ULTRA-LOW VERTICAL EMITTANCE AT THE SLS

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Abstract

Utilizing a large number of non-dispersive (24) and dispersive (6) skew quadrupoles the betatron coupling and the vertical spurious dispersion can be simultaneously reduced to extremely small values. As a result the achieved vertical emittance begins to approach its ultimate limit, set by the fundamental quantum nature of synchrotron radiation, which in the SLS case is ≈0.55 pm·rad. At the same time emittance measurements based on the fitting of a diffraction limited vertical photon beam from a dipole have been pushed to the limit in order to verify this ultra-low vertical emittance.

INTRODUCTION

As many 3rd generation synchrotron light sources the Swiss Light Source (SLS) features large numbers of BPMs (73) and dipole correctors (146) which are located adjacent to quadrupoles. The horizontal and vertical correctors are implemented as extra windings within the sextupoles. Due to the application of BPM-Quadrupole Beam-Based-Alignment (BBA) to a few ten μm and subsequent correction to the centers of quadrupoles having adjacent BPM/corrector combinations the vertical dispersion waves generated by quadrupoles and correctors are in antiphase and cancel each other as it is shown in Fig. 1. Since the influence of quadrupole roll errors appears to be negligible due to excellent alignment the vertical beam offsets in sextupoles leading to betatron coupling become the main driver for spurious vertical dispersion as it is shown in the the depicted simulation result. One way to eliminate this contribution is the determination of the sextupole centers with respect to adjacent BPMs by means of BBA techniques and to center the beam simultaneously in quadrupoles **and** sextupoles. But since the first order effect is only a small betatron tune shift with a very weak (through coupling) dependence on the vertical beam offset the variation of sextupole currents is not providing the needed measurement resolution of a few ten μm. Extra quadrupole windings on sextupoles can help since the task is reduced to a quadrupole BBA [1][2].

Another way to tackle the problem is the introduction of extra skew quadrupoles at dispersive (η_x>0) and non-dispersive (η_x=0) locations of the lattice in order to control spurious vertical dispersion η_y and betatron coupling. At the SLS 24 non-dispersive and 6 dispersive skew quadrupoles have been installed for this purpose up to date. All 120 sextupoles are equipped with extra windings where only 72 are dedicated as dipole correctors for orbit correction. The remaining 48 can be connected as desired to be for example skew quadrupoles or correction sextupoles. Since 12 of them have been devoted to nonlinear optics correction [3] 36 are left to be used as skew quadrupoles which in principle also opens the possibility to perform a BBA for 36 sextupoles by using those skew quadrupoles [2].

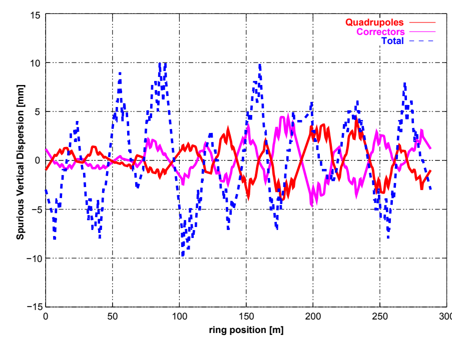

Figure 1: Due to the application of BPM-Quadrupole Beam-Based-Alignment (BBA) to a few ten μm and subsequent correction to the centers of quadrupoles having adjacent BPM/corrector combinations the vertical dispersion waves generated by quadrupoles (red curve) and correctors (magenta curve) are in antiphase and cancel each other. Vertical beam offsets in sextupoles leading to betatron coupling become the main driver for spurious vertical dispersion (blue) (taken from [4] for illustration).

DISPERSION CORRECTION

The setting for six dispersive (η_x≈0.3 m) skew quadrupoles is determined by applying the SVD "inverted" (no weighting factor cut) model-based [5][6] 73x6 sensitivity matrix $\partial\eta_{yi}/\partial k_{sj}$, where η_{yi} denotes η_y at the location of the BPM i and k_{sj} is the strength of the skew quadrupole j, to the measured spurious vertical dispersion η_y. As shown in Fig. 2 the initially measured η_y (magenta points $+$) of 4.1 mm RMS could be reduced to 2.2 mm RMS (red points $\times$). The model prediction (black line) for the residual η_y after correction is given for comparison indicating that a significant further reduction of η_y is not possible utilizing those six knobs. The maximum applied $|k_s|$ of ≈0.002 m^{-1} stays well below the maximum of 0.03 m^{-1} at 7 A (the six applied weigthing factors are in the range from 0.17 down to 0.03). In the near future a total number of 12 dispersive skew quadrupoles will be available for dispersion correction. But model predictions indicate that a further reduction of η_y below 2 mm is not feasible for the present η_y pattern. In order to approach the ultimate limit, which is given by the present η_y measurement resolution of ≈0.9 mm, sources of η_y need to be eliminated. Girder-to-girder misalignments in the arc centers, which are in the range of 50-100 μm, have been identified to be a major source of η_y. Consequently a realignment campaign has been initiated. As a side effect this realignment will reduce the RMS vertical dipole corrector strength from ≈140 μrad to <100 μrad.

