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THE NANOBENDER: A NEW X-RAY MIRROR BENDER WITH NANOMETER FIGURE CORRECTION

Carles Colldelram[1*], Josep Nicolas[2], Claude Ruget[1], Pablo Pedreira[1], Igors Sics[1], Llibert Ribó[1], Albert Tomas[3], Joan-Manel Casalta[3], Carlos-Martín Nuño[3], David Úbeda[3]
1 CELLS, Cerdanyola del Vallès, Spain
2 SLAC, Stanford, California, United States
3 Sener Ingeniería y sistemas, Cerdanyola del Vallès, Spain

Abstract

Over time X-Ray mirrors are demanded for better focusing, closer to sample refocusing, spot size as well as better beam uniformity at sample position. Based on the experience of ALBA Phase I beam lines a new alternative design of a mirror bender is proposed [1]. The system includes two main functionalities: the mirror bender mechanism and mirror figure error correction. Both mechanisms are based on the introduction of a force constrain on the mirror surface instead of a geometrical one. As being based on a force mechanism they could reach high resolution and especially for the correctors which can achieve nanometre resolution. The correctors are designed to provide high force stability in the mirror side, eliminating the crosstalk between bending and figure correction, and minimizing the sensitivity to drifts. With such controlled deformation of the mirror substrate it is possible to obtain the desired surface figure not only to correct mirror figure errors but also to adapt it to the incident wavefront, thus becoming adaptive system. The mechanical solutions are presented which are able to correct mirror surfaces with a resolution of 1 nm reaching slope errors below 100 nrad.

INTRODUCTION

This new X-Ray mirror bender system has been conceived in the ALBA Beam Lines Phase I framework. The protein crystallography beam line at ALBA, BL13 XALOC [2], has a quite simplified optical lay-out with a channel-cut crystal monochromator and a couple of focusing mirrors placed in a Kirkpatrick-Baez (KB) configuration [3]. The mirror system allows reaching a focus spot of 50×5.5 μm^2 FWHM (H×V). This both mirror system were outsourced. The spot quality at sample position is mainly depending of the optical surface quality of this vertical focusing mirror (VFM), of its slope error, and in order to minimize the striation in the beam it was requested to the manufacturer to include a number of gravity sag compensators to have the possibility to use them not only to correct gravity flexion but also for mirror optics figure corrections.

Already with these correctors [4], thought to compensate gravity sag errors, the system has already an initial rough but enough force resolution allowing the mirror figure correction based on the Elastic Beam Theory [5] and a high-accuracy profile metrology, the ALBA NOM optical metrology system (see Fig. 1).

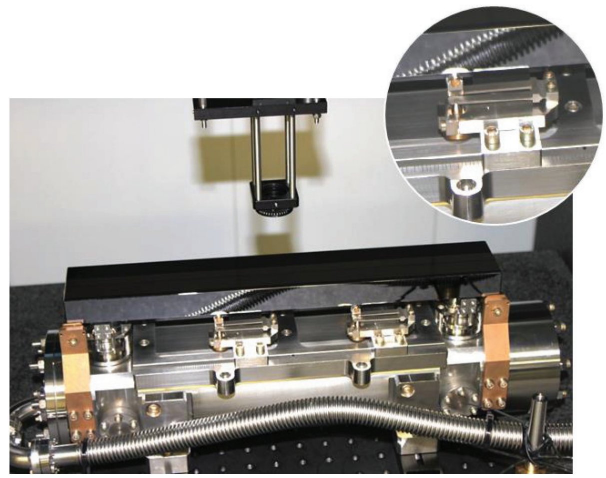

Figure 1: BL13 Xaloc VFM at ALBA NOM.

By means this analytical calculation, the actual surface error and an optimization algorithm we were able to calculate the number of correctors, setting force and position along the mirror to improve the mirror figure. Although these corrector were manual and not made to deal with this function the 300mm mirror was corrected from its initial slope error of 0,242µrad up to 0,055 µrad (see Fig. 2) by mean two of these gravity sag compensators and both pushing from below.

