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Commissioning of the Swiss Light Source

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COMMISSIONING OF THE SWISS LIGHT SOURCE

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Abstract

The Swiss Light Source SLS at PSI has started user operation by August 1, 2001. Here we report on the status of commissioning by September 2001: Linac and booster are operational at design performance. The storage ring commissioning has reached the essential design parameters by June 2001: Energy, emittance, current and lifetime according to specifications have been achieved. Top-up injection and transverse multi-bunch feedback are operational. Ongoing commissioning activities concern suppression of an instability, which is probably related to ion trapping, and minimisation of emittance coupling.

1 INTRODUCTION

The Swiss Light Source SLS is a national synchrotron radiation user facility for Switzerland. Main component of SLS is the storage ring of 288 m circumference, providing an emittance of 5 nm·rad at 2.4 GeV. A novel type of 3 Hz low emittance low power booster synchrotron of 270 m circumference mounted onto the inner wall of the storage ring tunnel, and a commercial 100 MeV linac serve as injector. An initial set of four insertion devices consists of the high field wiggler W61 for materials science, the in vacuum undulator U24 (on loan from Spring-8) for protein crystallography, the electromagnetic twin undulator 2×UE212 for surface interface spectroscopy and the Apple type twin undulator 2×UE56 for surface interface microscopy.

The SLS project started by end of 1991. Until September 1993 a conceptual design report had been elaborated. After funding of the project by the Swiss Government in June 1997, construction started and the new building was finished by June 1999. Commissioning of linac and booster synchrotron concluded by April, resp. July 2000. First beam in the ring was stored at Dec.15th, 2000. By June 2000 the design current of 400 mA was reached and first top up injections were performed. At July 11th, diffraction patterns of the first sample were measured at the protein crystallography beamline. Since August 1st, SLS is operating to 70 % for users. Further commissioning activities concern beam characterization and optimization, system integration and establishment of standard procedures for operation.

The total budget of SLS amounts to 159 MCHF, not including salaries, split into 63, 92 and 28 MCHF for the building, the accelerators and the first four beamlines.

2 THE SLS STORAGE RING

The SLS storage ring is a 12 TBA (8°/14°/8°) lattice with six short straights of 4 m length, three medium ones of 7 m and three long ones of 11 m. Four cavities of 650 kV peak voltage occupy two short straights, injection occupies one long straight. Two short straights accommodate the insertion devices U24 and W61, whereas 2×2UE56 and 2×UE212 require a medium, resp. a long straight.

The lattice is designed to provide an emittance of 5 nm·rad at 2.4 GeV with dispersionfree straights and an effective emittance of ≈ 4 nm·rad when allowing some dispersion. 174 quadrupoles with independent power supplies grouped into 22 soft families allow precise lattice adjustments (beam based alignment, gradient corrections etc.), 120 sextupoles in 9 families are carefully balanced to provide large dynamic apertures. Each 72 horizontal and vertical correctors and 72 BPMs control the orbit, 6 skew quadrupoles in 3 families suppress coupling. Figure 1 and table 1 show lattice functions and list basic parameters of the optics presently used. The concepts for storage ring dynamic alignment involving girder movers and various position monitoring systems are described elsewhere [1].

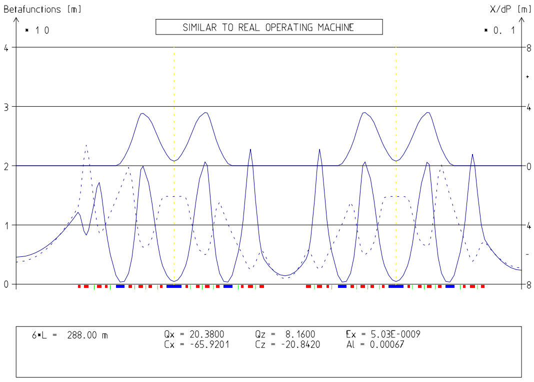

Figure 1: SLS storage ring optics (βx solid, βy dotted). One sixth of the ring is shown (L/2–TBA–S–TBA–M/2)

