EUROPEAN LABORATORY FOR PARTICLE PHYSICS

CERN/PS 93-08 (DI) Revised
24 May 1993

Beams in the PS Complex During the LHC Era

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Abstract

Considerable hardware modifications and additions are necessary in the PS Complex to produce proton beams of the brightness required for filling the LHC. These include:

- an increase of the PSB-PS transfer energy from 1 GeV to 1.4 GeV (kinetic),
- new RF systems in the PSB for proton acceleration on h=1 (0.6–1.75 MHz) with superposition of h=2 (1.2–3.9 MHz),
- new RF systems in the PS for rebunching protons on h=84 (40 MHz).

This report envisages the modification of the way in which all beams are handled in the PS Complex with, in many cases, improvements which come from exploiting the new hardware required for the LHC and from the proposed suppression of the h=5 RF system in the PSB and of the 114 MHz RF system used for lepton acceleration in the PS.

All beams which are presently operational are considered. A scheme for producing each of them is described, together with the beam and machine parameters at the critical moments of every sub-process. All present capabilities are retained and performance (beam quality) is generally expected to improve.

1 Introduction

Considerable hardware modifications and additions are necessary in the PS Complex to produce proton beams of the brightness required for filling the LHC [1]. These include:

- an increase of the PSB-PS transfer energy from 1 GeV to 1.4 GeV (kinetic),
- new RF systems in the PSB for proton acceleration on h=1 (0.6–1.75 MHz) with superposition of h=2 (1.2–3.9 MHz),
- new RF systems in the PS for rebunching protons on h=84 (40 MHz).

This report envisages the modification of the way in which all beams are handled in the PS Complex with, in many cases, improvements which come from exploiting the new hardware required for the LHC and from the proposed suppression of the h=5 RF system in the PSB and of the 114 MHz RF system used for lepton acceleration in the PS. The following advantages are expected:

- a reduction of the cost of the LHC. This would be achieved by recuperating the PSB h=5 RF system and modifying it to operate on h=2, and by relaxing the rise-time specifications of the kickers used for the PSB-PS beam transfer,
- a reduction of the amount of equipment to be operated and maintained,
- no more longitudinal coupled-bunch instabilities in the PSB,
- a reduction of the impedance seen by the beam due to the RF systems in both machines,
- the possibility of a controlled longitudinal blow-up in the PSB during the acceleration of high-intensity beams using the existing h=10 (6–17 MHz) RF system in a technique like the one employed routinely in the PS [2].

All beams which are presently operational are considered. A scheme for producing each of them is described, together with the beam and machine parameters at the critical moments of every sub-process. All present capabilities are retained and performance (beam quality) is generally expected to improve.

2 Longitudinal Aspects

2.1 Hardware Requirements

The transfer energy from PSB to PS is taken to rise to 1.4 GeV (kinetic) and ISOLDE transfers to remain at 1 GeV.

The RF systems listed in tables 1 and 2 are assumed to become available in the PSB and PS. The h=5 (3–8.5 MHz) system in the PSB disappears, as does the 114 MHz system in the PS.

NAME	FREQUENCY	VOLTAGE	COMMENTS
B1	0.6–1.75 MHz	8 kVp	New system
B2	1.2–3.9 MHz	8 kVp	Modified h=5 system
B3	6–16 MHz	6 kVp	Existing h=10 system

Table 1: PSB RF systems.

NAME	FREQUENCY	VOLTAGE	COMMENTS
P1	2.7–9.6 MHz	200 kVp	Existing h=20 system
P2a,b	40,80 MHz	300,600 kVp	P2b replaces 114 MHz system
P3	$\approx$ 200 MHz	240 kVp	Existing system

Table 2: PS RF systems.

2.2 Beams to be Supplied

Table 3 lists some of the characteristics of the beams which should, in principle, be delivered by the PS complex in the LHC era. A detailed description of the longitudinal processes involved in producing each of the beams listed is given in the appendix.

BEAM	PARTICLE	PSB (at extraction)			PS (at extraction)		
		Charges/ring	h	Batches	Charges	h	Bunches
ISO	p	8×10^{12}	1	1			
LHC	p	1.8×10^{12}	1	2	1.4×10^{13}	84+168	84
LHC "Scheme 0"	Pb^{53+}[a]	10^9	4	1	4×10^9	16	16
SFT	p	8×10^{12}	2	1	3×10^{13}	420	420
SFT	Pb^{53+}[a]	10^9	4	1	4×10^9	16	16
PHY	p	3×10^{11}	1	1	3×10^{11}		Debunched
AA	p	5×10^{12}	1	1	2×10^{13}	20	4
TST (h=8)	p	10^{11}	1	1	10^{11}	8	1
TST (h=10)	p	10^9	1	1	10^9	10	1
SPP	p	2×10^{11}	1	1	2×10^{11}	8	1
SPP/SPN	e^+/e^-				10^{11} (2×10^{11})	168	4 (8)
LEA	$\bar{p}$				10^{10}	10	1

Table 3: Beams foreseen in the LHC era.

[a] Other ions will be considered when the experimental physicists declare their needs.

The cryptic beam names derive from the so-called "User" group of the Programme Lines Sequencer matrices; ISO denotes the PSB beam supplying the ISOLDE isotope production facility, PHY is the beam produced by slow extraction from the PS for physics in the East Hall, LHC is the beam – either of protons or of ions – that will be supplied to the SPS for filling the LHC, AA is the beam for antiproton production at the AAC, SFT denotes SPS fixed-target physics – either with protons supplied by "Continuous Transfer" (five-turn extraction from the PS) or with ions, TST is a test beam – either for the AAC (h=8) or for checking deceleration in the PS (h=10), SPP/SPN are positive/negative lepton beams destined for LEP via the SPS – although SPP in the style of the $p\bar{p}$-collider is still retained for the fast extraction of a single, short proton bunch for calibration purposes, and LEA is the antiproton beam that is decelerated in the PS and transferred to LEAR.

3 Transverse Aspects

3.1 Space Charge in the PSB

3.1.1 Current Situation with h=5

At present, the PSB magnetic cycle is programmed to provide constant bucket area (including the reduction due to longitudinal space-charge defocussing) for the highest operational beam intensity of 7.5×10^{12} protons per ring. With the PSB RF voltage on h=5 rising to 13 kV at the end of a 500 μs adiabatic capture, this bucket area is about 0.12 eV.s (0.6 eV.s per ring) and is well-matched to the 170 keV 2σ-energy spread (half width) of Linac2. In fact, the bucket remains full during the first $\sim$ 200 ms after capture, so that the length of the bunch is approximately that of the bucket.

For a given RF voltage, the more slowly the magnetic field, $B(t)$, increases with time, t, the greater the longitudinal acceptance. However, the lower dB/dt at injection, the longer the beam has to suffer the large tune spread, ΔQ, due to space charge effects. This, in turn, exacerbates the losses on the second- and third-order stopbands (which are never fully compensated) and explains why numerous tests in the PSB have confirmed the following strategy [3] for minimum beam loss:

- make use of the maximum available RF voltage during the first part of the cycle,
- accelerate as rapidly as possible, that is, program $B(t)$ to provide constant bucket area.

It is worth mentioning that any attempts to use lower RF voltages during the critical first part of the cycle have invariably led to increased losses for high-intensity beams.

