LINEAR AND NON-LINEAR MODEL OPTIMISATION FOR SOLEIL STORAGE RING

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Abstract

Thanks to beam-based measurements, the theoretical model of the storage ring lattice has been improved. First, the quadrupole lengths in the hard edge model were finely tuned to get good agreement with the experimental measurements of betatron tunes for significantly different optics. Second, a machine model including the coupling errors has been built using the crosstalk closed orbit acquisitions. As a validation, the coupling effect of the 10m long HU640 undulator has been evaluated through this coupling model. Finally, the non-linear model was modified to better fit with beam-based on-momentum frequency map measurements. In addition to the thick sextupole model, the non-linear effect induced by the fringe field in the quadrupole magnets has been introduced. Simulated and measured on-momentum tune shifts with transverse amplitudes and dynamic aperture are then compared.

INTRODUCTION

Improving machine performance in term of beam dynamics is closely connected with reaching a very reliable linear and non-linear model. With a precise linear model, the exploration of different lattices is more convenient and the transition from one optics to another is safer. In particular, optics aiming at reaching very low momentum compaction factor values ($\alpha_1 \sim 1\ 10^{-6}$) are highly sensitive to the quadrupole tuning. Moreover, some simulations showed a rather high sensitivity of the non-linear beam dynamics to the distribution of coupling errors in the SOLEIL storage ring. This has been taken into account and precisely modelled as we will show later on. Concerning the non-linear model, since EPAC08 [1], it has been improved by introducing, in the tracking calculations, non linear kicks simulating the effects of the quadrupole fringe fields, for both BETA [2] and TRACYII [3] codes.

LINEAR MODEL IMPROVEMENT

The linear model was challenged on day 1 of the commissioning. The measured horizontal and vertical betatron tunes ν_x=17.84 and ν_z=10.13 were slightly different from those which had been predicted: 18.20 and 10.30. A relative scaling of +8 10^{-3} was then applied to all quadrupole gradients to recover the theoretical tunes. This scaling was not understood with respect to the quadrupole measurement bench qualities that had been estimated to 10^{-4} (reproducibility) and 2 10^{-3} (precision).

The initial linear model was including the fringe field in the dipoles together with an additional gradient due to the curved trajectory of the beam [4]. Full quadrupole current vs integrated gradient calibration had been measured including saturation effect [5]. Finally we cast doubt on the quadrupole hard edge model which was initially adjusted to the iron length of the magnet L_{shortQ}=0.320m (resp. L_{longQ}=0.460m).

Tune Calculation with the Measured Quadrupole Fringe Field

Calculation of the betatron tunes variation $\Delta\nu_{x,z}$ due to the fringe field has been made using the theoretical betatron function values $\beta_{x,z}(s)$ of the day 1 model, and the measured gradient curve G(s) for the different quadrupole parameters:

$$4\pi\Delta\nu_{x,z} = \int_{quadrupoles} \beta_{x,z}(s)\Delta K_{x,z}(s)\,ds$$

where $\Delta K_{x,z}$ is the difference between hard edge model and measured normalised gradient. A significant difference around half a unity was then obtained for the horizontal tune. As a consequence we searched for the hard edge model length that fits the realistic tunes on both planes. As a result, that length has been found to be a bit longer than the effective magnetic length.

Experimental Results

Tune measurements with beam led to a small adjustment of this new hard edge model length. Two significantly different optics configurations have been tested: the nominal working point with distributed dispersion, and the “low α” (α_1/100) lattice (Table 1). Finally, quadrupole lengths were set to L_{shortQ}=0.360m (resp. L_{longQ}=0.496m). They exceed the mean measured magnetic length by 6.4mm (resp. 4.5mm).

Table 1: Measured Tunes with the New Linear Model

Machine	**ν_x from model**	**(ν_z) from model**	***ν_x from measurement***	***(ν_z) from measurement***
Nominal Day 1 model	18.20	(10.30)	*17.84*	*(10.13)*
Nominal New Model	18.20	(10.30)	*18.232*	*(10.270)*
Low-alpha (α_1/100) New Model	20.30	(8.40)	*20.320*	*(8.350)*

Thanks to this new adjusted model, the current experiments to produce coherent synchrotron radiation (CSR) in THz region have been successfully done either by moving, with beam, from one "low α" lattice to another by changing the values of the quadrupoles, or by injecting directly to the required optics with rather good efficiency of 30%.

Final Tune Adjustment with LOCO

The quadrupole gradient dispersion of a few 10^{-3} due to magnet construction may explain the remaining detuning. We get rid of it experimentally with the help of the LOCO code [6]. All the 160 quadrupole individual power supplies are adjusted to restore optical function symmetry together with the theoretical tunes.

