Cheiron school 2012 , 25th Sep. 2012, SPring-8
X-ray beamline design Ⅱ

# *Optics Engineering for x-ray beamline design*

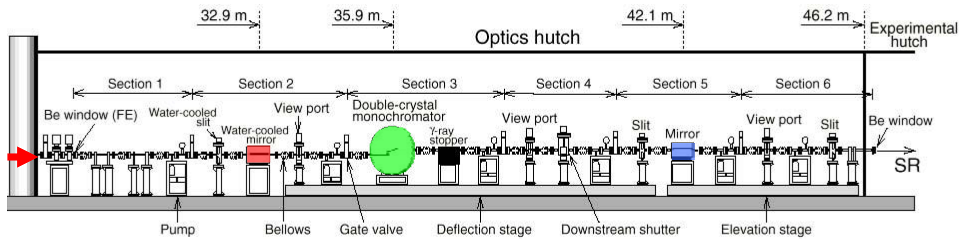
Haruhiko Ohashi
JASRI / SPring-8

# Introduction

## *"X-ray beamline looks complicated ?"*

*Storage ring*

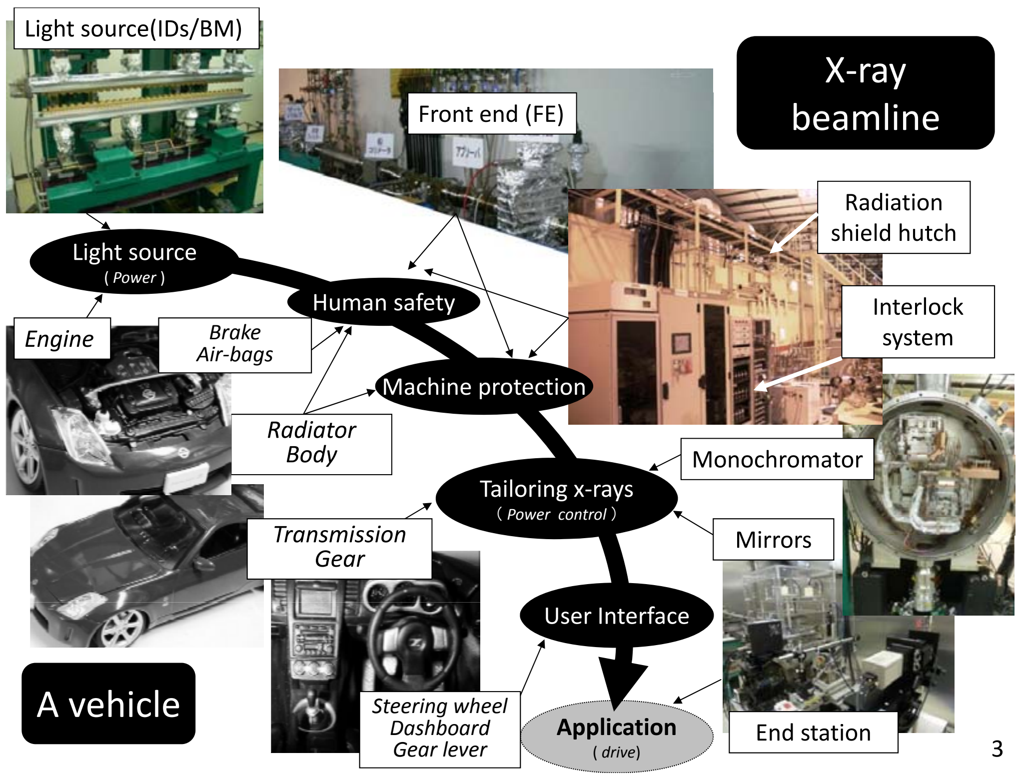
inside shielding tunnel (front end )




outside shielding tunnel (optics hutch )

*What function of each component ?*





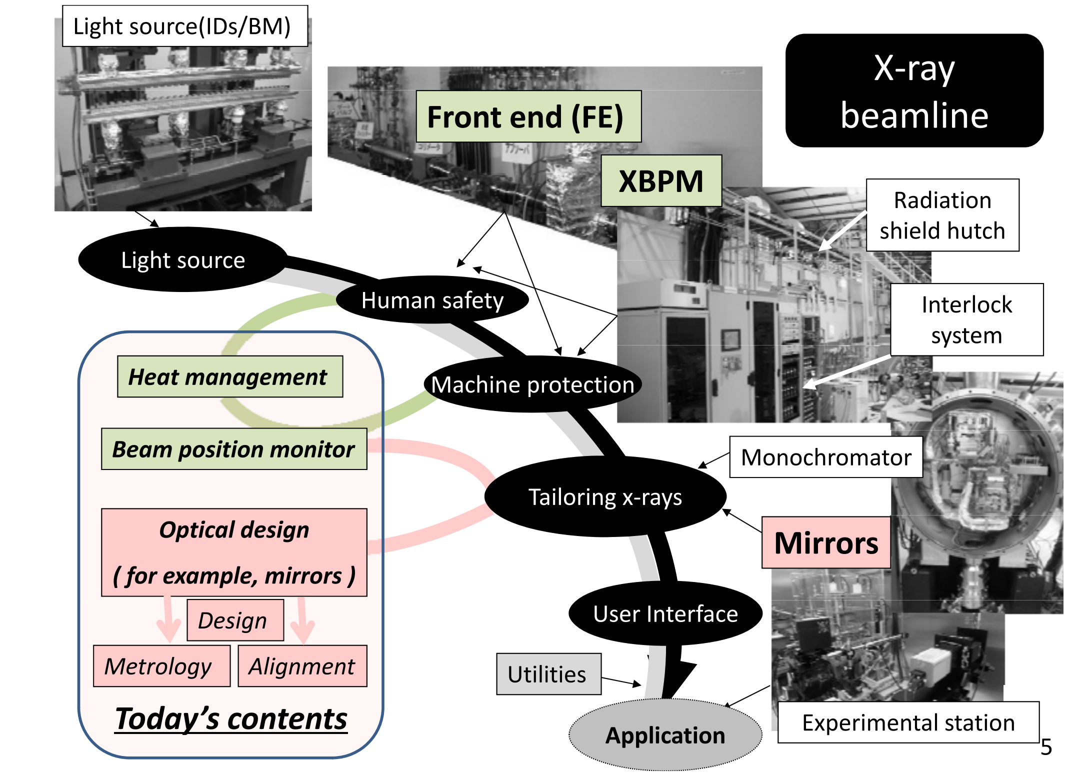



# Key issues for the beamline design

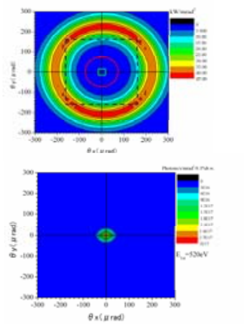
| *Key issues* | *Design components* |
|---|---|
| **Applications at the BL** ( scientific strategy, concept ) | • End station<br>• Sample environment ( pressure, temperature, magnetic field…)<br>• Detector, data processing … ( automation ) |
| – **Photon beam properties at sample**<br>• Photon energy, energy resolution<br>• Flux, flux density<br>• Beam size<br>• Polarization<br>• Spatial coherence<br>• Time resolution<br>Stability ( long , short term )<br>*Priority ?* | • Light source (ID, BM)<br>• Monochromator, higher order suppression…<br>• Focusing devices… ***Optics (ex. mirror)***<br>• Polarizer…<br>• Window… ***Beam position monitor***<br>• RF timing, chopper… |
| – **Human Safety & Machine protection**<br>• Protection from radiation hazard to health<br>• Protection from radiation damage to instruments | • Radiation shielding hutch …<br>• Interlock system<br>• Beam shutter…<br>***Front end***<br>• Absorber, FE slit<br>• Cooling method, cooling system<br>• Selection of light sources ( power, angular dist.)<br>• Electronics in hutch ( detector, controller … )<br>• Embrittlement (cable, tube )<br>• Contamination on optics |
| – **Utilities** | • Electricity, water, air, network, control<br>• Environments ( temperature, vibration… ) |

– Time schedule
– Human resources
– Available budget, space, technical level
– Maintenance & lifetime of BL( hardware, applications )

***Management of the beamline construction***





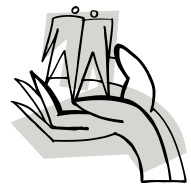



*Heat management*
*for*
*human safety & machine protection*

↓

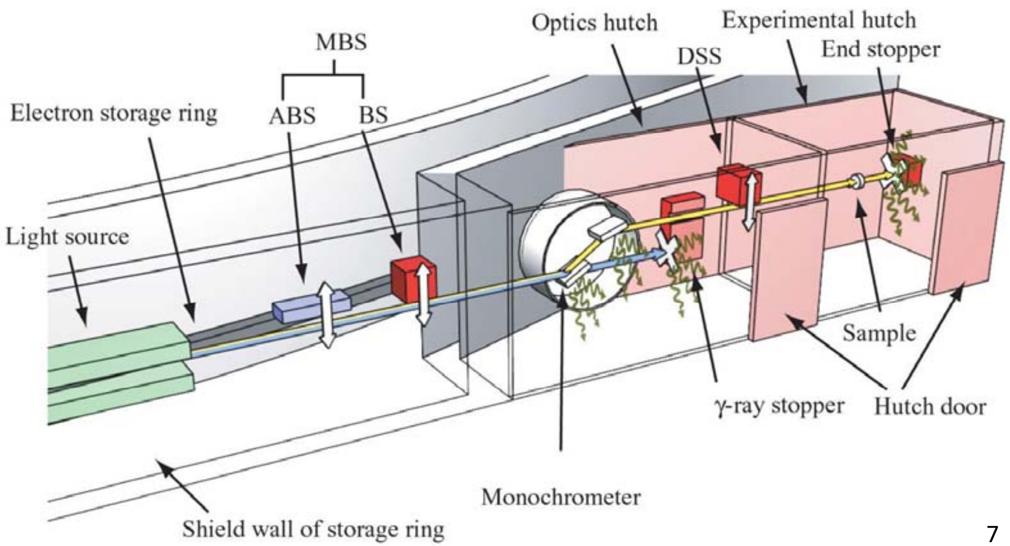
<u>Front end</u>

( FE )





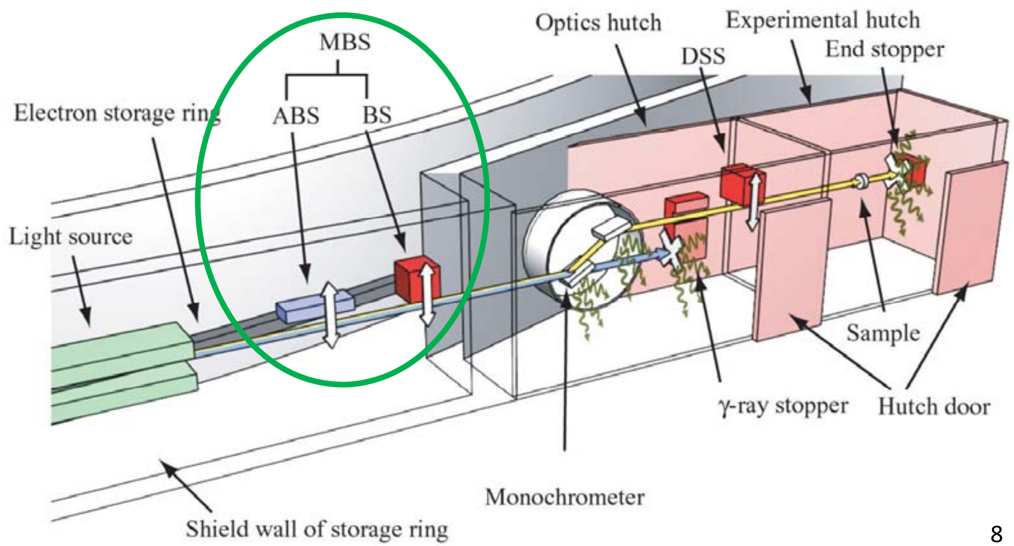
# Beamline components for safety

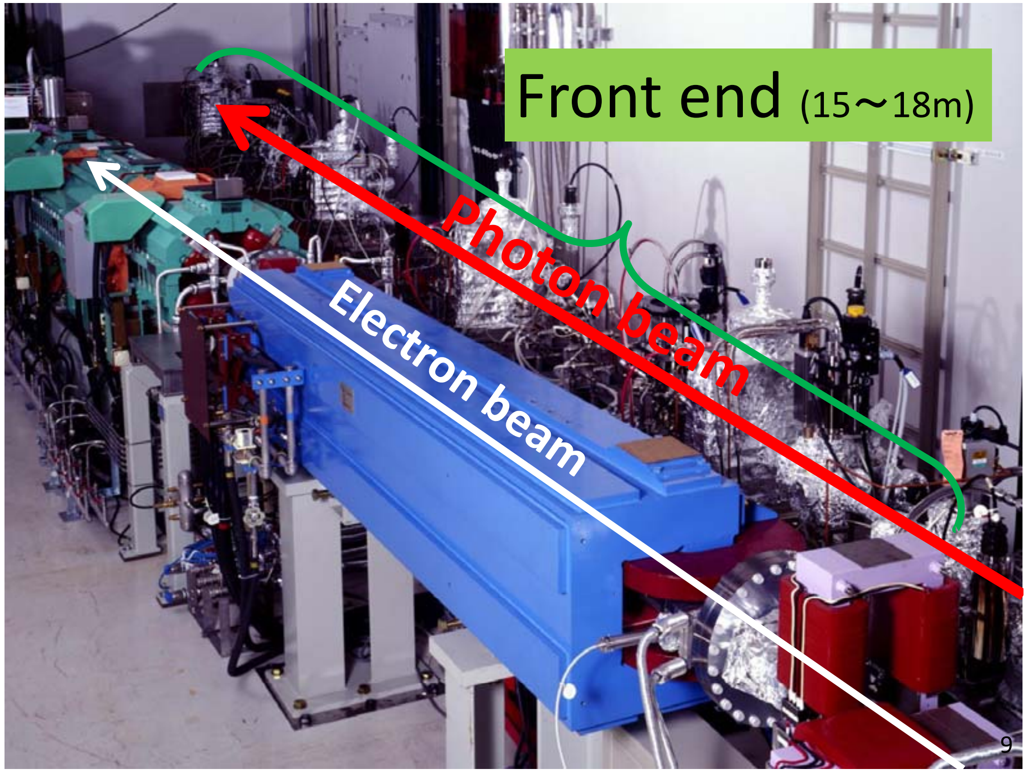





# Beamline components for safety

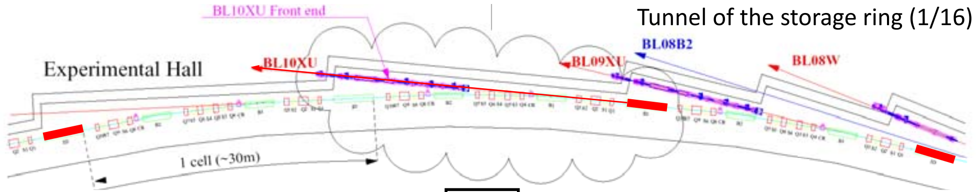
## Front end







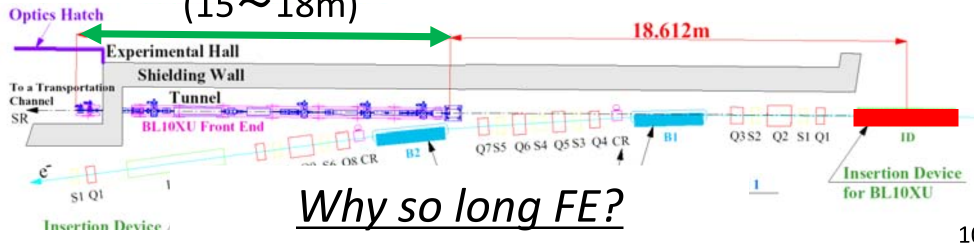

# Schematic Layout inside the SPring-8 Tunnel




Standard
in-vacuum undulator
Power density :
500 kW/mrad$^2$
Total power : 13 kW

## Front end (FE)

(15〜18m)

