CORRECTION OF IMPERFECTIONS IN THE SLS STORAGE RING

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Abstract

Recently the energy acceptance and Touschek lifetime of the storage ring of the Swiss Light Source (SLS) could be successfully set to values in agreement with simulations for an ideal lattice. This was finally achieved through control of linear coupling and symmetrization of the sextupole pattern. 36 small corrector magnets were installed for this purpose as additional windings on the ring sextupoles: 30 skew quadrupoles (24 at zero and 6 at maximum dispersion) and 6 auxiliary sextupoles. Base for the success of these measures were previous corrections of dipolar and quadrupolar errors, which we will summarize briefly.

INTRODUCTION

Installation of narrow gap insertion devices and operation at large positive chromaticities for suppression of coupled bunch instabilities had a negative impact on energy acceptance and beam lifetime in the SLS storage ring, because particles from Touschek scattering events were lost due to crossing resonances intersecting the beam's footprint in tune space. In particular, vertical losses of Touschek particles as predicted in simulations [1] had been seen in scraper measurements at SLS [2]. After installation of a high resolution monitor allowing direct observation of vertical emittance [3], a program for control of betatron coupling was instigated.

THE SLS STORAGE RING

SLS started top-up operation for users in June 2001 with four beam lines [4] and delivered beam at an availability of 96% (2002 – 2008 average). Presently 16 beam lines are in operation with 2 more under construction. Major upgrades included a superconducting 3rd harmonic twin cavity [5], three super-bends of 3 T peak field, and the FEMTO source for sub-ps X-ray pulses [6]. Key parameters of the present machine configuration are the following:

Circumference	288 m
Beam energy	2.4 GeV
Beam current	400 ± 1 mA
Radio frequency	500 MHz
Horizontal emittance	5.5 nm
Vertical emittance	$2.5 - 7.5$ pm
Betatron tunes	20.43, 8.74
Chromaticities	+5, +5
Beam lifetime	$5 - 10$ hrs

The period-3 lattice is composed from 12 dispersion-free straight sections of three different types (6×4 m, 3×7 m, 3×11.5 m) connected by 12 triple bend achromats (TBA) with $8° - 14° - 8°$ bending angles.

All 36 dipoles are connected in series, but there are additional circuits to adjust the 24 8°-dipoles and the 3 superbends. The 177 quadrupoles have individual power supplies. The odd number is due to local focusing required at the FEMTO installation [6]. 120 sextupoles are grouped in 9 families, 3 chromatic and 6 harmonic. Orbit control is based on 73 horizontal and vertical correctors, 72 of which are realized as additional coils in the sextupoles and one is discrete (FEMTO). 36 (30 at present) skew quadrupoles and 12 (6 at present) auxiliary sextupoles are also implemented as additional coils in the sextupoles.

LINEAR OPTICS

During the commissioning phase and then in parallel with user operation, the lattice imperfections were cured progressively by the following methods:

Beta Beat Correction

The average quadrupole beta functions are measured by variation of the current of each of the 177 quadrupoles and recording the corresponding changes of betatron tunes. Based on the model sensitivity matrix $\partial\langle\beta_i\rangle/\partial k_j$, the individual quadrupole strength errors causing deviations of beta functions from theoretical values are calculated by SVD, and the correction currents corresponding to the inverse strength errors are applied to the machine [7].

BPM Calibration

Transverse displacements between the magnetic centers of the quadrupoles and the centers of the adjacent beam position monitors are measured using the technique of beam-based alignment. This allows to center the beam in the quadrupoles [7].

Displacements of girders revealed in the process are corrected by careful mechanical realignment utilizing the remote girder alignment capability of the SLS [8]: each girder can be adjusted in five degrees of freedom (horizontal and vertical translations and all three rotations) by a system of five excenter-motors.

Insertion Device Effects

Efforts to counteract insertion device (ID) effects mainly serve the users by maintaining the photon beam position independent of ID parameter changes [11]. From the accelerator side, the fast orbit feedback (FOFB) system [9] compensates any ID dipole errors and decouples the different straights.

