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LINAC3, LEIR AND PS PERFORMANCE WITH IONS IN 2021 AND PROSPECTS FOR 2022

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Abstract

CERN accelerators underwent a period of long shutdown from the end of 2018 to 2020. During this time frame, significant hardware and software upgrades have been put in place to increase the performance of both proton and ion accelerator chains in the High Luminosity LHC era. In the context of the CERN lead ion chain, 2021 has been mainly devoted to restore the injectors' performance and to successfully prove the slip-stacking technique in SPS. In this paper we summarise the key milestones of the ion beam commissioning and the achieved beam performance for the Linac 3 (including the source), LEIR and PS accelerators, together with an outlook on 2022 operation.

INTRODUCTION

In 2020 the CERN proton and ion accelerator chains restarted operation after a period of long shutdown in which beam equipment was upgraded within the LIU (LHC Injectors Upgrade) project [1]. Concerning the ion chain, the majority of the upgrade activities were performed in the Linac 3, equipped with new digital Low-Level RF (dLLRF) cavity controllers, and in SPS, were a significant RF power upgrade was put in place to meet the LIU project requirements with both protons and ions [2]. The SPS dLLRF was also upgraded [3] to be able to reduce the ion bunch spacing from 100 ns to 50 ns by means of the slip-stacking technique [4]. The main challenge of 2021 was therefore to re-establish the pre-shutdown performance across the LHC ion chain and establish the new slip-stacking technique in SPS. This work is structured as follows: in the next section we will cover the performance reached by the beam at the source and in Linac 3, we will then cover LEIR performance, and eventually PS performance up to the injection in SPS.

SOURCE AND LINAC 3

The GTS-LHC source profited of a dedicated testing period at the beginning of 2021 (from week 2 to week 13). This operation mode proved to be a valuable investment as the source setting improvements could be transferred directly to source operation, and a better understanding of the source could be obtained. One of the main achievements was installing a ceramic beak close to the crucible orifice as shown in Fig. 1 together with Molflow+ simulations [5]. This is

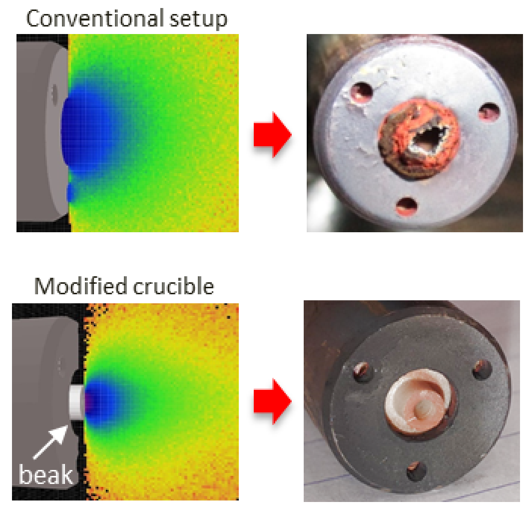

Figure 1: Modified source crucible to prevent lead oxides deposition and prolong the source fill duration. On the left, Molflow+ simulations of the lead extraction process without (top) and with (bottom) ceramic beak. On the right, typical corresponding status of the outer oven cover after source operation.

done to avoid lead condensation [6] which can block the outlet and reduce the number of lead refills needed. Thanks to this modification, source fills lasted about 40 days on average (previously it was about 2 weeks [7]). On the other hand, with the new crucible design, there are no clear signs of performance degradation before the oven empties. For 2022 operation, it is therefore foreseen to implement a scheduled refill plan to minimise possible performance impact to the LHC.

During the long shutdown important upgrades of the dLLRF were performed, mainly for the control of three cavities (buncher, ramping and debuncher). The main functionality of the dLLRF was systematically tested following dedicated procedures for hardware and beam commissioning [8,9]. With respect to the past analog system, the new dLLRF allows for precision measurements of the RF signals even on systems where the previous analogue system remains in control. This is of particular importance in view of the Linac3-LEIR joint effort to improve the beam per-

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formance stability. Figure 2 shows the improved accuracy reached with the new dLLRF with respect to the old analogue one for the Linac 3 cavity 1. Stability is well below the required 0.1% relative variation.

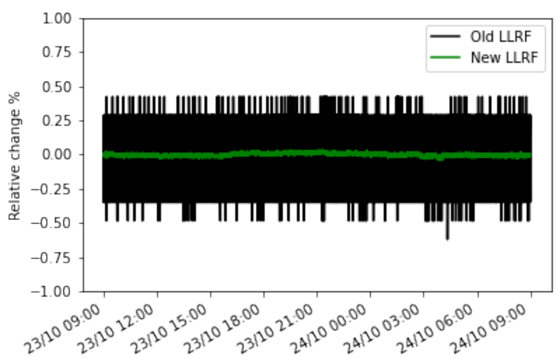

Figure 2: Relative cavity 1 field amplitude measured by the old analogue system and the new dLLRF system.

