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THE PS COMPLEX AS PART OF THE LHC INJECTOR CHAIN

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Abstract

The filling of the LHC proton-proton collider will require part of the CERN PS complex to deliver high intensity beams exceeding by a factor of three the highest transverse particle densities currently attained. This paper describes the various injection schemes and beam dynamics operations studied together with the hardware modifications necessary to achieve this goal. From the variety of schemes which fulfil the desired LHC beam characteristics, the one retained may be achieved in stages. Its choice is governed by the need for the shortest possible LHC filling time, mainly in order to reduce the effects of persistent currents in the superconducting magnets at LHC injection. The first stage involves double-pulsing the Proton Synchrotron Booster (PSB) and requires a Radio Frequency Quadrupole (RFQ2) as a preinjector for the Linear Accelerator (LINAC2), an increase of the PSB output energy and additional RF systems, both in the PSB and Proton Synchrotron (PS) machines.

1 Introduction

The luminosity of the LHC proton-proton collider is crucial for the feasibility of experiments because it determines the average number of events per bunch crossing for the proton-proton interaction. Increasing the luminosity requires the smallest cross-sectional area of the two interacting beams with the highest bunch beam intensities and the largest number of bunches, the latter being achieved with a shortest interbunch spacing. However the luminosity is limited by the beam-beam effect, so that all the beam parameters are not free to vary independently from each other. LHC parameters [1] relevant for the PS complex, yielding the highest possible luminosity at interaction points are reported in Table 1.

Maximum luminosity at $\beta = 0.5$ m	$1.65\,10^{34}$ cm^{-2}s^{-1}
Number of experimental areas	3
Number of bunches	4725
Interbunch spacing	15 ns, 4.5 m
Protons per bunch	10^{11}
Normalized emittances $[\epsilon^*_{x,y} = \beta\gamma\,\sigma^2_{x,y}/\beta_{x,y}]$	3.75 μm[1]
Longitudinal emittance at 450 GeV	1.0 eV.s

Table 1: LHC proton-proton performance

2 Requirements and present performance

The role of the PS in the injector chain for the LHC is to deliver a 26 GeV/c beam to the SPS. In order to reach the required LHC luminosity, the beam must have the characteristics shown in Table 2.

Number of bunches	140
Protons per bunch	10^{11}
Proton intensity in PS	$1.4\,10^{13}$
Bunch spacing	15 ns
Bunch length	< 9 ns
Longitudinal emittance	< 0.6 eV.s
PS normalized emittances	3.0 μm[2] [3]
(PSB normalized emittances)	2.5 μm[2] [3]

Table 2: Characteristics of LHC beam at ejection from the PS

According to the performance measured on the present high intensity beams, which are limited by the space charge induced tune spreads at injection in the PS, the PS complex could only provide $\frac{1}{3}$ of the required intensity in one batch within the proper emittances.

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[1] Round beam. Emittances are given at 1σ throughout.

[2] Mean normalized transverse emittances.

[3] Taking into account the transverse blow-up in the PS and at transfer between PSB and PS.

3 Injection schemes

The existing accelerators of the PS complex constitute adequate injectors for the LHC. Nevertheless, to reach the ultimate goal of $1.65\,10^{34}$ cm^{-2}s^{-1} in LHC, new operating schemes must be considered which imply appropriate upgrades of the injector chain. The schemes discussed here are those which satisfy the luminosity requirement.

The process of filling the LHC can be summarized as follows. A train of 140 bunches (10^{11} protons each) is formed in the PS and transferred at 26 GeV/c to the SPS. Only 135 of the total of 140 bunches can be delivered to the SPS because of the rise time of the PS extraction kicker. Three such PS trains can be placed in the SPS, one behind the other, yielding 405 bunches, or equivalently about $4\,10^{13}$ protons, which is the maximum intensity that the SPS can cope with at present owing to the beam loading limitation. These bunches are then accelerated to 450 GeV/c, transferred and injected into the LHC. Taking into account the rise times of the various injection and extraction kickers in SPS and LHC, eleven SPS pulses of three PS trains and one SPS pulse of two PS trains are necessary to fill in completely one LHC channel.

Several injection scenarios are conceivable at the level of the PS injector chain in order to fulfil the LHC beam characteristics. However they must yield short LHC filling times mainly on account of the persistent currents in the superconducting magnets. A number of operating schemes have been studied to satisfy the LHC specification without jeopardizing the current performance of the PS. They all involve substantial hardware modifications in the PS complex. Among the various alternatives, those yielding reasonable LHC filling times close to the fastest value attainable are reviewed below, along with the fastest filling schemes.

