SLS 2.0 COMMISSIONING PROGRESS

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Abstract

Commissioning of SLS 2.0, the first light-source storage ring employing a substantial number of permanent magnets, began in January 2025. The nominal beam current of 400 mA was achieved within the first three months of accelerator-dedicated commissioning. Since then, significant progress has been made. The Swiss Light Source facility upgraded to fourth-generation has reached a level of availability sufficient to begin user operation, delivering high-brightness photon beams to operational beamlines. First user operations have been carried out with internal and external users. We present the commissioning results, lessons learned, and experience gained during the initial user operation.

INTRODUCTION

The new storage ring at the Swiss Light Source (SLS), known as SLS 2.0, was successfully commissioned in 2025. It is the first light-source storage ring to employ a substantial number of permanent magnets to realize a compact multi-bend achromat lattice: the beam orbit and linear optics along the achromat arc are realized entirely with permanent magnets [1, 2]. The nominal beam current of 400 mA was achieved within the first three months of accelerator-dedicated commissioning [3]. Subsequently, the SLS facility upgraded to fourth-generation has reached a level of availability sufficient to begin user operation, delivering high-brightness photon beams to operational beamlines. First user operations have been carried out with both internal and external users. This paper highlights major commissioning progress achieved after the first three months, together with early user operation experience. The key parameters of SLS 2.0 are summarized in Table 1 for reference.

Table 1: Key Parameters of the New SLS Storage Ring

Parameters	Values
Beam energy	2.7 GeV
Circumference	288 m
Natural emittance	150 pm w/o IDs, w/o SC superbends
Lattice	7-BA, 12 sectors
Beam current	400 mA
Beam lifetime	9 hours w/o IDs

BEAMLINE COMMISSIONING AND ID INSTALLATION

Beamline commissioning followed the initial three months of accelerator commissioning. We began with dipole beamlines, which do not require additional machine-side preparation. For insertion-device (ID) beamlines, orbit feed-forward tables were established based on beam measurements and implemented in the control system. Characterization of the installed IDs is ongoing [4], and additional feed-forward tables are being developed to mitigate optics distortions.

The *first light* at each beamline was typically achieved within one day, allowing the subsequent mandatory radiation survey in the optical and/or experimental hutch to be completed the following day(s). As soon as the first set of beamlines was commissioned, it became apparent that orbit bumps of up to hundred µm at each photon source were required, indicating a misalignment between the photon beam directions and the reference axes of the beamlines. A realignment campaign was therefore scheduled to reduce these mismatches, as described later.

Undulators are currently installed in eight straight sections, while installation in three additional straight sections is planned. We encountered a serious vacuum pressure issue with a 2-meter-long APPLE-type undulator with a 9-mm inner-diameter vacuum chamber. Due to the proximity of the undulator permanent magnets, the NEG coating of the chamber could not be activated in-situ, and we relied only on beam vacuum conditioning for this short chamber. Vacuum conditioning with beam, however, was not effective, and hence high vacuum pressure along the chamber resulted in a significant reduction of beam lifetime. This problem was partially resolved by an unconventional in-situ activation method, in which pressurized hot water (about 140°C) was circulated through the chamber cooling-water channel. Technical details of the vacuum system can be found in Ref. [5].

BEAM STABILITY AND FEEDBACK

In parallel with the beamline commissioning, the fast orbit feedback system [6] was taken into operation. The feedback is implemented in the FPGA (programmable logic) part of a Multiprocessor System-On-Chip (MPSoC) that receives beam position monitor (BPM) data via dedicated multi-gigabit fiber optic links, using an in-house low-latency protocol. The same protocol and fiber links are used by the MPSoC to update the orbit corrector magnet power supply currents, combined with a beam momentum correction via the ring main RF frequency. With the present conservative settings, orbit stability on the order of 100 nm has been achieved in both transverse planes at 40 kHz correction rate (Fig. 1). The corresponding 0 dB points were 400 Hz and 500 Hz in the horizontal and vertical planes, respectively. With a future firmware upgrade, we expect to achieve >1 kHz 0 dB point at >80 kHz correction rate.

