INJECTORS BEAM PERFORMANCE EVOLUTION DURING RUN 2

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Abstract

This contribution gives an overview of the beam performance of the LHC injector chain during Run 2. In the first part the various beam types used for LHC luminosity production with protons (e.g. 25 ns standard, 25 ns BCMS, 8b4e, 8b4e BCS) are described. The present performance limitations along the injector chain together with the achieved beam parameters at LHC injection (e.g. transverse emittance, intensity, batch spacing) are summarised. Also the special high intensity beams, which were studied within the LIU framework and also extracted to the LHC for Machine Development studies, are mentioned. The second part describes the evolution of the ion beams for the LHC throughout Run 2 and their optimisation for luminosity production.

PROTONS

The LHC proton injectors, i.e. Linac2, PSB, PS and SPS, offer a large menu of proton beams. A variety of bunch patterns can be created thanks to the flexibility of the PS RF systems, which allowed optimising the LHC luminosity production during Run 2 [1]. In particular, the LHC used the 50 ns beam for the restart after LS1 and in August 2015 switched to the nominal 25 ns beam [2], which is nowadays referred to as the "standard" beam in the injectors jargon. In June 2016 the high brightness version of the 25 ns beam obtained through the Batch Compression Merging and Splitting (BCMS) scheme became operational for physics production [3–5]. In 2017, when several LHC fills were lost because of losses in 16L2 [6], the 8b4e beam [7–9] and later its high brightness variant 8b4e BCS with their low e-cloud buildup characteristics became operational and allowed reaching a decent integrated luminosity. In 2018 the LHC used again the BCMS beam for luminosity production. In addition to these operational beams, the injectors provided special beams such as the doublet beam for enhanced scrubbing [10], as well as high intensity single bunch and 25 ns beams for Machine Development (MD) studies.

The present performance limitations along the injector chain together with the performance improvements implemented during Run 2 and the achieved beam parameters at LHC injection (e.g. transverse emittance, intensity, batch spacing) are discussed in the following, for both the operational beams and the special beams mentioned above.

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Operational LHC beams

PSB The intensity reach of the PSB (e.g. ISOLDE beam) is far beyond the typical intensities required to produce the LHC beams, even when considering the intensities of the future LIU beams [11]. In this sense, the LHC beams have no intensity limitation in the PSB. The LHC beams are produced at constant brightness (intensity/emittance). The brightness limit of the PSB is imposed predominantly by direct space charge effects and thus depends critically on the longitudinal emittance and on the working point (transverse tunes) in the low energy part of the cycle. Figure 1 shows the measured transverse emittance (average between horizontal and vertical) as a function of intensity for all four PSB rings for the BCMS beam in 2018 at a fixed longitudinal emittance of 0.9 eVs. All four rings have been optimised and thus have a very similar brightness curve. The connection of Linac4 and the increased injection energy of 160 MeV as part of the LIU upgrade during LS2 is expected to allow the PSB to reach about twice the present brightness [11, 12].

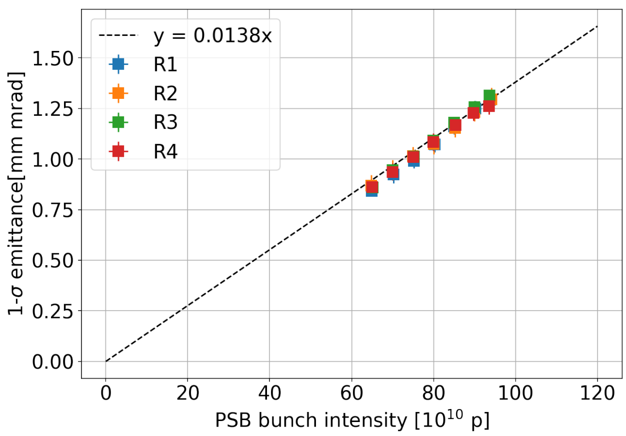

Figure 1: Measurement of the brightness curve in all four PSB rings before PSB extraction for the BCMS beam in 2018 with a working point of $Q_x/Q_y = 4.43/4.48$ at injection.

