ISBN: 978-3-95450-236-3 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2023-MO3C03

DEVELOPMENT OF THE SLS 2.0 BPM SYSTEM

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Abstract

After more than 20 years of operation, the storage ring of the Swiss Light Source (SLS) will be replaced. The new ring called SLS 2.0 will have 40 times higher brilliance, thanks to an innovative low-emittance magnet lattice and a beam pipe with smaller aperture. For SLS 2.0, the ageing SLS RF beam position monitor (BPM) electronics will be incrementally replaced for the whole accelerator, including linac, booster, transfer lines and storage ring. This contribution presents the development status and latest prototype test results of the SLS 2.0 BPM system, including pickups, mechanics, and electronics.

INTRODUCTION

Machine and Beam Parameters

Table 1 shows the parameters of the SLS 2.0 [1] compared to the present SLS ("1.0") ring. The nominal beam energy for user operation will be slightly increased from 2.4 GeV to 2.7 GeV, which is already supported by the SLS 1.0 full energy booster synchrotron that is re-used for SLS 2.0, as well as the linac and linac-to-booster transfer line. The booster-to-ring transfer lines will be modified, including a new magnet lattice and additional BPMs for improved control of the more critical injection process.

Table 1: SLS Storage Ring Beam Parameters

Parameter	Units	SLS 1.0	SLS 2.0
Circumference	m	288	
Beam Current	mA	400	
Injection Charge	nC	~0.15	
Beam Energy	GeV	2.4	2.7
Main RF	MHz	499.637	499.654
Harmonic No.	#	480	
Hor. Emittance	pm	5030	131-158
Vert. Emittance	pm	5-10	10
Ring BPMs	#	75	136

BPM REQUIREMENTS AND TYPES

Table 2 shows the BPM requirements for the SLS 2.0 storage ring, with an expected minimal beam size of $\sigma \geq 5$ µm at the BPMs, where <0.05 µm desired electronics RMS noise from 0.1 Hz to 1 kHz translates to 1% of this beam size. Like SLS 1.0, SLS 2.0 will operate in top-up injection mode at 400 mA with typ. 2-3 mA (max. 4 mA) periodic current variation within a few minutes. 430-460 of 480 successive RF buckets are typically filled with approximately the same charge, with ~10% charge variation between buckets, excluding an optional so-called "cam-shaft" bunch in the bunch gap with ~3-5 times higher charge. For the linac, booster and transfer lines operated with single bunches of ~0.15 nC at 3 Hz injection rate, the position resolution requirement is also <50 µm, aiming at <10 µm/week long-term drift of the averaged position readings in the booster-to-ring transfer line for negligible variations of bunch charge transfer efficiency to the ring.

Table 2: SLS 2.0 Storage Ring BPM Position Measurement Requirements

Parameter	Goal
RMS Noise, 0.1 Hz-1 kHz, 400 mA	0.05 µm
RMS Noise, 0.1 Hz-0.5 MHz, 400 mA	1 µm
RMS Noise, 1 Bunch, 0.15 nC	50 µm
Electronics Drift (400 mA Top-Up)	0.1 µm/h 0.4 µm/week 1 µm/year
Overall Drift (incl. Cables/Mechan.)	0.25 µm/h 1 µm/week 2.5 µm/year
Beam Current Dependence	0.02 µm/mA

Table 3: SLS 1.0 / 2.0 BPM Types

Location	Type	geom. factors kx/ky [mm]
Linac & Transfer Lines	Resonant Stripline	various
Booster	Button	8.3/7.7
SLS 1.0 Ring	Button	16.7/14.3
SLS 2.0 Ring	Button	7.1/7.2

Table 3 shows a list of BPM types used in SLS. Booster and storage ring have button BPMs with four diagonal electrodes. Linac and transfer lines have so-called resonant stripline BPMs, generating a decaying 500 MHz sine signal which can be processed by the normal storage ring BPM electronics also working at 500 MHz. The beam position is calculated by the BPM electronics from the button/stripline signal voltage amplitudes A, B, C and D (upper outer, upper inner, lower inner and lower outer button/stripline) for the horizontal (X) and vertical (Y) plane with the common approximation formulas

$$X = k_x * (A-B-C+D)/(A+B+C+D)$$
$$Y = k_y * (A+B-C-D)/(A+B+C+D)$$

Storage Ring Beam Pipe

Figure 1 shows the cross section of the SLS 1.0 storage ring beam pipe in blue and the smaller SLS 2.0 pipe in orange. The latter has an octagonal shape, usually with 18 mm aperture. While the SLS 1.0 pipe is made of stainless steel, SLS 2.0 uses a NEG-coated copper pipe. However, at the BPMs and their adjacent horizontal and vertical orbit corrector dipole magnets, the pipe is made of stainless