Regarding beam stability, stabilization of the RF voltage and phase is also essential, and the digital low-level RF system [7] plays a key role. The parameters of the internal feedback loops were optimized to minimize RF voltage and

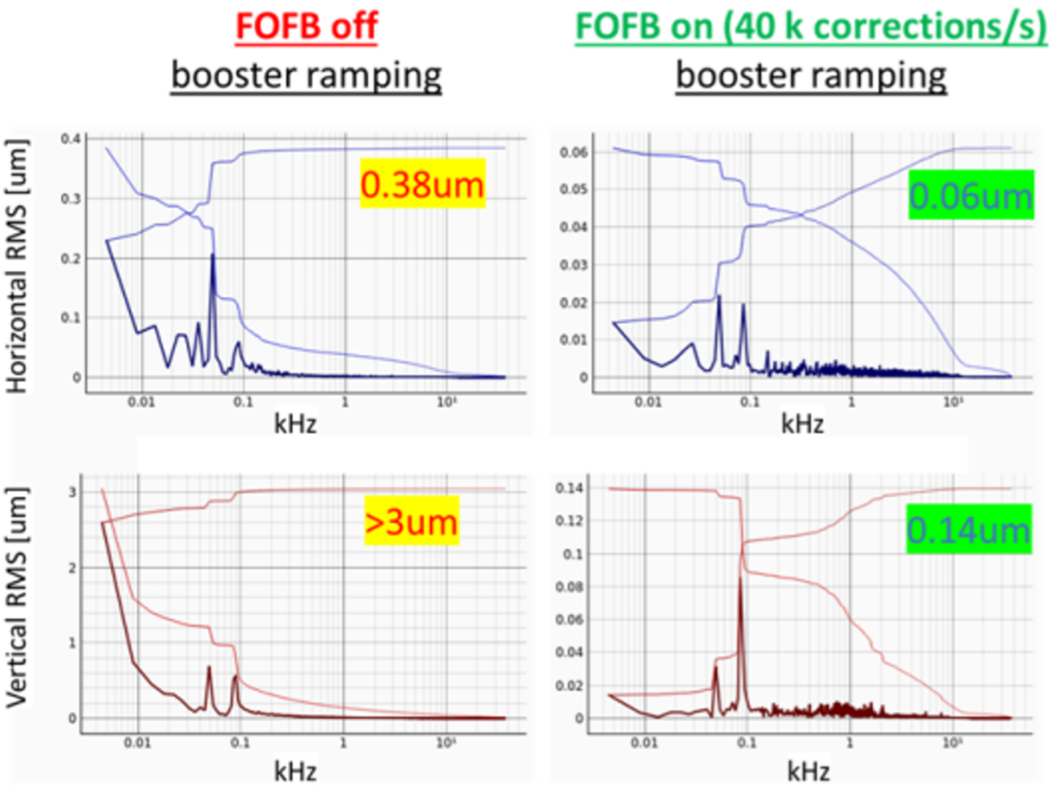

Figure 1: Frequency spectrum of beam jitter at a reference out-of-loop BPM. Integrated values up to 40 kHz are also shown. The two prominent peaks correspond to 50-Hz mains and 90-Hz girder eigenfrequency. Stability estimated using all BPMs was 144 nm and 91 nm in the horizontal and vertical planes, respectively.

phase jitters, as well as orbit fluctuations observed by BPMs located in the arcs, where the horizontal dispersion function is nonzero.

During commissioning, no beam instabilities were observed except for ion-induced instabilities. Consequently, the bunch-by-bunch feedback system is currently not used. The HOM damped cavity [1, 8] is the key component to avoid coupled bunch mode instability. Once the storage ring is fully equipped with all planned IDs, the threshold for head-tail instability may approach the nominal operating current, potentially requiring mitigation measures.

Tune feedback system is, so far, not required; the tunes remain essentially constant within a stable range over several days, and occasional manual adjustments are sufficient. This medium-term tune stability is attributed to the fact that both the closed orbit and the linear optics are primarily determined by permanent magnets.

