# COLLECTIVE EFFECTS IN THE LHC AND ITS INJECTORS

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*Abstract*

Operation during 4-8 hours at a constant luminosity of five times the nominal one (with “leveling”) is required for the CERN HL-(High Luminosity)-LHC project* to be able to reach integrated luminosities of ~ 250 $fb^{-1}$ per year and ~ 3 $ab^{-1}$ twelve years after the upgrade. This means that the potential peak luminosity should be at least two times larger than the leveled one, i.e. a factor more than ten compared to the nominal case is contemplated. Even though the LHC had a bold beginning, reaching one third of the nominal peak luminosity at the end of the 2011 run, a factor more than thirty remains to be gained, which will be achieved only if all the collective effects are deeply understood and mastered both in the LHC and its injectors. The observations made during the 2010-2011 runs are first reviewed and compared to predictions to try and identify possible bottlenecks. The lessons learned and the possible solutions and/or mitigation measures to implement in the HL-LHC and the LHC Injectors Upgrade (LIU) projects are then discussed.

## INTRODUCTION

The peak luminosity at the start of the collisions in the LHC can be expressed as [1] (see also Fig. 1)

$$L_{peak} = \left( \frac{e\,c^2}{8\,\pi^2\,E_0} \right) \left( B\,\frac{\rho}{R} \right) \left( \frac{N_b}{\varepsilon_n} \right) \left( N_b\,M \right) \times \frac{F\left(\theta_c, \sigma_z, \beta^*, \varepsilon_n / \gamma\right)}{\beta^*}, \tag{1}$$

with

$$F = \frac{1}{\sqrt{1+\Theta^2}}, \qquad \Theta = \frac{\theta_c\,\sigma_z}{2\sqrt{\beta^*\,\varepsilon_n/\gamma}}, \tag{2}$$

where $e$ is the elementary charge, $c$ the speed of light, $E_0$ the proton rest energy, $B$ the dipole’s magnetic field, $\rho$ the dipole’s bending radius, $R$ the machine average radius, $N_b$ the number of protons per bunch, $\varepsilon_n$ the normalized rms transverse emittance (of the round beam only discussed here), $M$ the number of bunches (per beam), $\beta^*$ the betatron function at the Interaction Point (IP) and $F$ is a geometric reduction factor (depending on the Piwinski angle $\Theta$) with $\theta_c$ the full crossing angle at the IP, $\sigma_z$ the rms bunch length (in m) and $\gamma$ the relativistic mass factor. The main parameters for the nominal LHC and HL-LHC are summarized in Table 1.

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Table 1: Main parameters for the nominal LHC and HL-LHC with protons at the IP at the start of the collisions [1 and 2, with some updates]. Leveling should be used for HL-LHC to keep the number of events / crossing below 100 (as requested by the experiments)

| Parameters | Nominal LHC | HL-LHC | |
|---|---|---|---|
| Ring average radius [m] | 4242.89 | | |
| Dipole’s magnetic field [T] | 8.33 | | |
| Dipole’s bending radius [m] | 2803.95 | | |
| Long. emittance [eV.s] | 2.5 | | |
| Rms bunch length [cm] | 7.55 | | |
| Rms momentum spread | 1.1 $10^{-4}$ | | |
| Bunch spacing [ns] | 25 | 25 | 50 |
| Bunch population [$10^{11}$ p/b] | 1.15 | 2.2 | 3.5 |
| # bunches / beam | 2808 | 2808 | 1404 |
| Norm. rms. trans. emit. [μm] | 3.75 | 2.5 | 3.0 |
| β* [cm] | 55 | 15 | 15 |
| IBS growth times [h]: L/H | 63/105 | ~ 15/24 | ~ 13/22 |
| Linear beam-beam parameter | 0.0033 | 0.009 | 0.0126 |
| Regular # long-range interactions | 120 | 120 | 60 |
| Regular # head-on interactions | 4 | 4 | 4 |
| Full crossing angle [μrad] | 285 | 590 | 590 |
| Beam separ. [rms beam size] | 9.5 | 12.5 | 11.4 |
| Piwinski angle | 0.65 | 3.14 | 2.87 |
| Geometric reduction factor *F* | 0.84 | 0.30 | 0.33 |
| Stored energy per beam [MJ] | 362 | 692 | 550 |
| Peak luminosity [$10^{34}$ $cm^{-2}s^{-1}$] | 1 | 7.3 | 8.4 |
| Potential peak lumi. [$10^{34}$ $cm^{-2}s^{-1}$] (*F* = 1 with crab cavities) | 1 | 24.3 | 25.5 |
| Events / crossing | 19 (for 60 mb inelast.) | ≤ 100 | ≤ 100 |

