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ON THE CHARACTERIZATION OF ULTRA-PRECISE VUV-FOCUSING MIRRORS BY MEANS OF SLOPE MEASURING DEFLECTOMETRY

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ABSTRACT

Slope measuring deflectometry allows the non-contact measuring of curves surfaces like ultra-precise elliptical cylinder shaped mirrors in use for the focusing of Synchrotron light. This paper will report on the measurement of synchrotron mirrors designed to guide and focus Synchrotron light in the variable polarization beamline P04 at the PETRA III synchrotron at DESY (Hamburg). These mirrors were optimized by deterministic finishing technology based on topography data provided by slope measuring deflectometry. We will show the results of the mirror inspection and discuss the expected beamline performance by ray-tracing results.

Index Terms - Metrology, Synchrotron Optics, Synchrotron Radiation

1. INTRODUCTION

In order to benefit from the high brilliance of 3rd generation storage rings ultra-precise optical elements are required to guide and focus the photons produced by such state-of-the-art accelerators. The transport and focusing of photons from its source in the undulator section in the storage ring to a defined focus position without significant loss of brilliance and coherence is an extremely challenging task in X-ray optics. Due to the use under grazing incidence condition [1], typical X-ray optical systems (beamlines) are at least very long and have a length of up to 100m at the PETRA III source at DESY (Hamburg). The focusing mirrors used in such cases are Kirkpatrick-Baez (KB)-mirrors [2] of elliptical cylinder shape characterized by a residual figure error of a few nanometre rms while the mid- and high-spatial frequency error requires a micro-roughness of <0.2 nm rms. The metrology used to characterize the optics is a limiting factor to manufacture such demanding optical elements and thus have to provide corresponding accuracy. The use of high angular resolution slope measuring deflectometry as applied for the operation of dedicated optical profilers like the Nanometer Optical Component Measuring Machine (NOM) [3] enables to measure such optics with the required accuracy. We will report on results on the inspection of elliptical cylinder shaped synchrotron mirrors of up to 600mm in length. The measurements were performed at the BESSY-II Optics Laboratory (BOL) of the Helmholtz Zentrum Berlin (HZB) by use of the BESSY-NOM. Achieved measurement results are used to optimize the mirror quality by use of deterministic surface finishing as well as to simulate the characteristics of the beamline performance hereafter demonstrated for the case of the variable polarization beamline P04 [4] at the PETRA III storage ring in Hamburg.

2. THE VARIABLE POLARIZATION BEAMLINE P04 AT PETRA III

Situated at the 6 GeV electron storage ring PETRA III [5] at DESY (Hamburg/Germany) beamline P04 offers unique parameters for the soft X-ray range [4]. The first harmonic of a 5 m APPLE-II-type undulator covers the photon energy range from about 250 to 3000 eV. The beamline simultaneously offers high photon flux (>10E+12 photons/s) with high energy (E/dE >10,000) and spatial resolution (10 µm FWHM diameter focal spot). Ray-tracing with Shadow/XOP [6] as well as Ray/Reflec [7] was used to optimize the design of the optics. For the horizontal focusing, the optics concept of beamline P04 relies on a large de-magnification factor due to a very large source distance to the second KB mirror. For the vertical focusing mirror, the exit slit of the monochromator represents the intermediate source. In order to simplify the handling both mirrors have a fixed geometry, i.e. no mirror benders are employed.

