ACHIEVEMENTS AND PERFORMANCE PROSPECTS OF THE UPGRADED LHC INJECTORS

V. Kain*, S. Albright, R. Alemany, M.E. Angoletta, F. Antoniou, T. Argyropoulos, F. Asvesta, B. Balhan, M. Barnes, D. Barrientos, H. Bartosik, P. Baudrenghien, G. Bellodi, N. Biancacci, A. Boccardi, J. Borburgh, C. Bracco, E. Carlier, J. Coupard, D. Cotte, H. Damerau, A. Findlay, M. Fraser, A. Funken, G.P. Di Giovanni, B. Goddard, G. Hagmann, K. Hanke, A. Huschauer, M. Jaussi, I. Karpov, T. Koevener, D. Kuchler, J.-B. Lallement, A. Lasheen, T. Levens, K. Li, A. Lombardi, N. Madysa, E. Mahner, M. Meddahi, L. Mether, B. Mikulec, J. Molendijk, E. Montesinos, D. Nisbet, F.-X. Nuiry, G. Papotti, K. Paraschou, F. Pedrosa, T. Prebibaj, S. Prodon, D. Quartullo, E. Renner, F. Roncarolo, G. Rumolo, B. Salvant, M. Schenk, R. Scrivens, E. Shaposhnikova, P. Skowronski, A. Spierer, F. Tecker, D. Valuch, F. Velotti, R. Wegner, C. Zannini
CERN, Geneva, Switzerland

Abstract

To provide HL-LHC performance, the CERN LHC injector chain underwent a major upgrade during an almost 2-year-long shutdown. In the first half of 2021 the injectors were gradually re-started with the aim to reach at least pre-shutdown parameters for LHC as well as for fixed target beams. The strategy of the commissioning across the complex, a summary of the many challenges and finally the achievements will be presented. Several lessons were learned and have been integrated to define the strategy for the performance ramp-up over the coming years. Remaining limitations and prospects for LHC beam parameters at the exit of the LHC injector chain in the years to come will be discussed. Finally, the emerging need for improved operability of the CERN complex will be addressed, with a description of the first efforts to meet the availability and flexibility requirements of the HL-LHC era while at the same time maximizing fixed target physics output.

SCOPE OF THE LHC INJECTORS UPGRADE

The LHC Injectors Upgrade (LIU) project aimed at increasing the intensity and brightness in the injectors to match the HL-LHC requirements [1] for both lead (Pb) ions and protons (shown in Fig.1). This goal required a series of major upgrades in all accelerators of the LHC injector chains, which are detailed in [2, 3]. The main items will be briefly summarised in the following.

To double the brightness reach of the PSB, the 50 MeV proton linac, was replaced by the 160 MeV Linac4 accelerating H^- and requiring a charge exchange injection into the four rings of the PSB. The higher PSB extraction energy required an increase of the PSB magnetic fields as well as the replacement of its main power supply and RF systems.

In the PS, the next accelerator in the chain, the injection energy increase to 2 GeV (in combination with optimized longitudinal beam parameters at the PSB-PS transfer) was needed in order to maintain the same space charge tune spread with double the beam brightness.

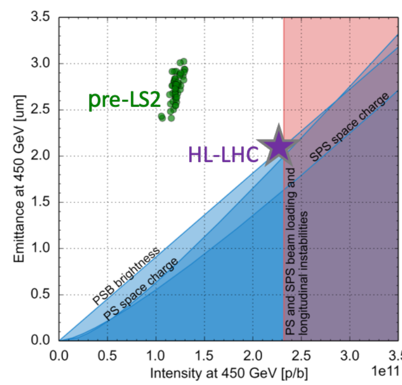

Figure 1: This plot shows the required emittance and bunch intensity for protons at the end of the injector chain. It corresponds to 2.3×10^{11} protons per bunch in $2.1\,\mu$m emittance. These parameters have to be achieved for 288 bunches of 25 ns spacing. The measured performance before Long Shutdown 2 (LS2), before the LIU upgrades were installed, are shown in green. The parameter limitations of the different machines after the upgrade are indicated with the shaded regions.

