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THE NEW SLS 2.0 BOOSTER-TO-RING TRANSFER LINE – DESIGN CRITERIA, DIAGNOSTICS LAYOUT AND FIRST BEAM RESULTS

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Abstract

Due to the limited transverse acceptance of fourth generation light sources, the characterization and control of the incoming beam from the booster to the storage ring is an important asset to achieve highly efficient and reproducible injection. For the upgraded Swiss Light Source (SLS 2.0) storage ring, a new booster-to-ring transfer line (BRTL) has been designed with a non-dispersive section for beam parameter measurements and a double-BPM-corrector configuration for position and angle feedback of the injected beam.

Based on the BRTL design criteria, first beam results during SLS 2.0 commissioning are presented, including experience with quadrupole scans to document emittance exchange at the end of the booster ramp and steering-stabilization of the beam at the injection point, resulting in a stepwise optimization of transmission into the storage ring.

INTRODUCTION

After 22 years of successful user operation with about 5000 h/year beam time for 18 user stations at excellent availability of 98.5 % and <1 µm rms photon beam stability in the front ends, the Swiss Light Source was upgraded to a modern diffraction limited light source. A regular 7-bend achromat lattice has been chosen for the new SLS 2.0 storage ring providing low horizontal emittance of 150 pm·rad, beam lifetime of ≈9 h at 400 mA and a sufficiently large transverse dynamic aperture to allow off-axis injection [1]. Together with the additional beam energy increase from 2.4 to 2.7 GeV, it results in a 60 times higher hard X-ray brightness (>10 keV), which will further be enhanced by new insertion devices with shorter periods and improved beamline optics. The variety of radiation sources ranging from period elliptic undulators to superconducting super-bends of up to 5 T peak field provides photon energy ranges from 6 eV to 80 keV for the users [2]. The 15 months "dark period" for storage ring exchange, beamline reconfiguration and infrastructure upgrades started in September 2023. By December 2024 the re-commissioning of the mostly unchanged injector consisting of the 100 MeV pre-injector LINAC and the 2.7 GeV booster synchrotron was accomplished without problems, allowing the start of storage ring commissioning in January 2025. All design parameters were achieved, by April 2025, so that beamline commissioning at full beam current could follow with first expert user operation for selected beamlines in July 2025.

BRTL DESIGN CRITERIA

For the limited dynamic apertures of fourth generation storage rings, the knowledge of beam parameters from the injector can be advantageous for achieving and keeping good injection efficiency, especially if manipulations like emittance exchange by coupling resonance crossing [3] are applied at the end of the booster ramp.

While the SLS injector remained so far unchanged (LINAC and linac-to-booster transfer line upgrades are foreseen during the shut-down periods in 2026), the geometric layout of the SLS 2.0 storage ring with a slightly moved injection point and the newly developed injection scheme consisting of a permanent magnet thick and a pulsed thin septum required a redesign of the BRTL. This remodeling presented the unique opportunity to integrate extended diagnostics capabilities for beam characterization and to implement full trajectory control (beam positions and angles) through the injection path.

In case of synchrotron light source upgrade projects, the disassembly of storage ring components offers a unique and cost-effective opportunity to re-use well proven and well characterized accelerator equipment (hardware and electronics) for the BRTL design. At SLS 2.0, we additionally benefited from the availability of spare parts from the former SwissFEL Injector Test Facility (SITF) [4] and integrated compact, high-gradient quadrupole magnets and combined diagnostics monitors, consisting of resonant stripline BPMs and screen monitors in the BRTL. Figure 1 shows a CAD overview with beam diagnostics, the main measurement locations and the steering capabilities indicated along the beam path. The insert provides a representation of the BRTL optical functions with a schematic illustration of magnets and diagnostics stations.

