ISBN: 978-3-95450-207-3 doi:10.18429/JACoW-MEDSI2018-WEPH31

OPTIMIZATION METHOD USING THERMAL AND MECHANICAL SIMULATIONS FOR SIRIUS HIGH-STABILITY MIRRORS*

L. M. Volpe†, G. V. Claudiano, R. R. Geraldes, S. A. L. Luiz, A. C. Pinto,
Brazilian Synchrotron Light Laboratory (LNLS), Brazilian Center for Research in Energy and Materials (CNPEM), 13083-970, Campinas, Sao Paulo, Brazil

Abstract

The mirrors for Sirius, the new 4th-generation synchrotron at the Brazilian Synchrotron Light Laboratory (LNLS), have strict requirements regarding thermo-mechanical stability and deformations, with figure height and slope errors limited to a few nanometers and tens of nanoradians, respectively. Therefore, fixed-shape mirrors have been defined with horizontally-reflecting orientation (except for vertically-reflecting mirrors of KB systems), whereas their cooling schemes (namely, air, water or liquid nitrogen cooling) depend on the particular power load. A thermal and mechanical optimization method was developed to guide the design of mirrors through the evaluation of deformations caused by power load, cooling, gravity, tightening of the fastening screws, manufacturing errors and modal analyses. Up to now, this method was already used to define the mirrors of Sirius' beamlines, which include plane, cylindrical, elliptical and ellipsoidal mirrors, as well as KB systems for microprobe and nanoprobe stations. Two examples are presented to illustrate the method.

INTRODUCTION

Mirrors are critical components to ensure a good beam quality on beamlines. With the emergence of 4th-generation synchrotron accelerators, in which it is desired to have the photon beam size near the diffraction limit and a higher coherence, the deformation and stability specifications for the mirror's design have become extremely tight.

To reach these specifications, a new fixation system was developed based on deterministic models. Thermal and mechanical simulations using finite element analysis (FEA) were done to determine the shape of the mirror, minimizing the expected deformation in its operating condition. The simulations were performed using Ansys Workbench [1].

Firstly, the works related to the design of mirrors and deterministic models are presented. In the following sections are shown the optimization methodology used to define the mirror shape, the results obtained and the conclusions.

RELATED WORKS

During the last decades several solutions of water cooling of mirrors were presented and optimized, and with the requirements increasingly tight, these solutions became more complex, requiring methods of correction of the mirror shape, for example using heaters or actuators [2-3].

* Work supported by Brazil's Ministry of Science, Technology, Innovation and Communication (MCTIC)
† lucas.volpe@lnls.br

Cryogenic cooling solutions can also be applied to mirrors, but are often avoided due to cost, even if better results can be obtained than water cooling. This type of cooling is widely used in monochromator crystals due to the good thermal properties of the silicon at temperatures close to 125 K, such as a coefficient of thermal expansion close to zero and high thermal conductivity [4-8].

In order to achieve movement accuracy and stiffness never seen before in double-crystal monochromators (DCM), the Sirius High Dynamic DCM utilized deterministic concepts in its design [9]. A deterministic design is made in order to obtain a system that is highly repetitive, where cause and effect relationships are well known and controlled and random behaviors are negligible [10]. Only using such techniques it is possible to achieve the necessary requirements without divergences between the design and the final product, as it was done in the present study.

CONCEPTUAL DESIGN

Since Sirius' mirrors absorb powers of at most 50W, a simple cryogenic cooling solution using cryostats and copper braids can be used, benefiting from the good properties of silicon in relation to deformation and decoupling the vibrations from the cryostat to the mirror. Thus, a new fixture concept was developed for Sirius' mirrors based on the deterministic concepts used in HD-DCM: the optical element is fixed in an exactly-constrained flexure-based support with threaded rods that passes through holes in the substrate, which achieves high stability (eigenfrequencies above 150 Hz) and still acommodates thermal deformations resultant from system cooling. More details of the conceptual design of the Sirius mirrors mechanics can be seen in [11].

MIRROR DESIGN METHOD

In order to define the shape of the mirror, a method was developed to evaluate and optimize the deformation caused by several different effects, so that each effect can be evaluated individually and the mirror design can be optimized iteratively considering each effect at a time in a way that when all effects are added, the specifications are met. The main specifications required for the development of the project are: optical area size, mirror orientation, absorbed power and maximum permissible deformation for thermal and mechanical deformations. To illustrate the method two examples of Sirius' mirrors are presented, CAT-1-HFM from the Cateretê beamline and CAR-5-KB-VFM from the Carnaúba beamline. The specifications for these mirrors are shown in Table 1.

