ADAPTIVE OPTICS

and

WAVEFRONT CONTROL

in the

HARD X-RAY DOMAIN

PAST, PRESENT AND ... FUTURE

Dr. Riccardo SIGNORATO
ACCEL Instruments
Where it all started...

Published on SPIE 1997 proceedings

Structured slope errors on real x-ray mirrors: Ray-tracing versus Experiment

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ABSTRACT

Ray-tracing plays an essential role for the design of a synchrotron radiation beamline optics. Nevertheless, it can also be extremely useful during the commissioning phase of a beamline. At that moment, it is possible to include real surface figure errors in the computer simulation of the optical devices. The resulting focal spot size and photon flux values are the final targets for the experimental optimization and alignment of the optics setup. We report on extensive ray-tracing of the mirror systems of the two beamlines placed at the ESRF insertion device 12. Slope errors measured after mirror delivery are included in the calculations. It is demonstrated how slope errors with characteristic periodicity between 1 and ca. 1/20 of the mirror length can affect the focal spot shape, size and position. In particular, they can create structures or satellites in the focal spot. The distortions from the ideal shape are generated by the polishing process itself and are intrinsic to each single mirror. Comparison between the effects of slope errors in ray-tracing using either real (measured) surfaces or numerically generated ones are also reported.

Keywords: ray-tracing, slope error, x-ray mirror, synchrotron radiation beamline, PSD, mirror metrology

![Diagram of mirror systems](image)

Figure 7. Left: Calculated spot shapes with Fourier filtered profiles for M1 and M2. The spot size is shown in two positions: at the experimental location 7.62 m from M2 (labeled Eo) and at the theoretical focus location at 17.14 m from M2 (labeled Tn). The n value means that the applied cutoff frequency is n/L. Right: the corresponding filtered profiles for M1 and M2. Filtered values are labelled with Fn, with the described meaning for n. E/T/Fixed stands for ideally spherical mirrors.
Figure 6. Left: SHADOW calculation for VF-2M focal spot (same as in Fig. 5 (center)). Right: Superposition of the experimental (A) and calculated (B) vertical intensity profile at the ID12A VF-2M focal position. The satellite structures S1 and S2, which are due to the mirror slope error are evident in both curves.

Figure 8. Top: Effect of progressive Fourier filtering on the PSD functions for ID12A mirrors M1 (left) and M2 (right). The higher curve corresponds to the PSD of the non-filtered profile. The other six curves refer to the filtered profiles shown in Fig. 7 (cutoff frequencies: 2/L, 3/L, 5/L, 13/L, 21/L and 24/L, respectively). Bottom: PSD for ID12B VFM (left) and PFM (right). Note that the low frequencies are enhanced in the non-filtered ID12A mirrors respect to the ID12B ones. These peaks in the low frequency range are responsible for the focal spot structures (see text).
1

PZT plate 1

PZT plate 2

2

P Z T plate

P Z T plate

3 (side view)

1

2

\[ \delta = 0 \]

\[ \delta_1 \neq \delta_2 \]
Available bimorph mirrors lengths:
100/150/200/300/450/600/750/900/1050/1200/1350/1500 mm

Driving Electrodes length from 140 mm down to < 20 mm

FOCUSING FROM A FEW 100′s of mm to ∞
Bending from R ~ 30 m to flat

POLISHED

Pzt
Pzt
Pzt
Pzt
Pzt
Pzt

could be POLISHED, too
Manufactured/Ordered Modular Bimorph mirrors:

Today’s Total: 55

Updated to September 31st, 2008

Total Bimorph Mirror Length
\(~33\,\text{m}\)

Total Number of Electrodes
\(~740\)
Advantages of bimorph mirrors

Fully Modular architecture (from 100 mm to 1650 mm)
  Simple, elegant and **fully standardized** design

