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A SUPERCONDUCTING LOW ENERGY ANTIPROTON RING (SUPER-LEAR)

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ABSTRACT

A 7 GeV/c proton-antiproton storage ring is considered as desired for charmonium and bottonium physics (see separate papers at this conference). Using superconducting magnets, a compact 120 m circumference ring (1.5 x LEAR) looks feasible. With 10^{12} antiprotons per day, it permits ultimate luminosities of the order of 3×10^{30} cm^{-2} s^{-1} for colliding beams and 10^{32} with internal targets.

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1. INTRODUCTION

Several groups[1,5] have expressed interest in an antiproton storage ring covering the range of, say, 2 to 7 GeV/c of circulating beam momenta. Working with internal targets and/or $\bar{p}$-p colliding beams, such a ring should permit precision measurements in a domain of centre of mass energies where a number of new particles and states containing c and b quarks have been found or are to be expected. This range (Figure 1) is currently not accessible with $\bar{p}$-p at CERN.

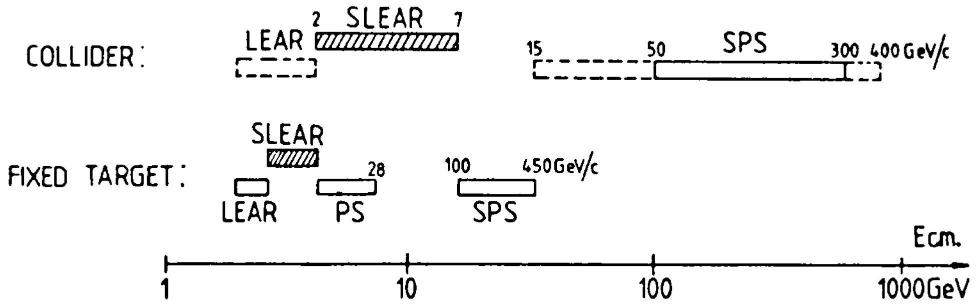

Fig. 1: Centre of mass energies available with $\bar{p}$+p

In the present note, we summarize some tentative machine aspects of a compact high luminosity storage ring to work in this "quarkonium[6] range". Our "design" is based on several new technologies including the use of superconducting magnets. They permit 10 GeV/c within a small circumference ("1.5 x LEAR") and hence cost effectiveness and fast revolution i.e. economic use of antiprotons and high luminosity.

2. LAYOUT

Basic parameters assumed are compiled in Table 1.

Momentum range	2-7 GeV/c
Injection momentum	3.5 GeV/c
Circumference	120 m
Intensity	$< 10^{12}\ \bar{p}$
Possible extension of momentum range (with superconducting quads and 9 Tesla instead of 4 Tesla bending magnets)	2-15 GeV/c

Table 1: SLEAR basic parameters

The tentative layout, which uses 8 superconducting 45° bending magnets and 16 normal conducting quadrupole doublets is sketched in Figure 2. The doublet structure has been chosen as it allows us to push transition energy above the working range.

