THE CERN LOW ENERGY ANTIPROTON RING (LEAR) PROJECT

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- Part 1 presented at the 5th European Symposium on
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THE LEAR PROJECT

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ABSTRACT

At the CERN PS the construction of a facility for experiments with intense beams of low energy $\bar{p}$'s, has been authorized. Antiprotons derived from a $\bar{p}$ accumulator at 3.5 GeV/c are decelerated in the PS and transferred to a strong focusing ring designed for momenta between 0.1 GeV/c and 2 GeV/c. An ultra slow ejection system will deliver beams of about 10^6 $\bar{p}$ /s into the experimental area. The use of internal gas targets and the interaction of the $\bar{p}$'s with co-rotating H^- ions or counter-rotating protons are also considered.

INTRODUCTION

LEAR (which stands for Low Energy Antiprotons Ring) will be a small synchrotron which will provide pure and intense beams of $\bar{p}$ for a variety of experiments at low energy. It will receive at regular intervals batches of $\bar{p}$ extracted from the Antiproton Accumulator (AA)¹⁾ and decelerated in the PS. This machine will primarily be used as an accelerator/decelerator and as a beam stretcher, i.e., the beam will be accelerated or slowed down from the fixed transfer momentum to that required by the experiments, where it will be extracted in a very long spill for fixed target experiments. Other options are being considered, such as fast extraction, the installation of internal jet targets, co-rotating H^- and $\bar{p}$ beams, and $p\bar{p}$ collision experiments.

At CERN, early versions²⁾ of such a machine were proposed in 1977, in papers submitted by U. Gastaldi, K. Kilian and D. Möhl to the International Accelerator Conference and by P. Dalpiaz to the CERN $p\bar{p}$ study week^{*)}. A summary of these proposals was presented by the "Lohrmann Group"³⁾ to the Workshop on the Future of Intermediate Energy Physics⁴⁾ held at CERN in the autumn of 1977 where it was given an enthusiastic response, and to the PS

*) References to earlier work are contained in these papers.

and SC Committees⁵⁾ who gave further support. The CERN Scientific Policy Committee in its meeting in November 1978, gave a positive recommendation for such a facility to be built at CERN. Thereafter, a Workshop⁶⁾ on Physics with Cooled Low-Energy Antiprotons was attended by more than 70 interested physicists in Karlsruhe on March 19-21, 1979 and on the basis of the physics proposed there, a report⁷⁾ was discussed by the PS + SC Experiments Committee. This Committee and the CERN Research Board recommended the construction of a facility for experiments with intense beams of low energy $\bar{p}$ in their meetings in June 1979. A detailed design study of the facility⁸⁾ was launched in September 1979 and construction was authorized in May 1980. It is expected to begin the running-in of the facility in the second half of 1982 and experiments with it in early 1983.

2. ANTIPROTON ACCUMULATION

The cross-section for antiproton production by 26 GeV protons incident on a fixed target shows a peak around 3.5 GeV/c $\bar{p}$ momentum (Fig. 1). Consequently, in the antiproton accumulator¹⁾ (AA) being built at CERN, 3.5 GeV/c $\bar{p}$'s produced by 26 GeV p's from the Proton Synchrotron are accumulated and condensed by phase-space cooling. When a sufficient number of $\bar{p}$ has been collected, they will be transferred to the Proton Synchrotron, accelerated or decelerated, and transferred to the SPS or ISR for high-energy experiments or to LEAR for low-energy experiments respectively (Fig. 2).

Figure 3 shows a plan of the AA, a large aperture storage ring of 157m circumference which cannot be dealt with in detail here. Figure 4 shows the expected $\bar{p}$ beam density distribution as a function of momentum (or radial beam position) as calculated for 24 hours of accumulation time.

Out of this "stack" portions are picked up by the RF acceleration system with a momentum width compatible with the momentum acceptance of the PS. The number of $\bar{p}$ contained in any such portion depends evidently on the accumulation time and on the position in the stack from where it is picked up and can hence vary within wide limits. The RF voltage applied will bunch this batch of particles and accelerate them onto the ejection orbit from where they are ejected by a fast deflector as a bunch of

about 100ns length.

