Cheiron school 2014 , 27th Sep. 2014, SPring-8
X-ray beamline design Ⅱ

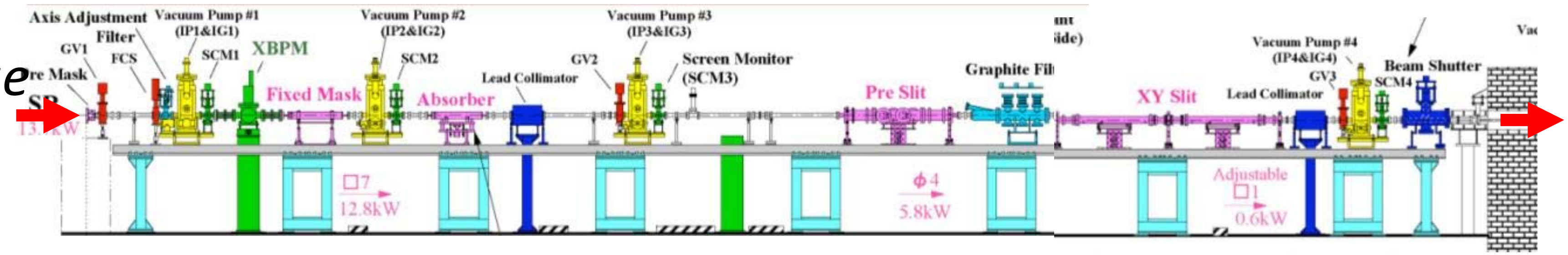
Optics Engineering for x-ray beamline design

Haruhiko Ohashi
JASRI / SPring-8

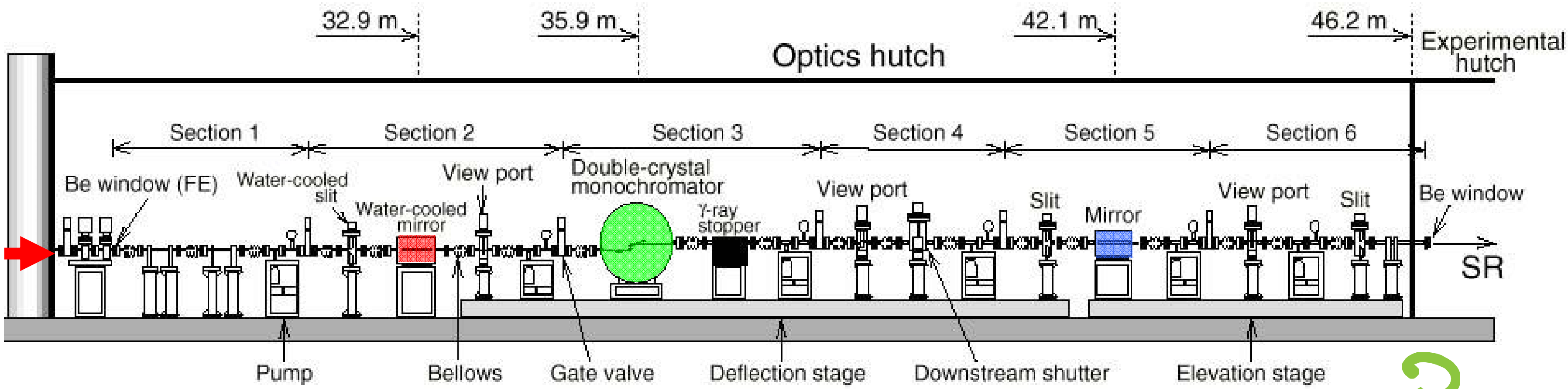
Introduction

"X-ray beamline looks complicated?"

Storage ring

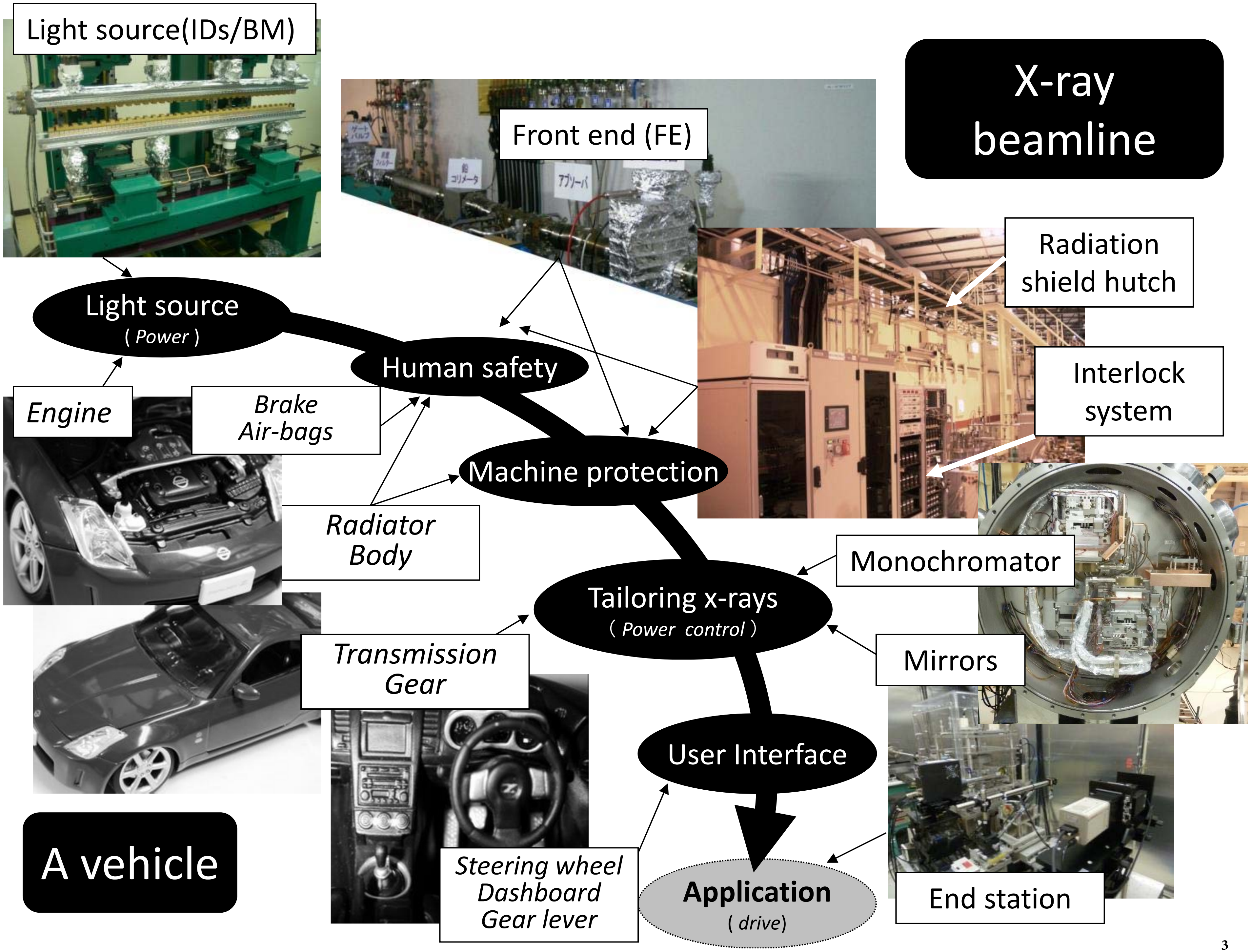


Inside shielding tunnel (front end)



Outside shielding tunnel (optics hutch)

What function of each component ?


X-ray beamline
Light source(IDs/BM)
Front end (FE)
Radiation shield hutch
Interlock system
Light source
(Power)
Human safety
Machine protection
Engine
Brake
Air-bags
Radiator
Body
Monochromator
Tailoring x-rays
(Power control)
Mirrors
Transmission
Gear
User Interface
Steering wheel
Dashboard
Gear lever
Application
(drive)
End station
A vehicle

Key issues for the beamline design

Key issues	***Design components***

Applications at the BL (scientific strategy, concept)

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

Photon beam properties at sample

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

Stability
(long , short term)

Priority ?

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

Human Safety & Machine protection

Protection from radiation hazard to health
Protection from radiation damage to instruments

- ✓ **Radiation shielding hutch …**
- ✓ **Interlock system**
- ✓ **Beam shutter…**

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

Utilities

- ✓ Electricity, water, air, network, control
- ✓ Environments

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

Management of the beamline construction

Key issues for the beamline design

Key issues	***Design components***
Applications at the BL (scientific strategy, concept)	✓ End station ✓ Sample environment (pressure, temperature, magnetic field...) ✓ Detector, data processing ... (automation)
Photon beam properties at sample ✓ **Photon energy, energy resolution** ✓ **Flux, flux density** ✓ **Beam size** ✓ **Polarization** ✓ **Spatial coherence** ✓ **Time resolution** Stability (long , short term) *Priority ?*	✓ **Light source (ID, BM)** ✓ **Monochromator, higher order suppression...** ✓ **Focusing devices...** ✓ **Polarizer...** ✓ **Window...** ✓ **RF timing, chopper...**

*You have to describe **beam parameters** for experiments.*
Sometimes these requests are competing.

Management of the beamline construction

Key issues for the beamline design

Key issues	Design components

Applications at the BL (scientific strategy, concept)

- ✓ End station
- ✓ Sample environment
- ✓ Detector, data processing …

(pressure, temperature, magnetic field…)
(automation)

Photon beam properties at sample

- ✓ **Photon energy, energy resolution**
- ✓ **Flux, flux density**
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- ✓ **Polarization**
- ✓ **Spatial coherence**
- ✓ **Time resolution**

Stability
(long , short term)

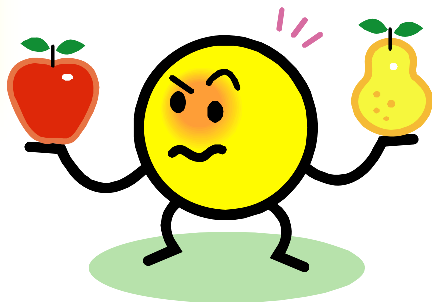
Priority ?

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

*You have to describe **beam parameters** for experiments.*
Sometimes these requests are competing.

↓

*You have to assign **priorities** to the beam performance.*



Management of the beamline construction

Key issues for the beamline design

Key issues	***Design components***

Applications at the BL (scientific strategy, concept)

→ Design components:
- ✓ End station
- ✓ Sample environment (pressure, temperature, magnetic field…)
- ✓ Detector, data processing … (automation)

Photon beam properties at sample

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

Stability
(long , short term)

Priority ?

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

Optics (ex. mirror)

Beam position monitor

Human Safety & Machine protection

Protection from radiation hazard to health
Protection from radiation damage to instruments

→ Design components:
- ✓ **Radiation shielding hutch …**
- ✓ **Interlock system**
- ✓ **Beam shutter…**

Front end

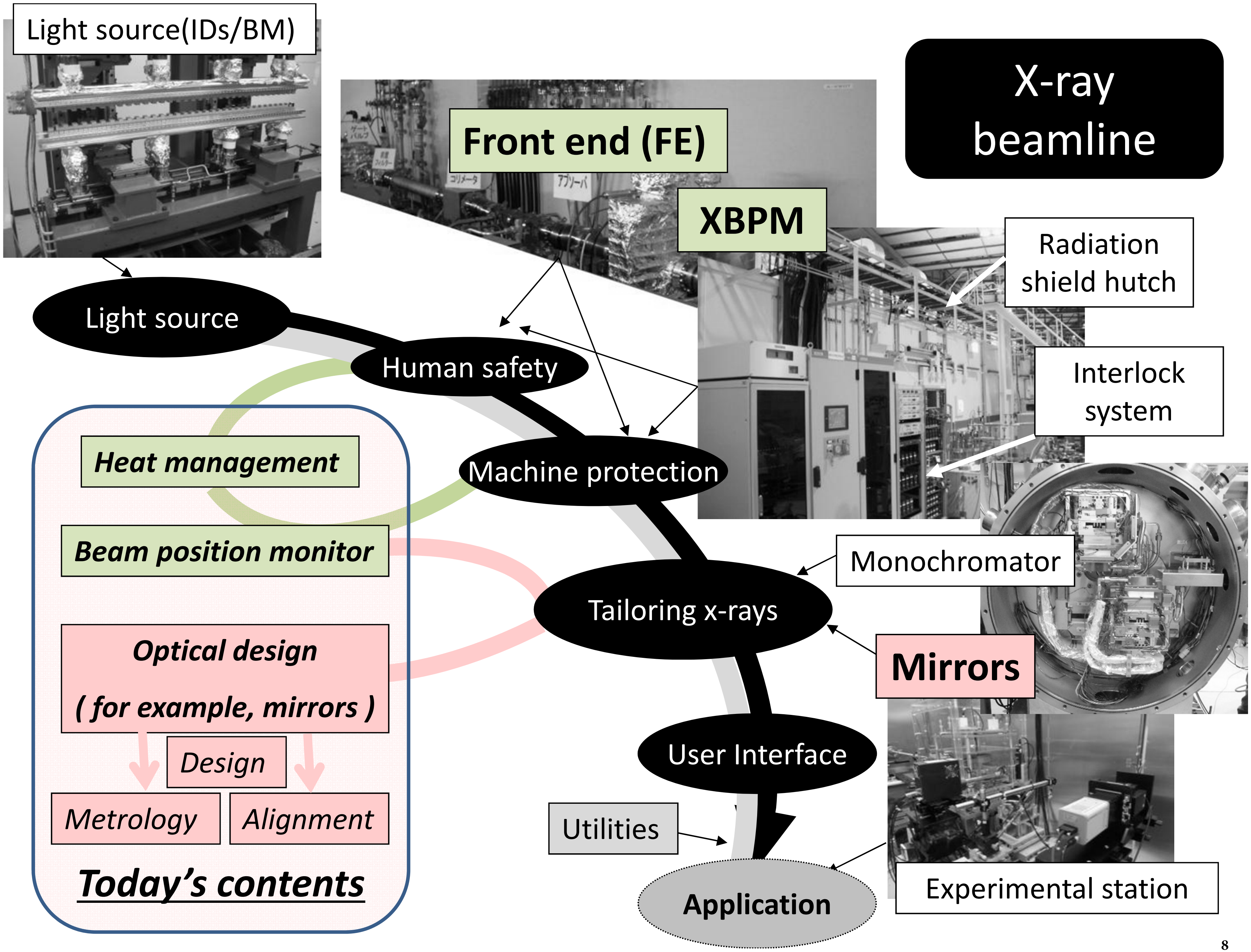
- ✓ **Absorber, FE slit**
- ✓ **Cooling method, cooling system**
- ✓ **Selection of light sources** (power, angular dist.)
- ✓ **Electronics in hutch** (detector, controller …)
- ✓ **Radiation damage** (cable, tube)
- ✓ **Contamination on optics**

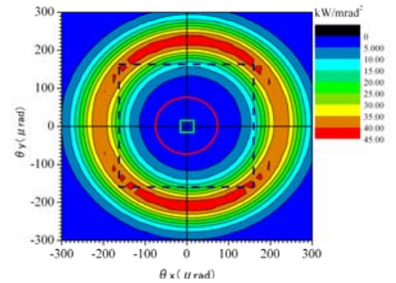
Utilities

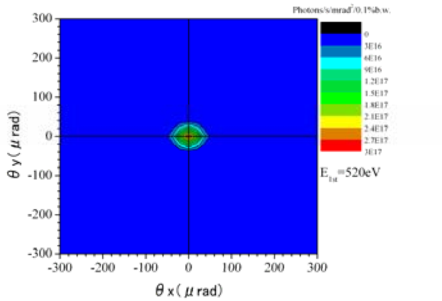
→ Design components:
- ✓ Electricity, water, air, network, control
- ✓ Environments

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

Management of the beamline construction


X-ray beamline
Light source(IDs/BM)
Front end (FE)
XBPM
Radiation shield hutch
Interlock system
Monochromator
Mirrors
Experimental station
Utilities
Light source
Human safety
Machine protection
Tailoring x-rays
User Interface
Application
Heat management
Beam position monitor
Optical design
(for example, mirrors)
Design
Metrology
Alignment
Today's contents





Heat management

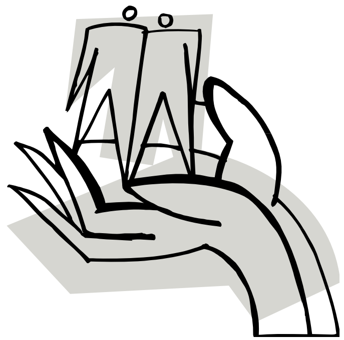
for

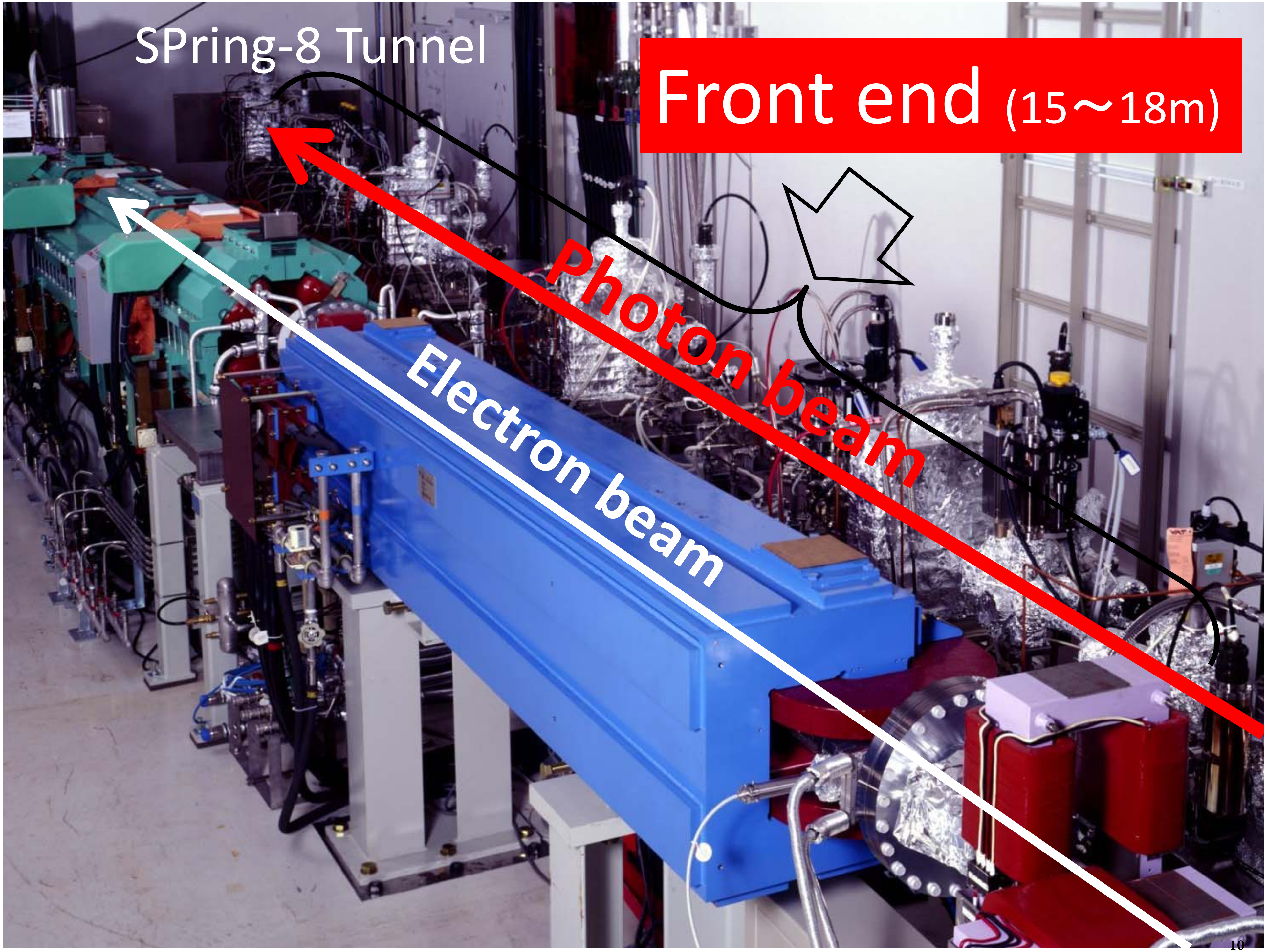
human safety & machine protection

↓

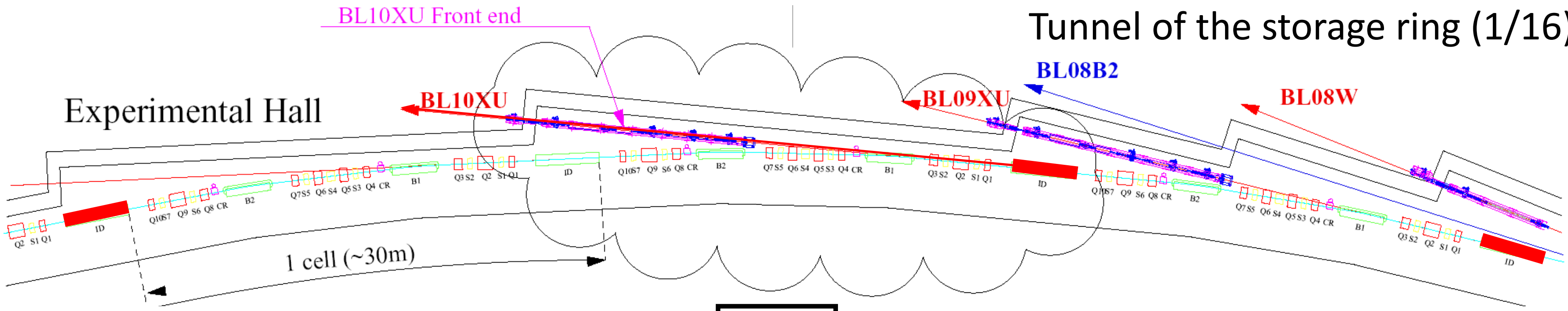
Front end

(FE)




SPring-8 Tunnel
Front end (15～18m)
Photon beam
Electron beam

Schematic Layout inside the SPring-8 Tunnel



Standard
in-vacuum undulator

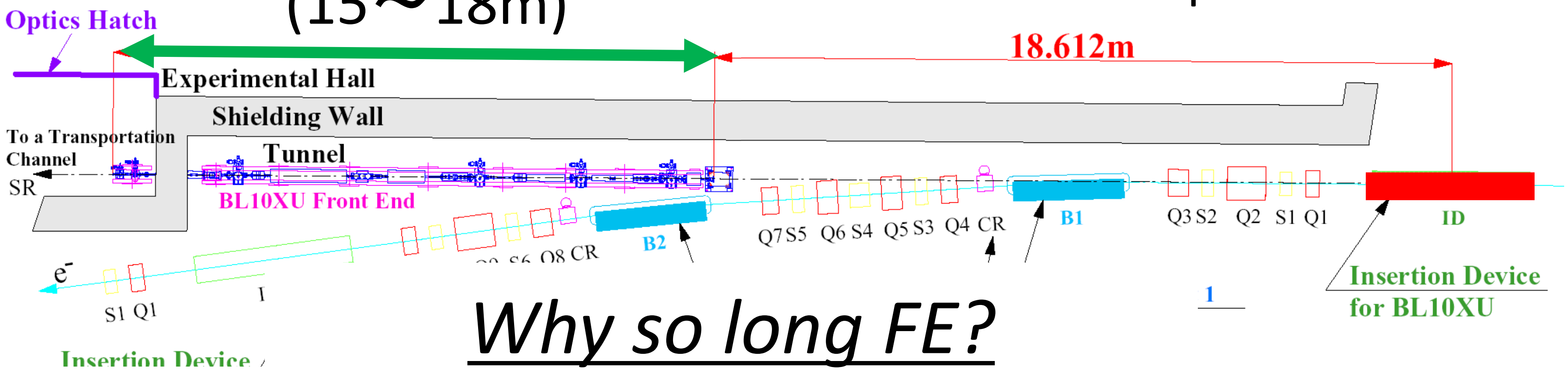
Power density :

500 kW/mrad^2

Total power :   13 kW

Front end (FE)

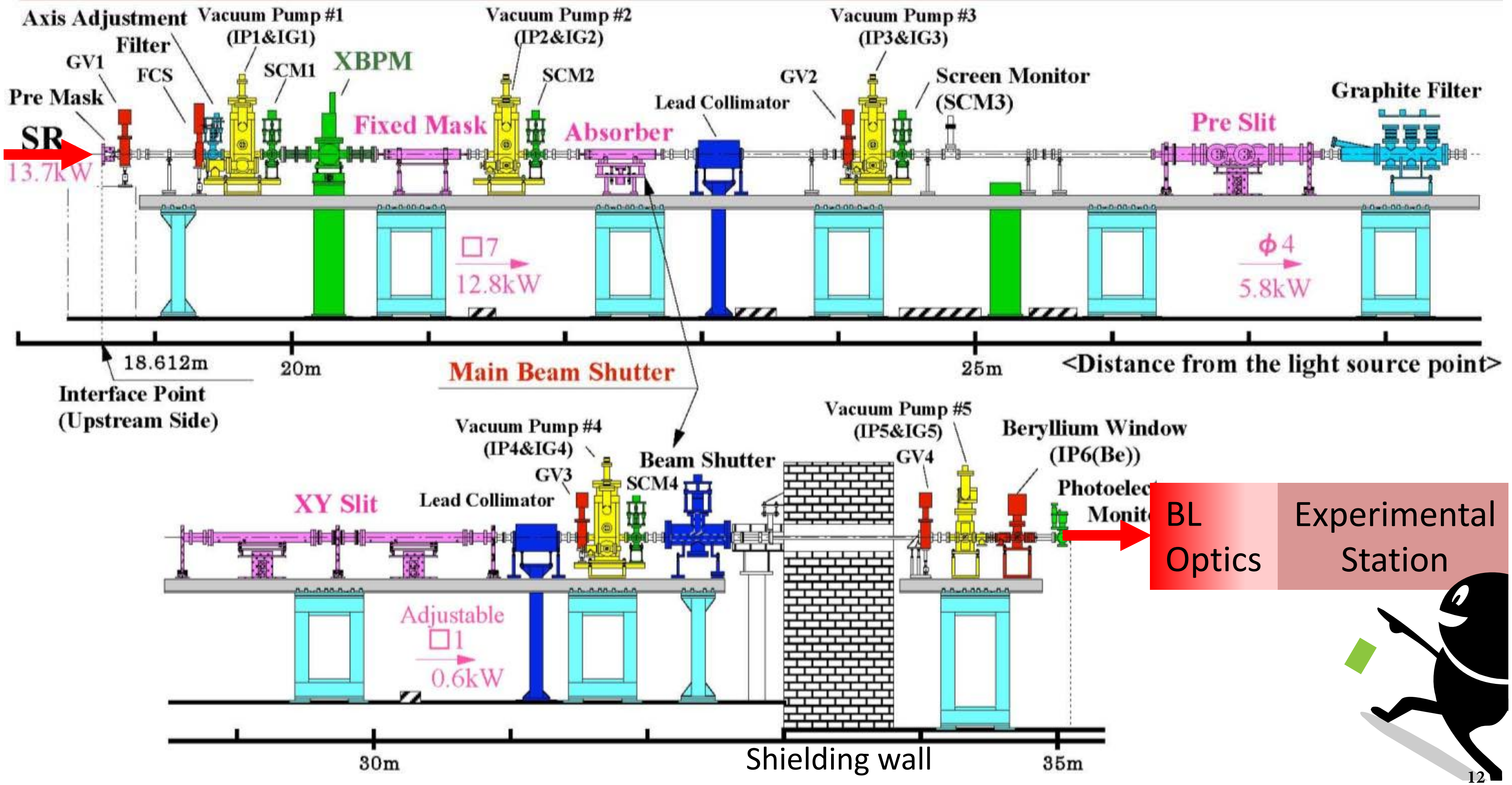
(15～18m)



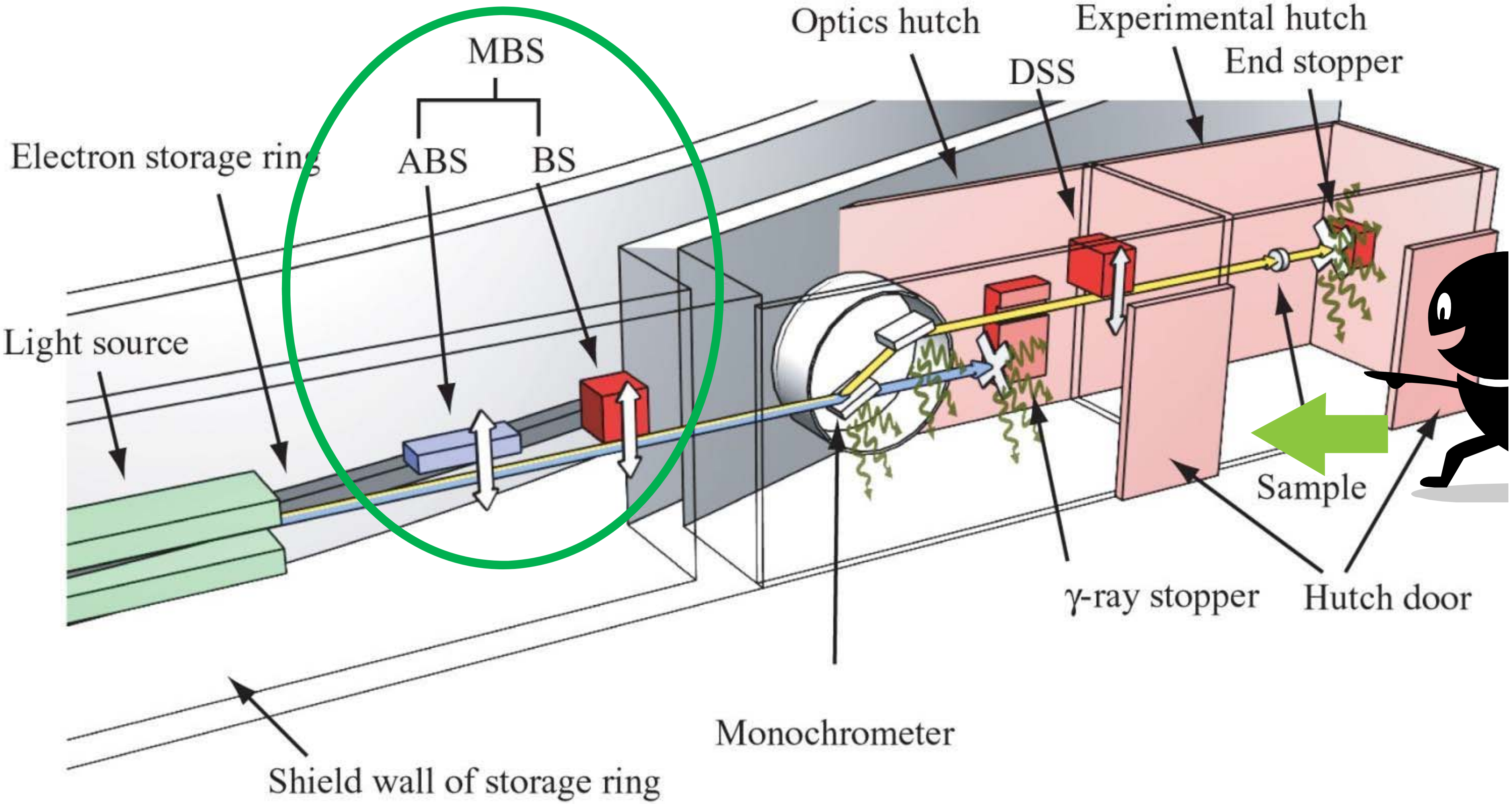
Why so long FE?

Key functions & components of FE

✓ *Shielding **for human safety***	**Beam shutter (BS)**, collimator
✓ *Handling high heat load **for safety***	**Absorber**, masks
✓ *Handling high heat load **for optics***	XY slit, filters
✓ *Monitoring the x-ray beam position*	XBPM (x-ray BPM), SCM (screen monitor)
✓ *Protection of the ring vacuum*	FCS (fast closing shutter), Vacuum system



What's "*Main Beam Shutter*" ?

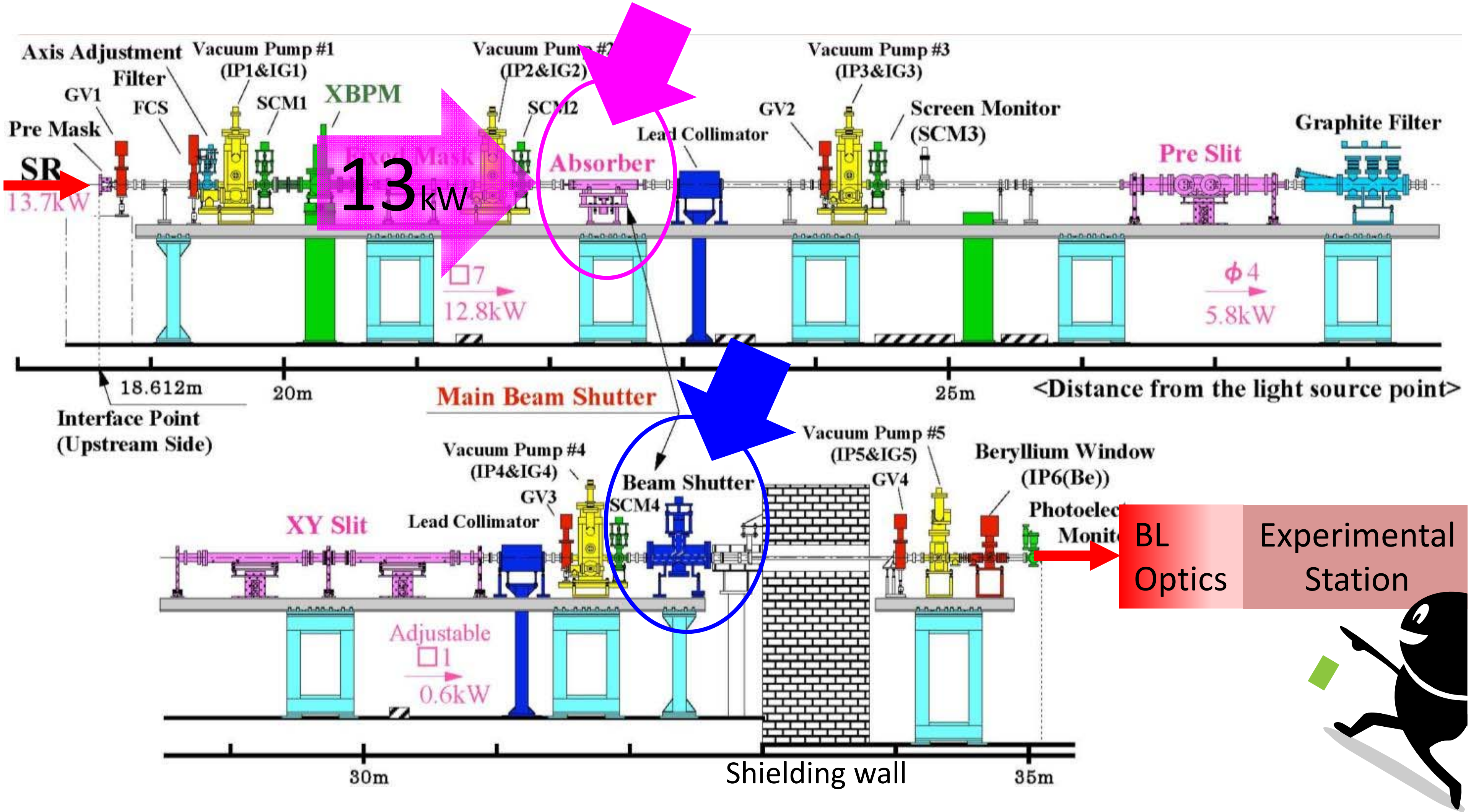


Key functions & components of FE

For safety

- ✓ *Shielding **for human safety***
- ✓ *Handling high heat load **for safety***

Beam shutter (BS), collimator
Absorber, masks



MBS (= ABS + BS) is closed → MBS accepts the incident power form ID.

