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COLLIDING BEAM FACILITIES WITH THE SPS

by

K. Hübner, E. Keil, B.W. Montague, C. Pellegrini* and B. Zotter

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* Laboratori Nazionali di Frascati (Italy)

The following report summarizes some findings about the requirements which the SPS would have to fulfil if it were to become an efficient injector into future high-energy storage rings, and about the usefulness of a beam bypass for the SPS. Our main conclusions may be found in Chapter 3.

Much of the work reported here was done in connection with the CERN Laboratory II Spring Study on Accelerator Theory.

1. SUPERCONDUCTING STORAGE RINGS

1.1. Introduction

When the SPS comes into operation, it will provide an intense proton beam at an energy about ten times higher than the CPS. Among other things, this will open up the possibility of continuing, at a much higher energy, the colliding beam physics which has started in the ISR about a year ago.

It seems appropriate, therefore, to investigate now the possible consequences of the design and beam parameters of the SPS on the performance of storage rings which might be filled from it at a later stage. This need not necessarily now lead to building actual equipment; rather, the important parameters influencing the performance of storage rings should be identified, and those affecting storage ring performance should - within the framework of the present project definition - be suitably chosen. Finally options and space should be left open for additional equipment required for storage ring operation.

We shall therefore limit our present studies to, firstly, an investigation of the effect of SPS beam parameters on the performance of a hypothetical set of storage rings, and, secondly, to a demonstration that beams with these parameters can be accumulated in it. A design study of the storage rings we consider to be outside the scope of the present report.

We expect that by the time the SPS is in full intensity operation and the energy range accessible with the ISR has been explored, superconducting magnet technology will be at an advanced state. We therefore propose to base the present investigation on a conversion of the present ISR to a superconducting magnet structure to be housed in the same tunnel. (The conclusions arrived at in the following would, however, not be significantly different if we instead assumed a completely new set of storage rings.)

Some parameters are needed in the following for these storage rings which we call SSR: The average radius R is fixed by the ISR tunnel, R = 150 m. The energy will be in the range between 100 and 150 GeV, depending on the field strength which will be available in superconducting dc magnets, and on the length of straight sections which has to be foreseen in the storage ring design. We assume that most of the other parameters, of which the transition energy appears to be the most important one, will be in the vicinity of ISR parameters.

1.2. Transfer schemes

The method used for transferring the proton beam from the CPS to the SPS also influences the methods which are available for transferring the proton beam from the SPS to the SSR. In the following, we shall therefore list various possible transfer schemes CPS - SPS and the resulting transfer schemes SPS - SSR. All transfer schemes require transfer tunnels from the SPS into the two rings of the SSR. It appears that they can be built by branching off from the transfer tunnel towards the West Area. We start with the two official schemes: bunch-by-bunch and continuous transfer.

1.2.1. Bunch-by-bunch and continuous transfer CPS - SPS

These two schemes are described in Ref. 1. The various phase space emittances are listed in Table 1 which is essentially copied from Table 3.1. in Ref. 1. The two schemes have in common that the whole SPS circumference is filled. Therefore the same transfer schemes into the SSR can be used in the two cases.

The emittances shown in Table 1 have been arrived at by a process in which quite a number of safety factors were included for beam blow-up at various stages of the proton acceleration in the PSB-CPS-SPS complex.

This procedure is most appropriate when the machine aperture and RF bucket size are being fixed. Furthermore, a beam with the resulting phase space density is usually adequate for use by internal targets and slow ejection. In addition, it is the easiest among all possible beams in a given machine as far as the handling of space charge phenomena is concerned.

For filling a storage ring, on the other hand, a reduction in phase space area immediately results in a gain in performance - provided the resulting density can be handled in the storage ring itself. With this application in mind, it is therefore important to investigate the consequences of avoiding some of the blow-up factors included in Table 1, in particular in connection with space charge phenomena in the SPS.

1.2.1.1. Single-turn transfer SPS to SSR

A pulse of up to about 3 μs duration is ejected from the SPS by a fast ejection system and injected into the SSR by a fast injection system, in a way which completely corresponds to the filling of the present ISR from the CPS. The expected emittances are listed in Table 2. This scheme requires an ejection kicker magnet with a flat pulse of the required duration, and reasonably short rise and fall times, possibly synchronised with gaps in the SPS beam.

1.2.1.2. Two-turn and three-turn transfer SPS to SSR

Since the SPS beam is 2.2π km long, two or three pieces of it, 300π m long, may be ejected successively, and injected into the ISR by clean two-turn or three-turn injection, as described in Ref. 2 and 3. The expected emittances are listed in Table 2.

