FUTURE MACHINE IMPROVEMENTS IN LEAR

P. Lefèvre, D. Möhl, D.J. Simon
CERN
CH-1211 Geneva, Switzerland

Introduction

So far, the CERN low energy antiproton ring LEAR (Fig. 1) has mainly worked as a duty cycle stretcher [1]. In typical operation, a bunch of, say, 3.10^9 well cooled antiprotons is unstacked from the antiproton accumulator (AA) once every 75 minutes. This bunch is decelerated in the 28 GeV proton synchrotron (PS) from 3.5 to 0.6 GeV/c. Further deceleration or acceleration in LEAR to momenta in the range of 0.1 to 2 GeV/c (design) interspersed with stochastic beam cooling on flat tops at different "strategic" momenta preceed the ultra slow extraction with a continuous spill of one hour duration. This corresponds to pulse stretching by more than 10^9 where on average less than one antiproton per turn leaves the machine.

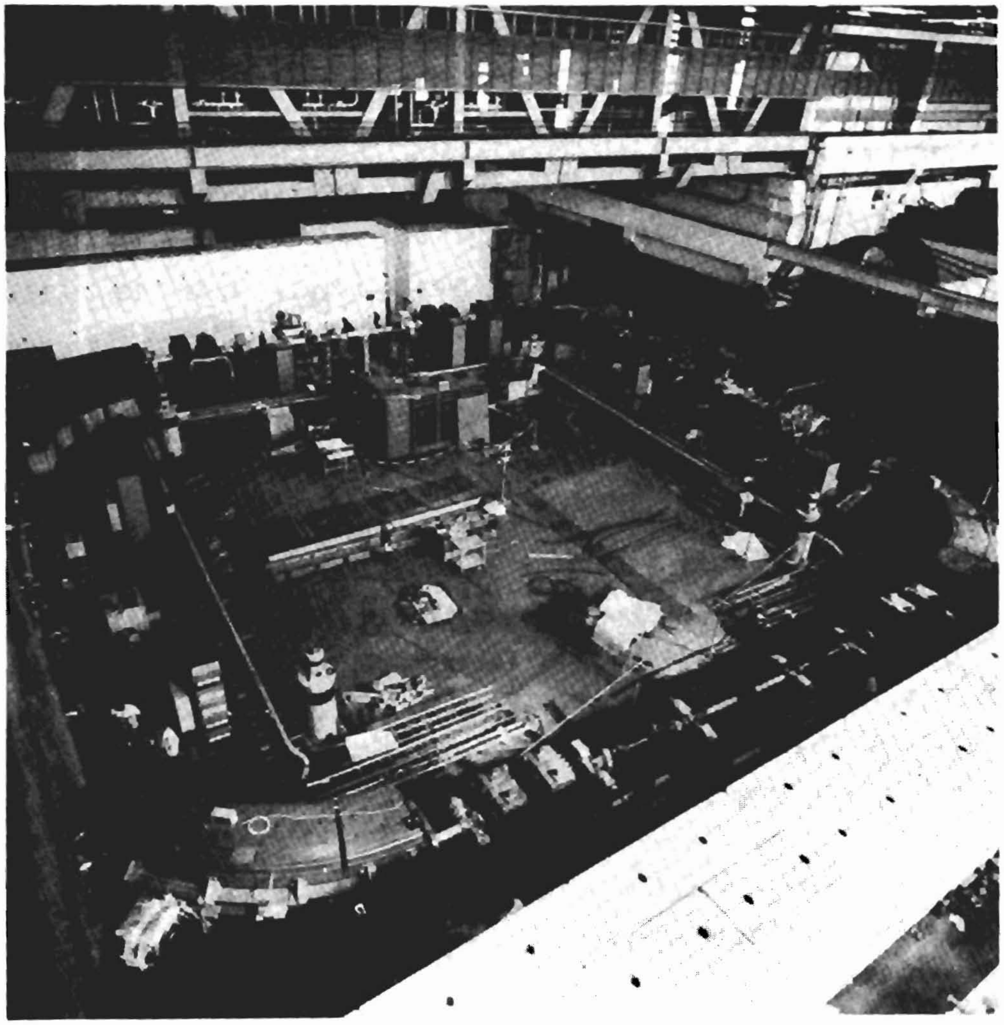

Fig. 1: The low energy antiproton ring LEAR

Statistics of the first three years of operation are summarized in Table 1.

