POSSIBLE IMPROVEMENTS TO THE EXISTING PRE-INJECTOR COMPLEX IN THE FRAMEWORK OF CONTINUED CONSOLIDATION

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Abstract

The situation of the present pre-injection complex will be discussed with particular emphasis on the performance limitations. Mitigation measures will be discussed assuming that substantial consolidation work can be devoted to such improvements. Possible scenarios for the implementation of these measures will be outlined, together with an analysis of the impact on the performance of the LHC machine.

SPACE CHARGE LIMITS IN PSB AND PS

For relatively low-energy machines, such as the PS Booster (PSB) and the PS, it is customary to consider space charge, and in particular the incoherent tune shift at injection, as the main limitation of the machine performance.

It is recalled here that the tune shift generated by space charge effects scales according to

$$\Delta Q \propto -\frac{N_b}{\beta \gamma^2 \varepsilon_n}, \qquad (1)$$

where N_b represents the bunch intensity, $\beta\gamma^2$ the relativistic factors, and ε_n the transverse normalised emittance.

The analysis of space charge limits was considered in the past to propose an increase of the PSB extraction energy to adapt the PSB and PS to the performance required to operate as LHC injectors [1]. Such an energy upgrade became one of main changes performed in the PSB in view of preparing the pre-injectors to the LHC [2].

At that time the key PS parameters used for the computations were:

- $\varepsilon_n(1\sigma)$=2.5 μm
- Total bunch length = 180 ns
- Harmonic number = 8
- $N_{b,\,max}=1.7\times10^{11}$ p
- |ΔQ| less than 0.3

The preservation of the transverse emittance all along the injectors' chain was a source of concern, which explains the rather tight limit imposed. Also, it is important to stress that the maximum intensity/bunch was determined by the specification of the ultimate LHC beam, which, in turn, was based on the maximum beam-beam tune shift tolerable in the LHC. The ultimate intensity was felt as a real hard limit for the LHC. The use of these parameters provided the value of the PSB extraction energy increase from 1 GeV (kinetic energy) to 1.4 GeV, which is the current value.

It is also important to mention that since that time the scheme to generate the nominal LHC beam in the injectors was changed [3], mainly due to a longitudinal microwave instability inducing a momentum blow-up during de-bunching at high energy in the PS [4]. In particular, the number of injected bunches in the PS was reduced to six, leaving one of the seven buckets in the PS empty at injection. These changes will not be considered in the following and, for the sake of comparison, the same parameters as those used in the past will be applied.

The approval of the Linac4 project [5] will push further the PSB performance. In fact, the increase of the injection energy in the PSB from 50 MeV to the proposed value of 160 MeV will bring, in terms of the relativistic factors $\beta\gamma^2$, an increase of a factor two. This automatically decreases the space charge tune shift proportionally, hence doubling the intensity that can be injected into the PSB within unchanged normalised transverse emittances. However, even if the space charge limit in the PSB will be lifted by Linac4, the next bottleneck, namely the limitations in the PS, will become visible.

A detailed analysis on the performance level of the current PSB/PS complex and of the new capabilities with the Linac4 was carried out in Ref. [6]. The current situation is such that the space charge limit is well-balanced between the PSB and the PS (neglecting a small margin due to the change of harmonic number from 8 to 7 since the increase of PSB extraction energy in preparation for the LHC). Therefore, the improved performance related to the advent of the Linac4 can be fully exploited only lifting the space charge limit in the PS, hence increasing the PSB extraction energy. The key figure, assuming Linac4 in operation, is then 3.6×10^{12}p per PSB ring, which corresponds to the maximum intensity that can be injected into the PSB while remaining within acceptable space charge limits.

In Fig. 1 the key quantities, namely the maximum space charge tune shift, the relative variation of the relativistic factors $\beta\gamma^2$, and the reduction of beam size are shown as a function of the relative strength increase in the PSB main dipole magnets.

Ideally, one should recover the factor of two in $\beta\gamma^2$ due to Linac4 in order to restore the equal limitation of the two machines. However, this is certainly excluded by hardware considerations. Hence, the region of interest is limited between an increase of magnet strength of 30-40 %. The choice of the actual value is mainly dictated by the capabilities of the PSB magnets, i.e., their remaining strength margin after already two energy upgrades (from initially 800 MeV to 1 GeV and then to 1.4 GeV for the LHC).

For the two limiting values of the PSB upgrade, the corresponding bunch intensity at PS extraction for a 25 ns spacing LHC beam might be:

- PSB main dipoles strength increase of 40 % (2.17 GeV kinetic energy) : $N_b = 3\times10^{11}$p
- PSB main dipoles strength increase of 30 % (2 GeV kinetic energy): $N_b = 2.7\times10^{11}$p

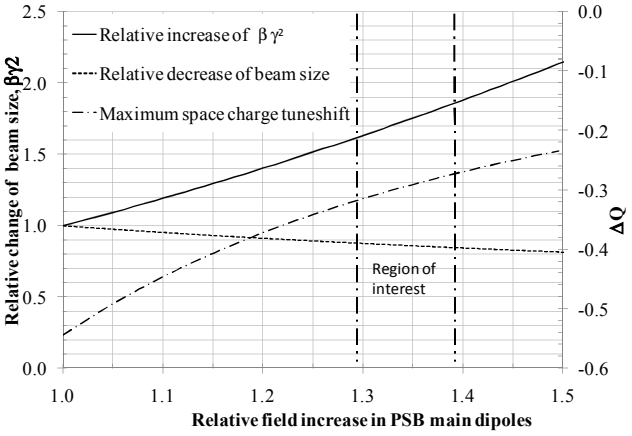

Figure 1: Key quantities for the proposed extraction energy upgrade of the PSB, namely maximum space charge tune shift (scale on right axis), relative variation of $\beta\gamma^2$, and relative change of beam size due to a variation of $\beta\gamma$ (scale on the left axis).

These two figures can be directly compared with the ultimate LHC beam intensity.