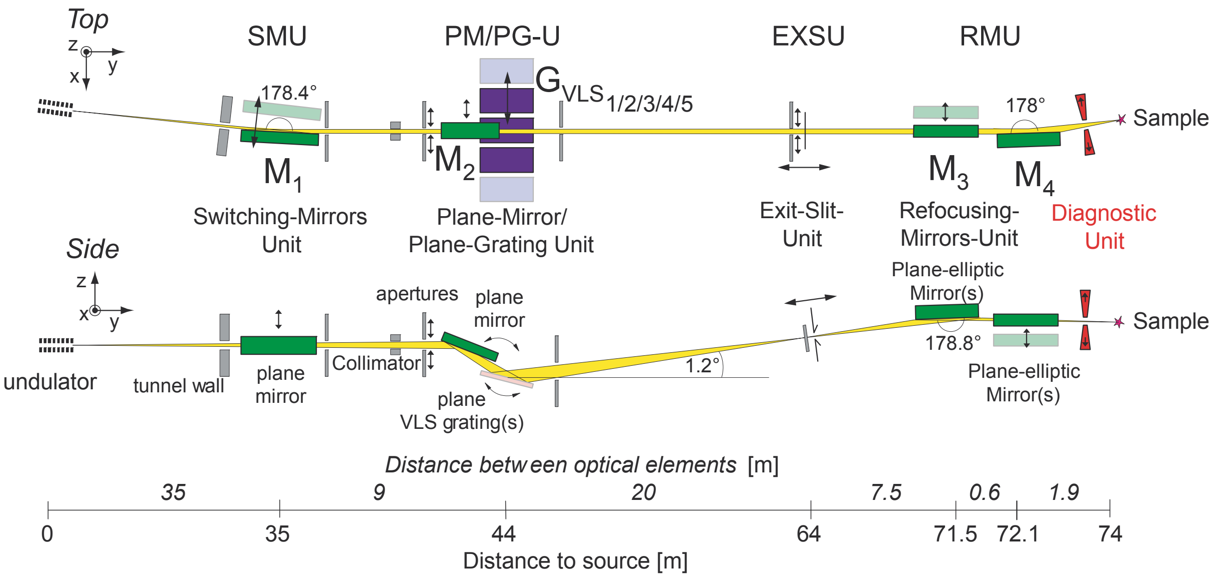

Figure 1. Optical layout of the variable polarization beamline P04 at the PETRA III storage ring at DESY.

3. SLOPE MEASURING DEFLECTOMETRY

Slope measuring deflectometry became a standard method to verify the quality of synchrotron optics in the late 80th early 90th of the last century. Instruments like the Long Trace Profiler (LTP) [8,9,10,11,12,13] and later on the Nanometer Optic component measuring Machine (NOM) [14,15,16,17,18] allow characterizing long mirrors or grating blanks up to a length of one meter and even longer with sub-nm precision [19] Figure 2 shows the principle set-up of the BESSY-NOM at Helmholtz Zentrum Berlin. A laser test beam is traced along the line of inspection of a surface under test. The test beam diameter is shaped by a diaphragm placed in a distance of 3mm to the surface under test. A short distance between diaphragm and surface under test limits the impact of vignetting and diffraction effects on the test beam. Recent investigations have shown a spatial resolution of 1.2mm achievable for the NOM if a diaphragm opening of 2.5mm is chosen [20].

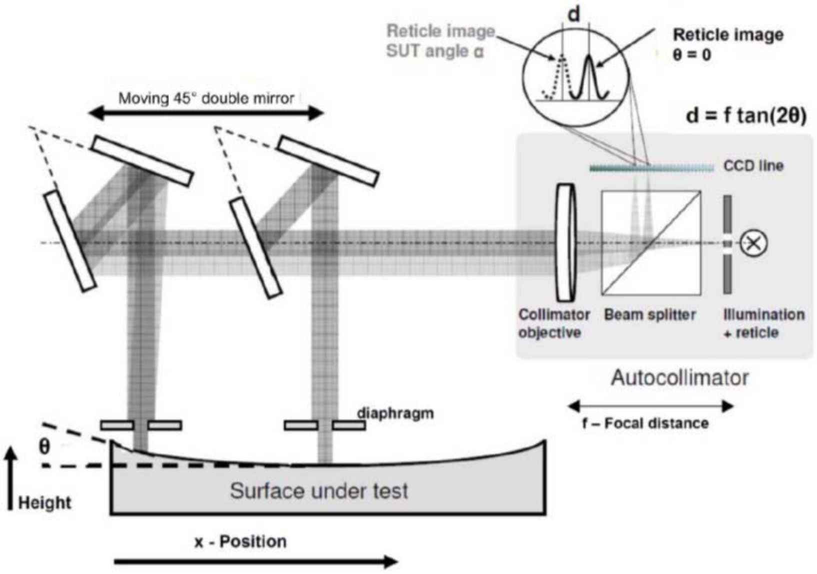

Figure 2. Principle design of an autocollimator based slope measuring profiler as realized in the concept of the BESSY-NOM.