Energy	2.4	GeV
Circumference	288	m
RF frequency	500	MHz
Tunes	20.38/8.16	
Natural chromaticities	-66/-21	
Momentum compaction	$6.5{\cdot}10^{-4}$	
Radiation loss per turn	512	keV
Damping times	9.0/9.0/4.5	ms
Emittance	5.03	nm· rad
Energy spread	$8.6{\cdot}10^{-4}$	
Bunch length	4	mm

Table 1: SLS storage ring parameters

Lattice calibration

Since all 174 quadrupoles at SLS are equipped with individual power supplies, it was straightforward to measure the betafunctions at each quadrupole from tune variation. The rms measurement error was 1.5 % horizontally and 1.0 % vertically. Individual quadrupole gradient errors were fitted to the measurements using an SVD procedure. The inverse of these errors was added to the gradients and the betafunctions were measured again. Eventually the rms deviation of measured to design betafunctions achieved was only 5 % in the horizontal and 2.8 % in the vertical, using 22 from the 174 SVD eigenvalues.

Several circumference measurements based on orbit correction or sextupole centering by variation of RF frequency confirmed the design value within 0.5 mm. Linear coupling as determined by closest tune approach was found to be $\kappa = 0.007$ without, and $\kappa = 0.001$ with excited skew quadrupole correctors. For the rms value of spurious vertical dispersion after closed orbit correction we measured 5 mm. From these values we estimate an emittance ratio of $\approx 4{\cdot}10^{-3}$. However this does not yet agree with the direct beamsize measurement by means of a pinhole array as shown in figure 2: Based on precise knowledge of betafunctions and horizontal dispersion at the source point and assuming a vertical dispersion of 1 cm, values of 1.5 % obtained for the emittance ratio and $1.4{\cdot}10^{-3}$ for the energy spread need further investigation. At least, the measurements of the horizontal emittance and synchrotron radiation opening angle agree perfectly with theory.

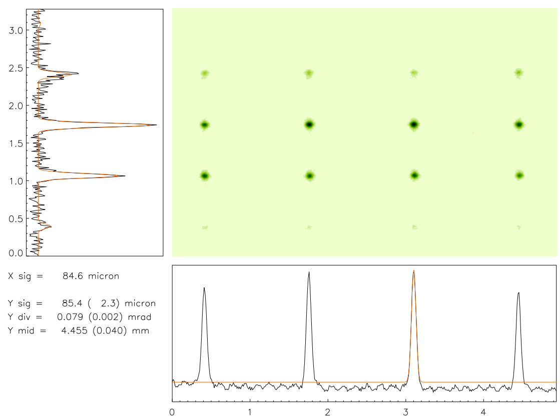

Figure 2: Beam image from pinhole array at 16 keV.
The envelope of the vertical profile shows the radiation opening angle of 80 µrad.

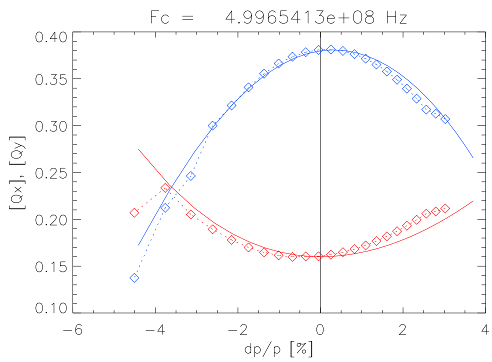

Figure 3: Fractional tunes as a function of relative momentum deviation. A frequency variation of +10/-12 kHz translates into a momentum deviation of -4.7/+3.0 % due to the large non-linear momentum compaction. The solid curves show the TRACY [14] simulation, the diamonds the measurements, upper curve (blue) is horizontal.