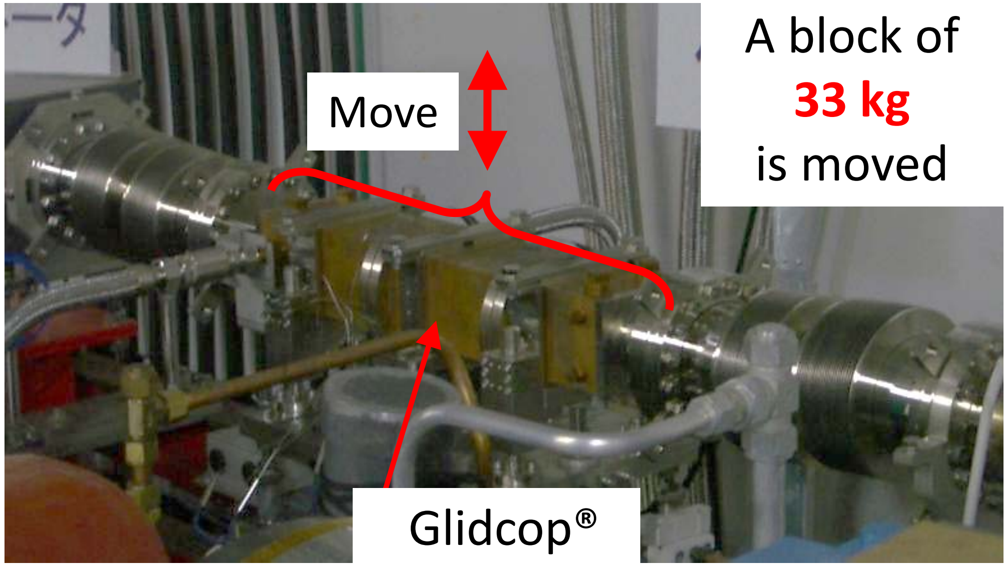
For safety

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

X-ray

Absorber (Abs)

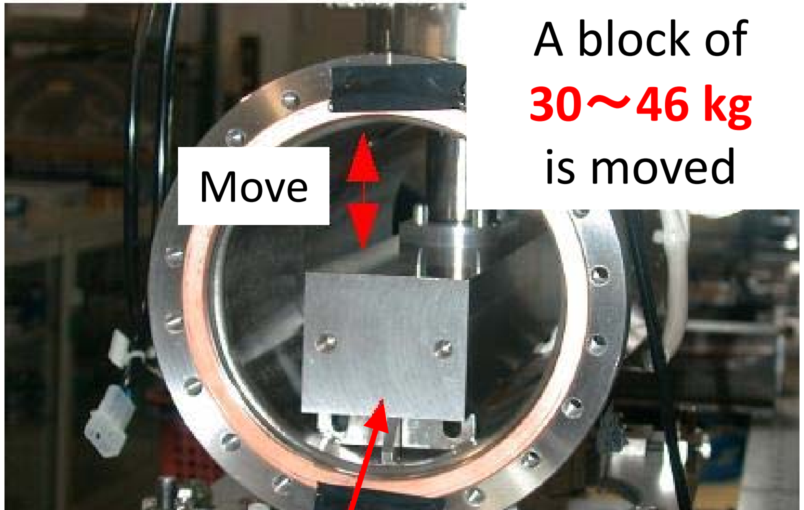
to protect BS from heat load



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

Beam shutter (BS)

to shield you against radiation



Heavy metal (alloy of tungsten)

the thermal conductivity not so high

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

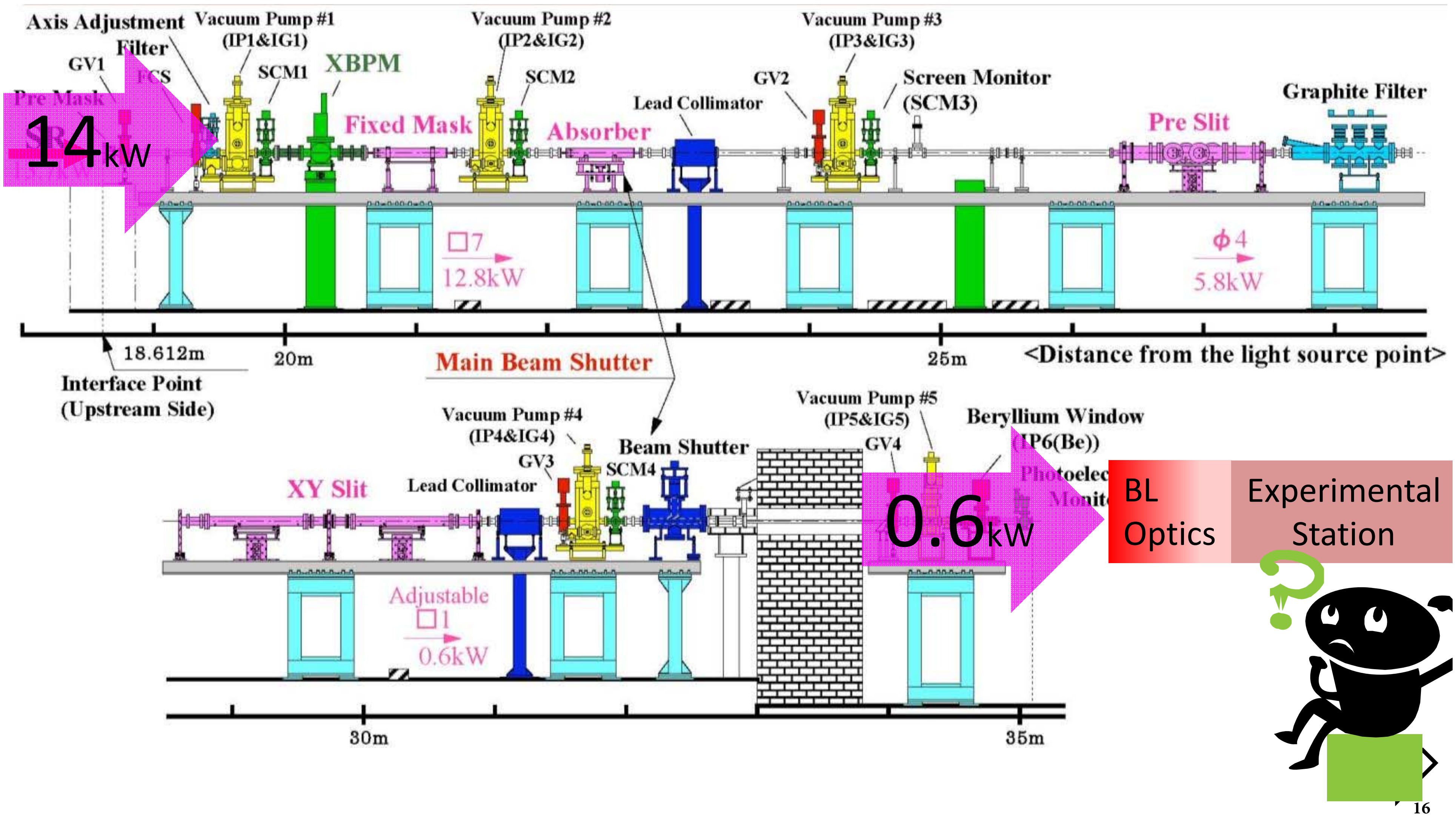
ABS and BS work on ways together to protect us from radiation when we enter the hutch.

*What components remove most "**power**" from ID ?*

For managing heat load

Total power from ID = 14 kW

The power through FE section = 0.6 kW



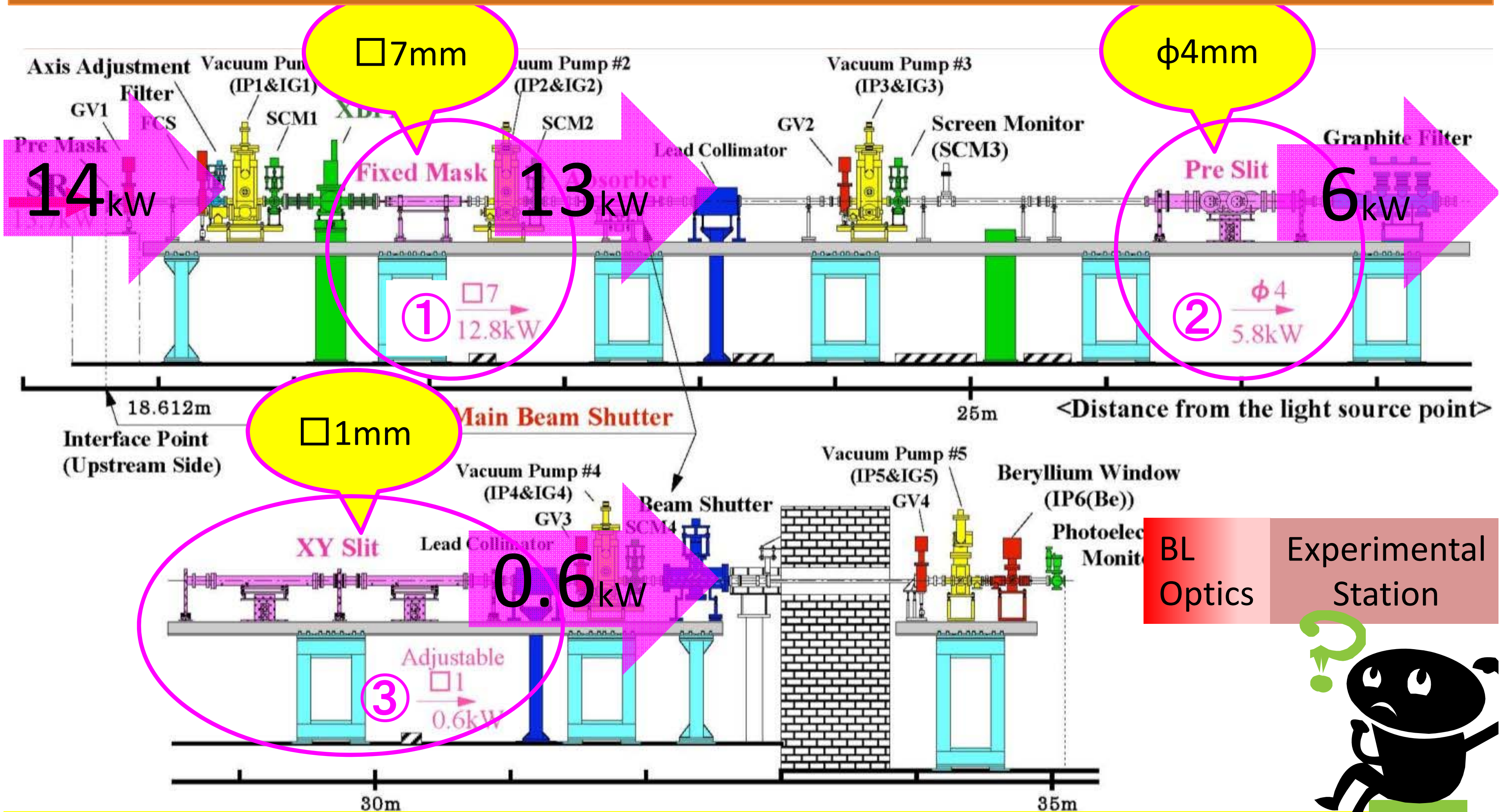
*What components remove most "**power**" from ID ?*

For managing heat load

Absorber, **masks** (to prevent BS from *melting*)

XY slit, filters (to prevent optics from *distorting*)

These components (①, ② and ③) *cut off the power to prevent optics from distorting by heat load.*



*Someone may enlarge opening of XY slit to get more "**flux**" → You can NOT get it!*

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

For managing heat load

Adding a spatial limitation to photon beam,

supplying <u>only a good quality part</u> around the central axis of ID

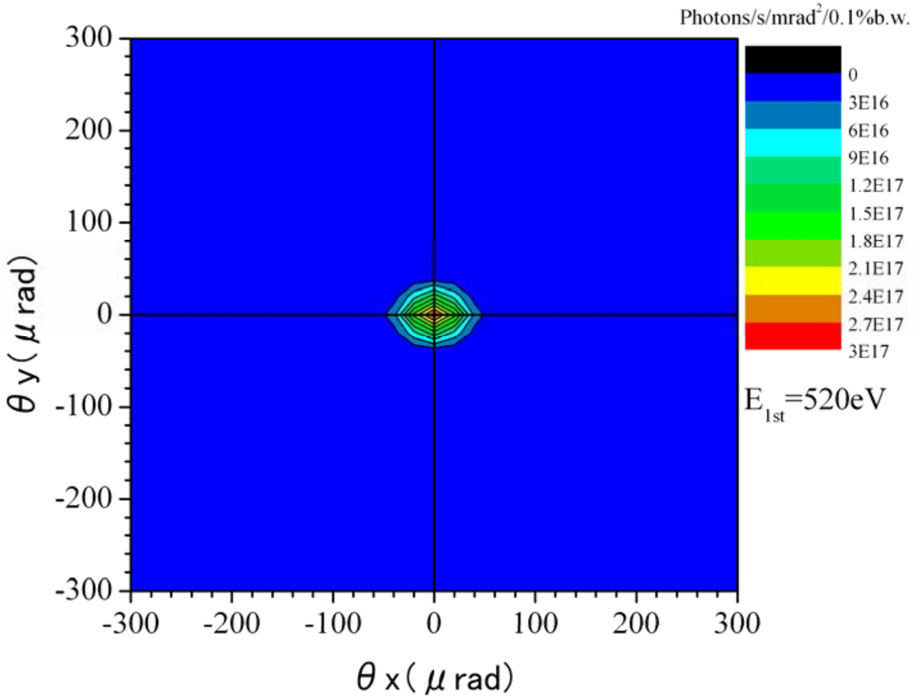
<u>to transport optical system safely and stably</u>.

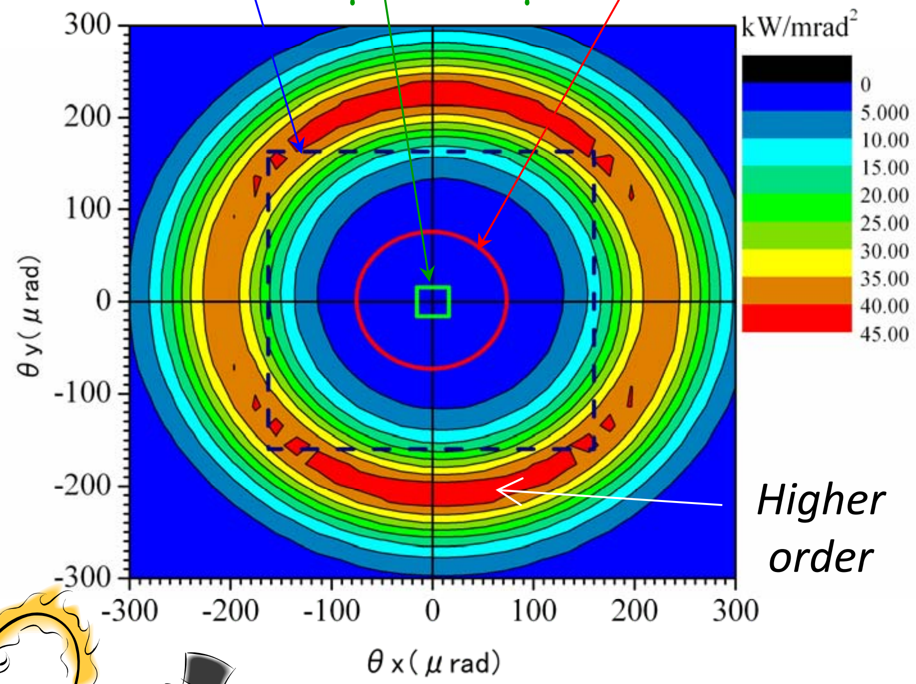
The size of XY slit is set to 1.05mm□.
XY slit is installed ～30m away from ID.

①Fixed Mask Aperture
322μrad x 322μrad

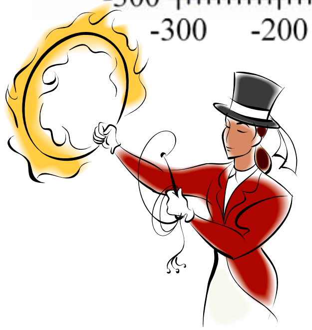
②Pre Slit Aperture
φ152μrad

③XY Slit Aperture
35μrad x 35μrad





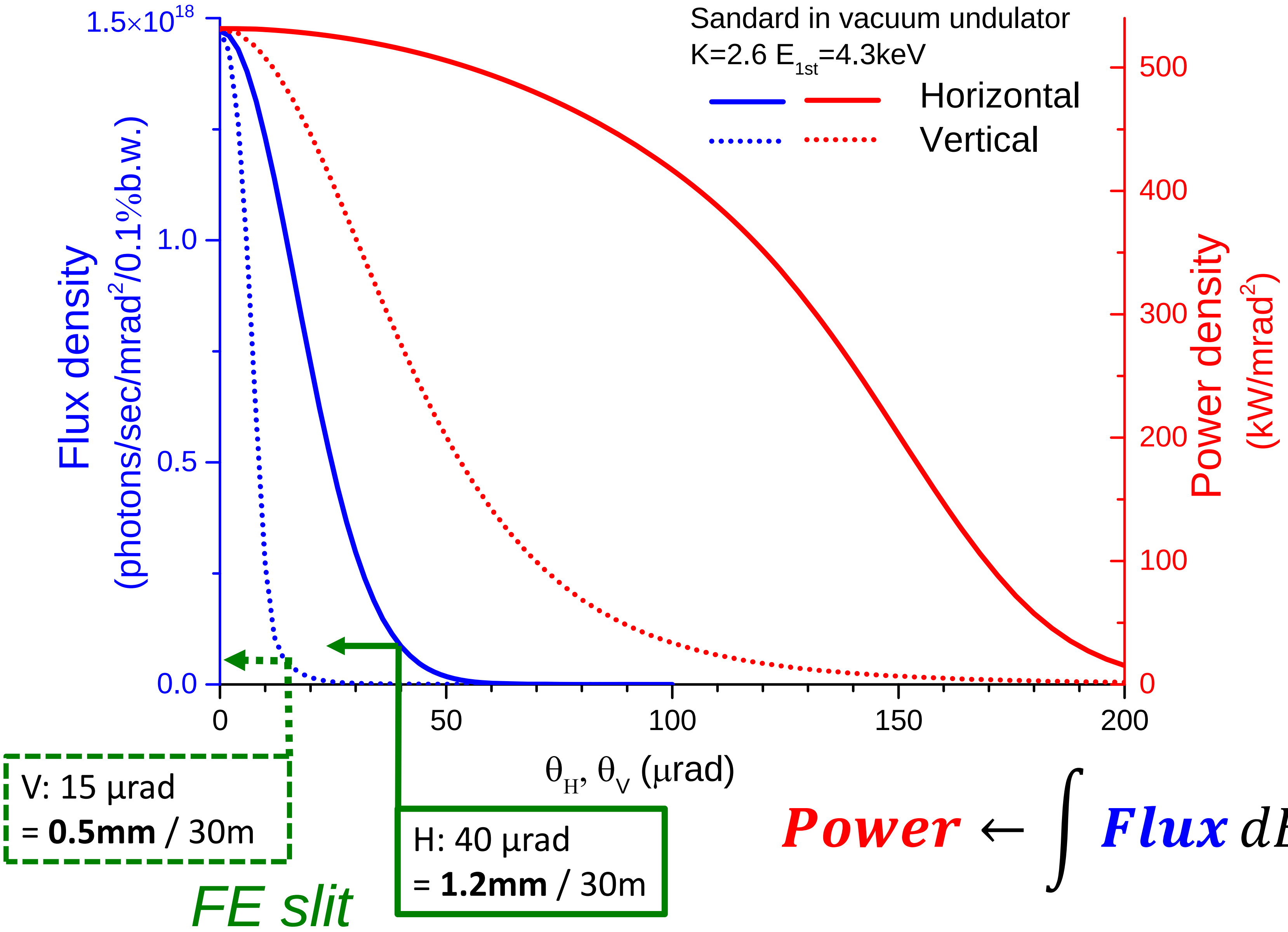
<u>1st harmonic</u>
<u>Flux Density</u>



<u>Power Density</u>

Helical Mode Operation
at BL15XU

Comparison of the **Spatial Distribution** between 1st harmonic Flux density and Power density

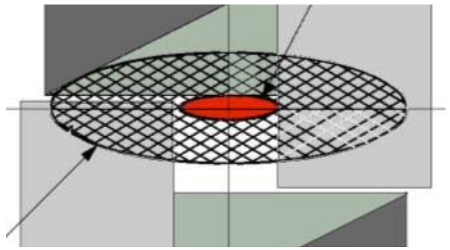


$$\textbf{Power} \leftarrow \int \textbf{Flux}\, dE$$

How to manage high heat load by FE XY slit ?

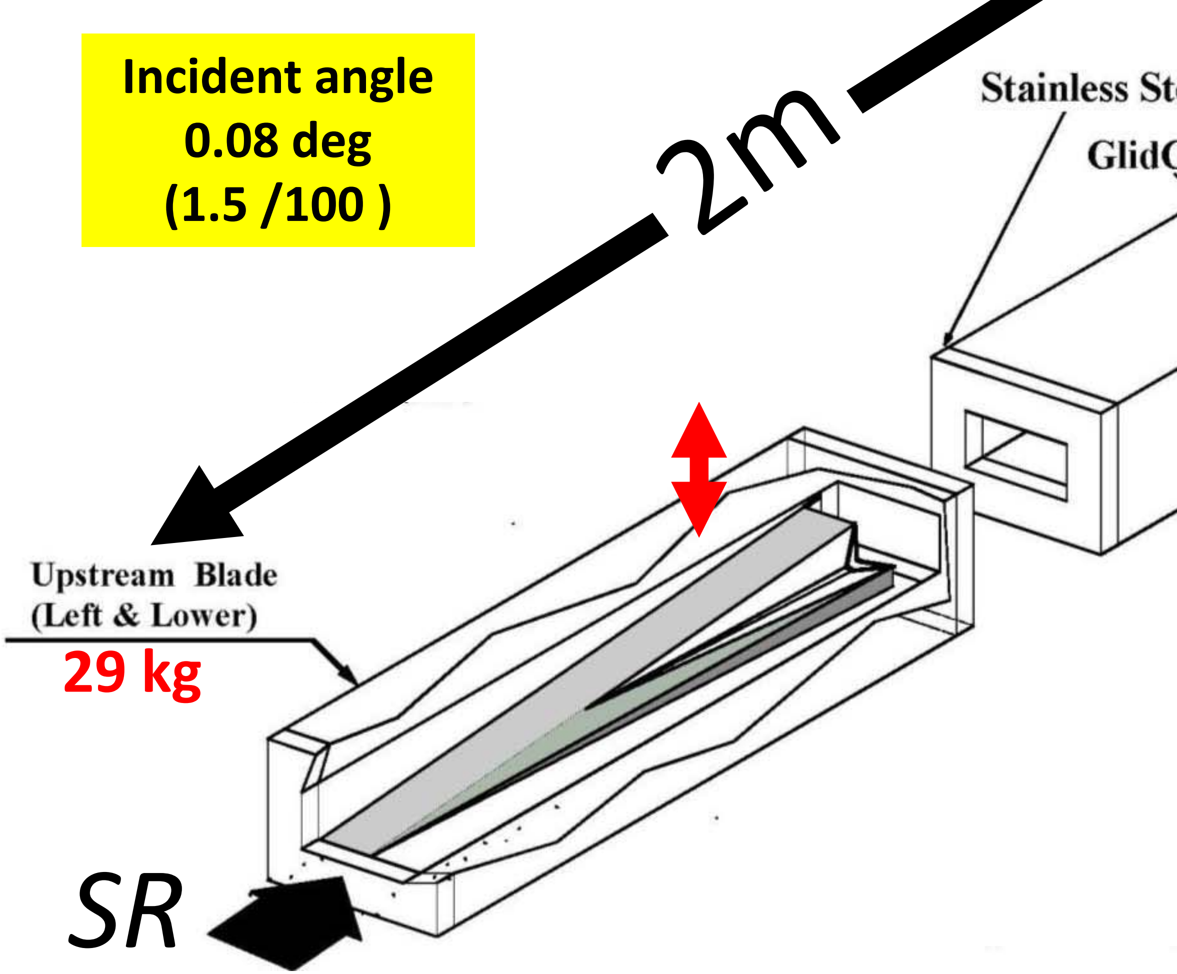
For managing heat load

1st harmonic flux



Spatial distribution of *power*

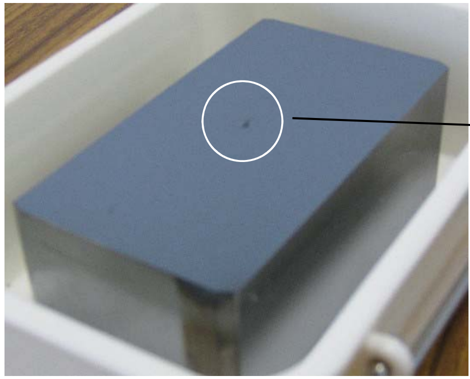
Incident angle 0.08 deg (1.5 /100)

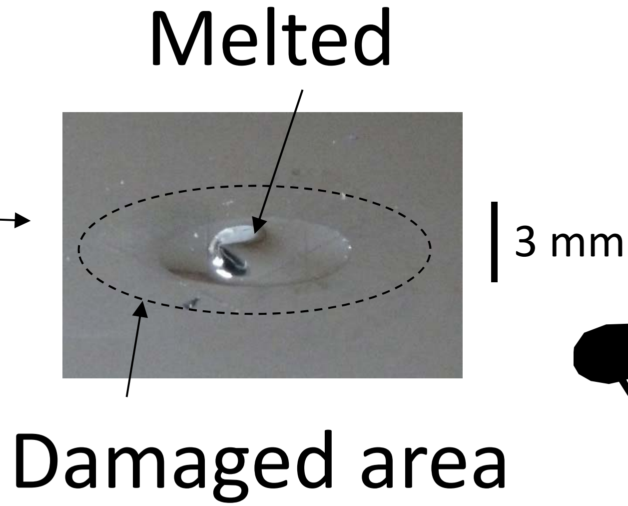


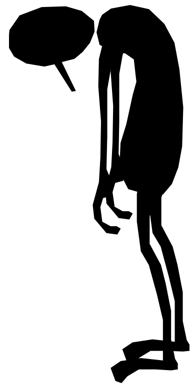
If an optical component is irradiated by too much power ….

One user opened FE slit excessively.

2kW







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

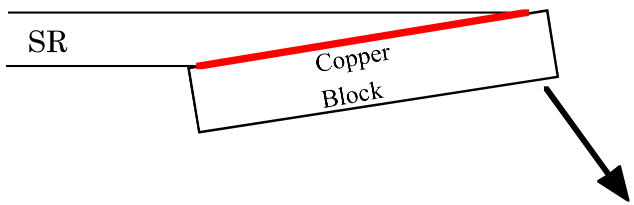
For managing heat load

Handling Technology of high heat load at SPring-8

SPring-8 Standard In-Vacuum Undulator : 13.7kW, 550kW/mrad^2

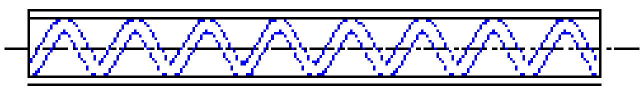
1. Grazed Angle Technology (Mask, Absorber, XY slit)

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



(2) Applying the advanced material => Glid Cop

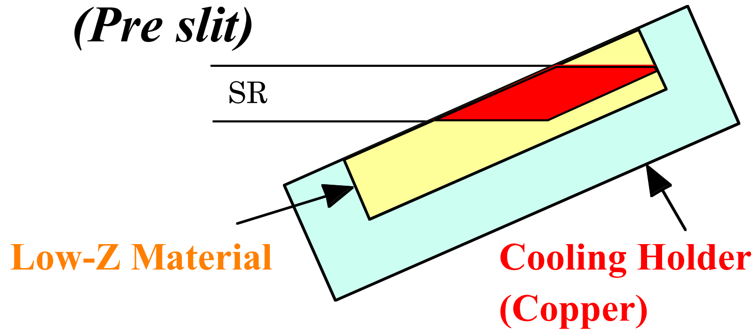
(3) Enhancing the heat transfer coefficient of the cooling channel
=> Copper wire coil (SPring-8)
Copper wire mesh (APS)



→ ～ 10 kW/m

To increase the cooling ability within a more compact space

2. Volumetric Heating Technology (Pre slit)



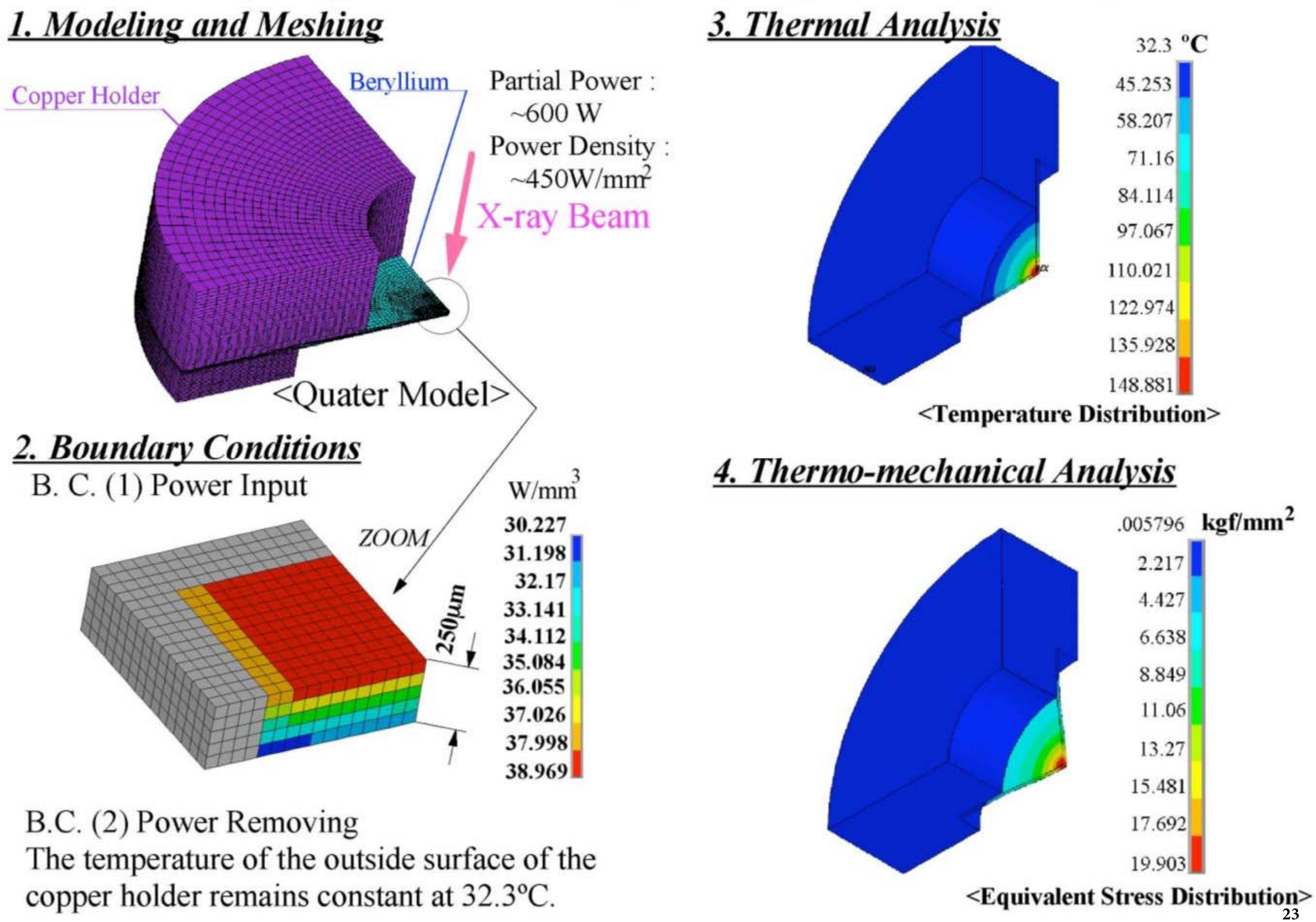
Dissipating high surface heat flux in depth by utilizing a low-Z material, such as graphite or beryllium.

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.

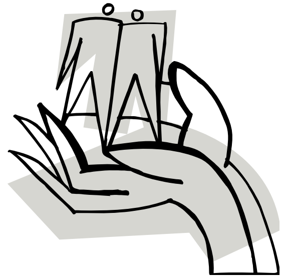
   They have to deal with every mode of ring operation and every mode of beamline activities.