TABLE 1 : STATISTICS OF FIRST THREE YEARS OF LEAR OPERATION

YEAR	1983	1984	1985	1986*	
Total running time	800	2000	4000	700	h
Total number of antiprotons from AA	0.2	0.3	0.6	0.1	x 10^{13}
Extracted beam momentum range	0.3-0.6	0.2-1.5	0.1-1.7	0.1-1.7	GeV/c
Number of different momenta	2	4	21	10	
Run in parallel with SPS collider	no	no	yes (68 days)	no (so far)	

* March and April only

As we have heard in K. Kilian's presentation [2], 17 experiments involving some 500 collaborators from more than 50 different institutions have taken data (including some 40 participants from 10 different universities and laboratories in the USA). Up to three users can receive beam simultaneously when the two splitter magnets installed in the external beam lines are operated.

The future experiments described in R. Landua's talk [3] and even some of the present apparatus make a further improvement of the stretcher mode and a redesign of the experimental area desirable. This will be the subject of the first part of our presentation. In part II, we want to discuss a number of options which have been foreseen in the design or emerged during operation of LEAR. These options use internal targets or colliding or co-rotating beams rather than extracted antiprotons.

Finally, we shall briefly discuss a 7 GeV/c antiproton storage ring for charmonium and bottonium physics to which only some modest design effort has been devoted so far.

1. Improvements of the stretcher mode

1.1 Machine

Some basic machine parameters, their design value, the achieved performance and the improvements aimed at within the next few years are given in Table 2. A few comments are in order here.

At momenta above 1.7 GeV/c, the machine is presently limited by the sextupole strength available. We recall that sextupolar correction is necessary to tune the chromaticity ($\xi = \Delta Q/Q \big/ \Delta p/p$) close to 0.6 for the horizontal and to 0 for the vertical betatron oscillation and to excite the extraction resonance $3Q_h = 7$. Both measures are essential for the ultra-slow extraction [4].

To achieve the required strength ($k' = \frac{\partial^2 B}{\partial x^2} \frac{1}{B\rho} = 2\ m^{-3}$)

up to 2 GeV/c the water cooling circuit and the ventilation of the air cored sextupoles installed in LEAR have to be re-inforced.

TABLE 2 : IMPROVEMENT OF STRETCHER MODE

Parameter	Design	Achieved	Planned	
Maximum momentum	2	1.7	2	GeV/c
Minimum momentum	0.1	0.105	0.06 (0.02)	GeV/c
Overall transfer efficiency	(70)	20-40	50-70	%
Pbar flux during spill	1E6	1-5E5	>1E6	pbar/s
Spill length	0.25	1 (5)	5	hours
Spill duty factor	90	70	80-90	%
Stochastic cooling time*	2 min	3 min	1-2 min	
Time for momentum scanning step	-	>2h	few minutes	

* at 600 MeV/c and $4 \times 10^9\ \bar{p}$.

The lower momentum limit, 100 MeV/c, has essentially been achieved although the stability of the main and the correction power supplies is critical at this low momentum. Yet the future experiments PS189 [5] and PS200 [6] which call for antiprotons "at rest" make momenta below 100 MeV/c ($\hat{=}$ 5.5 MeV kinetic energy) desirable.

A fast extracted beam of high density is required for post-deceleration in an RF quadrupole linac [6] [7] as foreseen by the LANL-PISA collaboration (PS 200). Great savings on the RFQ are possible when the LEAR extraction can be at 60 MeV/c ($\hat{=}$ 2 MeV kinetic) instead of 100 MeV/c. The experiment PS189 [5] calls for a 100 ms pulse of antiprotons at 20 MeV/c ($\hat{=}$ 200 keV kinetic). Such a beam length is beyond the technology of pulsed RFQ's and would need a device practically as expensive as a "dc RFQ". On the other hand, PS189 needs only relatively small intensity, so that the core of a "reduced performance beam" may suffice. There is hope that with decelerating down to 20 MeV/c in LEAR, a 100 ms spill usable for PS189 can be obtained.

In addition to low momentum, these experiments need special extraction: either "fast resonant" for the 100 ms spill or single turn kicker extraction for the RFQ of PS200. In fact, for PS200, it will be advantageous to break up the beam into a number of bunches and eject one bunch a time. As an example, 8 bunches with a length of 250 ns and a bunching factor (bunch length/bunch distance) of 1/2 seem obtainable at 60 MeV/c by running the RF at 2 MHz (harmonic 8 of the revolution at 60 MeV/c), which is well in the range of working frequencies of the normal RF system.

