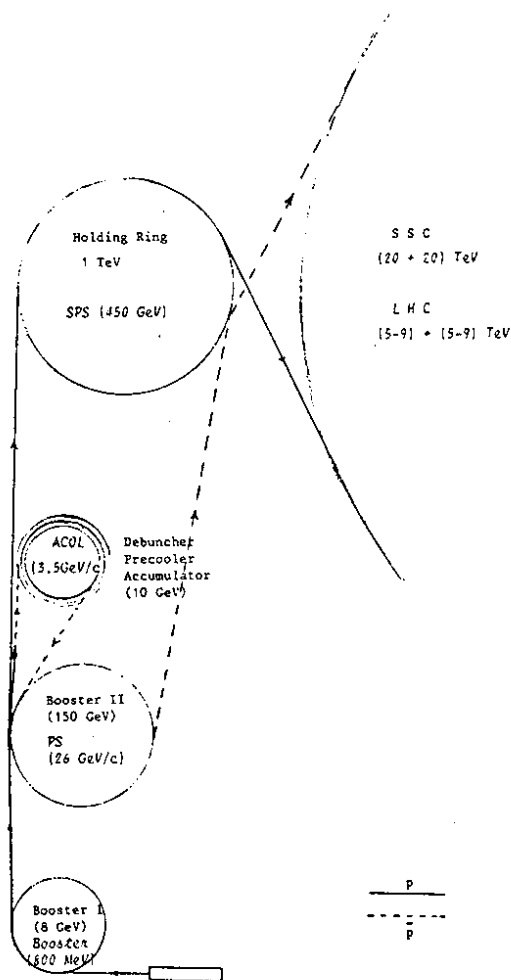


Fig. 8: Compared layouts of the antiproton option in LHC and SSC projects

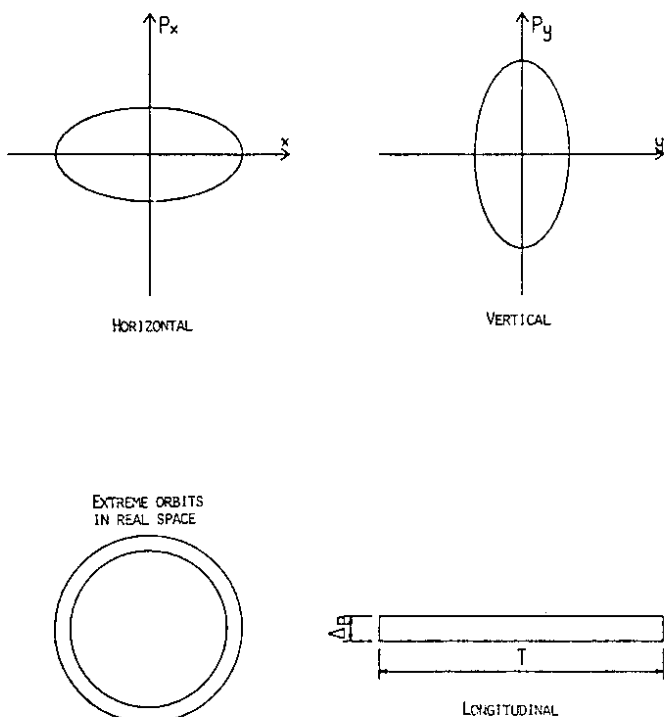


Fig. 9: Phase space in a storage ring

It is a property of linear beam optics that all particles are contained in the horizontal or vertical phase space inside ellipses (Fig. 8) whose shapes vary from point to point but whose areas, the transverse emittances, are constant. The connection between real space and longitudinal phase space is shown in Fig. 9. Particles whose energy is distributed over an interval ΔE turn on different orbits. The average revolution time is T and the product $T \cdot \Delta E$, the longitudinal emittance, is constant whether the beam is bunched, un-bunched or transferred from one to another machine. The emittances are no longer constant when stochastic cooling is applied to a particle beam, they decrease and the phase space gets denser.