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steel, with, with a ~5 µm copper coating (to reduce impedance) and ~0.5 µm NEG coating like in the surrounding solid copper pipe, where the button electrodes are only NEG coated but not copper coated.

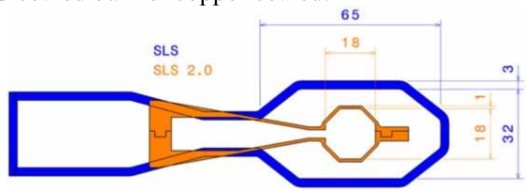

Figure 1: SLS 2.0 beam pipe (yellow) compared to the previous SLS pipe (blue), with dimensions in [mm].

BPM MECHANICS

The inner beam pipe aperture at the SLS 2.0 BPMs and correctors is tapered from the nominal 18 mm to 21 mm, thus shielding BPMs and correctors from synchrotron radiation, reducing beam-induced temperature variations and mechanical position drift (see Fig. 2).

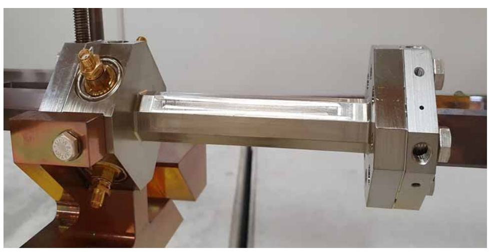

Figure 2: SLS2 BPM storage ring block with corrector magnet beam pipe.

The combined BPM/corrector beam pipe block has flanges to the surrounding copper beam pipe, and a dedicated rigid mechanical support for the BPM block, aiming at keeping the BPM position stable, while the softer surrounding copper pipe can float. The SLS 2.0 storage ring will have 136 BPMs overall. 115 of them have an adjacent horizontal and vertical corrector magnet to be used by the global fast orbit feedback (FOFB). The beam pipe at the corrector magnets is only 0.5 mm thick, compared to 2 mm for SLS 1.0, reducing eddy currents and improving the FOFB bandwidth.

The mechanical supports of the BPM blocks are double steel plates with a sealed compound of balsawood and viscoelastic glue in between that damps vibrations. The upper part of the BPM support is a water-cooled copper alloy block (CuCrZr), aiming at reducing the beam-induced temperature variation and thus thermal drift of the BPM block when the ring is filled from 0 mA to 400 mA. The expected remaining beam-induced power dissipation for the combined BPM/corrector beam pipe is ~2.6 W due to stray synchrotron radiation, and ~1 W losses due to the beam pipe impedance, assuming 400 mA and 9 ps worst-case bunch length (that is several times larger during normal user operation). Additional temperature sensors will enable feed-forward correction of any remaining temperature-induced position drift of the BPM block.

Button Electrode Design

Figure 3 shows the cross section of the SLS 2.0 storage ring button BPM at one electrode (left) and the button electrode before insertion into the steel BPM block (right). The electrode (red) with 6.5 mm diameter and 0.25 mm gap to the BPM block is round and symmetric towards the beam pipe surface, with a radial asymmetry of the part going through the borosilicate glass dielectric (dark blue), thus suppressing higher-order modes (HOMS) in the electrode. The TIG welding of the buttons into the BPM block is done at the upper side between the steel (grey) and outer button (light blue) body that is also made from steel. The electrode has an SMA male connector (red/orange/yellow), where a female-to-female connector is screwed from the outside, using RF cables with SMA male connectors.

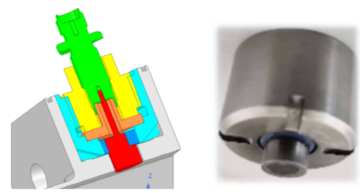

Figure 3: SLS 2.0 storage ring button BPM electrode.

