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BEAM DYNAMICS SIMULATIONS FOR OPERATING A ROBINSON WIGGLER AT THE MLS

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Abstract

A Robinson wiggler is planned to be installed in the storage ring of the Metrology Light Source (the MLS). The Robinson wiggler (RW) is a device consisting of a chain of combined-function magnets (CFMs), intended to manipulate the damping partition numbers and thus adjust the longitudinal emittance. The objective is to lengthen the bunch in order to improve the Touschek lifetime. However, the nonlinear perturbation of the beam dynamics due to the Robinson wiggler could limit the achievable improvement. Therefore, a symplectic method of modelling the wiggler has been established to study these nonlinear effects. Optimized solutions have been developed for both the ramping procedure and the future daily operation of the wiggler and are presented in this paper.

INTRODUCTION

The Metrology Light Source is an electron storage ring operated at the energies from 50 to 630 MeV for metrology applications in the THz to extreme UV spectral range [1]. As a ramped machine, it does not have the feature of Top-Up operation. With a decaying beam in the storage ring, the beam lifetime is a key parameter for the users, in terms of temporal stability and integrated photon flux . Great efforts have been put to improve the beam lifetime by optimizing the linear optics [2, 3] and nonlinear dynamics [4, 5] at the MLS are ongoing. By installing a RW, there is potential to double the lifetime compared to the present value.

In actual operation mode white noise exaction via striplines on the vertical plane is employed to suppress ion caused effects and to offer the users tailored vertical beam sizes for a given beam current. With a Robinson wiggler in a dispersive section, the longitudinal damping can be transferred to horizontal plane [6], so that the emittance is reduced and energy spread is increased. Thus the bunch is lengthened and transverse beam size is decreased. With the Robinson wiggler, the beam sizes during the operation at different beamlines can be maintained as present values by properly adjusting white noise exaction, so that the Touschek lifetime is improved due to a larger bunch volume without reducing the performance to the users .

The design of the Robinson wiggler has been finished in the year 2016, which has been published as Ph.D thesis [7]. Based on the design work, linear and nonlinear models have been studied to represent the wiggler during the lattice development and for each iteration the dynamic aperture was optimized.

MODELLING THE ROBINSON WIGGLER

The principle of manipulating the damping partition D is given in Eq. 1-3 [8, 9]. The Robinson wiggler introduces a dipole field together with quadrupole component in positive dispersive section, so that synchrotron radiation integrals I_4 and I_2 are changed, which results in the reduction of D [10]. The field map of the RW , which consists of 12 CFMs, is shown in Fig. 1.

$$I_2 = \oint \frac{1}{\rho^2} ds \qquad (1)$$

$$I_4 = \oint \frac{\eta_x}{\rho}\left(\frac{1}{\rho^2} + 2k_1\right) ds = \oint \left(\frac{\eta_x}{\rho^3} + \frac{2}{(B\rho)^2}\eta_x B_y \frac{\partial B_y}{\partial x}\right) ds \qquad (2)$$

$$D = \frac{I_4}{I_2} \qquad (3)$$

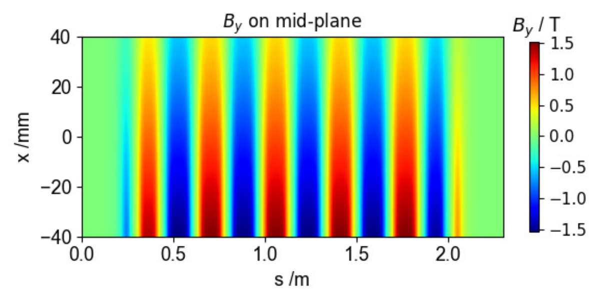

Figure 1: B_y strength on the mid-plane of the designed Robinson wiggler.

