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CERN 400 GeV PROTON STORAGE RINGS WITH SUPERCONDUCTING MAGNETS

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Summary

A design is presented for 400 GeV proton-proton storage rings to be added to the CERN SPS. An electron (20-25 GeV) ring is also foreseen and possibilities for antiproton-proton collisions. Eight interaction regions are planned (six for p-p and two for e-p) with high luminosity and good flexibility for physics experiments.

Introduction

Earlier studies at CERN of 400 GeV proton-proton storage rings [1] showed that, although adequate performance could be achieved using conventional steel/copper magnets, the power consumption and size would be unduly large, so recent studies have concentrated on a design with superconducting magnets. With the CERN SPS as injector, the nominal energy in each ring is 400 GeV and the site constrains the machine to a racetrack shape straddling the North Experimental Area. Injection at high energy permits a small beam aperture, advantageous for the cost of the superconducting magnets and for the overall size.

The design of these superconducting Large Storage Rings (LSR) includes optional colliding-beam possibilities, with special emphasis on an e-p facility with 20-25 GeV electrons and with two interaction regions independent of the six for p-p, thus permitting simultaneous p-p and e-p physics. The design of the e-p insertions follows essentially that of earlier work,[2] and includes wiggler magnets [3] and some modifications to rotate the electron polarisation vector into the longitudinal direction.[4] The parameters of the electron ring have been chosen to minimize the effect of depolarisation resonances over the most interesting energy range. The luminosity of the e-p regions can be up to 10^{32} cm^{-2} s^{-1} with a fully integrated detector system.[2]

Collisions of antiprotons with protons could be obtained in LSR by removing the magnets common to both beams in the low-β p-p insertions.

Experimental insertions

Of the six interaction regions for p-p physics, two are high-luminosity low-β insertions (LB) and four are general-purpose regions (GP) with medium luminosity and plenty of free space. With a new design for the optics, any one or more of the GP insertions can be retuned as a high-β insertion (HB). With extra quadrupoles, the change from GP to HB optics and back can be made without moving any elements. Parameters of the p-p insertions are summarized in Table I and the structure functions are shown in Fig. 1.

Table I - Parameters of LSR insertions

	LOW BETA (LB)	GENERAL PURPOSE (GP)	HIGH BETA (HB)
Luminosity (cm^{-2} s^{-1})	1.3×10^{33}	6.6×10^{31}	1.1×10^{31}
Beam current (A)	7.0	7.0	7.0
Vert. β-fn. β_V^* (m)	1.0	12.0	400.0
Horiz. β-fn. β_H^* (m)	3.5	24.0	317.0
Dispersion α_p (m)	0	0	0
Disp. slope α_p'	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
Vert. tune shift ΔQ_V	1.4×10^{-3}	9.3×10^{-4}	5.3×10^{-3}
Horiz. tune shift ΔQ_H	6.3×10^{-4}	5.5×10^{-6}	1.1×10^{-5}
Beam emittance (rad m) (both planes)	$30\pi \times 10^{-6}$	$30\pi \times 10^{-6}$	$30\pi \times 10^{-6}$

Low beta (LB)

Magnets common to both beams are used to obtain a near-zero crossing angle; the 12 m space between these magnets can accommodate a large detector for high p_t physics. In the adjacent quadrupoles, the β-function reaches ∿ 550 m. Since the dispersion rises to sufficiently high values at the quadrupoles, at least partial chromaticity correction can be obtained locally. These quadrupoles are arranged in side-by-side pairs in a common cryostat because of the limited beam separation.

