PS POTENTIAL PERFORMANCE WITH A HIGHER INJECTION ENERGY

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Abstract

In the context of the LHC Injectors upgrade project, the PS has to be brought up to − and to operate reliably at − the level of performance required by the HL-LHC until the end of the LHC lifetime. The study has started on the potential benefits of increasing the injection energy. An overview of the impact of this upgrade will be presented, with a preliminary estimate of the beam characteristics at the SPS entrance and the remaining performance limitations. The necessary hardware modifications will be described, highlighting the critical systems and the risks. The program for the 2011 machine studies and hardware interventions for refining these plans will be presented.

INTRODUCTION

As explained in [1], the role of the PS in the production of the LHC-type beams is to conserve the transverse emittances produced in the PSB and to produce the final longitudinal bunch spacings. Different causes of transverse emittance blow-up were already studied in the past, with the first and the most critical one indentified as the large Laslett tune shift from space charge. This blow-up affects particularly the first batch of the double-batch beams, while the beam is waiting for the second injection after 1.2 s. During this period, the first batch might experience an emittance blow-up if the tune shift is larger than -0.3. As proposed in [2], this effect can be reduced by increasing the injection energy in the PS by a suitable amount, as already done in the past when the PSB extraction energy was pushed from 1 GeV to 1.4 GeV, and at the same time it allows injecting higher beam intensities without a relevant blow-up. Other effects can also contribute to the final transverse emittance like head-tail instability at injection energy, TMCI at transition crossing, electron cloud at extraction, as discussed in the following sections.

The second and more fundamental role of the PS is to define the final longitudinal structure of the beam, in terms of bunch spacing, via a series of RF gymnastics. Again, many factors can contribute to spoil the longitudinal beam quality like coupled bunch instabilities or transient beam loading.

All these effects have to be considered and analyzed to finally determine the future possible performances of the PS as HL-LHC injector with an upgraded injection energy.

DRAFT FUTURE PERFORMANCES

As mentioned, the transverse emittance delivered by the PSB has to be conserved by the PS as much as possible. Thanks to a series of MDs in the 2010 run and thanks to the PS operation as LHC injector, the following conclusions could be drawn:

- For a Laslett tune shift smaller than -0.3, no significant transverse emittance blow-up is observed.
- For large Laslett tune shift, tests were done with a maximum $\Delta Q_x \approx -0.34$ and $\Delta Q_y \approx -0.56$, the emittance increases were lower than the ones measured in past studies. This does not authorize to draw any conclusion yet, like accepting by default very large tune shifts, but it indicates the necessity to repeat the studies with a very systematic measurement campaign.
- Tests with ultimate-like beams showed that more than 1.7 10^{11} ppb peak performance is achievable with 25 ns and 50 ns bunch spacing, but today only with reduced beam quality and operationally not maintainable.

According to the mentioned points, a very first and educated estimate of the future beam performances could be summarized as in Table 1, under the following hypothesis:

- Linac4 will be fully operational with nominal performances.
- The PSB transverse emittances will be uncorrelated from the beam intensities.
- The injection energy of the PS will be upgraded to 2 GeV.
- The beams will be produced in double batch.
- No transverse emittance blow-up is assumed between injection and extraction.
- The entire program proposed for the PS upgrade will be realized.

The future performances were determined, for the first block of Table 1, by a) assuming the best transverse emittance delivered today to the SPS for the LHC beams, i.e., 2.5 μm rad delivered already at PS injection and extracted without any blow-up; b) fixing the longitudinal emittance within the increased acceptance of the PS at 2 GeV and rescaling from the current performances; c) computing the

