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SLS 2.0 STORAGE RING UPGRADE OVERVIEW

R. Ganter on behalf of SLS 2.0 Team
PSI Center for Accelerator Science and Engineering, Villigen, Switzerland

Abstract

The Swiss Light Source (SLS) storage ring has been rebuilt as SLS 2.0, improving radiation brightness by approximately two orders of magnitude and increasing the photon energy range by about 50%. All components of the storage ring lattice and its supporting infrastructure were newly constructed and installed during a 15-month shutdown that began in October 2023.

The new seven-bend achromat arcs had to fit within the existing tunnel footprint and maintain alignment with the beamline exit ports, resulting in very small distances between magnets. Additionally, all bending (and reverse bending) magnets are based on permanent magnets, necessitating thorough cross-talk studies due to significant stray magnetic field effects. The high magnet density prevented the installation of vacuum bellows required for in-situ bake-out. Consequently, the twelve vacuum arc strings, each 17 meters long, were installed in the ring after NEG activation and pumping to a pressure of approximately 1×10^{-11} mbar. Four HOM-damped RF cavities operating at 500 MHz are installed in a row and powered by four 150 kW solid-state amplifiers. Compared with SLS the nominal energy is increased from 2.4 to 2.7 GeV, while the nominal beam current is maintained at 400mA. Two beamlines are dedicated to beam diagnostics, and newly developed BPM and feedback systems continuously monitor and stabilize the beam. The linac and booster synchrotron received only minor modifications, with the exception of a new power supply for the main magnet circuit.

This paper outlines the main challenges encountered during the SLS storage ring upgrade and provides an overview of the performance achieved to date. Beam commissioning details are presented in a companion paper.

STORAGE RING DESCRIPTION

General Layout

The ring consists of 12 identical arcs (Fig. 1), arranged with threefold symmetry [1]. This configuration results in three different types of straight sections [2], with a combined total length of 83.6 meters. Four new 500 MHz RF cavities with higher-order mode (HOM) damping [3] are installed in sequence in the long straight section 05L (Fig. 1), while the two-cell passive superconducting third-harmonic cavity (inherited from the original SLS) is located in the long straight 09L. The final long straight section, 01L, is dedicated to beam injection.

Injection Scheme

The linac and booster from the original SLS were largely retained, with the exception of the electron source pulser and the AC power supply for the booster dipole magnets (1 kA max and 3 Hz). The booster increases the beam energy from 100 MeV to 2.7 GeV. The booster-to-ring transfer line and the ring injection system were mostly renewed.

In the injection straight (01L), four kickers create a bump that brings the stored beam within 3 mm of the injected beam (Fig. 2). The injected beam is first deflected by a permanent-magnet-based thick septum providing a 120 mrad bend, followed by a pulsed thin septum magnet that provides the last 15 mrad. The thin septum itself, consists of stacked foils with a total thickness of only 1 mm. A 2.6 kA current pulse generates the magnetic field to provide the required deflection.

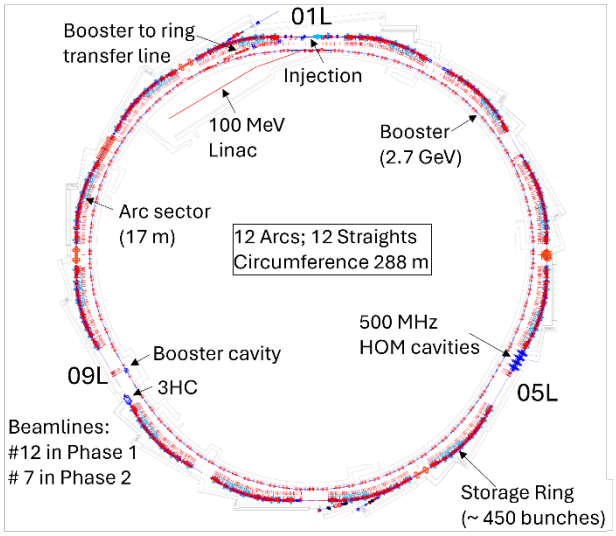


Figure 1: Overview SLS 2.0 ring and key components.

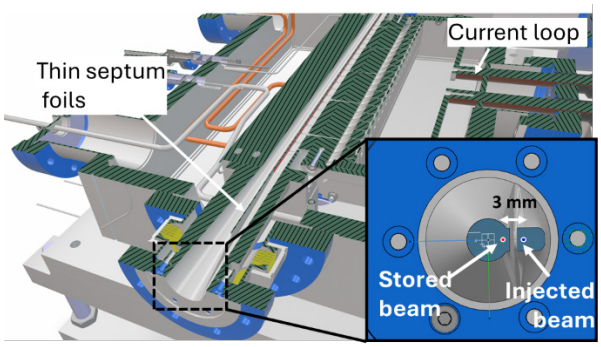


Figure 2: Drawing of thin septum.

During the initial commissioning, the injection in the ring was established very quickly but the booster-to-ring injection efficiency was hard limited to about 80%. This limitation was primarily caused by two misaligned vacuum components: a taper element located upstream of the third-harmonic cavity and a vacuum valve right after the thin septum. The issues were resolved in a recent shutdown.