In these schemes no allowance was made either for emittance blow-up due to mismatch and/or field errors, or for the thickness of the septa needed for two-turn and three-turn injection. Experience with the ISR has shown that the mismatch can be made negligible, and that errors in injected beam position and angle can be damped by a feedback system. Whenever appropriate, an interchange of the horizontal and vertical emittance in the transfer channel has been assumed.

Both schemes require ejection kicker magnets with flat pulses of 6 and 9 μs duration, respectively, and reasonably fast rise and fall times, possibly synchronised with gaps in the SPS beam. If one wants to avoid injection into the SSR near a half-integral resonance, then the transfer into the SSR must take place in two pieces at 3 SSR revolutions interval. This requires double-pulsing the SPS ejection kicker magnet.

Table 1 - Assumed emittances in the SPS

Transfer	bunch-by-bunch	continuous	
$E_H \beta\gamma$	$75\ \pi\ 10^{-6}$	$25\ \pi\ 10^{-6}$	rad m
$E_V \beta\gamma$	$36\ \pi\ 10^{-6}$	$36\ \pi\ 10^{-6}$	rad m
A	0.18	0.08	rad

Table 2 - Emittances in the SSR

Injection	Current/ pulse	bunch-by-bunch				continuous			
					Current				Current
	[mA]	$E_H\beta\gamma$	$E_V\beta\gamma$	A	$\Delta p/p$ [A/%]	$E_H\beta\gamma$	$E_V\beta\gamma$	A	$\Delta p/p$ [A/%]
		µradm	µradm	rad		µradm	µradm	rad	
1-turn	69.5	75 π	36 π	0.18	2.42	36 π	25 π	0.08	5.45
2-turn	139	82 π	75 π	0.18	4.84	57 π	36 π	0.08	10.9
3-turn	208.5	144 π	75 π	0.18	7.28	100 π	36 π	0.08	16.35
bunched	500	75 π	36 π	0.03	100				

Table 2 also gives the current which - for the phase space density resulting from the emittances shown - can be stacked in a momentum bite of $\Delta p/p$ = 1%, assuming 100% stacking efficiency and γ = 100. These current figures are meant to be an indication of the phase space density achieved in the various schemes. Whether space charge phenomena allow these currents to be stacked will be discussed below.

1.2.1.3. Multi-turn injection into SSR

Multi-turn injection is the reverse of multi-turn ejection by "peeling" the beam off over a number of turns. No detailed investigation of this process was undertaken. However, it appears that it is either rather inefficient in phase space density, i.e. it dilutes the emittance in one transverse phase plane by at least a factor of 2, or it is rather inefficient in protons, i.e. only about half the protons are injected, the remainder being lost.

1.2.2. Phase-space density conserving transfer schemes ("bunched transfer")

The basic defect of the schemes mentioned above is the large dilution in longitudinal phase space due to letting the CPS beam debunch either in the CPS or in the SPS.

This dilution is avoided when the bunches coming from the CPS are captured in RF buckets immediately 4). A CPS bunch of 17 ns length fills 3 to 4 buckets in the SPS. For 10^{13} p/p, the CPS bunch area is assumed to be A = 0.04; at a bunch length of 17 ns, this yields a momentum spread of $\Delta p/m_0c = 0.025$. Bunches with this height in the SPS have an area A = 0.2 rad. In total, 20 equally spaced groups of 4 bunches are circulating in the SPS. By a fast ejection system they can be ejected and transferred into the SSR. Injection into the SSR requires an injection kicker magnet which is capable of deflecting the 20 groups individually, which arrive at intervals of 1.15 μs but whose spacing in the SSR is only about 100 ns. It follows from the ratio of the SPS and SSR circumferences that the groups of bunches will occupy 20 out of 30 possible "buckets", with the empty buckets scattered over the whole circumference. It seems natural to capture them in RF buckets at h = 30, i.e. at the same frequency as in the ISR. The bunch area is then A = 0.03. Each pulse will correspond to the full intensity of the SPS, 10^{13} protons, yielding a circulating current of 0.5 A in the SSR. This would permit storing 200 pulses, or 100 A, in a momentum bite of 1% at $\gamma = 100$, assuming no particle loss, no phase space dilution, and ideal RF stacking. This is a factor of 6 better than the next best scheme listed in Table 2.

This scheme involves a number of problems beyond those encountered in the normal operation of the SPS 4). In addition, the transfer of the bunches into the SSR requires an array of fast kicker magnets designed for multiple pulsing in quick succession, and a rather tight tolerance of the ratio of CPS, SPS and SSR revolution frequencies at the moment of transfer.

An alternative scheme consists in ejecting the whole CPS beam in one revolution, and filling only 1/11 of the SPS circumference. This beam can be ejected from the SPS and injected into the SSR within one turn with kicker magnets rather similar to present models. The most serious problem is the beam loading created by 10^{13} protons concentrated in a small fraction of the SPS circumference. Within the accuracy of our estimates, this scheme would yield the same SSR performance as the scheme described above.

