LIU: EXPLORING ALTERNATIVE IDEAS

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Abstract

The baseline upgrade scenarios for the injector complex cover the connection of Linac4 to the PSB, the increase of the PSB-PS transfer energy from $1.4\,\mathrm{GeV}$ to $2\,\mathrm{GeV}$ and the major SPS RF upgrade during LS2. The achievable beam characteristics will nonetheless remain below the expectation of the HL-LHC project. Therefore, alternative or additional options like, e.g., special bunch distributions, the use of injection optics optimized for high space charge or extra RF systems will be discussed. The expected beam parameters, possible implementation and impact on beam availability for these more exotic options will be analysed and compared to the LIU baseline plan. Moreover, the potential interest of further batch compression schemes will be evaluated.

INTRODUCTION

The upgrades foreseen within the baseline plan of the LHC Injector Upgrade (LIU) project include the connection of Linac4 to the PSB, the increase of the PSB-PS transfer energy to $2\,\mathrm{GeV}$ and the $200\,\mathrm{MHz}$ RF upgrade in the SPS [1, 2]. Taking the various limitations in the injector chain into account, a bunch intensity of $N_b = 2 \cdot 10^{11}$ ppb with transverse emittances of slightly below $2\,\mu$m is expected at extraction from the SPS (round beams, $\varepsilon_x \simeq \varepsilon_y$). Figure 1 shows a summary plot of the brightness limit of the PSB with Linac4, together with the limitations from space charge in PS and SPS. The dashed vertical line indicates the maximum expected intensity per bunch after the RF power upgrade in the SPS (without beam quality deterioration with respect to present parameters). These beam parameters can be reached with the nominal production scheme of the LHC-type beams in the injector chain [3].

Alternative possibilities and additional improvements to this baseline which would allow to increase intensity or brightness of the beam available to the LHC have already been studied [4, 5, 6], not only in view of the foreseen upgrades within LIU. In particular LHC-beams with higher brightness were successfully commissioned and delivered to the LHC during the 2012 run using the batch compression merging and splitting (BCMS) scheme.

Various further alternative scenarios have been suggested and are studied in this paper, mainly targeted at reducing space charge effects in PS and SPS, as well as increasing intensity per bunch from the SPS (Table 1).

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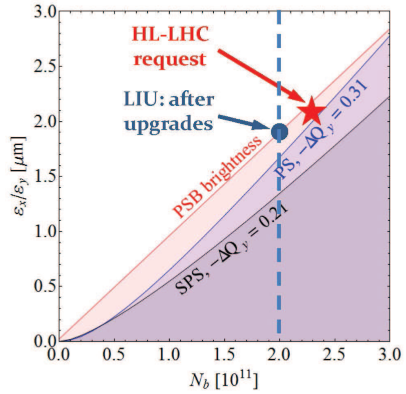

Figure 1: Brightness and space charge limitations following the baseline LIU upgrades. The dashed line marks the expected bunch intensity after RF power upgrade in the SPS.

The beam performance of these options is estimated and compared to the baseline upgrade path. It is important to point out that some considerations for the evaluation of beam parameters may be over-simplified due to the large variety of scenarios and possible combinations.

PERFORMANCE EVALUATION AND OPTIMIZATION

To compare alternative schemes in the LHC injector chain, their potential performance has been evaluated applying the same assumptions as for the baseline scenarios [7]. These constraints are summarized in Table 2. With the connection of Linac4 (L4) to the PSB, the brightness available to the PS will be doubled. In the PS, all RF manipulations are assumed to take place at a kinetic energy of $2.5\,\mathrm{GeV}$, independent of the energy at PS injection. At this energy, the available RF voltages for the manipulations result in comfortably large bucket areas (doubled with respect to $1.4\,\mathrm{GeV}$) and the synchrotron frequencies are still high enough for an acceptable duration. To minimize space charge at PS injection, the bunches at PSB-PS transfer are as long as possible. As consecutive bunches at PS injection may be produced by different rings of the PSB, an empty gap for the recombination kickers in the transfer line must be preserved between the tail of a given bunch and the head of the next. The duration of the switching time between rings (rise time of recombination kickers), $105\,\mathrm{ns}$ at $1.4\,\mathrm{GeV}$ and $110\,\mathrm{ns}$ at $2\,\mathrm{GeV}$ [8], defines the maximum bunch length at injection into the PS.

Table 1: Upgrade options for the injector complex. Baseline choices of the LIU project are marked in *italics* (BCMS: Batch Compression Merging and Splitting; BCS: Batch Compression and Splitting; PBC: Pure Batch Compression). The potential intensity gain (i.e. the equivalent brightness gain) is shown for some options in the last column.

	Scheme	Gain
PSB	*Linac4 connection*	
	Faster recombination kickers (1.4 GeV)	
	Long. flat or hollow bunches	+25 %
	2 GeV at PSB→PS transfer	
PS	Double batch or $h = 5$ single-batch inj.	
	3-split, BCMS, BCS or PBC	
	$8b \oplus 4e$ together with 3-split or BCMS	
	Resonance compensation	
	Special injection optics	
	Long. flat or hollow bunches	+25 %
	28 GeV at PS→SPS transfer	+15 %
SPS	*Baseline SPS RF upgrade*	+50 %
	Extended SPS RF upgrade	
	Relaxed ε_l with 200 MHz in LHC	
	Q20 optics	+10 %
	Q20/Q26 split-tune optics	+5 %
	Special injection optics	

Table 2: Basic assumptions for performance comparison.