All injection schemes discussed below need an increase of the present 1 GeV PSB output energy to ease the harmful space-charge effects at injection in the PS. All of them also require new RF manipulations for debunching and rebunching the beam on harmonic 140 at 26 GeV/c to provide the 15 ns distance between the bunches. However, the schemes can differ from each other in some of the various beam dynamics operations carried out (e.g. number of batches transferred from the PSB to the PS, number of bunches accelerated either in the PSB and in the PS, etc.).

Scheme label[4]	PSB batches per PS cycle	PSB p/ring [10^{12}]	LINAC output energy [MeV]	PSB injection	RFQ	RF dip	PSB harm	PS harm
S2_1_8	2	1.75	50 (70?)	monoturn[5]	yes[5]	no	1[6]+2[6]	8+140[7]
S3_1_12	3	1.167	50	monoturn	no	no	1[6]	12+140[7]
S4_1_16	4	0.875	50	monoturn	no	no	1[6]	16+140[7]
S2_2_16	2	1.9	50 (70?)	monoturn[5]	yes[5]	yes	5+2	16+140[7]
S1_2_8	1	3.5	100	H$^-$	no	no	1[6]+2[6]	8+140[7]
S1_5_20	1	3.5	100	H$^-$	no	no	5	20+140[7]

Table 3: LHC injector schemes under scrutiny at present

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[4] Injection schemes are labelled Sx_y_z throughout, where the letter S stands for "Scheme", x is the number of PSB batches per PS cycle, y is the PSB harmonic number at ejection, and z is the PS harmonic number at injection.

[5] Charge exchange [H$^-$] will have to be implemented instead if the expected performance is not met.

[6] New variable frequency RF system.

[7] New fixed frequency RF system.

Depending on the examined operating scheme, major additional improvements are required, in particular increasing of the LINAC2 energy, equipping LINAC2 with the Radio-Frequency-Quadrupole (RFQ2) pre-injector [2], implementing a charge exchange [H^-] injection into the PSB, installing variable frequency RF systems in the PSB working on harmonics 1 and 2 and putting a RF dipole [3] in the PSB–PS transfer line.

Table 3 is a summary of all the injection schemes which are discussed below, along with their outstanding features and important hardware modifications. Since both the increase of the PSB output energy and the new PS 66.8 MHz (h=140) RF system are improvements common to all injection scenarios, they will not be mentioned anymore subsequently.

4 Multi-batch injection schemes

4.1 Schemes S2_1_8, S3_1_12, S4_1_16

The first injection schemes devised will allow to fill the PS with multi-batch injections from the PSB (i.e. 2, 3 or 4 PSB batches) according to the degree of completion of LHC. These scenarios require a single turn injection process into the PSB and a new tunable RF system in the PSB for acceleration on harmonic 1.

Scheme S2_1_8 is the *basic* proposed injection scenario for LHC. It is considered separately because it requires two further equipments, namely the existing RFQ2 as LINAC2 pre-injector in order to deliver the desired proton intensity (i.e. $1.75\,10^{12}$ protons per ring) within the required emittances, and a new PSB RF system working at twice the frequency (*second harmonic*) [4] to flatten the longitudinal density distribution and reduce the tune spread in the PSB.

Scheme S2_1_8 delivers a beam with the required performance in all respects except with some increase in filling time. It can be tested before the LHC starts up, and extended to include options if this appears prudent or if the question of filling time is judged to be crucial from the point of view of beam survival at LHC injection.

With the *basic* scheme, one PS train is obtained through the following steps:

SCHEME S2_1_8

1. Do twice at 1.2 s interval
    1.1 delivery by LINAC2 of a 180 mA proton current at 50 MeV during 7 μs using the RFQ2 as preinjector *(i.e.* $\approx 7.5\,10^{12}$ *p),*
    1.2 single turn injection into the 4 PSB rings *(*$1.75\,10^{12}$ *p/ring),*
    1.3 acceleration up to 1.4 GeV using new tunable RF systems on h=1 and h=2 ("2nd harmonic") *(4 bunches of* $1.75\,10^{12}$ *p),*
    1.4 transfer of the 4 PSB rings into 4 PS buckets using the current RF system tuned on h=8 *(*$7\,10^{12}$ *in* $\frac{1}{2}$ *PS circumference).*
2. Acceleration up to 26 GeV/c followed by debunching and rebunching on h=140 with a new RF system[8].
3. Transfer to the SPS of these bunches with a fast extraction kicker[9].

Number of LHC bunches: 4725
LHC filling time per channel: 202 s[10]

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[8] The new PS 66.8 MHz RF system for rebunching on harmonic 140 needs a voltage of several hundred KV. In addition, a dedicated 66.8 MHz RF system will also be installed in the SPS for the bunch compression to 4 ns at 26 GeV/c, to allow the bunch capture into the existing 200 MHz RF system, with an interbunch spacing of 15 ns.

[9] Only 135 of a total of 140 bunches can be delivered to the SPS because of the rise time of the extraction kicker.