Table 1: Draft of LHC beam parameters after the PS upgrade

Intensity PS extract. (ppb)	**Bunch spacing** per ring	$\epsilon_{(x,y)}$ **PS extract. (1 σ norm)**	**Laslett** $\Delta Q_{x/y}$	$\epsilon_{longit.}$ **@ PSB**	**PSB int.**	**Comment**
3.0 10^{11}	25 ns	2.5 μm rad	-0.24 **-0.37**	$\leq$ 2 eVs (160 ns)	$\approx$400 10^{10}	*Streched goal*
1.9 10^{11}	25 ns	2.5 μm rad	-0.14 -0.22	$\leq$ 2 eVs (160 ns)	$\approx$240 10^{10}	**Baseline**
3.0 10^{11}	50 ns	2.5 μm rad	-0.11 -0.17	$\leq$ 2 eVs (160 ns)	$\approx$190 10^{10}	*Streched goal*
1.9 10^{11}	50 ns	2.5 μm rad	-0.07 -0.11	$\leq$ 2 eVs (160 ns)	$\approx$125 10^{10}	**Baseline**
1.7 10^{11}	25 ns	1.5 μm rad	-0.30 -0.30	$\leq$ 2 eVs (160 ns)	$\approx$220 10^{10}	Minimum $\epsilon_{(x,y)}$
2.0 10^{11}	25 ns	1.8 μm rad	-0.30 -0.30	$\leq$ 2 eVs (160 ns)	$\approx$250 10^{10}	Minimum $\epsilon_{(x,y)}$
2.7 10^{11}	50 ns	1.1 μm rad	-0.30 -0.30	$\leq$ 2 eVs (160 ns)	$\approx$170 10^{10}	Minimum $\epsilon_{(x,y)}$

intensity the PSB would have to deliver to reach a given intensity at extraction and adding 5-10% margin for losses.

In doing this, it became clear that going beyond the 1.9 - 2.0 10^{11} ppb would be difficult both on the transverse and on the longitudinal side. Whereas 2.0 10^{11} ppb seems to be feasible, going up to 3.0 10^{11} seems to be quite difficult, due to the large Laslett tune shift at injection and due to the large intensity per bunch that the RF would have to manipulate during the different bunch splittings.

The second part of Table 1 presents the performances considering the minimum transverse emittance reachable for a given intensity and a maximum Laslett tune shift of -0.3. In this case, no eventual transverse emittance blow-up was included, even if some would probably occur for such small emittances but it cannot be easily quantified yet.

The final intensity per bunch is expected to be within the longitudinal bunch length required by the SPS, i.e., 4 ns for a total emittance of 0.35 eVs.

INJECTION AT 2 GEV

The existing injection from the PSB is realized by a septum in straight section (SS) 42 which bends the beam on a slow bump formed by four independent bumpers. Finally the beam is deviated on the closed orbit by a full turn kicker (KFA45). The slow bump, with the amplitude shown in Fig. 1, last for about 0.8 ms (half sinus). A first analysis of the injection element operation at 2 GeV lead to the following conclusions. The existing septum cannot be upgraded for the 2 GeV operation: a new one that occupies the entire straight section was designed, with one of the injection bumpers installed in the primary vacuum vessel to make use of the maximum space available (see Fig. 2). The remaining three other bumpers might operate at 2 GeV, but they were designed with a captive vacuum chamber: in case of a magnet failure, an entire straight section have to be removed causing also the venting of the septum requiring the bake-out of the latter to recover the operational vacuum. A study has been launched to design new half-magnets.

The power converters of the magnets and the septum will be studied during 2011.

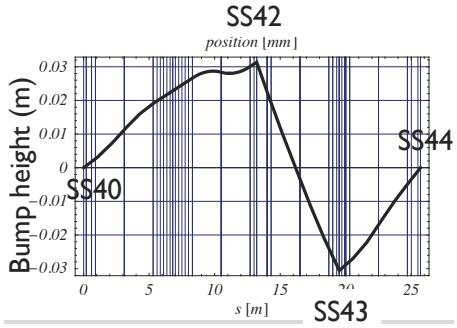

Figure 1: Beam trajectory at the maximum of the injection bump. The position of the bumpers are indicated by the numbering of the straight sections (SS) where they are installed