Synchronisation of the kicker flat-top, rise and fall to the bunch and the interbunch gaps will permit to kick single bunches in an efficient way. Similar techniques of fast extraction possibly at 100 MeV/c or higher are also required for the other $\bar{p}$- trapping experiment PS196 [8] which uses a degrader rather than an RFQ for post-deceleration.

A fast extraction system employing a kicker and the same magnetic septum also used for resonant ejection is installed and has been used for diagnostic purposes during machine studies. However, the acceptance of the extraction channel (A_h = 5 π mm.mrad) is small, so that only well cooled beams can be ejected efficiently.

Another parameter, probably the most delicate one at the moment, is the overall $\bar{p}$-transfer efficiency from AA to LEAR users. As losses occur at various stages in AA, PS, LEAR and in the transfer lines, work has to go into all these areas.

A critical point is the PS-LEAR transfer where up to 50% beam is lost when the emittances from the AA are large (> 2 π mm-mrad at 3.5 GeV/c) or when the PS ejects with an error in angle or position. A number of beam position monitors will be installed in the line for better diagnosis and probably part of the line will have to be rebuilt. Further, the ultraslow extraction is delicate in the presence of beam position fluctuations and tune ripple and in the presence of parasitic high order resonances. More than 80% extraction efficiency has been obtained at high momentum but with the present supplies it is hard - if not impossible - to achieve this performance at low momentum.

Finally, some losses occur during deceleration because the orbit steering is difficult with the present set unipolar power supplies for the correction dipoles. Imperfect orbit control leads to loss, especially when the beam is insufficiently cooled. At present, one has to compromise between the steering during deceleration and the orbit bumps necessary during extraction. These two requirements frequently demand opposite polarity of the dipoles.

As to the spill length, extraction times of 1 hour are now used routinely, except at momenta below 0.2 GeV/c where the beam lifetime is short. At energies above 0.6 GeV/c, spills of up to 4.5 hours have been used occasionally, an example is illustrated in Fig. 2. But at 100 MeV/c, the useful length was limited to about 15 min. Non-linear betatron resonances are probably responsible for the beam decay, which is faster than expected from interaction with the residual gas or from intra-beam scattering. By compensating these resonances and by careful control of the working point, one hopes to achieve operationally good spills of 5 hours at higher momenta and of up to 1 hour at 100 MeV/c.

It is not the place here to describe the LEAR cooling system [9] in detail. Let us just recall that beam cooling is necessary to avoid loss due to the adiabatic emittance increase during deceleration and to make high quality beams available for special experiments. At present, only stochastic cooling is used. The electron cooler [10] developed by a KfK-Karlsruhe (Germany)-CERN collaboration is planned to be installed early next year. A "fixed energy" stochastic cooling system (horizontal, vertical

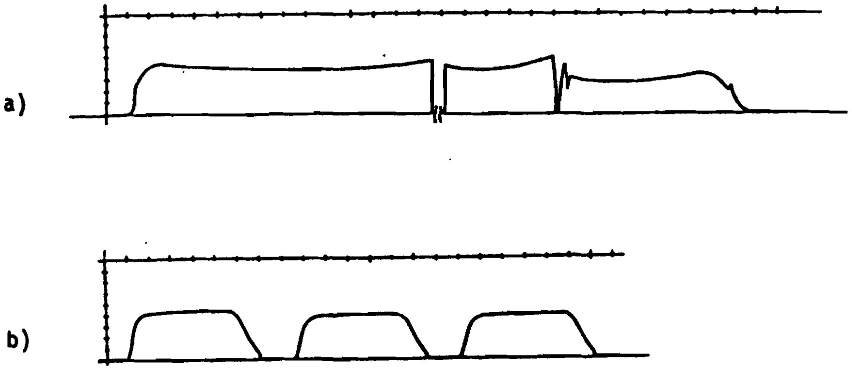

Fig. 2: examples of a "LEAR" spill

a) Number of particles per second recorded by the users group PS172 during a 4.5 h spill from LEAR at 700 MeV/c on December 13, 1985. The horizontal scale is 10 min/div. the vertical 30.000 $\bar{p}$ per second/div. After about two hours, the extraction was interupted at the request of the users who had to recondition a target. The remaining beam was kept circulating and extraction restarted when the target was ready. About an hour later, the spill was interrupted a second time and the RF noise used to diffuse particles into the $3Q_h = 7$ extraction resonance was re-adjusted to prevent the flux from exceeding 150.000 $\bar{p}$ per second, the saturation level of the experiment.