Nevertheless, the previous considerations concerning the changes in the generation of the LHC-type beams could be applied to push even a bit further the intensity limit. Indeed, the reduction in harmonic in the PS, from 8 to 7, makes it possible to inject slightly longer bunches. In principle bunch lengths of about 200 ns should be possible (to be confirmed, in any case, by dedicated experimental studies). Therefore, it is conceivable to use longer bunches and to increase the intensity estimates provided for the PSB energy upgrade by a factor of about 10 % (corresponding to the ratio 200/180).

BEAM DYNAMICS CHALLENGES

The estimated intensity reach derived in the previous section is simply based on considerations about the maximum space charge tune shift tolerable. This is certainly an important criterion, but does not ensure that the derived bunch intensity will be achievable without a number of additional measures.

The PSB should be capable of making use of the intensity at higher energy delivered by the Linac4, independently on whether an extraction energy upgrade takes place. Such an upgrade allows improving the PS performance by lifting the space charge limit at PS injection.

Therefore, the overview of beam dynamics challenges presented here focuses on the PS machine, only. A list of potential issues will be discussed, based on the current knowledge of PS performance and the results of numerous Machine Development (MD) studies performed in the past years. These results will serve as a basis for a preliminary estimate of the bottlenecks and required cures to overcome them. It is clear that a vigorous campaign of MDs should be planned in order to define the most appropriate strategy to make use of the increased performance due to the PSB upgrade.

Transverse issues

The injection process in the PS machine for LHC beams with 25 ns bunch spacing is based on the double-batch technique. This implies that a number of bunches remain at injection energy for 1.2 s while waiting for a second batch to be injected. Then the seven bunches are split and accelerated to top energy. During the long period at injection energy, space charge effects can lead to slow beam losses. This phenomenon can also be seeded by coupling between longitudinal and transverse motion induced by space charge. A transverse trapping/de-trapping mechanism was proposed to explain the slow losses at injection energy combined with bunch shortening (see Ref. [7] and references therein).

When reaching 26 GeV/*c* the beam is affected by transverse instabilities, whose type (single or coupled bunch) requires still some detailed analysis, but is certainly linked with electron could effects [8, 9]. An example of beam observation with an LHC-like beam made with a pick-up in the TT2 transfer line is shown in Fig. 2, where the impact of a solenoidal field in the suppression of the baseline drift is clearly visible. Such a drift is considered to be the signature of electron-cloud formation (see, e.g., the references in [10] for an overview of this topic).

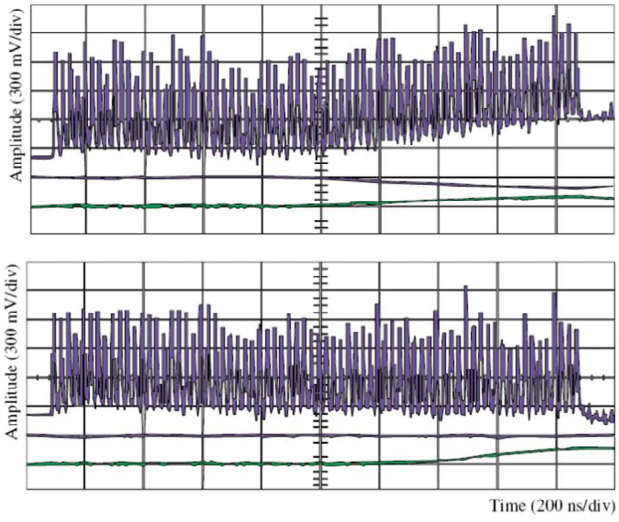

Figure 2: Sum signal from a pick-up in the TT2 transfer line without (upper) and with solenoid field (lower) due to the passage of 72 LHC-type proton bunches.

The signal from a LHC beam after bunch splittings and compression prior to ejection measured with a pick-up in the PS ring is shown in Fig. 3, where the horizontal,

vertical, and sum signals are visible. The signs of instability in the horizontal plane are clearly visible.

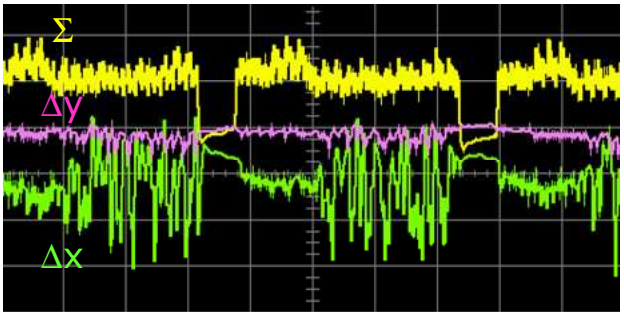

Figure 3: Horizontal, vertical, and sum signal from a pick-up in the PS ring for a LHC-like beam. The bunch intensity is 0.55×10^{11}p.

The performance achieved so far corresponds to a bunch intensity of about 1.3×10^{11}p with 25 ns bunch spacing, which becomes unstable at top energy whenever the bunch length is shorter than about 12 ns. The instability rise time is of a few ms [9].

Any extrapolation of such performance to higher bunch intensities is certainly not easy. However, it is definitely possible to list potential cures, namely:

- Injection energy:
  - Improved working point control (tune and chromaticity).
- Top energy:
  - Control bunch length in order to avoid too short bunches for a too long time. Therefore, a faster bunch rotation scheme (double bunch rotation) than the nominal gymnastics would be highly beneficial [11] (see Fig. 4 for a sketch of the nominal bunch rotation gymnastics at top energy).
  - Transverse damper to stabilise the beam (single and coupled bunch instabilities).
  - Cure electron-cloud effects with, e.g., appropriate coating of the PS vacuum chamber.

Longitudinal issues

The nominal LHC beam suffers from longitudinal coupled bunch instabilities of dipole mode. Presently, a mostly analogue longitudinal feedback is currently in operation in the PS machine, and the instabilities are cured by means of two 10 MHz cavities in sections 86 and 96. These two cavities are operated for acceleration and as longitudinal feedback kickers simultaneously, which limits the possible modes to be damped to those close to the RF harmonic. This is certainly non-optimal. In 2009 stabilisation through acceleration to top energy of a 25 ns spacing beam, 1.4×10^{11}p/bunch with a longitudinal emittance twice as small with respect to the nominal value, was achieved [12]. It is worth mentioning that this was made possible thanks to the spare 10 MHz cavity in section 11 used as dedicated longitudinal kicker for the existing feedback.

