Particle Accelerators, 1997, Vol. 58, pp. 103–119
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PS-*XXI*, A NEW SYNCHROTRON FOR THE LHC INJECTOR

B. AUTIN *, R. CAPPI, R. GAROBY, J. GRUBER,
J.P. RIUNAUD and K.H. SCHINDL

CERN, Geneva 23, Switzerland

(Received in final form 8 February 1997)

The CERN PS is the oldest link in the LHC injector chain. A separate function substitute synchrotron is discussed. It would keep the versatility of the present machine and have a higher extraction energy to relax the tolerance on the microwave instability threshold at injection into the SPS. Its essential property would be an adjustable η variation near the isochronous regime to meet the requirements imposed by bunch compression at ejection. It would also be equipped with all the correction systems of a modern machine.

Keywords: Proton synchrotron; Isochronous lattice

0 INTRODUCTION

The CERN PS was designed about forty years ago[1] and it is legitimate to wonder whether it will serve as an efficient injector for the LHC for several more decades. In fact, even leaving the new linac and the booster aside, the PS itself has considerably evolved since its original construction, to meet all the requirements imposed by a higher intensity, the great variety of particles it has to deal with and a complex beam distribution among many users in a same super-cycle. The component which has remained unchanged is the magnet system and it is basically the properties and the consequences of a new configuration of the magnetic field which will be discussed in this paper. In the acronym

* Corresponding author. Tel.: 41 22 76 77 25 25. Fax: 41 22 76 77 91 45.
E-mail: bruno.autin@cern.ch; autin@ps.msm.cern.ch.

chosen for this new machine, *XXI* stands for the twenty-first century. The replacement of the PS magnets will first be analyzed within the context of the projected operation of the LHC injector (Section 1). The performance limitations[2] are summarized in Section 2. The calculations of a FODO type quasi-isochronous lattice are presented in Section 3. Engineering aspects of the magnet and of the power supply are described in Section 4.

1 STRATEGIC ASPECTS

The replacement of a machine which accelerates almost all of the CERN beams has to be situated in a broad context. The criteria which have been retained concern the tasks the machine will have to fulfill, the technical risks related to an old machine and the likely organization of the accelerator complex in the future.

1.1 PS Tasks after 2000

The tasks foreseen for the PS[3] are not limited to LHC, as it is shown in Table I. A machine dedicated to LHC[4] would be simpler and cheaper from the construction and operation standpoints but it has been, at least up to now, the CERN scientific policy to diversify the physics and, in particular, to have active fixed target and medium energy

TABLE I PS beams after 2000

User	*Particle*	*Batches*	*Charges*	h_{RF}	*Bunches at extraction*
PS, East Hall	p	1	$2 \cdot 10^{12}$	8	1, 2, 3, 4 or de-bunched
AD, test beam	p	1	$1 \cdot 10^{11}$	8	1
AD	p	1	$2 \cdot 10^{13}$	$8 \to 20$	4 adjacent
LHC, test beam	p	$1+3/4$	$1.4 \cdot 10^{12}$	7, 21, 84	7
LHC, p–p	p	2	$1.6 \cdot 10^{13}$	8, 16, 84	80
LHC, ions from booster	Pb^{53+*}	1	$4 \cdot 10^{9}$	$16 \to 8$	8
LHC, ions from LEIR	Pb^{54+*}	1	$6 \cdot 10^{10}$	32, 17	4 adjacent
SPS, fixed target	p	1	$3 \cdot 10^{13}$	8, 16, 420	$420 * 5$
SPS, fixed target	Pb^{53+*}	1	$4 \cdot 10^{9}$	16	16
SPS, test beam	p	1	$2 \cdot 10^{11}$	8	1
LEP	e^+/e^-	1	$8, 16 \cdot 10^{10}$	168	4 (8)

programs in parallel with the big colliders. The present study assumes that this policy will be maintained and aims at a machine which should be able to produce all the beams with their required characteristics.