	Parameter	
L4 + PSB	Brightness, ε_x, ε_y per N_b (H$^-$ injection at 160 MeV)	$0.4\,\mu\mathrm{m}/10^{12}$
PS	Beam loss	5 %
	Transv. emittance growth	5 %
	Tolerable tune shift, ΔQ_y	-0.31
	Maximum bunch length at inj.	Recomb. kickers
SPS	Beam loss	10 %
	Transverse emittance growth	10 %
	Tolerable tune shift, ΔQ_y	-0.21
	Bunch intensity at extraction after RF upgrade	$2 \cdot 10^{11}$

ALTERNATIVE SCHEMES IN THE PRE-INJECTORS

The connection of Linac4, in combination with the increase of the PSB-PS transfer energy, will double the available brightness for almost any scenario. The performance reach of the two pre-injector synchrotrons, PSB and PS, is however closely interlinked via the RF manipulation scheme applied in the PS. Firstly, the RF harmonic number at PS injection, together with the ring-to-ring switching time, constrains the maximum bunch length at transfer and hence the space charge conditions in the PS. Additionally the overall splitting ratio in the PS, r_{split}, defines the bunch intensity required at injection for a given intensity per LHC-type bunch at transfer to the SPS. At constant brightness from the PSB [7] the minimum transverse emittance becomes directly proportional to the splitting ratio.

Beam manipulation schemes in the PS

The nominal production scheme of the LHC-type beams [3] in the injector chain consists of injecting 4+2 bunches in two batches from the PSB into the PS. With an initial harmonic number of $h = 7$, one bucket remains empty for the PS extraction kicker gap. Each bunch is then triple split, accelerated on $h = 21$ and further split in four parts (total splitting factor, $r_{\mathrm{split}} = 3 \cdot 4 = 12$) on the flat-top to generate a batch of 72 bunches spaced by 25 ns. Up to four of these 72-bunch batches are then accumulated in the SPS and finally transferred at an energy of 450 GeV to the LHC.

For all different RF manipulation schemes in the PS, the beam is accelerated at the pivotal harmonic number of $h = 21$ to allow using the fixed-frequency 20 MHz, 40 MHz and 80 MHz RF systems for quadruple splitting and bunch rotation on the PS flat-top.

To reduce the space charge tune shift on the PS flat-bottom, the incoming bunches must not only be as long as possible, but they should also be distributed over the maximum fraction of the PS circumference. Only after an acceleration to an intermediate flat-top at a kinetic energy of 2.5 GeV, they can be compressed to a smaller fraction of the circumference [9] and brought to the acceleration harmonic, $h = 21$. Batch compression is the iterative increase of the principal harmonic number to reduce the spacing in between bunches, hence reducing the batch length [10]. Empty buckets are literally added at the azimuth of the batch gap.

Batch compression, merging and splitting (BCMS) Beams produced with the BCMS scheme have been commissioned in the injectors during the 2012 run and successfully delivered to the LHC [11, 12]. The RF manipulation in the PS is illustrated by the mountain range density plot in Fig. 2 (measured data). In total 8 bunches are double-batch transferred from the PSB into $h = 9$ buckets in the PS. Following an acceleration to the intermediate flat-top, the harmonic number is incrementally increased to $h = 14$ (batch-compression). Pairs of bunches are subsequently merged together (main harmonic: $h = 7$) and finally triple split as with the nominal beam. The resulting splitting ratio on the intermediate flat-top of 1.5 becomes, after the usual quadruple splitting at 26 GeV, $r_{\mathrm{split}} = 6$ for the BCMS beam. This means that for an LHC-type bunch with a given intensity at PS extraction, the injected bunch from the PSB is only half the intensity compared to the nominal production scheme, resulting in at best twice smaller transverse

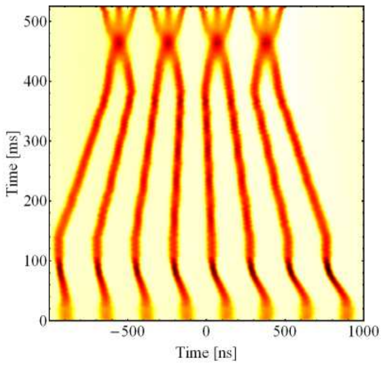

Figure 2: Batch compression, merging and splitting (BCMS).

emittance. This improvement has been confirmed by emittance measurements at SPS extraction, as well as by a luminosity increase in the LHC experiments [11].

Figure 3 shows the limit plot for the BCMS scheme. The

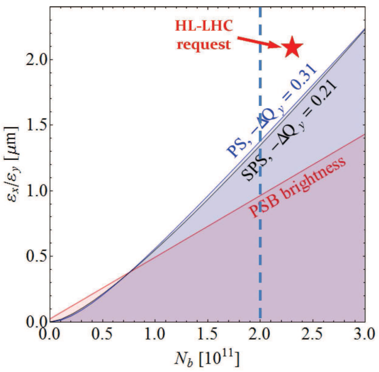

Figure 3: Limit plot for the BCMS beam (Linac4, PSB-PS at 2 GeV, 25 ns bunch spacing).

space charge tune shifts in both, PS and SPS, are perfectly matched for beams produced with the BCMS scheme. The brightness reach is beyond the HL-LHC request though the requested intensity cannot be fully reached; however, Linac4 and PSB could deliver even higher brightness incompatible with space charge in the PS and SPS. Due to the reduced splitting factor, each PS batch contains only 48 bunches (25 ns spacing) instead of 72, which propagates as a reduction of the total number of bunches per LHC ring by about 6 % and a 20 % longer LHC filling time.