The characteristics of the four sources are compared in Table I. The average phase space density ρ is defined as the ratio of the total number of particles N to the phase space volume Ω .

$$\Omega = \epsilon_H \epsilon_V \epsilon_L.$$

The density is actually not uniform. The lack of particles at large production angle is mainly responsible for the low initial value of ρ in ACOL as compared to AA. One can also notice the effect of the primary proton energy: there is more than one order of magnitude difference between TEV I and SSC on one hand and CERN machines on the other. However, in spite of the lower density gain

$$g = \frac{\rho_{out}}{\rho_{in}}$$

to be achieved, the turnover of TEV I is not substantially faster than ACOL's turnover because the stochastic cooling efficiency is superior at low density for identical frequency bandwidth of the stochastic systems. Theoretically, the frequency bandwidth can be scaled to the beam size; a small beam can be sampled at a high frequency rate, in this sense, the use of gigahertz bandwidths for ACOL is a dilemma which is solved by using mobile beam sensors which follow the beam envelope^{10,21)} as it shrinks. The application of these concepts (4 Ghz bandwidth, variable gap geometry for the couplers, minimum intensity in the accumulator) to the SSC explains the considerable improvement in turn over.

Table 1: Basic parameters of AA, ACOL, TEV I and SSC \bar{p} option

	<u>AA</u>	<u>ACOL</u>	<u>TEV I</u>	<u>SSC \bar{p}-option</u>
Proton momentum [GeV/c]	26	26	120	150
Number of protons on target [10^{13}]	1.3	1	0.2	0.3
Antiproton momentum [GeV/c]	3.5	3.5	8.89	10
Beam characteristics at collector input:				
- Number of antiprotons [10^8]	0.06	1	1	10
- ϵ_h [π mm.mrad]	80	200	20	40
- ϵ_v [π mm.mrad]	80	200	20	40
- ϵ_l [eV.s]	30	130	600	1260
- Phase space density [$\text{mm}^{-2} \text{eV}^{-1} \text{s}^{-1}$]	31	19	417	496
Accumulation time [h]	20	8	5	1/60
Accumulation rate [$10^9/\text{h}$]	5.2	75	48	3360
Beam characteristics at accumulator output:				
- Number of antiprotons* [10^{11}]	3×0.35	6×1	3×0.8	80×0.007
- ϵ_h [π mm.mrad]	2	2	2	0.5
- ϵ_v [π mm.mrad]	2	2	2	0.5
- ϵ_l^* [eV.s]	3×0.46	6×0.46	3×1.44	80×0.2
- Phase space density [$\text{mm}^{-2} \text{eV}^{-1} \text{s}^{-1}$]	1.9×10^{10}	5.4×10^{10}	1.4×10^{10}	1.4×10^{10}
Gain in phase space density	6.1×10^8	2.6×10^9	3.3×10^7	2.8×10^7

*) The number of antiprotons (or the longitudinal emittance) is expressed as the product of the number of bunches by the number of antiprotons (or the longitudinal emittance) per bunch.

These considerations are to be appreciated with a great prudence. The principles are well established but all their practical implications in the operation of an antiproton source for a super high energy collider have not yet been thoroughly studied. The number of rings, the lattice design, the technology of very broad band systems and the accumulation scheme require a detailed investigation.

Conclusion

One of the highlights of this workshop devoted to elastic and diffractive phenomena at the highest energies is the interest of pursuing the comparison between p - p and p - \bar{p} collisions. Experiments at the ISR suggest noticeable differences between the cross-sections of the two types of reaction. If these differences are confirmed, they should show up more dramatically at high energy.

Another point which is worth emphasizing is the great activity in the field of stochastic cooling. Its use for either proton or antiproton beams may open new realms to basic parameters like luminosity or beam lifetime of any future machine.

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