The filling-pattern feedback has been commissioned and is used during user operation. The nominal filling pattern, consisting of 450 bunches and a 30-bucket gap, can be maintained continuously through top-up operation.

STORAGE RING REALIGNMENT

Due to constraints associated with the installation and commissioning schedule, it was difficult to allocate sufficient time for optimal alignment, including tunnel temperature stabilization. Nevertheless, the initial survey alignment was already adequate to start beam commissioning, though a realignment campaign was later required as discussed earlier.

The girders are motorized, allowing remote alignment in the vertical plane. We therefore aligned all girders vertically to the reference mid-plane ($y = 0$). The storage ring and beamlines will thus lie on a common reference plane once the beamlines are aligned accordingly. In the horizontal plane, girder alignment requires time-consuming manual intervention in the accelerator tunnel. Therefore, we chose to align only a minimal number of girders horizontally in order to reduce the orbit bumps to adjust the photon beam direction.

In addition to the girder realignment described above, some individual magnets were also realigned. Since the beginning of commissioning, we observed an issue in which the horizontal orbit could not be fully corrected at three locations around the ring [3]. The source of the dipole errors responsible for this effect could not be identified; therefore, the issue was addressed by shifting combined-function magnets to introduce a compensating dipole component. The orbit can be fully corrected, after the alignment, within the dipole corrector capacity up to 60%. More details of the realignment campaign can be found in Ref. [9].

MACHINE PROTECTION

Machine protection is an important aspect of operating SLS 2.0, as an uncontrolled beam dump can potentially cause serious damage. Our primary concern is the very thin vacuum chamber walls (0.5–1.0 mm), which could be punctured and lead to a vacuum leak in the worst case [10].

To avoid such critical failures, a dedicated beam dump kicker and an internal beam dump are installed [11]. The machine protection system, integrated into the interlock system, is capable of detecting various fault conditions that require a beam dump. Postmortem analysis shows that the system operates effectively: approximately 80% of the stored electrons are typically directed to the internal dump, as designed.

MACHINE PERFORMANCE AND USER OPERATION

To prepare the machine for user operation, several tuning procedures were applied. The injection efficiency was maximized by optimizing the transport line from the booster to the storage ring, as well as by adjusting the fields of the injection septa and kickers. A high injection efficiency of >90% is routinely achieved, despite the limited acceptance, owing to the thin septum (1 mm blade) [12] and the emittance exchange in the booster [13]. The beam loss monitor system [14] proved highly useful for injection tuning.

Since the pulsed magnets are operated in a voltage-regulated mode, it was effective to implement a feedback scheme that keeps the actual current generating the pulsed magnetic field as constant as possible during injection. This is currently applied to the booster extraction septum, which is the most critical component for injection efficiency due to its relatively large deflection angle. We plan to extend this approach to other pulsed magnets. The four injection bump kickers were individually tuned to minimize perturbations to the stored beam. However, it is well known that the conventional injection scheme using bump kickers is not ideal, since the closed orbit bump cannot be perfectly realized in practice. This is further discussed in the next section.

The linear optics is corrected within the quad corrector capacity up to 70%. The nonlinear optics is optimized empirically to maximize the beam lifetime. The superconducting third-harmonic cavity [15] has been operational since the beginning of commissioning. The cavity was tuned to realize the design bunch lengthening factor of about 2.5 [14]. As a consequence of these tuning, we observe that the beam lifetime at the nominal beam current is actually longer than the design value, typically about 12 h compared with 9 h.

The vacuum lifetime was likely underestimated in the design, which assumed a constant pressure of 10^{-9} mbar dominated entirely by carbon monoxide molecules: the actual residual gas composition indicates a significant contribution from lighter species, and the average pressure can reach below 10^{-9} mbar. Empirical optimization of the nonlinear optics may also contribute to the improved lifetime. A more systematic approach to nonlinear optics control is currently under study [16].

The beam lifetime also depends strongly on the vertical emittance, which is close to zero in the ideal lattice. The storage ring skew quadrupoles are adjusted to increase the vertical emittance to 10 pm, the value assumed in the design lifetime calculations. The vertical emittance tuning is verified using beam profile monitors [14, 17]. Alternatively, the kicker of the bunch-by-bunch feedback system can be utilized, and this approach is to be tested.