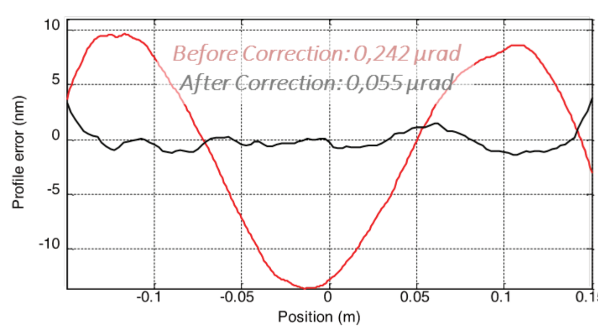

Figure 2: VFM optical surface height.

A ray tracing simulation of the mirror before and after the correction give a picture of the beam quality at sample position and its undesired striations improvement (see Fig. 3).

* ccolldelram@cells.es

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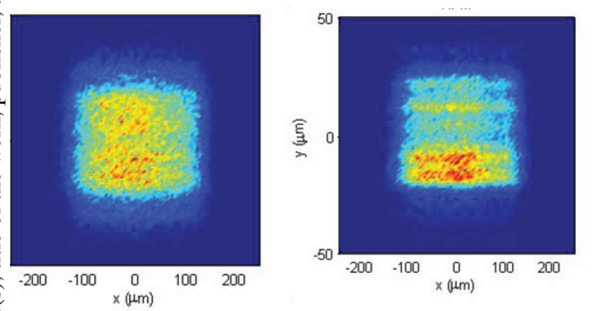

Figure 3: Beam spot ray tracing simulation at sample position.

Moreover beam line in-situ measurement (see Fig. 4) was possible to be performed by means pencil beam technics after 2 years of its installation at the beam line. These measurements show a very good agreement between the optics laboratory optimization and the in-situ test demonstrating the performance of this method and its high stability which motivates the design if a new bender concept developed in following chapters.

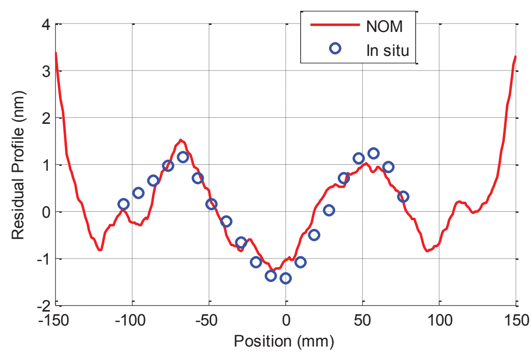

Figure 4: Laboratory measurement vs in-situ test after two years.

NEW CONCEPTS

Geometrical vs Force constrains

From the experience acquired with the optimization of this initial mirror new concepts were applied to a new bender design. A mirror substrate could be deformed in order to optimize its optical surface by means high resolution force actuators (see Fig. 5).

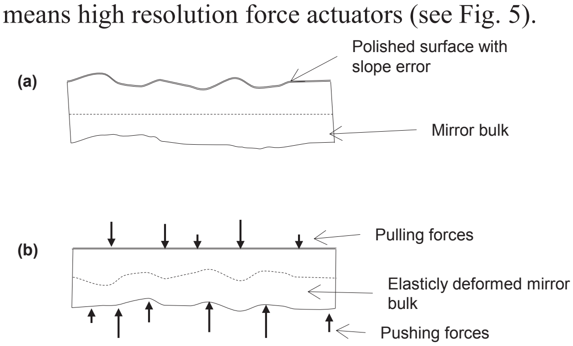

Figure 5: Illustration of surface correction by elastic deformation of the substrate. (a) Original mirror with surface errors. (b) mirror deformed compensating surface errors.

This optimization could be done by means two type of mechanisms. One could be based on rigid mechanics which introduce the desired deformation. Second option is the soft way by low rigidity mechanism as stable-force actuators which allow the introduction of a force with high resolution and much more insensitive to drift thus much more stable (see Fig. 6).

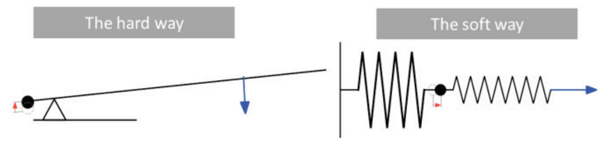

Figure 6: Possible mechanism concepts to bend a mirror.

