MEDSI 2023 Beijing
Mechanical Engineering Design of Synchrotron Radiation Equipment and Instrumentation
The 12th International Conference on Mechanical Engineering Design of Synchrotron Radiation Equipment and Instrumentation
November 06 - 10, 2023 · Beijing, China
HOST:

Shape Optimization Design of Monochromator Pre-mirror in FEL-1 at S³FEL

深圳综合粒子设施研究院
Institute of Advanced Science Facilities, Shenzhen

Zhongmin Xu [1], Chuan Yang [1], Yinpeng Zhong[1], Weiqing Zhang [1,2]

(1. Institute of Advanced Science Facilities, Shenzhen , 518107,China)
(2. Dalian Institute of Chemical Physics, Chinese Academy of Sciences, Dalian, 116023,China)

Introduction

The Shenzhen Superconducting Soft X-ray Free Electron Laser (S³FEL) is a new light source under construction phase at Institute of Advanced Science Facilities (IASF), Shenzhen. S³FEL consists of 2.5GeV CW superconducting linear accelerator and four initial undulator lines, aiming to generate X-rays between 40eV and 1keV at rates up to 1MHz. According to the Maréchal Criteria, in order to meet the needs of FEL wavefront coherent transmission, the height error RMS of the pre-mirror mirror should be less than 0.9nm and the slope error RMS should be less than 100nrad, which are more stringent than those of the mirrors in synchrotron radiation facilities. Therefore, it is necessary to choose an appropriate shape control scheme.

Monochromator Pre-mirror Model and Boundary Conditions

The structure of the monochromator shown as Figure1 is different with that of LCLS-II, European XFEL and SwissFEL. It consists of a front plane mirror and plane variable-line-spacing grating. During the course of the pre-mirror off-axis rotation, the spot centres of different wavelengths on the surface are moving. Meanwhile, the pre-mirror will absorb high heat load, resulting in serious local bulging and bending deformation. If the traditional cooling methods are adopted, the mirror shape is unlikely to meet all of the working conditions.

Table 1: Footprints Information for three wavelengths

Wavelength	Length of Footprint	Absorbed Power
1nm	150mm	5.46W
2nm	174mm	11.2W
3nm	200mm	16.65W

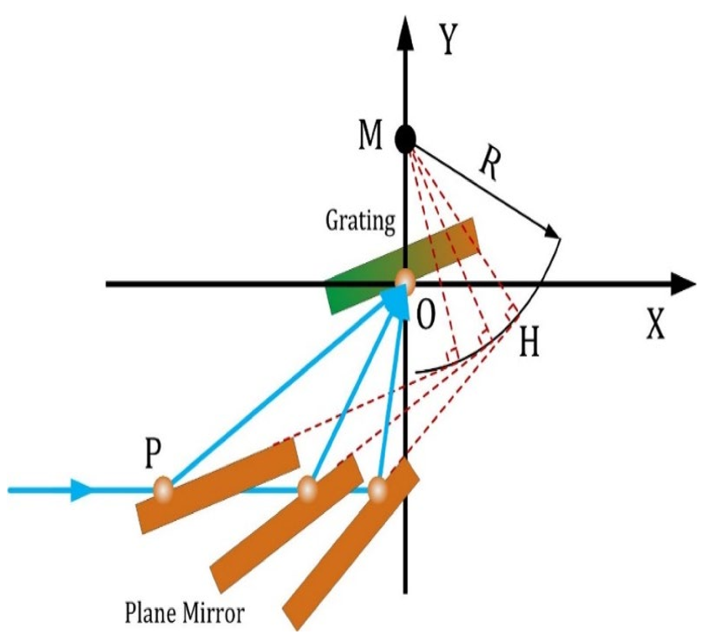

Figure 1: Structure of Grating monochromator in FEL-1.

Table 2: Specifications for the pre-mirror

Substrate	Silicon
Coating	B4C
Size	700×60×60mm³
Effective size	700×30mm²
Shape	Plane