Depending on the local curvature, the test beam will be reflected into the position sensitive detector of an autocollimator. In our case an Elcomat 3000 Spezial made by Moeller Wedel Optical is in use. The position of the reflected test beam on the CCD-line of the sensor is a direct expression of the local surface slope (see Figure 2). The reflection of the test beam along the optical axis of the instrument is determined by the angle between the mirror normal and the direction of the incident laser beam [21, 22]. Than the measured slope σ is given by:

$$\sigma(x) = \tan\theta = dy/dx \qquad (1)$$

The relative slope change is measured by scanning along the line of inspection. The sensor detects the change of the angle of reflection from one position x on the substrate to the next position x + Δx. A spatial integration of the slope data finally gives the topography profile $h(x_k)$:

$$h(x_k) = h(x_0) + \sum_{m=1}^{k} \frac{dx}{2}\left[\sigma(x_m) + \sigma(x_{m-1})\right] \qquad (2)$$

Figure 3 shows the profile of slope as measured at the central line on the mirror M3a and the corresponding profile of height.

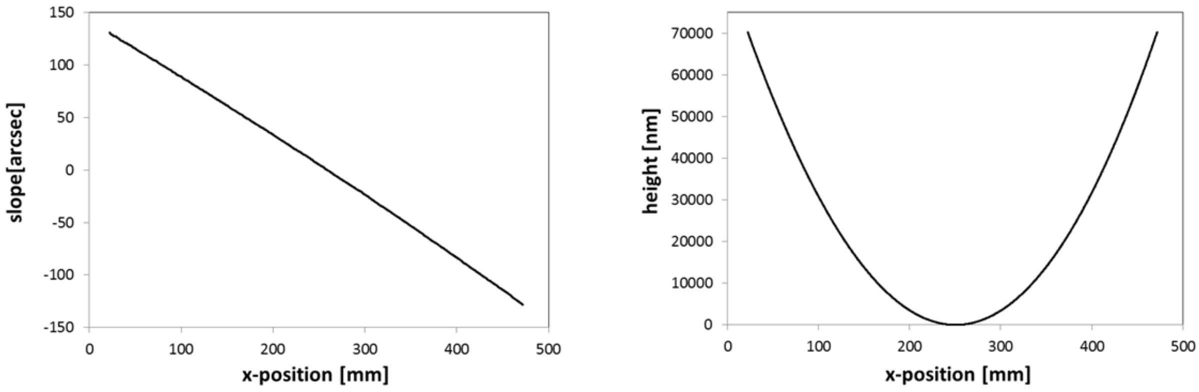

Figure 3. Mirror M3, profile of slope (left side) and the corresponding profile of height (right side) along central line of the mirror.

At least the residual slope error is the parameter of interest in synchrotron optics to verify the quality achieved. The residual slope error is obtained after the subtraction of an ideal profile of slope, given by an elliptical fit in the here discussed case based on the geometrical parameters as defined by the optical setup of the beamline. Equation 3 describes the ellipse in terms of slope related to the mirror center (pole) as proposed by Sutter and coworker [23]:

$$\sigma(x) = \frac{(r + r`)\sin\theta}{(r + r`)^2 - (r - r`)^2 \sin^2\theta}\Big(2rr` - \big[(r - r`)\cos\theta\big]x - 2(rr`)^{1/2}\big\{rr` - \big[(r - r`)\cos\theta\big]x - x^2\big\}^{1/2}\Big) \tag{3}$$

With the ellipse specified as the source to mirror pole distance defined as entrance arm length *r* and *r`* defined as the exit arm length between mirror pole and focal point at the experimental position, and the incidence angle of the photons *Θ* at the mirror pole – see also Figure 4. In our case the source point of the horizontal focusing mirror M3 is at the exit-slip position (working as secondary source) of the beamline with 7.5m distance to the mirror pole. The source point of the vertical focusing mirror M4 is at the undulator center in the storage ring in a distance of 72.1m to the mirror pole, see also at figure 1. Note: the advantage of choosing two elliptical cylinder like mirrors instead of a rotational ellipsoidal mirror is the higher finishing precision achievable for such mirrors - see also at reference [19] - and the option to have higher degree of freedom for the mirror alignment to the best horizontal and vertical focal conditions at the beamline.