PSB-to-PS transfer In 2016 it was realised that the wire scanner measurements performed at PSB extraction compared to the wire scanner measurements performed at PS injection show a distinct increase of the horizontal emittance for LHC-type beams [13]. The operationally used transfer line optics results in a significant mismatch of the horizontal dispersion at the PS injection point, which can however explain only part of the observed blow-up. The remaining discrepancy has been subject of MDs over the last years and is still under investigation [14]. Also systematic errors of the emittance calculation from the measured beam size could play an important role, given the large dispersive contribution to the profiles in both the PSB and the PS.

With the increase of the kinetic energy at the PSB-to-PS transfer from the present 1.4 GeV to 2 GeV, which is part of the LIU program, the transfer line will be rebuilt and the dispersion mismatch will be corrected [11].

PS The LHC beams are operated at the space charge limit on the PS injection plateau. Space charge remains also critical during the first ramp to the intermediate plateau at 2.5 GeV kinetic energy used for the RF manipulations: MDs in 2016 revealed a vertical emittance blow-up during the ramp due to the bunch shortening caused by the high RF voltage used, which enhanced the space charge effect and thus caused vertical emittance blow-up [15]. Implementing a voltage program with constant bucket area avoids the unnecessary bunch shortening and mitigates the blow-up. A clear improvement of the beam brightness at LHC injection was achieved after operational deployment of the constant bucket area voltage program on the BCMS cycle in 2017, as shown in Fig. 2. The achievable brightness in the PS will be roughly doubled with the LIU upgrade thanks to the increased injection energy of 2 GeV and using optimised parameters at the PSB-to-PS transfer such as large longitudinal emittance and momentum spread [11].

The main intensity limitation for LHC proton beams in the PS comes from longitudinal instabilities during the ramp

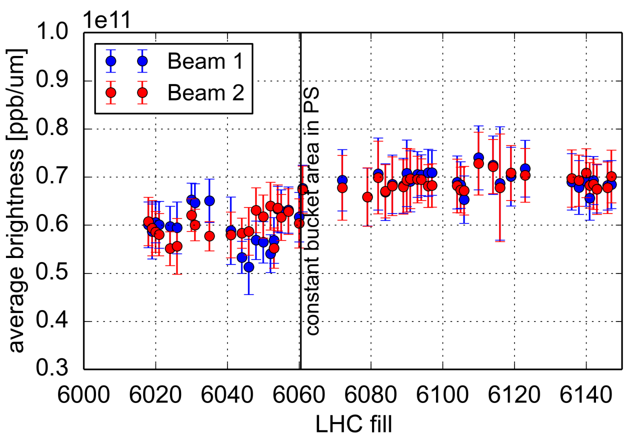

Figure 2: Brightness (intensity/transverse emittance) averaged over all bunches for the two beams at LHC injection as a function of the LHC fill number for the operational BCMS beam in 2017. The improvement after implementing the constant bucket area voltage program in the PS is clearly visible.

(after transition crossing) and at flat top. These instabilities have not limited the performance of the operational beams used for LHC filling, but required several upgrades of the RF system to reach the LIU target intensity as will be discussed below in the context of the MD beams.

PS-to-SPS transfer A bunch rotation scheme is used during the last turns in the PS before extraction for transferring the LHC beams from the 40 MHz RF buckets in the PS to the 200 MHz RF structure in the SPS. In the original scheme from the LHC design report [2], one 40 MHz cavity and two 80 MHz cavities are used for this RF manipulation, which however creates relatively large longitudinal tails exceeding the SPS RF bucket and thus results in capture losses. Figure 3 (top) shows a simulated bunch distribution with the nominal bunch rotation scheme. An optimised bunch rotation scheme using an already installed 40 MHz cavity in addition to the cavities used in the nominal scheme was developed and successfully tested already before LS1 [16]. In