Local compensation of the rather small ID focusing effects by adjacent quadrupoles would lead to serious deterioration of dynamic apertures due to changes of betatron phases at the sextupoles between the quadrupoles used for matching. These changes are larger than the phase advances introduced by the ID focusing and lead to a breakdown of the sextupole symmetry [10]. Instead the lattice tunes are globally compensated in a smooth way by adjusting all 177 quadrupoles, and a tune feedback function was implemented. An exception was only made for the strong FEMTO modulator wiggler: the FEMTO insertion contains 7 quadrupoles in order to provide an additional vertical focus in the straight without affecting the sextupole pattern [6]. These 7 quadrupoles are used for local tune compensation in a feed forward scheme based on tables for the tune change as a function of the modulator gap and tables of quadrupole currents as a function of desired tune variations [11].

MULTIPOLE CORRECTORS

All 120 sextupoles at the SLS are equipped with two sets of additional, air-cooled coils wired as horizontal and vertical correctors. Only 72 are needed for orbit correction, so by changing the connections at the 48 unused sextupoles, skew quadrupoles and auxiliary sextupoles can be created.

Skew Quadrupoles

Twelve skew quadrupoles in dispersive regions (6 presently installed) control the vertical dispersion and with it the vertical emittance. 36 skew quadrupoles in dispersion-free regions (30 presently installed) globally suppress the betatron coupling. They are also used to locally compensate coupling introduced by vertical beam excursions in sextupoles, if users require orbit bumps. Six non-dispersive skew quadrupoles were part of the lattice by design, based on studies on vertical lifetime limitations [1]. Another pair was installed later to compensate the coupling introduced by vertical orbit bumps for fast polarization switching at the PolLux beam line [12].

The skew quadrupole currents are calculated from measured vertical dispersion and from the measured BPM-Corrector response matrix, see Ref. [13] for details. A unique high resolution beam size monitor developed at the SLS was extensively used to control the success of the measures [3].

Some empirical manipulation of the three first order modes of the skew quadrupole Hamiltonian could further improve slightly the ratio of beam lifetime to beam height which was used as the figure of merit, since Touschek lifetime ideally scales with beam height.

Auxiliary Sextupoles

Optimization of lattice acceptance is a crucial problem in the design of low emittance light sources – and also when developing a new mode of operation at an existing machine. In particular, efficient injection into the storage ring for top-up operation requires a large horizontal acceptance, and long Touschek lifetime requires large energy acceptance, which basically translates to horizontal acceptance for off-energy particles.

Optimization of acceptances starts with the nine modes of the first order sextupole Hamiltonian [14],

$$h_{jklmp} \propto \sum_n^N (kL)_n \, \beta_{xn}^{\frac{j+k}{2}} \, \beta_{yn}^{\frac{l+m}{2}} \, \eta_n^p \, e^{i\{(j-k)\mu_{xn}+(l-m)\mu_{yn}\}}$$
$$[\quad + \quad \text{quadrupole contributions for } p \neq 0 \quad],$$

with j, k, l, m, p integers, (kL) the integrated sextupole strength, β, η, μ beta functions, dispersion and phase at the sextupole. Every sextupole is represented by a complex vector.

h_{11001} and h_{00111} are the linear chromaticities. h_{21000} and h_{11100} drive integer resonances (Q_x), h_{30000} the third integer ($3Q_x$) and h_{10200} and h_{10020} coupling resonances ($Q_x \pm 2Q_y$). h_{20001} and h_{00201} are sources of momentum dependent beta-beat and 2^{nd} order chromaticities.

This system of 16 equations (2 real, 7 complex) reduces to 9 equations due to symmetry of the lattice: seen from a symmetry point the imaginary parts of the vectors cancel. Furthermore particular phase advances between lattice sections need to be exploited if the system is degenerate [15]. At SLS this was the case for the half-integer modes h_{20001} and h_{00201}.