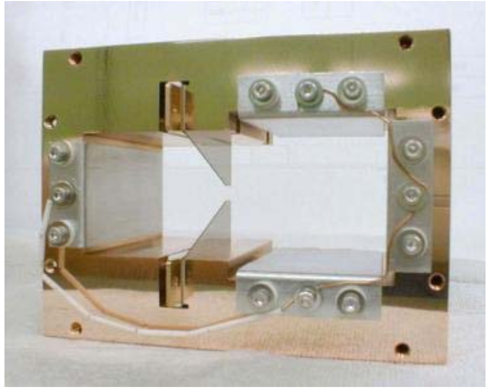
2. *Any troubles in one beamline should not make any negative effect to the other beamlines.*

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

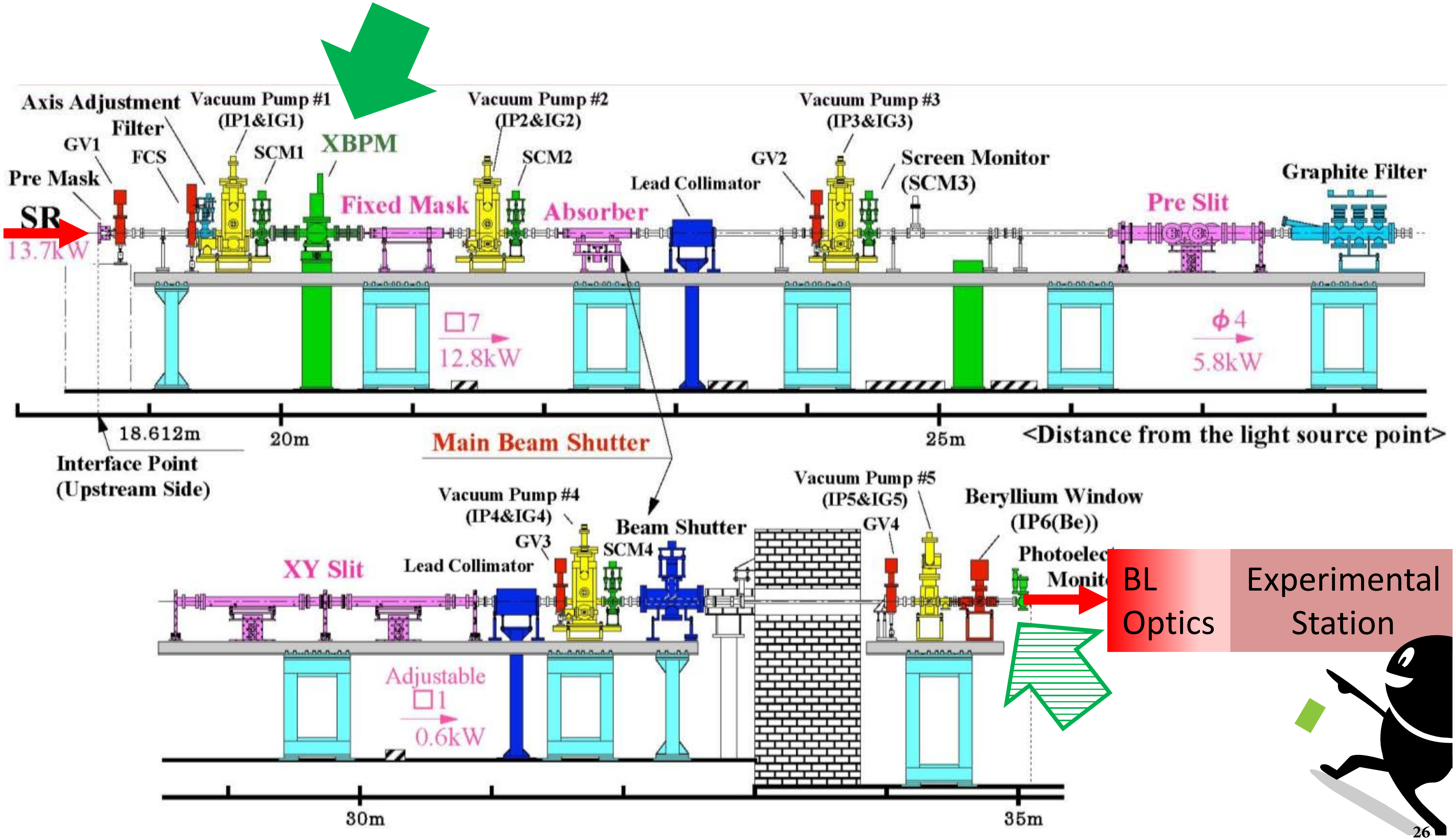
↓

<u>X-ray beam position monitor</u>

(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.*

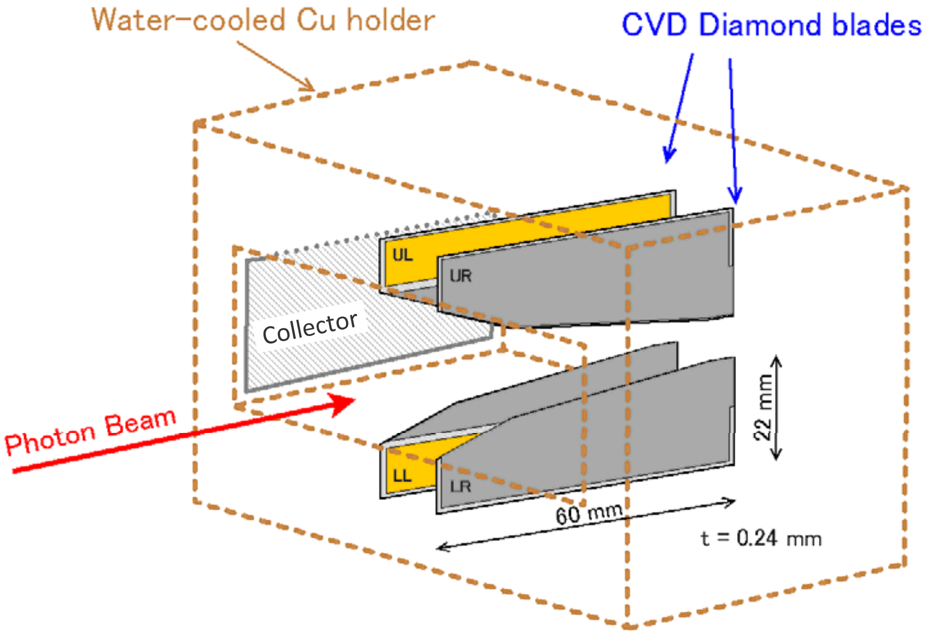


Structure of XBPM's detector head

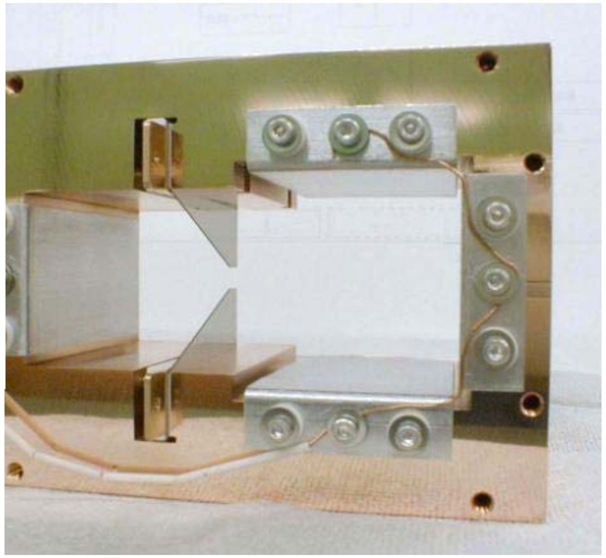
(Photo-emission type)

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

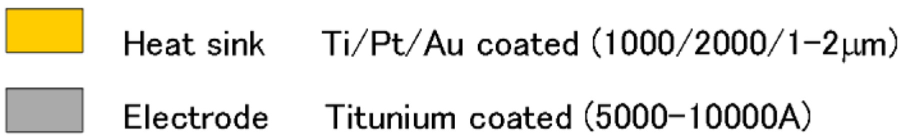
Electrons from each blade of Ti/Pt/Au on diamond emitted by ***outer side of photon beam***
The horizontal or vertical positions computed by each current



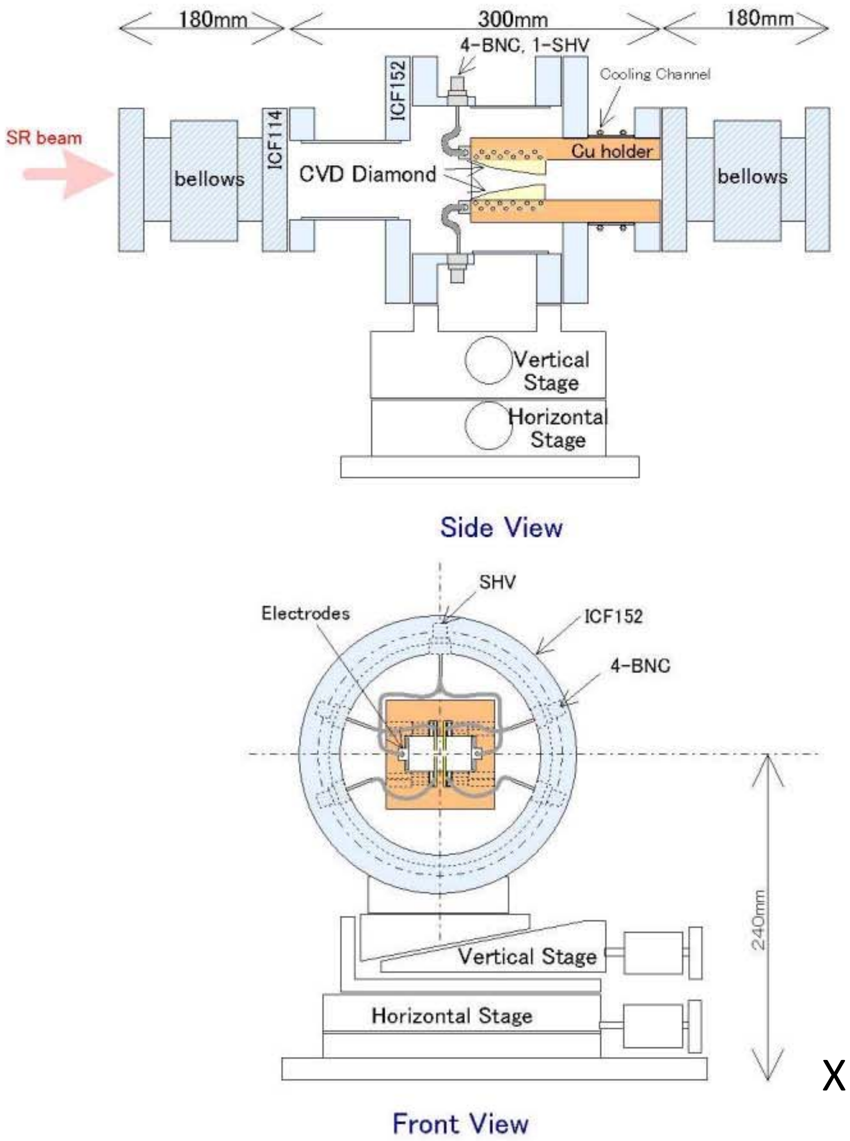
XBPM
for insertion device (ID) beamline

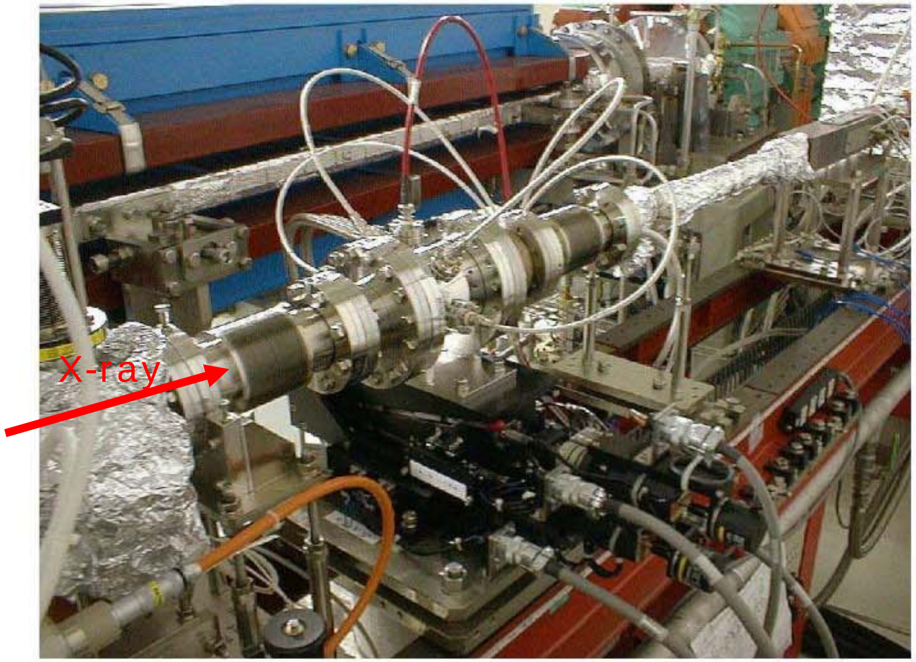


XBPM
for bending magnet (BM) beamline



Fixed-blade style XBPM



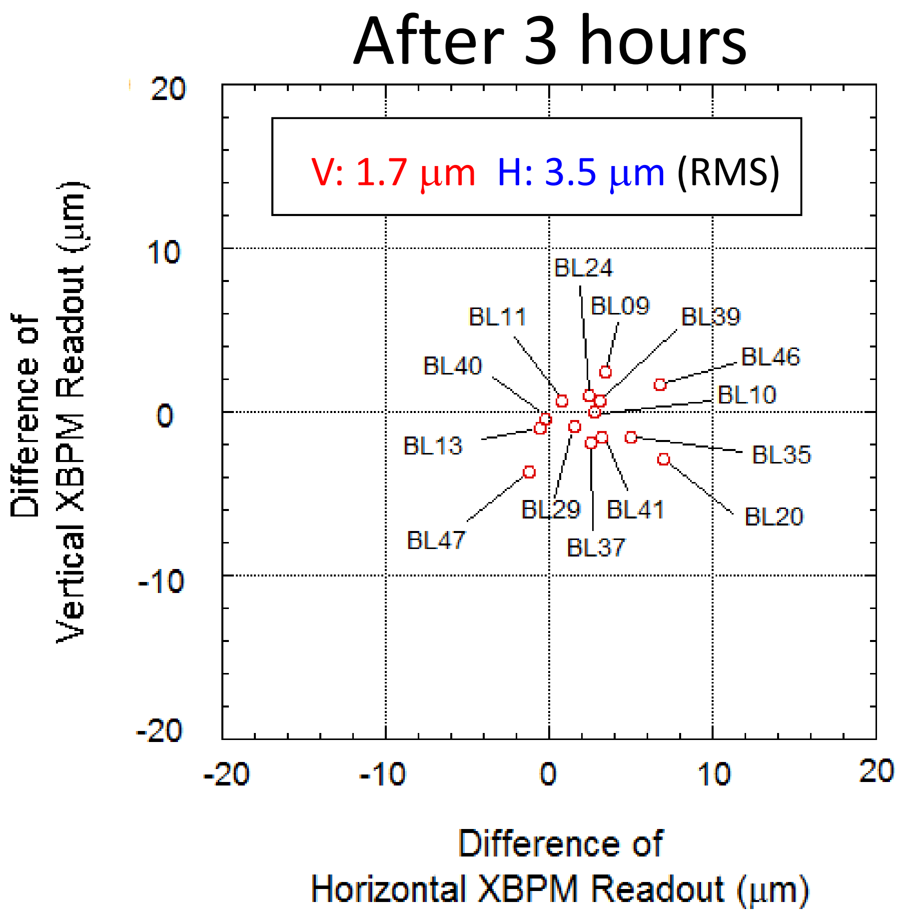


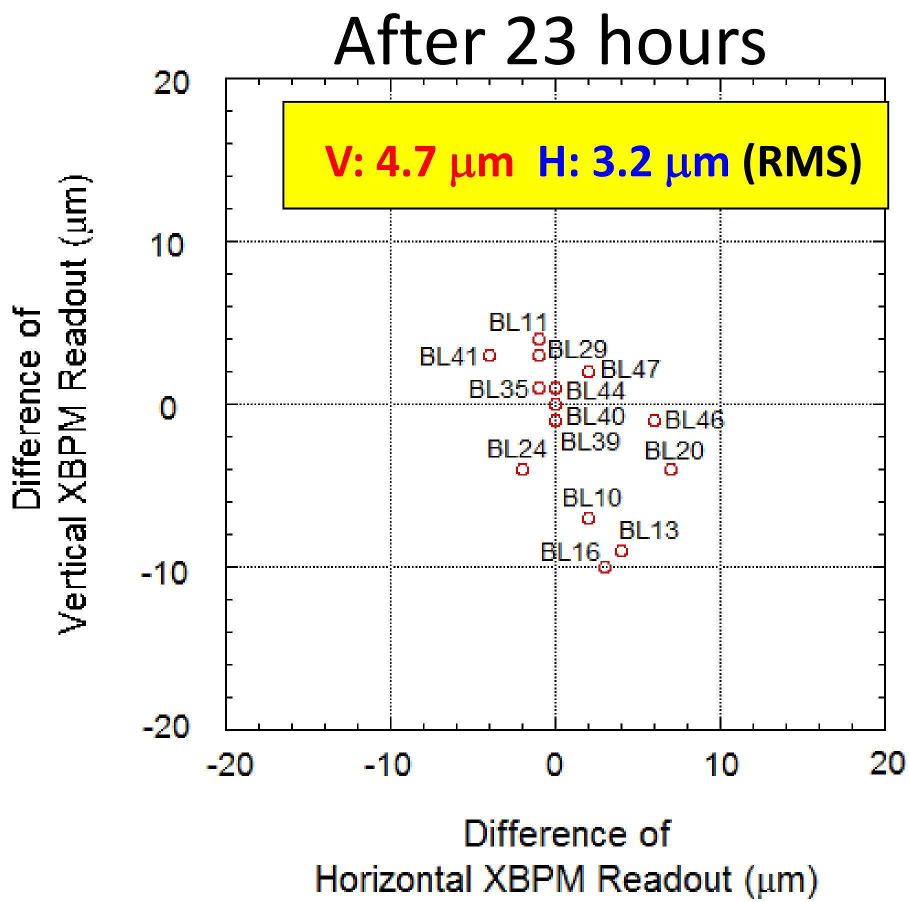
for SPring-8 in-vacuum undulator, etc. (19 beamlines)

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.



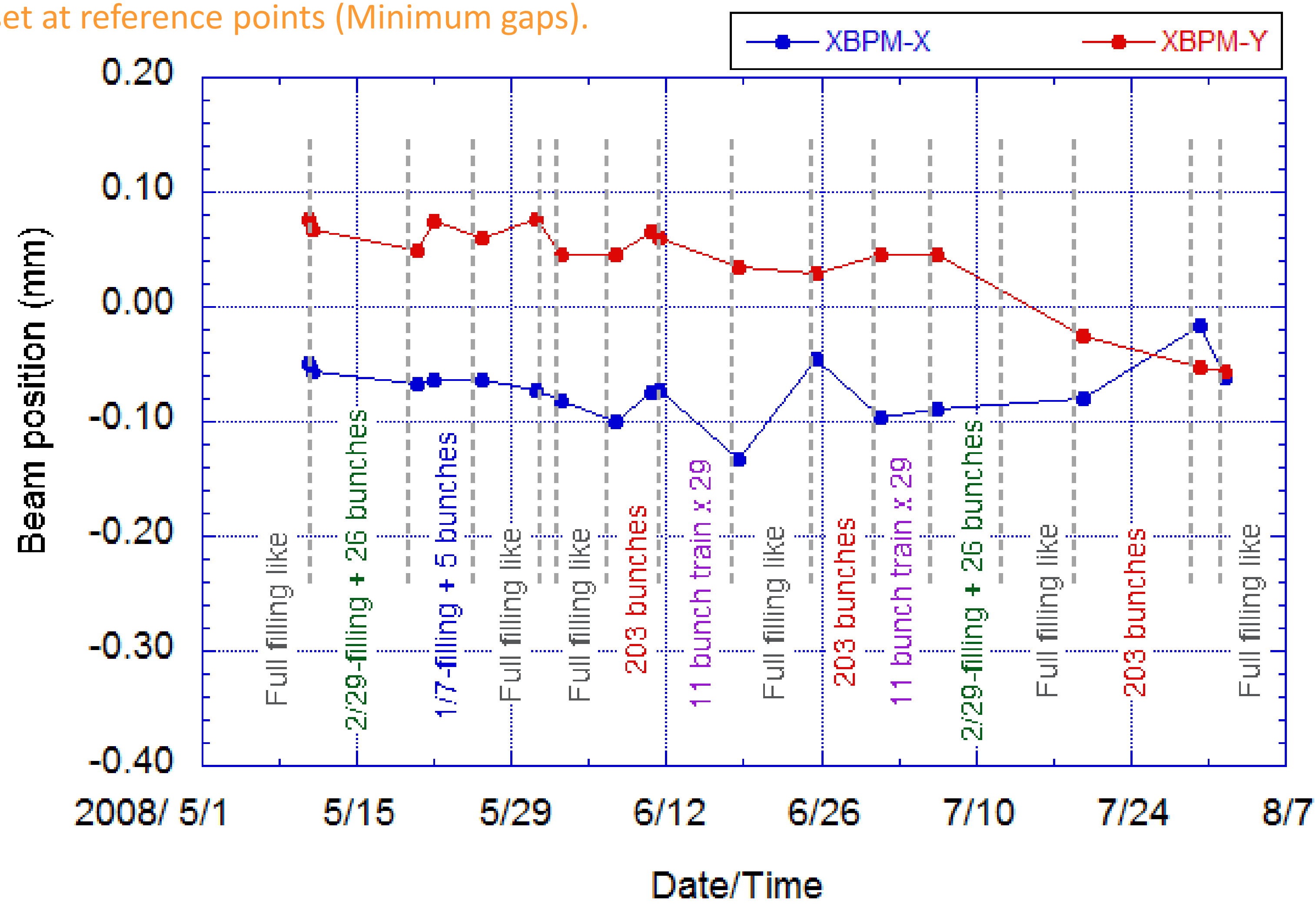


All Gaps are set at reference points (Minimum gaps).

<u>Stability of the XBPM is a few microns for a day</u>
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).



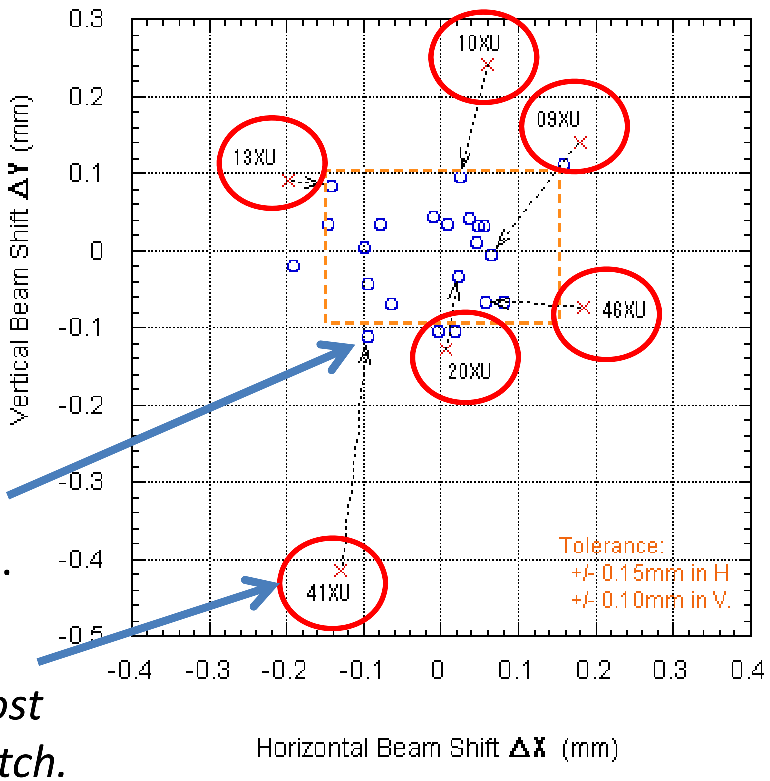
Orbit correction using XBPM

2007/02/27 Aoyagi

Check of ID beam orbits with XBPMs

at beginning of the 1st cycle, 2007

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



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	
	Horizontal (mm)	Vertical (mm)	Horizontal (mm)	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		

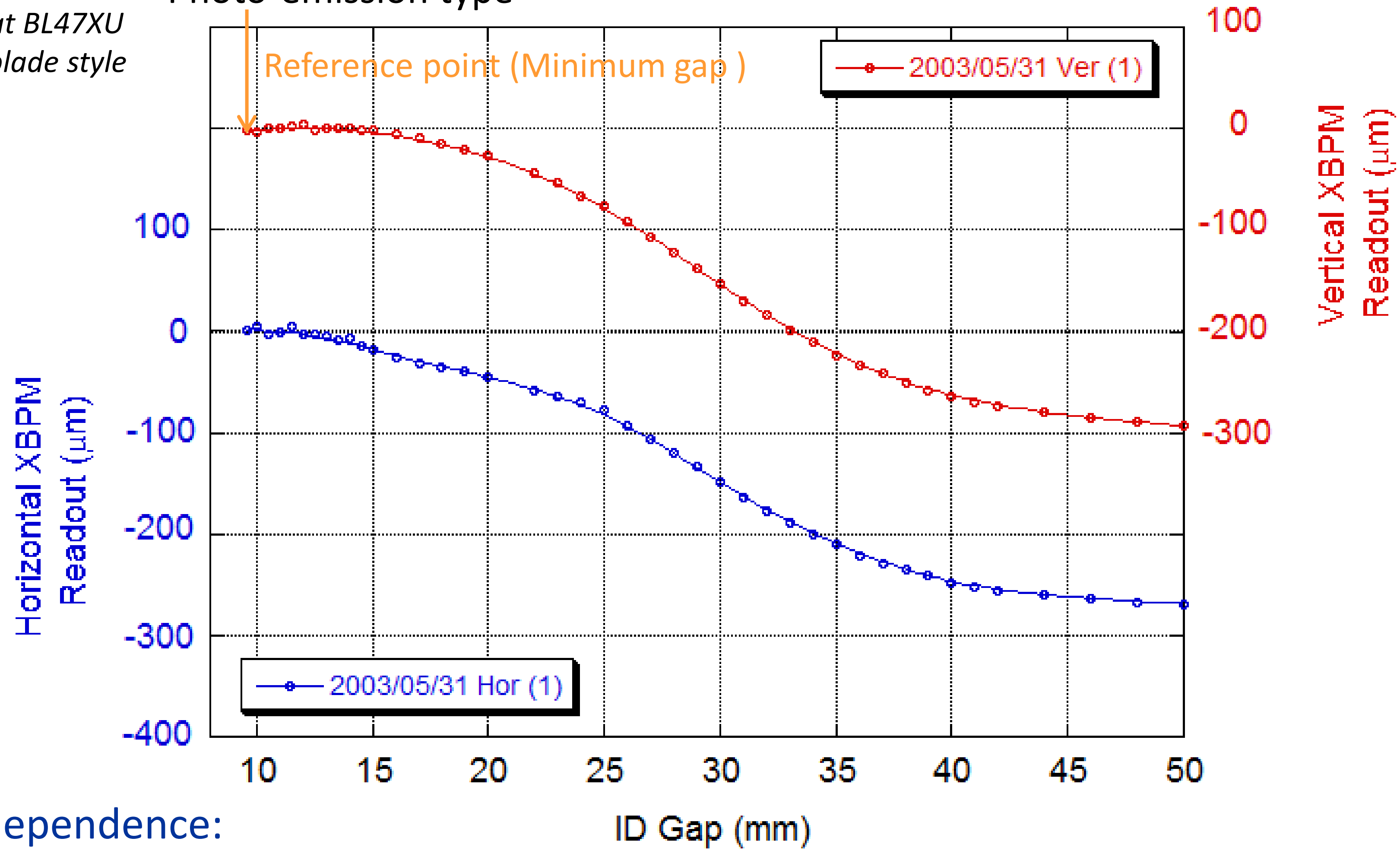
Orbit correctied for
BL08XU, BL09XU, BL10XU, BL13XU,
BL20XU, BL41XU, BL46XU

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

ID-Gap dependence of XBPM

Photo-emission type

Measured at BL47XU with fixed-blade style



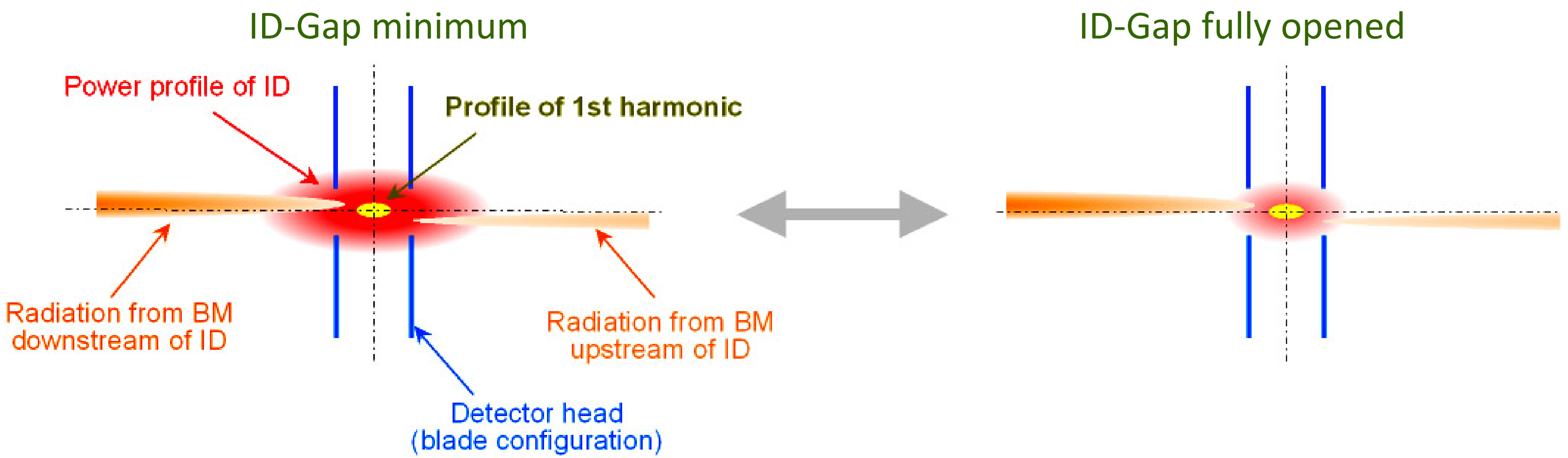
Gap dependence:

<u>～ 100μm for Gap : 9.6 ~ 25 mm , ～300μm for Gap : 9.6 ~ 50 mm</u>

The position of the beam at optics hutch was 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,

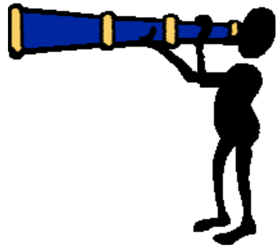
Background: < several keV near beam axis of ID

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

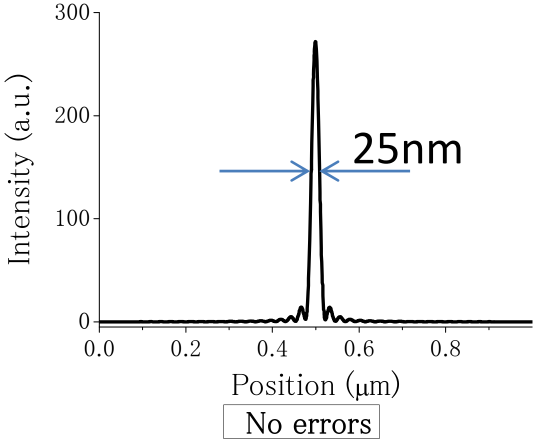
- Blade of diamond

  Max. power density is ~ **500 kW/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.

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>

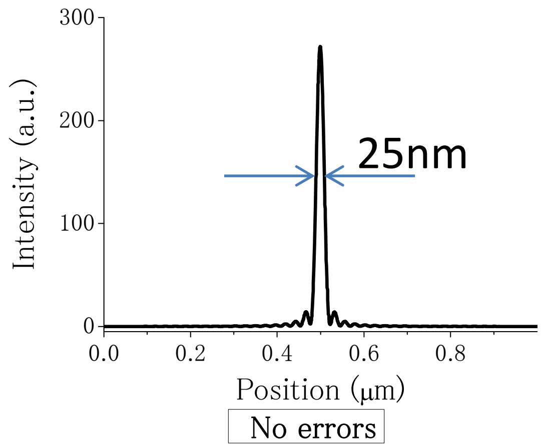
design, errors, metrology
& alignment

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

Requirement

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.

Design parameters

- ✓ 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…

In addition,

some errors such as figure error, roughness…

How to select coating material and incident angle ?

Reflectivity for grazing incident mirrors

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

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

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

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

$$\begin{cases} \delta = \dfrac{N r_0 \lambda^2}{2\pi} f_1(\lambda) \\ \beta = \dfrac{N r_0 \lambda^2}{2\pi} f_2(\lambda) \end{cases}$$

Small
for x-ray region

	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

$$r_0 = \frac{e^2}{4\pi m c^2} = 2.82 \times 10^{-15} m$$

N: Number of atoms per volume

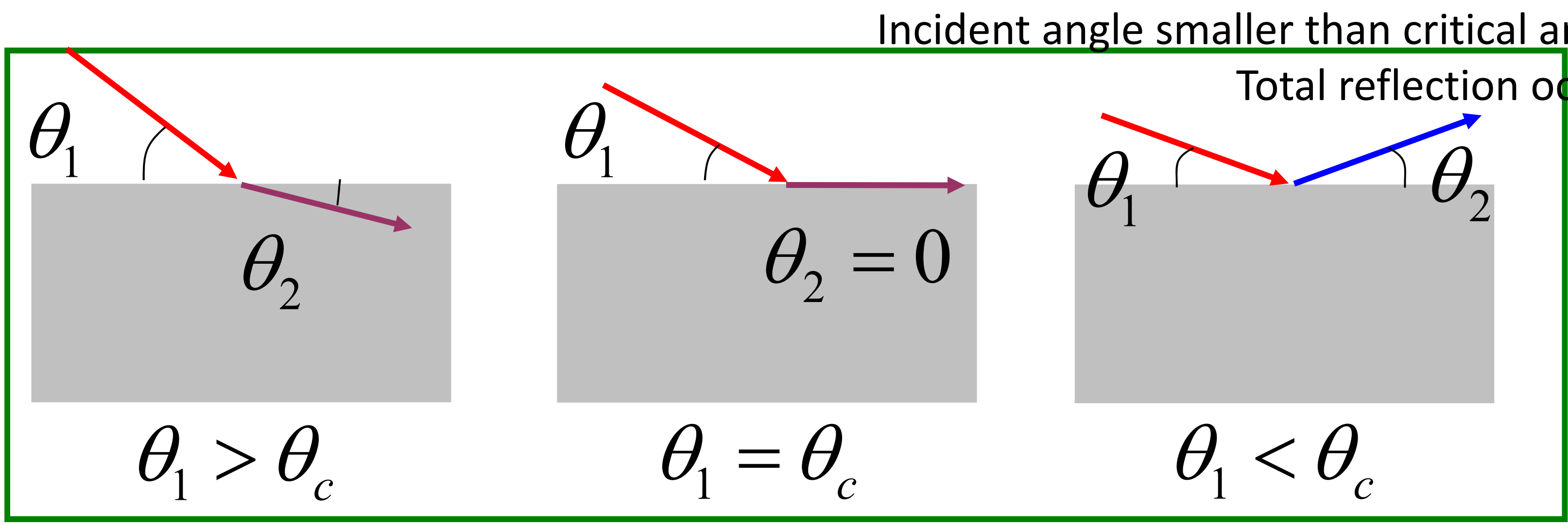
$$\beta = \frac{\mu\lambda}{4\pi}$$

*μ: linear **absorption** coefficient*

Coating material (2)

"total reflection"

$$\cos(\theta_1)/\cos(\theta_2) = n_2/n_1$$ ←Snell's law



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

$$\theta_c \cong \sqrt{2\delta} = 1.6\times10^{-2}\lambda\sqrt{\rho} = 20\sqrt{\rho}/E$$

For example, θ_c (rad), ρ (g / cm^3) , λ (nm) , E (eV)

Rh (ρ = 12.4 g /cm^3) λ=0.1nm, θ_c =5.68 mrad

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

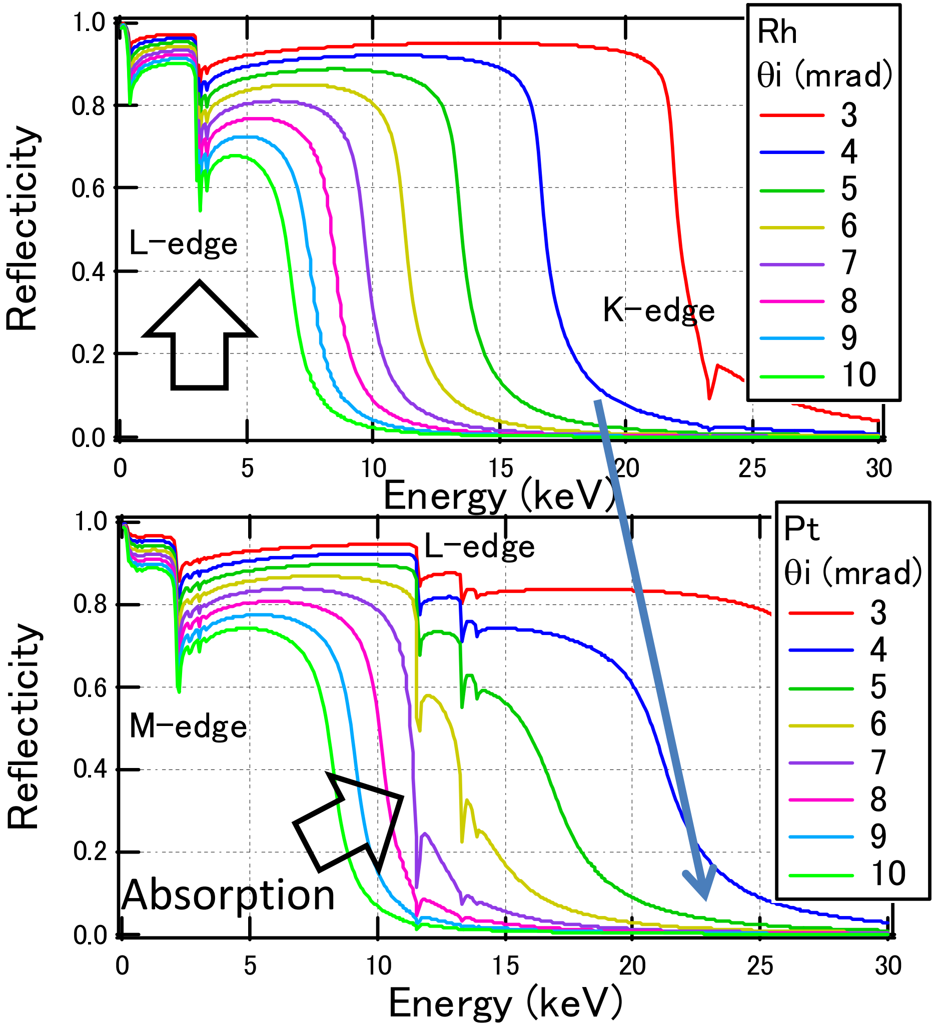
The cut off energy of total reflection Ec

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

E_c (eV) , ρ (g / cm^3), θ_c (mrad)

<ins>Rh (12.4 g / cm³)</ins>

<ins>Pt (21.4 g / cm³)</ins>



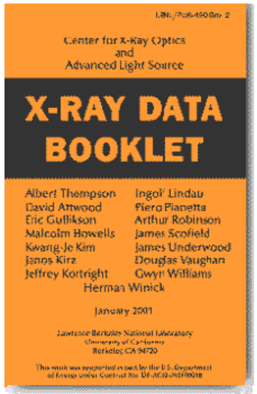
<ins>Cut off energy, absorption → incident angle</ins>

