LONGITUDINAL LIMITATIONS IN THE PS COMPLEX FOR THE GENERATION OF THE LHC PROTON BEAM

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The nominal operating scheme for feeding LHC with protons[1] makes use of the PS injectors' complex. Many new manipulations are used in the longitudinal phase plane. The radio-frequency systems of the PS Booster (PSB) operate on harmonics 1 and 2, harmonic 10 being used for controlled emittance blow-up during acceleration. The PS accelerates on harmonics 8 and 16. Debunching takes place at 26 GeV followed by rebunching on harmonic 84 (40 MHz) and bunch compression before ejection to the SPS. Although certainly capable of providing the nominal type of beam, these processes are marginal in terms of performance and have not all been experimentally demonstrated. These limitations are described together with possible improvements. New directions of investigation including the SPS are encouraged.

Keywords: Radio-frequency; Longitudinal blow-up; Debunching; Rebunching; Bunch compression

1 INTRODUCTION

The PS complex of injectors will be used to provide protons to LHC.[1] The nominal operating scheme of the injectors' complex has been defined in 1993,[2] and is described elsewhere in these proceedings.[3,4] The methods foreseen to achieve the required transverse beam brightness have been experimentally demonstrated at the end of the same year.[5]

But the longitudinal beam dynamics in the PS and, to a smaller extent, in the PSB, was only partly tested, because of the limited

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hardware available at that time (the PSB low frequency system was only providing 6 kV instead of 8, and the PS 40 and 80 MHz systems did not exist). The status of the various manipulations is summarised in Table I. In four cases (Items 3–6) the performance goals were met, and little doubts remain.

Difficulties were experienced during the setting-up of acceleration using harmonics 1 and 2 and of blow-up during acceleration in the PSB (items 1 and 2).

In these two cases a better understanding of the beam dynamics is required.

The debunching, rebunching and bunch compression processes in the PS (items 7 and 8) have been designed with little performance margin according to computer simulations.[6] Tests with beam depend upon the availability of the 40 and 80 MHz hardware. Experiments will begin in December 96, when the first prototype 40 MHz cavity will be available. Full scale trial are only planned in 1998, when the 80 MHz equipment will be ready.

The problem of the imperfection of the PS ejection process (item 9) has not yet been treated, and the reference design[1] assumes the loss of 3 bunches during the kicker rise-time. That situation is not satisfying, especially since it is now known that bunches at the edge of the bunch train will also suffer from incorrect deflection.

TABLE I   Status of longitudinal beam manipulations in the PS complex

Item	Description	Comment
1	1 bunch/ring in the PSB. Reduction of peak line density with second harmonic cavity.	Partly tested. Need for deeper analysis.
2	Controlled blow-up of longitudinal emittance during acceleration in the PSB. Aim for hollow particle distribution.	Difficulties during the tests in 93. More tests required.
3	Bunch to bucket transfer PSB to PS of 2 PSB batches.	Satisfying
4	Bunch splitting in the PS (8/16 bunches) at low energy.	Satisfying
5	Controlled longitudinal blow-ups during PS flat-tops.	Satisfying
6	Acceleration up to 26 GeV.	Satisfying
7	Debunching ($h = 16$) and rebunching ($h = 84$).	Little margin according to computer simulations.
8	Bunch compression (non-adiabatic, using $h = 84$ and $h = 168$).	Little margin according to computer simulations.
9	Fast ejection.	Not satisfying (3 bunches lost and incorrect deflection of edge bunches).

2   ANALYSIS OF THE LIMITING PROCESSES

2.1   Dual Harmonic Operation in the PSB (Item 1 in Table I)

A second harmonic RF can be superimposed to the first harmonic used for acceleration to increase the bunching factor and hence decrease the transverse space-charge tune spread.

An $h = 10$ RF system has been installed for that reason in the PSB in 1982, to add to the main acceleration system on $h = 5$. Although a number of performance records have since been achieved (up to 10^{13} protons per pulse per ring), the full theoretical benefit in terms of bunching factor have never been obtained[7] because high order within bunch modes (sextupolar, octupolar and decapolar) are driven by the second harmonic system. That is partly cured by locking the phase at $h = 10$ to the fundamental beam phase, as long as $V(h = 10)/V(h = 5) < 1/2$. For un-understood reasons, high intensity operation is notoriously delicate to optimize and uncomfortably prone to degradation.