Since quadrupole scans for emittance measurements in dispersive regions turned out to be complicated and unreliable [5], a dispersion-free section was designed between the first and the second BRTL dipoles for a more accurate determination of beam emittance and Twiss parameters. The emittance scans are performed by four pairs of SITF quadrupoles (two each connected in series) and the related beam profiles are recorded at the location of screen monitor SCRM-1 (see Fig.1). This arrangement allows for the usual single-quadrupole scans, or a scan of multiple quadruples simultaneously to restrict beam size changes in both directions while varying the phase advance over an adequate range. The latter method is our preferred option, since it has proven to provide more robust results, due to better fitting of Gaussian distributed beam profiles. The SCRM-2 screen monitor has been placed at the location of maximum dispersion to determine the energy distribution of the beam from the booster synchrotron. At the same location, BPM-4 (as part of the combined diagnostics station) is used for online monitoring of the beam energy stability. Full trajectory control of the injected beam into the storage ring has been obtained by placement of two beam position monitors

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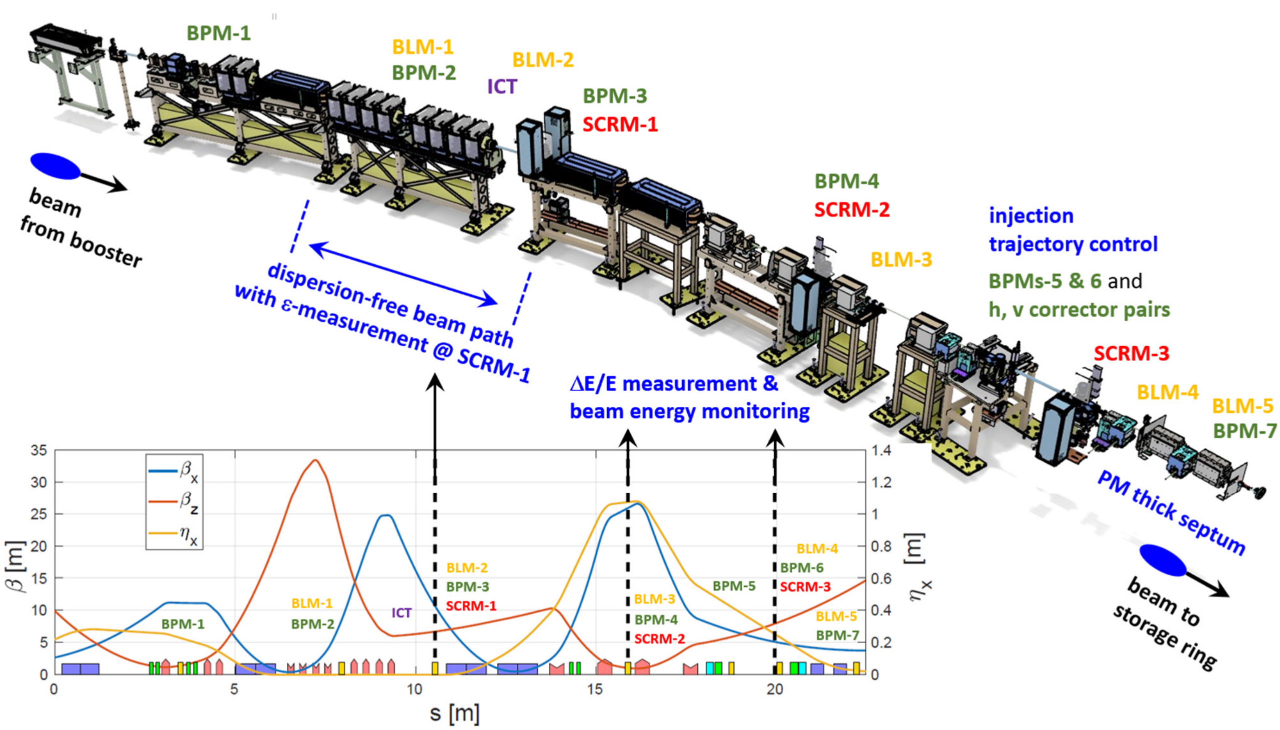

Figure 1: CAD overview drawing of the new SLS 2.0 BRTL with indication of diagnostics monitors and locations of beam measurement stations. The insert on the lower left shows the BRTL optical functions. Magnets are symbolized by squares (blue = dipoles and septa, red = quadrupoles, cyan and green are horizontal and vertical correctors).

