PERFORMANCE OF THE CERN INJECTOR COMPLEX AND TRANSMISSION STUDIES INTO THE LHC DURING THE SECOND PROTON-LEAD RUN

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Abstract

The LHC performance during the proton-lead run in 2016 relied on continuous monitoring and systematic improvement of the beam quality in all the injectors. The beam production and characteristics are explained in this paper, together with the improvements realised during the run to increase the lead beam intensity. Transmission studies from one accelerator to the next and beam quality evolution studies are summarised. In 2016, the LHC had to deliver the beams to the experiments at two different energies, 4Z TeV and 6.5Z TeV. The properties of the beams at these two energies are also presented.

INTRODUCTION

The second full one-month proton-lead (p-Pb) run of the LHC [1] was carried out from 7 November to 5 December, 2016. Previous runs took place in 2012 and 2013 [2] at a beam energy of $E_b = 4\,Z$ TeV. The diversity of physics discoveries arising from the p-Pb, Pb-Pb and p-p runs led the LHC experiments to request different collision energies, luminosity and pile-up for the 2016 run, making the LHC operation in so many different configurations extremely demanding within a month's time. Nevertheless, a plan to satisfy most of the requirements was successfully developed and carried out, concluding in two different beam energies, 4 Z TeV and 6.5 Z TeV. The peak luminosity exceeded the design value by a factor 7.8 [1] and the integrated luminosity substantially exceeded the experiments' requests. This success was partly due to the excellent performance of the ion injector chain, which is summarised in this paper.

BEAM PRODUCTION SCHEMES

The CERN accelerator complex produces its proton and ion beams in two different chains of sources and accelerators, which merge only in the CERN Proton Synchrotron (PS). Both chains are described in detail in [3].

In 2013, both the proton and ion beams in the LHC consisted of 12 trains of 24 bunches each, with a bunch spacing alternating between 200 ns and 225 ns [4]. The total number of bunches colliding in ATLAS, ALICE and CMS was of the order of 300, and in LHCb of the order of 40.

Since 2013, several improvements have been made:

- The Linac 3 intensity was increased from 25 to 40 $e\mu$A, mostly thanks to the elimination of an aperture restriction after the source [5].
- Extensive studies in the LEIR ring mitigated the space-charge detuning and compensated harmful resonances [6], raising the intensity limitation observed during the previous runs [7].
- The "Nominal" beam [3], already demonstrated before LS1 [8], consisting of 4 bunches spaced by 100 ns, was produced in the PS. Despite the bunch splitting, the bunches had about the same intensity as in 2015 [9], because of the higher intensity delivered from LEIR;
- The SPS injection kicker rise time was reduced to 200 ns for protons (the limiting particle due to the higher beam rigidity at SPS injection).

Those improvements allowed the average bunch spacing to be reduced, with the corresponding increase of the number of delivered trains to LHC. Consequently, 1.4 times more bunches were colliding in ATLAS, ALICE and CMS, and twice as many in LHCb as compared to 2013. The production scheme adopted in 2016, is schematically represented in Fig. 1.

TRANSMISSION STUDIES

In p-Pb operation, the more difficult beam to produce is the ion beam and its maximum achievable bunch intensity originally determined the proton bunch intensity with which it can collide. An analysis of the ion beam intensities produced and transported from one accelerator to the next as a function of the LHC fill number is summarised in Figs. 2

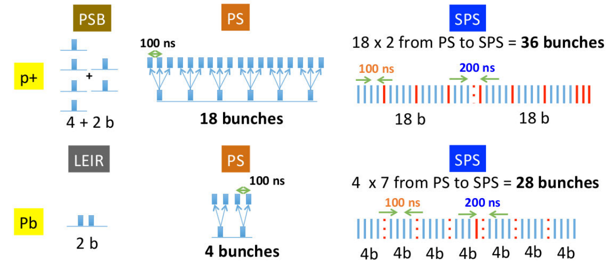

Figure 1: Production scheme for bunch trains from SPS. The red (dashed) lines in the SPS trains indicate the (missing) non-colliding bunches.

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and 3. The corresponding transmission rates are shown in Fig. 4. The values for each LHC fill number are the averages over all the injections and extractions into a given accelerator, for that fill. The error bars are the standard deviations around those averages.

In LEIR, only about 75% of the injected ions survive until the extraction because of space-charge induced losses due to bunch shortening at RF capture. From fill 5564 onwards, the transmission efficiency increased to approximately 85%, when the frequency offset modulation during RF capture was put into operation [10].

At around 90%, the transmission from LEIR extraction to PS extraction is very efficient.

In the middle of a low-beta insertion, located in the transfer line between PS and SPS, a 0.8 mm thick Al foil strips the remaining electrons from the Pb^{54+} ions to yield bare nuclei of $^{208}Pb^{82+}$. Whether the stripping foil is responsible for most of the beam losses between PS and SPS that are visible in Fig. 3 remains to be investigated but the stripping efficiency is about 96% [11].