<ins>→ Opening of the mirror, length, width of mirror, power density</ins>

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

- deflecting
- low pass filter
- focusing
- collimate

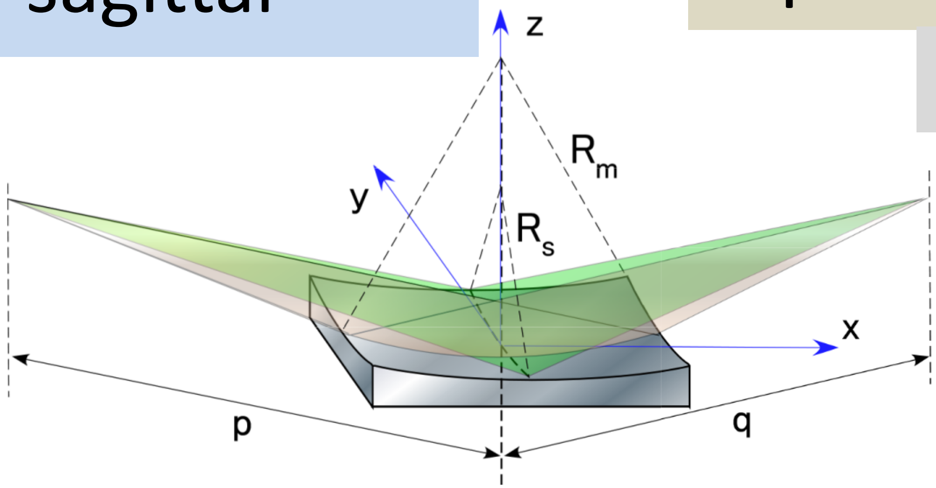
- meridional
- sagittal

for example, — *Easy to make or cost*

- flat ◎
- spherical ◎
- cylindrical ○
- toroidal ○
- elliptical △
- parabolic… △

adaptive △

Take care of aberration (spherical, cylindrical, toroidal)

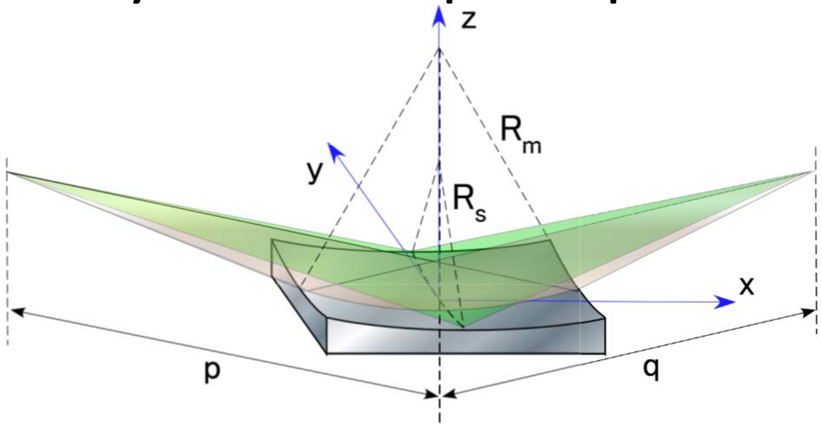


Surface shape (2) radius and depth

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

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

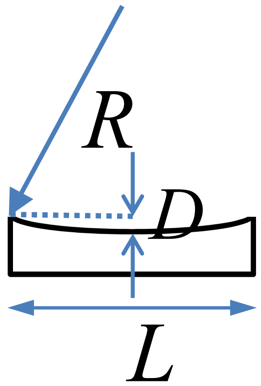
By Fermat's principle



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

Depth at the center

$$D = R - \sqrt{R^2 - \left(\frac{L}{2}\right)^2} \approx \frac{L^2}{8R}$$



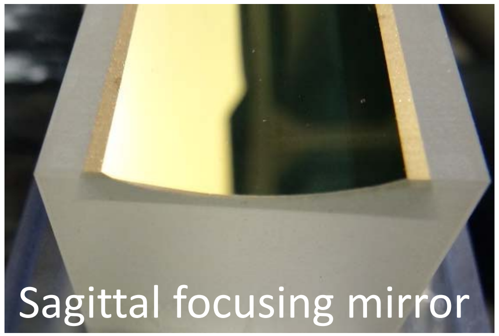
For example,

p=15～50m, q=5～20m, θ_i=1～10mrad

R_m=0.1～10 km, R_s= 30～100 mm

R_m= 1 km, L=1m → D = 125 μm

R_s=30 mm, L=20mm → D = 1.7 mm

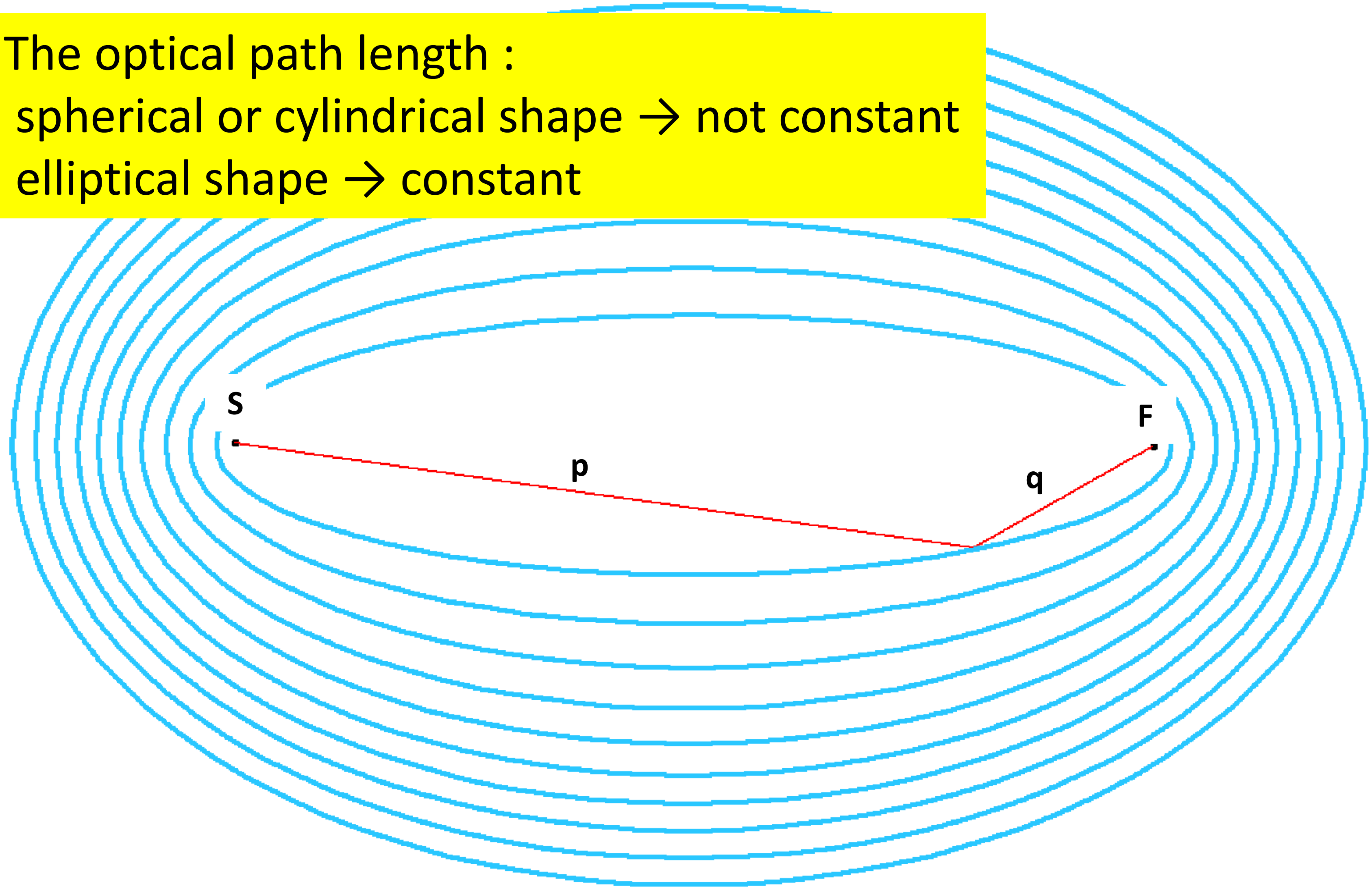


Sagittal focusing mirror

R_s～30mm

Basic geometry

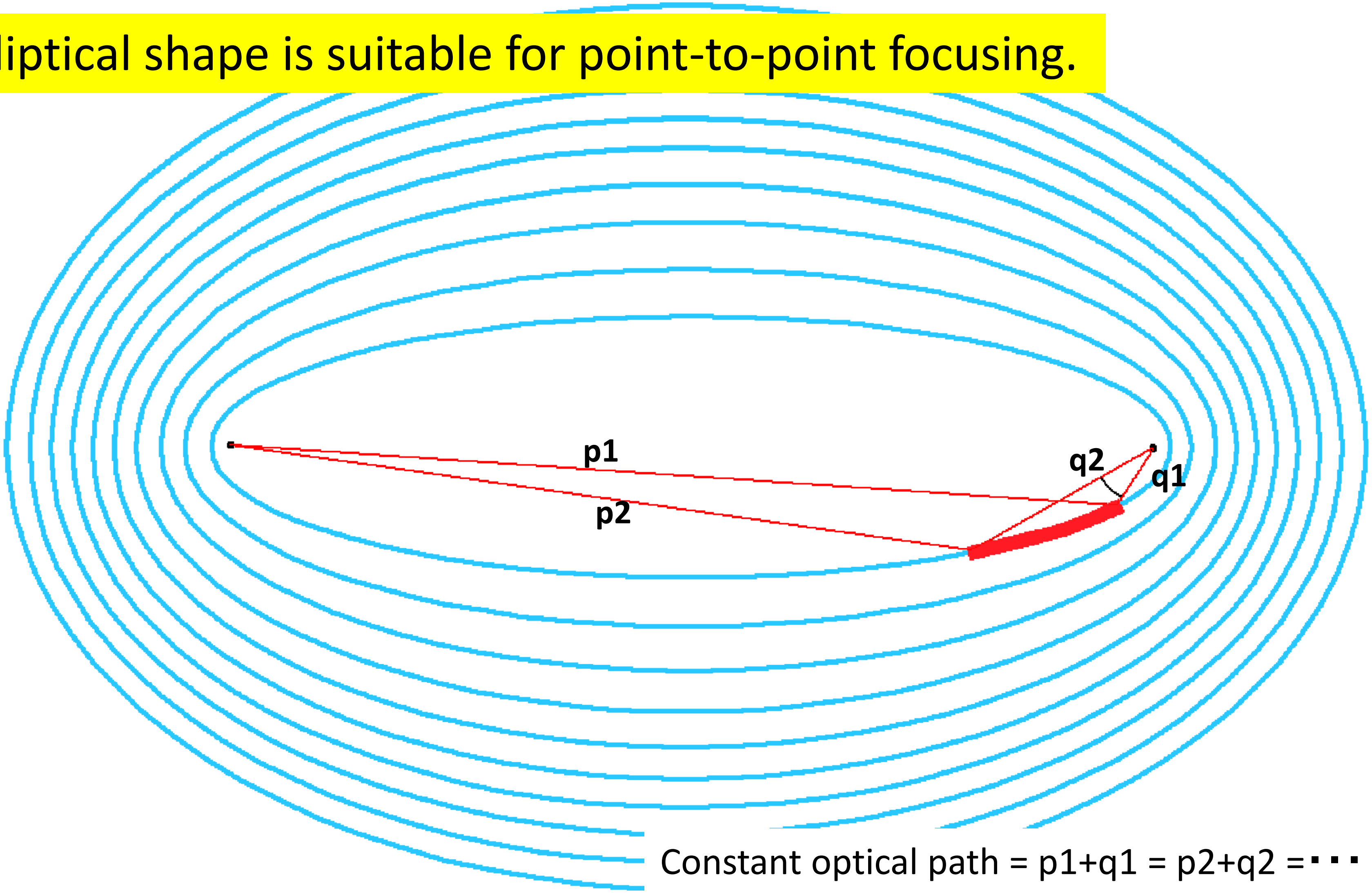
The optical path length :
spherical or cylindrical shape → not constant
elliptical shape → constant



by courtesy of Ch. Morawe

Mirror optics

Elliptical shape is suitable for point-to-point focusing.

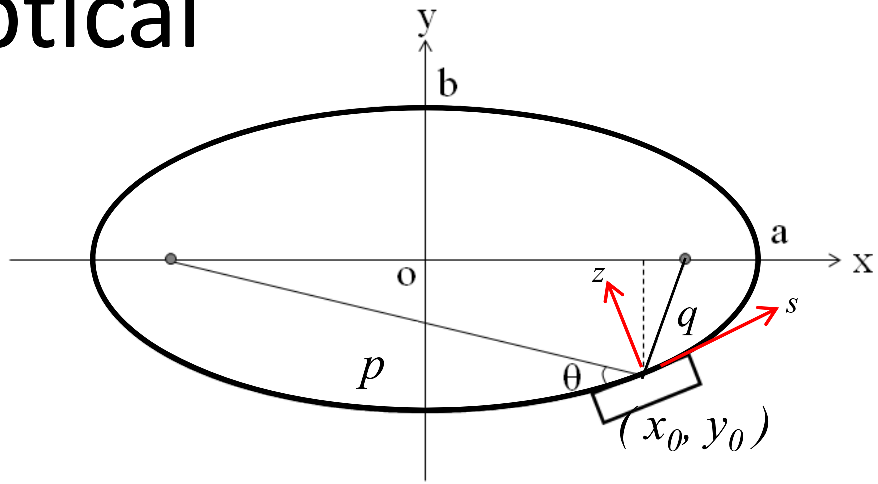


Constant optical path = p1+q1 = p2+q2 =···

by courtesy of Ch. Morawe

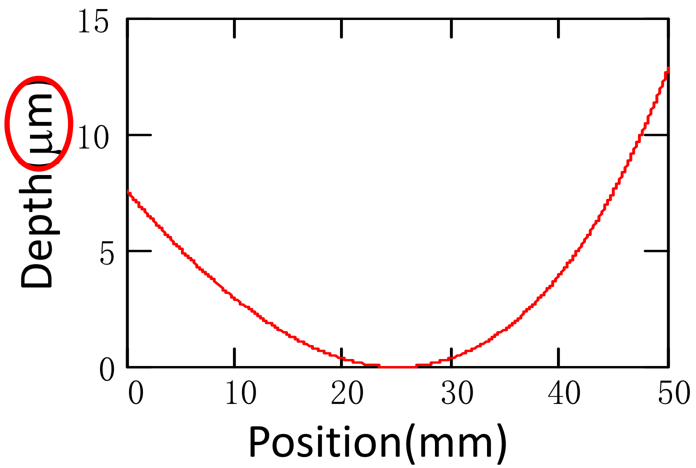
Surface shape (3) elliptical

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



For example,

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



$$a = \frac{p+q}{2}, b = \sin(\theta)\sqrt{pq}$$

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

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

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

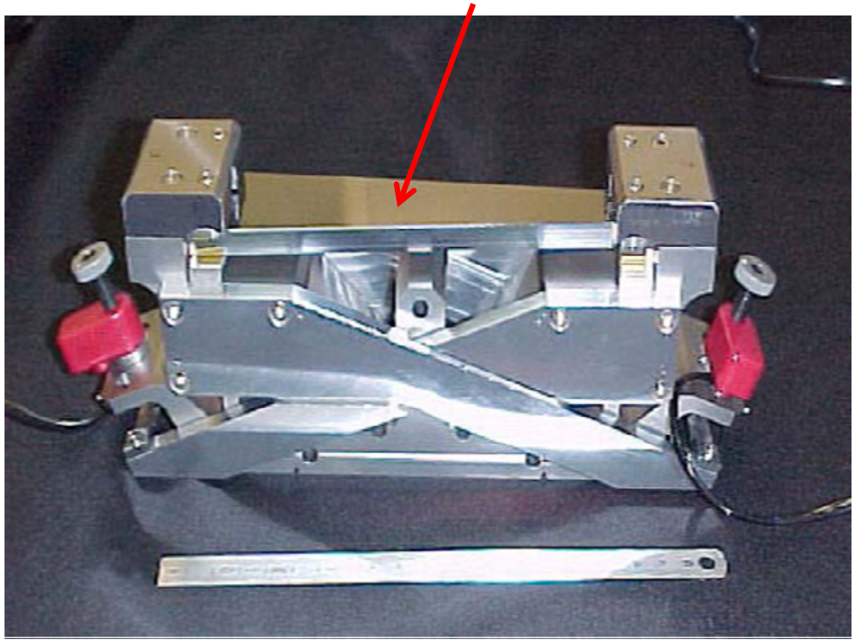
(Ref *)

__Precise fabrication is not easy.__

* 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

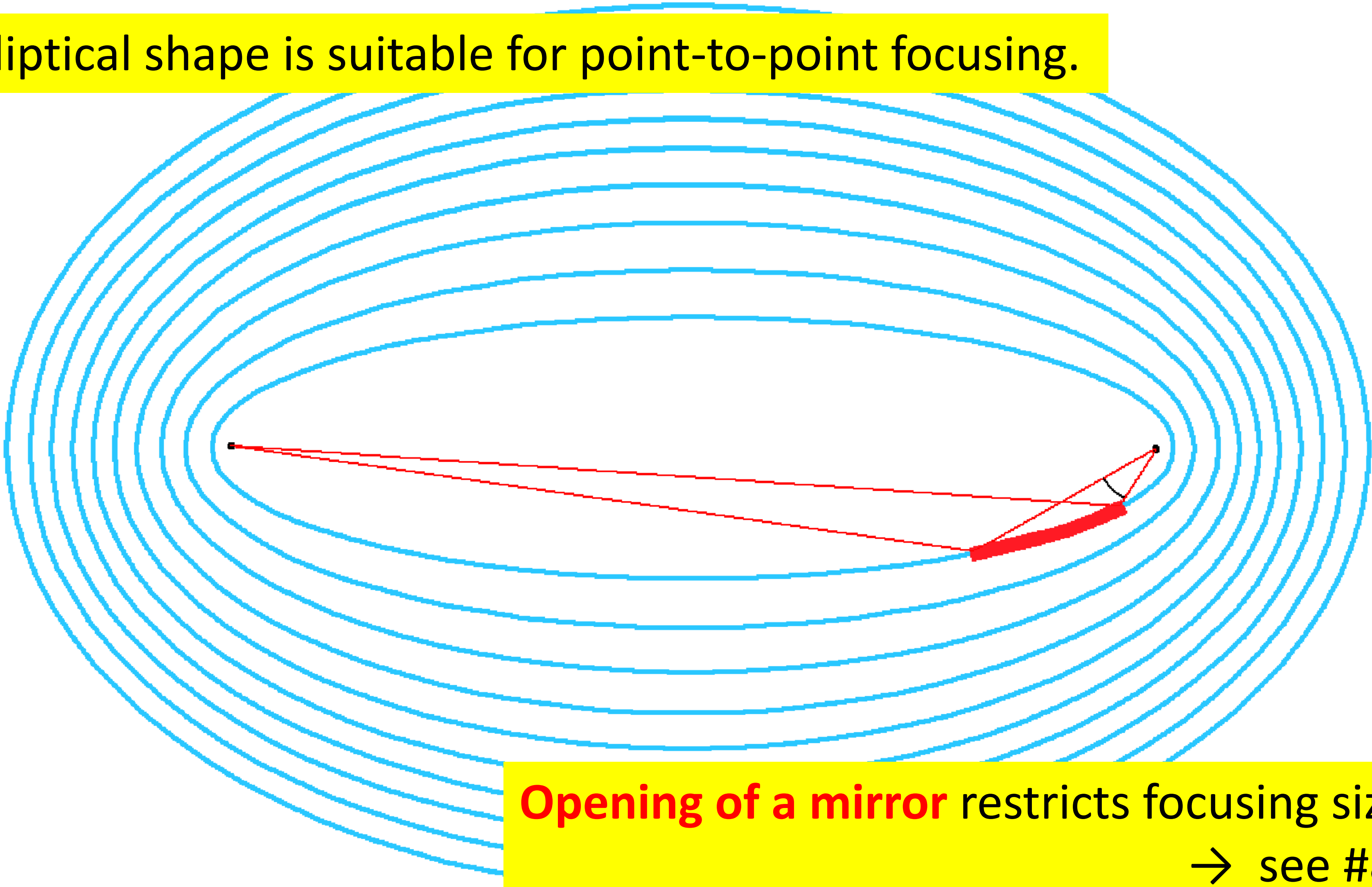
Trapezoidal mirror (L540mm)

Long bent focusing mirror at SPring-8

These system works fine to focus micro beam.

Mirror optics

Elliptical shape is suitable for point-to-point focusing.



Opening of a mirror restricts focusing size.

→ see #83

by courtesy of Ch. Morawe

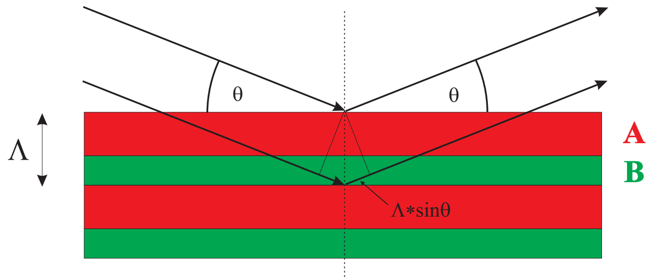
Multilayer coating mirror

<u>advantages</u>

enlarge opening of a mirror

higher critical angle

moderate energy resolution



<u>disadvantages</u>

chromatic

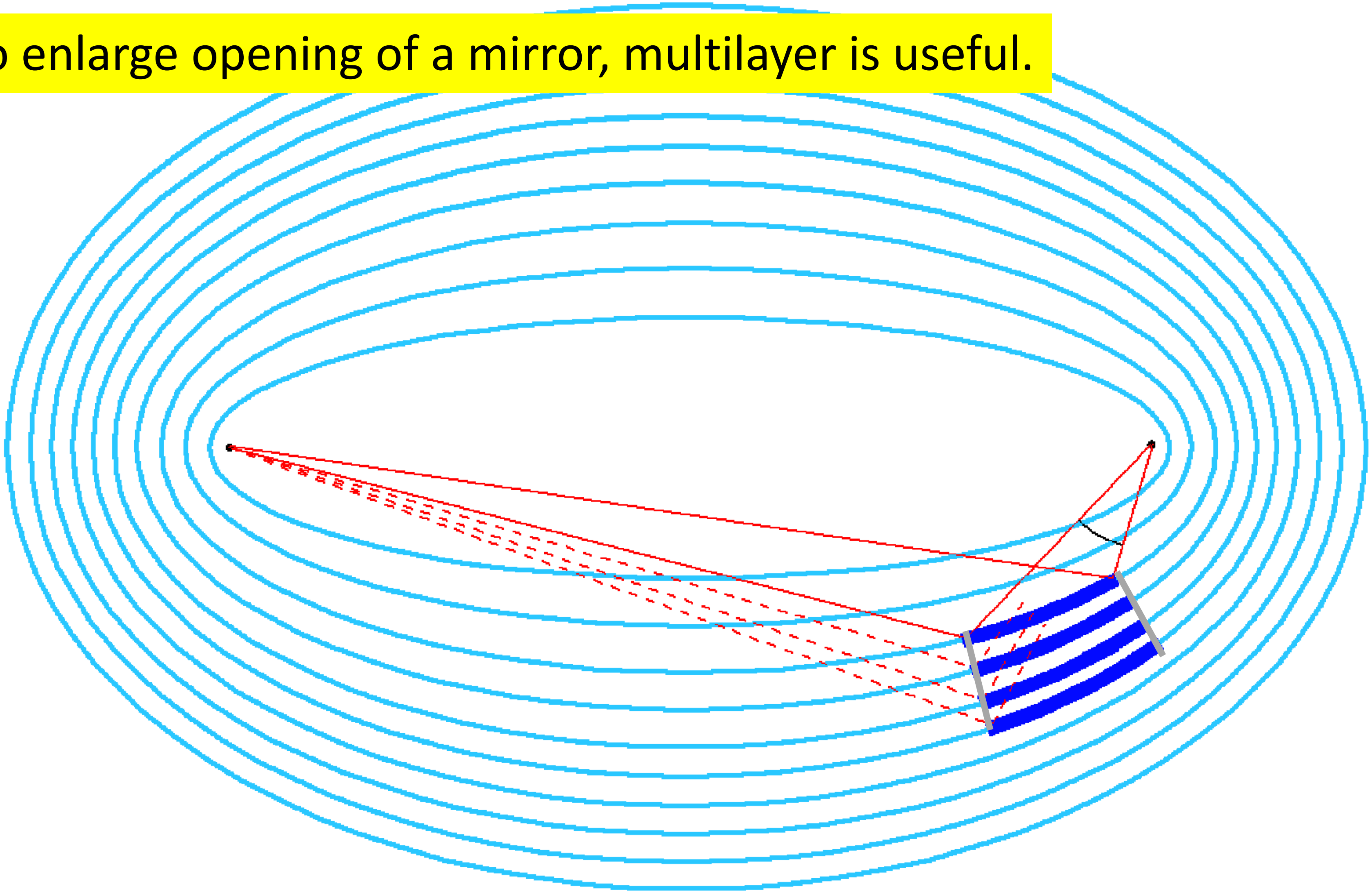
damage ?

cost ?

"Juni Hito-e"
a 12-layered ceremonial kimono

Multilayer optics

To enlarge opening of a mirror, multilayer is useful.



by courtesy of Ch. Morawe

X-ray multilayer reflectivity

$\theta_c \cong 20\sqrt{\rho}/E = 0.25\,\text{deg}$ → see #41
W : ρ=19.25g/cm^3

Numerical calculations

Main features

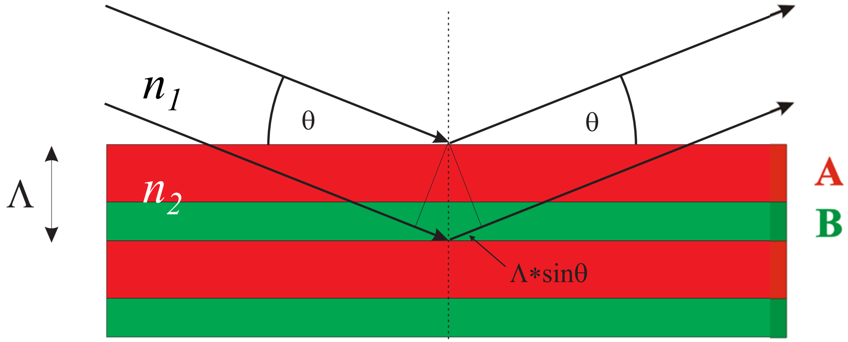
- **Bragg peaks and fringes due to interference**
- **Positions depend on E and Λ**
- **Intensities depend on Δρ, N, σ…**

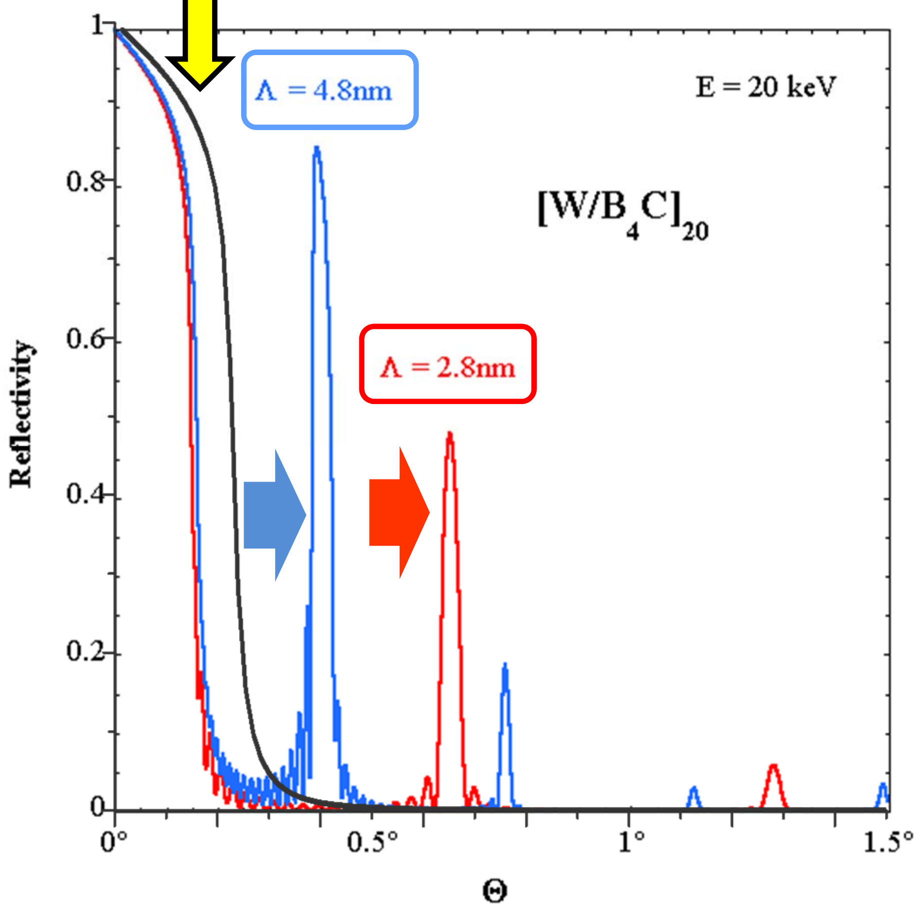
Corrected Bragg equation

Bragg Eq .& Snell's law

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

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

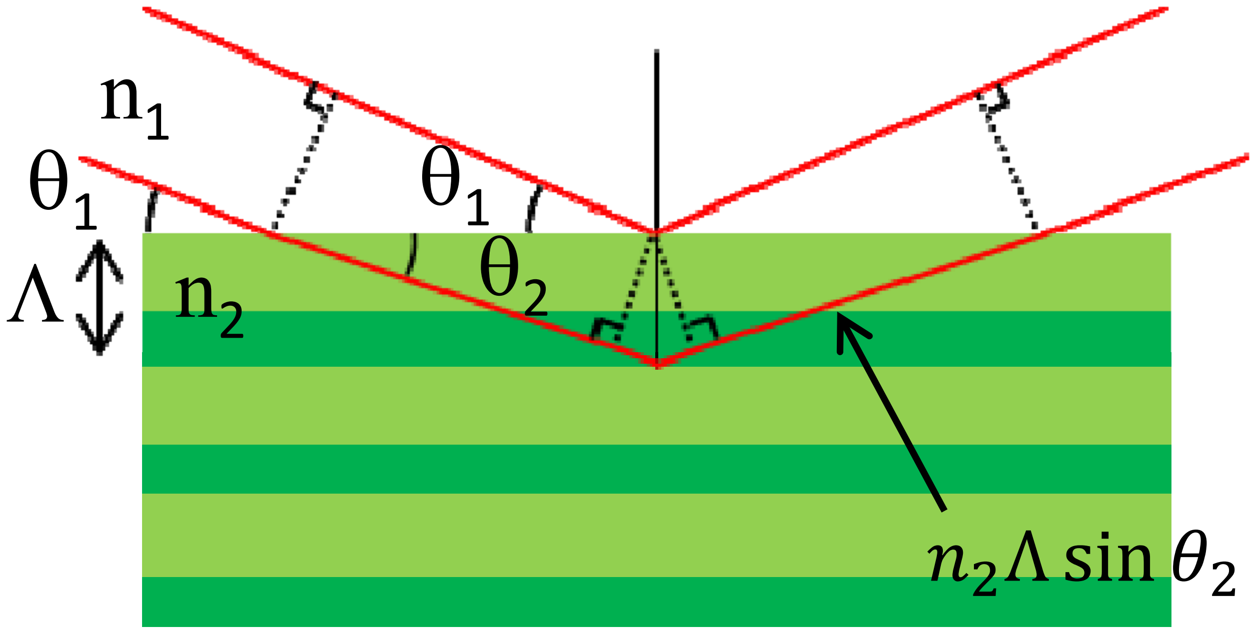




Two materials of high and low atomic number are alternately deposited to maximize the difference in electron density.

→ The multilayer coating allows larger incident angle for x-rays depending on the periodicity (Λ).

by courtesy of Ch. Morawe



Bragg's eq. : $m\lambda = 2n_2\Lambda \sin\theta_2$

$$= 2n_2\Lambda\sqrt{1-\cos^2\theta_2}$$

Snell's law : $\cos\theta_2 = n_1/n_2 \times \cos\theta_1$

$$\therefore \quad m\lambda = 2\Lambda\sqrt{{n_2}^2 - {n_1}^2\cos^2\theta_1}$$

X-ray multilayer characterization

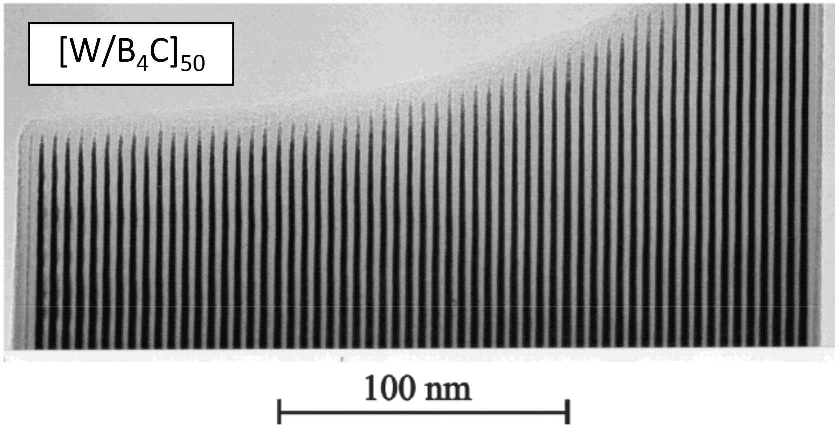
Transmission electron microscopy (TEM)

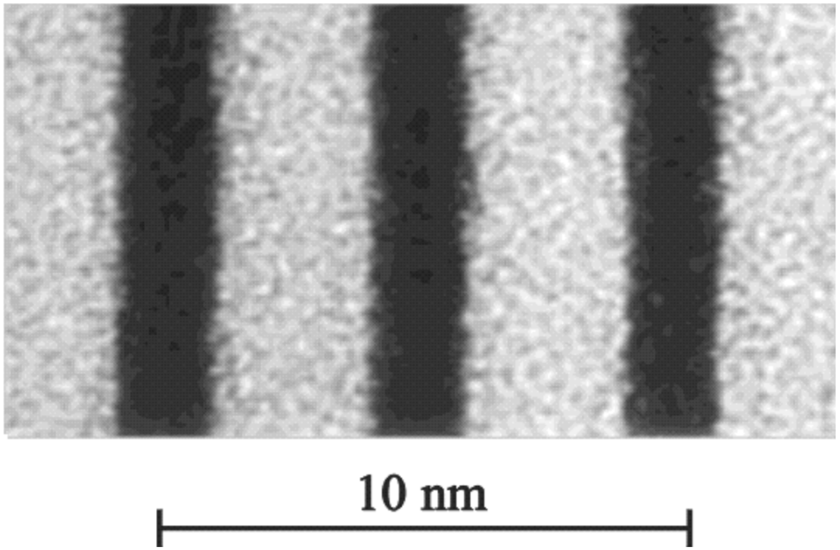
- **Fabrication errors**
- **Roughness evolution**
- **Crystallinity**
- **Interface diffusion**

↓

Complementary to x-ray measurements !