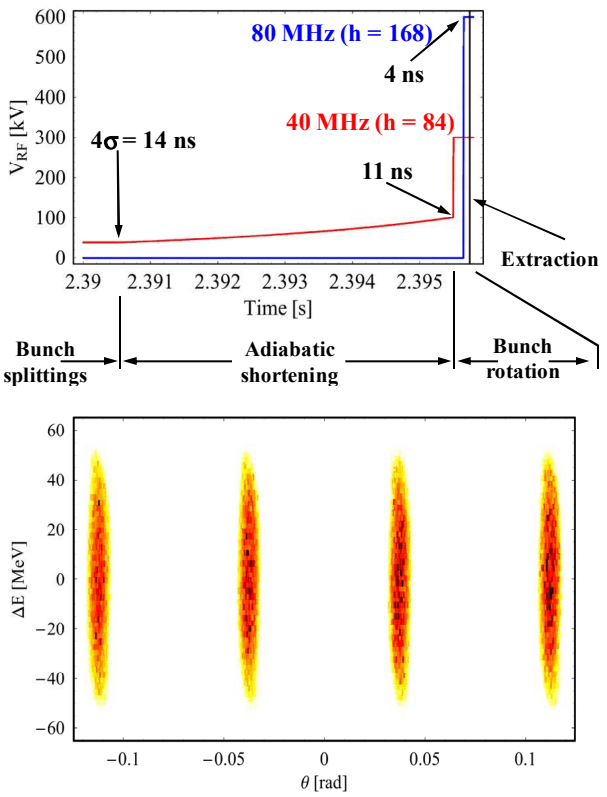

Figure 4: Sketch of the nominal bunch rotation gymnastics at top energy (upper) and final stage after the double bunch rotation as from numerical simulations (lower). The final bunch length is comparable to the nominal one, but the time to rotate the bunches is about 4.5 ms faster [11].

To extrapolate such a result to higher intensity needs some assumptions such as a scaling of the instability threshold with intensity and longitudinal emittance. A scaling according to N_b/ε_l seems justified as similar coupled-bunch instabilities are presently observed with 25 ns and 50 ns variants. Both of them are accelerated at the same harmonic number, but the 50 ns variant has twice less intensity and twice less longitudinal emittance compared to the 25 ns beam. Hence, intensity up to about 2.8×10^{11}p/b with a nominal longitudinal emittance might be stabilised during acceleration with a dedicated longitudinal feedback. It is essential to stress that during the dedicated MDs devoted to this topic further splitting in the longitudinal plane on the flat top was never attempted because of the small longitudinal emittance (twice too small). Furthermore, especially beam-loading issues in all RF systems will become much more important at higher intensities than at present, which must be carefully investigated. Therefore, even if the experimental observations provided encouraging results concerning the possibility of stabilising a higher-than-nominal bunch intensity, still numerous efforts need to be devoted to MD studies and theoretical analysis for specifying the requirements for the systems needed to stabilise the beam and to assess the actual intensity limit in the PS in terms of longitudinal instabilities.