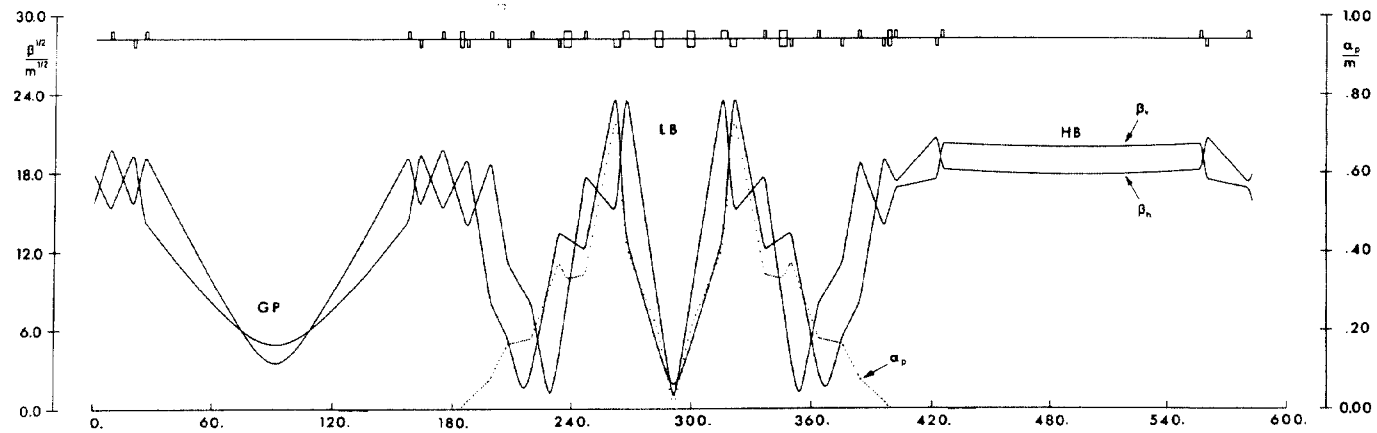

Fig. 1 - Structure functions of insertions

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General purpose (GP)

With a crossing angle of 11.9 mrad and a distance of 65 m from the crossing point, the beam separation at the nearest quadrupole is 77 cm, sufficient to use individual cryostats. The dispersion is zero throughout the crossing region which permits more freedom for the choice of the optics but requires chromaticity correction of the nearby quadrupoles outside this region. However, the maximum β-values are lower than those of the LB quadrupoles.

High beta (HB)

Since the geometry is identical to that of the GP optics and the dispersion is also zero, the change between GP and HB optics is simply performed by adjusting quadrupole strengths. The transformation properties of the HB optics permit measurement of scattering angles from < 20 μrad up to ∿ 300 μrad, thus bridging the Coulomb interference region around 100 μrad. The angular range above 300 μrad can be covered with GP optics which allow measurement down to < 200 μrad.

General machine properties

The overall layout of LSR is given in Fig. 2 which also shows the six p-p interaction regions (the low-β are in the middle) and the two e-p regions. The maximum ring separation between insertions is 110 cm and if access is required from both sides an enlarged tunnel will be needed between experimental halls. Injection and ejection insertions are opposite each other on the inner arcs at 45° to the straight sections. Ring separations at the e-p regions are 6 m which should be adequate for the detectors. In the arcs, the ring separation is 2.5 m which allows access from the centre and a smaller tunnel. In the centre of the arcs, there is a dummy crossing whose function is primarily that of a phase adjuster required when tuning the GP insertion to the HB configuration although it could also be used for machine studies. Some of the pertinent parameters of LSR are shown in Table II.

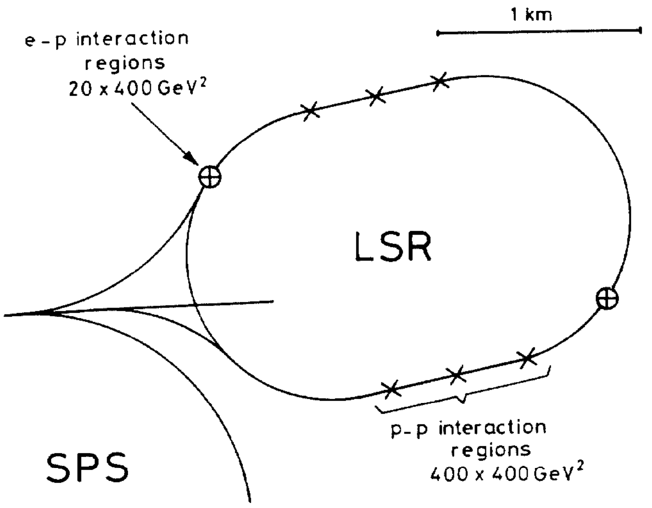

Fig. 2 - Layout of LSR

The chromaticity has been corrected in a previous version of the lattice [5] by using local correction for all insertion quadrupoles where the dispersion does not vanish, superimposing a sextupole of strength $\partial K/\partial x = K/\alpha_p$ on the quadrupole field of strength K. The remnant insertion chromaticity and the lattice chromaticity are corrected by adjusting the strengths of two sets of sextupoles in the lattice. A similar scheme will be applied in the present lattice.