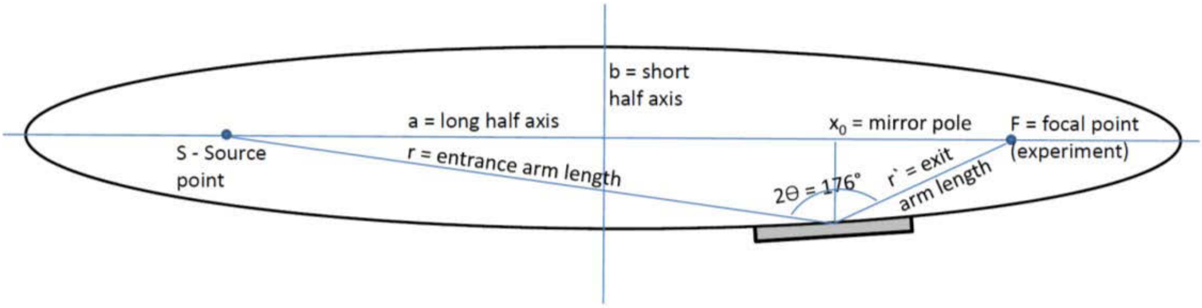

Figure 4. Ideal ellipse for a mirror imaging a source point S at a distance r to an image point in a distance r´ with the photons reflecting under incidence angle Θ at the mirror pole.

4. MEASUREMENT RESULTS – BEFORE AND AFTER ION BEAM FIGURING

Inspecting synchrotron mirrors by measuring just a single line scan in meridional direction is sufficient because of their very long and narrow aperture dimension. However providing topography data to enable an improvement of the mirror aperture area by deterministic surface finishing like Ion Beam Figuring (IBF) [24] or Elastic Emission Machining (EEM) [25] requires a surface mapping of the complete 3D topography. The BESSY-NOM allows such measurements as demonstrated in the past [26] plane mirrors and short elliptical cylinder like

KB-focusing mirrors up to a length of 300mm have been optimized based on NOM-slope mapping data [14, 26, 27]. In this chapter we will show measurement results for elliptical cylinder like shaped focusing mirrors of significant longer aperture length up to 580mm in the state before and after Ion Beam Figuring (IBF). Figure 5 shows mirror M3 in the state before and after IBF on an aperture section of 480x8mm^2 while Figure 6 gives the profile of residual slope and height along central line for both cases. There is slight improvement for the mirror slopes from 0.22 to 0.18arcsec rms achieved – see Figure 6. The residual height is improved by almost a factor of two from 14.14 to 8.29nm rms as shown for the 3D-mapping data (Figure5). While the profile of height along central line gives an improvement from initial 9.9nm rms to 3.9nm rms.

