Introduction

“X-ray beamline looks complicated?”

What function of each component?

Key issues for the beamline design

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<th>Key issues</th>
<th>Design components</th>
</tr>
</thead>
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<td><strong>Photon beam properties at sample</strong></td>
<td>• End station (pressure, temperature, magnetic field...)</td>
</tr>
<tr>
<td>• Photon energy, energy resolution</td>
<td>• Detector, data processing ... (automation)</td>
</tr>
<tr>
<td>• Flux, flux density</td>
<td>• Light source (ID, BM)</td>
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<td>• Beam size</td>
<td>• Monochromator, higher order suppression...</td>
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<tr>
<td>• Polarization</td>
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<tr>
<td>• Spatial coherence</td>
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</tr>
<tr>
<td>• Time resolution</td>
<td>• Beam position monitor</td>
</tr>
</tbody>
</table>
| **Human Safety & Machine protection** | • Radiation shielding hutch ...
| • Protection from radiation hazard to health | • Interlock system |
| • Protection from radiation damage to instruments | • Beam shutter... |
| **Utilities** | • Absorber, FE slit |
| • Time schedule | • Cooling method, cooling system |
| • Human resources | • Selection of light sources (power, angular dist.) |
| • Available budget, space, technical level | • Electronics in hutch (detector, controller ...) |
| • Maintenance & lifetime of BL (hardware, applications) | • Embrittlement (cable, tube) |
| • Contamination on optics | • Contamination on optics |

Management of the beamline construction

- Electricity, water, air, network, control
- Environments (temperature, vibration...)

Optics Engineering for x-ray beamline design

Haruhiko Ohashi
JASRI / SPring-8
**Today’s contents**

- Light source (IDs/BM)
- XBPM
- Front end (FE)
- Beamline components for safety

**Beamline components for safety**

- Light source
- Human safety
- Machine protection
- Interlock system
- Radiation shield hutch
- Interlock system
- Monochromator
- Tailoring x-rays
- Mirrors
- User Interface
- Beam position monitor
- Metrology
- Adjustment

**Heat management**

For human safety & machine protection

Front end (FE)

**Front end**

- Electron storage ring
- MBS
- Optics hutch
- DSS
- Experimental hutch
- End stopper
- Sample
- γ-ray stopper
- Hutch door
- Shield wall of storage ring
- Monochromator

**Experimental station**

- User Interface
- Design
- Optical design (for example, mirrors)
- Heat management
- Machine protection
- Metrology
- Alignment

**Application**
**Front end (15~18m)**

**Schematic Layout inside the SPring-8 Tunnel**

**Front end (FE)**

(15~18m)

Why so long FE?

---

**Key functions & components of FE**

(a) **Shielding for human safety**
(b) Handling high heat load for safety
(c) Handling high heat load for optics
(d) Monitoring the x-ray beam position
(e) Protection of the ring vacuum

**Beam shutter (BS)**, collimator (radiation shield)
Absorber, masks (to prevent BS from melting)
XY slit, filters (to prevent optics from distorting)
X BPM (x-ray BPM), SCM (screen monitor)
FCS (fast closing shutter), Vacuum system

---

**When we operate a main beam shutter (MBS), what happens?**

**X-ray**

Absorber (Abs) to protect BS from heat load

Beam shutter (BS) to shield you against radiation

After Abs is fully closed, BS is closed.
After BS is fully opened, Abs is opened.
The sequences are essential to keeping safety.

**ABS and BS work on ways together**

**to protect us from radiation when we enter the hutch.**
Other key function is to handle high heat load for optics

(a) Shielding for human safety
(b) Handling high heat load for safety
(c) Monitoring the x-ray beam position
(d) Protection of the ring vacuum

Beam shutter (BS), collimator (radiation shield)
Absorber, masks (to prevent BS from melting)
XY slit, filters (to prevent optics from distorting)
XBPM (x-ray BPM), SCM (screen monitor)
FCS (fast closing shutter), Vacuum system

These components cut off the power to prevent optics from distorting by heat load.

