Bendable Kirkpatrick-Baez mirrors for the ALS micro-diffraction beamline 12.3.2: optimal tuning and alignment for multiple focusing geometries

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Abstract. Using an example of Kirkpatrick-Baez mirrors for the micro-diffraction beamline 12.3.2, we present the recent development of bendable x-ray optics and experimental techniques used for focusing of beams of soft and hard x-rays at the Advanced Light Source (ALS). We briefly review the nature of the bending and analyze a generalized solution of the bending equation for a side-profiled elliptically bent mirror substrate. A scaling rule is derived to understand a range of reliable tunability of the bendable optics for different applications (e.g., different focal distances and grazing incidence angles). Original design approaches are developed for assembly of bendable mirrors with minimal spurious stress and misalignment and for final precision compensation of the residual stress, substrate twist, and roll-off misalignment of the mirrors. Procedures used for optimal shaping and alignment of bendable optics at the ALS optical metrology laboratory are also briefly reviewed.

1. Introduction
For simultaneous focusing of x-ray beams in two orthogonal directions, two elliptically cylindrical reflecting elements, a Kirkpatrick-Baez (KB) pair, are used [1]. Fabrication of high quality elliptical surfaces is rather complicated and time-consuming. Moreover, such optics cannot be easily readjusted for use in different experimental arrangements, e.g. at different focal distances.

On the contrary, flat optics are simpler to manufacture and easier to measure by conventional interferometry. The tangential figure of a flat mirror substrate is changed by placing torques (couples) at each end [2]. Depending on the applied couples, one can tune the shape close to a desired surface profile, including tangential cylinder, ellipse or parabola.

Using an example of KB mirrors for the Advanced Light Source (ALS) micro-diffraction beamline (BL) 12.3.2 [3], we present some recent developments of bendable x-ray optics and methods for optimal shaping and alignment of the optics used at different parameters of focusing of soft and hard x-ray beams at the ALS.

2. Analytical solution of the Bernoulli-Euler equation for optimal setting of bendable optics
In the case of bending of a sagittally-profiled substrate by applying two end couples $C_1$ and $C_2$, the Bernoulli-Euler equation that describes the surface shape of the substrate is [2,4]
where $E$ is Young’s modulus, $I(x)$ is the moment of inertia of the substrate cross section, the sagittal width of the substrate, with length $L$ and thickness $t$, is described with a function $w(x)$, and $y''_0(x)$ is the second derivative of the desired height profile of the bent substrate. For a given $y''_0(x)$, Eq. (1) provides an analytical expression for $w(x)$. In the case of optics bent in the shape of an off-axis elliptic cylinder, $w(x)$ as a function of the used geometrical parameters is [5]:

$$
\frac{E I(x) d^2 y}{dx^2} = E^2 \frac{t^3 w(x)}{12} y''_0(x) = \frac{C_1 + C_2 - C_1 - C_2}{2} x,
$$

(1)

where $r$ and $r'$ are the distances from the mirror center to the source and the focus, and $\theta$ is the incidence angle from the normal. Based on Eq. (2), one can derive an approximate scaling rule

$$
(1/r' - 1/r) \sin \theta = \text{const}
$$

(3)

for the conjugate parameters $r$, $r'$ and $\theta$ of elliptical surfaces that can be approximately tuned with the substrate optimized for a certain set of the parameters. The scaling rule (3) is valid within an accuracy of the order of $x^2/rr'$ with the assumption $x \leq L/2 \ll r' \ll r$, which is almost always true. Moreover, for most of the applications of grazing incidence x-ray mirrors, one may assume $\sin \theta \approx 1$.

