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PERFORMANCE OF THE ION CHAIN AT THE CERN INJECTOR COMPLEX AND TRANSMISSION STUDIES DURING THE 2023 SLIP STACKING COMMISSIONING

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Abstract

The 2023 run has been decisive for the Large Hadron Collider (LHC) Ion Injector Complex. It demonstrated the capability of producing full trains of momentum slip stacked lead ions in the Super Proton Synchrotron (SPS). Slip stacking is a technique of interleaving particle trains, reducing the bunch spacing in SPS from 100 ns to 50 ns. This bunch spacing is needed to reach the total ion intensity requested by the High Luminosity LHC (HL-LHC) project, as defined by updated common LHC Injectors Upgrade (LIU/HL-LHC) target beam parameters, and it cannot be provided by the PS (SPS injector). This paper reviews the lead beam characteristics across the Ion Injector Complex, including transmission efficiencies and beam quality up to the SPS extraction. It also documents the difficulties found during the commissioning and the solutions put in place.

INTRODUCTION

The first full-length lead collision production period at the Large Hadron Collider (LHC) in Run 3 is taking place between 26 September and 29 October 2023 at a beam energy of 6.8Z TeV. In 2022, the lead ions collided for two days at the LHC at the same energy, but at low beam intensity and interaction rate [1] as a test of the accelerator and experiments' equipment upgraded during Long Shutdown 2 (LS2). The last full-fledged lead collision period was in 2018 when lead beams collided at 6.5Z TeV. The previous comprehensive transmission and emittance study was done for the p-Pb period in 2016 [2].

This paper summarizes the performance of the ion injector complex at the start of the 2023 LHC ion physics run. It presents the main acceleration schemes and associated ion beam structure. It lists the issues encountered during beam commissioning and the solutions implemented to reach the performance required by the LHC.

ION BEAM PRODUCTION SCHEME

The CERN ion injector complex is shown in Fig. 1. The lead ion beam is produced through evaporation from a solid sample of lead and consequent ionization in the Electron Cyclotron Resonance (ECR) ion source [3,4]. Only Pb^{29+} is transported through Linac3 where the beam reaches a kinetic energy of 4.2 MeV/nucleon and the ions are stripped to Pb^{54+}. Linac3 produces a 200 µs long pulse every 200 ms. Up to seven of these pulses are injected into the Low Energy Ion Ring (LEIR), which employs several techniques to facilitate charge accumulation, such as multiturn injection and electron cooling [5]. The coasting beam is then bunched into two bunches, accelerated to 72 MeV/nucleon and extracted towards the Proton Synchrotron (PS). Here, each bunch is split in two and their separation is reduced to 100 ns. They are accelerated to 6 GeV/nucleon and longitudinally squeezed using bunch rotation to fit within the radio-frequency (RF) bucket of the Super Proton Synchrotron (SPS). The ions are fully stripped to Pb^{82+} in the TT2 transfer line between PS and SPS (see Fig.1). Up to fourteen injections are accumulated in the SPS at injection energy. Each injection consists of a 4-bunches batch from the PS, with 100 ns bunch spacing, amounting to 56 bunches at maximum. The beam is then accelerated to the slip stacking intermediate energy plateau at 300Z GeVwhere the bunch spacing is reduced to 50 ns, and further accelerated to 450Z GeV or 177 GeV/nucleon. Slip stacking is a technique that permits two particle beams of different momenta (and therefore different RF frequencies) to slip longitudinally relative to each other, in the same beam pipe [6, 7]. When the two beams are in the correct longitudinal position, the full beam is recaptured with a non-adiabatic voltage jump at the average RF frequency. The LHC takes on the order of 40 injections from the SPS, which corresponds to about 1200 bunches in each LHC ring. The bunch scheme evolution is sketched in Fig. 2.

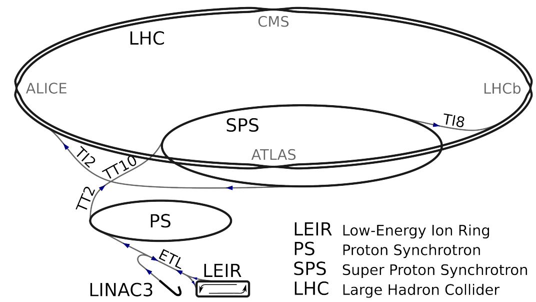

Figure 1: Layout of accelerators and transfer lines used for ion beam production for LHC.

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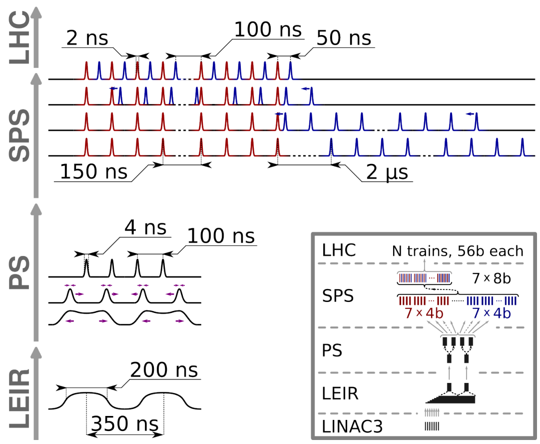

Figure 2: Evolution of longitudinal beam structure along the ion injector chain. The bunch spacings and lengths are indicative.