Slit: "Too much is as bad as too little"

Comparison of the Spatial Distributions between 1st Harmonic Flux Density and Power Density

How to manage high heat load by FE XY slit?

Stainless Steel
GildCap
Downstream Blade (Right & Upper)
Upstream Blade (Left & Lower)

Incident angle 0.08 deg (1.5/100)

1st harmonic flux

Power Density

1st harmonic Flux Density

Handling Technology of high heat load

SPRING-8 Standard In-Vacuum Undulator: 13.7kW, 550kW/mrad²

1. Grazed Angle Technology (Mask, Absorber, XY slit)
   (1) Inclining absorbing surface to X-ray beam
       → Decrease of power density of per unit area

2. Volumetric Heating Technology (Pre slit)
   (2) Applying the advanced material → GdCp
   (3) Enhancing the heat transfer coefficient of the cooling channel
       → Copper wire coil (SPRING-8)
       Copper wire mesh (APS)

Dissipating high surface heat flux in depth by utilizing a low-Z material, such as graphite or beryllium.

Developing the Volumetric Heating Mask

Target → ~ 5 kW/0.2m
Simulation: “better safe than sorry”

For instance, the distributions of temperature and stress of Be window at FE can be calculated by FEA (finite element analysis).

1. Modeling and Meshing

2. Boundary Conditions

B. C. (1) Power Input

B. C. (2) Power Removing

The temperature of the outside surface of the copper holder remains constant at 32.3°C.

3. Thermal Analysis

4. Thermo-mechanical Analysis

Key issues of FE design

1. There exists a category of the beamline front ends. They have their proper functions, proper missions based on the principles of human radiation safety, vacuum protection, heat-load and radiation damage protection of themselves. They have to deal with every mode of ring operation and every mode of beamline activities.

2. Any troubles in one beamline should not make any negative effect to the other beamlines.

3. Strongly required to be a reliable and stable system. We have to adopt key technologies which are reliable, stable and fully established as far as possible.

Higher the initial cost, the lower the running cost from the long-range cost-conscious point of view.

Where is XBPM installed?

XBPM is installed before any spatial limitation. You hardly find it. It is quietly monitoring beam position at any time.

Another monitor is installed after spatial limitation. It is useful to check the center of XY slit. Usually it is retracted.
Structure of XBPM’s detector head
( Photo-emission type )

- Four blades are placed in parallel to the beam axis to reduce heat load.
- CVD diamond is used because of excellent heat property

Electrons from each blade of Ti/Pt/Au on diamond emitted by outer side of photon beam
The horizontal or vertical positions computed by each current

Revised

High stability of XBPM
As the stability is compared with other monitors outside wall, the stability of XBPM for 3 hours and 23 hours are measured.

After 3 hours

V: 1.7 μm H: 3.5 μm (RMS)

After 23 hours

V: 4.7 μm H: 3.2 μm (RMS)

All Gaps are set at reference points (Minimum gaps).

Stability of the XBPM is a few microns for a day
under the same conditions (ID-gap, filling patter & ring current).

Long term stability of XBPM at BL47XU
Gaps is set at reference points (Minimum gaps).

Fixed-blade style XBPM

for SPring-8 in-vacuum undulator, etc. (19 beamlines)

XBPM is installed on stable stand and stages

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Orbit correction using XBPM

A fixed point observation of XBPM is helpful for a regular axis from ID.

What does the XBPM tell us?

Key issues of XBPM design

1. Dependence of ID gap, ring current, filling pattern

XBPM (photo-emission type) depends on these parameters.

2. High stability

XBPM has stability of microns for a day.

3. Resolution of x-ray beam position

- The resolution of micron order can be monitored.
- Beam divergences are \( \sim 20/5 \) μrad (hor./ver.), which correspond to beam sizes of \( \sim 400/100 \) μm (hor./ver.) at XBPM position (20 m from ID).