Also in the PS, longitudinal feedback, reduction of the impedance of the 10 MHz RF system and implementation of multi-harmonic feedback systems on the high frequency RF systems were required to increase the threshold of the longitudinal coupled bunch instabilities that previously limited LHC beams.

In the SPS, the 200 MHz RF power was increased by adding two new 200 MHz power plants, changing to a pulsed operation mode and rearranging the 200 MHz cavities to reduce their impedance and the beam loading effect with LHC-type beams. A reduction of the cavity High Order Modes (HOM) was achieved through the installation of specially designed couplers. A new low-level RF (LLRF) system for the 200 MHz RF system was also implemented to

* Verena.Kain@cern.ch

allow for more flexibility, beam loss reduction and new RF beam manipulations [4–6].

To increase the threshold for longitudinal beam instabilities the focusing quadrupole (QF) flanges were impedance shielded. The attached vacuum chambers were coated with amorphous carbon (a-C) to alleviate transverse electron cloud effects. However, beam induced scrubbing is still necessary to prepare the SPS for operation with the nominal 25 ns bunch spacing, as the vast majority of the main dipoles remains uncoated.

To cope with the larger beam intensity and brightness, the SPS injection protection devices were upgraded and a new main beam dump designed and installed. The extraction protection and collimators were exchanged, and new interlocking systems added.

Finally, an important fraction of the beam instrumentation, vacuum systems, and general services were renewed to increase performance and reliability. This included a completely new beam position electronics acquisition system.

For LHC-type Pb ions, HL-LHC performance per bunch was already achieved in 2018 due to the many previous improvements to Linac3 and LEIR [7], but only with 100 ns bunch spacing instead of the required 50 ns. An additional three bunch scheme in LEIR and 75 ns spacing in the PS was developed that could achieve 70 % of the HL-LHC luminosity performance. The remaining item to be established post LS2 to achieve the 50 ns spacing is momentum slip stacking in the SPS, requiring the new 200 MHz LLRF system.

START-UP STRATEGY

The overall commissioning schedule can be found in the LS2 master plan [8]. It included a 3 month shift due to the general lockdown for COVID-19 early 2020. No other schedule changes were integrated. To prepare for the restart of the injectors in 2020 - 2021, individual system tests by the equipment experts were scheduled during the shutdown period, followed by extended periods of hardware commissioning from the control room. The hardware commissioning period also included full integration tests (so-called dry runs) with operational software. The final commissioning phase was the period of stand-alone beam commissioning with variable length for each accelerator of the injector chain. The goal with beam for the year 2021 was to re-establish the 2018 performance for LHC as well as all fixed target beams and prove the technical feasibility of ion slip stacking with the new LLRF system of the SPS.

Given the number of accelerators and complexity of beam production involved, the common coordination meeting only discussed strategy, synergies and general controls infrastructure (e.g. online check lists). Additionally, dedicated commissioning teams were formed per accelerator with their own coordination structure and follow-up on beam dynamics, operations and equipment. To ensure consistent commissioning strategy with this decentralised approach, "Operational Readiness Analysis" (ORA) reviews were organised with the goal to review status, identify any missing components for machine commissioning and operation, define actions and timelines to follow up and to share knowledge and experience across machines. A number of experts across the machines joined these ORA reviewers. The general feedback from this exercise was that, despite the significant amount of preparation involved, the process and feedback was very beneficial and helped towards the success of the start-up.

Lessons Learned

The LIU project profited from a professional planning unit for the construction and installation phase of LS2 who organised the various teams, ensured readiness and reduced co-activity in the tunnel to a minimum. For software readiness no such coordination was available and in particular the final software layer in the form of control room applications was not part of the system project definitions or coordination. As a consequence, for many systems, software interfaces to equipment and full integration into control room software was late (in many cases tools only became available in the course of the 2021 physics run). As a possible improvement for the availability of the full software stack from day 1, a global software readiness coordinator for the next winter shutdowns as well as long shutdowns is under discussion.

Another point to be optimised is the contingency management between the various phases from shutdown to hardware commissioning and beam commissioning. Whereas the start dates for the various physics runs were kept unchanged, part of the shutdown work slipped into the hardware commissioning phase and part of the hardware commissioning and equipment check-out ended up during beam commissioning or even the physics run due to accumulated delays. The consequence was an important reduction of commissioning time. This strategy only worked for the post-LS2 start-up due to the flexibility and commitment of many teams. For future start-ups after long shutdowns, however, more emphasis needs to be placed on a realistic planning at sufficient detail including also electronics and controls infrastructure. In case of delays, clear prioritisation is required with potentially more frequent schedule updates for the entire complex.