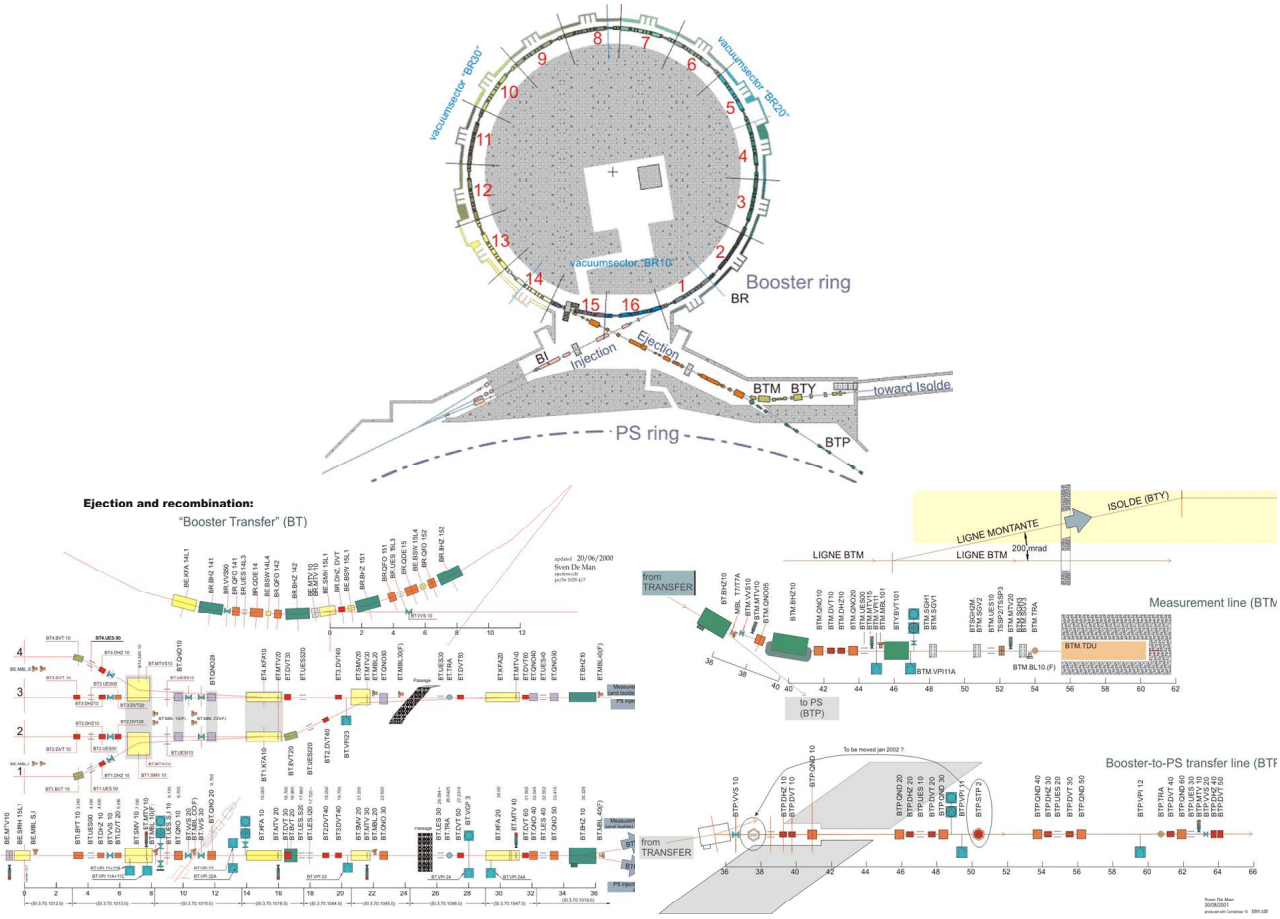

Figure 5: Overall layout of the PSB, the injection and extraction lines, and the transfer lines to ISOLDE and PS (upper part). Details of the BT line (lower left) and of the BTP and BTY lines (lower right).

IMPLICATIONS OF PSB ENERGY UPGRADE

The increase of the PSB extraction energy will have a deep impact on numerous systems in the PSB itself, but also in the transfer line to PS, the beam dump and possibly ISOLDE, as well as the injection process in the PS. It is important to stress that in this context it was assumed that the energy of the beam delivered to ISOLDE would not be changed. Of course, this scenario should be discussed with the ISOLDE management, which was not done in the framework of this study. Nevertheless, it is important to stress that leaving the energy of ISOLDE beam at 1.4 GeV would have the beneficial side effect of roughly doubling the beam intensity produced for the facility. Indeed, the faster pulsing imposed by the requirement of accelerating to 2 GeV within 1.2 s would imply that the 1.4 GeV could be delivered on a 0.6 s basis. Tests with the present PSB main power supply confirmed the feasibility of 0.6 s pulsing [13], hence this should be *a fortiori* possible with the new main power supply. Since the 0.6 s tests were performed, the Linac4 was approved and the new H^- injection hardware is designed in order to be compatible with 0.9 s pulsing of the PSB. This fact, together with the extraction septa performance (a novel septum coil fixation would be needed), the RMS current in the PSB main magnets, cooling capacity, RF systems performance, saturation effects due to the different extraction energies, and the transfer line elements should be carefully analysed in order to assess what needs to be changed to enable 0.6 s pulsing capabilities. The need of delivering 1 GeV beams to ISOLDE should also be re-discussed as it could have important impact in the PSB extraction energy upgrade, in particular, for the operation of the transfer lines (double of triple pulse-to-pulse modulation - PPM)

PSB magnets and main power converter

Numerical simulations have been performed to determine the actual capabilities of the PSB main magnets (dipoles and quadrupoles). In Fig. 6 the distribution of the field lines in the main dipoles is plotted for the proposed increased energy to 2 GeV.

The evaluation of the impact of the higher energy on the field quality is shown in Fig. 7, where the magnetic

field errors are reported as a function of the horizontal amplitude for Ring 3 and 4. In terms of magnetic multipoles, this would generate non-linear components, but the magnitude of these effects seems small and the impact on beam dynamics should be negligible. Of course, this qualitative statement must be confirmed by detailed numerical simulations. Different saturation effects in outer and inner rings lead to a lower magnetic field (dipolar component at the centre of the gap) in the outer rings in addition to multipolar effects. In order to obtain the same magnetic field in all four rings, the current exciting the magnetic field is increased for the outer rings by adding a trim power supply. This implies that a higher current differential should be applied with respect to the situation in operation nowadays.

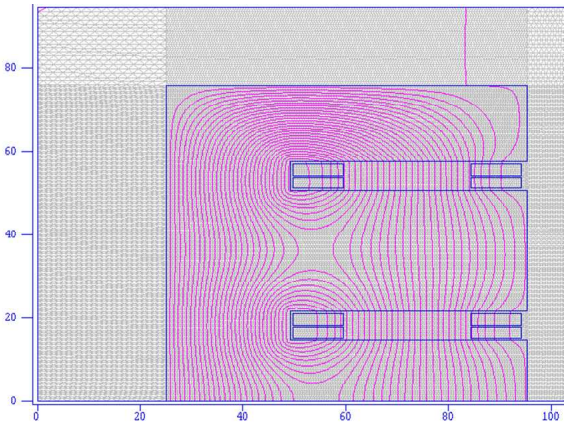

Figure 6: Distribution of field lines in the PSB main dipoles.

The findings are summarised in Table 1.

The main point to stress is that from the computations made the situation of the cooling power available will need to be reviewed. In principle, the additional cooling capacity as from Table 1 could be partially provided by an upgraded cooling station, the remaining fraction of heat load being absorbed by an increase of the operation temperature of the dipoles or an optimisation of the magnet cooling circuits and the magnetic cycle. Particular care shall be devoted to the analysis of the impact of a higher water flow rate to avoid corrosion issues as those observed in the SPS.

The situation for the main quadrupoles is very similar and the main results are summarised in Fig. 8, where the field lines, the quadrupolar gradient, and the magnetic errors are shown.

Also in this case no particular issue was found and the results are listed in Table 2 for focusing and defocusing quadrupoles. The situation of the cooling power does not seem to be a source of concern, but further studies are ongoing.

Lastly, it is believed that the orbit and the multipole correctors with nested quadrupoles, sextupole, and octupole windings have enough margins to allow increasing the extraction energy. However, more detailed studies are needed to confirm this.

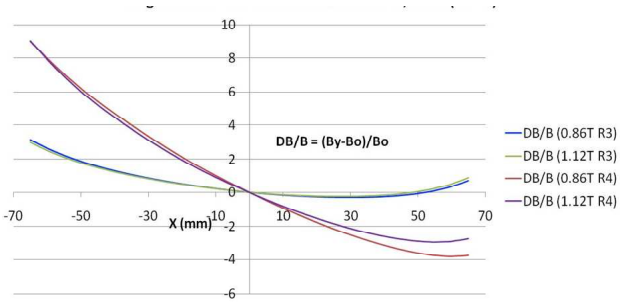

Figure 7: Magnetic field errors in units of 10^{-4} for Ring 3 and Ring 4. The situation for the current level of magnetic field as well as for the proposed one is shown in this plot.

