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BEAM PERFORMANCE AND OPERATIONAL EFFICIENCY AT THE CERN PROTON SYNCHROTRON

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Abstract

The injectors for the LHC at CERN underwent a major upgrade during a recent two-year long shutdown in the framework of the LHC Injectors Upgrade (LIU) project. Following this upgrade, the Proton Synchrotron (PS) was restarted in 2021, with the same beam quality as before the upgrade quickly achieved or surpassed. This contribution details the current beam performance for fixed-target and LHC-type beams in the PS and the ongoing activities to improve the operational efficiency by means of automating routine operational tasks.

BEAM PERFORMANCE

Following the recommissioning of the LHC injectors in 2021 after a two-year improvement programme, 2022 was the first complete physics production year after this upgrade. Operation at the PS was restarted in March 2022 and the last beams were delivered on 28 November 2022. Throughout the year beams were operationally delivered to all connected facilities and downstream accelerators, and significant progress was achieved in optimising the performance of the different beam types. Figure 1 shows the cumulative proton beam intensity extracted from the PS per year since 2009. Excluding the period when CERN sent neutrino beams to Gran Sasso from 2006 to 2012 (CNGS) [1], the 2022 total delivered intensity of 6.13×10^{19} protons surpassed previous years to a large extent.

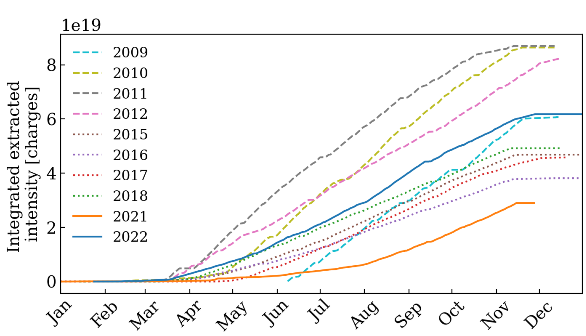

Figure 1: PS cumulative extracted proton beam intensity for different years. Excluding the years 2009-2012, when high-intensity beams for CNGS were produced, the intensity delivered in 2022 was the highest in recent years.

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Fixed Target Beams

The main experiments requesting the delivery of high-intensity beams are the neutron time-of-flight (n_TOF) [2] facility and the North experimental Area (NA) at the Super Proton Synchrotron (SPS) [3]. The n_TOF facility received 42% of the extracted protons, while 40% were delivered on the SPS fixed target proton (SFTPRO) beams for the NA.

The beam to n_TOF is a high-intensity single bunch at nominally 850×10^{10} protons. However, to increase the average proton flux for the facility a lower intensity bunch at around 350×10^{10} protons can be parasitically accelerated on the cycles sent to the PS East Area (EA). Following the removal of aperture restrictions in the transfer line, a new transfer line optics was implemented early 2022 for n_TOF beams [4]. With these optics transverse large beam sizes of $\sigma_x = 30$ mm, $\sigma_y = 11$ mm on the target were achieved, which was an important milestone to ensure longevity of the upgraded spallation target. Furthermore, significant effort was invested to optimise the longitudinal shape of the n_TOF bunch. Nominally, the requested full bunch length is 28 ns, which is achieved via a longitudinal bunch rotation before extraction. However, in 2022 the facility accepted to run with 40 ns length, which has a twofold benefit: (i) with reduced momentum spread the extraction losses are reduced due to the smaller dispersive beam size and (ii) the bunch rotation can be optimised to generate a sharp rising edge of the bunch and to remove any undesired pre-pulse that negatively impacts the energy distribution of the created neutrons. Today, the maximum permitted flux corresponds to 1.66×10^{12} protons per second, with 2.2×10^{12} protons per second successfully reached during tests in 2022. Currently, the duty cycle for n_TOF beams is adjusted for the nominal flux, however the facility could temporarily benefit from operating at higher maximum flux if other users do not request beam. A proposal to increase the maximum flux is under discussion with the Swiss and French authorities, and approval is expected by the second quarter of 2023.

The SFTPRO beams in the PS are produced using the Multi-Turn Extraction (MTE) technique [5], which is a resonant fourth-order extraction that separates the beam into one central core and four surrounding islands in the horizontal phase space. During 2022 the SPS NA requested very high-intensity beams, resulting in up to 2.5×10^{13} protons being extracted from the PS for a period of about two months. It has been the first time that such high intensities were operationally produced with the MTE scheme, marking the achievement of another important milestone.