Last but not least, a number of aperture bottlenecks impacted the beam commissioning. In the PS, a spurious object left in the aperture by mistake was not trivial to find. Local PS aperture measurements cannot be done easily with the available corrector strength at injection energy, and the problem caused in addition significant activation [9]. As a consequence, alternative strategies for aperture measurements in the PS were explored afterwards. As a recommendation for consolidation and new accelerators, the capability for local aperture measurements at injection or even lower energy should be included in the hardware requirements for all machines. In the SPS, several aperture problems were also encountered which could have been prevented with improved quality assurance at design time: however, as aperture measurements are routinely done during beam commissioning, they were detected and repaired quickly.

Impact of Hardware Faults in 2021

Given the amount of equipment installed during LS2, it was not surprising to have a long list of hardware faults or prolonged debugging in all machines during 2020 - 2021. Most faults were repaired during the run and only caused temporarily reduced availability. In the SPS, 2623 faults were registered. It is the last accelerator in the injector chain and thus this number also comprises faults in the chain upstream. The corresponding downtime was 885.3 h resulting in an average availability of only 73.4 % (some weeks with only about 40 %), compared to 85 % for a standard year. See Table 1 for an overview of the availability across the complex in 2021.

Some equipment issues needed the winter shutdown for final mitigation with significant impact on peak performance and/or integrated performance during 2021. In this category we find the faults with the new SPS access system, which was severely impacted by issues with non-radiation hard electronics in the tunnel, the limited RF voltage with the SPS 200 MHz cavities due to slow conditioning and arcing in two RF power lines as well as limitations coming from one of the vertical dump kickers (MKDV1) of the newly installed SPS beam dump system. The reduced RF power and kicker vacuum problems limited the achievable intensity and number of bunches with LHC-type beams in 2021, see Fig. 2 for the kicker vacuum behaviour with 25 ns beams. The access system in the SPS was upgraded during the winter shutdown 2021-2022, the weak vertical beam dump kicker was exchanged, the 200 MHz RF cavities further conditioned and the two power lines repaired during the time without beam.

Table 1: Average Availability of the Injectors During 2021

Accelerator	expected [%]	obtained 2021 [%]
LINAC4	95	97.4
PSB	90	94.5
PS	87	88.1
SPS	84	73.4

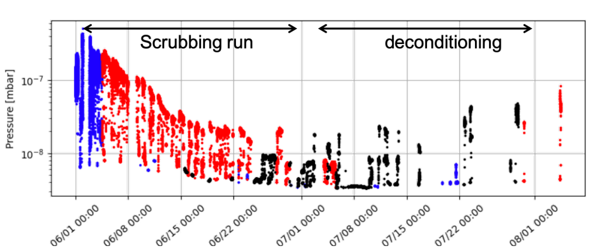

Figure 2: Vacuum behaviour of MKDV1 during 2021, showing deconditioning with time. The vacuum interlock threshold was set to 5×10^{-8} mbar due to poor HV performance.

Other Issues

The LIU upgrades had been thoroughly studied and prepared for many years. Nevertheless, surprises were still discovered with beams and in particular the new beam parameters at start-up. A few examples are given below.

The magnet of the new vertical Beam Gas Ionisation monitor in the PS introduced an unprecedentedly strong skew sextupole resonance [10], needing compensation when using the magnet for vertical profile measurements. The magnet was exchanged during the winter stop 2021-2022 for a magnet with improved multipolar behaviour [9].

The nominal optics for the HiRadMat facility led to breaking the Be vacuum window in the line twice due to the smaller LHC beam emittances for the same intensity out of the PSB. HiRadMat can currently only run with blown-up emittances corresponding to a brightness of 2.5 μm emittance at 1.2×10^{11} protons per bunch. An upgrade of the facility to cope with LIU brightness is being studied.

The smaller vertical emittance for the SPS fixed target beams increased the losses on the splitter magnets towards the North Area targets and hence the background in the experimental hall. As mitigation, the vertical emittance was increased in the PSB for this type of beam.

