DESIGN OPTIMIZATION OF PS2

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Abstract

The PS2 will replace the present CERN-PS in the cascade of LHC injectors. It will have twice the PS energy and twice the circumference. Extensive design optimization is presently ongoing to prepare a conceptual design report for project approval in 2012, with the aim of starting construction in 2013. The paper describes the various PS2 design constraints, the optimization steps, and the path towards the final design.

INTRODUCTION

The PS2 synchrotron is proposed to replace the ageing CERN PS in the chain of LHC injectors within the framework of the CERN accelerator complex upgrade programme [1], to fully exploit the LHC potential.

The first stage of the injector upgrade started in 2008 with the construction of Linac4 [2], which will supply an H^- beam at 160 MeV to the existing chain Booster-PS-SPS from 2013 onwards, replacing Linac2 and removing the space charge bottleneck at 50 MeV Booster injection.

The second stage is planned to start in 2013 and will see the construction of the 50 GeV PS2 and its injector, the Superconducting Proton Linac (SPL), replacing the 25 GeV PS and the 1.4 GeV Booster. The SPL [3] will use Linac4 as front-end and deliver, in its low-power option (LPSPL), a 4 GeV H^- beam at a repetition rate of 2 Hz. The SPS will also have to undergo a substantial upgrade programme [4] to be able to digest the beams with higher brightness and intensity delivered by the PS2 at up to 50 GeV injection energy.

An overview on the two-stage injector upgrade programme is shown in Fig. 1.

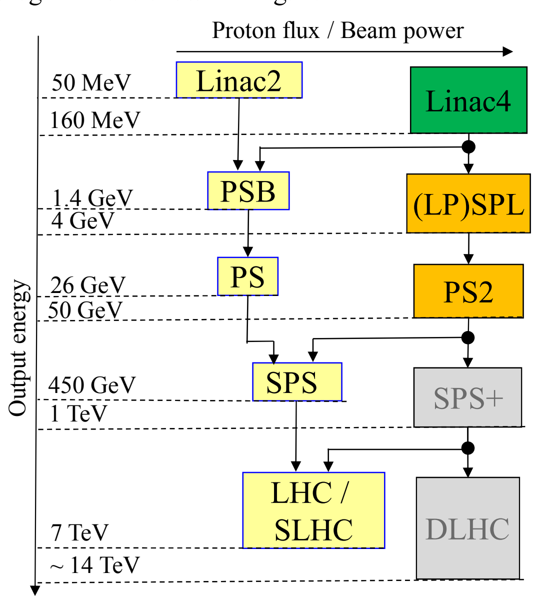

Figure 1: Overview on the CERN injector complex upgrade programme: stage 1 (green), stage 2 (orange).

DESIGN GOALS AND BASIC CHOICES

The LHC luminosity upgrade [5] defines the PS2 requirements and the main parameters and design choices for both proton and heavy ion operation. In addition to its main task of providing the highest brightness beams for the LHC, the PS2 should also be capable of supplying beams for a competitive fixed-target physics programme either directly or through the SPS. The design philosophy is to provide this potential either in line with LHC requirements or by further optimisation without diverting strongly from the baseline design.

The main PS2 design goals come from LHC operation:

- Higher beam brightness within nominal emittances.
- Flexibility for generating bunch patterns and spacing.
- Reduction of SPS injection plateau and LHC filling time.

General design goals are:

- High reliability and availability.
- Improved operation schemes for the complex.
- Low beam loss operation.
- Potential for future upgrades of the complex.

The target figure for beam brightness has been set at twice that of the so-called “ultimate” LHC beam [6]. This corresponds to 4×10^{11} protons per LHC bunch at PS2 ejection and incorporates an intensity reserve of 20%. Limiting the vertical incoherent space charge tune spread to below 0.2 fixes the PS2 injection energy to 4 GeV [7].