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A barrier bucket (BB) scheme was commissioned throughout the year. This allows a longitudinal gap for the extraction kicker rising edge to be generated in the continuous beam distribution to reduce extraction losses to a minimum [6]. Significant progress was made on the low-level RF (LLRF) side to develop, implement and commission a demonstrator synchronisation scheme between the position of the gap, the PS extraction and the SPS injection kickers, and the scheme was eventually put in place on 20 October 2022 for a test run until the end of the year. As a result of this, the so-called dummy septum (TPS15), a passive absorber installed to protect the magnetic extraction septum SMH16 during the conventional MTE cycle [8], could be moved into its parking position from early November. This led to a further reduction of extraction losses and increased the flexibility of adjusting the extraction trajectories for all other beam types, which previously had to pass through the narrow extraction channel between TPS15 and SMH16. Removal of the TPS15 especially simplifies the production of the n_TOF beam at 28 ns as the larger dispersive beam size can be more easily accommodated. The evolution of extracted intensity and extraction efficiency during 2022 for SFTPRO beams is shown in Fig. 2. Figure 3 shows two examples of extracted five-turn spills measured in the transfer line between PS and SPS, one using the conventional scheme and the second exhibiting the 200 ns long BB gaps. The presence of the BB gaps causes undesired high-intensity spikes close to the gap edges. The origin of this phenomenon and possible mitigations are currently being investigated.

The gain from this loss reduction could be maintained along the chain with the physics experiments not observing any adverse effect of operating with the BB [9, 10]. As a result of this very successful test period, it was decided to operate with the BB also in 2023, while focusing on a final

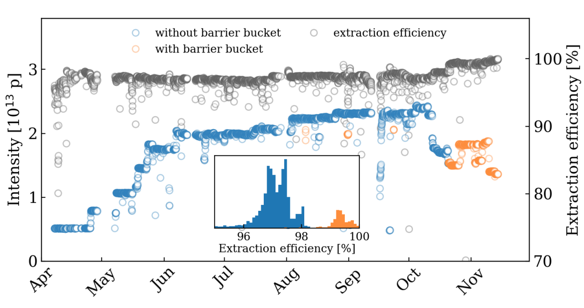

Figure 2: Evolution of extracted intensity (color) and extraction efficiency (grey, comparing ring and transfer line intensity measurements) for SFTPRO beams in the PS in 2022. SPS NA commissioning and intensity ramp-up started from April and record intensities with MTE beams were achieved during summer. Towards the end of the year a barrier bucket scheme was implemented with beneficial impact on the extraction efficiency visible on the time series and the inserted histograms. The dummy septum was moved out of beam on 7 November, leading to an additional increase of extraction efficiency.

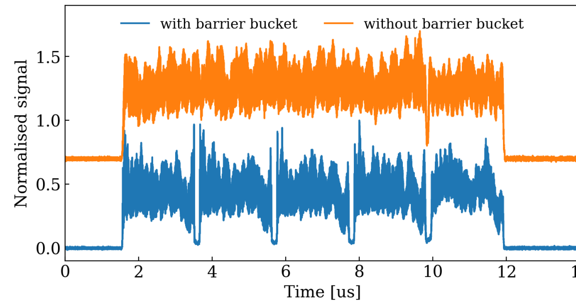

Figure 3: Examples of five-turn SFTPRO spills using the MTE with (blue) and without (orange) the BB. The islands are extracted during the first four turns and the core during the last one. The BB gap at around 10 μs is well synchronised with the rise time of the extraction kicker for the core, which generates the drop in intensity at the same position on the orange trace.

and operational LLRF implementation [10]. In addition, exploration of the intensity limits of operating with the BB is planned for 2023.

Performance of the beams delivered to the Antiproton Decelerator (AD) also improved in 2022, with some of the improvements only made possible through upgrades done to the accelerator chain in the framework of the LIU project. The main modification of the beam production scheme concerns the delivery of five instead of four bunches by the PS. Furthermore, tests were performed with higher delivered intensity to increase the number of antiprotons [11].

2022 also saw significant progress in understanding the PS slow extraction for beams delivered to the EA. The settings of the magnetic cycles and the auxiliary magnets controlling the slow extraction were modified to increase the reproducibility of the extracted spill and the versatility of the accelerator control system is now fully exploited following the implementation of high-level physical parameters [12]. Furthermore, different low-energy lead ion beams were delivered to irradiation experiments in the EA, and the setup of these beams fully benefited from the previously mentioned high-level parameters [12, 13]. During the last two weeks of the 2022 run, lead ion beams were also delivered to the SPS NA.

LHC-type Beams

In 2018 LHC-type beams in the PS had already reached the LIU intensities of 2.6×10^{11} protons per bunch (ppb). After the implementation of various LIU upgrades to the RF installations, the commissioning of these systems during 2021 and 2022, and several campaigns to push the intensity reach, bunch intensities of almost 3.0×10^{11} ppb can be reached today, providing important operational margin [14].