Reversibility of global & local bending momentum

Adaptive zonal control $\rightarrow$ PSD low frequency filtering possible
  Easy implementation of different electrodes density
  $N$ electrodes $\rightarrow$ control over $N^{th}$ degree in slope, $(N+1)^{th}$ in shape
  Can approximate $n+1$ (!) order polynomials $\rightarrow$ large focusing tunability
  Can improve their own slope error $\rightarrow$ lower polishing requirements
  Mirror performance does not depend on illuminated footprint
    - can freely approximate high order polynomials over any freely selectable illuminated length

Reconstruction of deformed wavefronts!!!
  Correct wavefront aberrations due to mirror & other optical elements
dynamical reconstruction possible $\rightarrow$ full 'optical flexibility'
In-situ X-ray wavefront reconstruction

*Possibility to control beam properties when operating out of focus:*

*Striations control & High Strehl ratio*

*Takes into account all possible perturbations sources*

No moving parts or mechanisms: **bending is intrinsic to the mirror**

→ **No Maintenance**

→ **Very Robust**

→ **UHV compatible (no lubricants)**

Compact & lightweight

*smaller vacuum vessels – fits in crowded Bl*

*allows installing fast feedback on fine pitch with pzt linear actuator*

Holder has NO effect on mirror operation

**NO clamping:** simple 3-points support

*Designed to protect mirror;*

*to allow simple & safe handling & installation*

*delivered as a ’ready-to-install’ device*
Backlash-free, NO ’lost-steps’ operation

Possibility to use same mirror as HFM / VFM

Gravity compensation not necessary – Isostatic mount possible
Possibility to polish both sides; reflection possible as:
→ Upwards / Downwards
→ Outboard / Inboard

Pre-polished to shape close to typical working position

No need to have specially shaped substrates optimized for one specific configuration only

No anticlastic effect

“Environmental friendly”: mirror can be recycled by:

Repolishing to different radius → adapt to drastic layout changes
Repolishing optical surface → keep up with state-of-the-art polishing
Strip-off & re-coating → remove surface damage due to X-rays
Bimorph bender itself has virtually UNLIMITED LIFETIME
Calibration / Encoding / Resolution

Calibration:  **INTRINSIC**  
NO effects due to
  - *Transportation*  \(\rightarrow\) proven
  - *Mounting*  \(\rightarrow\) proven
  - *Temperature*  \(\rightarrow\) proven

Encoding:  **INTRINSIC**  
Use HV supply 16-bit resolution readout

Resolution:  “*virtually UNLIMITED* ”  
limited only by HV supply noise (ripple)
1 - Active Mode

All the electrodes kept at the same voltage
UNIFORM VARIATION (SPHERICAL) OF THE BENDING RADIUS

2 - Adaptive Mode

Different voltages applied at each electrode

INTERACTION MATRIX (H)
CONTROL MATRIX (M)
SVD

\[
\begin{bmatrix}
V_{D,1} \\
V_{D,2} \\
V_{D,3} \\
V_{D,4} \\
V_{D,5}
\end{bmatrix}
= (H^T H)^{-1} H^T \delta f_0
\]

SELECTIVE ATTENUATION OF PSD LOW FREQUENCY COMPONENTS
First proof of Adaptive Correction @ ESRF in 1997

R. Signorato’s PhD thesis
Forensic Metrology

On corpse of long (450 mm) bimorph Prototype No.1 polished in winter 1996 – requiescat in pacem †

Long Trace Profiler results

<table>
<thead>
<tr>
<th>Date</th>
<th>Filename</th>
<th>Comment</th>
<th>Step (mm)</th>
<th>Length (mm)</th>
<th>g-removed</th>
<th>Radius of curvature</th>
<th>Slope error RMS (μrad)</th>
<th>Shape error RMS (nm)</th>
<th>Shape error PV (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>99 at 11:</td>
<td>OV_05mm</td>
<td>step 0.5 at 0 Volt</td>
<td>0.5</td>
<td>419.5</td>
<td>yes</td>
<td>4.517 km</td>
<td>5.2</td>
<td>134.8</td>
<td>440</td>
</tr>
<tr>
<td>03/11/05</td>
<td>bi-step0</td>
<td>step 0.5 mm</td>
<td>0.5</td>
<td>419.5</td>
<td>yes</td>
<td>3.466 km</td>
<td>5.5</td>
<td>122.3</td>
<td>425</td>
</tr>
</tbody>
</table>