3. ANTIPROTON TRANSFER TO LEAR

The $\bar{p}$ bunch is transferred back to the PS, decelerated during the falling part of the magnet cycle and ejected and transferred at a fixed momentum of 0.6 GeV/c to the low energy $\bar{p}$ ring. LEAR will be built up in the South experimental hall of the PS (Fig.5). Particles will be transferred through the tunnel indicated which will be built in the forthcoming fall shut-down of the PS. In addition to the $\bar{p}$ from the PS, protons and H^- ions will be available from the old 50 MeV linac for machine tests and for their use in the options (Fig. 6).

4. BRIEF DESCRIPTION OF LEAR⁸⁾

The circumference of LEAR (Fig. 7) is equal to one eighth of the PS or one half of the AA. It has an almost square shape in order to provide long straight sectors where large equipment can be installed (e.g., a low β section and/or large experiments around an internal target or a collision point). The four sector magnets and a quadrupole doublet at either side of it provide for short straights of 1m length between dipole and quadrupoles and long straights of 8m between the doublets. The beam height is 1.66m above the floor of the hall. The machine parameters are given in Table 1 and typical lattice functions are shown in Fig. 8.

The all metal vacuum system will be designed for baking at 300°C and with the ultimate goal of achieving the vacuum limits obtained in the ISR. The acceleration system consists of one or two ferrite cavities. Controls will be based on the PDP 11/45 computers of the Linac control system, to which a third CAMAC branch is being added.

Injection and ejection make use of a common septum magnet in SL1. The injected beam receives its final deflection by a fast ferrite kicker and space is reserved in SL4 for a second septum/kicker system for the case that a beam circulating in opposite direction is required. The ejected beam is deflected across the common magnetic septum by a thin electrostatic septum in SS11, and it receives a final deflection by a thick septum magnet.

A special ejection system providing a very long spill with a high duty cycle is necessary in order to obtain a continuous ejected beam between two refills. It is based on a normal resonant ejection where the beam is slowly driven into a betatron resonant condition. The driving mechanism is in this case a RF noise signal and the process is then referred to as stochastic ejection⁹⁾. Basically, one uses the phenomenon that a RF signal containing noise of a certain bandwidth induces in the beam a diffusion process inside a momentum band. This technique is used first to flatten and enlarge the particle distribution (Fig. 9a) and then to peel off particles on one side of the momentum band and to make them diffuse towards the momentum where they find themselves in the transverse resonance which leads to ejection (see Figs 9b and c). This diffusion process leads to a spill structure much less sensitive to ripple and hence to a higher duty-cycle than the normal resonant ejection.

The installation of stochastic cooling systems for transverse and momentum phase-space has been studied. Space is reserved for the necessary elements and provisions, in particular for the pick-ups, will be implemented in the design of the vacuum chambers from the outset (Fig. 10). Figure 11 shows as an example the result of computer simulation of the cooling of the vertical emittance. The gain of the electronic system must be adjusted in steps as indicated. Stochastic momentum cooling will also be important for maintaining the quality of the circulating beam during the stochastic ejection process.

5. OPERATION AND PERFORMANCE

5.1 Surveillance during operation

The machine will be set up and run in by the small team of machine physicists in charge of the project, and these will also be available for emergencies. The continuous surveillance during runs will, however, be the charge of some members of the teams running experiments at LEAR. LEAR will be controlled with the help of a small stand-alone computer system and it is not envisaged to involve Main Control Room operators in its running. The necessary information will be available on a terminal at the location of the experiment.