The machine obviously prefers a working point around 20.38/8.16 deviating from the design 20.82/8.28 but providing almost equal emittance. The tuning range is quite large: In the horizontal the integer 20 can be approached to 0.05, the half integer 20.5 to 0.005. The non systematic third integer

20.33 has to be crossed quickly in order to keep the beam. In the vertical the integer 8 can be approached by 0.01. The beam is not lost on the half integer 8.5 but shows some stochastic motion indicating a rather narrow resonance and stabilization due to detuning. The chromaticities were moved by design from the natural -66/-21 to +1/+1 and found to be +1.6/+0.5 actually. The variation of tune with momentum deviation shows excellent agreement with theory as shown in figure 3.

Tools for closed orbit correction were installed within the CORBA based software environment integrating CDEV and TRACY servers [2]. Iterative orbit correction and RF frequency adjustment succeeded in rms BPM readings on a few micron level, which also indicates the excellence of the digital BPM system [3]. Calibration of BPM centers relative to adjacent quadrupoles by means of beam based alignment has just been started [1].

Current limitations

When increasing the current towards the design value of 400 mA, several problems had to be overcome: Higher order modes (HOMs) in the four cavities had to be detuned by means of cavity temperature variation and the HOM frequency shifters in order not to coincide with the beam spectrum [4]. However, independently from the cavity HOMs a vertical multi-bunch oscillation occurs beyond some threshold current (threshold defined as current where the betatron peaks in the beam spectrum amount to 50 dB of the revolution peaks). In normal operating mode with both chromaticities set to +1 and uniform filling pattern, the threshold current is as low as 25 mA, but increases steeply with vertical chromaticity.
Recent observations support the assumption, that the instability is related to ion trapping:

- A gap of ≥100 buckets in the filling pattern dramatically increases the threshold.
- The threshold depends strongly on residual gas pressure.
- The instability kicks out single bunches or whole sections from the tail region of the bunch train.

Currently operation above 200 mA is done with an adequate gap in the filling pattern and large chromaticities of +6 in both planes. The transverse multi-bunch feedback system [6], recently set into operation, can partially replace the high chromaticity required for suppression of the instability as shown in figure 4. Also an horizontal oscillation can be excited by lowering the horizontal chromaticity to values below zero.

Due to the instability or due to a bad orbit, bending magnet radiation missing the absorbers can lead to local vacuum chamber overheating, which once even caused a leak. After installation of several temperature sensors all over the vacuum chamber, a "golden orbit" was established by creating "temperature bumps" for minimization of vacuum chamber heating. Other bumps were created over the insertion devices for optimum threading of the photon beams into the beamlines.

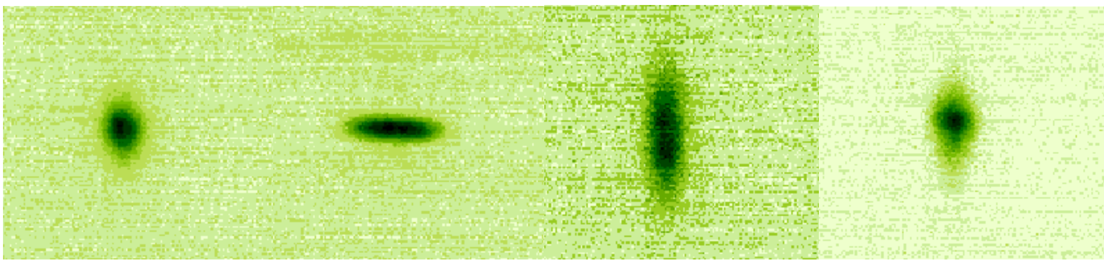

Figure 4: pinhole images of the electron beam for 100 mA beam current and uniform filling pattern as a function of horizontal and vertical chromaticities ξ_x, ξ_y : $\xi_x = \xi_y = +6$ / $\xi_x = -1$, $\xi_y = +6$ / $\xi_x = +6$, $\xi_y = +4$ / $\xi_x = +6$, $\xi_y = +4$ with TMBF running

Lifetime

After 110 Ampere hours of accumulated beam dose, the base pressure is $7.5 \cdot 10^{-10}$ mbar, composed to 25 % from carbon monoxide with the rest mainly hydrogen. Lifetime measurements as function of current done earlier [15] for both multi-bunch and single bunch operation agreed well with theoretical estimates on Touschek and gas scattering losses.