Conclusion: recent measurements are in a good agreement with data obtained in 1999. The figure error of this bimorph mirror has not been changed after few years of exposure to X-rays on ID32 beamline.
State-of-the-Art Metrology Data
(courtesy of ELETTRA Trieste)

Tangential Slope Error – measured on 550 mm over 600

APS mirror (16 electrodes) = 0.3 µrad rms (shape: 46 Å rms)

Dynamical Range: Flat - 0.8 km
Before and after...

INITIAL : 2.1 \( \mu \text{rad rms} \) / FINAL : 0.31 \( \mu \text{rad rms} \)

INITIAL : 307 nm rms / FINAL : 4.6 nm rms
Repeatability & Hysteresis (1)

**Monodirectional**
Delta R / R < ± 0.1%

**Bidirectional**
Delta R / R < ± 0.25%

Long Term Repeatability
@ SESO @ 1000V \(\rightarrow 437\) m!

Similar behaviour @ SP8

<table>
<thead>
<tr>
<th>Voltage ((V_p))</th>
<th>Spherical best fit radius ((m))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 / 0 / 0</td>
<td>632.0 / 631.1 / 631.7</td>
</tr>
<tr>
<td>+500</td>
<td>516.8</td>
</tr>
<tr>
<td>+1000</td>
<td>435.7</td>
</tr>
<tr>
<td>+500</td>
<td>517.7</td>
</tr>
<tr>
<td>+1000</td>
<td>436.4</td>
</tr>
<tr>
<td>+1500</td>
<td>374.2</td>
</tr>
<tr>
<td>+1000</td>
<td>434.1</td>
</tr>
<tr>
<td>+500</td>
<td>517.0</td>
</tr>
<tr>
<td>0</td>
<td>634.6</td>
</tr>
<tr>
<td>-500</td>
<td>842.5</td>
</tr>
<tr>
<td>+500</td>
<td>515.8</td>
</tr>
</tbody>
</table>

Data taken at APS metrology laboratory – Dr. L. Assoufid and Mr. J. Qian
Repeatability & Hysteresis (2)

Monodirectional
Delta R / R < ±0.05%

Bidirectional
Delta R / R < ±0.5%

Data taken at ELETTRA metrology laboratory – Dr. D. Cocco and Mr. G. Sostero
Repeatability & Hysteresis (3a)

Over 2 days

Over 3 days

Data taken at Diamond metrology laboratory – Dr. S. Alcock
Repeatability & Hysteresis (3b)

Data taken at Diamond metrology laboratory – Dr. S. Alcock
Repeatability of shape:

**Voltage off:**
- Shortly after delivery: \( R = 2020.1 \text{ m} \) Slope = 0.303 arcsec rms

**Voltage on:**
- 19 days after delivery: \( R = 2306.1 \text{ m} \) Slope = 0.233 arcsec rms

**Voltage off:**
- 20 days after delivery: \( R = 2018.6 \text{ m} \) Slope = 0.294 arcsec rms

**Voltage on:**
- 20 days + 5h after delivery: \( R = 2310.5 \text{ m} \) Slope = 0.233 arcsec rms

**APPLIED VOLTAGES**

115.65 / 196.91 / 106.96 / 80.87 / 48.22 / 117.78 / 123.16 / 232.41

*Data taken at BESSY metrology laboratory – Dr. F. Siewert*
**PSD Filtering**

[Top Left] shape error before – dashed - and after – solid - adaptive correction of the mirror shape. The bimorph can be shaped to a perfect sphere with a residual shape error as small as \(100 \text{ Å rms}\).

[Bottom Right] PSD function at \(V = 0\text{V} & 600\text{V}\) on all electrodes and after adaptive correction (each electrode is independently set at a different \(V_i\)). Low frequency components of the PSD could be reduced by as much as **4 orders of magnitude**.
PSD Filtering - Limits ??

