

MODEL-BASED ALGORITHM TO TUNE THE LCLS OPTICS

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Abstract

Transverse phase space matching of electron beam to the undulator optics is important for achieving good performance in free-electron lasers. Usually there are dedicated matching quadrupoles distributed in the beamline, by measuring the beam phase space the matching quadrupoles are calculated and adjusted to match to the designed Twiss parameters. Further adjustment of the quadrupoles to overcome collective effects or realistic beam line errors is typically required for performance improvement. In this paper, we studied a method to decompose the Twiss parameters for an independent control of the phase space. Mathematical analysis and numerical simulations are both presented to show that through combining the quadrupoles into some multi-knobs, we can control the Twiss parameters independently.

INTRODUCTION

The X-ray free-electron laser (XFEL) has established itself as the brightest available source of X-rays, extending the coherence and brilliance properties of conventional atomic lasers down to the sub-Angstrom level with the unequivocal success of existing XFEL facilities such as LCLS [1], and SACLA [2]. In the operation of an XFEL facility, the transverse phase space matching of electron beam to the undulator optics plays a very important role to achieve good performances, affecting the X-ray's available power and spectral properties [3–5]. In the beam line of an XFEL facility, for example, LCLS, there are many quadrupoles to control the envelope of the electron beam. Some of them are dedicated matching quadrupoles distributed in the beam line while others are set as the designed values. By measuring the beam phase space, the matching quadrupoles are calculated and adjusted to match to the designed Twiss parameters. In addition, further adjustment of the quadrupoles to overcome the collective effects of the electron beam or the realistic beam line errors is typically required for performance improvement. Usually these matching quadrupoles are optimized by matching GUI and operator manual tweaking. However, as the quadrupoles are coupled with all Twiss parameters and the collective effects are unpredictable, the optimization process is usually tedious, time-consuming and not fully repeatable.

Online optimization may provide an alternative approach to seek the optimal quadrupole setting. By tuning the quadrupoles to optimize FEL performance with an effective online optimization algorithm such as the robust conjugate direction search (RCDS) method [6], one could reach the desired optics matching condition directly, with all machine imperfections and collective effects included. When using

the RCDS method, it is important to combine optimization parameters to form conjugate knobs in order to achieve high optimization efficiency.

It has been proposed to combine quadrupoles into multi-knobs and to use them with the online optimization algorithm RCDS to improve transport line optics matching [6], where the response matrix of the second order moments of the electron beam distribution w.r.t. the quadrupoles are used to derive the independent knobs. In a 2014 experiment on BEPC-II, the response matrix of Twiss parameters and dispersion functions at the interaction point (IP) w.r.t. quadrupoles is used to derive knobs that change β_x , β_y , and D_x at the IP, respectively, while keeping α_x , α_y , and D'_x fixed [7]. The knobs were used with RCDS to optimize the luminosity of the collider. The same approach is applicable to optics matching for FEL.

In this paper, we study a method to decompose the Twiss parameters for an independent control of the phase space, which provides a strategy to tune the beam line optics automatically and efficiently and help improve and repeat the machine performance. Mathematical analysis and numerical simulations are both presented to show that through combining the quadrupoles into some multi-knobs, we can control the Twiss parameters independently.

MODEL-BASED QUADRUPOLE ANALYSIS

We analyze the effects of the matching quadrupoles on the beam transverse phase space based on designed or measured beam line optics. First we need to get the response matrix of the quadrupoles by adding a small deviation to the them in MAD [8] simulation, which can be defined as

$$R_{ij} = \frac{d\beta_i/\beta_i}{dK_j/K_j}, \quad (1)$$

where R_{ij} is the (i -th, j -th) element of the quadrupole response matrix $R \in M_{4 \times N}$ and N is the total number of used matching quadrupoles ($N \geq 4$). β_i respectively represents the four Twiss parameters ($\beta_x, \alpha_x, \beta_y, \alpha_y$) at the matching point when $i = 1, 2, 3, 4$ and K_j is the designed or nominal value of the j -th quadrupole. $d\beta_i$ is the variation of β_i after changing K_j with dK_j . In this paper, the Twiss parameters are monitored at the entrance of the undulator tunnel.