While the SLS 1.0 storage ring BPMs use Molybdenum button electrodes with brazed Al_2O_3 dielectric, the SLS 2.0 ring will have Inconel® electrodes with a borosilicate glass dielectric. Although Molybdenum has better thermal and electrical conductivity, we chose Inconel for several reasons. Firstly, the Swiss company that produces the buttons (designed by PSI) uses Inconel for nearly all their other borosilicate glass feedthroughs, mainly for non-RF industry applications in harsh environments, with proven mechanical robustness. Secondly, simulations showed that the expected Inconel button temperature for worst-case SLS 2.0 beam conditions (400 mA, 9 ps bunch length, 3rd harmonic cavity inactive) is 51.8 °C (for ~0.4 W power dissipation per button), which is only 11 °C higher than Molybdenum. The resulting simulated mechanical stress of the borosilicate glass is only 15% higher and well below any critical threshold. Last but not least, we exposed buttons in the lab to thermal stress (much higher than during production, beam operation and bake out procedures) without causing any vacuum leaks.

Production Status and Offset Measurements

About 25% of the BPM blocks have been produced so far, and one of twelve sectors of the SLS 2.0 beam pipe has been assembled, including 12 BPMs, where all BPMs passed all vacuum tests. The button electrodes were sorted by their transfer impedance which was measured before welding, thus reducing the resulting position offset from tens of microns without sorting to typically <1 µm with sorting. In addition, we estimated the beam position offset after welding using the Lambertson method, where the RF asymmetry of the BPM electrodes and general geometry is measured with a 4-port RF network analyzer. Combined with future pre-beam calibration of RF cables and BPM electronics, we aim for an overall position offset uncertainty of < 100 µm for SLS 2.0 beam commissioning.

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BPM ELECTRONICS

The SLS 2.0 BPM electronics is based on the so-called DBPM3 platform that was developed at PSI and is already used for cavity BPMs at SwissFEL [2]. The platform has a generic back-end with a Xilinx/AMD Zynq UltraScale+ (ZynqU+) MultiProcessing System-on-Chip (MPSoC), combined with accelerator-specific RF front-end modules (RFFEs) with integrated ADCs. The RFFEs are inserted at the rear side of the 19” DBPM3 unit (see Fig. 4). The MPSoC has a 2-core 32-bit CPU (“RPU”) for real-time signal processing in addition to the programmable logic (PL) of the chip, and a 4-core 64-bit CPU (“APU”) running Linux and an EPICS7 IOC for easy control and readout of the BPM system.

Figure 4: DBPM3 BPM electronics unit for SLS 2.0 with front-to-rear ventilation, redundant fans, and redundant power supply.

RF Front-End and ADC

For SLS 2.0, each DBPM3 unit has three RFFEs, one per BPM. Figure 5 shows a simplified block schematics of the RFFE. It has four SMA beam signal inputs, as well as an SMA output providing two mono-frequent “pilot tone” signals with adjustable frequencies and amplitudes.

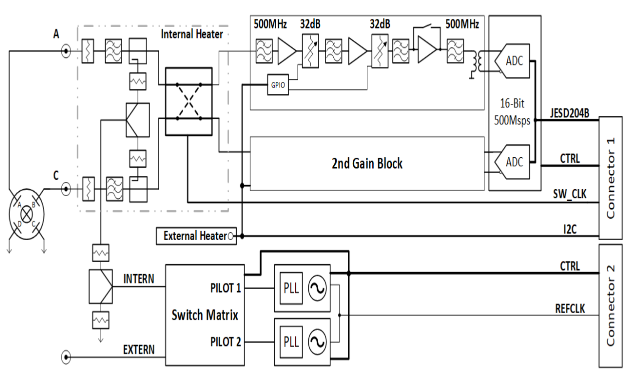

Figure 5: DBPM3 RF Front-End electronics with integrated 2-channel 16-bit 500 MS/s JESD204B ADC.