(LTP data courtesy of ELETTRA)
LAST BUT NOT LEAST:

High Voltage Bipolar Power Supply fully developed and tested

- linear fully bipolar state-of-the-art power supply (-2000 V → +2000 V)
- compact: up to 32 channels in a single 19” crate
- dedicated ’user-proof’ software for safe operation
- standalone operation (WEB interface) possible
- easily interfaced with EPICS, TANGO ...
- flexible, expandable, highly customized system
- dedicated high level software being continuously updated

Features
- Ethernet and GPIB full remote control
- RS232C remote configuration
- Fully encased on 19”-wide, 6U-high Euro mechanics rack

Main software features
- Multitasking embedded system supervisor
- System Configurator (via RS232C port)
- Self Diagnostic Test
- Remote Firmware Upgrade
- Communication Modules
  - IEEE488.2 (SCPI) Standard Command Syntax on Eth, GPIB, RS232C
  - TCP/IP communication (Labview, Python and Java libraries, EPICS)
  - HTTP Interface via standard Web Browser
In-situ HARTMANN test

X-RAY BEAM

SLITS

FOCAL PLANE

ELECTRODES

MIRROR
In-situ HARTMANN test

@ Spring - 8

X-RAY BEAM

SLITS

MIRROR

FOCAL PLANE

ELECTRODES
@ SPring - 8  Data obtained at 1km long Bl in year 2000

Intensity Gain: 40 x
Elliptical bending
slope error rms ~ 1 μrad rms
Checked ‘a-posteriori’ with LTP

Source-to-Sample distance = 990 m
Focusing Distance = 1 m
q = 2 mrad
Illuminated footprint = 225 mm

Data in SEMILOGARITHMIC scale!
OPTICAL GEOMETRY OF GM/CA ID in BL
(Beamline dedicated to protein crystallography)

0 m  65.8 m  67.3 m  74 m  74.3 m

Source  HFM  VFM  Guard slits  Sample

HFM → 1050 mm long (1000 mm useful)
     → 14 Electrodes → 14 Degrees of freedom!
VFM → 600 mm long (550 mm useful)
     → 16 Electrodes → 16 Degrees of freedom!
...and still 9 degrees of freedom available

Data taken @ GM/CA CAT – UNPUBLISHED RESULTS
HFM - At focus

**Focusing Distance = 8.5 m**

Data courtesy of GM/CA CAT – UNPUBLISHED RESULTS
HFM - At focus

Data courtesy of GM/CA CAT – UNPUBLISHED RESULTS
HFM - Out of focus – 350 mm upstream

Data courtesy of GM/CA CAT – UNPUBLISHED RESULTS
HFM - Out of focus - 350 mm upstream

Data courtesy of GM/CA CAT – UNPUBLISHED RESULTS
VFM - Automated Focusing - Starting Point

Thu Mar 22 01:11:17 2007
VFM - Automated Focusing - **One Shot**

Thu Mar 22 01:24:47 2007
Vertical beam profiles over 850 mm range

<table>
<thead>
<tr>
<th>Position</th>
<th>Distance (mm)</th>
<th>Beam Profile FWHM (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Focus</td>
<td>600</td>
<td>30</td>
</tr>
<tr>
<td>Sample</td>
<td>0</td>
<td>48</td>
</tr>
<tr>
<td>Slits</td>
<td>-250</td>
<td>53</td>
</tr>
</tbody>
</table>

To shift the beam focal position:
- Using automated focusing tools for a new position → 3 – 4 hours
- Using a lookup table for a previously determined position → minutes
SUPER-bent Mirror / APS Sector 3

Focusing geometry
\[ p = 33 \text{ m}; \quad q = 0.57 \text{ m} \rightarrow \text{demagnification } 58:1 \]

Incident angle
2.2 mrad

Coating
2/3 (24 mm) Pd, 500 Å thick, 1/3 (12 mm) Pt 500 Å

Mirror length: 600 mm / HFM / 16 Electrodes

0V = 250 m; -2000V = 135 m; +1700 V = 1000 m

Spherical Aberration
\(~ 200 \text{ \textmu m}\)
Best focus with all electrodes at same voltage
+100 V