The PS2 will provide beams at significantly higher energy than the PS. This will lead via adiabatic damping to smaller beam sizes and reduced losses when transferring to the SPS, where injection will take place significantly above the transition energy of 22 GeV, which is expected to reduce the impact of instabilities and collective effects. The higher transfer energy will also open the way for an SPS upgrade at a later stage aiming at an LHC injection energy around 1 TeV. The target for the PS2 energy was thus set to 50 GeV.

The doubling of the top energy compared to the PS also entails a larger circumference. The choice of circumference plays an important role for the operation of the overall complex since it determines the filling strategy for the SPS. A PS2 circumference of around twice the PS, or about one fifth of the SPS, represents an optimum since it halves the number of PS2 pulses to fill the SPS for the LHC, thereby reducing significantly the time the SPS spends at injection energy. A ratio of ~1/5 will also allow filling the SPS circumference completely, for fixed target operation, with a single five-turn extraction from the PS2. Presently this is achieved with two consecutive ejections from the PS, forcing the SPS to wait 1.2 s with a high intensity beam at low energy for the second batch. The exact length of the PS2 was fixed to 15/77 of the SPS, i.e., 1346.4 m, based on rf-synchronisation aspects [8].

Independently of the final choice of the main rf system, the PS2 will supply proton beams for the SPS with a 40 MHz structure (corresponding to harmonic h=180) with bunches shortened to 4 ns total length to fit the SPS 200 MHz system. Such a scheme is in place today for the LHC beam [9], but not for the high-intensity Fixed-Target (FT) beam, where instead a debunched beam with a 200 MHz pre-structure is transferred. Because of the clean bunch-to-bucket transfer, a reduction of injection losses for the FT beam is expected in the SPS.

The magnet and power systems of the PS2 will be designed for a cycle length of around 2.5 s for 50 GeV, so that the overall cycling scheme of the complex will be similar to today's operation.

Table 1 summarizes the main parameters of PS2.

Table 1: Main Parameters of the Proposed PS2 Accelerator.

Parameter	Unit	PS2	PS
p injection energy (kinetic)	GeV	4.0	1.4
p extraction energy (kinetic)	GeV	20-50	13-25
Circumference	m	1346.4	628.3
LHC bunch intensity (max.)	ppb	4.0×10^{11}	1.7×10^{11}
LHC pulse intensity (max.)	ppp	6.7×10^{13}	1.2×10^{13}
FT pulse intensity (max.)	ppp	1.0×10^{14}	3.2×10^{13}
Cycle time	s	~2.5	1.2 / 2.4
Energy per pulse (max.)	kJ	800	70
Beam power (max.)	kW	320	60

General technology choices for the PS2 will be based in particular on considerations on reliability, machine availability and operational complexity. Preference will be given wherever possible to well-proven and robust technologies to ensure the high availability required from PS2 as the future "work horse" of CERN's accelerator complex.

MACHINE INTEGRATION

The PS2 will receive an H^- beam from the SPL, ion beams from LEIR and possibly proton beams at low energy from the PS complex, during the commissioning phase. It will deliver proton and ion beams to the SPS and possibly also for physics directly, in which case an adequate experimental area for high-intensity operation might have to be constructed since the feasibility of upgrading any of the existing areas is not evident.

Positioning the PS2 tangentially to the end of the existing TT10 transfer line linking PS and SPS is considered the optimum choice (see Fig. 2). This has the following advantages:

- Minimum length of high-energy transfer line to the SPS and use of existing SPS injection channel.
- Avoiding large bending radii in the H^- injection line from LPSPL to minimise Lorentz stripping losses.
- Minimum length of the injection line from existing TT10 line for ions from LEIR and protons from PS complex.

As a consequence, all injection and extraction systems can be concentrated in a single straight section suggesting a racetrack shape of the machine.