ACHIEVEMENTS TOWARDS HL-LHC PARAMETERS

LINAC4 had an excellent availability in 2021, and also delivered very stable intensities for all LHC-type beams (about 0.3 - 0.6 % stability). See [11] for details.

The first brightness curves measured in the PSB were already close to the LIU target early in 2021. After a campaign of resonance compensation [12], optimisation of the working point as well as correction of the beta beating introduced by the injection chicane [13] in August 2021, the brightness could be even further improved, see Fig. 3 (the emittance plateaus at lower intensities due to e.g. scattering on the injection foil and injection errors). The PSB delivers beams at a brightness that surpasses expectations and is also not intensity-limited for LHC-type beams. Further parameter improvements can thus be expected.

The PS could recover LIU bunch intensities of 2.6×10^{11} protons per bunch with a stability margin up to $2.8 - 2.9 \times 10^{11}$ protons per bunch. Above these values longitudinal parameters are degraded and quadrupolar coupled-bunch instabilities are observed. If however the 40 MHz RF system is used as Landau system in bunch shortening mode, sufficient damping is provided at even the highest intensities.

The longitudinal emittance at the transfer from PSB to PS in 2021 was chosen to be 2-2.25 eVs (3 eVs is the final value for HL-LHC performance). The PS brightness under these conditions follows the prediction as can be seen in Fig. 4. More details about the performance of the PS in 2021 can be found in [9, 14].

As mentioned earlier, the 2021 bunch intensity reach in the SPS was limited due to the vacuum threshold on the first vertical dump kicker and insufficient RF voltage, but also due

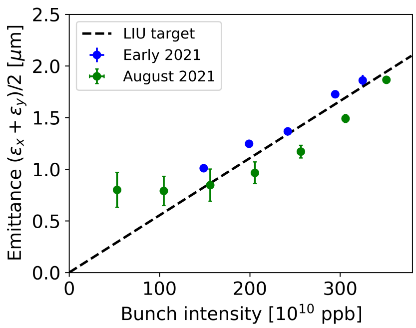

Figure 3: Emittance as function of intensity in the PSB early 2021 and August 2021. The brightness surpasses LIU project target values.

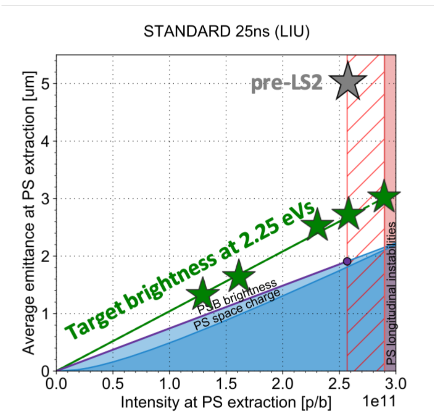

Figure 4: Obtained brightness for 25 ns beams in 2021 for the PS.

to spurious vacuum spikes of the horizontal dump kickers and beam induced heating of the four modules inside the last injection kicker magnet vacuum tank (MKP-L). Still, stable beam conditions could be established for HiRadMat runs in 2021 at 4 × 72 bunches with 1.2×10^{11} protons per bunch. The record bunch intensity in 2021 was 1.6×10^{11} protons per bunch accelerated to flattop in 72 bunches. The success of the longitudinal impedance reduction campaign was also demonstrated in measurements with long bunches. The peak at 1.4 GHz disappeared and the microwave instability for the high intensity single bunch beam for AWAKE was suppressed, see Fig. 5.

During the winter stop 2021 - 2022, the problematic vertical dump kicker was exchanged and the SPS access system modified. The kicker exchange required a prolonged period of scrubbing where also the limitations of the injection kicker had to be folded in (i.e. 50 % of time scrubbing, 50 % of time cooldown). Together with the additional voltage and RF power and optimised longitudinal blow-up, 1.85×10^{11} protons per bunch could be reached in 72 bunches at 450 GeV with the required LHC bunch length of 1.65 ns, see Fig. 6. More batches at this intensity are excluded currently due to the vacuum issues with the horizontal dump kickers. At injection energy, bunch intensities up to 2.2×10^{11} in 4 batches