For the needs of the LHC proton beam, the PSB will work with harmonics 1 and 2. One clear advantage is the absence of coupled bunch mode instabilities and of the corresponding feedback systems that noticeably complicate machine adjustment. Nevertheless the difficulty to operate with two simultaneous harmonics is expected to be similar to our present experience. The beam performance required for LHC has been achieved in one ring during the experiments in 1993 (Ip $\sim 2 \times 10^{12}$ ppp), and the need has again been found to lock the second harmonic RF on the beam itself.

Beam transfer functions for amplitude and phase modulations in dual RF systems have already been derived.[8] Further theoretical investigations are being pursued.[7] Extensive beam tests up to the highest intensity will take place in 1997, when one set of full performance RF systems will be available in ring 3.

2.2   Controlled Blow-up During Acceleration in the PSB (Item 2 in Table I)

In the case of a single harmonic RF, the bunching factor can nevertheless be increased by tailoring the distribution of particles in the longitudinal phase plane. For the benefit of the PS, where the first batch of 4 bunches is kept at injection energy during 1.2 s, it is then

interesting to optimise the longitudinal density of particles during acceleration in the PSB.

The technique,[9] developed in the PS, to generate flat-topped bunches involves two different RF manipulations:

(i) The phase of the accelerating RF ($h = 1$) is modulated at the synchrotron frequency to create bunch oscillations and depopulate the bunch core. According to the set-up required for system stability (see previous section), the phase of the RF on $h = 2$ follows the centre of gravity of the bunch.

(ii) Voltage is applied at a much higher frequency (slightly offset from $h = 9$) to accelerate filamentation and smooth out the bunch shape.

Adjustment proved to be unexpectedly much more delicate in the PSB than they were in the PS. We actually attribute that discrepancy to the effect of the second harmonic, which cancels the longitudinal focussing at the bunch centre and radically modifies the pattern of incoherent synchrotron frequencies of particles in the bunch. Confirmation of simulations by experimental observations is needed. Tests with beam will resume in 1997, when one PSB ring will be equipped with adequate RF hardware.

Bunches with increased bunching factor were nevertheless obtained (Figure 1),[5] and the transverse emittance blow-up suffered by the beam in the PS was reduced as expected.[5]
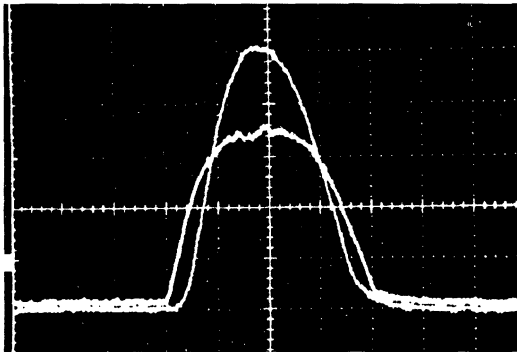

FIGURE 1   Bunch shape in the PSB before and after blow-up ($T = 1.4\,\text{GeV}$).

2.3 Debunching ($h = 16$)/Rebunching ($h = 84$) at 26 GeV in the PS (Item 7 in Table I)

At the end of the PS acceleration cycle the separation between bunches has to be brought to 25 ns, corresponding to harmonic 84 (40 MHz). That is achieved on the 26 GeV flat-top by adiabatic debunching (from $h = 16$) followed by rebunching on $h = 84$.[6]

Computer simulations have been done, with the following assumptions:

(i) The longitudinal emittance of each bunch arriving at 26 GeV on $h = 16$ is 1 eV s/bunch (16 eV s total). That figure is derived from past experience with the PS, linked to the generation of the anti-proton production beam.

(ii) At the nominal beam intensity for LHC ($\sim 9 \times 10^{12}$ ppp), the lowest controllable voltage on an existing PS ferrite cavity working on $h = 16$ is 1 kV, and the minimum RF voltage on the 40 MHz system is 3 kV.