Two-week pilot operation with friendly users was carried out in summer 2025, while the first normal user operation was conducted in November–December 2025, during which twelve beamlines were operational. The latter yielded promising operational statistics, as summarized in Table 2. More details of the initial user operation can be found in [18].

Table 2: Statistics from the first normal user operation, Nov.–Dec. 2025. ‘Availability with compensation’ is evaluated with the method defined in Ref. [19].

Parameters	**Values**
Scheduled time	960 hours
Total down time	54.1 hours
Number of faults	49
Availability	94.4%
Availability with compensation	99.3%
Mean time between failure	18.1 hours
Mean time to recover	1.1 hours

SHUTDOWN AND START-UP IN 2026

It was planned to install two superconducting superbends [20] during the winter shutdown (Dec. 2025–Mar. 2026), which can generate a variable, high peak magnetic field to provide high-energy photons for dipole beamlines. However, the magnets did not pass the site acceptance test, as not all conductors reached the superconducting state. As a result, the installation had to be postponed to late 2026. After intensive investigation, the issue was resolved by identifying and reducing unexpected thermal bridges. Figure 2 shows the dipole field profile of the superconducting superbend, reaching a peak field of 5.4 T.

The machine was restarted in April after the shutdown, during which one additional undulator was installed. It is an APPLE-type undulator installed next to the previously mentioned device that caused the vacuum issue. Although the two are identical devices, the installation procedure was improved by applying ex-situ bake-out, installation under neon gas atmosphere and further a week-long in-situ NEG activation with hot water. This procedure proved effective, smoothly recovering the beam lifetime.

During the shutdown, a prototype fast injection kicker [21] was also installed. It was once installed in ESRF-EBS storage ring and successfully demonstrated the designed deflection of about 2 ns with low-current beam. Some substantial temperature and pressure rise was, however, observed with higher beam current. The aim of the installation in SLS 2.0 was thus to verify the kicker design in terms of beam-induced heating. The temperature of the kicker blade remained below 90°C with 400-mA beam (Fig. 3), while the design allows

