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BEAM COMMISSIONING AND OPTIMISATION IN THE CERN PROTON SYNCHROTRON AFTER THE UPGRADE OF THE LHC INJECTORS

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Abstract

The CERN LHC injector chain underwent a major upgrade during the Long Shutdown 2 (LS2) in the framework of the LHC Injectors Upgrade (LIU) project. After 2 years of installation work, the Proton Synchrotron (PS) was restarted in 2021 with the goal to achieve pre-LS2 beam quality by the end of 2021. This contribution details the main beam commissioning milestones, difficulties encountered and lessons learned. The status of the fixed-target and LHC beams will be given and improvements in terms of performance, controls and tools will be described.

LS2 UPGRADES IN THE PS

In the PS, the main LIU activities [1] were related to the upgrade of the injection energy to 2 GeV kinetic energy to mitigate space charge issues and to improvements of the radio-frequency (RF) systems by reducing their impedance or implementing additional feedback systems (see also [2]). New beam instrumentation devices, such as new wire scanners, beam gas ionisation (BGI) monitors and beam loss monitors (BLMs) were installed to improve the diagnostic capabilities. Furthermore, important consolidation activities were performed during LS2, such as the renovation of 43 out of the 100 combined function main magnet units (MUs).

PS BEAM COMMISSIONING

Following a shutdown period of two years and three months, beam was again injected into the PS on the evening of 3 March 2021. Despite the many modifications during LS2, it took less than half a day to accelerate the beam to the maximum flat top momentum of 26 GeV/c and to extract it towards the external dump. During the following five days, commissioning progress was even faster than anticipated and low-intensity variants of the main beam types were quickly set up.

This initial quick progress was slowed down by a breakdown of the newly installed injection septum, requiring a stop of beam operations for eight days to repair the device and re-establish operational vacuum conditions. This inadvertent stop was also used to perform a first iteration of beam-based alignment of the combined function MUs, which was required due to the extensive consolidation campaign of the magnets during LS2. Following a second iteration, a total of eight MUs were aligned to improve the orbit, reducing the root mean square orbit excursions from 3.3 to 1.6 mm in the horizontal and from 1.9 to 0.9 mm in the vertical plane.

After this first phase of commissioning low-intensity beams, PS operations entered into the intensity ramp-up phase. During this period various issues were encountered, the majority of them related to unexpected beam loss at various locations along the accelerator.

Beam Loss Around Straight Section 88

The versatility of the PS is closely related to a multitude of RF cavities used for acceleration and longitudinal gymnastics such as bunch splittings or bunch rotations [3]. During the beam commissioning, one of the cavities used for bunch rotation, an 80 MHz system installed in straight section 88, could not be reliably used due to a high pressure level. In addition, increased beam losses were measured on the BLMs especially around this region, but also elsewhere in the accelerator delaying the intensity ramp-up.

Introducing a local vertical orbit bump at this specific cavity could reduce but not completely remove the losses. Therefore, an aperture restriction at the cavity was expected to be the source of both the beam loss and the increased pressure. A small misalignment of the cavity was subsequently corrected, but did not improve the issues described before. Furthermore, a radiation hot spot of 42 mSv/h at contact on top of the vacuum chamber just downstream of the RF cavity was observed. All these observations led to the suspicion of an obstacle inside the vacuum chamber and hence the decision was taken to break the vacuum and perform an endoscopy. Indeed, a sponge-like object was located just upstream of the RF cavity. This piece obstructed the lower half of the vacuum chamber and was a leftover from the MU consolidation program, where it was used to protect the vacuum chambers while they were stored in the workshop. In hindsight, all the observations were well explained by the presence of this object. The object actually acted as a scatterer and the interaction of the beam with it caused the increased vacuum pressure in the cavity as well as the increased beam losses. The radiation hot-spot, however, was generated by the local bump that was introduced to pass the object. Removal of the object allowed the beam commissioning activities to be pursued.

Electron Cloud Effects and Scrubbing

The first observation of electron cloud (EC) effects in the PS dates back to the early 2000s, during the commissioning of LHC-type beams in the PS. At that time the beam quality

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had not been impacted, but an EC signature was indirectly observed as baseline drifts of beam position monitor signals. At the same time an EC-induced instability could be triggered by modifying the longitudinal beam characteristics at extraction and storing the bunches for about 100 ms prior to extraction [4].

Following the first MU consolidation campaign in 2005, the operational LHC-type beams became horizontally unstable and suffered from large beam losses during the PS restart in 2006. This effect was understood to be EC-induced, as a large fraction of the vacuum chambers had been exposed to air, increasing their secondary electron yield, and the instability and losses clearly depended on the bunch length [5].