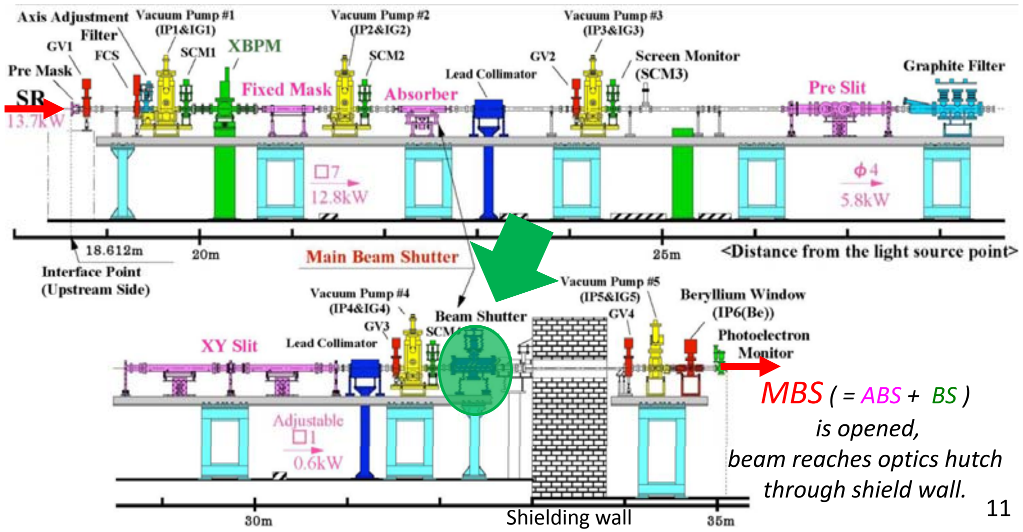



*Why so long FE?*



# Key functions & components of FE

(a) **Shielding *for human safety*** — **Beam shutter (BS)**, collimator ( radiation shield )
(b) Handling high heat load ***for safety*** — **Absorber**, masks (to prevent BS from *melting*)
(b') Handling high heat load *for optics* — XY slit, filters ( to prevent optics from *distorting* )
(c) Monitoring the x-ray beam position — XBPM (x-ray BPM ), SCM (screen monitor )
(d) Protection of the ring vacuum — FCS (fast closing shutter ), Vacuum system




*MBS ( = ABS + BS ) is opened, beam reaches optics hutch through shield wall.*

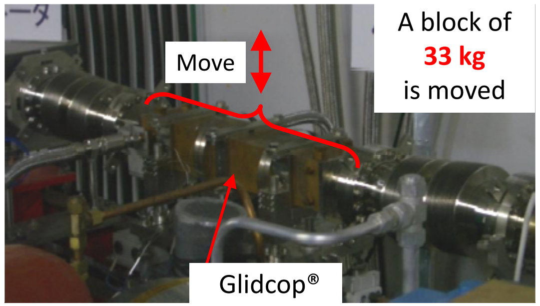
Shielding wall



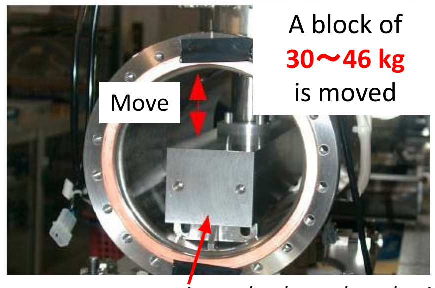
*When we operate a main beam shutter (MBS), what happens ?*

X-ray → **Absorber ( Abs )** → **Beam shutter ( BS )**

*to protect BS from heat load* — *to shield you against radiation*




(copper that is dispersion-strengthened with ultra-fine particles of aluminum oxide)




Heavy metal (alloy of tungsten)

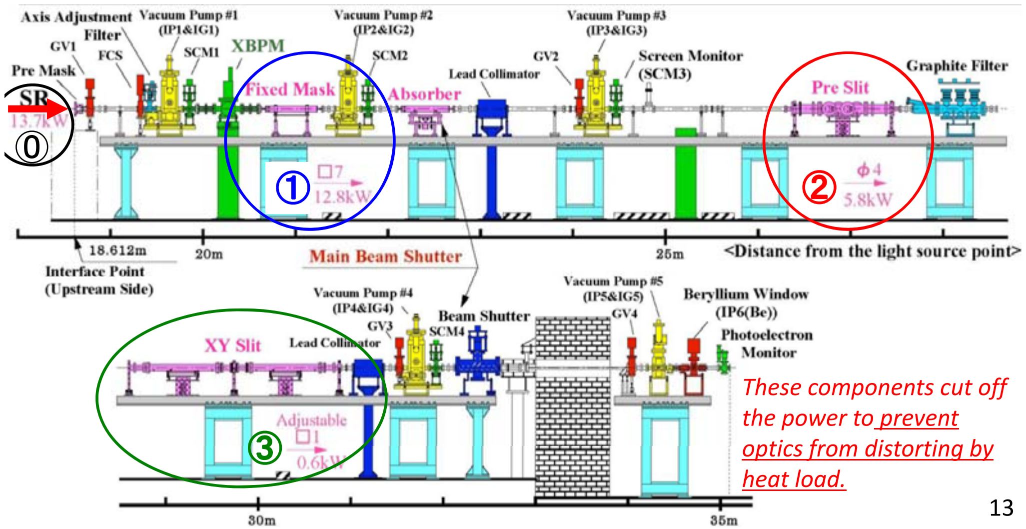
*the thermal conductivity not so high*

*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 — Beam shutter (BS), collimator ( radiation shield )
(b) Handling high heat load *for safety* — Absorber, **masks** (to prevent BS from *melting*)
(b') **Handling high heat load *for optics*** — **XY slit,** filters ( to prevent optics from *distorting* )
(c) Monitoring the x-ray beam position — XBPM (x-ray BPM ), SCM (screen monitor )
(d) Protection of the ring vacuum — FCS (fast closing shutter ), Vacuum system



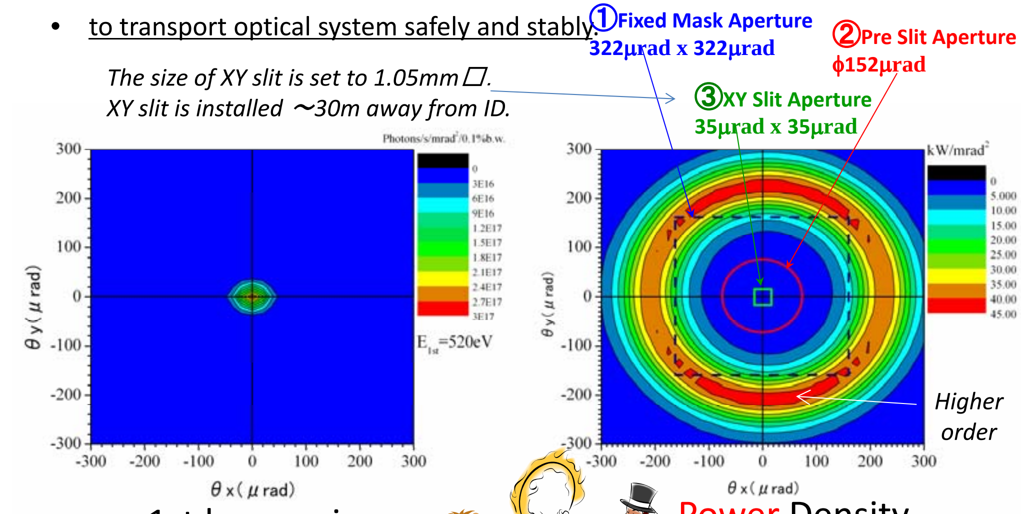

*These components cut off the power to prevent optics from distorting by heat load.*



## FE: *"For users to take lion's share"*

- Adding a spatial limitation to photon beam,
- supplying only a good quality part around the central axis of ID
- to transport optical system safely and stably.

*The size of XY slit is set to 1.05mm□.*
*XY slit is installed ∼30m away from ID.*



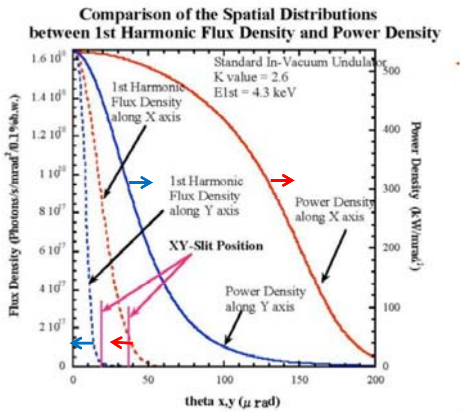

1st harmonic Flux Density

Power Density

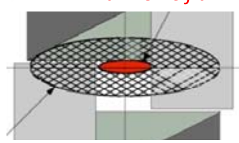
Helical Mode Operation at BL15XU



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

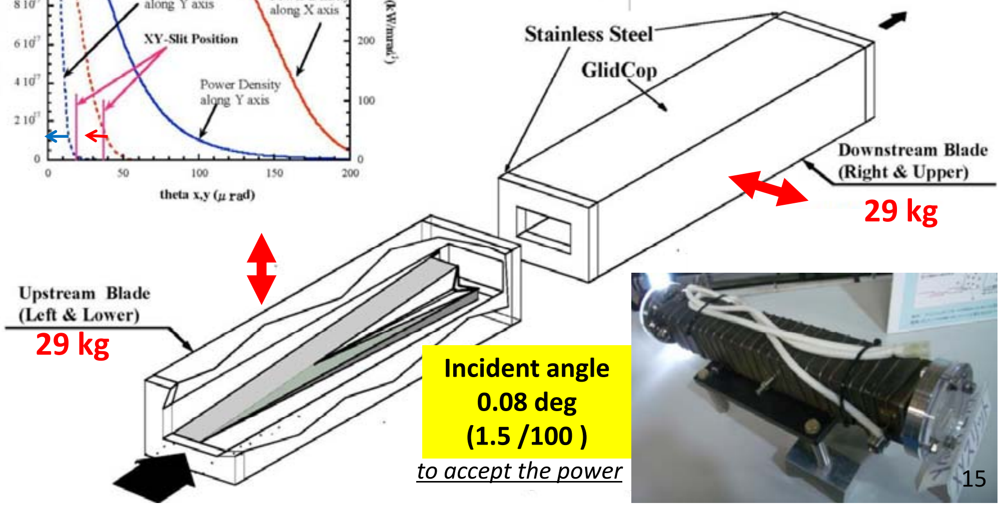



*1st harmonic flux*



Spatial distribution of *power*

***How to manage high heat load by FE XY slit ?***




*to accept the power*

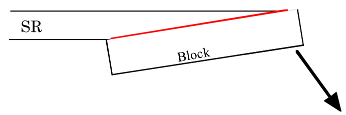


## Handling Technology of high heat load at SPring-8

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

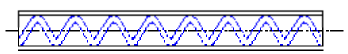
***1. Grazed Angle Technology (Mask, Absorber, XY slit)***

**(1) Inclining absorbing surface to X-ray beam**
**=> Decrease of power density of per unit area**



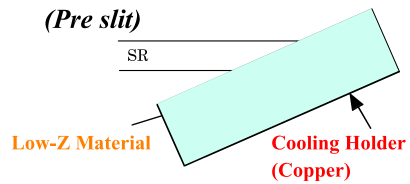

**(2) Applying the advanced material => Glid Cop**

**(3) Enhancing the heat transfer coefficient of the cooling channel**
**=> Copper wire coil (SPring-8)**
**Copper wire mesh (APS)**



**→ ∼ 10 kW/m**
**To increase the cooling ability within a more compact space**

***2. Volumetric Heating Technology (Pre slit)***



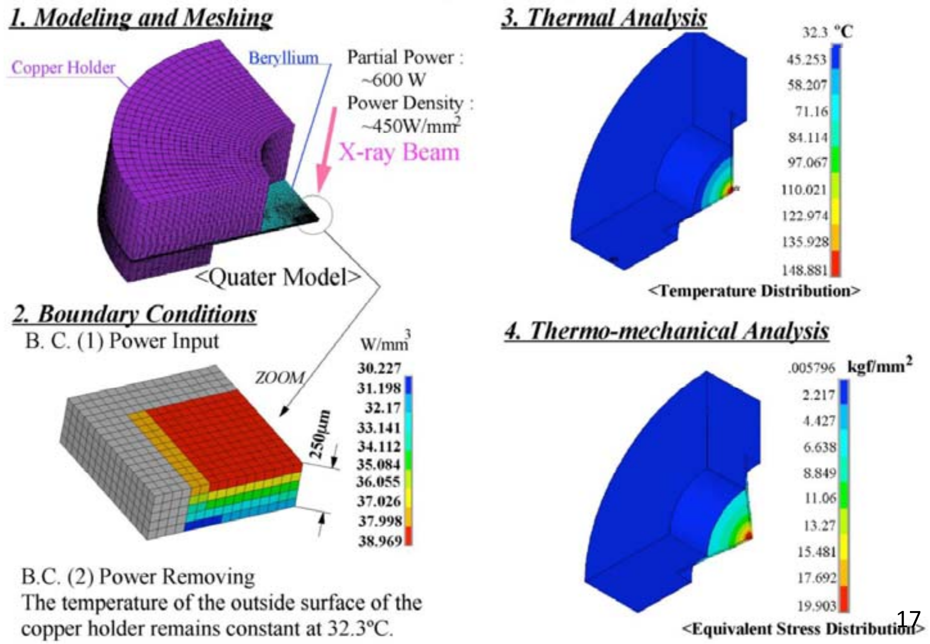

**Dissipating high surface heat flux in depth by utilizing a low-Z material, such as graphite or beryllium.**

***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 ).






# 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.

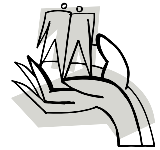
   They have to deal with every mode of ring operation and every mode of beamline activities.

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

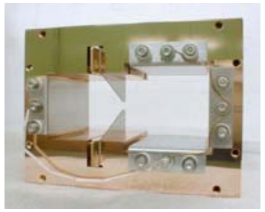
3. *Strongly required to be a reliable and stable system.*

   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.*







*Monitoring*
*stability of photon source*

↓

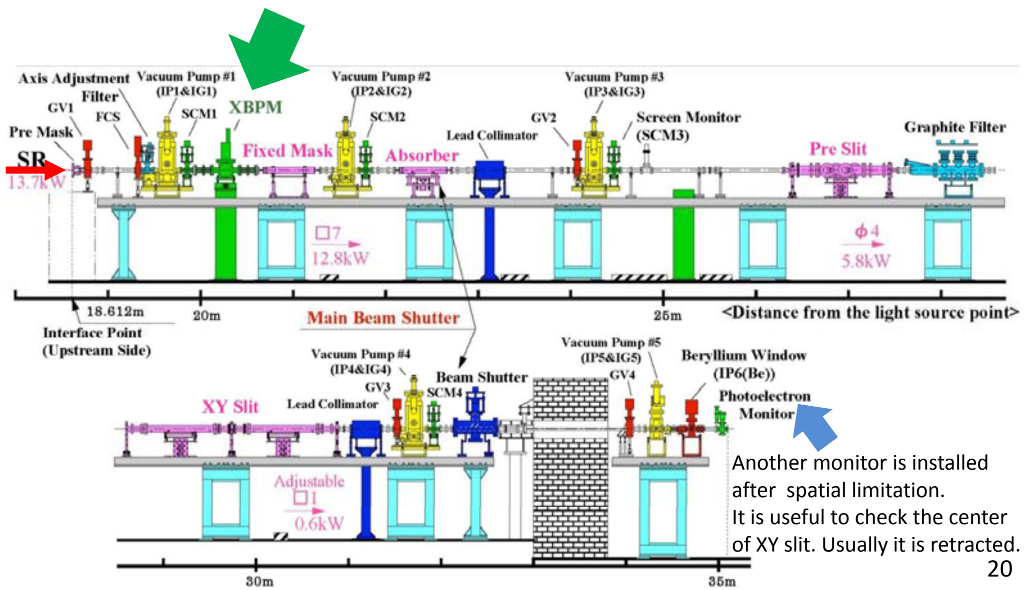
X-ray beam position monitor

( XBPM )