1.2 Technical Risks

Aging magnets suffer from the detrimental effect of radiation on organic materials and from the mechanical stresses due to repeated pulsing. The main coils are insulated with paper and mica; moreover, they are situated entirely above the beam and thus very resistant to radiation. The pole face windings are made of copper conductors embedded in resin reinforced with glass fibre; they were replaced in 1978 to provide stronger sextupolar fields[5] and should stay in good condition for many years. Weaker in the design may be the assembly of the laminations which are glued using paper impregnated with araldite. At the end of the magnet, there are no thick end plates, the forces pull the laminations outwards and there is a risk that the combined action of radiation on araldite and vibrations induced by field ramping damage the magnet. This degradation has indeed been observed and was cured in 1976 by consolidating the ends of the outer blocks with a collar made of thick plates and tie bars. In brief, the present PS magnet system seems robust enough and a new magnet has to be justified for reasons other than technological.

1.3 Operational Environment

The conditions of operation will not be the same at the time of the LHC as they are now. About a half of the present staff will have left and been replaced by forty new engineers and physicists. The people responsible for the development and the operation of the machines will thus not have the experience of the PS pioneers if no special action such as the construction of a new machine is undertaken. Within this context, the machine of the next century must be clean, simple and prone to improvement beyond its nominal performances.

1.3.1 Activation

The beam loss in the PS is a permanent subject of concern. Increasing the injection energy is expected to improve the situation but other causes will remain. The PS has no system of orbit correction at high energy and the tune-shifts are not controlled independently in the horizontal and vertical planes. Moreover, a process such as continuous transfer is notoriously particle consuming.

1.3.2 Simplicity

The knowledge accumulated in the science of strong focusing accelerators for the past forty years permits the design of machines which can be operated with very limited assistance and maintenance. In the PS complex for instance, this is the case of the LEP injector and of the Antiproton source. It is needless to elaborate on the impact of simplicity on the construction and operation cost. The combined functions of PS, AGS and ISR are no longer considered for modern machines. The reason lies in the difficulty of adjusting the focusing field which is tightly linked to the bending field through the pole shape of the magnets. The designers found a way out by introducing pole face windings, figure of eight loops and correction magnets but it is now generally acknowledged that it is by far preferable to foresee three types of magnets: pure dipoles for the bending function and two families of quadrupoles for independent control of the horizontal and vertical focusing. This point will be emphasized in the description of the quasi-isochronous lattice.

1.3.3 Scheduling and Possibilities of Development

Assuming money for the construction of a new PS can be found, it has to be decided where it could be located, namely instead of the present PS or in the ISR tunnel. Within the framework of the restructuring contemplated for the LHC, running one more machine does not seem consistent with the argument of simplicity and PS-XXI is supposed to simply replace the PS. There are nevertheless drawbacks. A full shutdown of one year is necessary to decommission the old machine and install the new one. The PS-XXI could be dedicated to LHC leaving all the other tasks to the PS. A larger tunnel such as the ISR offers more possibility for long term improvements especially if higher energies turn out to be necessary.

2 PS LIMITATIONS AS LHC INJECTOR

The arguments developed in the previous section have been at the origin of the study of a new synchrotron but a further investigation soon revealed that the official scheme of LHC injection was indeed feasible but at the limit of the PS possibilities. Little margin is thus left to achieve later improvements towards the so-called ultimate beam. One problem is related to the proximity of the injection γ to the transition γ in the SPS. Another concerns the technique of bunch compression in the PS. Transverse emittance preservation is also hard to cope with but it is a matter related to beam diagnostic and correction[6] which, to some extent, is common to any type of machine although the PS does not have all the flexibility one would wish.