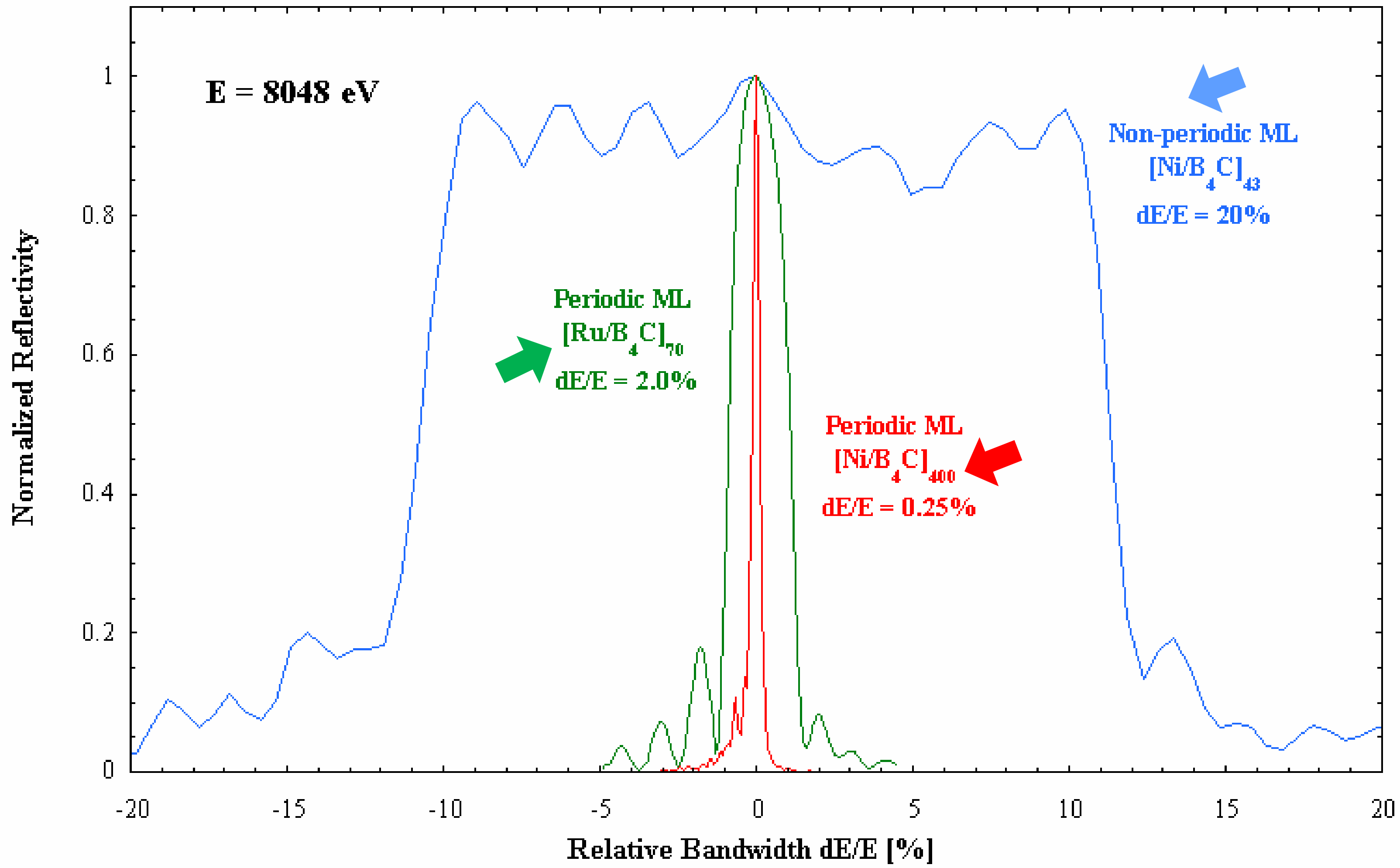
R. Scholz, MPI Halle, Germany





by courtesy of Ch. Morawe

Energy resolution of multilayers



by courtesy of Ch. Morawe

Ch. Morawe et al, Nucl. Instr. And Meth. A 493, 189 (2002)

X-ray multilayer design

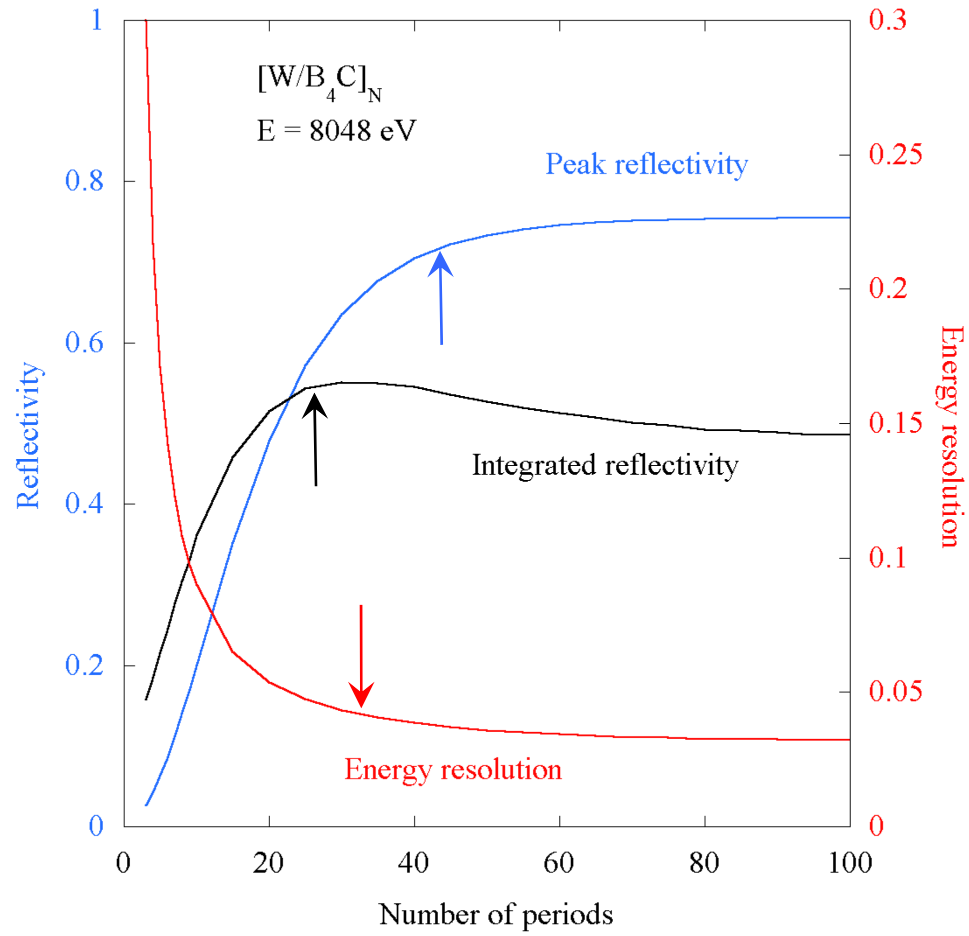
Period number N: ***can control reflectivity and energy resolution.***

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*

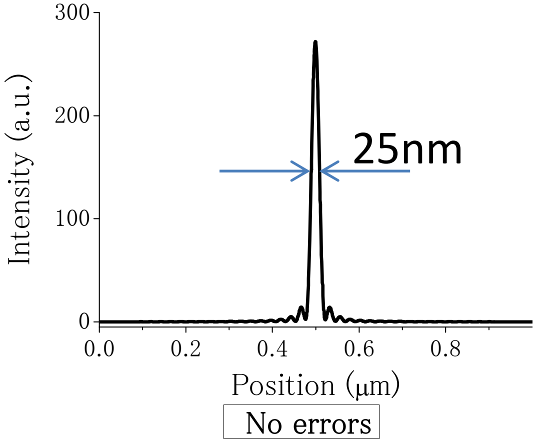
(*size, angular divergence / convergence, direction, energy region, power…*)

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

↓

<u>X-ray mirrors</u>

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 …

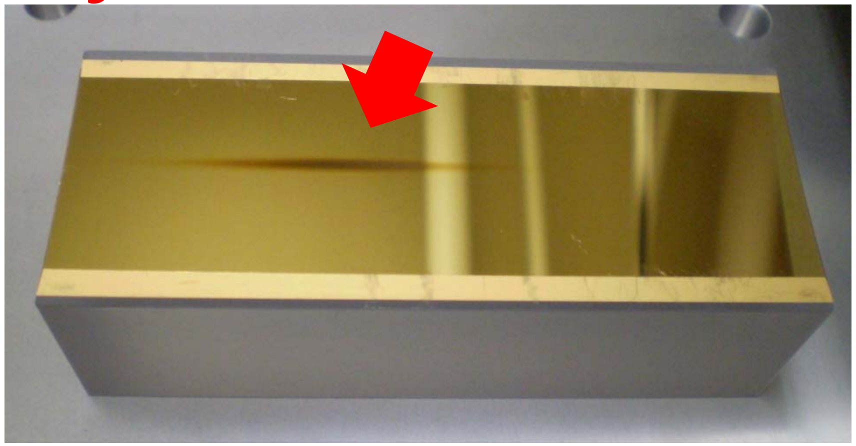
The cost (price and lead time) depends entirely on tolerance.
We must consider or discuss how to measure it.

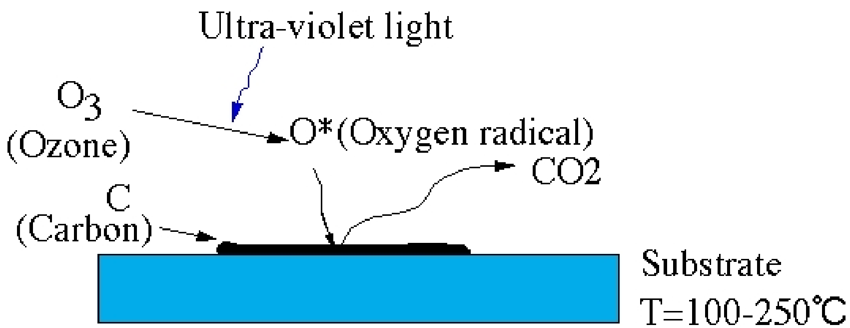
- ✓ Deformation by self-weight, coating and support …
- ✓ Figure error of adaptive mechanism
- ✓ Misalignment of mirror
- ✓ Stability of mirror's position (angle)
- ✓ Deposition of contamination by use
- ✓ Decomposition of substrate by use

- Environment
- Manipulator
- Cooling system …

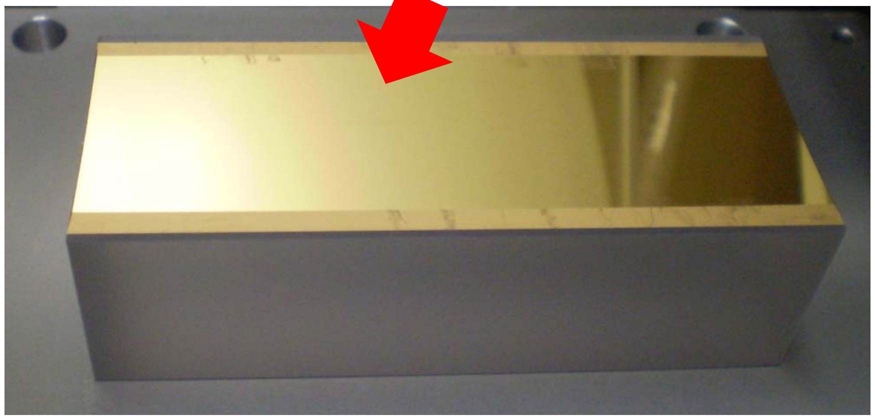
Contamination and removal

before





After cleaning



Advantage of UV/ozone cleaning

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

UV / ozone cleaning

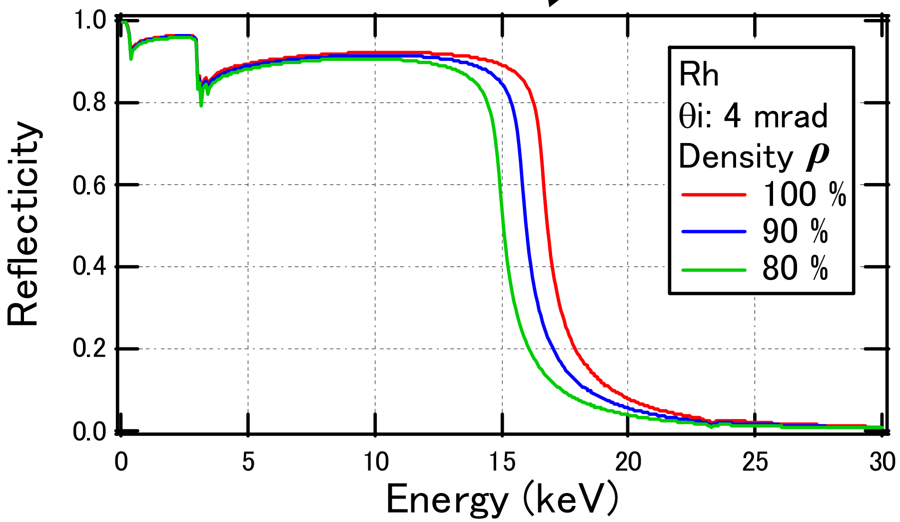
It takes from 10 min to a few hours.

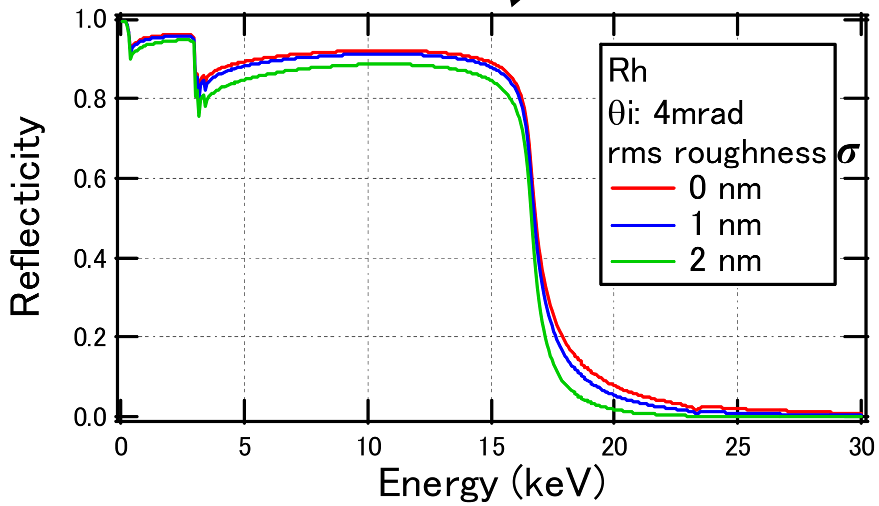
Errors (1)

"Density $\boldsymbol{\rho}$ *and surface roughness* $\boldsymbol{\sigma}$ *"*

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

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

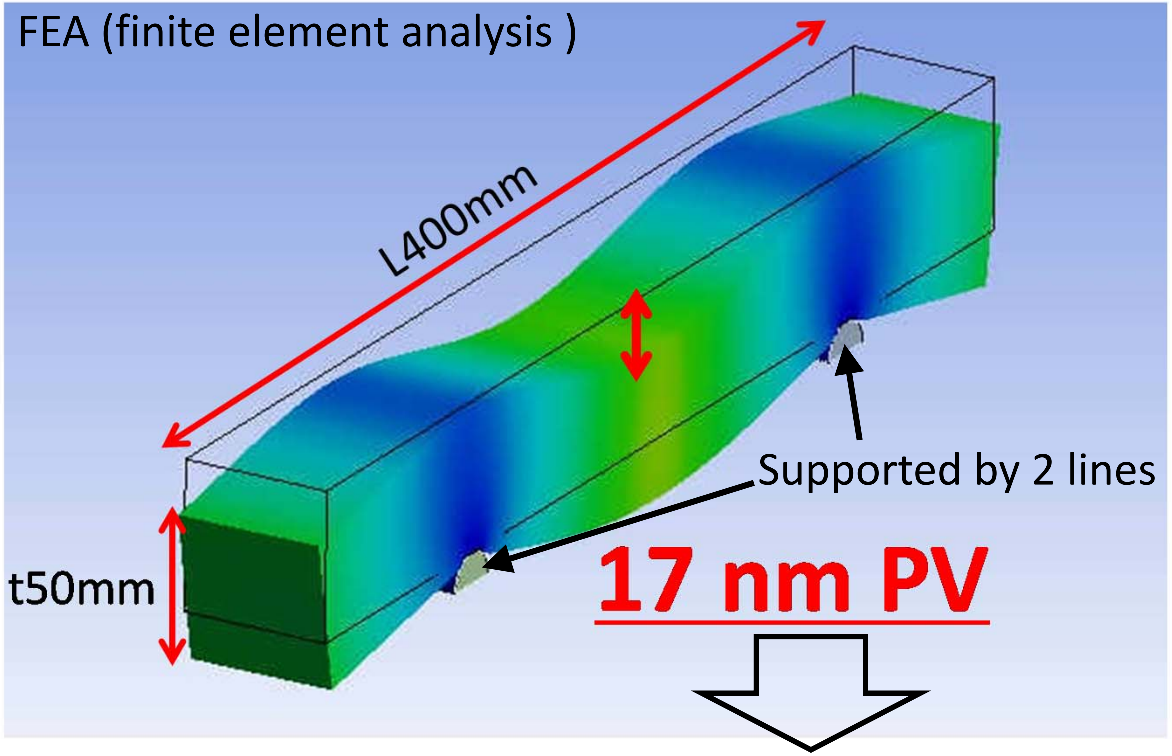




Coating on sample wafer at the same time is helpful to evaluate the density and roughness.

Errors (2)

“the self-weight deformation”



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

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

This value for nano-focusing is larger than figure error by Rayleigh’s rule.

(→See next page)

<u>Improvement</u> for nano-focusing

a) Substrate → Si (E ～ 190 GPa)

b) Optimization of supporting points and method

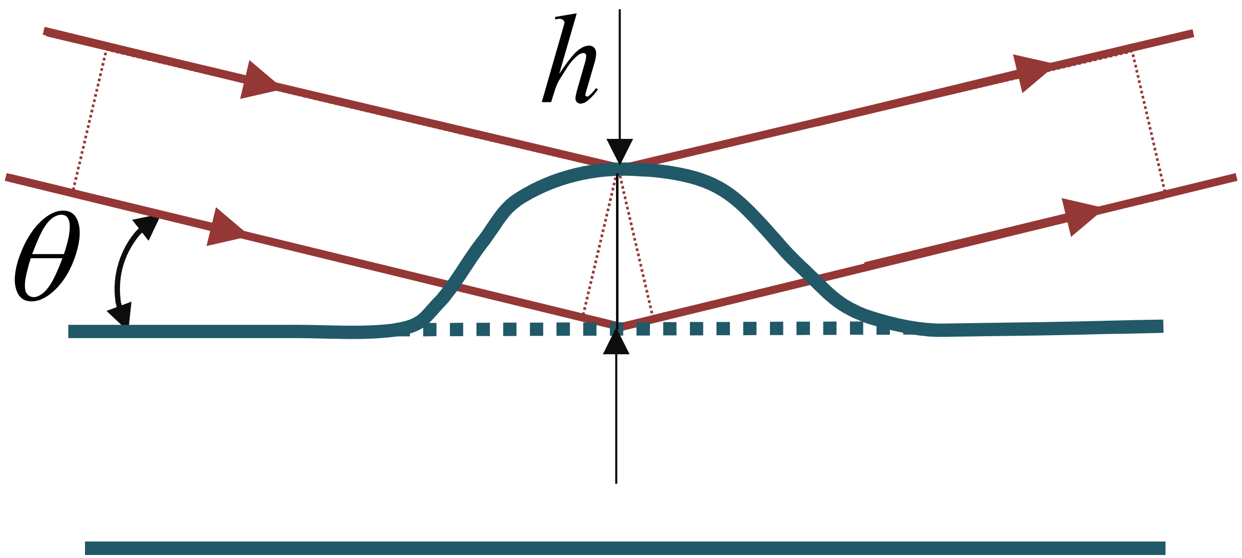
c) Figuring the surface in consideration of the deformation

Errors (3a)

"figure error estimated by Rayleigh's rule"

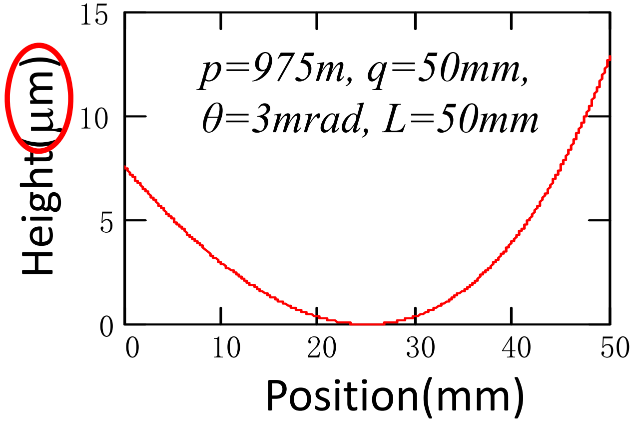
$$\phi = 2hk\sin(\theta) \to \pi/2 \qquad h_{\lambda/4} = \lambda/8\theta$$

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



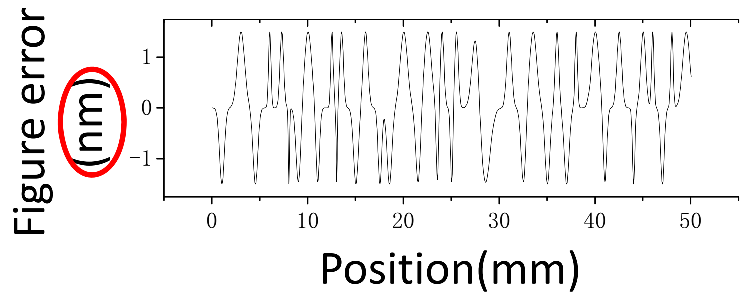
Errors (3b)

“ estimation by wavefront simulation ”



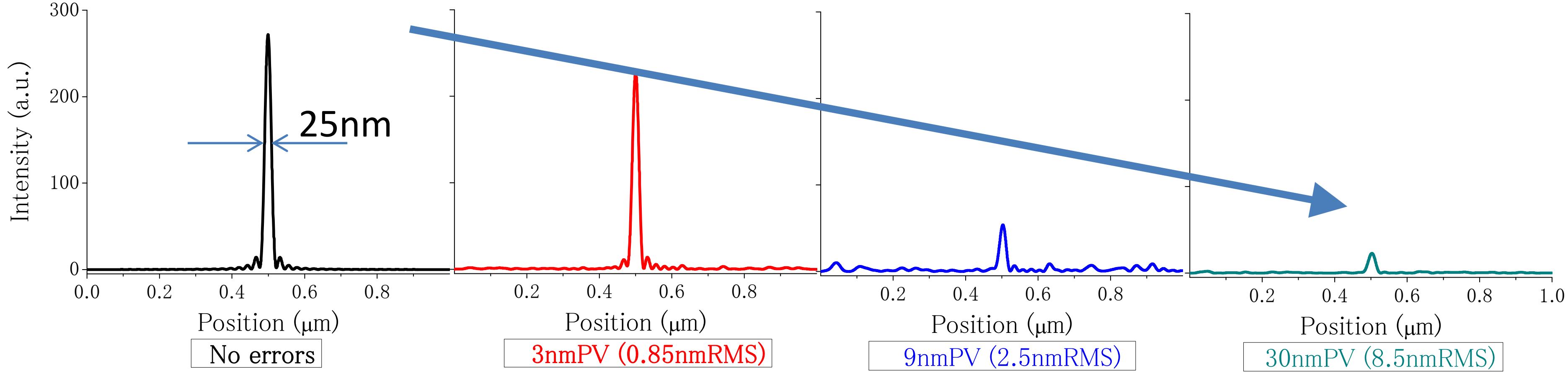
Designed surface

+



Errors of ***short*** range order

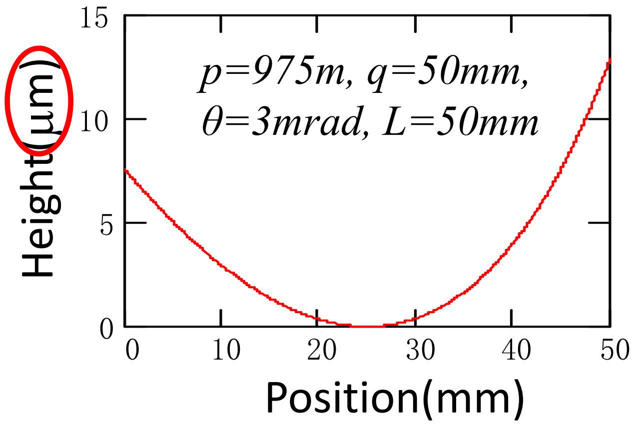
Intensity profiles of focusing beam by wavefront simulation



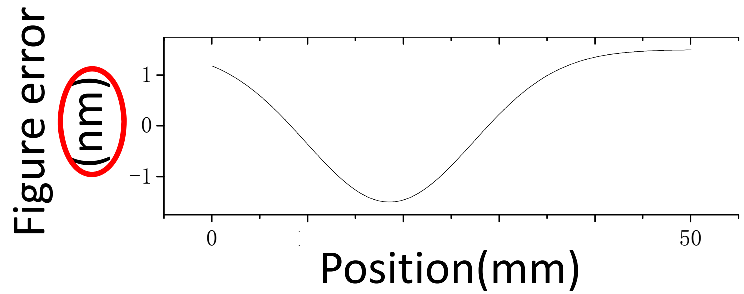
Errors of ***short*** range order ***decreases intensity***. → Roughness

Errors (3c)

“ estimation by wavefront simulation ”

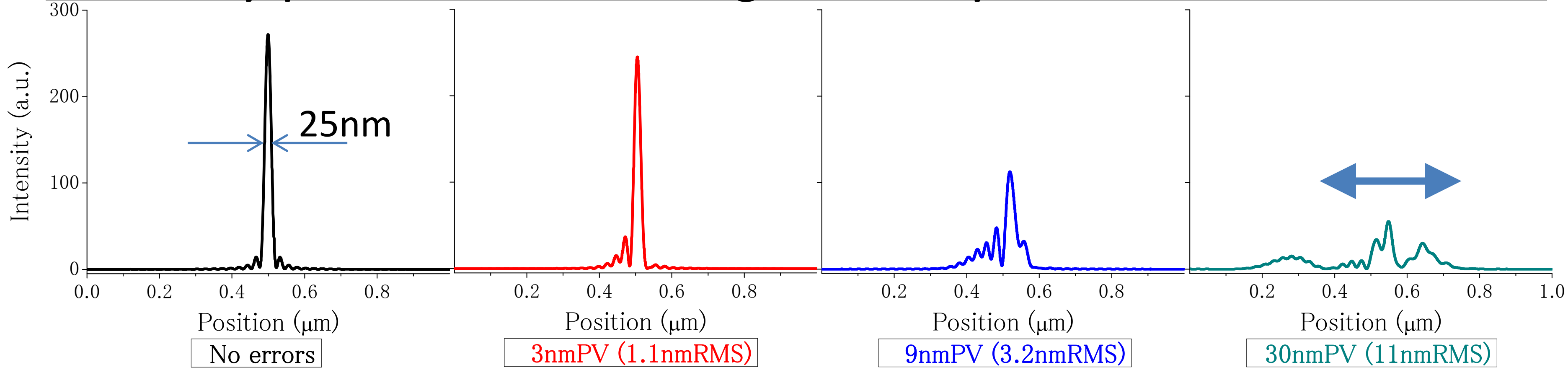


Designed surface



Errors of ***long*** range order

Intensity profiles of focusing beam by wavefront simulation

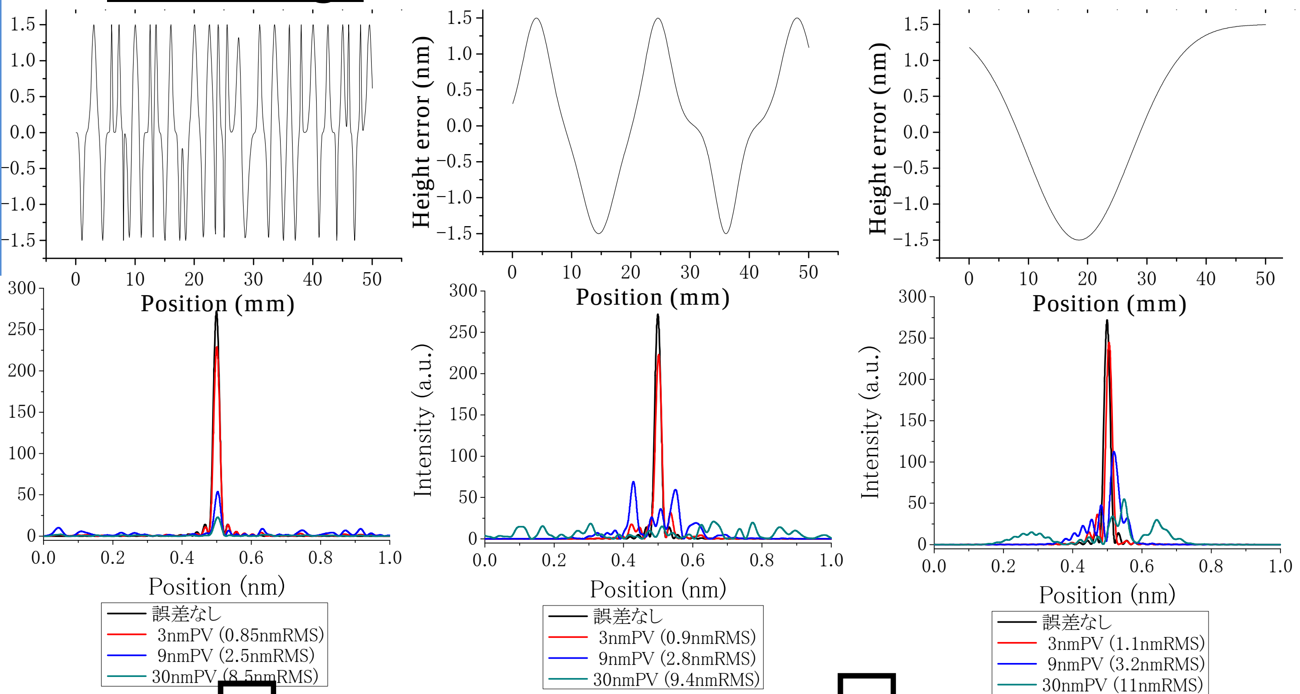


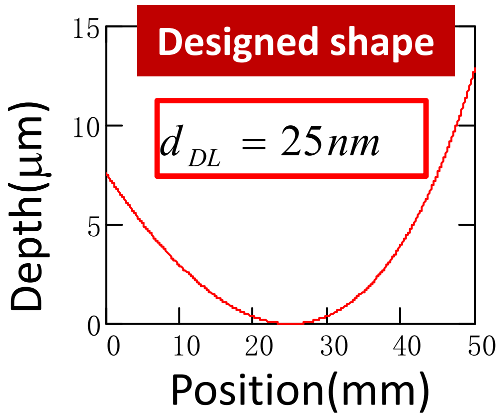
Errors of ***long*** range order ***loses shape***. → Figure

“ *estimation by wavefront simulation* ”

Figure error / **Intensity**

Short range | **Middle range** | **Long range**





Intensity reduced

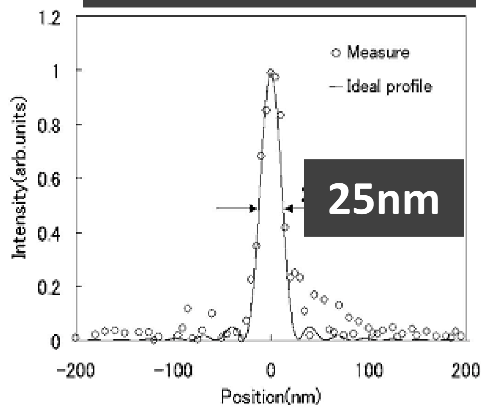
Shape loses

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.

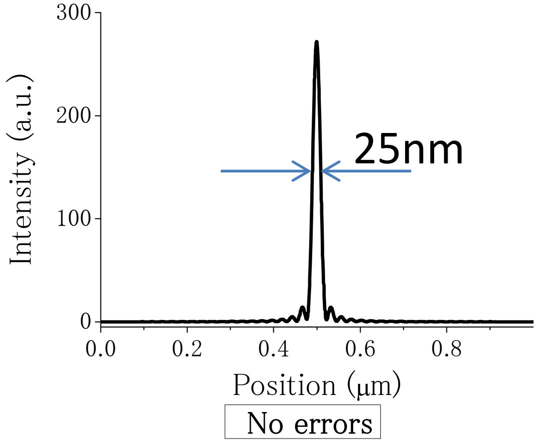
Performed 25nm



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

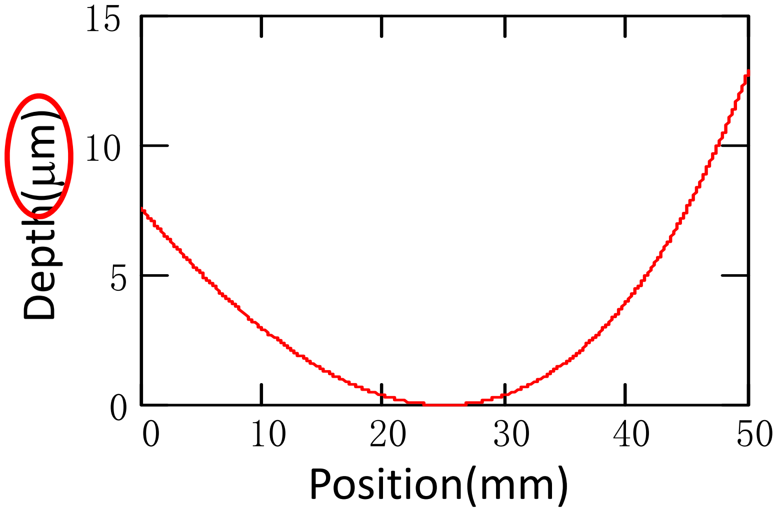
↓

X-ray mirrors

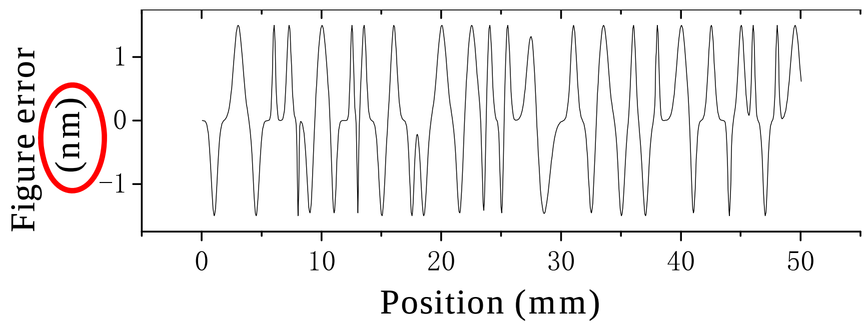
design, errors, metrology & alignment

How to evaluate the errors ?