Pure batch compression Even higher brightness can be achieved with the pure batch compression (PBC) scheme. As for the BCMS manipulation, twice 4 bunches are again transferred from the PSB into $h = 9$ in the PS. The acceleration to an intermediate flat-top on $h = 9$ is followed by a batch compression incrementally scanning through all harmonic numbers up to $h = 21$ (Fig. 4). The batch of 8 bunches is then accelerated to the flat-top where each bunch is again split in four, resulting in a 32-bunch batch with 25 ns spacing ($r_{\text{split}} = 4$).

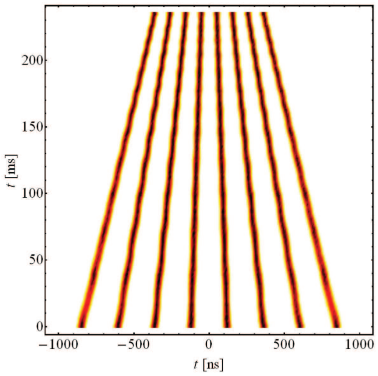

Figure 4: Pure batch compression (PBC).

The corresponding limit plot in Fig. 5 indicates that up to PS extraction a brightness well beyond the assumed SPS space charge limit can be produced. Unless this limitation

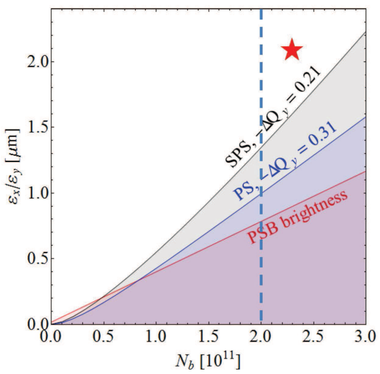

Figure 5: Limit plot for the PBC scheme (Linac4, PSB-PS at 2 GeV, 25 ns bunch spacing).

can be mitigated, the pure batch compression scheme will not provide any advantage with respect to BCMS. As the PS batches are only 32 bunches long, it even results in longer filling time and about 13 % fewer bunches in the LHC [6].

This alternative scheme will hence have its interest in exploring the limitations of the SPS. Pure batch compression will already become technically feasible after LS1, following the controls upgrade of the PS low-level RF. With the experience of the BCMS beam, its commissioning should be straightforward.

8b⊕4e bunch pattern schemes Schemes resulting in short batches in the LHC will become important in case there are issues with electron cloud (e-cloud) instabilities [13]. An extreme case, which is expected to significantly reduce e-cloud formation in the LHC, is $8b \oplus 4e$ micro-batches produced in the PS.

Replacing the triple splitting in the PS by a direct $h = 7 \rightarrow 21$ bunch pair splitting results in pairs of bunches with an empty bucket in between. On the flat-top each bunch and empty bucket subsequently split in four ($r_{\text{split}} = 8$). In combination with nominal injection of $4+2$ bunches into $h=7$ buckets in the PS, the bunch pattern from the PS becomes $6\otimes(8b\oplus 4e)\oplus 12e$ (Fig. 6, top), with the corresponding limit plot shown in Fig. 7. Possibly even $4+3$ bunches

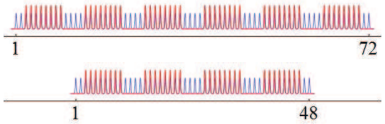

Figure 6: Bunch patterns of $8b\oplus 4e$ option (red) compared to the patterns of regular batches (blue). The first pattern (top) is achieved by changing the triple splitting to an $h=7\to 21$ double splitting, while the second pattern (bottom) is generated in combination with the modified BCMS scheme.

could be injected into the PS, yielding a $7\otimes(8b\oplus 4e)$ pattern at extraction [14, 15]. The remaining gaps of 4 empty buckets (about 100 ns) between the micro-batches are expected to be sufficiently long for the PS ejection kicker. Since the

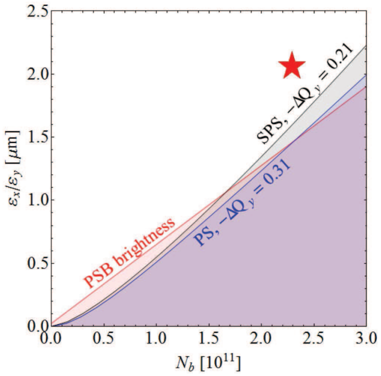

Figure 7: Limit plot for $8b\oplus 4e$ scheme (Linac4, PSB-PS at 2 GeV, 25 ns bunch spacing).

bunch splittings in the PS are lossless manipulations, the 8 bunches could theoretically have 50 % more intensity. As will be shown below, such an intensity cannot be digested by the SPS.

A derivation of the BCMS manipulation could be imagined by replacing merging and triple splitting by a regrouping of bunches with a direct hand-over from $h=14$ to $h=21$ ($r_{\mathrm{split}}=4$), but keeping in mind that the nominal $8b\oplus 4e$ scenario already pushes the SPS to the space charge limit, such a scheme would have no further benefit for the LHC.

Potential additional improvements

In addition to the main alternative scenarios in the pre-injectors mentioned above, further potential options reducing space charge have been investigated. They can be applied in combination with the RF manipulation schemes in the PS. In the longitudinal plane the bunches can be stretched or made longitudinally flat to reduce their peak line density. In the transverse plane the available space for the space charge necktie in the working point diagram can be increased by compensating resonances, while the space charge necktie can be reduced by applying a special optics at low energy, e.g., by introducing vertical dispersion [16], to keep the physical beam size as large as possible.