TABLE 1 - LEAR BASIC PARAMETERS

Momentum (kinetic energy) range	0.1-2 GeV/c (5.3 MeV-1.3 GeV)
Injection momentum (kinetic energy)	0.6 GeV/c (175.4 MeV)
Circumference	78.54m ($=2\pi \times 12.5$ m)
Typical cycle	10^9 $\bar{p}$ injected every 10^3 s
Typical extracted beam	10^6 $\bar{p}$ /s
Typical spill length	≈ 900 s
Long straight sections	4 of 8m length each
Short straight sections (between quadrupoles and bending magnet)	8 of 1m length each
Bending magnets, No. arc length, field at 2 GeV/c	4, 6.55 m, $B = 1.6$ T
Quadrupoles, No, magnetic length, max gradient at 2 GeV/c	16, 0.5 m, $k = 1.8 \text{ m}^{-2}$ ($g=12\text{T/m}$)
Focusing structure	4 superperiods, separated function BoDFOFDob
Betatron wavenumbers and momentum compaction (stretcher mode)	$Q_H \approx 2.3$ $Q_V \approx 2.7$ $\alpha = \gamma_t^{-2} = -4.8 \times 10^{-3}$
Aperture limitation	$a_H = \pm 70$ mm $a_V = \pm 29$ mm
Acceptances (stretcher mode)	$E_H = 240\pi \times 10^{-6}$ rad m $E_V = 48\pi \times 10^{-6}$ rad m $\Delta p/p = \pm 1.1\%$
Vacuum system, design pressure (N_2 - equivalent)	$10^{-11} - 10^{-12}$ Torr
Bake out temperature, bake out and pump down time	300°C , ≈ 40 h
RF - system frequency range ($h=1$)	0.4 - 3.5 MHz
Peak voltage per turn (stretcher mode)	12 KV
PS beam bunch properties at transfer ($h = 10$ in PS), area, total bunch length	$A = 15$ mrad, $l_b = 250-300$ ns $E_H = 40 \pi \times 10^{-6}$ rad m $E_V = 20 \pi \times 10^{-6}$ rad m $\Delta p/p = \pm 5 \times 10^{-3}$
Acceptance of transfer system	
Assumed AA beam properties at 3.5 GeV/c (unstacking of 10^9 $\bar{p}$)	$E_H \leq 3\pi \times 10^{-6}$ rad m $E_V \leq 1.5\pi \times 10^{-6}$ rad $A = 6$ mrad (at $h = 1$ in AA)

5.2 Beams for setting-up and tests

From the beginning, protons and low currents of H^- ions will be made available for LEAR. These will be essential for running-in LEAR and for setting-up experiments, the $\bar{p}$ being too scarce and precious for these purposes. Protons which are more easily available, have the disadvantage that polarities have to be inverted. Reversing the polarity of the electrostatic septum may take several hours' formation at high energy. The use of H^- ions, on the other hand, is limited by stripping on the rest gas and, at higher energies, by electromagnetic stripping in the bending magnets.

5.3 Initial development

Some running-in of experiments using the external beam can be expected to begin (on a parasite basis) concurrently with the development of the slow ejection system. Beam would first be available at the PS-LEAR transfer momentum i.e., 0.6 GeV/c approximately, and an increasing range of momenta would become accessible as the acceleration system comes into operation. It is now estimated that the momentum range 0.3 to 1.6 GeV/c will be accessible with the initial acceleration system early in 1983. Extension of the range down to 100 MeV/c can be expected once stochastic cooling and/or electron cooling come into operation so that the emittance, blown up adiabatically during deceleration and by scattering on the rest gas can be compressed again. A simple stochastic cooling system, partly consisting of available material, is included in the project. It is hoped that also a first electron cooling system can be obtained early on (see Chapter 6) so that this range can be explored in the course of 1983. A typical deceleration cycle of LEAR may then be as follows :

- 1) injection
- 2) stochastic cooling at 0.6 GeV/c
- 3) deceleration to 0.3 GeV/c
- 4) electron cooling at 0.3 GeV/c
- 5) deceleration to final energy
- 6) (possibly: electron cooling at final energy)
- 7) debunching
- 8) ejection

Acceleration is easier as the emittance shrinks rather than to blow up. Nevertheless, extension of the range up to 2 GeV/c may be limited by the efficiency of the extraction system and practical experience will be essential.

Fast ejection at medium momentum, using the inflection kicker could be available rather early. For high and low momenta (large beams) an additional fast kicker would be necessary.

5.4 Intensity

The Antiproton Accumulator is expected to accumulate $6 \cdot 10^{11}$ $\bar{p}$ per day when the PS runs for $\bar{p}$ production exclusively. Taking into account transfer losses, 4 to $5 \cdot 10^6$ p/s is the max. flux obtainable in the external beam from LEAR. It is unlikely that LEAR will be the only facility in operation and the possibilities of running in parallel with PS and SPS physics will be considered below.