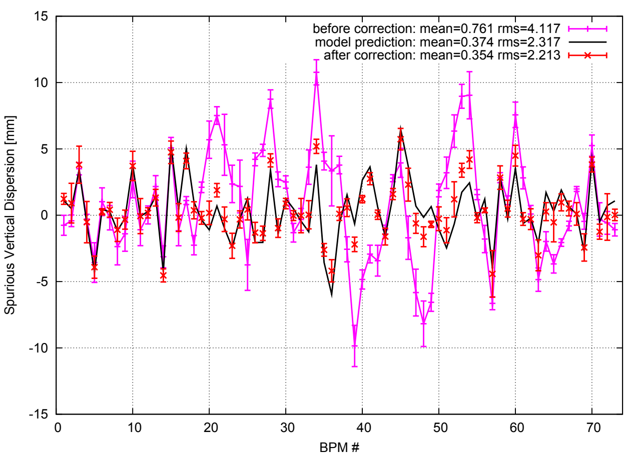

Figure 2: The setting for six dispersive (η_x ≈0.3 m) skew quadrupoles is determined by an SVD fit to the measured spurious vertical dispersion η_y (magenta points +) without any weighting factor cut. It reduces the initially measured η_y of 4.1 mm to 2.2 mm RMS (red points ×). The model prediction (black line) is given for comparison indicating that a significant further reduction of η_y is not possible utilizing those six knobs.

BETATRON COUPLING CORRECTION

The betatron coupling correction is performed after the dispersion correction since the dispersive skew quadrupoles have by design a non-negligible effect (≈10 % RMS increase of the coupling terms of the BPM/Corrector response matrix) on the betatron coupling as well. The 24 non-dispersive skew quadrupoles can correct for this effect without having an influence on the already corrected spurious vertical dispersion since they are at locations with η_X=0. The correction is performed by applying the SVD "inverted" (no weighting factor cut) model-based sensitivity tensor $\partial(\partial x_i/\partial c_j)/\partial k_{sk}$, where $\partial x_i/\partial c_j$ is the 146x146 coupled orbit (BPM/Corrector) response matrix and k_{sk} denotes the strength of the skew quadrupole k, to the measured coupled orbit response matrix (in order to perform the SVD "inversion" the tensor is actually squeezed into a 24x(146x146) matrix). Since two non-dispersive skew quadrupoles are at present exclusively used in a feed-forward coupling correction scheme for the dipole beam-line PolLux [7] the correction has been performed with only 22 actuators. Figure 3 depicts skew quadrupoles currents for three iterations of the correction procedure involving three subsequent orbit response matrix measurements. The maximum applied $|k_s|$ of ≈0.004 m^{-1} corresponding to ≈1 A stays well below the maximum of 0.03 m^{-1} at 7 A (the 22 applied weigthing factors are in the range from 16. down to 2.). The prediction for the third iteration (magenta bars) indicates that the betatron coupling correction limit with 22 skew quadrupoles has been reached at a current variation of 0.005+-0.041 A. After the application of two successive betatron coupling corrections the RMS of the coupling terms of the coupled BPM/Corrector response matrix was reduced by a factor ≈2.2 which corresponds to a factor ≈5 in the corresponding emittance contribution due to betatron coupling. Figure 4 depicts the response matrix after the last correction step illustrating the small remaining betatron coupling.

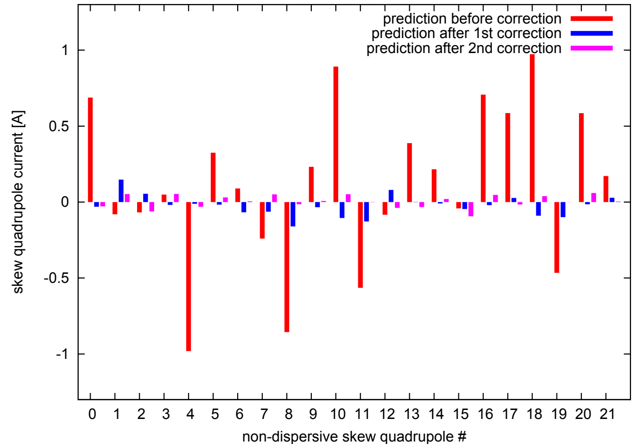

Figure 3: Skew quadrupoles currents for three iterations of the betatron coupling correction procedure involving three subsequent orbit response matrix measurements. The maximum applied skew quadrupole strength $|k_s|$ of ≈0.004 m^{-1} corresponding to ≈1 A stays well below the maximum of 0.03 m^{-1} at 7 A.

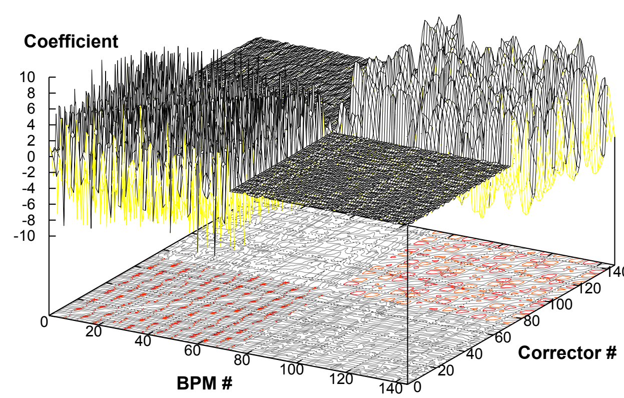

Figure 4: Coupled BPM/Corrector response matrix after the application of two successive betatron coupling correction steps. The RMS of the coupling terms has been reduced by a factor ≈2.2.