b) Three normal 1 hour spills (vertical scale 50.000 $\bar{p}$ per second/div.).

and longitudinal) is working on intermediate flat-tops at 609 MeV/c (injection), 309 MeV/c, and 200 MeV/c. In each step, emittances are "restored" to, say, 10 π mm.mrad and $\Delta p/p = 10^{-3}$ with about 5 minutes cooling at intensities up to 4×10^9 $\bar{p}$. Adjustment to the different beam velocities is performed, using "coaxial relays" to commute between different preadjusted cooling loops which use the same pick-ups and kickers.

In addition, a second set of "synthesized systems" with much longer cooling time constants is used to keep the beam in shape during extraction. This system can in principle be adjusted to all momenta. Both for the fixed and synthesized systems signal to noise problems occur at low beam velocity as all beam signals decrease with β. In addition, relatively low bandwidth has to be used at low energy to avoid excessive mixing of the beam samples.

To improve the situation, special low noise cryogenic amplifiers are being developed working in the 1 to 100 MHz range. In addition, the "normal" pick-ups will be connected in series at low momentum to support a travelling wave with the velocity of the beam particles and special helix type sum and difference pick-ups are under study. These measures should permit cooling at 100 MeV/c and below with time constants of the order of a few minutes.

Last but not least, it is desirable to speed up the momentum scanning procedure. At present, each change of extraction energy needs at least 2 hours and 10^9 antiprotons to be implemented and tested. By improved software and by the use of function generators, which permit adjustment during the course of a cycle, considerable gains are hoped for.

To implement these improvements, a "consolidation programme" has been established. It extends over the next two years and comprises amongst other things:

- improvement of power supplies;
- extension of the controls system;
- work on the RF system;
- upgrade of the stochastic cooling;
- installation of electron cooling;
- improvement of the diagnostic system;
- further improvement of the vacuum (from 2 to $1*10^{-12}$ Torr).

Notice that these improvements are necessitated by experiments which are already approved.

1.2 Experimental areas

The present area has been in use for nearly three years (July 1983-April 1986). Data taking of most of the 16 experiments actually on the floor will be finished at the end of August 1986, when the upgrading of the CERN antiproton source will start. During this shutdown, we plan to modify the LEAR area, to dismantle most of the first generation experiments and to install new experiments which are being discussed at the moment. We hope to be ready to restart antiproton physics in autumn 1987.

The layout of the present area has been described elsewhere (see for example the proceedings of the Second LEAR Workshop [11]). A plan is reproduced in Fig. 3 for convenience. Fig. 4 shows a possible new layout

