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STUDIES OF 400 GeV SUPERCONDUCTING PROTON STORAGE RINGS

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ABSTRACT

A study has been made of the feasibility of building Large Storage Rings (LSR) at CERN using superconducting dipoles and quadrupoles with the 400 GeV proton synchrotron, SPS, serving as injector. Proton-proton collisions at centre-of-mass energies of up to 800 GeV can be obtained in six interaction regions. Two of these provide luminosities exceeding $10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$ and would be dedicated to large-transverse-momentum physics. The other four p-p intersections offer much experimental flexibility at somewhat lower luminosity. Provision is made to add an electron storage ring of 20-25 GeV to obtain e-p collisions at up to 200 GeV centre-of-mass energy with a luminosity of $10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$ in each of two special e-p interaction regions. Antiproton-proton collisions could be obtained by a minor rearrangement of some elements in two of the interaction regions.

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1. INTRODUCTION

1.1 Aims, scope and history

Since the end of 1973 a small group in the CERN Intersecting Storage Rings (ISR) Division has been studying the performance possibilities and design constraints of colliding-beam proton storage rings in the energy range around 400 GeV per ring. The choice of 400 GeV as nominal energy for the Large Storage Rings (LSR) was a natural consequence of assuming injection from the SPS up to maximum energy, at the same time opening up a new c.m. energy region for p-p and p- $\bar{p}$ physics.

The first phase of the LSR studies was directed towards a machine using normal iron/copper magnets, in order to establish the basic scaling features and performance limitations of proton storage rings in this energy range. The results of this work¹⁾ indicated that such LSR could be built with a high performance, but at the expense of a very high power consumption (~ 120 MW), a rather voluminous magnet system, and an uncomfortably large circumference. These considerations, together with the steady improvement in superconducting-magnet technology, led us to concentrate, near the end of 1975, on a superconducting version of the LSR.

The study of the normal-magnet LSR resulted in a much improved understanding of performance limitations and design constraints in high-energy proton storage rings in general. The principle of designing insertion optics and crossing geometries specific to various classes of physics experiments was thoroughly explored. A review of the physics interest and possibilities, subsequently published²⁾, showed that the LSR design concepts would provide a powerful facility for European physics. A Performance Study³⁾ held at CERN in October 1974, in which accelerator experts from many laboratories participated, added much to the knowledge in this field, and suggested some improvements in the LSR design which were taken into account in Ref. 1. The AGS computer program underwent substantial modifications⁴⁾ to incorporate insertion-matching facilities. All these developments have been directly relevant to the studies on the superconducting LSR.

The second phase of the LSR studies has been directed towards a design using superconducting dipoles and quadrupoles, with the expectation of reducing the size, the power consumption, and the cost as compared with the normal-magnet version, and with equal or better performance. In this evolution most of the basic concepts have undergone little modification. We have found no reason to revise the number of interaction regions for p-p physics, nor to change their features dramatically, although improvements in performance and simplicity have been achieved. The main lattice parameters have been modified only to the extent of accommodating the characteristics of a superconducting-magnet system and of including as a basic feature the option of adding an electron storage ring with two e-p physics interaction regions²⁾. The vacuum system has received considerable attention, and new developments have been necessary to meet the constraints imposed by superconducting-magnet design.

By far the most important change with respect to a normal-magnet machine is the superconducting-magnet system and its associated cryogenics. In the absence of a CERN development program on superconducting dipoles for storage rings, we have based our assumptions on experience with the ISR low- β quadrupole⁵⁾ work and on the dipole development at other laboratories, mainly that for ISABELLE⁶⁾ at Brookhaven.

The LSR studies were essentially terminated around the end of 1976, but with some rounding-off work extending into 1977. A summary of these studies has already been presented⁷⁾. Because of the pressure of work from other project activities it has not been possible to finish certain aspects of the design and to present a complete, self-consistent, and well-balanced study at the level of detail that we would have wished. The major lacuna is our limited experience with large superconducting-magnet and cryogenic systems. Other areas in which the present report is incomplete are of lesser significance and simply reflect the curtailment of the studies before certain details had been worked out. The main points can be summarized as follows:

- i) The physics insertions presented here have not yet been fully matched into the lattice. However, their characteristics are sufficiently similar to those previously studied that no problem is anticipated here.
- ii) The preferred injection and beam-dumping systems have not been integrated into the lattice so far. An earlier version of the LSR⁸⁾ required enlarged apertures for some superconducting elements in the injection region, a complication which we would rather avoid. The corresponding beam-dumping system was based on sequential pulsing of ejection magnets and raises some misgivings about reliability. Injection and dumping systems more similar to those used in the normal-magnet LSR¹⁾ would avoid these objections.
- iii) In the absence of a complete machine lattice for the current design we have not systematically corrected chromatic effects. However, experience with other lattices and insertions gives us confidence that there is no major problem here.
- iv) No appreciable engineering design work has so far been undertaken for the LSR, although some limited model work was carried out on a few specialized components. However, the machine parameters and layout have been chosen to ensure, as far as possible, that no insurmountable technical problems would arise in a more detailed design study. Likewise, the civil engineering requirements, which present no special features, have not been examined in detail.

Despite the above reservations we believe that the conceptual design of the superconducting LSR presented here is soundly based and thoroughly feasible. During the course of the studies there has been close liaison and much exchange of information and ideas between the members of the LSR team and those of other laboratories engaged in similar studies. The evolution of the LSR design has greatly benefitted from these exchanges and has doubtless also made some contributions to other projects in this field. The present report should therefore provide a good starting point for a detailed design study of high-energy proton storage rings should Europe show a renewed interest in this kind of facility some time in the future. In such an event the study of this particular model of LSR would be largely applicable even to proton storage rings of a different energy or different site constraints.

1.2 Brief description of the LSR

The LSR as currently conceived is in the form of a racetrack, shown schematically in Fig. 1.1. In the bending arcs the two rings of superconducting dipoles and quadrupoles are located in the same horizontal plane near to opposite walls of the tunnel. At the centre of each arc the two beams interchange positions at a dummy crossing, introduced to preserve

a twofold geometrical periodicity of the machine. The dummy crossings also include betatron phase-shifting sections for tune adjustment.

The straight arms of the racetrack are each made up of three p-p physics interaction regions, together with their matching sections. This racetrack configuration was imposed at an early stage of the LSR studies to contain the machine within site boundaries close to the North Experimental Area of the SPS.

Injection into the LSR is from the SPS via the North Area extraction system and two transfer tunnels, one for each ring. Nominal injection energy is 400 GeV, although apertures have been chosen to permit injection down to about 100 GeV. The beam is accumulated by stacking in momentum space, in a similar manner to that used in the CERN ISR.

1.3 Outline of insertions and performance

Three types of p-p interaction regions are foreseen: a high-luminosity, low- β insertion (LB) dedicated to large p_T physics; a general-purpose insertion (GP); and a high- β insertion (HB) for measurement at very small scattering angles well down into the Coulomb interference region. The main parameters of these insertions are listed in Table 1.1.

Table 1.1

	Low-beta (LB)	General purpose (GP)	High-beta (HB)
Luminosity ($\text{cm}^{-2} \text{ sec}^{-1}$)	1.3×10^{33}	6.6×10^{31}	1.1×10^{31}
Free space (m)	± 6	± 65	± 65
Vertical beta (m)	1.0	12	400
Horizontal beta (m)	3.5	24	317

For the purposes of the present study, the six p-p interaction regions are assumed to be made up of two of each type, preserving twofold superperiodicity. However, the GP and HB insertions are readily convertible one into the other. We believe that these six p-p interaction regions, with the operational flexibility available, yield a good compromise for offering adequate physics facilities on a European scale within practical constraints of cost and machine design.

1.4 Further options

Provision is made in the LSR for the addition of a 20-25 GeV electron (positron) storage ring, offering $e^\pm$ -p colliding-beam physics at c.m. energies up to 200 GeV with a luminosity of $10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$. Two e-p interaction regions are foreseen, located in the main arcs of the LSR away from the p-p physics areas. This permits simultaneous e-p and p-p operation.

The e-p facility is incorporated into the general layout of the LSR ring arrangement in such a way that it could either form part of the initial construction project or be added at a later stage without changes in the lattice of the proton rings.

Proton-antiproton collisions can be obtained in the LSR if the common magnets in the low- β interaction regions are not in operation.

Proton-deuteron and deuteron-deuteron collisions are also amongst the options discussed further in Section 9.

Fig. 1.1 Proposed layout for the LSR

2. EXPERIMENTAL INSERTIONS FOR p-p PHYSICS

The configuration of the LSR, with the insertions next to each other in the two straight sections, is rather unorthodox and has both advantages and disadvantages. The physics requirements led naturally to the adoption of six interaction points of three different types: high luminosity, low-beta (LB); general-purpose (GP); and high-beta (HB). It is unlikely that the HB insertions would be required throughout the lifetime of the machine, and ideally they should be convertible into GP insertions without major rebuilding. This had not been achieved in an earlier design⁸⁾ where the two insertion types had different lengths, which was one of the factors that led to attempting a new design. However, this is not the only reason. Earlier LSR proposals used a short piece of standard lattice to separate insertions, each insertion being matched to the (more or less) standard configuration. This solution resulted in a considerable increase in circumference with no accompanying gain in performance. In this study a new technique is adopted in which each insertion is matched directly to the next in a cascade fashion. In addition, the ring-ring separation between insertions is only 1.1 m, instead of 2.5 m as in the arcs. This enables a smaller crossing angle to be used in the GP and HB insertions with a consequent increase in the luminosities. The performance of the insertions is listed in Table 2.1, and the structure functions of the whole insertion region are shown in Fig. 2.1. The individual insertions are discussed in detail in the following sections.

Table 2.1

Parameters of LSR insertions

	Low-beta (LB)	General purpose (GP)	High-beta (HB)
Luminosity ($\text{cm}^{-2} \text{ sec}^{-1}$)	1.3×10^{33}	6.6×10^{31}	1.1×10^{31}
Beam current (A)	7.0	7.0	7.0
Vertical β -fn β_V^* (m)	1.0	12.0	400.0
Horizontal β -fn β_H^* (m)	3.5	24.0	317.0
Dispersion D_x (m)	0	0	0
Dispersion slope D'_x	0.025	0	0
Crossing angle (mrad)	2.0	11.9	11.9
Free space (m)	± 6.0	± 65.0	± 65.0
Diamond length (m)	0.99	0.457	1.625
Beam-beam tune shifts ΔQ_V	1.4×10^{-3}	9.3×10^{-4}	5.3×10^{-3}
ΔQ_H	6.3×10^{-4}	5.5×10^{-6}	1.1×10^{-5}
Assumed beam emittance (rad m) (both planes)	$30\pi \times 10^{-6}$	$30\pi \times 10^{-6}$	$30\pi \times 10^{-6}$

2.1 Low-beta insertion

This insertion is primarily for wide-angle, high p_T physics, which require high luminosity and a short diamond length. In the course of the review of the physics interest in the LSR²⁾, a suitable detector was designed by Di Lella and is shown in Fig. 2.2. The total length is about 6 m which, leaving some space for eventual additions, cryostat ends, etc.,

leads to a free space of ± 6 m being adopted. A crossing angle of 2 mrad gives a source length of about 1 m, which is sufficiently small. A standard lattice dipole is used to provide sufficient separation of the beams at the low-beta quadrupoles, provided these are placed in side-by-side pairs in common cryostats. The betatron matching is shown in Fig. 2.3. The maximum beta values are around 540 m. The dispersion is zero at the intersection point but has a non-zero slope. This results in a dispersion of ~ 0.7 m at the low-beta quadrupoles and allows at least partial correction of the chromaticity by sextupole windings in the quadrupoles. The aperture requirement of these quadrupoles is ± 50 mm and the maximum gradient required is 60 T/m. A superconducting quadrupole with these characteristics (including the sextupole windings) has been examined in some detail in the course of another study⁹⁾ and appears technically quite feasible.