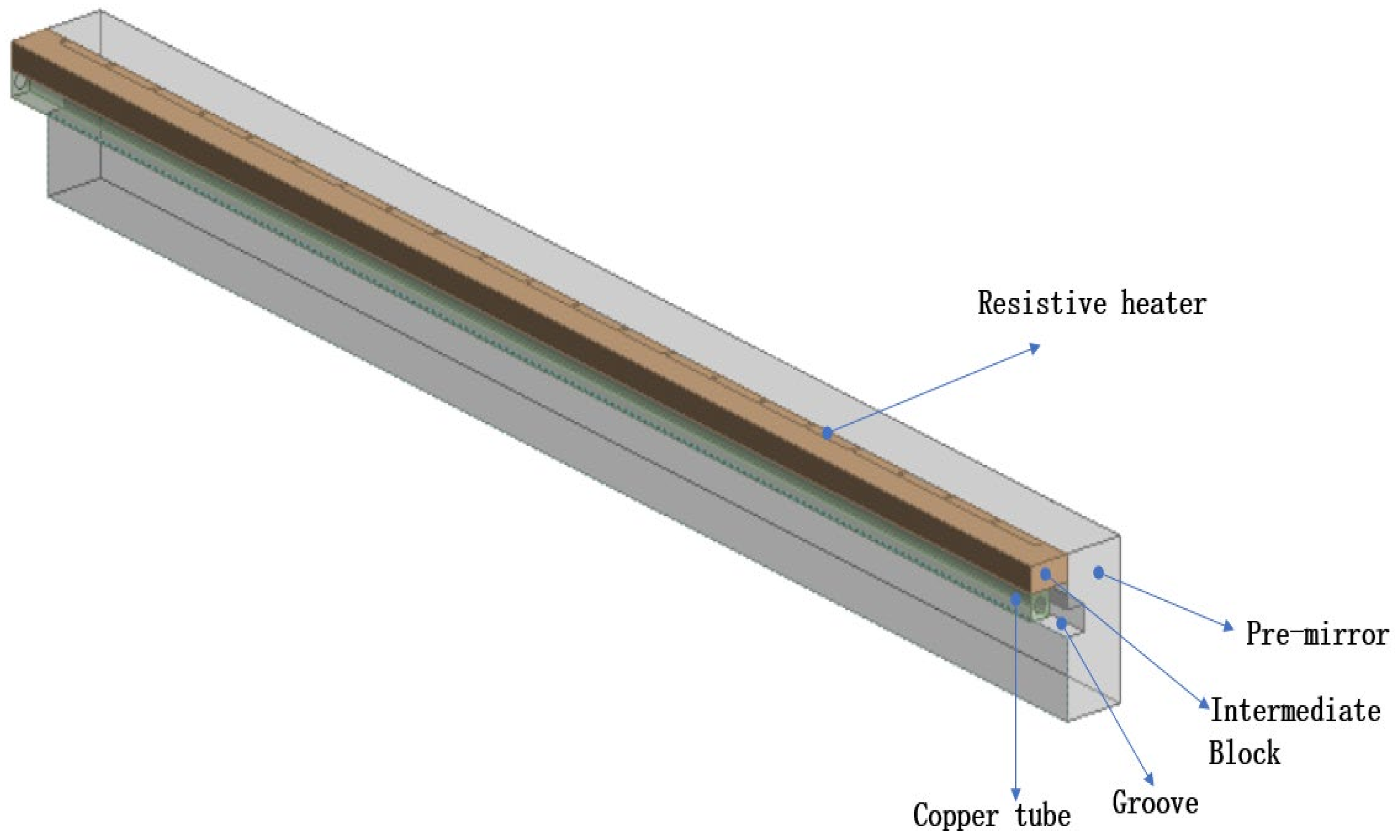

Figure 2: Pre-mirror and shape compensation system in FEL-1

According to REAL scheme proposed by Zhang, this paper establishes a 3D model and shape compensation system for the pre-mirror in Ansys Workbench. Considering the symmetry of the model and boundary conditions, only half of the model was used, as shown in Figure 2. As a plane mirror (grey part), its specifications are listed in Table 2. A groove is opened along the side of the mirror. while the copper tube is used to circulate cooling water. Its inner diameter of the tube is 6mm, and the applied heat transfer coefficient is 5E-3 W/mm²/° C. 21 electric heaters are attached to the intermediate block (made of silicon) for compensating the mirror shape. To simplify the model, all heaters have been omitted. Instead, 21 rectangles representing the positions of the heaters are drawn on the intermediate block, with each rectangle measuring 30mm*5mm, and a distance of 2mm between two rectangles. The corresponding heat flux generated by each heater is applied equivalently on the rectangle.

Mathematical model

In this case, the actual deformation of the pre-mirror is induced by processing, clamping, gravity and heat, etc. Taking the thermal compensation into account, the final deformation can be expressed by MHCKF model.

$$M(x)H + C(x) + K(x) = F(x) \qquad (1)$$

where *M(x)* is the response function of the electric heaters; *H* is a series of the heat fluxes; *C(x)* is the mirror initial deformation; *K(x)* is the deformation in the meridional direction caused by the X-ray power; *F(x)* represents the actual deformation generated by the three left terms.