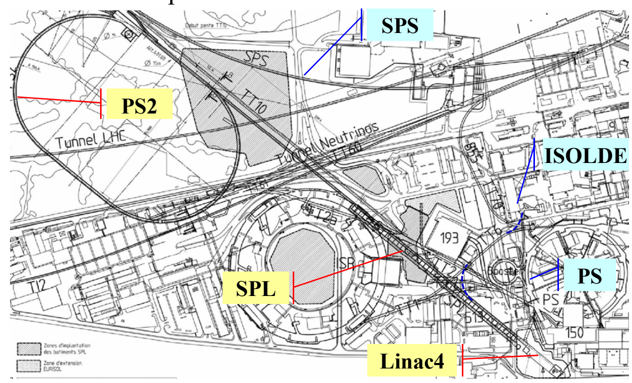

Figure 2: Integration of PS2 within the existing and future CERN accelerator complex.

RF AND ACCELERATION

As is presently the case in the PS, the bunch patterns for the LHC have to be established already at PS2 ejection for both proton and ion beams. The SPS will receive one or multiple batches and accelerate and transfer the bunch train to the LHC without changing the pattern. Therefore it is mandatory to use a 40 MHz or higher frequency system at PS2 ejection to provide the desired 25 ns bunch spacing.

Whereas the revolution frequency of protons during acceleration in the PS2 increases only by 1.8%, it more than doubles in the case of Pb^{54+} ions (see Table 2). Such a large swing can be achieved with conventional ferrite based systems at lower frequencies as in the PS, but is unprecedented in the range of 40 MHz.

Table 2: Proton and Pb^{54+} Revolution Frequency Swings.

	Revolution frequency [kHz]		Swing
	injection	ejection	$100\cdot(f_{ej}/f_{inj}-1)$
Protons	218.6	222.6	1.8
Pb^{54+} ions	108.4	222.1	104.9

Two possible routes for the PS2 main rf system have been identified and analysed [10,11].

The 10 MHz route follows the scheme applied in the PS [9] and is based on a low-frequency large-tuning range system (3–10 MHz). The bunch structure at ejection for protons is obtained by multiple splittings using additional 13, 20 and 40 MHz systems. The final bunch shortening to less than 4 ns total bunch length, to fit the SPS 200 MHz bucket, is achieved by a non-adiabatic voltage step with the 40 MHz system. For ions, the scheme is identical to the nominal ion beam in the PS [12].

The 40 MHz route is of particular interest for protons since the LPSPL as PS2 injector is capable to provide chopping at 40 MHz [13]. This offers the potential to create any bunch pattern up to 40 MHz for LHC operation already at PS2 injection and avoids any splitting and longitudinal gymnastics. This not only eases operation but also avoids the additional rf systems required for splitting, minimising equipment and the impedance of the machine.

The challenge for the 40 MHz route stems from the required frequency swing for ions (18.6–40.1 MHz) as no system covering that range is available to date. An R&D program is being launched for the development of a system based on ferrites with perpendicular bias [14,15] to circumvent the problem of high hysteresis losses inherent to parallel biased system in this frequency range.

Alternatively, one could aim for reduced tuning ranges, as the longitudinal gymnastics for ions could be performed with overlapping systems covering the ranges 18.6 to ~27 MHz and ~26.5 to 40.1 MHz. For proton operation all systems would work in the same range (~1.5 MV total installed voltage), while the ion gymnastics requires significantly lower voltages so that it is possible to split the cavities into two groups with independent tuning.

The 40 MHz route is at present the preferred variant for the PS2, even though a new additional rf system for LEIR is required [11,16]. For proton operation the basic harmonic is h=180 throughout the cycle for 25 ns spacing bunch trains. About 1.5 MV of installed voltage is required for a bucket acceptance of >1eV. If required, a 50 ns LHC bunch train can be achieved by merging before extraction, taking advantage of the frequency range needed for ion operation. The high intensity FT beam for SPS will be produced using the LHC scheme. The parameters of the LHC 25 ns, LHC 50 ns and the FT proton beams are summarized in Table 3.

Table 3: PS2 Beam Parameters for 40 MHz Operation.