2.2 General-purpose insertion

This insertion should have a reasonably high luminosity with a large unencumbered free space, suitable for a variety of detectors. In addition, the interchangeability with the HB insertion imposes further constraints. For the GP insertion the dispersion should be zero, while for the HB insertion, specific to physics at small scattering angles, the slope of the dispersion should be zero. Thus zero dispersion and slope is required over the insertions. For convenience the crossing angle has been set equal to the bending angle of a standard lattice dipole, and the beams are bent towards each other with a large-aperture (± 36 mm) bending magnet. Since the tunable part of the insertion starts from this point, the dispersion suppressor has been incorporated into the LB insertion (Fig. 2.3). The betatron functions of the GP insertion are shown in Fig. 2.4. With a free space of ± 65 mrad, there is sufficient beam separation for quadrupoles in individual cryostats. The aperture and gradient requirements of these quadrupoles are less stringent than those of the low-beta quadrupoles, and no sextupole component is required since no *in situ* correction of the chromaticity is possible. The p-p luminosity of $6.6 \times 10^{31} \text{ cm}^{-2} \text{ sec}^{-1}$ is quite high as a result of the rather small crossing angle, which is favourable for p- $\bar{p}$ operation where relatively low stacked currents of antiprotons are to be expected.

2.3 High-beta insertion

This insertion is used for small-angle scattering experiments for which it has been shown²⁾ that beta values of 300-400 m are required in both planes, together with zero slope for the dispersion. The solution obtained is shown in Fig. 2.5. The betatron parameters at either end of the insertion are identical to those of the GP insertion as required. The quadrupoles used are interleaved with those required for the GP so that both sets may be installed to give the possibility of tuning directly from one configuration to the other and with a range of values in between.

The transformation properties of the HB optics permit measurements at scattering angles from $< 20 \text{ } \mu\text{rad}$ up to $\sim 300 \text{ } \mu\text{rad}$, bridging the Coulomb interference region around $100 \text{ } \mu\text{rad}$. The GP optics can be used down to about $200 \text{ } \mu\text{rad}$, so together the two insertions cover the whole angular range of interest. The luminosity obtained, $1.1 \times 10^{31} \text{ cm}^{-2} \text{ sec}^{-1}$, is high for this type of insertion and corresponds to the vertical tune-shift limit. At lower energies the achievable luminosity will have to be reduced to stay within the beam-beam limit.

2.4 Experimental halls

The maximum beam separation between insertions is 1.1 m (centre-to-centre). It is therefore proposed that the magnets be placed in the centre of an enlarged (~ 5.3 m diameter) tunnel with access from both sides. This widened tunnel would extend over the entire 600 m insertion region (except where further enlarged for the experiments) in order to facilitate construction. The three insertions require experimental halls which are similar to those proposed previously¹⁾. Around each interaction point a 30×30 m² hall is provided, with the floor level 6 m below the beam height and a vertical clearance of 8 m to the (50 ton) crane hook (Fig. 2.6). In addition, the GP/HB insertions have a widened tunnel for a further 50 m either side of the hall, offset from the beam to facilitate the installation of bulky equipment.

Fig. 2.1 LSR cascaded insertions

Fig. 2.2 A large acceptance spectrometer to study high transverse momentum events:
a) top view; b) view along the magnetic field direction

Fig. 2.3 Low-beta insertion $\beta_V^* = 1.0$, $\beta_H^* = 3.5$

Fig. 2.4 General-purpose insertion $\beta_V^* = 12.0$, $\beta_H^* = 24.0$

Fig. 2.5 High-beta insertion $\beta_V^* = 397.2$, $\beta_H^* = 317.4$

Fig. 2.6 Schematic layout of the experimental halls

3. LATTICE AND GENERAL PROPERTIES OF PROTON RINGS

3.1 General design, choice of aperture and list of parameters

Experience with the ISR has shown that the Q-values have to be controlled with rather high precision if one is to avoid enhanced beam decay rates due to non-linear resonances in the stacked beam. This imposes tight tolerances on the power supplies and on the range of Q-values present in the beam. In particular, the design of the machine must ensure that the image-dominated incoherent tune shift is below the limit imposed, and that the circulating beam is transversely stabilized by the small Q-spread available. It turns out that these requirements can be met by choosing a sufficiently large aperture over most of the circumference of the machine. In contrast to conventional accelerators, the aperture of a large-radius storage ring is essentially determined by the requirement that the vacuum-chamber walls and magnet pole-pieces be far enough from the beam that their electromagnetic effect on it can be handled. As a check, the aperture required is also calculated from the beam size, the width of the stack, the expected closed-orbit distortions, etc. In the ISR, the aperture for low-background runs corresponds to at least 7 r.m.s. beam radii, and the closed orbits are corrected to a peak-to-peak distortion of about 4 mm. With these figures for beam size and closed-orbit distortions, the 50 mm aperture of the LSR is adequate for colliding-beam operation. However, this aperture would offer less than 50% probability of obtaining a circulating beam directly at the first trial, even when injecting on the chamber axis. This mediocre probability may be accepted, however, if adequate provisions are made to avoid the risk of magnet quenching due to beam losses around the ring during the steering process, by performing this operation at reduced energy and intensity. The effect of the aperture on the design of the LSR vacuum system is discussed in Section 6.

A formalism¹⁰⁾ which incorporates the most basic coasting beam space-charge phenomena leads to a first approximation for the parameters without insertions, and gives some guidance on the likely theoretical and practical performance limitations of a real machine. This basic set of parameters has then to be modified to take into account features which cannot be adequately expressed in the formalism because of complexity, theoretical inadequacies, or technological judgement.

In the present design some modifications to the basic parameters have resulted from the physics requirements of the experimental insertions. The reduction of the source length in the high-luminosity regions to an acceptable value has imposed an increase in the crossing angle and, consequently, an increase in the stacked current to maintain the design luminosity. The beam-beam tune shift is then a factor of about 3 below what is conventionally assumed to be tolerable. Stability criteria for longitudinal and transverse motion have been based on the smooth resistive-wall impedance, except for the RF system (cf. Section 8). Thus we assume that impedances due to cross-section variations (bellows, pumping ports, etc.) can be kept sufficiently low. Feedback systems could also be utilized. For longitudinal instabilities there is the additional safeguard that only the first few stacked pulses might be unstable.

Following up these and other considerations we arrive at a set of parameters which is not entirely optimal but, nevertheless, is a very good approximation. A re-optimization of the parameters would obviously be made before the final freezing of a design, taking into account the latest theoretical and experimental knowledge. The present parameters, however,

illustrate the potentialities of such a machine and provide for a practical final design. The basic parameters arrived at are listed in Table 3.1. The following further comments can be made on the details.

Table 3.1
LSR parameters

Maximum momentum ^{a)}	p	400 GeV/c	
Maximum field in bending magnets	B _{max}	4.07 T	
Circumference factor ^{b)}	R ₀ /ρ	1.7	
Bending radius	ρ	327 m	
Average radius of normal lattice	R ₀	565 m	
Total circumference of the machine ^{c)}	C	5370 m	
Aperture radius ^{d)}	a	25 mm	
Period length	L _p	40.4 m	
Orbit parameters		(V)	(H)
Betatron wave number ^{e)}	Q	34.60	34.60
Betatron functions in F-quadrupoles	β _F	11.9 m	68.3 m
Betatron functions in D-quadrupoles	β _D	68.3 m	11.9 m
Phase advance/cell	μ	90°	90°
Uncorrected chromaticity	Q'	-65.4	-69.6
Normalized beam emittance (upper limits)	E	30π × 10 ⁻⁶ rad m	30π × 10 ⁻⁶ rad m
Transition energy	γ _t	26.8	
Stored current ^{f)}	I	7 A	
Stored energy in beam ^{g)}	W _b	55 MJ	
Single beam tune-shift	ΔQ ₁	0.02	
Vacuum chamber conductivity	σ	1.3 × 10 ⁶ A V ⁻¹ m ⁻¹	
Resistive wall effect mode number ^{h)}	n-Q	0.75	
Required tune spread in beam	ΔQ	0.015	
Total stored momentum spread	Δp/p	5 × 10 ⁻³	

- a) The basic design has been made for an energy equal to the maximum energy of the SPS. This illustrates the maximum potentiality of such a project if one does not want to take into account the complication of further acceleration in the LSR. It is fairly easy to scale the design if later scientific, technical, or financial considerations make it desirable to choose a different energy.

- b) The circumference factor is further discussed in Section 3.2.
- c) The circumference is arrived at by adding to $2\pi R_0$ the lengths of the various insertions described in Section 2.
- d) The aperture has, to the first approximation, been determined by considerations of some of the main space-charge phenomena. However, the vacuum difficulties would also increase if the aperture were made smaller.
- e) The betatron wave numbers result from a contribution of about 22 in the normal lattice in both planes; the rest comes from the insertions.
- f) The choice of the circulating current has been based on many considerations. With the crossing geometry arrived at, it should not violate the space-charge criteria, it should not create pressure bumps (cf. Section 6), and it must be possible to dump the stored beam safely under all conditions (see Section 5). These criteria are met with 7 A.
- g) See Section 5.
- h) This is based on the assumption that Q is equal to an integer $+1/4$.

3.2 Lattice properties

3.2.1 Normal cell and dispersion suppressor cell

The normal cell is a straightforward FODO structure with phase advance $\pi/2$ per cell. The length of the short straight sections is close to the minimum required for a superconducting magnet lattice with a vacuum chamber at room temperature. In order to provide for greater free space at locations of extreme β values, the three dipoles in the half cell are placed asymmetrically. These medium straight sections could accommodate correction elements for any functions not included in the dipoles or quadrupoles, together with beam monitoring devices. Alternatively, these spaces could be regarded as basic reserve lattice space for "unknown" future demands. The ratio between the cell length and bending magnet length, the circumference factor R_0/ρ , is about 1.73. The parameters of the normal cell structure are given in Table 3.2. The orbit functions are shown in Fig. 3.1.

Table 3.2

Normal lattice parameters

Cell length	40.4 m
Magnetic dipole length	3.9 m
Number of dipoles in normal cell	6
Straight section between dipoles	1.3 m
Short dipole-quadrupole straight section	1.3 m
Medium dipole-quadrupole straight section	3.2 m
Magnetic quadrupole length	1.4 m
Quadrupole gradient	68.5 T/m

The presently adopted values of the maximum field in the coils of the superconducting dipoles and quadrupoles are of the order of 4 T, about 20% below the field level actually achieved in the ISR low-beta quadrupole prototype which is of rather similar design⁵⁾. If an LSR study were started now, a higher value for the maximum field might well be adopted.

The dispersion suppressor cell provides for zero dispersion D_x at the boundaries of the experimental insertion sequences and at the boundaries of the dummy crossing structures, thus enhancing the flexibility of the design of these insertions and increasing the range of phase advance achievable with the dummy crossing regions. A cell with five dipoles has been adopted for the basic dispersion suppressor in order to reduce the variation of the β functions introduced by it and to trim the phase advance with the objective of bringing closer together the horizontal and vertical tunes of the complete lattice.

3.2.2 Dummy crossing structure

Although the primary objective of this structure is to cross physically the two proton beams, a tunable structure is obtained by adding one more adjustable quadrupole to the minimum of four required for matching. In this manner, the nominal tunes can be maintained for various experimental insertion configurations. The phase advance can be varied over a range of about $\pi/2$, which is adequate for this purpose. The orbit functions for the dummy crossing are shown in Fig. 3.2.