4. Withstand high heat Load

- Blade of diamond
- Max. power density is \( \sim 500 \text{ kW/mrad}^2 \). Metal will melt immediately.

5. Fast Response

- Response time of < 1 msec needs for high frequency diagnostic.
- Simultaneous diagnostic over beamlines is important.

Origin of ID-gap dependence of XBPM:

- XBPM of photo-emission type has energy dependence.
- Radiation from ID changes drastically but not from BMs (backgrounds)
- Backgrounds are asymmetric and usually offset.
  1st harmonic: \( 6 \sim 18 \text{ keV} \)
  Background: \( < \text{several keV near beam axis of ID} \)

XBPM depends on ID-gap, filling pattern & ring current. The results of XBPM can be compared with the same condition.
Tailoring x-rays to application

X-ray mirrors

design, errors, metrology & alignment

The functions of x-ray mirrors

- Deflecting
- Low pass filter
- Focusing
- Collimating

- Separation from γ-ray
- Branch / switch beamline
- Higher order suppression
- Micro- / nano- probe
- Imaging
- Energy resolution w. multilayer or crystal mono.

Design parameters of x-ray mirror

Requirement

the beam properties both of incident and reflected x-rays
(size, angular divergence / convergence, direction, energy region, power...)

Design parameters

- Coating material: Rh, Pt, Ni ... (w/o binder, Cr), thickness
- multilayers (ML), laterally graded ML
- Incident angle: grazing angle (mrad)
- Surface shape: flat, sphere, cylinder, elliptic...
- adaptive (mechanically bent, bimorph)
- Substrate shape: rectangular, trapezoidal...
- Substrate size: length, thickness, width
- w/o cooling: indirect or direct, water or LN₂...
- Substrate material: Si, SiO₂, SiC, Glidcop...

In addition,
some errors such as figure error, roughness...
How to select coating material and incident angle?

Reflectivity for grazing incident mirrors

\[ R(\lambda, \theta, n) = \frac{|k_1 - k_2|^2}{|k_1 + k_2|^2} \]

\[ k_1 = \frac{2\pi}{\lambda} \cos \theta, \quad k_2 = \frac{2\pi}{\lambda} \sqrt{n^2 - \cos^2 \theta} \]

The complex index of refraction

\[ f = f_1 + if_2 \]

The complex index of refraction

\[ n = 1 - \delta - i\beta \]

\[ E \propto e^{-i(\alpha - kr)} \]

<table>
<thead>
<tr>
<th>Material</th>
<th>( \delta \times 10^{-5} )</th>
<th>( \beta \times 10^{-7} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>0.488</td>
<td>0.744</td>
</tr>
<tr>
<td>Quartz</td>
<td>0.555</td>
<td>2.33</td>
</tr>
<tr>
<td>Pt</td>
<td>3.26</td>
<td>20.7</td>
</tr>
<tr>
<td>Au</td>
<td>2.96</td>
<td>19.5</td>
</tr>
</tbody>
</table>

\[ r_0 = \frac{e^2}{4\pi mc^2} = 2.82 \times 10^{-15} m \]

\[ \beta = \frac{\mu \lambda}{4\pi} \]

\( \mu \): linear absorption coefficient

Coating material (1)

"the complex index of refraction"

The complex atomic scattering factor for the forward scattering

Coating material (2)

"total reflection"

\[ n_1/n_2 = \cos(\theta_1)/\cos(\theta_2) \]

Snell’s law

\[ \theta_1 > \theta_c \]
\[ \theta_1 = \theta_c \]
\[ \theta_1 = \theta_2 < \theta_c \]

\[ \cos(\theta_c) = n = 1 - \delta, \cos(\theta_c) \to 1 - \theta_c^2/2 \]

\[ \theta_c \approx \sqrt{2\delta} = 1.6 \times 10^{-2} \lambda \sqrt{\rho} = 20 \sqrt{\rho}/E \]