Two basic schemes of beam sharing are possible

i) sharing protons, i.e., using one or two 25 GeV cycles within a PS/SPS supercycle for $\bar{p}$ production, the AA being used for LEAR exclusively.

ii) sharing antiprotons, i.e., taking a small fraction of a $\bar{p}$ stack being prepared in the AA for the SPS (or ISR). The first of these possibilities looks quite straightforward. One would take one or two hours to create in the AA a stack of about $5 \cdot 10^{10}$ $\bar{p}$ and unstack batches of the order of 10^9 $\bar{p}$ at intervals of 1000 s which after transfer to LEAR would be available as an extracted beam with a flux of 10^6 $\bar{p}$ /s. The batch size of 10^9 $\bar{p}$ is the minimum which the present PS beam control system needs to function safely. The stack must of course be replenished continuously and that takes one or two 25 GeV cycles in every PS/SPS supercycle.

The second possibility, parasitic running during SPS $\bar{p}$ experiments, would be very interesting is, say, 5% of the stack could be allowed for low energy $\bar{p}$ physics. LEAR could then typically receive 30 batches of 10^9 $\bar{p}$, and run about 8 hours per day in the normal way. If the PS beam control, on the other hand, could be made more sensitive so that smaller batches can be transferred, or if the slow extraction of LEAR could be stretched out by another factor of three, a parasitic beam of 2 to $3 \cdot 10^5$ $\bar{p}$ /s

would be available around the clock.

5.5 Emittances of the external beam

While the vertical emittance E_V of the external beam is equal to that of the circulating beam, its horizontal emittance E_H and its momentum spread $\Delta p/p$ are essentially determined by the ejection system :

a) E_H is substantially reduced by the ejection process, in principle to a value near zero for an ejection as slow as envisaged here. Ripples occurring on all the elements involved will however produce variations in position and deflection angles and thus recreate an integrated "emittance" which is difficult to evaluate at the moment.

b) $\Delta p/p$ depends on the horizontal emittance of the circulating beam, $\Delta p/p = k \cdot E_H^{1/2}$, the resonance condition depending on betatron amplitude and momentum of the particles.

This leads to the following comments :

- 1) Longitudinal cooling in LEAR is not relevant for the momentum spread of the external beam ;
- 2) the horizontal emittance sets a lower limit to the momentum spread of the external beam and horizontal cooling will be beneficial for it ;
- 3) if the stability of ejection elements can be controlled well enough, the basically small E_H can be advantageous for momentum analysis of the external beam ;
- 4) the vertical emittance of the external beam can be controlled by cooling.

Table 2 gives, for illustration, a few estimated emittances without cooling, with stochastic horizontal, vertical, and momentum cooling during about 2 minutes at 0.6 GeV/c, and with additional electron cooling at 0.2 GeV/c until equilibrium conditions are reached (which takes less than 10s).

The momentum spread of the external beam can obviously be reduced by momentum analysis at the expense of intensity. Experiments where a minimum momentum spread is required should be done with the circulating beam interacting on an internal jet target. Full advantage can then be taken of momentum cooling.

TABLE 2 - Estimated emittances of the external beam
(in units of $10^{-6} \pi$ radm for E_H , E_V and in units of 10^{-3} for $\Delta p/p$)

	Internal beam			External beam
	E_H	E_V	$\Delta p/p$	$\Delta p/p$
As injected into LEAR (0.6 GeV/c)	30	15	3	2.7
Decelerated to 0.2 GeV/c w/o cooling	90	45	9	beam is too large to be ejected
Accelerated to 1.5 GeV/c w/o cooling	12	6	1.2	1.7
Stochastic cooling at 0.6 GeV/c				
- emittances at 0.6 GeV/c	7	3.5	0.8	1.3
0.2 GeV/c	20	10	2.3	2.2
1.5 GeV/c	2.8	1.4	0.3	.8
Additional electron cooling at 0.2 GeV/c	~ 1	~ 2	~ 0.1	.5

6. THE OPTIONS

Ever since the construction of LEAR was discussed, additional facilities and purposes other than the production of an external beam, described in the preceding chapters, have been considered. They are :

- phase-space cooling by an electron beam
- internal gas-jet targets
- experiments with co-rotating $\bar{p}$ and H^- beams
- experiments with colliding $\bar{p}$ and p beams.