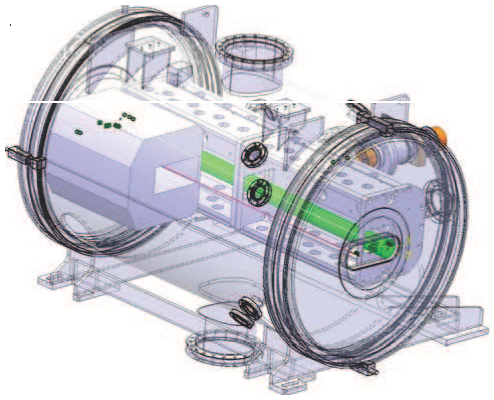

Figure 2: Desing of the new 2 GeV septum with the bumper embedded in the vacuum tank. The injected beam is represented by the green cylinder

Concerning the injection kicker, tests done in 2010 showed that the kicker could provide enough strength to inject 2 GeV LHC-type beams if operated in short-circuit. A predicted degradation of the kicker flat-top in this operation-mode caused an emittance blow-up of about 10% for the LHC beams: it is believed that this can be cured by the use

of the transverse damper, not yet operational at the time of the tests. This kind of operation, however, will not allow the injection of the multi-bunch non-LHC type beams at 2 GeV: this issue is still under investigation. In particular, a new kicker installed in SS53 was proposed to compensated the missing strength of the KFA45 for this kind of beams.

A preliminary study was also done to determine the impact of losses at 2 GeV, in particular the eventual increase of the dose levels at the Route Goward [3]. Preliminary FLUKA simulations showed that the dose levels, for the same amount of losses present today at 1.4 GeV, would bring to a more than linear increase of the dose. It is important to notice that, if only the LHC-beams will be injected at 2 GeV, the dose increase would be probably negligible: this is because already the current losses of the non-LHC beams are causing large doses, requiring already today an increase of the shielding on top of the tunnel. Further studies will be carried out during 2011 to better evaluate the eventual losses at 2 GeV and the required increase of the shielding, considering the operation of all the beams at 2 GeV and with the present losses.

FLAT BOTTOM AT 2 GEV

As mentioned in the previous sections, the production of the LHC-beam for high-brillance is done by injecting two batches, separated by 1.2 s. During this period, the first batch can experience a transverse emittance blow-up due to the Laslett tune shift, but also losses due to the well-known head-tail instability. The first mechanism is going to be deeply studied in 2011-2012, since some of the 2010 experimental results of do not fully agree with earlier studies [4]: it is of vital importance to understand as much as possible the emittance increase mechanism. Concerning the head-tail instabilities, further studies, both theoretical and with MDs, will be done in the next years since the rise time of the instability will be 50% smaller at 2 GeV. Losses and/or emittance blow-up could be cured by different methods like: a) using octupoles, as done in the past. The hardware is still installed in the PS, plus some more octupoles installed for the MTE (Multi-Turn Extraction) extraction could be also used; b) introducing linear coupling as done today by skew quadrupoles. In this case, as described later, it is of primary importance to assess the performance of the magnets and power converters at 2 GeV; c) the working point adjustment that is not done today but the Pole-Face-Windings (PFW) could be used to control the chromaticity. The use of the slow-extraction and MTE sextupoles could be also envisaged; d) the transverse feedback which is available but not operational. Studies should be done for the latter to determine if the instability frequency is well within the band-width of the system.

The hardware, in terms of magnets and power converters, used at 2 GeV were also analyzed. The 50 horizontal and the 40 vertical correctors will be tested at 2 GeV during MDs in 2011, since it seems that they reserve some margin. On top of this the new orbit correction procedure, using YASP with SVD [5], indicates that a dispersed correction around the ring lead to a small current for each magnet, well below the maximum current of the equipments. More concerns are the lattice and the skew quadrupoles. The lattice quadrupoles are iron-less magnets, air cooled, inserted in the combined function main magnets. Those quadrupoles are used as trim to control the working point at low energy. The skew quadrupoles are of the same type, some of them with extra coils to act as vertical correctors. For those magnets, in particular the last ones, the large RMS current required on the 1.2 s long injection flat-bottom might constitute an issue, in particular due to the overheating of the coils. Some tests done in 2010 already showed the need of replacing the skew-combined function magnets, whereas further studies in 2011 will assess the limits of the other magnets. Some tests will be also done to control the working point with the PFW at injection, to in case reduce the load on the trim quadrupoles. Concerning the power converters of the different magnets, a consolidation program was already launched, and new specifications for 2 GeV operation will be taken into account.