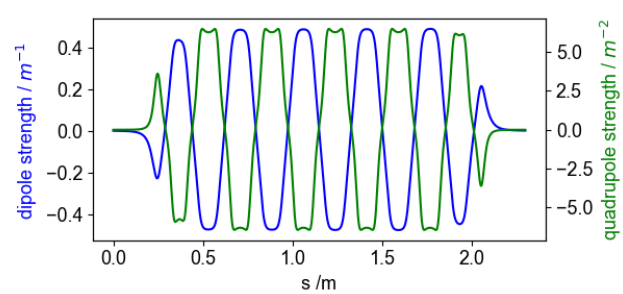

Figure 2: Dipole and quadrupole strength along the reference orbit, quadrupole strength refers to k_1 in Eq. 3.

The Model for Linear Optics

In order to make the calculation of damping partition numbers simpler, the Robinson wiggler is represented by 10000 slices of dipole field with transverse gradient k_1. The reference orbit inside the RW is determined by tracking a reference particle. The 10000 slices are

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distributed uniformly along and perpendicular to the reference orbit, and the gradient values are fitted from the field map corresponding to the reference orbit. The dipole field strength and gradients along the reference trajectory are plotted in Fig. 2 , which are of opposite sign. The transfer matrix of sliced-dipole model compared to that calculated from field map is presented in Eq. (4) and Eq. (5).

$$M_{sliced\ dipole} = \begin{pmatrix} 0.8240 & 2.1655 & 0 & 0 \\ -0.1163 & 0.9078 & 0 & 0 \\ 0 & 0 & 0.6173 & 1.9013 \\ 0 & 0 & -0.3516 & 0.5369 \end{pmatrix} \quad (4)$$

$$M_{field\ map} = \begin{pmatrix} 0.8238 & 2.1655 & 5.6103E\text{-}6 & 8.2740E\text{-}7 \\ -0.1164 & 0.9076 & 5.0739E\text{-}6 & 5.0739E\text{-}6 \\ 5.9191E\text{-}6 & 2.9399E\text{-}6 & 0.6171 & 1.9012 \\ 5.3166E\text{-}6 & 8.7883E\text{-}6 & -0.3518 & 0.5367 \end{pmatrix} \quad (5)$$

The Model for Nonlinear Dynamics

For the non-linear dynamics, a generating function (GF) is introduced to model the wiggler for symplectic tracking [11, 12]. A generating function is built with the initial particle positions q_{xi}, q_{yi} and the final momenta p_{xf}, p_{yf}, as described in Eq. (6) [13-15].

$$F(q_{xi}, q_{yi}, p_{xf}, p_{yf}) = \sum_{k+l+m+n=1}^{M} a_{klmn} q_{xi}^{\ k} q_{yi}^{\ l} p_{xf}^{\ m} p_{yf}^{\ n} \quad (6)$$

$$p_{xi} = \frac{\partial F}{\partial q_{xi}}, p_{yi} = \frac{\partial F}{\partial q_{yi}}, q_{xf} = \frac{\partial F}{\partial p_{xf}}, q_{yf} = \frac{\partial F}{\partial p_{yf}} \quad (7)$$

The effects of Robinson wiggler to particle motion are sampled by tracking a bunch of particles through the field map with fixed energy. The coefficients a_{klmn} are fitted from the initial and final momenta and positions. When the generating function F is built, p_{xf}, p_{yf}, q_{xf}, q_{yf} can be obtained successively by solving nonlinear equations in Eq. (7).

$$16 \cdot \chi^2 = (q_{xfGF} - q_{xfRK})^2 + (p_{xfGF} - p_{xfRK})^2 + (q_{yfGF} - q_{yfRK})^2 + (p_{yfGF} - p_{yfRK})^2 \quad (8)$$

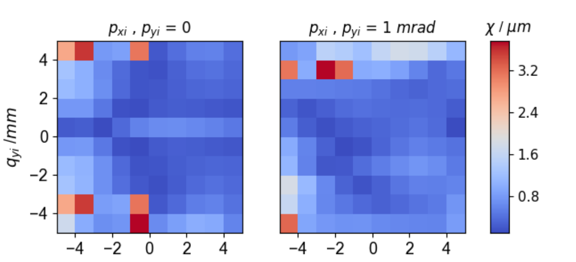

Figure 3: Discrepancy of GF compared to RK tracking.

