ISBN: 978-3-95450-250-9 ISSN: 2673-5520 doi:10.18429/JACoW-MEDSI2023-THPPP012

SHAPE OPTIMIZATION DESIGN OF MONOCHROMATOR PRE-MIRROR IN FEL-1 AT S^{3}FEL*

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Abstract

For the monochromator pre-mirror in FEL-1 at S^{3}FEL, the deformation induced by high heat load result in severe effects on the beam quality during its off-axis rotation. To meet the pre-mirror shape error requirement for X-ray coherent transport, an integration of passive cooling and active heating systems for thermal management of the monochromator pre-mirror has been proposed, developed, and modelled. An active heating system with multiple electric heaters is adopted to compensate for the pre-mirror shape further. Finally, using MHCKF model, the optimization of multiple heat fluxes generated by all electric heaters was accomplished. The results show that the thermal management using passive cooling and active heat schemes is effective to obtain high-precision surface shape for the pre-mirror.

INTRODUCTION

The Shenzhen Superconducting Soft X-ray Free Electron Laser (S^{3}FEL) is a new light source under construction phase at Institute of Advanced Science Facilities (IASF), Shenzhen. S^{3}FEL consists of 2.5 GeV CW superconducting linear accelerator and four initial undulator lines, aiming to generate X-rays between 40eV and 1 keV at rates up to 1 MHz [1]. According to the Maréchal Criteria [2], in order to meet the needs of FEL wavefront coherent transmission, the height error RMS of the pre-mirror mirror should be less than 0.9 nm and the slope error RMS should be less than 100 nrad, which are more stringent than those of the mirrors in synchrotron radiation facilities. Therefore, it is necessary to choose an appropriate shape control scheme.

PRE-MIRROR MODEL AND BOUNDARY CONDITIONS

The structure of the monochromator shown as Figure1 is different with that of LCLS-II, European XFEL [3]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 of 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.

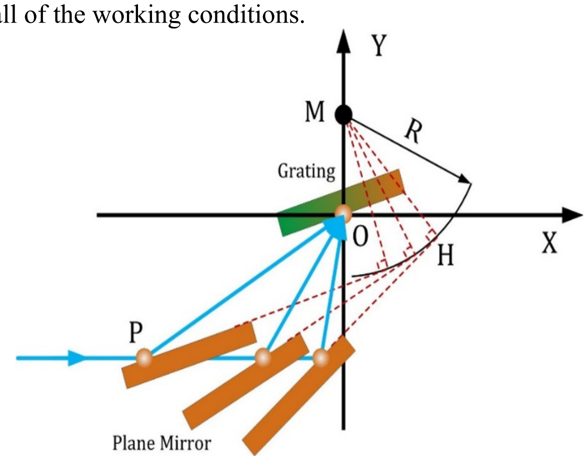

Figure 1: Structure of Grating monochromator in FEL-1.

Power density distributions of wavelength 1-3 nm absorbed by the pre-mirror in beamline FEL-1 are shown Figures. 2, 3 and 4. And the footprints information for three wavelengths are listed in Table 1. Footprint centre of 2 nm X-ray is located at the centre of pre-mirror, while those of other two wavelengths on either side. Though their maximum power density for each wavelength is not much different, the absorbed power of each wavelength is quite different.

Table 1: Footprints Information for Three Wavelengths

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

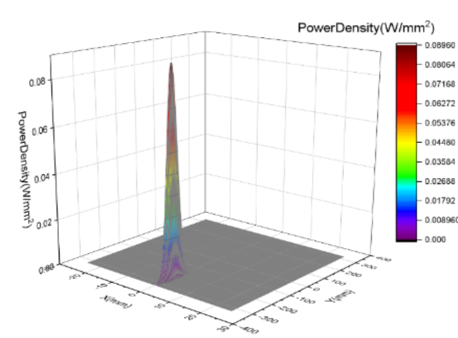

Figure 2: Power density distribution of wavelength 1 nm.

* Work supported 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)
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ISBN: 978-3-95450-250-9 ISSN: 2673-5520 doi:10.18429/JACoW-MEDSI2023-THPPP012

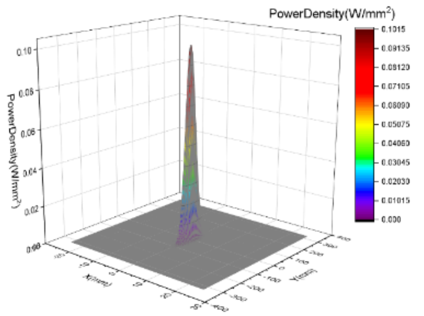

Figure 3: Power density distribution of wavelength 2 nm.

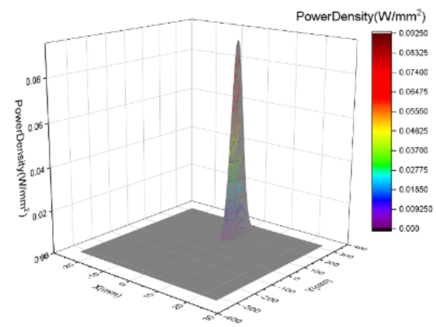

Figure 4: Power density distribution of wavelength 3 nm.