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Dump and Collimators

A dedicated kicker magnet was installed to dump the beam in a controlled manner into a copper block upstream the thin septum [4]. The beam dump controller monitors all critical machine systems and, in the event of a fault, initiates a beam dump within 20 µs. The stored beam is then deflected toward a dedicated beam dump, where over 80% of the bunches are lost in the copper block. This scheme greatly reduces the chance of an uncontrolled beam loss that can increase the radiation dose at the permanent magnets around the machine. During normal operation, 50% of the electrons are lost in two collimator pairs (tungsten blocks) located in straight 05L and 09L and in the thin septum, the rest being lost in the ring. Measurements show that 1 Gy of gamma rays are produced near the copper dump for every dump event at 400 mA. In average, during this commissioning period, about 2 Gy of gamma per day were produced near the dump and the collimators' locations while less than 0.04 Gy/day were produced near the permanent magnets of an arc.

Magnet Lattice

The unit cell of the seven-bend achromat deflects the beam by 5 degrees [5]. It consists (Fig. 3) of a longitudinal gradient bend (known as the "triplet") and two reverse bends—all based on permanent magnets—as well as electromagnetic sextupoles and correctors.

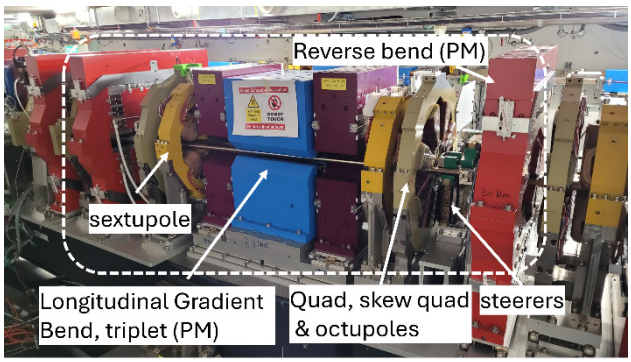


Figure 3: Magnets composing the unit cell (5° deflection) of an arc (PM=Permanent Magnet).

In total, 1019 magnets were measured at PSI for the completion of the ring [6]. Because permanent magnets produce large stray fields, careful simulation and measurement of magnetic cross-talk with neighboring magnets were required [7]. The longitudinal gradient bend magnets (triplet), composed of three independent parts, demanded positioning precision within 10 µm in order to achieve the required 0.2% accuracy in the dipole field integral. Fortunately, these C-shaped magnets, although they required more preparation time than initially planned, could still be installed after the vacuum chamber was already in place.

Cross-talk measurements, in combination with precise simulations of all neighboring magnet configurations, were essential for properly tuning the field integral (the field integral of permanent magnets is typically attenuated by 3–4% due to neighboring magnets). Simulated field values differed from measured ones by about 0.2%, necessitating fine-tuning of the shunt plate positions, in situ, for each reverse bend magnet.

Diagnostics

There are 115 beam position monitors (BPMs), and as many horizontal and vertical steering magnets, installed around the ring to ensure continuous orbit monitoring and stabilization [8]. Two front-end beamlines are dedicated to electron beam characterization by measuring the X-ray beam size [9]. One beamline is located in a low-dispersion region to measure the horizontal emittance, while the other is situated in a dispersion-dominated area to monitor the beam energy spread. Bunch length measurements are performed using a streak camera, which is also used to tune the third-harmonic cavity frequency. Two parametric current transformers (PCTs) measure the beam current and are also used to calibrate the BPM charge readings. The bunch filling pattern is monitored using both a BPM sum signal and a photodiode exposed to synchrotron radiation.

RING INSTALLATION

Operation of the original SLS ceased in October 2023, and dismantling of the old ring began immediately afterward. This process was completed within two months (Fig. 4). Installation of the new ring in the tunnel followed a defined sequence: first, the main cooling pipe—laid along the tunnel floor—was installed, followed by the cable trays for each arc sector. Next, the pre-assembled girders were brought into the tunnel. These girders, assembled with magnets in a separate building, were delivered to the SLS site with magnets already positioned to within 50 µm. After aligning the girders in the ring tunnel, the upper halves of the magnets were removed, and the C-shaped permanent magnets were shifted to the side to enable the installation of the 17-meter-long vacuum chamber strings (Fig. 5).

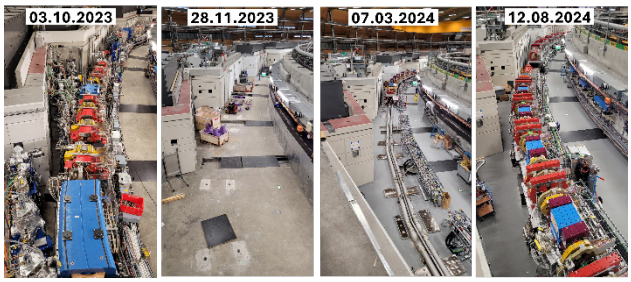


Figure 4: Snapshot of arc 09 area between October 2023 and August 2024.