For this case, it was found that the ideal form of *F(x)* is a straight line, and its intercept value in the Cartesian coordinate system is close to the maximum thermal deformation caused by X-rays. Therefore, *F(x)* can be written as follows.

$$F(x) = (max(K\ (x)) + \varepsilon)I \qquad (2)$$

where $max(K\ (x))$ is the maximum deformation value of *K(x)*; ε is a perturbation term; *I* is a column vector of all 1s.

The least squares solution of *H* can be calculated using expression (3).

$$H \approx \left(M^T(\mathrm{x})M(\mathrm{x})\right)^{-1} M^T(\mathrm{x})(-C(x) - K(x) + (max(K\ (x)) + \varepsilon)I) \qquad (3)$$

Heaters Response Functions

To obtain the response function of each heater shown in Figure 2, apply a heat flux of 0.001W/mm² sequentially to each rectangle on the intermediate block using Ansys Workbench. After thermal analysis, all deformation curves are shown in Figure 3. Finally, these deformations values are divided by 0.001W/mm² to obtain the Heaters Response Functions (HRF) of the heaters.

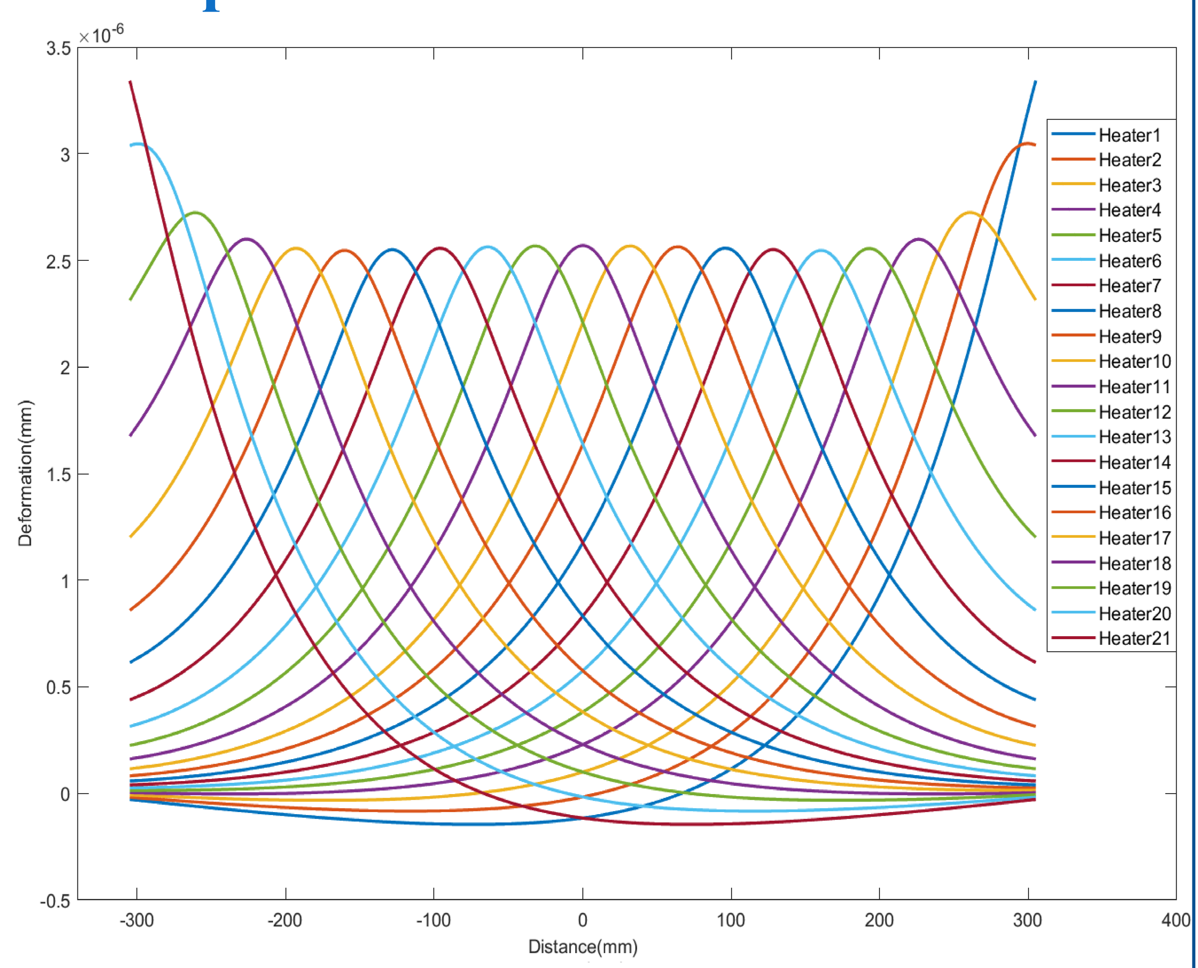

Figure 3: The deformation curves calculated by Ansys sequentially.

