ACTOP-08

2nd Workshop on X-ray and XUV Active Optics
October 9-11, 2008, Trieste, Italy

BERKELEY LAB

Bendable X-ray optics at the ALS:
design, tuning, performance, and applications

(as these are seen by the eyes of an optical metrologist)

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Bendable x-ray optics at the ALS

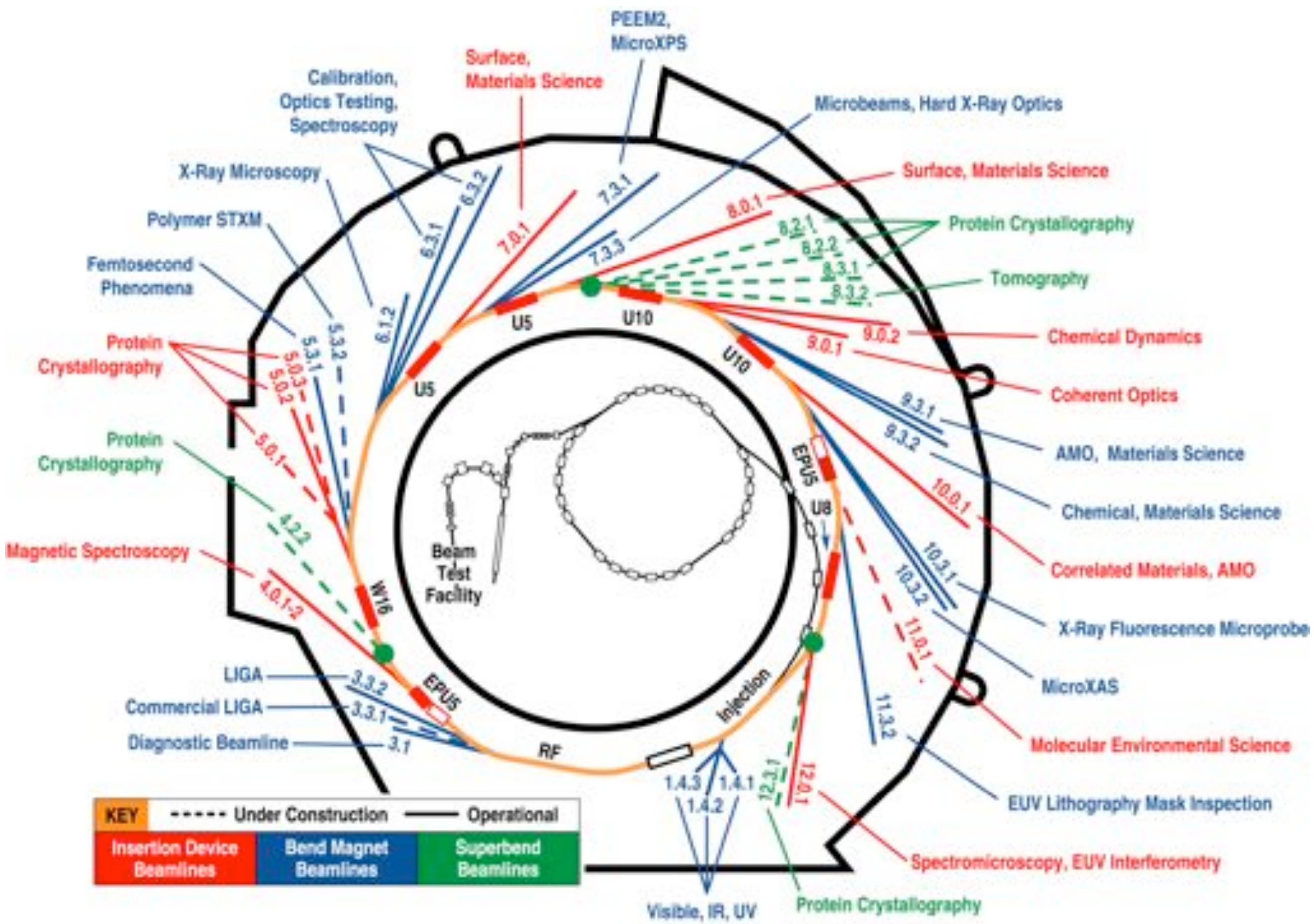
– *as a part of pre-focusing and end-station Kirkpatrick-Baez (KB) focusing systems*

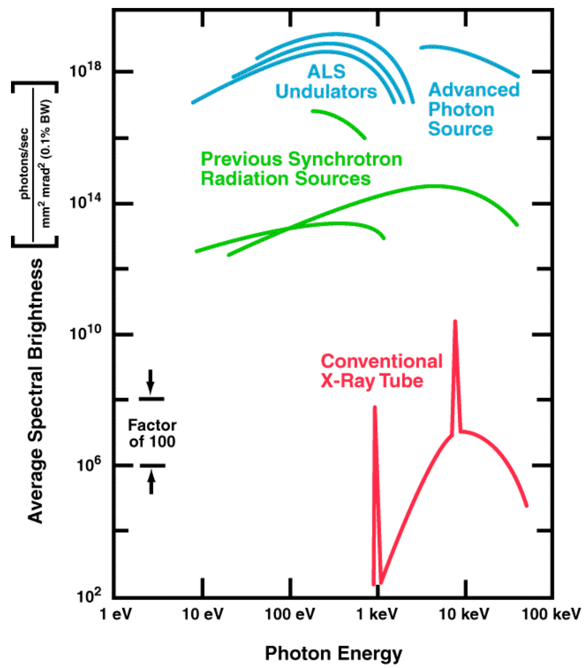
P. Kirkpatrick, and A. V Baez, *J. Optical Society of America* 38, 766-774 (1948)

– *based on controlled bending of a flat substrate with unequal end couples*

– *and controlled variation of the mirror width*

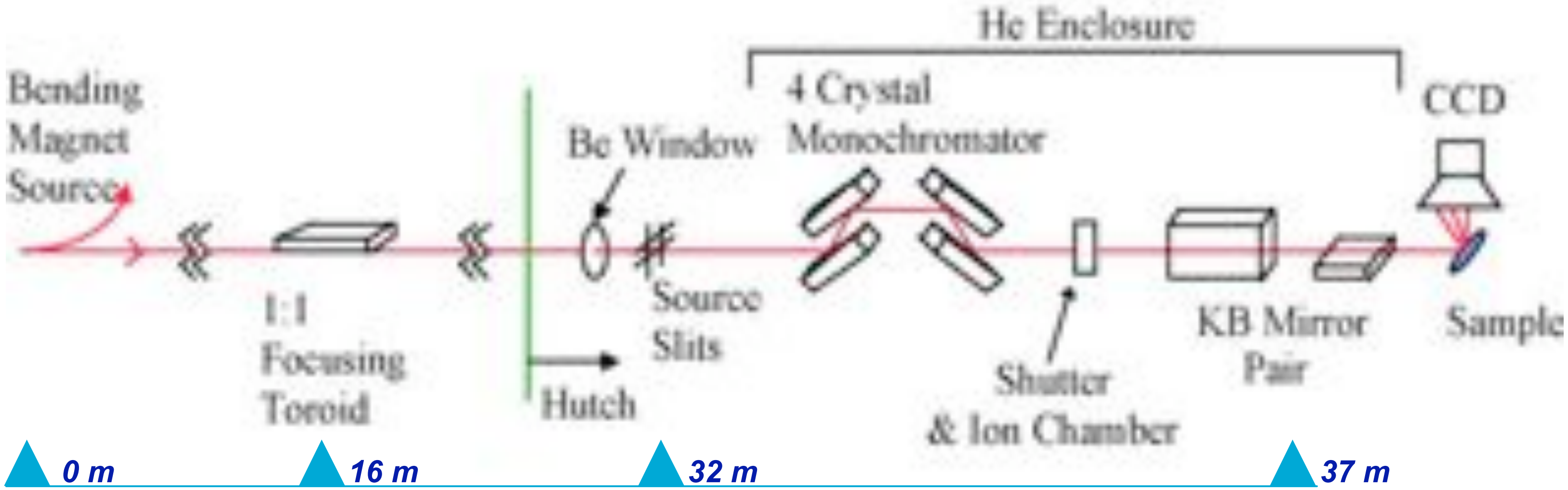
M. R. Howells, et al., *Theory and practice of elliptically bent x-ray mirrors,* Opt. Eng.39(10), 2748-61 (2000)

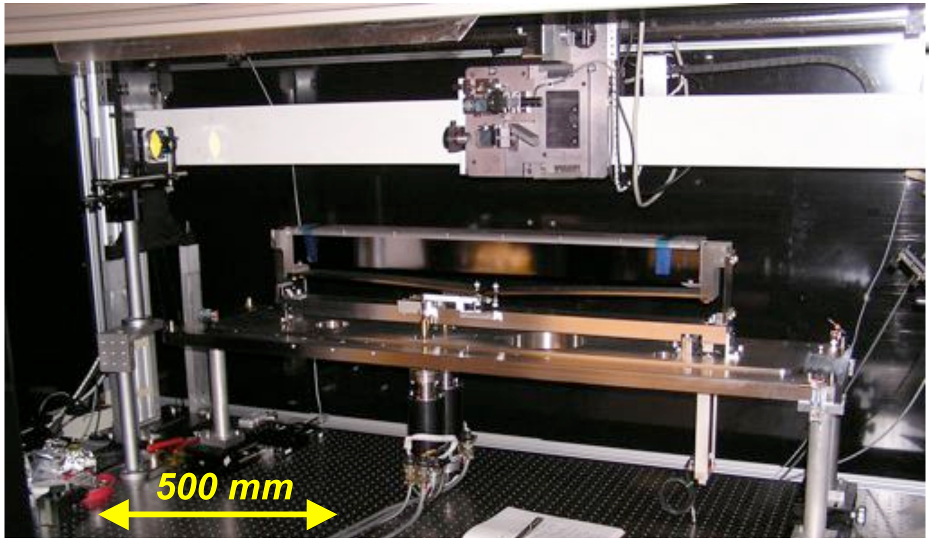




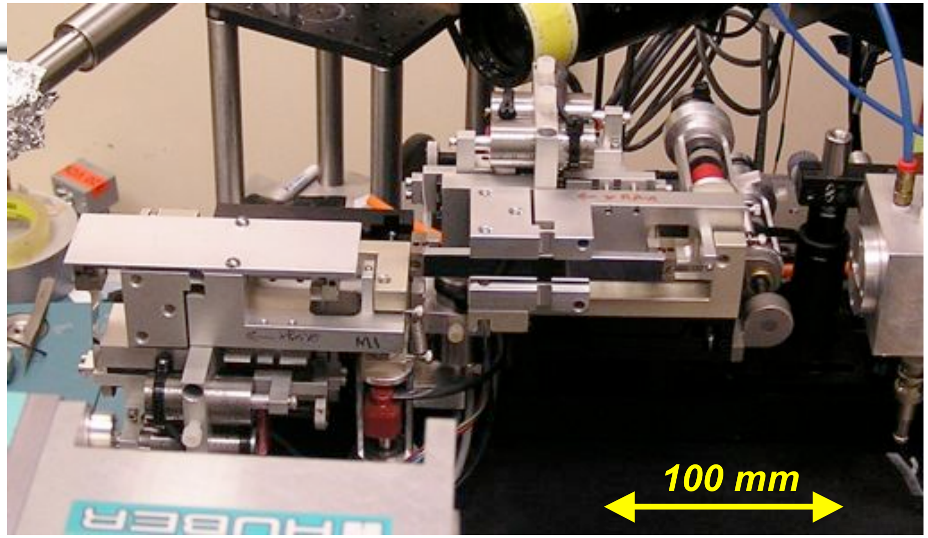
Total number of bendable optics at the ALS is > 50 units

BL 12.3.2/7.3.3 for X-ray Micro-diffraction





BL12.3.2 pre-focusing M1 toroidal mirror on the LTP
(backside-cantilever bending mechanism)



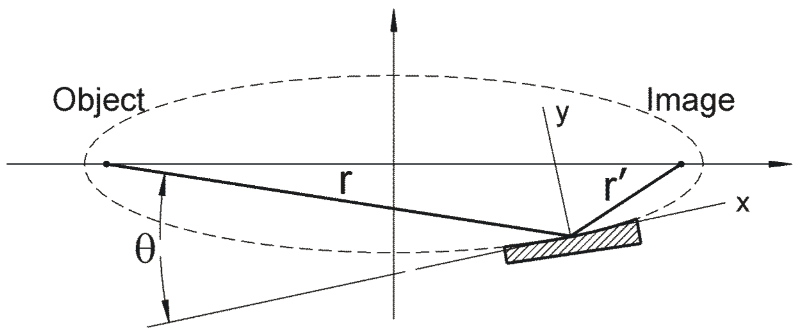
BL7.3.3 end station KB elliptical mirrors
(S-shaped-leaf-spring bending mechanism)