The pilot signals will be recombined with the four SLS 2.0 BPM beam signals close to the beam pipe, using a so-called “pilot combiner box”, with four ~2 m long RF cables from the pickup to the pilot combiner box, and five 20-36 m long RF cables from the pilot combiner box to the electronics racks: One cable delivers the pilot tone from the DBPM3 unit to the pilot combiner box, and four cables with the combined beam/pilot signals go back to the DBPM3 unit in the electronics racks located in the SLS technical gallery. This setup enables pilot-tone-based compensation of beam position drift and low-frequent noise caused by cables and electronics. The DBPM3 RFFE performs low pass and bandpass filtering and amplification/attenuation with 63 dB overall dynamic range for the incoming beam/pilot signals. In addition to the support of an external beam-pilot signal combiner, the DBPM3 RFFE also has an additional internal beam-pilot signal combiner on the RFFE PCB, close to the SMA inputs. The user can select for each of the two generated pilot tones if it goes to the internal combiner (used e.g. for pre-beam tests and calibration of the electronics after production), or to the external combiner, or both. The DBPM3 RFFE also has two 2x2 crossbar switches close to the SMA beam signal inputs, where the switch swaps the RFFE channels used for the input signals of opposite BPM button electrodes. This enables suppression of gain asymmetries and drift of the RFFE channels by sufficiently fast switching (and digital uncrossing of ADC output signals in the ZynqU+).

ADCs and Digital Signal Processing

The present DBPM3 RFFE prototype for SLS 2.0 uses two dual-channel 16-bit 500 MSPS JESD204B ADCs. Digital down-converters (DDCs) in the ZynqU+ MPSoC process the beam and the two pilot signals simultaneously in separate DDC channels. The DDC, implemented at PSI, decimates and lowpass filters the ADC data in three successive stages with decreasing data rates and bandwidth. For the tests presented in this paper, we used an ADC sample rate of ~433 MSPS, thus enabling an integer fraction of ADC samples both for the storage ring and booster that have slightly different revolution frequencies. The ADC data was decimated to ~1 MSPS (beam revolution frequency) with ~0.5 MHz bandwidth, to 20 kSPS with 3.3 kHz bandwidth, and to 20 SPS with 11 Hz bandwidth. The DDC data rates, filters and filter bandwidths can be reprogrammed during operation using a Python GUI.

Drift Suppression

The ZynqU+ provides beam position readings calculated only from the beam signal (representing the real beam position in the accelerator), from the pilot signals (result is ideally zero, with a small offset mainly due to electronics and cable drift), and from the difference of both. This difference represents the beam position, but suppresses measurement errors caused by drift of the insertion loss / gain of each BPM channel, including all components downstream of the beam/pilot signal combiner, including the ADCs. The 2x2 crossbar switches serve the same purpose, thus supporting two different methods of drift suppression. The pilot tones provide the additional benefit of including RF cable induced drifts. It also enables easy pre-beam tests and calibration of the cables before 1st SLS beam, as well as monitoring cable attenuation and general health during beam operation and after maintenance shutdowns.

In addition to these active drift suppression approaches, we plan to sort all SLS 2.0 BPM RF cables from beam pipe to electronics by measured time of flight (TOF) and attenuation, and then install cables with similar TOF and attenuation for each BPM. Combined with a common thermal isolation of these cables, we thus aim at reducing cable-

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induced beam position drift by equalizing cable properties and related drift for each BPM.

BEAM TEST RESULTS

Booster and Transfer Lines

We tested the DBPM3 electronics in the SLS 1.0 booster that has similar BPM signal level and geometry factor like the SLS 2.0 storage ring. The measured turn-by-turn single bunch turn-by-turn position resolution was <40 µm RMS at 0.15 nC, thus meeting our goal of <50 µm for booster and SLS 2.0 ring. For the SLS 1.0 transfer line resonant striplines, we measured <10 µm single bunch resolution at 0.15 nC, thanks to the larger signal levels and matched signal spectrum. We improved the single-bunch noise performance by feeding only ADC data near the beam signal peaks into the DDCs, zeroing all other ADC samples near the noise level (not using pilot tones here). This optional function is implemented in programmable logic and can run continuously at the full ADC sample rate, with adjustable signal level and pre-/post peak sample counts, thus improving position resolution for all DDC decimation stages of the booster BPMs.