Equation (1) is composed of five terms, whose first one is a constant. The second term depends on the magnetic field of the superconducting dipoles, limited to 8.33 T, corresponding to an energy of 7 TeV per beam. The third term is the bunch brightness, which is proportional to the Space Charge (SC) and Beam-Beam Head-On (BBHO) tune shifts. It might therefore be a limit in the LHC or in the injectors if the corresponding tune footprints cannot be accommodated in the tune diagrams. This term could also be limited by Intra Beam Scattering (IBS), as discussed below. Finally, it could also be limited by the Transverse Coupled-Bunch Instability (TCBI) of higher order head-tail modes stabilized by octupoles through Landau damping as the stability diagram is proportional to the emittance and the complex tune shifts are proportional to the bunch intensity. The fourth term is proportional to the total current in one beam, which might be limited by collective instabilities (in particular TCBI of head-tail mode 0, Transverse Mode-Coupling Instability (TMCI) [3,4] and electron cloud, called e-cloud below), the Beam-Beam Long-Range (BBLR) effects, the cryogenic load arising from synchrotron radiation and induced wall currents, and the ability to handle the large beam stored energy without quenching the superconducting magnets. Finally, the fifth term is limited by the lattice with the minimum betatron function, which can be achieved at the IP (determined by the available technology of high gradient quadrupole lenses and the interaction region geometry) and the BBLR, which strongly depends on $\beta^*$, as can be seen from the scalings of the BB and SC tune shifts given by (assuming a round beam and neglecting dispersion for simplicity) [1]

$$\Delta Q_{\rm BBHO} \propto \frac{\kappa_{\rm HO}\, N_b}{\varepsilon_n}, \; \Delta Q_{\rm BBLR} \propto \frac{\kappa_{\rm LR}\, N_b\, \varepsilon_n}{\theta_c^2\, \beta^*\, \gamma}, \; \Delta Q_{\rm SC} \propto \frac{N_b\, R}{\varepsilon_n\, \beta\, \gamma^2\, \sigma_z}, \quad (3)$$

where $\kappa_{\rm HO}$ and $\kappa_{\rm LR}$ are the total number of BBHO and BBLR interactions and $\beta$ is the relativistic velocity factor. Note that the crossing angle is vertical in IP1 and horizontal in IP5 to compensate the effects of the BBLR interactions to first order (in particular the tune shifts of the bunches are compensated). Equation (3) reveals that if $\beta^*$ is decreased then the crossing angle has to be increased to keep the same BBLR tune shift. This leads to the behaviour of the peak luminosity vs $\beta^*$ depicted in Fig. 1. Therefore, if one wants to increase the luminosity by reducing $\beta^*$, one has to decrease the crossing angle (either because the BBLR limit is not reached yet or by using crab cavities [2]), or implement a BBLR compensation [5], or decrease the bunch length (which is also good to avoid the possible debunching due to the interplay between beam-beam and IBS, but which would have a huge impact on the RF heating [6]). The IBS emittance growth times (long. and horiz.) are given by [7]

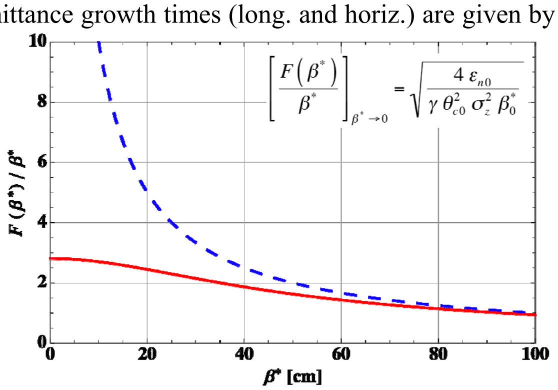


Figure 1: (Red, full line) Luminosity factor vs. $\beta^*$ for a constant beam separation (to keep the same nominal BBLR tune shift, with $\theta_{c0}$, $\beta_0^*$ and $\varepsilon_{n0}$ corresponding to the nominal values) and (blue, dashed line) the maximum which can be reached theoretically (given by $1 / \beta^*$). Note that the hour glass effect [8] (which leads to another luminosity reduction when $\beta^*$ becomes comparable or smaller than the rms bunch length, without crossing angle) has been neglected here.