# *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.

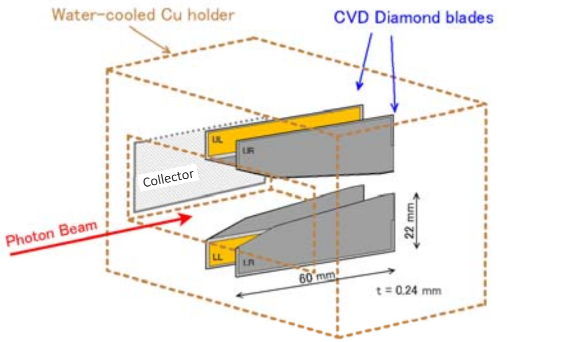
*Revised*

# Structure of XBPM's detector head

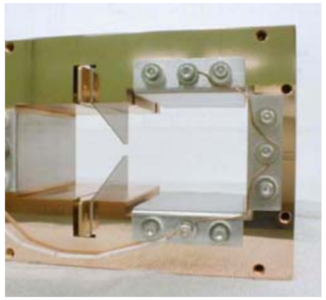
( Photo-emission type )

- 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*




XBPM
for insertion device (ID) beamline



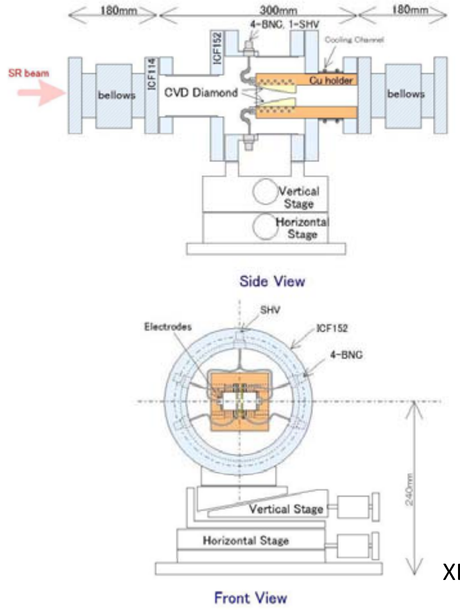
XBPM
for bending magnet (BM) beamline

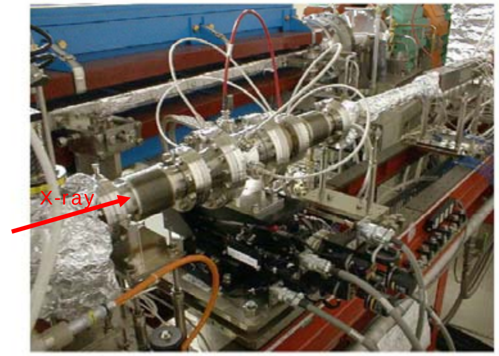
Heat sink Ti/Pt/Au coated (1000/2000/1-2μm)

Electrode Titunium coated (5000-10000A)



# Fixed-blade style XBPM




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

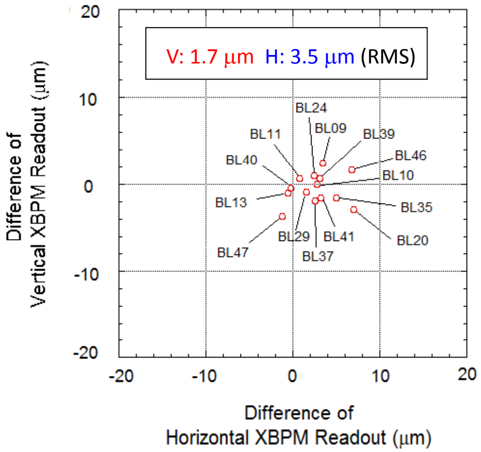
XBPM is installed on stable stand and stages



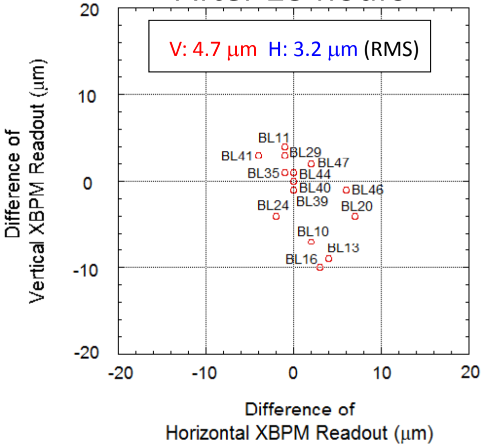
# High stability of XBPM

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




After 23 hours



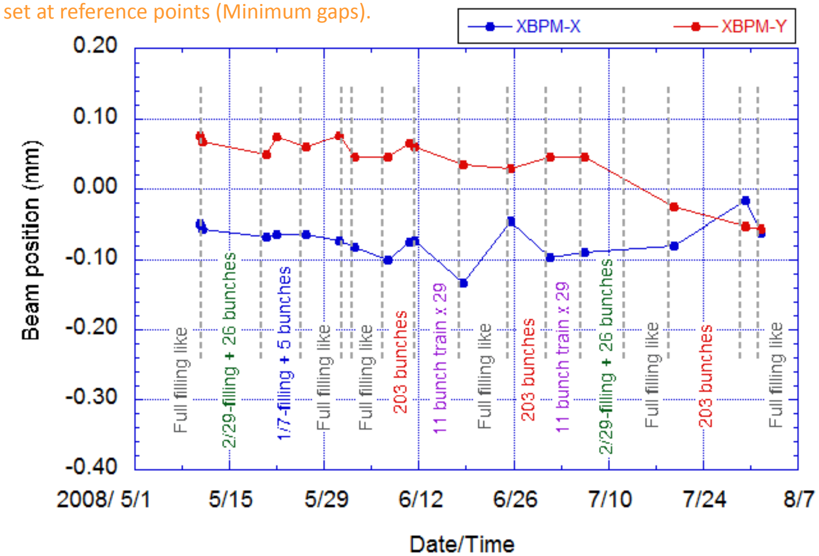

All Gaps are set at reference points (Minimum gaps).

**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).



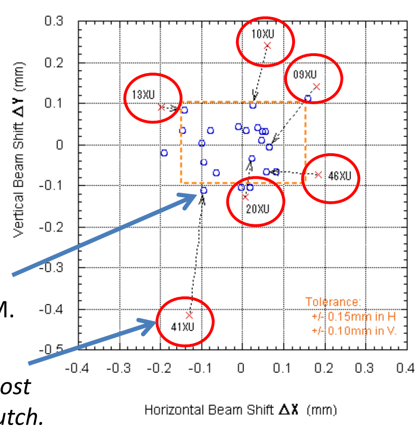
# Orbit correction using XBPM

Check of ID beam orbits with XBPMs

at beginning of the 1st cycle, 2007

Reference orbit: 2006/12/18 11:14:18

2007/02/27 Aoyagi




The beam recovered using XBPM.

*The beam lost at optics hutch.*
*Electron beam monitored same orbit before.*

<After Correction> 2007/02/26 20:51:49 — <Before Correction> 2007/02/26 19:09:24

| | After Correction Horizontal (mm) | After Correction Vertical (mm) | Before Correction Horizontal (mm) | Before Correction Vertical (mm) |
|---|---|---|---|---|
| BL08W | --- | --- | --- | --- |
| BL09XU | 0.064 | -0.006 | 0.180 | 0.141 |
| BL10XU | 0.024 | 0.096 | 0.060 | 0.241 |
| BL11XU | 0.008 | 0.035 | | |
| BL12XU | 0.055 | 0.033 | | |
| BL13XU | -0.141 | 0.084 | -0.199 | 0.090 |
| BL15XU | -0.011 | 0.043 | | |
| BL16XU | -0.190 | -0.019 | | |
| BL17SU | --- | --- | --- | --- |
| BL19LXU | --- | --- | --- | --- |
| BL20XU | 0.022 | -0.033 | 0.006 | -0.129 |
| BL22XU | 0.045 | 0.011 | | |
| BL23SU | -0.064 | -0.070 | | |
| BL24XU | -0.078 | 0.035 | | |
| BL25SU | 0.081 | -0.067 | | |
| BL27SU | 0.018 | -0.105 | | |
| BL29XU | 0.049 | 0.031 | | |
| BL35XU | -0.095 | -0.043 | | |
| BL37XU | -0.100 | 0.003 | | |
| BL39XU | --- | --- | --- | --- |
| BL40XU | 0.037 | 0.041 | | |
| BL41XU | -0.094 | -0.112 | -0.129 | -0.416 |
| BL44XU | -0.004 | -0.104 | | |
| BL45XU | -0.147 | 0.035 | | |
| BL46XU | 0.058 | -0.066 | 0.185 | -0.075 |
| BL47XU | 0.159 | 0.112 | | |

Orbit correctied for BL08XU, BL09XU, BL10XU, BL13XU, BL20XU, BL41XU, BL46XU

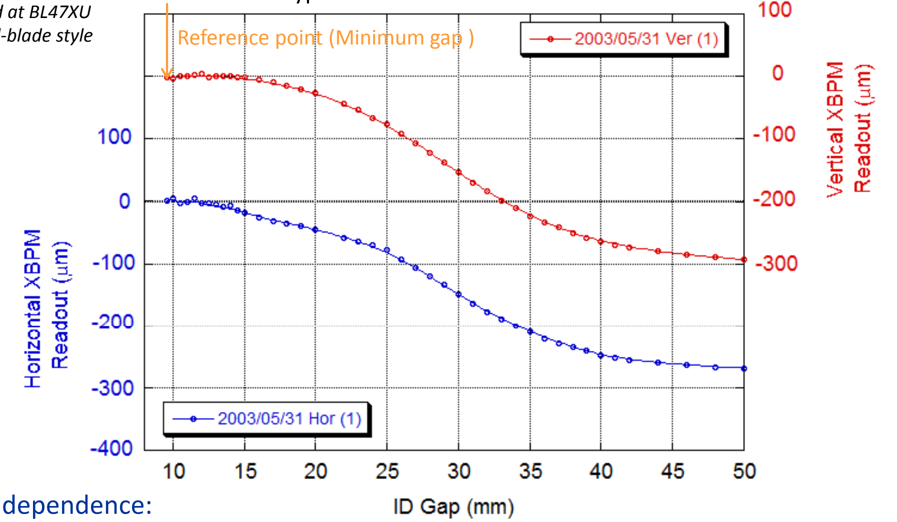
*A fixed point observation of XBPM is helpful for a regular axis from ID.*



# XBPM of ID-Gap dependence

*Measured at BL47XU with fixed-blade style*

Photo-emission type




Gap dependence:

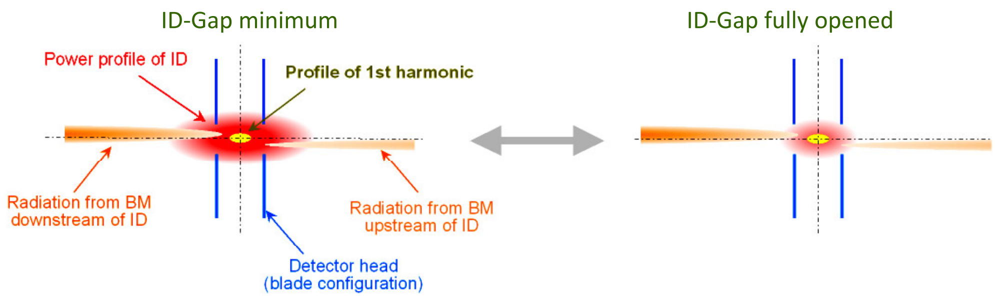
~ 100μm for Gap : 9.6 ~ 25 mm , ~300μm for Gap : 9.6 ~ 50 mm

***The position of the beam at optics hutch is fixed for changing ID gap.***

*What does the XBPM tell us ?*



# *What does the XBPM tell us ?*




**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 ~ 18 keV,

**Background:** < 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.



# Key issues of XBPM design

*for high power undulator radiation in SPring-8*

**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 ~ 20 / 5 μrad ( hor. / ver. ), which correspond to beam sizes of ~ 400 / 100 μm ( hor. / ver. ) at XBPM position (20 m from ID).

**4. Withstand high heat Load**

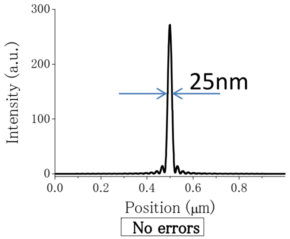
- Blade of diamond

  Max. power density is ~ **500 kW/mrad²**. Metal will melt immediately.

**5. Fast Response**

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

Ref. of XBPM : for example, H. Aoyagi et al., "High-speed and simultaneous photon beam diagnostic system using optical cables at SPring-8", AIP Conf.Proc.705-593 (2004).




*Tailoring x-rays*
*to application*
↓
<u>X-ray mirrors</u>
design, errors, metrology
& alignment



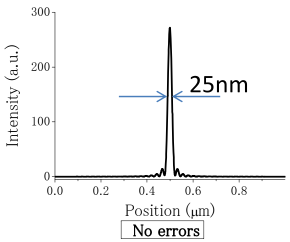
# The functions of x-ray mirrors

- 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.*






*Tailoring x-rays*
*to application*
↓
<u>X-ray mirrors</u>
design, errors, metrology
& alignment



# Design parameters of x-ray mirror

<u>Requirement</u>

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

*We have to know well what kinds beam irradiate on the mirror.*

<u>Design parameters</u>

- Coating material : Rh, Pt, Ni … ( w/o binder , Cr ), thickness
  : multilayers ( ML ), laterally graded ML
- Incident angle : grazing angle ( mrad ) ⇨ How to select
- 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 $LN_2$…
- Substrate material : Si, SiO2, SiC, Glidcop…

<u>In addition,</u>

some errors such as figure error, roughness…

*How to select coating material and incident angle ?*

Reflectivity for grazing incident mirrors

$$R(\lambda,\theta,n) = \left| \frac{k_1 - k_2}{k_1 + k_2} \right|^2$$

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

The complex index of refraction



# Coating material (1)

## *"the complex index of refraction"*

The complex atomic scattering factor for the *forward scattering*

$$f = f_1 + if_2$$

The complex index of refraction

$$n = 1 - \delta - i\beta \qquad E \propto e^{-i(\varpi t - kr)}$$

$$\begin{cases} \delta = \dfrac{Nr_0\lambda^2}{2\pi} f_1(\lambda) \\ \beta = \dfrac{Nr_0\lambda^2}{2\pi} f_2(\lambda) \end{cases}$$

| | δ (×10 $^{-5}$) | β(×10 $^{-7}$) |
|---|---|---|
| Si | 0.488 | 0.744 |
| Quartz | 0.555 | 2.33 |
| Pt | 3.26 | 20.7 |
| Au | 2.96 | 19.5 |

$$r_0 = \frac{e^2}{4\pi mc^2} = 2.82\times 10^{-15} m \qquad \beta = \frac{\mu\lambda}{4\pi}$$

N: Number of atoms per volume

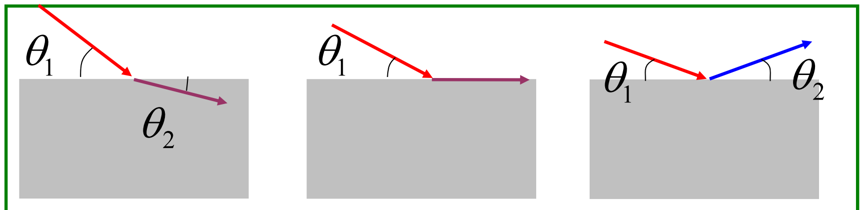
*μ: linear absorption coefficient*



# Coating material ( 2 )

## *"total reflection"*

$$n_1/n_2 = \cos(\theta_1)/\cos(\theta_2) \qquad \text{Snell's law}$$




$\theta_1 > \theta_c$ $\theta_1 = \theta_c$ $\theta_1 = \theta_2 < \theta_c$

$$\cos(\theta_c) = n = 1 - \delta, \cos(\theta_c) \to 1 - \theta_c^{\,2}/2$$

$$\theta_c \cong \sqrt{2\delta} = 1.6\times 10^{-2}\lambda\sqrt{\rho} = 20\sqrt{\rho}/E$$

*For example,* $\theta_c$ ( rad ), $\rho$ ( g / cm$^3$ ) , $\lambda$ ( nm ) , $E$ ( eV )