$E = 14.4125 \text{ keV}$
Best focus with visual optimization on a YAG

Voltages: 1430 1430 1140 1010 830 630 130 -360

Horizontal Acceptance = 1.2 mm
E = 14.4125 keV

Theoretical Reflectivity
95.7 %

Measured Reflectivity
94 %

$I_{REFL} / I_0$

Horizontal Acceptance = 1.2 mm

Best focus with **FOCUSING SOFTWARE TOOL**

Voltages: 1351.3 1510.8 1010.8 1003.5 899.9 400 -100 -108.5

manuel’: 1430 1430 1140 1010 830 630 130 -360
FWHM = 19.7 μm / LOG SCALE

INTEGRITY [ a. u. ]

-6.530 -6.520 -6.510 -6.500 -6.490 -6.480

HORIZONTAL BEAM SIZE [ mm ]
Depth of Field

Counts

$\Delta z$ [mm]

$x$ [$\mu$m]
... after upgrade to full 16 HVBPS channels:

<table>
<thead>
<tr>
<th>Focusing geometry</th>
<th>( p = 33 \text{ m}; \ q = 0.53 \text{ m} \rightarrow \text{demagnification 62:1} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incident angle</td>
<td>2.8 mrad</td>
</tr>
<tr>
<td>Horizontal acceptance</td>
<td>1.6 mm</td>
</tr>
</tbody>
</table>

![Horizontal Focusing Performance at 3-ID, APS](image)

-10 µm FWHM
After scanning slits size deconvolution

**Gain:** ∼Factor of 2 in spot size

**Voltages:**

<table>
<thead>
<tr>
<th>Voltage</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1492.3</td>
<td>1301.3</td>
</tr>
<tr>
<td>817.5</td>
<td>707.8</td>
</tr>
<tr>
<td>1109.4</td>
<td>619.2</td>
</tr>
<tr>
<td>509.1</td>
<td>628.4</td>
</tr>
<tr>
<td>353.5</td>
<td>327.3</td>
</tr>
<tr>
<td>63.6</td>
<td>530.6</td>
</tr>
<tr>
<td>-820.1</td>
<td>820.1</td>
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<tr>
<td>1320</td>
<td>1320</td>
</tr>
<tr>
<td>-1697</td>
<td>-1697</td>
</tr>
<tr>
<td>-100</td>
<td>-108.5</td>
</tr>
<tr>
<td>1351.3</td>
<td>1510.8</td>
</tr>
<tr>
<td>1010.8</td>
<td>1003.5</td>
</tr>
<tr>
<td>899.9</td>
<td>400</td>
</tr>
<tr>
<td>-100</td>
<td>-108.5</td>
</tr>
</tbody>
</table>
Sometimes beam can be ‘Ugly’
THE PRESENT...

1) Make sure that the beam is ´clean and stable´
2) Make sure that the beam is ´clean and stable´
3) Make sure that the beam is ´clean and stable´
4) If it vibrates... Quantify it!
5) If you can stabilize it... Do it!

BEAM DIAGNOSTICS is KEY!!

The new HVBPS system is built following an `integrated approach` incorporating:
• Fast 4-channels low noise picoammeter
• ´On-line´ BPM readout with statistics calculation
• ´Real –time´ FFT available
• Triple PID/feedback available (hor., vert. & intensity)
• Remote support available via WEB-based GUI
THE FUTURE ...

1. Use a ‘Condenser + Corrector’ approach?
2. Deterministic superpolishing?
3. nm-level surface control capability?
4. Denser electrodes?
5. Simple wavefront measurement tools available to ‘non-optician’ Bl scientist?
6. In-situ feedback?

→ Can adaptive optics be...

