HIGH-BRIGHTNESS CHALLENGES FOR THE OPERATION OF THE CERN INJECTOR COMPLEX

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Abstract

CERN's LHC injectors are delivering high-brightness proton and ion beams for the Large Hadron Collider LHC. We review the present operation modes and beam performance, and highlight the limitations. We will then give an overview of the upgrade program that has been put in place to meet the demands of the LHC during the High-Luminosity LHC era.

INTRODUCTION

The proton injector chain of CERN's Large Hadron Collider (LHC) consists presently of a 50 MeV proton linac (Linac2), the Proton Synchrotron Booster (PSB), the Proton Synchrotron (PS) and the Super Proton Synchrotron (SPS).

Linac2 is equipped with a duoplasmatron source and a three-tank drift tube linac operating at 202.56 MHz, which accelerates the protons up to 50 MeV. At injection into the PSB a beam current of 140-150 mA protons is operationally achieved.

Before arriving at the PSB, the beam pulse coming from Linac2 is distributed vertically into four parts, which are then sequentially injected into the four PSB rings. The PSB is a stack of four superposed rings, which accelerate the protons up to 1.4 GeV before the beams are vertically recombined and transferred to the PS. The injection process into the PSB is a multi-turn injection using an injection septum and a horizontal injection bump that is reduced in amplitude during the injection process. The incoming beamlets are scraped by the septum at their first passage, but also during their following turns in the PSB rings, which leads to beam loss in the order of 50% during injection. In combination with space charge at low energy, the resulting transverse emittance of the beams produced by the PSB is a linear function of the number of injected turns. Typically, for high-intensity beams as for example delivered to the isotope separator facility ISOLDE, around 10-13 turns are injected. This results in a large transverse emittance, which is however not critical for these types of beams. Beams for the LHC, where the transverse emittance and hence the beam brightness are critical, are produced with about 2-3 injected turns. Figure 1 illustrates the principle of multi-turn injection into the PSB. Figure 2 shows the measured transverse emittance in the PSB as a function of the extracted intensity for today's operation with Linac2 (upper curves) as well as a simulation for the operation with Linac4 (lower curve) [1].

The PS accelerates further the beams coming from the PSB to 26 GeV for the LHC-type beams. Moreover, the PS performs complex RF manipulations during the cycle, which split, merge or approach the bunches coming from the PSB longitudinally. With these RF manipulations, the longitudinal parameters of the beams going to the LHC are defined.

The last stage of acceleration happens in the SPS, where the protons are accumulated from multiple injections from the PS, and are accelerated from 26 GeV to 450 GeV before being transferred to the LHC. The challenge in the SPS is to minimise beam loss and to preserve the transverse emittances despite the long injection plateau of several seconds.

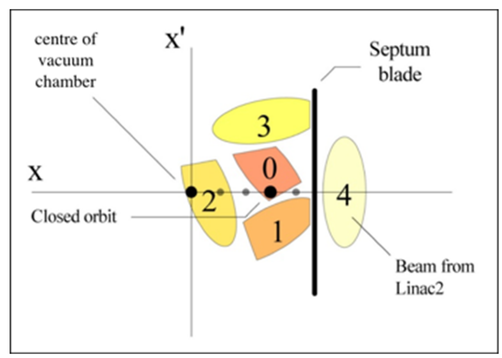

Figure 1: Multi-turn injection of the beam coming from Linac2 into the PSB.

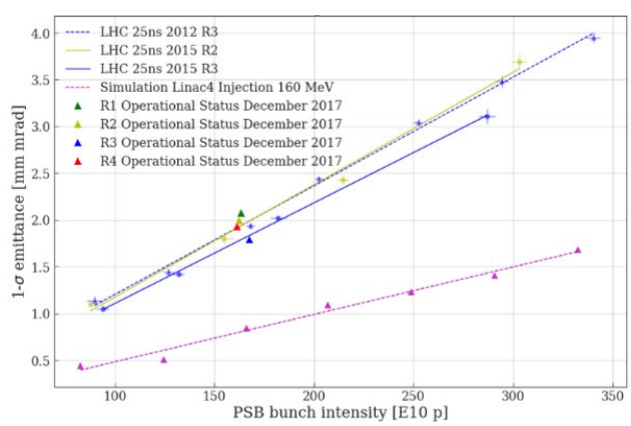

Figure 2: Transverse emittance versus bunch intensity in the PSB. The upper data are measured for different PSB rings and correspond to today's production scheme with Linac2. The lower curve is a simulation for Linac4 injecting into the PSB.