3.3 Chromaticity corrections

Because of the large contributions of the insertions, the uncorrected over-all chromaticity $Q' = dQ/(dp/p)$ is quite large and negative. Since small positive values of the chromaticities are needed for Landau damping of transverse coherent instabilities (see Section 8) and minimum length of the working line in the Q_x - Q_y diagram, chromaticity correction by sextupoles is necessary. In order to demonstrate the feasibility of a chromaticity correction scheme, a quick solution has been worked out for the lattice described in Ref. 8. A sextupole component of strength $K' = K/D_x$ is superimposed to all experimental insertion quadrupoles where the dispersion D_x is non-zero. Sextupole and octupole components are also superimposed in all normal-cell elements. Their strengths are adjusted such that $Q' = +1$ and $Q'' = 0$. Somewhat arbitrarily, no sextupole elements were introduced in the injection/ejection lattice and dispersion modification sections.

A sample of the results is shown in Fig. 3.3 for the variation of the tune with the momentum error, and in Fig. 3.4 for the variation of the amplitude functions β_x and β_y in the LB and GP insertions of Ref. 8. At present, these results should only be taken as an indication that the chromaticity of the lattice can be corrected satisfactorily.

If the LSR studies were taken up again in the future, the sextupole arrangement would have to be revised according to the current design parameters with the aim of reducing to an acceptable level the undesirable side effects of chromaticity correction using the minimum number of independently powered sextupole families. Methods for achieving these aims have been developed at CERN and elsewhere in the context of the studies of other machines¹¹⁻¹³⁾.

3.4 Complete LSR

3.4.1 *Superperiodicity*

The elongated shape of the assumed LSR site imposes a racetrack-shaped machine with fundamental twofold periodicity. This feature has influenced the arrangement of the p-p physics insertions, which are grouped in sets of three along each long arm of the racetrack. A superperiodicity of two is already rather low, and it seems advisable at this stage of the design to avoid a configuration containing a systematic component of superperiodicity one. In addition to prescribing the grouping of the p-p physics insertions, this constraint imposes the position and beam optics of the beam-dumping insertions in the arcs opposite to the injection insertions. The arrangement of the latter is fixed by the geometry of the transfer tunnels from the SPS.

The 20 GeV electron ring is located in the same tunnel as the proton rings over most of its circumference. By locating the e-p insertions in the curved part of the proton lattice and by designing the e-ring with an orbit sufficiently displaced in the region of the p-p insertions, an over-all structure with minimum interference between the p-p and e-p physics is obtained. Moreover, by placing the e-p insertion in Ring 1 adjacent to the injection insertion for Ring 2, the e-p option can be provided without increasing the circumference of the proton rings.

3.4.2 *Ring arrangement*

The design of the near-contiguous physics insertions results in a beam separation of 1.1 m at their ends, a distance which is maintained between insertions. Where the insertions join the main arcs, special matching sections increase the beam separation to the 2.5 m required in the normal tunnel.

In the interaction regions the beams cross in the horizontal plane. This simplifies the layout, access, and civil engineering, as compared with vertical crossings. Both physics considerations and some aspects of machine performance lead also to a slight preference for horizontal crossings. On the other hand, we know of no strong argument in favour of vertical crossings for this type of machine. This conclusion is in agreement with that reached for ISABELLE⁶⁾.

Horizontal crossings and 2.5 m beam separation lead naturally to horizontal ring spacing in the main bending arcs, with magnet units close to the tunnel walls and a central access passage. The machine then contains no vertical bending, but requires two extra horizontal cross-overs ("dummy crossings"), one at the centre of each main bending arc, to preserve the twofold superperiodicity. There are, however, arguments in favour of placing the two rings one above the other in the main bending arcs^{3h)}. This could lead to a reduction in tunnel and vacuum costs, and to the elimination of the two extra cross-overs which add to the machine circumference. On the other hand, extra circumference would be needed to convert the small vertical beam separation in the main bending arcs into the relatively large horizontal separation at the intersections.

For the present design we have adopted the horizontal ring separation, although a more detailed study might lead to a preference for vertical ring separation.

3.4.3 Over-all layout

The outcome of these considerations is shown in Fig. 3.5 and Fig. 1.1. Figure 3.5 gives a schematic layout indicating how the various insertions and lattice components are arranged, and how the two rings cross in various places, while Fig. 1.1 shows a scale layout drawing. The two rings are too close to each other to appear separately. The nomenclature of the insertions is also indicated in Fig. 3.5. Rather detailed descriptions of the experimental physics insertions and the other lattice components are given in Sections 2 and 3.2, respectively.

Fig. 3.1 Orbit functions in normal cell and dispersion suppressor

Fig. 3.2 Orbit functions in dummy crossing regions

Fig. 3.3 $dQ = f(dp/p)$; first order chromaticity correction of the superconducting LSR. $Q' = +1$, at $(dp/p) = 0$, set with normal cell sextupoles.

Fig. 3.4 $(d\beta/\beta) = f(dp/p)$ at the low-beta insertion crossing point, and at the GP insertion crossing point

Fig. 3.5 Schematic layout of the LSR

4. MAGNET SYSTEM FOR PROTON RINGS

The magnet system of the LSR proton rings consists of 576 dipoles and 192 quadrupoles per ring in the regular lattice and 76 special magnets in the insertions. In the conceptual design of the system, attention has been concentrated on the regular lattice components, owing to their large number.

The main parameters of such components are shown in Tables 4.1 and 4.2 and their cross-sections in Figs. 4.1 and 4.2. The geometry and structure of the magnets have been equally inspired by BNL developments for ISABELLE⁶⁾ and by the experience of the ISR prototype quadrupole for a high luminosity insertion⁵⁾.

Both in the dipoles and in the quadrupoles, the main windings form a compact cylindrical structure, in which the conductors are so positioned as to suppress the lower parasitic multipoles in the useful aperture for the beam¹⁴⁾. The dipoles have two 180° sector coils, the quadrupoles four 90° sector coils. Each coil consists of three compact blocks of monolithic multifilamentary superconducting wires of rectangular cross-section wound around a central stainless-steel post and wedge-shaped copper spacers. The coil ends have a "constant perimeter" profile, in which the resultant of the tensions applied to the conductor, while it is being wound, is perpendicular to the supporting surface: thus successive layers can be wound from bottom to top and from top to bottom without slipping. The spacing of the conductor layers at the ends is determined by the required dipole and quadrupole purity of the integrated fields.

Table 4.1

Lattice dipole parameters

Nominal field	4 T
Useful aperture diameter	50 mm
Cold bore	80 mm
Inner diameter of dipole coils	100 mm
Inner steel diameter	154 mm
Outer steel diameter	380 mm
Magnetic length	3.7 m
Core length	3.9 m
Over-all cryostat length	4.3 m
Over-all cryostat diameter	600 mm
Number of turns per coil	150
Nominal current	1700 A
Stored energy	350 kJ
Number of dipoles per ring	576
Total inductance per ring	140 H
Inductive voltage for 5 min rise-time	800 V
Estimated circuit resistance (junctions and cables)	100 mΩ
Power supply voltage	1000 V

Table 4.2

Lattice quadrupole parameters

Nominal gradient	60 T/m
Useful aperture diameter	50 mm
Cold bore	80 mm
Inner diameter of quadrupole coils	100 mm
Inner steel diameter	154 mm
Outer steel diameter	300 mm
Magnetic length	1.6 m
Core length	1.8 m
Over-all cryostat length	2.2 m
Over-all cryostat diameter	520 mm
Number of turns per coil	78
Nominal current	1800 A
Stored energy	60 kJ
Number of quadrupoles per circuit	96
Lattice quadrupole circuits per ring	2
Total inductance per circuit	3.6 H
Inductive voltage for 5 min rise-time	22 V
Estimated circuit resistance (junctions and cables)	100 m Ω
Power supply voltage	250 V

The main windings are tightly banded with glass-epoxy tapes, leaving adequate channels for circulation of the coolant, and are prestressed by a laminated steel yoke and an external stainless-steel cylinder. The ring-shaped steel laminations are locally slotted along the axes of the magnetic poles, so that they behave like springs. At magnet assembly, the stack, temporarily held together by longitudinal bolts, is slightly opened by means of hydraulic cushions, to receive the windings at room temperature. The pre-heated stainless-steel cylinder is next shrunk-fitted onto both. Thus the prestress on the main coils is low at room temperature, at which plastic flow of the organic insulation might be feared, and is built up at cooldown by thermal shrinkage of the stainless-steel cylinder. This "cold iron" structure, which is very compact and rigid, seems best suited for ensuring mechanical stability and positional tolerances. It has the disadvantage that the whole mass of iron has to be cooled and encapsulated into the cryostat, but the advantage that the suspensions are simple and the heat intake is low.

For the purpose of this study, designs have been worked out for a $1.8 \times 3.6 \text{ mm}^2$ (bare) conductor, with Cu/SC = 1.5 and 50 μm filaments, insulated by 0.1 mm enamel and Kapton, which is being used for the quadrupoles of the ISR low-beta insertion. Safe operating currents are 1700 A at 4 T in the dipoles and 1800 A at 60 T/m in the quadrupoles. Details of both

types of coils are given in Table 4.3. All dipoles are powered in series, whereas there are two powering circuits for the quadrupoles F and D, respectively.

Auxiliary windings are incorporated into the dipoles and the quadrupoles. In particular, sextupole coils for chromaticity corrections are in the dipoles, whereas vertical and horizontal dipoles for closed-orbit corrections are in the quadrupoles (vertical dipoles in the Q_F 's and horizontal ones in the Q_D 's). The quadrupoles contain also octupole, decapole,

Table 4.3

Composition of the main dipole and quadrupole coils

Dipoles and quadrupoles				
Inner diameter of main windings			100 mm	
Winding thickness			23 mm	
Conductor dimensions: bare			1.8 mm × 3.6 mm	
insulated			2.0 mm × 3.8 mm	
Copper to superconductor ratio			1.5	
Filament diameter			50 μm	
Dipoles				
Number of turns per winding block in each coil:				
block	1	2	3	
turns	30	48	72	
Quadrupoles				
Number of turns per winding block in each coil:				
block	1	2	3	
turns	12	24	42	

and dodecapole windings for working line shaping, and skew quadrupole windings for coupling compensation. These windings are located into slots in the wall of the inner stainless-steel cylinder, which is part of the helium enclosure. They are constrained by an aluminium alloy bandage, which is tensioned by thermal shrinkage: a clearance for helium flow remains between this bandage and the self-supporting main coils. The parameters of the most important auxiliary windings (sextupoles and dipoles) are given in Table 4.4.

Each magnet is contained in its own independent cryostat, but a number of cryostats in a row will be connected in series cryogenically. As already said, the inner and outer cylinders of the helium vessel are parts of the magnet structure itself. Each cryostat has its own warm bore tube: this will allow measuring of the magnetic axes and median planes in the laboratory and positioning of the alignment targets on the outer vacuum vessels with respect to them, before installation.

Table 4.4

Parameters of some auxiliary windings in the lattice

Sextupoles (in two-thirds of the dipole magnets)	
Maximum B''	40 T/m ²
Turns per pole	10
Current	100 A
Number of sextupoles per circuit	192
Sextupole circuits per ring	2
Estimated circuit resistance (leads, junctions and cables)	2 Ω
Power supply voltage	250 V
Orbit correcting dipoles (in the quadrupole magnets)	
Maximum field	0.1 T
Turns per pole	100
Current	50 A
Number of vertical dipoles	96
Number of horizontal dipoles	96
Estimated circuit resistance	1 Ω
Power supply voltage	50 V
Number of power supplies per ring	192

The magnets are intended to be cooled by forced circulation of high pressure (15 bar) helium at temperatures between 2.8 K and 4.4 K, according to the method developed at BNL for the ISABELLE⁶⁾ project. In this study, the parameters of the cryogenic system are simply scaled from those of ISABELLE, for lack of relevant experience of our own. In the LSR, however, magnet excitation takes place at a much slower rate, since beam acceleration is not required. Therefore, the compact blocks of the coils are adequately cooled by helium circulation along their sides and through the copper spacers.