$$\tau_{IBS} \propto \frac{\varepsilon_n^2\, \varepsilon_l}{N_b}\, G_{IBS}\,, \quad (4)$$

where $\varepsilon_l$ is the longitudinal bunch emittance (in eV.s) and $G_{IBS}$ is a complicated form factor depending on machine and beam parameters (almost independent of energy for LHC). Therefore, if the beam brightness has been optimised, the IBS (and the longitudinal instabilities) has to be controlled by the longitudinal emittance. Apart from that, the longitudinal emittance has no influence on the luminosity (only the bunch length matters).

## LHC

The two main challenges involved in the design of the LHC were the very high magnetic field and the very high luminosity necessary to provide significant event rates for rare events. Therefore, there were several significant challenges in accelerator physics related to the flexibility of the lattice, the long-term particles' stability, the synchrotron radiation, collective effects from the machine impedance and from the e-cloud, beam-beam and beam losses (which should not quench the superconducting magnets, and which require a very efficient collimation system with many highly resistive collimators at few mm from the beam [9]).

The best LHC performance reached so far is summarized in Table 2 and compared to the nominal case. It can be seen in particular that slightly more than half the nominal peak luminosity has already been reached, with 57% of the nominal energy and half the number of bunches, thanks to the smaller than nominal transverse emittances and higher than nominal bunch intensities, but also larger aperture in the triplets, which allowed to go lower in $\beta^*$. Several studies have been performed to reach such results and operational choices have been made:

1) The 50 ns bunch spacing beam has been used instead of the 25 ns one for two reasons. The first is that the 25 ns beam leads to more electron cloud effects in both the LHC and the SPS (see Fig. 2.1) [10,11]. The second reason is linked to the way the beam is produced between the PSB and the PS (see below), which leads to larger transverse emittances for the 25 ns beam.

2) The transverse feedback has to damp the TCBI of head-tail mode 0 from injection till the end of the fill. The instability rise-times at injection are very close to the predicted ones [4] but ~ 2-3 times shorter rise times have been observed at high energy (with some uncertainty on the chromaticities), which remains to be re-investigated.

3) Landau octupoles are used to damp the single-bunch and TCBI of head-tail mode - 1 (see Fig. 2.2) [12,13]. Currently, 450 A are used in operation at 4 TeV (i.e. ~ 2 $10^{-4}$ rms tune spread) with transverse chromaticities of ~ 1-2 units, which is much larger than the predicted current (~ 50-100 A with our current impedance model). Studies are planned to measure the exact octupole current at the instability threshold, because if this large value is confirmed, it can be a potential limitation in the future (550 A is the maximum).




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Table 2: Parameters used for the LHC maximum peak luminosity performance reached so far (in 2012) on the fill number 2536. A peak luminosity of ~ 2 $10^{33}$ $cm^{-2}s^{-1}$ was reached in 2010 and ~ 3.6 $10^{33}$ $cm^{-2}s^{-1}$ in 2011

| **Parameter** | **Achieved 2012** | **Nominal** |
|---|---|---|
| Bunch population [$10^{11}$ p/b] | 1.35 | 1.15 |
| Number of bunches / beam | 1380 | 2808 |
| Bunch spacing [ns] | 50 | 25 |
| Colliding bunch pairs | 1331 | 2808 |
| Proton energy [TeV] | 4.0 | 7 |
| β* [cm] | 60 | 55 |
| Norm. rms.trans. emittance [µm] | ~ 2.1 | 3.75 |
| Full crossing angle [µrad] | 290 | 285 |
| Rms bunch length [cm] | 10 | 7.5 |
| Peak luminosity [$10^{34}$ $cm^{-2}s^{-1}$] | ~ **0.56** | 1 |