1.3. Storage Ring RF system parameters

The purpose of the RF system is to provide stacking in synchrotron phase space similar to that of the ISR. We assume that no special manipulations take place in the SPS, and, hence, that we have to accept the bunch shape delivered by the SPS.

We assume that the RF frequency in the SSR is the same as that of the SPS in all schemes except the bunched transfer. This avoids the phase space dilution associated with debunching and rebunching. It implies a harmonic number of 630 in the SSR. For the bunched transfer the harmonic number is 30 as in the ISR.

Table 3 gives the voltage which creates buckets fitting tightly around the bunches for two values of η. A certain minimum voltage is required to accelerate the beam within a SPS cycle from the injection orbit to the vicinity of the stacking orbit in the SSR. A voltage of 10 kV/turn seems to be adequate. Per second, it yields a 1% change in momentum. As shown in the table, this voltage is exceeded in most cases. Hence, full buckets can be accelerated. This has the advantage of providing good damping of longitudinal instabilities.

TABLE 3

	h_{SSR} = 630				h_{SSR} = 30	
	A = 0,08		A = 0,18		A = 0,03	
η	10^{-2}	¼ . 10^{-2}	10^{-2}	¼ . 10^{-2}	10^{-2}	¼ . 10^{-2}
Minimum final Voltage V_f [V]	62.10^{3}	16.10^{3}	314.10^{3}	78.10^{3}	420	105
Synchrotron oscillation Q_s at final Voltage	$6,7.10^{-4}$	$1,7.10^{-4}$	15.10^{-4}	$3,8.10^{-4}$	$2,5.10^{-4}$	$0,64.10^{-4}$
RF-matching						
Matched buckets, V_{SSR} [V]	$6,5.10^{6}$	26.10^{6}	$6,5.10^{6}$	26.10^{6}	137.10^{6}	550.10^{6}
ISR-method, V_{match} [V]	$7,4.10^{3}$	$1,9.10^{3}$	85.10^{3}	21.10^{3}	$2,3.10^{3*}$	$4,6.10^{3*}$
Dwell time at the unstable fixed point [sec]	$1,7.10^{-3}$	$6,7.10^{-3}$	$0,6.10^{-3}$	$2,4.10^{-3}$	$3,9.10^{-3*}$	15.10^{-3}
					* V_{inj} = 10 kV	

Injection of the SPS bunches into matched SSR buckets requires a voltage of the order of MV/turn. RF matching by a voltage jump as it is done in the ISR requires only a fraction of the final voltage, and may cause beam loading difficulties in the SSR. Matching at the unstable fixed point which worked well in the ISR appears to be feasible.

1.4. Limitations of phase space density imposed by collective phenomena in the SSR

1.4.1. Transverse space charge detuning

For a deneutralized unbunched beam, at high γ, the space charge detuning is given by

$$\Delta Q = - \frac{N r_o R}{\pi Q \beta^2 \gamma} \left(\frac{\varepsilon_1}{h^2} + \frac{\varepsilon_2 \beta^2}{g^2} \right) \tag{1}$$

Here, the first term in the bracket is caused by electric images due to the vacuum chamber wall, and vanishes for a beam centered in a circular chamber. The second term is caused by magnetic images due to iron poles. If there is any iron in superconducting magnet structures, it is likely to be rather far away from the beam. We therefore neglect this term. Even if we are pessimistic and assume that ε_1 takes its maximum value, $\varepsilon_1 \doteq 0.2$, and that the half height of the chamber is $h = 3$ cm, we obtain at $\gamma = 100$ only

$$\frac{\Delta Q}{I} \simeq - 3.10^{-4} \quad A^{-1}$$

It should therefore be possible to store currents up to 100 A without exceeding the Q shift which has been used in the ISR. For a neutralized beam, the detuning is considerably higher. Clearing of the beam is therefore essential.

The detuning due to the collision with an unbunched beam of N protons over a length ℓ is

$$\Delta Q = \frac{N \ell r_o \beta_z}{\pi^2 \beta^2 \gamma \; Rb(a+b)} \qquad (2)$$

where β_z is the vertical β-value at the intersection. This yields for the bunched beam case in Table 2 ($E_H = 0.75\ \pi$, $E_V = 0.36\ \pi\ 10^{-6}$ rad m), assuming $\beta_x = \beta_z = 1$ m and $\gamma = 100$

$$\frac{\Delta Q}{I\ell} = 2.3 \times 10^{-4} \quad A^{-1} m^{-1}$$

Thus the beam-beam limit, $\Delta Q \cong 0.025$, known from electron storage rings, will be reached at a current of about 110 A, for $\ell = 1$ m. Whether this limit applies also for proton storage rings is still unclear.