TRANSITION CROSSING

Transition crossing is a delicate moment in the acceleration cycle due to the frozen longitudinal motion. The extrapolation to determine the stability of the upgraded LHC-beam was done by considering the current beam operation.

For the longitudinal plane, no limitations at transition crossing would be expected for beyond-ultimate LHC beams. Considering the peak current of the non-LHC beams, which only allows an estimation and not a direct scaling for future operation, no longitudinal instabilities are expected up to 2 10^{11} ppb (for the 25 ns beam and at PS extraction), according to observations during the ultimate LHC25 tests. The peak current of the different beams is presented in Table 2, together with the other non-LHC beams: clearly the AD and the TOF beams are more challenging in the current operation than the upgraded LHC beams.

Transverse instabilities were observed for the TOF-like beams in the past [6] in agreement with more recent studies [7]. The vertical TMCI (Transverse-mode coupling instability) can cause relevant beam losses or a significant transverse emittance blow-up: the threshold of this instability however is above the parameters of the future LHC-beams and should not constitute a problem. Further studies will be carried out in 2011-2012.

Table 2: Beam parameters at transition crossing

LHC spac. ns	10^{11} ppb at eject.	Int. 10^{11} ppb	ϵ_l eVs	Pk. curr. at γ_{tr} A
25 nom.	1.3	5.2	0.65	8.4
25 ult.	2.1	8.4	0.65	14
50 nom.	1.3	2.6	0.65	4.2
50 bey. ult.	3.0	6.0	0.65	9.7
CNGS		17	1.4	15
AD		40	2.3	23
TOF		89	2.6	40

RF RELATED ISSUES

The LHC-beam bunch spacings are produced in the PS by 2-3 bunch splittings produced by 4 different RF systems with different frequencies: 10, 20, 40 and 80 MHz cavities have to manipulate the beam during the PS cycle. The production of the LHC25 beam, as described in [1], is done thanks to a triple splitting at injection energy plus two consecutive bunch splittings at 26 GeV/c to produce the final 72 bunches. Finally, before extraction the beam is phase rotated in the longitudinal phase space, i.e., the bunch length and the energy spread are exchanged to shorten the bunches to 4 ns, fitting then in the 5 ns long buckets in the SPS. At every bunch splitting, and close to the ultimate intensity, the transient beam loading causes a relative intensity errors of up to 20% ($\pm$ 10%) in bunch intensity: the final intensity per bunch over the 72 bunches before extraction typically features a modulation as presented in Fig. 3. This effect creates a bunch intensity modulation in the LHC, but also decrease the transfer efficiency in the SPS.

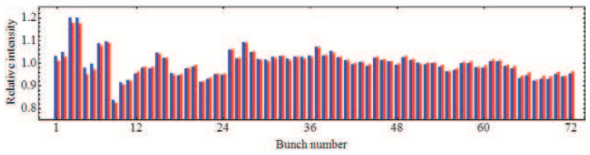

Figure 3: Bunch intensity along the batch for the 25 ns nominal LHC beam prior extractions averaged on ten cycles. The two colors indicate two different analysis techniques

A second deleterious effect is produced by a coupled-bunch instability observed during acceleration and flat top, which causes a degradation of the longitudinal emittance. It is important to notice that, as presented in [8], the SPS longitudinal acceptance sets very stringent limits around the nominal parameters, i.e., the bunches should not be longer than 4 ns and the emittance at 0.35 eVs, otherwise significant losses are observed in the SPS well beyond the few percents. To cure this kind of instabilities, new one-turn delay feed-backs will be studied and installed, not only for the 10 MHz RF cavities, but probably also for the 20 MHz, 40 MHz and 80 MHz cavities. Additionally, an improved coupled-bunch feedback with a dedicated kicker is going to be studied.