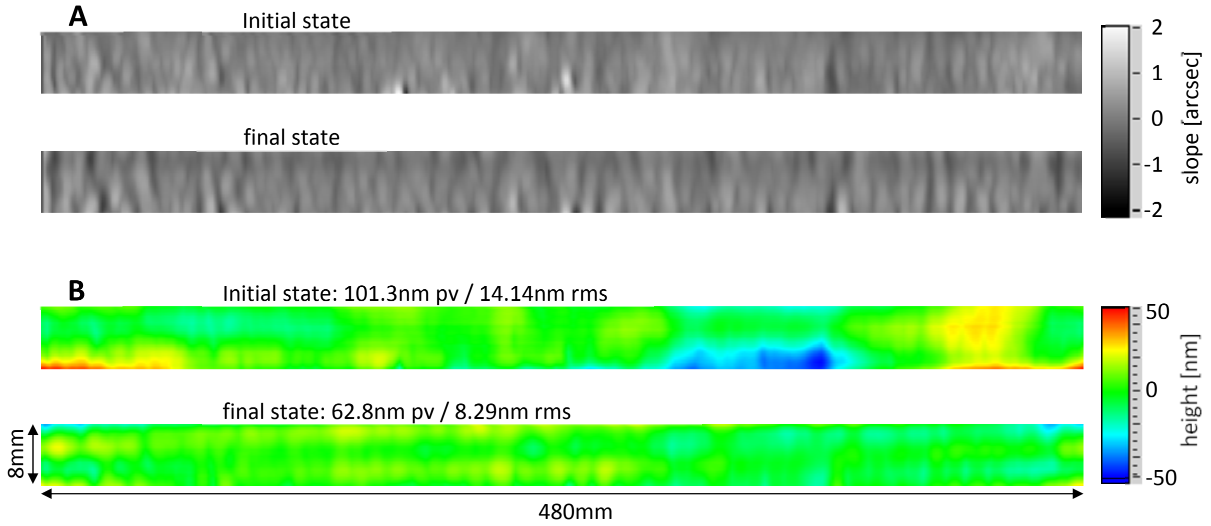

Figure 5. Mirror M3, mirror 3D topography in terms of slope (section A) and height (section B) before and after mirror improvement by IBF

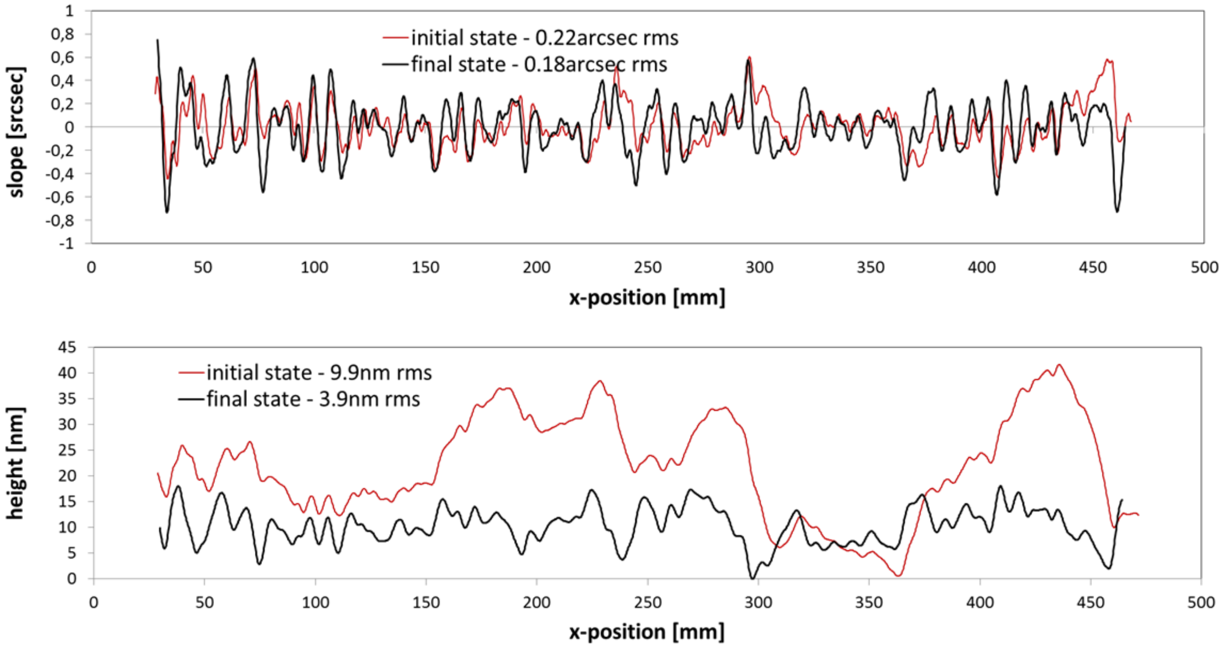

Figure 6. Mirror M3, profile of residual slope (top) and residual height (bottom) along central line of the mirror