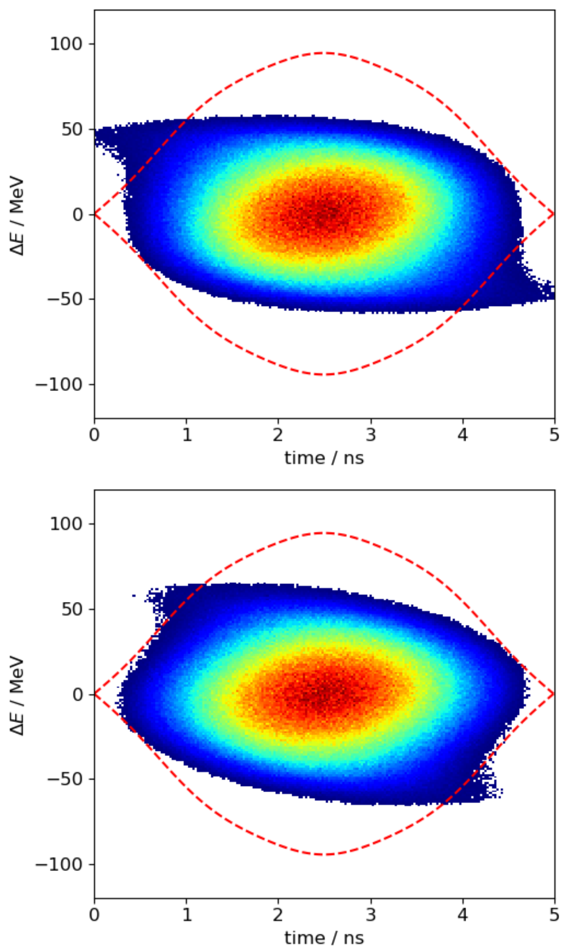

Figure 3: Simulated longitudinal distribution obtained after bunch rotation in the PS using the nominal scheme (top) and using the optimised scheme with an additional 40 MHz cavity (bottom), where the colour indicates particle density. The dashed line shows the SPS separatrix.

this case the longitudinal tails are clearly reduced as can be observed in the simulated longitudinal phase space shown in Fig. 3 (bottom). As a result, the total losses of the LHC 25 ns beams with nominal intensity are reduced from about 8% to about 5% in the SPS. Furthermore also "longitudinal" losses at LHC injection and ghost bunch population are reduced. This new bunch rotation scheme is used in routine operation since mid 2016. Since the additional 40 MHz cavity, which previously served as hot spare, is now in use by default, the operation has to fall back to the old bunch rotation scheme using only one 40 MHz cavity in case of a cavity failure. This happened only once up to now. New power converters for the RF amplifiers installed during the 2017/2018 Year End Technical Stop further improve reliability.

SPS The long injection plateau of the SPS cycle for LHC beams is challenging for transverse emittance growth and losses. Mitigating the electron cloud effect requires regular scrubbing runs after long machine stops (like Extended Year End Technical Stops). The space charge tune spread is about 0.1 for the present 25 ns BCMS beams, but will be doubled with the LIU beam parameters.

The main intensity limitations in the SPS for LHC beams is due to longitudinal instabilities, as well as losses on the flat bottom and during the first part of acceleration. The present intensity limit for long bunch trains of the 25 ns beam is at around 1.3e11 p/b at the 450 GeV/c extraction momentum. Detailed experimental studies performed during Run 2 have shown that the main origin for the losses increasing with intensity can be attributed to insufficient beam loading compensation in combination with the full RF buckets resulting from the capture of the longitudinal distribution after the PS bunch rotation [17]. This intensity limitation will be lifted with the major upgrade of the SPS main 200 MHz RF system, which will significantly increase the available RF power while reducing the cavity impedance [11].

The achievable batch spacing in the SPS depends on the rise-time of the MKP injection kickers. In 2016 the fine synchronisation of the MKP switches and the delay settings were optimised by the experts. Compared to the 250 ns batch spacing used until 2016, a batch spacing of 200 ns was achieved for the proton beam during the 2016 Pb-p physics run. The 200 ns batch spacing became operational for LHC proton physics production in 2017, which allowed increasing the total number of bunches in the LHC by a few percent. Figure 4 shows the MKP rise-time obtained from beam based measurements at 26 GeV/c after optimisation of the MKP switches. The 200 ns batch spacing is at the limit of the ±2% tolerance of the MKP waveform. Figure 5 shows the horizontal oscillation amplitude of the last bunch of the last circulating batch and the first bunch of the injected batch as a function of the MKP delay setting for 200 ns batch spacing (optimum at a delay of 72.63 μs). With optimised settings, both these bunches have a residual oscillation amplitude of about 5 mm. The SPS transverse damper mitigates emittance growth and losses of these bunches sufficiently for the LHC beam quality requirements.

