RECENT BEAM PERFORMANCE ACHIEVEMENTS WITH THE Pb-ION BEAM IN THE SPS FOR LHC PHYSICS RUNS

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Abstract

In the SPS, which is the last accelerator in the LHC ion injector chain, multiple injections of the Pb-ion beam have to be accumulated. On this injection plateau the beam suffers from considerable degradation such as emittance growth and losses. This paper summarises the achievements on improving the beam parameters and maximising the performance of the Pb-ion beam for the LHC physics run in 2018. The results are discussed in view of the target beam parameters of the LHC injectors upgrade project, which is being deployed during the presently ongoing long shutdown.

INTRODUCTION

The LHC (Large Hadron Collider) injector chain for heavy-ion beams at CERN consists of Linac3, the accumulator ring LEIR (Low Energy Ion Ring), the PS (CERN Proton Synchrotron) and the SPS (Super Proton Synchrotron) [1]. The LHC injectors upgrade project (LIU) [2, 3] aims at upgrading the existing accelerator chain in view of the increased beam performance required for the High Luminosity LHC (HL-LHC) era. This starts for the heavy-ion program in 2021 after the upgrade of the ALICE detector in Long Shutdown 2 (LS2).

An intense effort has been made in the last years in order to maximize the intensity from the ion injector chain in the frame of the LIU project, which directly improved the performance of Pb-ion beams for the LHC during Run 2 (2015-2018). The injectors provided Pb-ions for the Pb-Pb runs in 2015 and 2018, and the p-Pb run in 2016 [4]. In addition, Xe-ion beams were produced for a pilot physics run in the LHC in 2017 and partially stripped Pb-ions (Pb81+) have been provided to the LHC for tests in view of the Gamma Factory proposal [5, 6]. In the following, the Pb-ion beam intensities achieved so far are summarised and compared to the LIU target parameters. The main remaining limitations and milestones for the LIU ion project are discussed.

PRE-INJECTORS

An impressive improvement of the Pb-ion injector performance has been reached during Run 2. In 2016 the source extraction system was re-designed, and in combination with the removal of aperture limitations resulted in a significant increase of the beam intensity from Linac3 [7], with a 40% higher total transmission from the source to LEIR. The intensity reach of LEIR could be practically doubled as compared to the Run 1 machine performance, as shown in Fig. 1. Since 2016, LEIR is operating comfortably above the LIU target intensity [2]. This required the optimisation of the machine settings to avoid losses at resonances (e.g. working point, closed orbit, e-cooler, resonance compensation, among others) and the optimisation of the RF capture for bunch profile flattening in the double harmonic RF system to minimise transverse space charge effects [8–11]. The frequency modulated RF capture also reduces shot-to-shot intensity variations [12]. Tools for automatic machine tuning have been developed in 2018 to improve the performance reproducibility.

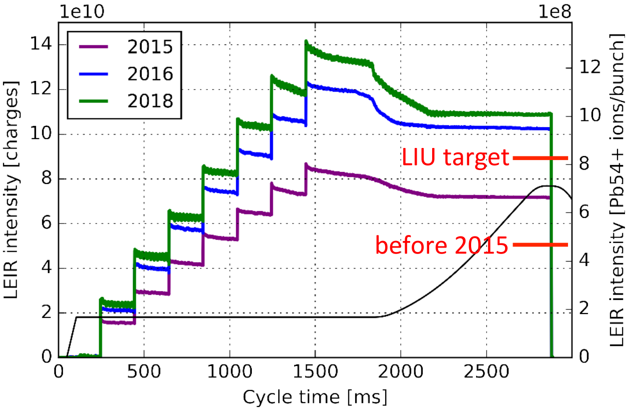

Figure 1: Evolution of the intensity along the LEIR cycle including Run 1 performance records.

The Pb-ion beams do not suffer from 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 instability can be suppressed by controlled longitudinal blow-up with a beam quality still sufficient for injection into the SPS.