Space charge reduction from longitudinal improvements Longitudinally flat bunches can be generated by two techniques. A higher-harmonic RF system can be added to the main RF system to reduce the peak line density. This technique is applied in the PSB [17]. However, the transfer of a flat-bunch generated by this technique requires double-harmonic RF systems in both the sending and receiving accelerators. Bunches with a longitudinally flat profile can also be achieved by depleting the central part of the distribution in longitudinal phase space [18, 19]. This technique has the advantage of requiring only a single-harmonic RF system. Hence a flat bunch can be easily transferred from PSB to PS [7], and the flat bunch is even expected to preserve its distribution through certain RF manipulations like batch-compression or bunch pair splitting and merging. The reduction of the space charge tune shift achieved by longitudinal flat or hollow bunches corresponds to the reduction of peak line density and the increase of the momentum spread, and is of the order of 25 %.

Increasing bunch length can also be a means to reduce the longitudinal density and space charge. At PSB-PS transfer the maximum bunch length is given by the minimum gap between two consecutive bunches, which is constrained by the switching time between the different rings of the PSB. Figure 8 illustrates the double batch transfer of $4+2$ bunches into $h=7$ buckets or $4+4$ bunches into $h=9$ buckets in the PS [12]. Assuming that the

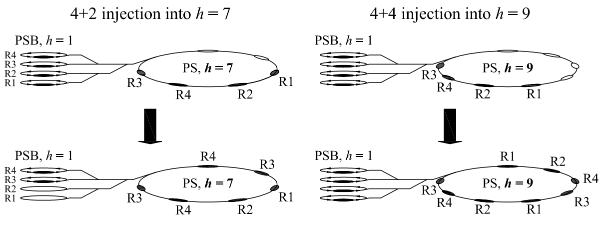

Figure 8: Beam transfer between PSB and PS.

rise time of the recombination kickers can be reduced by 50 ns, the bunch length at PS injection could be increased by this amount. The effect of the corresponding mitigation of the space charge limit is shown in Fig. 9, resulting in a reduction of about 15 % at 1.4 GeV. However, reducing the recombination kicker switching times by 50 ns would be a challenging task already for the kick strength required at a transfer energy of 1.4 GeV. Additionally the gain from this option becomes marginal after the upgrade of the PSB-PS transfer energy to 2 GeV.

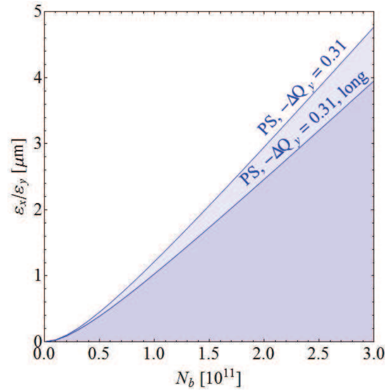

Figure 9: Brightness limit improvement of longer bunches with faster recombination kickers (Linac4, PSB-PS at 1.4 GeV, 25 ns bunch spacing).

Space charge reduction from transverse improvements Studies to compensate lattice resonances with skew sextupole magnets for LHC-type beams in the PS have started in 2013, following the installation of 4 sextupole magnets during the winter stop. At the nominal (fractional) working point of $q_x = 0.21$ and $q_y = 0.24$ the closest 4th order resonance is excited by space charge itself and cannot be easily compensated. Successful compensation of the $2q_x + q_y = 1$ and $3q_y = 1$ resonance lines has nonetheless been demonstrated [20] and a study program with the objective of simultaneous compensation of multiple resonances will continue after LS1.

Space charge effects may also be reduced by maximizing the physical beam size at low energies. The regular lattice of the PS features 10 lattice super-periods with 10 magnet units each [21]. The vertical dispersion, D_y, is ideally zero all around the ring. Introducing perturbations using the already existing skew quadrupoles, an irregular lattice with non-zero vertical dispersion (fully coupled optics) can be obtained [16]. Beta functions and dispersion around the PS circumference for an extreme case are plotted in Fig. 10. This would ideally provide a Laslett tune-

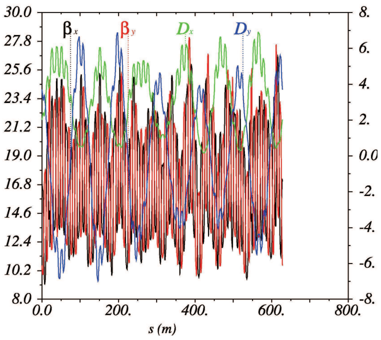

Figure 10: Lattice functions for the case of an extreme optics with vertical dispersion.

shift reduction of a factor of 1.5 in both planes. It is important to point out that extensive upgrades of various skew quadrupoles and their power converters would be required to reach such a configuration. As the optics functions are very irregular, simulations including space charge should be performed; especially the sensitivities with respect to coupling resonances remain to be studied. Assuming that no show-stoppers are identified by these simulations, first beam studies to evaluate the potential benefit of non-zero vertical-dispersion optics can be initiated after LS1.

Alternatives for special cases of limited upgrades

In the unlikely case of Linac4 connection before the upgrade of the PSB-PS transfer energy, space charge on the PS flat-bottom will become the most stringent limitation in the injector chain, essentially independent from the RF manipulation scheme. Figure 11 presents a limit plot for an injection energy into the PS of 1.4 GeV. The brightness deliverable by the PSB and acceptable for the SPS becomes almost twice the brightness which the PS can digest and almost nothing would be gained for LHC-type beams with Linac4.