Doing singular value decomposition (SVD) on the response matrix, we can obtain

$$R = USV^T, \quad (2)$$

where $U \in M_{4 \times 4}$ and $V \in M_{N \times N}$ are unitary matrix and $S \in M_{4 \times N}$ is rectangular diagonal matrix which can be

written as

$$S = \begin{pmatrix} s_1 & 0 & 0 & 0 & 0 & \dots \\ 0 & s_2 & 0 & 0 & 0 & \dots \\ 0 & 0 & s_3 & 0 & 0 & \dots \\ 0 & 0 & 0 & s_4 & 0 & \dots \end{pmatrix}. \quad (3)$$

Let $V = (\vec{v}_1, \vec{v}_2, \vec{v}_3, \vec{v}_4, \dots)$ and $\vec{v}_j \in M_{N \times 1}$ is a vector representing a combination of changes of all quadrupoles. Then we can find that only the first four vectors ($\vec{v}_1, \vec{v}_2, \vec{v}_4, \vec{v}_4$) will have influence on the beam transverse phase space. Other combinations are invalid changes, at least at small change range. So we only need to focus on the first four vectors of V and S can be simplified to $\hat{S} = \text{diag}(s_1, s_2, s_3, s_4)$.

Then we can recombine the quadrupoles based on the new four base vectors ($\vec{v}_1, \vec{v}_2, \vec{v}_4, \vec{v}_4$), and the new response matrix will become

$$\begin{pmatrix} \beta_x \\ \alpha_x \\ \beta_y \\ \alpha_y \end{pmatrix} = U \hat{S} \begin{pmatrix} q_1 \\ q_2 \\ q_2 \\ q_3 \end{pmatrix}, \quad (4)$$

where $(q_1, q_2, q_3, q_4)^T$ is the vector of quadrupole adjustment on the new base vectors, i.e. $(q_1, 0, 0, 0)^T = q_1 \vec{v}_1$.

Letting $(\beta_x, \alpha_x, \beta_y, \alpha_y)^T = (1, 0, 0, 0)^T$, we can obtain the solution that only varies β_x and keeps others almost constant,

$$\begin{pmatrix} q_1 \\ q_2 \\ q_2 \\ q_3 \end{pmatrix}_{\beta_x} = (U \hat{S})^{-1} \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix}. \quad (5)$$

After doing similar procedures for the other three parameters, we can get four knobs and each of them only varies one of the Twiss parameters. This will be very useful and efficient knobs in the operation of XFEL facilities to optimize the beam matching and machine performances.

APPLICATION IN THE LCLS

We apply the above method that can generate four knobs to control the Twiss parameters independently to the linac-to-undulator (LTU) matching in the LCLS. We analyze the effects of matching quadrupoles based on the designed optics at the hard x-ray operation [5]. We use the four quadrupoles in the LTU area which are referred as QEM1~QEM4. First in the MAD simulation we add 1% deviation for each quadrupole and monitor the variation of Twiss parameters at the undulator entrance (marked as DBMARKER37) to obtain the response matrix. We choose the target at the undulator entrance so we can control the transverse phase space independently just before lasing. The values of the matrix element are presented in Fig. 1.

Then using the method of SVD above, we can generate four independently knobs. We test these knobs in the simulation by scanning the change of quadrupole strength and monitoring the Twiss parameters at the matching point. The results of four knobs are presented in the Fig 2~ Fig. 5.

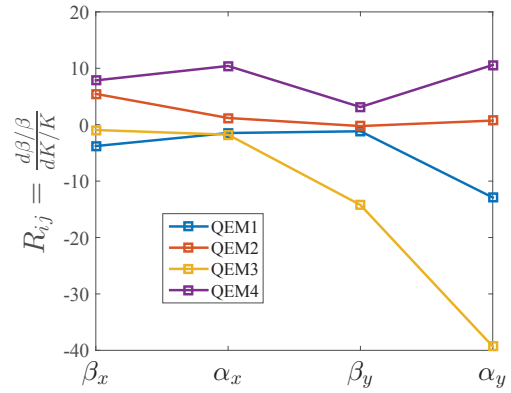


Figure 1: Values of response matrix elements for QEM1~QEM4.