The main connections between the magnets are also superconducting and are immersed in the transfer lines of the coolant. Electrical protection in case of quench is ensured by suitable power diodes, which have a conduction threshold of about 20 V at 4 K, but a very low voltage drop when heated by the passage of current¹⁵⁾. Each magnet is equipped with its own diode, which short-circuits it automatically in case of quench: the diodes are so placed as to be shielded against radiation damage. Automatic valves can discharge the over-pressure from a quenching magnet fast enough to prevent thermal propagation of the quench to neighbouring magnets and to obtain quick re-cooling by cold helium flow.

Auxiliary multipole windings and dipole windings for closed-orbit correction are powered via ordinary warm cables and current leads. The corresponding heat intake through the leads is not prohibitive, because of the relatively modest operating currents.

The main return flow of pressurized helium is used to cool the external heat screens of the cryostats. In addition to the direct cryogenic interconnections between the magnets of each sector, general cryogenic lines for helium distribution and return run all along the machine.

The refrigeration requirements are difficult to determine analytically, because of our lack of experience with the proposed system. Scaling from the static load estimates for ISABELLE⁶⁾, we should foresee a single refrigeration plant, common to the two rings, of 40,000 W capacity.

The power supplies are so rated as to allow full excitation of the magnets in not more than 5 minutes. This requirement is determinant only for the power supplies of the main dipoles, whose circuits, taking into account the resistance of cables and junctions, have time constants of about 20 minutes. The number and ratings of the power supplies for the main components in the normal lattice of one ring are given in each of the relevant tables (4.1, 4.2, and 4.4).

Fig. 4.1 Cross-section of an LSR dipole

Fig. 4.2 Cross-section of an LSR quadrupole

5. INJECTION AND EJECTION

It was pointed out in the Introduction that the injection and beam-dumping systems for the LSR have not yet been fully worked out and incorporated into the lattice systematically. Although there are no fundamental difficulties to be expected, this machine does have a particular constraint, namely that injection must be possible up to top energy, where the safety margin on temperature rise in the superconducting magnets is smallest. Thus special care is required to minimize beam losses at injection and to ensure that lost particles are adequately stopped by collimators. Similarly, with over 50 MJ stored energy in a stacked beam, the beam ejection and dumping system must be extremely reliable.

The main considerations involved in the design of injection and beam-dumping systems for the LSR are discussed below.

5.1 Injection

Three types of injection scheme have been considered for the LSR:

- a) injection with small-aperture kicker magnets whose stray field is shielded by a movable shutter closing the gap;
- b) small-aperture kicker magnets whose stray field is attenuated by a special pole shaping or by fixed, open screens;
- c) injection with full-aperture kicker magnets.

For all three methods the beam is brought close to injection orbit by septum magnets, and after injection is stacked in momentum space by RF as in the ISR.

5.1.1 Moving shutter

This scheme has been used in the ISR since the beginning of operation. In order to obtain the same screening efficiency in the LSR, the shutter thickness must be greater than in the ISR by a factor of $\sqrt{20/3}$, because of the longer revolution time and injection pulse length (Appendix 5.1). A 1 mm thickness is sufficient for screening in the ISR, therefore a safe value for LSR would be 2.5 mm. For this scheme there is no constraint in the vertical aperture of the kicker magnet gap. The horizontal separation $(\Delta x_{inj})_k$ at kicker location is then given by the horizontal betatron width, plus shutter thickness and some safety margin. At 400 GeV/c and for a normalized emittance of $30\pi \times 10^{-6}$ rad m, one gets (for a 4σ radius):

$$(\Delta x_{inj})_k = 8.8 + 2.5 + 2 = 13.3 \text{ mm} .$$

Supposing the space allowed for injection $(\Delta x_{inj})_\ell$ is 5 mm in the normal lattice where the dispersion D_x has a maximum value of 1.8 m, the required D_x at the kicker is

$$D_{xk} \approx \frac{13.3}{5} \times 1.8 = 4.8 \text{ m} .$$

5.1.2 Fixed screens or split-pole solutions

The use of screens has been considered also for the ISR, and a model of a static screen has been tested. This scheme has also been considered for LSR, since it avoids any moving parts in the injection hardware and possibly reduces some instability effects during stacking of the first pulses. Here we have three different solutions:

- a) horizontal kick with static screens (as proposed for the ISR);
- b) vertical kick with static screens;
- c) split-pole kicker¹⁶⁾.

In these three solutions the vertical height h of the gap between screens for (a) and (b) (Appendix 5.2) or between the "noses" of (c) is not free and must be minimized in order to minimize the horizontal separation between injection orbit and the bottom of the stack. To achieve a sufficient attenuation from 99% field to 0.3% field, a separation of

$$2.5 h \text{ for (a)}$$

$$\approx 2 h \text{ for (b)}$$

$$\approx 3 h \text{ for (c)}$$

is needed. These figures have been obtained by measurements on resistive paper models for all three cases, and by calculations with conformal transformation for (a) and (b) and by computer for (c). The results for (a) agree very well with the measurements on the ISR screen model. The minimum h that can be considered is

$$h = 2\sqrt{\epsilon_V \beta_V} + \text{safety margin}$$

(for alignment tolerance after bake-out). With the vertical emittance $\epsilon_V = 30\pi \times 10^{-6}$ rad m, $\beta_V = 20$ m, and safety margin = 2 mm, one gets (for 4σ beam radius) at 400 GeV/c:

$$h = 6.5 \text{ mm} .$$

The corresponding horizontal separations $(\Delta x_{inj})_k$ are (for 4σ and $\beta_H \approx 70$ m)

$$\text{a) horizontal/screen } (\Delta x_{inj})_k = 16.8 \text{ mm} + 8.85 \text{ mm} = 25.60 \text{ mm}$$

$$\text{b) vertical/screen } (\Delta x_{inj})_k = 13.4 \text{ mm} + 8.85 \text{ mm} = 22.25 \text{ mm}$$

$$\text{c) split-pole } (\Delta x_{inj})_k = 20.1 \text{ mm} + 8.85 \text{ mm} = 28.95 \text{ mm} .$$

Then the required dispersions are

$$\text{a) } D_{xk} = 9.2 \text{ m}$$

$$\text{b) } D_{xk} = 8 \text{ m}$$

$$\text{c) } D_{xk} = 10.4 \text{ m} .$$

These values are very high, and the design of an injection insertion of a reasonable length becomes rather difficult.

5.1.3 Full-aperture kickers

This scheme has been considered at Fermilab for POPAE Storage Rings¹⁷⁾ and is very similar to the schemes used in electron machines. The principle, shown in Fig. 5.1, is the following: two kickers make a fast (one turn) bump on the stack and the injection orbit. The injected beam goes through only the downstream kicker. The kicker magnets are energized for less than one turn duration and are therefore switched off for the injected beam when it arrives at the upstream kicker. Two questions immediately arise: the effect on the stack of repeated fast bumps and the safety of the system in the event of one kicker only being accidentally triggered. The second problem can be resolved, and the first one partially, by using a single pulse generator for the two kickers, with a delay corresponding to the

transit time of particles between them. By choosing the septum thickness about the same as that of a moving shutter, the same value of $(\Delta x_{inj})_k$ and D_x (i.e. 4.8 m) is required. For this scheme it is obviously interesting to have $D_x \approx 0$ at the kicker locations.

5.1.4 Injection insertion

In the previous investigation, made for comparison of the various schemes, some typical parameters have been chosen as examples. However, no detailed conclusions can be drawn from such a comparison without specific insertion designs for the corresponding injection schemes. The main difficulty in the design of an insertion is in obtaining a large dispersion D_x with moderate values of β_H and β_V and with the required phase advance of $\pi/2$ between kicker and septum magnets.

5.1.5 Conclusions and guidelines for future studies

All schemes are feasible in principle and should be considered. Each of them needs the design of its special insertion. Since the solution with moving shutter tends to lead to a moderate value of D_x , it seems a logical first choice for a detailed study of insertion optics, hardware, and estimates of particle losses at injection over the full energy range of LSR. Similar studies could then be made for the other methods.

Figure 5.2 summarizes the specification of the insertion required with a shutter-type injection.

5.2 Beam dumping

In the design of a safe beam-dumping system for the LSR, the two most important beam characteristics are the stored energy in the beam, which is 56 MJ for 7 A intensity, and the beam density, which is about 1 A/mm². It would be impracticable to blow up the beam cross-section in the ring artificially before dumping; furthermore, the stacked beam would heat an internal absorber too much. It is therefore proposed to have a fast, external beam-dumping system made of fast kicker magnets, septum magnets, a short transfer tunnel, and an absorber block. The system must be ready to dump the beam completely and at any time¹⁸⁾, and must therefore be permanently energized using d.c. charged capacitors able to withstand the high voltage over long periods. All kicker magnets should be fed in parallel by one single pulse generator in order to prevent the catastrophic consequences of losing the beam somewhere in the ring, a situation which would result from an incomplete kick due to faulty triggering of only part of the high-current switches. Furthermore, experience with the ISR has shown that it is of the utmost importance to reduce as far as possible the number of HV switches in order to obtain an acceptably low spontaneous firing rate. Another stringent specification is the short rise-time and response-time of the system. This is necessary in order to minimize the beam losses during extraction (which are proportional to the ratio between the rise-time and the revolution-time), and to provide safe dumping even if the machine or the beam-dumping system itself is not under normal conditions. Typical figures of the beam-dumping system are given in Table 5.1.

Using existing equipment in our laboratory, we have studied experimentally the feasibility of high-voltage spark-gap switches (up to 70 kV), with very short rise-time (100 nsec), high-current capability (20 kA during 30 μ sec), and perfect reliability. The experiment has been made with a 7 μ F capacitor discharged in a low inductance circuit of 3.5 Ω , which

Table 5.1

Beam dumping parameters

Rectangular pulse length	24 μ sec
HV	60 kV
Total capacitance	8 μ F
Characteristic impedance	1.5 Ω
Maximum current of the pulse generator	20 kA
Number of kicker units	10
Kicker magnet aperture ($D_x = 0$)	15 mm $\times$ 25 mm
Magnetic field	0.1 T
Total magnetic length	5.4 m
Deflexion (with 60 m lever arm)	24 mm
Magnet time constant	13 nsec
Pulse generator time constant	33 nsec
Rise-time	102 nsec

simulates the rectangular pulse of 24 μ sec. A linear, high-pressure, field distortion hexode spark-gap (Fig. 5.4) has been designed, built, and tested. The surface of the electrodes, and consequently the lifetime, can be increased with their length to achieve at least 5×10^5 pulses without any decrease in performance. The switch performance has been thoroughly tested; the spontaneous firing rate was found to be zero over periods of 200 h and no apparent erosion of the electrodes was seen after 10^5 pulses. The rise-time was 100 nsec at 20 kV and 80 nsec at 60 kV, showing a net decrease of the switch inductance with increasing discharge current. The dumping efficiency that can be expected for LSR is therefore about 99.7%, i.e. 190 kJ will be lost on internal collimators whereas the beam energy will be properly dissipated on the dump block¹⁹⁾.

The beam cross-section on the dump block will be spread over about 30 cm², simply by using the dispersive properties of the septum magnets and bending magnets of the transfer line, which contains no quadrupoles. This beam enlargement at the dump block would also permit a measurement of the beam dimensions.

5.3 Scraping and collimation

In proton storage rings, where the particle detectors are in close proximity to the machine, the amount of uncontrolled beam losses has to be kept to a very low level. In addition, the superconducting magnets of the LSR must be protected against quenching due to beam losses. The experience gained in the ISR has clearly shown that

- it is important to localize particle losses and their effects by, wherever possible, a scraping system made of a thin foil obstructing the unwanted trajectories and an absorber block limiting the aperture just beyond the scraper position;
- there are residual losses due to scraping, localized downstream from the scraper regions, where collimators have to be added to protect the nearest intersections.