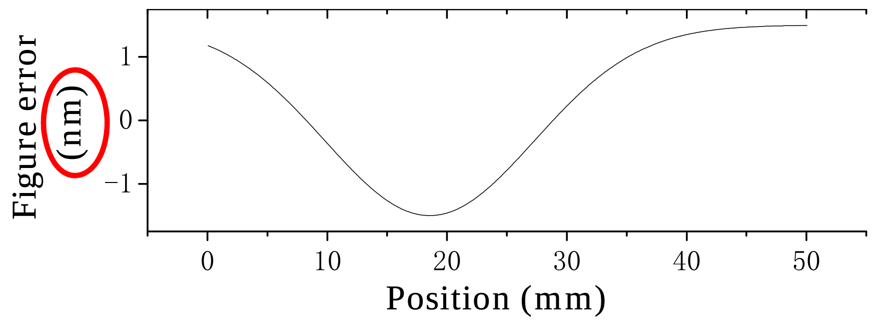
Designed surface



Errors (short range)



Errors (long range)



Metrology instruments for x-ray optics

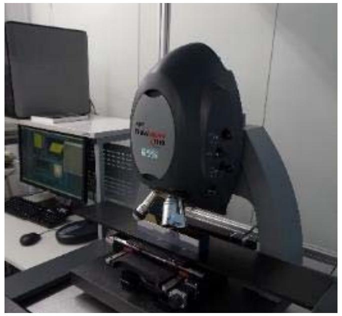
Field of view, lateral resolution

Short
～10 µm,
0.1 nm
Roughness

Scanning probe microscope

z (0.1nm)

Short / middle
～10 mm,
1 µm
Roughness, figure



Scanning white light interferometer

z (0.1nm)

Long / middle
～ 0.1 m,
0.1 mm
Figure

Fizeau interferometer

z (0.1nm)

Long / middle
～1m,
1 mm
Slope

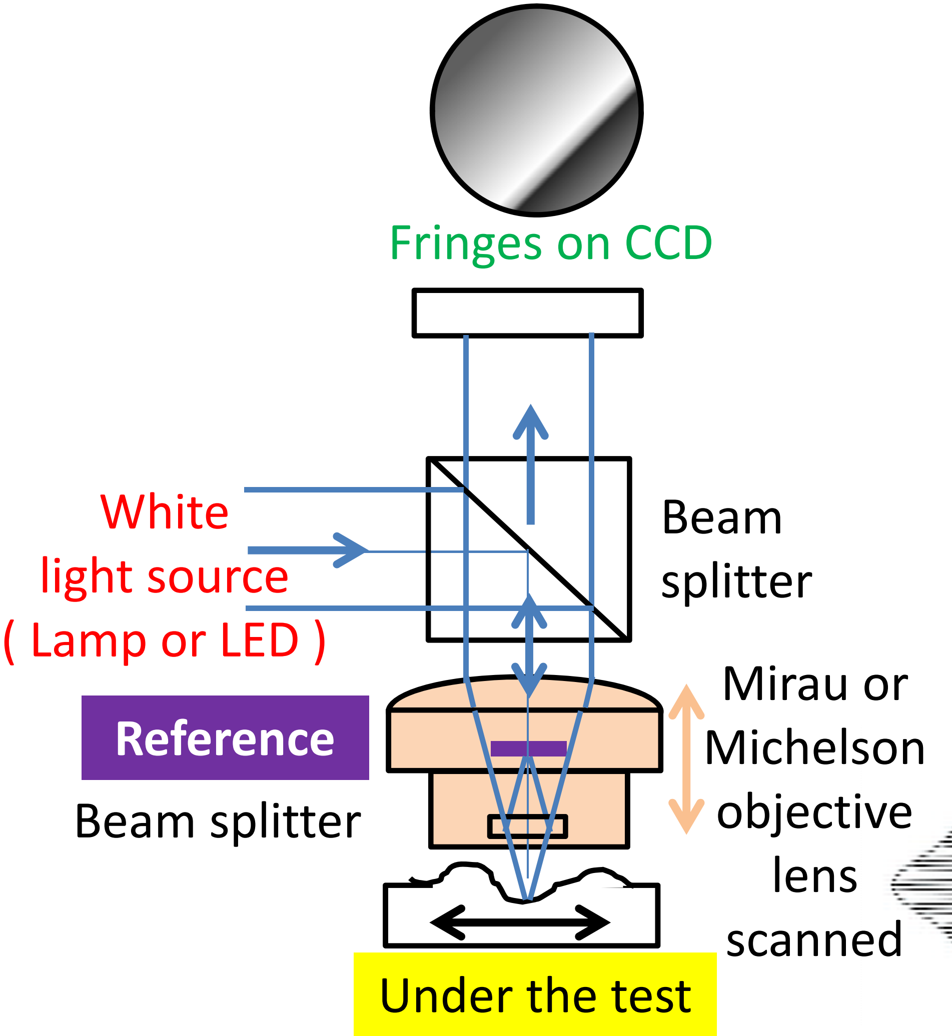
Long Trace Profiler (LTP)

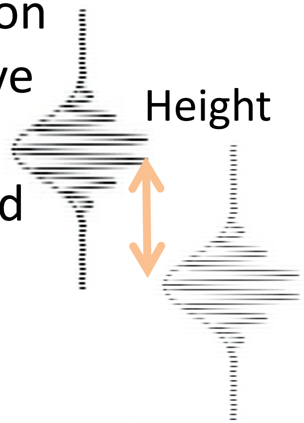
slope (0.1µrad)

Vertical resolution (rms)

Scanning white light interferometer

Interference fringe → **Height**

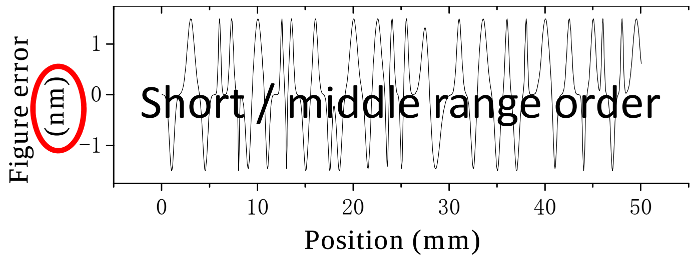




Zygo Corp. NewVeiw®,
Bruker AXS (Veeco) Contour GT® ....

__*Commercially available*__

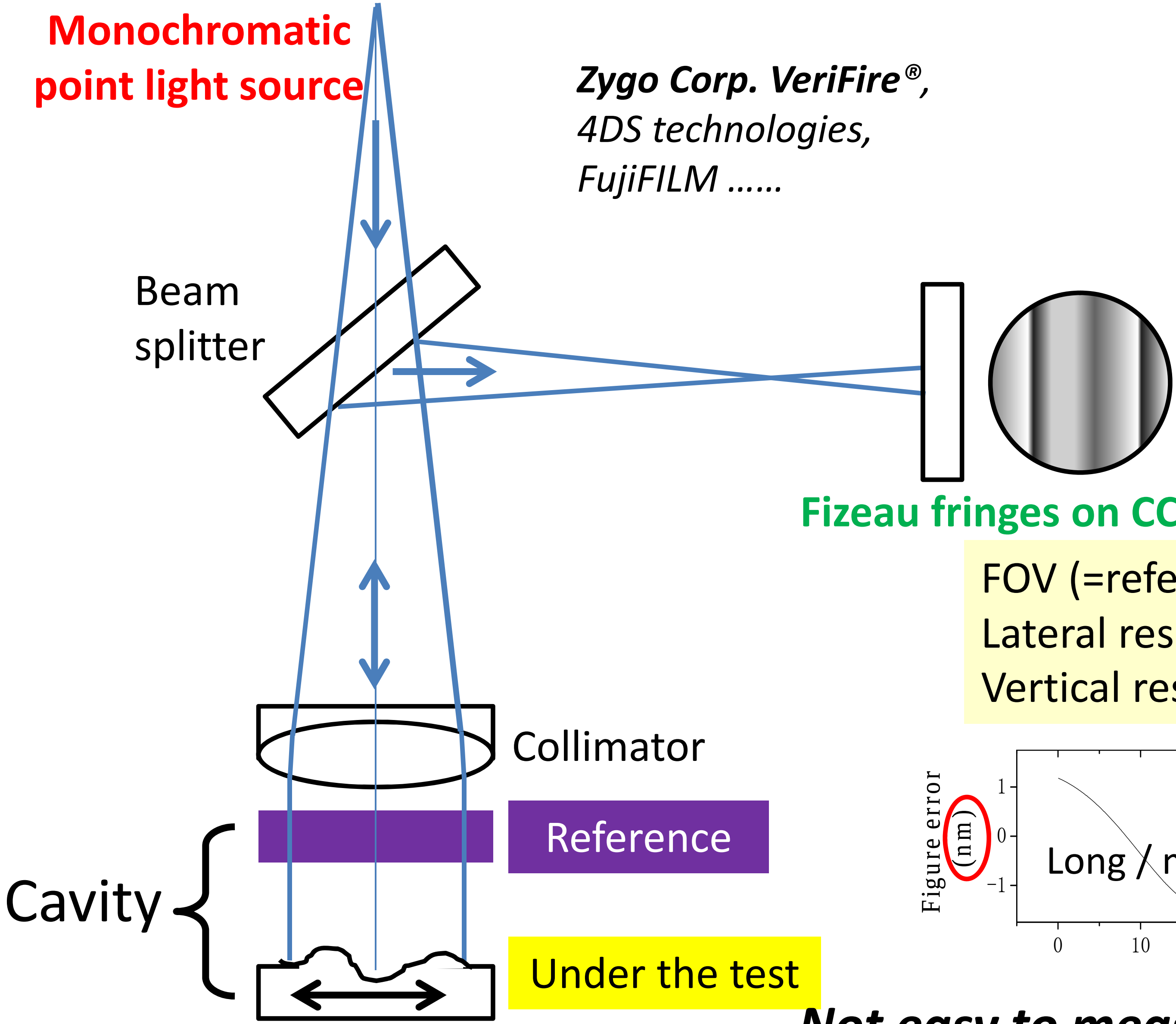
FOV (=lens) 50um～10 mm
Lateral resolution 1 µm～
Vertical resolution 0.1 nm



Fizeau interferometer

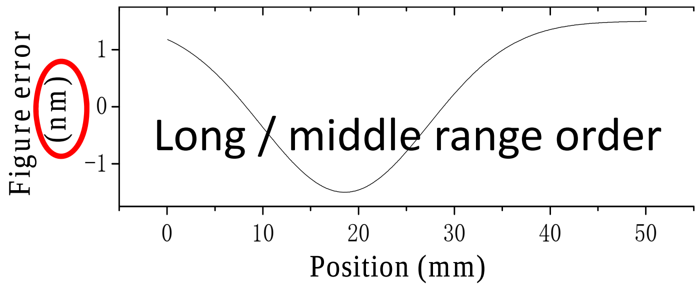
Interference pattern → **Height**

<u>*Commercially available*</u>



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

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

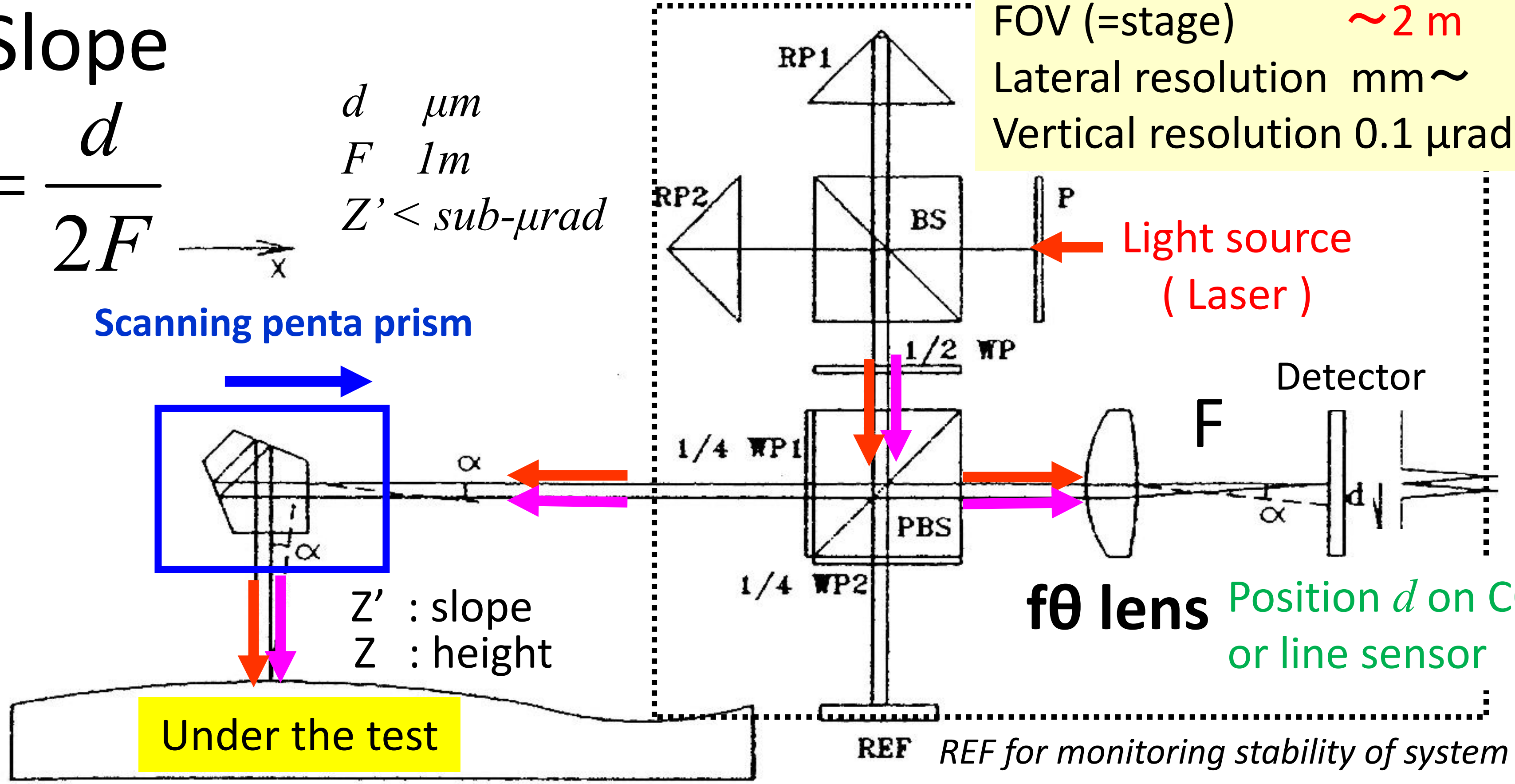
Direction of laser reflected on the surface → **Slope**

Slope

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

d μm
F 1m
$Z' <$ sub-μrad

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



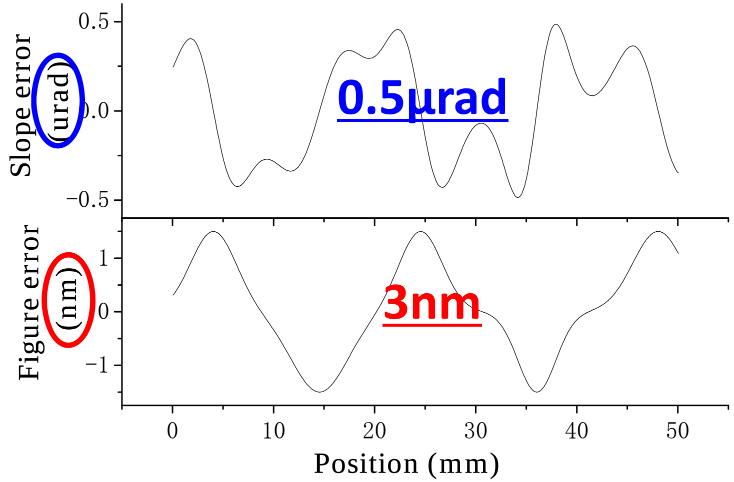
Easy to measure slope of sub-μrad on large mirror by NO reference

Many kinds of LTPs are developing among SR facilities.

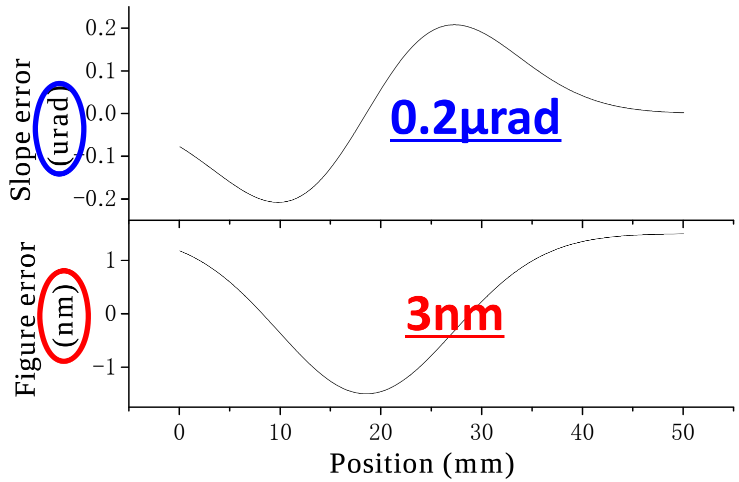
For example, S. Qian, G. Sostero and P. Z. Takacs, Opt. Eng. **39**, 304-310 (2000).

Figure error and slope error

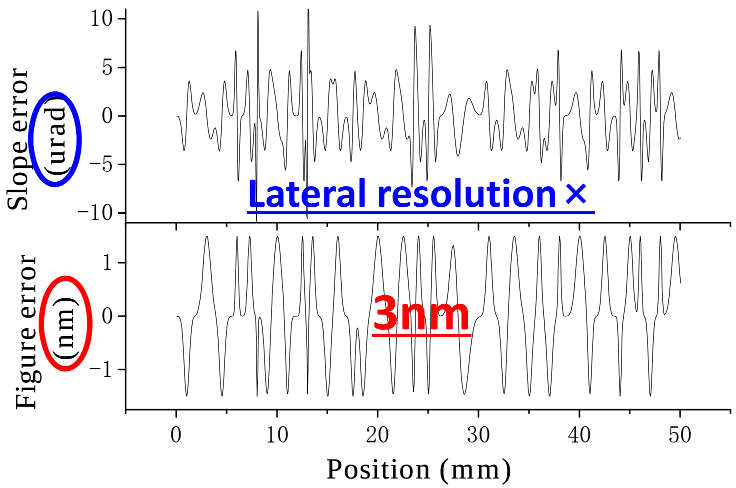
Errors (middle range)

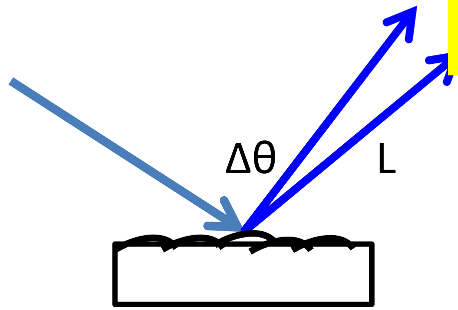


Errors (long range)



Errors (short range)





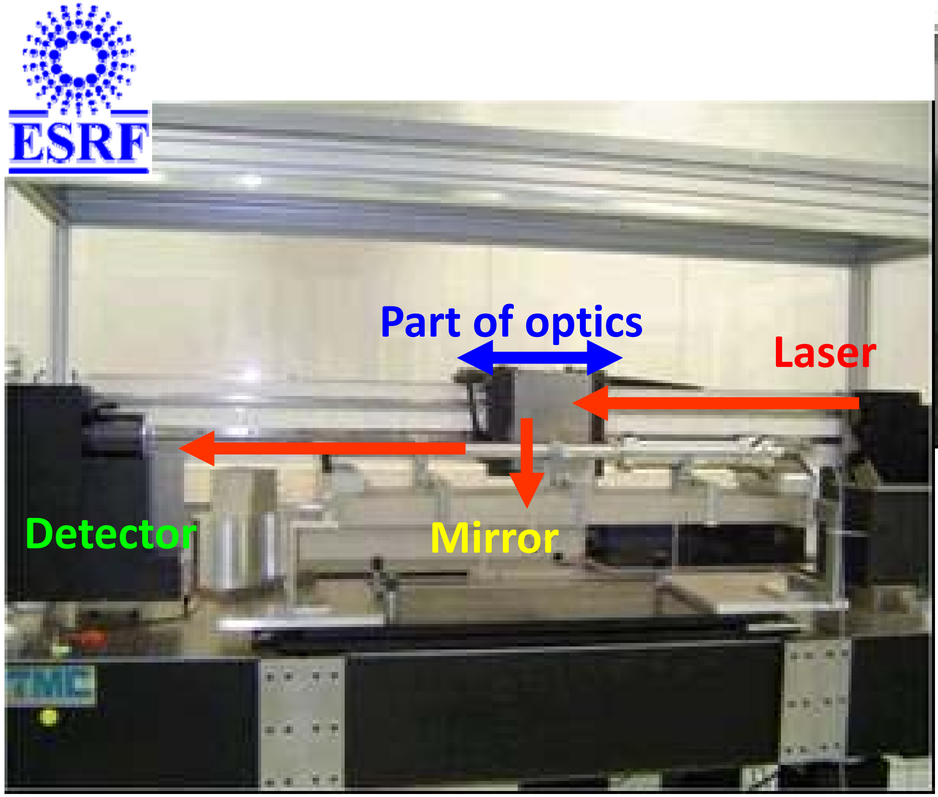
～Δθrms × L

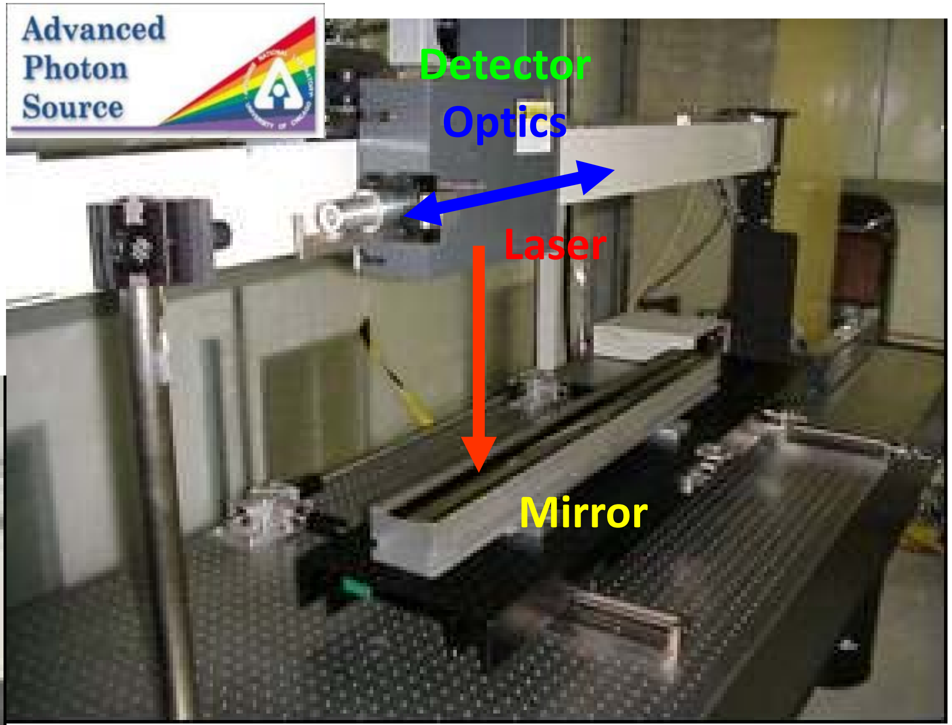
LTP :

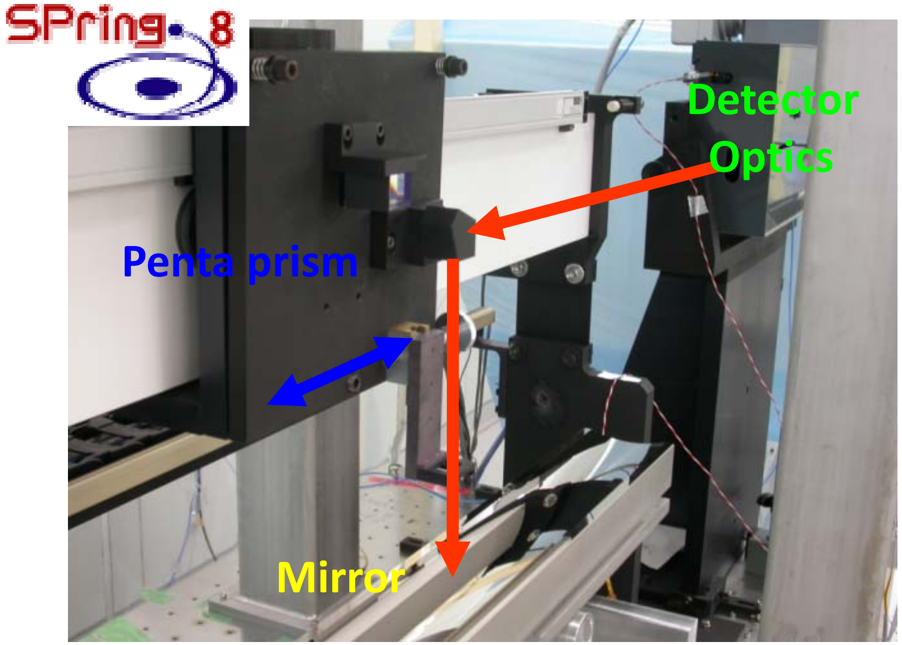
Lateral resolution mm～

Vertical resolution 0.1 μrad

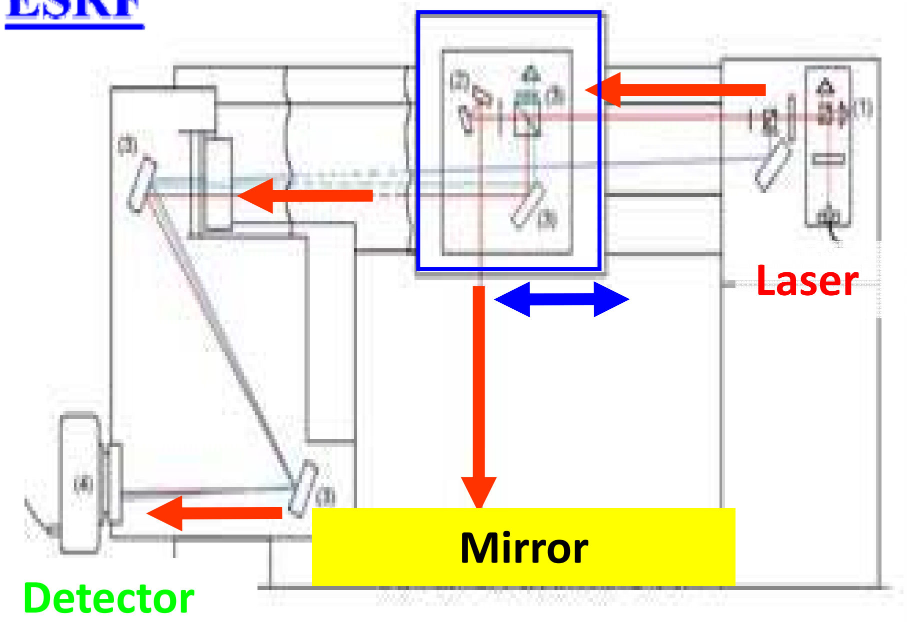
LTP
of ESRF, APS, SPring-8

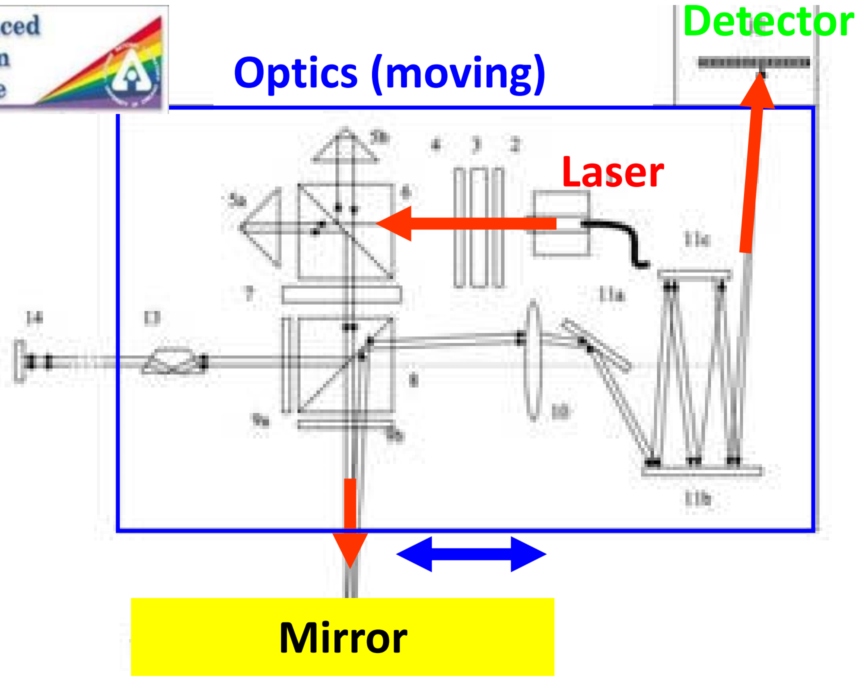


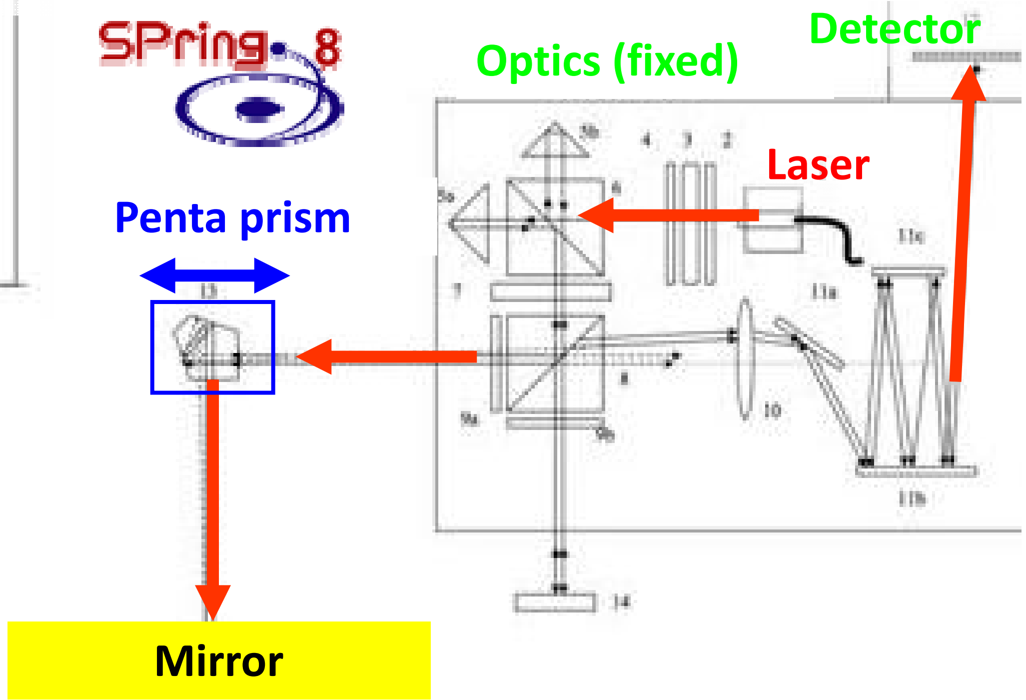




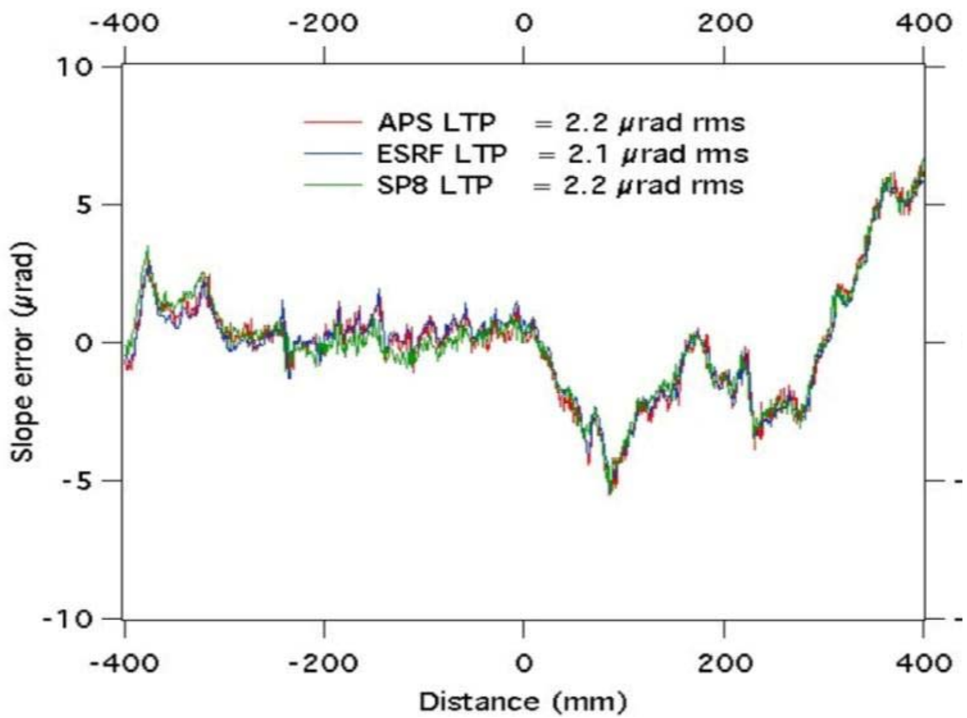
LTP
of ESRF, APS, SPring-8







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



Slope error profile

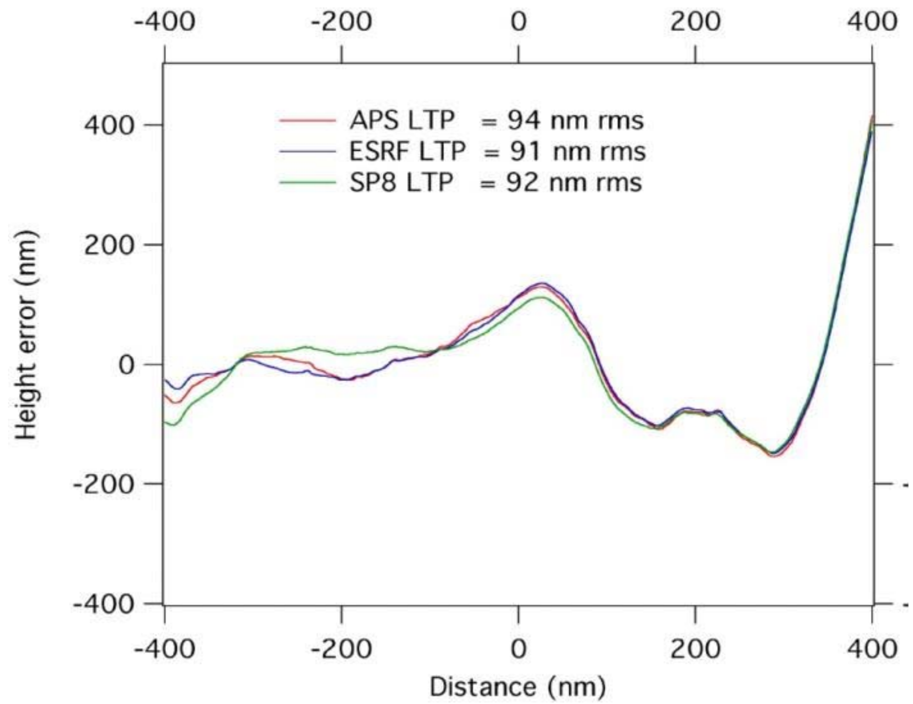


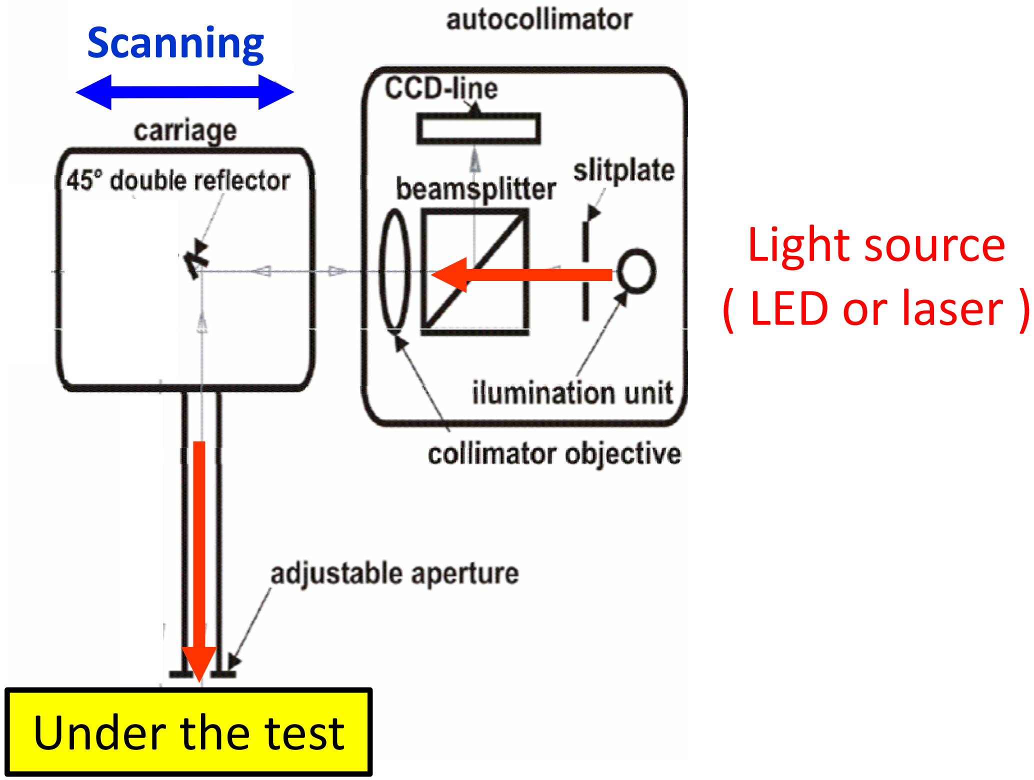
Figure error profile

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



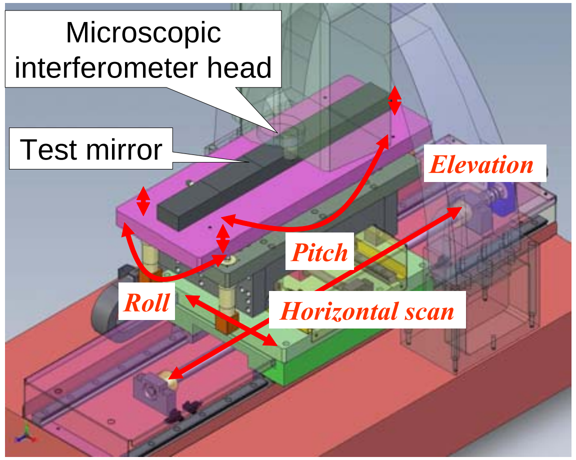
F. Siewert et al.: „The Nanometer Optic Component Measuring Machine: a new Sub-nm Topography " SRI 2003, AIP Conf. Proc.

