Focusing and defocusing using mechanically corrected mirrors at the MX beamline at Alba

J Nicolas, C Ruget, J Juanhuix, J Benach and S Ferrer
Alba Synchrotron, ctra. BP1413 km 3.3, 08290 Cerdanyola, Catalonia, Spain

E-mail: jnicolas@cells.es

Abstract. A practical limitation of X-ray focusing mirrors is that, while providing nice gaussian photon distributions at the focal plane, they usually produce inhomogeneous beam profiles upon defocusing that are caused by the mirror polishing errors. This can become a limitation in order to match the beam size with the sample dimensions, as the sample is not uniformly illuminated. We outline a method to achieve well shaped unfocused beams that has been successfully proven at BL13-XALOC, the macromolecular crystallography beamline at the ALBA synchrotron. As received from the manufacturer, the mirrors had rms slope errors of 180 nrad rms (vertically focusing mirror, VFM) and 210 nrad rms (horizontally focusing mirror, HFM). Ray tracing simulations suggested that pronounced stripes arising from the surface waviness would appear upon defocusing. By using the elastic beam theory to model the deformations and calculating the necessary correcting forces exerted by a few mechanical actuators that were installed in the mirror mechanical holders, we were able to reduce the slope errors of the mirrors to 55 nrad rms (VFM) and 83 nrad rms (HFM). The corrected mirrors were installed at the beamline and they were tested with the X-ray beam from the undulator source.

1. Introduction
ALBA is a third generation synchrotron light source with a 3 GeV low-emittance storage ring [1]. XALOC is the beamline dedicated to macromolecular crystallography [2]. The beamline is fed by an in-vacuum undulator, delivering photons from 5 to 24 keV. The optical layout of the beamline is outlined in figure 1. The monochromator is a cryogenically cooled channel cut Si (111) crystal monochromator, optimized for energy and position stability. The beam is focused by means of a Kirkpatrick Baez mirror pair (KB). Each one of the mirrors is polished flat in a rectangular substrate and bent onto plane elliptic figure by means of motorized mechanical benders. In order to match the beam size at the sample position to the actual size of the sample, the bending condition of the mirrors can be changed. This is, the focusing plane can be set at any position between the sample position and infinity. Correspondingly, the radii of curvature range from 2.51 km and 1.89 km to flat for the VFM and HFM respectively.

The capability of the beamline to provide uniform illumination of large samples by defocusing the beam is limited by the striations that appear. They correspond to local variations of the mirror curvature which produce a number of secondary foci and cause inhomogeneity of the flux distribution [3]. For a given geometry and source size, the visibility of the striations is proportional to the slope error of the mirrors. Ray-tracing simulations of the beamline showed that high quality mirrors were required to optimize the beam homogeneity out of focus. The mirrors, polished by InSync Optics, Inc. were delivered with excellent slope error values of 0.18 μrad rms over 300 mm (VFM), and 0.21 μrad rms over 600 mm (HFM). Although these are very good values, they would induce intensity variations up to 50% when defocusing the beam vertically to get an illuminated area of about 50 μm or larger – see figure 2 (left). A much more homogeneous illumination was predicted for slope errors
in the order of 50-70 nrad rms as shown in figure 2 (right) – there we show the beam profile corresponding to the slope error achieved by the optimization we present). Because of this, we decided to investigate how to improve the slope error of the mirrors of the beamline.

**Figure 1.** Optical scheme of the XALOC beamline. The KB system is designed to change the beam size at the sample position.

### 2. Mirror optimization

The principle of the correction technique consists in introducing a deformation of the mirror substrate that cancels the figure error due to polishing. To do this, the following requirements must be fulfilled: optical metrology accurate to the nanometer level, a precise description of the substrate deformation in terms of the applied forces, and a method to introduce and adjust the required forces.

Regarding the accuracy of the metrology, the Optics Laboratory of Alba is equipped with a high accuracy slope measuring instrument, based on the Bessy-NOM concept [4]. It can provide measurements with accuracy in the range of a few tens of nanoradian [5], and well below the nanometer.

**Figure 2.** Ray tracing simulation of the beam at the sample position of XALOC, focusing at 600 mm downstream to get a 250×40 μm² fwhm spot. (left) Using original slope error. (right) Using corrected slope error.

The second aspect to take into account is the deformation model. The classic elastic beam theory provides the analytic relationships between the deformation of the mirror substrate and the set of forces applied to it [6]. A noticeable property of the elastic beam theory is that it predicts a linear dependence between the surface deformation and each one of the applied forces. Thanks to this, one can decouple the surface correction from the adjustment of the ellipse parameters, and one can apply an iterative correction.

Finally, it is necessary to be able to apply the forces resulting from the optimization. To do this, the four-point type mirror benders, manufactured by Irelec, were modified. They have fixed seats at the ends of the mirrors, which allow pitch rotation in both ends, and roll rotation in one end, to avoid introducing any twist. The bending force is given by two pulling actuators which allow pitch and roll, so as to avoid introducing undesired torsion efforts. The bender structure is provided with slots where flexure spring actuators can be installed, and located at any position of the mirror. The contact of the springs to the mirror is done by a ball bearing, to avoid friction. The design, originally intended for gravitational sag compensation, was modified to allow setting springs pushing the mirror substrate from below or from above, so as to apply positive or negative forces if necessary. The force applied by each spring actuator is controlled by simple adjustment screws. Because of this, the forces applied by the actuators cannot be properly quantified, and the adjustment of the actuators needs to be done in
several iterations (about 10 iterations were enough for each mirror). At each iteration, the mirror profile is measured and the forces required to correct the measured profile are calculated and applied.