For example,

Rh \( (\rho = 12.4 \text{ g/cm}^3) \) \( \lambda = 0.1 \text{ nm}, \theta_c = 5.68 \text{ mrad} \)

Pt \( (21.4 \text{ g/cm}^3) \)

Coating material (3): “cut off, absorption”

The cut off energy of total reflection \( E_c \)

\[ E_c \approx 20\sqrt{\rho}/\theta_i \]

Rh \( (12.4 \text{ g/cm}^3) \)

Pt \( (21.4 \text{ g/cm}^3) \)

Cut off energy, absorption \( \to \) incident angle

Opening of the mirror, length, width of mirror, power density
Atomic scattering factors, Reflectivity

You can easily find optical property in “X-Ray Data Booklet” by Center for X-ray Optics and Advanced Light Source, Lawrence Berkeley National Lab.

In the site the reflectivity of x-ray mirrors can be calculated.

http://xdb.lbl.gov/

Many thanks to the authors!

Surface shape (1)

Purpose of the mirror

- deflecting
- low pass filter
- focusing
- collimate

Easy to make or cost

- flat
- spherical
- cylindrical
- toroidal
- elliptical
- parabolic...

Take care of aberration

Surface shape (2) radius and depth

By Fermat’s principle

For parallel beam \( q \to \infty, 1/q = 0 \)

Depth at the center \( D = R - \sqrt{R^2 - \left( \frac{L}{2R} \right)^2} \approx \frac{L^2}{8R} \)

For example,

\[ p = 15 \sim 50m, \ q = 5 \sim 20m, \ \theta_i = 1 \sim 10mrad \]

\[ R_m = 0.1 \sim 10 \ km, \ R_s = 30 \sim 100 \ mm \]

\[ R = 1 \ km, \ L = 1m \to D = 125 \ \mu m \]
Mirror optics

Surface shape (3) elliptical

\[
\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1
\]

For example,

\[ p = 975 \text{ m}, \ q = 50 \text{ mm}, \ \theta = 3 \text{ mrad} \]

\[ a = \frac{p + q}{2} \]

\[ b = \frac{\sqrt{2pq(1 - \cos(2\theta))}}{2} \]

\[ x_0 = \frac{p^2 - q^2}{2\sqrt{p^4 + 2pq \cos(2\theta) + q^2}} \]

\[ y_0 = -b\left(1 - \frac{x_0}{a}\right) \]

\[ u = \frac{h}{a}x_0 \]

\[ z(s) = -\cos(u) \times b \left[1 - \left(\frac{s \times \cos(u) + x_0}{a}\right)^2 + s \times \cos(u) \sin(-u)\right] \]

Precise fabrication is difficult.  

**Multilayer optics**

**X-ray multilayer reflectivity**

### Numerical calculations

**Main features**
- Bragg peaks and fringes due to interference
- Positions depend on $E$ and $\Lambda$
- Intensities depend on $\Delta \rho$, $N$, $\sigma$...

**Corrected Bragg equation**

$$m \cdot \lambda = 2 \cdot \Lambda \cdot \sqrt{n^2_A - n^2} \cos^2 \theta$$

For $\theta >> \theta_C$ → $m \cdot \lambda \approx 2 \cdot \Lambda \cdot \sin \theta$

**X-ray multilayer characterization**

- Transmission electron microscopy (TEM)
  - Fabrication errors
  - Roughness evolution
  - Crystallinity
  - Interface diffusion

Complementary to x-ray measurements!

**X-ray reflectivity**

**Reflectivity and phase**

- Ni/Si
- [Ni/B₄C]₂₀/Si

by courtesy of Ch. Morawe
Energy resolution of multilayers

X-ray multilayer design

Period number $N$:

- $R_{\text{peak}}$ increases with $N$ up to extinction
- $\Delta E/E$ decreases $\sim 1/N$ in kinematical range
- $R_{\text{int}}$ is maximum before extinction

High and low resolution MLs

Optimize $N$ according to needs!