LHC-TYPE BEAMS FROM THE EXISTING CERN INJECTORS

CERN's injectors are able to produce a whole spectrum of beams for the LHC. This ranges from low-intensity single-bunch beams for LHC commissioning to the production beams for luminosity runs. Apart from that, a whole range of special beams can be produced for machine studies or to adapt to special situations. In the following paragraphs we will focus on the two main production beams for the LHC, the 25 ns bunch spacing beam and the so-called BCMS (Batch Compression, Merging and Splitting) beam.

Standard 25 ns Beam

As outlined in the previous section, the transverse emittance and hence the beam brightness is presently defined through the multi-turn injection process into the PSB. For a standard 25 ns bunch spacing beam for the LHC, about 2-3 turns need to be injected into the PSB rings, which results in 160×10^{10} protons per bunch with a normalised transverse emittance of about 2 π mm mrad (note that the original specification for this beam was 2.5 π mm mrad).

The PSB executes two cycles to fill the PS, one using all four rings with one bunch each at extraction ($h = 1$) and a second one using only two of the four rings. With this scheme the PSB produces six bunches at 1.4 GeV energy, which are transferred in two extractions (4 + 2 bunches) to the PS. As the time delay between two PSB extractions is 1.2 s, the first injected batch has to wait at the PS flat bottom.

In the PS the beam is accelerated to a top energy of 26 GeV and at the same time the bunches are longitudinally split at an intermediate and final energy. This scheme employs consecutively the RF harmonics 7, 21, 42 and 84, which leads to a 12-fold splitting of each bunch. The resulting number of bunches produced from the six bunches coming from the PSB is hence 72. The longitudinal emittance of these resulting bunches is 0.35 eVs. Figure 3 is a tomographic picture which shows the triple splitting of the six (4 + 2) bunches coming from the PSB.

The 72 bunches coming from the PS are then transferred to the SPS where the challenge is to inject them with a minimum of beam loss and to accelerate them while conserving the beam brightness.

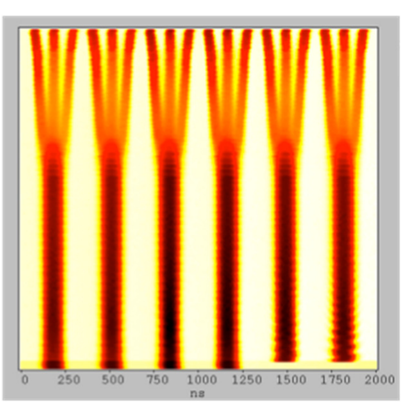

Figure 3: Triple splitting of six PSB bunches in the PS generating the bunch structure for the 25 ns LHC beam.

BCMS Beam

In addition to the standard 25 ns beam, a scheme has been developed to improve the beam brightness. Due to the multi-turn injection into the PSB, the transverse emittance can be reduced by injecting fewer turns into the PSB rings. In the BCMS scheme, instead of taking six PSB bunches into $h = 7$ buckets, the PS takes eight bunches into $h = 9$. The total intensity is then distributed across eight PSB bunches rather than six ones. Accordingly, the injected intensity per PSB ring and thus the transverse emittance can be reduced. A new scheme had to be implemented to obtain the required LHC beam parameters from eight bunches instead of six: the BCMS injection scheme. First, a compression is performed by incrementing the harmonic number from $h = 9$ to 14. Then, a bunch merging puts the harmonic number back to $h = 7$. From this point, the RF gymnastics are similar to the nominal beam, with the bunches split in three, then two and two again. The number of bunches produced is different from the normal scheme: eight bunches are merged into four, multiplied by three, two and two again. The result is 48 bunches spaced by 25 ns, which is less than the nominal 72 bunches. Therefore, the PS and SPS have to perform more cycles to fill the entire LHC, but the gain in transverse emittance leads to higher beam brightness. Figure 4 is a tomographic picture of the BCMS process in the PS. Eight bunches coming in two injections from the PSB are first merged and undergo then a triple splitting.