ISBN: 978-3-95450-207-3 doi:10.18429/JACoW-MEDSI2018-WEPH31

Table 1: Specifications (Mirror 1: CAT-1-VFM, Mirror 2: CAR-5-KB-VFM)

Parameter	Mirror 1	Mirror 2
Orientation	Side	Up
Figure	Cylindrical	Elliptical
Length [mm]	200	210
Power [W]	6	0
Power Area [mm]	180x0.55	200x0.55
Peak-to-Valley Error [nm]	4	1
Height Error RMS [nm]	1.3	0.5
Slope Error RMS [nrad]	110	20

Using the size of the optical area, the reflection orientation and taking into account the limitations of the production process, it's possible to define the size of the substrate and the method of fixation. An important point is that the mass and inertia should be minimized and the center of gravity kept low for greater stability. Basically, two mirror shapes have been defined according to the orientation of the optical surface. For side-bounce mirrors, a rectangular shape with the fixation preload applied on the upper surface was chosen. For the other ones, lateral flaps were added for fixation to avoid direct deformations on the polished face of the mirror and to increase the assembly lever arms length, improving the stability. The final design of the mirrors are shown in Fig. 1.

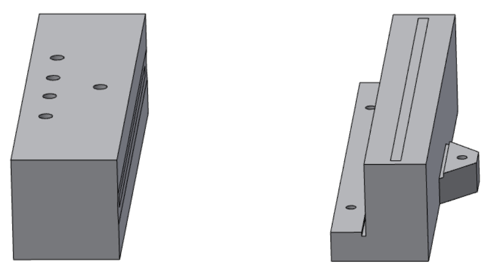

Figure 1: Example mirrors design.

The first analysis to be made is due to the gravity and tightness of the bolts. Firstly, the deformation due to gravity in the production process is evaluated by simulating the supported mirror in the same way as the optical surface is measured during the polishing process. Then the mirror is simulated on a generic support with the flexures and hinges, considering all clamping forces and the gravity. The deformation obtained in the gravity analysis is then subtracted from the deformation of the mirror fixed in the support, obtaining the deformation curve actually expected in the mirror mounted in its base. It is from this last curve that one must optimize the position of the fixation holes, the shape of the mirror and, if necessary, the support position of the mirror during the measurement in the polishing process. This procedure is done in all simulations that consider the effects of gravity and tightening forces.

In general, the mirror is supported at its Bessel points during the polishing process. It results in a very small deformation due to gravity in the optical face in mirrors with horizontal reflection, but in a significant one in cases of vertical reflection. Therefore, it is needed to change the mirror support position during the polishing to a position closer to where the mirror will be fixed in its support. It is done in order to reduce the impacts of the gravity on the total deformation that the mirror will have under work conditions. The already optimized results are presented in Fig. 2.

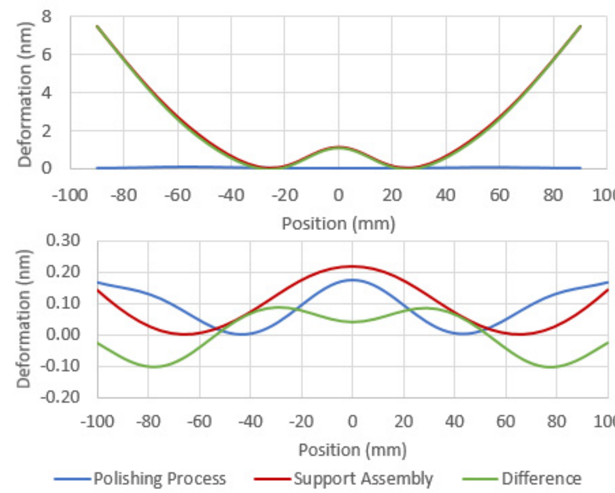

Figure 2: Polishing process, assembly and resulted deformations. CAT-1-VFM (top), CAR-5-KB-VFM (down).

A modal analysis is also performed iterativelly with the previous simulation to verify if the stability conditions were reached. As an eigenfrequency above 150 Hz is desired for the a ssembled mirror mechanism, it has been established that the first frequency should be above 300 Hz for the case of the mirror mounted only on a dummy flexured-base.

Another important point to check is the deformation due to the mechanical manufacturing tolerances. Gaps between the mirror and the support due to the flatness of the parts will also result in deformations in the mirror when it is mounted. It is expected to obtain gaps of at most 1 µm using shimming techniques in the hinge spacers between the support and the mirror. To verify the maximum deformation expected, two cases are simulated, one on which the gap is applied in the central spacer and another on which the gap is applied in one of the lateral spacers. To perform this type of simulation, the type of contact used is rough, with Lagrange Normal formulation and interface treatment adjust to touch. The results for the examples are shown in Fig. 3.