Fig. 1 shows how the relevant parameters evolve with time during the critical, RF voltage-limited part of the PSB acceleration cycle. The effect of the second-harmonic (h=10) cavities, which serve to increase the bunching factor and the longitudinal acceptance, are not included in this analysis because it turned out that neither the h=5 RF voltage programme nor $B(t)$ had to be re-optimized after their introduction. The dashed lines of fig. 1 are for h=5; the h=1 cases are discussed in section 3.1.2. The parameters presented (as functions of time with respect to the timing BX.RBI, which precedes injection by 10 ms) are:

- the magnetic field, $B(t)$,
- the longitudinal acceptance per ring *including* the reduction due to space-charge defocussing,
- the *relative* Laslett detuning (neglecting image field contributions),

$$\frac{\Delta Q(t)}{\Delta Q_{\text{inj}}} = \frac{(\beta\gamma^2 B_f)_{\text{inj}}}{(\beta\gamma^2 B_f)_t} \sim \frac{(\beta\gamma^2 l_b)_{\text{inj}}}{(\beta\gamma^2 l_b)_t} \tag{1}$$

  where ΔQ_{inj} is the detuning at injection for h=5 (that is, tune shifts are expressed relative to the current situation), the bunching factor, B_f, is the mean-to-peak line charge density ratio (with the mean taken over one RF period), the bunch length, l_b, is expressed in metres, and where β and γ are the usual relativistic parameters.

The most destructive stopband in the PSB is the structural one, $3Q_z = 16$. The beam is considered to be "safe" as soon as it can be accommodated between $Q_z = 5.33$ and $Q_z = 5$, that is, when $\Delta Q(t) \leq 0.33$. For 7.5×10^{12} protons per ring, $\Delta Q_{\text{inj}} \sim 0.6$ and so what is important is the time required for $\Delta Q(t)/\Delta Q_{\text{inj}}$ to fall to a half. From fig. 1, this is currently about 150 ms.

3.1.2 Strategy Proposed for h=1

Although the h=1 cavities will operate at lower RF voltage (6 to 8 kV compared with the 13 kV at present), the available longitudinal acceptance will be significantly larger. In addition, the reduction of the same due to longitudinal space-charge forces will be smaller ($\sim$ 10% compared with $\sim$ 30% for 7.5×10^{12} protons per ring). A longitudinal acceptance greater than 1 eV.s per ring on h=1 is proposed for the following reasons:

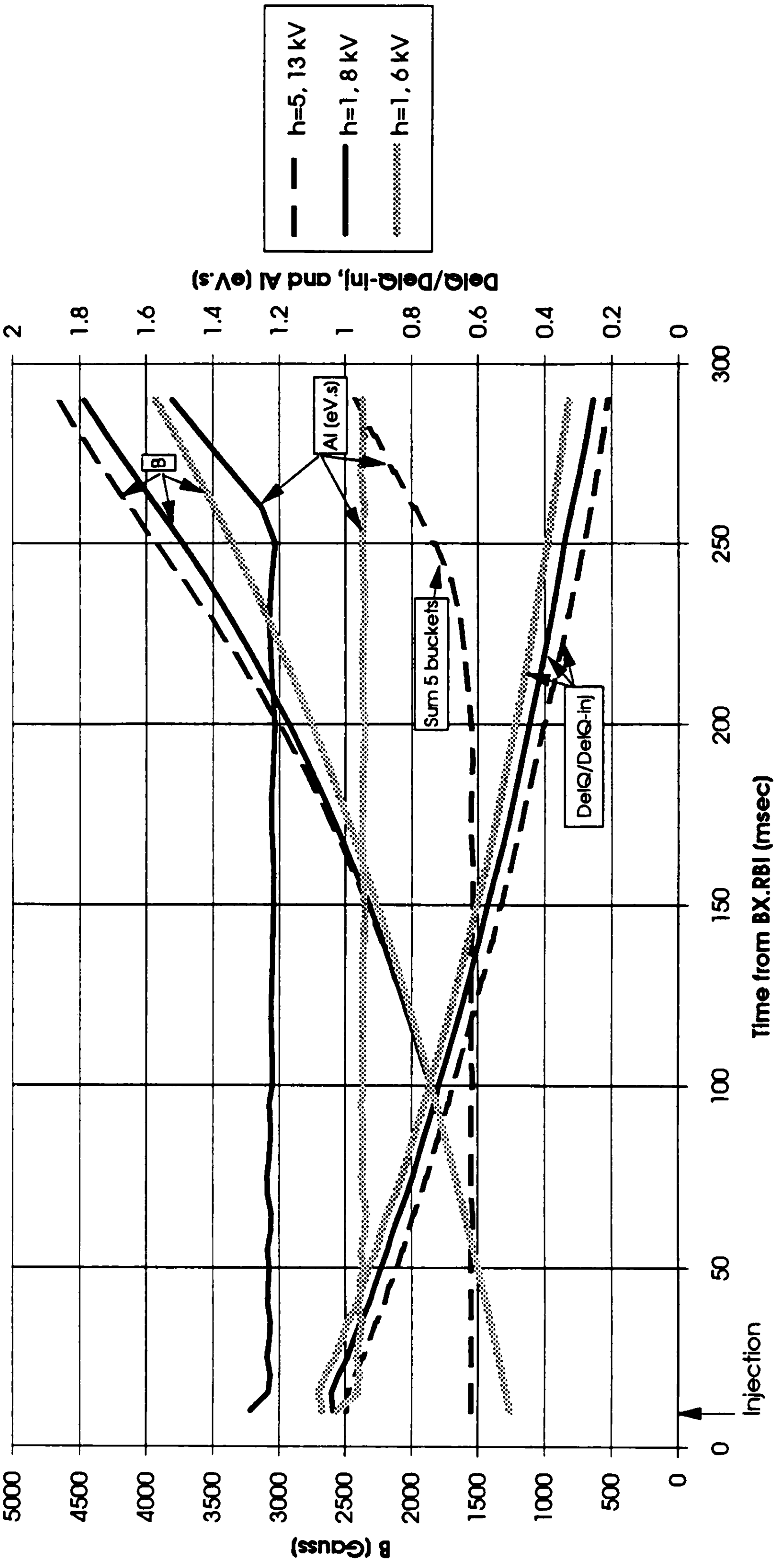

Figure 1: Relative tune spread, longitudinal acceptance and optimized magnetic field for h=5 and h=1 for 7.5 x 10^{12} protons per ring in the PSB.

- a large bunch area enables long bunches (i.e., with a large bunching factor) to be obtained without excessively reducing dB/dt. This is the only way to stay near the present tune shift at injection and still reduce $\Delta Q(t)$ fairly quickly,
- a larger bucket area leads to a higher trapping efficiency of the Linac2 beam (the RF voltage currently available on h=5 represents a severe performance limitation),
- the increased longitudinal emittance at PSB extraction approaches the figure required by the PS for matching and beam stability (although additional controlled longitudinal blow-up may still be necessary).

Following the method employed for h=5, the magnetic cycle, $B(t)$, has been tailored to provide constant longitudinal acceptance (from the end of the adiabatic capture and including the reduction due to space charge for 7.5×10^{12} protons per ring) for two different RF voltages, 6 and 8 kV. The results are presented in fig. 1, together with those for h=5, and the key parameters for both are summarized in table 4.

h	RF Voltage [kV]	Long. Emittance (per ring) [eV.s]	Relative Tune Shift at Injection	Time to Reach Relative Tune Shift of 0.5 [ms]
5	13	0.62	1	150
1	6	0.95	1.08	185
1	8	1.22	1.04	165

Table 4: Parameters during the critical first part of the PSB cycle.