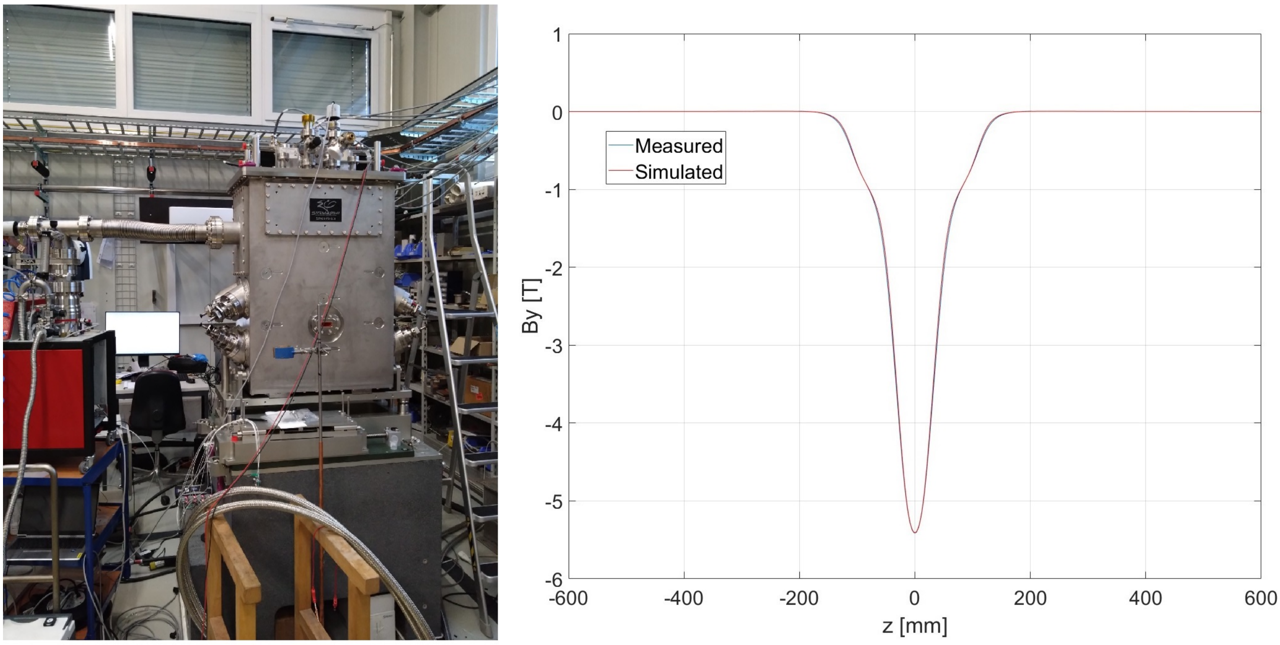

Figure 2: (Left) Superconducting superbend on a test bench. (Right) Dipole field profile of superconducting superbend, measured vs. simulated field. A peak field of 5.4 T is achieved with a field profile matching the simulation.

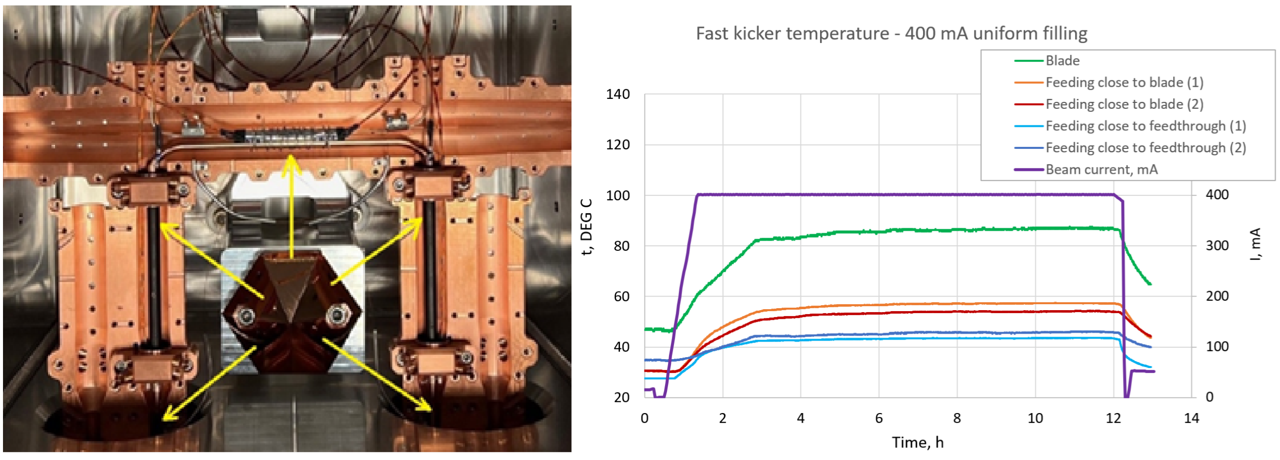

Figure 3: (Left) Set up of infrared (IR) camera calibration with a heater and temperature sensors. The pyramidal IR mirror allows us to measure the temperatures of five locations indicated by yellow arrows at one time. (Right) Measured temperature rise of the fast kicker parts with nominal 400-mA beam.

up to 400°C. Now we plan to fabricate and install a full-scale kicker system consisting of eight stripline kickers, whereas the prototype consists of a single module. The fast kicker will replace the bump kickers and realize a quasi-transparent top-up injection.

SUMMARY

SLS2.0 commissioning is progressing well despite minor issues and schedule updates. The newly constructed ring is the first light-source storage ring to employ a substantial number of permanent magnets to realize a compact multi-bend achromat lattice: the beam orbit and linear optics along the achromat arc are realized entirely with permanent magnets. The commissioning results demonstrate that such a ring can be successfully operated and achieve the design performance. Our achievements pave the way for more aggressive accelerator designs based on extensive use of permanent magnets.

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