BEAM COMMISSIONING IN 2023

In 2023, Linac3's RF amplifiers for the RFQ and Cavity1 were upgraded to solid-state technology [8]. The associated change of low-level RF controls required the operational parameters to be set up from beam-based measurements.

Initial beam commissioning in LEIR with the "EARLY" cycle, using only one injection from Linac3 resulting in low overall beam intensity, went smoothly. After optimizing the trajectory in the transfer line and injection bumps, the injected intensity reached 2×10^{10} elementary charges, with injection efficiency of 40%. Two unresolved issues remained: the electron cooler could not cool the entire beam longitudinally, and the injection efficiency was 10% short with respect to the design value of 50%. These issues were not critical for the "EARLY" cycle. However, without adequate cooling in the "NOMINAL" cycle (with seven injections from Linac3), part of the circulating beam was still occupying the same phase space as the incoming beam from the following injection, resulting in losses.

The problem was mitigated by:

- Tuning expert analogue parameters in Cavity2 and Cavity3 of Linac3 to improve the pulse stability and leading edge slope.
- Slightly changing Linac3 operational parameters of the RFQ, Bunching cavity, and Cavity1 to eliminate irregular front part of the beam pulse featuring excessive intensity levels.
- Increasing the pulse length out of Linac3 from 200 to 240 µs and delaying the LEIR injection system pulsing by 40 µs, to avoid injecting the first, irregular part of the beam.
- Increasing the electron-beam current to enhance cooling.

Finally for LEIR, the recurring problem is the electromagnetic interference of pulsing PS magnets on the beam trajectory in the nearby transfer line from Linac3 to LEIR. While the installation of magnetic field shielding during LS2 significantly improved the situation, the magnetic stray fields still cause intensity losses of up to 25% when the beam passes through the transfer line at the same time as PS magnets pulse.

The PS ion beam commissioning was smooth. Standard optimization of the injection line, injection septum settings and energy was needed in the PS, and common synchronisation adjustments had to be made to match PS and SPS.

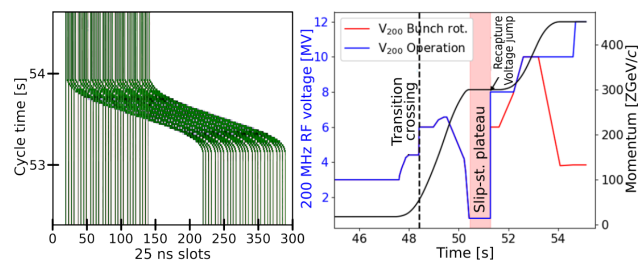

Figure 3: Left: Time (vertical axis) evolution of the 56 SPS bunches versus 25 ns slots on the slip stacking intermediate-energy plateau in SPS. Right: RF voltage functions (red, blue) are overlaid on top of main bending magnets' field function (black). Red voltage function refers to the bunch rotation option, the blue voltage (w/o bunch rotation) is the operational baseline.

SPS slip stacking was commissioned in 2021 (see [9] for beam results and RF manipulations) with only two PS batches per train while LHC filling requires up to fourteen batches. The slip stacking SPS cycle is shown in Fig. 3. The first tests in 2023 resulted in unacceptable bunch-to-bunch variation in bunch length at transfer to the LHC. One possible explanation is the effect of intra-beam scattering and RF noise on the first injected batches along the 47-seconds-long injection plateau. Some bunches were becoming longitudinally unstable after recapture and during the second ramp, resulting in the average bunch length at extraction of ≈3 ns, too long for the LHC, which requires bunch lengths below 1.8 ns. Controlled longitudinal emittance blow-up applied during the first ramp resulted in a small spread of bunch lengths, at the cost of an elevated average value (2.2 ns). Bunch rotation at extraction was applied to obtain acceptable longitudinal parameters (average length of 1.6 ± 0.2 ns). Further improvements to the voltage program allowed to extract 1.7 ± 0.2 ns bunch length without bunch rotation, which is preferable for operation (see Fig. 3).

Figure 3 shows the interleaving of the two beams: each train originally consists of seven 4-bunch batches with 100 ns spacing. They are merged into 56 bunches with 50 ns spacing. The observation is triggered synchronously with the RF of the first bunch-train, explaining the apparent asymmetry.

LEAD BEAM CHARACTERISTICS

Transmission Efficiency

The transmission efficiencies along the ion injector chain are shown in Fig. 4 and intensities per bunch in Fig. 5. Two of the datasets in the plot show the historical performance

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from 2016 [2] and 2022. In 2022 only two batches of four bunches were slip stacked in the SPS. The third dataset from 2023 represents full-intensity slip stacked trains of 56 bunches, that were transferred to LHC and collided (fill numbers 9192, 9193 and 9194). The efficiency values on the plot are averages from all beam cycles. The error bars represent standard deviations around these averages.