The next effect to be evaluated is the deformation relative to the temperature difference between the assembly and the work condition of the mirror, also considering the power absorbed. The temperature of the clean room for assembly is 22°C. Then, the simulation is performed for cooling the mirror to 125 K and the aluminum support to

ISBN: 978-3-95450-207-3 doi:10.18429/JACoW-MEDSI2018-WEPH31

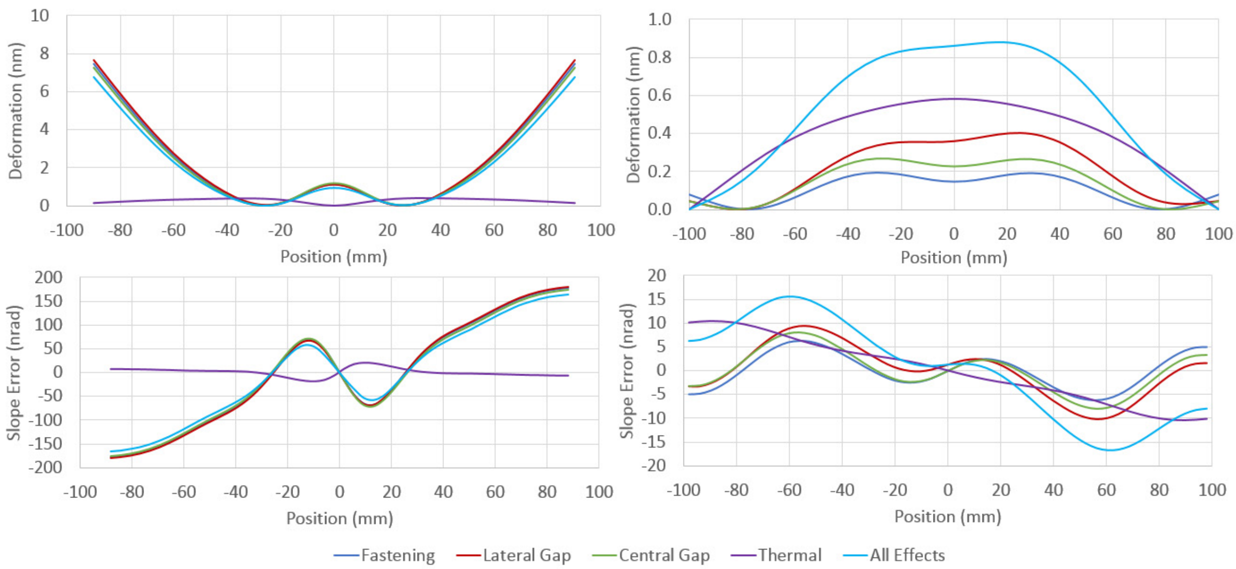

Figure 3: Deformation and slope error curves for each simulation. CAT-1-VFM (left), CAR-5-KB-VFM (right).

10.7°C in the case of cryogenic mirrors and to 24°C for mirrors without cooling (which is the temperature inside of the optical hutches). The temperature difference between the mirror and the support for the first case are chosen in a way that both components have the same thermal deformation. This simulation must be performed with the mirror mounted on the flexured-support but without considering the tightening forces, to evaluate only the thermal condition. The results for the examples are shown in Fig. 3.

A final simulation is performed to evaluate the deformation considering all the effects, analyzing the maximum deformation expected in the mirror in operating conditions. With the deformation within the specification, an optical simulation considering this deformation should be done by the Optics group to confirm that the beam profile is within the specifications for the beamline.

RESULTS

All deformation curves for the examples are shown in Fig. 3. The results optical simulation are presented in Fig. 4, demonstrating a small variation in the beam size. The final results and its criteria are shown in Table 2. It is noticed that the requirements have been met in all cases.

Table 2: Results (Mir. 1: CAT-1-VFM, Mir. 2: CAR-5-KB-VFM , criteria in parenthesis)

Requirement	Mir. 1	Mir. 2
Peak-to-Valley Error [nm]	6.8 (< 10)	0.88 (< 1.0)
Height Error RMS [nm]	2.0 (< 2.5)	0.31 (< 0.5)
Slope Error RMS [nrad]	101 (< 110)	10.4 (< 20)
1st Eigenfrequency [Hz]	571 (> 300)	969 (> 300)

To validate the deformation simulations due to the tightening force, a measurement was made on the CAR-1-MC mirror using the Fizeau Zygo Dynafiz for the mirror only supported on the base with the clamping force. The measured and expected results are presented in Fig. 5, demonstrating an agreement between the simulation and the low-frequency deformation of the mirror (high-frequency is due to measurement noise). Subsequently, another deformation measurement will be performed with the mirror cooled. The same agreement of results are expected.