1.4.2. Coherent transverse instabilities

1.4.2.1. Coasting beam

The chromaticity needed to damp coherent transverse instabilities due to beam-equipment interaction at low mode numbers is, scaling from the ISR

$$\left(\frac{\partial Q}{\partial p/p}\right)_{SSR} = \left(\frac{\partial Q}{\partial p/p}\right)_{ISR} \frac{(I/AQ)_{SSR}}{(I/AQ)_{ISR}} \qquad (3)$$

With the ISR parameters

$$I = 0.07\ A \qquad \partial Q \Big/ \frac{\partial p}{p} = 1$$

$$A = 0.02\ \text{rad} \qquad I/A = 3.5\ \ A/\text{rad}$$

and $Q_{SSR} = Q_{ISR}$ we get

$$\left(\frac{\partial Q}{\partial p/p}\right)_{SSR} = 0.3\ (I/A)_{SSR}$$

The chromaticity needed for the various injection schemes is shown in Table 4. Although it has been assumed that no special measures are taken to reduce the strength of the beam-equipment interaction compared to the ISR, the chromaticity is much smaller than in the ISR in most cases. Only the bunched transfer requires a higher chromaticity.

Table 4

Injection mode	Current/pulse [A]	Bunch by Bunch A_{SSR}	 $\left(\partial Q/\frac{\partial p}{p}\right)_{SSR}$	Continuous transfer A_{SSR}	 $\left(\partial Q/\frac{\partial p}{p}\right)_{SSR}$
1 turn	0.0695	0.18	0.16	0.08	0.26
2 turn	0.139	0.18	0.23	0.08	0.52
3 turn	0.209	0.18	0.36	0.08	0.78
bunched	0.500	0.03	5		

For higher modes scaling from the ISR is impossible because they were never observed. The reason is that the resistive wall instability becomes less dangerous as the skin-effect decreases like $(n - Q)^{-\frac{1}{2}}$ whereas the spread increases proprotional to n for positive values of $\partial Q/\frac{\partial p}{p}$. Items which might resonate with the beam, e.g. cavities and plates, will be damped anyway to prevent longitudinal instabilities. Also their number will be kept to a strict minimum.

1.4.2.2. Bunched beams

We have considered the stability of the transverse motion of rigid bunches for the two transfer schemes which give a high line density, i.e. the 3 turn injection mode combined with continuous transfer and the density conserving transfer scheme. We assumed equally spaced identical bunches. The risetimes fo the instability are in both cases so short that suppression of the instability by Landau damping seems desirable. However, it turns out that the chromaticity needed to stabilize the coasting beam is also largely sufficient to cope with the bunched beam motion.

1.4.2.3. Electron-proton instability

The threshold neutralization η for instability (with Landau damping) is given by

$$\eta = \frac{16\beta^2\gamma}{9\pi^2} \frac{m_p}{m_e} \frac{b(a+b)}{Rr_e} \frac{Q\,\Omega\, e}{I} \frac{\Delta_e}{Q_e} \tag{4}$$

where

$$Q_e^2 = \frac{4Rr_e}{(a+b)b} \frac{I}{\beta^2 \Omega\, e} \tag{5}$$

is the "bounce frequency" of the electrons in the potential well of the protons, and Δ_e is the spread of Q_e. $\Omega/2\pi$ is the revolution frequency.

For larger values of Q and γ the threshold will be higher, but larger I and smaller beam dimensions will have the opposite effect. However, in comparison with the ISR none of the parameters change enough such as to yield threshold neutralizations above the per mille range. This means, that very good clearing will be required again and neutralization pockets should be avoided from the start. These are mainly due to cross section variations which are also undesirable for their high longitudinal coupling impedance.

1.4.3. Longitudinal density limitation

No longitudinal instability is observed in the ISR, when 2×10^{12} protons are injected in bunches of A = 0.02 rad area, which are released from moving buckets of the same area. We use the stability 1) criterion

$$A \geqslant \left(\frac{64\pi}{0.7} \frac{\beta\gamma}{|\eta|} \frac{|Z|/n}{Z_0} \frac{Nr_p}{R} \right)^{\frac{1}{2}} \tag{6}$$

and scale from the known ISR situation

$$\frac{A_2}{A_1} = \left(\frac{\gamma_2 \, I_2}{\gamma_1 \, I_1} \left| \frac{\eta_1 \, Z_2}{\eta_2 \, Z_1} \right| \right)^{\frac{1}{2}} \tag{7}$$

where the index 1 refers to the ISR and the index 2 to the SSR.

We assume $\gamma_1 = 25$, $\gamma_2 = 100$, $I_1 = 150$ mA, $\eta_1 = 0.01$, and, being rather pessimistic, $Z_2 = Z_1$. We then find for two values of η_2 the minimum permissible emittances shown in Table 5.