2.1 Injection Energy into SPS

To satisfy the Keil–Schnell criterion on microwave instability, the bunch injected into the SPS must have a certain relative momentum spread $\Delta p/p$ for given values of the impedance threshold Z/n and of the dispersion in revolution time η:

$$\frac{|Z|}{n} \leq F \cdot \frac{E_0}{e} \cdot \gamma\beta^2 \cdot \frac{|\eta|}{I} \cdot \left(\frac{\Delta p}{p}\right)^2.$$

This momentum spread is difficult to achieve in the present PS and limited by the momentum acceptance of the transfer line between PS and SPS. Moreover, the RF voltage required for longitudinal matching is proportional to the parameter

$$k = \gamma\beta^2|\eta|.$$

Because the γ value of the beam at injection is only slightly above the γ at transition, the η value is small. As a consequence, the RF voltage is not high enough to avoid a detrimental effect of the transient beam loading on bunch capture. These conditions lead to a rather limited working space in the parameter set.[2] The variations of k, normalized to its value at 26 GeV/c, are plotted against γ in Figure 1. A factor 2 margin is obtained by increasing the injection energy to 32 GeV.

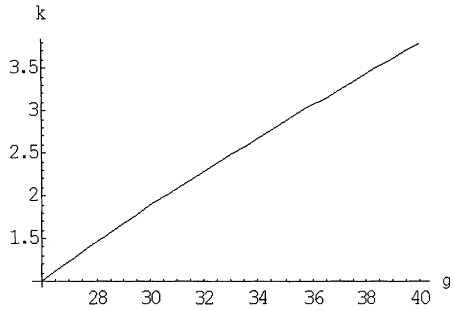

FIGURE 1 Variations of the scaling parameter k with γ.

The PS-XXI is thus designed for a higher extraction energy than the PS. Clearly, actions can also be taken on the SPS side by reducing the machine impedance[7] and increasing η.[8]

2.2 Bunch Compression in the PS

Having selected the transfer energy, the η value of PS-XXI can be defined with the constraint that the presently designed RF systems must provide the expected beam with adiabatic manipulations. The scaling factor k is plotted for the PS as a function of η in Figure 2 at constant γ. A factor 5 can be gained on the RF voltage by operating with an absolute value of η smaller than $5 \cdot 10^{-3}$.

Unfortunately the instability threshold is degraded by the same factor but the vacuum chamber will in any case be changed for aperture reasons and redesigned for a minimum impedance.

This problem of instability is the most acute during the de-bunching stage when the RF wave switches from the harmonic number 16 to 84. In Figure 3, the initial bunch is represented by a white rectangle in the ΔE–Δt phase space, the transition towards a coasting beam is in gray and the five final bunches generated from the initial bunch are in black. The bunching factor B is approximately the same at the end and at the beginning of the process. The η parameter is varied to approach zero when B is about one third of its final value so that the harmonic change is adiabatic. If the sign of η is irrelevant for RF, it matters for beam stability. Following the PS experience, no head–tail instability is observed below transition and a negative value of η is chosen to get rid of the sextupolar fields.

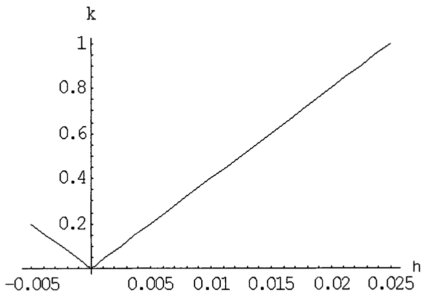

FIGURE 2 Variations of the scaling parameter k with η.