INCLUDING TRANSVERSE EMITTANCE COUPLING IN THE MODEL

Coupling is modelled using "virtual" skew quadrupoles located in the sextupoles. As shown before [7], for the SOLEIL optics, the vertical displacement of sextupoles is the main contribution to the coupling compared to the quadrupole tilt, taking into account the following alignment errors: σ_z=50µm (sextupoles) for a mean sextupolar integrated strength of 3.4m^{-2} and $\sigma_{\theta s}$=50µrad (quadrupole tilt). The contribution of the residual vertical orbit in the sextupoles σ_{zCO}<100µm may be neglected. Other virtual skew quadrupoles are inserted in the straight sections for a possible contribution from insertion devices.

Method of Modelling

The method is based on the Vertical Dispersion (D_z) and the Cross-Talk Closed Orbit (CTCO's) measurements, i.e. the non-zero vertical closed orbit created by the 56 horizontal dipolar correctors. The measurement duration is reasonable (10mn) and enables an immediate coupling correction on the real machine together with this coupling model. It is obtained in correcting the CTCOs and D_z by the virtual correctors with realistic number of eigenvalues and weigth factor for the dispersion correction. Vertical orbit and D_z have to be corrected from cross-talk errors coming from the Beam Position Monitor (BPM) and their electronics. These corrections together with the BPM gains in both planes are obtained from the LOCO fit.

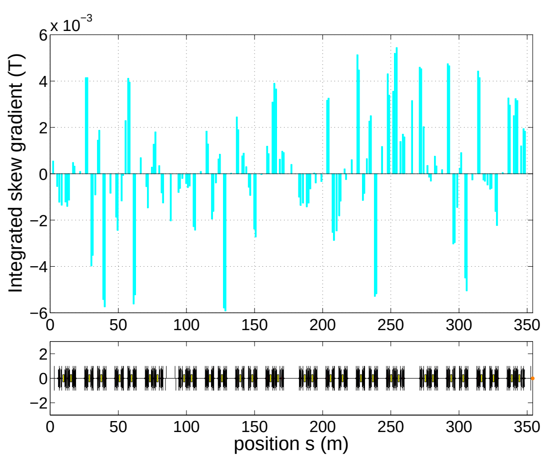

Figure 1: Model of coupling error distribution for the bare machine.

Experimental Check of the Model with Specific Coupling Configurations

Specific sets generated with the 32 real skew quadrupoles have been checked, inducing either some betatron coupling or pure vertical dispersion (as used in 8 bunch operation). The precise location of coupling errors is well restored except for subsequent sextupoles where the vertical betatron phase advance is small. The residual noise, as high as σ_{Gx}=3 10^{-4}T (integrated skew gradient) in the virtual skew correctors, corresponds to an equivalent displacement of the sextupoles of σ_z=5µm which is negligible.

Coupling Modelling for the Bare Machine

Figure 1 shows the coupling error distribution along the bare machine. The R.M.S. value of the virtual skew gradients is σ_{Gx}=25 10^{-4}T that corresponds to a vertical alignment error in sextupoles of $\sigma_{z\ sextupole}$=40µm, consistent with our real alignment measurements when taking into account correlation due to the girder system. Spurious vertical dispersion from the simulation fits very well the measured one, as shown in figure 2. Resulting simulated coupling is slightly lower than the real one measured by the pinhole camera [8]: 0.47% instead of the measured 0.59% at low beam current.

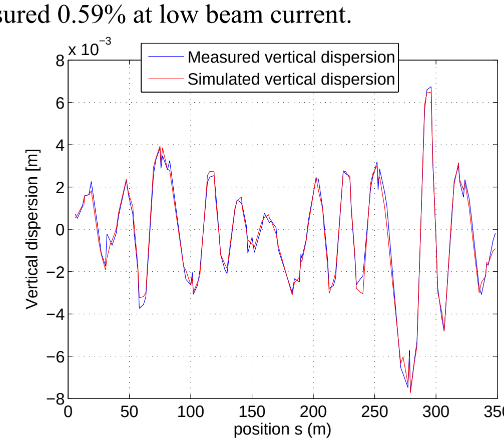

Figure 2: Spurious vertical dispersion from measurement and from simulation, for the bare machine.

Model with the HU640 Undulator

The 10m long HU640 electromagnetic undulator contributes to the coupling in a non negligible manner especially in the horizontal field mode [9]. Measuring the closed orbit distortion versus horizontal beam displacements in the undulator enabled us to deduce its integrated skew gradient for several horizontal field values. This skew gradient was introduced in the coupling model. Figure 3 shows the comparison with the real coupling measured by the pinhole camera, which leads to a very satisfactory agreement

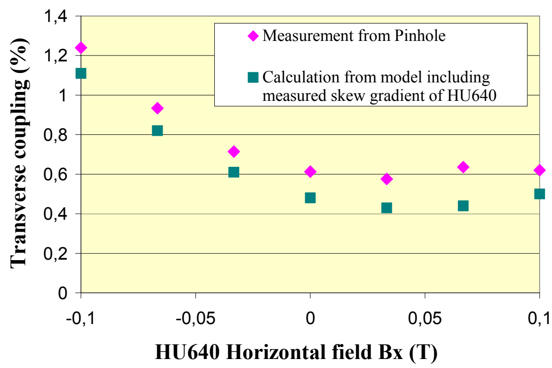

Figure 3: Coupling induced by the HU640 undulator in horizontal field mode.