There are clear advantages in operating the PSB on h=1 with an RF voltage approaching 8 kV rather than the 6 kV previously foreseen [4]. The disadvantages with respect to h=5 are minor; the magnetic field rise is marginally slower, with 10% longer spent on the stopband $3Q_z = 16$, and the initial ΔQ is a few percent higher. However, these are outweighed by the improved capture efficiency, better beam stability (there are no longitudinal coupled-bunch modes for h=1) and larger natural longitudinal emittances at PSB ejection.

3.2 PSB-PS Beam Transport at 1.4 GeV

3.2.1 Transverse Acceptance

Although raising the PSB-PS transfer energy leads to smaller transverse emittances, the horizontal size of the beam will not necessarily be reduced because its momentum spread is larger with h=1 in the PSB. The vertical beam size will, however, be ~ 10% smaller (assuming that the additional acceleration from 1 to 1.4 GeV is achieved without transverse blow-up in the PSB) and hence it will fit the acceptance of the PSB-PS transfer line. As for the horizontal beam size in the dispersive regions of the line, the pertinent figure is the momentum spread at 1.4 GeV which yields a horizontal dimension which is no larger, everywhere along the line, than that at 1 GeV. It can be shown that this allowable momentum spread is[1]

$$\left(\frac{\Delta p_2}{p_2}\right)^2 \leq \left(\frac{\Delta p_1}{p_1}\right)^2 + \frac{4\mathcal{E}_x^*}{\beta_1\gamma_1} \min_s \left[\frac{\beta_x(s)}{D_x^2(s)}\right] \left(1 - \frac{\beta_2\gamma_2}{\beta_1\gamma_1}\right) \quad (2)$$

where $\Delta p/p$ is the 2σ-momentum spread, $\beta_x(s)$ the horizontal amplitude function, $D_x(s)$ the horizontal dispersion, $\mathcal{E}_x^*$ the (normalized) 1σ-horizontal emittance, and β, γ the usual relativistic factors.

[1]Subscript 1 refers to 1 GeV, 2 to 1.4 GeV.

The function $\beta_x(s)/D_x^2(s)$ has its minimum at quadrupole BT.QNO50 and hence it is this location which determines the allowable momentum spread. The resulting permissible $\Delta p/p$ at 1.4 GeV is plotted in fig. 2.

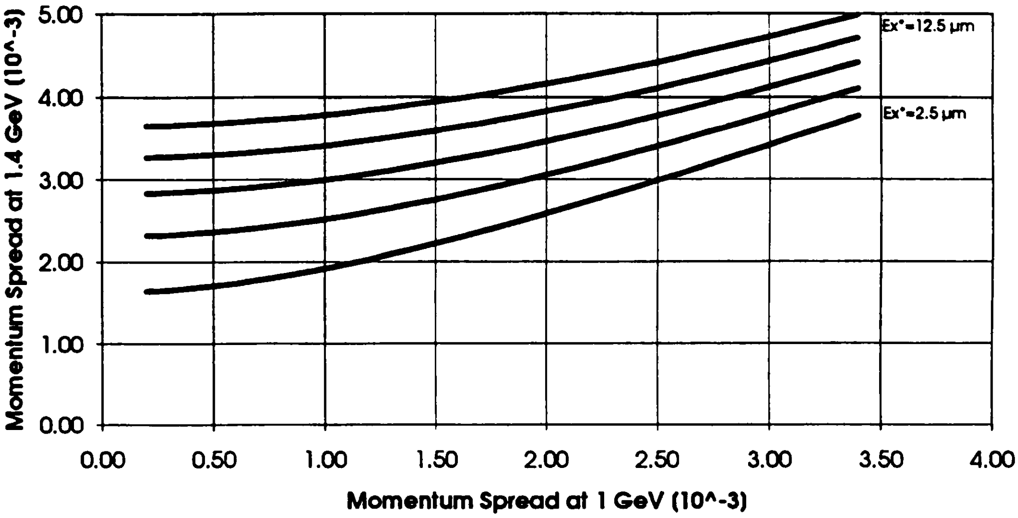

Figure 2: Momentum spread, $\Delta p/p$, at 1.4 GeV which results in no increase in horizontal beam size in the PS-PSB transfer line plotted as a function of $\Delta p/p$ for various (normalized) horizontal emittances at 1 GeV.

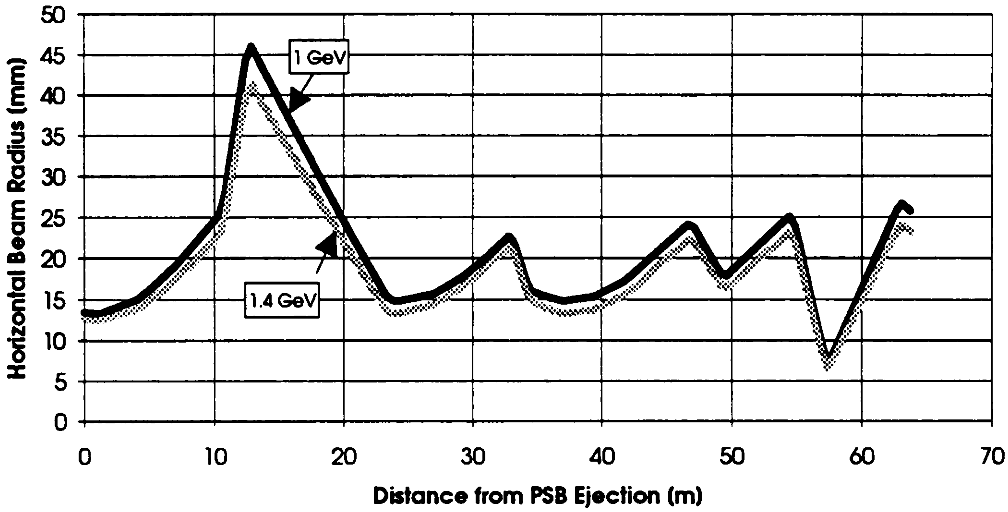

Figure 3: Horizontal beam sizes in the PSB-PS transfer line for the SFT beam at 1 GeV ($\mathcal{E}_x^*$=12.5 μm, $\Delta p/p = 0.12\%$) and at 1.4 GeV ($\mathcal{E}_x^*$=12.5 μm, $\Delta p/p = 0.29\%$).

The SFT beam (SPS fixed-target physics with protons) is the most critical from the emittance standpoint. However, from fig. 2, a momentum spread of up to 0.3% at 1.4 GeV would still lead to a horizontal beam size smaller than that at 1 GeV. The horizontal beam envelope of this beam is shown at the two energies in fig. 3; the beam at 1.4 GeV is smaller everywhere. The conclusion is that *all currently operational beams will be transversally smaller at 1.4 GeV* and passing them through the available acceptance of the PSB-PS line should be easier.

3.2.2 Kicker Rise-times and Pulse Lengths

At present, the handling of five bunches per PSB ring requires the four PSB ejection kickers (BE.KFA), the three vertical recombination kickers (BT.KFA) and the PS injection kicker magnet (PI.KFA45) to have fairly fast rise-times ($\sim$ 60 ns). At 1.4 GeV, all these kickers have to provide 26% more kick strength and it is proposed [5] to modify the hardware in order to raise the pulsed current by this amount at the expense of an increase in rise-time. The tradeoff is considered acceptable since it is anticipated that, with h=1 in the PSB, the distance between bunches will be larger. The relevant data for the beams of the LHC era are listed in table 5.

