THE FIRST LHC p-Pb RUN: PERFORMANCE OF THE HEAVY ION PRODUCTION COMPLEX

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Abstract

The first LHC proton-ion run took place in January-February 2013; it was the first extension to the collider programme, as this mode was not included in the design report. This paper presents the performance of the heavy ion and proton production complex, and details the issues encountered, in particular the creation of the same bunch pattern in both beams.

INTRODUCTION

Heavy ion collisions were included in the design of the LHC from an early stage [1], and the first collisions between beams of fully stripped lead took place in Autumn 2010, immediately after the end of the first proton run [2]. The success of the first two Pb-Pb runs, which respectively accumulated 10 and 160 μb^{-1} of integrated luminosity in 2010 and 2011, led the experiments to request a proton-ion run, as a first extension to the LHC design, for the last exploitation period before the long shutdown [3]. A pilot run, using single bunches, was performed in September 2012 [4]. The actual physics run, originally planned for autumn 2012, eventually took place in January-February 2013 [5], after the LHC programme had been prolonged to increase the p-p integrated luminosity at a beam energy of 4 TeV.

FILLING SCHEMES

In order to fill both LHC rings with a similar bunch train pattern, the proton and ion beam production schemes had to be adapted, compared to the usual production schemes for p-p or Pb-Pb collisions. Several bunch and batch spacings were considered, but the final choice was eventually defined by the requirements of the collider. The trains supplied by the injector chain to the LHC consisted of 24 bunches, alternately spaced by 200 ns and 225 ns. Both proton and ion beams production schemes, detailed below, are summarized in Fig. 1.

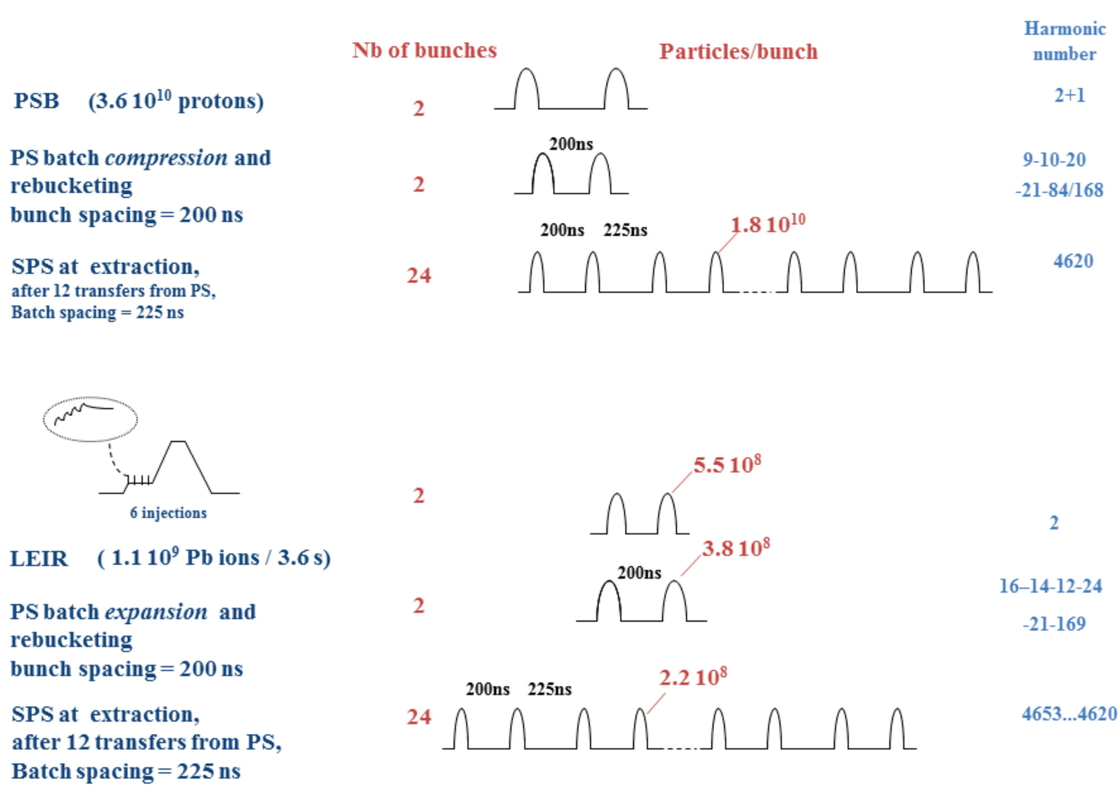

Figure 1: Proton (top) and Pb ion (bottom) production schemes.

Proton Filling Scheme

The proton injector chain consists of the Linac 2, the Proton Synchrotron Booster (PSB), the Proton Synchrotron (PS), and the Super Proton Synchrotron (SPS).