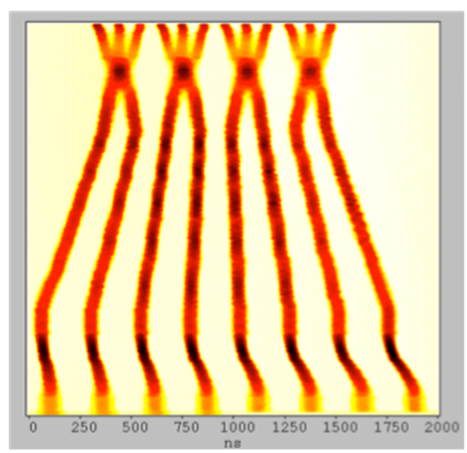

Figure 4: RF gymnastics performed in the PS in order to generate the BCMS beam.

Beam Transfer and Injection

In order to deliver high-brightness beams to the LHC, it is critical to transfer the beam from one injector synchrotron to the next with a minimum of beam loss and emittance blow-up.

Some unexplained blow-up of the transverse emittance during transfer from the PSB to the PS is presently subject of intense studies [2, 3]. One of the possible causes being investigated is betatron and dispersion mismatch at PS injection. It is hoped that more insight can be gained by installing a turn-by-turn profile measurement in the PS, planned in the course of 2018. This monitor would give important information about transverse beam size oscillations at injection, which would point to injection mismatch. While the suspected mismatch is mainly present in the horizontal plane, there is also some vertical blow-up observed along the PS cycle [4].

Regarding the transfer of the beam from the PS to the SPS, the critical issues are mostly found in the longitudinal plane. A bunch rotation is performed in the PS, originally using one 40 MHz and two 80 MHz cavities in order to fit the bunches into the 5 ns SPS RF buckets. The development of uncaptured tails due to non-linear forces is an issue, which has been improved by employing two 40 MHz cavities. This scheme has successfully been used during the 2017 run. Nevertheless, there are remaining longitudinal losses at capture, flat bottom, and start of the acceleration in the SPS. The capture losses are mostly due to the longitudinal distribution after bunch rotation in the PS and to RF transients during the first few ms in the SPS. The losses on the flat bottom are due to particles close to the separatrix. Minimizing the capture losses by increasing the RF voltage in the SPS is limited by the requirement to have a matched particle distribution, the momentum acceptance and the available RF voltage needed to maintain the bucket area during the ramp.

Limitations of the Present Scheme

The various processes described in the previous sections ensure the delivery of high-brightness beams well within the requirements of the LHC. However, the multi-turn injection into the PSB and a number of other effects (e.g. emittance blow up due to space charge, instabilities) lead to a limitation in the brightness that can be achieved. For the SPS, the main limitations come from the beam-loading at very high beam intensity which reduces the available RF voltage, longitudinal instabilities linked to the machine impedance, the electron cloud effect, which at 25 ns spacing can make operation impossible through high vacuum or transverse instabilities, and the high stored beam energy, which requires significant upgrades of all beam intercepting protection devices in the ring and transfer lines.

Figure 5 shows the measured 2017 performance of the injector chain for the LHC 25 ns beam and for the BCMS beam. The various lines indicate processes, which limit the achievable beam brightness, the most stringent one being the brightness curve due to the PSB injection scheme discussed earlier. The green point indicates the beam performance achieved in 2017. It can be seen that the operationally achieved beam brightness is very close to the identified limitations, and that further improvement of the beam brightness as required by the High-Luminosity LHC project (orange point) is not achievable with the present scheme.