[10] Assuming PSB, PS and SPS cycles of 1.2 s, 3.6 s and 16.8 s respectively.

In this scheme, the PS and the SPS accelerate on 3.6 s and 16.8 s magnetic cycles with 1.2 s and 7.2 s flat bottoms respectively at injection. With an LHC filling achieved by eleven SPS pulses each made up of three PS trains and a twelfth SPS pulse made of two PS trains, a total of $(11 \times 3 + 2) \times 135 = 4725$ bunches can be placed around one LHC channel. The corresponding filling time is then equal to $12 \times 16.8 = 201.6$ s. The LHC filling time of one channel is therefore increased by $11 \times 2 \times 1.2 = 26.4$ s as compared to the fastest possible scheme involving a 2.4 s PS cycle time.

If the expected performance is not met after installation of RFQ2, charge exchange [H^-] injection into the PSB will have to be implemented. It will allow for a higher horizontal density within the tune spread limit at 50 MeV in the PSB. However, it will not replace the present injection scheme which is still required for ions.

Scenarios S3_1_12 and S4_1_16 need neither the RFQ2 nor the *second harmonic* PSB RF system because high-intensity bunches are not required. For these two schemes, single turn injection will be used as well, and the intensity will then be reduced by beam shavers.

These injection schemes can be outlined as follows:

SCHEMES S3_1_12 & S4_1_16

1. Do N times at 1.2 s interval (N=3 or N=4)
   1.1 delivery by LINAC2 of a 130 mA proton current at 50 MeV during 7 μs (*i.e.* $\approx 5.4\,10^{12}$ *p)*,
   1.2 single turn injection into the 4 PSB rings ($1.35\,10^{12}$ *p/ring)* followed by beam shaving,
   1.3 acceleration up to 1.4 GeV using a new tunable RF system on h=1 *(4 bunches of* $3.5\,10^{12}/N$ *p)*,
   1.4 transfer of the 4 PSB rings into 4 PS buckets using the current RF system tuned on h=4×N ($1.4\,10^{13}/N$ *in* $\frac{1}{N}$ *PS circumference)* (Cf. Fig. 1).
2. Acceleration up to 26 GeV/c followed by debunching and rebunching on h=140 with a new RF system[8].
3. Transfer to the SPS of these bunches with a fast extraction kicker[9].

Number of LHC bunches: 4725
LHC filling time per channel: 230.4, 259.2 s/ring for N=3, 4[11]

Unfortunately, these scenarios cannot be carried on to achieve one single PSB batch injection into the PS. This restriction occurs because the beam brightness cannot be obtained with a single turn injection, even after installation of RFQ2, and also because the capture on harmonic 4 is not feasible with the present 2.6–9.5 MHz PS RF cavities. Consequently, the above injection schemes have to be strongly modified to deal with only one PSB batch. The corresponding *extended* scheme is described later (scheme S1_2_8).

4.2 Scheme S2_2_16

The next scenario considered, S2_2_16, uses two batch injection to fill the PS. It requires specifically *monoturn* injection coupled with the RFQ2 (or possibly a charge exchange [H^-] injection into the PSB), and an efficient square-wave (possibly trapezoidal) RF dipole to steer each bunch vertically in the PSB–PS transfer line.

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[8] Cf. above.

[9] Cf. above.

[11] Assuming PSB, PS and SPS cycles of 1.2 s, 4.8 s and 19.2 s for N=3, and 1.2 s, 6.0 s and 21.6 s for N=4 respectively.

One PS train is obtained through the following steps:

SCHEME S2_2_16

1. Do twice at 1.2 s interval
   - 1.1 delivery by LINAC2 of a 190 mA proton current at 50 MeV during 7 μs using the RFQ2 as preinjector *(i.e.* $\approx 8\,10^{12}$ *p)*,
   - 1.2 single turn injection into the 4 PSB rings *(*$1.9\,10^{12}$ *p/ring)*,
   - 1.3 acceleration up to 1.4 GeV using the present RF systems on h=5 and h=10 ("2nd harmonic") *(20 bunches of* $3.8\,10^{11}$ *p)*,
   - 1.4 debunching and rebunching on h=2 *(8 bunches of* $8.75\,10^{11}$ *p after 10% losses)*,
   - 1.5 merging of the 4 PSB rings with a new RF dipole and transfer into 8 PS buckets using the present RF system tuned on h=16 *(*$7\,10^{12}$ *in* $\frac{1}{2}$ *PS circumference)*.
2. Acceleration up to 26 GeV/c followed by debunching and rebunching on h=140 with a new RF system[8].
3. Transfer to the SPS of these bunches with a fast extraction kicker[9].