At the same time as the exploration of the intensity reach, a ramp up of the brightness was taking place for the standard LHC beam production scheme that can provide up to 72 bunches at PS extraction with two injections from the PS Booster (PSB) [15]. The LIU target brightness critically

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depends on transferring beams with a large longitudinal emittance of 3 eVs from the PSB to the PS to mitigate space charge induced transverse emittance blow-up at injection energy in the PS. Initial studies in 2021 and early 2022 were performed with PSB beams at a longitudinal emittance of 2 eVs and the corresponding brightness is shown in Fig. 4.

The increase in brightness to LIU target values was eventually achieved in mid-2022 after producing beams with longitudinal emittances of 3 eVs. Measurements performed at the end of 2022 with beams at slightly larger than LIU intensity nevertheless showed some additional transverse blow-up. This was overcome early 2023 following a meticulous setup of the longitudinal and transverse parameters during the commissioning phase after the usual winter stop. On 14 April 2023 LIU brightness was measured for the first time for beams at LIU intensity just before PS extraction. At this point it has to be noted that the LHC cycles with these beam parameters exhibit excellent transmission of 99% and that the theoretical predictions [16] are in perfect agreement with the actual measurement results.

During 2022 the operational beam for the LHC was using the batch compression merging and splitting (BCMS) scheme [15], which is superior in terms of brightness compared to the standard scheme. However, with the recent improvements to the standard beam, the BCMS beams only show marginally higher brightness in the SPS [17]. Therefore, it was decided to use standard beams for LHC physics production in 2023 due to their more efficient production

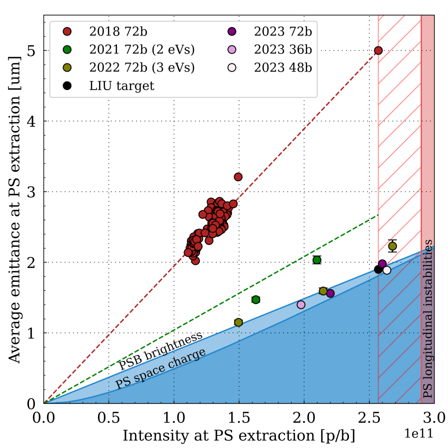

Figure 4: Limitation diagram for standard LHC-type beams showing the average transverse emittance versus the bunch intensity at PS extraction. Shaded areas show theoretically inaccessible beam parameters due to the mentioned limitations. The red hashed area indicates the operational margin in terms of intensity. The red and green dashed lines indicate the achieved brightness before the long shutdown and the theoretically expected brightness for longitudinal emittance of 2 eVs, respectively. The LIU target brightness was reached for the first time in 2022 and in April 2023 also for LIU intensities. 36 and 48 bunches refer to cycles with only a single injection from the PSB.

scheme. To mitigate electron cloud effects in the LHC a special hybrid scheme with 8b4e [15] and standard beams will actually be used.

OPERATIONAL EFFICIENCY

Over the last ten years the operational flexibility of the PS has significantly increased based on continuous improvement of the accelerator control system and the implementation of the LIU upgrades. Increased capabilities are accompanied by an increase in complexity, necessitating the implementation of new approaches to control the accelerator. Classical automation, such as automatic sequencing of sequential tasks, has been in place in the LHC since day one and has also been deployed elsewhere in the complex. Completely new opportunities have been enabled through CERNML, a framework to bring numerical optimisation and machine learning (ML) into the control room [18].

During beam commissioning numerical optimisation is now performed on a regular basis. Beam loss during the slow extraction for the EA, for example, is mitigated by optimising the strengths of the two magnetic septa and the amplitudes of the extraction bumps. In several transfer lines, where observation is difficult due to the absence of beam position monitors, trajectory steering is done using numerical optimisation with the objective of reducing beam loss along the lines.

Another example of successfully applying optimisation algorithms is the automated drift correction of the MTE splitting efficiency, i.e. the equalisation of intensity between core and islands. Adjustment is done on a regular basis by the operators in the control room to account for changes in intensity or magnetic history. Dedicated studies proved that the Extremum Seeking algorithm can very well serve to automatically control the intensity sharing, and the operational implementation is expected to be finalised by summer 2023 [19].

Operating LHC-type beams in the PS requires regular fine tuning of the triple and double splittings. Reinforcement learning (RL) agents were developed and are now operationally used to adjust cavity voltages and phases as required [20]. However, the absence of continuous online monitoring of the splitting quality requires manual intervention to start the RL-based adjustments for the time being.

CONCLUSIONS

2022 was a very successful year of beam operation, with the PS flexibly delivering very high integrated beam intensities to all facilities. Beam performance of all fixed target and LHC-type beams was further improved with the LIU beam parameters reached for the first time at PS extraction in early 2023. Deployment of numerical optimisation and ML algorithms to improve the operational efficiency is ongoing but improved online monitoring of beam-related quantities is needed to advance further.

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