Table 1: Main parameters for PSB main dipoles (current situation and proposed upgrade)

	Present	**+30%**
Field strength (T)	0.86	1.12
Peak current (A)		
Inner Rings	4032	5255
Outer Rings	4065	5515
Power consumption (kW)	49	83
Q (at ΔT= 8 K) (l/min)	26	44
ΔT at Q = 26 l/min) (K)	28	47

It is clear that such a major upgrade cannot take place without a revision also of the power supplies of the main magnets. Indeed, the currently installed main power converter cannot cope with the increased extraction energy. A new one is required as well as a new trim power converter for the gaps of the outer rings. The multipole magnets should not require any new power converter.

PSB RF

The proposed increase in extraction energy would bring f_{rev} to 1.81 MHz, hence slightly outside the range of the C02 cavities. However, this can be brought easily within the tuning range capabilities by shifting up the frequency interval of the cavities. This is made possible by the increased injection energy with the advent of the Linac4.

Apart from this point it is clear that the increased intensity in the PSB would require re-considering the whole system, in particular in terms of power requirements. This consideration applies also to the C04 cavities, which do not suffer from any need to shift the frequency range, but might need revision of the power part. In this respect, however, it will be easy to find synergies with the vigorous consolidation programme required in any case for maintaining in operation the PSB for the coming 25 years [14] and upgrades needed to fully profit of Linac4 for high intensity beams.

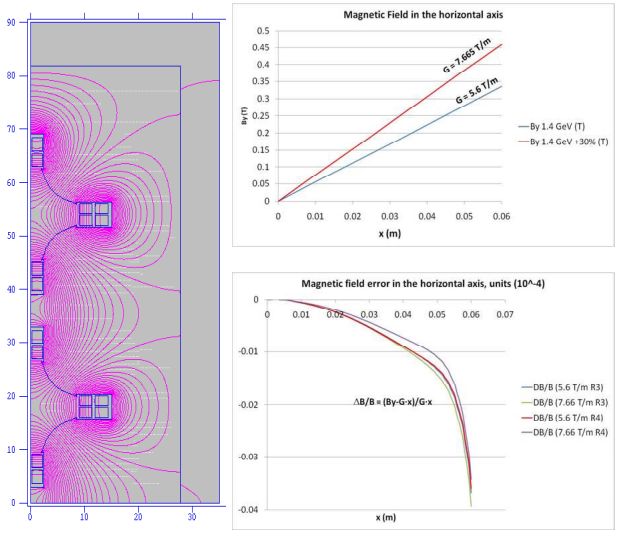

Figure 8: Field lines for the PSB main quadrupoles (left); quadrupolar gradient vs. amplitude (upper right); magnetic field error in units of 10^{-4} vs. amplitude for Ring 3 and Ring 4 (lower right).

Table 2: Main parameters for PSB main quadrupoles (current situation and proposed upgrade) estimated from the main power supply current without taking into account trims.

Focusing quadrupoles	**Present**	**+30%**
Field gradient (T/m)	5.60	7.66
Peak current (A)	4032	5255
Power consumption (kW)	16	27
Q (at ΔT= 20 K) (l/min)	12	20
ΔT at Q = 12 l/min) (K)	20	34
Defocusing quadrupoles		
Field gradient (T/m)	5.60	7.66
Peak current (A)	4032	5255
Power consumption (kW)	11	19
Q (at ΔT= 20 K) (l/min)	8	14
ΔT at Q = 8.3 l/min) (K)	20	34

Transfer line magnets and power converters

The proposed strategy implies to review the situation of the transfer line magnets for the BT, BTP, and BTM lines (see Fig. 5). Under these assumptions the BTY transfer line (see Fig. 5) should remain in its current state. A detailed analysis of the situation, namely which magnets can be re-used and which ones should be replaced, is not done to-date. Still, it is worth stressing that saturation effects due to the two extraction energies (transfer to PS or ISOLDE) should be looked at carefully once the analysis will be made.

The original specification of the power converters can be found in Ref. [2]. The current performance, i.e., the minimum and maximum operational current values of the common part of the lines was adapted to the need of a PPM use of the transfer lines between ISOLDE and PS as final destination of the beams. This means that there is margin on the BTP line for re-adjusting the operational interval of the power converter to re-use at least some of them in the scenario of an increased PSB extraction energy. The gap between a 1.4 GeV ISOLDE cycle and a 2 GeV PS cycle will drastically increase the power needed for the BT and BTM power converters. As already mentioned, the need to deliver 1 GeV beams to ISOLDE would require triple PPM operation.

Kickers

Kicker magnets are needed for extracting the beam from the PSB, for recombining bunches from the four PSB rings prior to PS injection, and for injecting into the PS ring.

Booster extraction BE.KFA14L1: The kicker consists of 4 delay line magnets (Z_0 = 25 Ω) pulsed in parallel for each PSB ring. Their generator consists of a gas filled Pulse Forming Line (PFL) rated 60 kV and discharged by a 60 kV thyratron.

The maximum PFL voltage required at 1.4 GeV is about 42.5 kV. At 2 GeV the voltage required will be about 55 kV. The kicker rise time is expected to be longer by a few nanoseconds as a consequence of the voltage increase. The thyratron lifetime is also expected to decrease due to a higher current. A new ejection kicker tank will be required due to magnet ferrite saturation and the actual tank should also be upgraded to serve as a spare which does not exist for the moment. No operational margin will be left.

Booster extraction bumpers BE.BSW14L4, 15L1, 15L4: The magnet current at 1.4 GeV is 525 A. At 2 GeV the current will be within the limits of booster magnet type 5 (I_{max} = 765 A) and type 6 (I_{max} = 845 A) and can be used. Also the generator voltage will be within the capabilities of the current system.

Booster transfer kickers BT1.KFA10, BT4.KFA10: Each kicker consists of 2 delay line magnets (Z_0 = 12.5 Ω) pulsed in parallel. Each generator consists of a gas filled PFL discharged by a 60 kV thyratron. The pulse generators have the same limitations as the BE.KFA ones. Hence, all considerations already made would apply for this case. In particular it is recommended a change of ferrite grade, which would have also a positive impact on the vacuum performance.