Table 3: Summary of RF-HW interventions for the different RF systems

Priority	Item	When
[1]	New coupled-bunch FB	2012
2	Dedicated kicker cavity	2015-20
10 MHz		
[1]	1-turn delay FB	2011
1	Renovate FB amplifiers	2011-15(?)
1	Slow ph. loops for each cavity	2013-14
2	New amplifier (1 tube/gap)	2014-18 (?)
20 MHz		
1	1-turn delay FB	2012
2	Slow ph. loops for each cavity	2012
40 MHz		
[1]	Automatic tuning system	2011
1	1-turn delay FB	2012
2	New FB amplifier in grooves	2014
2	Slow ph. loops for each cavity	2012
3	Study more voltage per cavity	2013
3	New power supplies	2014-(?)
80 MHz		
1	1-turn delay FB	2012
1	Automatic tuning system	2011-12
2	Slow ph. loops for each cavity	2012
2	New FB amplifier in grooves	2014
2	Fast ferrite tuner	2016
3	Study more voltage per cavity	2013
3	New power supplies	2014-(?)
3	Extra 80 MHz cavity	not scheduled

A preliminary list of interventions required to improve the current RF systems, considering or not the 2 GeV upgrade plus the interventions needed to increase the final intensity per bunch, can be found in Table 3, under the following assumptions: a) the years of completion are crudely estimated, some of the items may only be fully implemented beyond 2017; b) items with priorities in brackets indicate activities already ongoing before the upgrade studies started; c) the priorities may change according to the outcome of the studies proposed. A more complete and detailed review of the PS-upgrade related RF issues and possible cures can be found in [9].

ELECTRON CLOUD STUDIES

Electron cloud formation was observed in the past during transition crossing and during the bunch shortening and

rotation on the 26 GeV/c flat top [10]: the current LHC beam production scheme with a fast phase rotation was decided to avoid transverse instability probably electron-cloud driven. In the most recent measurements, a net increase of the pressure was observed during the bunch shortening, with a clear correlation with the number of bunches present in the machine (see Fig. 4 [11]). Only on one occasion, in 2006, a beam instability was observed, spoiling the transverse emittance of the beam: this would happen if the bunch length of the 25 ns beam before the last phase rotation is shorter than 11-12 ns. Unfortunately it was not possible to prove that it was due to electron cloud. In 2011-2012, a new campaign of measurements and simulations will be done, since there is still no guarantee that electron cloud would not constitute an issue for the LHC-type beams for the upgrade.

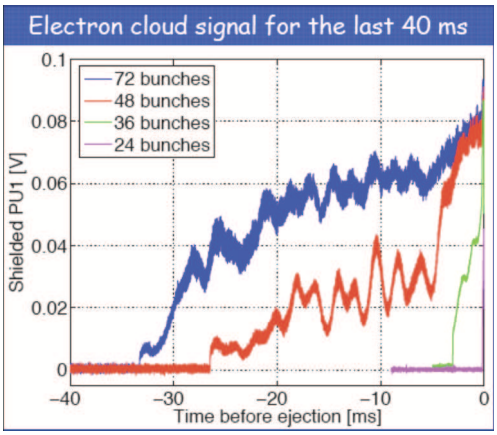

Figure 4: Electron-cloud signal measured by one of the detectors of the PS during the last 40 ms of an LHC cycle. Clearly, the signal increases with the number of bunches for a fixed 25 ns bunch spacing [11]

MDS FOR 2011

A first plan of MDs was elaborated to determine the machine limitations, both in terms of existing hardware and beam performances. A preliminary list is shown in Table 4:

The list of MDs appeared to be quite long, and most of the studies will start in 2011 and will continue in 2012, also to avoid interfering with the normal machine operation and the studies in the other injectors.

A list of priorities will be set up in the first part of the run, according also to a first revision of the beam dynamics studies that could constitute a limitation for the final performances, as presented in [12].

CONCLUSION

The injection energy increase to 2 GeV, together with the Linac4 injection in the PSB and a relevant upgrade of the PS RF systems, could lead to a maximum intensity delivered to the SPS up to 3.0 10^{11} ppb with an emittance of 2.5 μm rad (1 σ normalized) for the 25/50 ns (double batch, 72/36 bunches with 6 PSB rings) or smaller emittances could be produced at the price of the intensity per bunch for 25 ns bunch spacing. However, the intensity of 3.0 10^{11} ppb should be considered as the upper limit or the streched goal of the upgrade. A lower intensity of 2.0 10^{11} ppb will be considered as the baseline for the PS upgrade since the final machine performances, i.e., the maximum intensity per bunch will depend on how far the RF limitations could be finally pushed.