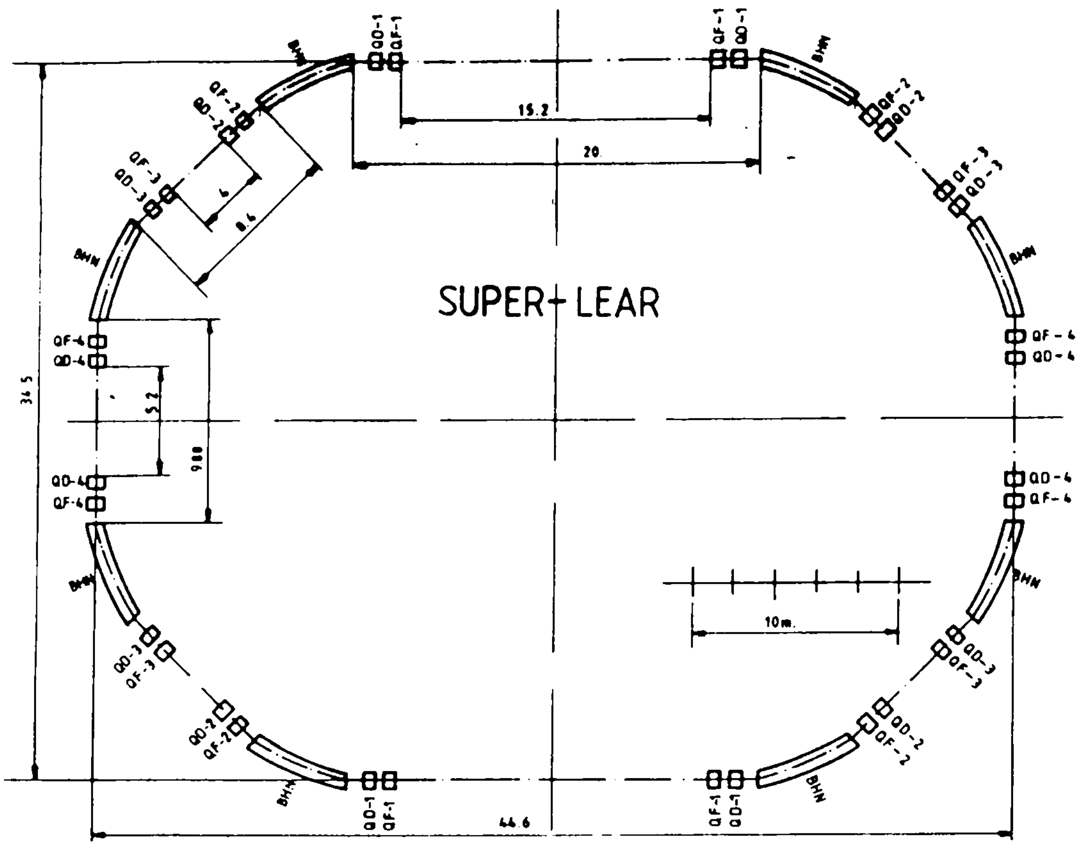

Fig. 2: SLEAR tentative layout

Table 2 summarizes the optical properties in the straight sections and equipment to be installed. Note that the medium straight sections have small beta (small beam size - large angular acceptance) and zero dispersion for the installation of the collision region and/or relatively thick targets. The short straights have large beta and large dispersion for targets or other applications requiring parallel beam and orbit separation by momentum.

Type :	Long	Medium	Short
Number	2	2	4
Length [m]	15	5	4
Typic. Beta(h) [m]	10	1.5	10
Beta(v) [m]	12	0.8	5
D [m]	-1.3	0	4.5
Equipment	Injection diagnostic corrections	Collisions targets RF	Cooling diagnostic targets

Table 2: Straight sections

Some characteristics of the bending magnets are given in Table 3. As an example, a 5 m long version (I) requiring 5 Tesla at 10 GeV/c and a shorter 4 m, 6.5 Tesla version (II) are considered. These fields are within the realm of present technology. With new types of superconductors now under development, fields of, say, 9 Tesla corresponding to 15 GeV/c in SLEAR could be aimed at. To work up to this momentum in a future extension, the quadrupoles also would have to be converted to a superconducting design (gradients of 30 Tesla/m instead of 15 Tesla/m assumed in the "normal" layout). Ramping of the fields from injection (3.5 GeV/c) to the final momentum can be done very slowly (dB/dt < 1 Tesla/min), so that essentially "d.c." magnets can be used.

Superconducting magnets	Version I	Version II
Length (cent. orbit) [m]	5.0	4.0
Bending angle [deg]	45	45
Bending radius [m]	6.37	5.09
Sagitta (m)	0.5	0.4
Field at 10 GeV/c [T]	5.3	6.6
Bore diameter [mm]	100	100
Gradient (nominal)	0	0
Tolerances DB/B	1E-4	1E-4

Table 3: Superconducting bending magnets

Injection uses a septum in one of the long- and a fast kicker in the subsequent short straight sector. Antiprotons are directly transferred from ACOL-AA at 3.5 GeV/c. Proton injection (from the PS) for the collider mode can be done in the same long section or in the second one, depending on the location chosen for SLEAR. To save cost, location in an existing hall (West Hall ?, ISR service building 181 ?, East Hall ?) should be envisaged.

A vacuum of a few 10^{-12} Torr N_2 would give sufficient beam life ≈ 100 h) even at lowest energy.

A modest RF system (about 15 kV at 2.5 MHz, 10% frequency swing) is sufficient in the internal target mode to accelerate or decelerate the beam but very powerful systems are required to compress the beam into a very short bunch for head-on collisions; see Table 4 where a two and a three stage version are considered. The high voltage bunch compression cavity could possibly be superconducting.

Phase-space cooling both stochastic (with time constants of several hours at 10^{12} $\bar{p}$) and electron cooling are desirable to prepare the beam and to keep it in shape. This is to be discussed in L. Tecchio's talk[7].

This concludes our overview of the layout considered. Work is needed to arrive at a more detailed design but the considerations presented should allow us to make performance estimates. This will be the subject of the rest of this talk.

System	Harmonic	Frequency	Amplitude	Bunch length
RF1	1	2.5 MHz	15 kV	100-10 m
RF2	10	25.	100 kV	10--1 m
		Alternative	:	
RF1	1	2.5 MHz	15 kV	100-10 m
RF2	10	25. MHz	20 kV	10--3 m
RF3	30	75. MHz	40 kV	3--1 m

Table 4: RF systems to compress the bunch to a length of 1 m. In all cases, cooling is assumed to have a momentum spread of < 1E-3 of the bunch.