The voltage programmes used in the simulation are shown in Figure 2. The computed emittance for the recaptured beam is
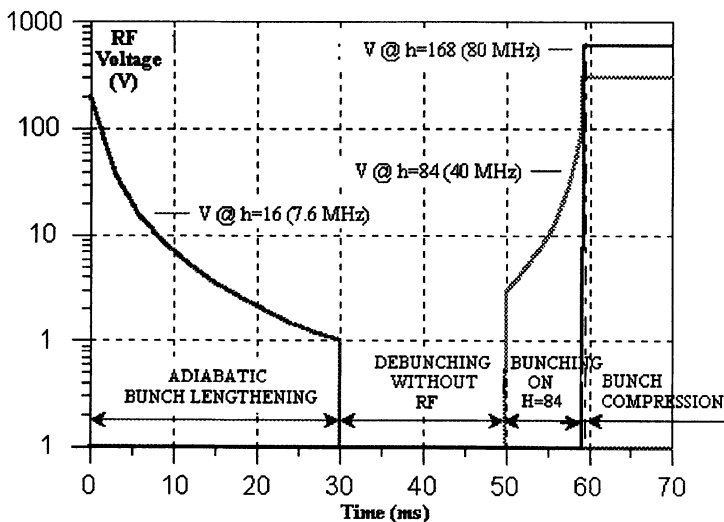

FIGURE 2   Voltage programmes for debunching/rebunching in the PS.

0.35 eV s/bunch ($\sim$ 30 eV s total).[6] Since that fits exactly with the SPS requirement (see Section 2.4), there is actually no margin for blow-up due to imperfections neglected in the simulations.

2.4   Bunch Compression at 26 GeV in the PS (Item 8 in Table I)

Bunch characteristics in the longitudinal phase plane at injection in the SPS are constrained by:

(i) the dimensions of the 200 MHz RF bucket,
(ii) the microwave instability threshold,
(iii) the transient beam loading on the SPS travelling wave cavities,
(iv) the acceptance in $\Delta p/p$ of the PS ejection channel.

These limitations are graphically illustrated in Figure 3, adapted from Ref. 6. Total bunch length is on the x-axis, while bunch emittance is on the y-axis. Consideration of the RF period (i) combined with the RF phase shift in the cavities along the bunch train due to transient beam loading (iii) leads to the limit curve labelled (a). The microwave instability threshold (ii), scaled from practical experience with the SPS as a p–p bar collider, requires the bunch characteristics to be in the region above the parabola (b) aligned along the x-axis. Energy acceptance of the transfer system (iv) requires the beam parameters to be below the solid straight line (c) passing through the origin.
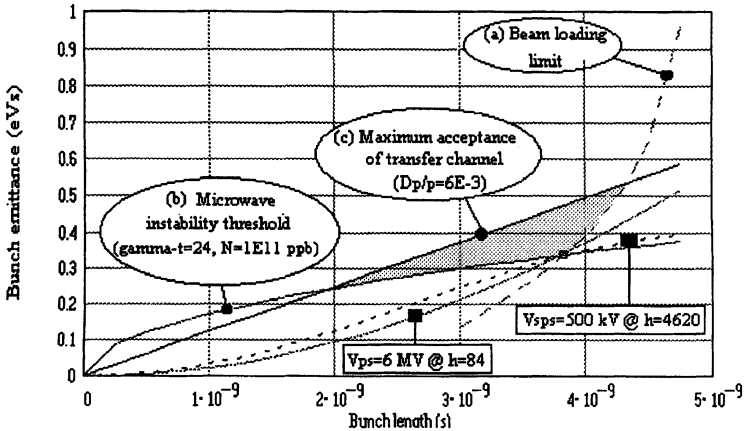

FIGURE 3   Bunch characteristic at injection in the SPS at 26 GeV.

The allowed region satisfying all criteria is shown in grey. The square box in its lower right corner ($\varepsilon_1 = 0.35$ eV s, $l_b = 3.8$ ns) defines the nominal proton beam parameters for LHC at the PS output.[2] It corresponds to the stable beam characteristics that can be achieved with the least amount of RF voltage in the PS. For a stationary particle distribution (case of adiabatic beam manipulation) it is attained with 6 MV at 40 MHz in the PS, and the matching voltage in SPS is as small as 500 kV at 200 MHz.