Parameter	LHC 25	LHC 50	FT SPS
Harmonic injection/ejection	180	180/90	180
Bunches injection/ejection	168	168/84	128-168
Bunch intensity injection	4.2×10^{11}	3.1×10^{11}	6.2×10^{11}
Bunch intensity ejection	4.0×10^{11}	5.9×10^{11}	6.0×10^{11}
Total intensity ejection	6.7×10^{13}	5.0×10^{13}	1.0×10^{14}
Long. emittance inj. [eVs]	<0.4	<0.3	<0.4
Long. emittance ej. [eVs]	0.6	0.7	<0.6

Due to the 40 MHz structure all along the cycle, electron cloud effects are expected in the PS2 and are confirmed by first simulations [17]. The strategy is to counteract at the level of the vacuum system by reducing the secondary emission yield below the threshold value.

LATTICE CONSIDERATIONS

Basing a machine with PS2 parameters on a classical FODO lattice would usually imply crossing transition with protons. Such lattices have been designed [18] and an analysis of the required gamma jump height for crossing transition with the desired bunch intensities has shown that, for the beam parameters quoted in Table 3, a transition jump of typically $\Delta\gamma$~3 total height in about 1 ms has to be performed, which is considered at the limit of what can be achieved in a jump scheme with acceptable optics distortion [19]. It should be noted that, in the derivation of these parameters, it was assumed that the longitudinal and transverse impedances in PS2 would be no larger than those of the PS.

Based on the conclusions of the analysis [19] and also to avoid the operational complication of a jump scheme, lattices with Negative Momentum Compaction (NMC) and thus imaginary transition gamma have been studied. The rather stringent optics requirements from injection and extraction systems limit the usability of the long straight sections for tuning. Therefore the arcs not only have to provide the imaginary transition gamma but also some tuning flexibility for operation. One approach satisfying these requirements is to build the arcs from regular modules that produce the desired negative dispersion and to use dedicated dispersion suppressor modules at each end [20]. This also results in a matched dispersion in the arc, in contrast to the approach of the "resonant" NMC lattice [21]

Each arc consists of five modules and a matching module on each end to suppress dispersion and match to the straight sections. The total arc length is 528 m. The two long straight sections are based on FODO cells, similar to those in the arc module, and a split-triplet insertion with a 22 m drift in the centre, optimized to house the H^- injection chicane on one side of the ring. The opposite straight section will house the rf system and the collimation system [22]. Each straight section is 145 m long. Fig. 3 shows the optics functions for a quarter of the PS2 lattice between the mirror symmetry axis mid arc and mid straight section. The main optics parameters of the PS2 ring are given in Table 4 [20].

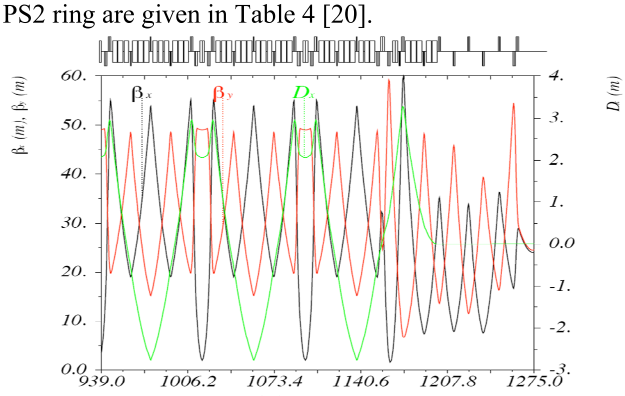

Figure 3: Optical functions for a quarter of the PS2 ring.

Table 4: PS2 Main Optics Parameters.

Parameter	PS2
Tune (hor./vert.)	(13.25/8.25)
Transition gamma	37i
Maximum beta function (hor./vert.)	(59/59)
Maximum/minimum dispersion [m]	(3.3/-2.8)
Relative chromaticity (hor./vert.)	(-1.65/-1.59)

The racetrack shape of the machine corresponds best to the requirements of integration but has the drawback of the low symmetry of two, with the consequence that structure resonances, $(n{\cdot}Q_{hor}+m{\cdot}Q_{vert})/2$=integer will limit the number and size of potential working point areas. Choosing a three-fold symmetry, as e.g. the JPARC machine [21], is considered an alternative. Shortening the straight sections would however require relocation of some elements, most probably the slow extraction, which would in turn also imply a second extraction channel. This is not only uneconomic in terms of equipment but also in terms of space. Efforts are being focused to understand better the impact of low symmetry and systematic resonances on the machine performance and in parallel three-fold NMC lattices are being studied [20].