3. PERFORMANCES

In any interaction, the luminosity attainable is ultimately limited by the flux of particles available. Matching the consumption

$$dN/dt = L \cdot \sigma_{loss} \qquad (1)$$

to the production rate ($\phi \approx 10^7$/s in our case) and taking a total cross-section of $\sigma \approx 100$ mb ($\hat{=} 10^{-25}$ cm^2) to approximate $\bar{p}$-p interactions in the 2-10 GeV/c range, one obtains:

$$L < \phi / \sigma \approx 10^{32} \text{ cm}^{-2}\text{s}^{-1} \qquad (2)$$

For the internal target mode, conditions close to this performance limit can (in principle) be reached by a judicious choice of target thickness and filling cycle. As an example, let us assume a filling cycle ($1/t_f$) of once per 10^5 s ($\approx$ 24 h) with a transfer of 10^{12} $\bar{p}$, as a result of a production rate of 10^7/s. A matched target uses up this beam (to say 1/e) in 10^5 s. It has a density

$$nd = (f_{rev} \; \sigma \; t_f)^{-1} = 4 \times 10^{13} \text{ (H atoms/cm}^2) \hat{=} 0.7 \times 10^{-10} \text{ g/cm}^2 \qquad (3)$$

This is about half the density of the ISR gas target [8] and thus perfectly feasible. In fact, it may be preferable to work with a, say, 5 times thicker target ($\rho d \approx 3 \times 10^{-10}$ g/cm^2) needing transfers of $\approx 2 \times 10^{11}$ $\bar{p}$ once every 5 hours. In both cases, $L \to 10^{32}$ cm^{-2}s^{-1}.

For the colliding beams, various intensity and beam density limitations enter into play which make it difficult to reach the limit of $L \to 10^{32}$cm^{-2}s^{-1} Probably most stringent is the beam-beam effect [9] and only this effect will be discussed here: current understanding is [9] that the nonlinear space-charge field of beam 1 experienced by beam 2 in the interaction region leads to a degradation of beam 2 (and vice versa for the effect of beam 2 on beam 1). The linear part (ΔQ) of the tune shift is used as a measure of the beam-beam effect and rapid beam degradation is expected in hadron colliders when $\Delta Q > 5 \times 10^{-3}$.

The tune shift of the antiprotons can be approximated by [9]

$$\Delta Q_{\bar{p}} = r_o \frac{N_p \beta_v^*}{A} \left(\frac{1 + \beta^{-2}}{4 \gamma} \right) \qquad (4)$$

where r_o = 1.5×10^{-18} m

β_v^* = focussing function of storage ring in interaction point (1 m assumed)

$A \approx \pi(\sigma_h \times \sigma_v)$ = effective transverse beam area in the interaction region: a horizontal beam size $\sigma_h \gg \sigma_v$ much larger than the vertical one is assumed.

This expression (4) as well as the corresponding relation for the proton tune shift depends in much the same way on beam density N/A as does the luminosity

$$L = \frac{N_{\bar{p}} \; N_p \; f_{rev}}{4 \; A} \qquad (5)$$

Combining (4) and (5) we find a luminosity limit

$$L = \frac{N_{\bar{p}} \; f_{rev} \; \Delta Q}{r_o \; \beta^*_v} \left(\frac{\gamma}{1 + \beta^2} \right) \qquad (6)$$

For a given $N_{\bar{p}}$ (equal to N_p in an optimised design) and given revolution frequency f_{rev} (large for our small ring!), the only "free" parameter is the focusing strength $(1/\beta^*)$ of the storage ring at the interaction point. This dependence on β^* expresses the fact that stronger space-charge forces are acceptable at points where the focusing is strong, i.e. where the beta function is small. However. it is well known [9] that the focusing strength decreases rapidly with the distance (s) from a low beta point $(\beta = \beta^* + s^2/\beta^*)$ and, to avoid interaction outside the small beta region, the beams have to be well separated at $\Delta s = \pm \beta^*$ from the centre of the interaction region. In the head-on collision scheme, this is realized having a bunch length $\ell < \beta^*$. Since the RF voltage to make short bunches becomes very high (se table 4) and since the longitudinal and transverse stability of a bunch of 10^{12} p become very critical for bunches shorter than 1 m, we choose $\ell = 1$ m and adjust $\beta^* = \ell = 1$ m.