- The beam produced by the PSB for p-Pb collisions is similar to the one formerly known as "probe beam" [6]. It corresponds to a low transverse emittance (<1µm) single bunch per ring, with an intensity below 2×10^{10} protons.
- For p-Pb operation, two such bunches are accelerated to 2.13 GeV/c in the PSB, in rings 3 and 4, and injected into two successive $h = 9$ buckets in the PS.
- The batch is compressed, rebucketed, and compressed again, by a series of harmonic changes (h = 9-10-20-21) before being accelerated on $h = 21$ to 26 GeV/c where the bunch spacing is then 200 ns. At top energy the bunches are transferred to h =84+168 buckets and rotated (40 MHz and 80 MHz cavities).
- Up to 12 such bunch pairs – sometimes less, for collision pattern reasons – are ejected every 2.4 seconds towards the SPS where they are captured on $h = 4620$. The duration of the injection flat bottom is thus 26.4 s (Fig. 2, top). The rise time of the injection kicker imposes a batch spacing of 225 ns.
- The SPS accelerates the (maximum) 24 bunches to 450 GeV/c and ejects them to the LHC proton ring. This sequence is repeated 15 times to fill the LHC with 338 proton bunches.

Pb Filling Scheme

Once the proton ring is filled, the complex switches to the ion filling sequence. The ion injector chain consists of the Linac3, the Low Energy Ion Ring (LEIR), the PS and the SPS. The Pb ion beam used for p-Pb collisions is identical to the high-density "intermediate" beam formerly used for Pb-Pb collisions [7], only with slightly improved performance:

- At the exit of Linac3, the 25 µA, 200 µs long pulse of 4.2 MeV/u Pb^{29+} is stripped to Pb^{54+}, then accumulated over 70 turns in LEIR. The injection process is repeated 6 times, under continuous electron cooling.
- The Pb^{54+} beam is bunched on $h = 2$, accelerated to 72 MeV/u and transferred to the PS, with an intensity of 5.5×10^{8} ions/bunch.
- In the PS, the bunches are injected into two successive $h = 16$ buckets and accelerated to a 370 MeV/u intermediate plateau. The batch is then expanded, rebucketed, and expanded again, by a series of harmonic changes (h = 16-14-12-24-21).
- After acceleration to 5.9 GeV/u on $h = 21$, the batch undergoes a final rebucketing to $h = 169$ (80 MHz).
- The resulting bunch pair, with a spacing of 200 ns, is then extracted towards the SPS. The ions are fully stripped to Pb^{82+} by a 0.8 mm thick Al foil in the transfer line.
- Up to 12 such bunch pairs are injected every 3.6 seconds – imposed by the duration of the LEIR cycle – in the SPS. As for the protons, the batch spacing is 225 ns.
- At the end of its 39.6 seconds long flat bottom (Fig. 2, bottom), the SPS accelerates the beam to 177 GeV/nucleon, using the now well-established fixed-frequency acceleration technique [8].
- At top energy, the (maximum) 24 bunches of average intensity 2.2×10^{8} ions are extracted towards the LHC ion ring. As for the protons, the ion sequence is repeated 15 times to fill the LHC with 338 bunches.

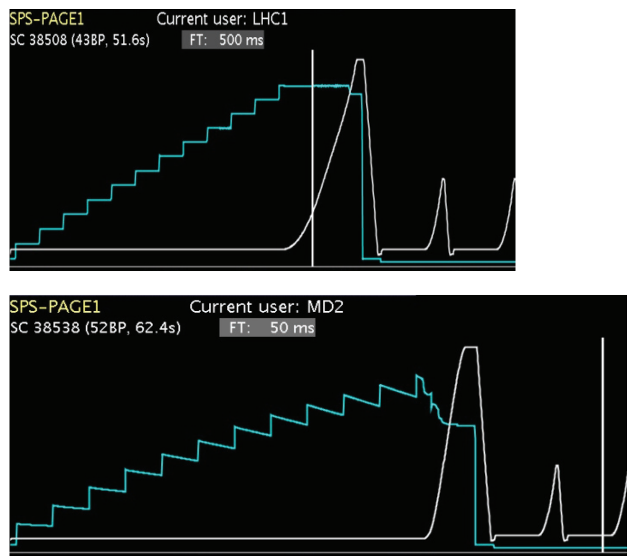

Figure 2: SPS proton (top) and ion (bottom) supercycles: magnetic field (white) and beam intensity (cyan). The supercycles, respectively 51.6 and 62.4 seconds long, consist of one p or Pb LHC filling cycle, followed by two dummy cycles.

SUMMARY OF PERFORMANCE

Table 1 lists the main beam properties delivered to the LHC by the injector chain, at the exit of the SPS.

The proton beam density and intensity are deliberately much weaker than for proton-proton collisions [9], in order to match the Pb ion beam charge per bunch of 1.8×10^{10} for beam-beam reasons in the collider.

For the ions, a comparison with the design values [10] shows that in average, the achieved beam brightness is about three times higher than design. Indeed, the three-month delay of the run, combined with the necessity of preparing the lead beam for fixed target operations [11], allowed a long period of parallel machine development to improve the beam quality in the ion injectors.