and a pair of horizontal and vertical corrector magnets in front of the storage ring injection channel, where a novel concept has been followed, by combining a “thick injection septum” consisting of two permanent magnet (PM) dipoles with a DC electromagnet in the middle for adjustments with a pulsed thin septum with a 1 mm blade made from copper and mu-metal in a layered configuration. The approximately 1.5 m distance between BPMs 5 and 6 and the two corrector pairs provide independent control of beam position and angle along the injection channel. A compact button-type “witness BPM” (BPM-7) has been added as integral part of the thick septum chamber close to the injection point into the storage ring. Beam loss monitors (BLM) have been placed behind the booster extraction and storage ring injection septa, behind the bending magnets and at the location of highest dispersion in the BRTL. An integrating current transformer (ICT) is used to measure the beam charge and to determine the overall transmission from the injector to the storage ring by comparison with all other charge and current monitors throughout the accelerator.

BRTL DIAGNOSTICS

The SLS 2.0 injector is operated in single bunch mode with bunch charges as low as 10-100 pC for topping up and up to 800 pC for fast and efficient filling of the storage ring. The BRTL diagnostics systems profited from SwissFEL beam instrumentation developments, which were targeted on high dynamic ranges and excellent single-shot resolution at low beam charges. The monitors are briefly described in the following passages. Detailed hardware and electronics concepts can be taken from the references.

Beam Position Monitors

Resonant stripline BPM pick-ups were developed for the SITF at PSI [6] and have been installed in the BRTL as a cost-effective alternative to cavity BPMs. Their resonant frequency is tuned to 500 MHz so that it matches the newly developed SLS 2.0 BPM system [7]. With their geometric factors k_x and k_y of 16.2 mm, single-shot RMS noise of 50 µm are obtainable for typical top-up bunch charges, which provides good trajectory control in the BRTL and in the storage ring injection channel.

Screen Monitors

Three screen monitors [8] are installed along the BRTL. They serve as “beam finder” during the (early) commissioning phase and can be used for transverse emittance measurements (SCRM-1) and the determination of the beam energy spread (SCRM-2). They are equipped with Ce:YAG crystals and OTR screens, which are inserted in the beam by pneumatic actuators and provide excellent spatial resolution of <10 µm at 20 mm field-of-view.

Beam Loss Monitors

Five cost-effective CMOS based BLMs [9] are used for beam loss detection along the BRTL. The light pulses, which are induced by beam losses in a scintillating block, are transferred via duplex plastic optical fibers to a single CMOS camera for signal readout. In this way, a maximum of 28 channels, of which only 5 are used for the BRTL beam loss detection, can be measured during the CMOS camera exposure time of 300 ms, which is sufficient for

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detecting beam losses in the BRTL during each of the 3 Hz injection cycles.

COMMISSIONING RESULTS

Emittance Measurements

Careful orbit and tune corrections along the booster ramp resulted in excellent (>90 %) transmission through the injector into the BRTL. The determination of transverse beam parameters, which allows the adjustment of the downstream optics for matching storage ring injection was achieved by quadrupole scans in the non-dispersive part of the BRTL as shown in Fig. 2. The measurements resulted in ε_x = 14 nm·rad / ε_y = 1.1 nm·rad without emittance exchange and ε_x = 4.8 nm·rad / ε_y = 11.3 nm·rad with emittance exchange. Corresponding beam images on screen monitor SCRM-1 are shown in Fig. 3.

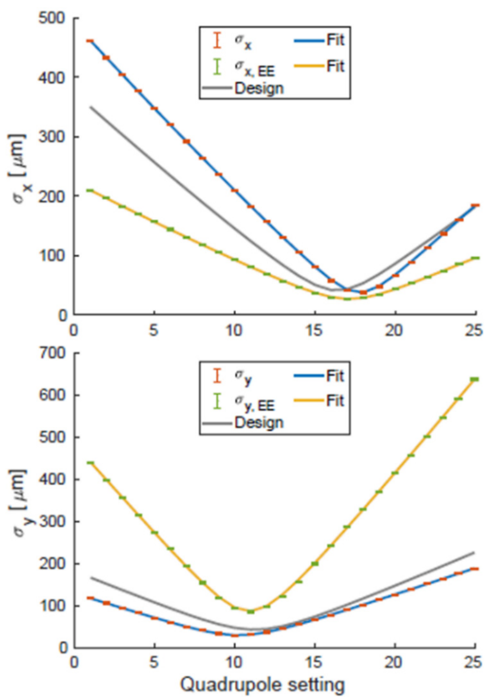

Figure 2: Horizontal (top) and vertical (bottom) quadrupole scans at the non-dispersive BRTL SCRM-1 with and without emittance exchange (EE).