Such a voltage is uncomfortably high for the PS because of the large beam currents to be accelerated, of the coupling impedance presented by the RF cavities (particularly in conjunction with the wide range of beam revolution frequency) and of the limited number of free straight sections. Non-adiabatic manipulations are then applied in the nominal scheme,[6] using one 40 MHz cavity providing 300 kV and two 80 MHz cavities providing 600 kV.

These longitudinal characteristics are only marginal for stability of the nominal beam in SPS,[10] and there is no solution for the ultimate type of beam. Moreover and although powerful RF systems must be installed in the PS, non-adiabatic gymnastics have to be used, so that beam ejection will take place during hardware transients and subsequently under limited control by regulation loops.

2.5   Fast Ejection to the SPS (Item 9 in Table I)

The gap without beam in the PS before ejection is of 21 ns. The present kicker equipment has a kick rise-time in the vicinity of 80 ns and contains some modulation on its flat-top.[4] Consequently 3 bunches are systematically lost in the machine, and a few more could suffer from an imperfect deflection leading to an increased transverse emittance after filamentation.

3   POSSIBLE IMPROVEMENTS

3.1   Modification to the PS Longitudinal Parameters

Bunch compression at high energy in the PS (item 8 in Table I) would be eased if the bucket could be made higher. At a given energy, the height of a stationary bucket depends upon the RF voltage V_{PS} and

the transition energy γ_{T_PS} according to:

$$\left(\frac{\Delta p}{p}\right)_B \propto \sqrt{\frac{V_{PS}}{|\eta_{PS}|}} \quad \text{with } \eta_{PS} = \frac{1}{\gamma_{T\_PS}^2} - \frac{1}{\gamma^2}. \tag{1}$$

(i) The RF systems presently under construction are designed for the maximum voltage per straight section. The RF voltage required to make the bunch compression adiabatic ($\sim 6\,\mathrm{MV}$ @ $40\,\mathrm{MHz}$ – Section 2.4) is impossible to attain with the limited free space available in the PS accelerator. However, an increase by a factor of up to 2 is manageable, although costly, and will constitute a possible alternative at the conclusion of the tests with beam of the present nominal scenario.

(ii) The PS is already equipped with a "γ_T jump scheme", capable to modulate γ_{T_PS} by ± 1 unit near transition. To make the $26\,\mathrm{GeV}$ bunch compression adiabatic, the γ_{T_PS} must typically be doubled ($+6$ units), which requires a much more involved scheme, and high power hardware. No solution has yet been imagined, but the possibility of a breakthrough cannot be discarded.

3.2 Generation of a Gap in the Train of 84 Bunches

The fast ejection process (item 9 in Table I) can be made clean if the train of bunches has a gap without beam which is longer than the kick rise-time. Little effort has yet been invested in that domain, apart from listing different methods:

(i) Suppression of bunches once the bunch train is formed. A dedicated, fast and small amplitude deflection system selectively eliminates certain bunches by resonant excitation of transverse oscillations. Beam loss can be concentrated at the location of aperture restriction devices.

(ii) Creation of a gap during the debunching process, and gap preservation during recapture. Lossless techniques based on barrier-bucket systems (single sine-wave generators) can be considered, with the predictable spurious effect of a modulation of the characteristics of the edge bunches (number of particles, emittance and longitudinal density).

(iii) Generation of a train of 20 consecutive bunches on $h = 21$ early in the acceleration cycle, and formation of 80 bunches on $h = 84$ by cascading 2 bunch splitting processes. That method has much appeal because it is potentially lossless and the final bunches are as evenly populated as the original bunches. Figure 4 illustrates bunch splitting, which requires a fixed frequency RF system on $h = 42$ ($\sim 10\,\mathrm{kV}$ @ 20 MHz). During bunch splitting experiments using $h = 8$ and 16 in the PS,[5] unmeasurable longitudinal emittance blow-up have been observed as well as complete preservation of pre-existing voids in the bunch train.