Booster transfer kickers BT.KFA20: The kicker consists of 2 delay line magnets (Z_0 = 12.5 Ω) pulsed in parallel. The magnets are identical to the BTI.KFA10 ones, except the ferrite that has already been upgraded, but the pulse generator configuration is not. In order to gain a few nanosecond rise time, the magnets are part of the PFL and are then charged to the full PFL voltage. Operation at 2 GeV requires a PFL voltage of 37 kV, which is at the limit of the magnet voltage hold-off.

If necessary, the system could be reconfigured to be identical to the BTI.KFA with a loss of about 13 ns rise time.

PS injection kicker PI.KFA45: Each of the four magnet modules can be used in terminated or short-circuit mode.

Table 3: Main parameters and comments concerning kickers' upgrade

	BE.KFA			BSW			
Beam energy (GeV)	**Required voltage (kV)**	**Magnet**	**Switch**	**PFN**	**Required current (A)**	**Magnet**	**Generator**
1.4	42.5	Ok	Ok	Ok	525	Ok	ok
2.0	55.25	New magnets and tank	Ok	Ok	682.5	Ok	ok

	BT.KFA10					BT.KFA20		
Beam energy (GeV)	**Required voltage (kV)**	**Magnet**	**Switch**	**PFN**	**Required voltage (kV)**	**Magnet**	**Switch**	**PFN**
1.4	42.5	Ok	Ok	Ok	28	Ok	Ok	Ok
2.0	55.25	Ok, but ferrite change recommended and new tank possibly	Ok	Ok	36.4	Ok	Ok	Ok

PI.KFA45				
Required voltage (kV/module)	**Magnet**	**Switch**	**PFN**	**Module in short-circuit mode**
80	Ok	Ok	Ok	No
104	Ok	Ok	Ok	Yes

The generators consist of a gas filled PFL discharged by a 100 kV thyratron. Another thyratron is used to short-circuit the magnet terminator when the short-circuit mode is requested. When used in short-circuit mode, the kick is increased by 82 % at full PFL voltage (80 kV). The main drawbacks of the short-circuit mode are:

- increase of flattop ripple from ± 2 % to ± 3 %
- increase of post pulse ripple from ± 1.25 % to ± 1.5 %
- increase of rise time (2-98)% from 42 to 68 ns
- increase of fall time (98-2)% from 68 to 87 ns

The first two items might have an impact on the emittance blow-up of the injected beams. Preliminary computations seem to indicate that such an impact is negligible. The longer PS injection kicker fall times have no impact since they are still shorter than the recombination kicker rise times (and, in particular for LHC beams, since a longer gap - one missing bunch - is available for the kicker).

If the short-circuit mode is deemed not suitable, then two new 80 kV magnet – generator systems have to be added to the present one. The main concerns are:

- Unavailability of high voltage gas filled cables used for the PFL and transmission. At present, no potential manufacturer has been identified.
- No space available in the present 365 building

Therefore, if more detailed analysis indicates that the system cannot be used in short-circuit mode then development of new generators with PFL or Pulse Forming Network (PFN) is required. The solution with PFL is highly desirable for complexity reduction and optimized performance but it depends on the availability of critical components from industry.

A summary of the kicker capabilities and upgrades required is reported in Table 3.

Septa

Septa magnets are needed for extracting the beam from the PSB, for recombining bunches from the four PSB rings prior to PS injection, and for injecting into the PS ring.

PSB extraction: Up to 40 % strength margin is available. This makes it possible to re-use the septa with only modifications at the level of the internal bus bars and cooling.

BT: Up to 20% strength margin is available, which is not enough for re-using the septa.

PS injection: the septum has definitely no strength margin and it is not possible to envisage increasing the magnetic field any more. Therefore, the upgrade should be based on increasing the magnet length. This has rather serious impact on the overall layout of the PS injection.

The septum is located in straight section 42 in which there is no room for any additional device (see Fig. 9). Therefore, two options should be studied, namely:

- Displace the bumper magnet elsewhere. This would leave an empty short straight section for a stronger septum. However, a new layout of the slow bump should be evaluated (see Fig. 10 for a plot of the current version of the slow bump).
- Displace the septum magnet elsewhere. This would imply changing the geometry of the transfer line between PSB and PS.

In general, more detailed studies are needed to assess whether the septa power converters can be re-used.

IMPACT ON OTHER SYSTEMS

In the previous sections the main systems were reviewed to assess the type of changes and upgrade required to increase the PSB extraction energy. It is clear that a global analysis should be performed including also,

e.g., beam instrumentation, controls, and machine protection.

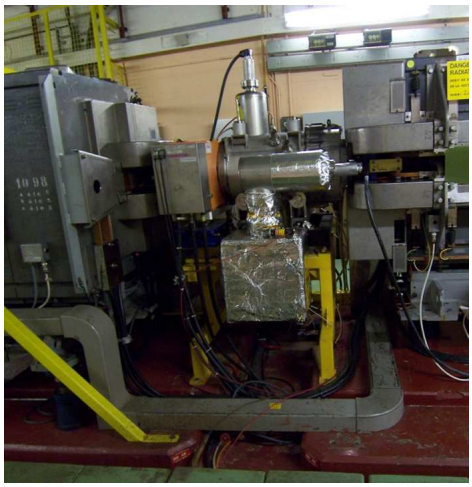

Figure 9: Layout of the PS straight section 42 where the injection septum is located. Two main magnets (unit 41 and 42) are visible on the left and right part of the picture. The bumper dipole is visible on the left side of the straight section, while the septum tank is visible on the right side of the straight section.

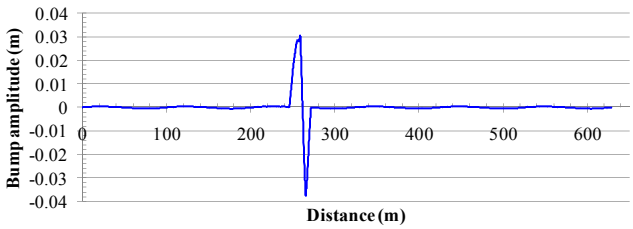

Figure 10: Layout of the PS slow injection bump. Such a bump is generated by means of magnets located in straight sections 40, 42, 43, 44.