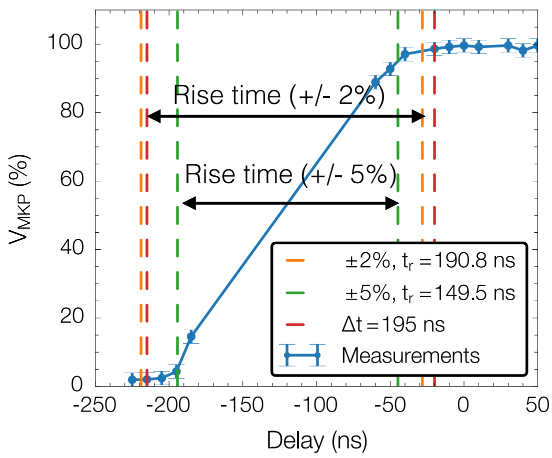

Figure 4: Beam based measurement of the MKP waveform.

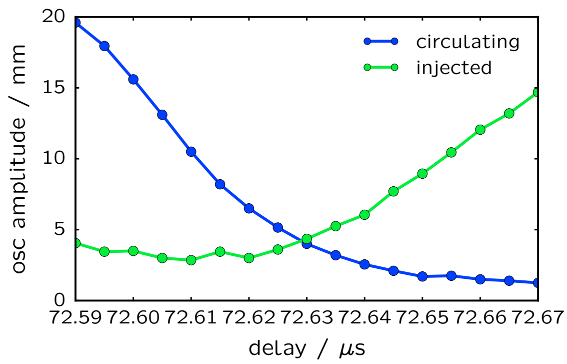

Figure 5: Oscillation amplitude of the last bunch of the last circulating batch and the first bunch of the injected batch as a function of the MKP delay setting for 200 ns batch spacing.

Proton performance evolution The performance limitations of the injector complex discussed above can be summarised in a limitation diagram, where the brightness limitations (due to space charge) and the intensity limit of each machine are translated to parameters at SPS extraction assuming budgets for emittance growth and losses (PS: 5%, SPS: 10%). These limits depend on the beam type due to different longitudinal emittances in the PSB and due to different bunch splitting factors in the PS. Figure 6 shows these limitation diagrams for the beam types used during Run 2, together with the average emittance measured with the BSRT at LHC injection as a function of intensity. The green dots indicate the measured beam parameters, the coloured shaded areas indicate beam parameter configurations that are not accessible. As can be seen, the operational performance of the injectors was in general quite close to the expected performance limit. Worth highlighting is the change of the constant bucket area in the PS for the BCMS beam in 2017, which results in 2 clusters of points: points with lower emittance, i.e. higher brightness, were achieved after the modification. Note that the BCMS beam performance in 2018 was particularly good.