The 2 GeV injection will require a major upgrade of the injection elements, except probably the injection kicker if the non-LHC beam would operate at 1.4 GeV.

During the following years, a revision of the limit of the emittance blow-up due to the Laslett tune shift will be done to determine the maximum intensity at injection without causing a relevant transverse emittance increase.
A large number of studies is foreseen already for 2011, both as MDs as on the simulation side to better extrapolate the limits to the 2 GeV upgrade.

Non-LHC beam injection at 2 GeV was also analyzed, with some concerns about the eventual increase of the radiation levels in the ring.

Table 4: MDs proposed for 2011

Subject	**Goals**
Injection/matching studies	Improve inj. optics
Acceleration on h=7 at 2 GeV	Porch for longitudinal and transverse studies
HW limitations at 2 GeV	Orb. correctors trim quadrupoles
Working point using the PFW	Control chromaticity and WP at 2 GeV
RF manipulations at 2 GeV	Tests of first splitting
Emittance evolution on 2 GeV	Head-tail instability, Laslett tune shift
Shorter flat bottom	Double injection in less than 1.2 s
Transition crossing	TMCI related studies
e-cloud	Study electron cloud at 26 GeV/c
Longitudinal instability	Determine upgrade longit. beam quality
Optimum transfer to SPS	Study best longit. beam characteristics

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REFERENCES

[1] R. Steerenberg *et al.*, "Performance reach of the injectors in 2011", these proceedings.

[2] M. Giovannozzi *et al.*, "Possible improvements to the existing pre-injector complex in the framework of continued consolidation", LHC Performance Workshop - Chamonix 2010.

[3] S. Damjanovic, T. Otto, M. Widorski, "Radiation levels on Route Goward", to be published as EDMS document.

[4] E. Métral, and H. Burkhardt, "Achievable Space-Charge Tune Shift with Long Lifetime in the CERN PS and SPS", Hadron Beam 2008, Nashville, August 2008, WGA03, p. 48 (2008), and references therein.

[5] M. Gourber-Pace, "Validation of beam steering in the PS with YASP", presented at the MSWG, available at https://espace.cern.ch/be-dep/MSWG/Presentations%202010/YASP_MSWG%2003Dec2010.pptx.

[6] E. Métral, "Crossing Transition with TMCI", CERN internal RLC meeting 19/09/2006, see http://ab-abp-rlc.web.cern.ch/ab-abp-rlc/Meetings/2006/2006.09.19/CrossingTransitionWithTMCI_RLC_19-09-06.pdf.

[7] S. Aumon *et al.*, "Transverse Mode Coupling Instability Measurements at Transition Crossing in the CERN PS", CERN-ATS-2010-030.

[8] E. Shaposhnikova *et al.*, "Lessons from SPS studies in 2010", these proceedings.

[9] H. Damerau *et al.*, "RF issues with (beyond) ultimate LHC beams in the PS in the LINAC4 era", presented at the LIU-Day, December 2010, Thoiry, France, available at http://indico.cern.ch/getFile.py/access?contribId=6&sessionId=1&resId=1&materialId=slides&confId=112934

[10] E. Mahner *et al.*, "Electron cloud detection and characterization in the CERN Proton Synchrotron", Phys. Rev. Spec. Top. Accel. Beams 11 (2008) 094401.

[11] T. Kroyer, and E. Mahner, "Electron cloud in the PS for different beams and cycles", presented at the APC, available at https://ab-div.web.cern.ch/ab%2Ddiv/Meetings/APC/2007/apc071123/TK-APC-23-11-2007.pdf

[12] G. Rumolo, "PS beam dynamics issues for LHC beams upgrade: brief status and prospects", presented at the LIU-Day, December 2010, Thoiry, France, available at http://indico.cern.ch/getFile.py/access?contribId=7&sessionId=1&resId=1&materialId=slides&confId=112934