Table II - General LSR parameters

Maximum momentum	p = 400 GeV/c
No. bending magnets/period	n_M = 6
Nominal mag. bending field	B_M = 3.93 T
Nominal mag. bending radius	ρ = 340 m
Nominal length of each bend. magnet	ℓ_M = 3.7 m
β-osc. phase-advance/period	μ = $\pi/2$
Nominal quadrupole gradient	dB/dx = 60 T/m
Nominal quadrupole length	ℓ_q = 1.6 m
Length of period	L_p = 40.4 m
Aver. bend. radius in lattice	R_0 = 617.3 m
Max. β-fn. in lattice	β_{max} = 68.28 m
Max. dispersion in lattice	α_{pmax} = 1.785 m
Inner radius of vacuum pipe	r_a = 25 mm

Three types of injection have been considered. The first, well understood through use at the ISR, has C-shaped horizontal kicker magnets whose stray field is cut by a moving shutter that for LSR would need to be 2.5 mm thick because of the pulse duration. The injection insertion should have a dispersion $\alpha_p \geq 4.8$ m to ensure adequate safety margins. This is less than that required for the second scheme where vertical kicker magnets would have their stray field attenuated by a special profile shape [5] or by fixed screens.[6] This solution has been studied in detail for LSR [5] but the aperture enlargement needed at injection seems to become prohibitive unless the vertical emittance is less than the 30π μrad-m assumed. Experimental measurements in the SPS may clarify this point. The third solution, with double full-aperture kicker magnets, holds out promise of smaller beam losses than the other two schemes and will receive further attention in the future.

The beam dumping system must cope with up to 50 MJ and meet stringent specifications: short rise time, short response time, parallel feeding of all pulsed elements, trigger redundancy, etc. The high power needs an external beam dump and the ejection transport elements are used to enlarge the beam size at the dump block. Computer simulation of energy deposition in the dump [7] and experimental tests on a pulse generator indicate that a safe system can be built with about 190 kJ lost in the ring of which 60 kJ would go into the collimator protecting the first septum magnet.

With superconducting elements, beam loss around the ring must be minimized not only for dumping but also for all procedures where losses can occur: injection, stacking, shaving, acceleration (if any), clearing, etc. This requires careful design of collimators (at least eight) whose position is varied correlative with the scraping target.

Superconducting magnets

The superconducting magnets of LSR are similar in geometry to those of ISABELLE but, because of their DC operation, they can be wound from monolithic multifilamentary superconducting wires of rectangular cross-section. Such composites are readily available from industry up to about 6 mm^2 cross-sectional area with thin, strong insulation.

In a prototype quadrupole for the ISR,[8] the coils consist of three compact blocks of 1.8×3.6 mm^2 conductor, with ratio Cu/sc = 1.5 and 40 μm filaments, wound around a central steel post and wedge-shaped copper spacers. Mechanical stability is ensured by a large compressive prestress. Tests of that quadrupole have confirmed expectations on performance (second quench at 5.3 T, 1560 A, in windings), field quality (error on gradient integral $< 10^{-3}$) and safety at quench. In similar dipoles with 4-block coils, the error on field integral can be kept below 2×10^{-4}.

With a main conductor the same as that of the ISR quadrupoles, a safe operating current is about 1800 A at 4 T in the dipoles and at 60 T/m in the quadrupoles of the normal lattice. Auxiliary windings, including substantial sextupole coils for chromaticity corrections, are located in the 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.

As in the dipoles of ISABELLE, the yoke of an LSR magnet is a stack of ring-shaped steel laminations inside a stainless steel cylinder, but the laminations here are locally slotted so that they behave like springs. A dipole section is shown in Fig. 3. At magnet assembly, the stack, temporarily held together by longitudinal bolts, is slightly opened by means of hydraulic cushions to receive the winding at room temperature. The preheated cylinder is next fitted on to both. Thus, the prestress on the main coils is low at room temperature, at which flow of the organic insulation might be feared, and is built up during cool-down by the thermal shrinkage of the stainless steel cylinder.