The installation of an electron cooling system is of most general interest, as it would improve the performance of the basic machine as well as of two of the other options (jet target, H^- beams). A system designed to specification for LEAR (momenta up to about 0.6 GeV/c, short cooling times) will constitute a major development and take some time to build ; it could hardly become usable before 1984 even if seriously undertaken in the second half of 1980. The possibility to adapt as a first step, avail-

able in 1983, the demonstration set-up used in the Initial Cooling Equipment (ICE)¹⁰⁾ is therefore being investigated¹¹⁾. Gas jet targets are at present being developed for possible use in the SPS and the ISR, the main problem being compatibility with the vacuum requirements in these machines. If these developments were successful, a jet for LEAR presumable of the cryogenic cluster type could probably be obtained on a rather short time-scale. A target of low luminosity, with a total thickness no larger than the integrated rest-gas density, could be installed rather early on. A target of high luminosity, typically one used for antineutron production, will have to await the availability of the electron cooling system for the compensation of multiple Coulomb scattering.

The two further options, co-rotating H^- and $\bar{p}$ beams and $p\bar{p}$ collision experiments, impose more stringent requirements on the machine in order to reach full potential. Though week ($p\bar{p}$) beams will be obtained as soon as H^- ions are injected, electron cooling of the H^- beam is essential for more sophisticated experiments, and then a very precise velocity match between the electrons and the H^- ions must be maintained to avoid stripping. Similarly, the luminosity obtained in $p\bar{p}$ collisions in the "bare" machine would be very low. The electron cooling system¹²⁾ required to improve the luminosity in this option would have to work at momenta around 2 GeV/c which is a high momentum for the conventional electron cooling and low for relativistic electron cooling. The short bunch length required in the collider option necessitates a special high voltage RF system.

At the present stage, parameters and choices have been avoided which would exclude the implementation of any of the options and the necessary space is provided in the machine (Fig. 7): the location of a jet target for experiments on the circulating beam is planned in straight sector SL 2, where also the quadrupoles for the low beta scheme will be installed. One or two jet targets for the production of secondary $\bar{n}$ beams can be located in the center of the magnet sectors 1 and 2. Space for the electron cooling system is reserved in straight sector SL 3 or SL 4.

For the experiments with co-rotating $\bar{p}$ and H^- beams, the neutral ($p\bar{p}$) states formed in SS11, SL 1 and SS12 fly along the neutral beam line indicated in Fig. 6. The collision region in the $p\bar{p}$ collision option would be in SL 2, replacing the jet target.

The studies to date have established the probable feasibility of the jet target in conjunction with cooling. The implementation of the other two options will still need much study and development and will not be possible before 1985.

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FIG. 1

FIG.2 OVERALL SITE LAYOUT

FIG.3 ANTIPROTON ACCUMULATOR

GENERAL LAYOUT

ANTIPROTON ACCUMULATOR	SCALE 1:500
GENERAL LAYOUT	DATE 1980.12

FIG.4 SCHEMATIC CROSS SECTION IN COOLING RING

68870

CERN PS
H and NORTH AREA
Layout of beams
from 26th Mar. 1980
n 70-726-0

Fig. 5

CERN PS

Layout of LEAR
from 26th Mar. 1980
n° 70.725.0

100 METERS
Fig. 6

Fig. 7
LEAR General Lay out

(TENTATIVE, ELEMENTS OUT OF SCALE)

SCALE 1:50

Fig. 8: Plot of twiss parameters for Lear doublet lattice QH = 2.3, QV = 2.7

Fig. 9

Fig. 10 IMPLEMENTATION OF STOCHASTIC COOLING SYSTEM (schematic)

Fig. 11 : Cooling of vertical emittance at $0.6 \text{ GeV}/c$

THE CERN LOW ENERGY ANTIPROTON RING (LEAR) PROJECT

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ABSTRACT

The idea to add to the CERN Antiproton Accumulator (AA) a facility for experiments with dense and pure beams of low energy antiprotons has received enthusiastic support from many members of the physics community. After conceptual studies^{1,2)} done since 1977 the following scheme³ was authorized in May 1980 :

Small batches of cooled antiprotons will be skimmed off from the AA at regular intervals, decelerated in the CERN PS and transferred into a small storage ring (LEAR). In its first stage LEAR will work as a beam stretcher providing a high duty cycle spill of 10^6 $\bar{p}$ /s into an experimental area. Future options (not yet authorized) foresee internal jet targets together with cooling, co-rotating beams of p and H^- , proton antiproton colliding beams, fast extraction with slowing down of $\bar{p}$'s to rest^{4,5)}.