For LSR it is likely that losses will occur at injection and during stacking at up to 400 GeV (and during acceleration, if any, to higher energies), and finally on dumping. The problem of scraping losses is rather complicated, but the following approach can be considered. Particles are scattered by a (vertical) scraper foil at a random angle with a normal distribution. Since these particles are scattered from the primary beam envelope, the probability distribution oscillates beyond the boundary of this envelope, though its central trajectory does not go outside. It is therefore possible to catch the particles on the dump block when they have enough relative amplitude. It can be shown that the maximum of particles is dumped after one traversal of the scraper foil when $\cos \Psi_D = \pm \sqrt{\epsilon \beta_D / z_D}$, Ψ_D being the phase advance between the scraper and the dump block, ϵ the scraped emittance, and z_D the block radial position. It can then be seen that if we want to dump a maximum of particles just after their scattering in the foil at their first passage in the dump block, this block should be in two parts (or a dump block plus a large collimator), located at phase advances given by the previous formula. As $\sqrt{\epsilon \beta_D} \approx z_D$, $\cos \Psi_D \approx \pm 1$ and Ψ_D values are near 0 and π . A diagram in the common betatron phase plane explains this point in Fig. 5.5. We can go further and find an expression for the survival probability P_1 after one traversal of the scraper:

$$P_1 = \operatorname{erf} \left(\frac{\sqrt{z_D^2 - \epsilon \beta_D}}{K\sqrt{2}} \right),$$

with

$$K = \sqrt{\langle \theta^2 \rangle} \beta_{ST} \beta_D \quad \text{and} \quad \sqrt{\langle \theta^2 \rangle} = \frac{15}{p(\text{MeV})} \sqrt{\frac{L}{L_{\text{rad}}}}$$

with self-explanatory notations.

It can also be shown that this probability, after n traversals, is

$$P_n = \exp \left[-n(L/L_a - \ln P_1) \right],$$

where L_a is the absorption length. The target inefficiency $1 - \eta$ is given by:

$$1 - \eta = \frac{1 - \exp(-L/L_a)}{1 - P_1 \exp(-L/L_a)}.$$

Numerical calculations made with the previous formulae clearly show that the main parameter in the scraping efficiency is the clearance between the scraper radial position and the dump block position; it is proposed to couple the position of the dump blocks according to the scraper movement in order to avoid scraping with the blocks not limiting the aperture. Remote control of the block position being needed for other reasons, it would be straightforward to command this common movement from the control computer.

When a beam is vertically scraped, particles are scattered both vertically and horizontally, and we can find expressions for P_1 taking this fact into account. There will be residual losses due to the "grey zone" of the absorber, small asperities of the block hole, inaccurate positions or tilt, etc. In addition to these sources of losses, there will also be secondary particles from nuclear interactions in the scraper itself. A relatively large number of collimators downstream from the scraping system will therefore be needed to protect the superconducting magnets. The possible locations of these collimators should be at $\pi/2$, π , $3\pi/2$, and 2π phase advances from the source of scattered particles, and the final layout in the LSR will take this requirement into account.

APPENDIX 5.1

REMARKS ABOUT THE SHIELD DEPTH

The equation for the magnetic field in the shield is

$$\Delta H - \sigma\mu \frac{\partial H}{\partial t} = 0$$

where σ is the conductivity and μ the permeability. Then supposing a step function for the time variation of the outer field, we get

$$H = H_0(1 - \operatorname{erf} \xi) ,$$

with

$$\xi = \frac{x}{2\sqrt{t/\sigma\mu}} \quad (x = \text{depth of shield}) .$$

Similarly to the a.c. case, one can define a "skin depth" S ,

$$S = 2\sqrt{\frac{t}{\sigma\mu}} .$$

For a shield depth d equal to S , the field is 16% of the outer field. For a better shielding, e.g. $< 1\%$ of the outer field, the depth d is given by

$$d \geq 3.67\sqrt{\frac{t}{\sigma\mu}} .$$

Using aluminium, and for a pulse duration of 30 μsec ,

$$d \approx 3 \text{ mm} .$$

Thus to get a shielding as good as it would be for a 2.2 μsec pulse, the shield depth must be multiplied by the square root of the ratio of the pulse durations, i.e. $\sim \sqrt{20/3}$ for LSR.

COMPARISON BETWEEN THE SHIELDING OF A
VERTICAL OR HORIZONTAL FIELD WITH STATIC SCREENS

Supposing the shielding is perfect, the boundary conditions for pulsed magnets and shields become

$$\begin{aligned} \text{on conductor} \quad \quad \quad \bar{n} \cdot \bar{B} &= 0 \quad (\text{or } B_{\text{normal}} = 0) \\ \text{on ferrite (if any)} \quad \bar{n} \times \bar{B} &= 0 \quad (\text{or } B_{\text{tangential}} = 0) . \end{aligned}$$

The field lines are the equipotential lines of the analogue problem of electrostatics (for two dimensions only).

If we compare the stray fields corresponding to the two situations illustrated in Fig. 5.3, we can see that the field lines have different symmetries, resulting in a faster decrease of the stray field inside the shield for the horizontal field magnet (vertical deflection).

Approximately, the distance x between the good field region in the magnet (99% homogeneity) and the point where the field is reduced by a factor $f < 1$, is given by

$$\begin{aligned} \frac{x}{h} &\approx 0.65 + \frac{1}{\pi} \ln f^{-1} \quad (\text{vertical field}) \\ \frac{x}{h} &\approx 0.9 + \frac{1}{2\pi} \ln f^{-1} \quad (\text{horizontal field}) . \end{aligned}$$

Fig. 5.1 Injection with full-aperture kickers

Fig. 5.2 Injection insertion specifications

Fig. 5.3 Comparison of vertical field and horizontal field screening

Fig. 5.4 Cross-section of the hexode spark-gap for dumping application

Fig. 5.5 Optimal phase advances of dump blocks for scraping

6. VACUUM AND CLEARING SYSTEMS FOR PROTON RINGS

6.1 Pressure requirement

In order to maintain the beam loss rate due to nuclear scattering with the residual gas as low as in the ISR, i.e. < 1 ppm/min, an average pressure of less than 4×10^{-11} Torr N_2 -equivalent must be provided in the LSR. This requirement must also be satisfied with a stored beam, which, by ion desorption from the beam pipe wall, enhances the total outgassing rate. The average static pressure should therefore be in the 10^{-12} Torr range.

The neutralization of the stored beam by electrons, produced in ionizing collisions of the protons with the residual gas, should be below the threshold of e-p instability (coherent, transverse oscillations of the protons leading to beam blow-up and consequent particle loss). A local pressure of less than 4×10^{-11} Torr gives a residual gas ionization rate that can still be balanced even by the lowest clearing rates expected in the LSR.

Another source of beam blow-up and consequent loss of luminosity is multiple Coulomb scattering. The blow-up rate at 4×10^{-11} Torr is, however, less than 3% of that in the ISR owing to the higher proton momentum; it is therefore completely negligible.

The average pressure $\bar{P}$ (Torr) in a vacuum system with lumped pumps of speed S_L (ℓ/sec) is given by

$$\bar{P} \approx P_L + 50 \cdot q (L/r)^2$$

if $S_L > 50 r^3/L$; however, with distributed pumps of speed S_D (ℓ sec⁻¹ m⁻¹) it is

$$\bar{P} \approx P_D + 630 \cdot qr/S_D ,$$

where P_L and P_D denote the low-pressure limit of the pumps ($\approx 3 \times 10^{-12}$ Torr), q (Torr ℓ sec⁻¹ cm⁻²) the specific N_2 -equivalent thermal outgassing rate, r (cm) the radius of the (circular) beam pipe aperture, and L (m) the distance between lumped pumps. If we scale from the ISR where $\bar{P} = 7 \times 10^{-12}$ Torr, the lowest pressure that could be achieved is $\bar{P} \approx 4 \times 10^{-11}$ Torr in a warm-bore LSR vacuum system with $S_L > 150$ ℓ/sec, using stainless steel and the same pretreatment as for ISR vacuum chambers (with $r = 2.5$ cm and $L = 5.1$ m). With distributed pumps having $S_D > 40$ ℓ sec⁻¹ m⁻¹, however, the design pressure $\bar{P} < 1 \times 10^{-11}$ Torr could be achieved.

A more difficult problem than that of achieving a low average pressure is maintaining the vacuum stable when a beam of up to design current is stored. Vacuum instability is caused by positive ions produced in beam-gas collisions and accelerated in the beam space-charge field, bombarding the beam chamber wall where they desorb gas²⁰). Beyond a critical beam current I_C (A), the pressure rises exponentially owing to this feedback process. In a vacuum system with lumped pumps it is given by

$$I_C \approx 10 r^3/\eta_D L^2 ,$$

and with distributed pumps

$$I_C \approx S/\eta_D ,$$

where η_D is the net increase of molecules in the gas phase per ionizing collision. Scaling from the ISR gives $\eta_D > 3.5$ mol/ion at the worst place. Hence in the LSR only $I_C = 1.7$ A

would be obtained with a lumped-pump system, and the same beam chamber material and conditioning as in the ISR. The design current can only be achieved with distributed pumping of $S_D = 40 \text{ l sec}^{-1} \text{ m}^{-1}$.

Therefore the vacuum requirements of the LSR cannot be met with a warm-bore vacuum system, such as the ISR, using lumped pumps only; with a distributed-pump system $S_D > 40 \text{ l sec}^{-1} \text{ m}^{-1}$, however, this is possible.

A cold-bore vacuum system with very low or negligible thermal outgassing rate and acting as a linear pump looks quite attractive²¹⁾. However, uncertainties as to whether a technically suitable solution exists and whether it provides the specified vacuum stability have led us, in this study, to adopt a warm-bore or a "cool"-bore vacuum system where the beam pipe temperature within the cryomagnets is kept at room temperature or at about liquid-nitrogen temperature²²⁾, respectively.

6.2 Lumped pumping stations

The LSR vacuum system is divided into 48 vacuum sectors; on the average, each sector is about 160 m long and comprises 24 long dipole magnets and 8 quadrupole magnets. In the space available between these magnets or in equivalent distances in straight sections, manifolds are mounted for the installation of lumped sputter-ion pumps of 80 l/sec, a UHV pressure gauge, an electron clearing plate, and a pair of bellows to allow for thermal expansion of the beam pipe during bakeout and for contraction if it is operated as a "cool" bore.

Pump stations at each end of a long superconducting dipole also incorporate special manipulators that permit *in situ* treatment of the beam pipe which provides the required distributed pumping speed. Some stations are also provided with a UHV valve permitting connection of the system to a mobile roughing station, and others with a special valve to inject the argon gas needed for the *in situ* treatment.

A full-size LSR vacuum system for a long dipole magnet has been built and studied, as this is the most difficult part of the vacuum system²³⁾. Figure 6.1 is a photograph of one of its lumped-pump stations.

The LSR vacuum system is evacuated with 30 m³/h double-stage roughing pumps and 100 l per sec turbomolecular pumps assembled in mobile pump stations. This concept has the following advantages:

- the number of (rather expensive) pump groups can be considerably reduced;
- another great cost saving is obtained using manually instead of remotely controlled components such as valves or gauges;
- the control system can be virtually eliminated.

The mechanical pumps are deliberately oversized to minimize the roughing pump-down time and hence the backstreaming of oil through the turbomolecular pumps at reduced rotor speed.

At the end of the bakeout period and after the *in situ* conditioning cycle to provide linear pumping, the triode-type 80 l/sec sputter-ion pumps are switched on and the roughing pump is separated from the system by closing the UHV valve. The average system base pressure in the test system achieved *without* linear pumping is about 4×10^{-10} Torr; it could be

reduced by optional Ti-sublimation pumps to $\approx 3 \times 10^{-11}$ Torr. Although sufficient space for these types of pumps has been reserved at the top of the manifold, they were found to be superfluous with linear pumping.

A perforated tubular sleeve is mounted inside the lumped-pump station manifold to minimize the beam-wall coupling impedance. Sliding contacts of RF type provide the electrical connection between the beam pipes on either end across the manifold despite their thermal axial motion. A special screen protects the UHV gauges against the gas discharge during *in situ* conditioning.