During the 2021 beam commissioning a dynamic pressure rise on all vacuum gauges around the machine was observed when LHC-type beams were produced. Initially, the pressure rise was believed to be correlated with high beam loss during the early commissioning phase. However, after mitigation of these losses by adjusting tunes and chromaticities, the pressure rise still remained. Further investigations revealed that the vacuum activity was triggered by the presence of 25 ns bunch spacings and hence EC effects were suspected to be at the origin of the pressure increase. This was confirmed by injecting trains with less than the nominal 72 bunches, as the pressure rise was clearly decreased. The induced vacuum activity turned out to be blocking the commissioning progress, as the PS injection kicker vacuum interlock would be triggered almost every cycle, even if using significantly lower than nominal intensity. Therefore, it was decided to start scrubbing the vacuum chamber surfaces by playing as many LHC-type cycles as the injection kicker interlock allowed. A trade-off between number of played cycles, number of bunches, bunch length and total intensity had to be found and regularly adjusted to push the performance to the limit and to scrub efficiently. Figure 1 shows an overview of this 2021 PS scrubbing run. About five days of scrubbing turned out to be sufficient to condition the machine, which then allowed to further push the intensity for LHC-type beams.

Beam Loss Close to $Q_y = 6.33$

During the setup of the fixed target proton beams for the Super Proton Synchrotron (SPS), referred to as the the SFTPRO beams, unacceptably high beam loss was observed when the vertical tune was moved close to $Q_y = 6.33$. Loss map measurements performed before LS2 had never shown strong excitation of this skew sextupolar resonance [6] and hence investigations were started to identify the source of this unexpected phenomenon. Figure 2 shows a loss map measured in 2021, where the excitation of the two strong skew sextupolar resonances $3Q_y = 19$ and $2Q_x + Q_y = 19$ is clearly visible.

In a first attempt to mitigate the observed losses, resonance compensation with three skew sextupole magnets was performed. This was achieved by using the CERN generic optimisation framework [7] and the BOBYQA optimisation algorithm [8] implemented therein. Excellent compensation could be quickly achieved within 15 iterations.

Subsequently it was understood that the resonance excitation was actually caused by the newly installed magnet of the vertical BGI monitor [9], and specifically its shielding plates (see also [10]). These plates were designed to concentrate the fringe field of the adjacent MUs at the extremities of the magnet rather than its center, where the actual measurement device is located. During the winter shutdown 2021/22 the

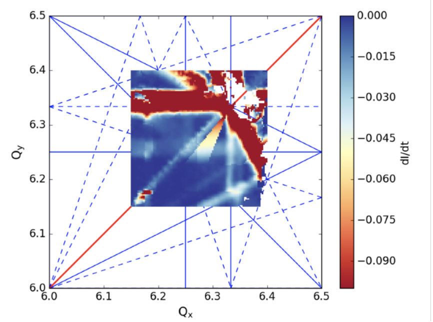

Figure 2: Measured loss map using dynamic tune scans. Two very strong skew sextupolar resonances were identified, leading to almost full beam loss when crossing them.

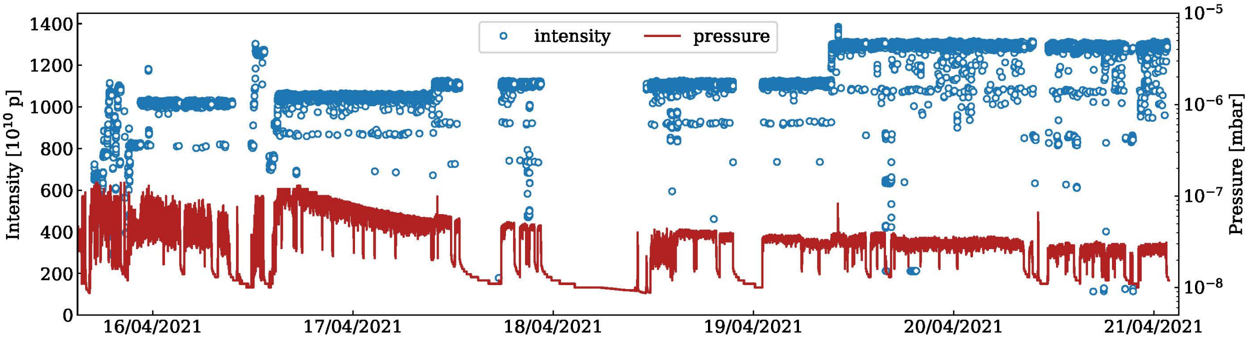

Figure 1: Overview of the 2021 PS scrubbing run. Different intensity steps and the correlated decrease of the dynamic pressure rise are clearly visible. After five days of scrubbing, sufficiently good operational conditions could be established to progress with the commissioning of LHC-type beams.

plates were redesigned [11] and beam measurements confirmed an important reduction of the resonance excitation.