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



# Coating material ( 3 ) : *"cut off, absorption"*

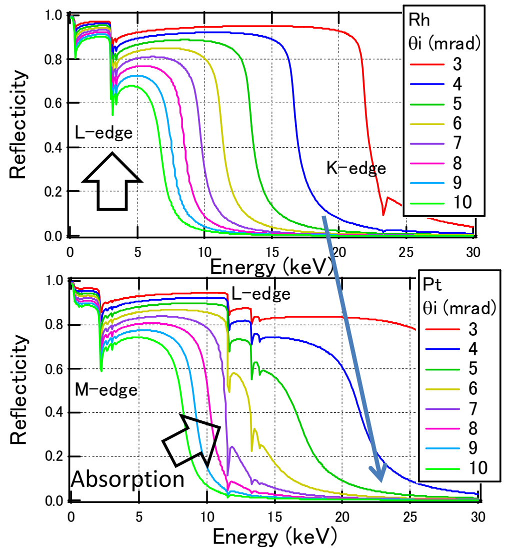
The cut off energy of total reflection $Ec$

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

$E_c$ ( eV ) , $\rho$ ( g / cm$^3$ ), $\theta_c$ ( mrad )

Rh ( 12.4 g / cm$^3$ )

Pt ( 21.4 g / cm$^3$ )



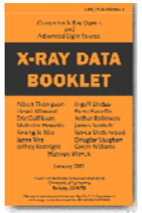

*Cut off energy, absorption → incident angle*

*→ 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/



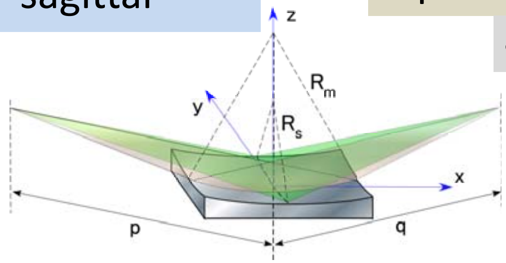

***<u>Many thanks to the authors !</u>***



# Surface shape (1)

| Purpose of the mirror | *for example,* | *Easy to make or cost* |
|---|---|---|
| • deflecting | • flat | ◎ |
| • low pass filter | • spherical | ◎ |
| • focusing | • cylindrical | ○ |
| • collimate | • toroidal | ○ |
| • meridional | • elliptical | △ |
| • sagittal | • parabolic… | △ |
| | adaptive | △ |

*Take care of aberration*



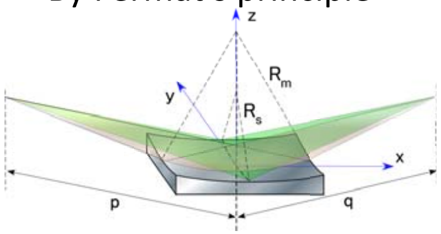



# Surface shape (2) radius and depth

$$R_m = \frac{2}{(1/p + 1/q)\sin(\theta_i)}$$

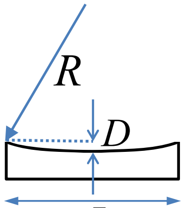
$$R_s = \frac{2\sin(\theta_i)}{(1/p + 1/q)} = R_m \sin^2(\theta_i)$$

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,

$p$=15～50m, $q$=5～20m $\theta_i$=1～10mrad

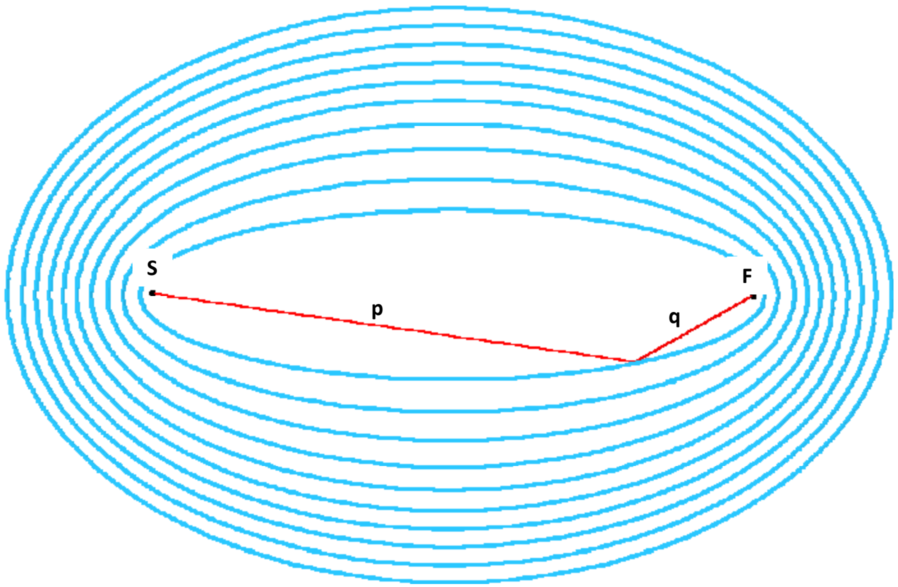
$R_m$=0.1～10 km, $R_s$= 30～100 mm

$R$=1 km, $L$=1m → $D$ = 125 μm



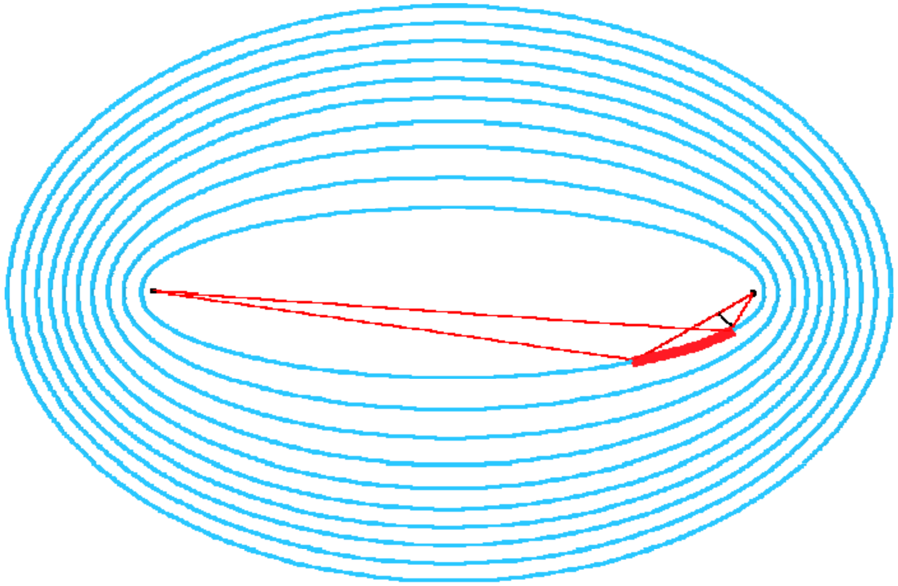
ESRF

## Basic geometry




by courtesy of Ch. Morawe

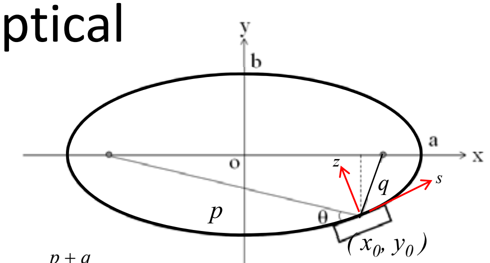
## Mirror optics



by courtesy of Ch. Morawe

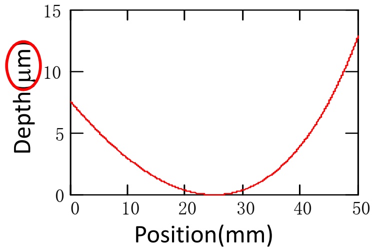
## Surface shape (3) elliptical

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




For example,

$p = 975\ m, q = 50\ mm, \theta = 3\,mrad$




$$a=\frac{p+q}{2}$$

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

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

$$y_0=-b\sqrt{1-\frac{x_0^2}{a^2}}$$

$$u=\frac{\frac{b}{a}\times x_0}{\sqrt{a^2-x_0^2}}$$

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

*Precise fabrication is difficult.*

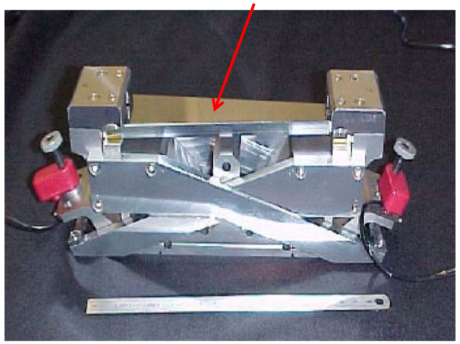
( Ref * )

* M.R Howells et al., “Theory and practice of elliptically bent X-ray mirrors”, Optical Eng. **39**, 2748 (2000).



## Elliptical mirror mechanically bent using trapezoidal substrate

Trapezoidal mirror (L170mm)



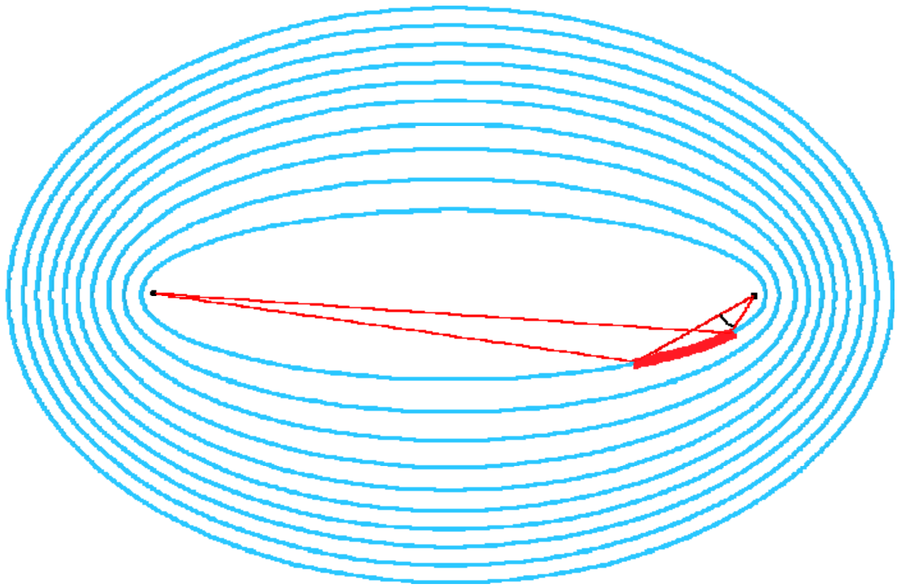
Dynamically bent KB mirror at ESRF

Trapezoidal mirror (L540mm)

Long bent focusing mirror at SPring-8

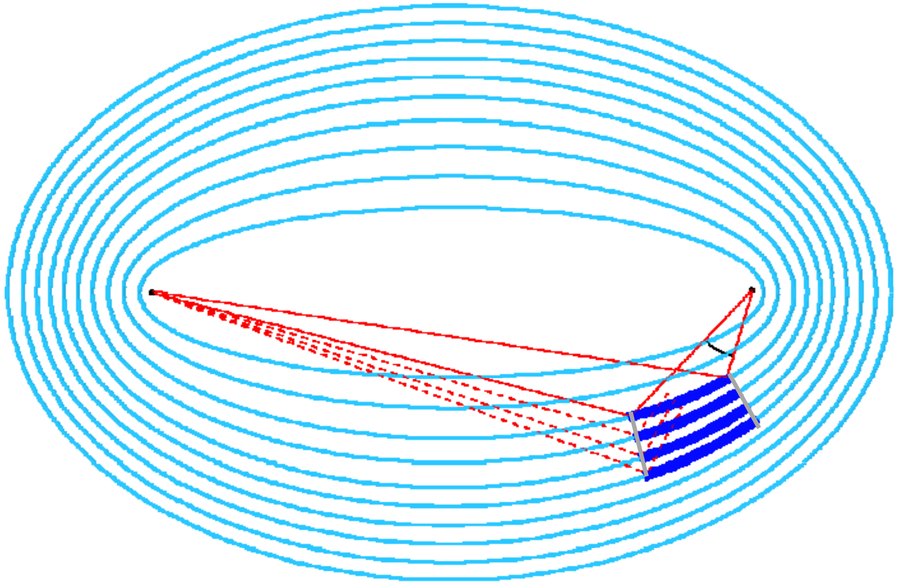


## Mirror optics



by courtesy of Ch. Morawe

# Multilayer optics



by courtesy of Ch. Morawe

# X-ray multilayer reflectivity

**Numerical calculations**

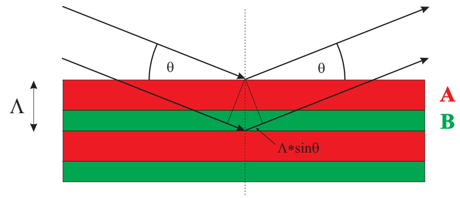
**Main features**

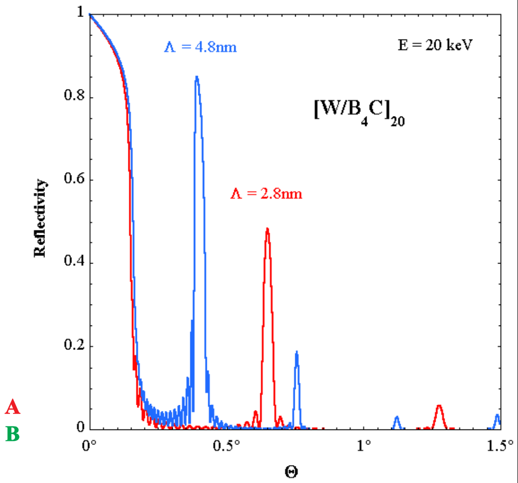
- Bragg peaks and fringes due to interference
- Positions depend on E and Λ
- Intensities depend on Δρ, N, σ…

**Corrected Bragg equation**

$$m \cdot \lambda = 2 \cdot \Lambda \cdot \sqrt{n_2^{\,2} - n_1^{\,2} \cos^2 \theta}$$

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




by courtesy of Ch. Morawe

# X-ray multilayer characterization

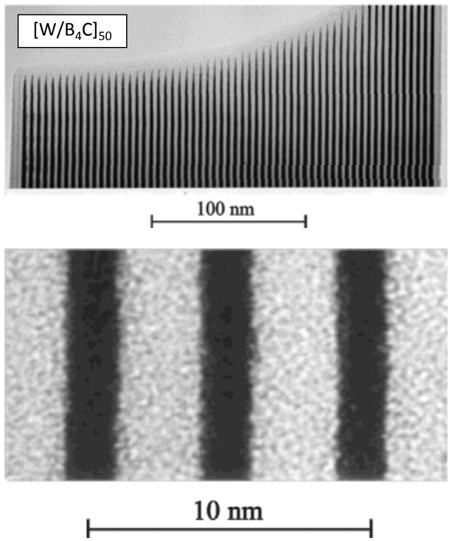
**Transmission electron microscopy (TEM)**