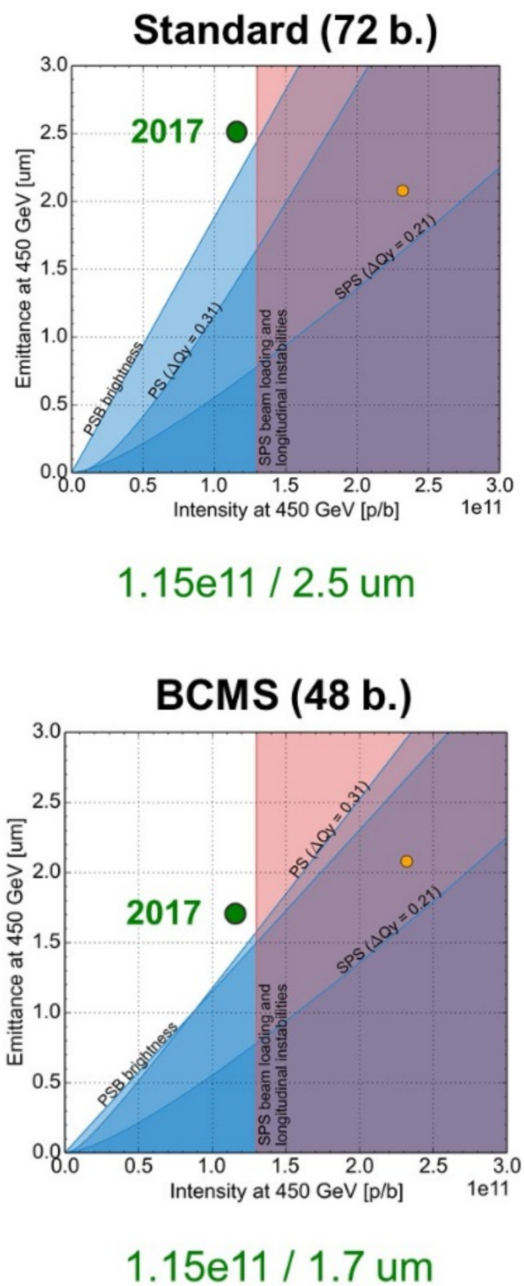

Figure 5: Measured 2017 beam performance for the standard 25 ns beam and BCMS beam. The present beam performance is very close to the theoretical limitations of the present scheme.

LHC INJECTORS UPGRADE

In order to deliver high-brightness beams to the LHC in the High-Luminosity LHC era, CERN has put in place the LHC Injectors Upgrade (LIU) project. This project comprises the replacement of Linac2 by a new H^- linac (Linac4) with an increased injection energy in the PSB, the increase of the top energy of the PSB from 1.4 GeV to 2.0 GeV and upgrades of the PS and SPS synchrotrons [5].

Linac4

Linac4 is a 160 GeV H^- linac, which has been constructed over the past decade at CERN and which is presently performing a reliability run. Due to the increased energy, the H^- injection, horizontal phase-space painting and the possibility of energy variability and longitudinal micro-bunch tailoring via a fast chopper located at low energy, Linac4 will allow removing the current space charge detuning bottleneck reached with the high-current Linac2 beam.

PSB Upgrade

The upgrade of the PSB consists of two major parts. With the connection of Linac4 to the PSB, the injection scheme will be upgraded to charge exchange injection of H^- ions. This change will significantly reduce beam loss in the injection area and will allow for tailoring the horizontal emittance by means of phase space painting. At the same time, the injection energy will be increased from 50 MeV to 160 MeV. With this increase in beam energy the relativistic $\beta\gamma^2$ factor increases by a factor of 2. The space charge tune shift decreases hence by a factor 2, thus doubling the intensity that can be accumulated within a given emittance.

The second component of the upgrade program is the increase of the extraction energy from presently 1.4 GeV to 2.0 GeV. The underlying idea is to reduce space charge effects at injection into the PS, thus removing this bottleneck. The expected gain can again be deduced from the ratio of the $\beta\gamma^2$ factor at 1.4 GeV and 2.0 GeV, which is 1.63 and corresponds to an intensity increase of 60% within given emittance values.

PS Upgrade

The upgrade program of the PS focuses on issues both in the transverse and longitudinal plane. In the transverse plane, the direct space-charge tune spread pushes the beam on betatronic resonances causing beam loss and transverse emittance blow up. The upgrade of the injection energy to 2 GeV will help to overcome this limitation. The transverse damper was also upgraded to cope with transverse instabilities and to reduce injection errors.

Concerning the longitudinal plane, coupled bunch instabilities appearing after the transition energy would limit the maximum intensity per bunch well below the 2.6×10^{11} p+ per bunch of the future HL-LHC type beam if no countermeasures were taken. A new dedicated longitudinal damper, based on a Finemet® cavity and a new low-level RF (LLRF) have been installed during LS1 to stabilise the beam. The electronics of the 1-turn delay feedback was also renovated with a new digital system for the main accelerating cavities. The high-frequency cavities are being equipped with additional multi-harmonic feedbacks.

Beyond these main upgrade items, new hardware items are being constructed, as for example beam instrumentation, RF upgrade and beam dumps.

SPS Upgrade

The present baseline for the LIU-SPS upgrade results from the extensive effort invested in the analysis and understanding of the SPS limitations during the past decade. Main upgrade items are the 200 MHz RF system and its low-level RF. The LLRF and power system of the fourth harmonic 800 MHz RF system has also been already upgraded. The existing transverse damper system is also being upgraded with new low-level controls and dedicated pick-ups. The preparation for the upgrade of the 200 MHz RF continues with the prototyping of the power amplifiers now under way, the design of the new power and HOM couplers in progress and the layout change to the RF cavities and associated SPS straight section defined.