The second concept it has been applied for the design of this new bender mechanisms in both mirror bender and mirror figure correctors mechanics.

BENDER DESIGN

Lay-Out

In this project, this novel concept of mirror bender is proposed (see Fig7). A bender mechanism that introduce a force constrain close to the support ends introducing the flexion torque which deforms the mirror in a way that can be predicted by the above mentioned theory which can be resolved by a third degree polynomial. But the novel technics is a system of correctors which applies controlled forces at the different points of the mirror, to induce the controlled deformation of the substrate that compensates the polishing errors. With this, the resulting figure errors can be reduced below one nanometre.

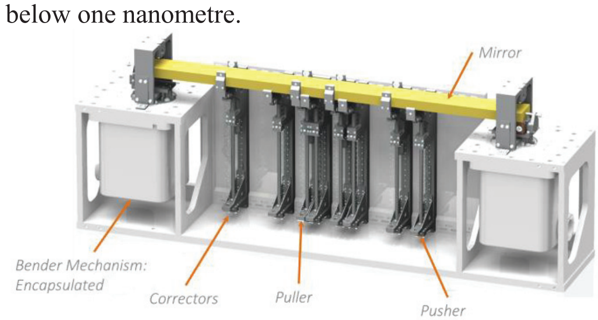

Figure 7: Nanoberder model.

The design of the correctors must be able to apply forces up to 40 N, with a resolution and stability of 0.01 N, in order to preserve the correction of the mirror. By analysing the initial mirror flatness the method calculates the force and the position of each actuator to reach ultimate correction of the mirror reflective surface and thus minimum incident wavefront aberrations and thus to be able of even incident wavefront correction.

Bender Mechanism

The mechanism for controlling the elliptic shape of the optical surface of the mirror (See Fig. 7) is based on the elastic bending of the mirror substrate under two

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torques applied at its extremes. These torques are obtained by applying forces, normal to the mirror surface, at offset positions from the points where the mirror is simply supported, without embedment. The system is designed to accommodate mirrors from 300 mm to 1500 mm with a cross section of 50 mm width by 20 mm thick.

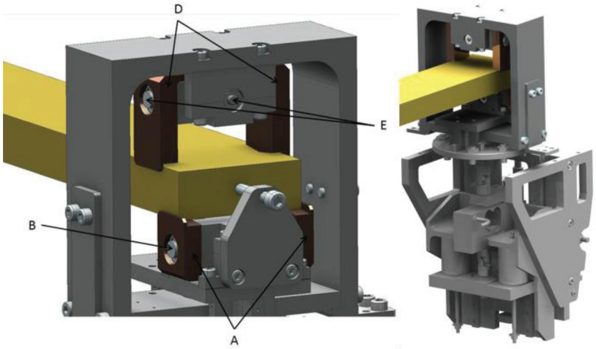

Figure 8: Bender mechanism.

The mirror support contacts the ends of the mirror at four contact points (see. Fig. 8, A). The support points have articulated mounts on the contacting parts to avoid introducing any force other than purely normal to the mirror surface. An articulated rotation (see Fig. 8, B) on the transversal direction allows the mount accommodating to the bottom face of the mirror substrate, thus avoiding introducing longitudinal components of force. Similarly, one of the two supports includes a rotation about the longitudinal direction of the mirror (see Fig. 8, C). With this, the support can accommodate to the mirror face, whose orientation is determined by the other support, which does not include this rotation. The bending forces are introduced by contact points offset 25 mm from the vertical of the supports, towards the centre of the mirror (see Fig. 3, D). The bending actuators have double articulated contacts (see Fig. 3, E) to ensure that the applied force is purely vertical. All mentioned contacts are doom shaped, to avoid excessive stress at the surface contact points. All the bearings used in the articulations are deep grove bearings, which have certain play or clearance, allowing a minimum rotation on the transverse directions of bearing axis. This helps on avoiding undesired loads. All of them are also hybrid bearings, fully Ultra High Vacuum compatible.