- Fabrication errors
- Roughness evolution
- Crystallinity
- Interface diffusion

↓

**Complementary to x-ray measurements !**

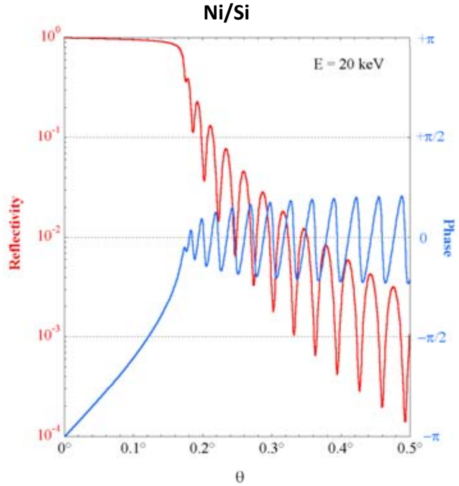
R. Scholz, MPI Halle, Germany

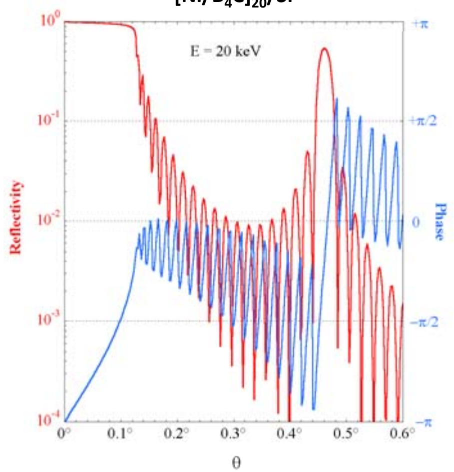



by courtesy of Ch. Morawe

# X-ray reflectivity

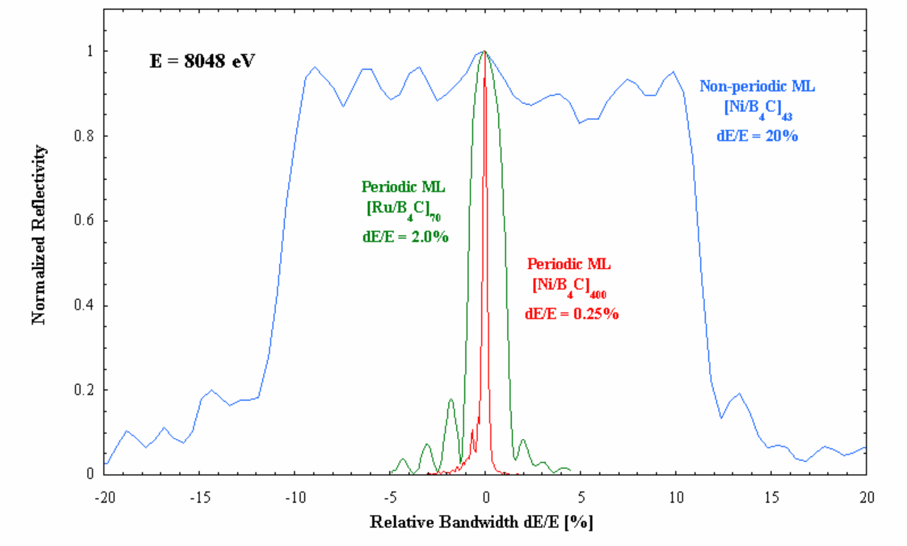
**Reflectivity and phase**




by courtesy of Ch. Morawe

## Energy resolution of multilayers




by courtesy of Ch. Morawe

## X-ray multilayer design

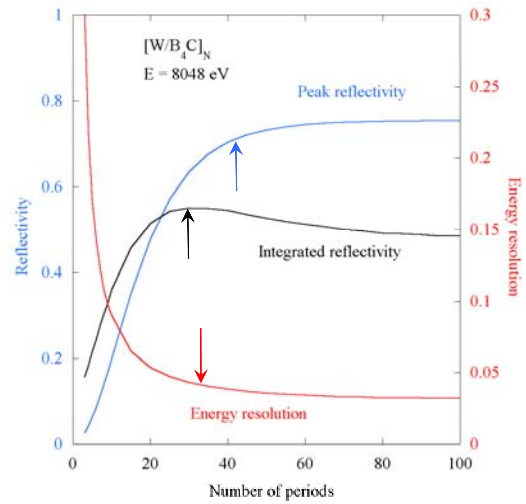
**Period number N:**

**Peak versus integrated reflectivity:**

- **$R_{peak}$ increases with N up to extinction**
- **ΔE/E decreases ~ 1/N in kinematical range**
- **$R_{int}$ is maximum before extinction**

**High and low resolution MLs**

**Optimize N according to needs !**




by courtesy of Ch. Morawe

# 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…* )

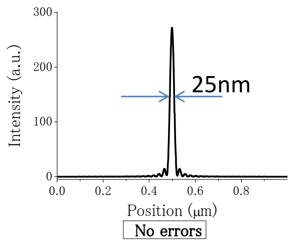
Design parameters

- 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 $LN_2$…
- Substrate material : Si, SiO2, SiC, Glidcop…

In addition,

some errors such as figure error, roughness…



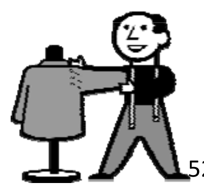



*Tailoring x-rays to application*

↓

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*

- Reflectivity
- Beam size
- Distortion
- Deformation …

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

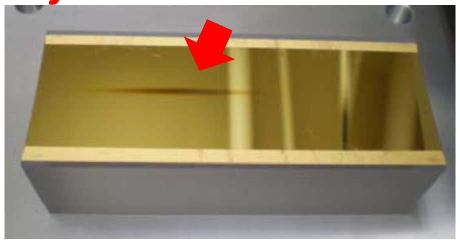
- Deformation by self-weight, coating and support …
- Figure error of adaptive mechanism
- Misalignment of mirror
- Stability of mirror's position ( angle )
- Deposition of contamination by use
- Decomposition of substrate by use

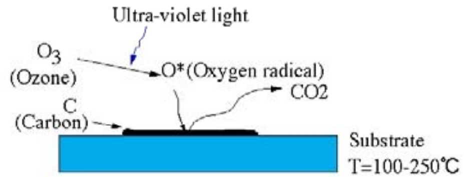
- Environment
- Stages
- Cooling system …



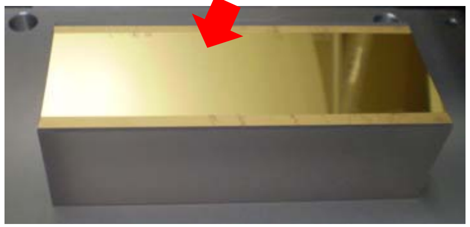
# Contamination and removal

***before***






***After cleaning***



Advantage of UV/ozone cleaning

1. Low Damage
2. Contamination-free
3. Non-contact

UV / ozone cleaning

*It takes from 10 min to a few hours.*

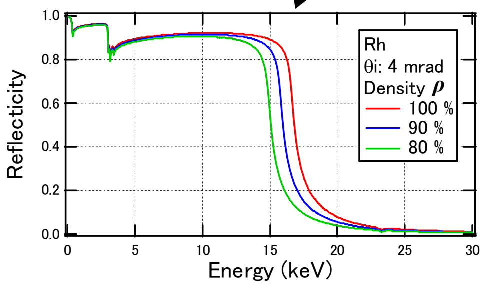


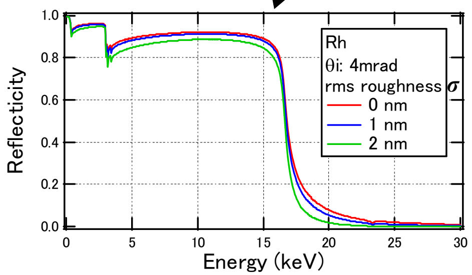
# Errors ( 1 )

## *"Density* **ρ** *and surface roughness* **σ** *"*

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

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



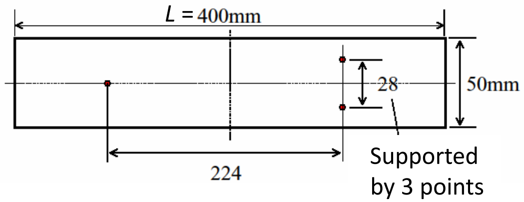




Coating on sample wafer at the same time is helpful to evaluate the density and roughness.



# Errors ( 2 )

## *"the self-weight deformation"*

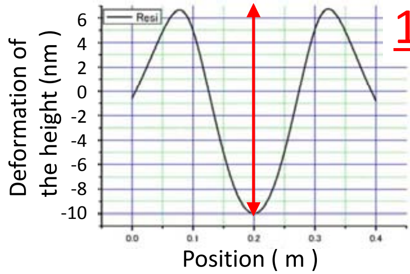



Bottom view — Thickness $t$ = 50mm

| | |
|---|---|
| Material | $SiO_2$ |
| Density | 2.2 g / cm$^3$ |
| Poisson's ratio | 0.22 |
| Young's modulus | E = 70 Gpa |

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

By FEA (finite element analysis )




The self-weight deformation on the surface of mirror ( $SiO_2$ )

**16.7 nm PV**

*This value is larger than figure error by Rayleigh's rule.* ( →See next page )

*Improvement for nano-focusing*

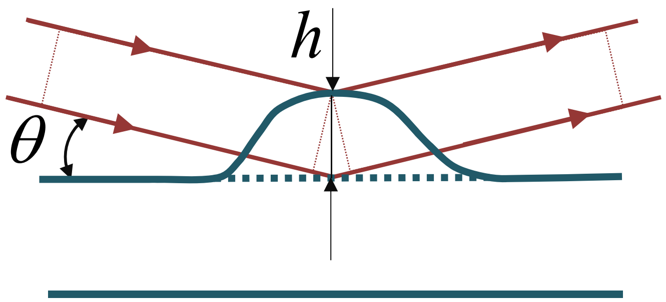
*a) Substrate → Si ( E ~ 190 GPa )*
*b) Optimization of supporting points and method*
*c) Figuring in consideration of the deformation*

# Errors (3a)

## *"figure error estimated by Rayleigh's rule"*

$$\phi = 2hk\sin(\theta) \rightarrow \pi/2 \qquad h_{\lambda/4} = \lambda/8\theta$$

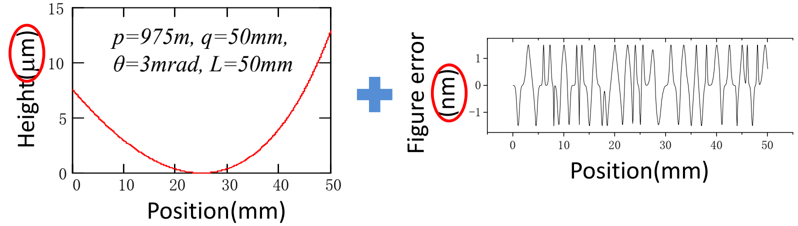
| | | |
|---|---|---|
| 0.06nm (20keV) | 3mrad | 2nm |
| 0.08nm (15keV) | 3mrad | 3nm |
| 1 nm ( 1keV) | 10mrad | 12nm |





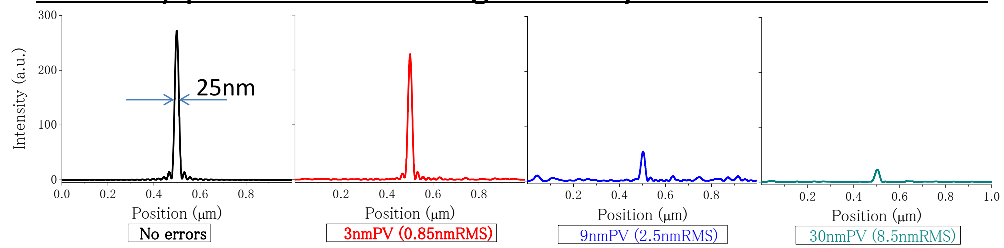

# Errors (3b)

## *" estimation by wavefront simulation "*




Designed surface Errors of ***short*** range order

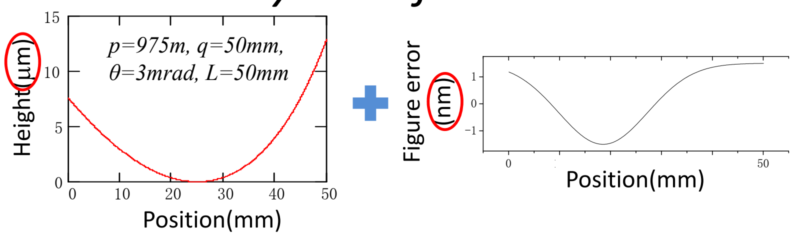
Intensity profiles of focusing beam by wavefront simulation




Errors of short range order *decreases intensity*. → Roughness

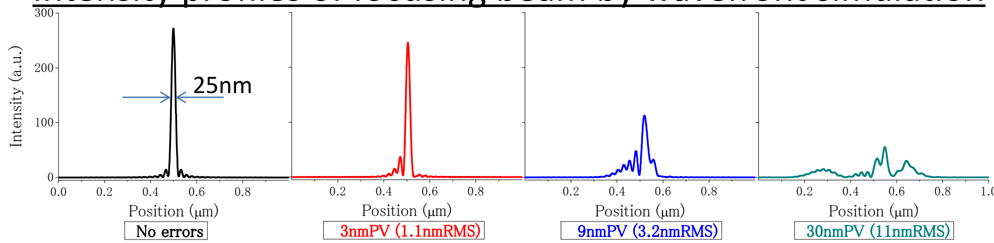
# Errors (3c)

## *" estimation by wavefront simulation "*




Designed surface Errors of ***long*** range order

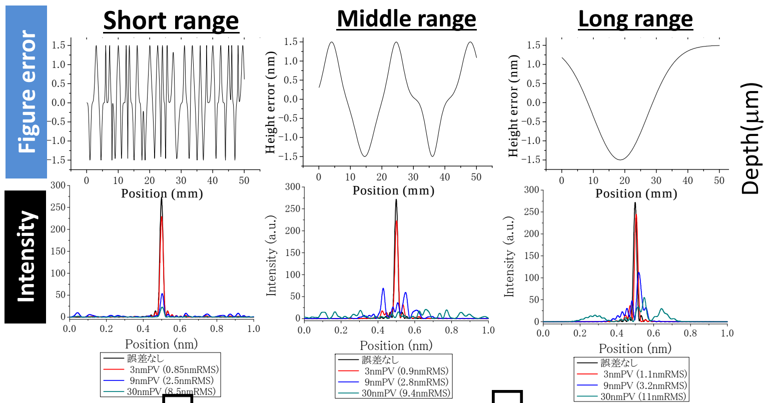
Intensity profiles of focusing beam by wavefront simulation

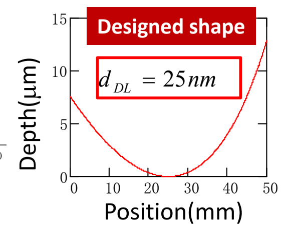



Errors of long range order *loses shape.*



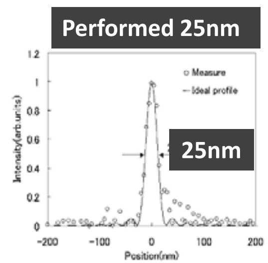
## *" estimation by wavefront simulation "*



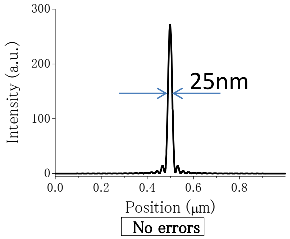

**Intensity reduced** **Shape loses**

If the figure error < 3nmPV ***for all spatial range***,
the estimated focusing size performs 25 nm.
The value corresponds to the result of Rayleigh's rule.




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

*H. Mimura, H. Yumoto, K. Yamauchi et.al, Appl. Phys. Lett. **90**, 051903 (2007).