Design parameters of x-ray mirror

**Requirement**

*the beam properties both of incident and reflected x-rays*

(size, angular divergence / convergence, direction, energy region, power...)

**Design parameters**

- Coating material: Rh, Pt, Ni ... (w/o binder, Cr), thickness
- multilayers (ML), laterally graded ML
- Incident angle: grazing angle (mrad)
- Surface shape: flat, sphere, cylinder, elliptic ...
- adaptive (mechanically bent, bimorph)
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- Substrate size: length, thickness, width
- w/o cooling: indirect or direct, water or LN$_2$...
- Substrate material: Si, SiO$_2$, SiC, Glidcop...

In addition,

some errors such as figure error, roughness...

Tailoring x-rays to application

↓

X-ray mirrors design, errors, metrology & alignment
An actual mirror has some errors.

The tolerance should be specified to order the mirror:
- Roughness
- Density of coating material
- Radius error
- Figure error

The cost (price and lead time) depends entirely on tolerance. We must consider or discuss how to measure it.

- Deformation by self-weight, coating and support...
- Figure error of adaptive mechanism
- Misalignment of mirror
- Stability of mirror’s position (angle)
- Deposition of mirror’s position (angle)
- Decomposition of contamination by use

Errors (1)

“Density $\rho$ and surface roughness $\sigma$”

$$E_c \approx 20 \sqrt{\rho/\theta_i}$$

$$R = R_0 e^{- \left( \frac{4\pi\sigma \sin(\theta_i)}{\lambda} \right)^2}$$

Coating on sample wafer at the same time is helpful to evaluate the density and roughness.

Contamination and removal

Before

Ultra-violet light

(Ozone)

(Oxygen radical)

Substrate

T=100-250°C

After cleaning

Advantage of UV/ozone cleaning

1. Non-Thermal
2. Contamination free
3. Non-contact

$\text{UV} / \text{ozone cleaning}$

It takes from 10 min to a few hours.

Errors (2)

“the self-weight deformation”

Material $\text{SiO}_2$

Density $2.2 \text{ g/cm}^3$

Poisson’s ratio 0.22

Young’s modulus $E = 70 \text{ GPa}$

$$D \propto \frac{L^4}{E \times t^3}$$

$16.7 \text{ nm PV}$

This value is larger than figure error by Rayleigh’s rule.

(➔See next page)

Improvement for nano-focusing

a) Substrate $\rightarrow$ Si ($E \sim 190 \text{ GPa}$)

b) Optimization of supporting points and method

c) Figuring in consideration of the deformation
Errors (3a)
“figure error estimated by Rayleigh’s rule”

\[
\phi = 2hk \sin(\theta) \to \frac{\pi}{2}, \quad h = \frac{\lambda}{4\theta}
\]

- 0.06 nm (20 keV) 3 mrad 2 nm
- 0.08 nm (15 keV) 3 mrad 3 nm
- 1 nm (1 keV) 10 mrad 12 nm

Errors of short range order decreases intensity. → Roughness

Errors of long range order loses shape.

Errors (3b)
“estimation by wavefront simulation”

- Designed surface
- Errors of short range order
- Intensity profiles of focusing beam by wavefront simulation

Errors of short range order decreases intensity. → Roughness

Errors of long range order loses shape.

The focusing beam of 25 nm was realized using high precision mirror with figure error of 3 nm PV

Tailoring x-rays to application

\[ \text{X-ray mirrors} \]

design, errors, metrology & alignment

How to evaluate the errors?