TIMELINE OF IMPLEMENTATION

In general, the hardware modifications or the design of brand new hardware should require between three to four years before having the devices ready for installation.

The actual installation should need about eight months of work. This means that either two standard shutdown periods or one single long shutdown should be scheduled for the completion of the upgrade.

It is important to stress that these rather approximate estimates would need a more detailed study to be confirmed. Furthermore, they assume full availability of resources, meaning that in case of sharing between the upgrade activities and normal shutdown or design activities, the overall length of the upgrade task should be increased.

OTHER AREAS OF IMPROVEMENT

In addition to the increase of the PSB extraction energy, there are a number of measures that could be considered in view of lifting performance limitations in the PS. The situation of the main magnets is currently under control thanks to the vigorous maintenance and refurbishment programme put in place in the last years [15-17]. Therefore, in the analysis presented here it will be assumed that the PS can be maintained for the coming 25 year in good operational state.

It is worth stressing that in some cases it is difficult to quantify the current limitation and, consequently, to evaluate the potential improvement. Therefore, detailed studies should be carried out to quantify the limitation, prior to any consideration on whether mitigation measures might be useful.

PS working point control

It is well-known that the PS main magnets are made of combined function magnets. Each dipole consists of two half-unit with focusing and defocusing quadrupole components [18]. A schematic view of the main magnet is plotted in Fig. 11.

The horizontal and vertical tunes are controlled by two families of quadrupoles at low energy, while at higher energies a set of special coils are used. These coils allow introducing a non-linear dependence with amplitude of the field in the main magnets, thus generating both quadrupolar and sextupolar fields. This enables controlling not only the tunes, but also the chromaticities. Three main circuits are available, namely the figure-of-eight and pole-face-windings, which are divided into a focusing and a defocusing circuit. Each of these is then split into a narrow and a wide component according to the type of windings. A sketch of these additional coils is shown in Fig. 12, while in Fig. 13 a picture is reported.

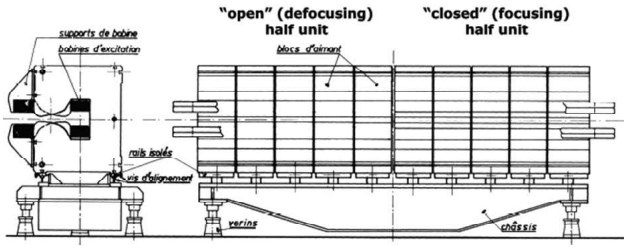

Figure 11: Layout of the PS main magnet with a side view of the pole profile.

Originally, only three circuits were available for controlling the four physical observables, which imposed to set up the machine by leaving one of the four quantities floating.

Then, the narrow and wide components of the circuits were split to provide five independent control knobs [19]. Even if the flexibility of tuning the working point of the PS has been greatly increased, there is still a difficulty due to the choice to be made about the use of the fifth degree-of-freedom. Furthermore, to-date no predictive magnetic model exists to determine the currents to be used to obtain a given working point. From an operational point of view a set of matrices representing the variation of the tunes and chromaticities in the neighbourhood of predefined current settings were measured at different energies. The inversion of these matrices, with the special

care imposed by the fact that these matrices are not square, allows controlling the PS working point. High-intensity and high brightness beams are the most demanding in terms of working point control. Therefore, an improvement in the way the tunes and the chromaticities are set-up would be highly welcome. It is certainly very beneficial to pursue the efforts put in the development of a reliable magnetic model of these circuits in view of making more effective the setting up of the machine.

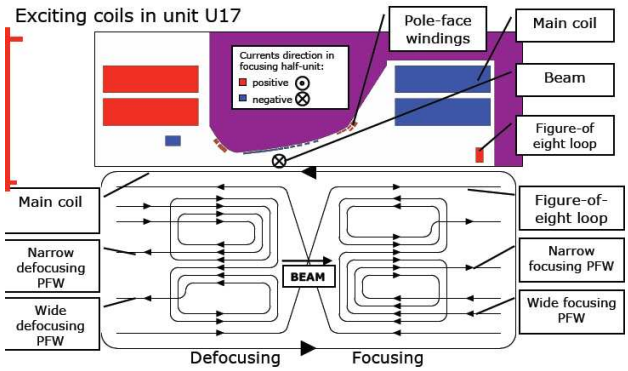

Figure 12: Schematic layout of the additional coils used to control the tunes and the chromaticities of the PS.

Faster ramping of PS

As it is stated in the document specifying the new PS power converter [20], pulsing the PS magnets to 26 GeV/*c* in 1.2 s should be possible at least from the point of view of the main power supply (indeed flat top length is a bit too short for any beam manipulation different from a simple fast extraction without any longitudinal or transverse manipulation). Still, one might wonder what would be the gain in case of pulsing the PS faster for, e.g., the filling time of the LHC. It turns out that a marginal reduction (about 15 %) should be expected. Hence, this option does not seem particularly useful, also taking into account the potential adverse consequence this could have on the magnet lifetime, due to the increased mechanical stress, and the higher voltage. The only interesting application for pulsing the PS faster might be for a new way of generating the fixed target beams (see later).

Vacuum pipe layout

It is proposed to pursue a review of the vacuum system layout (see Fig. 14 for an example of the horizontal cross-section of the PS vacuum chambers) in order to

- Analyse the potential aperture bottleneck in view of proposing mitigation measures. This review was already started in the framework of the PS Multi-Turn Extraction (MTE) project [21] where a number of limitations were considered and improved. The proposed upgrade of the PSB extraction energy will have a marginal beneficial impact on the beam size (reduction at the level of 10 %) at PS injection, but a detailed analysis is certainly important.
- Evaluate the impact on the longitudinal impedance of the missing tapering between vacuum chambers of different cross-section. This analysis should indicate whether an impedance reduction campaign should be launched.
- Study means to combat e-could effects, which will be certainly a potential issue due to the increased intensity/bunch.