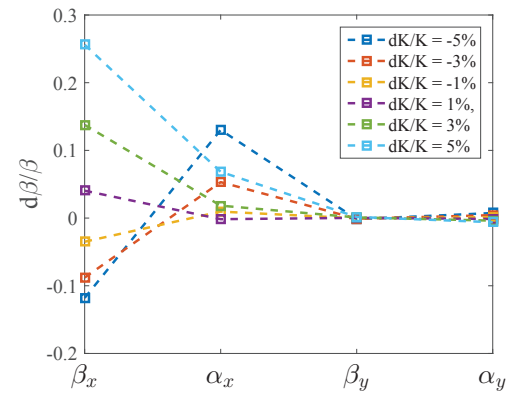


Figure 2: Knob for β_x .

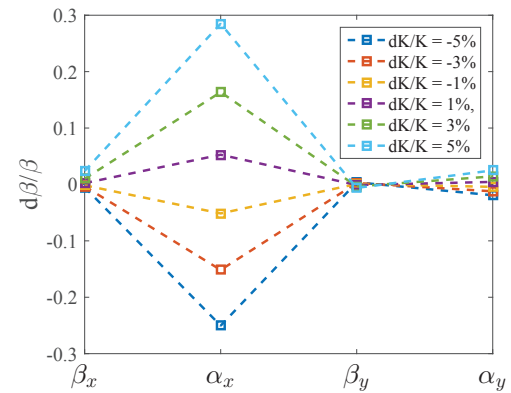


Figure 3: Knob for α_x .

It can be seen that the knobs for α_x and α_y perform well and they have little effects on the other parameters. But the knobs for β_x and β_y are not full independent as they will also respectively vary α_x and α_y . This may be because the values of α_x and α_y are very small and their responses to the change of quadrupoles are not very linear at the range of interest. In the operation we can first adjust β_x and β_y and then vary α_x and α_y .

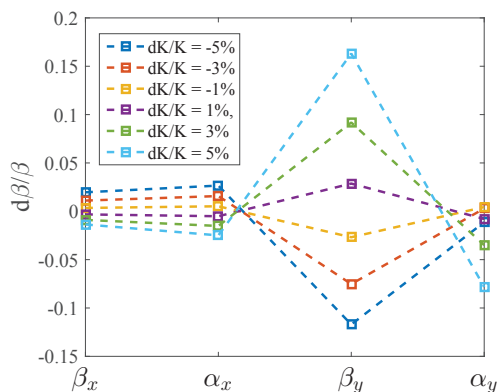


Figure 4: Knob for β_y .

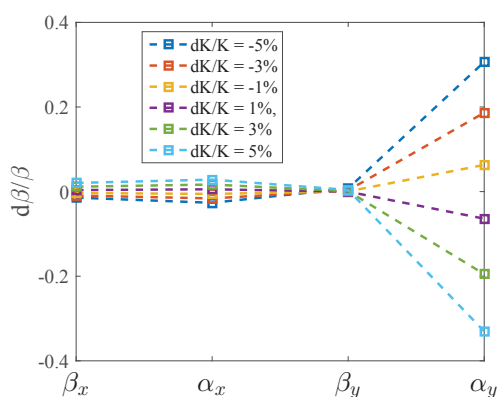


Figure 5: Knob for α_y .

We use the above LTU four quads as an example to demonstrate the method. In the LCLS machine, there are a few other matching stations which can also be adopted to obtain different sets of knobs. For example, in the LI26 area after BC2 there are 8 matching quads and we have also used them to generate four knobs controlling the Twiss parameters independently. With these combined knobs, we use them as variables in the RCDS method to search solutions for achieving best FEL performance.

Recently at the LCLS, we did one test based on a solution from the MAD designed optics at high beam energy (13 GeV). We used the LI26 eight quads and set the target at an emittance station so we can measure the beam Twiss parameters. This preliminary test results show that the α_y knob responded very well, that is, we could adjust α_y independently using the derived knob without affecting others. But other Twiss parameters seem still coupled together. One possible reason could be that the real optics during our measurement deviates from the designed MAD optics, which affects the validity of the derived knobs. More experimental study will follow, and a machine-based response matrix development would be also very helpful.

DISCUSSION

In this paper we study the effects of matching quadrupoles on the beam transverse phase space and recombine them into four knobs to control the four Twiss parameters independently. We show the mathematical analysis to decompose the four knobs and verify them by MAD simulation with the LCLS designed optics. Combined with other searching methods, the four independent knobs can help search for the best work point and improve the performance of the XFELs. For application in an XFEL facility, the key of this method is to get the response matrix for the matching quadrupoles, as there is always difference between the designed optics and the real optics. More work will be done to apply this method in the LCLS.

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