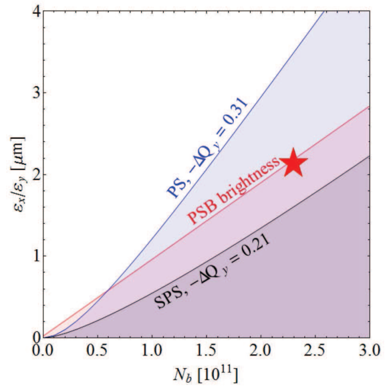

Figure 11: Limit plot for double-batch injection of 8 bunches into $h = 9$ and subsequent generation of 64 bunch batches (Linac4, PSB-PS at 1.4 GeV, 25 ns bunch spacing). The bunches are double split on the flat-bottom and again twice on the flat-top, $r_{\mathrm{split}} = 8$ [5].

To profit in this case from the significantly higher brightness with Linac4, single-batch transfer of 4 bunches into $h = 5$ buckets in the PS has been suggested [22]. As becomes clear from Fig. 12, the space charge limit in the PS matches again with the brightness deliverable by the PSB with Linac4.

After injection, each bunch is double split twice, resulting in 16 bunches at harmonic $h = 20$. Following a single harmonic number hand-over to $h = 21$ (Fig. 13), the 16 bunches are accelerated to the flat-top where each of them passes through the usual quadruple splitting ($r_{\mathrm{split}} = 16$), hence the PS produces batches of 64 bunches. These shorter batches would reduce the total number of bunches in the LHC by only about 3 %, but with reduced filling time thanks to the one third shorter cycle in the PS.

The lowest harmonic number, $h = 5$ (2.18 MHz), re-

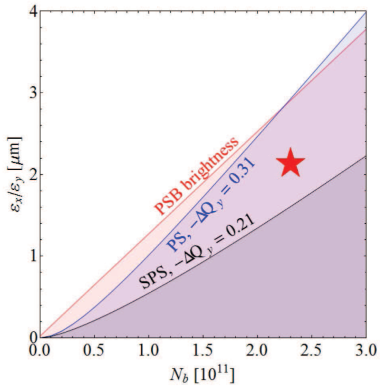

Figure 12: Limit plot for single-batch injection into $h = 5$ and subsequent generation of 64 bunch batches (Linac4, PSB-PS at $1.4\,$GeV, $25\,$ns bunch spacing).

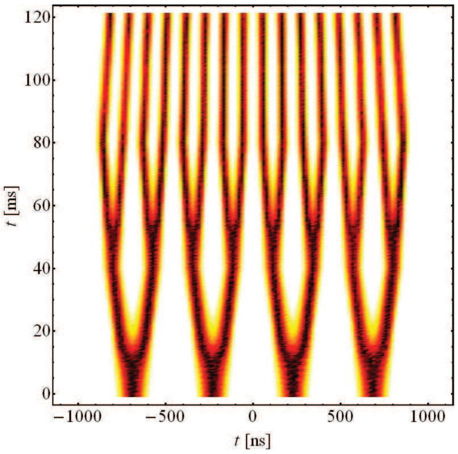

Figure 13: Single-batch injection of 4 bunches from the PSB into $h = 5$ in the PS.

quired with this alternative scheme at injection, is below the lower limit of the frequency range of the main RF cavities, but the development of a dedicated or the modification of an existing cavity could be envisaged.

ALTERNATIVE SCHEMES IN THE SPS

In the framework of the LIU upgrades the integer working point of the SPS has recently been moved from $Q_h/Q_v = 26$ to 20, operating with a new low transition energy optics which significantly improves longitudinal and transverse beam stability for LHC-type beams, but requires higher RF voltage [23]. The future baseline upgrades include measures against e-cloud instabilities and a major upgrade of the main $200\,$MHz RF system of the SPS. The latter mainly foresees the regrouping of the traveling wave cavities into four 3-section and two 4-section cavities [24, 25], the installation of two additional $1.6\,$MW RF power amplifiers and an upgrade of the beam control system.

Beyond this baseline, even further splitting to a larger number of shorter cavities has been considered, as well as the effect of the $8b\oplus4e$ scheme or a possible $200\,$MHz main RF system in the LHC. As part of the upgrade baseline, the successful mitigation of electron cloud instabilities by amorphous carbon coating [26] or scrubbing of the SPS beam pipe is assumed.

RF power considerations at extraction to LHC

At transfer to the LHC, the $200\,$MHz RF system in the SPS has to provide sufficient RF voltage to keep the bunch length below $1.7\,$ns (4σ Gaussian fit) to fit into the $2.5\,$ns long buckets of the LHC. Two effects determine the RF voltage and power requirements which are beam loading and longitudinal beam stability.

At fixed maximum RF power the voltage generated by the traveling wave accelerating cavities of the SPS [27] decreases with increasing beam intensity [28] due to beam loading. This voltage decrease at given RF power is illustrated for different RF system configurations in Fig. 14. The grey curve shows the voltage decrease for the present

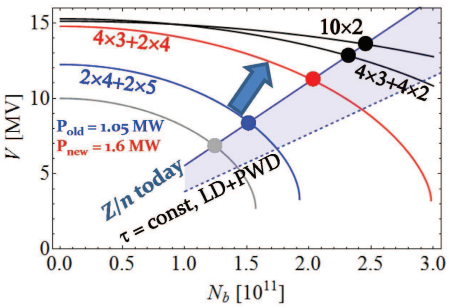

Figure 14: Beam loading ($25\,$ns bunch spacing) and single bunch stability limits for various arrangements of the $200\,$MHz cavities [25].

cavity configuration (two 4-section and two 5-section cavities) and an RF power of $0.7\,$MW per cavity. Pulsing the RF amplifiers with the revolution frequency following the upgrade of the LLRF system allows a power increase to about $1.05\,$MW per amplifier (blue curve). Following the LIU baseline upgrade, two new transmitters with an RF power of $1.6\,$MW each will become available. Together with the planned re-grouping of the cavity sections to four 3-section cavities and two 4-section cavities, the available voltage is increased significantly (red curve). Thanks to the addition of two more sections (in total 20 instead of 18 section), low- and high-intensity beams will profit from the baseline upgrade.