6.3 Distributed pumping system

The available beam-pipe aperture excludes any kind of conventional distributed pumping system. The simplest way, however, of providing linear pumping is to coat the inner wall of the beam pipe with an active film of titanium. A pumping speed of over $4000 \text{ l sec}^{-1} \text{ m}^{-1}$ for CO -- the predominant gas observed near the vacuum stability limit -- is expected from molecular sticking factors as quoted in the literature²⁴⁾. This is one hundred times more than is needed.

It has been shown that it is rather easy to create such a film by sputtering *in situ* from a titanium wire in an argon gas discharge^{22,23)}. This wire, of about 1 mm diameter, is strung out along the beam pipe axis during sputtering by a special manipulator (Fig. 6.2) but retracted during normal machine operation.

The sputtering was usually carried out after bakeout and when the system had cooled down almost to ambient temperature. We used commercial > 99.999% pure argon gas at discharge pressure of $\approx 3 \times 10^{-2}$ Torr. Best results were obtained with a wire potential of about -400 V (beam-pipe grounded) and a discharge current of 100-120 mA, with the discharge on for about 20 min. The choice of this relatively low cathode wire potential reduces the amount of implanted argon; a subsequent bakeout to remove the argon is thus superfluous. After the sputtering process, the argon gas is evacuated via the roughing stations.

An average pressure of $< 2 \times 10^{-11}$ Torr is typically achieved within 24 hours after sputtering, and less than 10^{-10} Torr already within 1-2 hours. The typical residual gas composition halfway between lumped-pump stations (which were at $L = 5.1 \text{ m}$ distance), after 150°C bakeout and sputtering *in situ*, is > 90% H_2 , $\approx 2\%$ CH_4 , < 1% H_2O , $\approx 6\%$ CO, < 0.1% Ar, and < 1% CO_2 . The titanium film does not pump Ar or CH_4 , and pumps only a little H_2O ; these gas species, however, are almost absent at the surface after bakeout, and they also do not take part in the pressure bump phenomenon.

A new method²²⁾ permits assessing the vacuum stability limit after a specific treatment in the laboratory and *in situ*. It gives a critical current of $I_c > 100 \text{ A}$ after titanium sputtering *in situ*, which is far more than is needed. The titanium film, which is ~ 100 monolayers thick, has a pumping capacity of about $5 \times 10^{-3} \text{ Torr l/cm}^2$ for H_2 ; hence, with $q = 2 \times 10^{-13} \text{ Torr l sec}^{-1} \text{ cm}^{-2}$ it would last for several hundred years.

This method to provide distributed pumping by *in situ* conditioning of the beam pipe is an inexpensive and easy way to obtain the specified LSR vacuum performance. Another important advantage is that it can be applied instantly and whenever required, for example as a recovery from a small leak. When the beam pipe is allowed to cool down within the cryostats, the average pressure is further reduced to below 10^{-11} Torr.

6.4 Vacuum pipe material and conditioning

Extensive measurements have been carried out on the LSR prototype vacuum section with different beam pipes made of stainless steel (either untreated or electropolished and subsequently heat-treated), pure titanium, and aluminium alloy. Various conditioning procedures such as

- bakeout at 150°C and 300°C,
- glow-discharge cleaning,
- titanium sputtering,
- cooling to 77 K,

and various combinations of these treatments *in situ* and after exposure to air were investigated. Hereafter only the material and procedure proposed as the best choice for the LSR are given: other results are discussed elsewhere²³⁾.

The best results were obtained with untreated stainless steel 304 L. It was baked at 300°C for 24 hours and glow-discharge cleaned with pure argon gas at a total dose of $> 10^{18}$ ions/cm², prior to installation. Higher bakeout temperatures or the use of an argon-oxygen mixture, as for the cleaning of the ISR beam chambers²⁵⁾, might be an advantage.

After installation and pump-down, the vacuum system was baked at only 150°C for compatibility with cheaper superinsulation. The LSR vacuum system, however, should be designed for a bakeout temperature of 300°C, provided by heater jackets or tapes as in the ISR. Within the cryomagnets, however, resistive heating is proposed; it proved to be a very simple and inexpensive method particularly well suited to the small beam-pipe diameter.

After bakeout and when the vacuum system had cooled down, *in situ* sputtering of titanium was carried out. The temperature within long superconducting dipoles, which is expected to drop to almost liquid-nitrogen temperature without external heating, reduces the residual pressure to $< 5 \times 10^{-12}$ Torr and yields a critical current of over 100 A.

6.5 Clearing

The generally accepted neutralization threshold for e-p coherent oscillation and consequent beam blow-up is $\eta_{th} < 2 \times 10^{-5}$ electron/proton in the ISR. This threshold scales with²⁶⁾

$$\eta_{th} \propto \gamma^{-1/2} R^{-3} I^{-3/2},$$

where R is the machine radius. Thus the neutralization threshold in the LSR is found to be $\eta_{th} \approx 1 \times 10^{-6}$ electron/proton.

With an average pressure $\bar{P} < 10^{-11}$ Torr nitrogen equivalent, the electron production rate per circulating proton is, at the worst place,

$$R_p^{max} = \sigma k P^{max} < 1.6 \times 10^{-2} \text{ sec}^{-1},$$

since $\sigma = 1.51 \times 10^{-18}$ cm² for 400 GeV/c protons in nitrogen gas²⁷⁾ and $k = 3.5 \times 10^{16}$ mol Torr⁻¹ cm⁻³ at 300 K. Hence a minimum clearing rate of

$$R_c^{min} = R_p / \eta_{th} = 1.6 \times 10^4 \text{ sec}^{-1}$$

must be provided.

Without a clearing system, the only mechanism leading to a reduction of the electrons trapped in the beam potential are collisions with the circulating protons. The corresponding clearing rate at 20 A is approximately

$$R_{c,s} \approx \frac{I r_e^2}{\pi a b e} \approx 1 \text{ sec}^{-1}$$

and is thus completely insufficient. In this relation $\pi a b \approx 9 \times 10^{-2} \text{ cm}^2$ is the beam cross-section area; r_e denotes the classical electron radius determined from $e^2/r_e = m_e c^2$. Thus all "electron pockets", i.e. uncleared beam potential minima such as a locally enlarged beam chamber, have to be carefully avoided. The smooth beam pipe in the regular lattice part of the machine fulfils this requirement.

Clearing plates at a potential of about +5 kV, 90 mm long and 40 mm wide, are cut out from the RF screen within pump manifolds on either side of each magnet. They extract electrons created within the adjacent magnet sections. The clearing rate is given by the crossed field drift along the beam axis:

$$R_{c,m} = \frac{E_t}{BL} \text{ sec}^{-1},$$

where B is the magnetic field (T), L the distance between clearing plates (m), and E_t the average transverse electric field acting on the electrons. Assuming that the electrons oscillate predominantly in the Poisson region of the beam field, because of their low energy, we have at 20 A

$$E_t = \frac{I}{8\epsilon_0 \sqrt{ab/\pi}} \approx 6 \times 10^5 \text{ V/m}.$$

Hence, with the longest distance over a dipole magnet $L = 5.1 \text{ m}$, we find $R_{c,m} \approx 3 \times 10^4 \text{ sec}^{-1}$, which is just about sufficient.

In the long straight sections, clearing relies on the longitudinal beam potential difference $\Delta\phi$ caused by beam envelope variations. The corresponding clearing rate is given by

$$R_{c,t} = \frac{1}{L} \sqrt{\frac{2e \Delta\phi}{m}} \text{ sec}^{-1}.$$

Clearing rates in straight sections are generally sufficiently high, with potential differences of a few V/m; with electrodes placed at appropriate distances and suitable locations, there should be no problem.

In conclusion, the LSR performance will not suffer from e-p instabilities, mainly because of the smoothness of the vacuum chamber, provided that the average N_2 -equivalent pressure is maintained below 10^{-11} Torr. Clearing plates must be mounted on either side of each magnet, at appropriate distances in the straight sections and in each region which might act as an electron pocket or where the pressure is locally higher.

Fig. 6.1 Main lumped-pump station. In the upper part the horizontal beam pipe with the manifold can be seen. To the left is the argon gas injection valve *in situ* conditioning and to the right the manipulator of the Ti wire for sputtering. Below the manifold -- almost hidden by the turbomolecular pump -- is the sputter-ion pump, and in the centre the main valve. The UHV gauge is hidden behind the manifold, the clearing electrode feedthrough is on the top.

a)

b)

Fig. 6.2 Manipulator of the titanium wire for *in situ* sputtering

7. RF SYSTEM AND STACKING

7.1 General scheme for filling and stacking

The filling and stacking process and the layout of the RF system do not differ very much from those described in the proposal for large CERN proton storage rings with conventional magnets¹⁾. The only exception is that, from the different options for the beam transfer scheme, it is much easier to make a definite choice in favour of a high-intensity beam transfer. This is because the possible injector, the CERN Super Proton Synchrotron (SPS), has now been in operation for more than one year and information about its actual behaviour is available. Furthermore, in the meantime a construction program has been launched to increase the intensity of the SPS by a substantial factor. It has also been decided to install a Landau damping system working on the fourth harmonic of the regular RF frequency of the SPS. There is much hope that this system will suppress the coupled bunch-mode instabilities, if necessary backed up by special feedback systems; hence the limiting factor for the maximum obtainable phase-space density will probably be the local bunch intensity.

It is a fact that this density can be increased proportionally to the square root of the beam current if a constant parasitic coupling impedance Z/n in the machine is assumed. For filling storage rings, it is therefore in our interest to transfer beams of an intensity as high as possible. Apart from the beam-handling capacity of the injector, the PS, we are limited in so doing by the maximum emittance which can be handled by the SPS and by the maximum beam loading the RF system can support. It should be mentioned here that the SPS RF system, different from most other RF systems, can support rather high beam loading if the acceleration rate is gradually reduced. This, however, can easily be accepted for the filling of storage rings. An upper limit of the beam intensity under such working conditions would be about 10^{14} particles per pulse if they were more or less evenly distributed around the SPS.

As the average radius of the LSR is smaller than that of the SPS, only a fraction of the circumference of the SPS corresponding to the ratio of the two radii would be filled with particles anyway. Therefore, it is the ratio of the average radii of the LSR and the preinjector which matters. For one pulse, either eight PS fillings can be transferred, one after the other, or four such fillings split to twice the length by the continuous transfer system; the choice depends mostly on the intensity handling capability of the SPS. With an average radius of somewhat over 850 m, about 94% of the circumference would be filled. In any case, the gap is needed for the inflection kickers into the SPS (8 times ~ 200 nsec, or 4 times ~ 400 nsec) and for the kickers involved in the transfer from the SPS to the LSR. It is not possible to suppress the empty buckets in the LSR during such short times, but the resulting dilution of phase-space density is certainly tolerable.

7.2 Phase-space considerations

Apart from the transition region, where fortunately growth times of instabilities are long, the most critical conditions for the longitudinal stability are always given at the highest momentum. As the parasitic impedances are mostly found in the GHz range, the situation can be improved if the bunch length is adjusted down to the order of the wavelength of these frequencies. From measurements, both on installed equipment and on the circulating beam, the effective Z/n of the SPS is estimated at about 20Ω with, of course, the exception

of the RF cavities. This, together with the bunch length of down to one-fifth of the bucket length, determines the maximum possible beam current if the bucket area is given by the available RF voltage, which in turn is determined not only by the installed power but also by the amount of beam loading.

With $\gamma_{tr} = 24$, we obtain at 400 GeV/c:

$$\Delta p/p \approx \pm 0.85 \times 10^{-9} \sqrt{N_p/B_f} \quad 0.2 < B_f \leq 1$$

with N_p = number of particles in one bunch and B_f = the ratio of bunch to bucket length.