Storage Ring

For tests of the new DBPM3 electronics with the SLS 1.0 storage ring beam, we installed a DBPM3 unit with two RFFEs in a prototype SLS 2.0 rack that is water-cooled and has an active temperature stabilization. The RFFEs received signals from two unused SLS 1.0 storage ring BPMs, where their four button signals were going to a 4x RF combiner. The sum signal was then combined with the pilot output signal of a DBPM3 RFFE. The combined beam/pilot signal was split 4 times to the four signal inputs of the RFFE, using only short (<20 cm) cables for our first tests to characterize the electronics alone. This setup simulates a centered beam with a signal spectrum similar to the real SLS beam (at ~400 mA beam current and the usual bunch filling pattern). We used the SLS 2.0 storage ring geometry factors to calculate the beam positions. So far, we only used one pilot tone, with a frequency offset of 0.531 MHz (0.5 times the beam revolution frequency of 1.04 MHz plus 10 kHz) above the beam signal frequency of ~499.637 MHz. The ADC sample rate was ~433 MS/s, the crossbar switching frequency ~130 kHz, both synchronized to the accelerator main RF. As shown in Figs. 6 and 7, the measured noise and 24 hour drift of the present DBPM3 prototype meets SLS 2.0 requirements.

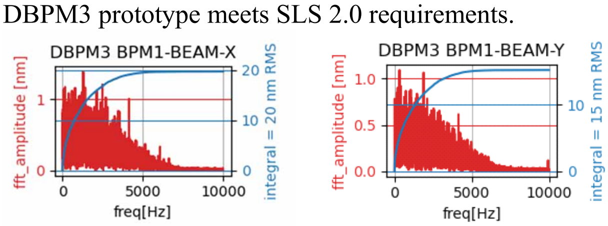

Figure 6: 20 nm horizontal (X) and 15 nm vertical (Y) RMS beam position noise of DBPM3 (0.001-3.3 kHz bandwidth, 50% ADC full scale, one pilot tone active, same signal level as beam signal).

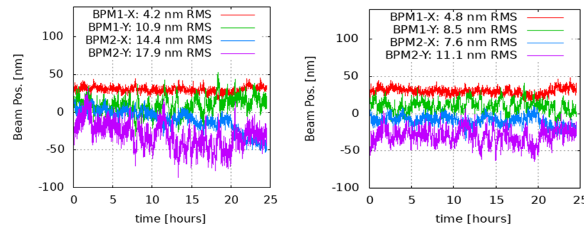

Figure 7: Horizontal and vertical beam position drift of two DBPM3 RFFEs (11 Hz bandwidth) over ~24 hours, using the pure beam signal (left side, no pilot-based drift suppression), and the pilot subtracted from the beam signal position (right side), with one data point every ~30 seconds.

SUMMARY AND OUTLOOK

The SLS 2.0 BPM system design and first electronics prototype test results at SLS 1.0 were presented. The present basic ZynqU+ firmware and software will be extended, supporting presently unused hardware features like the integrated temperature regulation of the RFFEs using 14 heating zones. The signal processing will also be improved, including the digital suppression of crossbar switching noise and balancing of signal levels and phases of the different RFFE channels. Long-term measurements with larger quantities are needed to investigate if the performance of present prototypes is reached reliably for every single BPM and large quantities over longer time scales, where only two prototypes of the latest RFFE version were available during two weeks for the results presented in this paper.

The "dark time" during which SLS 1.0 is replaced by SLS 2.0 starts 1.10.2023. For 1st SLS 2.0 beam in January 2025, we will equip only the SLS 2.0 ring mainly with the present 1st generation of DBPM3 electronics, keeping the old SLS 1.0 DBPM1 electronics for linac, booster, transfer lines and some uncritical ring BPMs. We intend to install a 2nd DBPM3 generation in the ring during a 2nd shorter dark time in Q1/2026, then moving the 1st generation to the linac, booster and transfer lines, thus finally replacing all DBPM1 systems. This incremental upgrade is aiming to reduce risks and get experience with production and operation of DBPM3 gen. 1, allowing to improve and optimize DBPM3 gen. 2 for highest ring performance.

ACKNOWLEDGEMENTS

The authors would like to thank all contributing colleagues from the SLS 2.0 project team for their support with the design, production, procurement, installation and test of the mechanical and electrical BPM system components and related infrastructure.

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