A storage ring to fulfill this variety of tasks has to combine some unusual machine features which are summarized in the present report.

1. GENERAL DESCRIPTION

To meet the physics requirements LEAR has to be a multipurpose storage ring working in the momentum range of 0.1 to 2 GeV/c (Table 1).

The circumference 78.5m (i.e., one eighth of the PS) is the maximum size of a regular machine that reasonably fits into the existing South Hall of the PS (Fig. 1). A symmetric four-period lattice with compact 90° bending magnets and eight quadrupole doublets was adopted. It provides four long straight sections each of 8m free length into which large equipment can be installed, including apparatus for experiments with internal beams and for electron-cooling, and eight short straight sections of 1m length (Fig. 2).

FIG. 1

TABLE 1
LEAR BASIC PARAMETERS - STRETCHER MODE

Momentum (kin. energy) range	0.1 GeV/c (5.3 MeV)-2 GeV/c (1.3 GeV)
Injection momentum (kin. energy)	0.6 GeV/c (175.4 MeV)
Circumference	78.54m ($2\pi \times 12.5$ m)
Typical cycle	10^9 $\bar{p}$ injected every 10^3 s
Extracted intensity-spill time	10^6 $\bar{p}$ /s 900 s
Straight sections	4x8m + 8x1m
Bending magnets	4x6.55m B=1.6 T
Quadrupoles	16x0.5m K=1.8m ⁻² (g=12 T/m)
Focusing structure	4 super periods BODFOFDOB
Betatron wave numbers	$Q_H=2.3$ $Q_V=2.7$
Momentum compaction	$\alpha=\gamma_t^{-2}=-4.8 \cdot 10^{-3}$
Aperture limitations	$a_H=\pm 70$ $a_V=\pm 29$ mm
Acceptances : machine	$E_H=240, E_V=48$ ($\pi \times 10^{-6}$ radm) $\Delta p/p=\pm 1.1 \cdot 10^{-2}$
Acceptances transfer PS LEAR	$E_H=40$ $E_V=20$ ($\pi \times 10^{-6}$ radm) $\Delta p/p=\pm 5 \cdot 10^{-3}$
PS bunch at transfer	$L_b=250-300$ ns A=15 mrad (h=10)
RF frequency range-peak voltage	0.4-3.5 MHz 12 kV (h=1)
Vacuum design pressure	$10^{-11} - 10^{-12}$ Torr (N ₂ equivalent)
Bake out temperature and time	300°C - 40 h

Fig. 2
LEAR General Lay out (tentative)
including stochastic cooling
SCALE 1 50

During periods where the AA works entirely for LEAR only a fraction of the PS protons can be used for $\bar{p}$ production the rest being reserved for SPS, ISR and 26 GeV physics. During periods where the AA runs at its full capability most antiprotons will be used for the bigger machines.

Injection into LEAR is a classical single turn procedure with septum and fast kicker in the same long straight section. For some of the options multiple injection is contemplated using stacking in betatron space or bunching and injection on the free part of the circumference. For machine tests H^- or protons can be transferred to LEAR at 0.3 GeV/c directly from the old PS linac, as indicated in Fig. 1.

An $h=1$ RF system with ferrite tuned cavities providing 12 kV per turn decelerates or accelerates the beam in LEAR. An unusually large frequency range (0.4-3.5 MHz) is required (2-0.4 MHz for deceleration, 2-3.5 MHz for acceleration).

A vacuum of 10^{-11} Torr or better is essential for low energy operation to reduce single scattering on the residual gas to a level tolerable during 15 min storage time. An all metal vacuum system bakable at 300°C will be used.

Ultra slow extraction is necessary to provide a continuous spill of 10^3 sec length between two subsequent refills. The technique employed is described in a separate contribution to this conference⁶).