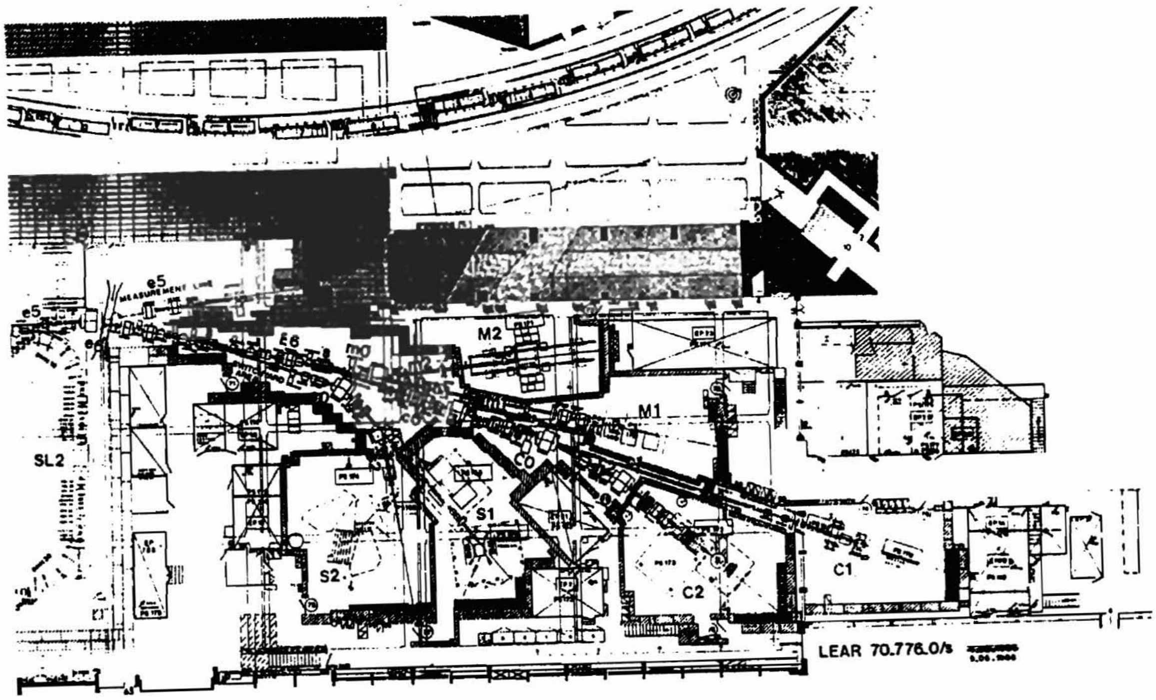

Fig. 3: The LEAR experimental area - Present situation

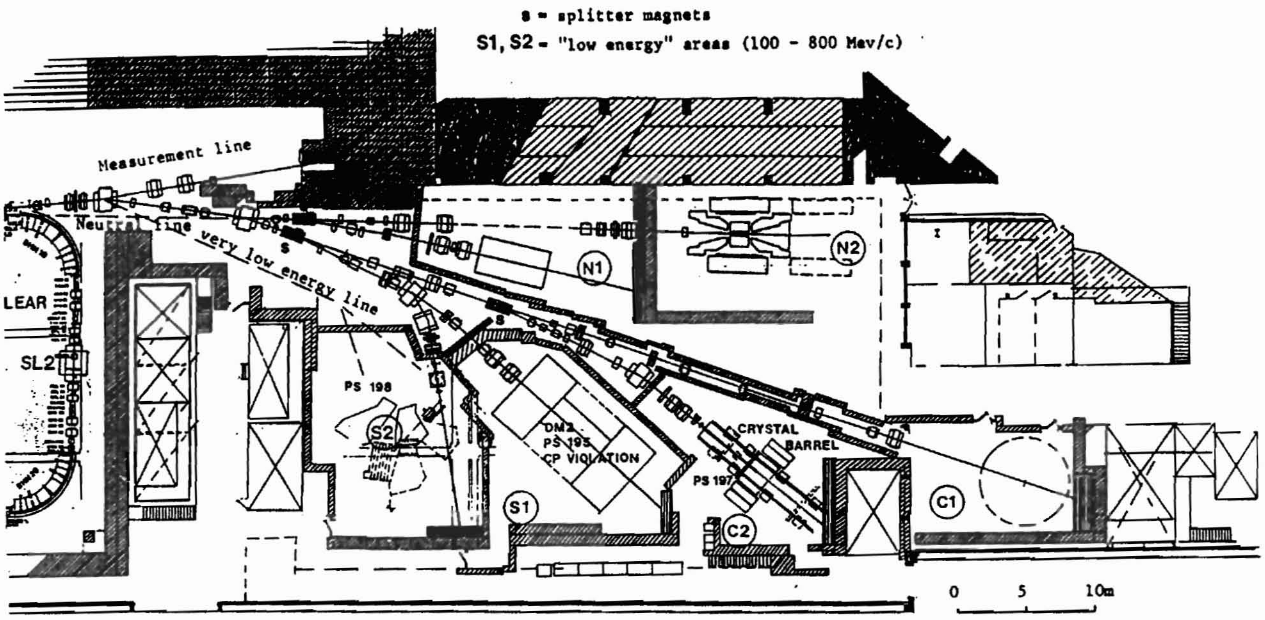

Fig. 4: Project of the LEAR experimental area after the start of ACOL

which is presently being discussed. Rather drastical modifications are required. The total area (PS South Hall) occupied remains about 1900 m^2 and the number of separated areas is 6 again. But the following changes are necessary:

- possibility to use the "neutral line" from the straight section 1 of LEAR (studies of protonium, etc.);
- possibility to install larger experiments and to test them with a better flexibility (use of 3 splitter magnets instead of 2 in the actual layout);
- possibility to feed one area with very low energy antiprotons ($p < 20$ MeV/c).