Alternatively, the same number of total cavity sections can be assembled to more but shorter cavities. The black curves of Fig. 14 show the available RF voltage for extreme cases of four 3-section with four 2-section cavities (two additional $1.6\,$MW RF transmitters compared to the baseline upgrade), as well as ten 2-section cavities (four additional transmitters). Essentially no further voltage gain can be achieved for lower intensity beams.

To finally estimate the voltage requirements at a fixed bunch length at transfer to LHC, longitudinal instabilities must be taken into account [25]. Considering only the voltage reduction by potential-well distortion (PWD) and the single-bunch instability due to loss of Landau damping (LD), a scaling law for the minimum longitudinal emittance emittance assuring stability can be derived [29, 30]. Assuming constant bunch length τ, it can be shown that the RF voltage must increase proportionally to the bunch intensity. The nominal LHC beam with 25 ns with an intensity of $1.3 \cdot 10^{11}$ ppb and a longitudinal emittance of $\varepsilon_l \simeq 0.35$ eVs can be taken as a reference case for the linear increase of RF voltage with intensity. Measurements have shown that it is indeed close to the longitudinal stability limit on the flat-top in the SPS [25]. Combining the intensity dependent voltage requirement with the available voltage at fixed RF power results in an estimation of the maximum intensity for the different RF system configurations (Fig. 14).

The grey point again indicates the present cavity configuration (two 4-section and two 5-section cavities). With a maximum voltage of about 7 MV an intensity of $1.3 \cdot 10^{11}$ ppb has been achieved on the flat-top. Upgrading the low-level RF system to operate the cavities in pulsed mode increases the available RF power per amplifier from 0.7 MW to 1.05 MW, allowing a maximum intensity of $1.5 \cdot 10^{11}$ ppb. A major improvement will be introduced by the re-grouping of the cavities as foreseen within the LIU baseline. Without any increase of bunch length, an intensity of $2.0 \cdot 10^{11}$ ppb can be obtained. It is important to point out that the contribution from loss of Landau damping to the gradient of the line in Fig. 14 scales with $\varepsilon_l^{-5/2}$ and is directly proportional to the broadband impedance, Z/n. Permitting only 10 % longer bunches at transfer to the LHC increases the maximum intensity estimate to $2.5 \cdot 10^{11}$ ppb.

The effect of further shortening the RF cavities is shown in Fig. 15, indicating the maximum achievable intensity per bunch versus total RF power. Clearly, the step for the baseline upgrade from two 4-section and two 5-section to four 3-section and two 4-section cavities, adding two 1.6 MW amplifiers, results in the most efficient intensity increase. The next step to four 2-section and four 3-section cavities, requiring two more additional power amplifiers, gains only half of the previous step. Moving to an extreme case of ten 2-section cavities demands for excessive RF power with little effect on maximum intensity per bunch.

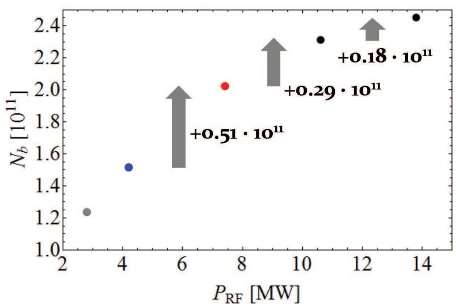

Figure 15: Total RF power versus maximum bunch intensity (25 ns bunch spacing). The colours correspond to those of Fig. 14.

8b⊕4e bunch pattern schemes At fixed bunch intensity, the line density averaged over 300 ns is reduced by 2/3 using the $8b \oplus 4e$ bunch pattern schemes. With a filling time of the RF cavities in the SPS of about twice that duration, one can expect 50 % higher bunch intensity for the same voltage as illustrated in Fig. 16. However, as potential well distortion and loss of Landau damping are single-bunch effects, no scaling is applied to the instability line (with respect to Fig. 14). The potential gain with the $8b \oplus 4e$ schemes is thus below 50 % and to reach a bunch intensity of $3 \cdot 10^{11}$ ppb with the baseline RF upgrade would require an impedance reduction by approximately 50 % (Fig. 16, blue shaded area).

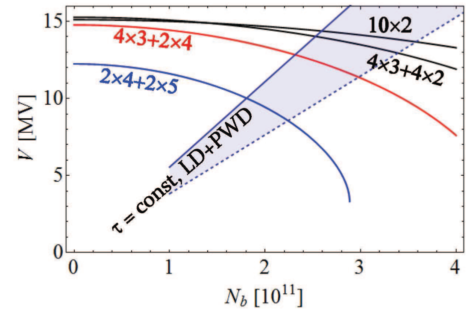

Figure 16: Improvements with the 8b+4e bunch pattern scheme (25 ns bunch spacing).

Proof-of-principle beam tests of the $8b \oplus 4e$ scheme in the whole accelerator complex will become possible after LS1 at reduced performance level to evaluate its potential gain with respect to the nominal filling scheme.