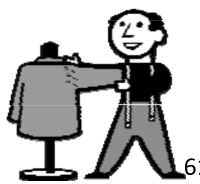

*Tailoring x-rays*
*to application*

↓

<u>X-ray mirrors</u>

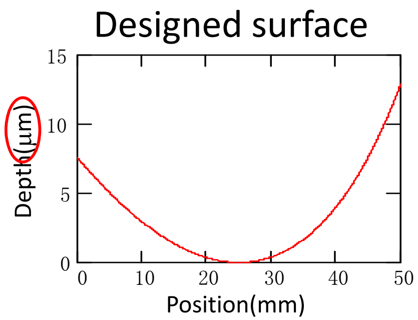
design, errors, metrology

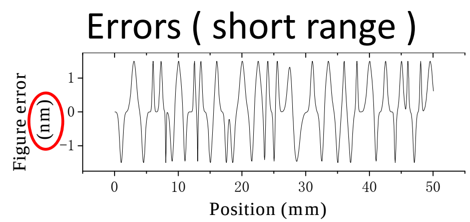
& alignment

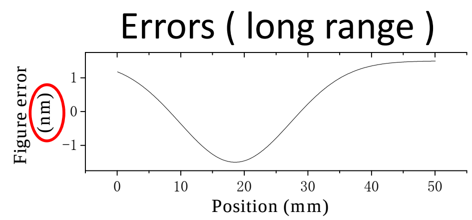




# *How to evaluate the errors ?*



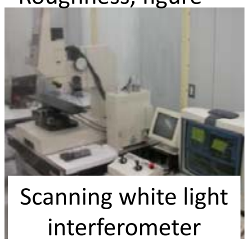






# Metrology instruments for x-ray optics

Field of view, lateral resolution

| *Short* | *Short / middle* | *Long / middle* | *Long / middle* |
|---|---|---|---|
| ～10 µm, 0.1 nm | ～10 mm, 1 µm | ～ 0.1 m, 0.1 mm | ～1m, 1 mm |
| Roughness | Roughness, figure | Figure | Slope |




*z* (0.1nm) | *z* (0.1nm) | *z* (0.1nm) | *slope* (0.1urad)

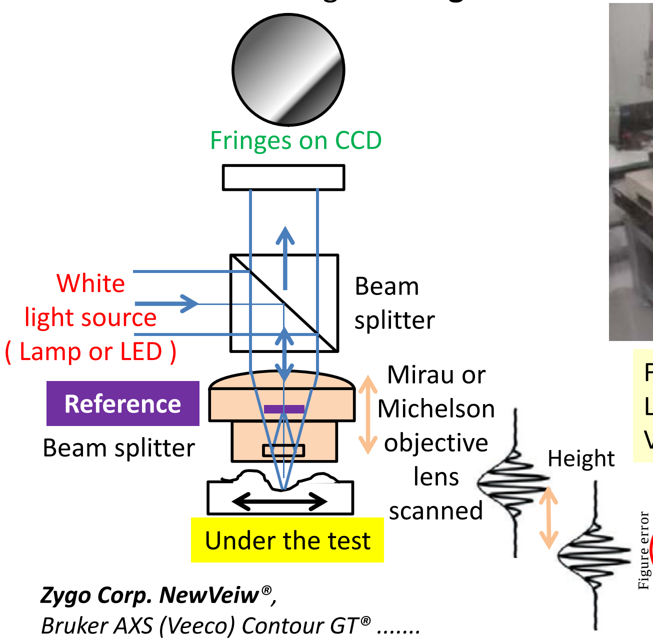
Vertical resolution (rms)



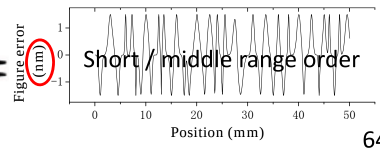
# Scanning white light interferometer

Interference fringe → **Height**

<u>*Commercially available*</u>




FOV (=lens) ～10 mm
Lateral resolution 1 µm～
Vertical resolution 0.1 nm



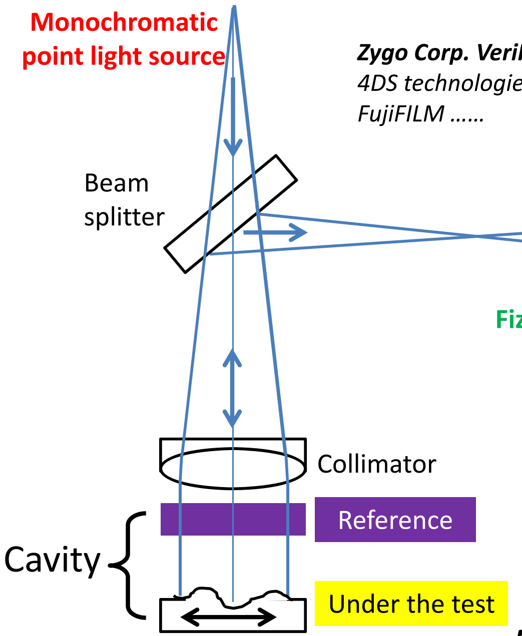

***Zygo Corp. NewVeiw®,***
*Bruker AXS (Veeco) Contour GT® .......*

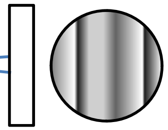
# Fizeau interferometer

Interference pattern → **Height**

*Commercially available*

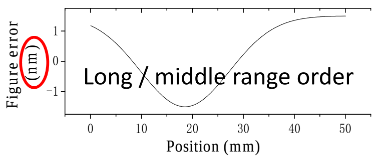
*Zygo Corp. VeriFire®,*
*4DS technologies,*
*FujiFILM ……*



Fizeau fringes on CCD

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




***Not easy to measure large mirror***



# Long trace profiler ( LTP )

*Homemade*

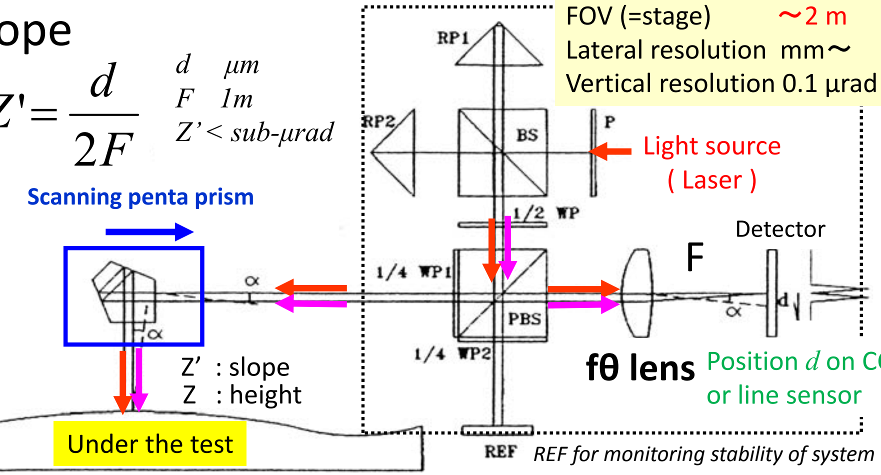
Direction of laser reflected on the surface → **Slope**

Slope

$$Z' = \frac{d}{2F}$$

$d$ $\mu m$
$F$ $1m$
$Z' <$ sub-$\mu rad$

FOV (=stage) ∼2 m
Lateral resolution mm∼
Vertical resolution 0.1 µrad




***Easy to measure slope of sub-µrad on large mirror by NO reference***

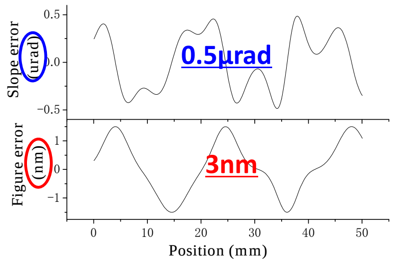
*Many kinds of LTPs are developing among SR facilities.*

*For example*, S. Qian, G. Sostero and P. Z. Takacs, Opt. Eng. **39**, 304-310 (2000).

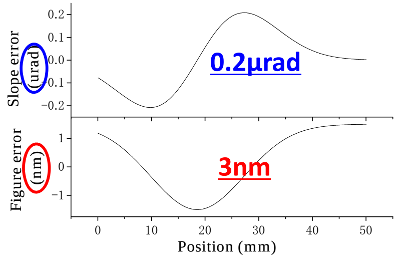


# *Figure error and slope error*

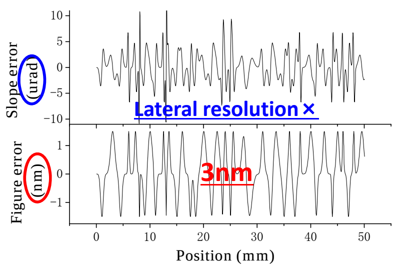
Errors ( middle range )

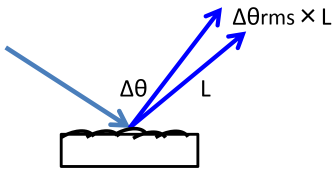



Errors ( long range )




Errors ( short range )

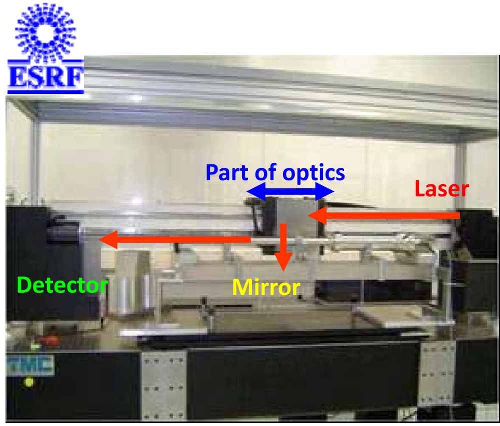


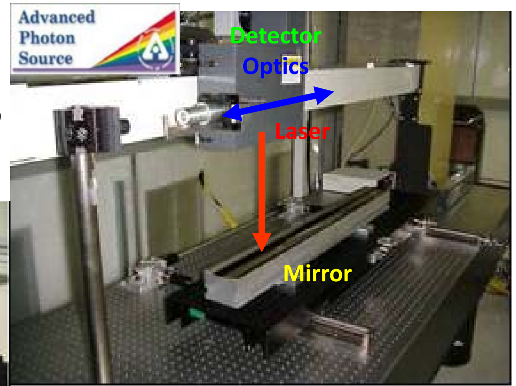



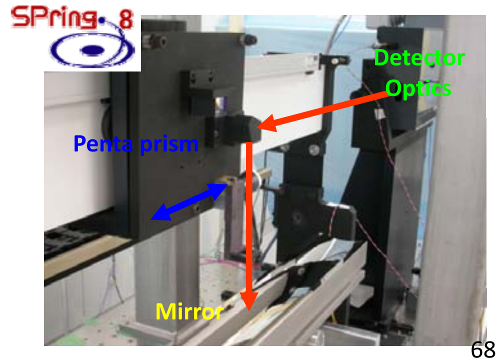

LTP :
Lateral resolution mm∼
Vertical resolution 0.1 µrad



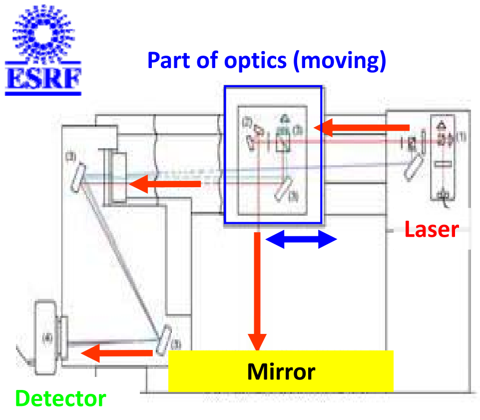
# LTP
# of ESRF, APS, SPring-8

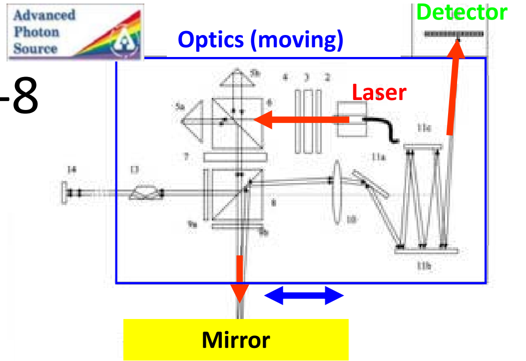


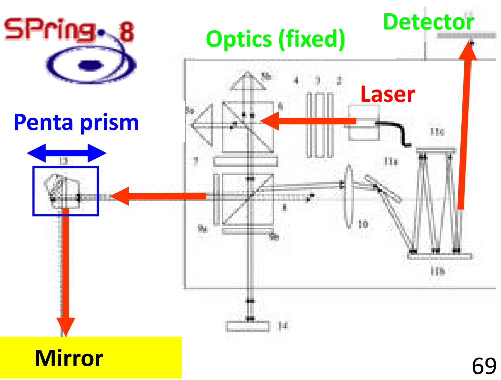



# LTP of ESRF, APS, SPring-8

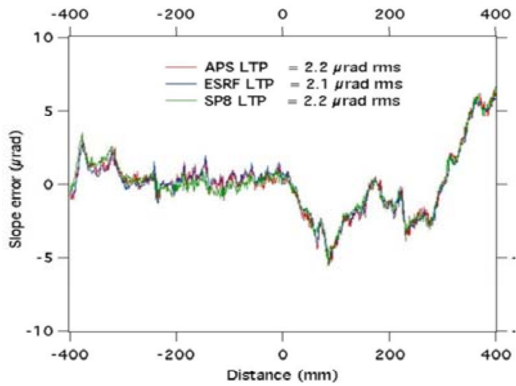





# Round robin measurement of **1m-long** toroidal mirror




Slope error profile

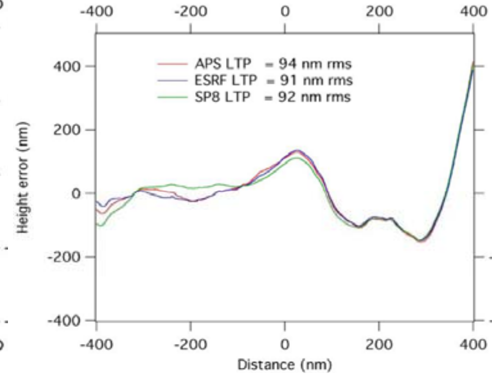



Figure error profile

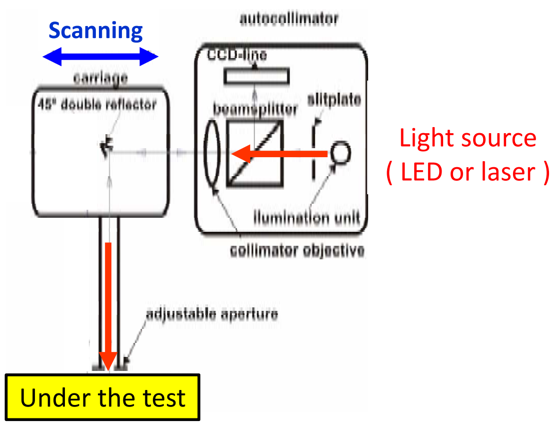
*L. Assoufid, A. Rommeveaux, H. Ohashi, K. Yamauchi, H. Mimura, J. Qian, O. Hignette, T. Ishikawa, C. Morawe, A. T. Macrander and S. Goto, SPIE Proc. 5921-21, 2005, pp.129-140.*



# Nanometer Optical Component Measuring Machine (NOM) @HZB

Autocollimator → **Slope**

*Homemade*




Light source
( LED or laser )

*F. Siewert et al.: „The Nanometer Optic Component Measuring Machine: a new Sub-nm Topography " SRI 2003, AIP Conf. Proc.*

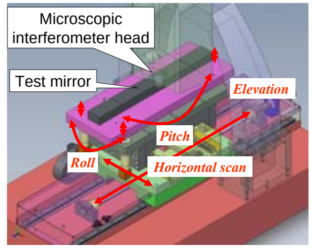


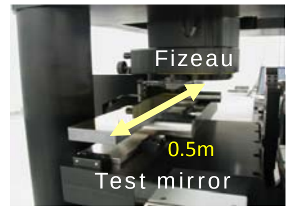
# Stitching interferometer for large mirror

*Homemade*

MSI
( micro-stitching interferometer )

RADSI
( relative angle determinable stitching interferometer )



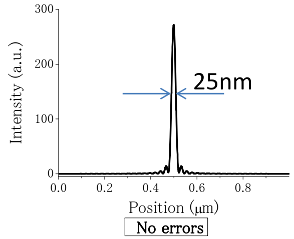




Collaboration with Osaka Univ., JTEC and SPring-8

H. Ohashi et al., Proc. Of SPIE **6704**, 670405-1 (2007).

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

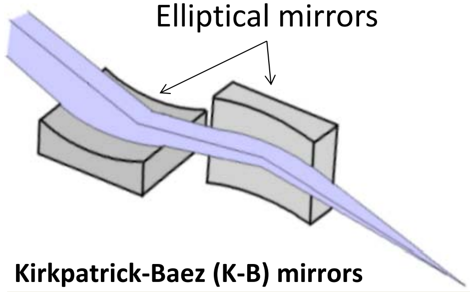
*Necessity is the mother of invention.*




*Tailoring x-rays*
*to application*
↓
<u>X-ray mirrors</u>
design, errors, metrology
& alignment



# Introduction of KB mirrors




In 1948, P. Kirkpatrick and A. V. Baez proposed the focusing optical system.