The production scheme for the LHC Pb-ion beams for the LHC has been evolving during Run 2 for optimisation of the integrated luminosity according to the performance of the injectors (in particular LEIR). Figure 2 shows an overview of the associated RF gymnastics in the PS. In 2015 the PS provided 2 bunches spaced by 100 ns per batch to the SPS, which is the same scheme as in Run 1. With the increased intensity available from LEIR in 2016, bunch splitting at flat top was introduced in the PS to provide 4 bunches spaced by 100 ns per batch to the SPS (nominal scheme [1]). This scheme was also used in the first half of the run in 2018. In the second half, a new scheme with 3 bunches from LEIR was introduced with a batch compression at PS flat top resulting in 3 bunches spaced by 75 ns per batch injected into the SPS.

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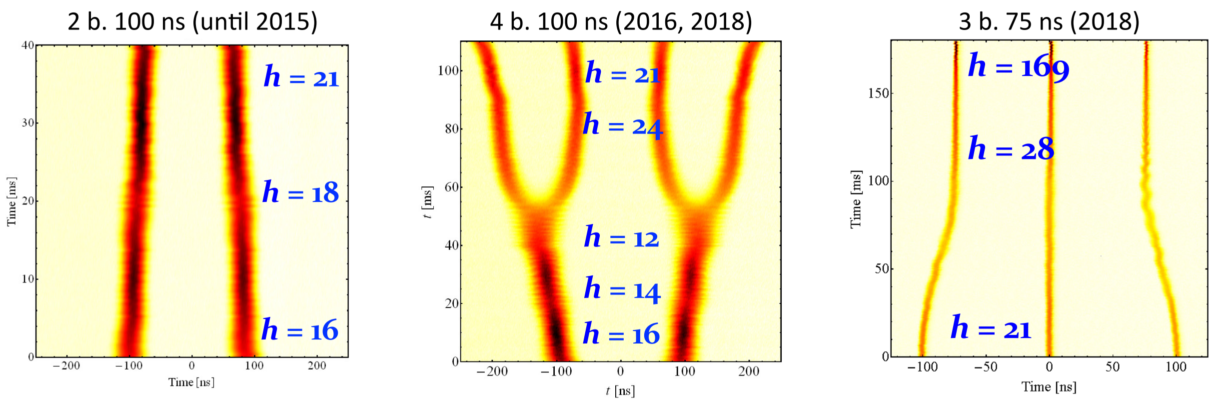

Figure 2: Overview of beam production schemes for Pb-ions in the PS used during Run 2: the waterfall plots of the wall current monitor are shown at an intermediate energy plateau for the 2 bunches spaced by 100 ns (left) and the 4 bunches spaced by 100 ns (center), while the 3 bunches spaced by 75 ns are obtained by batch-compression at flat-top (right).

SPS

The length of the ion batches from the PS (2 or 4 bunches with 100 ns spacing, or 3 bunches with 75 ns spacing) is comparable to the 150 ns injection kicker rise time of the SPS, but much shorter than the 800 ns LHC injection kicker rise time. Thus, cycles with a long injection plateau and many injections are required in the SPS to maximise the total number of bunches in the LHC. Beam degradation along the long SPS flat bottom (storage time of tens of seconds) results in a large spread of the bunch parameters in terms of intensity, bunch length and transverse emittances. The beam degradation mainly arises from transverse space charge and intra-beam scattering, and it strongly depends on the *intensity per bunch*. In addition, RF noise is suspected to contribute to losses out of the RF buckets. The number of injections into the SPS is optimised to achieve the best compromise between beam degradation on the SPS flat bottom and luminosity in the LHC [13]. Figure 3 shows the intensity evolution along the SPS cycle 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 better transmission was achieved by switching to the 4-bunch scheme, i.e. by reducing the intensity per bunch. Due to the 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 for 12 injections, but the LHC abort gap had been already setup for the 3-bunch scheme. Thus, only 9 injections from the PS could be used operationally. A total of 14 injections into the SPS were used for the 3-bunch scheme, resulting in an increased overall intensity for a reduced total batch length.