Table 5 - Minimum longitudinal emittances

Injection	Current/ pulse mA	$\eta = 0.01$	$\eta = 0.0025$
1-turn	69.5	0.027	0.054
2-turn	139.0	0.038	0.076
3-turn	208.5	0.047	0.094
bunched	500.0	0.073	0.146

Comparing these figures to the emittances given in Table 2 shows that all transfer schemes which only involve gymnastics in the SSR are longitudinally safe. The bunched transfer requires careful control of the beam-equipment interaction in the SSR, and a low value of the transition energy.

1.5. Luminosity

The luminosity obtained when two unbunched beam cross over a length ℓ is

$$\mathcal{L} = \frac{2}{\pi} \; \frac{c\ell}{ab} \left(\frac{N}{2 \, \pi R} \right)^2 \tag{8}$$

Here a and b are the horizontal and vertical radii of the elliptical beam at the crossing point. As an indication of the parameters necessary we take $N = 2\cdot 10^{14}$ corresponding to an average current of 10 A in a machine with R = 150 m. A luminosity $\mathcal{L} = 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ is obtained if $ab/\ell = 8\cdot 10^{-7}\mathrm{m}$. Taking $\ell = 1$ m yields $ab = 0.8\ \mathrm{mm}^2$. With typical emittances shown in Table 2 this cross section is achieved if $\beta_H = \beta_V \approx 1$ m. This would require a crossing angle as small as 2 mrad. If currents of a few tens of ampères can be stored, luminosities in the $10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ range would be reached.

1.6. Electron-proton storage rings

So far, the discussion was focused on filling two proton storage rings and doing proton-proton colliding beam experiments. Should it appear attractive, in future, to perform electron-proton colliding beam experiments, one may contemplate either, building an electron storage ring instead of one of the proton storage rings or, if certain technological problems are soluble, making one of the storage rings suitable for both electrons and protons, still in the ISR tunnel.

The concept of an electron-proton colliding beam facility is developed in more detail in connection with a bypass in 2.2.4. We can, therefore, restrict ourselves to some qualitative comments here.

The proton energy in a proton storage ring will be a factor 3 to 4 lower than in the bypass. This cannot be compensated by an increase in the electron energy although the radius of the electron storage ring is almost a factor of 3 bigger than in the bypass scheme. These two things together will yield a centre of mass energy which is a factor of 1.5 to 2 lower than in the bypass scheme.

Both schemes can be designed to the same luminosity. However, since the duty cycle of the storage ring is very close to unity, the required current and RF power are much smaller than in the bypass scheme. Conversely, the same RF power as in the bypass scheme could be used and the electron energy increased accordingly.

1.7. Proton-antiproton storage rings

The ejected SPS beam with its high intensity and energy is an interesting source for antiprotons. Consider the "bunched transfer scheme" where 20 groups of 4 adjacent SPS buckets, containing in total 10^{13} particles, are ejected at 200 GeV/c in the way which gives 20 full and 10 empty buckets in the SSR. A suitable target in the beam line converts them into antiprotons of 28 GeV/c. They are inflected into Ring 1 of the ISR and stacked in the usual way in synchrotron phase space.

With the following parameters

$E_H = E_V = 10\pi \cdot 10^{-6}$ mrad	Kicker acceptance
$\frac{\Delta p}{p} = 1\%$	Stackwidth
36.8%	Target efficiency
2 mm	Target diameter
$\frac{\partial N}{\partial \Omega \partial p} = 1\ \mathrm{GeV}^{-1} \mathrm{sr}^{-1}$	Production of $\bar{p}$ (thermodynamic model)

we expect a stack population of $3 \cdot 10^8$ antiprotons.

A number of schemes is available for proton-antiproton colliding-beam experiments. The antiprotons could be stored in Ring 1 of the ISR, using them for 56 GeV p-$\bar{p}$ physics. One ring of the SSR could be filled at about 25 GeV and the antiprotons be slowly accelerated to full energy by phase displacement, thus permitting 200 GeV p-$\bar{p}$ physics.

2. A BEAM BY-PASS

2.1. Historical review

2.1.1. CERN

The investigation, in 1967, of a by-pass for the original 300 GeV Design Study arose essentially from two considerations:

(i) From the beginning of the 300 GeV studies it had been clear that, to keep radiation damage and induced activity down to an acceptable level, only a limited amount of internal-target operation could be permitted. The design of the machine and experimental areas was, therefore, based on the assumption of fast and slow extracted beams for the main exploitation. Fast extraction was known to work efficiently and slow-extraction efficiencies in excess of 90% were predicted theoretically.

(ii) In contrast with the predictions, the efficiency of the CPS slow-extraction system was at that time less than 50%, for reasons then unknown, and despite much effort over some months.