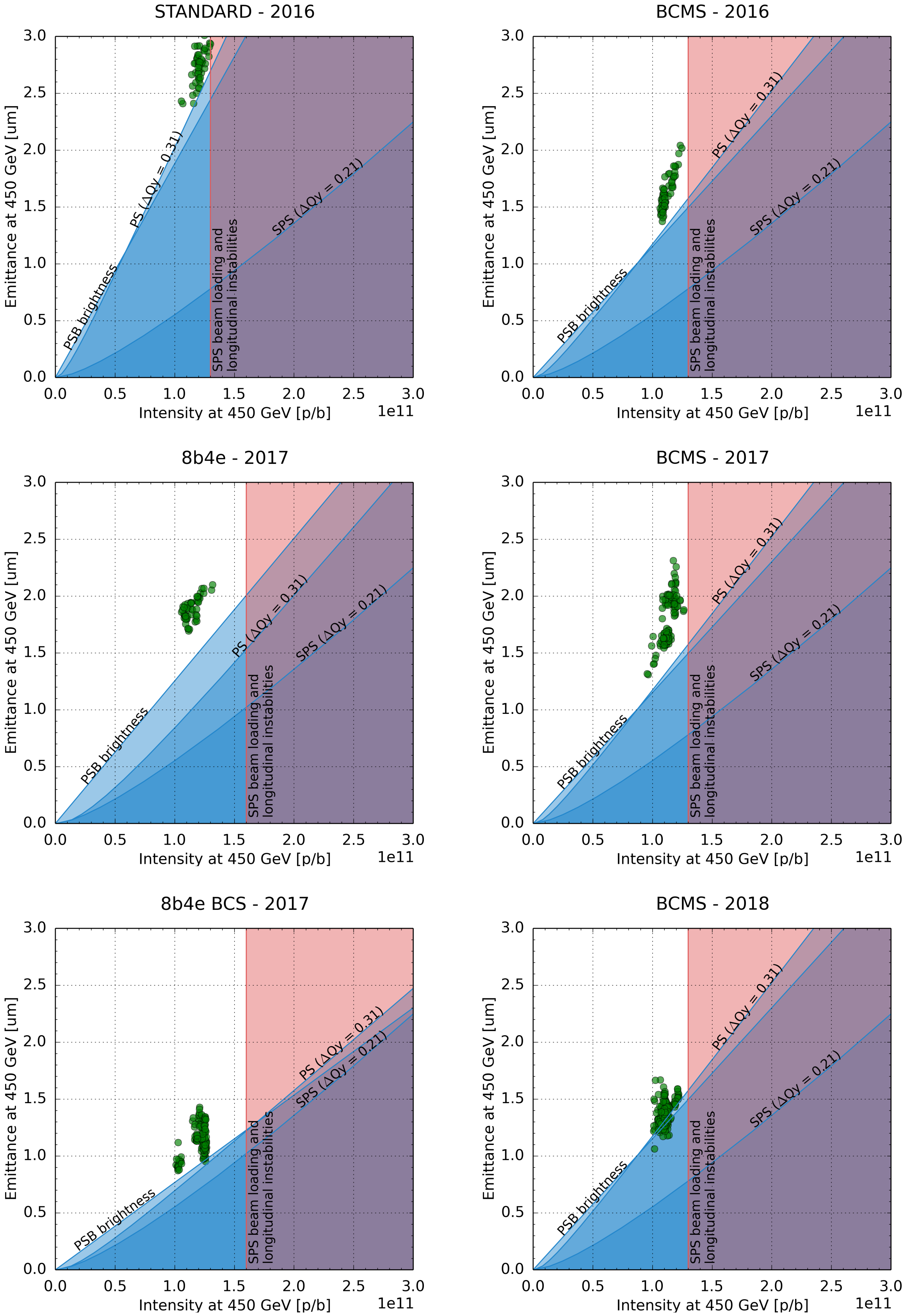

Figure 6: Injectors limitation diagrams with the average emittance measured by the BSRT at LHC injection as a function of intensity for the operational LHC beams (green dots): standard in 2016 (top, left), BCMS in 2016 (top, right), 8b4e in 2017 (centre, left), BCMS in 2017 (centre, right), 8b4e BCS (bottom, left) and BCMS in 2018 (bottom, right).

MD beams

An extensive MD program was completed in the injectors during Run 2. Most of the studies were focused on LHC beams in preparation of the upgrades during LS2 and the ramp up to the LIU beam parameters. An impressive performance evolution has been achieved for the LHC beams in the PS. As shown in Fig. 7, the successive implementation of the LIU upgrades for the PS RF system and their commissioning during MDs allowed reaching the LIU target parameters in terms of intensity and longitudinal parameters at PS extraction in 2018 for the 25 ns standard beam.

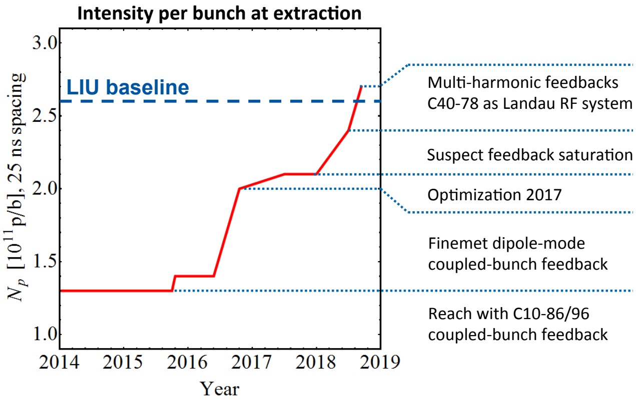

Figure 7: Evolution of the PS intensity reach of the nominal 25 ns beam with 72 bunches with beam quality according to LHC requirements. The different stages of the LIU upgrades resulting in each step of intensity gain are also indicated.