Outline

- ***Bendable X-ray Optics at the ALS***
  - *Introduction*
- ***Design** considerations for bendable X-ray optics*
  - *Formation of an Elliptical Surface by Beam Bending*
    - *Bird-like shape, anti-clastic bending, and sagittal shaping*
  - *Roll angle alignment*
  - *Anti-twist correction*
- ***Tuning** of Benders at the ALS Optical Metrology Laboratory*
  - *Formulation of the problem*
  - *Introduction to regression analysis*
  - *Algorithm, procedure, and software for fast tuning of bendable optics*
- ***Performance***
  - *Beamline performance is the figure-of-merit rather than rms slope variation*
  - *Performance limitations: vibration and temperature drifts*
- ***Application** of developed methods to the ALS BL12.3.2*
- ***Conclusions***

Motivation for bendable focusing optics

Micro- and nano- focusing require precisely shaped x-ray optics



r – object-to-mirror distance

r′ – mirror-to-image distance

θ *– grazing angle*

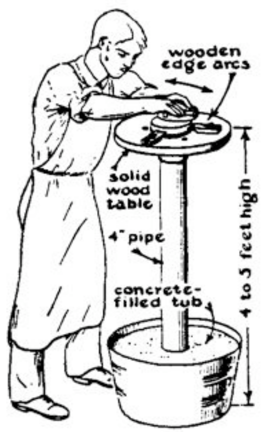
Figure-of-merit:

$\delta\alpha$ *– slope deviation (rms) of mirror surface from an ideal elliptical shape*

Modern Requirements:

$\delta\alpha$ *< 0.2 μrad*

Fabrication methods:



- ***Traditional grinding and polishing***

  good for flats, cylinders, and spheres

- ***Zone polishing*** *(with a flexible lap, magneto-rheological, ion-beam finishing)*

  requires expensive and time consuming processing and metrology

- ***Differential deposition***

  requires expensive and time consuming processing and metrology

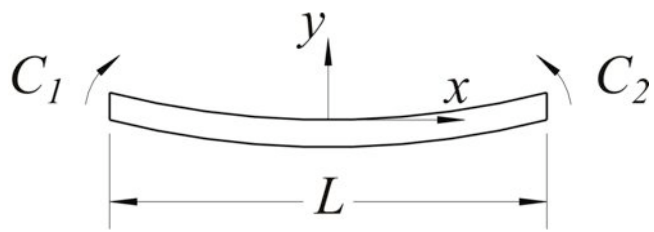
- ***Mechanical shaping of traditionally polished substrates***

  substrates with super high quality surface figure and finish are routinely available at reasonable cost

  easily re-adjustable and suitable for

Mechanical design approaches

Beam theory applied to a bent structure:



$$EI(x)\frac{\partial^2 y}{\partial x^2} = \frac{C_1 + C_2}{2} - \frac{C_1 - C_2}{L}x$$

E is Young's modulus of the mirror material

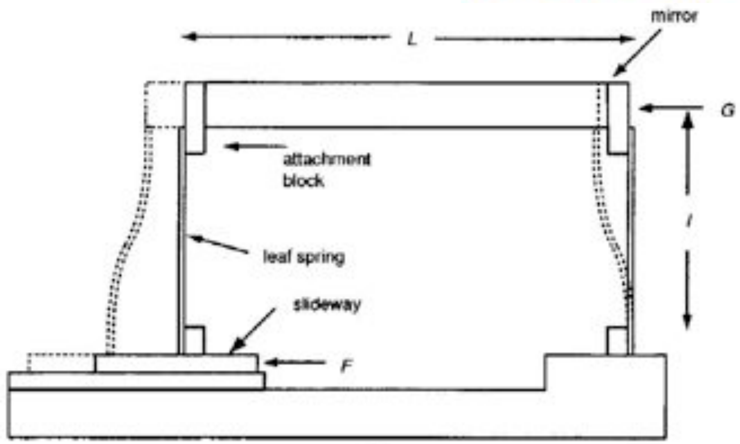
$I(x)$ is the moment of inertia as a function of position along the beam, or mirror

C_1 and C_2 are the end couples producing bending moments

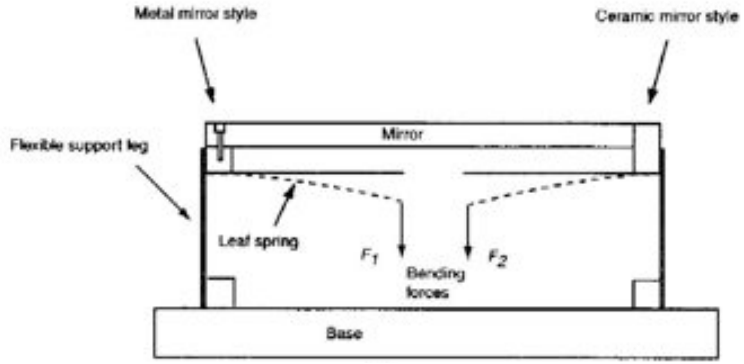
$$I(x) = I_0 = \frac{b\,h^3}{12}$$

bird-like shape

anti-clastic bending



(a) "s" spring bender



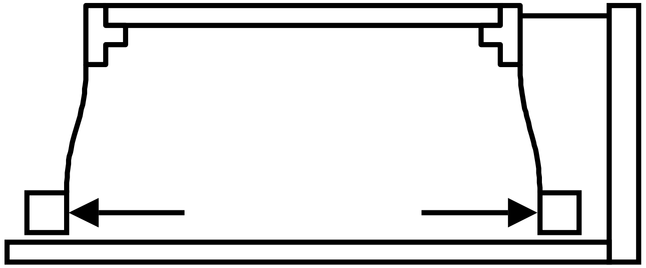
(b) cantilever spring bender

Fig. 3 (a) An "S" spring bender in which equal and opposite couples are applied by moving the slideway to the left (force *F*), while couples of the same sign are applied by pushing the whole mirror to the left (force *G*). (b) Avoids the mirror tension implicit in (a) by applying the couples by means of forces transverse to the mirror. The latter scheme has also the advantage of being all-flexural.

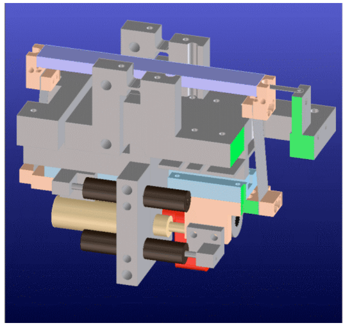
M. R. Howells, et al., *Theory and practice of elliptically bent x-ray mirrors,* Opt. Eng.39(10), 2748-61 (2000)

Mechanical design approaches

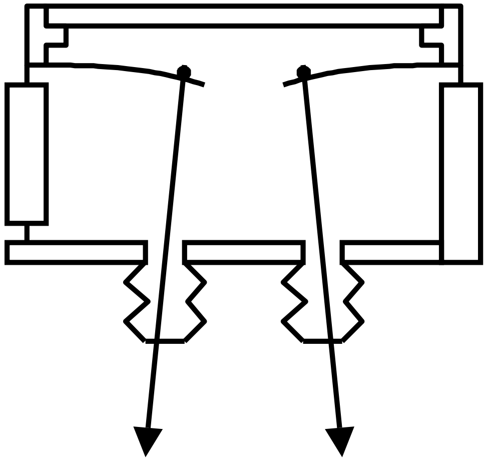
(a) "s" spring bender



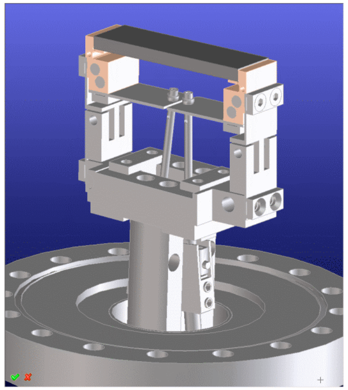
- Mirror bent using off-axis tensile force through s-springs.
- Low sprung mass
- Insensitive to length changes
- Produces large quantities of undesirable tensile stress in mirror
- Requires space at end to hold mirror in place
- Ball bearing slides produce unrepeatable errors

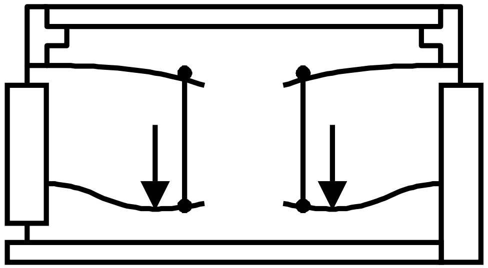


(b) cantilever spring designs

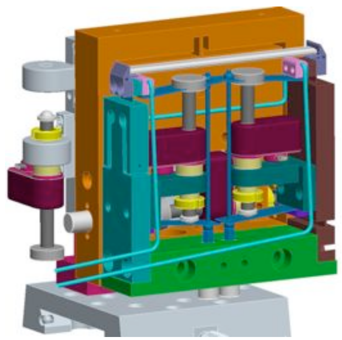


- Low sprung mass
- Ball Coupling can have stick/slip problems
- Pull motors require large amounts of adjacent space
- Can produce moderate amounts of tensile stress.



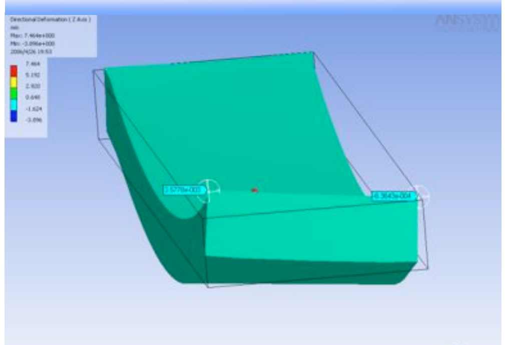


- Compact Design
- Tensile stress not dependent on degree of bend
- Large sprung mass includes motor
- Long linkage vulnerable to thermal expansion issues