2. COOLING

Stochastic cooling in all three planes will be used to compensate for emittance growths of various origins (adiabatic antidamping during deceleration, multiple scattering on the residual gas, diffusion due to resonances, etc.). The layout, difficult because of the space requirements for pick-ups and correctors, is shown in Fig. 2. The horizontal and vertical systems use each a short path for cooling at injection and lower energy, and a diagonal path from the same pick-up for cooling at higher energies. The shorter path avoids mixing between pick-up and corrector, important at low energy where η is largest, and the diagonal shortcut permits the correction signal to catch up with the particles at high energy ($v \approx 0.9 c$) despite the signal delays. The filter system for longitudinal cooling can in principle work in the whole energy range because efficient Δp cooling can be obtained using a relatively low frequency band, thus avoiding unwanted mixing.

The pick-ups for transverse cooling are the most critical as they have to be long ($\sim 2m$) to obtain adequate signals. Operation in the 250-750 MHz band has been chosen to make them as short as possible. The momentum pick-up can be made more compact by using ferrite and the correctors are made short at the expense of somewhat higher power requirement for the amplifiers.

In a first stage cooling will be done at injection energy prior to deceleration. Later the system can also work at intermediate energies and during extraction. To this end the electrical length will be changed by remotely switchable delays and possibly more than one filter line for Δp cooling will be used as practised in the Initial Cooling Experiment (ICE). For intensities up to $10^{10} \bar{p}$, emittance and Δp cooling time constants are of the order of 0.5 to 1 min if a relatively simple "ICE type" system is used. At injection and intermediate energy the beam will stay bunched but the RF voltage will be reduced during cooling to keep the bunch long.

Electron cooling is most effective at lower energies and for beams which are already relatively cool. It can thus naturally complement the stochastic system, especially for

experiments with internal beams which can profit from momentum spreads $\Delta p/p \lesssim 5 \cdot 10^{-4}$ and a beam size of a few millimeters resulting from an equilibrium between cooling and intra beam and residual gas scattering. A system tailor-made for LEAR (proton energy $T_p \lesssim 175$ MeV, overall length ≈ 2.5 m, cooling times $\tau \lesssim 10$ s) will need time to develop. The possibility is therefore being investigated to adapt as a first step the set-up used in ICE.

3. OPTIONS

An internal gas jet target permits to take full advantage of beam cooling as the momentum and angular resolution are no longer degraded neither by the extraction process nor by multiple Coulomb scattering in the target, the latter being compensated by cooling the circulating beam. With the simple stochastic cooling ($\tau \approx 0.5$ to 1 min) it is appropriate to have a thin target and use up and refill 10^{10} antiprotons every 10^4 s whereas with electron cooling ($\tau \approx 0.1$ min) a thicker target using up the beam in 10^3 s and hence the usual filling cycle of LEAR can be employed. It is advantageous to place the target in a low beta point of the lattice to improve the angular acceptance $\theta_a^2 = (\text{acceptance of vacuum chamber}) / \pi \beta$ as particles scattered by $\theta > \theta_a$ are lost (single scattering loss).

By tuning to a suitable working point β values of about 2 to 4 m ($\theta_a = 5$ to 6 mrad) can be obtained both at the target in the straight section and a target for antineutron production placed in the center of a magnet. In this position the $\bar{n}$ beam will suffer less restriction of solid angle by the magnet gap. A low beta insertion will further increase θ_a in the straight section to 12 to 15 mrad.

The two further options, co-rotating $\bar{p}$ and H^- beams for spectroscopy of protonium in flight⁵⁾ and the "minicollider" for precision experiments in the charmonium region⁴⁾, impose more stringent conditions on the machine. Both depend on strong cooling, i.e., electron cooling, for exploiting the full potential. In fact, a very precise velocity match between $\bar{p}$, H^- and the cooling electron beam is essential to avoid stripping of H^- by other H^- , $\bar{p}$ or e^- . The collider option is particularly attractive at high energies. Hence, an electron cooling system working up to 2 GeV/c is essential to reach the maximum luminosity of about $10^{29} \text{ cm}^{-2} \text{ s}^{-1}$ obtainable with a beam-beam tune shift of $\Delta Q = 5 \cdot 10^{-3}$.

These options need further study, but care has been taken to avoid parameters and choices which could exclude their later implementation.

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