Number of LHC bunches:	4725
LHC filling time per channel:	202 s[10]

Likewise, if the expected performance is not met after installation of RFQ2, charge exchange [H$^-$] injection into the PSB will have to be implemented.

Unlike scheme S2_1_8, scheme S2_2_16 cannot be part of an evolutive scenario starting with four or three batch injections into the PS because the ring merging in the PSB–PS line by a RF dipole can only be done twice to fill the PS ring. Moreover some 10% losses are unavoidable due to the limited time allowed for debunching and rebunching, which implies 10% more beam current from the LINAC. However, no new RF system in the PSB is needed for rebunching the beam on harmonic 2 because this operation can be carried out using the current 3–8 MHz PSB RF cavities.

Both schemes S2_1_8 and S2_2_16 yield identical performance, and, though scheme S2_2_16 requires a smaller quantity of new equipments, scheme S2_1_8 seems more appropriate to handle a progressive evolution towards the highest LHC luminosity.

5 Single batch injection schemes

5.1 Extended scheme (S1_2_8)

If the LHC filling time must be brought down to the absolute minimum, e.g. in order to reduce the harmful effects of the persistent currents in the superconducting magnets at injection into the LHC, the proposed *basic* scheme S2_1_8 can evolve towards the *extended* scheme S1_2_8 at the cost of further upgrades. The fastest filling of LHC would then be achieved with a single batch transfer of eight PSB bunches into the PS (i.e. $3.5\,10^{12}$ protons and two bunches per PSB ring). Such an intensity is not attainable in the PSB (even with a H$^-$ injection) owing to excessive space charge tune spreads.

To achieve this goal, the *extended* scheme needs both charge exchange [H$^-$] injection into the PSB and a higher LINAC2 energy of 100 MeV instead of the present 50 MeV. Moreover, like scheme S2_1_8, it requires two new tunable RF systems in the PSB, one for acceleration on harmonic 1, the other working at twice the frequency (*second harmonic*) to both flatten the longitudinal density distribution around injection energy and rebunch the beam on harmonic 2 at 1.4 GeV.

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[8] Cf. above.

[9] Cf. above.

[10] Cf. above.

Scheme S1_2_8

1. Delivery by LINAC2 of a 50 mA H^- current at 100 MeV during $\approx 50\ \mu$s using a new H^- source *(i.e.* $\approx 1.5\,10^{13}$ H^-*)*.
2. Charge exchange [H^-] injection into the 4 PSB rings *(*$3.5\,10^{12}$ *p/ring)*.
3. Acceleration up to 1.4 GeV using new tunable RF systems on h=1 and h=2 ("2nd harmonic") *(4 bunches of* $3.5\,10^{12}$ *p)*.
4. Debunching and rebunching on h=2 *(8 bunches of* $1.75\,10^{12}$ *p)*.
5. Transfer of the 4 PSB rings into 8 PS buckets using the present RF system tuned on h=8 *(*$1.4\,10^{13}$ *p in the full PS circumference)*.
6. Acceleration up to 26 GeV/c followed by debunching and rebunching on h=140 with a new RF system[8].
7. Transfer to the SPS of these bunches with a fast extraction kicker[9].

Number of LHC bunches: 4725
LHC filling time per channel: 173 s[12]

In this scheme the PS and the SPS accelerate on 2.4 s and 14.4 s magnetic cycles respectively, with a SPS 4.8 s flat bottom at injection. Thus, the LHC filling time is equal to $12 \times 14.4 = 172.8$ s.

Scheme S1_2_8 offers the same gains as the *original* (Boussard-Gareyte) injection scheme (see below). The main difference between these two schemes is that the former requires new PSB RF systems working on harmonics 1 and 2 to provide the bunch pattern, whereas the latter makes use of the existing PSB RF system. Nevertheless, since the most plausible scheme to begin with is scheme S2_1_8 (possibly S3_1_12 or S4_1_16), it follows that scheme S1_2_8 can be more easily implemented than the *original* scenario once scheme S2_1_8 is in operation. Thus, starting with a less ambitious injection scenario, improved scenario S1_2_8 could be the final step of a policy for upgrading the LHC performance.

5.2 Original scheme (S1_5_20)

The *original* straightforward injection process S1_5_20 is finally considered. Historically it was the first proposed injection scheme. Together with scheme S1_2_8, they provide the lowest LHC filling time achievable. However, to deal with the high performance figures of the LHC beam, scheme S1_5_20 also requires an increase of the LINAC2 output energy and charge exchange [H^-] injection into the PSB.