INJECTION AND EXTRACTION

The layout of all injection and extraction elements in the long straight section is shown in Fig. 4. It is proposed to use a single extraction channel (magnetic septa MS1 and MS2) for all three extraction modes: fast extraction to the SPS for LHC type beams, five-turn extraction for filling the SPS for fixed-target physics and, if requested, slow resonant extraction for physics at the PS2.

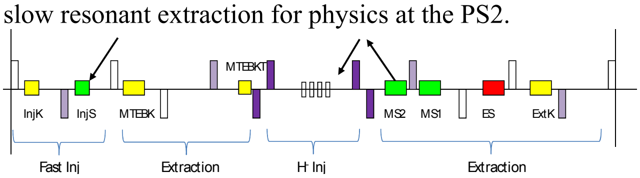

Figure 4: Layout of injection and extraction elements in the long straight section. (MS1, MS2 magnetic septa, ES electrostatic septum, ExtK: fast extraction kicker, MTEBK(T): fast kickers to close 5-turn extraction bump, InjS: ion injection septum, InjK: ion injection kicker).

H^- Injection

The baseline for PS2 injection is a classical foil stripping scheme with fast horizontal and vertical orbit bumps in the machine to allow the possibility of correlated and uncorrelated phase space painting. Fig. 5 shows the injection system in the centre of the split-triplet insertion [23], which is similar to the Fermilab Project X injection insertion layout [24].

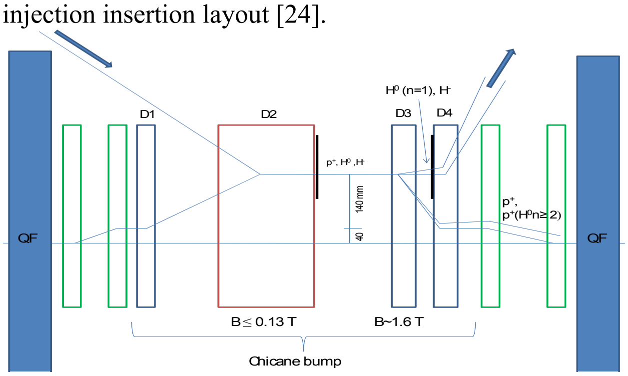

Figure 5: H^- Injection. The first chicane dipole (red) has low field $B \leq 0.13$ T to avoid Lorentz stripping of the incoming H^-. Kickers (green) make the painting bump.

Studies are being conducted to find an insertion solution that can also be tuned for a laser stripping scheme to be integrated between the central two chicane dipoles D2 and D3 [23].

Longitudinal Injection Painting

In longitudinal phase space the design goal is to create a beam with an emittance of ~0.4 eVs and a bunching factor of at least 0.5 with a bucket filling factor of ~70%. This requires a 40 MHz voltage of about 700 kV which, together with $\gamma_{tr} \approx 40$ i, results in a synchrotron frequency of ~3 kHz. H^- injection will typically last for 100 to 300 turns, corresponding to up to 1 ms or 3 synchrotron periods. Various injection painting schemes based on fixed energy offset and chopping techniques are being studied to achieve the goals by "passive" painting, i.e. without energy modulation of the LPSPL beam [25], as shown in the example of Fig. 6.

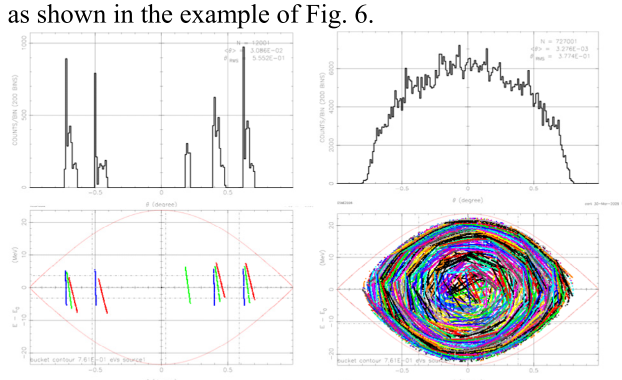

Figure 6: Longitudinal painting with a complex chopping scheme to depopulate the central phase space region [25].