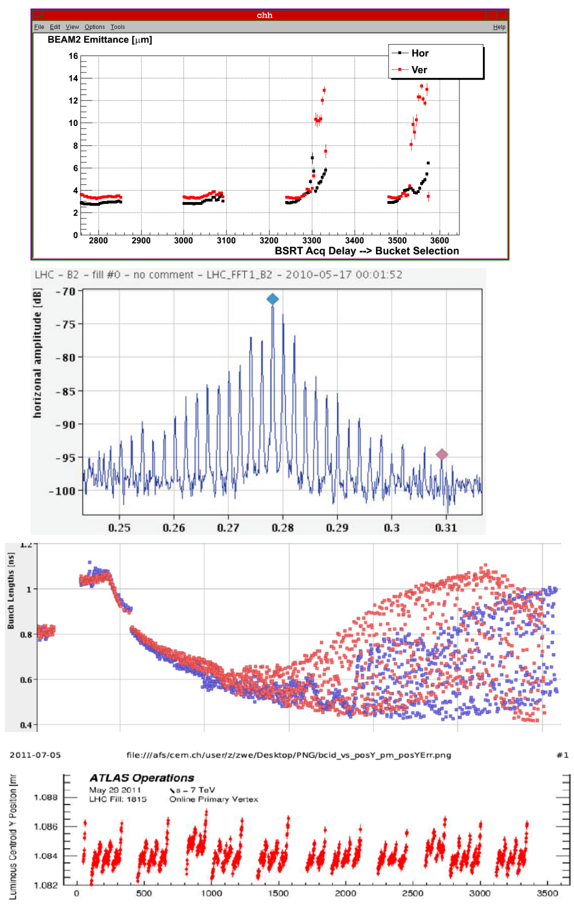



Figure 2: (1) Transverse emittance blow-up from e-cloud on some batches of the 50 ns beam, which disappears after scrubbing [10]. (2) "Christmas tree" on the (horizontal) tune application due the loss of transverse Landau damping of the head-tail mode - 1, which is cured by Landau octupoles [12]. (3) Longitudinal instability during the ramp when the longitudinal emittance is too small leading to a loss of longitudinal Landau damping [14]. (4) Bunch-by-bunch orbit measurements variation (in mm) of the vertex centroid in IP1 [15].

4) A controlled longitudinal emittance blow-up is performed during the ramp (as expected) to avoid longitudinal instabilities, which were observed during the commissioning phase when the longitudinal emittance was too small (see Fig. 2.3) [14]. This led to a loss of Landau damping and an estimate of the imaginary part of the longitudinal effective normalized impedance very close to the design value (~ 0.09 Ω when all the collimators are included [16]).

5) A BBHO tune shift much larger (~ 0.017) than nominal (which is ~ 0.0033) can be accepted in the LHC (i.e. ~ 5 times larger at least as bunches with ~ 1.9 $10^{11}$ p/b within ~ 1.1 - 1.2 µm have collided with no obvious emittance increase or lifetime problems) [17]. With two collision points (IP1 and IP5), ~ 0.034 was also reached without any visible detrimental effects.

6) Coherent beam-beam modes colliding two bunches have been clearly identified, behaving as expected [18].

7) A strong beam-beam interaction with static offset produces coherent dipole kicks which are different for the PACMAN bunches (having different integrated beam-beam effects), which leads to different orbits. This cannot be fully compensated by alternating crossing schemes but minimized and made symmetric (see Fig. 2.4, which is very similar to past predictions [17]).

8) Leveling by a transverse offset has been demonstrated (~ 4 σ for IP2 and ~ 0.5 σ - 1.4 σ for IP8). It is now routinely used without detrimental effects [17].

9) Several beam-induced heatings have been observed in 2011, which are still under investigations [6]. Synchronous phase shifts revealed very interesting results for both the impedance of some movable equipments and for the e-cloud, for which the bunch-by-bunch energy loss could be reproduced by simulations with a remarkable precision [11].

11) "Unidentified Falling Objects (macro particles)" (UFOs) are potentially a major luminosity limitation for the nominal LHC operation. In 2010 and 2011, in total 35 LHC fills were dumped due to UFOs [19].