The resulting bunch area necessary is a function of $\Delta p/p$ and B_f . There is, however, the other problem of incoherent Q-shift due to space-charge forces, which may limit the maximum tolerable number of particles per bunch at injection. The highest injection level possible is 14 GeV/c and there we obtain a $\Delta Q \approx -0.1$ for a $N_p = 10^{10}$ (already for full stationary buckets). This seems to exclude the transfer of a non-split PS batch. If split once, we feel rather confident that we can trap 10^{13} particles in 840 buckets and therefore we obtain as $N_p = 1.2 \times 10^{10}$.

It is not desirable to make the bunches higher than necessary before they are transferred into the storage rings because this would lead to high trapping voltages.

On the other hand, the bunch size on the ramp approaching the 400 GeV/c level is now determined by

$$(\Delta p/p) \times \sqrt{B_f} = \pm 9.3 \times 10^{-5}$$

because of the stability limit.

A relatively higher phase-space density can be obtained for shortest-possible bunch, because the bunch length appears under the square root in the above formula. The power amplifier installation proposed for the storage rings and described in the next paragraph will be capable of producing a voltage of 380 kV for a short moment. With this voltage, the height of a stationary bucket is $\pm 3.45 \times 10^{-4}$.

The bunches can be shaped in the SPS before transfer so that they fit into this bucket, which of course will only be partially filled. This shaping is determined by the following equation:

$$3.45 \times 10^{-4} \sqrt{(1 - \cos \pi B_f) \times B_f/2} = 9.3 \times 10^{-5}.$$

With the resulting $B_f = 0.317$, we obtain a bunch height of $\pm 1.65 \times 10^{-3}$ and a corresponding bunch area of ~ 220 mrad. A smaller bunch area, and consequently a higher phase-space density, is possible if the injected bunches are rotated in the storage rings by 90° with subsequent voltage reduction, provided the height of the injected bunches is not much higher than about $2/3$ of the bucket in order to avoid too strong a filamentation. With this condition, i.e. $\Delta p/p = \pm 2.3 \times 10^{-4}$, we obtain a $B_f = 0.1635$ for a bunch in the SPS when it approaches the 400 GeV/c level. The bunch area which goes with these bunch dimensions is ~ 160 mrad.

The correct bunch dimensions on the ramp of the SPS can be adjusted either by working with rather high phase angles (in the case of bunch rotation, for example, $\sim 40^\circ$), or by reduction of both the acceleration rate and also, to a certain extent, of the accelerating voltage. The advantage of the second method is that the moving buckets are only partially filled, and consequently the oval shape of the bunches is less distorted if one wants to eject directly from the ramp.

7.3 Parameters of RF system

The coupling impedance of the RF cavity can be kept down to $Z/n = 8 \Omega$. If we fill the specified momentum width of 0.35% with the design current of 7 A, we may work with lower phase-space densities than are given in the preceding paragraph. Under these conditions, even the single pulse will be stable under all circumstances, provided the total impedance of the machine can be kept lower than about this value at all frequencies. At very low frequencies the resistive wall impedance is somewhat larger; however, the growth times of the low-frequency modes are very long. With the highest density available, the decelerated beam will be stable, as well as the stack; however, the first adiabatically debunched pulses may tend to get unstable.

One 500 kW amplifier, as used in the SPS, gives sufficient power; it can be switched to the ring being filled. For several milliseconds it can be pulsed up to a power of 600 kW and more. The corresponding voltage of 380 kV would only be required for trapping or bunch rotation after injection from the ramp of the SPS. After this, stacking can be started immediately with reduced power, and the stacking rates are still such that the full repetition rate of the SPS can be used. Each ring can be filled in about three minutes.

7.4 Remarks on stacking

If the SPS is filled by four PS batches, each twice 200π m long with an intensity of 10^{13} particles, then about every 5 to 7 sec the SPS could deliver a batch, 1600π m long, of 4×10^{13} particles. As was mentioned earlier, there is a small dilution in phase-space density owing to the slightly larger circumference of the LSR.

Another 5-10% density dilution is the result of the difference in bunch and bucket shapes, at least in the case of bunch rotation. The above-mentioned bunch area of 160 mrad would then blow up to about 200 mrad including filamentation, and perhaps a bit more for the first pulses because of longitudinal instabilities. For the specified momentum width of 0.35% we obtain with this density more than twice the design current of 7 A. This would permit a stacking efficiency of 50% or better; in fact, even with the rather safe area of 270 mrad, blown up to ~ 300 mrad, this efficiency would still be around 70%.

8. BEAM STABILITY

We will limit our discussion to single-beam effects such as the incoherent tune shift and the longitudinal as well as the transverse stability of both injected (bunched) and stacked (coasting) beams. The interaction of protons with electrons created by ionization of the residual gas (e-p instability) is negligible at the very low pressures required for low background in experiments. The beam-beam effect has already been taken into account in the design of the intersections by keeping the beam-beam tune shift below 0.005.

8.1 Incoherent tune shift

This is made up of three contributions: the electrostatic, the magnetic, and the space-charge forces. All of these depend inversely on energy and tune, but are proportional to particle number and machine radius. The space-charge contribution is further multiplied by a factor $(\gamma^{-2} - \eta_e)$, where η_e is the neutralization. At very high energies, it may become difficult to reduce the neutralization below $2\gamma^{-2}$, and the space-charge term thus may become dominant.

In the usually more critical vertical plane the total incoherent tune shift is given by²⁸⁾

$$\Delta Q_V = - \frac{N r_0 R}{\pi \beta^2 \gamma Q_V} \left[(1 - \eta_e) \frac{\epsilon_1}{h^2} + \beta^2 \frac{\rho}{R} \frac{\epsilon_2}{g^2} + \left(\frac{1}{\gamma^2} - \eta_e \right) \frac{\epsilon_{SC}}{b^2} \right],$$

where ϵ_1 and ϵ_2 are the electrostatic and magnetic image coefficients, and ϵ_{SC} is an equivalent space-charge coefficient given by

$$\epsilon_{SC} = \frac{b}{a + b}$$

at the centre of an elliptic beam with half-width a and half-height b ; h and g are the vacuum-chamber and magnet-gap half-heights, ρ the bending and R the average machine radii. The number of particles N is related to the beam current I_0 by

$$N = \frac{2\pi R}{e\beta c} I_0.$$

In the centre of a circular chamber or iron shield $\epsilon_1 = \epsilon_2 = 0$, and we need only consider the space-charge term. For a Gaussian density distribution, the average beam half-height is $\sqrt{2\sigma}$, or

$$b = \sqrt{\frac{\epsilon_V R}{2\pi\beta\gamma Q_V}},$$

where ϵ_V is the invariant emittance. Substitution then yields

$$\Delta Q_V \approx \left(\eta_e - \frac{1}{\gamma^2} \right) \frac{R \epsilon_{SC}}{\beta^2 \epsilon_V} \frac{Z_0 I_0}{E_0/e},$$

where $Z_0 = 120\pi$ (Ω), and $E_0 = 938$ MeV.

If $\eta_e \gg 1/\gamma^2 \approx 5.5 \times 10^{-6}$, we get for the LSR ($R = 10^3$ m, $\epsilon_{SC} = 1/6$, $I_0 = 7$ A, $\epsilon_V = 15\pi \times 10^{-6}$ m),

$$\Delta Q_V \approx 10 \eta_e.$$

To keep the tune shift below 0.025 requires a neutralization of less than 2.5%. This is easily satisfied by the clearing system (Section 6.5), designed to avoid the e-p instability.

8.2 Longitudinal stability

The longitudinal stability of the injected, i.e. bunched, beam usually yields the most restrictive limitations. For wavelengths that are short compared with the bunch length, we have to use a local stability criterion²⁹⁾

$$\left| \frac{Z}{n} \right| < F \frac{E_0}{e} \frac{|\eta|}{\gamma I_p} \left(\frac{\delta p}{m_0 c} \right)^2 ,$$

where F is a form factor of order unity, $\eta = \gamma^{-2} - \gamma_{tr}^{-2}$, δp is the full momentum spread at half-height, and I_p the peak current:

$$I_p = G \frac{h}{M} \frac{2\pi}{\Delta\phi} I_0 ,$$

where G is another form factor of order unity, h the harmonic number, and M the number of bunches of length $\Delta\phi$ in RF radians. For a parabolic momentum distribution, $F = 4/5$ and $G = 3/2$, while the momentum spread at the bottom is $\Delta p = 4/3 \delta p$. With the normalized bunch area

$$A = \frac{\pi}{4} \Delta\phi \frac{\Delta p}{m_0 c} ,$$

we obtain the stability criterion at injection³⁰⁾ (small bunches in large buckets):

$$\left| \frac{Z}{n} \right| = \frac{12}{5\pi^3} \frac{M}{h} \frac{E_0}{e} \frac{|\eta|}{\gamma I_0} \frac{A^2}{\Delta\phi} .$$

For the preferred transfer scheme from the SPS, we have 4×10^{13} particles (320 mA) with a normalized area of 270 mrad and a length of 95° , filling 90% of the LSR circumference. With $|\eta| = 1.1 \times 10^{-3}$ and $\gamma = 426$ we thus obtain

$$\left| \frac{Z}{n} \right| < 23.2 \, \Omega .$$

After matching, the bunches usually become longer. During acceleration with voltage V and stable phase angle ϕ_s , we find

$$\Delta\phi = \left(\frac{32}{\pi\gamma} \frac{h|\eta|A^2E_0}{\cos\phi_s e V} \right)^{1/4} ,$$

which yields $\Delta\phi = 132^\circ$ for $V = 500$ kV, and $\phi_s = 30^\circ$. The threshold is then decreased to $16.8 \, \Omega$. When the voltage is reduced until the bunches fill the buckets, the stability criterion becomes even more stringent. We can write it in the form³⁰⁾

$$\left| \frac{Z}{n} \right| < \frac{3}{160} \frac{M}{h} \frac{E_0}{e} \frac{|\eta|A^2}{\gamma I_0} R(\Gamma) ,$$

where

$$R(\Gamma) = \frac{\Delta\phi(\Gamma) Y^2(\Gamma)}{4\pi\alpha^2(\Gamma)}$$

is unity for stationary buckets, and larger than one for moving ones ($\Gamma = \sin\phi_s$). For $\Gamma = 1/2$, $R = 1.617$ and we find

$$\left| \frac{Z}{n} \right| < 15.1 \, \Omega .$$

When the stable phase-angle is reduced to zero at the end of the acceleration, the threshold decreases until we obtain

$$\left| \frac{Z}{n} \right| < 9.3 \, \Omega .$$

The coupling impedance of the RF cavities has therefore been limited to $8 \, \Omega$.

The longitudinal impedance becomes most critical during debunching. If the RF voltage is switched off suddenly, the bunches start to filament and will always reach the stability limit as the momentum spread of the filaments becomes gradually smaller. The resulting "microwave instability" will blow-up the momentum spread, but without overshoot as the threshold is reached gradually. Therefore the coasting beam will have the same momentum spread as the bunches, which corresponds to a loss in longitudinal density. However, in the ISR it has been found that owing to the "shielding" of the particles already present, the effect is reduced after the first few pulses have been stacked. If debunching is done adiabatically, filamentation can be avoided. However, the threshold will be decreased by a factor $(2/\pi)^2$, and become less than $4 \, \Omega$. The impedance of the RF cavities of $8 \, \Omega$ will blow up the momentum spread to values similar to those obtained with sudden voltage reduction.