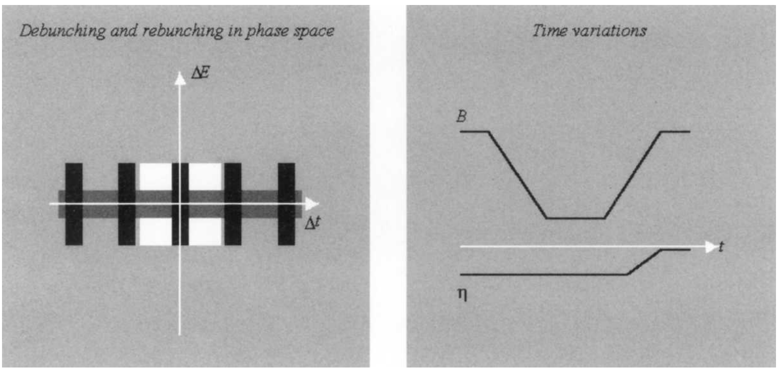

FIGURE 3 De-bunching and re-bunching before extraction towards the SPS.

3 QUASI-ISOCHRONOUS LATTICE

For all the above considerations, PS-XXI is tuned near transition and this is the reason why such a lattice is said to be quasi-isochronous. The same philosophy is actually adopted by many other advanced machines.[9] The lattice is based on FODO cells with missing magnets. The basic theory of alternating gradient structures shows indeed that the off-momentum orbits may oscillate about the reference orbit when the betatron tune is close to an integer. A classical FODO cell exists only if the total phase advance is smaller than π. It can therefore have a negative dispersion only if the distribution of the bending fields is perturbed, for instance by missing magnets and it is this property which is exploited.

3.1 Superperiod Structure

There are many ways to create a modified FODO cell with negative momentum compaction. The phase advance μ is chosen here close to $2\pi/5$ to have a small β-value and free straight sections $3\pi/5$ apart so that elements such as kicker and septum are well located. The superperiod (Figure 4) is thus made of five FODO cells and magnets are missing in positions 4 and 7. The superperiod is symmetric and its characteristics are calculated with *BeamOptics*.[10] The length of each FODO cell and the deflection angle per bend are normalized to unity. The analytical expressions of the orbit dispersion D_0 at the entrance to the superperiod and of the derivative of the path length ΔL with respect to the relative momentum error $\Delta p/p$ in the half superperiod are then

$$D_0 = \frac{f(1 + 8f - 20f^2 - 152f^3 + 64f^4 + 512f^5)}{1 - 20f^2 + 80f^4},$$

$$\frac{\Delta L}{\Delta p/p} = \frac{-1 + 74f^2 - 2f^3 - 1136f^4 + 4096f^6}{2(1 - 20f^2 + 80f^4)}.$$

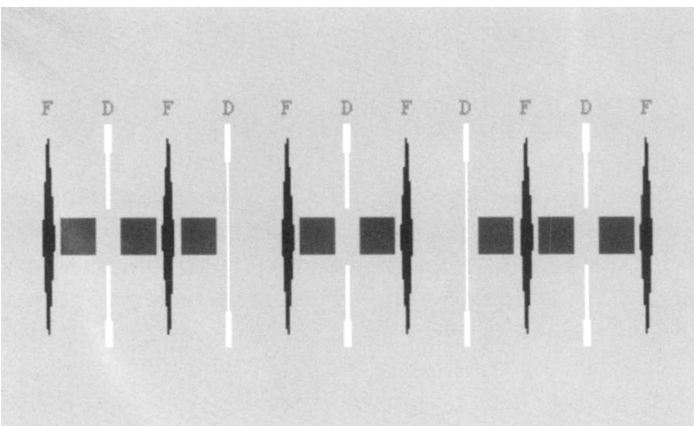

FIGURE 4 PS-XXI superperiod.

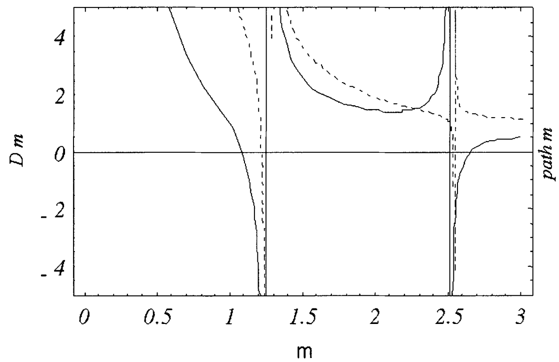

FIGURE 5 Variations of orbit dispersion (black) and incremental path length (dashed) versus cell phase advance.