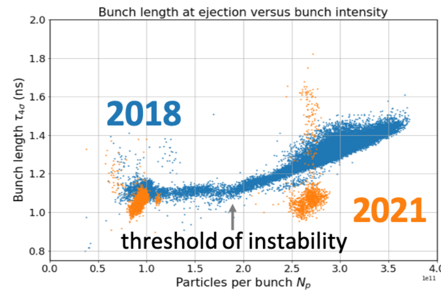

Figure 5: Bunch length extracted to AWAKE at 400 GeV as a function of bunch intensity. AWAKE requires 1 ns long bunches after bunch rotation, which is achievable after LS2 for higher bunch intensity.

were achieved. More work is required to obtain HL-LHC brightness, Fig. 7, although a test at 3 eVs longitudinal emittance from the PSB gave emittances at injection with significant margin to the HL-LHC brightness target (purple dots in Fig. 7).

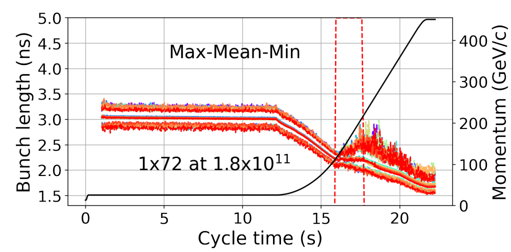

Figure 6: Evolution of maximum, mean and minimum bunch length through the SPS cycle with controlled longitudinal blow-up for a bunch intensity of 1.8×10^{11} protons per bunch. The bunch length at the end of acceleration is compatible with LHC injection requirements.

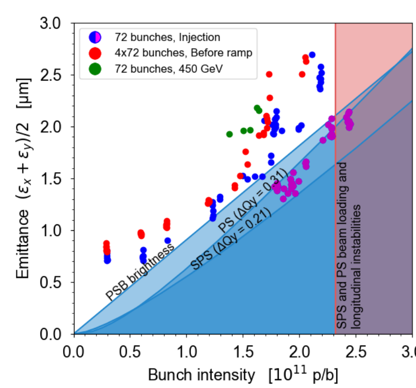

Figure 7: Emittance as a function of bunch intensity for 72 bunches at injection in blue (≈ 2 eVs in PSB) and purple (3 eVs in PSB), 4 × 72 before the ramp in red and 72 bunches at 450 GeV (the SPS-to-LHC transfer energy) in green.

As the final highlight during 2021, the technical feasibility of momentum slip stacking could be demonstrated in the SPS with 6 + 6 batches of 4 Pb ion bunches, reducing the bunch spacing from 100 ns to 50 ns at a 300 GeV intermediate plateau in the ion cycle, see Fig. 8 for slip stacking with two 4-bunch batches. For details on the successful Linac3 and LEIR commissioning in 2021, see [15].

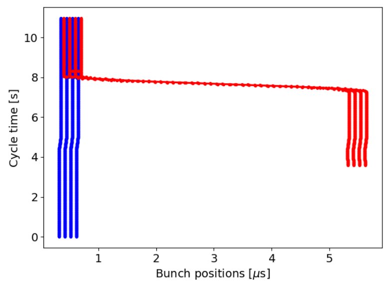

Figure 8: Evolution of the bunch position measured by the wall current monitor during slip stacking of 2 4-bunch batches on 11/11/2021.

CHALLENGES DURING RUN 3

The LHC had only a two week pilot run in 2021 and will start its first physics run after LS2 at an increased energy of 6.8 TeV per beam in 2022. LHC Run 3 will end at the end of 2025 with the start of LS3 for the HL-LHC installation. The planned bunch intensity ramp-up in the injectors for the coming years is shown in Fig. 9. In 2023, the LHC can expect 1.8×10^{11} protons per bunch routinely out of the SPS.

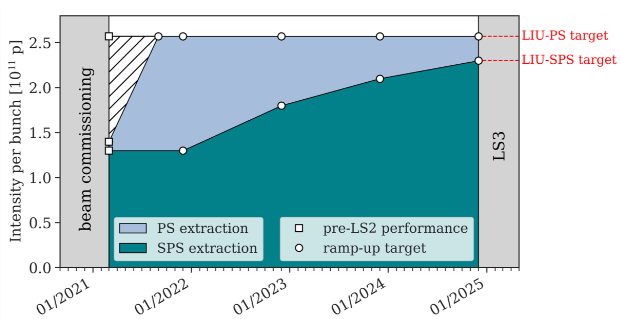

Figure 9: Planned bunch intensity ramp-up in the injectors until installation of HL-LHC.

