ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-TUPAB313

ARRANGEMENT OPTIMIZATION OF QUADRUPOLES AND CORRECTORS FOR BEAM ALIGNMENT

Liang Xu[1], Qingmin Zhang*
School of Nuclear Science and Technology, Xi'an Jiaotong University, Xi'an, China
NanShun Huang[2], HaiXiao Deng[3]
Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai, China
[1]also at Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai, China
[2]also at University of Chinese Academy of Sciences, Beijing, China
[3]also at Shanghai Advanced Research Institute, Chinese Academy of Sciences, Shanghai, China

Abstract

In the X-ray free-electron laser (XFEL), the alignment and stability of beam orbit have a great impact on power and qualities of the generated X-ray pulses. Currently, the beam-based alignment (BBA) is the most widely used technique in beam alignment. In order to find the best arrangement of quadrupoles and correctors, a mathematical model is established based on the transmission matrix method. With this model, several simple arrangements of quadrupoles and correctors are selected to simulate the beam alignment process. It is found that when two correctors adjust two quadrupoles, the beam can pass through the center of quadrupoles approximately collimated.

INTRODUCTION

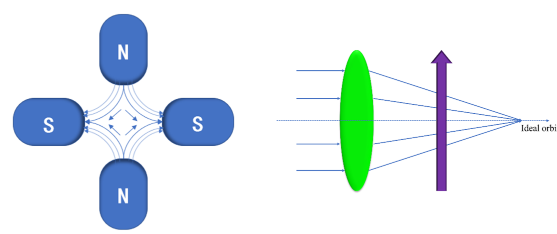
The XFEL uses relativistic electron beams as the medium to generate X-rays, whose wavelength can be easily changed by changing the electron energy or the undulator [1]. The relativistic electron beam is accelerated by a linear accelerator, and then enters the undulator section after passing through the beam transmission system, which consists of drift, corrector and quadrupole. If the beam does not pass through the center of the quadrupole, it will be disturbed by a transverse dipole magnetic field generated by the quadrupole so that its orbit deviate from the ideal orbit. As a result, the internal structure of the electron beams is changed, which has adverse effects for lasing [2]. The deviation of electron beam with respect to the desired orbit is required to be within several microns to ensure the quality of the laser [3]. This orbit can be achieved by the BBA technique which was proposed in 1980s.

Generally, the corrector is used to change the beam direction deviation, BPM is used to measure the beam position, and the quadrupole is applied a changing magnetic field to judge whether the beam passes through the center. In order to use quadrupole, corrector and BPM to correct the beam orbit so that the beam passes through the center of the quadrupole and follows the ideal orbit to reduce the deviation, different structures are simulated to find the best arrangement in this paper.

* zhangqingmin@mail.xjtu.edu.cn

BEAM-BASED ALIGNMENT

In the control of the storage ring of the synchrotron radiation light source, a beam orbit collimation method named "beam-based alignment" is proposed. It can be seen in Fig. 1(a) that the magnetic field intensity at the center of the quadrupole is zero. Therefore, when the beam passes through the center of the quadrupole, its main orbit will not be affected by the quadrupole magnetic fields, which only has a focusing or defocusing effect on the electron beam. In addition, the kick angle of the quadrupole to the electron beam is proportional to the distance from beam position to the quadrupole center and the quadrupole magnetic field strength, shown in Fig. 1(b). When the current of the quadrupole is constant, the farther the beam position is from the center of the quadrupole, the greater the kick angle.



(a) (b)

Figure 1: (a)Magnetic field distribution of quadrupole. (b)The effect of focusing quadrupole on beam.

The kick angle of the electron beam at the same position will change with the focusing intensity of the quadrupole changing, which is proportional to the focusing intensity and expressed by the formula [4]:

$$\Delta\theta = K \cdot \Delta l. \tag{1}$$

We can use BPM to measure the position of the beam and the position change measured by the BPM downstream of the quadrupole can be expressed:

$$\Delta y \propto \Delta\theta, \tag{2}$$

where $\Delta\theta$ is the change in the kick angle of the quadrupole to the beam, K is the focusing intensity of the quadrupole, Δl is the distance between the beam and the center of the quadrupole, and Δy is the position change measured by BPM.

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-TUPAB313

It can be seen from the above formula that the change of the beam position measured by the BPM downstream of the quadrupole is proportional to the distance between the position where the beam passes through the quadrupole and the center of the quadrupole. Therefore, the constant reading of BPM when changing the focusing intensity of the quadrupole indicates that the electron beam orbit passes through the center of the quadrupole [5]. This method is called the ”quadrupole scanning method”.

Scanning quadrupole generally chooses the “alternating modulation of K method”, which is to add a period of sinusoidal change with an amplitude of ΔK to focusing intensity K. The focusing intensity K changes according to the following formula:

$$K = \Delta K \cdot cos(2\pi \cdot \frac{t}{T}) + K_0, \quad (3)$$

where ΔK is the change range of the focusing intensity, t is the current time, T is the period, and K_0 is the fixed focusing intensity of the quadrupole.