The reduced transmission through LEIR in 2023 is mainly caused by the aforementioned problems with beam accumulation at the injection plateau. Consequently, at RF capture there are considerable losses of the off-energy tails. Between LEIR extraction and PS injection, the transmission is about 8% lower than in 2016. While the situation has slightly improved since 2021, the issue at this stage is not well understood. The same is true for the PS cycle, where we see 5% less transmission than in 2016. Transmission between PS extraction and SPS injection is presently at 80%, which is also lower compared to the 90% in 2016. The SPS-cycle efficiency has improved by 5% since 2016. In 2022 the SPS beams were less intense, with shorter injection plateau, so their better transmission is understood. The transmission efficiency through the SPS cycle includes the beam losses at injection plateau due to intra-beam scattering, space charge and likely RF noise, together with the losses of uncaptured beam at the beginning of the two acceleration sections, transition crossing and possible losses during slip stacking.

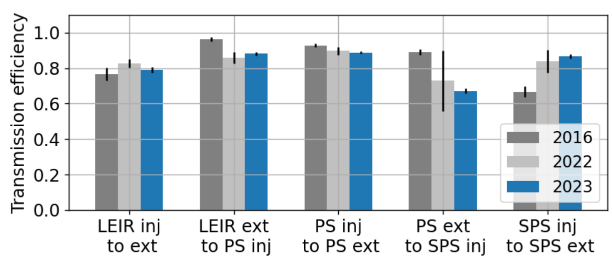

Figure 4: Transmission efficiencies in 2016, 2022, and beginning of the ion run in 2023.

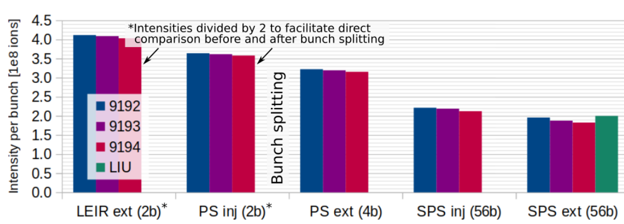

Figure 5: Bunch intensities across the ion complex for the first three LHC fills in 2023 together with the LIU target parameters [10] at SPS extraction.

Transverse Emittance

The emittance evolution across the CERN ion injector complex is shown in Fig. 6. The gray bars are shown for reference, and correspond to the measurements done in 2016 [2] and 2022 [1]. The emittance measurements are only done on demand, at different times in different machines (the use of wire scanners is destructive to the partially stripped ion beam in the PS). The emittances at LEIR were measured for the ”NOMINAL“ cycle with the ionization profile monitor (IPM). At PS injection they were measured with the beam-gas IPM (BGI), and at PS extraction and at the SPS with the wire scanners. The PS and SPS measurements were done during 14-injection slip stacking commissioning at SPS.

In 2023, the emittance measurements were performed with non-fully-commissioned beams. It partly explains why the emittances were systematically larger than in 2016 and 2022. The large horizontal emittance measured at LEIR RF capture seems inconsistent with the other measurements and needs to be revisited. The emittances in the PS match those from the past within the uncertainties. The worst-case evolution of emittances on the long injection plateau at SPS can be judged by comparing the SPS:INJ14 and SPS:INJ1 bars. They show that emittances of the first group of four bunches in SPS measured at the end of the injection plateau (SPS:INJ14) are significantly larger than emittances of the same group of bunches soon after they were injected (SPS:INJ1). The emittances may still be reduced in the course of the remaining commissioning time. The slip stacking, which takes place on an intermediate-energy plateau, does not cause any significant transverse emittance growth.

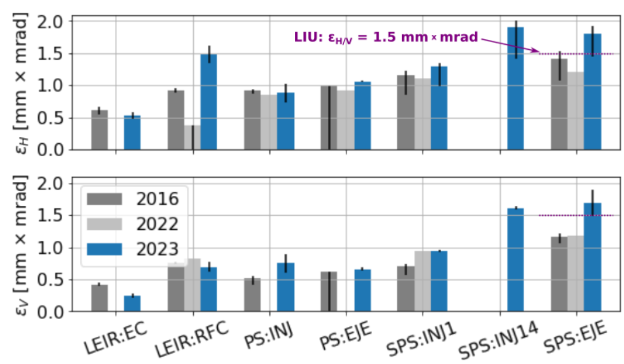

Figure 6: Evolution of horizontal and vertical normalized emittance between LEIR electron cooler (EC) and SPS ejection along with the LIU target [10]. The origin of reference data from 2016 is [2], and from 2022 is [1].

CONCLUSIONS

The first high-intensity trains with 190 bunches of slip stacked lead beams in 2023 reached stable beams status and collided at the LHC on the 26th September. On the first days of the ion run, the beam transmission, intensities and transverse emittances through the injector complex are already close to the LIU requirements. We expect further progress in the reproducibility of LEIR operation, and understanding of transmission losses along the complex. The ion injector chain is ready to deliver beams for the LHC ion run.

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