Ion Injection

The ion beam from LEIR will be injected into the PS2 machine with a classical single-turn scheme using a septum and fast kicker separated by around 90 degrees in betatron phase [26]. The ion injection system could also be used to inject a proton beam from the PS complex into the PS2 to allow commissioning independently of LPSPL.

Five-turn Extraction

Filling the SPS quasi continuously for fixed-target physics will be achieved by extracting the PS2 beam over five consecutive turns. For this the horizontal fractional tune is set to 0.25 (or 0.75) and the circulating beam is split into five beamlets (one core and four islands) using fourth order phase space topology and perturbations from sextupoles and octupoles, as established in 2008 at the PS [27]. Once the beam is split, the first island is pushed into the extraction channel by means of the fast ejection kicker. A closed bump around the septa is achieved with a second kicker 360 degrees downstream of the ejection kicker. By keeping the bump constant over four turns, the four outer islands are extracted. Finally, the core is extracted by increasing the strength of the first kicker.

Fast Extraction and Slow Resonant Extraction

The fast ejection system will be based on a fast kicker with a typical rise time of <300 ns and on an array of magnetic septa spaced by ~90 degrees. The required kicker gap will be produced at injection by the LPSPL chopper by leaving 12 consecutive 40 MHz buckets of the 180 unfilled.

The slow resonant extraction scheme [28] uses an electrostatic septum in the half-cell upstream of the magnetic septa and a separation in phase of around 75 degrees. Resonance sextupoles will be located in the zero-dispersion straights to avoid any coupling with chromaticity.

PS2 BEAMS FOR SPS

The PS2 will provide beams to the SPS for LHC and for FT physics. Assuming an LHC filling scheme similar to the present nominal scheme [29], the SPS will receive two batches each of 168 bunches with 25 ns bunch spacing and with 2.5 s between injections. This is to be compared with four batches today from the PS with 3.6 s between batches. This represents an important shortening of the SPS injection plateau from 10.8 s to ~2.5 s nearly halving the SPS cycle for the LHC, as shown in Fig. 7.

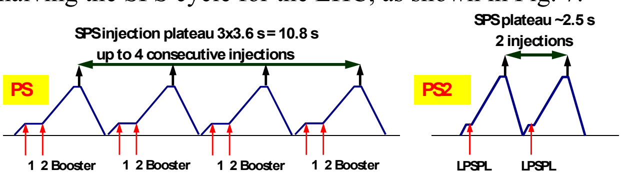

Figure 7: LHC cycle in SPS with PS and PS2 as injector.

For the high-intensity (1.0×10^{14} protons) FT beam, the SPS will be filled from the PS2 by a single five-turn extraction. It should be noted that for the LHC beam with 4.0×10^{11} protons per bunch, the total intensity of the two PS2 batches will be $2 \times 168 \times 4\times10^{11}=1.34\times10^{14}$ protons, which is significantly above the intensity record of the SPS of 5.3×10^{13} achieved for an FT beam [30]. In order to cope with such intensities and beam densities, a major upgrade programme of the SPS is being prepared [4]. The main areas of attention are:

- RF system to cope with larger beam power.
- Vacuum system to mitigate electron cloud effects.
- Impedance reduction programmes to improve beam stability and avoid equipment heating.

A new 50 GeV injection system will also be required.

SUMMARY AND OUTLOOK

The basic design choices for the PS2 have been made. After decisions on the lattice and rf concepts foreseen towards the end of 2009, the focus will switch to technical pre-designs of various equipment in the period 2010–11. The aim of the PS2 working group is to prepare a conceptual design report and a cost estimate to enable a decision on the project by mid-2012. The same planning applies to the LPSPL as injector for PS2.

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