For the coasting beam we also have to consider impedances at low frequencies. The direct space-charge contribution is small, but the skin effect of a pipe of radius h gives

$$\frac{Z}{n} = (1 + j) \frac{Z_0 \delta}{2h} ,$$

where the skin depth

$$\delta = \sqrt{\frac{2}{\omega \mu_0 \sigma}}$$

is about 2 mm at the lowest mode for 48 kHz revolution frequency and stainless-steel walls with $\sigma = 1.3 \times 10^6 \, \text{Sm}^{-1}$. For a chamber radius of 25 mm, we thus get at $n = 1$,

$$\left| \frac{Z}{n} \right| = 21.5 \, \Omega ,$$

to which we have to add the contributions of all unavoidable cross-section variations, such as any unshielded bellows, pick-up and clearing plates, kicker tanks, etc. These are usually inductive at low frequencies and will not change the growth rates, which are several 100 sec for the lowest modes. Hence it should be possible to add enough pulses before the blow-up becomes excessive. For the final stack, the stability criterion can be written

$$\left| \frac{Z}{n} \right| < 4F \frac{E_0}{e} \frac{|\eta| \gamma}{I_0} \left(\frac{\delta p_s}{p} \right) \left(\frac{\delta p_f}{p} \right) ,$$

where δp_s is the half-width of the stack, and δp_f the width of the lower flank (at half-height). Taking for the flank width the width of a single (parabolic) pulse $\delta p_f/p = 5 \times 10^{-5}$, and a stack half-width of 2.5%, we get

$$\left| \frac{Z}{n} \right| < 31.4 \, \Omega .$$

In reality, the lower flank is usually widened by spill-out, and the threshold will be higher. It thus appears that the full stack will be stable at low frequencies. At high frequencies, the stack will also be stable because of the much more stringent criteria for the bunched beam, which will blow up the momentum spread unless all high-frequency impedances are reduced below the lowest thresholds discussed.

8.3 Transverse stability

Transverse oscillations of the head-tail type can drive single bunches unstable and/or excite coupled-bunch modes. The lowest modes can be suppressed by making the chromaticity zero or slightly positive. Higher-order modes are usually not observed, but can be stabilized by octupoles or feedback systems. The transverse stability of coasting beams requires a tune spread³¹⁾

$$\delta Q > \frac{RI_0 |Z_T|}{\pi F E_0 / e Q_Y}$$

at low frequencies. The contribution of the direct space-charge term is again very small at the energy of 400 GeV, while the skin effect contributes

$$Z_T = (1 + j) Z_0 R \frac{\delta}{h^3}$$

for a circular chamber of radius h.

The skin depth is approximately

$$\delta = \frac{2}{\sqrt{n - Q}} \text{ (mm) } ,$$

and for $n - Q = 0.7$ we get $|Z_T| = 81.6 \text{ M}\Omega/\text{m}$. We thus require $\delta Q > 1.5 \times 10^{-2}$, or -- for a total momentum spread of 0.5% -- $Q' > 3.0$. However, if the three lowest modes are stabilized by feedback, the low-frequency stability requires only $Q' > 1.3$.

At higher frequencies the revolution frequency spread adds to the tune spread and the required chromaticity is less. We always assume that the impedance of resonant cross-section variations have been reduced for longitudinal stability.

8.4 Summary

Summarizing the results, we conclude that tune shifts will be tolerable since the neutralization is kept below 2.5%. Longitudinal instabilities will blow up the momentum spread during debunching and during stacking of the first few pulses, but should stabilize after that. The full stack is stable against longitudinal oscillations, if cross-section variations such as bellows, etc., are sufficiently damped or shielded. Transverse stability requires a small positive chromaticity, and would further benefit from a feedback system covering only a few of the lowest modes.

9. ADDITIONAL OPTIONS

The possibilities of adding a separate electron ring³²⁾ and of storing deuterons³³⁾ or antiprotons³⁴⁾ in one of the proton rings is an important potential of such a facility⁶⁾, which can be exploited fully with the layout described before.

9.1 Electron-proton collisions

The choice of the maximum electron energy is a compromise between conflicting requirements. From the point of view of physics, the primary lepton energy should be as high as possible, making available a momentum transfer of around $q^2 \geq 10,000$, where weak interactions are expected to dominate over electromagnetic interactions and completely new domains of physics would be open³⁵⁾. On the other hand, the power loss into synchrotron radiation should not be excessive, so that a reasonably sized RF system is sufficient and conventional technology can cope with the strong synchrotron radiation in the vacuum system and the detector region.

To this end a nominal electron energy of 20 GeV is chosen with a possible extension to 25 GeV and with provisions for scanning over lower energies with good luminosity. At nominal energy, a luminosity close to $10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$ per intersection point can be achieved. Two intersection points are foreseen in the arcs as shown in Fig. 3.5. If one is prepared to sacrifice some of the p-p physics in favour of e-p physics at a later stage, p-p insertions in the long straight sections could be converted into e-p crossing points.

During the studies most of the attention was directed to the insertion, which is the most critical part of an e-p facility. Since the design of an insertion must take into account the detector requirements, an attempt was made to design the detector and the insertion in parallel, which revealed a surprising degree of mutual dependence. In this example, it is proposed to use a dipolar magnetic field in the crossing point to provide a very small effective crossing angle and good divergence of the two beams outside the crossing region; the magnetic field is used at the same time for particle analysis. The principle that machine components should also serve as part of the experimental apparatus is extended to the septum magnets, following the central field on both sides; these magnets also function as hadron calorimeters.

The background generated by synchrotron radiation was studied very carefully³⁶⁾, and a number of preventive measures are incorporated to reduce it to an acceptable level. Other sources of background were scrutinized but found to be manageable.

This type of insertion does not permit operation with positrons without partial dismantling of the experiment. An insertion³⁷⁾ as proposed for the CHEEP e-p facility with the common elements outside the intersection region may be preferable when frequent switching between electrons and positrons is required. This latter insertion has also the considerable advantage that the radiative transverse polarization can be rotated into the longitudinal direction³⁸⁾ over a wider range of energies. Negative and positive helicities are then available at will in the crossing point, a feature which is highly desirable in order to distinguish between electromagnetic and weak interactions³⁹⁾.

An injector of about 5 GeV energy (with final acceleration in the storage ring itself) would be needed, and some thought was given to the possibility of using one of the ISR rings, either in its present tunnel or relocated nearer to the LSR³³⁾. The use of the NINA magnets for an injector synchrotron could also be considered.

A brief parameter list referring to the first insertion described above is given in Table 9.1; a more exhaustive list can be found elsewhere³²⁾.

Table 9.1

Parameter list

		Electrons	Protons
Beam energy	E (GeV)	20	400
Luminosity	L ($\text{cm}^{-2} \text{ sec}^{-1}$)	0.7×10^{32}	
Circumference	$2\pi R$ (m)	6150	6132
Bending radius	ρ (m)	721	718
Beam current	I (mA)	0.25	7
Synchrotron radiation	P (MW)	6.9	-
Total RF power	P_t (MW)	10	-
Energy loss/turn	U (MV)	28	-
Number of bunches	k_b	4100	unbunched
Crossing angles	α_x/α_z (mrad)	$\sim 1.5/\text{variable}$	
Beta functions	β_x^*/β_z^* (m)	1/0.3	5/1
Tune shifts	ΔQ	0.014	8×10^{-5}

9.2 Proton-deuteron and deuteron-deuteron collisions

This option can be obtained at almost no cost, as no modifications on the LSR are required. The deuterons, like the protons, would be accelerated through the linac, PS, and SPS. The first two machines have already operated successfully with deuterons, providing more than 5×10^{11} particles/pulse at 26 GeV/c. Intense stacks of 1.8×10^{14} deuterons have been built in the ISR for regular physics runs, providing a p-d luminosity of $1.6 \times 10^{30} \text{ cm}^{-2} \text{ sec}^{-1}$ ⁴⁰⁾, half of the ISR p-p design luminosity.

Since acceleration of deuterons in the SPS looks very straightforward, we expect, by scaling from the ISR results, to have p-d luminosities that are only about a factor of 3 lower than the p-p luminosities. Filling both rings with deuterons provides d-d luminosities that are one-tenth of the p-p luminosities.

The possibility of storing polarized deuterons in at least one ring was examined in terms of the feasibility of avoiding depolarizing resonances during acceleration and storage³³⁾. It turned out that only a few resonances have to be crossed during acceleration and none during storage owing to the favourably low anomalous magnetic moment of the deuteron. The phase-space density of a polarized beam is estimated to be lower by a factor of 20, which leads to a p- $\vec{d}$ luminosity lower by at least the same factor in comparison with the p-p luminosity.

In the case of an electron ring being added, collisions of electrons or positrons with deuterons can be arranged without any extra expense.

9.3 Antiproton-proton collisions

The necessary antiprotons can be generated either by primary protons from the LSR or from the PS. Depending on the mode of antiproton generation, two schemes can be worked out.

In the first case³⁴⁾, a full LSR proton stack is ejected vertically and strikes a target; the resulting antiprotons at 30 GeV, the energy where the yield is maximum, are trapped in the SPS. After acceleration to 400 GeV they are stored in the other LSR ring. During accumulation of a new proton stack, the antiproton beam is cooled stochastically⁴¹⁾ to reduce its momentum spread by about a factor of 10, thus making space for many subsequent pulses within the momentum acceptance of the ring. This cycle is repeated for 24 hours until 1.6×10^{11} antiprotons are accumulated. Then the proton ring is filled for the last time and the protons are left coasting to collide with the antiprotons. A luminosity of $2 \times 10^{29} \text{ cm}^{-2} \text{ sec}^{-1}$ is expected, a factor of 2×10^{-4} times lower than the p-p luminosity. However, this rather straightforward but coarse method has the drawback that it blocks the SPS for a substantial time.

This inconvenience can be avoided by using an antiproton accumulation ring⁴²⁾. Such a ring is expected to provide 5×10^{11} cooled antiprotons of 3.5 GeV/c in 24 hours⁴³⁾. These antiprotons can be injected into the LSR after acceleration in the SPS. With 7 A of protons in the other ring a luminosity of $5 \times 10^{29} \text{ cm}^{-2} \text{ sec}^{-1}$ may be expected. Since the beam lifetime in the LSR certainly exceeds 24 hours by an order of magnitude, it is hoped to stack a few of these pulses in order to increase the luminosity.

10. CONCLUSIONS

The LSR studies have confirmed the feasibility of building a large proton-proton colliding-beam facility at CERN and have established that a very satisfactory performance can be achieved using the SPS as a high-energy injector. The effort devoted to clarifying the performance limitations of storage rings in this energy range has led to a much better understanding of important features of machine design, whose impact extends beyond the LSR itself.

The theoretical study of collective phenomena, essential to the LSR design, has been backed up by experimental investigations at the ISR and has contributed to the improved performance of this machine. Vacuum studies of the LSR and the ISR have been closely inter-related and have led to technical advances in this field. The problems of chromaticity correction in large machines with low-beta insertions became evident at an early stage of the LSR work; the evolution of suitable correction methods has carried on into the field of large e^+e^- storage rings where the problem is even more acute. Similar progress has been made in the design of interaction regions. In seeking the highest luminosities obtainable with reasonable stacked currents, the practical constraints on interaction-region geometry and beam optics have been thoroughly investigated.

The results of these studies, whilst incomplete in certain details, form a good basis for a possible future design study of proton-proton storage rings in the energy range of several hundreds of GeV. In such a future study certain basic assumptions of the LSR model would be reviewed. If future site constraints permitted, there would be some advantages in adopting a higher superperiodicity than two, by a different distribution of interaction regions. At the same time one would re-examine the desirable number of interaction regions as well as the preferred types and combinations. Already, the increased interest in e-p physics over the past two years suggests that the two e-p interaction regions originally assumed might not fulfil the demands of a full-scale European physics programme.

An increase in the maximum energy of such a facility would certainly be considered in any future review. Phase-displacement acceleration, which has developed so promisingly at the ISR, would permit energies considerably above 400 GeV, still using injection from the SPS. The maximum energy attainable will depend on the site constraints, the state of superconducting-magnet technology and the economics prevailing at the time. As an example, with magnets operating at 5 tesla and a tunnel of about the same circumference as the SPS, a c.m. energy well above 1 TeV would be feasible, with a performance and flexibility at least as high as that of the machine described in this report.

Finally, other superconducting materials (e.g. Nb_3Sn), currently under investigation in many laboratories, have the potential of operating in stronger fields than NiTi and offer the future possibility of going to even higher energies for a machine of a given size.

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