The combination of (i) and (ii) raised some misgivings inside ECFA on the wisdom of putting all the experimental eggs in the extracted-beam basket. Although the CPS and 300 GeV groups were confident that slow extraction could be made to work efficiently, a beam by-pass was studied as a means of obtaining internal target facilities whilst reducing and localising the radiation damage and activity problems. The situation was summarised in the ECFA Report 1967 5), page 12:

> "Targeting and beam extraction: Because of the problems caused by induced radio-activity, maximum emphasis has been laid on the use of ejected proton beams; while at the time of writing the efficiency of slow extractions at the CERN PS has not exceeded about 50%, there are good reasons for believing that in some year's time at least 90% efficiency will be obtained.

Provision for possible future development of an internal target area should, however, be included in the planning stage in two forms:

(i) enlargement of the tunnel in one straight section;

(ii) provision for a "by-pas" which could also be used in a future colliding beam system or other development."

The concept of a beam by-pass was originally proposed by Collins and developed at the CEA in order to provide colliding-beam facilities in an existing accelerator. The CERN by-pass study also included a preliminary survey of possible colliding-beam configurations with one or more storage rings, in order to explore the range of possibilities of the by-pass 6).

Not long afterwards, the difficulties with the CPS slow extraction were overcome and efficiencies close to the theoretical figure were consistently achieved. The main purpose of the by-pass in the context of the CERN 300 GeV project therefore disappeared.

2.1.2. NAL

Following the work at CERN, interest was aroused at NAL in the possibility of adding a by-pass/storage ring facility to the 200/400 GeV machine 7). The emphasis in this study was on the colliding-beam aspects rather than the internal-targetting facility.

By the time of the NAL Storage Ring Design Study in 1968 3), the by-pass/SR scheme was abandoned in favour of intersecting storage rings, mainly for reasons of luminosity, main ring vacuum limitations and interference between colliding-beam and normal physics experimentation.

2.2. Possible uses of a beam by-pass

Some of these have already appeared in 2.1. but are repeated here with more explanation and comments.

2.2.1. Internal targets

A long, straight by-pass would require only a low density of focusing elements and no bending over most of its length. Internal targets could be located in the straight region, adjacent to an experimental area, with considerably reduced problems of protecting equipment from radiation damage as compared with similar target operation in the vicinity of the main ring structure.

Since efficient slow extraction is now firmly established, this particular application of a by-pass seems to be no longer of interest.

2.2.2. Installation of experiments during machine operation

Experiments could be installed in the by-pass region whilst the accelerator is operating in the normal mode to serve other experimental areas.

This sort of flexibility is available to at least the same degree, however, with extracted beams. Furthermore, secondary beams tend nowadays to be complex and have a long life. One concludes that this advantage of a by-pass is of little consequence in the present context.

2.2.3. Colliding-beam proton experiments with a single storage ring

A single storage ring, intersecting the by-pass, would be filled from the main ring by stacking in betatron and/or synchrotron phase space. The by-pass would have a low-β insertion, made easier than in a normal machine by the absence of bending magnets. Then, either the stack would be made to collide with a single accelerated pulse from the main ring circulating in the by-pass, or part of the stack would be re-injected into the main ring and made to collide with the remainder. The second alternative gives a potentially higher luminosity. Apart from the by-pass one would need an additional transfer line.

Such arrangements were considered at NAL 7) and luminosities were calculated for stored currents limited by transverse, unneutralised Q-shifts. Experience with the ISR, together with a better theoretical understanding of collective effects, now make it clear that stacked currents are limited at a lower level by phenomena other than simple Q-shifts, and that the earlier luminosity estimates were excessively optimistic.

If we take the figure of 100 A in the 1% momentum bite from Table 2 for a 100 GeV storage ring on a by-pass, and assume collisions with a single pulse of 10^{13} protons in the SPS at 400 GeV we find, with a low-β section of 4 m, a peak luminosity of $4 \times 10^{31} cm^{-2}s^{-1}$. However, magnet power restrictions and normal physics operation impose a duty-cycle limitation of about 25%, leading to an average luminosity of $10^{31} cm^{-2}s^{-1}$. This facility would require the by-pass, the single storage ring, an extra beam transfer line and an experimental hall, all underground to protect the environment. It would also require some confidence in achieving 100 A in the storage ring, in the face of known vacuum and instability problems. In view of the modest luminosity limit we do not consider this to be a viable proposition, despite the 400 GeV C.-M. energy.