PARAMETER	BEAM					
	ISO	PHY	TST (h=8)	LHC (p) & AA	SFT (p)	SFT (Pb^{53+})
Kinetic energy [GeV]	1	1.4	1.4	1.4	1.4	0.1481/u
Bunch length [ns]	217	190	139	190	169	78
PSB harmonic number	1	1	1	1	2	4
PSB bunch spacing [ns]	599	572	572	572	286	259
PS harmonic number		8	8	8	8	16
PS bunch spacing [ns]		572	572	286	286	259
Max. rise-time [ns] BE.KFA	382	382	433	382	117	181
Max. rise-time [ns] BT.KFA and PI.KFA45[a]	382	382	433	**96**	117	181

Table 5: Data relevant to kicker rise-times for PSB beams in the LHC era.

[a]Not used for ISOLDE.

The rise-times of the BE.KFA ejection kickers will not be critical, whereas those of the BT.KFA and PI.KFA45 kickers have to be less than 96 ns, in particular for the LHC (p) beam. The deflection angles of these elements are large (in the 5–10 mrad range), so that specifying the kicker rise-time in the usual way (5–95%) would lead to a transverse emittance growth in both planes. This would be unacceptable for the LHC. Consequently, including some allowance for timing or thyratron jitter, the rise-times (2–98%) of the BT.KFA and PI.KFA45 kickers must be less than 90 ns.

In the case of lead ions (see the appendix), the present 2.5 μs pulse-forming networks of PI.KFA45 do not provide a suitable kick. They will be replaced by new PFN's of 4 μs length.

3.3 Space Charge in the PS

High beam intensity and brightness can dramatically affect beam dynamics and can lead to instabilities and detuning due to space charge effects. A straightforward evaluation of the incoherent self-field detuning (in the centre of the beam) can be made using the Laslett formula, which (neglecting image field contributions) may be written

$$\Delta Q_x = -\frac{NRr_0}{\pi B_f Q_x \beta^2 \gamma^3} \frac{G}{a(a+b)} \quad (3)$$

$$\Delta Q_z = -\frac{NRr_0}{\pi B_f Q_z \beta^2 \gamma^3} \frac{G}{b(a+b)} \quad (4)$$

Here, N is the total number of circulating particles, $Q_{x,z}$ the machine tune, R the machine radius, r_0 the classical particle radius, and β, γ the usual relativistic parameters. For a parabolic longitudinal distribution, the bunching factor, $B_f = k_b l_b / 3\pi R$, where k_b is the number of bunches and l_b their length. G is a form factor depending on the transverse charge distribution; $G = \frac{1}{2}$ for a uniform charge density and $G = 1$ for a Gaussian charge density within the bunches. The quantities a and b are the transverse beam dimensions defined as $a = \sqrt{2}\,\sigma_x$ and $b = \sqrt{2}\,\sigma_z$, where σ_x and σ_z are the r.m.s. values of the horizontal and vertical spatial distributions, respectively, and where $\Delta p/p$ is twice the r.m.s. value of the momentum distribution. Equivalently,

$$a = \sqrt{\frac{2\beta_x \mathcal{E}_x^*}{\beta\gamma} + \frac{D_x^2}{2}\left(\frac{\Delta p}{p}\right)^2} \qquad b = \sqrt{\frac{2\beta_z \mathcal{E}_z^*}{\beta\gamma} + \frac{D_z^2}{2}\left(\frac{\Delta p}{p}\right)^2} \tag{5}$$

where $\mathcal{E}_{x,z}^*$ are the (normalized) 1σ-emittances[2].

PARAMETER	BEAM		
	LHC (p)	SFT (p)	AA
Total number of charges	1.6×10^{13}	3×10^{13}	2×10^{13}
Number of bunches	8	8	4
PS harmonic number	8	8	8
Bunch length [ns]	190	169	190
Emittances, $\mathcal{E}_x^*, \mathcal{E}_z^*$ [μm]	3.5, 1.75[a]	12.5, 6.25	10.0, 5.0
Kinetic energy [GeV]	1.4	1.4	1.4
Momentum spread [10^{-3}]	2.5	2.9	2.5
Laslett tune shifts, $\Delta Q_x, \Delta Q_z$	-0.20, -0.33	-0.14, -0.21	-0.20, -0.31

Table 6: Characteristics of the highest intensity LHC era beams at injection in the PS.

[a] Allows for transverse blow-up in the PSB-PS transfer and during acceleration in the PS.

The characteristics of the beams which, at injection in the PS, will be the most critical from the space charge standpoint are listed in table 6. The maximum incoherent space charge tune shifts have been evaluated using eqns. 3 and 4 with $G = 1$. The normalized emittances required by the LHC are seen to be by far the smallest. If the PSB output energy were kept at 1 GeV for this beam, the tune spreads would be 1.5 times larger than those of the present high-intensity beams (which already correspond to the space charge limit of the PS machine). The expected tune shifts of the beam for the LHC are made comparable to the present values for SFT and AA by raising the PSB output energy from 1 to 1.4 GeV.

4 Beam Instabilities [6]

4.1 PSB Instabilities

4.1.1 Present Situation

The present PSB dampers, both longitudinal and transverse, operate at their limits during the acceleration of the highest intensity beams with the current h=5 RF system. The limit in the transverse plane is straightforward to raise: the aging tube power amplifiers of the transverse system will be replaced by solid-state devices and a modest increase of the (filter-determined) bandwidth is envisaged. However, stability against longitudinal coupled-bunch instabilities is far from being satisfactory: impedances have increased over the years (kicker modifications have worsened the situation in all planes) or widened (due to electronic damping of the RF cavities) and the phase tracking system of the damper is too coarse to ensure its full effect throughout the acceleration cycle up to 1 GeV. In addition, the beam control loops of the two RF systems suffer from marginal stability, even to the extent that this sometimes dominates the effect of the "natural" impedances.

Thus, it is entirely legitimate to ask about the situation at 1.4 GeV in the presence of an h=1 RF system and with the other changes of beam environment that are foreseen for the LHC era.

[2] $\mathcal{E}_{x,z}^* = \sigma_{x_\beta,z_\beta}^2/\beta\gamma\beta_{x,z}$, with σ_{x_β,z_β} the r.m.s. values of the betatron motion and $\beta_{x,z}$ the usual lattice parameters.

4.1.2 Investigations

The consequences for beam stability of the major transformations of the PSB that are proposed to fulfill the requirements of the LHC have been investigated. The most significant change is the new RF harmonic number, h=1, which excludes the longitudinal coupled-bunch instabilities that are currently difficult to control. As will be shown, the single bunch also benefits from remarkable transverse stability. This latter is the more important since one of the hardware modifications foreseen, namely the short-circuiting of one port of the ejection kicker and the installation of new low-loss high-voltage cables, entails a substantial increase in the coupling impedances compared with the present situation.

Although no longitudinal coupled-bunch instabilities are expected, the computer code BBI [7] has been used to check for possible single-bunch modes. Since, for all but very narrow (resonance-like) impedances the effect of higher and lower sidebands nearly cancel, only differences due to a slope of the spectral envelope of the rather narrow (because the bunches are long) mode spectrum may drive an instability. The following impedances were assumed:

- the vacuum pipe and its discontinuities were summarized by a broad-band impedance with magnitude, $|Z_{\|}/\mathrm{n}| = 20\Omega$ at low frequencies, resonant frequency, $f_c = 1.3$ GHz and quality factor, $Q = 1$,
- the fundamental and second-harmonic RF cavities (as detuned by beam loading) were represented by two resonators with estimated values of (damped) Q and shunt resistance, R_s, of 4 and 400 Ω, respectively,
- a low-Q resonator with $f_c = 12.5$ MHz and $R_s = 30\ \Omega$ was used to describe the envelope of the rather complicated impedance structure of the ejection kicker plus its open-circuited cables (cf. the transverse impedance plotted in fig. 4).