Seven new experiments are already accepted; a few of them are indicated on Fig. 1. Others will certainly be approved in the coming months. The final layout can only be determined thereafter.

2. Future options

Future options using internal targets or colliding or co-rotating beams have been discussed in detail at the Third LEAR Workshop [12]. Provisions made in the design of LEAR to implement the corresponding equipment are sketched in Fig. 5. The options include:

A gas jet target.

Installed in straight section 2 of LEAR, it will be used very efficiently in conjunction with stochastic and/or electron cooling of the circulating $\bar{p}$ beam. Such a thin target would permit high resolution and highest possible luminosity achievable in continuous operation:

$$(1) \qquad L = \frac{dN/dt}{\sigma_t} \approx 10^{31} . \beta \quad (cm^{-2} s^{-1})$$

where a useful $\bar{p}$ production rate $dN/dt = 10^6/s$ and a total cross-section $\sigma = 100\ mb/\beta$ inversely proportional to particle velocity $\beta = v/c$ has been

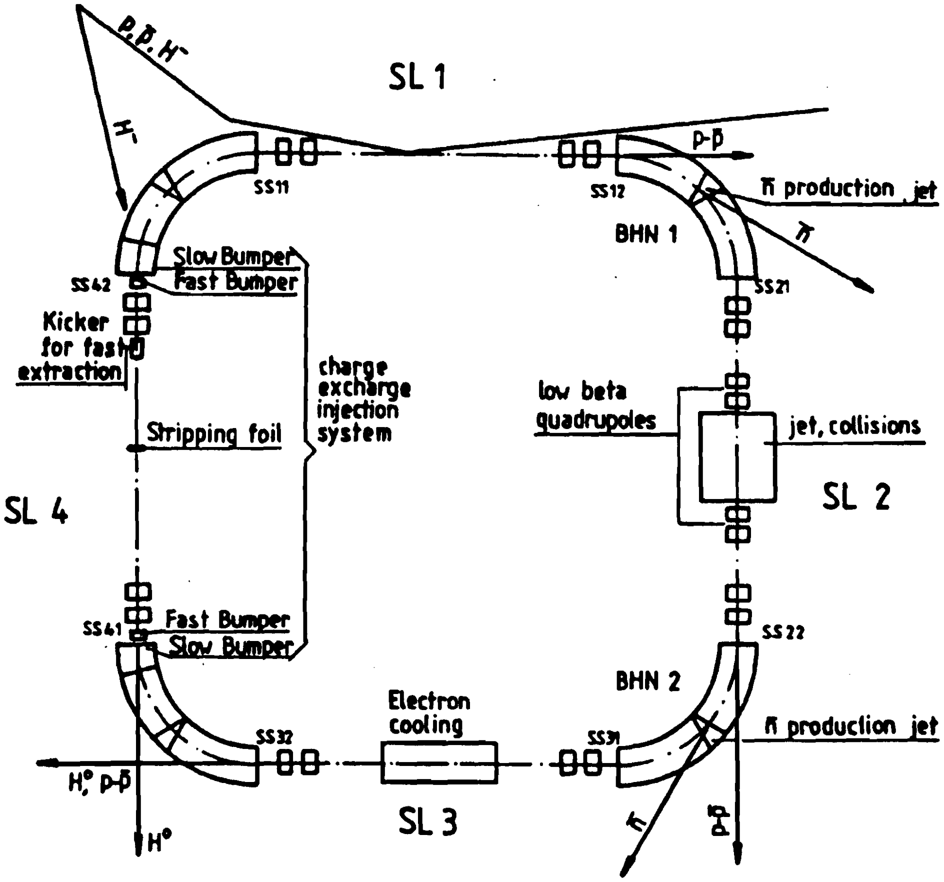

Fig. 5: Provisions for future options in the layout of LEAR

taken. The assumption is that the beam decay rate due to this total cross-section is matched to the production rate. The figure of 100 mb/β implies that only strong interactions occur and that the undesired beam heating due to multiple- and the loss due to single large angle Coulomb scattering are compensated by a strong enough cooling system and by a special "low beta optics", which increases the angular acceptance at the target position. A proposal [13] to install into LEAR the gas target previously used in the ISR has been submitted to the PSCC committee which recommends priorities for LEAR experiments.