200 MHz RF system in the LHC The major constraint of short bunches at transfer from SPS to LHC is relaxed with a 200 MHz RF system in the LHC. Further benefits of a lower frequency main RF system in the collider are discussed in [15]. While the beam loading curves remain unchanged (Fig. 17), the single bunch instabilities are well suppressed thanks to the strong dependence of the loss of Landau damping on longitudinal emittance. Assuming a longitudinal emittance of 1 eVs, the RF voltage for matched transfer into a 200 MHz/3 MV bucket in the LHC requires an intensity independent voltage of 7.5 MV in the SPS. In conjunction with the baseline RF upgrade the maximum intensity per bunch on the SPS flat-top is estimated at above $2.5 \cdot 10^{11}$ ppb, clearly highlighting the benefit of a 200 MHz RF system in the LHC for the injectors.

Performance during acceleration in the SPS

Next to the constraints at transfer to the LHC, the available RF power also limits the maximum intensity during

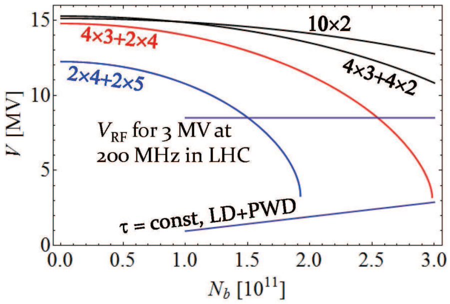

Figure 17: Larger longitudinal emittance anticipating a 200 MHz RF system in the LHC (25 ns bunch spacing).

the acceleration ramp. Assuming the present cavity configuration and magnetic cycle for LHC-type beams, the bucket area during the first part of the cycle is limited to $A_b = 0.6$ eVs at an intensity of, e.g., $1.2 \cdot 10^{11}$ ppb (Fig. 18). Without reducing the ramp rate and hence stretching the

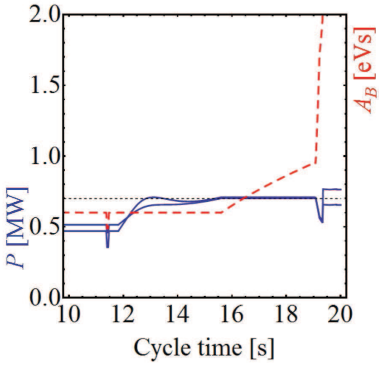

Figure 18: RF power and resulting bucket area along the LHC cycle in the SPS for the present configuration with a bunch population of $N_b = 1.2 \cdot 10^{11}$ (25 ns bunch spacing). The different blue curves show the RF power for the 4-section and 5-section cavities.

acceleration cycle, this leaves little margin for further intensity increase.

Already the baseline RF upgrade will provide a larger bucket area ($A_b = 0.75$ eVs at the start of acceleration with margin for increase during the cycle) for an intensity of $2.3 \cdot 10^{11}$ ppb (Fig. 19), beyond the limitation at transfer to the LHC discussed above. In combination with the $8b \oplus 4e$ scheme, an intensity of up to $3.0 \cdot 10^{11}$ ppb is expected to be accelerated, thanks to the 50 % reduction of the average line density. Clearly, the baseline RF upgrade remains indispensable to profit from the benefit of a new 200 MHz RF system in the LHC.

Extending the upgrade to four 2-section cavities and four 3-section cavities (in total four new 1.6 MW RF amplifiers), the intensity reach for the 25 ns beam could be pushed above $3 \cdot 10^{11}$ ppb. Figure 20 illustrates RF power and bucket area for a bunch population of $3.2 \cdot 10^{11}$ ppb.

As shown above, the baseline upgrade of the 200 MHz including the re-grouping of cavity sections and the con-

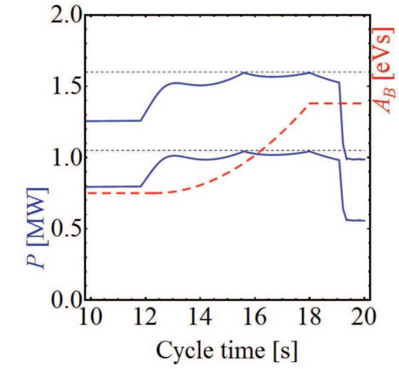

Figure 19: RF power and resulting bucket area along the LHC cycle in the SPS for the baseline upgrade configuration with a bunch population of $N_b = 2.3 \cdot 10^{11}$ (25 ns bunch spacing). The blue traces indicate the power of a new amplifier connected to a 4-section cavity (top) and an existing amplifier connected to 3-section cavity (bottom).

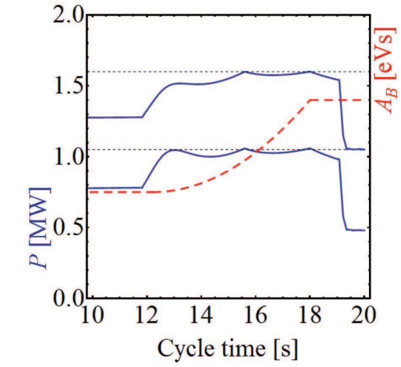

Figure 20: RF power and resulting bucket area along the LHC cycle in the SPS for in total 8 cavities (4 additional power plants) configuration with a bunch population of $N_b = 3.2 \cdot 10^{11}$ (25 ns bunch spacing). The two blue curves show again the power with new (top) and existing (bottom) RF amplifiers.

struction of two new power amplifiers represents a major gain in bunch intensity during acceleration, as well as at transfer to the LHC. Alternative options to further split the cavities, and add even more RF power, may be beneficial, but the incremental gain becomes less significant.