In the case of re-tuning of bendable optics to another elliptical shape, change of the overall value of the third factor in Eq. (2) that is $rr'[(r + r') \cos \theta]$ can be compensated by inversely proportional change of the bending couples $C_1$ and $C_2$ in the second factor. The scaling rule (3) allows the last factor in Eq. (2) to remain nearly unchanged. Note that better optimization than the one provided by the scaling rule (3) is possible in each particular case by minimizing the overall surface error, accounting for the term quadratic in $x$ in the square brackets of Eq. (2). An original method for thorough optimization of the conjugate parameters is discussed in Sec. 4.

Table 1 illustrates the efficacy of the developed retuning procedure. A mirror substrate, originally designed for $r = 2165$ mm, $r' = 270$ mm, $\pi/2 - \theta = 3.5$ mrad, was retuned for new parameters optimized for BL5.3.1 application [6]. The residual RMS slope error (with respect to the slope profile of the exact new ellipse) measured with the LTP-II is 0.24 $\mu$m. For comparison, the same mirror substrate in use at BL12.3.2 at the preset near-optimal geometry has noticeably larger error. The bending moments for use at BL 5.3.1 must be $\sim 2.33$ times larger than that of BL 12.3.2 [see Eq. (2)].

| Beamline | $r$, mm | $r'$, mm | $\pi/2 - \theta$ | $(1/r' - 1/r) \sin \theta$ | RMS Slope Error |
|----------|---------|-----------|-----------------|-----------------|----------------|
| 5.3.1    | 1525.76 | 244.59    | 8.0 mrad        | 0.00343 mm$^{-1}$ | 0.24 $\mu$mrad |
| 12.3.2   | 2089.1  | 270.0     | 3.5 mrad        | 0.00322 mm$^{-1}$ | 0.33 $\mu$mrad |

3. Design of bendable KB mirrors for the ALS micro-diffraction beamline 12.3.2

Design of the bendable KB mirrors developed for the ALS micro-diffraction beamline 12.3.2 is close to the one described in Ref. [6]. The mirrors have super-polished Si substrates of 102 mm length (80-mm clear aperture) coated with tungsten. The width of the substrates is profiled according to a third order polynomial approximation of an ideal width function [2]. The substrates are mounted with glued molybdenum end-pieces to the adjustable supports that allow precise compensation of twist errors and tensile forces, for example, due to fabrication and assembly tolerances. The bending mechanism of the
leaf-spring design provides automated control of the bender coupling. Additionally, the design includes automated control of the in-beam position, and pitch (grazing incidence) and roll angles of the mirrors. The pivot point of the pitch adjustment is placed at the tangential center of the mirror surface. Similarly, the mechanism for manual compensation of twist error pivots on the sagittal center of the adjoining edge of the substrate. The roll mechanism was re-designed, compared to the previous design [6], to have the pivot point of the roll angular adjustment much closer to the surface of the mirror. Placing the pivot point closer to the mirror surface ensures that in situ automated roll adjustments have a minimal effect on the overall positioning of the mirror surface. All the automated tunings and adjustments are driven with Picomotor actuators and monitored with linear variable differential transformers (LVDT) with an accuracy of approximately 100 nm over the useful range. Active temperature stabilization is based on a Peltier element attached directly to the mirror body [6].

4. Optimal alignment and setting of bendable mirrors at the ALS optical metrology laboratory

Ex situ tuning of the KB mirrors is performed at the ALS optical metrology lab (OML) in three steps.

First, observing the fringe pattern of the mirror surface, generated by a 6-in aperture ZYGO™-GPI interferometer, we assemble the mirror substrates with minimum possible twist and tension.

Second, using the ZYGO™-GPI interferometer, the mirrors are bent close to the desired elliptical shape; and the roll and twist angular misalignments are compensated to the level of better than 100 μrad. As mentioned the twist adjustment is designed with a virtual pivot axis to be along the mirror surface. Therefore, the anti-twist correction does not stress the mirror substrate in other directions.