P. Kirkpatrick and A. V. Baez, "Formation of Optical Images by X-Rays", J. Opt. Soc. Am. **38**, 766 (1948).

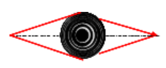
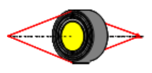
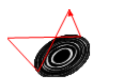
**Advantages**
- Large acceptable aperture and High efficiency
- No chromatic aberration
- Long working distance

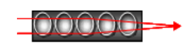
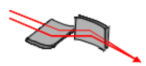
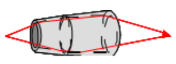
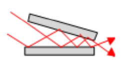
} *Suitable for x-ray nano-probe*

**Disadvantages**
- <u>Difficulty in mirror alignments</u>
- <u>Difficulty in mirror fabrications</u>
- Large system



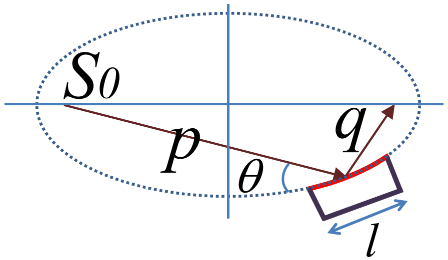
# Overview of x-ray focusing devices

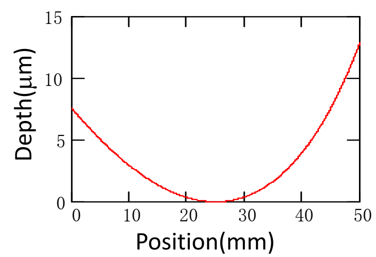
| Diffraction | focus size, focal length [energy] | energy range | aberration -coma -chromatic -figure error |
|---|---|---|---|
|  Fresnel Zone Plate | 12 nm, f = 0.16 mm [0.7 keV], 30 nm, f = 8 cm [8 keV] | soft x-ray hard x-ray | -coma small -chromatic exist -figure error small |
|  Sputter sliced FZP | 0.3 μm, f = 22 cm [12.4 keV], 0.5 μm, f = 90 cm [100 keV] | 8-100 keV | -coma small -chromatic exist -figure error large→small |
|  Bragg FZP | 2.4 μm, f = 70 cm [13.3 keV] | mainly hard x-ray | -coma small -chromatic exist -figure error small |
|  Multilayer Laue Lens | 16 nm(1D), f = 2.6 mm [19.5 keV], 25nm×40nm, f=2.6mm,4.7mm [19.5 keV] | mainly hard x-ray | -coma large -chromatic exist -figure error small |

| Refraction | focus size, focal length [energy] | energy range | aberration -coma -chromatic -figure error |
|---|---|---|---|
|  Pressed Lens | 1.5 μm, f = 80 cm [18.4 keV], 1.6 μm, f = 1.3 m [15 keV] | mainly hard x-ray | -coma small -chromatic exist -figure error large |
|  Etching Lens | 47nm×55nm, f = 1cm, 2cm [21 keV] | mainly hard x-ray | -coma small -chromatic exist -figure error small |
| **Reflection** | | | |
|  Kirkpatrick-Baez Mirror | 36nm×48nm, f=15cm,25cm [15 keV], 7 nm(1D), f=7.5cm [20 keV] | soft x-ray hard x-ray | -coma large -chromatic not exist -figure error small |
|  Wolter Mirror | 0.7 μm, f = 35 cm [9 keV] | <10 keV | -coma small -chromatic not exist -figure error large |
|  X-ray Waveguide | 95 nm, [10 keV] | soft x-ray hard x-ray | -coma large -chromatic not exist -figure error large |

# *How small is x-ray focused ?*

For example, by elliptical mirror




<u>Geometrical size</u>

$$d_G = \frac{q}{p} \times S_0$$

<u>Diffraction limited size</u>(FWHM)

$$d_{DL} = \lambda \times \frac{0.88q}{l\sin(\theta)}$$

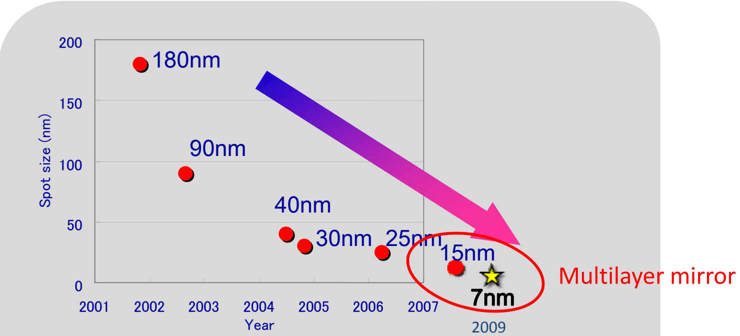
$p = 975m, q = 50mm, \theta = 3mrad, l = 50mm, \lambda = 0.083\,nm, S_0 = 100\,\mu m$

Mag. = 1 / 19500 !

$$d_G = 5nm < d_{DL} = 25nm$$

*<u>The opening of the mirror restricts the focused size even if magnification is large.</u>*

# Nano-focusing by KB mirror History since the century




World Record of Spot Size Focused by KB optics

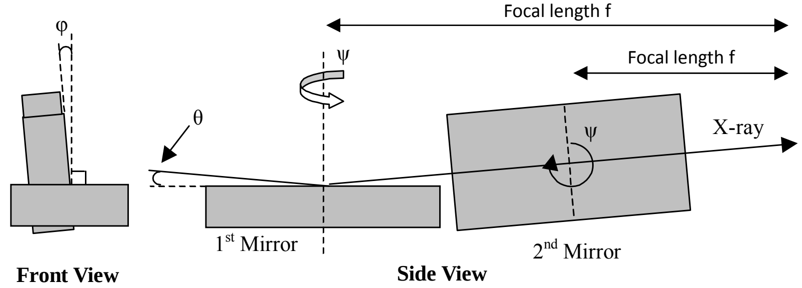
World Record of spot size is **7** nm (by Osaka Univ., in 2009 *).

Routinely obtained spot size is up to **30** nm.

Ref * : H. Mimura et al., "Breaking the 10 nm barrier in hard-X-ray focusing", Nature Physics **6**, 122 (2010).



# Difficulty in mirror alignments

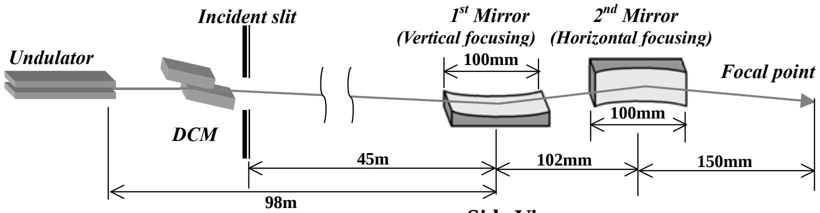



Positioning two mirrors is difficult because there are at least 7 degree of freedom.

It is difficult to use KB mirrors.



# KB optics installed in BL29XU-L



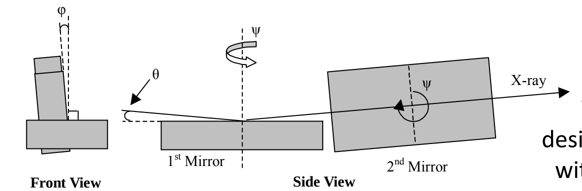

Side View

| | 1st Mirror | 2nd Mirror |
|---|---|---|
| Glancing angle (mrad) | 3.80 | 3.60 |
| Mirror length (mm) | 100 | 100 |
| Mirror aperture (μm) | 382 | 365 |
| Focal length (mm) | 252 | 150 |
| Demagnification | 189 | 318 |
| Numerical aperture | $0.75\times10^{-3}$ | $1.20\times10^{-3}$ |
| Coefficient *a* of elliptic function (mm) | $23.876 \times 10^3$ | $23.825 \times 10^3$ |
| Coefficient *b* of elliptic function (mm) | 13.147 | 9.609 |
| Diffraction limited focal size (nm, FWHM) | 48 | 29 |

Ref :H. Mimura, H. Yumoto, K. Yamauchi et.al, Appl. Phys. Lett. **90**, 051903 (2007).

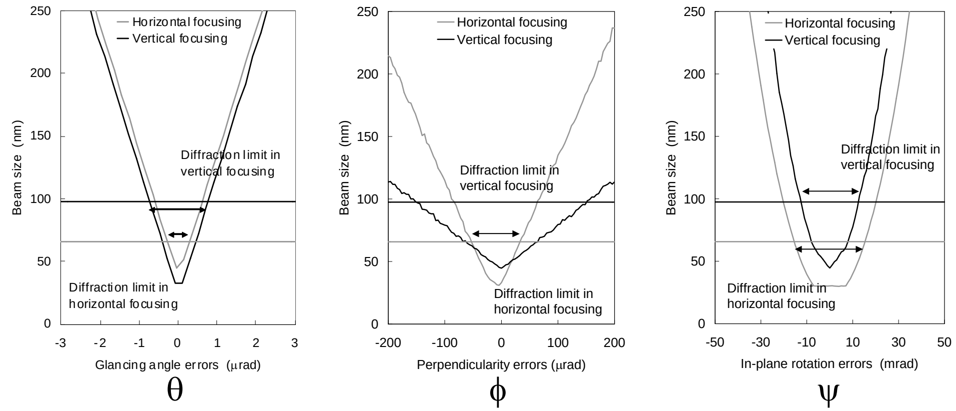


# Tolerance limits of mirror alignments




Severe positioning of two mirrors is required.

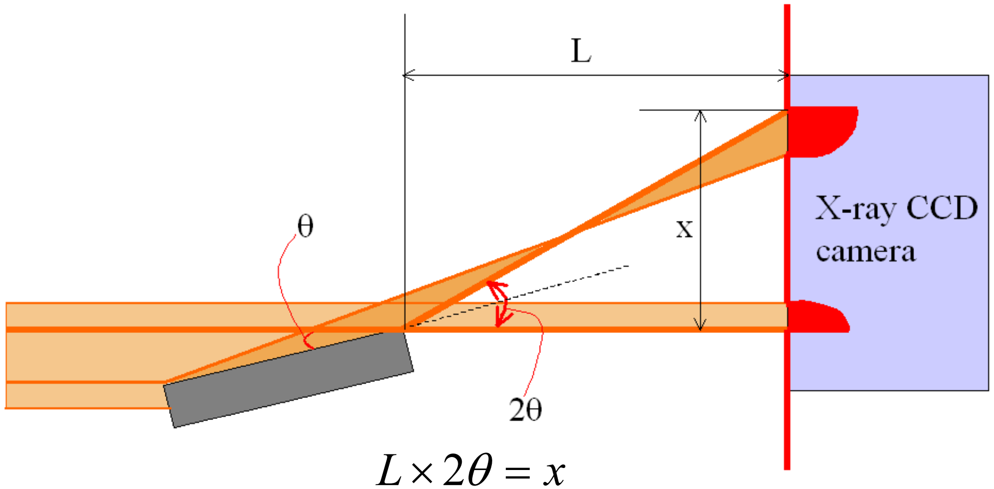
The manipulator should be designed for these freedom of axis with the resolution & the range.




***Freedom of axis, Resolution, range***

Ref: S. Matsuyama, H. Mimura, H. Yumoto et al., "Development of mirror manipulator for hard-x-ray nanofocusing at sub-50-nm level", Rev. Sci. Instrum. **77**, 093107 (2006).

# Image on X-ray CCD camera

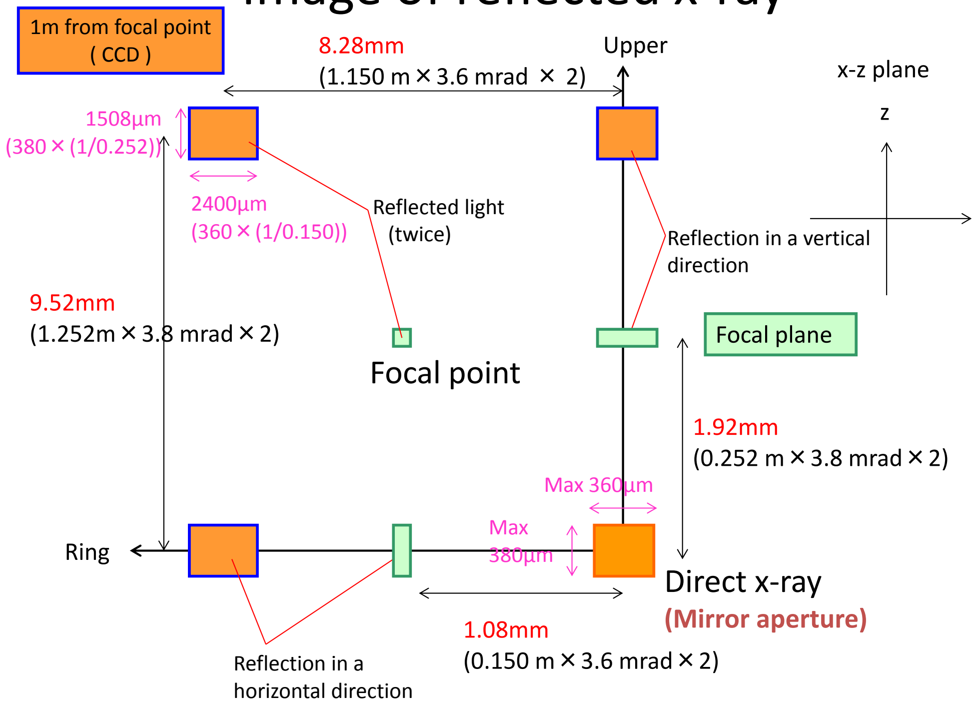



$$L \times 2\theta = x$$

$$\theta = \frac{x}{2L}$$

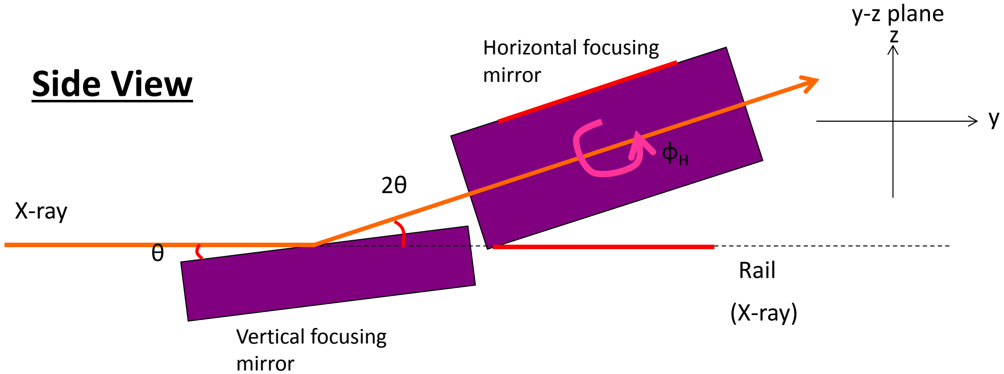


# Image of reflected x-ray






# Alignment of in-plane rotation (Horizontal focusing mirror)




θ: 3.8mrad→ 2θ: 7.6mrad

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



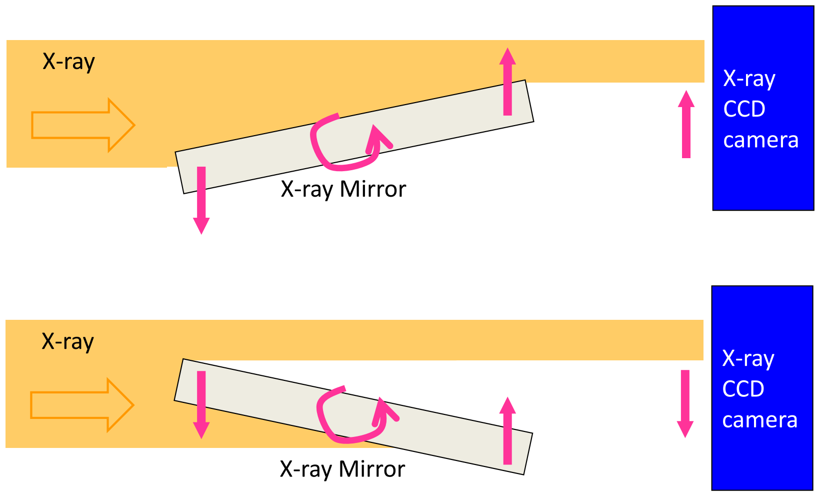
# Alignment of incident angle

- **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*.

