PS/LR/Note 78.8
PS/DL/Note 79-1
20 January 1979

CONCEPTUAL STUDY OF A FACILITY FOR LOW ENERGY ANTIPROTON EXPERIMENTS

Status report in preparation of the Karlsruhe Workshop on Physics with Cooled Low Energy Antiprotons, 19 to 21 March 1979, by

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1. INTRODUCTION

The idea to add to the Antiproton Accumulator 1) (AA) which is being built at CERN, a facility for experiments with low energy antiprotons 2),3) has received enthusiastic support from many members of the CERN physicists community. It would provide improvements by several orders of magnitude in experimental conditions (rate, momentum definition, pion contamination) and open new fields of experimentation.

In this study the following scheme is considered : antiprotons would be taken at suitable intervals from Antiproton Accumulator, injected anticlockwise into the PS, decelerated, and injected into a small storage ring (LEAR for Low Energy Antiproton Ring) where they would be available for various types of experiments.

Experiments with an external $\bar{p}$ beam are amongst the most important so far proposed and the use of this ring as "stretcher", providing a $\bar{p}$ beam with a high duty cycle, is considered here as its main purpose. The storage ring could eventually also be used for collision experiments, for work with an internal target or other purposes. Some typical options are commented in Chapter 5.

2. AVAILABILITY OF ANTIPROTONS

The construction of a facility for low energy $\bar{p}$ experiments will bring the number of $\bar{p}$ facilities at CERN to three : SPS, ISR, LEAR. The question whether enough $\bar{p}$ can be produced to support three lines of physics must be answered.

The SPS will always have top priority, irrespective of whether it runs protons or antiprotons. It is currently assumed that the SPS will run as $p\bar{p}$ collider for about three months per year and the normal annual shutdown of the CERN machines is of the order of 2 months. ISR and LEAR can then be allowed to run during the remaining seven months in parallel with SPS proton physics and sharing the remaining protons with other customers. Some allowance must also be made for the further development of stochastic cooling and stacking techniques.

Although details of the PS/SPS schedule for the years beyond 1980 are not yet fixed, the proton economy can be approximately evaluated as follows. The normal duration of the SPS cycle is about 12 s, of which filling by 5 batches from the PS will take about 2.5 s. During the remaining 9.5s the PS can produce 4 bursts of 26 GeV protons.

One sees that for about 80% of the time the PS is available for the combination of LEAR and ISR $\bar{p}$ physics, and other users, during about six months per year (allowing one month for AA machine development). As will be shown later (Chapter 4.3) LEAR can produce an external $\bar{p}$ beam of more than 10^6 $\bar{p}$/s (time average) by using two of the four bursts available from the PS, leaving the other two for other users (25 GeV physics)

It appears too early to discuss the sharing of the six months per year available between ISR and LEAR but one can imagine that LEAR (and 25 GeV physics) operation would alternate with ISR filling. It is currently assumed 4) that ISR would stack during five days and then run on for as long as is useful.

The reader will realize two implications of the above :

- the AA is assumed to run continuously like any other fully operational machine, rather than being "part of an experiment" as sometimes thought previously ;
- 25 GeV physics will see the amount of PS time available seriously decrease due to the $\bar{p}$ programme.

3. SURVEY OF POSSIBLE SCHEMES

For the project of the high energy $p\bar{p}$ facility, the 3.5 GeV/c $\bar{p}$ from the AA are being brought to the PS for acceleration to 26 GeV/c prior to injection into the SPS. Similarly, the $\bar{p}$ for the low energy facility would be decelerated in the PS and then be transferred to a storage ring located in one of the existing experimental areas.

The preferred experimental area is the South Hall, which provides the required surface area and adequate infrastructure for the storage ring as well as for experiments installed on it or along ejected $\bar{p}$ beams from it. It is possible to transfer the $\bar{p}$ from the PS to the South Hall (by going through the tunnel of the old linac) by modifying equipment in the PS used for the inflection of 50 MeV protons, without requiring additional straight section space. This is an important consideration as straight section space is an invariant and extremely rare quantity in the PS. Also, 50 MeV protons and H^- ions obtained from the old linac could be brought to the $\bar{p}$ storage ring through the same channel.