In this paper a 6th order GF with 209 coefficients is used to model the Robinson wiggler. The coefficients are fitted from the multi-particle tracking with the initial condition of [-5mm < x_i , y_i< 5mm, -1 mrad< p_{xi}, p_{yi} < 1 mrad]. The discrepancy of GF compared to Runge-Kutta (RK) tracking for each particle is defined in Eq. 8. The discrepancy of GF tracking is depicted Fig. 3, the average χ is ~ 1 μm. It is shown in Fig. 4 that the symplecticity is conserved in tracking a particle through the RW for 10000 turns with GF method.

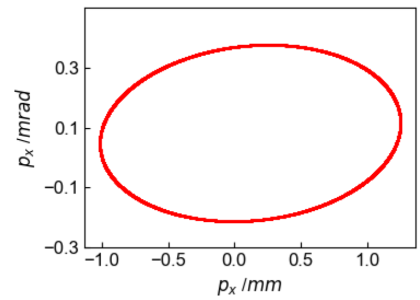

Figure 4: Phase space tracked with GF method.

LATTICE OPTIMIZATION RESULTS

Touschek Lifetime Optimization

The Robinson wiggler has strong focusing effect, therefore the existing optics should be rematched and optimized for a good Touschek lifetime. The magnet lattice of MLS is characterized by 4-fold double-bend achromat (DBA) symmetry. In the lattice optimization the symmetry is broken and the 24 independently powered quadrupoles are used for tuning.

A Python code is used to calculate the linear optics. The Touschek lifetime calculation module is included based on [15], which has been verified with routine operation data. A multi-objective particle swarm optimization algorithm [16] is used to explore the expected optics. The objective function contains:

1. Constraints:
    - Maxium beta functions: $\beta_{x,y}$ < 20 m
    - Maxmum dispersion: $|\eta_x|$< 2 m
    - Damping partition: D > -1.7
    - Transverse beam sizes and divergences at user beamlines less than existing values
2. Objectives to optimize:
    - Horizontal emittance
    - Touscheck lifetime
    - Dispersion $|\eta_x|$ at the septum
    - Working point deviation $(\upsilon_x-\upsilon_{x0})^2+(\upsilon_y-\upsilon_{y0})^2$

To sum up, it is expected to find a solution with small emittance and long Touschek lifetime without increasing the transverse beam sizes at the beamlines. Keeping the work point (υ_x, υ_y) same as the present one (υ_{x0},υ_{y0}) will make ramping the RW easier to achieve without crossing the resonance lines. Since the transverse geometric aperture at the injection point is narrowest of the whole storage ring, zero dispersion at the septum is preferred. Damping partition should also be kept larger than -1.7, because the overall lifetime will drop sharply due to the impact of longitudinal quantum lifetime if it is less than -1.93 [2].

The optimized optics in Fig. 5 yields 10.6 h Touschek lifetime with smaller horizontal emittance compared to 6.5 h in standard user mode. If the beam sizes at beamlines are kept same as present values, larger white

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noise excitation amplitude is needed, thus leading to 13.5 h Touschek lifetime.

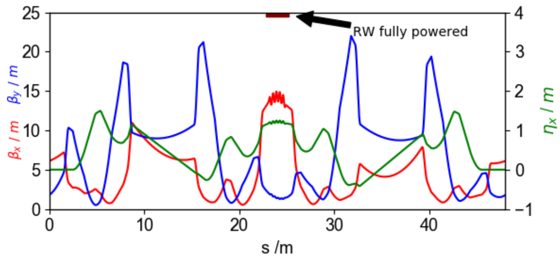

Figure 5: Optimized optics with fully powered RW.