SIMULATION

There are many correctors in XFEL facility to change the beam trajectory so that the beam passes through the center of the quadrupole to reduce the influence of the transverse dipole field generated by the quadrupole on the beam trajectory. In order to simulate the beam alignment under different arrangements of correctors and quadrupoles, a simple simulation program was written using Python and PyQt. The program can construct a system model based on the transmission matrix of the elements to simulate the evolution of the transverse beam position [6]. We assume that the BPM electrical center and the quadrupole ferromagnetic center are both on the ideal orbit. The beam control in the horizontal direction and the vertical direction are the same, so only the beam alignment in the horizontal direction is simulated.

We have selected three arrangement structures, one-to-one correction, two-to-one correction and two-to-two correction, as shown in the Fig. 2 and the parameters are shown in Table 1.

Table 1: Parameters of Device and Initial Information of Beam

Description	Parameters
Drift	Width: 0.25 m
BPM1 & BPM2	Width: 0 m
Q1 & Q2	Width: 0.2 m
	K: 10
	ΔK: 5
C1 & C2	Width: 0 m
Beam Initial Information	x: 15.527 4 µm
	x′: 7.316 9 µrad
	Energy: 800 MeV

One-to-one correction means that a corrector adjusts the beam orbit to make it pass through the center of a quadrupole.

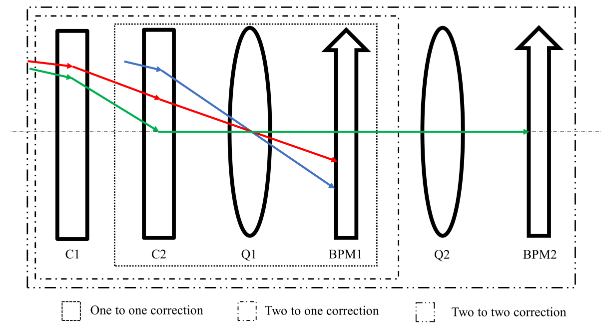


Figure 2: Schematic diagram of the three arrangements. The blue line represents the beam orbit after one-to-one correction, the red line represents the possible beam orbit after two-to-one correction, and the green line represents the target beam orbit.

In simulation, the initial beam position amplitude measured by BPM1 is 3.5606 µm. When the kick angle provided by corrector C1 is -75.9658 µrad, the beam position amplitude reaches the lowest value of 0.0021 µm. Within a certain error range, it can be considered that the beam passes through the center of Q1.

Although this method is very simple, after adjustment, it is found that because of the beam is not at the level of the magnetic center of Q1 when passing through the C2, the beam will pass through the center of Q1 with a certain angle, as shown the blue line in the Fig. 2. Because of the angle, the beam orbit deviates from the ideal orbit, which adversely affects the subsequent correction.

Two-to-one correction means that two correctors adjust the beam orbit so that it passes through the center of a quadrupole. In the one-to-one correction, the position of the beam reaching C2 cannot be changed, so a corrector C1 can be added to change the position of the beam reaching C2. The initial amplitude measured by BPM1 during the simulation is 3.4971 µm. When the kick angle of C1 is -21.53 µrad and C2 is -31.64 µrad, the amplitude measured by BPM1 is 0.0020 µm. But at the same time, it is found that there are multiple combinations of C1 and C2 to make the amplitude measured by BPM1 at the minimum. Therefore, when only referring to the amplitude measured by BPM1, the beam orbit also may pass through the center of the quadrupole at a certain angle, as shown the red line in the Fig. 2.

In the two-to-one correction, it is impossible to determine whether the beam orbit passes through the center of the quadrupole along the ideal orbit. For this reason, a quadrupole Q2 is added to form a structure of two-to-two correction. When the amplitudes measured by BPM1 and BPM2 are both close to zero, it indicates that the beam orbit coincides with the ideal orbit, and the correction purpose is achieved, as shown the green orbit in the Fig. 2. The adjustment process is to adjust C1 until the amplitude measured by BPM1 is the minimum, and then adjust C2 until the amplitude measured by BPM2 is the minimum, and repeat the above steps until the amplitude measured by the two BPMs are both at the minimum to obtain the optimal beam orbit.

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-TUPAB313

Simulating the two-to-two correction, the initial amplitude measured by BPM1 is 3.4971 µm and measured by BPM2 is 16.4828 µm. After 20 adjustments, the final angle of C1 and C2 are -74.14 µrad and 74.18 µrad respectively, the measured amplitude of BPM1 is 0.0261 µm and the measured amplitude of BPM2 is 0.0029 µm, as shown in the Fig. 3. Within a certain error range, it can be considered that the beam orbit passes through the centers of two quadrupoles. From the Fig. 4, we can see that the beam orbit the beam orbit coincides with the ideal orbit after correction. It can be seen from the Fig. 5 that the beam orbit changes during the correction process.

