COUPLING CONTROL AT THE SLS

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Abstract

The vertical beam size measurement at the Swiss Light Source (SLS) is based on vertically polarized visual light and allows to verify a vertical emittance of a few pm rad corresponding to an emittance ratio in the 10^{-4} range regularly obtained in 400 mA top-up "user operation" mode by tuning the lattice by means of up to 24 dedicated skew quadrupoles. Suppression of betatron coupling by local and global coupling correction has the potential to prevent losses of Touschek scattered particles at the narrow vertical gaps of the in-vacuum undulators thus protecting these devices and increasing beam lifetime which prolongates the top-up injection interval. We are reporting on methods of coupling control and on the achievements in vertical emittance and beam lifetime.

SOURCES OF EMITTANCE COUPLING

Spurious vertical dispersion is a main source of emittance coupling at the SLS. A feature of the SLS orbit correction strategy is that the vertical dispersion originating from quadrupoles is nicely compensated by the dispersion generated by the almost adjacent orbit correctors in the sextupoles after proper (≈5 μm rms) Beam-Based Alignment (BBA) of the adjacent BPMs with respect to the neighbouring quadrupoles and successive orbit correction to the BPM centers ("BBA orbit") as depicted in Fig. 1. Thus the remaining vertical dispersion of ≈3 mm rms is mainly induced by sextupoles (≈2.5-3 mm rms are typically measured after correction to the "BBA orbit"). Another source of emittance coupling is the feed down of horizontal dispersion through skew quadrupole components induced by non-zero vertical orbits in sextupoles, quadrupole roll errors and insertion device (ID) imperfections. This contribution can be minimized utilizing dedicated skew quadrupoles Q^s. In a first step three families with two magnets per family paired around the three long straight sections ($\sqrt{\beta_x\beta_y}$ = 7 m, η_x = 0) were installed. The spare additional corrector windings on sextupoles without dipole correctors were rewired to generate a skew quadrupolar field of ≈±0.02 m$^-1$ at ±7 A. Early simulations [3] for 200 machine realizations before the commissioning of the SLS already indicated that an emittance coupling reduction from 0.25% to 0.1% should be achievable utilizing these skew quadrupoles. It also became apparent that this residual coupling is dominated by the sextupoles since quadrupoles plus correctors account for only ≈10% of this corrected coupling.

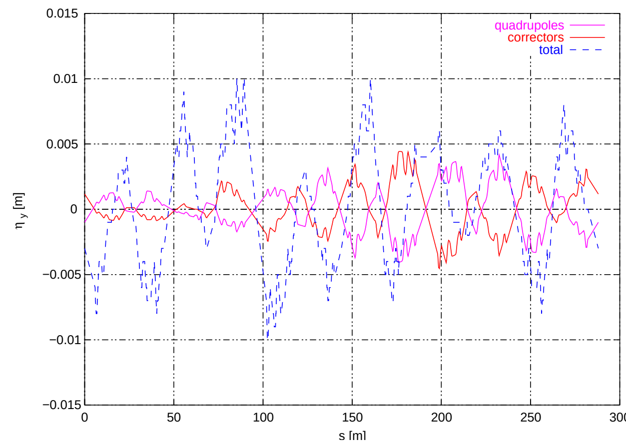

Figure 1: The TRACY-2 [1][2] simulation shows that the vertical dispersion originating from quadrupoles (magenta line) is nicely compensated by the dispersion generated by the nearly adjacent orbit correctors (red line) after proper beam-based alignment of the adjacent BPMs with respect to the neighbouring quadrupoles. The remaining vertical dispersion of 3 mm rms ("total", blue dashed line) is mainly induced by sextupoles.

COUPLING CORRECTION ALGORITHM

The coupling correction algorithm is based on a least square fit of the model based Corrector/BPM response matrix A_{ij}^{mod} ($i = [1,m]$ BPM index, $j = [1,n]$ corrector index) to the measured coupled response matrix A_{ij}^{meas}. To this end sensitivity matrices $\delta A_{ij}^{mod}/\delta Q_k^s$ are set up for l skew quadrupoles Q_k^s with $k = [1,l]$. In the following the difference A^{mod}-A^{meas} ist minimized in a least square sense by means of the Q_k^s using Singular Value Decomposition (SVD) which determines the necessary corrections $-Q_k^s$ which correct the coupling contained in A_{ij}^{meas}. Weighting factor cut-offs have to be carefully chosen in order to achieve the minimum betatron coupling at the expense of the smallest possible strength of the Q_k^s.

COUPLING MEASUREMENTS AND CORRECTION

Fig. 2 depicts a measured coupled 146×146 orbit response matrix A_{ij}^{meas} for the present BPM(73) / Corrector(146) layout in the SLS "user operation" mode (the rms betatron coupling estimated from the cross terms of the matrix in this case is ≈0.04%).