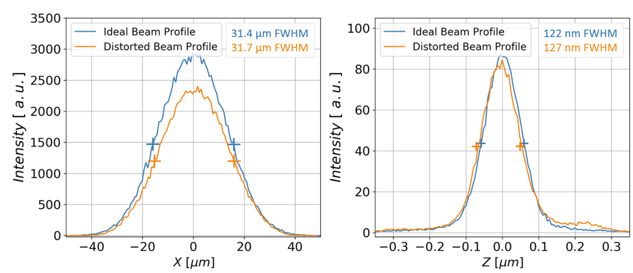

Figure 4: Beam profile from optical simulation. CAT-1-VFM (left), CAR-5-KB-VFM (right).

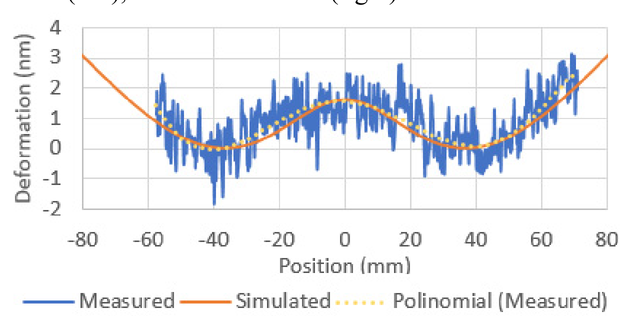

Figure 5: Measured and simulated deformation.

CONCLUSION

An optimization method through thermal and mechanical simulations was developed to define the design of the mirrors that will be used in Sirius. Through this method it was possible to reach the specified deformation levels, reaching in some cases slope error levels below 10 nrad RMS. As the mirror design and its support were made based on deterministic concepts, the results obtained in the simulations are expected to be close to the reality.

ISBN: 978-3-95450-207-3 doi:10.18429/JACoW-MEDSI2018-WEPH31

ACKNOWLEDGEMENTS

The authors would like to gratefully acknowledge the contribution of Murilo Bazan da Silva, Lucas Sanfelici, Harry Westfahl Jr., Hélio C. N. Tolentino, Bernd C. Meyer and all other members of the LNLS team that was involved with this work.

REFERENCES

[1] *ANSYS® Academic Research Mechanical, Release 19.1.*

[2] L. Zhang *et al.*, "Optimizing X-ray mirror thermal performance using matched profile cooling", in *Journal of synchrotron radiation*, vol. 22, n. 5, pp. 1170-1181, 2015.

[3] J. Nicolas *et al.*, "Focusing and defocusing using mechanically corrected mirrors at the MX beamline at Alba", in *Journal of Physics: Conference Series*, vol. 425, n. 5, p. 052016, 2013.

[4] G. Marot *et al.*, "Cryogenic cooling of monochromators", in *Review of scientific instruments*, vol. 63, n. 1, pp. 477-480, 1992.

[5] W. K. Lee *et al.*, "High heat load monochromator development at the Advanced Photon Source", in *Optical Engineering*, vol. 34, n. 2, pp. 418-426, 1995.

[6] D. H. Bilderback *et al.*, "The historical development of cryogenically cooled monochromators for third-generation synchrotron radiation sources", in *Journal of synchrotron radiation*, vol. 7, n. 2, pp. 53-60, 2000.

[7] L. Zhang *et al.*, "Thermal deformation of cryogenically cooled silicon crystals under intense X-ray beams: measurement and finite-element predictions of the surface shape", in *Journal of synchrotron radiation*, vol. 20, n. 4, pp. 567-580, 2013.

[8] M. Saveri Silva *et al.*, "Thermal Management and Crystal Clamping Concepts for the New High-Dynamics DCM for Sirius", in *Proc. MEDSI'16*, Barcelona, Spain, Sep. 2016, paper TUPE15, pp. 194-197.

[9] R. R. Geraldes *et al.*, "The new high dynamics DCM for Sirius", in *Proc. MEDSI'16*, Barcelona, Spain, Sep. 2016, paper TUCA05, pp. 141-146.

[10] J. B. Bryan. "The deterministic approach in metrology and manufacturing", in *Proceedings of the 1993 International Forum on Dimensional Tolerancing and Metrology*, Dearborn, MI, USA, Jun. 1993, pp. 85-96.

[11] R. R. Geraldes *et al.*, "The design of exactly-constrained X-ray mirror systems for Sirius", presented at MEDSI'18, Paris, France, Jun. 2018, paper WEOAMA04, this conference.