For the potentially most unstable beams, longitudinal stability has been checked at the injection energy, at high dB/dt (in mid-cycle) and on the flat-top. The input parameter bunch length was either measured (for h=5) or computed using the computer code RAMA [8] (for h=1). The maximum available RF voltage was taken to be 6 kV (peak).

In order to assess transverse beam stability, the computer code TFB has been updated to include a model [9] of a kicker terminated via lossy cables.

4.1.3 Results

BBI results for longitudinal stability are presented in table 7. They support the proposed h=1 system as the growth of the single-bunch mode is slower than that of the coupled ones. Furthermore, the dipole mode is taken care of by the phase loop and the predicted growth of the quadrupole mode at 1 GeV (for the ISOLDE beam) is slow and could be damped by a feedback system as at present.

Fig. 4 shows the horizontal transverse impedance due to the present kicker configuration and fig. 5 that for the proposed 1.4 GeV layout. The irregular and extremely narrow peaks result from the resonances of the high-voltage cables. They have a common periodic envelope; the "period" is determined by the kicker length and the amplitude by the mismatch at its terminals and by the losses in the kicker itself. The calculations presented here have neglected these kicker losses, which are the determining ones if those of the cables are low. The calculated growth rates (without Landau damping) for a high-intensity h=5 beam with the present lossy cables, but with the over-simplistic kicker model, indicate brief fast growth (e-folding times of 5–50 ms) when a spectral line crosses one of the narrow resonance peaks. However, operational experience shows that this situation can be tolerated with the help of feedback, Landau damping and kicker losses.

BEAM	Injection			Mid-cycle			Flat Top		
	T [MeV]	m	τ [ms]	T [GeV]	m	τ [ms]	T [GeV]	m	τ [ms]
ISO[a] (h=5)	50	3	400	0.44	3	41	1	1	10.8
ISO	50	< 4	LD[b]	0.44	3	130	1	2	176
SFT (p) before bunch splitting	50	< 4	LD[b]	0.61	3	250	1.4	1	27
SFT (p) after bunch splitting							1.4	1	37

Table 7: Calculated growth times, τ, for single- and/or multi-bunch longitudinal instabilities in the PSB.

[a]For comparison, the present situation is given; τ for the least stable coupled-bunch mode ($n = 1$) is listed.
[b]Landau damped.

The low-loss cables to be installed in 1994 within the framework of the lead ion programme will tend to reduce the above e-folding times and their impact on the stability of the five bunches will have to be studied with a more refined model.

For the h=1 RF system of the LHC era, all head-tail modes up to oscillation mode number, $m \leq 10$ are unconditionally stable, that is, in the absence of any damping and for the pessimistic kicker model. This may be explained by:

- the longer bunches which result in a correspondingly narrower spectrum confined to the harmless positive real part of the impedances,
- the denser spectrum (lines every revolution frequency cancel resistive wall impedances).

Some of the higher modes (checked up to $m = 33$) appear unstable but can safely be stabilized with the slightly upgraded transverse damper and are, anyway, probably Landau damped.

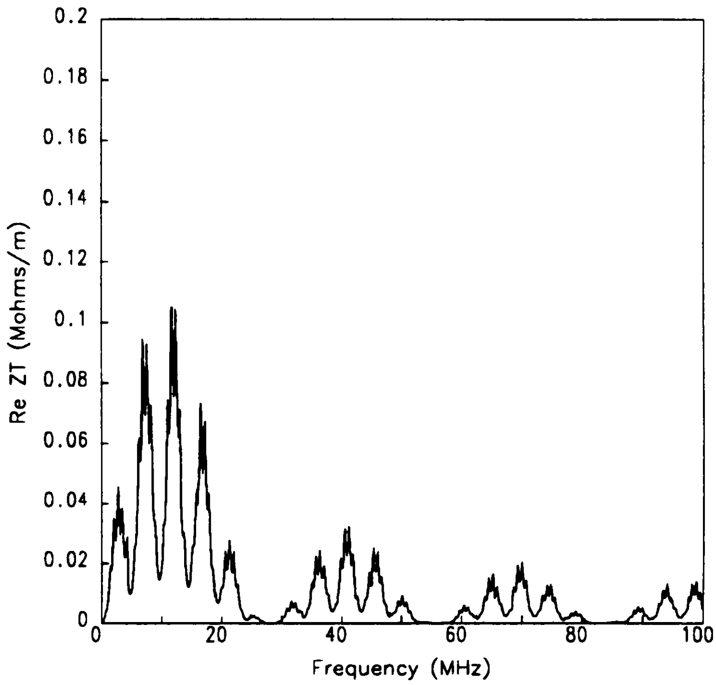

Figure 4: Real part of the horizontal coupling impedance of the PSB ejection kickers with the present HT cable configuration.

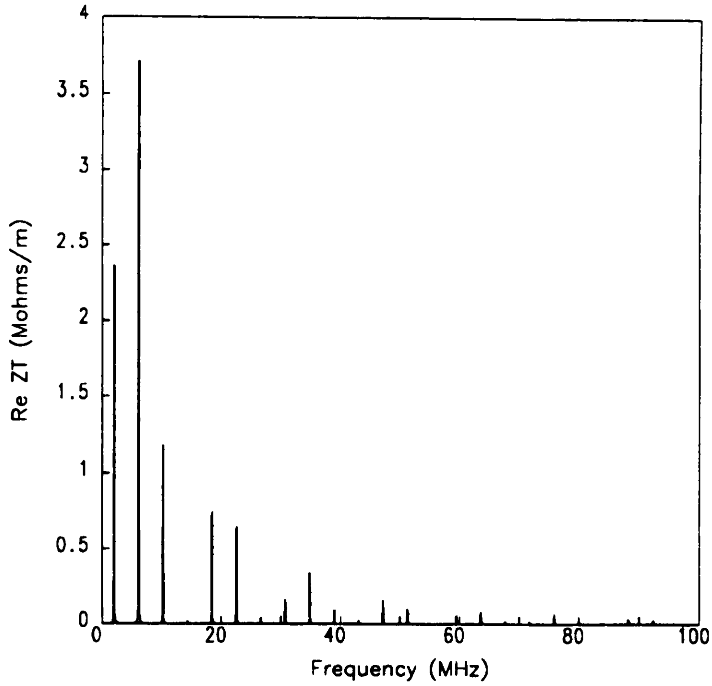

Figure 5: As fig. 4 but with the HT cable configuration of the LHC era. (Note the factor of twenty change in the vertical scale.)

4.2 PS Instabilities

The impedances of the PS machine considered in this preliminary assessment of beam stability are:

- the resistive wall impedance,
- the broad-band impedance, with magnitude, $|Z_{\|}/\mathrm{n}| = 18\Omega$, resonant frequency, $f_c = 1.4$ GHz and quality factor, $Q = 1$,
- the impedance of the main (P1) RF cavities ($Q \sim 10$),
- the impedance of the new 40 and 80 MHz (P2) cavities ($Q \gg 10^4$).

The resistive wall impedance is responsible for single- or multi-bunch transverse (horizontal) instabilities at frequencies $f_{n,m}$ given by

$$f_{n,m} = (n + Q_x)f_0 + mf_s \tag{6}$$

where $n = -7, -8, -9, \ldots$ (modes with $n < 0$ and $|n| > Q_x$ are potentially unstable), $m = \ldots, -2, -1, 0, 1, 2, \ldots, Q_x$ is the horizontal tune (≈ 6.25), f_0 is the revolution frequency and f_s the synchrotron frequency. For example, the present high-intensity ($> 5 \times 10^{12}$ protons per pulse) beams are typically unstable on the coupling mode $n = -7$ with oscillation modes $m = 0$ or $m = 1$ and a rise-time ~ 5 ms. A transverse feedback system operating in the horizontal plane has been implemented to control these instabilities.