Figure 7 shows mirror M4 in the state before and after IBF on an aperture section of 580x20mm^2 while Figure 8 gives the profile of residual slope and height along central line for both cases. In comparison to mirror M3 a significant improvement can be seen for both the mirror slopes as well as for the residual height. The slope error is improved by a factor of three from 0.60arcsec rms to 0.17arcsec rms. The height data show an improvement by factor of six from 29.65nm rms to 4.83nm rms as shown in the 3D-mapping results, see Figure 7. The same tendency is found for the height profile line at central axis, see Figure 8.

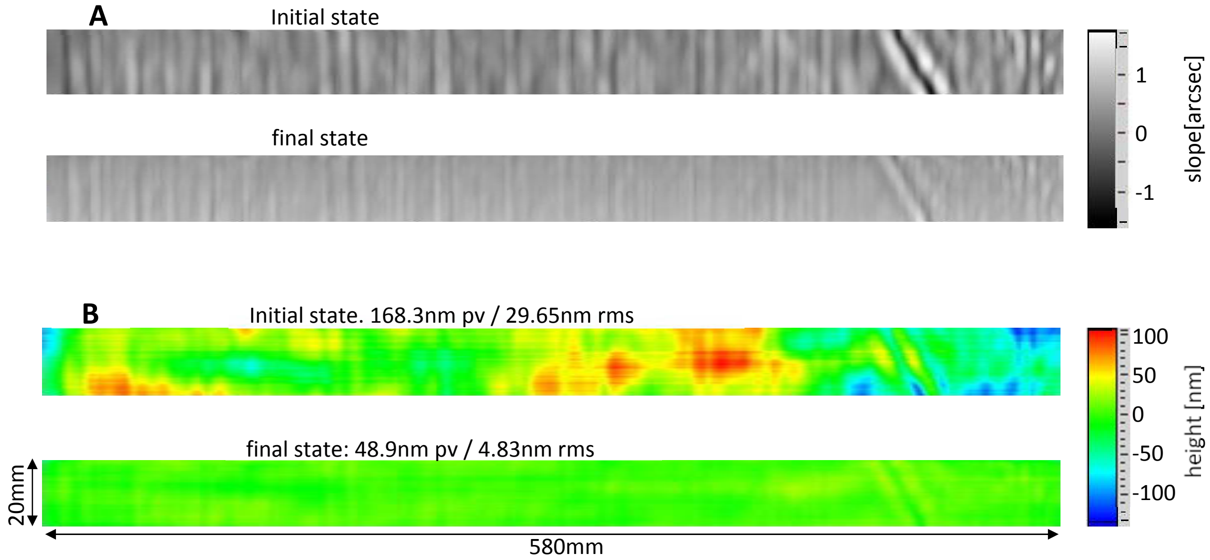

Figure 7. Mirror M4, mirror 3D topography in terms of slope (section A) and height (section B) before and after mirror improvement by IBF