Most of the remaining challenges to reach HL-LHC parameters in the injectors concern the SPS. At this moment it is not clear yet whether conditioning of the horizontal dump kickers can be expected in the long run. Machine development studies are aimed at investigating the cause of the spurious vacuum spikes. In addition, studies are required to define the optimal working point at injection energy taking into account bunch-by-bunch tune shifts and space charge at the highest brightness and bunch intensities [16]. Strategies need to be developed for setting up the longitudinal blow-up for maximum robustness [17]. Transmission at 26 GeV is strongly influenced by the longitudinal beam quality from the PS and the optimal transfer parameters and methods need to be established. The continuous loss mechanism in the SPS at flat bottom energy needs to be understood, and reproducibility is also a concern. The energy matching (between PS and SPS, as well as SPS and LHC) together with various other parameters need to be adjusted whenever LHC-type beam is taken. Hysteresis seems to be playing a significant detrimental role. All these aspects are being studied in machine development sessions with the strong limitations currently of the MKP-L beam-induced heating. The present MKP-L tank will be replaced, during the winter shutdown 2022-2023, by a tank containing four modules with a specially designed serigraphy to significantly reduce beam induced heating [18].

To address reproducibility (and counteract hysteresis), a test of so-called ”dedicated LHC filling” is planned for summer 2022. In this mode the SPS would only serve LHC physics during the LHC filling period without playing other beams in parallel. In addition, machine learning algorithms are being developed to predict hysteresis and dynamic effects from eddy currents for different magnet types. Automation, together with machine learning and numerical optimisation, has become part of the operational toolkit for efficient commissioning, fault finding and performance stabilisation. Optimisation algorithms are routinely used at most accelerators. Examples are setting-up of 200 ns batch spacing in the SPS with constraints from injection kickers and transverse dampers, resonance compensation in the PSB and the PS, LEIR injection efficiency optimisation and stabilisation and e-cooling optimisation in LEIR with reinforcement learning and computer vision on Schottky spectra [19, 20]. This is only the beginning of a general effort to globally optimise the throughput of the injectors for fixed target physics and in particular also minimise the turn-around time for the LHC while running with beam parameters at the edge of stability.

CONCLUSION

During Long Shutdown 2 in the years 2019-2020, the upgrade of the LHC injectors to reach the brightness and intensity target for the HL-LHC era was completed. Equipment installation was followed by an extended commissioning phase where the functionality of the different equipment upgrades was tested and new operational modes prepared. The goal of the first run after the shutdown was to re-establish pre-shutdown parameters for LHC as well as fixed target beams in the CERN accelerators. Nevertheless, LINAC4 and PSB were already delivering HL-LHC parameters in 2021 and PS early 2022. The remaining challenges concern the SPS, where limitations from various kicker systems and slow conditioning of the RF cavities define the pace towards HL-LHC bunch intensities. As of 2023, bunch intensities $> 1.8 \times 10^{11}$ protons per bunch can be expected at the end of the injector chain. Reproducibility and efficiency remain a concern with beams at the edge of stability. Automation, machine learning and various optimisation techniques are being developed to globally optimise the CERN accelerator complex performance.

REFERENCES

[1] R. Tomás *et al.*, "Beam parameter requirements from HL-LHC", presented at the LHC Injectors Upgrade (LIU) Workshop, Montreux, Switzerland, Feb. 2019, unpublished.

[2] J. Coupard *et al.*, "LIU Technical Design Report - Volume I: Protons", CERN, Geneva, Switzerland, Rep. CERN-ACC-2014-0337, Dec. 2014.

[3] J. Coupard *et al.*,"LIU Technical Design Report - Volume II: Ions", CERN, Geneva, Switzerland, Rep. CERN-ACC-2016-0041, April 2016.

[4] A. Spierer *et al.*, "The CERN SPS Low Level RF: The Beam-Control", presented at IPAC'22, Bangkok, Thailand, Jun. 2022, paper TUPOST021, this conference.