Linac3

Several RF optimizations took place during the period preceding the p-Pb run. In particular, phase adjustments between tanks led to a better transmission through the transfer line and a larger injection efficiency into the LEIR machine. As the beam size appears to be affected in zero dispersion locations of the transfer line, the improvements cannot be due only to a smaller momentum spread, but also to transverse effects [12].

LEIR

An extensive, parallel machine studies programme was performed on LEIR before and during the run, to try and understand the cause for a loss during acceleration which hampered the performance over the previous run [7]. Although the studies could not clearly identify the reason for the loss, continuous improvements allowed to retrieve, then routinely surpass, the nominal intensity of 4.5×10^8 Pb^{54+}/ions per bunch.

PS

During the p-Pb run, however difficult to quantify, the vacuum in the PS benefitted from the absence of high intensity proton beams for CNGS, antiproton and neutron production, and for SPS fixed target experiments in the supercycle.

SPS

On the SPS flat bottom, the first injected bunches are subjected to Intra-Beam Scattering (IBS), space-charge detuning, and RF noise, for 39.6 seconds longer compared to the ones injected last. These effects have been mitigated by two actions:

- Lower tune optics, "Q20", has been implemented. The resulting wider beam size makes the beam less sensitive to IBS and also decreases the space charge detuning [13].
- A series of modifications in the low level RF have significantly decreased the noise level [14].

As a consequence, the ratio between the highest and lowest bunch intensity in the train has decreased from 1.8 to less than 1.5, with an average beam brightness of 22.1×10^7 Pb^{82+}/ µm at SPS extraction.

Table 1: proton and ion beam properties at SPS extraction.

	p^+ 2013	**Pb^{82+} 2013**	**Pb^{82+} design**	
N_B	1.8×10^{10}	2.2×10^8	9×10^7	Particles/bunch
ε_H	0.73	1.1	1.2	µm (norm. RMS)
ε_V	0.45	0.9	1.2	µm (norm. RMS)
N_B/ε	3140	22.1	7.5	10^7 Particles/µm

CONCLUSION

The contribution of the injector chain was essential to the success of the first extension to the LHC programme, proton-ion collisions. The achieved beam quality allowed the collider to reach a peak luminosity 40% higher (1.1×10^{29} w.r.t. 8.3×10^{28} $cm^{-2}.s^{-1}$), and to deliver 40% more integrated luminosity (31 w.r.t 22.3 nb^{-1}), than expected at the time of planning the run [15]. Overall, the performance of the ion beam now gives good indications for the Pb-Pb collisions after future upgrades [16].

ACKNOWLEDGMENTS

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REFERENCES

[1] LHC design report, Vol I, Chap. 21, "The LHC as a Lead Ion Collider".

[2] J. M. Jowett et al, "Luminosity and beam parameter evolution for lead ion beams in the LHC", TUPZ017, IPAC'11, San Sebastian, September 2011.

[3] B. Gorini and E. Meschi, "Experiments expectations, plans and constraints", Proc. Chamonix 2012 Workshop on LHC Performance, Chamonix, February 2012.

[4] R. Versteegen et al., "First proton-nucleus Collisions in the LHC: the p-Pb pilot physics", CERN-ATS-Note-2012-094 MD.

[5] J.M. Jowett et al., "Proton-nucleus Collisions in the LHC", MOODB201, these proceedings.

[6] B. Mikulec et al., "LHC Beams from the CERN PS Booster", TU6PFP086, PAC'09, Vancouver, May 2009.

[7] D. Manglunki et al., "Performance of the CERN Heavy Ion Production Complex", IPAC'12, New Orleans, May 2012, THPPP012, CERN-ATS-2012-104.

[8] D. Boussard et al., "Non Integer Harmonic Number Acceleration of Lead Ions in the CERN SPS", PAC95, Dallas, 1995 and CERN SL-95-022.

[9] M. Lamont, "The First Years of LHC Operation for Luminosity Production", MOYAB101, these proceedings.

[10] LHC design report, Vol III, Part 4, Chap. 38, "The LHC Ion Injector Chain: SPS".

[11] NA61/SHINE Physics Programme; http://cern.ch/na61

[12] M. Bodendorfer, D. Kuchler and R Scrivens, "Effect of the Tank2 Phase on Ion Injection into LEIR", December 2012 (unpublished).

[13] F. Antoniou et al., "Considerations on SPS Low Transition Energy Optics for LHC Ion Beams", TUPME046, these proceedings.

[14] T. Bohl and U. Wehrle, "I-LHC Beam in the SPS 2012-2013, Present Status of the Analysis of Observations Concerning the Longitudinal Plane", Machine Studies Working Group April 23rd 2013 (unpublished).

[15] J.M. Jowett et al., "Heavy Ions in 2012 and the Programme until 2022", Proc. Chamonix 2012 Workshop on LHC Performance, Chamonix, February 2012.

[16] D. Manglunki et al., "Plans for the Upgrade of CERN's Heavy Ion Complex", WEPEA060, these proceedings.