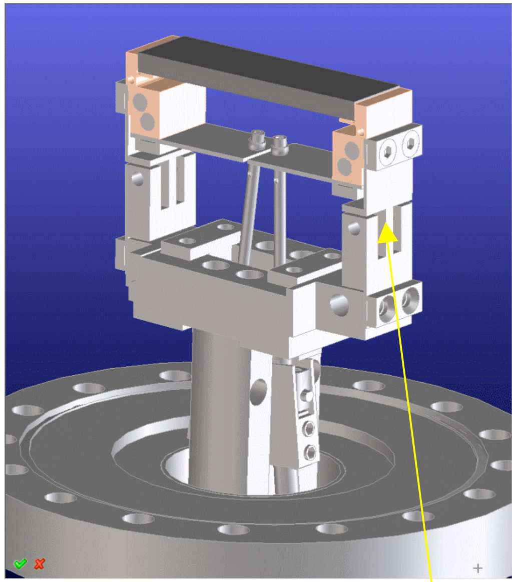


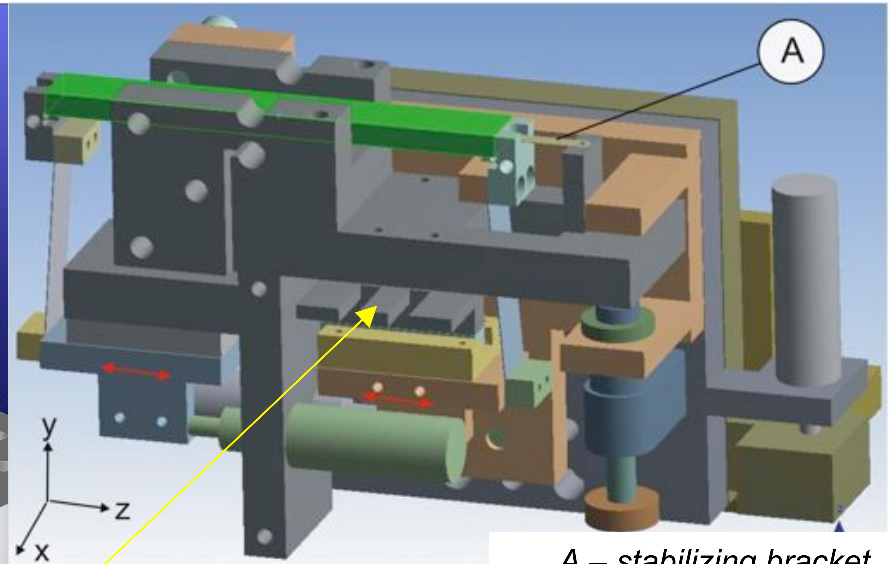
Anti-twist Correction

Twist Simulation



Anti-twist correction should not stress the mirror substrate in other directions

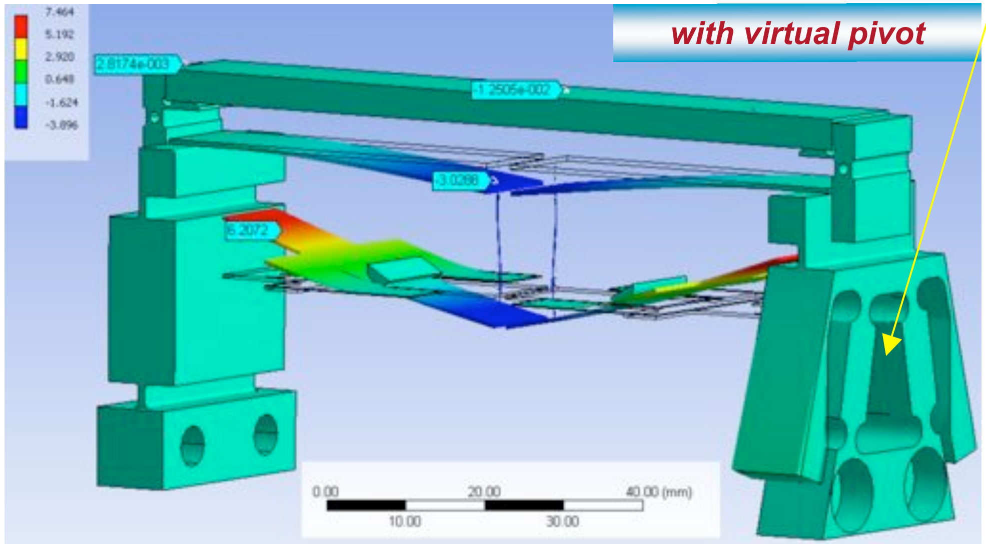




A – stabilizing bracket

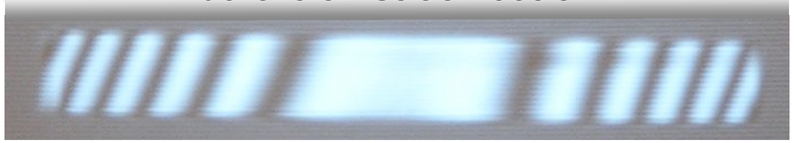
Anti-twist mechanisms

with virtual pivot



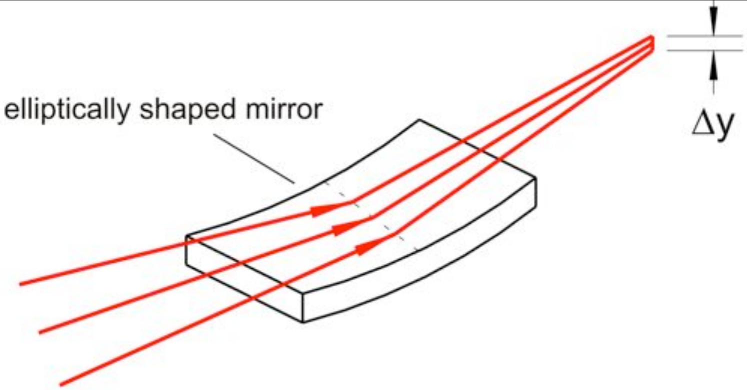
Visualization and correction of surface twist with ZYGO GPI™

before twist correction

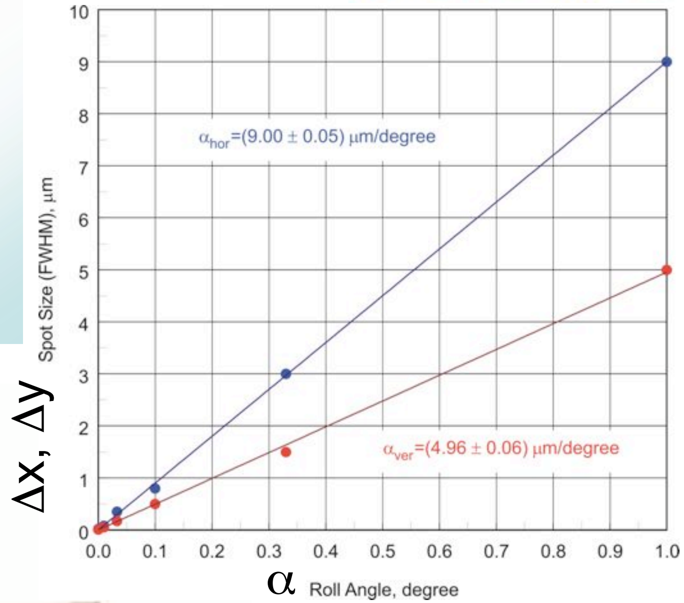


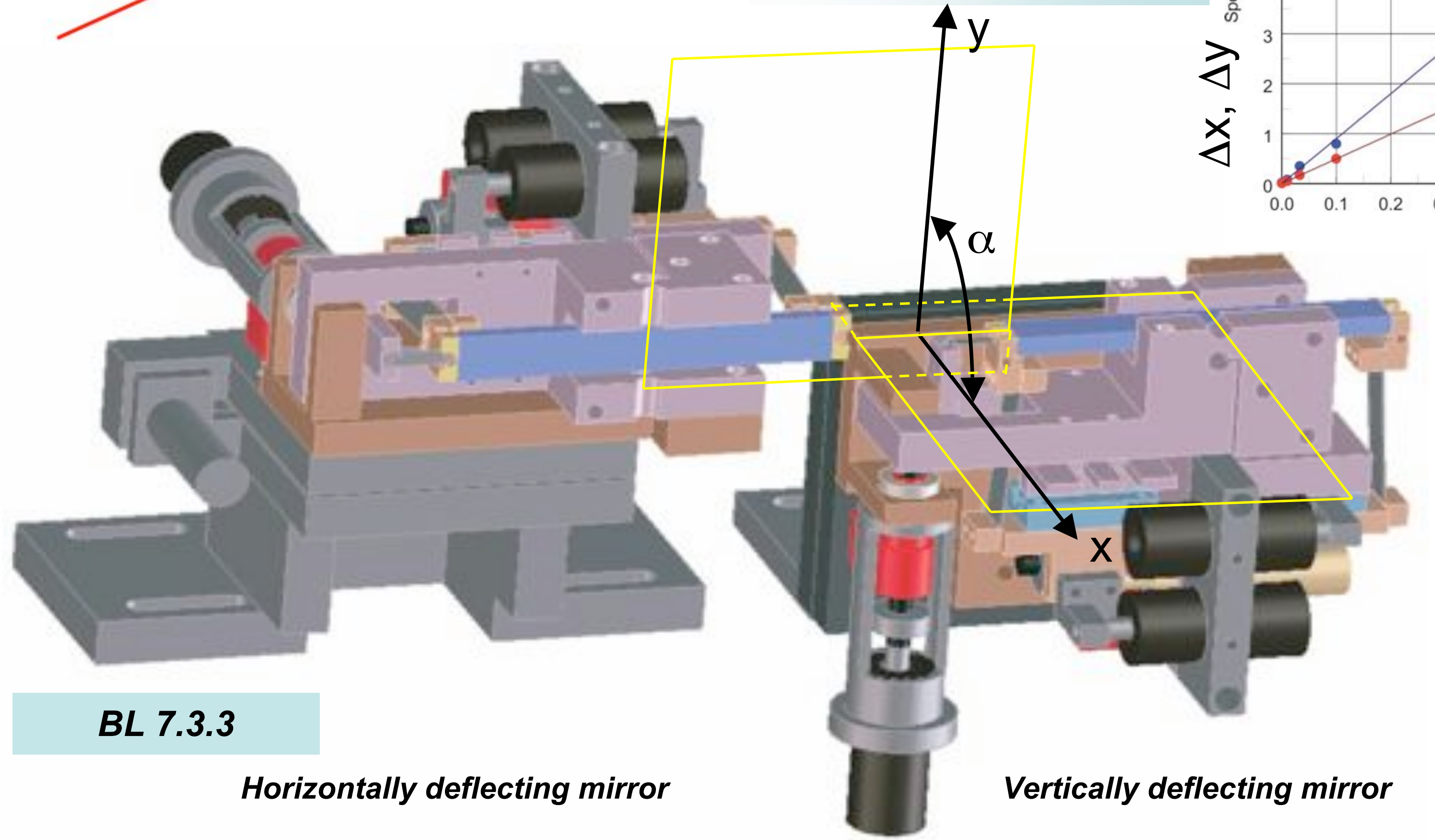
after twist correction

Orthogonality (Roll-of) one mirror with respect to the other



For both mirrors, beams reflected from different positions across the mirror width were focusing at different spots.





Similar effect can be due to a twist of the mirror surface

BL 7.3.3

Horizontally deflecting mirror

Vertically deflecting mirror

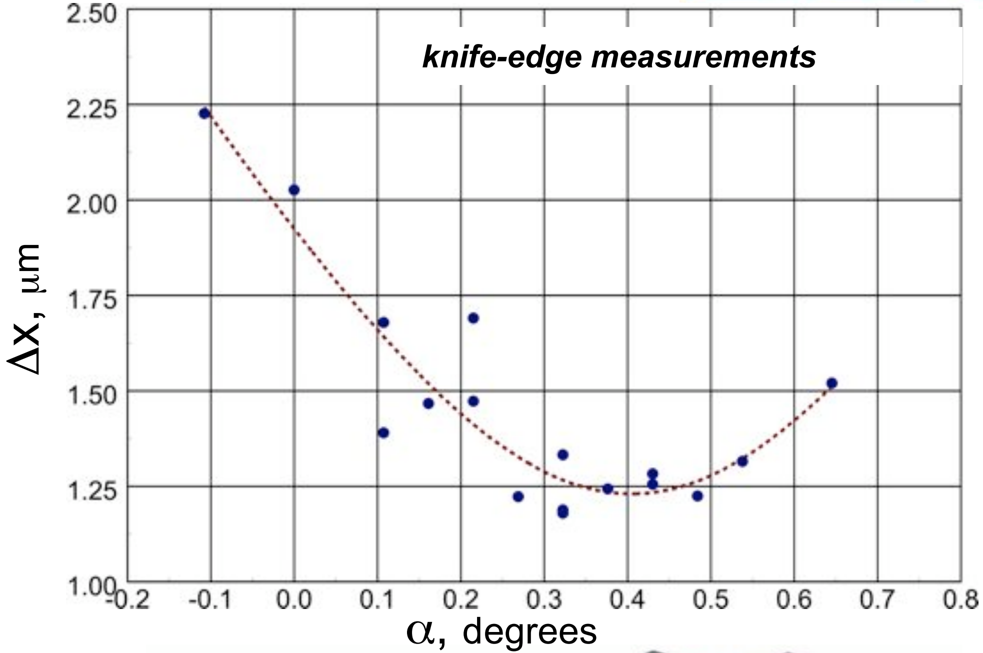
Alignment of Roll Angle of KB mirrors

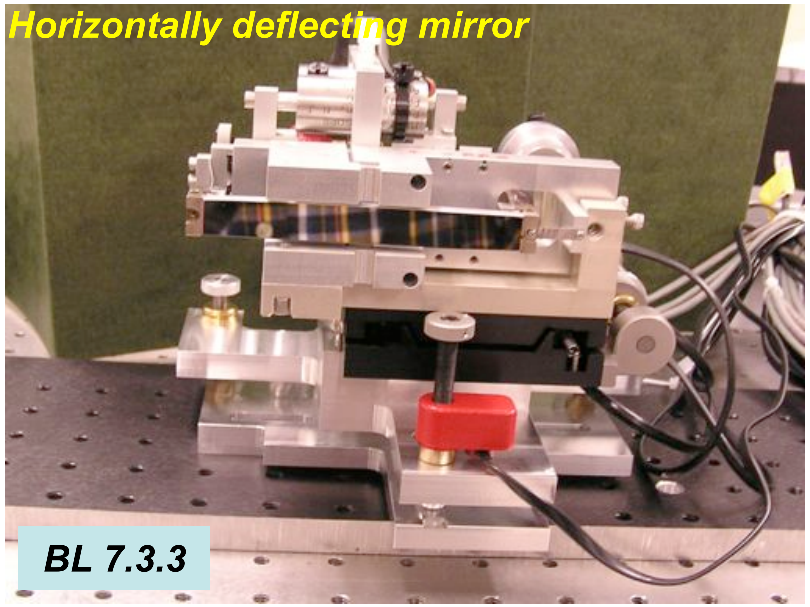
$$\Delta x^2 = \sigma_{Roll}^2 + \sigma_{Roll=0}^2$$