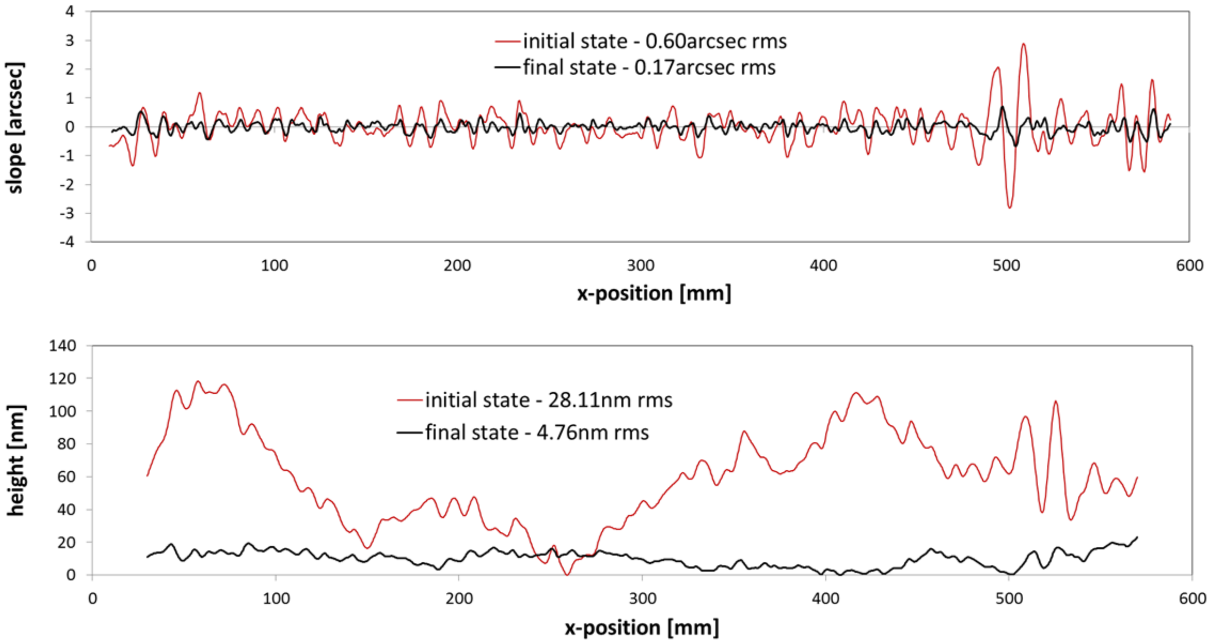

Figure 8. Mirror M4, profile of residual slope (top) and residual height (bottom) along central line of the mirror

Table 1 gives a comparison of the mirror parameter as specified and finally measured by use of the BESSY-NOM. Because of the small width of the finally used aperture we show the results of the slope line scans along the central line of the mirror. Due to technological limitations related to the IBF the final aperture length became shorter than specified. However this is of sufficient size for the use at the beamline.

Table 1: Parameter of the two KB-focusing mirrors as specified and measured.

Parameter	Mirror M3		Mirror M4	
	specification	measurement	specification	measurement
Substrate size [mm^3]	500x30x60		600x30x60	
Aperture size [mm^2]	490x24	480	590x24	580
Ellipse parameter:				
Entrance arm length r [mm]	7500	7500	72100	72100.00278
Exit arm length r`[mm]	2500	2500	1900	1900
Glancing angle	0.6°	0.5993°	1.0°	1.0°
Meridional slope error σ (at mirror central axis)	0.2	0.18	0.2	0.17
Residual figure error [nm pv/rms] (at mirror central axis)	-	18.05/3.9	-	29.32/4.76

5. RAY TRACING

In the following we concentrate on the ray tracing results showing the consequences of the optical quality of the pair of KB-mirrors. Figure 9 shows ray tracing results of the focus which is defined by this KB-mirror stage. On the left hand side the case for ideal optics with no figure errors for all mirrors is shown. In the middle panel, the ray tracing results take into account the profile traces obtained for the actually manufactured mirrors using the BESSY-NOM as described above. The focus size is increased with respect to the ideal case, but still a close to 10-µm-diameter focus can be achieved.

In order to assess the focal size at the real beamline, a so-called “focus finder” device was developed which allows to rapidly moving a fluorescent screen under UHV-conditions along the optical axis and simultaneously recording high resolution images of the SR beam footprint on the screen. Figure 10 shows one of the images close to the ideal focus position (pixel size 0.7 µm) taken during initial alignment of the KB-mirrors. The corresponding values are approximately 14 µm by 12 µm for the horizontal and vertical FWHM, respectively.