It has been suggested to also consider the use of the ICE ring, (in its present location), which might possibly be the cheapest way to obtain a low energy $\bar{p}$ facility of limited potential. We discard this suggestion here because of its inherent limitations and because of the arguments given in the previous paragraph : the infrastructure for an experimental area around ejected $\bar{p}$ beams from the ICE ring would have to be created, and a new ejection point and external beam, including major civil engineering work would have to be implemented on the PS in order to bring the $\bar{p}$ which turn in counterclockwise direction in the PS, into ICE. It appears more interesting to use ICE with a $\bar{p}$ beam derived from a target in the ex-neutrino tunnel and so bridge the time in between now and the operation of LEAR.

Figure 1 shows a layout of LEAR in the PS South Hall. We assume four fixed sector magnets with strong focusing elements in between. The magnets should preferably be laminated in order to permit a reasonable acceleration rate, but an existing solid core magnet (g-2 ring) could in the limit also be used to start with. The focussing properties of the machine would be modified as required by the various experimental purposes envisaged (cp. Chapter 5).

4. THE PROPOSED LOW ENERGY $\bar{p}$ FACILITY

4.1 Typical lattice

It is not trivial to design a lattice for this small ring that permits to have long free straight sectors and to shift the transition energy out of the working range.

In Table 1 possible lattice parameters for a low energy stretcher ring are listed. More work is needed to optimize the lattice. However, the model presented here should suffice to permit cost and performance estimates. The bending radius of the magnet quadrants is chosen corresponding to the envisaged momentum range of the ring, 0.1 to 1.7 GeV/c. For comparison, parameters are given in Table 2 for a ring with a bending radius of 7m, which is the bending radius of the g-2 ring magnet now used for the ICE set-up.

4.2 Acceleration

It is proposed to include an acceleration cavity in the machine. On the one hand this will permit to attain energies lower than 50 MeV, and on the other hand, the beam could be transferred from the PS at a fixed energy higher than 50 MeV, the advantage being a constant and correspondingly smaller emittance at transfer. The energy would then be adjusted in the storage ring as required for the experiments.

Finally, H^- would only be available at 50 MeV from the old linac ; for experiments at any other energy acceleration in the storage ring would be a prerequisite.

The required frequency range would be in the band which the cavities of the PS can be tuned to. There are still cavities of the old PS RF system available. A laminated magnet permitting a reasonable acceleration rate would then be essential.

4.3 Slow ejection from a stretcher

It was initially though that each batch of $\bar{p}$ was to be separately stacked and cooled in the AA. A slow ejection of a duration similar to the cooling time, at least one hour, would then be necessary and this appeared as a major obstacle to the realization of a stretcher ring. Two ideas have helped to open the impass :

- it was realized that it will be possible to create in the AA a stack of $\bar{p}$ of a desired density from which small batches can be skimmed off ("unstacked") by the RF system at suitable intervals, the stack being continuously replenished.
- The proposal of "stochastic ejection" 5),6), i.e., an ejection process stimulated by RF noise, opens a way to producing spills of hitherto impossible duration.

The problem is then reduced to the one of finding a set of paramaters which will yield useful $\bar{p}$ rates in the ejected beam and a high duty cycle.

The expected rates look roughly as follows :
the AA is designed to make available about 6.10^{11} $\bar{p}$/day or 7.10^{6} $\bar{p}$/s as a time average if the PS runs for $\bar{p}$ production exclusively *). We make the

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*) 1 PS pulse per 2.6s is assumed in the AA design study 1). This cycle is dictated by the present assumptions about the speed of momentum cooling. The PS could provide one pulse every 2s approximately.

assumption that $\bar{p}$ production for LEAR will be done in parallel with SPS and 25 GeV proton physics and that about 40% of the above $\bar{p}$ production rate can be obtained (cp. Chapter 2). Assuming furthermore a total $\bar{p}$ transfer efficiency of 60% from the AA through the PS and LEAR into the external $\bar{p}$ beam, (5 ejection and injection operations with an average efficiency of 90%), one obtains an average rate at the experiment of $7 \times 0.4 \times 0.6 \times 10^6 = 1.7 \cdot 10^6\ \bar{p}/s$.