These high intensity beams could be used in the SPS for studying instabilities and losses on the injection plateau, but also for producing high intensity beams in short trains with acceleration to 450 GeV/c for special MDs in the LHC. The following MD beams were injected into the LHC:

- **Doublet beam:** a special beam for scrubbing, produced by injecting a 25 ns beam into the SPS on the unstable phase to split bunches into doublets (with 5 ns spacing within the doublets); this beam was tested during the 2016 LHC scrubbing run with an intensity of up to 1.6e11 p/doublet;

- **80 bunches scheme:** the 80 bunch scheme is obtained through the standard 25 ns scheme but starting from 7 PSB bunches (instead of the usual 6) and eliminating one out of 21 bunches after triple splitting in the PS; this beam was injected into the LHC for MDs in 2016 with the nominal intensity of 1.1e11 p/b;

- **High intensity 25 ns bunch trains for LHC MDs:** Trains of 4 x 12 bunches BCMS beam with 2e11 p/b could be reached in the SPS (less beam loading compared to long trains) and even extracted to the LHC for MDs on heat load and instabilities in 2018;

- **High intensity 8b4e:** Trains of 2 x 48 bunches of the 8b4e beam with 1.6e11 p/b were injected into the LHC for heat load MDs in 2018;

IONS

Details on the heavy ion runs of the LHC during Run 2 are given in [18]. The injectors provided Pb-ions for the Pb-Pb run in 2015, for the p-Pb run in 2016 and for the Pb-Pb run in 2018. In addition, Xe-ion beams were produced for a pilot physics run in the LHC in 2017. An impressive improvement of the Pb-ion injector performance has been reached during Run 2, as described below.

Linac3 The re-design of the source extraction system in 2016 in combination with the removal of aperture limitations resulted in a significant increase of the beam intensity from Linac3 due to a 40% higher total transmission from the source to LEIR, and eases the source tuning. The source stability is still an issue for the performance reproducibility and efforts are now focusing on automatic source tuning.

LEIR The intensity reach of LEIR could be practically doubled as compared to the pre-LS1 machine performance, as shown in Fig. 8. Since 2016, LEIR is operating comfortably above the LIU target intensity [19]. This required optimisation of machine settings to avoid losses at resonances (e.g. working point, closed orbit, e-cooler, resonance compensation, ...) and RF capture optimised for bunch profile flattening in the double harmonic RF system to minimise transverse space charge effects [20, 21]. Frequency modulated RF capture reduces shot-to-shot intensity variations. Tools for automatic machine tuning have been developed in 2018 to improve the performance reproducibility.

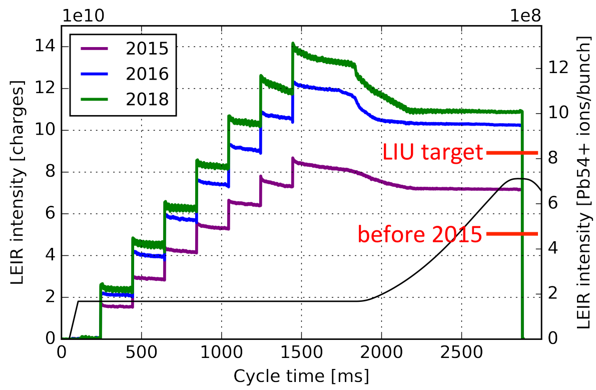

Figure 8: Evolution of the intensity along the LEIR cycle showing records achieved from pre-LS1 to 2018.

PS Pb-ion beams have no strong intensity limitations in the PS. For high bunch intensities the beam becomes unstable just after transition crossing, but this is not of big concern as the beam quality is sufficient for the LHC requirements.