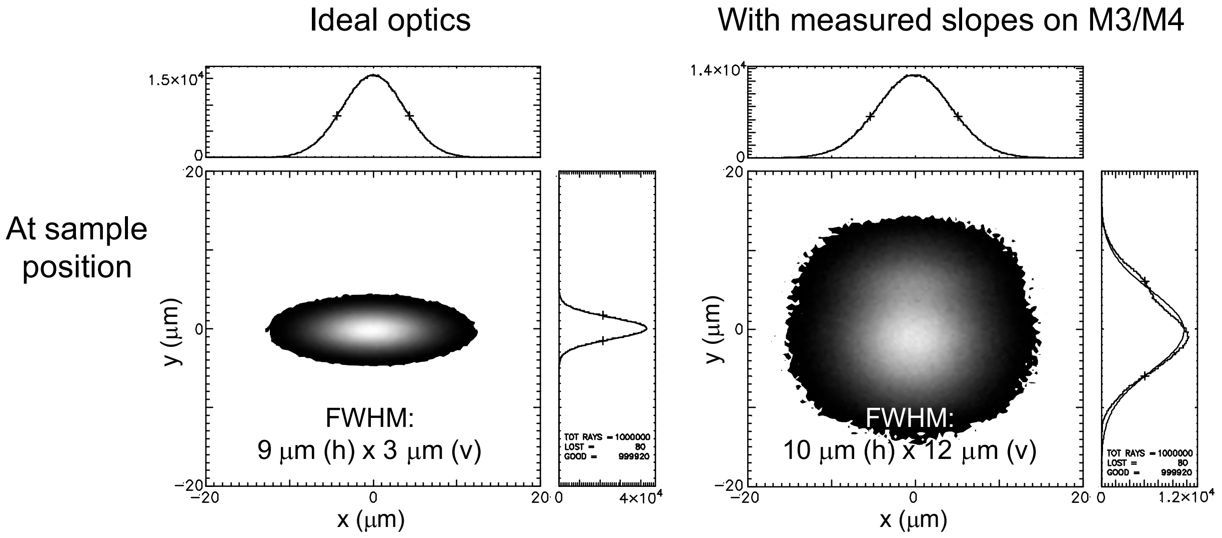

Figure 9. Raytracing results for the focus at the sample position for ideal optics (left) and taking into account the measured residual height errors of both focusing mirrors (right), respectively.

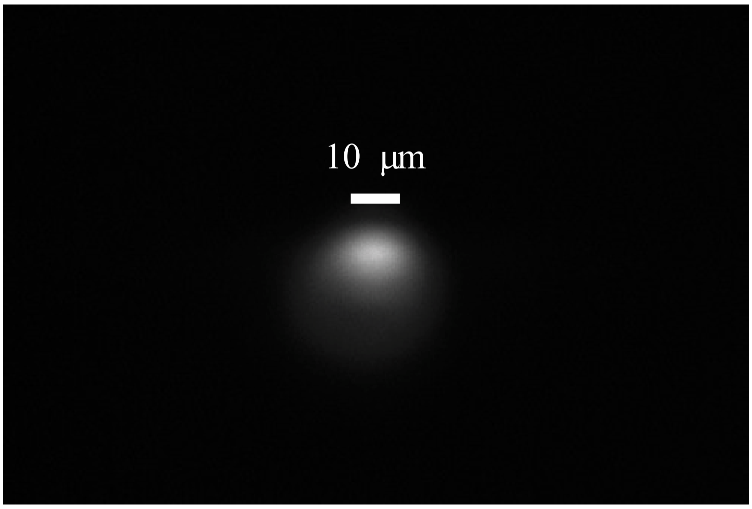

Figure 10. Measured focus image close to the sample position. Field of view: 150μm x 100μm.

6. RESULTS, OUTLOOK AND CONCLUSIONS

We have shown the capability of measuring elliptical cylinder-like VUV focusing mirrors by means of slope measuring deflectometry up to a figure precision of 0.17arcsec rms for half a meter long mirror length. For both mirrors an rms figure error of a few nm is found. The measured ellipse parameters are in excellent agreement to the specification for both mirrors, see Table 1. Based on 3D slope mapping data an improvement of up to a factor of six in terms of the rms figure error can be achieved if such topography data are available for deterministic surface finishing like Ion Beam Figuring (IBF). Raytracing results based on the 2D slope mapping data are in good agreement with actual measurements performed at beamline P04 at PETRA III.

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