The expected duty cycle will depend on the success of stochastic ejection. As the filling of LEAR once it has become routine, should only take a few seconds for preparing the settings, and spills of a few hundred seconds appear possible according to theoretical work, a duty cycle of 90% or more can be expected. Tests made at the PS have so far shown the mechanism to work, but the demonstration of very long spills requires special running conditions of the PS at low energy and these will be available for spring 79. Taking a very pessimistic view one would expect at least 15 to 20% duty cycle, typical of the beams in the East Hall, using in the limit a classical resonant extraction.

4.4 Vacuum

The residual gas pressure is an obvious limit to the beam lifetime in a storage ring, in particular at low energies. It has, however, been demonstrated in the ICE experiment that the effect of multiple scattering can be cancelled by stochastic cooling at a pressure of a few 10^{-9} Torr. Hence, for stretcher operation only, a "normal" vacuum system, rather than ISR type, would be sufficient.

For the operation of LEAR as $p\bar{p}$ collider (option 5.1) an extreme vacuum will be required in order to reduce the background in the interaction region. As the vacuum system is one of the basic components of the machine which cannot easily be changed later, it is proposed to provide for an ISR type vacuum system in the initial design of LEAR.

4.5 Cooling

It seems that cooling will become indispensable for the optional uses of LEAR, but it is also advantageous for the stretcher operation for two reasons :

i) cooling could allow to extend the limits imposed by adiabatic anti-damping when decelerating further down ;

ii) cooling alleviates the vacuum requirement (see Chapter 4.4)

A crude estimate shows that with stochastic cooling, cooling rates of an interesting order of magnitude can be obtained : the minimum cooling time for perfect mixing and negligible noise is given by the bandwidth W used and the number of particles N

$$\tau_{\text{emitt}} \geq \frac{N}{W}$$

and one obtains the order of ten seconds for the stretcher mode. This means that deceleration by a factor 2.7 in momentum (with compensation of the adiabatic blow-up) would take about 10 seconds, and this seems quite acceptable. The cooling rate would also compensate Coulomb scattering at about 10^{-9} Torr down to approx. 200 MeV/c. For electron cooling, cooling times about one order of magnitude smaller have been obtained at Novosibirsk.

It appears at the moment that the installation of a cooling system will have to be delayed for reasons of availability of manpower and budget.

4.6 Deceleration in the PS

The low energy $\bar{p}$ facility will require beam in two different conditions : small batches of $\bar{p}$ if used in stretcher mode (cp. 4.3), or the full stack of the AA (6 10^{11} $\bar{p}$) if used for some of the options. The batches must contain more than 10^9 $\bar{p}$, the lower limit for safe operation of the PS instrumentation (with some minor modifications).

4.6.1 RF matching

i) Transfer of small batches for the stretcher

The small batches are obtained in the AA by creating a stack of a few 10^3 $\bar{p}$/eV density and unstacking a momentum bite, typically about 1 MeV wide, such that a few 10^9 $\bar{p}$ can then be ejected. The required RF bucket is about the same as used in the unstacking procedure for the SPS, only the density of the $\bar{p}$ bunch is smaller. The precise parameters can , of course, only be determined once the AA has run.

Several transfer schemes are possible with the radius ratio of 10/2·5/1 between PS/AA/LEAR. As an example assume that the normal bucket of 6 mrad in the AA is compressed to a length smaller than $2\pi \times 10$m to fit into one h = 10 PS bucket. In Table 5, last column, the available and the required buckets areas are listed. The bunch can conveniently be decelerated down to $\beta = 0.5$ ($\simeq$ 0.6 GeV/c) until it meets the frequency limit (f_{min} = 2.5 MHz) of the PS cavities.