Optimization Results

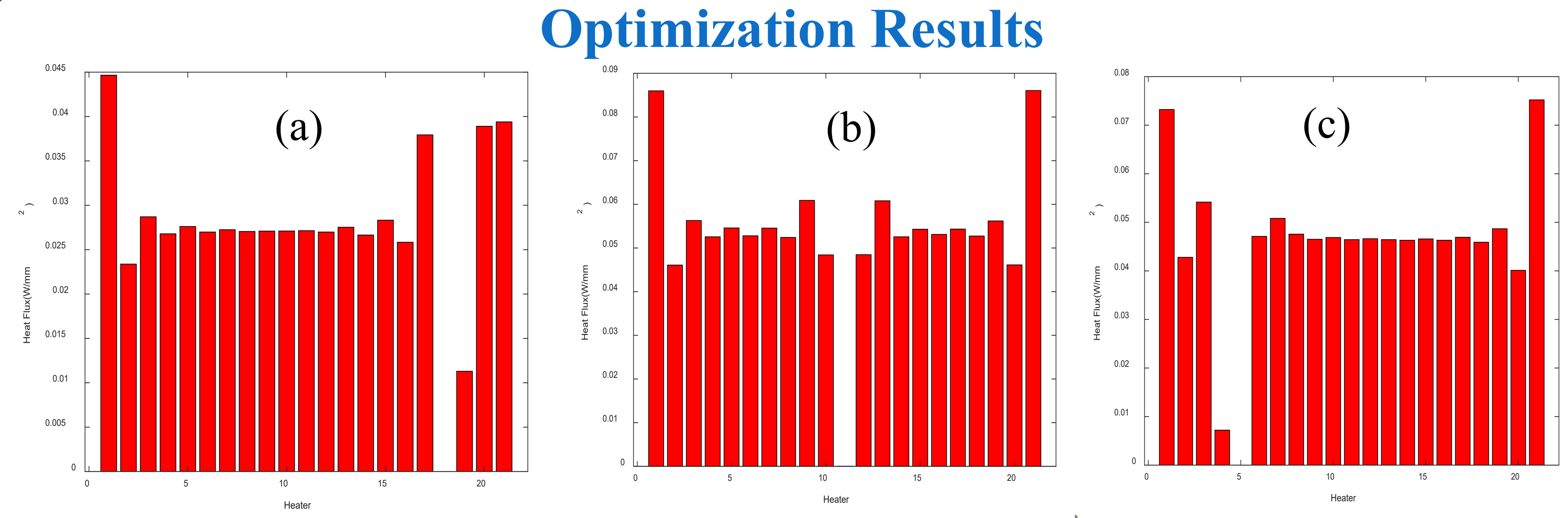

Figure 4: Heat Fluxes through optimization for (a) 1nm X-ray;(b)2nm X-ray;(c)3nm X-ray.

It is assumed that the initial deformation for the pre-mirror is negligible in the simulation, so that *C(x)* doesn't need to be considered. Thus, to solve *H* in expression (3), only perturbation term, ε, is unknown. Therefore, by continuously searching for ε, the heat flux values applied to all electric heaters can be found, shown as Figure 4.Then, all heat fluxes are used as boundary conditions to evaluate the thermal, deformation, and surface shape results using finite element analysis software. From Table3, both height and slope error RMS are much less than required.

Table 3: Shape error for three wavelengths

Wavelength	Height error RMS	Slope error RMS
1 nm	0.29 nm	11.85 nrad
2 nm	0.31 nm	13.03 nrad
3 nm	0.27 nm	10.81 nrad

Conclusions

In this paper we only calculated the shape compensation at the left, middle, and right positions of the pre-mirror for three wavelengths. It can be seen that the shape compensation scheme using the electric heaters and the MHCKF model are effective for solving the pre-mirror shape problem caused by the moving X-ray.

Acknowledgements

This research was funded by the National Natural Science Foundation of China (Grant No. 22288201) and Scientific Instrument Developing Project of the Chinese Academy of Sciences (Grant No. GJJSTD20190002).