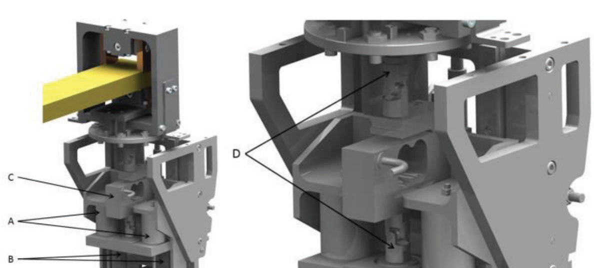

Figure 9: Bender mechanism.

The bending mechanism (see Fig. 9) is a spring based loading system that allows introducing a force up to 500 N, corresponding to a bending torque of 10.5 Nm. The spring (Fig. 9, A) is compressed by a conventional linear stage, which includes two linear guides (see Fig. 4, B) and is driven by a ball bearing nut and spindle system. The spindle is actuated by a stepper motor with a reduction factor 1:276. This allows for a resolution of 0.05 μm, equivalent to a force resolution about 0.0004 N. The spring can be compressed by 60 mm which allows for a versatile force range, and reduces in turn the system sensitivity to thermal drifts which may change the spring compression length and mirror ellipse correspondingly.

The force is transmitted to the mirror by means of a mechanical chain which includes a strain gauge (see Fig. 9, C) placed between two bearing gimbal articulations (see Fig. 4, D) which ensure that the applied force is purely vertical, and along the measuring axis of the gauge. All this mechanism is not Ultra High Vacuum compatible, and is therefore enclosed in an air volume, surrounded by vacuum. The force is transmitted through a double edge-welded bellow (see Fig. 4, E) which self-compensates vacuum forces. As shown in the next chapter the focus of the ellipse generated by this bending is independent of the figure correction.

The Correctors

The correctors deals with the slope error compensation or mirror optical surface shape correction. This small mechanism allows the introduction from 0 to 40N forces on the mirror in-between the two extremes bending mechanisms (see Fig. 7). It can be placed at any position along the mirror as function of the mirror initial flatness and its optimized correction values on force, position and number of correctors with a minimum separation of 22mm. It can be settled in pushing or pulling forces at convenience of the force value.

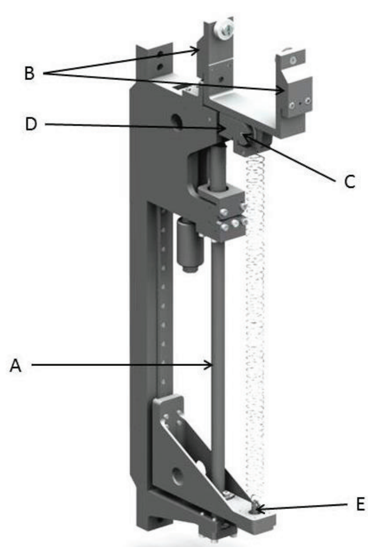

Figure 10: Corrector mechanism.

The correctors consist on a long traction spring with a very small spring constant that allows for a force

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resolution below 0.001N (see Fig. 10). The long spring allows the system also for high robustness to thermal drifts, and allow for reproducible correction after dismounting and re-mounting the mirror.

The spring is elongated by means of lead screw (see Fig. 10, A) actuated by a stepper motor. The correction force is applied to the mirror by two deep grove bearings (see Fig. 10, B), which contact directly the mirror surface. The bearings are held on a frame that is linked to the spring by a rolled articulation (see Fig. 10, C), to accommodate both contacts without introducing any twist or torsion on the mirror. This articulation can move only in the vertical direction, as is attached itself to a pivoting beam (see Fig. 10, D). The spring end can be attached to different points of the pivoting beam, which allows converting the corrector from pusher to puller. It also allows scaling the resulting spring force to obtain higher force resolution. The bottom fixation of the spring includes a bearing to allow the spring torsion and thus to avoid any residual transverse force. A linear guide allows placing the spring fixation at the vertical of the attachment at the upper end (see Fig 10, E). 20 N is the force estimated to correct 0.5 µrad rms mirrors for errors with period down to 22 mm.

With this low spring constant correctors the crosstalk between curvature adjustment and figure correction is completely eliminated as the micron level deformation of the ellipse setting does not introduce a significant change on the corrector as it is a negligible displacement for such week spring to introduce a real change of the corrector set force.

MANUFACTURING

Detailed design and manufacturing and assembly have been performed by Sener. Two prototypes have been built first one as prove of concept and second as industrialization optimization (see Fig. 11).