The variable f is the focal length of the quadrupoles and is related to the cell phase advance through

$$f = \frac{1}{4\sin\frac{1}{2}\mu}.$$

The denominator is even in f, the poles occur for opposite values of f and there are four families of solutions: two for the F–D and two for the D–F configuration. The resonances correspond to μ equal to $2\pi/5$ and $4\pi/5$. After comparison of the various possibilities, the neighborhood of the first resonance has been chosen. Figure 5 shows the variations of D_0 and of $\Delta L/(\Delta p/p)$ at 32 GeV with $\mu/2\pi$. The isochronous regime corresponds to a zero value of η.

3.2 Cell Length

To achieve the lattice design the actual length l_c of a FODO cell has to be determined for given magnetic field and ring circumference. For a packing factor k, a dipole length l_b and a quadrupole length l_q, the cell length is

$$l_c = 2k(l_b + l_q).$$

Let n, n_c, n_s, m, ϕ, R and ρ be, respectively, the number of cells per superperiod, the total number of cells, the number of superperiods, the number of missing magnets in a superperiod, the deflection per magnet, the radius of the machine and the radius of curvature in a magnet. The total deflection must be 2π:

$$(2n - m)n_{\mathrm{s}}\phi = 2\pi.$$

The length of the circumference is

$$n_{\mathrm{c}}l_{\mathrm{c}} = 2\pi R.$$

The deflection per dipole is

$$\phi = \frac{l_{\mathrm{b}}}{\rho}.$$

After the various substitutions, the dipole length is given by

$$l_{\mathrm{b}} = \frac{\rho}{R}\frac{n}{2n - m}l_{\mathrm{c}}.$$

The quadrupole length is based on the focal length

$$f l_{\mathrm{c}} = \frac{1}{K l_{\mathrm{q}}},$$

where K is the focusing strength of a particle of momentum p for a field B_{q} at the quadrupole pole tip:

$$K = \frac{0.3}{p}\frac{B_{\mathrm{q}}}{r}.$$

The radius r of the quadrupole is

$$r = \sqrt{2xy}$$

with

$$x = \sqrt{\varepsilon\beta_{\max} l_{\mathrm{c}}} + \left| D\frac{\Delta p}{p}\phi l_{\mathrm{c}} \right| \quad \text{and} \quad y = \sqrt{\varepsilon\beta_{\min} l_{\mathrm{c}}},$$

where ε is the beam emittance and $\Delta p/p$ the relative momentum error. In a FODO cell, the β-values satisfy the relations

$$\beta_{\min} = 2|f|\sqrt{\frac{4|f|-1}{4|f|+1}}, \qquad \beta_{\min}\beta_{\max} = 4f^2.$$

The orbit dispersion D is taken at the end of the superperiod where it has already been calculated as a function of f. After substitution, the quadrupole length is

$$l_q = \frac{p\sqrt{2}}{eB_q f}\left(\sqrt{\frac{2\varepsilon f}{l_c}} + \frac{nD\sqrt{\varepsilon\beta_{\min} l_c}}{(2n-m)R}\frac{\Delta p}{p}\right).$$

The dipole and quadrupole lengths being defined as functions of l_c, it remains to solve the first equation of this section. This equation is quadratic in $l_c^{3/2}$ and can be written

$$2\varepsilon f + \frac{nD\sqrt{\varepsilon\beta_{\min}}}{R(2n-m)}\frac{\Delta p}{p} l_c^{3/2} - \frac{e}{p}\frac{(B_q f)^2}{2}\left(\frac{1}{2k} - \frac{n}{2n-m}\frac{\rho}{R}\right)^2 l_c^3 = 0.$$

Provided the existence condition

$$\frac{R}{\rho} > \frac{2kn}{2n-m}$$

is fulfilled, the equation has two solutions, the one with the – sign is chosen to have a short cell and thus low β and D values.