Another possibility would be to re-inject say one half of the 100 A stored beam back into the SPS in the opposite direction for subsequent collision with the remaining half in the storage ring. This would increase the luminosity by a factor of around 50, depending on the details of the scheme, leading to a peak luminosity in the range of $2 \times 10^{33} cm^{-2}s^{-1}$. The C.-M. energy would be limited to twice the maximum energy either of the storage ring or of the SPS in d.c. flat top, whichever were the smaller, since it does not appear feasible to accelerate a 50 A beam in the SPS. There are two serious drawbacks to this scheme. Firstly, the beam lifetime would be limited to an hour or two by the design pressure of the SPS vacuum system. Secondly, during colliding-beam experiments the SPS would be monopolised to the exclusion of normal physics experiments.

2.2.4. Electron-proton colliding beam experiments with a single electron storage ring

Electron-proton collisions with a centre of mass energy in the 100 GeV region, and a luminosity of the order of 10^{31} to $10^{32}\text{cm}^{-2}\text{s}^{-1}$ can be obtained by colliding the SPS proton-beam with the electron beam circulating in a small storage ring.

After acceleration in the SPS to maximum energy, the proton beam is switched into a by-pass and kept circulating there at constant energy for a period of about two seconds. In this time, head-on collisions take place with the stored electron beam in a specially designed intersection region in the by-pass. The low values of β for both electrons and protons allow the desired luminosity to be achieved.

At the end of the flat top the SPS beam could be used for fast extraction, thus allowing it to be used simultaneously for colliding beam physics and conventional experiments based on fast extracted beams.

In a collision between 5 GeV electrons and 400 GeV protons a total centre of mass energy of about 90 GeV is reached. Assuming head-on collision and bunched beams the luminosity per crossing can be written as

$$L = f_1 K_1 \frac{N_1 N_2}{A} d \qquad (9)$$

where f_1 is the SPS revolution frequency, K_1 is the number of bunches in the SPS, N_1 and N_2 are the number of particles per bunch in the SPS and in the ESR (electron storage ring), A is the transverse beam cross section, and d is the SPS duty cycle (ratio of flat-top time to the machine period). Formula (9) holds provided that one satisfies the "synchronism condition"

$$\frac{R_1}{\beta_1 K_1} = \frac{R_2}{\beta_2 K_2} \qquad (10)$$

where R_1, R_2 are the radii of SPS and ESR, and K_1, K_2 are the number of bunches respectively. β_1 and β_2 are their velocities in units of the velocity of light.

To satisfy the condition (10) we assume

$$\frac{R_1}{R_2} \cong 20$$

Since, for the CERN SPS, R_1 = 1100 m, we obtain $R_2 \cong 55$ m which is enough to accomodate 5 GeV electrons.

We recall that for the electron-proton case the luminosity is limited by the amount of radio-frequency power, P, available to compensate the electron synchrotron radiation loss and by the incoherent beam-beam Q-shift (Ref. 8).

Hence we can write

$$K_2 N_2 = P/f_2 V \qquad (11)$$

and

$$\frac{N_1}{A} = \frac{\Delta Q \cdot \gamma_e}{2 r_e \, \beta^*_e} \qquad (12)$$

where f_2 is the ESR revolution frequency, V is the electron energy loss per turn, r_e is the classical electron radius, γ_e the electron energy in rest-mass units, β_e^* the vertical betatron function of the ESR at the crossing point and ΔQ is the beam-beam limit which has been found to be of the order of 0.025.

Using (10), (11) and (12) we can write the luminosity as

$$L = \left(\frac{P}{V}\right)\left(\frac{\Delta Q\ \gamma_e}{2r_e\ \beta_e^*}\right) d \tag{13}$$

The radiation loss per turn, V, is given by

$$V = \frac{4}{3}\pi\ \frac{r_e}{\rho_e}\ \gamma_e^4\ m_e c^2 \tag{14}$$

where $m_e c^2$ is the electron rest energy and ρ_e is the ESR radius of curvature. Assuming $\gamma_e = 10^4$ and $\rho_e = 30$ m, which corresponds to a magnetic guide field of about 0.5 T, we obtain V = 2 MeV. For the parameters d and β_e^* we use the value d = 0.25, $\beta_e^* = 10$ cm. It follows from (13) that to obtain a luminosity of the order of $10^{32}\text{cm}^{-2}\text{s}^{-1}$, we need about 3 MW of RF power, or a circulating electron current of 1.5 A corresponding to 1.2×10^{13} electrons.

We can now determine the parameters of the proton beam. From (12) we have

$$\frac{N_1}{A} = 0.4 \times 10^{13}\text{cm}^{-2}$$

The transverse section of the proton-beam is determined by the values of the β functions at the crossing point and by the horizontal and vertical emittances, E_H, E_V.