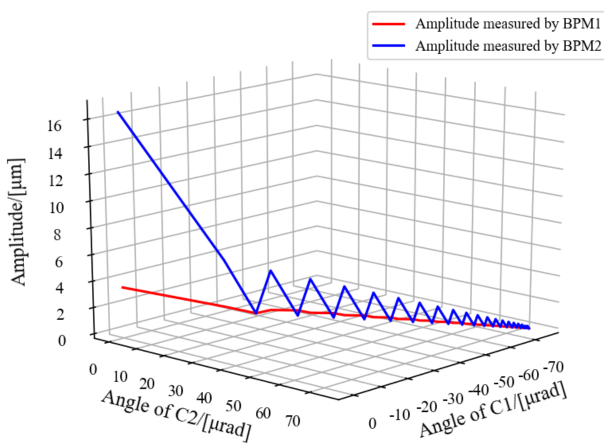


Figure 3: Changes of beam position amplitude in two-to-two correction adjustment.

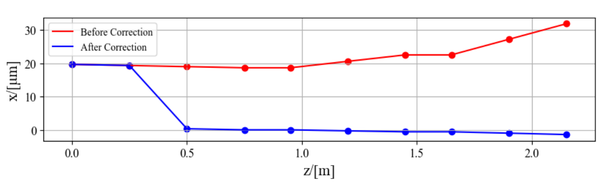


Figure 4: The beam orbits before and after two-to-two correction.

Through the above simulation, the two-to-two correction can kick the beam orbit back to the ideal orbit and horizontally pass through the center of the quadrupole. The two-to-two correction can avoide the beam orbit from passing through the center of quadrupoles with a large direction deviation which will have a bad effect on beam focusing and existing many deflections.

CONCLUSION

In this paper, We simulate three structures and can get the following conclusion that to make the beam pass through the quadrupole center and ensure that the orbit is basically consistent with the ideal orbit, and at least two BPM-Quadrupole units are required to judge the orbit collimation degree. Therefore, in the design of the beam transmission system,

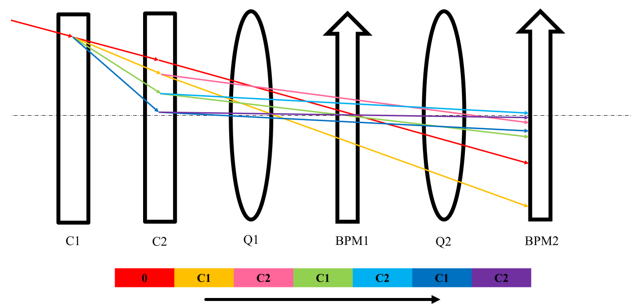


Figure 5: Changes of beam orbit during the correction process. The arrows indicate the order of corrections and the word corresponding to the color indicates the corrector which is adjusted in corresponding correction.

this kind of structural unit can be used for the efficient and convenient beam adjustment work in the later stage. The manual optimization process is a repetitive work, and the automatic optimization program is compiled in the later stage to realize the automation of beam adjustment. At the same time, in order to improve the efficiency of optimization, intelligent optimization algorithms (genetic algorithm, particle swarm algorithm, etc.) can be introduced.

ACKNOWLEDGMENT

The authors would like to thank H.X. Yang and D. Gu for helpful discussions on beam alignment. This work was partially supported by the National Key Research and Development Program of China (Grants No.2016YFA0401901, No.2018YFEO103100) and the National Natural Science Foundation of China (Grants No.11935020, No.11775293).

REFERENCES

[1] N. Huang *et al.*, "Features and futures of X-ray free-electron lasers", *The Innovation.*, vol. 2, no. 2, p. 100097, 2021. doi:10.1016/j.xinn.2021.100097

[2] D. Gu, Q. Gu, D. Huang, M. Zhang, and M. H. Zhao, "Study of Beam-Based Alignment for Shanghai Soft X-Ray FEL Facility", in *Proc. 26th Linear Accelerator Conf. (LINAC'12)*, Tel Aviv, Israel, Sep. 2012, paper SUPB006, pp. 10–12.

[3] T. Tanaka, H. Kitamura, and T. Shintake, "Consideration on the BPM alignment tolerance in X-ray FELs", *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 528, pp. 72-178, 2004. doi:101016/jnima200404040

[4] G. Duan and Z. MinGhua, "Beam alignment for SXFEL", *High Power Laser and Particle Beams*, vol. 24, no. 09, pp. 2183-2168, 2012. doi:10.3788/hplpb20122409.2183

[5] Y. Cao *et al.*, "Methods of measurement for the Beam-based alignment system in HLS", *IEEE Symposium Conference Record Nuclear Science 2004*, vol. 3, 2004. doi:10.1109/NSSMIC.2004.1462593.

[6] T. Hu *et al.*, "Beam Diagnostic of the LINAC for the Compact High-Performance THz-FEL", in *Proc. 6th Int. Particle Accelerator Conf. (IPAC'15)*, Richmond, VA, USA, May 2015, pp. 987–989. doi:10.18429/JACoW-IPAC2015-MOPTY023