Metrology instruments for x-ray optics

<table>
<thead>
<tr>
<th>Field of view, lateral resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short</td>
</tr>
<tr>
<td>middle</td>
</tr>
<tr>
<td>~10 mm, 1 μm</td>
</tr>
</tbody>
</table>

0.1 nm Roughness

<table>
<thead>
<tr>
<th>Short / middle</th>
<th>Long / middle</th>
</tr>
</thead>
<tbody>
<tr>
<td>~10 μm, 1 μm</td>
<td>~0.1 m, 0.1 mm</td>
</tr>
</tbody>
</table>

Roughness, figure

<table>
<thead>
<tr>
<th>Zernike Fringe interferometer</th>
<th>Fizeau interferometer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fringes on CCD</td>
<td>Long Trace Profiler (LTP)</td>
</tr>
</tbody>
</table>

slope (0.1 nm)

Vertical resolution (rms)

Scanning white light interferometer

Interference fringe \( \rightarrow \) Height

Commercially available

<table>
<thead>
<tr>
<th>FOV (lens)</th>
<th>~10 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lateral resolution</td>
<td>1 μm~</td>
</tr>
<tr>
<td>Vertical resolution</td>
<td>0.1 nm</td>
</tr>
</tbody>
</table>

Zygo Corp. NewView®, Bruker AXS (Veeco) Contour GT* .......
Fizeau interferometer

Interference pattern → Height

Commercially available

Monochromatic point light source

Zygo Corp. VeriFire®, 4DS technologies, FujiFILM …..

Beam splitter

Collimator

Cavity

Reference

Under the test

Fizeau fringes on CCD

FOV (=reference) ~ 0.1 m
Lateral resolution ~ 0.1 mm
Vertical resolution 0.1 nm

Under the test

Not easy to measure large mirror

Fizeau interferometer

Interference pattern → Height

Commercially available

Monochromatic point light source

Zygo Corp. VeriFire®, 4DS technologies, FujiFILM …..

Beam splitter

Collimator

Cavity

Reference

Under the test

Fizeau fringes on CCD

FOV (=reference) ~ 0.1 m
Lateral resolution ~ 0.1 mm
Vertical resolution 0.1 nm

Under the test

Not easy to measure large mirror

Long trace profiler (LTP)

Direction of laser reflected on the surface → Slope

Homemade

Slope

Z' = \frac{d}{2F} \text{ μm}

Lateral resolution mm ~
Vertical resolution 0.1 μrad

Easy to measure slope of sub-μrad on large mirror by NO reference
Many kinds of LTPs are developing among SR facilities.


Figure error and slope error

Errors (middle range)

Errors (long range)

Errors (short range)

LTP of ESRF, APS, SPring-8

Part of optics

Laser

Mirror

Detector

LTP:

Lateral resolution mm ~
Vertical resolution 0.1 μrad

ESRF

Penta prism

Detector

Mirror

Detector

Detector
LTP of ESRF, APS, SPring-8

Part of optics (moving)
Laser
Mirror
Optics (moving)
Detector

Part of optics (fixed)
Laser
Mirror
Optics (fixed)
Detector

Optics
Detector
LTP
f
Laser
o
f
ESRF,
APS,
SPring
-8

Nanometer Optical Component Measuring Machine (NOM) @HZB

Autocollimator → Slope

Homemade

Light source (LED or laser)

Stitching interferometer for large mirror

Homemade

MSI
( micro-stitching interferometer )

RADSJ
( relative angle determinable stitching interferometer )

Collaboration with Osaka Univ., JTEC and SPring-8

Height error of wide range order for a long and aspherical mirror
with 1μm of lateral and 0.1 nm of vertical resolution.