Third, fine compensation of roll and twist misalignments to <10 μrad, and precision optimal tuning of bending couples are performed with the upgraded LTP-II [7] and autocollimator based DLTP [8] surface slope profilers. The profilers are capable of tangential slope measurements with absolute accuracy of <100 nrad (~50 nrad RMS) with plane and slightly curved optics, and <250 nrad (~150 nrad RMS) with significantly curved x-ray optics. Sensitivity to the sagittal slope is ~2 μrad.

For optimal setting of bendable mirrors based on ex situ surface slope metrology, we use a regression analysis method [9]. The method consists of experimentally finding the surface slope alterations, \( \delta \alpha_{C_1}(x) \) and \( \delta \alpha_{C_2}(x) \), resulting from changes of each bending moment, \( \delta C_1 \) and \( \delta C_2 \). These are the characteristic functions of the benders: \( f_{C_1C_2}(x) = \delta \alpha_{C_1}(x) / \delta C_2 \), that are used to fit by linear regression the difference between the measured and the desired surface slope profiles and determine optimal adjustments, \( \Delta C_1 \) and \( \Delta C_2 \), of the couples. In the course of surface shape optimization, only two bender couples plus one free parameter are extracted from the multipoint surface slope trace measurements [9]. This ensures a high accuracy of the optimization even in the presence of a noticeable high-spatial-frequency-correlated instrumental systematic error.

We modified the bender tuning software [9] to be able (in addition to the optimal setting of couples) to optimize the conjugates of a bendable mirror for a new geometry of use. In this case, we calculate slope alterations of the ideal ellipse, \( \delta \alpha_p(x) \), to small changes \( \delta P \) of the conjugate parameters \( P, P \in \{r, r', \theta\} \). The characteristic functions of the conjugates, \( f_p(x) = \delta \alpha_p(x) / \delta P \), are used to fit the difference between the measured slope profile and the new ellipse (corresponding to an approximate new geometry of use) and determine the optimal changes of the parameters. We have empirically verified a fast convergence, after a few iterations, of the method in spite of the inherent non-linearity of the problem. Note that the first approximation to the new elliptical geometry of use can be numerically calculated based on the width function Eq. (2) and the scaling rule Eq. (3) (Sec. 2).

5. Mirror-surface-figure-limited performance of the retuned KB mirrors

Using the OML experimental techniques briefly discussed in Sec. 4, we optimally aligned and bent the BL 12.3.2 KB mirrors for the conjugate parameters shown in Table 1. At the beamline, the in-beam positions and the pitch (grazing incidence) angle were adjusted correspondingly. The performance of the developed mirror alignment and bender setting procedures can be understood from the results of
scanning slit tests [10] presented in Fig. 1. The tests are conducted using JJ X-Ray™ slit system with a narrow opening (~10 µm) to isolate each part of the mirror in a series of discrete steps. The beam position in the focal plane as a function of the slit position is recorded. If the mirror tuning and alignment were perfect, all parts of the mirror would focus light at the same place and the measured beam would not move with the slit position.

The scanning slit tests allow the characterization of the mirror-surface-figure-limited focusing, rather than the entire system focusing determined by all the beamline set-up and environmental parameters such as vibration and temperature drifts. The obtained RMS variation of the beam position on the level of 100 nm is approximately the same as the estimated diffraction limit for the mirrors when used to focus the soft x-ray beam.

6. Conclusion
We have presented the recent development of bendable x-ray optics and experimental methods for optimal shaping and alignment of the optics used at different conjugate parameters of focusing (different focal distances and grazing incidence angles).

A simple scaling rule, derived here for the first time, allows one to understand a range of reliable tunability of bendable focusing grazing incidence optics and to reliably retune the optics for significantly different geometries of use. We have also shown that an optimal re-tuning, better than the one provided by the scaling rule, is still possible in each particular case by using an original regression-analysis-based procedure suggested and demonstrated here for the first time. The procedure allows accounting for the exact width profile of the mirror substrate and optimally determining the optimal mirror conjugate parameters by minimizing the overall surface error.

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