Upgraded Beam Instrumentation

Several beam instrumentation devices were upgraded in the framework of the LIU project [12]. The new wire scanners now allow bunch-by-bunch beam size measurements to be performed with increased accuracy compared to the previous generation of scanners. These devices are the workhorses for emittance qualification of high-brightness LHC-type beams across the injectors chain and have therefore been standardised to use the same technology in the different accelerators. All five scanners of the PS, i.e. three horizontal and two vertical devices, were replaced with this new generation during LS2.

The PS now also contains a horizontal and a vertical BGI monitor based on Timepix3 silicon pixel detectors. The advantage is their capability of providing continuous and non-destructive beam size measurements all along the PS cycle, eventually opening the door to online emittance monitoring [9]. BGI data analysis is more involved compared to the wire scanners and studies are ongoing to exploit the systems to their maximum.

The new BLM system is based on LHC-type ionisation chambers, which provide several advantages compared to the legacy BLM system, like signal proportionality to beam loss and improved time resolution. During the commissioning, some of the BLM signals were unfortunately significantly perturbed by noise, compromising the beam loss measurements. The noise was understood to be caused by cable trays not being grounded and by routing of signal and power cables in the same cable trays. Significant noise mitigation - by more than three orders of magnitude - was eventually obtained during the 2021/22 winter shutdown through rerouting the signal cables, adding metallic shielding ducts and installing nanocrystalline ferrite filters.

STATUS OF THE DIFFERENT BEAMS

During LS2, significant effort had been invested into preparing the PS optics control using high-level physics parameters. Therefore, a new optics repository [13] had been established to facilitate the link with the controls infrastructure. This modernisation allowed settings of magnetic elements to be generated based on the simulation models, and simplified the initial setup of the accelerator. Furthermore, online kick response measurements could be performed to identify polarity and calibration errors.

The main goals of beam operation in 2021 were to recommission the PS with all the modifications implemented during LS2 and to re-establish the pre-LS2 beam performance for the different users. The beam preparation was driven by the needs of the SPS team and their commissioning plans. Hence, the first beams to be prepared in 2021 were low-intensity single bunch LHC-type beams and several variants of the SFTPRO beam, which uses the resonant multi-turn extraction (MTE) [14]. Throughout the year the SFTPRO beam intensities were increased to 2018 levels and performance improvements continue to be implemented also during 2022, especially to improve the transmission between the PS and the SPS.

The slow extraction towards the renovated EAST experimental area [15] and the operation of the primary transfer line with multiple targets was also successfully managed. However, fluctuations of the extracted intensity were observed and understood to be caused by dynamic effects perturbing the start of the extraction. During the 2022 startup stability could be significantly improved by slightly delaying the start of the slow extraction on the PS flat top. Furthermore, slow extraction with lead ions was demonstrated for a wide range of intensities.

The high-intensity single bunch delivered to the n_TOF facility [16] was also successfully commissioned up to $850\text{x}10^{10}$ protons in the ring. Following the redesign of the spallation target, Gaussian beam sizes of 15x15 mm (1 σ) at the target were requested. However, this could not be immediately achieved due to aperture restrictions in the transfer line. The restricting quadrupoles were removed during the 2021/22 winter shutdown, and a new optics was implemented during the 2022 startup that eventually allowed to deliver appropriate beam parameters.

Despite the LHC not taking beam in 2021, the commissioning of LHC-type beams was also rigorously pursued. The achieved beam brightness closely followed the expected LIU ramp-up plan and the bunch intensity was pushed even beyond the LIU target value [2, 17].

CONCLUSIONS

2021 was the first year of operation after the upgrade of the injector complex during LS2 and the goal of re-establishing pre-LS2 performance was successfully met. Despite the meticulous preparation of the beam commissioning, several surprises were encountered along the way. In the future scrubbing runs should be included into the restart planning if large fractions of the machine are exposed to air. Furthermore, clear specifications of the maximum acceptable higher order multipole components are required for new magnetic elements and the feasibility of local aperture measurements to spot obstacles at an early stage should be investigated.

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