Necessity is the mother of invention.
Tailoring x-rays to application

X-ray mirrors design, errors, metrology & alignment

Overview of x-ray focusing devices

<table>
<thead>
<tr>
<th>Diffraction</th>
<th>focus size, focal length</th>
<th>energy range</th>
<th>aberration</th>
<th>chromatic figure error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fresnel Zone Plate</td>
<td>12 mm, f = 50 cm (0.06 keV)</td>
<td>8-100 keV</td>
<td>-coma small</td>
<td>-chromatic figure error</td>
</tr>
<tr>
<td>Sputter sliced FZP</td>
<td>0.5 μm, f = 22 cm (12.4 keV)</td>
<td>0.5 μm, f = 200 keV</td>
<td>-coma small</td>
<td>-chromatic figure error</td>
</tr>
<tr>
<td>Bragg FZP</td>
<td>2.4 μm, f = 70 cm (13.2 keV)</td>
<td>8-100 keV</td>
<td>-coma small</td>
<td>-chromatic figure error</td>
</tr>
<tr>
<td>Wolter Mirror</td>
<td>0.7 μm, f = 55 cm (0.9 keV)</td>
<td>&lt;10 keV</td>
<td>-coma small</td>
<td>-chromatic figure error</td>
</tr>
<tr>
<td>Multi-layer Lens</td>
<td>16 mm (ID), 2.5 mm (19.5 KeV), 25mm x 40mm, 6.2 mm x 4.1 mm (19.5 KeV)</td>
<td>8-100 keV</td>
<td>-coma small</td>
<td>-chromatic figure error</td>
</tr>
</tbody>
</table>

Introduction of KB mirrors

Kirkpatrick-Baez (K-B) mirrors

Advantages
- Large acceptable aperture and High efficiency
- No chromatic aberration
- Long working distance

Disadvantages
- Difficulty in mirror alignments
- Difficulty in mirror fabrications
- Large system

Suitable for x-ray nano-probe

How small is x-ray focused?

For example, by elliptical mirror

\[ d_G = \frac{q}{p} \times S_0 \]

Geometrical size

\[ d_{DL} = \lambda \times \frac{0.88q}{1 \sin(\theta)} \]

Diffraction limited size (FWHM)

\[ p = 975 \text{ m}, q = 50 \text{ mm}, \theta = 3 \text{ mrad}, l = 50 \text{ mm}, \lambda = 0.083 \text{ nm}, S_0 = 100 \mu \text{m} \]

\[ d_G = 5 \text{ nm} < d_{DL} = 25 \text{ nm} \]

The opening of the mirror restricts the focused size even if magnification is large.
Nanofocusing by KB Mirror

**History since the century**

World Record of Spot Size

Focied by KB optics

World Record of spot size is 7 nm (by Osaka Univ., in 2009 *).

Routinely obtained spot size is up to 30 nm.


**KB optics installed in BL29XU-L**

<table>
<thead>
<tr>
<th>Glancing angle (mrad)</th>
<th>1st Mirror</th>
<th>2nd Mirror</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mirror length (mm)</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Mirror aperture (μm)</td>
<td>382</td>
<td>365</td>
</tr>
<tr>
<td>Focal length (mm)</td>
<td>252</td>
<td>150</td>
</tr>
<tr>
<td>Demagnification</td>
<td>189</td>
<td>314</td>
</tr>
<tr>
<td>Numerical aperture</td>
<td>0.73 x 10^-3</td>
<td>1.20 x 10^-3</td>
</tr>
<tr>
<td>Coefficient a of elliptic function (mm)</td>
<td>23.876 x 10^3</td>
<td>23.825 x 10^3</td>
</tr>
<tr>
<td>Coefficient b of elliptic function (mm)</td>
<td>13.147</td>
<td>9.609</td>
</tr>
<tr>
<td>Diffraction limited focal size (mm, FWHM)</td>
<td>48</td>
<td>29</td>
</tr>
</tbody>
</table>


**Difficulty in mirror alignments**

Positioning two mirrors is difficult because there are at least 7 degrees of freedom.

It is difficult to use KB mirrors.

**Tolerance limits of mirror alignments**

Severe positioning of two mirrors is required.

The manipulator should be designed for these freedom of axis with the resolution & the range.

Alignment of in-plane rotation
(Horizontal focusing mirror)

Side View

Horizontal focusing mirror

Vertical focusing mirror

X-ray

2θ

θ: 3.8 mrad → 2θ: 7.6 mrad

Reflected angle of vertical-focusing mirror needs to be considered, in the alignment of in-plane rotation of horizontal-focusing mirror.