3.3 Lattice Parameters

The solution of the above equation does not warrant that the ratio $2\pi R/l_c$ is an integer. A slight adjustment is thus necessary to find the lattice parameters which are listed in Table II.

The β-functions and the orbit dispersion are plotted in Figure 6 for a half superperiod with long magnets. Slight distortion due to edge effects in the dipoles due to the edge effect of the dipoles could be corrected with independent focusing strengths in the F and D quadrupoles; the fine adjustment of the lattice is treated in Section 3.4.

TABLE II Lattice parameters

Superperiods	12
Cells	60
Cell length [m]	10.472
Dipole field [T]	1.778445
Dipole length [m]	3.91231
Deflection angle [radian]	0.0654498
Quadrupole radius [m]	0.02748
Quadrupole length [m]	0.8
Quadrupole strength [m^{-2}]	0.288458
Horizontal tune	11.695
Vertical tune	11.788
Momentum compaction	$-6.8 \cdot 10^{-4}$

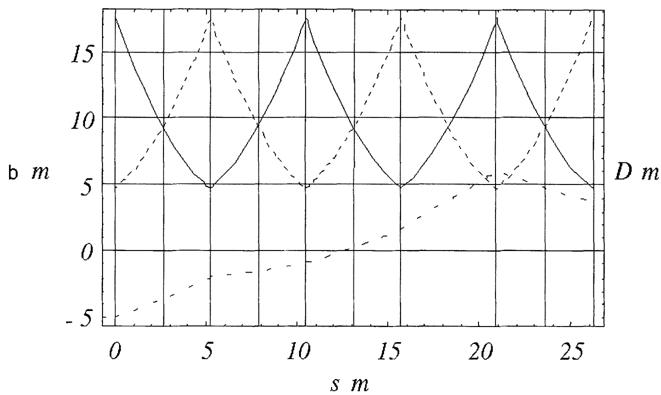

FIGURE 6 β_h (black), β_v (dotted) and D (dashed) functions over half a superperiod.

3.4 Fine Adjustments

It has been seen in Sections 2.1 and 2.2 that bunch compression takes advantage of a variable η-value. As it has been presented up to now, η is obtained by tuning the machine near the integer. For variations about the reference value, it is useful to keep the betatron tunes under control. As η is controlled via the orbit dispersion, three independent families are required. In a half superperiod, the first F-quadrupole has a strong influence on the orbit dispersion and all the quadrupoles of that type are connected to form the family F_1. In a similar way, the other F-quadrupoles act on the horizontal tune and are linked to make the family F_2. All the D-quadrupoles are in series to adjust the vertical tune.

Local orbit deformations are necessary to limit the kicker strengths at injection or ejection. The first and fifth dipoles of a superperiod are ideally placed to create an orbit bump since they are phase shifted by π and the kicker is $3\pi/5$ or $2\pi/5$ far from each of them. They are called *bumpers*. The η-value is almost unaffected because the deflection angle is small and the orbit dispersion has opposite values in these magnets. As a consequence, a single kicker would be sufficient in the whole machine for all the types of injection and ejection and the septum magnets could be standardized with identical modules. The topology of the various transfer lines is almost the same as for the present PS and the full machine layout is shown in Figure 7. Finally, the orbit distortions can be corrected at all energies by adding to the bumpers all the third dipoles of the superperiods equipped with identical correction coils.