In "user operation" mode extra, especially vertical, orbit steerings for the experiments are applied which lead to additional betatron coupling due to vertical excursions in sextupoles plus some spurious vertical dispersion. As a starting point for the correction a manual tuning of the 6 initially installed skew quadrupoles was performed by minimizing the beam size observed at the emittance monitor [4] to 6.5 μm corresponding to a vertical emittance of 3.2 pm rad and an emittance coupling of 0.05%. In addition a dispersion bump over the injection straight was used to limit the rms spurious vertical dispersion to <3 mm. It should be noted that the minimization of the beam size at the monitor by means of these skew quadrupoles minimizes the invariant normal mode II emittance [5] as well [4] which corresponds to a global reduction of the betatron coupling. By applying the described SVD based correction on the measured coupled response matrix the betatron coupling could be further reduced by a factor of two. The emittance coupling did not change significantly which indicates its domination by the remaining spurious vertical dispersion of 2.8 mm. The modulus of the applied integrated skew quadrupole strength stayed well below 0.003 m^{-1} (1 A) by properly choosing the cut-off ($\leq$0.1) for the 6 SVD weighting factors with a range of $\approx$0.06 to 6.0.

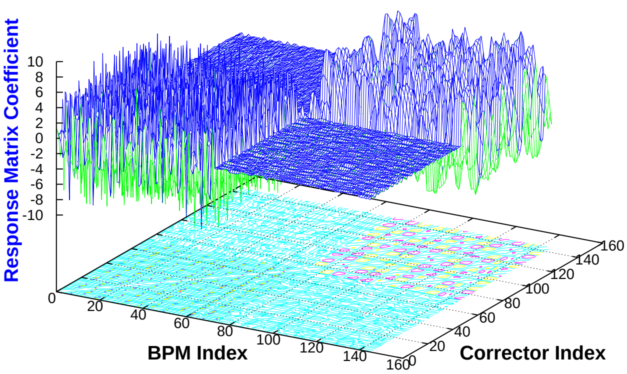

Figure 2: Coupled 146$\times$146 orbit response matrix A_{ij}^{meas} for the present BPM(73) / Corrector(146) layout in the SLS "user operation" mode with six skew quadrupoles tuned for minimum betatron coupling using an SVD based correction algorithm (the rms betatron coupling estimated from the cross terms of the matrix is $\approx$0.04%).

TOUCHEK LIFETIME MEASUREMENTS

It is well known and proven by various experiments (e.g. [6]) that vertical apertures, which are small in the undulator sections of a synchrotron light source, may determine the Touschek lifetime due to betatron coupling. After a Touschek scattering event in a dispersive region, particles start to perform large horizontal oscillations. The vertical amplitude acquired depends on the betatron coupling, given by skew quadrupolar moments, and on the distance to a coupling resonance [7].

The initial set of 6 skew quadrupoles is employed to minimize the betatron coupling to minimize the vertical emittance. In case of lifetime restrictions (e.g. operation mode with high single bunch currents) it however may be desirable to adjust vertical emittance to an appropriate value, which is done preferably by exciting vertical dispersion using skew quadrupoles in dispersive regions while still suppressing betatron coupling using the skew quadrupoles in dispersion free regions.

At an user operation current of 400 mA in 390 bunches chromaticities of the SLS storage ring need to be set to positive values in order to suppress coupled bunch instabilities. This leads to a wide spread of tunes for the energy range of $\pm$3% as provided by the acceptance of the radio-frequency system, and to crossing of the coupling resonance ($Q_x + Q_y$ = 29) at an energy deviation of only -1.6% as shown in Fig. 3. Previous measurements of life-

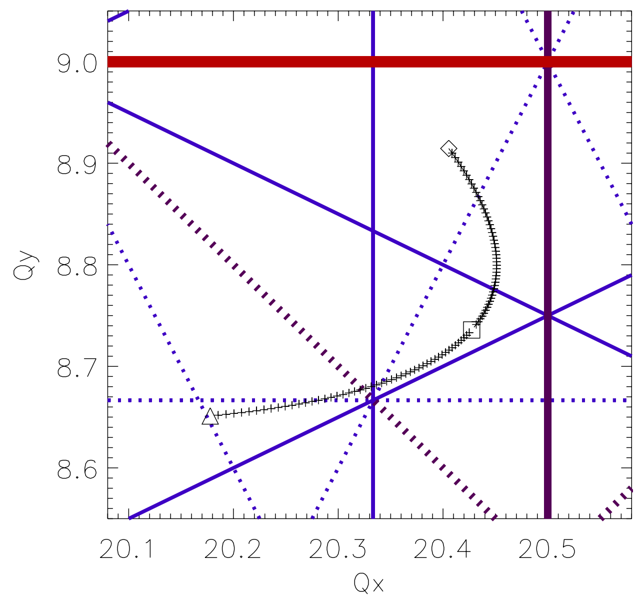

Figure 3: SLS working point (square) and tune spread for energy deviations from -3% ($\triangle$) to +3% ($\diamond$) at nominal (high) chromaticities.

time vs. the position of a horizontal, dispersive scraper, exhibited in fact a restriction of $\approx$1.5%, whereas full agreement with the model was found for low chromaticity [8].