Figure 4 shows the evolution of the intensity during the Pb-ion run in 2018. The injectors were operating already at the LIU target in terms of intensity per bunch with the 4-bunch scheme (100 ns) during the first part of the run. A

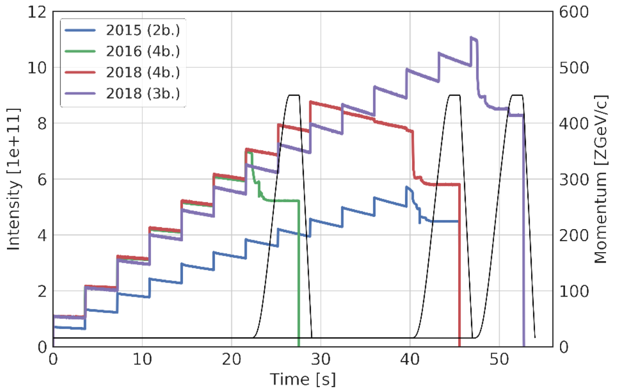

Figure 3: Intensity (in charge) from the beam current transformer along the SPS cycles for the ion runs from 2015 to 2018. The number of bunches per PS batch is indicated in the legend. The momentum along the cycle is also shown.

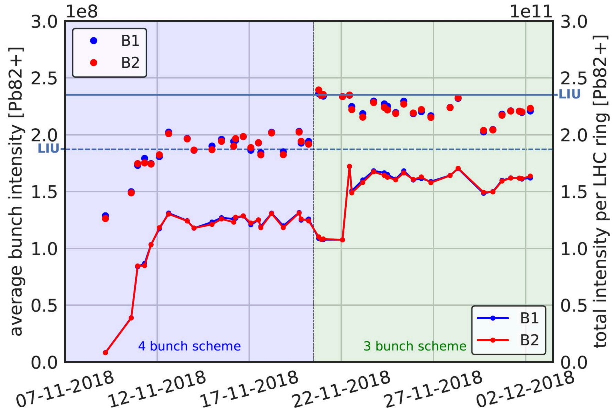

Figure 4: Average bunch intensity (points) and total beam intensity (solid lines) at LHC injection in the 2018 Pb-Pb run. The LIU goals are shown as horizontal lines (dashed for bunch intensity and solid for total beam intensity).

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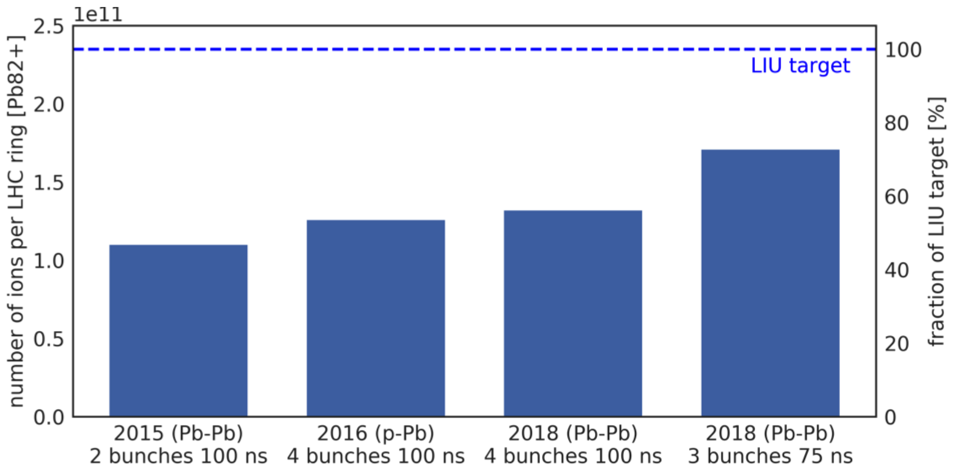

Figure 5: Total number of ions per LHC ring for the beam production schemes used during Run 2.

clear increase of the intensity per bunch, as well as the total intensity in the LHC, were achieved when switching to the 3-bunch scheme (75 ns bunch spacing).

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 good figure of merit for the luminosity performance. Figure 5 shows the evolution of the number of Pb^{82+} ions per LHC ring for the beam production schemes used during Run 2. A summary of the parameter evolution is also given in Table 1. 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).