We assume that it is possible to build, in the by-pass, a suitable low-β straight section. We also assume the momentum compaction function to be zero in the crossing region. The expected beam emittance at 400 GeV is

$$E_H = 0.3\pi \times 10^{-6} \text{ rad m}$$

$$E_V = 0.2\pi \times 10^{-6} \text{ rad m}$$

$$\Delta p/p = \pm 3 \times 10^{-4}$$

A value of β of one metre in both the horizontal and vertical direction gives for the beam half width, and half height at the crossing point $w = 0.6$ mm, $h = 0.5$ mm. Assuming the transverse dimensions of the ESR beam to be smaller or equal than those of the SPS, we obtain a value $A \approx \pi wh \approx 10^{-2}\text{cm}^2$. With $N_1/A = 4 \times 10^{12}$, it follows that the number of protons per bunch must be $N_1 = 4 \times 10^{10}$. The length ℓ of the proton bunches cannot be arbitrary. Condition (4) is valid only as long as the bunch length is smaller or equal than twice β_e^*, i.e. 20 cm. This requirement on bunch length restricts the choice of the number of bunches K_1.

Assuming a longitudinal emittance

$$E_\ell = \pi \, \Delta \, \phi_{RF}\left(\frac{\Delta p}{p}\right)\beta\gamma \simeq 0.1$$

and

$$\Delta\phi_{RF} = \frac{\ell}{R_1} K_1 \approx 4 \times 10^{-4} K_1$$

we obtain

$$\frac{\Delta p}{p} \simeq \frac{2 \times 10^{-1}}{K_1}$$

or, for $K_1 \approx 200$,

$$\frac{\Delta p}{p} \simeq 10^{-3}$$

The minimum radio-frequency voltage required for a given bunch length is obtained when the harmonic number, K, is given by $2\pi R_1/\ell$. In this case one has

$$eV = \frac{\pi}{2} K \; |\eta| \; \beta^2 \gamma \left(\frac{\Delta p}{p} \right)^2 m_p c^2$$

Assuming $\eta = 1/625$, $\gamma = 400$, $\Delta p/p \approx 10^{-3}$ and $K = 1.5 \times 10^4$ we obtain

$$eV \approx \frac{\pi}{2} \; 10 \text{ MeV}$$

It is clear that a new and different radio-frequency system is needed to operate the SPS as a colliding beam facility with electrons. Also, one would require, in addition to the by-pass and the ESR, means for injecting and accelerating 5 GeV electrons.

Finally we notice that, for $K_1 = 200$, the total number of protons needed to obtain the required luminosity is of the order of 10^{13}, which is the design goal for the SPS intensity.

3. CONCLUSIONS

We have looked into the performance of storage rings which are filled from the SPS. Two schemes were considered: a pair of superconducting storage rings with an energy between 100 and 150 GeV to be housed in the ISR tunnel, and a single storage ring attached to the SPS by a by-pass.

With the transverse emittances from the SPS and some reasonable optimism about the smallness of β values and the crossing angle we find that currents of a few tens of ampères are required to reach luminosities in the $10^{34}\text{cm}^{-2}\text{s}^{-1}$ range. There is a high premium on keeping the momentum bite small, and current densities in the range of 100 A/% momentum spread should be aimed for. Such densities cannot be reached by using the normal SPS beam and betatron and synchrotron stacking in the storage rings. Therefore other schemes are required for transferring the CPS beam into the SPS which avoid the phase space dilution associated with debunching the beam in the SPS before acceleration. A scheme whereby the CPS bunches are directly injected into SPS buckets would yield the required current density.

We have also convinced ourselves that the current densities which we believe to be necessary for storage ring operation, can actually be handled as far as the known coherent and incoherent space charge phenomena are concerned.

For electron-proton storage rings the difficulties seem to be concentrated in the electron storage ring. The demands on the proton ring are much less than in the proton-proton case.

Since internal targetting is no longer relevant to the discussion, the case for a by-pass stands or falls at the present time on its utility in connection with colliding beam experimentation.

For p-p collisions, a single storage ring offers either insufficient luminosity at 400 GeV C.-M. energy or adequate luminosity at a less impressive C.-M. energy but with some serious disadvantages. We believe, therefore, that a by-pass plus single proton storage ring does not compete in performance with an optimised pair of proton storage rings of comparable cost. Such a system would only merit a more detailed study if a by-pass were necessary for other reasons.

For colliding electron-proton beams the situation is somewhat different. The limitation on electron energy, due to synchrotron-radiation losses, puts a premium on using the highest available proton energy, and hence on the by-pass plus electron storage-ring scheme. However, also in this case the use of a higher energy electron storage ring together with a proton storage ring should be carefully considered before any conclusion could be drawn as to the most favourable solution.

In conclusion, we should like to stress the strong influence of phase space density on the performance of storage rings which might be filled from the SPS. It therefore seems to be important to investigate whether high density beams can be accelerated in the SPS according to its present design. If this is not so, equipment preventing the SPS from accelerating high density beams should be avoided, if at all possible, and space should be reserved for any new components required.

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