If one wants to decelerate down to 50 MeV, the harmonic number 20 must be used in the PS. In this case the unstacking bucket must be chosen to be smaller than 4 mrad in order to be able to decelerate the beam in one PS bucket.

The required RF voltages in the PS are given by

$$\frac{U_{PS}}{U_{AA}} = \left(\frac{R_{PS}}{R_{AA}}\right)^2 \frac{h_{AA}}{h_{PS}} \cdot \left|\frac{\eta_{PS}}{\eta_{AA}}\right|$$

The AA beam being bunched at full voltage (14 kV), 7 kV and 3.5 kV will be needed in the PS for harmonic number 10 and 20 respectively. For the lower value, some improvement of the system may be needed.

ii) Transfer of the full AA stack

For the modes where one wants to put the whole AA beam with a bucket area of 72 mrad into one bucket of LEAR, one will proceed in a way similar to transferring $\bar{p}$ to the SPS. The beam must be unstacked into a number of batches e.g., 10. These would be transferred into the PS buckets at a suitable PS harmonic number, decelerated either one by one or all in one PS cycle, and injected into LEAR by a multi-turn injection process.

4.6.2 Transverse acceptances

The transverse beam emittances are limited by the AA ejection channel and can be expected to be about the same in i) and ii).

Proton beams have been decelerated in the PS for injection into ICE from 800 MeV down to as low as 50 MeV with no losses other than to be expected from adiabatic growth of the emittances, and a total blow up less than a factor of two on the well compensated stop bands in the domain of strong space charge 9).

To work out the beam emittances that can be decelerated without loss we assume that emittances of 40π mm mrad horizontally and 20π mm mrad vertically can be safely handled and transferred. Actually the acceptance of the PS chamber is larger (say hor. x vert. = 100π x 40π) but it is impossible to eject and transfer such large beams.

In Table 5 the required beam properties at 3.5 GeV/c (AA ejection) are summarized as a function of the final energy after deceleration.

For the purpose of comparison the table includes the design properties of the AA beam at transfer (after 24h of accumulation). One notes that even for deceleration to the lowest energy the PS transverse acceptances are safely larger than the AA beam with 6×10^{11} $\bar{p}$ leaving enough margin for possible blow-up on stop bands.

4.7 Beam transfer from the PS to LEAR

Several possibilities exist to feed LEAR with a $\bar{p}$ beam from the PS. As an example we mention one solution where the $\bar{p}$ beam is fast ejected from ss 26. The beam transfer line is chosen parallel to the old linac and passes through the Linac building (Fig. 1).

The transverse emittances of the PS beam are assumed to be ≤ 40 and $\leq 20\pi$ mm mrad in the horizontal and vertical plane, respectively. The ejection septum (with an aperture of 70×45 mm^2) is supposed to deflect the $\bar{p}$ beam 70 mrad.

The transfer line ($\sim$ 100m) can transport $\bar{p}$ with a momentum ≤ 1.7 GeV/c using standard PS elements. High vacuum (without windows) is required to transport $\bar{p}$ of low momentum. Some special elements (collimators, etc.) and instrumentation have to be envisaged. A large part of the equipment from the ICE transfer line could be used.

Some civil engineering work is required for passage through the Linac building.

4.8 Experimental area

In the South Hall, two experimental areas may be available if two (or three) of the five test beams are abandoned.

The $\bar{p}$ beam ejected from LEAR could feed simultaneously two experiments by using a splitter magnet. By means of a bending magnet placed in one branch, one could in addition feed alternately a third experiment.

Two vertical steering magnets placed in front of the splitter magnet would make possible the adjustment of the intensity in each branch between 0 and 100% with low losses.

The elements needed are supposed to exist, except the external splitter magnet and the necessary instrumentation.

Some power supplies have to be moved from the East Area to the South Generator Building. Cooling water and general services which may be required exist in the South Area.