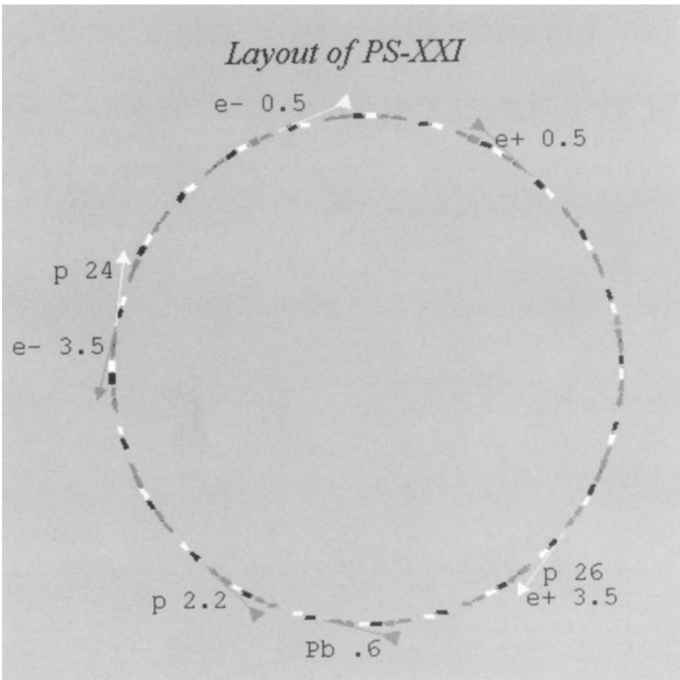

FIGURE 7 Layout of PS-XXI.

4 MAGNETS AND POWER SUPPLIES

The key parameter in the specification of a machine is the aperture. In a first analysis, the vertical aperture affects the dipoles and the horizontal one matters for the quadrupoles. The PS-XXI is optimized for the LHC beams which are bright and have thus a small cross-section. It is nevertheless fully realized that very high intensities such as the ones needed for neutrino physics or muon colliders[11] could be contemplated to give a new machine its full potential, but then the aperture should be increased. The only step in this direction is an increase of the repetition rate by a factor 2. The compatibility of PS-XXI with the new power supply[12] envisaged for the existing PS has also been taken into account.

4.1 Vertical Acceptance

Table III compares the characteristics of the injected beams, as they are now for high intensities and as they are planned for LHC and PS-XXI. The fourth and last columns are the normalized emittance and the inner chamber height. The reduction of a factor 2 in gap height for PS-XXI is due to several facts. First and most important, the poles of the bending magnets are parallel and do no longer include a quadrupolar component. Then, the machine has a greater focusing strength and the vertical β-function is smaller. Finally, tolerances on orbit distortion and betatron mismatch are tighter because it is expected that the correction systems will be more efficient. Injection at 2 GeV[2] would add an appreciable safety margin in beam emittance. A further reduction of gap height would make the magnet cheaper and easier to pulse but, besides geometric limitations imposed by the beam size, the image field of the beam in the vacuum chamber has adverse effects, both for space charge limits (Figure 8) and for collective instabilities.

TABLE III Beam characteristics at injection

Machine	*Kinetic energy* (GeV)	$\beta\gamma$	ε *at* 2σ (μm)	*Beam height* (mm)	*Gap height* (mm)	*Chamber height* (mm)
PS	1	1.8	30	39	100	70
PS-LHC	1.4	2.28	10	20	100	70
PS-XXI	1.4	2.28	10	17	50	46

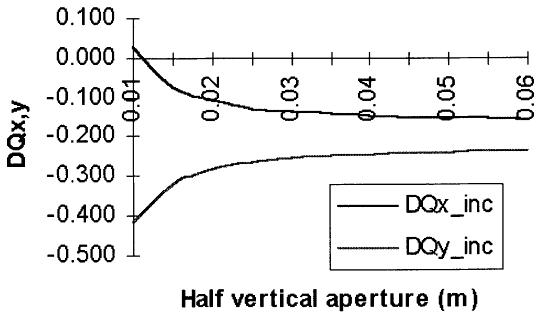

FIGURE 8 Incoherent tune shift variations for ultimate LHC beam.