Scheme S1_5_20

1. Delivery by LINAC2 of a 50 mA H^- current at 100 MeV during $\approx 50\ \mu$s using a new H^- source *(i.e.* $\approx 1.5\,10^{13}$ H^-*)*.
2. Charge exchange [H^-] injection into the 4 PSB rings *(*$3.5\,10^{12}$ *p/ring)*.
3. Acceleration up to 1.4 GeV using the present RF systems on h=5 and h=10 ("2nd harmonic") *(20 bunches of* $7\,10^{11}$ *p)*.
4. Transfer of the 4 PSB rings into 20 PS buckets using the present RF system on h=20 *(*$1.4\,10^{13}$ *p in the full PS circumference)*.
5. Acceleration up to 26 GeV/c followed by debunching and rebunching on h=140 with a new RF system[8].
6. Transfer to the SPS of these bunches with a fast extraction kicker[9].

Number of LHC bunches: 4725
LHC filling time per channel: 173 s[12]

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[8] Cf. above.

[9] Cf. above.

[12] Assuming PSB, PS and SPS cycles of 1.2 s, 2.4 s and 14.4 s respectively.

It is worth recalling that scheme S1_5_20 is not part of a fully evolutive scenario foreseen to reach the absolute minimum LHC filling time. Consequently, even if it involves less new equipment than the previous scenario studied, it seems less attractive than scheme S1_2_8.

6 Comments on hardware implications

6.1 Change of the pre-injector of LINAC2

The obvious choice is an RFQ, replacing the 750 KeV Cockcroft-Walton generator. RFQ2 has proven to deliver more than 200 mA of a beam which is basically better matched to an Alvarez LINAC. Thus it may be expected that after its installation, the intensity (> 150 mA) and brightness of the LINAC2 beam will be substantially boosted beyond present performance. This is particularly attractive in connection with *monoturn* injection into the PSB, enabling high-brightness beams to be studied in PSB and PS, and later on to be used for the LHC.

6.2 Increase of LINAC2 energy

The nominal beam of scheme S1_5_20 (with normalized emittances 2.5 μm) leads to a space-charge de-tuning in the PSB, at 50 MeV, in *both* planes, of $\Delta Q_{x,y} \approx 0.6$, which is not manageable. This figure reduces to $\Delta Q_{x,y} \approx 0.5$ at 70 MeV, and $\Delta Q_{x,y} \approx 0.4$ at 100 MeV LINAC energy. For all other schemes, $\Delta Q_{x,y} \leq 0.3$ at 50 MeV. As scheme S1_5_20 is straightforward and enables the LHC to be filled very fast, an increase of LINAC2 energy is under study.

A high-gradient option (additional length only 20 m) would bring the p (or charge exchange [H$^-$]) beam from 50 to 100 MeV, with a new 800 MHz system (no spares common with existing 200 MHz system) and 20 MW of installed peak RF power.

For schemes S2_1_8 and S2_2_16, an increase to only 70 MeV (one tank at 200 MHz, well-known equipment, little civil engineering etc.) may be attractive. Obviously, both upgrades should be able to cope with both protons and H$^-$ beams.

6.3 Charge exchange [H$^-$] injection

All operational hadron beams are produced by betatron stacking into the PSB. It has the advantage of banalizing the pulse sharing between protons and ions, but "wastes" horizontal phase space, the brightness falling short of a factor 2–3 compared to what is needed to fill the LHC with protons in the shortest possible time. Charge exchange [H$^-$] injection is needed to satisfy the LHC requirements in schemes S1_5_20, S1_2_8, and possibly S2_2_16, S2_1_8. Charge exchange [H$^-$] injection is also attractive in terms of beam losses: whereas betatron stacking involves inherent losses of 30% – 60%, charge-exchange injection works at virtually 100%, very advantageous considering high intensity proton users (e.g. ISOLDE) and PSB machine irradiation.

However, ions (O,S,Pb) can only be injected by betatron stacking, thus it appears likely that the PSB would have to provide both injection schemes in parallel.

In all cases, a H$^-$ source of about 50 mA, 200 μs pulse length, would be needed (within reach of present technology). Because of the increased pulse length, the modulator of LINAC2 has to be modified, as well as the vertical distributor in the LINAC2–PSB line. The other changes in this line and at PSB injection depend on the (unknown) combination of PSB users at LHC start-up: an educated guess is given below.

i. The PSB is used for both ions and protons, but *not* in cycle sharing. Most elements of the 50 MeV lines would have to be rendered bi-polar, and the PSB injection region (4 levels) would have to be partially reconstructed (programmable bumpers and vertical steerers for "painting", stripping foil mechanisms). Note that this particular item is a major accelerator design job which is being worked out.

ii. The PSB is used for both ions and protons, in cycle sharing. Most elements mentioned in the previous point have to change their polarity from cycle to cycle; injection devices like bumpers, stripper foil, etc are activated in cycle sharing. In this case, it may be simpler to build an extra injection line for H^-, although preliminary studies suggest that using the existing line for both species could be feasible.