Antiproton and negative hydrogen beams co-rotating in LEAR.

The aim is to form highly excited states of protonium in flight [14]. The formation cross-section [15] for this Auger-process is of the order of $5x10^{-16}$ cm^2, so that 10^5-10^6 protonium atoms per second will be formed. About 1/8 of them will merge into each of the neutral beam exit tubes attached to the LEAR straight sections. Notice that the formation only occurs for a window $0.5 \times 10^{-14} < \Delta v/c < 2 \times 10^{-4}$ of relative $\bar{p}$ H^- velocities and that various H^- stripping mechanisms have two to three orders of magnitude higher probability. Even under the best conditions, some hundred times more H^0 than protonium will merge into the neutral beam lines.

Proton-antiproton colliding beams.

The aim is to extend the c.m. energy into the charmonium range [16]. As in most colliders, the ultimate luminosity limit is determined by the non-linear detuning of the beam by the space-charge field of the other beam ("beam-beam effect"). Admitting a linear detuning $\Delta Q = 5 \times 10^{-3}$, a bunch length (and a low beta) of 5 m and 5×10^{11} $\bar{p}$ circulating, the luminosity limit at 2 GeV/c is about 1.5×10^{29} $cm^{-2}s^{-1}$ i.e. only 1% of the flux limit (1) attainable with an internal target. This naturally leads to the idea to do the charmonium spectroscopy in a higher energy (3-7 GeV/c) storage ring with a hydrogen jet target.

3. Super-LEAR

Several groups have expressed interest in a high luminosity antiproton storage ring covering the range of 2 to 7 GeV/c of circulating beam momenta. Such a ring should permit precision measurements in the charmonium range when internal hydrogen targets are employed and in the botonium range when $\bar{p}$-p colliding beams are used.

High luminosity is most efficiently reached in a small ring where particles make many turns per second. The tentative design of a compact 120 m circumference ring (called Super-LEAR or SLEAR) which uses superconducting magnets was presented at the Third LEAR Workshop [17]. Assuming a flux of 10^7 $\bar{p}$/s (as hoped for after improvement of the CERN $\bar{p}$ source by the addition of the collector ring ACOL in 1987), the flux limited Luminosity (1) is

$$L = 10^{32}\ cm^{-2}s^{-1}. \tag{2}$$

With an internal target conditions close to this limit can in principle be reached by judicious choice of target thickness and filling cycle [17] (e.g. transfers of 10^{12} $\bar{p}$ every 10^5 s together with a matched target with nd = 4.10^{13} H atoms/cm^2 $\hat{=}$ 0.7×10^{-10} g/cm^2).

For the colliding beams, various intensity and density limitations enter into play. Probably most limiting again is the beam-beam effect which (assuming a 1 m long bunch with 10^{12} $\bar{p}$ and admitting a linear detuning of 5×10^{-3}) limits the luminosity to 3×10^{-30} $cm^{-2}s^{-1}$.

With strong phase-space cooling, larger detuning and hence higher luminosity may be obtainable but it seems hard to approach the flux limit (2) with colliding beams. More details are given in ref. 17. Notice from Fig. 6 that with the addition SLEAR $\bar{p}$-p centre of mass energies available at CERN would cover the full range from almost rest to 600 GeV.

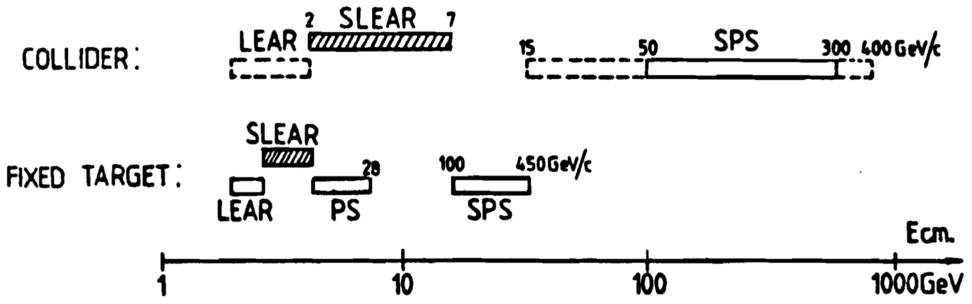

Fig. 6: Centre of mass energies available with $\bar{p}$+p

CONCLUSIONS

1. The very high demand for LEAR beam makes improvements of the stretcher mode as well as new types of operation desirable.