Figure 11: Second prototype.

MEASUREMENTS AND RESULTS

ALBA NOM

ALBA optical laboratory includes a Nanometer Optical Metrology bench. This is a 1,5m long highly accurate scanning deflectometer guided by means air bearings (see Fig. 12).

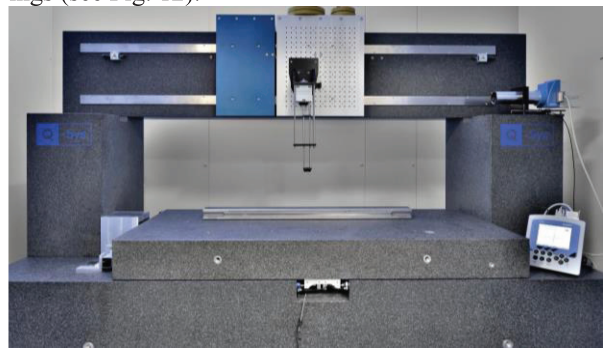

Figure 12: ALBA NOM.

The measuring axis, longitudinal, it is a smooth direct drive motion equipped with a ironless linear servo actuator.

The optical set up is composed by an autocollimator which measures directly the optical mirror surface slope and a pentaprism to deviate orthogonally the autocollimator beam from its horizontal pedestal to normal to the mirror surface eliminating at the same time pitch guidance errors.

The laboratory temperature is stabilized by means of a PID controlled post-heating system and well isolated from surrounding rooms (which are stabilized already at 1º around 23º) by means rockwood isolation. The NOM is encapsulated in a last isolation cabinet which dumps further temperature oscillation down to a hundredth of degrees.

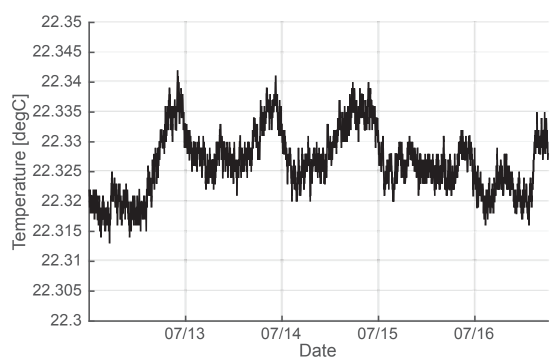

Figure 13: Optics laboratory temperature stabilization.

The ALBA-NOM can provide measurements that are accurate in the range of a few tens of nanoradians, and well below the nanometer [6].

Mathematical Deformation Model

The mathematical model is analytical an based on Euler Bernoulli-law [Eq. (1)].

$$EI\frac{d^4}{dx^4}z(x) = \sum_{n=1}^{N} F_n\,\delta(x - x_n) \tag{1}$$

The model is linear and allows superposition, thus the curvature of the deformation is a piecewise linear function and the surface curvature is a piecewise cubic polynomial.

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With a theory dummy 1 meter long mirror the model predict that it is possible to correct a mirror that needs and induced deformation of 600nm, after removing the curvature, the model is accurate below 1 nm (see Fig.14).

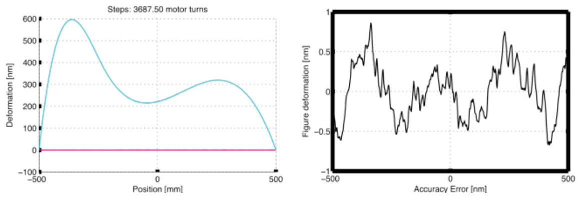

Figure 14: mirror correction mathematical model accuracy.

Bending Mechanism Performances

Table 1 shows the results of the bender mechanism.

Table 1: Bender Mechanism Performances

Performance	**Figure**
Bending range	0 – 500 N
Bending resolution	< 0.001 N
Strange gauge sensitivity	16 nrad (RMS)
Actuator linearity	35 nrad
Bending repeatability	15 nrad (RMS)
Stability	< 15 nrad / 5 days

Corrector Performances

Figure 15 shows the resolution homogeneity of the corrector. It is very regular around 1 mN.