Top-up Injection

The SLS injection chain had been designed with the option of top-up in mind: The booster synchrotron can provide single injection shots for frequent refills, since it is not powered by a White circuit but by a digital power supply with arbitrary waveform [10]. Its relatively low power consumption of 200 kW at 3 Hz operation also allows continuous top up. The low final emittance of 10 nm provides efficient injection. The four storage ring kickers forming a closed 4-bump in one long straight have been carefully balanced suppressing the residual kick on the stored beam causing an orbit oscillation of $\approx 150\ \mu$m rms in the horizontal and too small to be measured in the vertical. Measurements of radiation levels allow injection with closed gaps without damaging the insertion devices and injection with open shutters without exceeding the personnel safety limits in the experimental hutches.

Presently top up is suffering from bad injection efficiency due to restricted dynamic apertures at large chromaticities required for suppression of the instability (see above). Further, the users are still in the process of evaluation, whether top-up is advantageous for their needs or not.

3 COMMISSIONING OF THE INJECTOR

Linac

The 100 MeV linac has been described earlier [8] including the commissioning results. All parameters fulfill or exceed the design specifications. By September 2001 the linac had acquired 3200 hours of operation. Reliability and reproducibility are very good. The main problem concerns persistent multipactoring in the 500 MHz prebuncher, which therefore will be replaced by October 2001.

Booster synchrotron

The SLS booster synchrotron follows a novel concept to provide a low emittance beam for efficient filling of the ring while saving costs of both building and booster operation [9]. The machine is mounted onto the inner wall of the storage ring tunnel. The circumference is 270 m, 45 horizontally and 48 vertically focusing bending magnets (also containing the sextupolar fields) in three achromatic arcs provide a low emittance of 10 nm·rad at 2.4 GeV. Three quadrupole families in three straight sections allow variation of the tunes. Two additional discrete sextupole families for manipulation of the chromaticity have never been used. The diameters of the elliptical vacuum chamber are 30 mm in the horizontal and 20 mm in the vertical. Ramping to 2.4 GeV in a 3 Hz cycle is done by a digital power supply [10], also single cycles may be triggered for top up injection.

It was found to be more efficient, to start the ramp at 60 MeV and inject the 100 MeV beam from the linac on the slope for faster acceleration in order to decrease losses due to gas scattering at low energy. With a maximum current of 1 mA extracted at 2.4~GeV a full fill of the storage can be done within three minutes. Injection efficiency from booster to ring amounts to 100 %, from linac to booster up to 85 % after careful optimization [11].

By September 2001 the booster had acquired 3100 operating hours at excellent reliability and reproducibility and without any major faults.

4 CONCLUSION

Construction and commissioning of all three machines of the SLS complex was straightforward and well within time schedule and budget. The achievements on the performance are based on three factors:

1. Risk of innovative in house developments was deliberately accepted. This included
   - reliable and flexible digital power supplies [10]
   - dynamic alignment concepts [1]
   - high precision injection system [5]
   - the novel booster concept as described above [9]
   - rich and powerful diagnostics including turn by turn BPM [3] and μs-shutter cameras [12]
   - flexible and powerful environments for machine control and application development [2]
2. Cautious outsourcing:
   - in house engineering and outside production with strict quality control
   - clear contracts with experienced companies
   - building up and keeping the competence in house
3. A high sense of responsibility and identification from all PSI employees. As a striking example we would like to mention, that there was not a single cabling error in the whole SLS complex!

5 OUTLOOK

Three of the four initial insertion devices have been implemented by July 2001, the fourth will follow in October 2001. Currently, 70 % of the beam time is scheduled for user operation. By end of 2001 the systems for position control, for multi-bunch feedback and for fast orbit feedback should become operational. Spring 2002 will already see installation of a 3rd harmonic superconducting twin cavity for increasing the beam lifetime. Generation of femtosecond X-ray pulses by means of laser beam slicing is planned for 2003 [13].

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