Following the improved source stability, Linac 3 showed very good performance reach and stability as well as high overall availability (above 97%) [10]. Figure 3 shows the current measured at the ITH.BCT41 beam current transformer (BCT) at the end of the Linac 3: a significantly narrower distribution was achieved in 2021 than in 2018, with a typical current of (31 ± 4) μA delivered to LEIR.

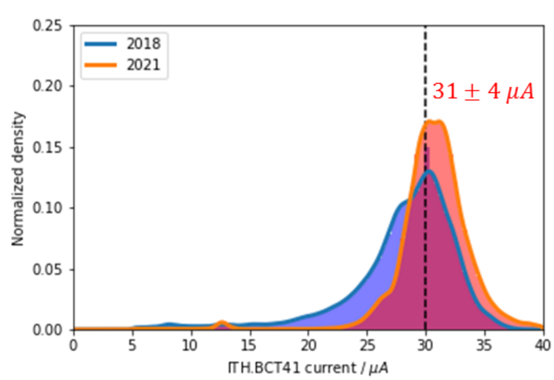

Figure 3: Current distribution measured at the ITH.BCT41 current transformer at the end of the Linac 3. Data for 2021 is shown in red, while data for 2018 is shown in blue. The black dashed line marks the operational current requested by LEIR (30 μA).

With respect to 2018, remarkable advancements have been done in the momentum monitoring measurements. In order to ensure high injection efficiency in LEIR, the beam momentum out of Linac 3 needs to be linearly swept with the help of a ramping and a debunching cavity [11]: the first provides a tunable energy offset to the beam; the second provides the required energy sweep. The output energy of Linac 3 was monitored with dedicated measurements in the ITFS line after the ramping cavity (see e.g. [12] for the measurement procedure). The typical measurement result is shown in Fig. 4: the momentum spread of the beam increases with time, indicating the aging of the stripper foil in use. LEIR injection efficiency significantly dropped when the bunch momentum spread reached $2.5 \cdot 10^{-3}$. This parameter will be further monitored in 2022 in order to promptly avoid performance loss in LEIR.

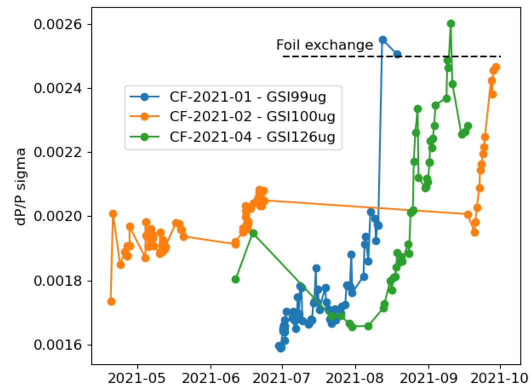

Figure 4: Evolution of the momentum spread measured after the Linac 3 ramping cavity. Different colors refer to different stripper foils.

LEIR

Beam was delivered from Linac 3 to LEIR starting from week 26. A few beam tests in March were also scheduled in order to test the new signal processing of the beam position monitors (BPMs) in the ITE and ETL injection lines. After a difficult start due to simultaneous polarity switch of three key equipment (the last injection line BPM, the ring fast BCT and the ring screen monitor), beam commissioning in the ring successfully started and proceeded smoothly thanks to the accurate reference measurements acquired in 2018, the detailed beam commissioning documentation [13] and the well defined set of key performance indicators against which the performance was measured and adjusted [14]. The good machine operation and stability of Linac 3 allowed LEIR to reach the highest performance in terms of intensity and stability (Fig. 5) and the LEIR team to closely investigate sources of machine performance drift (e.g. PS stray field, stripper foil degradation, etc.) and identify current regulation issues both in the transfer lines and in the ring.

The machine operation was greatly improved by the new automatic optimizers available as a support to repetitive tasks. Optimizers were a time saver for lengthy manual optimizations or re-steering activities. The Generic Optimization Framework [15] developed at CERN allowed to rapidly develop highly customized optimizers (e.g. automatic steerers for injection bumps, cooler bumps, extraction to PS, etc.).