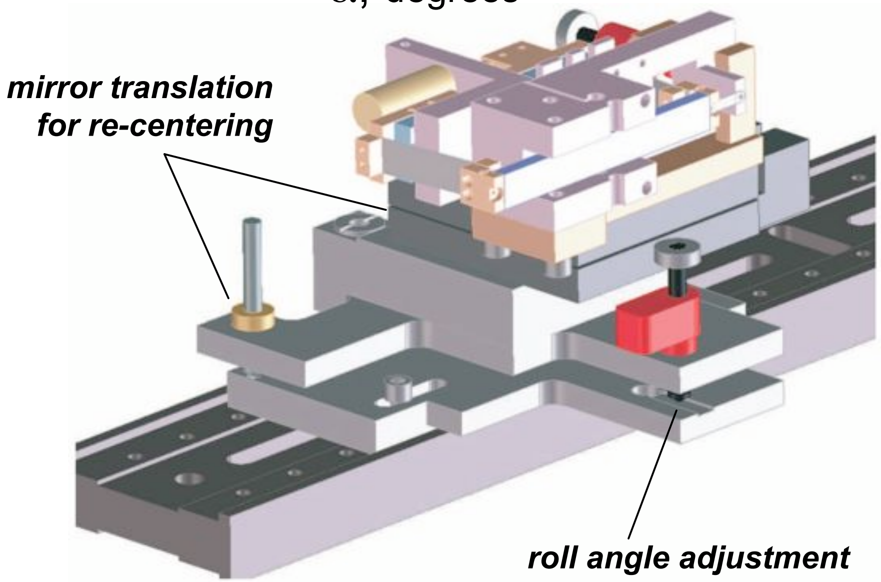
$$\sigma_{Roll} = \xi \left(\alpha_{Roll} - \alpha_{Roll=0} \right)$$

The roll angle of the horizontally deflecting mirror was adjusted by

$$\Delta\alpha_{Roll} \approx 1.5 \text{ degrees}$$







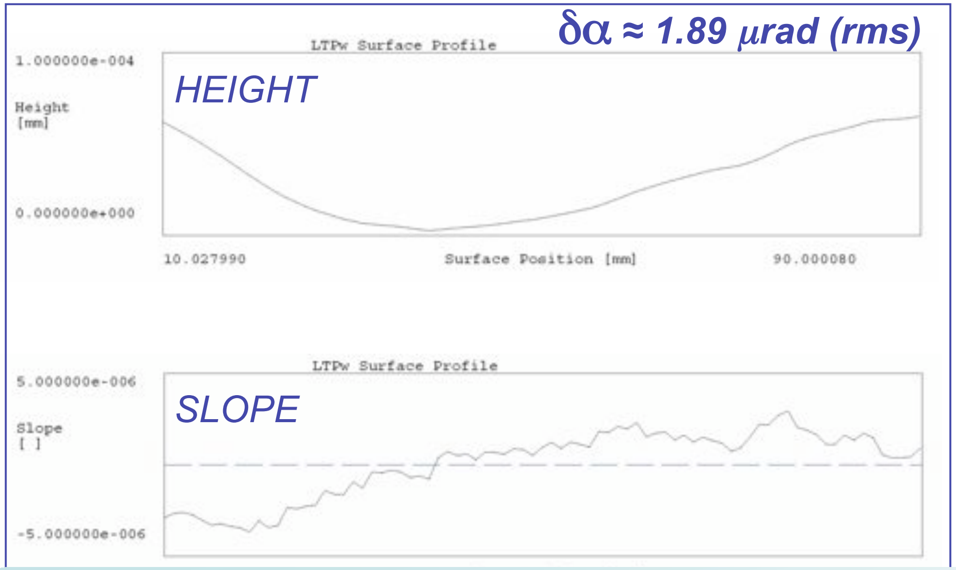
Bendable mirror tuning with the LTP:
Problem to be solved

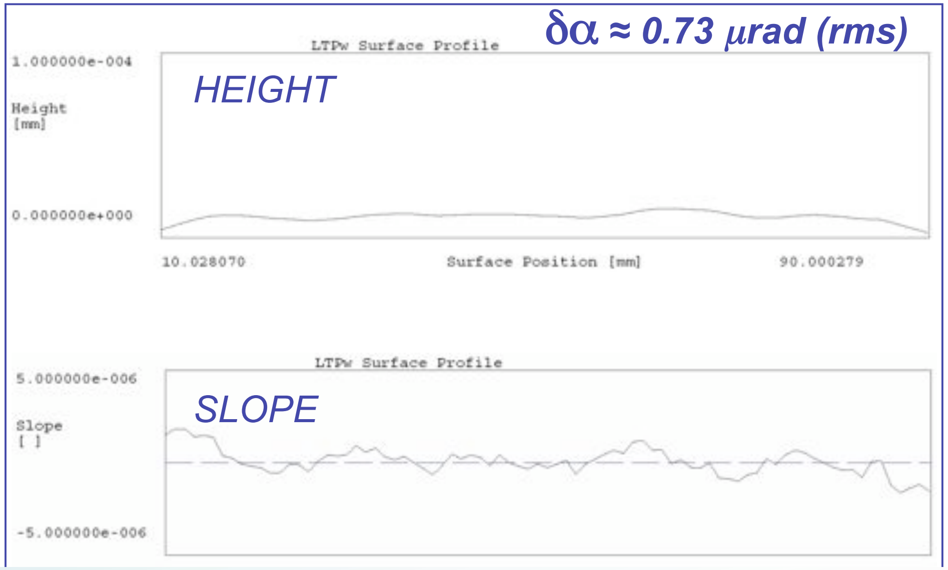
100-mm-long elliptical mirror specified with:

r = 18.901 m, r' = 0.120 m, θ = 0.0031 rad

Figure-of-merit for adjustment:

$\delta\alpha \leq 1\ \mu rad$ (rms)





The problem:

How can the operator reliably chose the settings for the next iteration of bendable mirror adjustment?

Settings: V_{US} = 3.250 V V_{DS} = 1.650 V	V_{US} = 3.275 V V_{DS} = 1.650 V

W. R. McKinney, S. C. Irick, J. L. Kirschman, A. A. MacDowell, A. Warwick, V. V. Yashchuk, *New Procedure for the Adjustment of Elliptically Bent Mirrors with the Long Trace profiler,* SPIE Proc. 6704-15 (2007)

Review of linear regression method

Conditional distribution of two variables: a mean value of y vs (x,θ)

$$\mathrm{E}(y\,|\,x) = \eta(x,\theta)$$

Observation: $y_i = \eta(x_i,\theta) + \varepsilon_i;$ *where:* ε_i *is the error variable*

$$\eta(x,\theta) = \theta_0\, f_0(x) + \theta_1\, f_1(x) + \ldots + \theta_r\, f_r(x)$$

is a linear combination of functions.

Simple transformations to apply Method of Least Squares:

$$\varepsilon_i = y_i - \theta_0\, f_0(x_i) - \theta_1\, f_1(x_i) - \ldots - \theta_r\, f_r(x_i),\ i = 1,2,\ldots,n$$

$$S = \sum_{i=1}^{n} \varepsilon_i^2 = \sum_{i=1}^{n} (y_i - \theta_0\, f_0(x_i) - \theta_1\, f_1(x_i) - \ldots - \theta_r\, f_r(x_i))^2$$

$$\frac{\partial S}{\partial \theta_\rho} = 0,\quad \rho = 0,1,\ldots,r.$$

R. L. Plackett, Principles of Regression Analysis (Oxford, At The Clarendon Press, 1960).

D. J. Hudson, Statistics: Lectures on Elementary Statistics and Probability (Geneva, 1964);
In Russian: Д. Худсон, Статистика для физиков, Москва, Мир, 1970.

J. Neter and W. Wasserman, Applied Linear Statistical Models (London, Inwin-Dorsey International, 1974).

M. Kendall and A. Stuart, The Advanced theory of Statistics, vol.2 (New York, Oxford University Press, 1979).

V. V. Yashchuk, Positioning errors of pencil-beam interferometers for long-trace profilers, SPIE Proceedings 6317, pp. 6317-10 (San Diego, California, USA, 13-17 August 2006)

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$$S = \sum_{i=1}^{n} \varepsilon_i^2 = \sum_{i=1}^{n} (y_i - \theta_0\, f_0(x_i) - \theta_1\, f_1(x_i) - \ldots - \theta_r\, f_r(x_i))^2$$

$$\frac{\partial S}{\partial \theta_\rho} = 0,\quad \rho = 0,1,\ldots,r.$$

Introduce a regression matrix:

$$\hat{A} = \begin{bmatrix} f_0(x_1) & f_1(x_1) & f_2(x_1)\ldots & f_r(x_1) \\ f_0(x_2) & f_1(x_2) & f_2(x_2)\ldots & f_r(x_2) \\ \vdots & \vdots & \vdots & \vdots \\ f_0(x_n) & f_1(x_n) & f_2(x_n)\ldots & f_r(x_n) \end{bmatrix}$$

Then:

$$\hat{\varepsilon} = \hat{y} - \hat{A}\hat{\theta}$$

$$S = \hat{\varepsilon}'\,\hat{\varepsilon} = \hat{y}'\,\hat{y} - 2\hat{\theta}'\,\hat{A}'\,\hat{y} + \hat{\theta}'\,\hat{A}'\,\hat{A}\hat{\theta}$$

$$-\hat{A}'\,\hat{y} + \hat{A}'\,\hat{A}\,\hat{\theta} = 0;$$

Solution:

$$\hat{\theta}^* = (\hat{A}'\,\hat{A})^{-1}\,\hat{A}'\,\hat{y}$$

$$D\hat{y} = \sigma^2\,\hat{I}$$

$$D\hat{\theta}^* = ((\hat{A}'\,\hat{A})^{-1}\,\hat{A}')\,D\hat{y}\,((\hat{A}'\,\hat{A})^{-1}\,\hat{A}')' = \sigma^2\,(\hat{A}'\,\hat{A})^{-1}$$

R. L. Plackett, Principles of Regression Analysis (Oxford, At The Clarendon Press, 1960).

D. [illegible]

J. N [illegible]

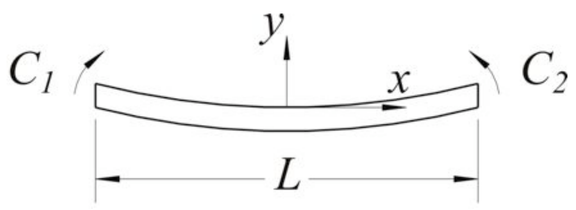
M. [illegible]

V. [illegible] *0*

Bendable mirror tuning with the LTP: Theory

Beam theory applied to a bent structure:

M. R. Howells, et al., *Theory and practice of elliptically bent x-ray mirrors,* Opt. Eng. 39(10), 2748-61 (2000)



$$EI(x)\frac{\partial^2 y}{\partial x^2} = \frac{C_1 + C_2}{2} - \frac{C_1 - C_2}{L}x$$

E is the mirror elastic modulus;
$I(x)$ is the mirror section moment;
C_1 and C_2 are the bending moments

After simple transformations:

$$\frac{\partial^2 y}{\partial x^2} = C_1\left(\frac{1}{2} - \frac{1}{L}x\right)\frac{1}{EI(x)} + C_2\left(\frac{1}{2} + \frac{1}{L}x\right)\frac{1}{EI(x)}$$

$$\frac{\partial^2 y}{\partial x^2} = C_1 g_1(x) + C_2 g_2(x)$$

where: $g_1(x) = \left(\frac{1}{2} - \frac{1}{L}x\right)\frac{1}{EI(x)}$; $g_2(x) = \left(\frac{1}{2} + \frac{1}{L}x\right)\frac{1}{EI(x)}$

After integrations:

$$\alpha(x,C) = \frac{\partial y}{\partial x} = C_0 + C_1 f_1(x) + C_2 f_2(x)$$

where: $f_1(x) = \int g_1(x)\,dx$; $f_2(x) = \int g_2(x)\,dx$;

For ideal elliptical surface:

$$\alpha^0(x,C) = C_0^0 + C_1^0 f_1(x) + C_2^0 f_2(x) \longrightarrow \Delta\alpha(x,C) = \Delta C_0 + \Delta C_1 f_1(x) + \Delta C_2 f_2(x)$$

The surface slope error is a linear combination of unknown functions

?Method to find the characteristic functions?