4.9 Cost

For a cost estimate, we assume that this facility be treated like an experiment, or a series of experiments, in one of the 25 GeV areas, whose normal services and infrastructure are available free of charge : beam transport, power supplies, water, etc. It is also assumed that available control computers are used (e.g., those available in the South Hall in the New Linac Control Room) as well as obsolete quadrupoles from the PS. Only items that are acquired specifically for the present purpose are accounted for.

Under these assumptions we arrive at costs of about

7.5 MFr	for a new ring
5 MFr	for a ring using the magnet and a few other components of the ICE ring.

The cost of cooling equipment and the options (Chapter 5) are not included in these figures.

5. OPTIONAL USES OF THIS FACILITY

The use as a beam stretcher is the prime motive for the construction of this facility. Some other uses have also been proposed and the present, still very preliminary, status of the technical considerations is summarized in this Chapter.

5.1 Luminosity in $p\bar{p}$ collision operation

To work out an upper limit for the luminosity we assume head-on collisions *) of a proton and an antiproton bunch of 6×10^{11} particles (each design figure for the AA beam after 24 hours of stacking) at 1.7 GeV/c.

The luminosity obtainable depends on the transverse beam size and on the amount of bunching which in turn is limited by the available RF, by longitudinal and transverse space-charge effects, and by intra-beam scattering. It is given by

$$L = \frac{N^2 f_{rev}}{A_{int}}$$

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*) The alternative of having long bunches or coasting beams with separation of $\bar{p}$ and p beam and crossing in the interaction region will be investigated.

In an optimised collider, designed to the beam-beam limit 7) the luminosity is given by

$$L = \frac{f_{rev}\ \gamma\ N\Delta\nu}{(1+\beta^{-2})r_p\beta^*_v} \qquad \text{(see Appendix 2 for a glossary of symbols)}$$

and the beam parameters summarized in Table 3, (especially $\beta^*_v = 5\text{m}$) and $\Delta\nu = 5\cdot 10^{-3}$ yield an upper limit for the luminosity of

$$L = 1.5 \times 10^{29}\text{cm}^{-2}\text{sec}^{-1} \text{ at } 1.7 \text{ GeV/c}.$$

The beam satisfies the classical criteria for longitudinal and transverse stability (cp. App. 1). However, the luminosity depends critically on the assumed tight bunching (< 1/10)and small momentum spread ($\Delta p/p < 10^{-4}$). This necessitates a strong RF system and strong momentum cooling. In this context one can argue that several hours could be spent for cooling each injected batch.

The small momentum spread may also lead to fast beam decay due to intra-beam scattering. It is not yet clear whether the existing theory of this effect 8) is applicable to the present problem, and this matter is being investigated.

We estimate that a luminosity about one order of magnitude below the above limiting value could be realistically expected to start with. Note that for the lattice, Table 2, with the larger magnets, the luminosity would be lower by at least 5 because the circumference is larger, β_H, β_V bigger and the acceptance smaller.

Assuming a layout as indicated in Fig. 1, protons could be rather easily obtained from a septum magnet to be installed in ss 2 of the PS. The fast ejection kickers and orbit deformation magnets are already available in the PS, and only the septum magnet need be added.

5.2 Operation with an internal target

Two things are needed in order to run LEAR with an internal target (gas jet or foil) :

i) strong transverse cooling (stochastic or electron beam) is necessary in order to compensate the beam blow-up due to multiple scattering.

ii) A low β value at the target is necessary in order to reduce the losses due to single Coulomb scattering, and may also ease the design of the jet target.

In Table 4 some parameters for a modified working point giving $\beta_V = 0.2$m and $\beta_H = 2$m are summarized. The largest scattering angle which does not lead to losing the $\bar{p}$ out of the beam, is then 7 mrad rather than 2.5 mrad for the working point of Table 1, and losses are reduced by a factor of 6. Still smaller β values may be possible using a special low β insertion.