NON-LINEAR MODEL STATUS

Our non linear model now takes into account thick sextupoles, measured high order multipolar components of dipolar, sextupolar and quadrupolar fields, and the quadrupole fringe field effect. The physical aperture used in simulation is an important parameter, especially for energy acceptance calculations. When U20 in vacuum undulators are open, the theoretical vertical aperture is limited to +/- 5mm by the ID chamber height in medium straight sections. Measurements using scrapers have shown that the vertical aperture is smaller than the expected one and corresponds to +/-4.3mm in medium straight sections. This value was confirmed by height chamber probing using beam orbit displacements in straight sections. Realignment of concerned chambers is progressively done during each shutdown period. The reduced vertical aperture has been used in calculations.

For the bare lattice corresponding to the nominal working point (ν_x=18.20, ν_z=10.30, ξ_x= ξ_z=2, natural coupling of 0.55%), the calculated tune shifts with amplitude are close to the measured ones as shown on figure 4. Some difference persists for the horizontal tune. The corresponding dynamic aperture (figure 5) is compared with the measured one. The agreement in terms of diffusion and aperture is rather good.

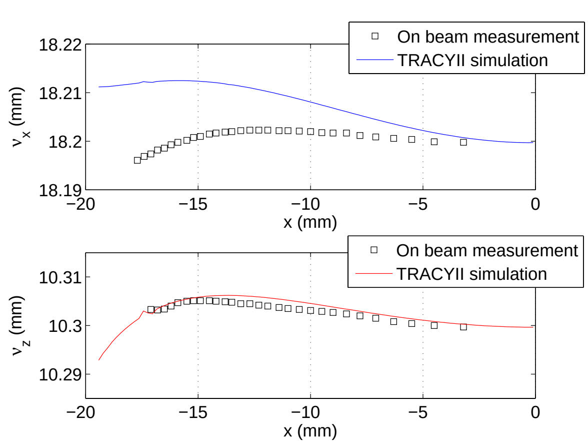

Figure 4: Tune shifts with amplitude for the bare lattice.

Note that the natural coupling is here created by a set of random rotations of the 160 quadrupoles, the model of coupling errors presented above being not yet implemented in the Tracy II lattice model.

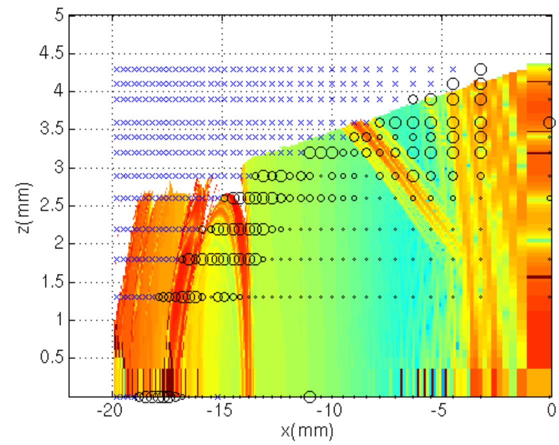

Figure 5: Dynamic aperture for the bare lattice. Colours for the calculated one, black circles (partial beam losses) and blue crosses (total beam losses) for the measured one.

CONCLUSION

The linear model for the SOLEIL storage ring is now optimised and very reliable. The coupling error model which seems to be robust will be used soon to update the beam dynamics calculations. The non linear model has to be further improved in order to have a better agreement between calculated and measured on and off momentum dynamics, for the bare lattice first, then for simulating the non linear effects of insertions devices.

REFERENCES

[1] L. S. Nadolski and al., “First Frequency Maps for Probing the Non-linear Dynamics of SOLEIL”, EPAC’08, Genoa, June 2008, pp. 3128-3130.

[2] J. Payet et al., BETA code, LNS version, modified for SOLEIL.

[3) J. Bengtsson, E. Forest and H. Nishimura, “Tracy User Manual”, unpublished (ALS Berkeley).

[4] P. Brunelle and al., “Non linear beam dynamics and beam lifetime on the SOLEIL storage ring”, EPAC’04, Lucerne, June 2004, pp. 2035-2037.

[5] P. Brunelle and al., “Magnetic measurements results of the dipoles, quadrupoles and sextupoles of the SOLEIL storage ring”, EPAC’06, Edinburgh, June 2006, pp. 3278-3280.

[6] L.S. Nadolski, ”Use of LOCO at Synchrotron SOLEIL”, EPAC'08, Genoa, Italy, pp. 3131-3133.

[7] P. Nghiem et al., “Study on coupling and coupling correction for the SOLEIL ring”, NIM section A 480 (2002), pp. 339-348.

[8] M.-A. Tordeux et al., “Ultimate resolution of SOLEIL X-ray pinhole camera”, DIPAC’07, Venice, May 2007.

[9] P. Brunelle and al., “Experimental characterization of the insertion device effects on beam dynamics at SOLEIL”, EPAC’08, Genoa, June 2008, pp. 2097-2099.