The situation is expected to be better for high-intensity beams in the LHC era as the bunches will be much longer than the present ~ 50 ns at low energy. For these long bunches, the bunch oscillation spectrum, shifted by the chromatic frequency[3], f_ξ, only overlaps positive frequencies (or

[3] $f_\xi = -Q_x f_0 \xi / \eta$, where ξ and η are the usual chromaticity and phase slip factors: $\frac{\Delta Q}{Q} = \xi \frac{\Delta p}{p}$, $\frac{\Delta f}{f} = \eta \frac{\Delta p}{p}$.

frequencies where there is only a positive resistive impedance), leading to beam stability. Fig. 6 shows such a spectrum for the 190 ns bunches of the LHC (p) beam. Computations using the computer code BBI confirm that there are no instabilities even for $m = 3$. For higher modes, any instabilities will have relatively slow rise-times, > 50 ms (proportional to $1/m$), and the existing transverse feedback together with Landau damping should be able to cope with them.

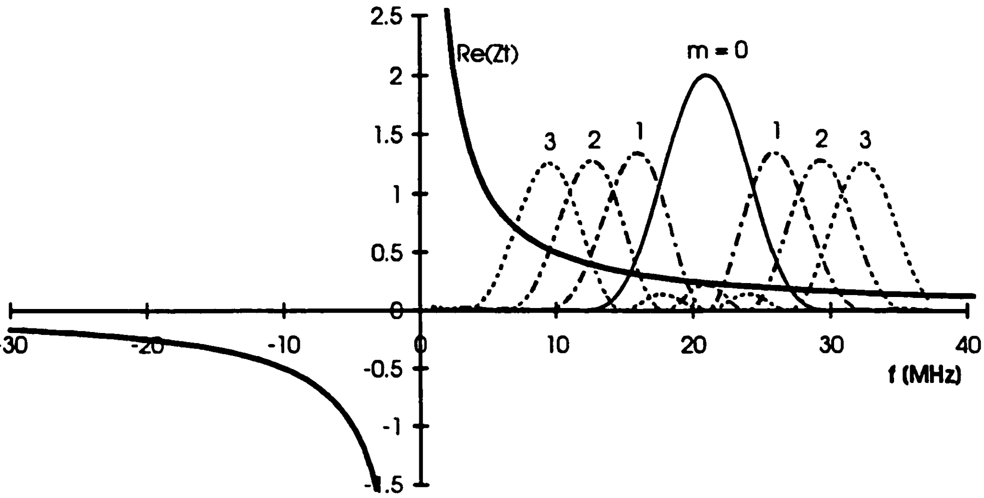

Figure 6: Bunch oscillation spectrum for $m = 0, 1, 2, 3$ for the SFT (p) beam at T=1.4 GeV ($f_\xi \sim 20$ MHz). This is the worst-case beam. (The vertical scale is in arbitrary units.)

The broad-band, vacuum chamber impedance is responsible for single-bunch longitudinal and transverse instabilities. These include the so-called "head-tail" instability, which is avoided by changing the chromaticity from negative to positive upon crossing transition by careful adjustment of the poleface windings (PFW's). The use of octupoles also helps to stabilize the beam. Nevertheless, it is felt that an improvement of the control of the PFW settings is essential for the LHC (p) beam, as any transverse blow-up is considered costly in this case.

The impedance of the main RF cavities can cause longitudinal coupled-bunch instabilities at frequencies ($(\mathrm{h} \pm 1)f_0$ or $(\mathrm{h} \pm 2)f_0$) near the RF carrier. These instabilities are currently avoided by increasing the longitudinal emittance of the beam as much as possible with a controlled blow-up [2] and by careful adjustment of the RF voltage during acceleration to maximize Landau damping. The situation in the LHC era will be almost the same as the present one; the beam frequency components close to the RF frequency are hardly changed, their amplitudes being essentially proportional to the average beam intensity. There is currently no longitudinal feedback, only a fast, one-turn-delay feedback to reduce transient beam loading and, consequently, the effective cavity impedance at harmonics of the revolution frequency. If necessary, a longitudinal feedback system could be implemented.

The fundamental and higher-order modes (HOM's) of the 40 and 80 MHz cavities must, of course, be heavily damped during acceleration. (The situation is similar to that for the existing 114 MHz cavities used for lepton acceleration; these will be replaced by the 80 MHz cavities.) Since the design of the new cavities is not yet finalized, one can only estimate the damping factor required. As a rough guide, in order to avoid coupled-bunch instabilities, the quality factor of the fundamental and HOM's of the 40 MHz cavity should be damped such that

$$Q \ll \frac{\pi f_r}{k_b f_0} \approx 16 \text{ at } f_r = 40 \text{ MHz} \tag{7}$$

where f_r is the (undamped) fundamental or HOM frequency of the cavity and k_b is the number of bunches.

5 Conclusions

A proposal has been considered to exploit to the fullest the hardware modifications to the PS Complex that are foreseen as a consequence of the LHC. All beams which are presently operational or in preparation have been re-examined in the light of the new hardware and a modified production scheme for each has been analysed in detail.

The results show that these beams may be supplied without compromising current performance. Indeed, beam quality is generally expected to improve, not least due to the exclusion of longitudinal coupled-bunch instabilities in the PSB, the minimization of machine impedances and increased bunch lengths. Operational flexibility is enhanced by the possibility of a controlled longitudinal blow-up in the PSB and yet the amount of equipment to be operated and maintained is reduced.

Acknowledgments

The authors thank Kurt Hübner, Erk Jensen, Klaus Metzmacher and Flemming Pedersen who provided valuable contributions to, or comments on, the contents of this report.

A Longitudinal Beam Manipulations

The following tables list the main longitudinal beam and machine parameters at the essential stages in the production of all beams foreseen in the LHC era. Each row represents one step of the process and the values of the parameters given pertain to the end of that step. Time increases from top to bottom and the principal parameters that change with respect to the previous row are emphasized in boldface type. (The PSB and PS RF systems are defined in tables 1 and 2, and, for an elliptical bunch, the longitudinal emittance, $\mathcal{E}_l$, is defined as $\frac{\pi}{4}$ times the full energy spread of the beam times the bunch length.)

A.1 ISO

PROCESS and MACHINE		MACHINE PARAMETERS					BEAM PARAMETERS			
		RF System	h	V [kV] (on main system)	f [MHz] (on main system)	B [Gauss]	Energy	$\mathcal{E}_l$ (per bunch) [eV.s]	Bunch Length [ns]	$\Delta p/p$ $[10^{-3}]$
Capture	**PSB**	B1 (B2)	1 (2)	**0 → 8**	0.6	1257	T=50 MeV	1.2		
Acceleration	PSB	B1 (B2)	1 (2)	8	**→ 1.67**	**6867**	T=1 GeV	1.2	217	2.4

Table 8: Isotope production beam for ISOLDE.

A.2 LHC (p)

In the reference operating scheme for supplying the LHC [1], the PS receives two batches of four bunches at 1.4 GeV thereby filling all RF buckets on h=8. Acceleration could proceed on this harmonic up to 26 GeV/c, when adiabatic debunching is performed prior to imposing the required 25 ns bunch spacing on the beam. However, a higher harmonic number would improve the debunching because

- the degree of adiabaticity (for a given debunching duration) would be increased since synchrotron oscillation period is inversely proportional to $\sqrt{h}$,
- the resultant energy spread (for a given minimum controllable RF voltage) would be reduced since bucket height is also inversely proportional to $\sqrt{h}$.