6.4 Single turn injection into the PSB

Potentially this injection scheme is capable of yielding a circulating beam without loss of brightness (for comparison: betatron stacking spoils the brightness, whereas charge exchange [H^-] may increase it if not limited by space-charge effects in the synchrotron).

After re-installation of the fast injection kickers, single-turn injection was tested successfully and is available to provide test beams in view of studying the behaviour of LHC-like beams in both PSB and PS. These tests should be given priority as the final choice of the LHC injection scheme will critically depend on their outcome. The scheme becomes particularly attractive with the high brightness beams from LINAC2 with RFQ2 as pre-injector. Installing RFQ2 should be done as soon as possible.

It should be stressed that *monoturn* injection into the PSB may probably cover the needs of LHC in schemes S3_1_12, S4_1_16 and possibly S2_1_8, S2_2_16. It is almost straightforward to operate betatron stacking and *monoturn* injection on alternate cycles (at the expense of new fast injection kickers). However, the overwhelming advantage of charge exchange [H^-] injection also for beams other than LHC (small loss, more flexibility, variation of intensity "a la carte", tailoring phase space distribution to user's requests by "painting") strongly favours charge exchange [H^-] injection as the final PSB scheme.

6.5 Increasing the PSB output energy to 1.4 GeV

In order to increase the magnetic rigidity by the 26% required, some of the machine components will have to be remade. The most important are the kickers and the septa of the four rings, some dipoles and quadrupoles in the PSB–PS line, the transverse feedback amplifiers and the PS injection septum [5]. Fortunately, the main PSB magnet has a substantial margin concerning the power dissipation, magnetic saturation and voltage breakdown. The main magnet power supply, however, needs some upgrading.

It is probably preferable to pulse the new magnets, as opposed to the present d.c. mode of operation. But as the most important power increase is caused by the main magnet and supply, the water cooling plant will have to be almost completely rebuilt.

6.6 New RF systems

i. A new PSB RF system covering a frequency range from 0.6 MHz to 1.75 MHz is needed for acceleration on harmonic 1 with a peak voltage of 6 kV. This system works in conjunction with a new *second harmonic* system (1.2 MHz to 3.5 MHz) providing a peak voltage of 3 kV, to flatten the longitudinal density distribution, and to re-bunch at h=2 (for scheme S1_2_8). Both installations must be able to cope with a beam loading comparable to the one encountered by the present PSB RF systems.

ii. A new RF system at 66.8 MHz has to be installed in the PS for rebunching the beam on harmonic 140 at 26 GeV/c. It must be able to cope with a heavy beam loading at low voltage during adiabatic capture. Its impedance has to be strongly reduced during the acceleration of high intensity beams (the final specifications will be established later). The peak voltage required to ensure SPS beam stability at 26 GeV/c is 600 kV [6], and three straight sections are necessary in the PS ring.

7 Beam dynamics

7.1 Space charge tune shifts in the PS at injection

In the following, the space charge limitations of the present PS machine and the means to overcome these are discussed. The characteristics of the PS beam after injection from the PSB are examined in the light of the proposed scheme S2_1_8. Two of the high intensity configurations of today [7] are compared with those for LHC in Table 4.

i. Beam for SPS fixed target (20 bunches from 4 PSB rings inserted into 20 PS buckets).

ii. AA production beam (20 bunches from 4 PSB rings recombined by a RF dipole into 10 PS buckets, followed by a merging into 5 buckets using quasi-adiabatic RF manipulations at 3.5 GeV/c).

PS beam use	LHC scheme S2_1_8	SPS Fixed target physics	AAC Antiproton production
Total number of particles	$1.4\,10^{13}$	$2.3\,10^{13}$	$1.5\,10^{13}$
Number of bunches	8	20	10
PS harmonic number	8	20	20
Total bunch length [ns]	197	55	90[13]
Emittances $\epsilon_x^*, \epsilon_y^*$ [μm]	3.5, 1.8	12.5, 6.3	10.0, 5.0
Kinetic energy [GeV]	1.4	1	1
Energy spread [MeV]	3.1	1.3	1.8
$\beta\gamma^2$	5.7	3.7	3.7
Tune shifts $\Delta Q_x, \Delta Q_y$	-0.13, -0.19	-0.15, -0.22	-0.15, -0.22

Table 4: Characteristics of various beams at PS injection

At a given energy, for negligible momentum spread and for a constant aspect ratio of the emittances, the space charge detuning is proportional to the number of particles per bunch N_b, and inversely proportional to the bunch length l_b, to the normalized emittances $\epsilon_{x,y}^*$ and to the relativistic parameter $\beta\gamma^2$. Assuming similar tune values in both planes, the vertical detuning writes

$$\Delta Q_y \propto \frac{N_b}{l_b \beta\gamma^2 \epsilon_y^*}\left(1+\sqrt{\frac{\epsilon_x^*}{\epsilon_y^*}}\right)^{-1}$$