Number of particles per beam	$N_{\bar{p}} = N_p = 10^{12}$
Beam-beam tune shift	$\Delta Q = 5 \times 10^{-3}$
Lattice function at interaction point	$\beta^* = 1$ m
Bunch length	$\ell_b = 1$ m
Number of bunches per beam	$n_b = 1$
Revolution frequency	$f_{rev} = 2.5$ MHz
Resulting luminosity	$L = 3 \times 10^{30}$ cm^{-2}s^{-1}

Table 5: Colliding beam parameters at 7 GeV/c

We then arrive at a set of parameters given in table 5 which yields a luminosity of 3×10^{30} $cm^{-2}s^{-1}$. This is a factor of ≈ 30 below the "flux limit" (2) and to come closer to this limit ways to beat the beam-beam effect or to further decrease β^* are desired.

In Fig. 3, we reproduce results of ISR measurements[10] which show the very steep dependence of beam life (τ_b) on the tune shift discussed. One may hope to stabilize the effect with a cooling system of sufficient strength ($\tau_{cooling} \ll \tau_b$). This agrees with results from electron storage rings which - for radiation cooling times of the order of 0.1 to 1 s - manage to work with $\Delta Q = 0.025$. In SLEAR, assuming very powerful electron cooling[7] at 7 GeV with time constants of the order of a minute, we may hope to go to $\Delta Q = 0.015$-0.02 and thus gain a factor 3-4 in luminosity.

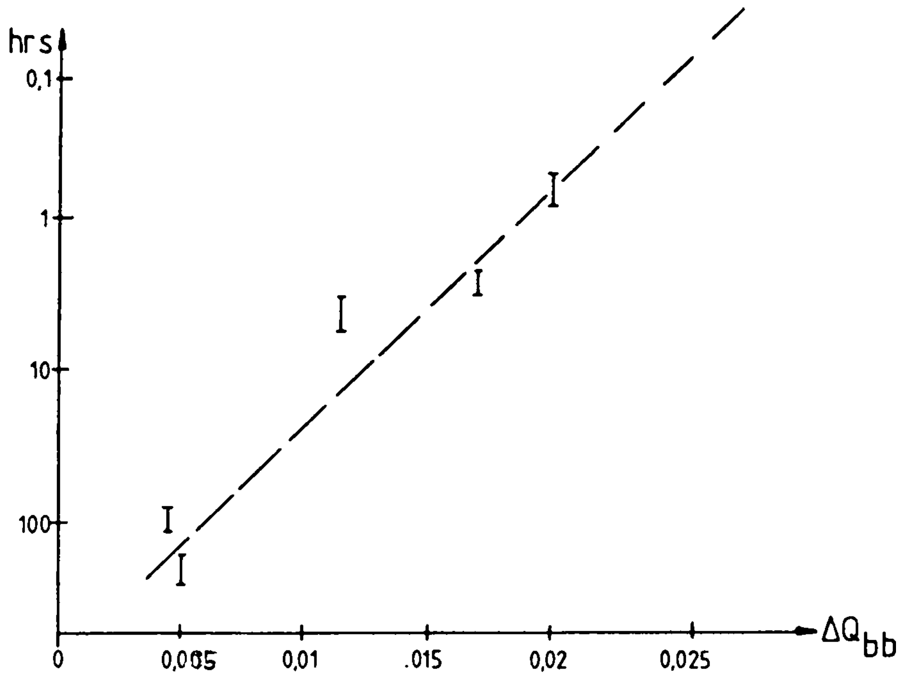

Fig. 3: Beam lifetime (without cooling) versus beam-beam tune shift. From reference 10.

Any further improvement has probably to come from a (still) lower beta. In the head-on scheme, this may pose difficulties for the detector - in addition to the storage ring problems sketched above - as the short bunch tends to introduce momentum spread and strong "modulation" of the interaction rate.

The solution then could be to have two rings with unbunched beams crossing at an angle as advocated by Bizzarri et al [11].

This could be a future extension to aim at luminosities beyond $10^{31} cm^{-2}s^{-1}$.

CONCLUSIONS

A compact high luminosity antiproton ring working in the 2 to 10 GeV/c range looks (so far) quite feasible. Small circumference and hence efficient use of antiprotons become possible by use of superconducting magnets. Ultimate luminosities of 10^{32} $cm^{-2}s^{-1}$ in the internal target mode and 3 x 10^{30} $cm^{-2}s^{-1}$ with $\bar{p}$-p colliding beams at 7 GeV/c can be expected for a single ring scheme with head-on collision. Strong phase-space cooling, a powerful RF system with superconducting cavities to make very short bunches and/or - perhaps - a two ring scheme with coasting beams may allow us also for the collider to aim at $L \rightarrow 10^{32} cm^{-2}s^{-1}$ which is the best obtainable with an antiproton production rate of 10^7/s.

Apart from being a valuable tool for particle physics, such a machine could be an attractive "test bed" of new accelerator technology.

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