Hence, the introduction of the new process "bunch splitting" at 3.5 GeV/c in the PS to change the harmonic number from 8 to 16 and double the number of bunches.

The technique is the reverse of the "merging" one that is currently employed routinely in the PS for the antiproton production beam. The RF voltage of the principal harmonic cavities is gradually reduced while that of a second group of cavities tuned on h=16 is increased, the unstable phase of the second harmonic being centred on the stable h=8 phase. The resultant bunch lengthening is well-known, but this is followed by the progressive splitting and separation of each bunch into two equal ones. The technique has been demonstrated experimentally [10].

PROCESS and MACHINE		MACHINE PARAMETERS					BEAM PARAMETERS			
		RF System	h	V [kV] (on main system)	f [MHz] (on main system)	B [Gauss]	Energy	$\mathcal{E}_l$ (per bunch) [eV.s]	Bunch Length [ns]	$\Delta p/p$ [10^{-3}]
Capture	**PSB**	B1 (B2)	1 (2)	**0 → 8**	0.6	1257	T=50 MeV	1.2		
Acceleration and blow-up[a]	PSB	B1 (B2,B3)	1 (2,10)	8	**→ 1.75**	**8671**	**T=1.4** GeV	1.45	190	2.5
Transfer to PS (double)	**PS**	**P1**	8	27	3.5	1019	T=1.4 GeV	1.45	190	2.5
Acceleration	PS	P1	8	→ 200	**→ 3.69**	**1695**	**pc=3.56** GeV	1.5	66	4.1
Bunch splitting and blow-up[b]	PS	P1 P1 (P3)	8 **16** (433)	**→ 0** **0 → 200**	3.69 7.38	1695	pc=3.56 GeV	**1**	**46**	**4**
Acceleration	PS	P1	16	200	**→ 7.6**	**12560**	**pc=26.4** GeV	1	24	1
Debunching and rebunching[c]	PS	P1 **P2a** **P2b** (P3)	16 **84** **168** (420)	**→ 0** **0 → 300** **0 → 600**	7.6 40 80	12560	pc=26.4 GeV	**0.7**	**9.3**	**2.0**

Table 9: Proton beam for filling the LHC.

[a] 20% controlled longitudinal blow-up using RF system B3 during acceleration.

[b] Bunch splitting required to improve transition cossing and debunching at 26 GeV. 33% controlled longitudinal blow-up using RF system P3.

[c] Longitudinal blow-up by an estimated factor of 3.7 during debunching and rebunching.

A.3 LHC ("Scheme 0" for Pb^{53+})

PROCESS and MACHINE		MACHINE PARAMETERS					BEAM PARAMETERS			
		RF System	h	V [kV] (on main system)	f [MHz] (on main system)	B [Gauss]	Energy	$\mathcal{E}_l$ (per bunch) [eV.s/u]	Bunch Length [ns]	$\Delta p/p$ [10^{-3}]
Capture	**PSB**	B1	4	**0 → 8**	0.723	1407	T=4.2 MeV/u	0.02		
Acceleration with system B1	PSB	B1	4	8	**→ 1.71**	3400	**T=24.3** MeV/u	0.02	208	1.3
Acceleration with system B2	**PSB**	**B2**	4	8	**→ 3.86**	**8671**	T=148.1 MeV/u	0.02	78	0.59
Transfer to the PS[a]	**PS**	**P1**	16	32	3.86	1019	T=148.1 MeV/u	0.02	78	0.59
Acceleration[b]	PS	P1	16	→ 200	**→ 7.43**	**7284**	**pc=3.9** GeV/u	0.02	8	0.42

Table 10: Lead ions for the LHC.

[a] The length of the PS injection kicker pulse has to be increased to 4.2 μs.

[b] The bunch length compression required to inject into an SPS bucket at 200 MHz is not described.

A.4 SFT (p)

PROCESS and MACHINE		MACHINE PARAMETERS					BEAM PARAMETERS			
		RF System	h	V [kV] (on main system)	f [MHz] (on main system)	B [Gauss]	Energy	$\mathcal{E}_l$ (per bunch) [eV.s]	Bunch Length [ns]	$\Delta p/p$ $[10^{-3}]$
Capture	**PSB**	B1 (B2)	1 (2)	**$0 \rightarrow 8$**	0.6	1257	T=50 MeV	1.2		
Acceleration and blow-up	PSB	B1 (B2,B3)	1 (2,10)	8	**$\rightarrow$ 1.75**	**8671**	**T=1.4** GeV	1.2	171	2.3
Bunch splitting and blow-up[a]	PSB	**B1** **B2** (B3)	1 2 (10)	$\rightarrow 0$ $3 \rightarrow 8$	1.75 3.5	8671	T=1.4 GeV	1.45	169	2.9
Transfer to the PS	**PS**	**P1**	8	42	3.5	1019	T=1.4 GeV	1.45	169	2.9
Acceleration	PS	P1	8	$\rightarrow$ 200	**$\rightarrow$ 3.69**	**1695**	**pc=3.56** GeV	1.5	66	4.1
Bunch splitting and blow-up[a]	PS	P1 P1 (P3)	8 **16** (433)	**$\rightarrow 0$** **$0 \rightarrow 200$**	3.69 7.38	1695	pc=3.56 GeV	**1**	**46**	**4**
Acceleration	PS	P1	16	200	**$\rightarrow$ 7.6**	**6663**	**pc=14** GeV	1	28	1.6
Debunching and rebunching[b]	PS	P1 **P3**	16 **420**	**$\rightarrow 0$** **$0 \rightarrow 240$**	7.6 199.95	6663	pc=14 GeV	**0.1**	**5**	**1**

Table 11: High-intensity proton beam with "Continuous Transfer" to the SPS.

[a]Bunch splitting required to improve transition crossing and debunching at 14 GeV/c. Controlled longitudinal blow-up in each case.

[b]Longitudinal blow-up by an estimated factor of 2.6 during debunching and rebunching.

A.5 SFT (Pb^{53+})

PROCESS and MACHINE		MACHINE PARAMETERS					BEAM PARAMETERS			
		RF System	h	V [kV] (on main system)	f [MHz] (on main system)	B [Gauss]	Energy	$\mathcal{E}_l$ (per bunch) [eV.s/u]	Bunch Length [ns]	$\Delta p/p$ $[10^{-3}]$
Capture	**PSB**	B1	4	**$0 \rightarrow 8$**	0.723	1407	T=4.2 MeV/u	0.02		
Acceleration with system B1	PSB	B1	4	8	**$\rightarrow$ 1.71**	3400	**T=24.3** MeV/u	0.02	208	1.3
Acceleration with system B2	**PSB**	**B2**	4	8	**$\rightarrow$ 3.86**	**8671**	T=148.1 MeV/u	0.02	78	0.59
Transfer to the PS[a]	**PS**	**P1**	16	32	3.86	1019	T=148.1 MeV/u	0.02	78	0.59
Acceleration	PS	P1	16	$\rightarrow$ 200	**$\rightarrow$ 7.51**	**9512**	**pc=5.09** GeV/u	0.02	5	0.51

Table 12: Lead ions for fixed-target physics at the SPS.

[a]The length of the PS injection kicker pulse has to be increased to 4.2 μs.