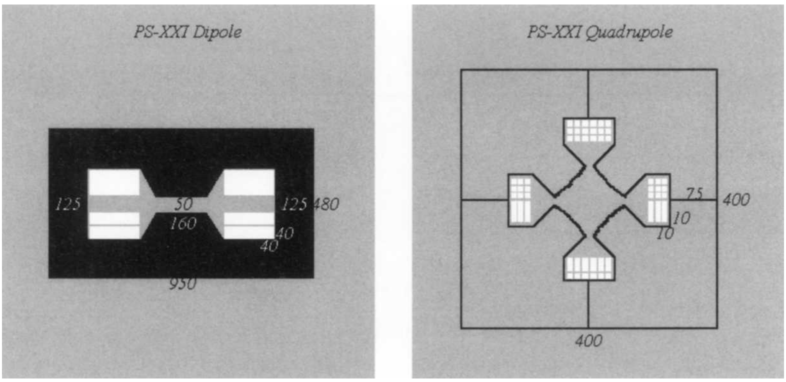

FIGURE 9 PS-XXI magnets.

4.2 Magnets

The magnet design (Figure 9) is still very preliminary and has mainly served to establish the electrical characteristics of the synchrotron (Tables IV and V). The reduction in gap height by a factor 2 leads to a saving of a factor near 4 in power consumption for identical conditions of operation and even to a reduced consumption at 32 GeV with respect to the present PS running at 26 GeV. Within the context of the continuous transfer of beams towards the SPS, it has also been shown that the magnet system could be pulsed to 32 GeV in 1.2 s; this means a gain of a factor 2 over the present repetition rate.

TABLE IV Dipole characteristics

Number	96
Gap height [m]	0.05
Number of turns of the main coil	8
Number of turns of the correction coil	10
Maximum current of the main coil [A]	5000
Maximum correction current [A]	250
Average coil length [m]	4.35
Average coil width [m]	0.5
Resistance [mΩ]	2.11
Total resistance with bus bars [mΩ]	240
Inductance [mH]	7
Total inductance [mH]	680
dB/dt [T/s]	2.05
Installed power [MV A]	43.8
Dissipated power in a 2.4 s cycle [MW]	1.75

TABLE V Quadrupole characteristics

Number	$2 * 60$
Maximum current [A]	1000
Turns per pole	9
Length [m]	0.8
Pole tip radius [m]	0.03
Average coil width [m]	0.15
Resistance [mΩ]	7.3
Resistance per quadrupole circuit [mΩ]	458
Inductance [mH]	2.6
Inductance per quadrupole circuit [mH]	156
Installed power [kV A]	$2 * 810$
Dissipated power per cycle [kW]	$2 * 160$

5 CONCLUSION

A conceptual design of a new synchrotron which fulfills the tasks foreseen for the LHC era has been presented and can serve as a reference to decide on the future of the present PS. Separate function magnets and absence of transition result in energy saving, higher extraction energy, adiabatic RF manipulations and possible increase of the repetition frequency by a factor 2. The machine would be equipped with all the necessary corrections at all energies. Several systems, such as γ_t-jump quadrupoles, pole face windings or figure-of-eight loops become obsolete. The regularity of the lattice reduces the number of kickers and makes possible the use of identical septum modules. The PS-XXI could be operated with a reduced and experienced staff. This being said, an investment of approximately 40 MCHF for magnets and vacuum chamber is necessary. Detailed engineering study is essential both to assess the performances contemplated at the conceptual stage and to minimize the estimated cost. The PS-XXI is a link in the LHC injector and its final parameters must result from a global optimization including the SPS. The choice of its site either in the PS or in the ISR tunnel is pending and is fundamental for cost evaluation, installation schedule and ultimate performances.

Acknowledgments

We are grateful to D. Cornuet for his contribution to the magnet predesign.

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