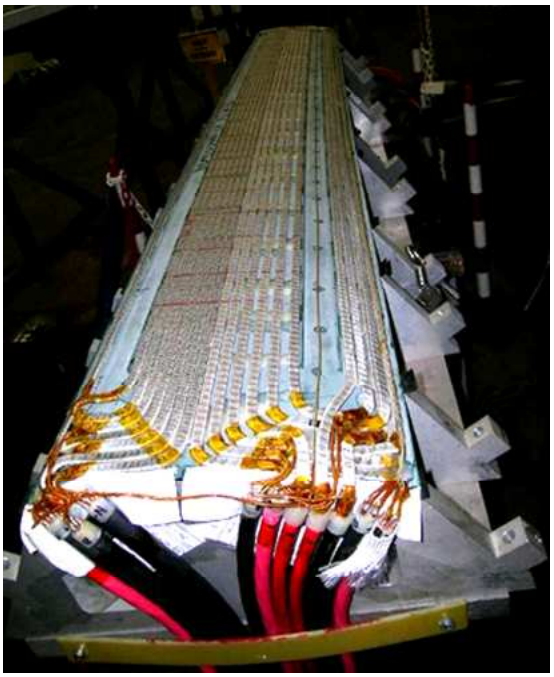

Figure 13: Picture of the pole-face-windings before being embedded in the plastic support.

Losses at PS extraction

The MTE beam has removed the losses on the electrostatic septum in straight section 31 due to the Continuous Transfer (CT) beam. The choice of the longitudinal structure, de-bunched beam, imposed by the optimisation of the SPS performance [22] has introduced localised beam losses on the magnetic septum in straight section 16. Under these conditions, the beam losses are unavoidable and systematic at each extraction, corresponding to about 2-3 % of the total beam intensity. Mitigation measures were already anticipated in the MTE design report [21] and consist essentially in replacing the magnetic septum with a thinner one, still magnetic. Of course, the use of an electrostatic septum would be even more appropriate due to its reduced thickness. However, it is worth listing the many constraints to be considered in view of finding an appropriate solution to this problem, namely:

- The electrostatic septum in section 31 (or its spare) cannot be re-used. In fact, it fits a long straight section, which, in the extraction region, corresponds

to section 11. Even neglecting that a spare RF cavity is installed there (it could be moved to section 31) both the slow and fast bumps have zero amplitude in section 11, thus making useless the presence of a septum there.

- A new electrostatic septum could be installed only in section 15 (the others being already filled or with a very small bump amplitude). Nonetheless, in section 15 only about 0.4 m are available and displacement of the bumper and the gamma-jump quadrupole does not seem possible.

In any case a detailed study is mandatory before drawing any conclusions.

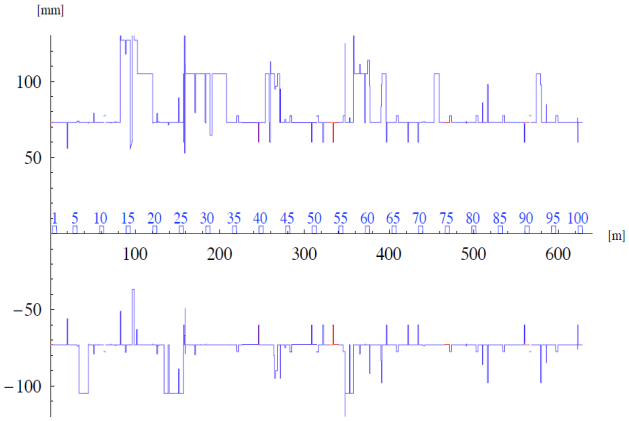

Figure 14: Horizontal cross section of the PS vacuum chambers.

New generation of Fixed Target physics beams from PS

It is sometimes mentioned [23] that the SPS could profit from higher extraction energy from the PS of the beam for the fixed target physics programme. The reason behind this request is that transition crossing in the SPS would be avoided. This argument immediately fixes the value of the PS extraction energy to 26 GeV/*c*. This is the first source of limitations, as the strength of the kickers for MTE is adapted to 14 GeV/*c* with no margin. Upgrading the kickers would be extremely expensive, not to mention the difficulty in finding the place for additional elements. On the other hand, adding few more magnets could be an easy way to increase the strength of the non-linear magnets (sextupoles and octupoles) used to generate the stable islands) It is important to stress, however, that the strength is not the only limitation. Indeed, in particular for the neutrino experiments, what counts is the flux of protons. Hence, unless with the new PS main power supply it is possible to pulse faster (with the warnings already mentioned in previous sections), the beneficial effect of increasing the extraction energy would be quickly lost by the reduced duty factor imposed by the 2.4 s period between PS extractions. Mitigation measures would involve a study of potential optimisation of the PS and SPS cycles in view of reducing the overhead imposed by the longer time between extractions. This because, as already mentioned, the option of pulsing the PS faster does not seem feasible.

CONCLUSIONS AND OUTLOOK

In this paper the limiting factors of the PSB and PS machines have been analysed in view of improving the performance of the proton beams for the LHC.

With the advent of the Linac4, the beam intensity will be limited by space charge effects at PS injection, thus making an increase of the PSB extraction energy an attractive option in view of lifting this fundamental limit.

The analysis made shows that the PSB main magnets can indeed sustain an energy upgrade to 2 GeV, and this would enable generating LHC beams with about 2.7×10^{11} p/b. This potential improvement entails a number of beam dynamics challenges that have been outlined in the paper. It is worth mentioning that a positive side effect of this upgrade would be a reduction of the losses at injection in the PS for the fixed target physics beams.

In terms of hardware modifications, the PSB upgrade features attractive synergies with the ongoing and already planned consolidation programme aimed at keeping the CERN machines in good operational state for the next 25 years. In this paper a detailed analysis of the changes to be carried out was presented.

It is clear that this proposal aims at pushing further the performance of the existing machines, while not improving the situation in terms of age of the low energy LHC injectors.

Other areas of study of potential limitations of the PS machine have been outlined and should be further studied in the future to assess their relevance for machine performance.

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