Alignment of incident angle

- **Foucault test**
  
  *Rough* assessment of focusing beam profile. This method is used for *seeking focal point*.

- **Wire (Knife-edge) scan method**
  
  *Final* assessment of focusing beam profile.

  *Precise adjustment of the glancing angle and focal distance is performed until the best focusing is achieved, while monitoring the intensity profile.*
Alignment of incident angle

Foucault test

Foucault test 1
Wire is at downstream of focal point.
Image on CCD become dark from lower side.

Foucault test 2
Wire is at upstream of focal point.
Image on CCD become dark from upper side.
Foucault test 3

Wire is at the focal point. Whole bright-area gradually becomes dark.

X-ray CCD camera

Wire (Knife-edge) scan method for measuring beam profiles

The sharp knife edge is scanned across the beam axis, and the total intensity of the transmitting beam is recorded along the edge position.

The line-spread function of the focused beam was derived from the numerical differential of the measured knife-edge scan profiles.

Wire scan profile

Differential profile

Relationship between incident angle and focal position

Incident angle → Large ⇒ Focal point → downstream
Incident angle → Small ⇒ Focal point → upstream

Relationship between Beam size and Source size

Beam size changes depending on source size (or virtual source size).

Beam size = Source size / M (M: demagnification)
AND
Beam size ≥ Diffraction limit

Beam size is selectable for each application.
**Key issues of x-ray mirror design**

1. **To select the functions of x-ray mirror**
   - Deflecting, low pass filtering, focusing and collimating → Shape of the mirror

2. **To specify the incident and reflected beam properties**
   - Energy range, flux → absorption, cut off energy → coating material → incident angle
   - The beam size and the power of incident beam → opening of the mirror, incident angle
   - Absorbed power density on the mirror → w/o cooling, substrate
   - Angular divergence / convergence, the reflected beam size → incident angle, position of the mirror (source, image to mirror)
   - Direction of the beam → effect of polarization, self-weight deformation

3. **To specify the tolerance of designed parameters**
   - Roughness, density of coating material, radius error, figure error
   - The cost (price and lead time) depends entirely on the tolerance.

4. **To consider the alignment**
   - The freedom, resolution and range of the manipulator

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**Key issues for the beamline design**

**Which application is the most important at the BL?**

**Can you specify who uses the property at the BL?**

- Photon energy, energy resolution
- Flux, flux density
- Beam size
- Polarization
- Spatial coherence
- Time resolution

**Simplify the property. Get your priorities right.**

**Design components**

- End station (pressure, temperature, magnetic field...)
- Sample environment: Sample, detector, data processing...
- Deterioration: Folding, filtering...
- Deflecting, focusing, collimating...
- Mirror, polarizer,...: Stability enough to measure

- Light source (ID, BM)
- Monochromator, higher order suppression...
- Focusing devices...
- Polarizer...
- Window...
- RF timing, chopper...

- Radiation shielding (hutch, interlock system)
- Beam shutter...
- Safety first!

- Absorber, FE slit
- Cooling method, cooling system
- Selection of light sources (power, angular dist.)
- Electronics in hutch (detector, controller...)
- Embrittlement (cable, tube)
- Contamination on optics

- Electricity, water, air, network, control
- Environment (temperature, vibration...)

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**Simple and clear design to accelerate your research**
Ongoing x-ray beamline

X-ray beamline looks complicated, but the function of each component is simple. To specify the beam properties is to design the beamline.

New x-ray beamline for next generation light source such as XFEL is newly constructed. The components for heat management, x-ray beam monitors and x-ray optics including metrology are newly developed to perform the beam properties.

Challenges at XFEL beamline:
- coherence preservation
- wavefront disturbance or control at wavelength technique
- ultra-short & high intense pulse
- high stability
- shot-by-shot diagnosis of x-rays
- timing control of x-ray pulse
- synchronization with other source...


Thank you for your kind attention.

Enjoy Cheiron school
Enjoy SPring-8
and
Enjoy Japan!