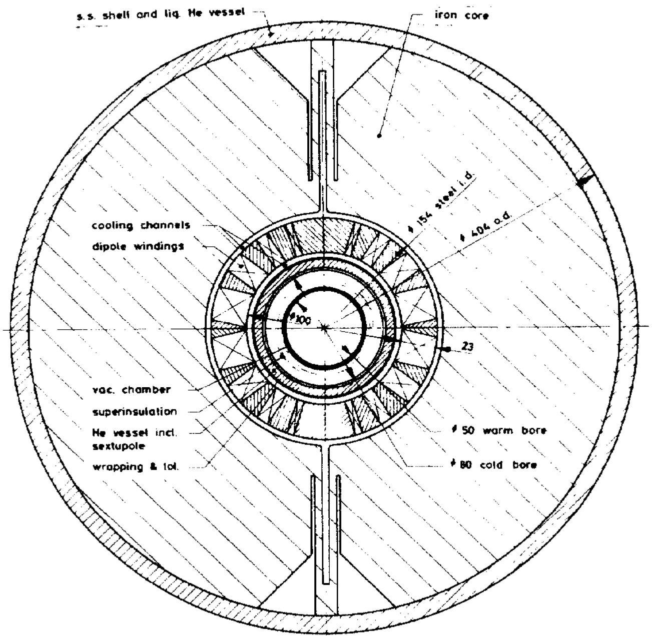

Fig. 3 - Cross-section of an LSR dipole

Vacuum

The design of the vacuum system was determined by the 5 cm-diam. circular aperture and by the 5.1 m distance between lumped pumps. For a beam-gas nuclear scattering rate as low as in the ISR, the average pressure should be $< 2 \times 10^{-11}$ Torr N_2-equiv. even in the presence of beams. Thus, the static base pressure should be in the 10^{-12} Torr range and the critical current >> 10 A. Simple scaling from ISR to LSR geometry shows that these specifications cannot be met with a lumped pumping system. At present, even the best choice of beam-pipe material and the most sophisticated pre-treatments would not be sufficient, as most of their benefits are lost upon exposure to air.

A warm-bore system is assumed. The available aperture excludes conventional distributed pumping. Instead it is proposed to install a retractable Ti wire which normally stays at the bottom of the beam pipe but can be stretched over the distance between lumped pumps by a simple manipulator (Fig. 4). The wire can be used as the cathode in an argon gas discharge to sputter an active film of Ti in-situ on to the pipe wall. This film provides sufficient distributed getter-pumping speed to meet the required vacuum-stability limit.[9] If the beam pipe temperature floats within the cryostat, it may easily drop to below 100 K at the centre ("cool bore") which helps to meet the pressure specification. This new technique has been studied in detail by a method that can infer the vacuum-stability limit from laboratory measurements with a full-scale model.[9] As a result, stainless steel is proposed for the beam-pipe material, baked at > 300° C and glow-discharge cleaned prior to installation. The sputter deposition of Ti would be done after an in-situ bakeout by resistive heating at 150° C.

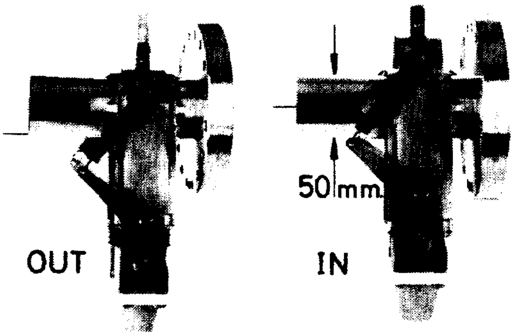

Fig. 4 - Titanium sputter-wire manipulator

Each pumping station[10] is equipped with an 80 ℓ/s sputter-ion pump; some stations have a 100 ℓ/s turbo-molecular pump. Conventional sublimation pumps are not needed. A station may be replaced without moving magnets. Pressures in the system may be measured either by conventional gauges or from the electron-clearing current.

An electric screen, transparent for vacuum, provides a smooth transition across the pumping station and its bellows. Because of the uniformity of cross-section of the vacuum chamber, electron pockets do not form and electron clearing is not difficult. Clearing within the long dipoles by crossed-field drift results in a neutralization of $< 10^{-5}$ electron/proton at the specified pressure with extraction electrodes at the end of each magnet.