**SIMPLE??**

*AdaptoGyzmotron needed?*

...To be continued at the Rocca Bernarda castle Round Table!!
Automated Focusing at GM/CA-CAT

Bob Fischetti
Associate Director, GM/CA-CAT,
Biosciences Division,
Argonne National Laboratory

ACTOP 2008
Trieste, Italy
October 9, 2008
Design Parameters for the ID lines

- Energy range: 3.5 – 35 keV
- Energy resolution: $\Delta E/E < 0.02\%$
- Harmonic rejection: < 0.01% at all energies
- Intensity: $>1 \times 10^{13}$ photons/sec/0.1%BW
- Energy scan rate: 0.3°/sec, 350 – 3500 eV/sec
- Focal size: 50 x 200 µm
- Goniometry sphere-of-confusion: 10 µm

- High degree of beam intensity and positional stability
- Appropriate beam convergence/divergence angles for protein crystals
- 200 mA beam current
Delivering a stable beam monochromatic beam

- Independent supports of vacuum and optical structures

- Double Crystal Monochromator stabilization
  - Vibration characterization and dampening
  - Both crystals cryogenically cooled to avoid dispersion
  - Compton scatter shields around 1st and 2nd crystals
  - Thermal stabilization of DCM mechanics
  - No detuning of 1st and 2nd crystals vs. energy
  - Beam position stable to +/- 5 μm over the range 4 – 20 keV

- Beam Position monitors after each optical component
  - Intensity feedback
  - Positional feedback
Beam Position Monitors – after each optical component


Beamline Stability is Very Good!

- 1-2% RMS intensity fluctuation at low heat load (time scales up to ½ hour)
- Better crystallographic data are collected *without* intensity feedback
- Positional stability has not been quantitatively measured, although some conclusions can be drawn from the intensity numbers
  - 2% intensity fluctuation $\rightarrow$ 3 µm beam motion
Compact K-B “bimorph” mirrors

Why use bimorphs mirrors
• In situ adjustment of slope error
• Not just small beam
• Uniform profile “off-focus”

Uniform electrode voltages – sets curvature
Differential electrode voltages – correct slope error

<table>
<thead>
<tr>
<th></th>
<th>Length (mm)</th>
<th># of segments</th>
<th>Electrodes / segment</th>
<th>Total Electrodes</th>
<th>Demag</th>
</tr>
</thead>
<tbody>
<tr>
<td>HFM</td>
<td>1050</td>
<td>7</td>
<td>2</td>
<td>14</td>
<td>6:1 – 10:1</td>
</tr>
<tr>
<td>VFM</td>
<td>600</td>
<td>4</td>
<td>4</td>
<td>16</td>
<td>7:1 – 12.5:1</td>
</tr>
</tbody>
</table>

Silica optical surface
Piezo-electric ceramics
Electrodes

Conventional SESO elliptical bender
**Focusing Technique**

- Focusing in almost completely automated via deterministic matrix inversion
- Time to collect data for new matrix and focus using slit scans about 3 hours
- Can refocus using look up table or matrix
- BPM would take about 1 hr to collect matrix and focus

- Beamlets converge at one location
- Beamlets are of equal width
- BPM detects all at the same location
- Focal slit scan shows that beamlets originating from different electrodes overlap at the focal position
Automated focusing and beam profile homogeneity

To shift the beam focal position:
- Generate new interaction matrix → 3 – 4 hours
- Use existing interaction matrix → 15 minutes
- Load voltages from lookup table → 2 minutes

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<tr>
<td>Slits</td>
<td>-250</td>
<td>53</td>
</tr>
</tbody>
</table>
Full Beam Application - Large Unit Cells

Diffraction pattern from HK97 virus capsid. Unit cell dimensions: 1010 x 1010 x 732 Å

**Triple mini-beam collimator**

5 and 10 micron mini-beam defining apertures, and 300 micron scatter guard aperture

User selectable via Blulce buttons
Prealigned
Highly reproducible

Fischetti *et. al.* submitted

Shenglan Xu
Mini-beam Application - Radiation Sensitivity

β2 adrenergic G-protein-coupled receptor at 3.4 Å resolution

Images courtesy Brian Kobilka and Bill Weis, Stanford University.