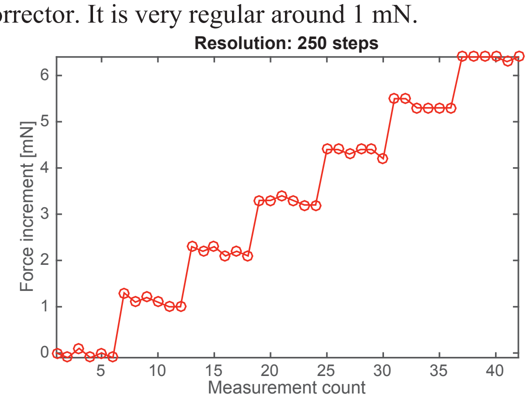

Figure 15: Corrector resolution.

The repeatability of the corrector also have been tested. By lifting the corrector contact and leaving it back to its contact position without resetting the corrector but measuring the force exerted on the mirror this is around 1 mN. Figure 16 shows the low force dispersion of the corrector.

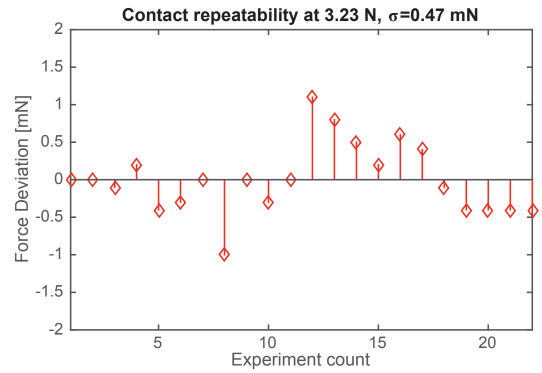

Figure 16: Corrector repeatability

Stability test shows that over 130h the stability is below ±30mN (see Fig. 17).

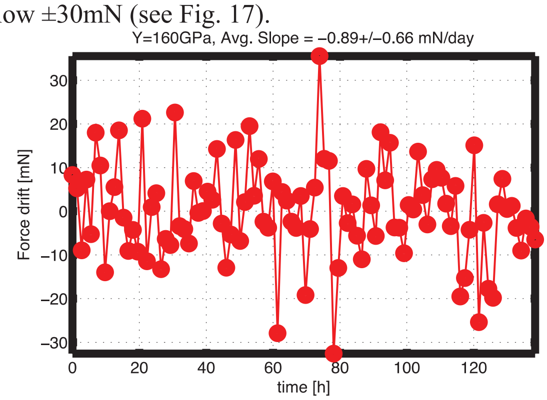

Figure 17: Corrector stability

Corrector motion repeatability is done by recovering the position from random positions, with this corrector setting repeatability is about ±20mN (see Fig. 18).

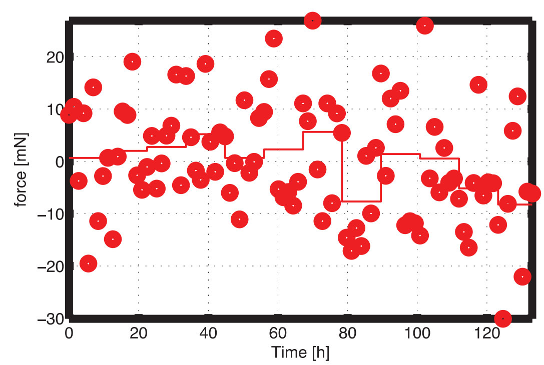

Figure 18: Corrector motion repeatability.

Table 2 summarizes the results of the corrector mechanism.

Table 2: Bender Mechanism Performances

Performance	**Figure**
Corrector range	±40 N
Corrector resolution	~ 0.001 N
Contact repeatability	0,47 mN (RMS)
Stability (130h)	±30mN (PTV)
Motion repeatability	±20mN (PTV)

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Mirror Optimization

A test mirror has been optimized with the two prototypes. The figure optimization is shown in the Fig. 19 and Table 3 summarizes the final corrected mirror figures.