## LHC INJECTORS

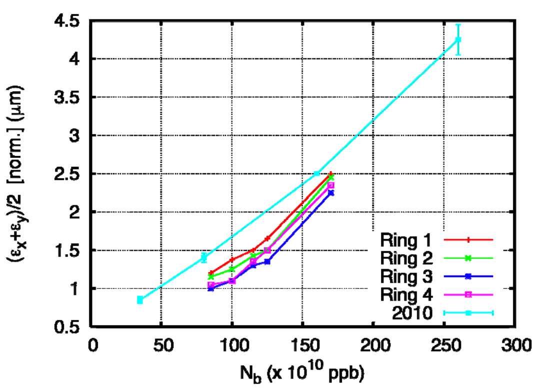
The two main challenges of the LHC injectors were the preservation of the transverse emittance along the injector chain (composed of the duoplasmatron source, LINAC2, PSB, PS and SPS) and the generation of the longitudinal structure (25 ns bunch spacing) with very short bunches (~ 1-1.5 ns at 4σ) at SPS extraction starting from very long bunches (~ 180 ns at 4σ) at PSB-PS transfer [20]. The generation of the required bunch spacing is done in the PS using multiple bunch splittings. The nominal beam emittance at the end of LINAC2 is ~ 1.2 µm. As the PSB could not deliver beams with sufficient brightness, a double-batch scheme was proposed to inject the beam in the PS. Due to the large SC at the PS injection, the PSB extraction kinetic energy was raised from 1 to 1.4 GeV.

### *LINAC2(4) and PSB*

The LINAC2-PSB performance for LHC is summarized in Fig. 3.1, where it can be seen that the PSB operates at about constant brightness. In the future, LINAC4 will replace LINAC2 to inject in the PSB at 160 MeV instead of 50 MeV (to gain a factor 2 in the SC tune shift). Therefore about two times brighter beams can be expected from the PSB, and to be able to profit from that in the PS, the PSB extraction kinetic energy should be increased from 1.4 to 2 GeV, recovering a factor ~ 1.6 in the SC tune shift. Transverse coherent instabilities are not (should not be) an issue for the LHC beams [21].

### *PS*

A horizontal head-tail instability with (absolute) head-tail mode 6 has been observed on the long injection flat-bottom and cured by linear coupling between the transverse planes for more than a decade (with neither octupoles nor transverse feedback) [22]. The SC limit has not been identified yet, but it has been shown in the past that a vertical tune shift of ~ - 0.26 can be accommodated.



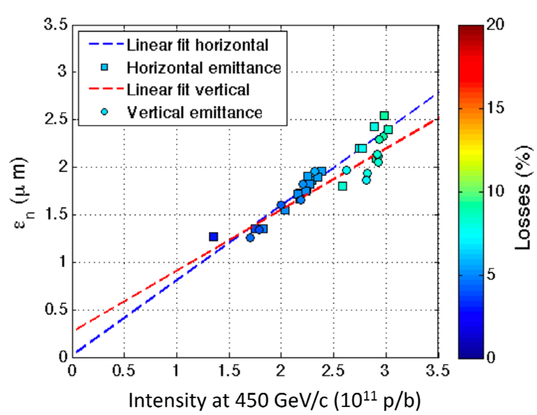




Figure 3: (1) LINAC2-PSB performance for LHC in 2011 [23]. This PSB bunch will then have to be split in 12 in the PS to reach the 25 ns structure (and in 6 for 50 ns). Therefore, the number of protons has to be divided by 12 for the 25 ns beam and by 6 for the 50 ns one to compare with the SPS and LHC figures. Transverse emittances below ~ 1 µm are possible by transverse shaving. (2) SPS performance with a single bunch and the new Q20 optics (a vertical tune shift of ~ - 0.19 has been achieved so far).

In the framework of the LIU project [24], a huge measurement campaign has been restarted recently including simulations to try and push the limit further.

At high energy, e-cloud effects were observed in the past at the end of the cycle when the 25 ns structure is created if the bunch length is too small for too long a time [25]. Careful studies are ongoing to investigate possible issues with the future high-intensity beams [26].

In the longitudinal plane, coupled-bunch instabilities are observed during the ramp after transition (due to the main 10 MHz RF system) and on the flat top (due to other impedances as 9/10 of the cavities are short-circuited and the mode pattern is very different) [27]. The instabilities with 25 ns and 50 ns bunch spacing behave very similarly, with a threshold which scales with the longitudinal phase space density. With the present system the longitudinal coupled-bunch limit (for both 25 and 50 ns bunch spacings) is ~ 1.9 $10^{11}$ p/b. A dedicated wideband kicker should be installed during the 2013-2014 long shutdown to damp all the possible modes. The second limitation in the longitudinal plane of the PS is the transient beam loading during bunch splitting, where the relative phase of the two cavities participating in the bunch splitting shifts along the batch. This is planned to be improved with new one-turn-delay feedbacks.