5.3 Overlapping beams

It is proposed to have two beams (H^- and $\bar{p}$) circulate in the same ring in the same direction. If the two species are kept by the same RF system the difference in mean radial position at the interaction point and in velocity will be given by

$$r = \alpha_p \gamma_t^2 \left(\frac{1}{\gamma_t^2 - \gamma^2}\right) \frac{\Delta m_o}{m_o}$$

and

$$\frac{\Delta\beta}{\beta} = \left(\frac{1}{\gamma_t^2 - \gamma^2}\right) \frac{\Delta m_o}{m_o}$$

(see App. 1 for glossary of symbols)

With $\Delta m/m = 10^{-3}$, $\alpha_p = 1.9$m, $\gamma_t^2 = -5.3$, $\gamma \simeq 1$

one obtains

$$\frac{\Delta\beta}{\beta} = 1.6 \times 10^{-4}$$

and

$$r = 1.6 \text{ mm}$$

Assuming the same parameters as in the collider mode this deviation in average position seems negligible as it represents less than 10% of the beam radius. The luminosity will be the same as in colliding beam mode multiplied by the velocity spread ($\Delta v/\beta c$) in the c.m. system.

The H^- ions of 50 MeV energy could be obtained from the old PS linac if an H source was installed instead of the present proton source. H^- sources have in fact been developed and are operational in other laboratories (NAL, LAMPF, RHEL). If a layout as in Fig. 1 was used, the H^- beam could be transferred from the old linac into the $\bar{p}$ transfer line by a 180° bend beyond the end of the linac.

The H^- lifetime due to stripping on the rest gas at 10^{-10} Torr is between 1 and 10s in the momentum range of LEAR. It will therefore be essential to devise an injection scheme that permits frequent H^- refilling without disturbing the circulating $\bar{p}$.

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TABLE 1

PRELIMINARY STRETCHER RING LATTICE WITH ρ = 3.5m BENDS

Momentum range	0.1 - 1.7 GeV/c
Circumference	62.8 m
Length of SS	10 m
Free length (regular lattice)	5.5 m
Number of SS	4
Maxima of lattice functions	$\beta_H \simeq$ 10m (5m in bends)
	$\beta_V \simeq$ 25m (15m in bends)
	$\alpha_p \simeq$ 2.2m (1.5m in bends)
Aperture of vac. chamber	$a_H = \pm$ 70 mm $a_V = \pm$ 32 mm
Beam apertures	$a_{H\beta} = \pm$ 45 mm
	$a_{H\rho} = \pm$ 45 mm
	$a_V = \pm$ 27 mm
Acceptances	E_H = 200 π mm mrad
	E_V = 30 π mm mrad
	$\Delta p/p = \pm$ 2.2 %

	1.7 GeV/c	0.1 GeV/c
Bending field	16 KGauss	0.9 KGauss
Integrated quad gradient (old PS quadrupoles)	411 G/cm.m	24 G/cm·m

Q values $Q_H \simeq 2.75$ $Q_V \simeq 2.75$

Transition energy $\gamma_t^2 = -(2.3)^2$

TABLE 2

PRELIMINARY STRETCHER RING LATTICE WITH ICE (0 GRADIENT) BENDING MAGNETS

Momentum range	0.3 - 1.7 GeV/c	
Circumference	≃ 85 m	
Length of SS	10.4 m	
Free length of SS (regular lattice cell)	5.5 m	
Number of SS	4	
Maximum of lattice functions	β_H = 18 m (12 m in bends)	
	β_V = 25 m (18 m in bends)	
	α_ρ = 3.5 m	
Aperture of vac. chamber	$a_H = \pm 70$ mm	$a_V = \pm 32$ mm
Acceptances	E_H = 100 π mm mrad	
	E_V = 27 π mm mrad	
	$\Delta p/p = \pm 1.2$ %	
	1.7 GeV/c	0.3 GeV/c
Bending field	8 KGauss	1.4 KGauss
Integrated gradient in quads (old PS quadrupoles)	≃ 400 Gm/cm	70 Gm/cm
Q values	$Q_H \simeq 2.75$	$Q_V \simeq 2.75$
	$\gamma_t^2 = -5.3$	