In 2021, the new Schottky acquisition hardware and control software allowed for improved monitoring on the beam momentum delivered by Linac 3. Complementary to the measurements done in the ITFS line, a dedicated energy

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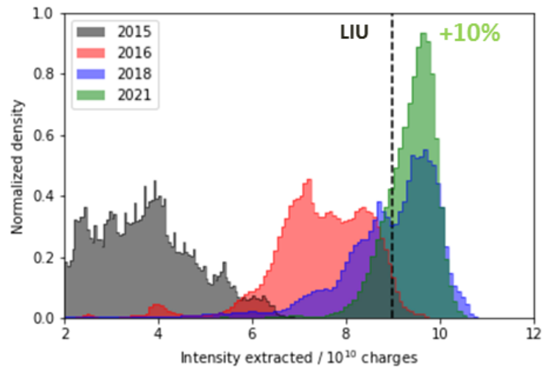

Figure 5: LEIR extracted intensity overview with lead ions. The dashed line shows the LIU target of $9 \cdot 10^{10}$ charges.

monitoring cycle was put in place to control the injected momentum distribution. Figure 6 shows the comparison of measured and simulated [16] injected momentum distribution for different debuncher phase settings: the monitoring of each slice momentum distribution will be a powerful tool for probing potential drifts in energy and will be fully exploited in 2022.

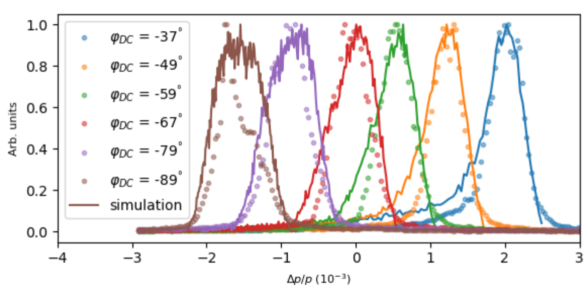

Figure 6: Measured and simulated Schottky energy distribution at the entrance of LEIR as a function of the debuncher cavity (DC) phase.

Several new insights were brought by the new injection line BPMs. Following the upgrade to the high frequency operation mode [13], the BPMs were used to: monitor the injected beam pulse shape and detect possible Linac 3 RF malfunctioning; perform transfer line optics measurements; quantify the PS stray field disturbance. This last activity motivated the installation of additional shielding panels in the ITE line [17] performed during the end of the year technical stop. Beam measurements will be performed in 2022 in order to verify the reduction of the PS stray fields effect.

Concerning the electron cooler activities, a grid modulator was installed to modulate the electron beam current. The orbit BPMs in the cooler straight section were used to provide the first measurement of the electron beam position [18]. The measurement will be finalised in 2022 and will provide an essential tool to adjust and monitor the overlap of electron and ion beams.

During the 2021 run, no fast horizontal instabilities were observed [19] as in 2018. The instability could be observed only configuring the transverse damper with 2018 settings which were found not to be fully optimized in terms of damper gain and delay [10]. Similarly, no lifetime degradation was observed as a function of the beam position in the straight section 4 (see details in [13]): this could be related to the removal of the old scraper blades performed before machine startup [20].

PS

Ions were sent to the PS as a low intensity single bunch (so called "EARLY" beam) on week 30, and high intensity multi-bunch (so called "NOMINAL" beam) two weeks later. During shutdown there were no major hardware changes for ions in the PS. The RF gymnastics was therefore restored for EARLY and NOMINAL beams without major issues both for the 100 ns and 75 ns spacing. The beam was then extracted and delivered to the SPS in week 40.

Figure 7 shows the overall intensity transmission between LEIR extraction to SPS injection. In 2021 the transmission did not reach the 95% target due to time and resources limitations. A systematic optimization will be done in 2022 and potential collective effects with increased intensity in the PS evaluated [21].

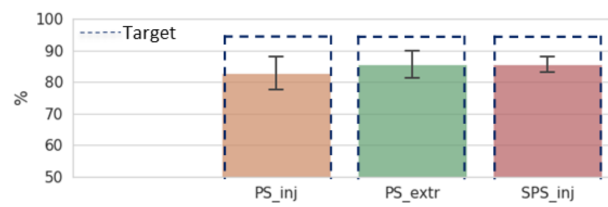

Figure 7: From left to right: transmission from LEIR to PS, within PS, and from PS to SPS for the NOMINAL 100 ns beam. The dashed line shows the 95% target.

CONCLUSIONS

The ions operation from source to SPS was restarted in 2021. Several upgrades were finalised during the long shutdown period: in particular part of the old analogue LLRF of Linac 3 was upgraded to dLLRF, and SPS underwent a major RF power and dLLRF upgrade. The recovery of 2018 operation was demonstrated both in terms of performance reach and stability: Linac 3 profited of the new source configuration which allowed longer and stable fills, while LEIR preserved the good beam quality reaching the highest performance in terms of intensity and stability. The energy monitoring between Linac 3 and LEIR was largely improved thanks to automated beam energy measurements in the ITFS line and Schottky spectra studies performed in LEIR. Additional studies are on-going to limit the effect of PS stray fields and mitigate the current regulation issues in transfer lines and the LEIR ring. High intensity beams were setup in the PS and delivered to the SPS with no showstoppers. The beam intensity preservation between accelerators will be further optimized in 2022.

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