RF and stacking

The stacking process and layout of the RF system are similar to those described earlier [1] but the properties of the injected beam are now known from SPS operation. A proposal being considered for raising the SPS intensity above its design value can be important for LSR because it implies a higher phase-space density of the transferred beam, shorter filling time, and simpler transfer procedure. The maximum bunch area that the improved SPS could handle at 10 GeV/c might be 270 mrad, and a DC beam current might be of the order of 400 mA. With supplementary equipment in the SPS, e.g., Landau damping cavities, etc., the phase-space density might be increased further.

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 s the SPS could deliver a batch 1600π m long of 4×10^{13} particles. Hence, about 90% of the LSR circumference would be filled by one transferred pulse. There is no need to suppress buckets during the few percent of the unfilled circumference. In fact, if we accept the consequent dilution and a stacking efficiency of 70%, we obtain the LSR design current of 7 A within the specified momentum width of 0.35%.

For a travelling-wave RF cavity of the SPS type, adjusted to the beam-coupling impedance $|Z/n| = 8\ \Omega$ required for beam stability, the voltage over a cavity length of ~ 3 m is 380 kV for an RF power input of 600 kW. This voltage would only be required for 5 ms after injection from the ramp of the SPS (transfer from the ramp avoids possible bunch blow-up on the flat-top of the SPS). The injected bunches will be rotated by 90° during these 5 ms and stacking can be started immediately after the rotation, with reduced power. Some density dilution of $\sim 10\%$, due to the difference in bunch and bucket shapes, has already been taken into account. One 500 kW amplifier, as used in the SPS, gives sufficient power; it can be switched to the ring being filled. Stacking rates are such that the full repetition rate of the SPS can be used. Each ring of LSR can be filled in about 3 min.

Beam stability

The longitudinal microwave instability usually yields the most restrictive limitations on the permissible coupling impedance. As can be seen from Table III, the threshold decreases continuously until the RF buckets are shrunk around the bunch. However, even when the stable phase angle is reduced to zero, the threshold for Z/n is still high enough that adiabatic debunching should be possible. This would avoid the local instability of the filaments of a debunching beam which occurs when the RF voltage is switched off suddenly.

The threshold for the first few coasting pulses is smaller than the resistive wall impedance at the lowest mode numbers. However, the rise times are very long at these low frequencies [11] and, as further pulses are added, the threshold increases.

The inductance due to cross-sectional variations of the vacuum chamber should be kept small by making the wall as smooth as possible. Resonances of pairs of cross-section variations increase the impedance at higher frequencies, especially for repeated elements. The resonant impedance of the bellows is so high that the bellows should be shielded from the beam.

Transverse stability of the coasting beam requires a small positive chromaticity ($Q' > 2.3$) which will also stabilize head-tail modes. Multibunch oscillations may be suppressed by a not too fast feedback system. The incoherent Q-shifts due to image and space-charge fields will be < 0.01 in both planes and should not present any problems.

Table III - Longitudinal thresholds and impedances

	Z/n (Ω)
1. Thresholds	
after injection ($\Delta\phi = 95^{\circ}$)	37.1
after matching (V = 330 kV)	31.0
during acceleration ($\Gamma = 0.5$)	28.8
during acceleration ($\Gamma = 0$)	17.8
after adiabatic debunching	8.0
10 A stack ($\delta p_F/p = 1.4 \times 10^{-4}$)	54.0
2. Coupling impedances	
resistive wall (n = 1)	24.0
bellows inductance (5%)	5.0
bellows resonance (4 GHz)	> 1000.0

Concluding remarks

The addition of a set of 400 GeV storage rings to the CERN SPS appears to be feasible. Eight interaction regions (six for p-p and two for e-p) have high luminosity and considerable flexibility for physics experiments.

The present parameters should be treated as an illustration of the potential of such a machine rather than as a completely optimized design. Some upgrading of the maximum energy may be possible within the safety margin of this design since experience with quadrupole models at CERN [8] raises hopes that the magnet design presented here may be capable of operation up to 10 to 20% above the nominal value. If injection, with the greatest danger of beam losses, takes place at a field of 4 T the top energy of LSR could be raised by the same percentage as the field, using phase-displacement acceleration as in the ISR.[12]

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