The first column of Table 4 shows that the normalized emittances required by the LHC are much smaller. All other parameters being equal the tune shift would be three times larger than at present. When the bunch pattern is taken into account this becomes only a factor of 1.5. However, the only remaining parameter to compensate for this and bring the tune shift down to the present

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[13] After filamentation of longitudinal phase space (longitudinal emittance of about 0.45 eV.s per bunch).

values, is the $\beta\gamma^2$. Consequently, by increasing the PSB output energy from 1 to 1.4 GeV the condition can be satisfied. This new PSB output energy holds for all injection schemes considered. A similar analysis can also be performed at injection into the PSB. Hence, the resulting upgraded LINAC2 energy is found to be equal to 100 MeV for schemes S1_2_8 and S1_5_20, and possibly 70 MeV for schemes S2_1_8 and S2_2_16, if the expected performance is not met using the RFQ2 coupled with single turn injection.

In order to extrapolate with confidence from present performance, a 2:1 aspect ratio for the emittances has been considered. Taking into account transverse blow-up between PSB and PS, and in the PS itself, $\epsilon_x^* = 3.5\,\mu$m and $\epsilon_y^* = 1.8\,\mu$m have been assumed for the $1.4\,10^{13}$ proton beam from the PSB. The final value for this ratio will be chosen in the light of experience with the complete injection system.

Then, for all the injection schemes discussed above, the maximum incoherent space-charge tune shifts have been evaluated using the ACCSIM code [8, 9]. Elliptic particle density distributions in transverse and longitudinal phase planes have been assumed, yielding parabolic beam profiles and bunch shape (typical for proton beams). The results are summarized in Table 5.

Scheme label	PSB batches per PS cycle	PS p/bunch at 1.4 GeV	PS harm	PS bunch length	Energy spread [MeV]	Tune shifts	
						ΔQ_x	ΔQ_y
S2_1_8	2	$1.75\,10^{12}$	8	197 ns	3.15	-0.13	-0.19
S3_1_12	3	$1.17\,10^{12}$	12	131 ns	2.92	-0.13	-0.19
S4_1_16, S2_2_16	4, 2	$8.75\,10^{11}$	16	99 ns	3.89	-0.14	-0.20
S1_2_8	1	$1.75\,10^{12}$	8	197 ns	3.81	-0.13	-0.19
S1_5_20	1	$0.70\,10^{12}$	20	79 ns	4.85	-0.13	-0.19

Table 5: Calculated tune shifts in the PS for the LHC injections schemes

All calculated tune shifts are approximately identical, which means that the scaling analysis performed above is accurate enough.

7.2 Other collective phenomena in the PS

To reveal potential longitudinal and transverse instabilities, thresholds and growth rates for various collective effects have been calculated using the BBI program [10]. The beam characteristics shown in Table 6 have been chosen as a worst case.

Results of the analysis show that globally no instability is expected, at least due to short range wakefield (wideband impedance). In particular, the potential well bunch lengthening is negligible in the order of 4%.

At higher energy the incoherent tune shift decrease and transverse coupled bunch instabilities generated by the resistive wall impedance can be expected. However, the rise time should be slow enough to be counteracted by the transverse feedback system. Longitudinal coupled bunch instabilities due to narrow band resonators (e.g. the RF cavities) will be cured with a multi-mode longitudinal feedback. The total longitudinal emittance at injection into the PS is $8 \times 0.8 = 6.4$ eV.s while at extraction is $140 \times 0.5 = 70$ eV.s. This leaves some margin to apply controlled blow-up to avoid microwave instabilities at transition and during debunching-rebunching at 26 GeV/c.

Kinetic energy	1.4 GeV
Number of protons per bunch	$1.75\,10^{12}$
PS harmonic number	8
Total bunch length	197 ns
Half momentum spread	$1.6\,10^{-3}$
Longitudinal emittance	1.0 eV.s
Transverse emittances $\epsilon_x^*, \epsilon_y^*$	3.5, 1.8 μm
Longitudinal impedance	18 Ω
PSB RF voltage	3 kV
PS RF voltage	11 kV

Table 6: Characteristics of LHC beam at injection into the PS

8 Conclusion

Several scenarios have been analyzed which all satisfy the LHC requirements. Among these, the single batch injection schemes S1_2_8 and S1_5_20 yield the absolute minimum filling time of LHC but require rather expensive modifications (increase of the LINAC2 energy and H^- injection into the PSB), whilst the other schemes can be implemented at a lower expenditure. Guidelines are proposed to prepare the decision concerning the choice of an injection process for LHC.

i. The *original* scheme S1_5_20 is not favoured due to the high costs involved in its implementation, and also because it cannot be implemented gradually, starting with a minimum cost scheme and then evolving later towards the fastest LHC filling scheme.