Other than the quadrupoles, the 120 sextupoles at the SLS storage ring do not have individual power supplies, but are connected in 9 symmetric families. The family strengths are optimized to adjust the 9 first order modes and also some of the 13 second order terms like amplitude dependent tune shifts in order to obtain the required acceptances in simulation. The symmetry of the sextupole families however does not allow to compensate even distortions of symmetry, as they exist in the real machine, because the variation of the Hamiltonian modes is confined to a line in the complex plane. Therefore small auxiliary sextupoles were installed by using additional coils on sextupoles of the SF-family, which is responsible for the horizontal chromaticity. Since beta functions and dispersion are identical at all these sextupoles, h_{21000} and h_{11100} can not be adjusted independently. The two chromaticities h_{11001} and h_{00111} are also coupled to each other, so it is sufficient to control only one. This leaves a system of 9 equations for one chromaticity (h_{11001}) and four complex resonance driving modes ($h_{21000}, h_{30000}, h_{10200}, h_{10020}$) to be solved by the vector of auxiliary sextupole strengths.

With 6 auxiliary sextupoles so far installed, the system is yet under-determined, but nevertheless can be solved by SVD and adjusting some weight factors. Upgrade to 12 sextupoles is planned. Presently, the auxiliary sextupoles are used in an empirical way by selecting one of the complex modes and optimizing its real and imaginary part for maximum beam lifetime.

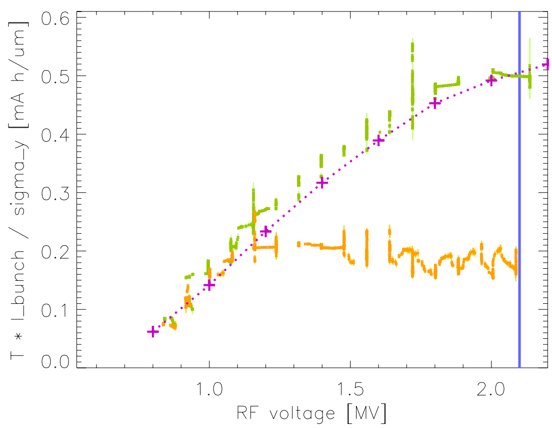

Figure 1: Measurement of beam lifetime (normalized to beam height and bunch current) as a function of RF voltage: the upper(green) and lower (orange) data points were respectively measured with optimum and zero settings of the skew quadrupoles and auxiliary sextupoles. The crosses connected by the dotted line (purple) are a TRACY 6-d tracking simulation for the ideal lattice. The line at right (blue) marks the RF-voltage as used in normal operation.

PERFORMANCE RESULTS

The combination of all the measures described above was able to deliver the performance that matched that calculated for the ideal, error-free lattice:

An excellent agreement of measured beam lifetime with data obtained from simulations of the ideal lattice was obtained and is shown in Fig. 1. The energy acceptance corresponds to $\pm 3\%$.

An ultra-low vertical emittance of 2.5 pm, just a factor of 5 away from the ultimate radiation limit has been achieved, corresponding to a ratio of vertical to horizontal emittance of 0.05% [13].

An injection efficiency of virtually 100% has been achieved. This enables one to fill the storage ring to 400 mA within 7 minutes and largely avoids any radiation background during top-up operation.

In user operation, lifetime may be increased at the expense of vertical emittance in a controlled way, since the ideal scaling of lifetime with emittance has been largely achieved.

CONCLUSION AND OUTLOOK

Agreement of measured Touschek lifetime with simulations for the ideal lattice was achieved through coupling correction preventing losses at the narrow vertical apertures, and through symmetrization of the sextupole pattern. These measures also lead to a minimum emittance coupling of 0.05% and to 100% injection efficiency into the storage ring.

However, the optimum settings obtained remain affected by certain changes in the machine status such as the opening or closing of insertion devices. In daily operation, lifetime typically is about 70% of the optimum value, emittance ratio $\approx 0.1\%$ and injection efficiency $90 - 100\%$. Therefore future work will further automatize the procedures and replace the empirical tuning procedures by theory based algorithms.

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