Table 1: Beam Parameters after Injection into LHC

Scheme	Pb^{82+}/bunch	Pb^{82+} total	bunches
2015, 2 bunch	2.1e8	1.10e11	518
2016, 4 bunch	2.3e8	1.25e11	548
2018, 4 bunch	2.0e8	1.32e11	648
2018, 3 bunch	2.3e8	1.70e11	733
LIU, 4 bunch	1.9e8	2.37e11	1248

PATH TO LIU PERFORMANCE

Reaching the LIU target requires the implementation of momentum slip stacking in the SPS to reduce the bunch spacing and increase the number of bunches in the LHC [2]. This complex RF gymnastics is not possible with the existing SPS RF system, but will be enabled with the LIU upgrade of the 200 MHz RF system including the new LLRF. In the meantime, simulation studies are performed to define the operational slip stacking scenario [14, 15]. It is expected that the longitudinal emittance after the slip stacking will be quite large and the transfer of the bunches into the 400 MHz RF system of the LHC could become critical. The different optics configurations available for the SPS have been compared in the simulation studies. It was found that the “Q26” optics (SPS design) is preferable compared to the “Q20” optics (lower transition energy) [16], as the latter would require a bunch rotation scheme to achieve sufficiently short bunches with the available RF voltage (even after the RF upgrade) [14]. Therefore the Q26 optics was used operationally already in 2018 in preparation of the LIU beam production scenario, while the Q20 optics had been used in the previous years. The change of optics did not have an impact on the achieved beam parameters compared to previous years.

The Pb-ion beams suffer from longitudinal instabilities after transition crossing in the SPS, especially with the intensities achieved with the 3-bunch scheme in 2018. The transition timing had to be optimized such that a deliberate longitudinal emittance blow-up was generated to stabilise the beam. Studies are ongoing to find better means of beam stabilisation in view of the implementation of momentum slip stacking. In addition, the resulting longitudinal distribution of the bunches will have a depleted core ("hollow bunches"). Thus, longitudinal beam stability after the momentum slip stacking becomes challenging and is the subject of simulation studies [17].

CONCLUSIONS

Intense machine studies and continuous optimisation of the beam production scheme of the Pb-ion beams for the LHC resulted in a significant performance improvement during Run 2. With the 3-bunch (75 ns) scheme newly introduced in 2018, about 70% of the LIU target intensity was reached. The LIU beam production scheme relies on momentum slip stacking in the SPS to reduce the bunch spacing, which will become possible after the SPS RF upgrade but will be challenging due to its complexity and due to longitudinal instabilities.

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REFERENCES

[1] M. Benedikt, P. Collier, V. Mertens, J. Poole, and K. Schindl (eds.), "LHC Design Report", Volume III, CERN, Geneva, Switzerland (2004).

[2] J. Coupard et al. (eds.), "LHC Injectors Upgrade, Technical Design Report, Vol. II: Ions", CERN-ACC-2016-0041.

[3] M. Meddahi *et al.*, "LHC Injectors Upgrade Project: Towards New Territory Beam Parameters", in *Proc. 10th Int. Particle Accelerator Conf. (IPAC'19)*, Melbourne, Australia, May 2019, paper THXPLM1, this conference.

[4] J.M. Jowett *et al.*, "The 2018 Heavy-Ion Run of the LHC)", in *Proc. 10th Int. Particle Accelerator Conf. (IPAC'19)*, Melbourne, Australia, May 2019, paper WEYYPLM2, this conference.

[5] M. Schaumann *et al.*, "First Partially Stripped Ions in the LHC (208Pb81+)", in *Proc. 10th Int. Particle Accelerator Conf. (IPAC'19)*, Melbourne, Australia, May 2019, paper MOPRB055, this conference.