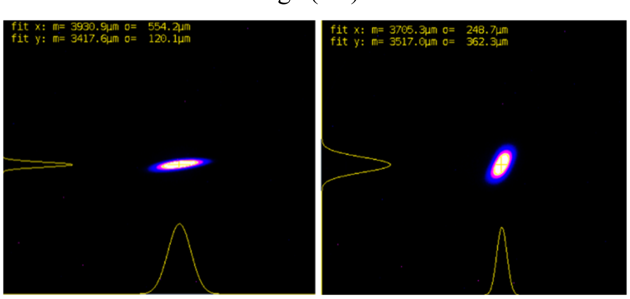

Figure 3: Beam images taken at BRTL SCRM-1 with (right) and without (left) emittance exchange.

Energy Spread Measurements

Based on the optical functions, which were taken from the emittance measurements, the beam optics model predicts a dispersion η_x of 1.07 m at the location of the BRTL SCRM-2 screen monitor. Beam energy scans of the booster resulted in a fairly consistent value of η_x = 1.15 m. By knowing the beam emittance and the propagated beta-functions, the energy spread can be determined as

$$\sigma_\delta = \sqrt{\frac{\sigma_x^2 - \beta_x \varepsilon_x}{\eta_x^2}} \tag{1}$$

From the beam profile measured at SCRM-2, an energy spread of $9.4 \cdot 10^{-4}$ was deduced, which is similar to the nominal booster energy spread of $8.4 \cdot 10^{-4}$.

Injection Control and Transmission

Matching from the BRTL to the storage ring was set up according to the beam parameter measurements and the optics model. The beam transport through the injection channel could be optimized with the set of horizontal and vertical correctors in front of the thick septum, leading to first turns in the storage ring and only shortly after to stored beam. The high sensitivity of all BRTL diagnostics components allowed the limitation of the single bunch charge to 10-20 pC during the early commissioning phase for protection of the PM thick septum and the PM magnets in the storage ring by radiation-induced damage.

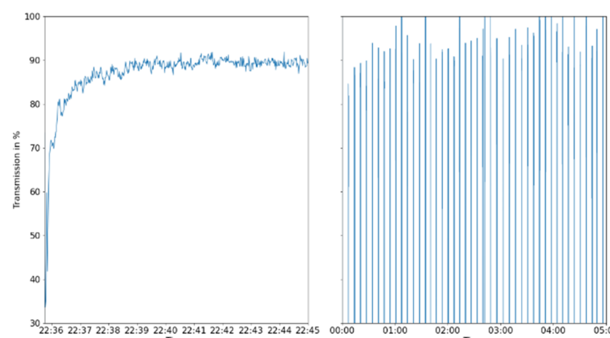

Figure 4: Optimization procedure of transmission through BRTL by using the set of horizontal and vertical correctors in front of the thick septum (left side). Transmission from booster to storage ring during the following user run in top-up operation mode (right side).

After completion of storage ring commissioning, an overall transmission from booster through the BRTL of typically ≥95 % has been reached and a variety of bunch charges can be selected by the operators, depending on the filling mode (fast filling or top-up) and filling pattern (uniform or camshaft) in the storage ring. Figure 4 shows a 90 % transmission from booster to storage ring after an optimization procedure during storage ring filling (left side) and the typical ≥95 % transmission during top up user operation (right side). This slightly improved transmission is due to the warm-up of the storage ring at 400 mA with orbit feedback running. With the stable operation of the SLS injector chain, no active feedbacks have been implemented in the BRTL so far. Further details on the SLS 2.0 storage ring commissioning are given in [10].

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