Transverse improvements

In terms of alternative improvements in the transverse plane, the SPS offers less possibilities and flexibility than the pre-injectors. Firstly, similar to the increase of the extraction energy of the PSB, the PS may have a small margin to extract above the present (total) energy of 26 GeV. At its initial commissioning in the late 1950s, a flat-top energy of 28 GeV had been reached [31], but such beams were not extracted. Even though the PS ejection elements, as well as the SPS injection elements have not been designed for this high energy, the LHC-type beams have small transverse emittances compared to fixed target beams. Hence slightly too small kick angles at PS ejection and SPS injection are not expected to cause losses and can most likely be corrected. Raising the transfer to 28 GeV results in a space charge tune shift reduction in the SPS of 15 % with an immediate gain for all schemes limited by the SPS space charge. First studies to extract beams above 26 GeV from the PS are planned for 2014.

Secondly, instead of moving both horizontal and vertical integer tunes from $Q_h/Q_v = 26$ to 20, a split-tune optics with $Q_h = 20$ and $Q_v = 26$ has been proposed [32]. Fig. 21 illustrates the normalized space charge tune shifts at SPS injection versus transverse emittance. The most favorable situation can be achieved with the split-tune optics. Additionally, the kick strength required at injection is reduced when moving from $Q_v = 20$ back to $Q_v = 26$, leaving some margin for the injection at energies above 26 GeV. Transverse instability thresholds can be slightly increased by the reduction of the vertical beta function for $Q_v = 26$.

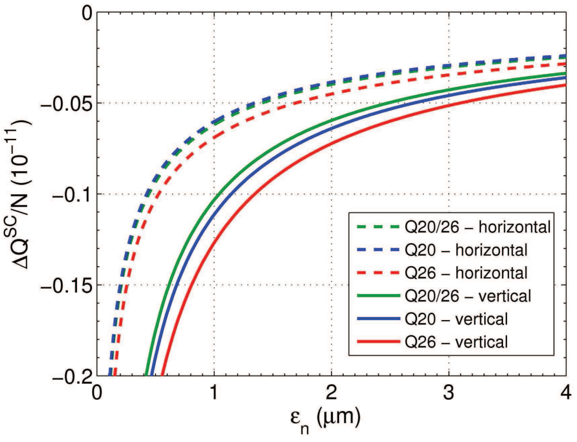

Figure 21: Normalized horizontal and vertical space charge tune shift versus transverse emittance for Q20, Q26 and split-tune optics.

Finally, as in the PS, a lattice with non-zero vertical dispersion could be envisaged in the SPS. However, important changes to the cabling and the supply of the skew quadrupole magnets, which are presently grouped in families, would be required.

CONCLUSIONS

No magic alternative to the present baseline upgrades, including Linac4, the increase of the PSB-PS transfer energy to 2 GeV and a major RF upgrade in the SPS, has been identified. The flexibility of the pre-injectors allows an important number of different production schemes to increase bunch intensity and beam brightness. Some of these schemes deliver sufficiently high brightness to push the SPS to its space charge limit.

The acceleration and transfer to LHC of bunches with larger longitudinal emittance and higher intensity in the SPS will become possible following the major RF upgrade. A new RF system at 200 MHz in the LHC would additionally have beneficial effects for the injectors as it further relaxes the constraints on bunch length and longitudinal emittance at transfer from the SPS, estimating a maximum bunch intensity beyond $2.5 \cdot 10^{11}$ ppb and shifting possible limits to the lower energy part of acceleration. However, the brute-force approach of adding even more than two 1.6 MW power amplifiers has only limited reach as the absolute intensity gain when moving from 6 to 8 cavities is half of the extra intensity reach when moving from 4 to 6 cavities.

A number of interesting alternatives have been identified which will be accessible to machine development studies after LS1 to validate their potential benefits:

- **PSB:** hollow bunches,
- **PS:** flat or hollow bunches, special flat-bottom optics, PBC, $8b \oplus 4e$ schemes, PS-SPS transfer energy above 26 GeV,
- **SPS:** split-tune optics, higher intensity at transfer to the LHC with slightly longer bunches.

Even more combinations of the various alternatives can be imagined.

Finally, the flexibility of producing a wide range of beam parameters represents an important asset of the injector chain which allows to quickly react to requests from the LHC in case of unforeseen issues. The $8b \oplus 4e$ scheme is one example of an alternative in case of persistent electron cloud issues in the LHC with 25 ns bunch spacing after LS1. This flexibility of CERN's injector chain should be preserved in the future.

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APPENDIX

Many alternative options have already been studied by numerous authors and have therefore not been reconsidered in the present report. Table 3 gives a non-exhaustive list of these alternative options.

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Table 3: Non-exhaustive list of further alternative options studied by other authors.

	Alternative scheme	Remark	Reference
PSB	Vertical painting at PSB injection with Linac4	Minor improvement	[33]
	Replacement of the PSB by a Rapid Cycling Synchrotron	Study not continued	[34]
PS	H^- injection from SPL-like Linac into the PS	Together with 40 MHz RF	[4, 35, 36]
	40 MHz-based main RF system	Needs Linac for 40 MHz structure	[4]
	Separated function lattice with 30 GeV energy	Essentially new accelerator in PS tunnel	[37]
SPS	Low frequency (40 MHz capture cavity in the SPS)	Issues with beam stability	[38]
	Splitting or merging	Would require low-frequency cavity	
	Slip stacking to increase bunch intensity	Issues with beam loading and ε_l	[39]

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