Although the increase in Pb intensity extracted from LEIR from fill 5564 onwards translated directly into an increased intensity injected into the SPS (Fig. 3), the extracted intensity from the SPS was only slightly better. This is due to strong, intensity-dependent effects such as intra-beam scattering and space-charge, that occur on the long low-energy plateau, while the SPS accumulates seven PS injections. As can be seen in Fig. 4, the SPS remains the bottleneck of the Pb-ion injector chain with transmission efficiencies below 70%.

The transmission efficiency through the LHC operational cycle along the 2016 run can be seen in Fig. 5. The transmission from injection to flat top (max. energy) improved and was more reproducible during the Pb-p collision phase, i.e., Pb in Beam 1 and protons in Beam 2. The transmission through the squeeze and collision set-up was slightly better during the p-Pb collisions at 6.5 *Z* TeV. The overall transmission from injection to collisions is better than 95%, a remarkable result that has improved the Pb-Pb luminosity prospects for the ion runs in the High Luminosity LHC (HL-LHC) era; the value previously assumed was 90%.

Fig. 6 shows the evolution of the average bunch intensities from LHC injection up to collisions. Besides the statistical uncertainty of $\sim 0.2\%$, indicated in the plot with the error bars, there is a systematic error of 3.5% due to a recurrent calibration issue of the fast LHC transformer used for the measurement. The observed increase in bunch intensity from fill 5564 corresponds to the increase in LEIR extracted intensity as mentioned above. A remarkable result of all the efforts made to increase the ion intensity transmitted through the injector chain, is that the average bunch charge in 2016 was almost 15% higher than the goal for HL-LHC [12], and 3 times the design value $0.57\times10^{10}e$. Besides increasing the number of bunches by slip-stacking in the SPS, the challenge will be to establish this performance early and sustain it throughout future runs.

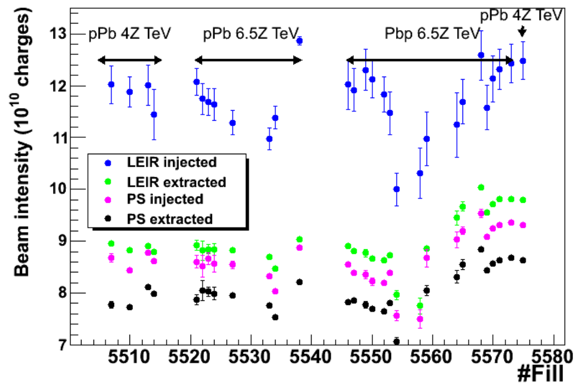

Figure 2: LEIR and PS injection and extraction intensities.

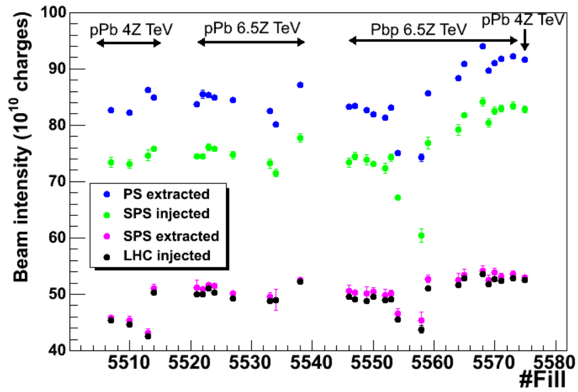

Figure 3: Pb intensities at PS extraction, SPS injection and extraction, and LHC injection.

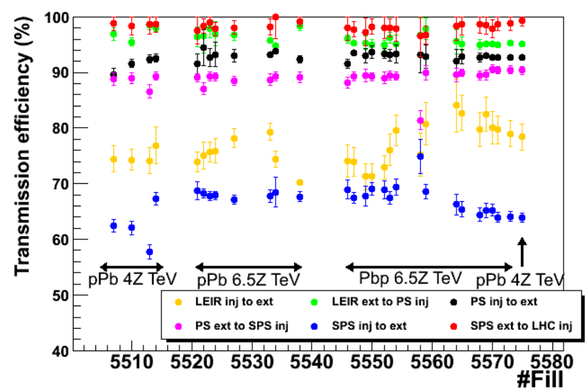

Figure 4: Pb transmission efficiencies: LEIR to LHC.

EMITTANCE MEASUREMENTS

Different emittance measurement techniques are used across the injector chain. Along Linac 3, the injection and extraction line of LEIR (ETL), and the transfer line (TT2) from the PS to the SPS, secondary-electron emission monitor (SEM) grids are used. These semi-destructive devices affect the beam and cannot be used on beams destined for the LHC. Two beam-gas ionisation (BGI) monitors, one per plane, are used in LEIR to monitor the emittance evolution from injection almost throughout the whole cycle. While Wire Scanners (WS) are installed in the PS, SPS and LHC, the ones in the PS cannot be used due to ionisation losses of partially stripped ions. The WS in the LHC can only be trig-

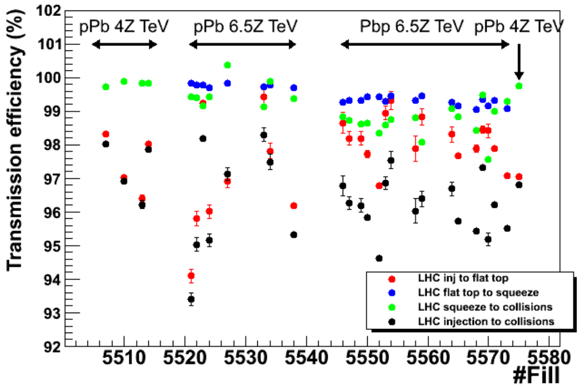

Figure 5: Pb transmission efficiencies: LHC injection to collisions.