EMITTANCE MEASUREMENT

To enable an emittance measurement at a synchrotron light source an image formation method is typically used for the determination of the beam size. The emittance determination thus relies on a beam size measurement and knowledge, through other means, of the beta and dispersion values at the observation point. A determination of an RMS beam size of $<10\ \mu$m requires a large instrumental und theoretical effort. At the SLS "the π-polarization method" has been chosen in order to reach this ambitioned goal [8][9]. In this setup images are formed from vertically polarized

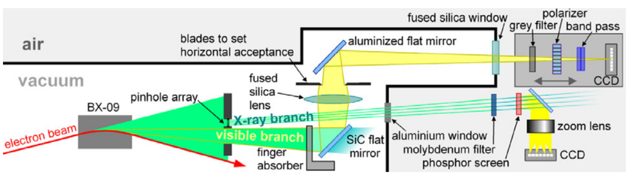

Figure 5: Layout of the high resolution emittance measurement beam-line operated at the central dipole ARIMA-BX-09, showing the X-ray branch with pinhole array and the vis-UV branch [8][9].

vis-UV synchrotron radiation. It has been demonstrated at the SLS that this method is capable of determining beam sizes σ_e to well below 10 μm with a resolution of $\approx$0.5 μm. Figure 5 depicts a top view of the diagnostics beam-line located at the central dipole ARIMA-BX-09 in sector 9 of the SLS. Since the vertical beam size σ_{ey} is only observed

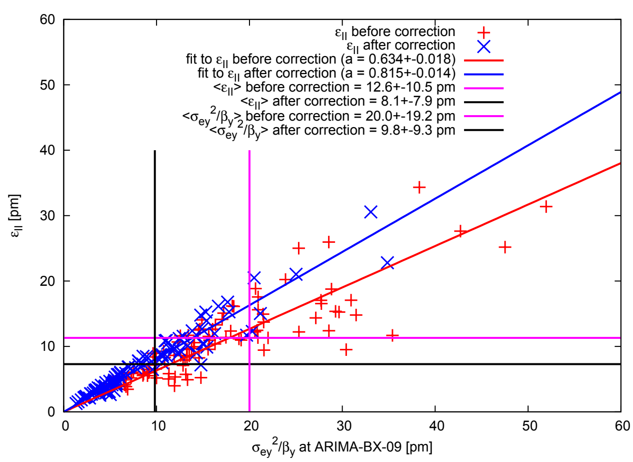

Figure 6: Simulation result for 100 randomly distorted SLS lattices. Shown is ϵ_{II} vs. σ_{ey}^2/β_y before (red points $+$) and after coupling correction (blue points $\times$) utilizing 22 non-dispersive skew quadrupoles. Both quantities σ_{ey}^2/β_y and ϵ_{II} are clearly reduced (magenta compared to black lines) and appear to be highly correlated after the applied coupling correction.

at one particular location in the ring (ARIMA-BX-09) it is of great importance to demonstrate the correlation between the global minimization of the betatron coupling by means of non-dispersive skew quadrupoles leading to a minimization of the globally preserved mode-II (approximately vertical) emittance ϵ_{II} and the locally determined emittance σ_{ey}^2/β_y. Figure 6 summarizes the simulation result for 100 randomly distorted SLS lattices. Shown is ϵ_{II} vs. σ_{ey}^2/β_y before (red points $+$) and after coupling correction (blue points $\times$) utilizing 22 skew quadrupoles. Both quantities σ_{ey}^2/β_y and ϵ_{II} are clearly reduced (magenta compared to black lines) and, what is even more important, appear to be highly correlated after the applied coupling correction. Thus the measured vertical beam size is minimized at the same time as the mode-II emittance and vice versa (for an extensive discussion of this topic see also [8]).

The presented correction of spurious vertical dispersion and betatron coupling leads to a reduction of σ_{ey} at the monitor location from 13 μm to $<6\ \mu$m. From this the locally evaluated vertical emittance ϵ_y taking into account the vertical beta functions, the dispersion values and the beam ellipse twist at the monitor location is calculated to be <3 pm·rad which is already very close to the ultimate limit, set by the fundamental quantum nature of synchrotron radiation, which is for the SLS $\approx$0.55 pm·rad.

CONCLUSION

The vertical emittance has been systematically reduced to <3 pm·rad by means of dispersion and betatron coupling correction utilizing 22+6 skew dedicated skew quadrupoles. A further reduction of the emittance can be achieved by a careful girder-to-girder realignment which would reduce the spurious vertical dispersion to less than 1 mm. A precise sextupole BBA utilizing the built-in skew quadrupoles can help to reduce the remaining betatron coupling.

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