O. Hignette, et al, *Incoherent X-ray Mirror Surface Metrology,* Proc. SPIE 3152, 188-199 (2000)

Bendable mirror tuning with the LTP:

Application of regression analysis

Observation: surface slope error (deviation from ideal ellipse) measured with LTP

$$\delta\alpha(x_i) = \eta(x_i, C) + \varepsilon_i;$$

where: ε_i is the error variable;
C are the bending parameters
x_i are the sampling points on the surface

The model is a linear combination of unknown functions:

$$\eta(x_i, C) = \Delta C_0 + \Delta C_1 f_1(x_i) + \Delta C_2 f_2(x_i)$$

Method to find the model functions:

$$-\quad \delta\alpha_{20}(x_i) = \Delta C_0 + \Delta C_1 f_1(x_i) + \Delta C_2 f_2(x_i) + \varepsilon_{oi}$$

$$+\quad \delta\alpha_{21}(x_i) = \Delta C_0 + (\Delta C_1 + \delta C_1) f_1(x_i) + \Delta C_2 f_2(x_i) + \varepsilon_{1i}$$

$$\delta\alpha_{21}(x_i) - \delta\alpha_{20}(x_i) = \delta C_1 f_1(x_i) + \varepsilon_{10i}$$

$$f_1^*(x_i) = \frac{\delta\alpha_{21}(x_i) - \delta\alpha_{20}(x_i)}{\delta C_1}$$

$$f_2^*(x_i) = \frac{\delta\alpha_{22}(x_i) - \delta\alpha_{20}(x_i)}{\delta C_2}$$

$$-\quad \delta\alpha_{20}(x_i) = \Delta C_0 + \Delta C_1 f_1(x_i) + \Delta C_2 f_2(x_i) + \varepsilon_{oi}$$

$$+\quad \delta\alpha_{22}(x_i) = \Delta C_0 + \Delta C_1 f_1(x_i) + (\Delta C_2 + \delta C_2) f_2(x_i) + \varepsilon_{2i};$$

$$\delta\alpha_{22}(x_i) - \delta\alpha_{20}(x_i) = \delta C_2 f_2(x_i) + \varepsilon_{20i}$$

Regression matrix:

$$\hat{A} = \begin{bmatrix} 1 & f_1(x_1) & f_2(x_1) \\ 1 & f_1(x_2) & f_2(x_2) \\ \vdots & \vdots & \vdots \\ 1 & f_1(x_m) & f_2(x_m) \end{bmatrix}$$

$$\hat{A} \approx \begin{bmatrix} 1 & f_1^*(x_1) & f_2^*(x_1) \\ 1 & f_1^*(x_2) & f_2^*(x_2) \\ \vdots & \vdots & \vdots \\ 1 & f_1^*(x_m) & f_2^*(x_m) \end{bmatrix}$$

Solution:

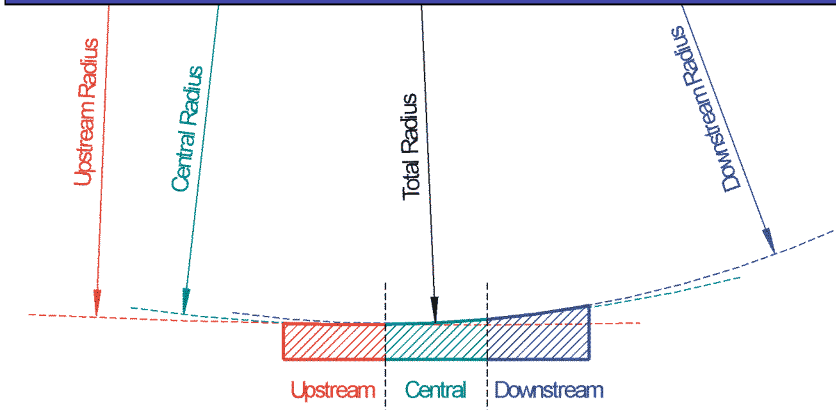
$$\Delta\hat{C}^* = (\hat{A}'\hat{A})^{-1}\hat{A}'\delta\alpha_{20}$$

$$D(\Delta\hat{C}^*) = \sigma^2(\hat{A}'\hat{A})^{-1}$$

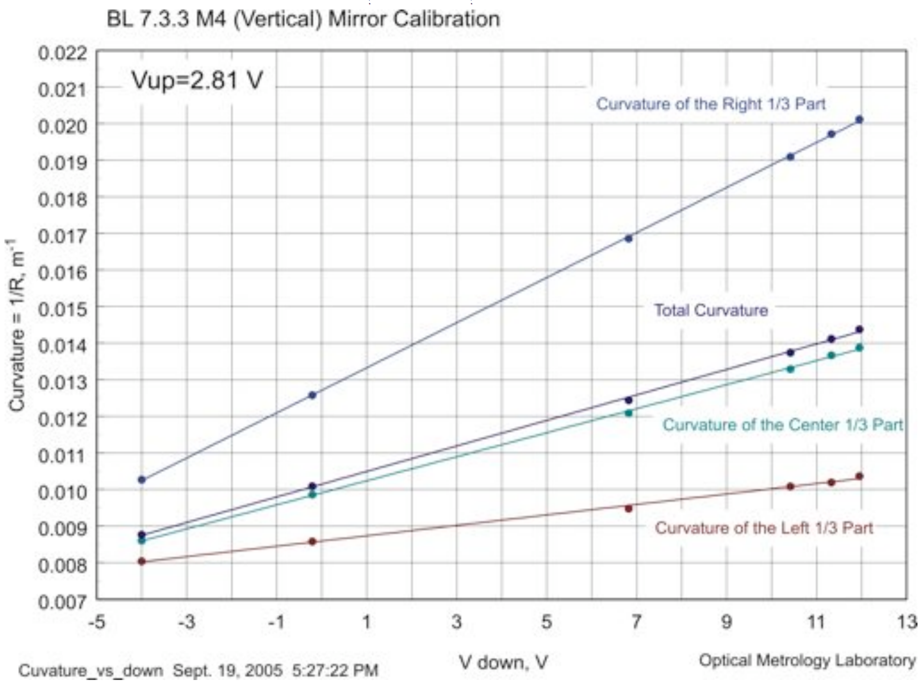
$$D\hat{y} = \sigma^2 \hat{I}$$

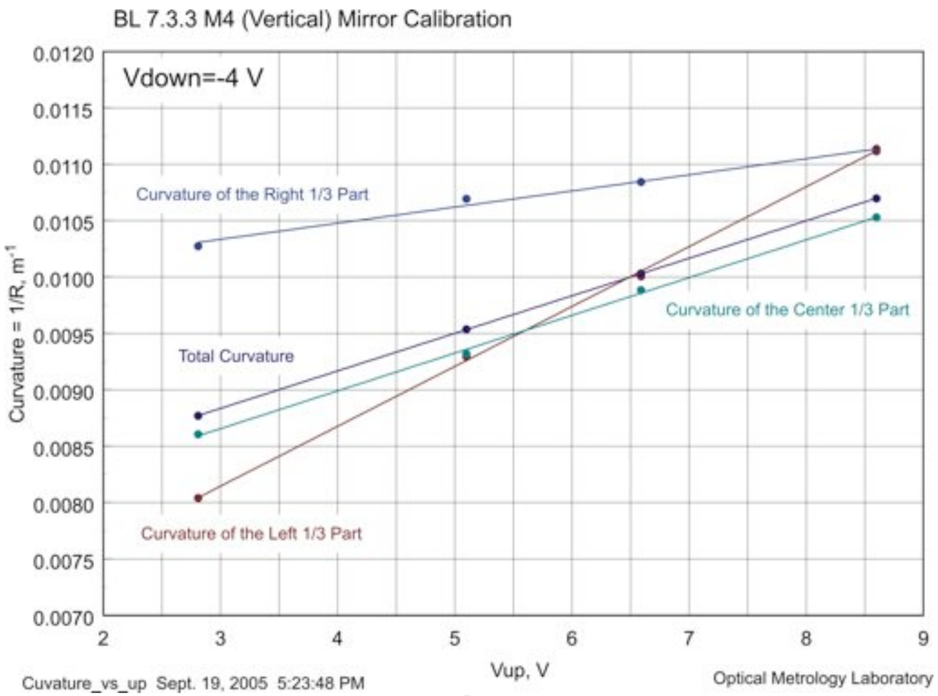
$$\sigma^2 \approx \frac{\sum_i [\delta\alpha_{20} - \Delta C_1^* f_1^*(x_i) - \Delta C_2^* f_2^*(x_i)]^2}{m - p}$$

Relative independence of the benders



- *Can be used for fast tuning of bendable optics*
- *Can be used to check stability of the design and assembly (backlash, slack)*



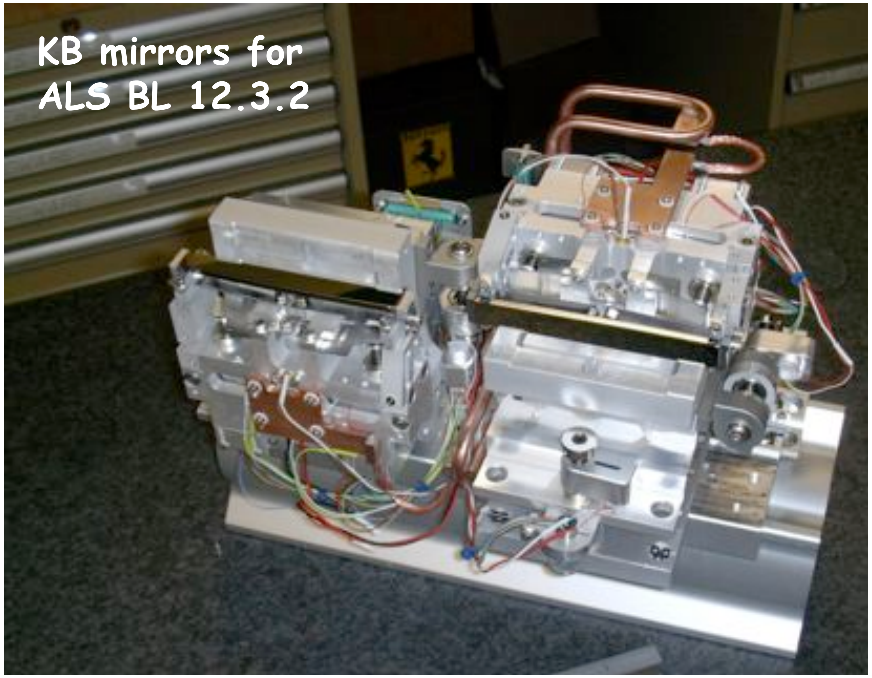


Vertically focusing 100-mm-long elliptical mirror specified with ***r = 3.528 m; r' = 0.133 m; θ = 0.004 rad***

W. R. McKinney, S. C. Irick, A. A. MacDowell, T. Warwick, and V. V. Yashchuk, *Optimal Use of LTP or Interferometer Data for the Adjustment of Bendable Mirrors,* AIP Conference on Synchrotron Radiation Instrumentation SRI-2006, III Workshop on Optical Metrology (Daegu, South Korea, May 27, 2006).