Stitching interferometer for large mirror

Homemade

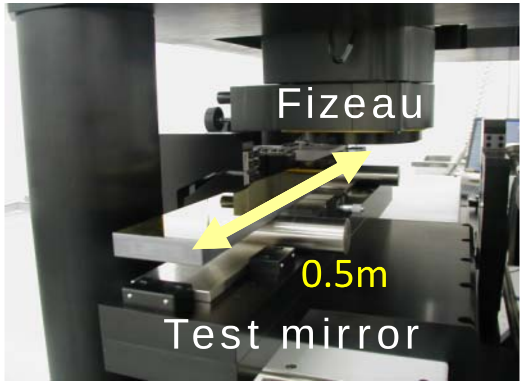
MSI

(micro-stitching interferometer)



RADSI

(relative angle determinable stitching interferometer)

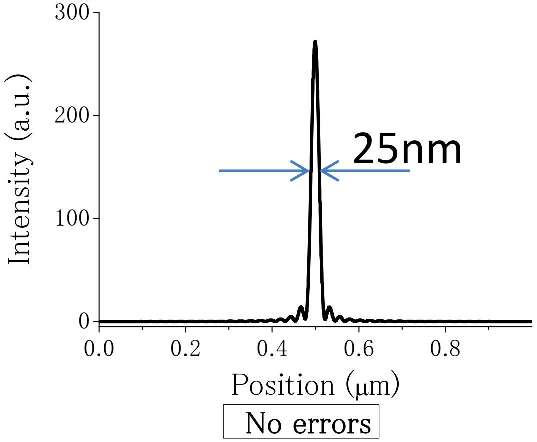


Collaboration with Osaka Univ., JTEC and SPring-8

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

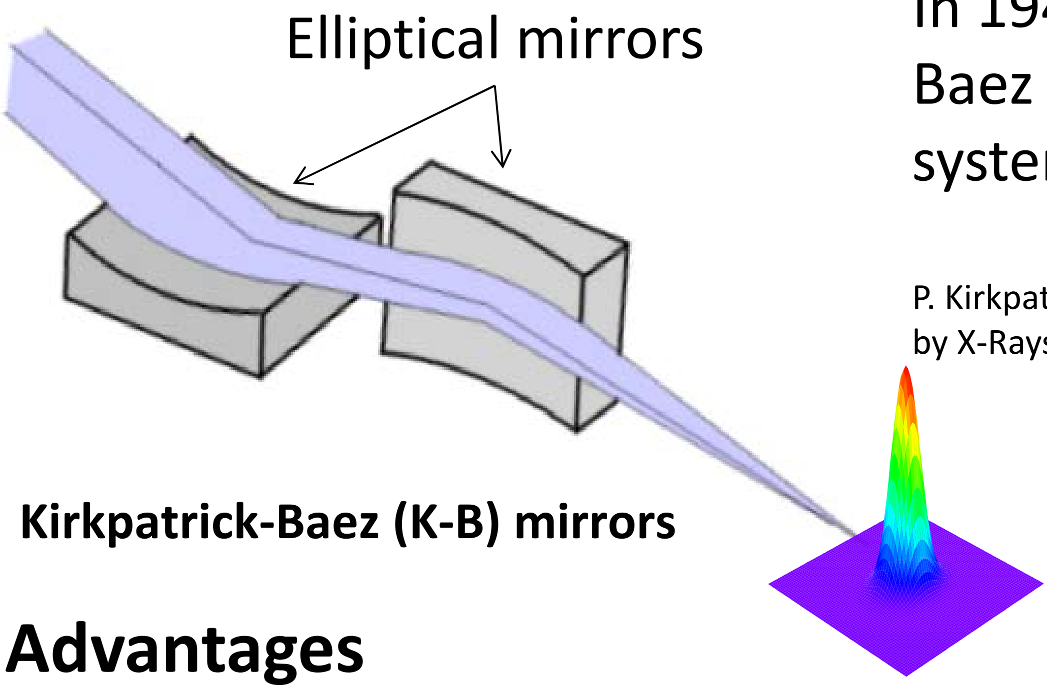
↓

<u>X-ray mirrors</u>

design, errors, metrology

& alignment

Introduction of KB mirrors



Kirkpatrick-Baez (K-B) 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

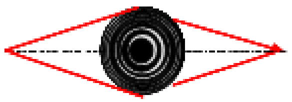
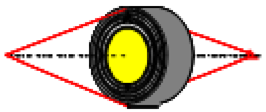
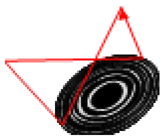
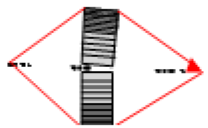
- Large acceptable aperture and High efficiency
- No chromatic aberration
- Long working distance

Disadvantages

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

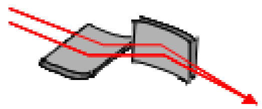
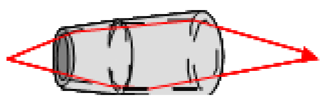
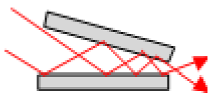
Suitable for x-ray nano-probe

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

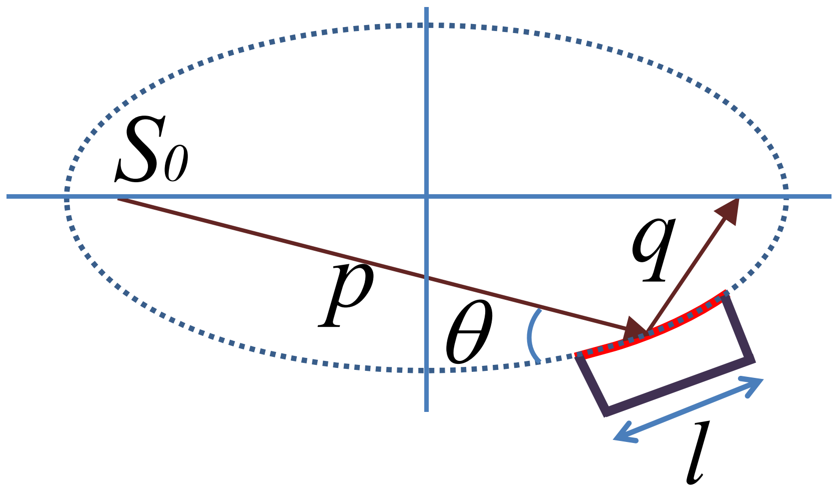
Refraction	focus size, focal length [energy]	energy range	aberration -coma -chromatic -figure error
 Pressed Lens	1.5 μm, f = 80 cm [18.4 keV], 1.6 μm, f = 1.3 m [15 keV]	mainly hard x-ray	-coma small -chromatic exist -figure error large
 Etching Lens	47nm × 55nm, f = 1cm, 2cm [21 keV]	mainly hard x-ray	-coma small -chromatic exist -figure error small

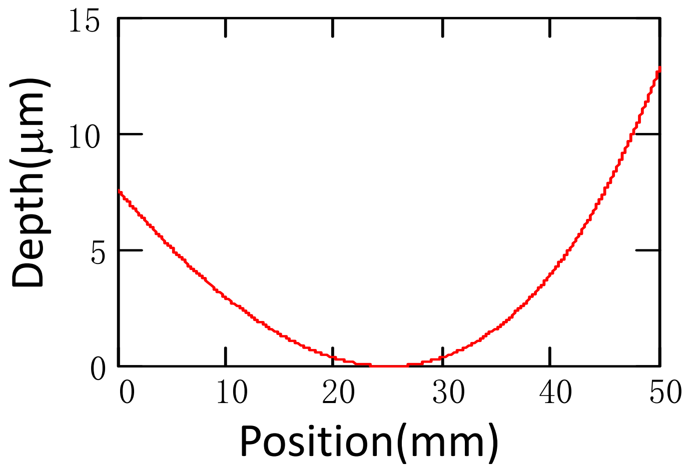
Reflection

 Kirkpatrick-Baez Mirror	7 nm × 8nm, 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)

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

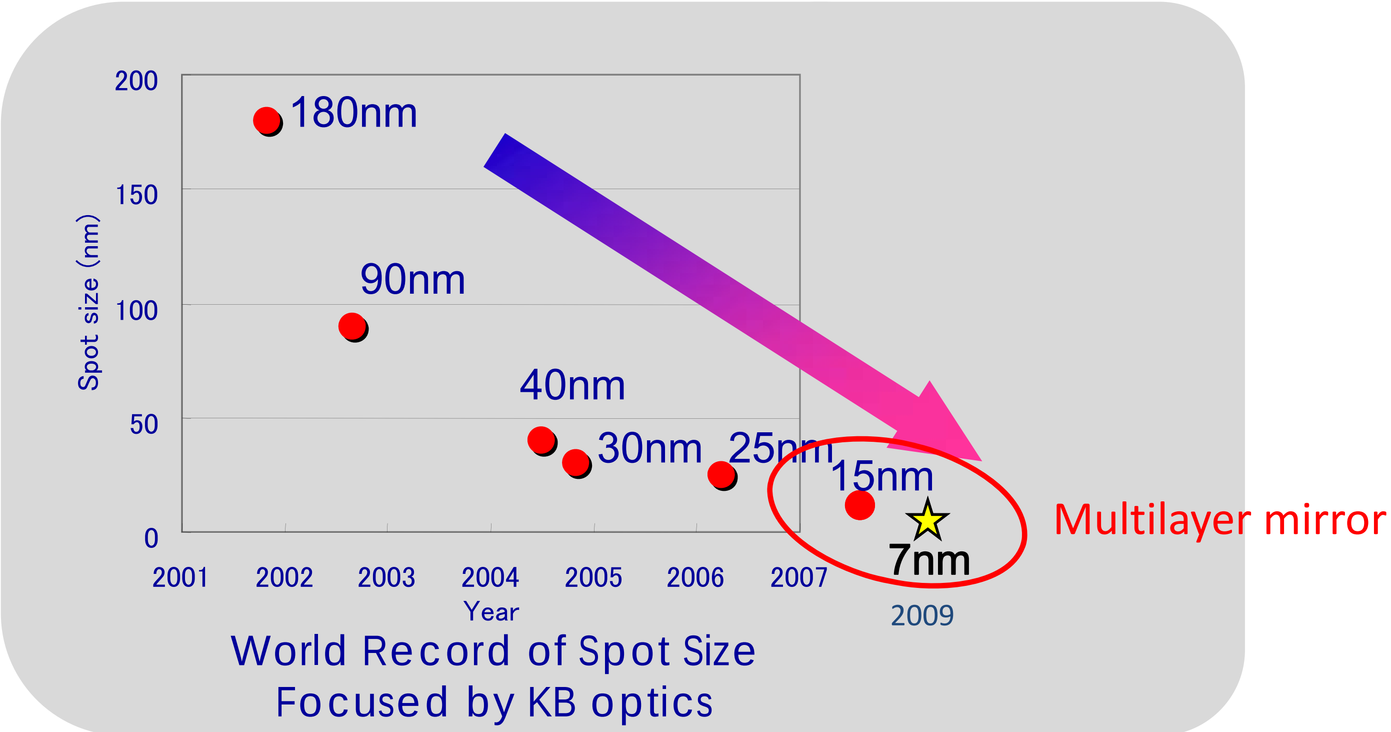
$p = 975\,m,\ q = 50\,mm,\ \theta = 3\,mrad,\ l = 50\,mm,\ \lambda = 0.083\,nm,\ S_0 = 100\,\mu m$

Mag. = 1 / 19500 !

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

<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

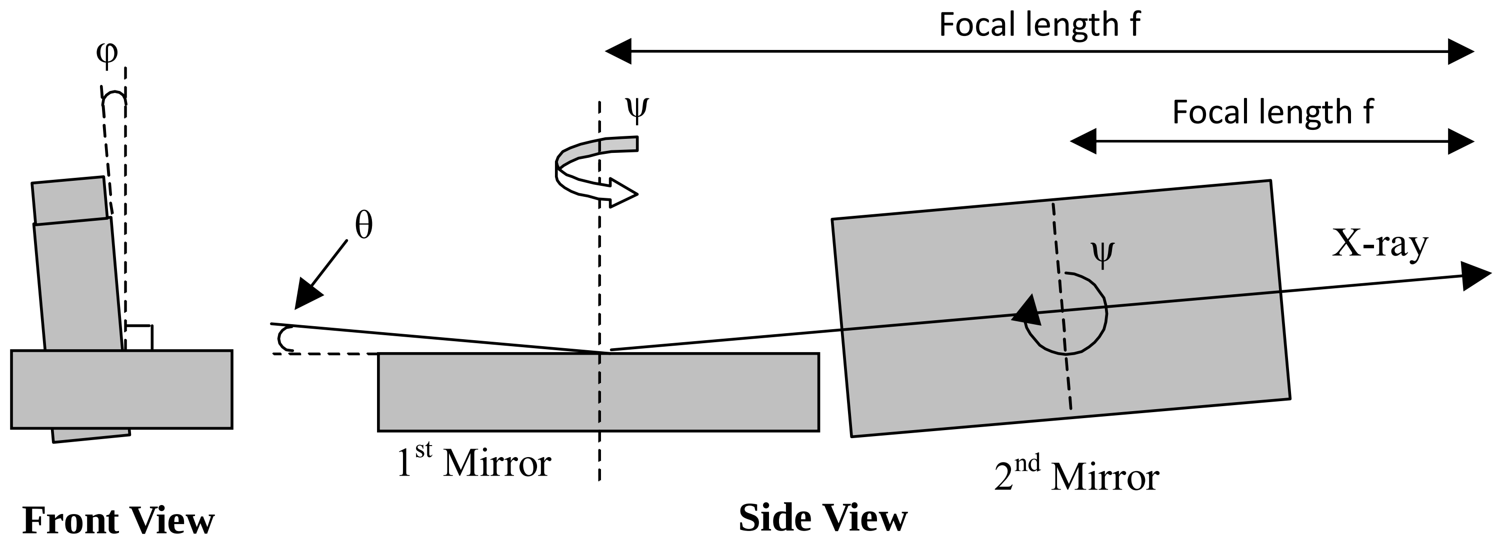


World Record of spot size is **7** nm (by Osaka Univ., in 2009 *).

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).

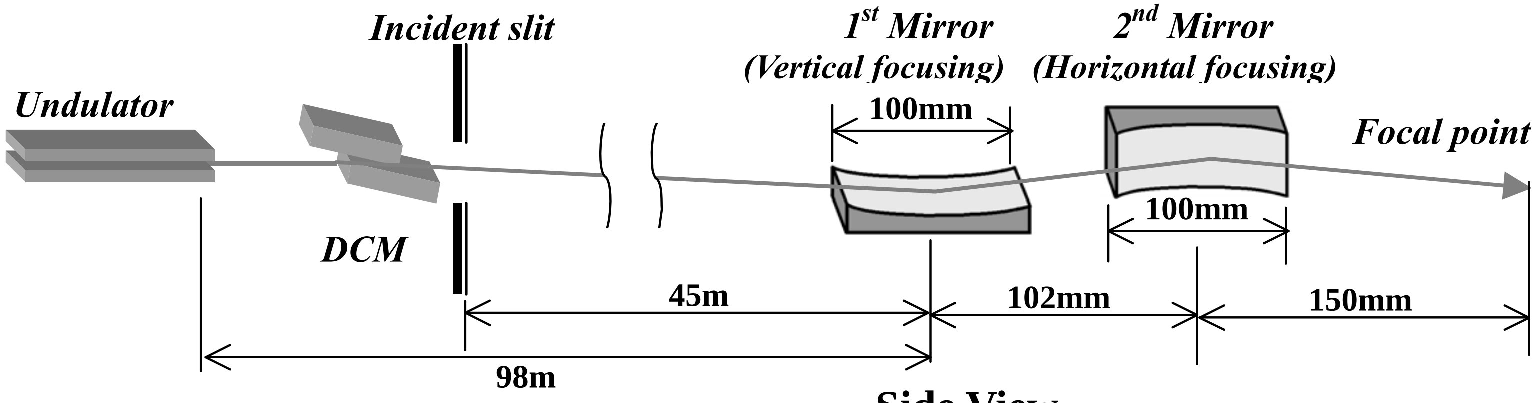
Difficulty in mirror alignments



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

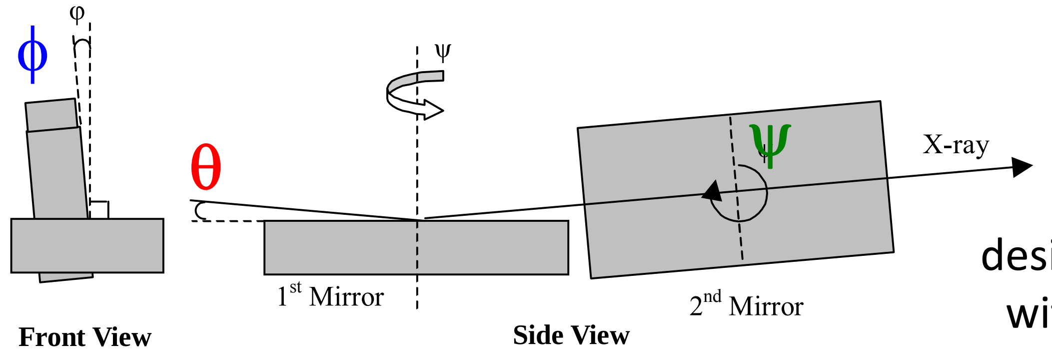


Side View

	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	0.75×10^{-3}	1.20×10^{-3}
Coefficient *a* of elliptic function (mm)	23.876×10^{3}	23.825×10^{3}
Coefficient *b* of elliptic function (mm)	13.147	9.609
Diffraction limited focal size (nm, FWHM)	48	29

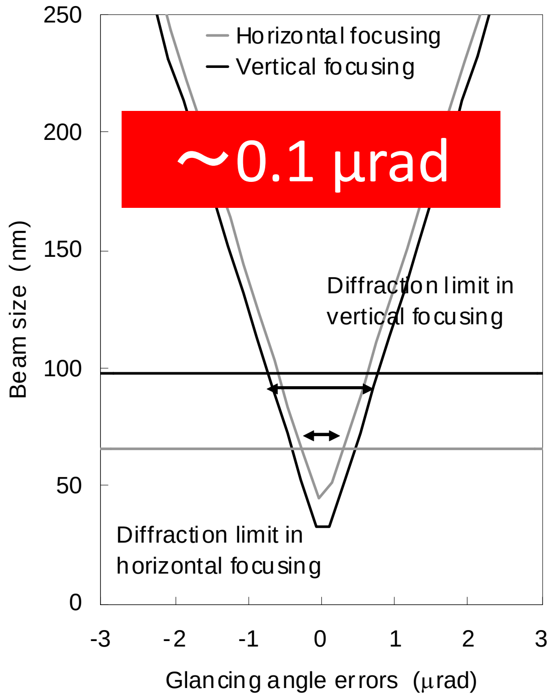
Ref :H. Mimura, H. Yumoto, K. Yamauchi et.al, Appl. Phys. Lett. **90**, 051903 (2007).

Tolerance limits of mirror alignments

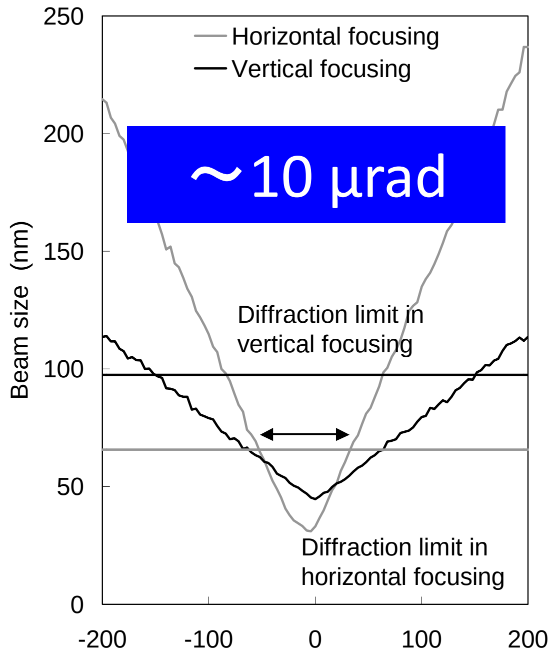


Severe positioning of two mirrors is required.

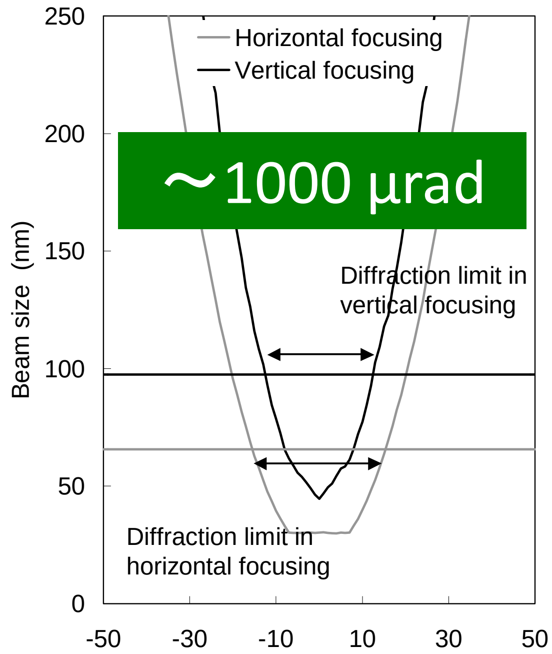
The manipulator should be designed for these freedom of axis with the resolution & the range.



Errors of θ



Perpendicularity errors Δϕ (μrad)

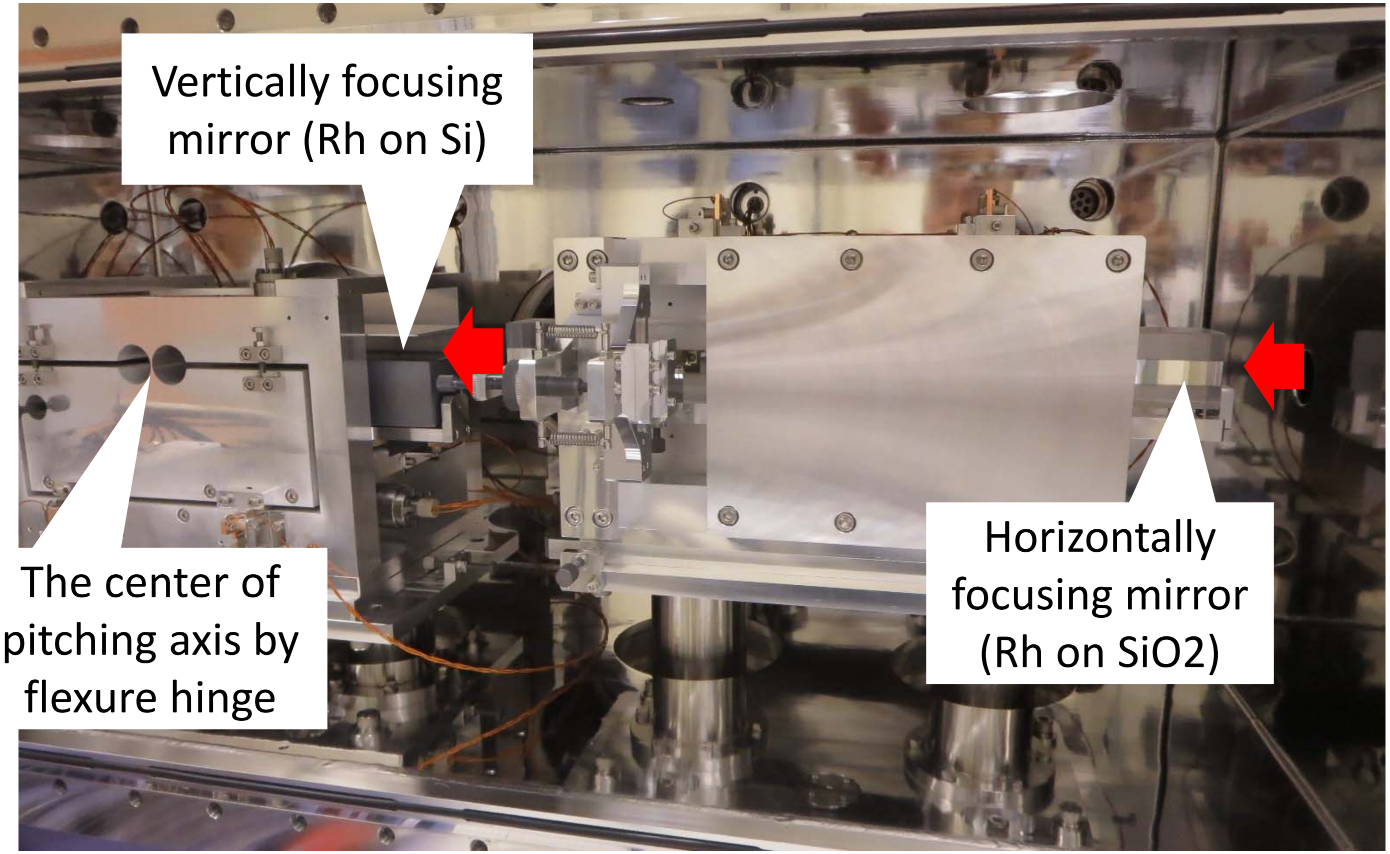


In-plane rotation errors Δψ (mrad)

<u>Freedom of axis, Resolution, range</u>

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).

A typical manipulator of KB optics

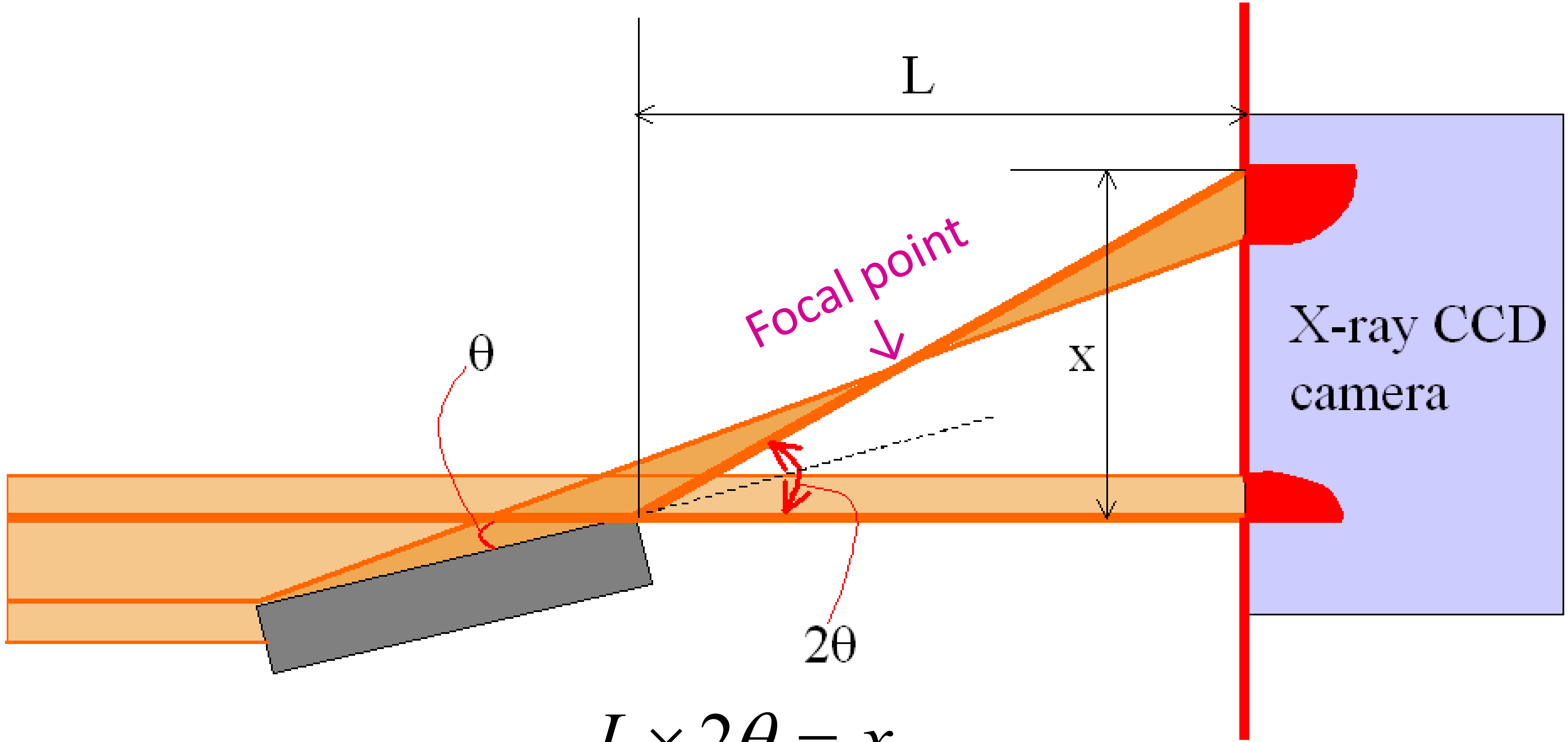


- ✓ Precise manipulation of mirrors
- ✓ Highly stable system
- ✓ Ultra-high vacuum (or He environment)

For example,

- ☐ *Resolution of pitching axis = 0.1 μrad*
  → *Res. of the actuator at 100 mm = 10 nm*
- ☐ *The focal length = 1 m and beam size = 1 μm*
  → *Angular stability of the mirror ～0.1 μrad*

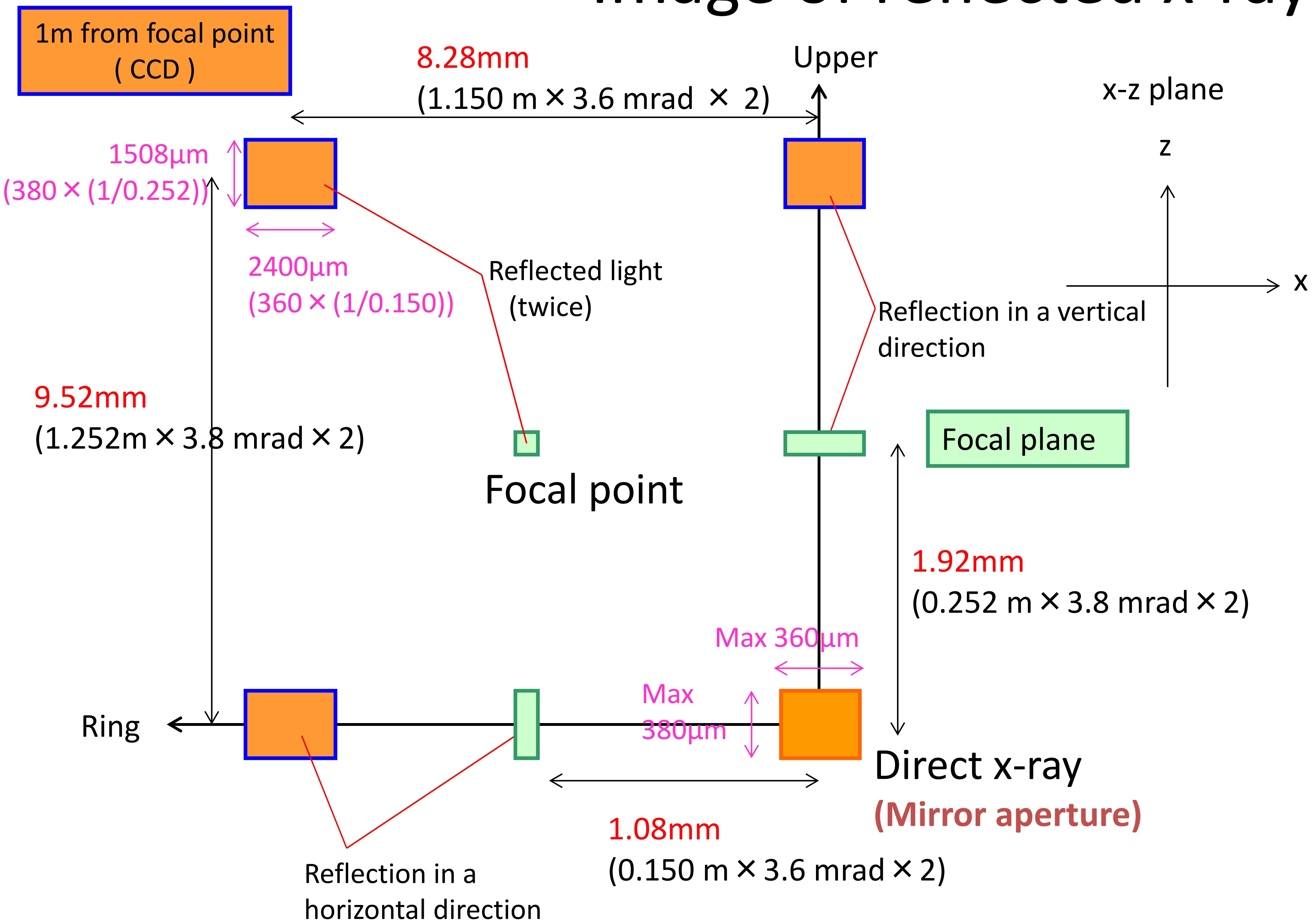
Image on X-ray CCD camera



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

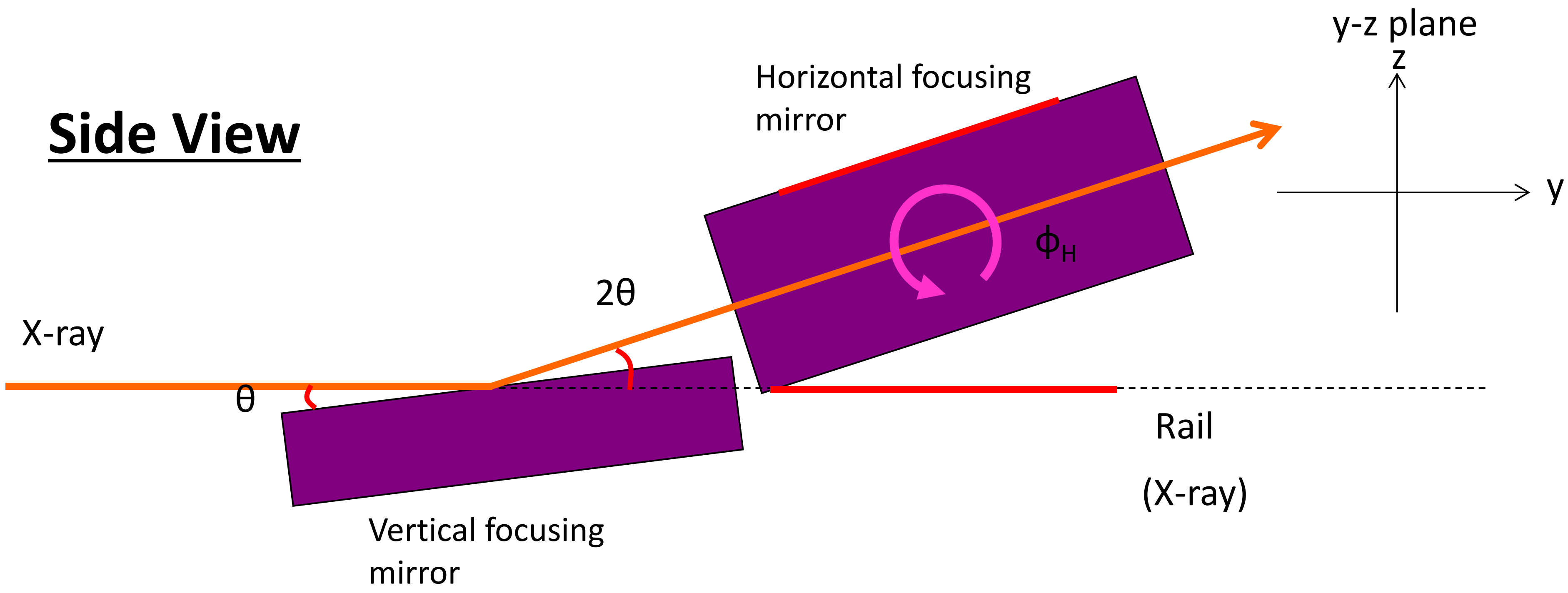
$$\theta = \frac{x}{2L}$$

Image of reflected x-ray



Alignment

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**

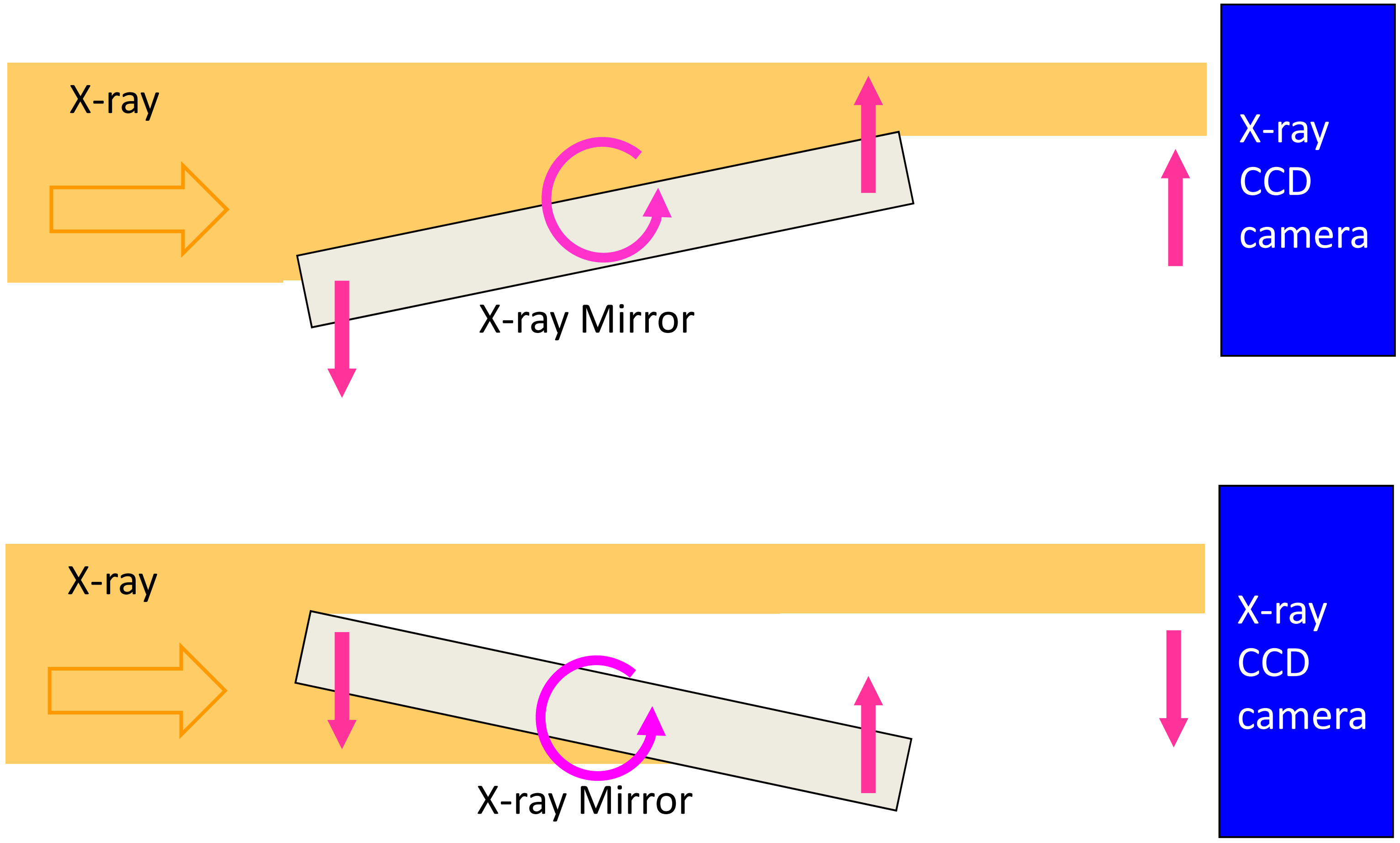
Rough assessment of focusing beam profile.
This method is used for *seeking focal point*.