Dynamic Aperture Optimization

The sextupoles in the MLS storage ring are grouped into 6 independent powered families, which are used to correct the chromaticities and adjust the dynamic aperture. Two octupole families are also used to compensate possible octupole contributions from the RW.

The preliminarily optimized sextupole and octupole settings for the RW optics yield the dynamic aperture plot after tracking 5000 turns in Fig. 6. It shows good results compared to the transverse beam size in the order of 0.5 mm. Nevertheless, it indicates that the nonlinear effect of Robinson wiggler is not negligible, while the dynamic aperture of the present standard user operation mode is larger than geometric aperture. Moreover the tracking should be verified with mature codes.

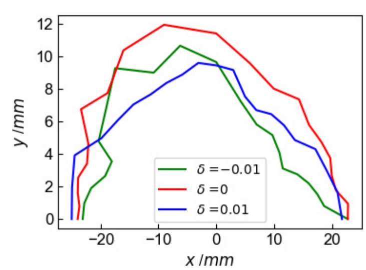

Figure 6: Dynamic aperture for 100% powered RW.

Ramping Process

Ramping process means increasing the current in coils of the RW to a fully powered state. The optics should be adjusted corresponding to the coil current of the RW with the aim of preserving the beam. In the smooth transition of optics, the transverse working point are kept constant (3.178, 2.232), these are the values of standard user mode. The Touschek lifetime is also optimized to lower the beam loss during the transition.

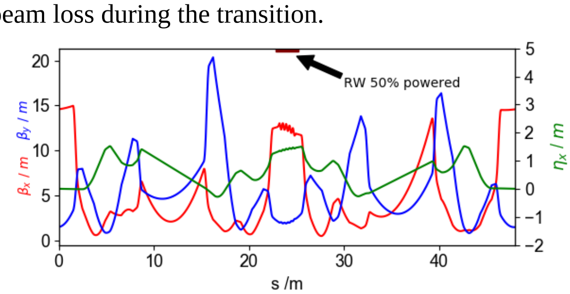

Figure 7: Optimized optics with 50% powered RW.

Several intermediate optics have been developed for the ramping process. As an example, the linear optics and its dynamic aperture for the 50% powered Robinson wiggler are plotted in Fig. 7 and 8.

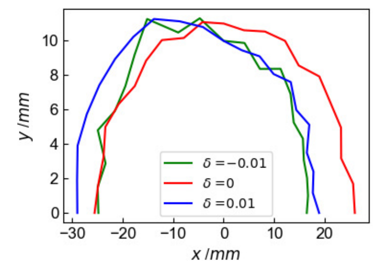

Figure 8: Dynamic aperture for 50% powered RW.

CONCLUSION AND OUTLOOK

The models of Robinson wiggler have been established for the linear optics and nonlinear dynamics. Simulation results indicate that the RW can be smoothly ramped up to fully powered state without crossing the resonance lines. In the mean time, the Touschek lifetime can be maintained based on proper matched linear optics and optimized sextupole and octupole settings.

As a starting point for systematical study, the GF method shows the advantages of speed and symplecticity. However, the number of coefficients depends on the order of the GF. When the higher order multipole components in the wiggler play a significant role in nonlinear dynamics, a higher order generating function is required, which makes the coefficients fitting difficult. Moreover, the generating function method is implicit, the output positions and momenta need to be solved from the nonlinear equations. Numerical errors could be introduced in the solving of the nonlinear equations and may result in symplecticity not being conserved during the tracking

For future operation at the MLS, in-depth study of modeling the Robinson wiggler is ongoing. More detailed simulations should be done and crosschecked with other codes to guarantee ramping up the wiggler smoothly with minimum beam loss and promising Touschek lifetime increase in operation.

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