Bendable mirror tuning with the LTP:

Application to ALS BL12.3.2 KB mirrors



Sequence of measurements:

1. $\alpha(x_i, C_1, C_2)$
2. $\alpha(x_i, C_1 + \delta C_1, C_2)$
3. $\alpha(x_i, C_1, C_2 + \delta C_2)$
4. $\alpha(x_i, C_1^0, C_2^0)$

Sequence of data analysis:

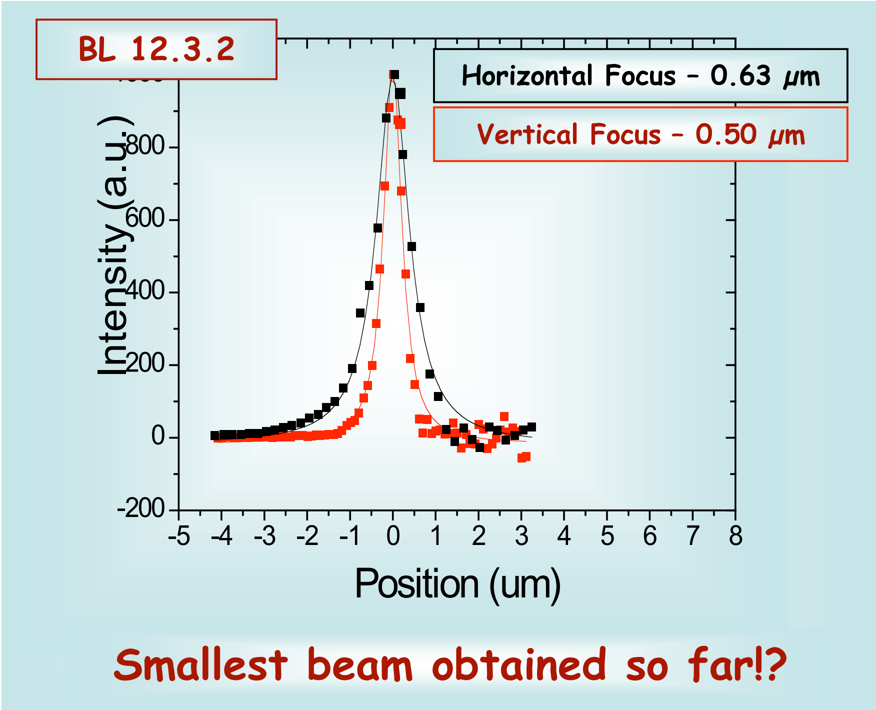
1. Evaluate the bender characteristic functions

$$f_1^*(x_i) \quad \text{and} \quad f_2^*(x_i)$$

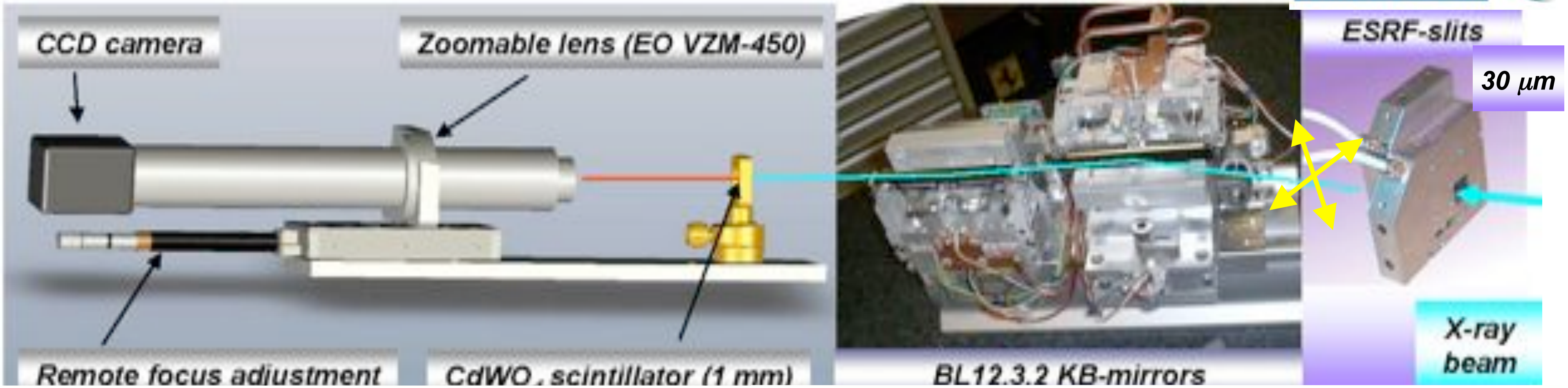
2. Use regression analysis to predict the optimal settings

$$C_1^{0*} \quad \text{and} \quad C_2^{0*}$$

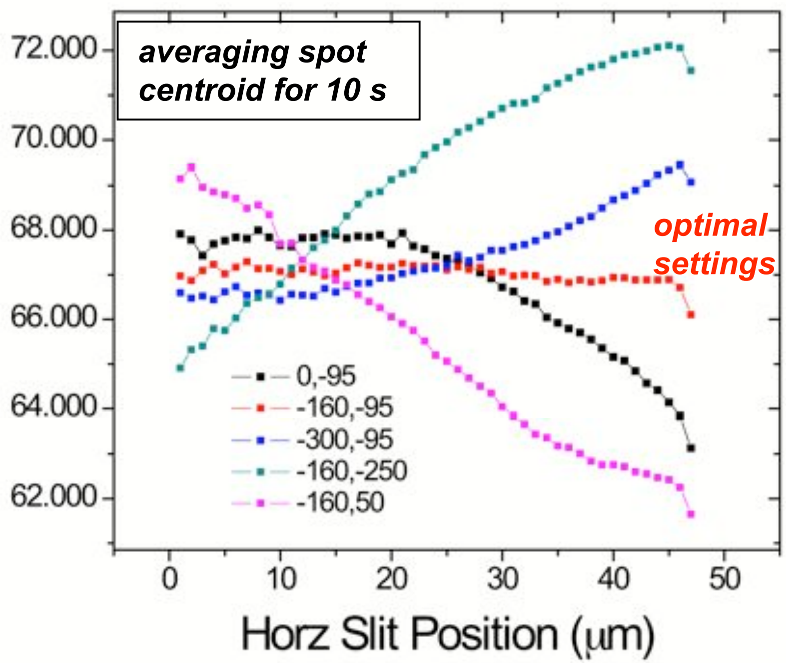
3. Simulate the mirror beamline performance