The production scheme for the Pb-ion beams for the LHC has been evolving along Run 2 in order to optimise the in-

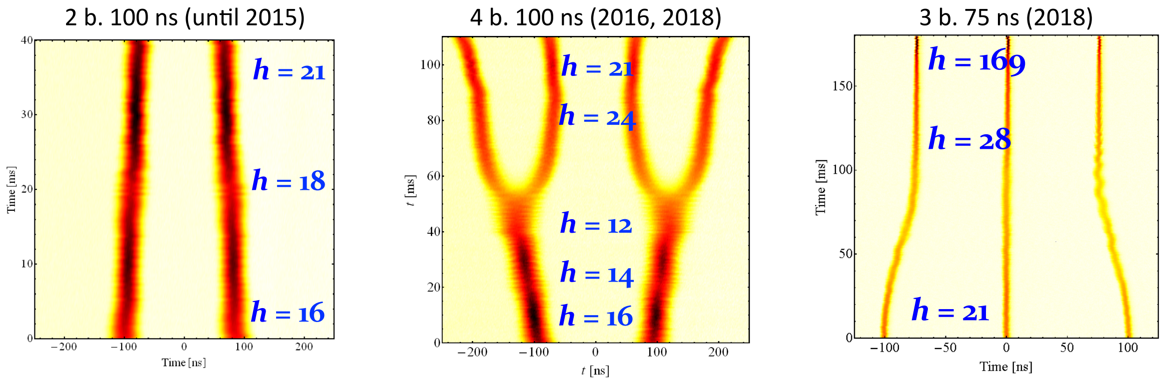

Figure 9: Overview of the beam production schemes for Pb-ions in the PS used for LHC luminosity production during Run 2, i.e. the 2 bunches spaced by 100 ns (left), the 4 bunches spaced by 100 ns (center) and the 3 bunches spaced by 75 ns as obtained by batch-compression at flat-top (right).

tegrated luminosity according to the performance of the injectors (in particular LEIR), as shown in Fig. 9. In 2015 the PS provided 2 bunches spaced by 100 ns per batch to the SPS, which is the same scheme as was used before LS1. With the increased intensity available from LEIR in 2016, bunch splitting at flat top was introduced in the PS so as to provide 4 bunches spaced by 100 ns per batch to the SPS (nominal scheme [2]). This scheme was also used in the first part of the run in 2018. In the second half, a new scheme with 3 bunches from LEIR was introduced where the PS is performing a batch compression at flat top resulting in 3 bunches spaced by 75 ns per batch to the SPS [22].

SPS The ion batches from the PS are short compared to the 800 ns injection kicker rise time in the LHC, while the SPS injection kicker rise time is relatively short. Thus, cycles with a long injection plateau for many injections are required in the SPS to maximise the total intensity in the LHC. This results in a large spread in bunch parameters in terms of intensity, bunch length and transverse emittances, with a strong dependence on bunch intensity due to beam degradation along the flat bottom arising from space charge, intra-beam scattering and possibly RF noise.

Figure 10 shows the intensity evolution along the SPS cycles for the different years. The losses along the flat bottom are clearly visible, especially for the 2015 cycle where each injection consisted of 2 bunches from the PS with 12 injections in total. In 2016, a clearly better transmission was achieved by switching to the 4 bunch scheme, i.e. reducing the intensity per bunch. Due to LHC injection kicker limitations the batch length was limited to 7 PS injections in this case. In 2018 the cycle for the 4 bunch scheme was prepared with 12 injections, but the LHC abort gap was already setup for the 75 ns scheme and thus only 9 injections from the PS could be used operationally. A total of 14 injections into the SPS were used for the 3 bunches with 75 ns spacing, resulting in a clearly increased total intensity for a reduced total batch length. Unlike the years before, the Q26 optics was used in 2018 in preparation of the LIU beam production