The vacuum arc sections were pre-assembled in a clean room and each was subsequently transported in a vacuum oven to activate the non-evaporable getter (NEG) coating on the inner surface. The copper chamber strings, with a wall thickness of only one millimeter, were sufficiently robust to withstand crane transport while maintaining a vacuum pressure of approximately 1×10^{-11} mbar [10, 11].

Installation of all twelve arcs in the tunnel was completed by October 2024. The four 500 MHz RF cavities

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with high-order mode (HOM) damping were first conditioned on a test stand up to 600 kV and are operated at 440 kV for 400 mA beam current. They were then installed in the tunnel and connected to the new 150 kW solid-state amplifiers. This installation required venting the cavities, followed by a second conditioning phase. Fortunately, this reconditioning proceeded more quickly and could be carried out in parallel with other installation activities in the tunnel. In general, the straight sections were completed in the final months of 2024. These included the installation of five undulators from the original SLS ring, two pairs of collimators, and the passive third-harmonic cavity, which was also reused from the old ring.

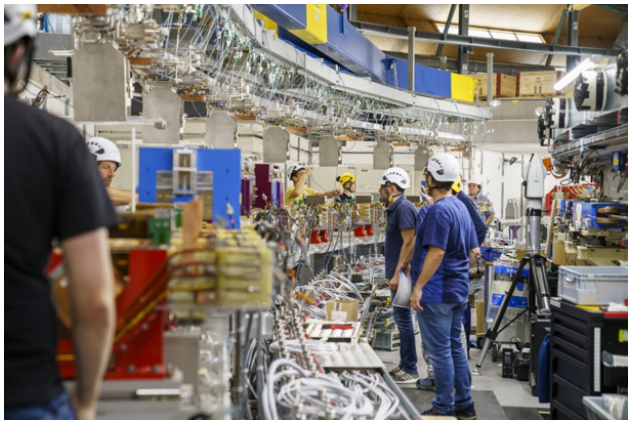


Figure 5: Installation of the vacuum chamber string into the magnets.

COMMISSIONING PHASE

Booster commissioning with the new dipole magnet power supply began in the week before Christmas 2024, and the nominal energy of 2.7 GeV was successfully achieved within a few days. Ring commissioning [1] started in the second half of January 2025, immediately after the installation of the thin septum. The first complete beam turn was achieved with minimal use of dipole corrector magnets, indicating that the tuning and alignment of the permanent magnets had been performed without major errors. Initially, a misaligned vacuum component prevented multi-turn operation. Once corrected, the first beam was successfully stored on January 23rd, using 3 out of the 4 RF cavities. The following month was focused on beam-based alignment and beam optics tuning at moderate current. While vacuum conditioning had already begun in February, a significant current increase was only possible in March 2025, after the commissioning of diagnostic instruments for monitoring potential instabilities.

The nominal beam current of 400 mA was reached at the beginning of April 2025, after delivering a total beam dose of 80 A·h, with an average vacuum pressure of 2×10^{-9} mbar (Fig. 6).

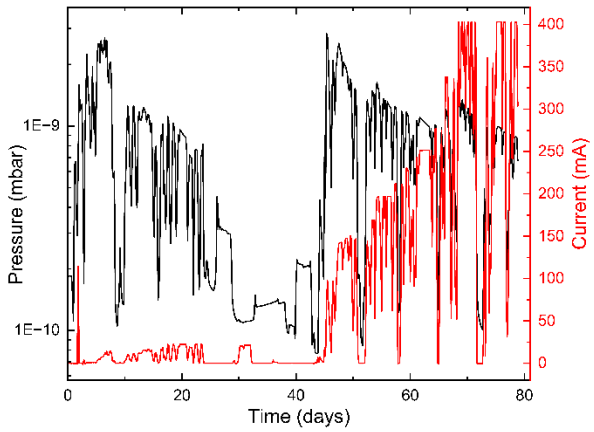


Figure 6: Evolution of the average pressure and beam current during the storage ring commissioning (January 25th to April 15th 2025).

The parameters achieved after three months of commissioning are summarized in Table 1. The main commissioning phase of the storage ring is nearly complete, and the focus has now shifted to the commissioning of the beamlines.

Table 1: SLS 2.0 Design and Achieved Parameters

Parameter	Design Value	Achieved in April 2025
Beam Energy	2.7 GeV	2.7 GeV
Current	400 mA	400 mA
Lifetime	9.5 h	8.5 h
Natural Emittance	158 pm.rad (w/o IDs)	?
Pressure at 400 mA	1.e-9 mbar	8.e-10 mbar
Injection efficiency	100%	100%
Beamlines in operation	19	2

In addition to the improvement in beam brightness, electrical power consumption has been reduced by 30%, thanks to the use of permanent magnets, efficient RF solid-state amplifiers, and state-of-the-art air and water cooling infrastructure. In the first half of 2026, a three month shutdown will enable the installation of two superconducting superbends (5 T peak field) in Arcs 01 and 02. This will increase the photons flux by a factor 5 and double the photon energy range for those beamlines.

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