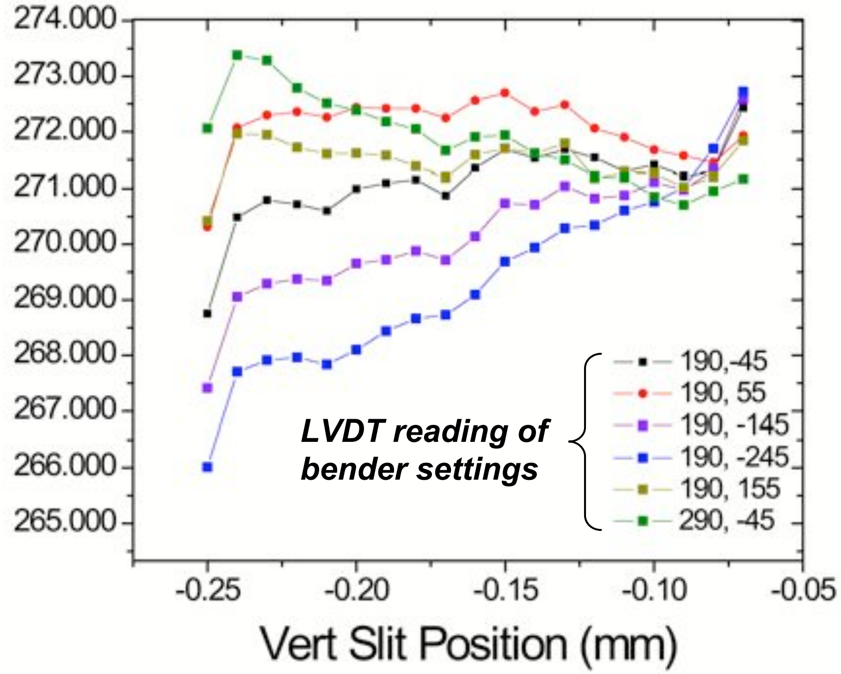


Hartmann slit tests on beamline 12.3.2

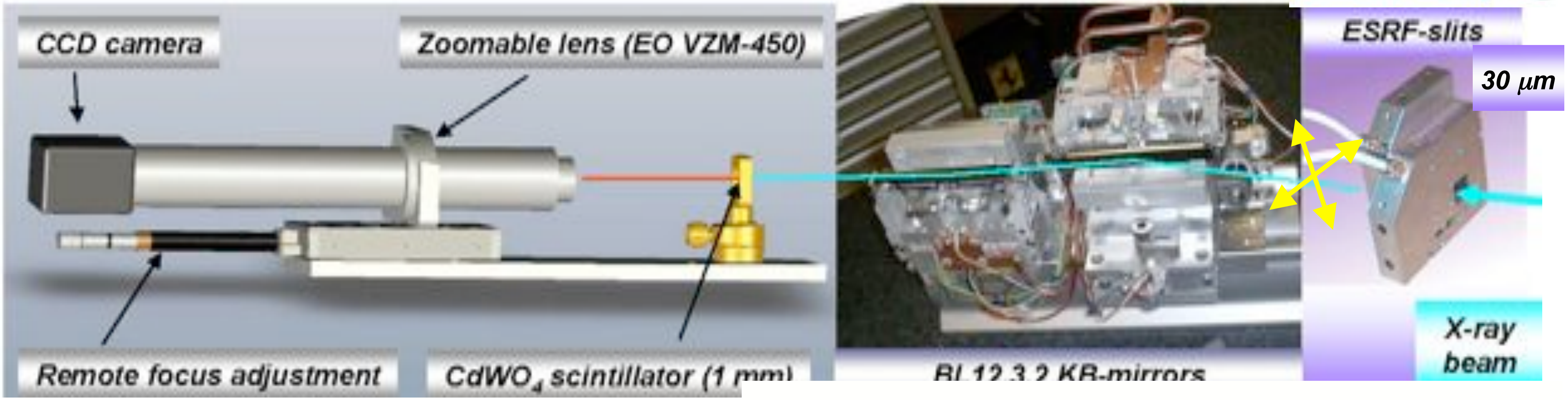


Focus Spot position vs slit position



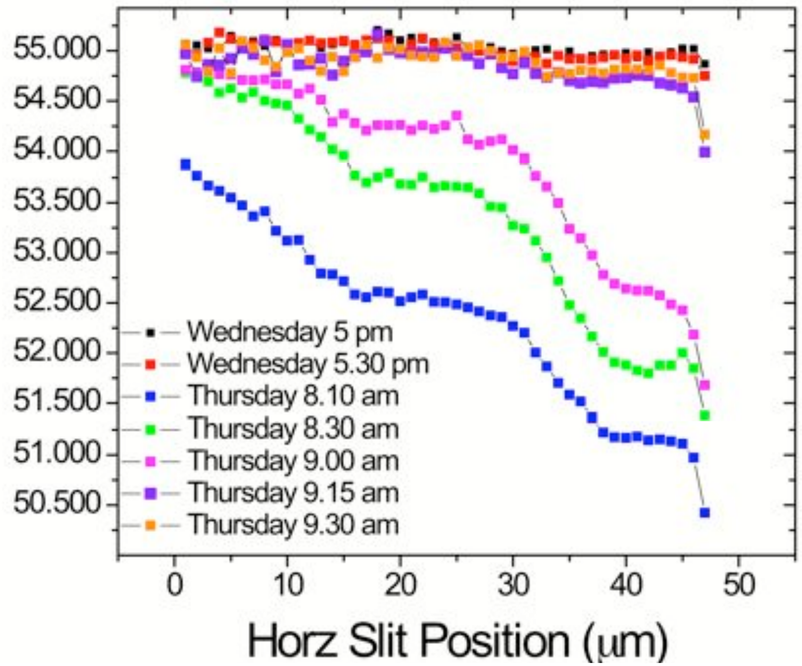


Hartmann slit tests on beamline 12.3.2

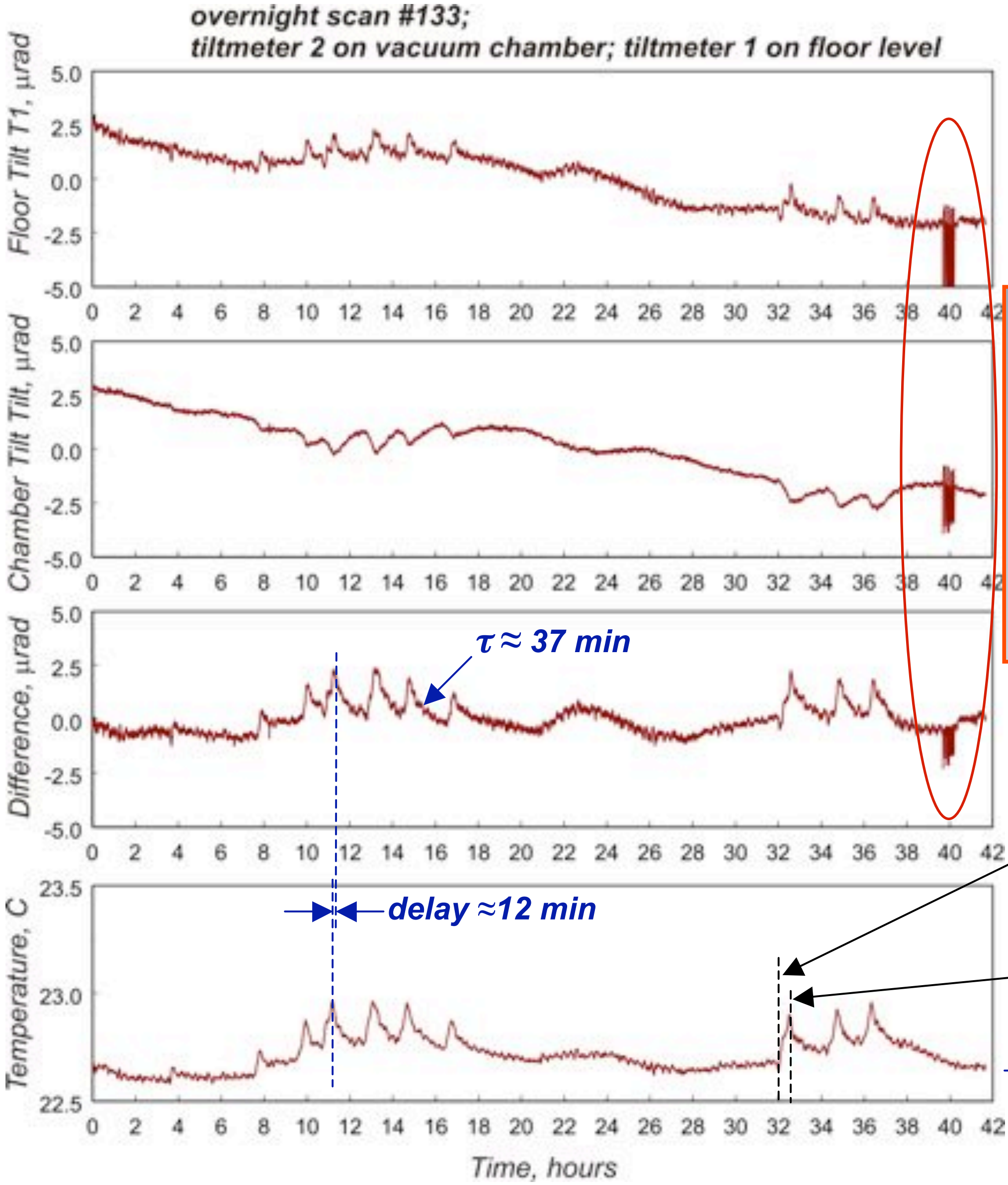


Time dependence

- Thermal effect?



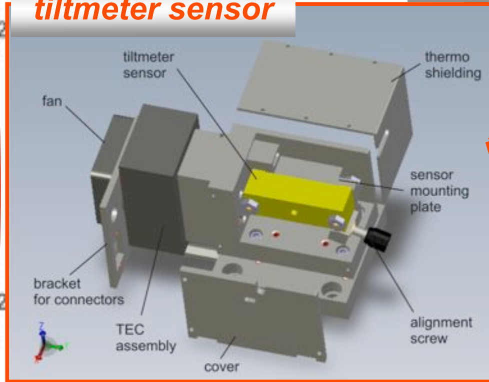
Environmental factors: ~~temperature variation~~...?...



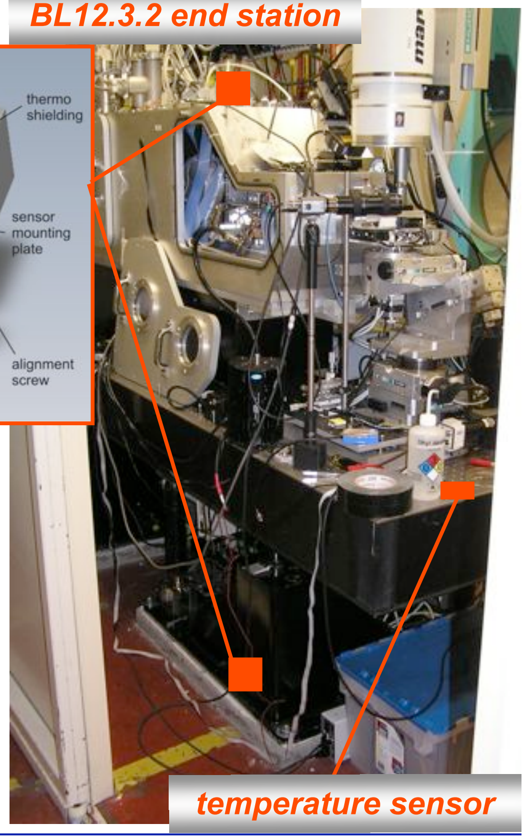
Leveling stability of the Beamline 12.3.2 end station was measured

- *with a system of two actively temperature stabilized tiltmeters*)*
- *in differential mode.*

tiltmeter sensor



BL12.3.2 end station



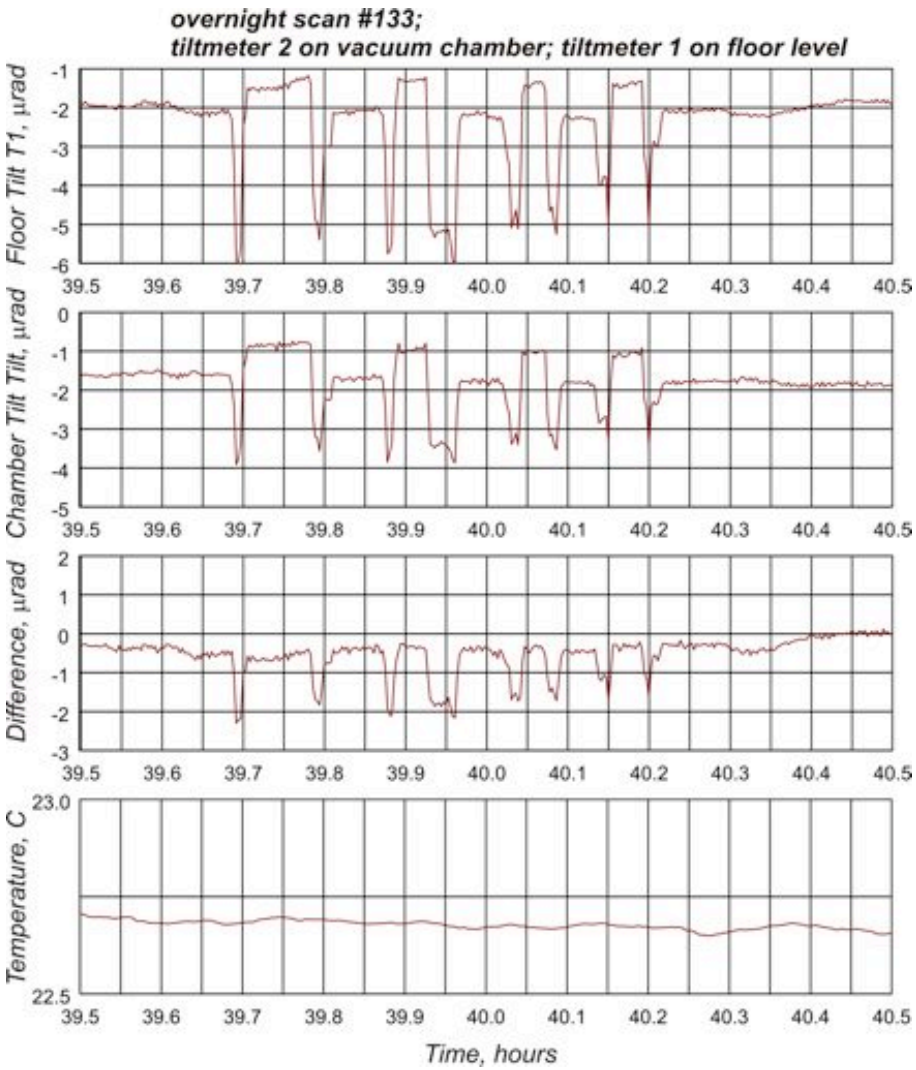
temperature sensor

an investigator enters the hutch and the hutch door is opened (?)

an investigator leaves the hutch and the hutch door is closed (?)

*) J. L. Kirschman, E. E. Domning, G. Y. Morrison, B. V. Smith, V. V. Yashchuk, *Precision Tiltmeter as a Reference for Slope Measuring Instruments*, Proc. of SPIE Vol. 6704, 670409 (2007).

Other environmental factors: *crane motion...*

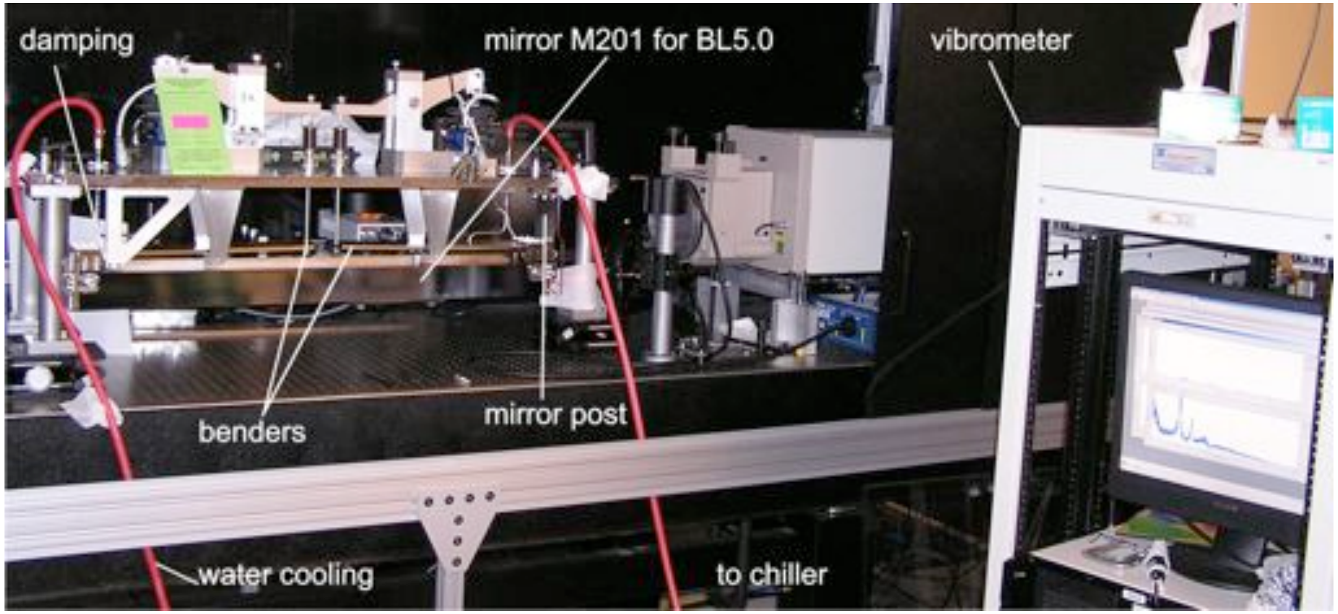


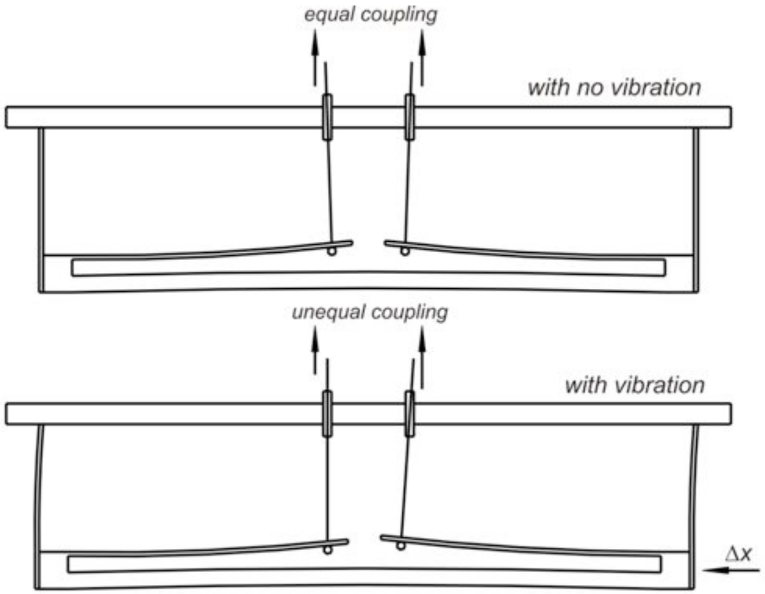
Motion of a 30 T crane on the main floor can cause