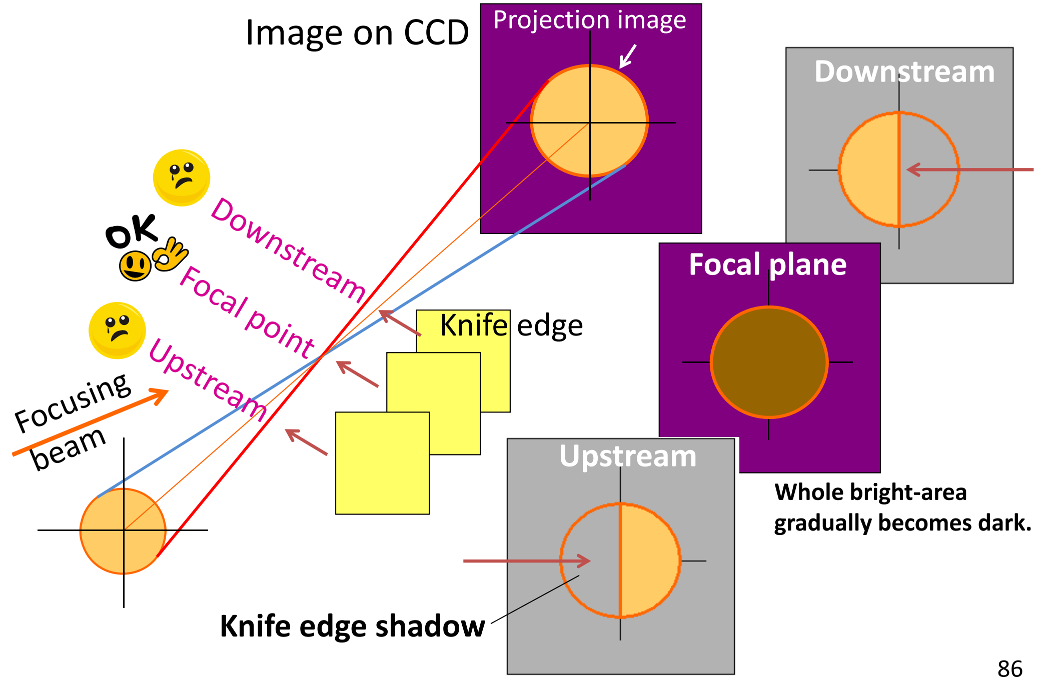
*Precise adjustment of the glancing angle and focal distance is performed until the best focusing is achieved, while monitoring the intensity profile.*

# Alignment of incident angle





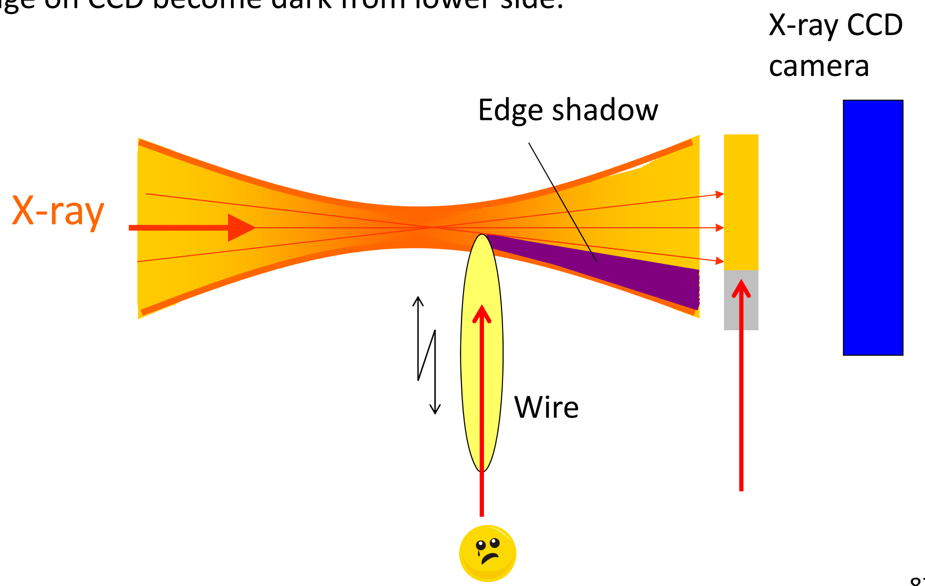

# Foucault test






# Foucault test 1

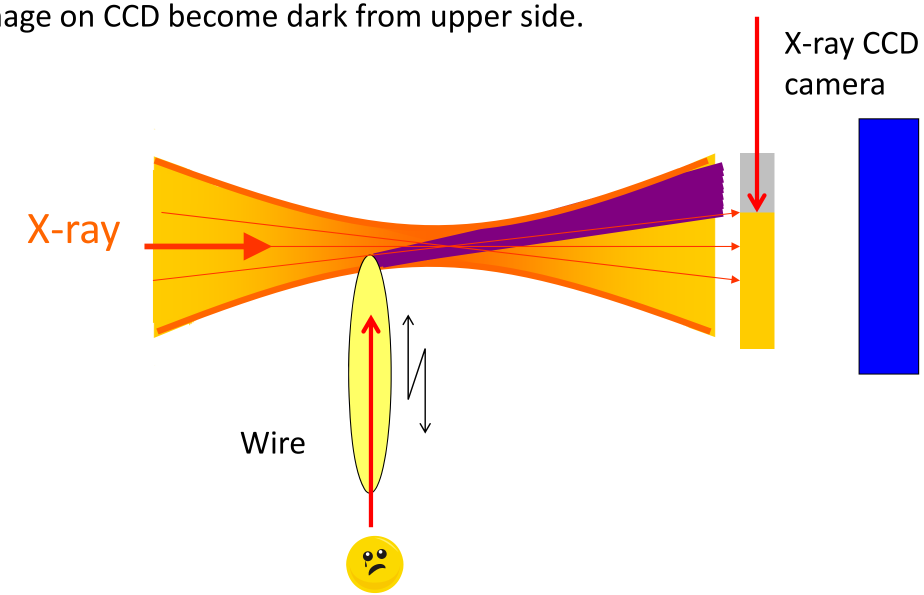
Wire is at downstream of focal point.
Image on CCD become dark from lower side.





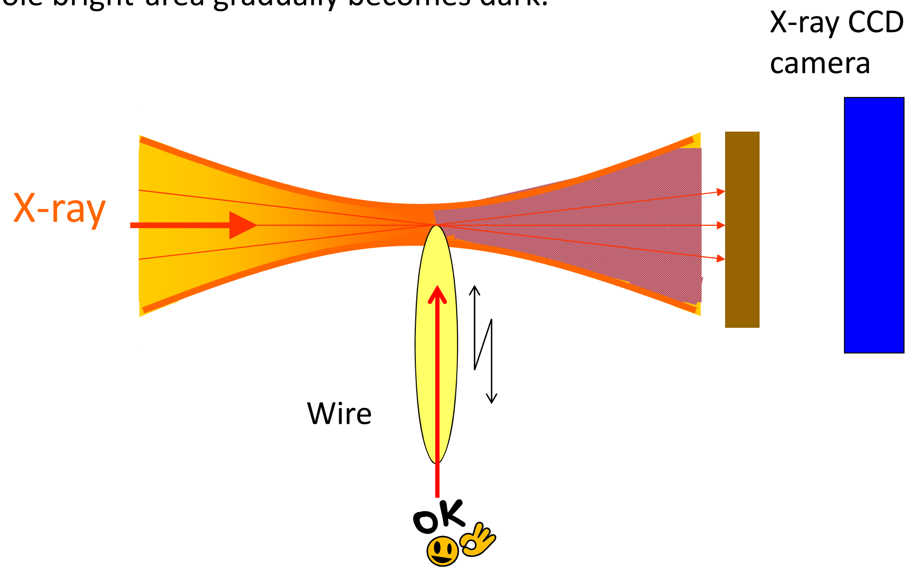

# Foucault test 2

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



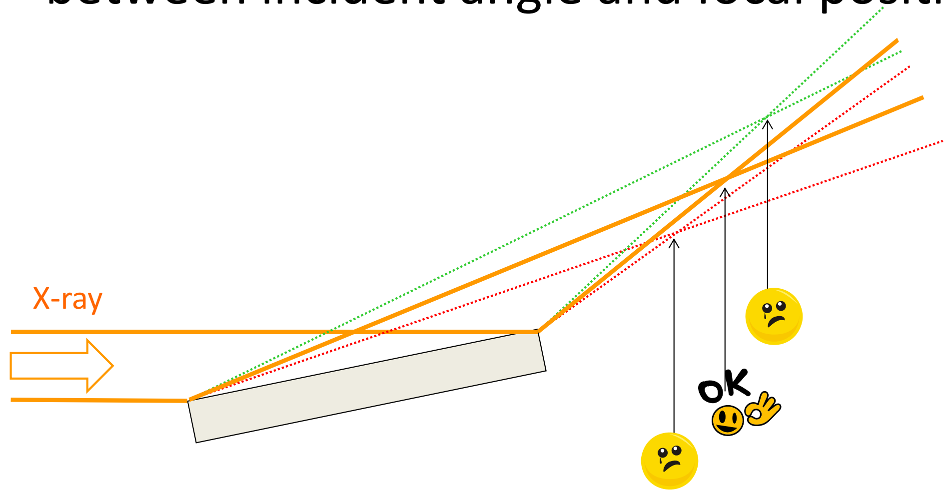
# Foucault test 3

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






# Relationship between incident angle and focal position

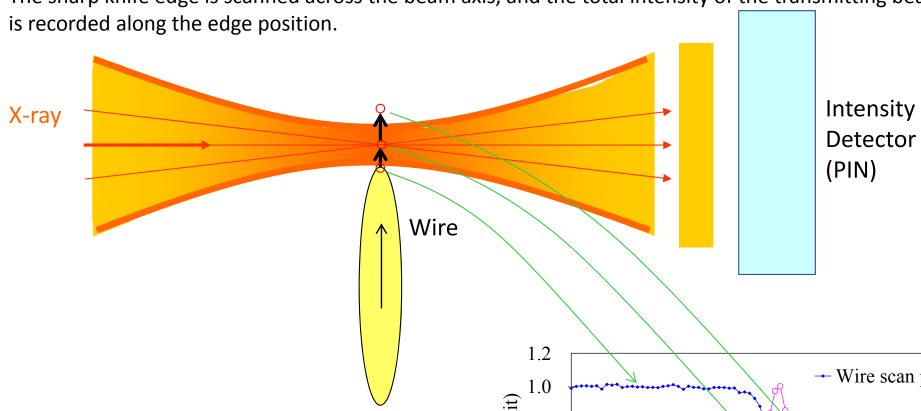



**Incident angle→Large ⇒ Focal point → downstream**
**Incident angle→Small ⇒ Focal point → upstream**

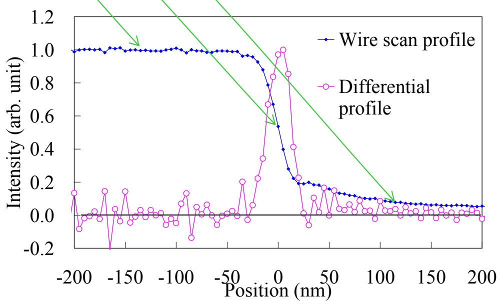


# Wire (Knife-edge) scan method for measuring beam profiles

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



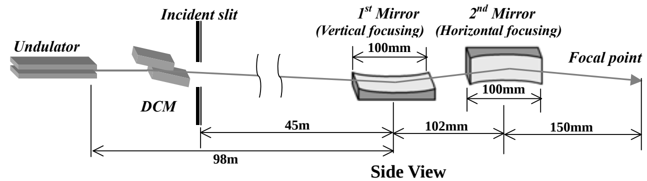

The line-spread function of the focused beam was derived from the numerical differential of the measured knife-edge scan profiles.





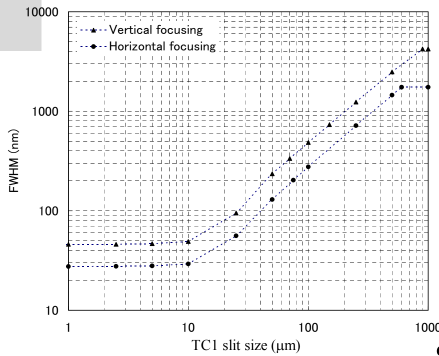

# Relationship between Beam size and Source size

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

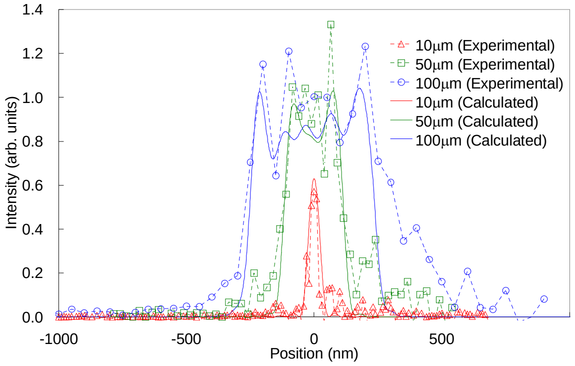



Beam size = Source size / M (M: demagnification)
AND
Beam size ≥ Diffraction limit

Beam size is selectable for each application.

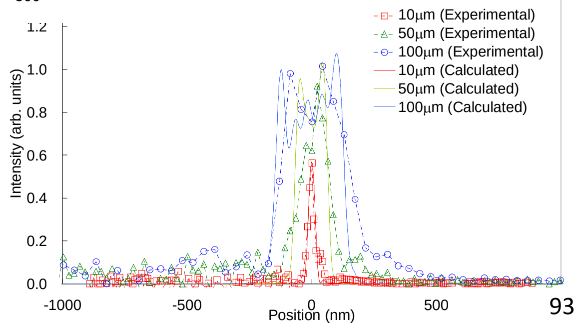


# Relationship between Beam size and Source size



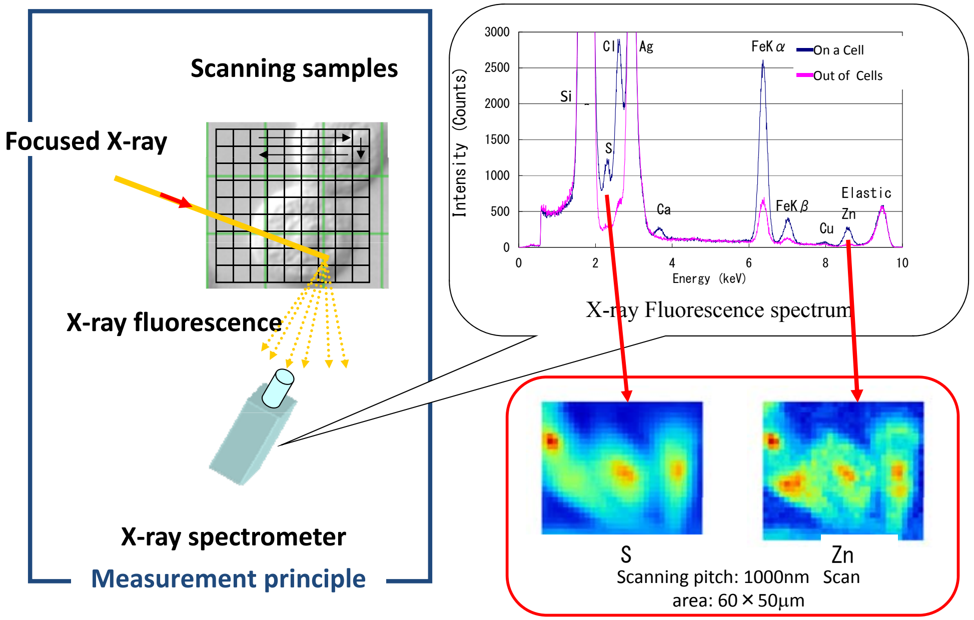

Vertical focusing

Horizontal focusing






# Scanning X-ray Fluorescence Microscope: SXFM




Ref: M. Shimura et al., "Element array by scanning X-ray fluorescence microscopy after cis-diamminedichloro-platinum(II) treatment", Cancer research **65**, 4998 (2005).



# 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

4. *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.*

5. *To consider the alignment*

   The freedom, resolution and range of the manipulator



# Key issues for the beamline design

***Key issues***

***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

*The higher, the better ?*
*The smaller, the better ?*
*More is NOT always better !*
***Simplify the property.***
***Get your priorities right.***

– Time schedule
– Human resources
– Available budget, space, technical level
– Maintenance for keeping performance
– Lifetime of the BL ( hardware and application )

***What to include or not ?***
***What to develop or not ?***

***Design components***

- End station
- Sample environment ( pressure, temperature, magnetic field…)
- Detector, data processing … ( automation )

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

*Stability enough to measure*

- 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
- Environments ( temperature, vibration… )

*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 …*



# Acknowledgment

*S. Takahashi* ( front end ), *H. Aoyagi* (XBPM),
*T. Matsushita* ( interlock ),
*H. Takano, Y. Kohmura, T. Koyama,* ( focusing devices )
*T. Uruga, Y. Senba* ( mirrors ),
*S. Matsuyama, H. Yumoto, H. Mimura, K. Yamauchi*
( ultimate focusing mirror, alignment ),
*C. Morawe* ( multilayer ) ESRF
*S. Goto and T. Ishikawa*



*Thank you for your kind attention.*

***Enjoy Cheiron school***
***Enjoy SPring-8***
***and***
***Enjoy Japan!***