For each mirror, we estimated the resulting slope error as a function of the number of correcting forces. By adding actuators, the correction improves rapidly for the first few ones, and then it stabilizes with very little improvement for a larger number of actuators. For instance, for VFM we used two actuators because using up to five was improving the result only from 55 nrad rms to 45 nrad rms. In addition, as the number of actuators increases, the required force stability becomes tighter. Best, more equilibrated solution was based upon 2 and 4 actuators for VFM and HFM respectively.

The result of the optimization is shown in figure 3. The original slope error for the VFM was improved from 0.180 μrad rms to 0.055 μrad rms, and the HFM, initially 0.210 μrad rms, was optimized to 0.083 μrad rms. In both cases, the limit was the impossibility to set the forces with enough accuracy. Once the residual error was optimized, the nominal ellipse was attained by properly setting the motorized bending actuators. The central 250 mm of the mirror preserved the residual figure error measured flat, and only the ends of the optical surface were affected by a local deformation induced by the pulling mechanism. Figure 2 (right) shows a ray tracing simulation of the improvement of the beam homogeneity after applying the slope error correction.  

Figure 3. Metrology result of the optimization of the VFM (left) and HFM (right) mirrors of XALOC. The gray dashed line corresponds to the original height error with respect to the best fit sphere, while the solid black line corresponds to the residual profile after optimization. The magnitude and position of the correcting forces is given in the annotations.

3. In situ results
The focusing and defocusing capabilities were tested during the commissioning of the beamline. For this, a 20 μm thick YAG crystal plate was installed at the sample position, and its fluorescence was imaged by using the sample alignment microscope of the endstation, with variable magnification, and a field of view which ranges from 169×127 μm² to 389×292 μm².

Figure 4 shows two images of the beam at the sample position obtained at two different focusing conditions of the KB mirrors. In both cases, the photon energy was 12.658 keV, the whole vertical size of the beam was accepted, while one fwhm was accepted horizontally. The image at the left corresponds to the focused beam, 50×10 μm² fwhm in size. Although the spatial resolution of the imaging system is too coarse to measure the vertical spot size, the measure of the horizontal spot size is in good agreement with the theoretical value (53×5.1 μm² fwhm). Figure 4 (right) corresponds to a beam vertically defocused, obtained by changing the bending of VFM to focus 2.6 m downstream the sample. It shows that although the beam size is more than 20 times larger than the theoretical value of the focused spot, the striations are very weak, and the residual beam modulation is limited to 10% of its maximum amplitude (15% if the low resolution of the imaging system is compensated).

In order to estimate the slope error of the mirror in the working conditions of the beamline, we have used the pencil beam method [7]. To do so, a set of slits installed upstream the VFM were scanned vertically, with a constant aperture of 10 μm, while we measured the vertical displacement of the focused spot at the YAG diagnostics installed at the sample position. Since each one of the KB
mirrors is the only focusing element along the beamline for the horizontal and vertical planes, the method provides a direct measurement of the slope error of each one of the mirrors.

Figure 4. Beam at the sample position obtained by using a YAG crystal diagnostics. (a) Focused beam. (b) Beam vertically defocused showing very weak stripes. The beam profile is compared with a ray-tracing simulation (including the resolution of the imaging system).

The result of the in situ measurement for VFM is given in figure 5. The gray line corresponds to the surface departure from the nominal ellipse, measured at the Alba-NOM, and the square points correspond to the profile error as reconstructed from the in situ measurement. The agreement between the two measurements provides evidence of the long term stability of the correction technique, from the initial adjustment at the metrology laboratory, to the in situ measurement, two years later, and after the installation of the mirror at the beamline and many bending-unbending cycles.

Figure 5. Residual profile of the VFM. In-situ measurement (square points) fully agree with the Alba-NOM result (gray continuous line).

4. Conclusions

The figure of the mirrors of the XALOC beamline have been optimized by means of spring actuators, achieving slope errors of 60 and 80 nrad rms approximately for the VFM and HFM respectively. To do this, accurate metrology, as well as a well suited optimization model, and appropriate mechanics have been required. In situ measurements, which agree with the measurements obtained in the metrology laboratory, demonstrate the long term stability of the correction.

References

[1] Einfeld D, 2012 Proc. of IPAC2011, San Sebastián, Spain 1
[2] Juanhuix J, Benach J, Cuni G, Colledelram C, Nicolas J, Lidón J and Gil-Ortiz, F, (These proceedings)
[3] Moreno M, Belkhoul R, Cauchon G and Idir M, 2005 Proc. SPIE 5921 59210F
[4] Siewert F, Noll T, Schlegel T, Zeschke T and Lammert T, 2004 AIP Conf. Proc. 705 pg.847
[5] Nicolas J and Martinez J C NIM A (in press)
[6] Goodwine B, Engineering differential Equations: Theory and Applications, Springer, (2011)
[7] Hignette O, Freund A K, Chinchio E, Proc. SPIE 3152, (1997) pg.188