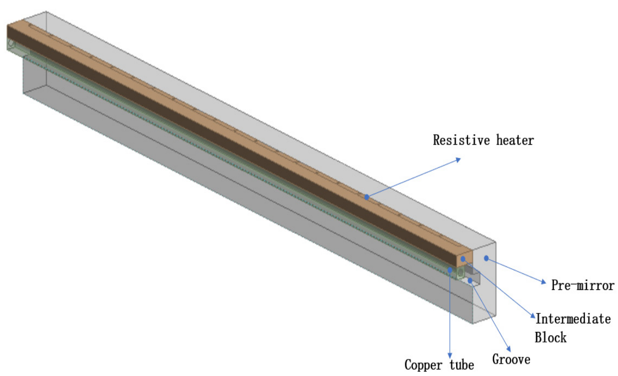

Figure 5: Pre-mirror and shape compensation system in FEL-1.

Table 2: Specifications for the Pre-mirror

Substrate	Silicon
Coating	B_4C
size (mm^3)	700×60×60
Effective size (mm^2)	700×30
Shape	Plane

According to REAL scheme proposed by Zhang [4], this paper establishes a 3D model and shape compensation system for the FEL-1 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 5. 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/mm^2/°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 30 mm*5 mm, and a distance of 2 mm 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 [5].

$$M(x)H + C(x) + K(x) = F(x) \tag{1}$$

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 caused by the processing, clamping, and gravity, etc.; *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.

In our 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.

$$F(x) = (max(K\ (x)) + \varepsilon)I \tag{2}$$

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).

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

HEATERS RESPONSE FUNCTIONS (HRF)

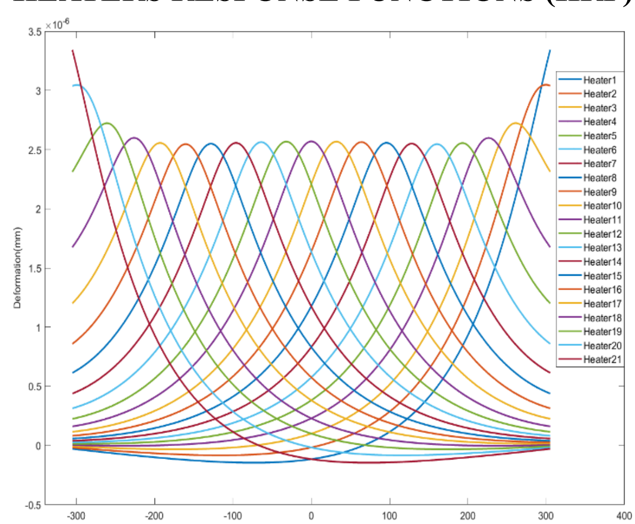

Figure 6: The deformation curves calculated by Ansys sequentially.

To obtain the response function of each heater shown in Figure 5, apply a heat flux of 0.001 W/mm^2 sequentially to each rectangle on the intermediate block using Ansys Workbench. After thermal analysis, all deformation curves are shown in Figure 6. Finally, these deformations values are divided by 0.001 W/mm^2 to obtain the Heaters Response Functions (HRF) of the heaters.

OPTIMIZATION RESULTS

It is assumed that the initial deformation for the pre-mirror is negligible in this 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 7.

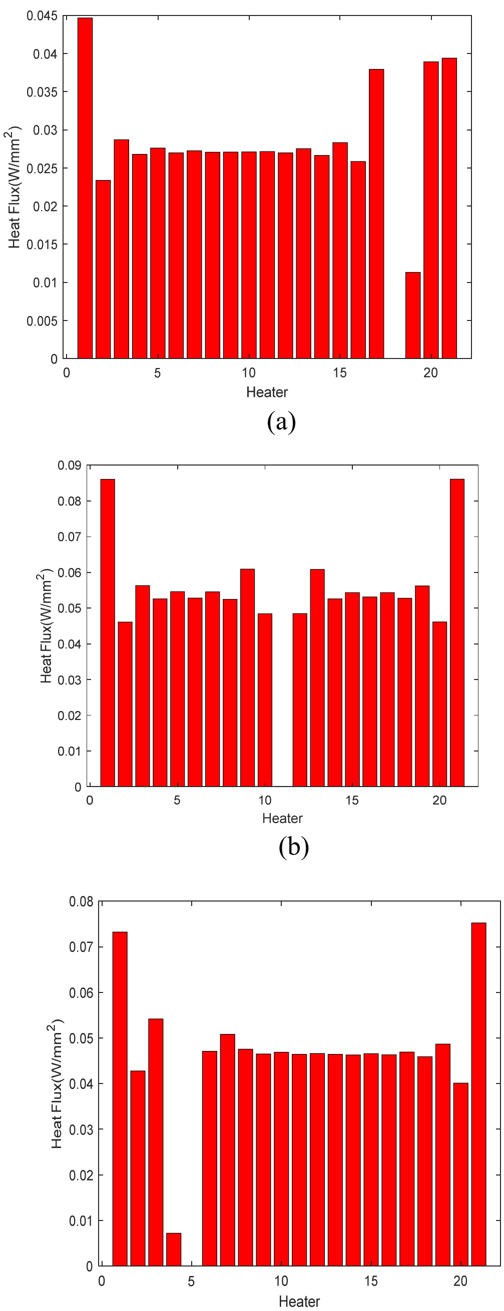

Figure 7: Heat Fluxes through optimization for (a) 1 nm X-ray; (b) 2 nm X-ray; (c) 3 nm X-ray.

Then, all heat fluxes are used as boundary conditions to evaluate the thermal, deformation, and surface shape results using finite element analysis software. From Table 3, 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

CONCLUSION

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. From this, it can be inferred that the pre-mirror shape can be compensated well during the course of X-ray footprint movement at any position on its surface.

ACKNOWLEDGEMENTS

The authors would like to thank the S^{3}FEL project team for all their efforts and support.

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