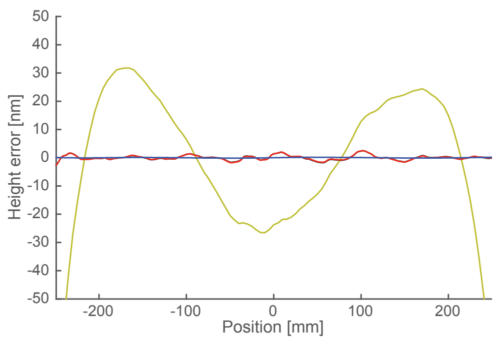

Figure 19: Test mirror optimization.

Clearly the optics mirror surface is corrected at nanometre level.

Table 3: Bender Mechanism Performances

Performance	Figure
Initial slope error	0,87 μrad (RMS)
Corrected slope error	0,115 μrad (RMS)
Initial surface error	23,2 nm (RMS)
Corrector surface error	0,858 nm (RMS)

With the mathematical model it is possible to optimize the correctors position, the force and its sense.

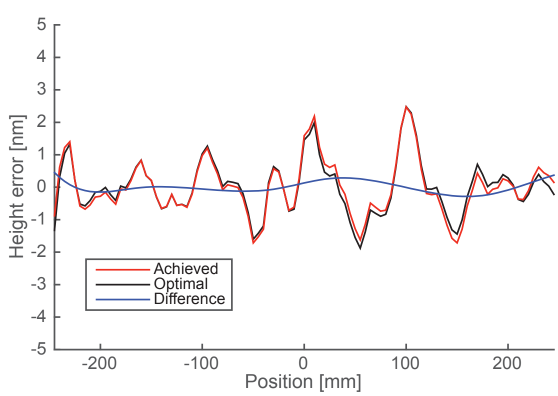

Figure 20: Test mirror height errors.

The model is able to predict the deformation of the mirror with an accuracy better than 0,08 nm RMS.

NEXT STEPS

Bender and Corrector Improvements

The corrector repeatability has already been improved with the evolution from the first and the second prototype. Nevertheless the bender mechanism it is still encapsulated complicating the hardware and its cost. Due the low rigidity of the correctors springs make the bender to be too tall and thus ending to a much bulky instrument. Thus the most relevant improvements to introduce would be:

- Remove the bender mechanics encapsulation.
- Compact the bender mechanism.
- Compact the correctors.

Bender mechanism compaction would need for new proposals while correctors could be reduced by means the already proposals with magnets stabilization concepts developed in the paper and patents [7,8,9] for spring in which the corrector spring constant could be increased as the force application could be stabilized in a range of almost 1 mm of drift, the motion have already enough resolution to absorb this reduction. This rigidity increase of the spring allows reducing its length while still maintaining its force range. The articulation bearing friction and also stability, as the bearing has some play, could be also improved by the stabilized flexures proposed in these publications.

Active Optics

The design of the mechanical system is thought to allow an easy design upgrade to an active optics bender able not only to improve mirror figure polishing errors but also able to correct incident wavefront aberrations.

For this purpose correctors must allow its adjustment after installation or even in beam line operation phase. For this purpose the correctors includes already a motorization, only it is needed to change the selected stepper motor by a UHV compatible one, market already have options on this sense.

The next issue is ensuring that force could change its sense. This could be easily solved by means mounting two spring on each level arm extreme one that could deal with the range and the opposite extreme a spring that could compensate twice the range. Optimizations shows that typically with few correctors are enough, just by mounting as much as possible, separated by the minimum needed separation, active optics must be possible as each corrector could set pushing or pulling force on its point depending on optimization request.

CONCLUSIONS

With these new proposed concepts based on high resolution and low rigidity force actuators a new bender with figure correctors have successful results at nanometre level, with an optimization mathematical model that predicts the corrected curvature down to 0,08 nm and improve mirrors slope errors easily below 0,1 μrad.

The bender mechanism with null crosstalk between curvature setting and figure correction is achieved.

The new correctors are very stable and with high force resolution to correct the mirror at nanometer level.

New –k compensated correctors have been designed and tested. They keep force constant within 1 mN in a range of motion of the mirror up to 2 mm. This will

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allow friendly mirror dismantling and remounting and insensitive to drifts.

New, frictionless, torque free articulation has been designed, and is being currently tested in order to substitute the articulation bearing.

With all these bender characteristics X-Ray mirror can be curved with at the desired focus without introducing beam aberration or even correct incident beam ones.

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