[5] P. Baudrenghien, J. Egli, A. Spierer, T. Wlostowski, and G. Hagmann, "THE CERN SPS LOW LEVEL RF: LEAD IONS ACCELERATION", presented at IPAC'22, Bangkok, Thailand, Jun. 2022, paper TUPOST022, this conference.

[6] G. Hagmann, P. Baudrenghien, J. Egli, A. Spierer, M. Suminski, and T. Wlostowski, "The CERN SPS Low level RF: The Cavity-Controller", presented at IPAC'22, Bangkok, Thailand, Jun. 2022, paper TUPOST023, this conference.

[7] S. Albright *et al.*, "Review of LEIR operation in 2018", CERN-ACC-NOTE-2020-0023.

[8] J. Coupard *et al.*,"Master schedule of the Long Shutdown 2 (2019-2020)", Rep. CERN EDMS 1687788, Nov. 2020.

[9] A. Huschauer *et al.*, "Beam Commissioning and Optimisation in the CERN Proton Synchrotron After the Upgrade of the LHC Injectors", presented at IPAC'22, Bangkok, Thailand, Jun. 2022, paper MOPOST006, this conference.

[10] S. J. Horney, A. Huschauer, and E. H. Maclean, "Beam-Based Measurement of Skew-Sextupole Errors in the CERN Proton Synchrotron", presented at IPAC'22, Bangkok, Thailand, Jun. 2022, paper MOPOST004, this conference.

[11] P. K. Skowronski *et al.*, "Summary of the First Fully Operational Run of LINAC4 at CERN", presented at IPAC'22, Bangkok, Thailand, Jun. 2022, paper MOPOST007, this conference.

[12] F. Asvesta *et al.*, "Resonance Compensation for High Intensity and High Brightness Beams in the CERN PSB", in *Proc. HB'21*, Batavia, IL, USA, Oct. 2021, pp. 40–45. doi:10.18429/JACoW-HB2021-MOP06

[13] T. Prebibaj *et al.*, "Injection Chicane Beta-Beating Correction for Enhancing the Brightness of the CERN PSB Beams", in *Proc. HB'21*, Batavia, IL, USA, Oct. 2021, pp. 112–117. doi:10.18429/JACoW-HB2021-MOP18

[14] H. Damerau *et al.*, "Improved Longitudinal Performance of the LHC Beam in the CERN PS", presented at IPAC'22, Bangkok, Thailand, Jun. 2022, paper WEPOTK046, this conference.

[15] N. Biancacci *et al.*, "Linac3, LEIR and PS Performance in 2021 and Prospects for 2022", presented at IPAC'22, Bangkok, Thailand, Jun. 2022, paper WEPOPT055, this conference.

[16] I. Mases, H. Bartosik, V. Kain, C. Zannini, and M. Schenk, "Characterisation of Bunch-by-Bunch Tune Shift Effects in the SPS", presented at IPAC'22, Bangkok, Thailand, Jun. 2022, paper MOPOST037, this conference.

[17] N. Bruchon, G. Papotti, N. Madysa, C. Zisou, I. Karpov, and D. Quartullo, "Towards the Automatic Setup of Longitudinal Emittance Blow-Up in the CERN SPS", presented at IPAC'22, Bangkok, Thailand, Jun. 2022, paper TUPOST042, this conference.

[18] M. J. Barnes *et al.*, "Mitigation of High Voltage Breakdown of the Beam Screen of a CERN SPS Injection Kicker Magnet", presented at IPAC'22, Bangkok, Thailand, Jun. 2022, paper THPOTK043, this conference.

[19] N. Madysa, R. Alemany-Fernandez, V. Kain, F. M. Velotti, N. Biancacci, and B. Goddard, "Automated Intensity Optimisation Using Reinforcement Learning at LEIR", presented at IPAC'22, Bangkok, Thailand, Jun. 2022, paper TUPOST040, this conference.

[20] F. M. Velotti *et al.*, "Overview of the Machine Learning and Numerical Optimiser Applications on Beam Transfer Systems for LHC and Its Injectors", presented at IPAC'22, Bangkok, Thailand, Jun. 2022, paper TUPOST045, this conference.