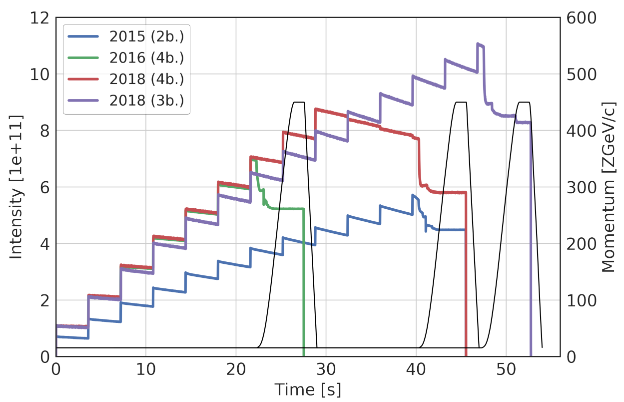

Figure 10: Intensity in the SPS from 2015 to 2018. The number of bunches per batch is indicated in the legend.

scenario (after the momentum slip stacking foreseen with the LIU upgrades, the longitudinal emittance will be quite large and the Q26 optics allows reaching the required bunch length for injection into the LHC). It should be mentioned that the Pb-ion beams suffer from longitudinal instabilities after transition crossing, especially with the pushed intensities with the 3 bunch scheme in 2018. A deliberate degradation of the transition crossing delay had to be programmed in 2018 to generate longitudinal emittance blow-up for stabilising the beam. Simulation studies are ongoing to find better means of beam stabilisation in view of the implementation of momentum slip stacking.

The SPS injection kicker rise-time was optimised also for the ion beams. Compared to the 200 ns batch spacing used before LS1, batch spacings of 150 ns could be achieved operationally (possible only with the rigidity of ions) after deploying the transverse damper on the injection plateau.

Pb-ion performance evolution Since the LHC luminosity production with heavy ions is in the strong burn-off regime, the total number of ions per beam in the LHC is a

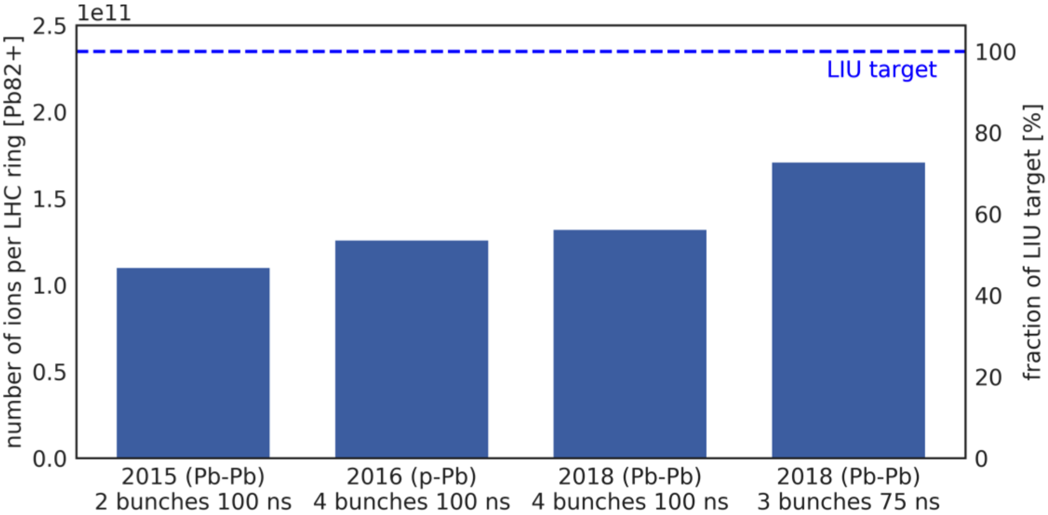

Figure 11: Total number of ions per LHC ring for the beam production schemes used during Run 2.

good figure of merit for the luminosity performance. Figure 11 shows the evolution of the number of Pb^{82+} ions per LHC ring for the beam production schemes used during Run 2. The intensity increase achieved over the years is impressive. In particular, the 75 ns scheme introduced in 2018 allowed reaching about 70% of the LIU target intensity (with single bunch parameters already exceeding the target). Reaching the LIU target requires the implementation of momentum slip stacking for reducing the bunch spacing and increasing the number of bunches in the LHC.

SUMMARY

The excellent performance and in particular the flexibility of the LHC injector chain to produce various types of bunch trains have been key to the outstanding luminosity production performance of the LHC during Run 2. In preparation of reaching the LIU target parameters after LS2, numerous studies have been performed in the injectors, which have led to improved performance already during Run 2 also thanks to LIU upgrades already partly in place.

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