2. The improvements should permit: higher flux, faster setting-up and momentum scanning, an even longer and smoother spill and momenta below the design minimum. A redesign of the experimental areas and lines is necessary to accomodate the new experiments in an efficient way.

3. Options involving internal targets and/or co-rotating or colliding beams will permit to take full advantage of the high quality circulating beam.

4. Postdeceleration after LEAR will provide cool beams of $\bar{p}$'s "at rest".

5. Despite all these improvements it will be difficult to meet the demands of en ever growing community with just one LEAR.

REFERENCES

1. P. Lefèvre, LEAR, present status, future developments, in: Proc. of Third LEAR Workshop (1985), "Physics with antiprotons at LEAR in the ACOL ERA", Tignes (France), 1985. (Edited by U. Gastaldi et al.) Editions Frontières, Gif-sur-Yvette, France, 1985, p. 33 . (cited hereafter as "Proc. Third LEAR Workshop").

2. K. Kilian, Results from LEAR, this Workshop.

3. R. Landua, Future physics at LEAR, this Workshop.

4. R. Cappi, R. Giannini, W. Hardt, Ultra-slow extraction, in: Proc. Second LEAR Workshop, "Physics at LEAR with Low Energy Cooled Antiprotons", Erice (Italy) 1982, (U. Gastaldi et R. Klapish, ed.), Plenum Press New York, London 1984, p. 49 (cited hereafter as "Proc. Second LEAR Workshop".).
   See also W. Hardt, "Moulding the noise spectrum for much better ultraslow extraction, PS/DL/LEAR Note 84-2.

5. C. Thibault et al., Present status of the radiofrequency mass spectrometer for PS189, Proc. Third LEAR Workshop, p. 675.
   C. Thibault, High precision p-$\bar{p}$ mass comparison, Proc. Second LEAR Workshop, p. 761.

6. M.V. Hynes, this workshop. See also Proc. Third LEAR Workshop, p. 657.

7. J.H. Billen et al., An RFQ as a Particle decelerator, Proc. Third LEAR Workshop, p. 107.
   C. Biscari, F. Iazzourene, Post-deceleration of the LEAR beam by a radiofrequency quadrupole, Proc. Third LEAR Workshop, p. 115.

8. G. Gabrielse, this Workshop. See also: G. Gabrielse et al., Precision comparison of antiproton and proton masses in a Penning trap, Proc. Third LEAR Workshop, p. 665.

9. G. Carron et al., Status and future possibilities of the stochastic cooling system for LEAR, Proc. Third LEAR Workshop, p. 121.
See also D. Möhl, Phase-space cooling techniques and their combination in LEAR, Proc. second LEAR Workshop, p. 27.

10. A. Wolf et al., Status and perspectives of the electron cooling device under construction at CERN, Proc. Third LEAR Workshop, p. 129.

11. D.J. Simon, The LEAR experimental areas, Proc. Second LEAR Workshop, p. 55.

12. D. Möhl, Technical implications of possible future options for LEAR Proc. Third LEAR Workshop, p. 65.

13. A. Santroni, Spectroscopy at LEAR using an internal hydrogen jet target, Proc. Third LEAR Workshop, p. 409.
M. Macri, A clustered H_2 beam, Proc. Second LEAR Workshop, p. 691.

14. U. Gastaldi et al., High resolution spectroscopy of $p\bar{p}$ atoms produced in flight ..., Proc. Third LEAR Workshop, p. 681.

15. L. Bracci, G. Fiorentini, O. Pitzurra, Phys. lett. 85B (1979), p. 280.

16. P. Dalpiaz, Experimental possibilities of charmonium and bottonium spectroscopy, Proc. Second LEAR Workshop, p. 725.
P. Dalpiaz, Charmmonium and other onia at minimum energy, Proc. First LEAR Workshop, "Physics with cooled low energy antiprotons", Karlsruhe (Germany) 1979, p. 111 (Kernforschungszentrum Karlsruhe, KfK report 2836 , ed. H. Poth).

17. E. Gianfelice et al., A superconducting low energy antiproton ring (Super-LEAR), Proc. Third LEAR Workshop, p. 83.