### *SPS*

A fast vertical single-bunch instability can be observed at injection with very low positive chromaticity. It has been extensively studied in the past [28] and the threshold was found to be at ~ 1.6 $10^{11}$ p/b in quite good agreement with the current impedance model without space charge. With space charge, HEADTAIL simulations revealed only a minor change in the intensity threshold (~ 10%) [29]. Further space charge studies are ongoing as a lot of progress has been done in the last few years on the understanding of the effects of space charge on transverse coherent instabilities [30-32]. This instability is believed to be a TMCI and as TMCI depends on the distance to the transition, a new optics has been proposed to increase the slippage factor (by lowering the gamma transition), called Q20 optics [33]. The threshold for Q20, expected to be at ~ 3.5 $10^{11}$ p/b, was not clearly identified yet, despite very high intensities already sent into the SPS (up to ~ 5 $10^{11}$ p/b but with a lot of losses) [34]. It seems that TMCI should not be a limitation for LIU if the Q20 optics is used.

In the longitudinal plane, the main intensity limitation is an instability (which depends on single-bunch and total beam intensity) during the ramp with very low intensity threshold, which reduces with energy (~ 2 $10^{10}$ p/b at the end of the ramp) [35]. It is cured by a 4th harmonic RF system (800 MHz) and a controlled longitudinal emittance blow-up. The beneficial effect of the lower transition energy is currently under investigation. Another issue is linked to beam loading which requires an upgrade of the RF power [36] to be able to produce the larger longitudinal emittances requested by LIU [37].

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Space charge in the SPS is not a limitation for the current LHC beams but is currently under study (as in the PSB and PS) in the framework of the LIU project. Results from 2011 measurements for the nominal fractional tunes and the Q20 optics are summarized in Fig. 3.2.

Finally, the 25 ns beam with nominal intensity has been suffering from e-cloud for many years, leading to pressure rises and instabilities with a low vertical chromaticity [38], but the beam quality seems to be acceptable since 2011 (which still needs to be fully understood). However for higher intensities, the problem is serious and the baseline is to coat large parts of the inside of the SPS vacuum chambers with amorphous carbon during the second long shutdown, i.e. ~ 2018 [37]. Note that the Q20 optics should also be better for the e-cloud instability [39] and detailed studies are ongoing.

## CONCLUSION

The best performances achieved so far in the different accelerators are summarized in Table 3 [23], with LHC data added. A detailed upgrade plan has been clearly defined within LIU, with two scenarios (for both 25 ns and 50 ns): the "baseline" and the "stretched" [37]. The first cannot provide the required parameters for HL-LHC with a missing factor of about two, whereas the second one almost meets the goals (within few percents). The potential improvements before the LINAC4 could come from alternative schemes using for instance batch compressions in the PS [27]. In the LHC, the possible limitations should come from the loss of Landau damping for the TCBI of head-tail mode - 1, e-cloud effects for the 25 ns beam, RF heating (MKI injection kicker, TDI injection dump, etc.) and beam-beam (with its variety of effects and in particular its interplay with the transverse impedance and Landau damping through octupoles, which needs to be investigated in detail), with some perturbations expected from the UFOs. It is worth reminding that ~ 80% of the maximum available octupole current is currently used at 4 TeV, whereas only ~ 10-20% is expected from our predictions. As some past dedicated measurements were in relatively good agreement with predictions [4,12], this issue should be studied and clarified as soon as possible.

Table 3: Best performance achieved so far in all the accelerators (not necessarily at the same time)

| | 50 ns | | 25 ns | | Single bunch | |
|---|---|---|---|---|---|---|
| | # p/b $[10^{11}]$ | $(\varepsilon_{nx}+\varepsilon_{ny})$ / 2 [μm] | # p/b $[10^{11}]$ | $(\varepsilon_{nx}+\varepsilon_{ny})$ / 2 [μm] | # p/b $[10^{11}]$ | $(\varepsilon_{nx}+\varepsilon_{ny})$ / 2 [μm] |
| PSB | See Fig. 3.1: emittance vs. intensity | | | | 4.0 | 2.2 |
| PS | 1.9 | 1.9 | 1.4 | 3.0 | 4.0 | 2.4 |
| SPS nom | 1.6 | 1.9 | 1.15 | 2.6 | 2.5 | 2.5 |
| SPS Q20 | 1.7 | ? | 1.2 | 2.7 | 3.0 | 2.2 |
| LHC | 1.45<br>1.35 | ~ 2.3<br>~ 2.1 | | | 1.9<br>2.4 | 1.1-1.2<br>2.5-3.0 |