In order to fight electron cloud effects, amorphous carbon coating of the vacuum chamber was fully validated as a mitigation measure using a sputtering technique, which does not require the removal of the vacuum chamber from the magnet. This technique will be applied to selected elements of the machine.

To cope with the increased intensity, various machine protection elements will be upgraded and a new internal beam dump will be installed.

Concerning beam instrumentation, performance upgrades of almost every system have been defined and specified, for example the installation of new high-resolution wire scanners.

Ions

The HL-LHC is requested to deliver Pb-Pb collisions with an integrated luminosity of 10 nb^{-1} at top energy to each of the ALICE, ATLAS and CMS experiments in four heavy-ion runs between LS2 and LS4 [6]. From this requirement, the following target parameters, based on extrapolated performance with seven injections in 2016, can be derived: A total of 1256 bunches per ring in the LHC with 1.9×10^8 lead ions per bunch and 1.5 µm rad of normalized emittance at injection.

The strategy to reach the required performance is:

- Increase of the beam intensity by modification of the Linac3 source extraction system to remove an aperture limitation. This upgrade took place in 2015 and allowed 40% beam intensity increase.
- An intensive program of machine studies, starting in 2015 for optimization and understanding of the machine limitations in LEIR and SPS. As a result of the LEIR studies an increment of 30% in extracted intensity could be achieved. However, the SPS remains the bottleneck of the Pb-ion injector chain and more studies will be conducted to lift this limitation.
- Batch expansion and bunch splitting in the PS to reach a bunch spacing of 100 ns, which was already demonstrated before the Long Shutdown 1 (LS1).
- Implementation of the momentum slip stacking in the SPS during LS2 with a new low-level RF system reducing the bunch spacing down to 50 ns, the only way to double the number of bunches in LHC.

Thanks to the Linac3 modifications and LEIR machine studies, these two machines are the first ones in the Pb-ion injector chain that demonstrated the capability of delivering the required HL-LHC beam parameters during operation in 2016.

Expected Performance after LIU Upgrade

With the various upgrades foreseen by the LIU project in place after the second long LHC shutdown (LS2), many of the present intensity limitations will disappear or be mitigated. In particular, the H^- stripping injection in the PSB and the increase of the top energy of the PSB are expected to push the brightness limitations of the injector chain. As can be seen in Fig. 2, the simulated PSB brightness curve with Linac4 lies well below the present measured ones and has a smaller slope. Figure 6 illustrates the extrapolated performance reach of the injector chain with the full LIU upgrade in place. The request of the High-Luminosity LHC can be met.

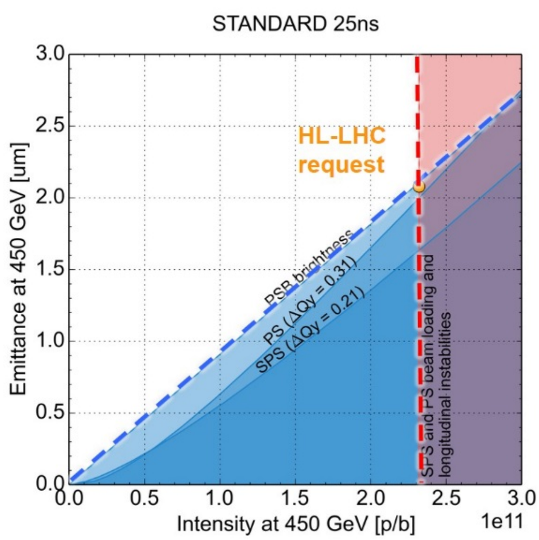

Figure 6: Performance reach of the injector complex after LIU upgrade. The request of the High-Luminosity LHC can be met.

CONCLUSION

CERN's LHC injectors deliver today a variety of high-brightness beams to the LHC. While the present request of the LHC can be satisfied or exceeded, the future HL-LHC program is requesting beam parameters which are out of reach of the present injector complex. In order to enable the injectors to deliver the requested beam intensity and beam brightness, CERN has put in place a massive upgrade program, the LIU project. The upgrade will be performed during LS2 in 2019/20. Simulations show that the upgraded machines will meet the brightness requirements in the HL-LHC era.

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