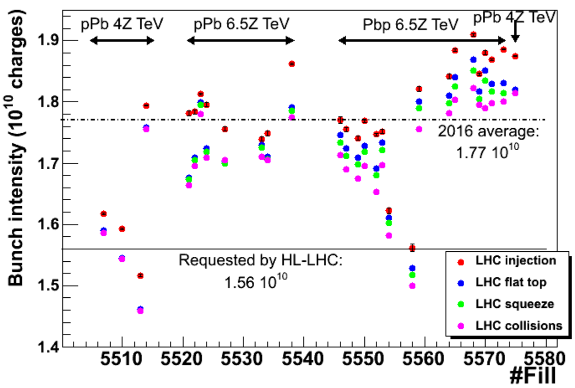

Figure 6: Average bunch intensities in elementary charges from LHC injection up to collisions. The average bunch intensities at injection in 2016 and requested by HL-LHC are indicated in the plot.

gered for low circulating intensity (few tens of ion bunches). In the LHC, the beam synchrotron radiation telescopes are not subject to intensity limits but heavy ions do not produce sufficient synchrotron light for emittance measurements at injection energy.

The ion beam coming from Linac 3 is injected into LEIR by using multi-turn injection, phase space painting and electron cooling in all three planes. This process resets the emittances arriving from Linac 3 so that LEIR defines the emittances relevant for the LHC beam. For this reason we exclude measurements from the SEM grids in Linac 3 and the injection line into LEIR from this analysis.

All emittance-measuring instruments in the injector chain require a manual trigger, so automatic measurements of all bunches through the injectors up to LHC top energy is not feasible. The emittances of a few test bunches were measured only on a few occasions. WS measurements of the bunches injected into LHC were performed regularly in the SPS. Figure 7 shows the transmission of normalised emittances through the injector chain. Up to TT2, data was taken only twice during the run and at different times in different sectors (LEIR on 4 Nov, ETL and TT2 on 17 Nov). The resulting statistics are poor. Furthermore, the beam intensities were lower than for the measurements in the SPS and the LHC. In LEIR, the emittance values shown are those at the end of

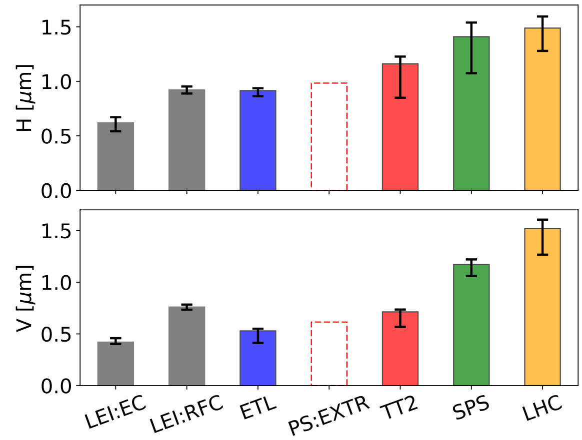

Figure 7: Transmission of emittances (top: horizontal, bottom: vertical).

electron cooling (EC) and the end of RF capture (RFC). The value at PS extraction is obtained from the measurements in TT2 by subtracting an estimate of the transverse blow-up due to the stripper foil [13].

In the SPS and the LHC, on the other hand, wire scans were performed several times throughout the run. In the SPS, an average emittance over all circulating bunches is measured, while in the LHC the single bunch emittances are available. For each bunch, the measurement soonest after injection was selected and all bunches were averaged, in order to obtain an average emittance value equivalent to that of the SPS. The emittances in Fig. 7 correspond to the median values over all available data sets and the error bars represent the 25% and 75% percentiles. The error on the β-function, estimated to be around 10–20%, is not taken into account.

During the transfer of the nuclear beam from the SPS to the LHC, the horizontal emittance is well preserved, while some blow-up is observed in the vertical plane.

CONCLUSION

With the improvements in performance of the injector complex and transmission efficiency into the LHC during the 2016 p-Pb run, average Pb bunch intensities of $N_b = 2.2 \times 10^8$ ions and normalised RMS transverse emittances of $\varepsilon_n = 1.5\,\mu$m, were achieved at 6.5Z TeV in the LHC. One can expect peak Pb-Pb luminosities of $L \sim 6 \times 10^{27}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ in 2018 with the current injection scheme ($k_b \sim 600$ bunches). After the next long shutdown, with momentum slip-stacking in the SPS giving $k_b \sim 1230$, and a β^* reduced down to 50 cm, one can expect a (potential unlevelled) $L \sim 15 \times 10^{27}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ at 7 Z TeV, more than an order of magnitude beyond the original LHC design and comfortably within the requirements of HL-LHC [14–16].

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