TABLE 3

COLLIDING BEAM PROPERTIES

1. Lattice parameters	
Lattice functions (average) in interaction region	
$\beta_H \simeq \beta_V$(m)	5
Momentum compaction α_p (m)	1.9
Transition energy γ_t^2	$-(2.3)^{-2}$
2. Beam parameters and luminosity	
Momentum (GeV/c)	1.7
No of particles ($N_{\bar{p}} = N_p$)	6×10^{11}
Beam size (2 rms) hor.xvert. (mm^2)	29 x 10
Corresponding emittances $E_h x E_v$ (πmm mrad)^2	170πx 20π
Bunched beam momentum spread $\pm\Delta p/p$	1×10^{-3}
Bunch length (total m)	5
Luminosity (cm^{-2}sec^{-1})	1.7×10^{29}
3. Auxiliary quantities	
RF voltage/turn (kV)	60
Frequency, h=1 (MHz)	4.2
Off energy function $1/\gamma^2 - 1/\gamma_t^2$	0.42
Beam beam tune shift $\Delta\nu$	5×10^{-3}
Laslett space-charge limit N_{ic}	2.2×10^{13}
Tolerable impedance/n at nth Revolution harmonic : $\lvert Z_n/n \rvert$(Ω)	120

TABLE 4

MODIFIED WORKING POINT FOR INTERNAL TARGET OPERATION

Lattice function			
maxima	$\beta_H = 30$ m	$\beta_V = 30$ m	$\alpha_p = 1.8$ m
in center of straight sectors	$\beta_H = 2.1$ m	$\beta_V = 0.3$ m	$\alpha_p = 0.8$ m
in bending magnets	$\beta_H = 27$ m	$\beta_V = 6$ m	$\alpha_p = 1.6$ m
Acceptances	$E_n = 80\pi$mm mrad	$E_V = 25\pi$mm mrad	
	$\Delta p/p = \pm 2.2$ %		
Maximum acceptable angles at center of SS	$\Theta_H = 6$ mrad		
	$\Theta_V = 9$ mrad		
	$\sqrt{\Theta_H \Theta_V} = 7.5$ mrad		
Q values	$Q_h = 3.25$	$Q_V = 3.25$	$\gamma_t = 3.02$

TABLE 5

PS ACCEPTANCES REFERRED TO 3.5 GeV/c

Energy after deceleration		Maximum acceptable beam at 3.5 GeV/c			
		Transverse emittance		longitudinal emittance	
pc (GeV)	T (GeV)	E_H (πmm mrad)	E_V (πmm mrad)	A (mrad)	
				h = 20	h = 10
1.7	1.0	19	9.5	63	89
0.64	0.2	7.3	3.6	28	40
0.55	0.15	6.3	3.1	26	-
0.44	0.1	5	2.5	25	-
0.31	0.05	3.5	1.7	23	-
AA design values		1.4	1	6*) 30	15

Acceptances of $E_h = 40\pi$ mm mrad, $E_v = \frac{1}{2}E_h$ at transfer to the stretcher have been taken together with adiabatic scaling $E\beta\gamma$=const. The longitudinal PS acceptance has been worked out assuming stationary PS buckets supplied by the maximum available RF voltage (200 kV) and the usual PS frequence (h=20). For h=10 A is larger by $\sqrt{2}$.

*) If the AA bunch is transferred into one single PS bucket the area matching 6 mrad of the AA is 30 mrad at h = 20 in the PS and 15 mrad at h = 10. For deceleration with h = 20 it is proposed to use an unstacking bucket of 4 mrad in the AA which leads to bucket of 20 mrad in the PS.