Two scenarios are considered to generate the initial 20 bunches:

- the easiest one assumes that a properly chopped Linac beam is directly injected into the PS in $h = 21$ buckets (description of the other aspects of that solution are given in Section 3.5).
- the second one involves a 3-step operation (see Figure 5). (a) Ten bunches are injected into the PS running on $h = 11$ from 3 PSB batches of 4, 4 and 2 bunches. (b) Bunch splitting is applied which gives 20 consecutive bunches on $h = 22$. (c) Changing the harmonic number adiabatically from $h = 22$ to $h = 21$, one empty bucket is eliminated. Unfortunately the kickers equipment used to recombine beam from the four PSB levels has 100 ns rise-time and should be rebuilt to comply with the requirement in step (a) (beam gap $\sim 60\,\mathrm{ns}$).
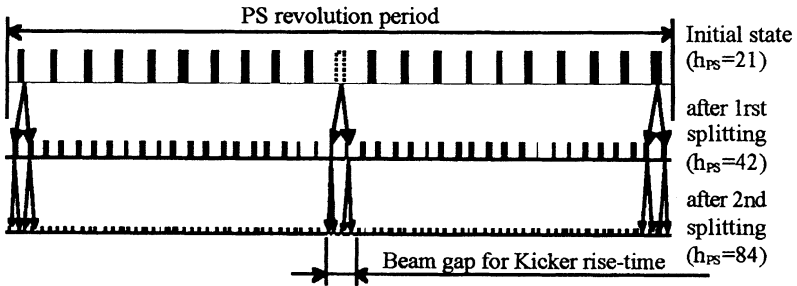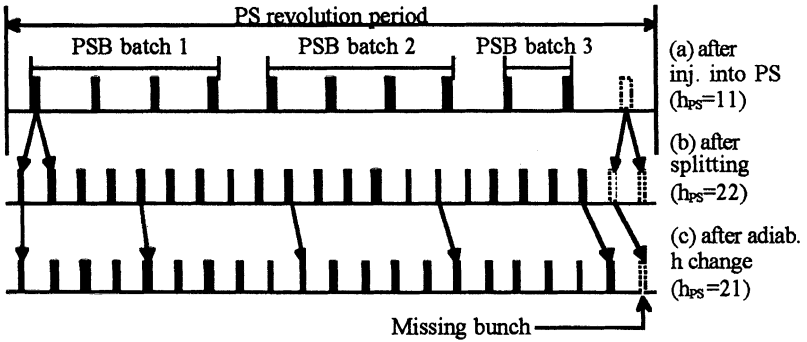

FIGURE 4   Double bunch splitting at 26 GeV.

FIGURE 5   Generation of 20 bunches on $h = 21$.

3.3   Modification to the SPS Longitudinal Parameters

The threshold of the microwave instability at 26 GeV in the SPS is the dominant constraint for the beam characteristics at the transfer from PS to SPS (curve (b) in Figure 3). It scales with the wide-band impedance Z/n and the transition energy γ_{T_SPS} according to:

$$\left(\frac{\varepsilon_L^2}{l_b}\right)_B \propto \left|\frac{Z}{n}\right|\sqrt{\frac{1}{|\eta_{SPS}|}} \quad \text{with } \eta_{SPS} = \frac{1}{\gamma_{T\_SPS}^2} - \frac{1}{\gamma^2}. \qquad (2)$$

(i) Reducing $|Z/n|$ is beneficial not only at injection energy, but is also likely to improve beam stability elsewhere in the SPS cycle. Since the most offending source of impedance has been recently experimentally localised,[10] effort will be made to correct it. The improvement factor will only be known from experiments after implementation of the corrective actions.

(ii) The value of $|\eta_{SPS}|$ at 26 GeV is very small because of the proximity of the transition energy ($\gamma_{T\_SPS} \approx 24$, $\gamma = 28.1 \Rightarrow |\eta_{SPS}| \approx 4.7 \times 10^{-4}$). That results into a very low microwave instability threshold, and in an uncomfortably small matching voltage for beam capture at 200 MHz. Increasing $|\eta_{SPS}|$ would help in both domains. Contrarily to the PS case, large effects can be obtained with moderate changes of the transition energy and the separate function lattice of the SPS gives more opportunity to modulate it.

3.4   Replacing the PS ("PS XXI")[11]

A drastic means to change the situation for the transfer from PS to SPS is to assume the replacement of the PS by a new machine, designed for improving beam performance during the LHC era. The results of such a study keeping the same circumference ("PS-XXI") are presented elsewhere in these proceedings.[11]

It has to be designed for a minimum beam impedance and the key parameters are the transition energy γ_{T_PS} and the maximum energy γ.