According to 6D-simulations with TRACY-2 [1][2], Touschek lifetime for the present working point at 20.43 / 8.74 and an RF-voltage of 2 MV providing 3% energy acceptance is given by:

$$T\,[\text{hrs}] \approx 13.9 \frac{\sqrt{g}\,[\%]}{I_{\text{bunch}}\,[\text{mA}]},$$

where g is the ratio of vertical to horizontal emittance which is derived from a measurement of the vertical beam size [4]. Fig. 4 shows total and pure Touschek lifetime measured as a function of **vertical** scraper position for g = 0.13$\pm$0.02% and 1 mA single bunch current for high (+3.8 / +4.4) and low (+0.8 / +2.4) chromaticites.

Pure Touschek lifetime was obtained by subtracting the losses due to elastic scattering vs. scraper position from the measured lifetime [8].

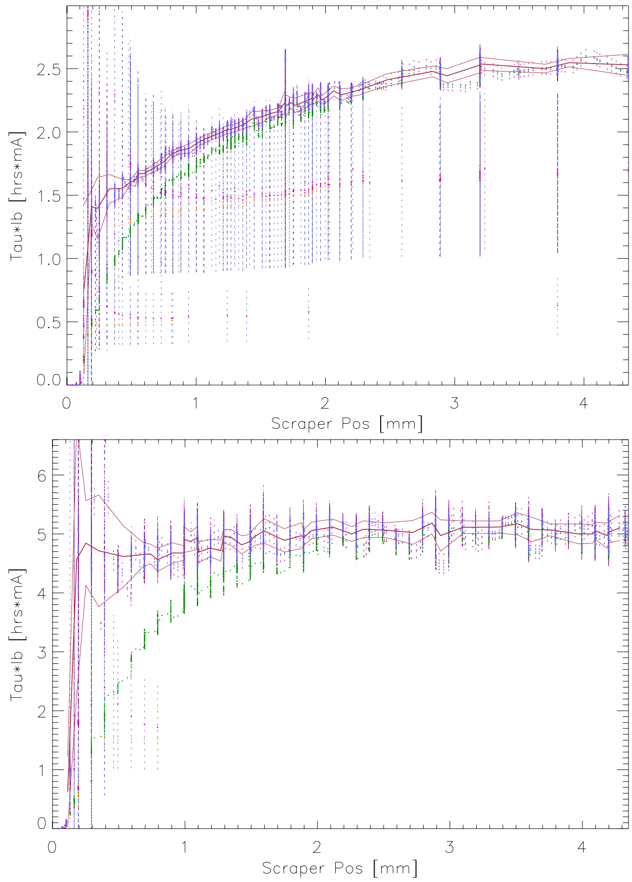

Figure 4: Touschek lifetime as a function of vertical scraper position for high (top) and low (bottom) chromaticity. Green dots are measured values, blue dots connected by the purple center line are pure Touschek lifetime values after subtraction of the contribution from elastic scattering (Purple side lines give an error estimate).

- For **low chromaticity**, Touschek lifetime is virtually not affected by the scraper position due to well suppressed coupling and avoiding crossing the coupling resonance, since the tune spread area is more compact. If the scraper is out, Touschek lifetime determines the total lifetime completely, since the experiment was done with a short train of 50×1 mA bunches. The lifetime of ≈5 hrs agrees perfectly with the simulation result of 5.1±0.3 hrs.

- For **high chromaticity**, Touschek lifetime is strongly affected by the vertical scraper, proving the influence of coupling. Although betatron coupling was suppressed by means of skew quadrupoles no lifetime was gained, since the Touschek particles do not only approach the coupling resonance but really cross it. In this case any non-zero betatron coupling causes a fully coupled beam [7].

Obviously, preventing Touschek particles from crossing the coupling resonance would double the SLS lifetime. A new optics for another working point is under development.

UPGRADES

Recently 18 additional non-dispersive skew quadrupoles have been installed which allow a more localized betatron coupling control especially in the vicinity of the insertion devices (IDs). One pair is already used as part of a feed-forward scheme in order to locally compensate for the betatron coupling generated by a large (up to ±300 μm) time varying (≈1 Hz) asymmetrical 4-bump for the PolLux dipole beam-line [9]. First coupling minimizations utilizing 24 skew quadrupoles instead of 6 improved the local betatron coupling but had a marginal influence on the emittance coupling. In order to reduce the coupling below 0.05% a better control of the remaining spurious vertical dispersion is needed. For this reason 6 skew quadrupoles at locations with large horizontal dispersion η_x = 0.33 m will be installed in the near future. Furthermore it is planned to integrate the skew quadrupoles into the Fast Orbit Feedback (FOFB) [10] loop in order to allow for a fast (4 kHz sampling rate) control of the betatron coupling which is mainly changing due to ID operation.

CONCLUSIONS

Up to 24 non-dispersive skew quadrupoles have been utilized in an SVD based correction procedure in order to minimize betatron and emittance coupling in the "user operation" mode. In conjunction with the correction of the remaining spurious vertical dispersion to <3 mm the emittance coupling could be reduced to 0.05% corresponding to a vertical emittance of 3.2 pm rad.

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