[6] M. W. Krasny *et al.*, "The CERN Gamma Factory Initiative: An Ultra-High Intensity Gamma Source", in *Proc. 9th Int. Particle Accelerator Conf. (IPAC'18)*, Vancouver, Canada, Apr.-May 2018, pp. 1780–1783. `doi:10.18429/JACoW-IPAC2018-WEYGBD3`

[7] V. Toivanen *et al.*, "Recent Developments with the GTS-LHC ECR Ion Source at CERN", in *Proc. 22nd Int. Workshop on ECR Ion Sources (ECRIS'16)*, Busan, Korea, Aug.-Sep. 2016, pp. 50–54. `doi:10.18429/JACoW-ECRIS2016-WEAO01`

[8] H. Bartosik, S. Hancock, A. Huschauer, and V. Kain, "Space Charge Driven Beam Loss for Cooled Beams and Mitigation Measures in the CERN Low Energy Ion Ring", in *Proc. 57th ICFA Advanced Beam Dynamics Workshop on High-Intensity and High-Brightness Hadron Beams (HB'16)*, Malmö, Sweden, Jul. 2016, pp. 272–277. `doi:10.18429/JACoW-HB2016-TUAM5X01`

[9] A. Huschauer, H. Bartosik, S. Hancock, and V. Kain, "Progress in the Understanding of the Performance Limitations in the CERN Low Energy Ion Ring", in *Proc. 8th Int. Particle Accelerator Conf. (IPAC'17)*, Copenhagen, Denmark, May 2017, pp. 3819–3822. `doi:10.18429/JACoW-IPAC2017-THPAB049`

[10] A. Saa Hernandez, H. Bartosik, N. Biancacci, S. Hirlaender, A. Huschauer, and D. Moreno Garcia, "Space Charge Studies on LEIR", in *Proc. 9th Int. Particle Accelerator Conf. (IPAC'18)*, Vancouver, Canada, Apr.-May 2018, pp. 3095–3098. `doi:10.18429/JACoW-IPAC2018-THPAF055`

[11] A. Saa Hernandez, H. Bartosik, N. Biancacci, S. Hirlaender, D. Moreno Garcia, and M. Zampetakis, "Detailed Characterisation of the LEIR Intensity Limitations for a Pb Ion Beam", presented at the 10th Int. Particle Accelerator Conf. (IPAC'19), Melbourne, Australia, May 2019, paper WEPTS042, this conference.

[12] S. Albright, M.E. Angoletta, "Frequency Modulated Capture of Cooled Coasting Ion Beams", in *Proc. 10th Int. Particle Accelerator Conf. (IPAC'19)*, Melbourne, Australia, May 2019, paper WEPMP021, this conference.

[13] H. Bartosik *et al.*, "The LHC Injectors Upgrade (LIU) Project at CERN: Ion Injector Chain", in *Proc. 8th Int. Particle Accelerator Conf. (IPAC'17)*, Copenhagen, Denmark, May 2017, pp. 2089–2092. `doi:10.18429/JACoW-IPAC2017-TUPVA020`

[14] D. Quartullo, T. Argyropoulos, and A. Lasheen, "Momentum Slip-Stacking Simulations for CERN SPS Ion Beams with Collective Effects", in *Proc. 61st ICFA Advanced Beam Dynamics Workshop on High-Intensity and High-Brightness Hadron Beams (HB'18)*, Daejeon, Korea, Jun. 2018, pp. 174–179. `doi:10.18429/JACoW-HB2018-TUP2WA02`

[15] T. Argyropoulos *et al.*, "Momentum slip-stacking in CERN SPS for the ion beams", in *Proc. 10th Int. Particle Accelerator Conf. (IPAC'19)*, Melbourne, Australia, May 2019, paper WEPTS039, this conference.

[16] H. Bartosik, G. Arduini, and Y. Papaphilippou, "Optics Considerations for Lowering Transition Energy in the SPS", in *Proc. 2nd Int. Particle Accelerator Conf. (IPAC'11)*, San Sebastian, Spain, Sep. 2011, paper MOPS012, pp. 619–621.

[17] T. Argyropoulos *et al.*, "Longitudinal stability of the hollow ion bunches after momentum slip-stacking in CERN SPS", in *Proc. 10th Int. Particle Accelerator Conf. (IPAC'19)*, Melbourne, Australia, May 2019, paper MOPGW070, this conference.