(i) Assuming that the SPS is unchanged, one can demonstrate that, for a beam of constant energy spread $\Delta p/p$ and length l_b, the number of protons per bunch at the microwave instability threshold N (μw) and the matching voltage in SPS V_{SPS} (matching), both scale like:

$$N\,(\mu w) \propto V_{SPS}\,(\text{matching}) \propto \gamma\beta^2 \left| \frac{1}{\gamma^2_{T\_SPS}} - \frac{1}{\gamma^2} \right|. \qquad (3)$$

For a factor of 2 improvement the transfer energy has to be brought up to 32 GeV ($\gamma = 34$).

(ii) Formula (3) is also valid for the PS. γ being defined and the RF voltage in the PS being set at the level of the systems presently under construction, γ_{T_PS} can then be selected to permit adiabatic bunch shaping. The favoured value[11] corresponds to an "imaginary" transition energy:

$$\frac{1}{\gamma^2_{T\_PS}} = -0.0033. \qquad (4)$$

Moreover, the proposal is to make γ_{T_PS} variable at high energy, such that the debunching and the beginning of rebunching are fast, while the final value (4) is only attained for the bunch shaping before extraction.

Among the numerous arguments in favour of the replacement of the PS, the performance advantage for LHC could be decisive if the other least expensive methods fall short of the needs of the ultimate beam.

3.5   Replacing the PS Injectors by a 2 GeV Linac ("SPL")[12]

The transverse emittance budget through the PS complex is very tight.[4] Improvement of the ultimate transverse beam brightness requires important changes, because it results from the Laslett tune-shift at low energy in the PSB as well as in the PS. Replacing the PS injectors by a single high energy Linac is the most powerful and flexible solution.

The proposal[12] is to build a Super-conducting Proton Linac ("SPL") using decommissioned RF hardware from LEP-2, with the tentative specifications given in Table II.

Comments

1. An H^- beam minimises the injection losses into the PS and the transverse emittance of the accumulated beam and insures an efficient use of the Linac RF power.
2. Raising the PS injection energy to 2 GeV reduces the transverse emittance of the ultimate LHC beam by a factor 2/3 [Annex 2 of Ref. 11]. Since there is no waiting time on the injection porch, the improvement factor is estimated at 1/2.
3. The 10 mA mean beam current during the pulse is within the capability of proven H^- sources and comfortably achievable with the available RF power.
4. Pulsed operation of the Linac is sufficient to supply the PS. It is important to reduce the electrical power consumption due to the heat generated at 4.5 K and therefore the size of the cryoplants.
5. Transverse emittance of the Linac beam has to be small enough to attain the ultimate transverse beam density after the multi-turn charge-exchange injection process (see comment no. 2).

TABLE II   Tentative specifications for the PS injector

1	Beam type	H^-
2	Kinetic energy	2 GeV
3	Mean beam current during pulse	10 mA
4	Beam pulse length/repetition period	500 μs/1.2 s
5	Transverse emittance (r.m.s. normalised)	0.8 mm mrad
6	ΔT (total beam energy spread)	3 MeV
7	Time structure (chopping) (Figure 6)	At T_{rev} (PS rev. period) and at T_{RF} (PS RF period)

6. The total energy spread is defined for capture in the PS buckets on $h = 21$.
7. Chopping at the PS RF frequency is necessary for a high longitudinal capture efficiency. Chopping at the revolution frequency is interesting for improving the generation of the LHC type of beam. With the time structure illustrated in Figure 6, it is possible to suppress debunching/rebunching in the PS and to generate a train of 80 bunches on $h = 84$ with a minimum of longitudinal blow-up (see Section 3.2).

In the proposal,[12] the beam from the H$^-$ source is bunched and accelerated to 750 keV in a 50 MHz RFQ. The following part of the Linac (up to 50 MeV kinetic energy) re-uses the 200 MHz Alvarez tanks of the existing Linac-2. Between 50 and 600 MeV new accelerating structures must be built. Room temperature resonators at 352 MHz are envisaged up to 300 MeV (Drift Tube Linac, followed by a Coupled Cavity Linac) and supraconducting equipment above. Beyond 600 MeV the existing unmodified LEP supraconducting cavities can be used. The main characteristics of that 1155 m long Linac are listed in Table III.