A.6 PHY

PROCESS and MACHINE		MACHINE PARAMETERS					BEAM PARAMETERS			
		RF System	h	V [kV] (on main system)	f [MHz] (on main system)	B [Gauss]	Energy	$\mathcal{E}_l$ (per bunch) [eV.s]	Bunch Length [ns]	Δp/p [10^{-3}]
Capture	**PSB**	B1	1	**0 → 8**	0.6	1257	T=50 MeV	1.2		
Acceleration and blow-up[a]	PSB	B1 (B3)	1 (10)	8	**→ 1.75**	**8671**	**T=1.4** GeV	1.45	190	2.5
Transfer to the PS	**PS**	**P1**	8	27	3.5	1019	T=1.4 GeV	1.45	190	2.5
Acceleration	PS	P1	8	→ 200	**→ 3.8**	**11425**	**pc=24** GeV	1.45	2090 (deb.)	variable (b. rot.)

Table 13: East Hall beam.

[a]20% controlled longitudinal blow-up using RF system B3 during acceleration.

A.7 AA

PROCESS and MACHINE		MACHINE PARAMETERS					BEAM PARAMETERS			
		RF System	h	V [kV] (on main system)	f [MHz] (on main system)	B [Gauss]	Energy	$\mathcal{E}_l$ (per bunch) [eV.s]	Bunch Length [ns]	Δp/p [10^{-3}]
Capture	**PSB**	B1 (B2)	1 (2)	**0 → 8**	0.6	1257	T=50 MeV	1.2		
Acceleration and blow-up[a]	PSB	B1 (B2,B3)	1 (2,10)	8	**→ 1.75**	**8671**	**T=1.4** GeV	1.45	190	2.5
Transfer to the PS	**PS**	**P1**	8	27	3.5	1019	T=1.4 GeV	1.45	190	2.5
Acceleration	PS	P1	8	→ 200	**→ 3.81**	**12560**	**pc=26.4** GeV	1.5	35	1
Batch compression[b]	PS	P1 (P3)	8 → 20 (419)	**200 → 0** **0 → 200**	**3.81** **→ 9.54**	12560	pc=26.4 GeV	**2**	**33**	**1.5**

Table 14: Antiproton production beam.

[a]20% controlled longitudinal blow-up using RF system B3 during acceleration.

[b]Batch compression similar to the present operational process, but with one supplementary step to change from h=8 to h=10. 33% blow-up during this operation.

A.8 TST (h=8)

PROCESS and MACHINE		MACHINE PARAMETERS					BEAM PARAMETERS			
		RF System	h	V [kV] (on main system)	f [MHz] (on main system)	B [Gauss]	Energy	$\mathcal{E}_l$ (per bunch) [eV.s]	Bunch Length [ns]	Δp/p [10^{-3}]
Capture	**PSB**	B1	1	**0 → 6**	0.6	1257	T=50 MeV	0.7		
Acceleration	PSB	B1	1	6	**→ 1.75**	**8671**	**T=1.4** GeV	0.7	139	1.64
Transfer to PS (1 bunch)	**PS**	**P1**	8	20	3.5	1019	T=1.4 GeV	0.7	139	1.64
Acceleration	PS	P1	8	→ 200	**→ 3.69**	**1695**	**pc=3.56** GeV	0.7	45	2.9
Matching to AA	PS	P1	8	**→ 5**	3.69	1695	pc=3.56 GeV	0.7	**119**	**1.1**

Table 15: AAC test beam.

A.9 TST (h=10)

PROCESS and MACHINE		MACHINE PARAMETERS					BEAM PARAMETERS			
		RF System	h	V [kV] (on main system)	f [MHz] (on main system)	B [Gauss]	Energy	$\mathcal{E}_l$ (per bunch) [eV.s]	Bunch Length [ns]	Δp/p [10^{-3}]
Capture	**PSB**	B1	1	**0 → 6**	0.6	1257	T=50 MeV	0.25[a]		
Acceleration	PSB	B1	1	6	**→ 1.75**	**8671**	**T=1.4** GeV	0.25	82	0.98
Transfer to PS (1 bunch)	**PS**	**P1**	8	20	3.5	1019	T=1.4 GeV	0.25	82	0.98
Acceleration	PS	P1	8	→ 200	**→ 3.69**	**1695**	**pc=3.56** GeV	0.25	27	1.7
Change from h=8 to h=10	PS	P1 P1	8 10	**→ 0** **0 → 160**	3.69 4.61	1695	pc=3.56 GeV	0.25	27	1.7
Deceleration and Matching to LEAR	PS	P1	10	**→ 60**	2.6	290	pc=609 MeV	0.25	**190**	**2.6**

Table 16: Deceleration test beam.

[a]Capture in the PSB is assumed to limit the emittance of the bunch to 0.25 eVs.

A.10 SPP (p)

PROCESS and MACHINE		MACHINE PARAMETERS					BEAM PARAMETERS			
		RF System	h	V [kV] (on main system)	f [MHz] (on main system)	B [Gauss]	Energy	$\mathcal{E}_l$ (per bunch) [eV.s]	Bunch Length [ns]	$\Delta p/p$ $[10^{-3}]$
Capture	**PSB**	B1	1	**0 → 6**	0.6	1257	T=50 MeV	0.7		
Acceleration	PSB	B1	1	6	**→ 1.75**	**8671**	**T=1.4** GeV	0.7	139	1.64
Transfer to PS (1 bunch)	**PS**	**P1**	8	20	3.5	1019	T=1.4 GeV	0.7	139	1.64
Acceleration[a]	PS	P1	8	→ 200	**→ 3.81**	**12560**	**pc=26.4** GeV	0.7	25	0.7

Table 17: Single proton bunch for the SPS.

[a]Bunch characteristics at the time of transfer are given for the static situation at full voltage on h=8. Non-adiabatic bunch compression is not taken into account.

A.11 SPP/SPN (e^+/e^-)

A particular advantage of the proposed suppression of the 114 MHz (h=240) RF system and the use instead of the 80 MHz (h=168) one for lepton acceleration is the prospect of an increased number of particles in longer bunches. Moreover, the new harmonic is compatible with both 4- and 8-bunch modes of operation.

PROCESS and MACHINE		MACHINE PARAMETERS					BEAM PARAMETERS			
		RF System	h	V [kV] (on main system)	f [MHz] (on main system)	B [Gauss]	Energy	$\mathcal{E}_l$ (per bunch) [eV.s]	Bunch Length[a] [ns]	$\Delta p/p$ $[10^{-3}]$
Capture	**PS**	P2b	168	50	80	238	E=500 MeV		3	1.4
Acceleration	PS	P2b	168	→ 500	80	**1667**	**E=3.5** GeV		3	1.5
Bunch lengthening	PS	P2b **P1**	168 8	→ 250 0 → 200	80 3.8	1667	E=3.5 GeV		**5**	**2**

Table 18: Leptons for LEP.

[a]Bunch length is given at 4σ and energy spread at 2σ.

A.12 LEA

PROCESS and MACHINE		MACHINE PARAMETERS					BEAM PARAMETERS			
		RF System	h	V [kV] (on main system)	f [MHz] (on main system)	B [Gauss]	Energy	$\mathcal{E}_l$ (per bunch) [eV.s]	Bunch Length [ns]	$\Delta p/p$ $[10^{-3}]$
Capture	**PS**	P1	10	**7** (→ 160)	4.61	1695	pc=3.56 GeV	0.25	**59** (27)	**0.77** (1.7)
Deceleration and Matching to LEAR	PS	P1	10	**→ 60**	2.6	290	pc=609 MeV	0.25	**190**	**2.6**

Table 19: Antiprotons for LEAR.

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