- ***basement tilt by up to ~4 µrad***
- ***irreversible tilt of a damped set-up by up to 0.5 µrad***

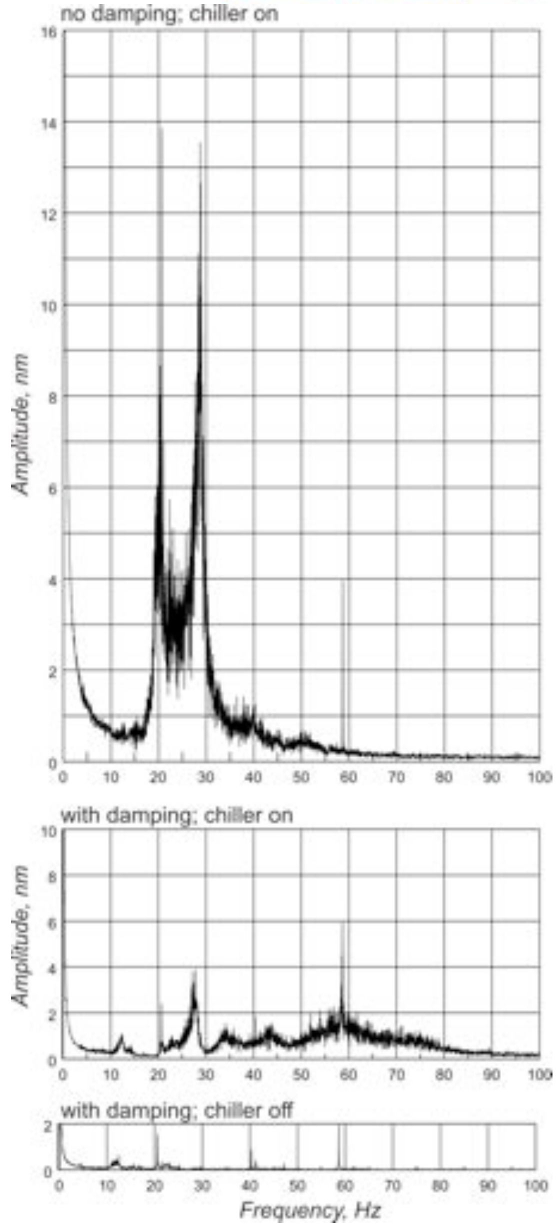
even if the crane is always returned in the same position

Vibration... sometimes has a rather unexpected effect...





- ***Longitudinal instability of the design***
- ***Environmental vibration excites the longitudinal modes of mirror vibration***
- ***Longitudinal vibration leads to periodic change of bender coupling forces***
- ***Resulting in ~100 μm walk of the x-ray beam at a distance of ~20 m***



Mirror substrates and coatings...

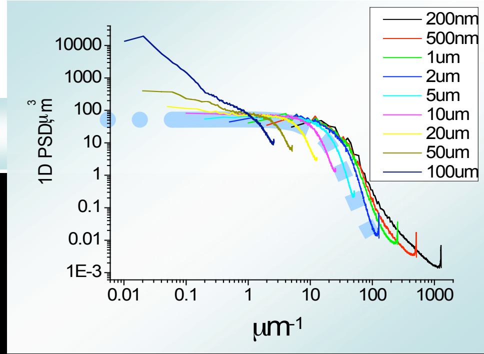
KB mirror substrate after x-ray exposure for a few years

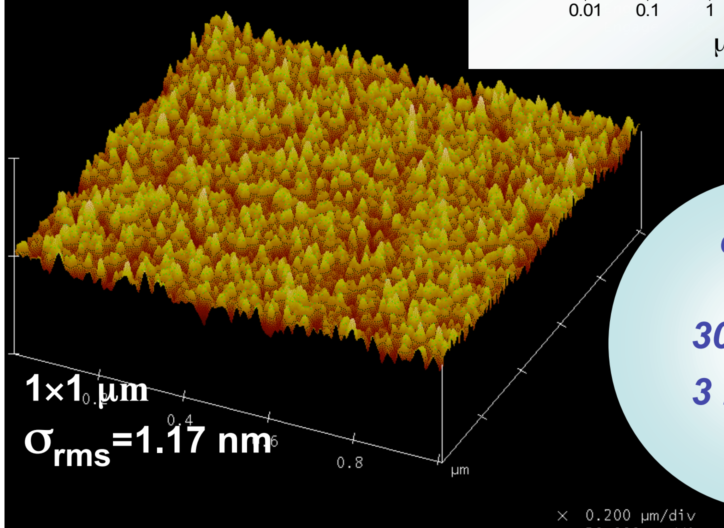
Optics performance depends on

-fabrication technology and
-past history...

Thermal evaporation

SPM data are courtesy of Dima Voronov





1×1 µm

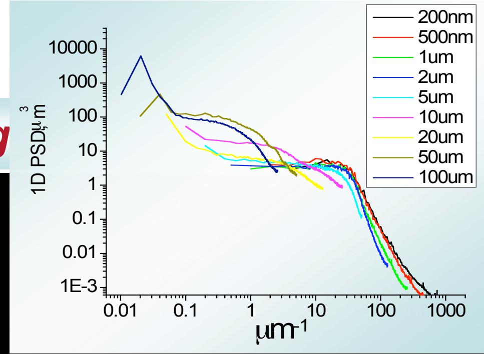
σ_{rms}=1.17 nm

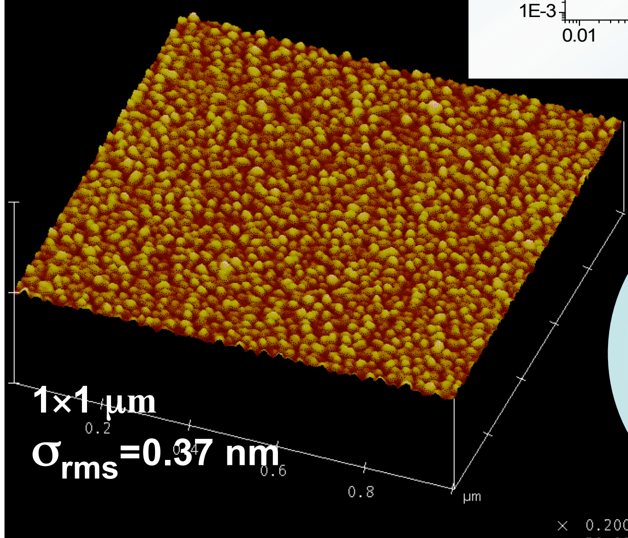
coating:

30 nm Pt

3 nm Cr

Magnetron Sputtering





1×1 µm

σ_{rms}=0.37 nm

coating:

8 nm Ru

25 nm Au

5 nm Cr

Effect of the granulation via multiple reflections to the x-ray distribution in the focus plane?

tests on the BL 5.3.1 in the manner of:

U. Bonse and M. Hart, *Tailless X-ray Single-crystal Reflection Curves obtained by Multiple reflection*, Appl. Phys. Lett. 7(9), 238-40 (1965)

Conclusions

✓Backgrounds of bendable x-ray optics for focusing of soft and hard x-ray beams have been considered based on experience at the ALS

✓The developed method and dedicated software allows for more accurately adjusting bendable grazing incidence x-ray mirrors at a significant saving of time for the adjustment at the optical metrology laboratory; code is available to the community for Beta Test

✓ The method is based on the actual design of the bender mechanisms and provides calibration dependences for the bender adjustments, which can be used for fine tuning of mirrors at the beamline

✓ Performance of adjustment of bendable optics at an optical lab strongly depends on accuracy of optical metrology

✓ The value of rms slope variation can not be generally used as a figure-of-merit characterizing the mirror performance on the beamline; direct ray-trace calculation or at wavelength metrology has to be applied in order to verify beamline performance of the bendable x-ray optics

✓ However, we should convince users not to re-adjust benders after we have finished in the Optical Metrology Lab but investigate environmental conditions of the set up

Acknowledgements

For extremely useful discussions, the authors are grateful to

Malcolm Howells and Tino Noll

*The Advanced Light Source is supported by the Director, Office of Science, Office of Basic Energy Sciences, Material Science Division, of the **U.S. Department of Energy** under Contract No. DE-AC02-05CH11231 at Lawrence Berkeley National Laboratory.*

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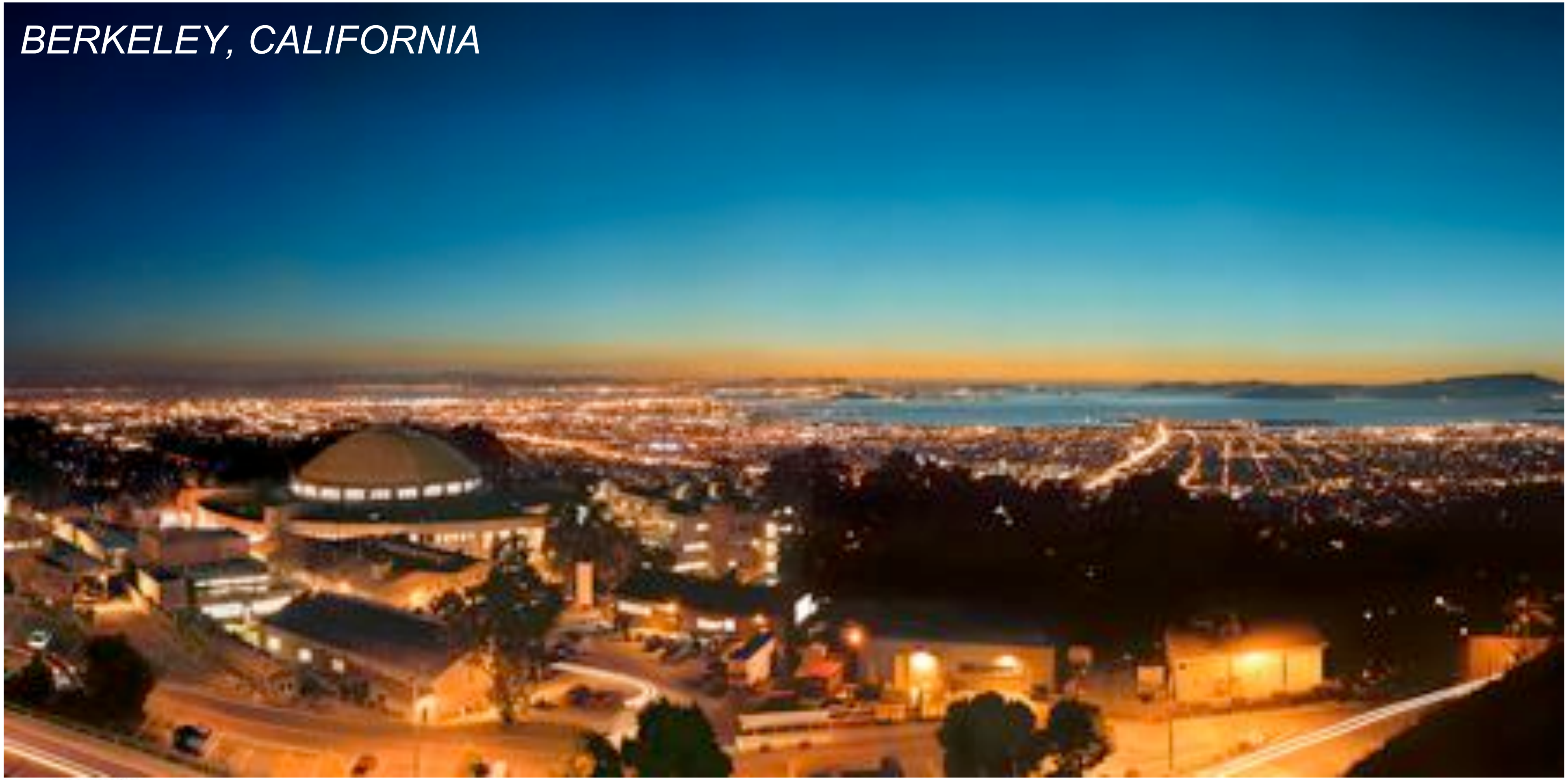
THANKS!



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