ii. The *extended* scheme S1_2_8 can be left aside for a first stage implementation on account of the costly hardware modifications required. However, it could be considered later as an improved scenario, leading to the fastest filling time of the LHC.

iii. Scheme S2_2_16 is interesting because it does not require new RF systems working on harmonics 1 and 2 in the PSB, but it needs a new RF dipole in the PSB–PS transfer line. However this RF dipole might be of trapezoidal-wave, and consequently it could be possibly built at a lower cost. The major drawback of scheme S2_2_16 is that it is not part of a fully evolutionary scenario.

iv. The *basic* scheme S2_1_8 seems the most promising scenario at this stage of study. It is a low cost scheme to start with on account on the reasonable hardware modifications involved (even if new RF cavities in the PSB must be built), and constitutes an adequate starting point of an evolutive scheme which can be extended to yield ultimate LHC performance.

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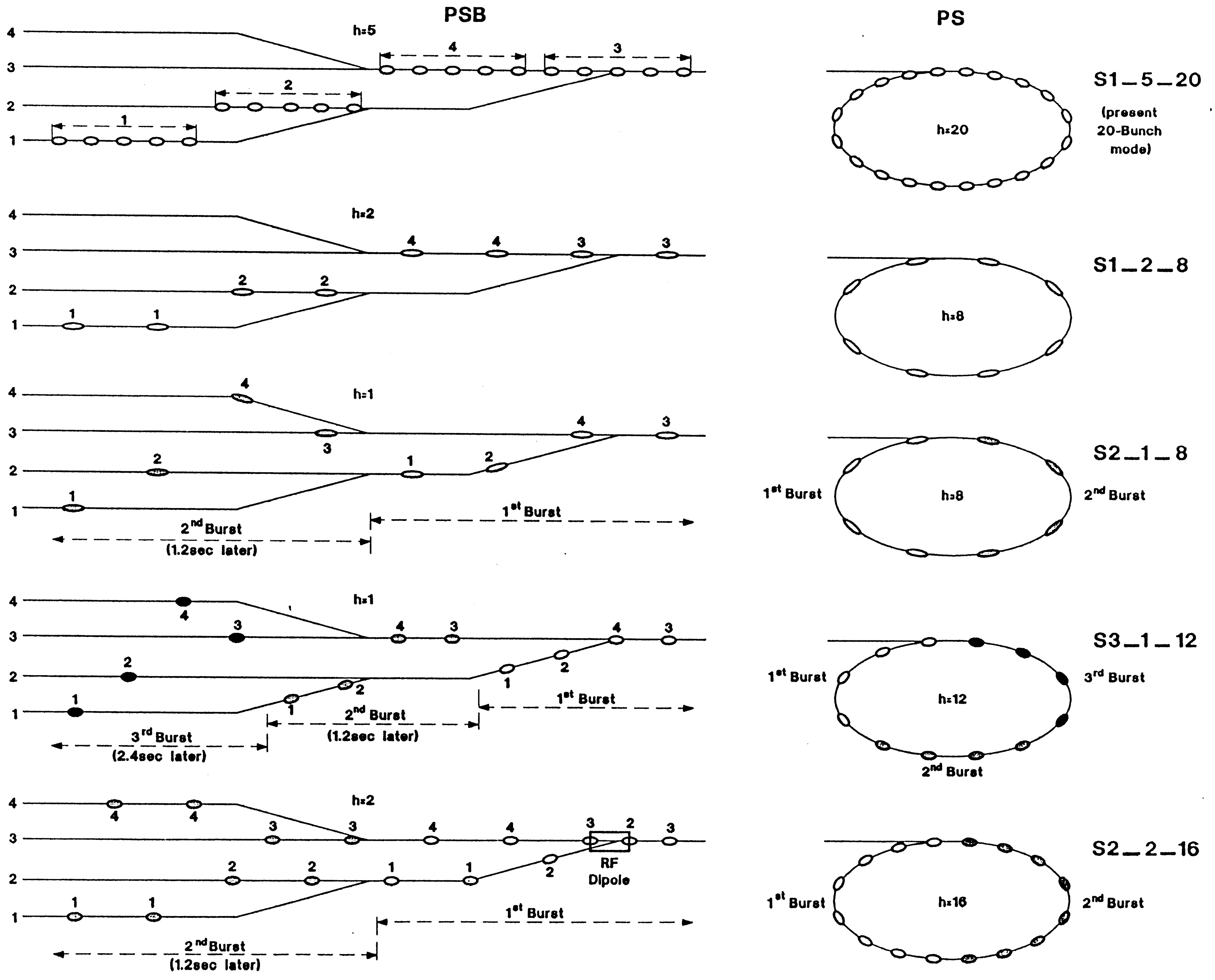

Fig. 1