Although a number of technical design issues are still unsettled, the realisation of the Supraconducting Proton Linac is an attracting solution which deserves a deeper analysis because:

(i) the transverse beam brightness at low energy in the PS is increased, which should permit either to achieve the presently required characteristics for LHC but with a comfortable operational margin, or to obtain a much denser beam at the entrance of the LHC itself,

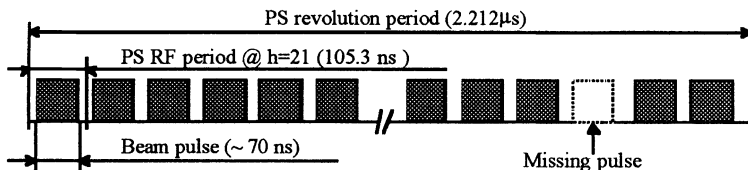(ii) the longitudinal beam manipulation in the PS can be made more adiabatic, while keeping a gap in the bunch train,

FIGURE 6   Time structure of the Linac beam at injection into the PS.

TABLE III Linac description

Desc.	W_{in} (MeV)	W_{out} (MeV)	Freq. (MHz)	Grad. (MeV/m)	No. of cav.	Struct. Length (m)	ZT^2 (MΩ/m)	No. of klystr.	Length (m)
RFQ	0.09	~1	50.31	—	1	~5	—	—	5
Linac-2	~1	50	201.26	1.5	3	34	29	—	40
DTL	50	150	352.2	2	8	50	35	8	55
CCL	150	300	352.2	2	48	75	30	12	85
LEP-2 3π/4	300	600	352.2	1.58	60	190	—	3	220
LEP-2	600	2000	352.2	1.85	220	680	—	14	750
Totals						1034		37	1155

TABLE IV Summary of improvements

Domain (sect. no.)	Action	Benefits (Item in Table I)	Comments
PS longitudinal parameters (3.1)	increase V_{RF} reduce $|\eta_{PS}|$	better bunch compression (8)	expensive and of limited effect to be investigated but no clear solution yet
Gap in the beam (3.2)	"killer" kicker "barrier-bucket" bunch splitting	no badly deflected bunches (9)	beam losses to be investigated needs high energy Linac or rebuilt PSB ejection kickers
SPS longitudinal parameters (3.3)	reduce $|Z/n|$ increase $|\eta_{SPS}|$	improved stability in SPS ⇒ relaxed requirements on the PS (8)	under investigation (source of dominant impedance localised)
New PS ("PS-XXI") (3.4)	increase transfer energy imaginary variable γ_{T_PS}	improved stability in SPS + better bunch compression (8) + improved reliability and simplified operation	major investment needs upgrade of the transfer channel to SPS needs further studies
High energy Linac ("SPL") (3.5)	increased injection energy in the PS (2 GeV) no waiting time at PS injection energy chopped injected beam	minimal long. blow-up (7) + better bunch compression (8) + no badly deflected bunches (9) + reduced transverse emittances + improved reliability and simplified operation	major investment most effective solution to increase LHC beam brightness needs further studies

(iii) the overall reliability of that new Linac is likely to be much better compared to the present cascade Linac-2/PSB, thanks to its modern and highly repetitive hardware,

(iv) the foreseen availability of a huge amount of RF hardware decommissioned from LEP-2 will permit major savings on the construction cost.

3.6   Summary

Salient features of the considered improvements are listed in Table IV.

4   CONCLUSION

The performance required by LHC from its injectors is still an ambitious objective which has not yet been experimentally attained. The on-going project of preparation of the PS for LHC will implement the most economical means to reach the goals of the nominal beam, but with little margin. The longitudinal emittance budget in the PS complex is especially tight, and the foreseen PS ejection process at 26 GeV is not satisfying.

Improvements must aim at an overall optimisation of the complete injectors' chain, including Linac, PSB, PS and SPS. Possible modifications to the existing machines have to be investigated with the highest priority. Drastic changes like building a new PS or a new Linac injector for the PS have also to be considered since they could remove performance bottlenecks and provide for more capabilities and reliable beam characteristics over the long term.

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