APPENDIX 1

FURTHER COMMENTS ON THE COLLIDER OPTION

The parameters of Table 3 meet the condition (for $k_B=1$)

$$A_{int} = \frac{\pi}{4}\, hw = \frac{N^2 f_{rev}}{4L} \qquad \text{(see Appendix 2 for glossary of symbols)}$$

with a beam size that fits into the aperture. Also the intensity is below the Laslett limit :

$$N = \frac{\pi h(h+w)}{r_p \beta_v}\, \beta^2 \gamma^3\, \Delta Q$$

at 1.7 GeV/c. The assumed momentum spread can be contained in a 5m long bunch with an RF voltage

$$U = \frac{\pi}{2} |\eta| \beta^2 \gamma \left(\frac{\Delta p}{p}\,\frac{1}{y}\right)^2 938 \text{ MV} \simeq 60 \text{ kV}$$

(y = bunch $\Delta p/p$ / bucket $\Delta p/p \simeq 0.13$ for
B = bunch length / bucket length = 5/63)

This spread meets the longitudinal stability limit (local Keil-Schnell criterion)

$$\left| Z_n/n \right| \leq \frac{B \eta p \beta}{I} (\Delta p/p)^2$$

for a coupling impedance $Z_n/n \leq 120\Omega$ (25Ω seem to be obtained in PS and ISR).

We note that strong cooling will be necessary to reduce the momentum spread to a value which permits the tight bunching assumed.

The assumption $\beta_V^* \simeq \beta_H^* \simeq 5$m needs some further comment. For head-on collision the optimum luminosity (p. 10) can only be reached if the bunch length ℓ is $\ell \lesssim \beta$ or in other words there is no use in making $\beta < \ell$. The value $\ell = 5$m corresponds to the free length of the straight section and is also a lower limit of what can be obtained with a reasonable RF system.

Finally for our model lattice the average values of β_V and β_H over the straight section are close to 5m so that no special insertion is necessary.

APPENDIX 2

GLOSSARY OF SYMBOLS

A	Bunch area in units of $\Delta(\beta\gamma)\cdot\phi_{RF}$
A_{int}	effective colliding beam interaction area
	$A_{int} = \frac{\pi}{4}\,hwk_B = \frac{\pi}{4}\,a_V\,a_{H\beta}k_B$
$a_{H\beta}$, a_{Hp}, a_V	peak amplitudes (2σ) for horizontal betatron motion, synchrotron motion and vertical betatron motion respectively.
$a_H=(a_{H\beta}^2+a_{Hp}^2)^{\frac{1}{2}}$	horizontal beam half-width (2σ)
B	bunching factor = average current over peak current
E_H, E_V	horizontal, vertical emittances, respectively
	$E_H = \pi a_{H\beta}^2/\beta_H$ $\qquad E_V = \pi a_V^2/\beta_V$
$f_{rev}=\frac{\beta c}{2\pi R}$	revolution frequency
h_{PS}, h_{AA}	harmonic numbers for RF systems in the PS and AA respectively
k_B	number of bunches per beam
L	luminosity
ℓ	total bunch length
$N(N_p,N_{\bar{p}})$	number of particles (protons, antiprotons) per beam
Q_H, Q_V	number of horizontal, or vertical, betatron oscillations per turn
ΔQ	Laslett tune shift (single beam)
$2\pi R$	circumference of machine
r_p	classical proton radius ($1.53\cdot10^{-18}$m)

r	horizontal (radial) deviation from equilibrium orbit
U	RF peak voltage (amplitude)
W	bandwidth of stochastic cooling system
y	bunch height/bucket height
$\lvert Z_n \rvert$	modulus of beam equipment coupling impedance at frequency $n \cdot f_{rev}$
α_p	$r/(\Delta p/p)$ momentum compaction function
β_H, β_V	horizontal, vertical reduced instantaneous wavelength for betatron motion
β^*, β^*_H, β^*_V	beta values in the interaction region
β, γ	relativistic velocity, total energy $\beta = v/c \qquad \gamma = (1-\beta^2)^{-\frac{1}{2}}$
γ_t	γ at transition energy
η	off-momentum function $(\Delta f/f)/(\Delta p/p) = \frac{1}{\gamma^2} - \frac{1}{\gamma_t^2}$
$\Delta\nu$	beam-beam tuneshift
ρ	magnetic bending radius