## REFERENCES

[1] O. Bruning et al., CERN-2004-003 (Vol I), 2004.
[2] O. Bruning, HL-LHC / LIU Joint Workshop, 30/03/2012.
[3] E. Métral, LHC Performance Workshop, Chamonix, France, 24-28/01/2011.
[4] N. Mounet, The LHC transverse coupled-bunch instability, PHD thesis from EPFL, Lausanne, Switzerland, 2012.
[5] T. Rijoff, these proceedings.
[6] E. Métral, LHC Performance Workshop, Chamonix, France, 06-10/02/2012.
[7] J. Gareyte, Particle Accelerators, 1997, Vol. 58, pp. 53-61.
[8] W. Herr and B. Muratori, CAS 2010, Varna.
[9] F. Roncarolo et al., Phys. Rev. ST-AB, 12(084401), 2009.
[10] G. Arduini, LHC Performance Workshop, Chamonix, France, 06-10/02/2012.
[11] G. Rumolo, LHC Performance Workshop, Chamonix, France, 06-10/02/2012.
[12] E. Métral et al., Proc. IPAC11, San Sebastian, Spain, September 4-9, 2011.
[13] E. Métral and A. Verdier, CERN-AB-2004-019-ABP, 2004.
[14] E. Shaposhnikova et al., CERN-ATS-2011-035, 2011.
[15] R. Bartoldus, TIPP 2011, Int. Conf. on Tech. and Instr. in Particle Physics, Chicago (2011).
[16] E. Métral et al., Conceptual Design Review LHC Phase II Collimation, CERN, 02-03/04/2009.
[17] W. Herr, LHC Performance Workshop, Chamonix, France, 06-10/02/2012.
[18] X. Buffat, Proc. IPAC11, San Sebastian, Spain, 4-9/09/2011.
[19] T. Baer, LHC Performance Workshop, Chamonix, France, 06-10/02/2012.
[20] M. Benedikt et al., CERN-2004-003 (Vol. III), 2004.
[21] G. Rumolo, Beam instabilities in the PSB operation with high intensity beams, CERN MSWG meeting, August 27th, 2010.
[22] R. Cappi et al., Proc. Workshop on Instabilities of High Intensity Hadron Beams in Rings, BNL, 1999.
[23] G. Rumolo, HL-LHC / LIU Joint Workshop, 30/03/2012.
[24] R. Garoby, these proceedings.
[25] R. Cappi, et al., Phys. Rev. ST Accel. Beams 5, 094401, September 2002.
[26] G. Iadarola, these proceedings.
[27] H. Damerau, LHC Performance Workshop, Chamonix, France, 06-10/02/2012.
[28] B. Salvant, Impedance Model of the CERN SPS and Aspects of LHC Single-Bunch Stability, PHD thesis from EPFL, Lausanne, Switzerland, 2010.
[29] D. Quatraro and G. Rumolo, IPAC 2010, Kyoto, Japan.
[30] A. Burov, Phys. Rev. ST Accel. Beams 12, 044202 and erratum 109901 (2009).
[31] V. Balbekov, Phys. Rev. ST Accel. Beams 14, 094401(2011).
[32] V. Kornilov and O.B. Frankenheim, Proc. of HB2010, Morschach, Switzerland, 2010.
[33] H. Bartosik et al., CERN-ATS-2011-088, 2011.
[34] H. Bartosik et al., these proceedings (WEPPR078).
[35] E. Shaposhnikova, LHC Performance Workshop, Chamonix, France, 24-28/01/2011.
[36] E. Shaposhnikova, CERN-ATS-2011-042, 2011.
[37] B. Goddard, HL-LHC / LIU Joint Workshop, 30/03/2012.
[38] G. Arduini, ECLOUD'04 workshop, Napa, California, USA, April 19-23, 2004.
[39] H. Bartosik et al., CERN-ATS-2011-087, 2011.