・**Wire (Knife-edge) scan method**

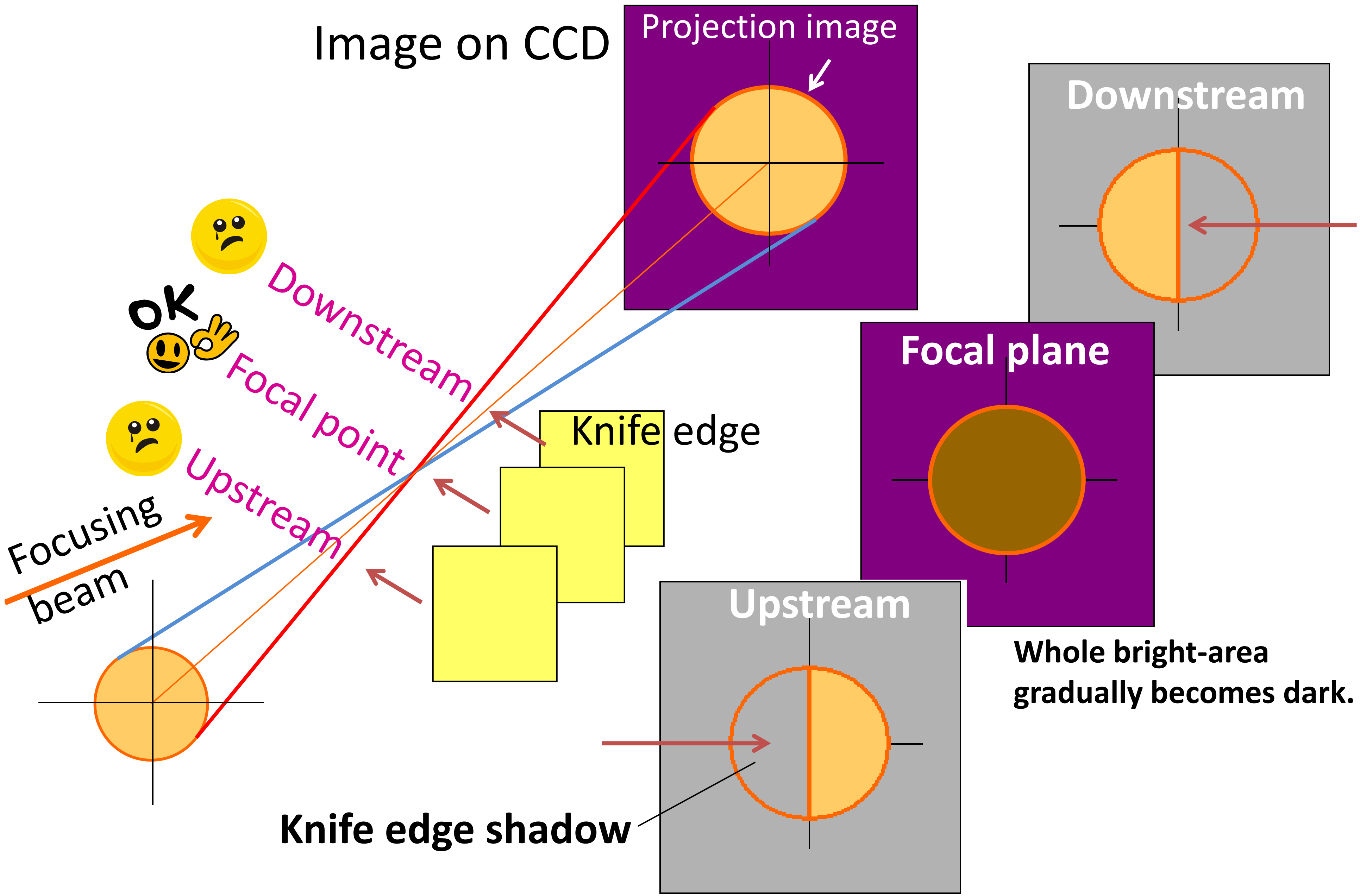
Final assessment of *focusing beam profile*.

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



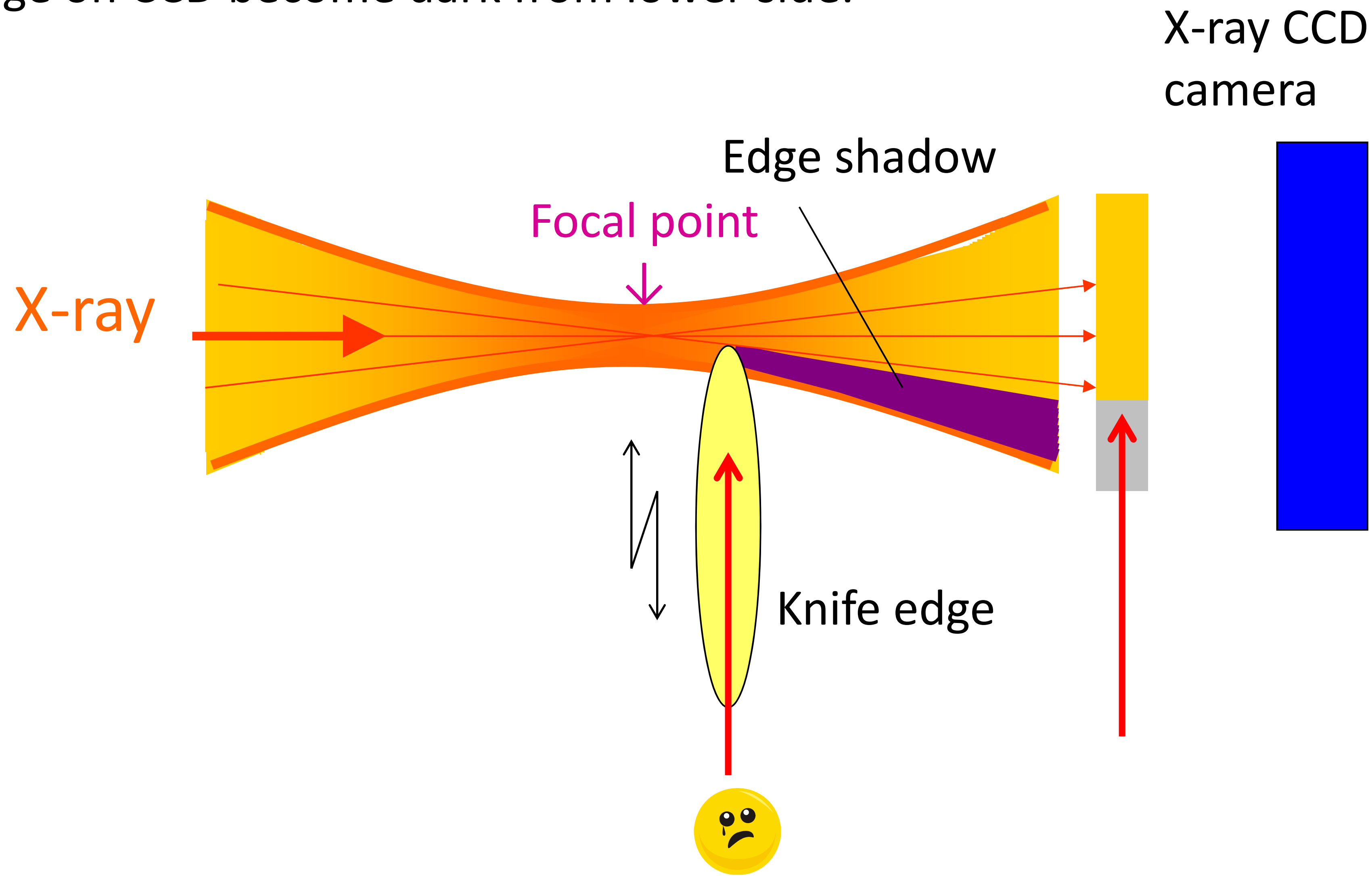
Foucault test



Foucault test 1

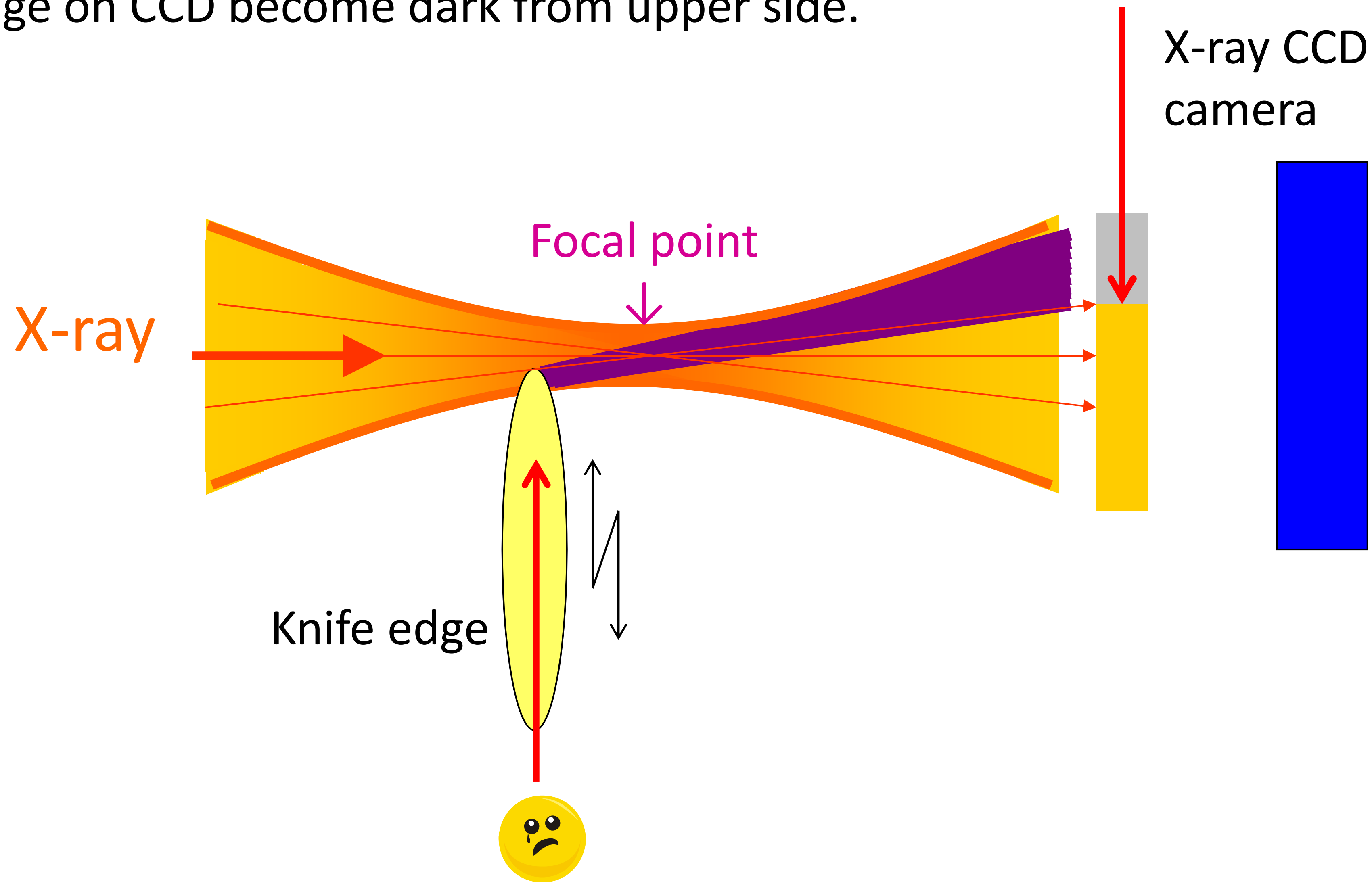
Alignment

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



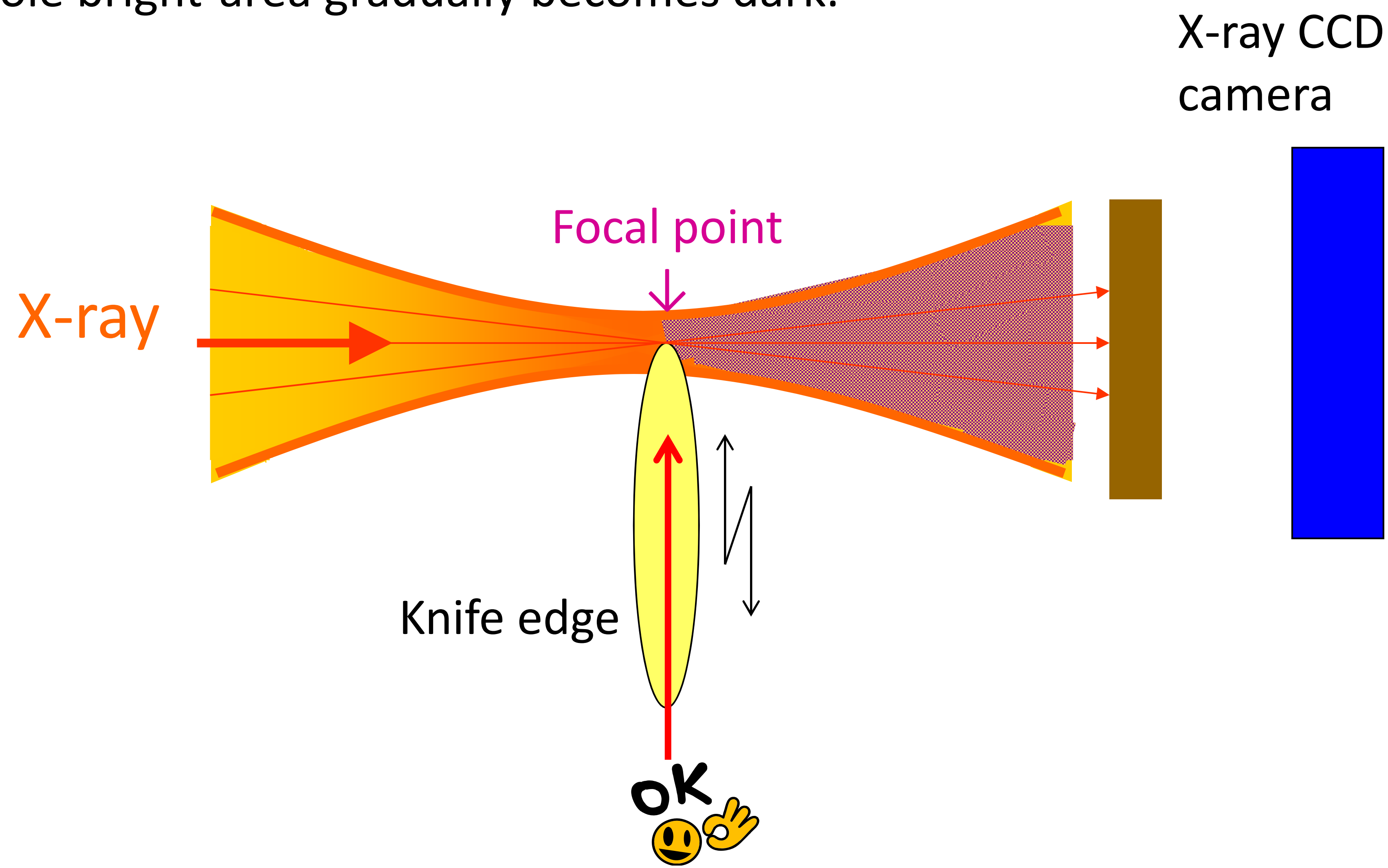
Foucault test 2

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



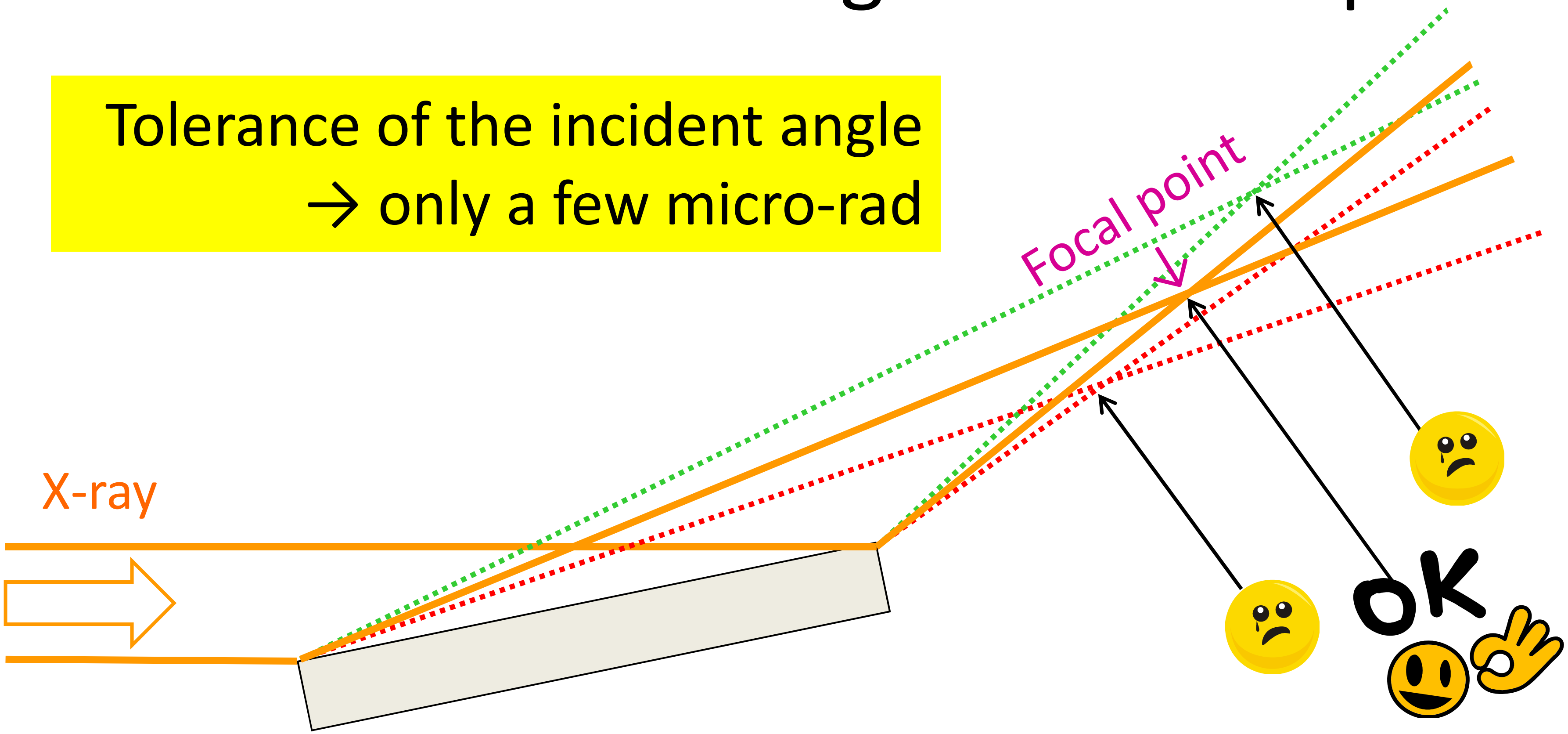
Foucault test 3

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



Relationship between incident angle and focal position

Tolerance of the incident angle
→ only a few micro-rad

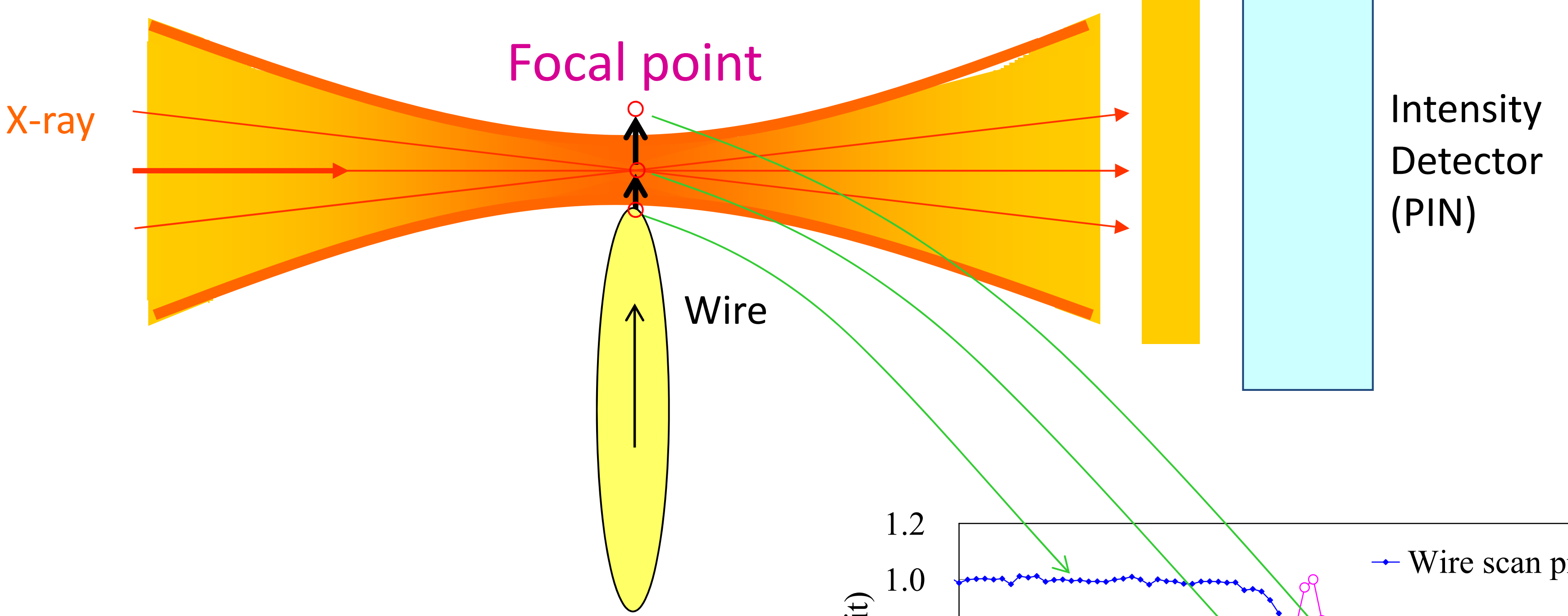


Incident angle→Large ⇒ Focal point → downstream

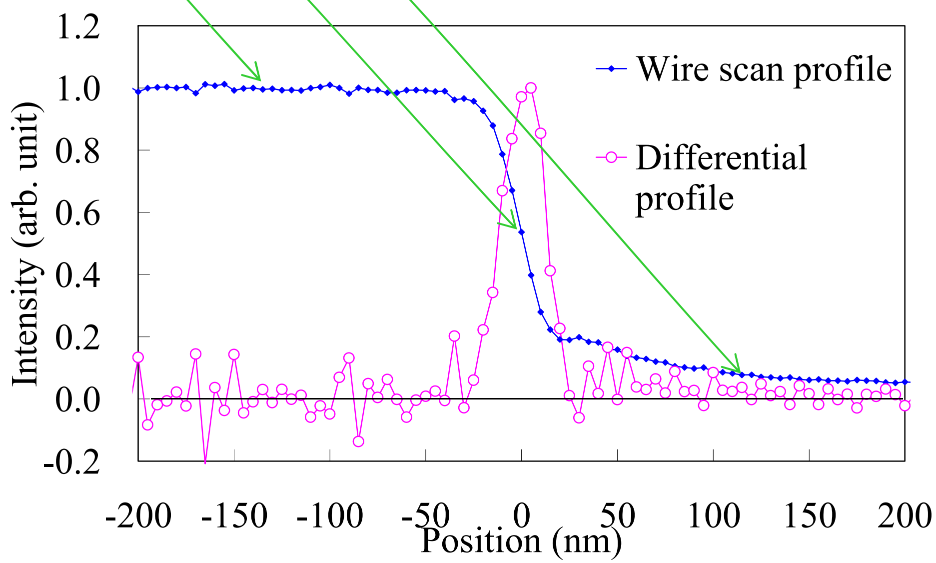
Incident angle→Small ⇒ Focal point → upstream

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.

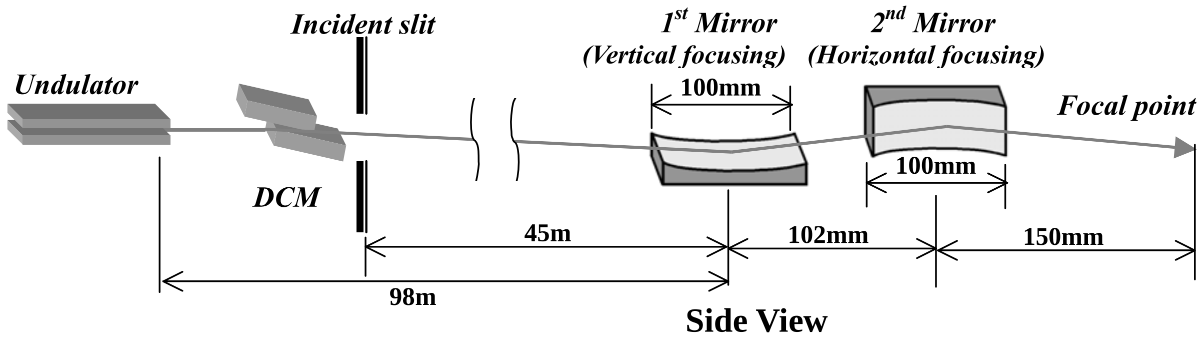


The line-spread function of the focused beam was derived from the numerical differential of the measured knife-edge scan profiles.



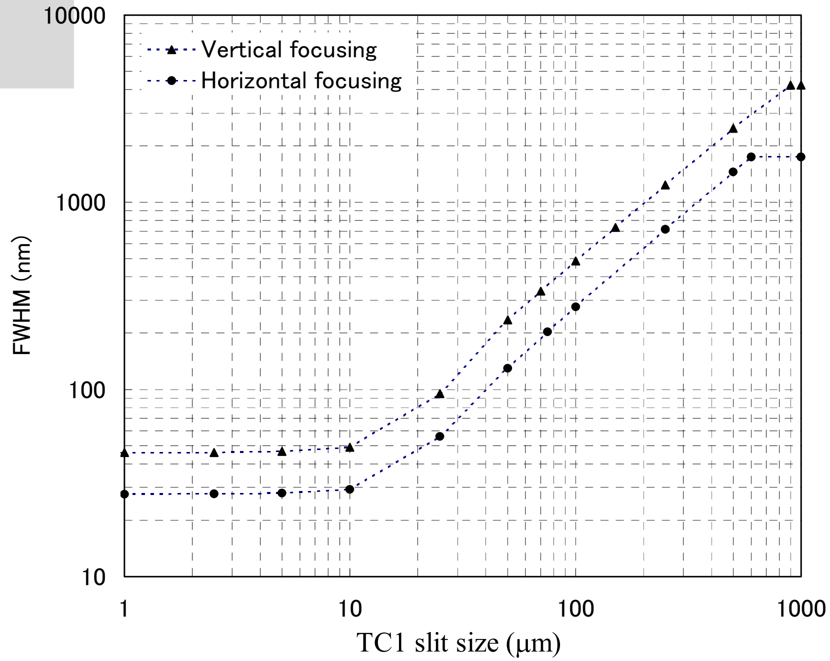
Relationship between Beam size and Source size

<u>Beam size changes depending on source size (or virtual source size).</u>

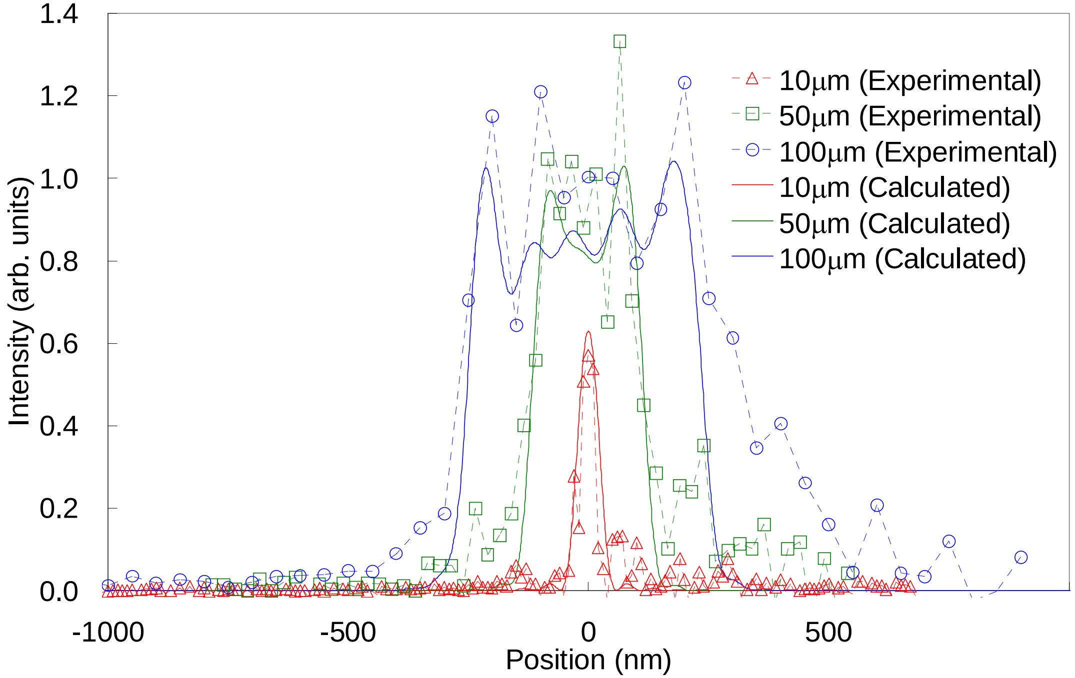


Beam size = Source size / M (M: demagnification)
AND
Beam size ≥ Diffraction limit

Beam size is selectable for each application.

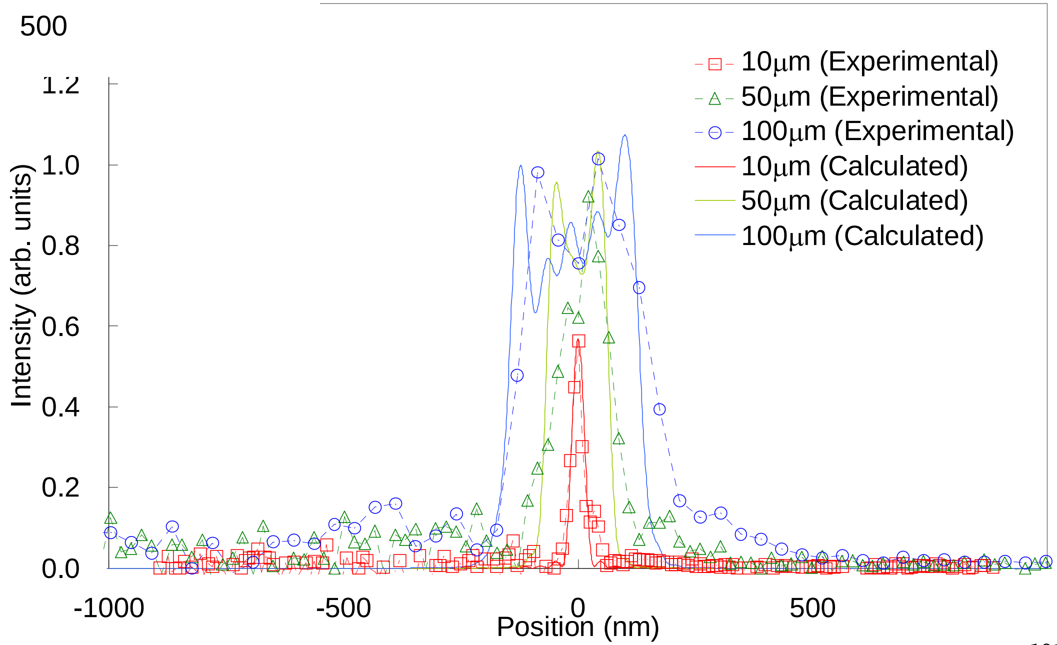


Relationship between Beam size and Source size

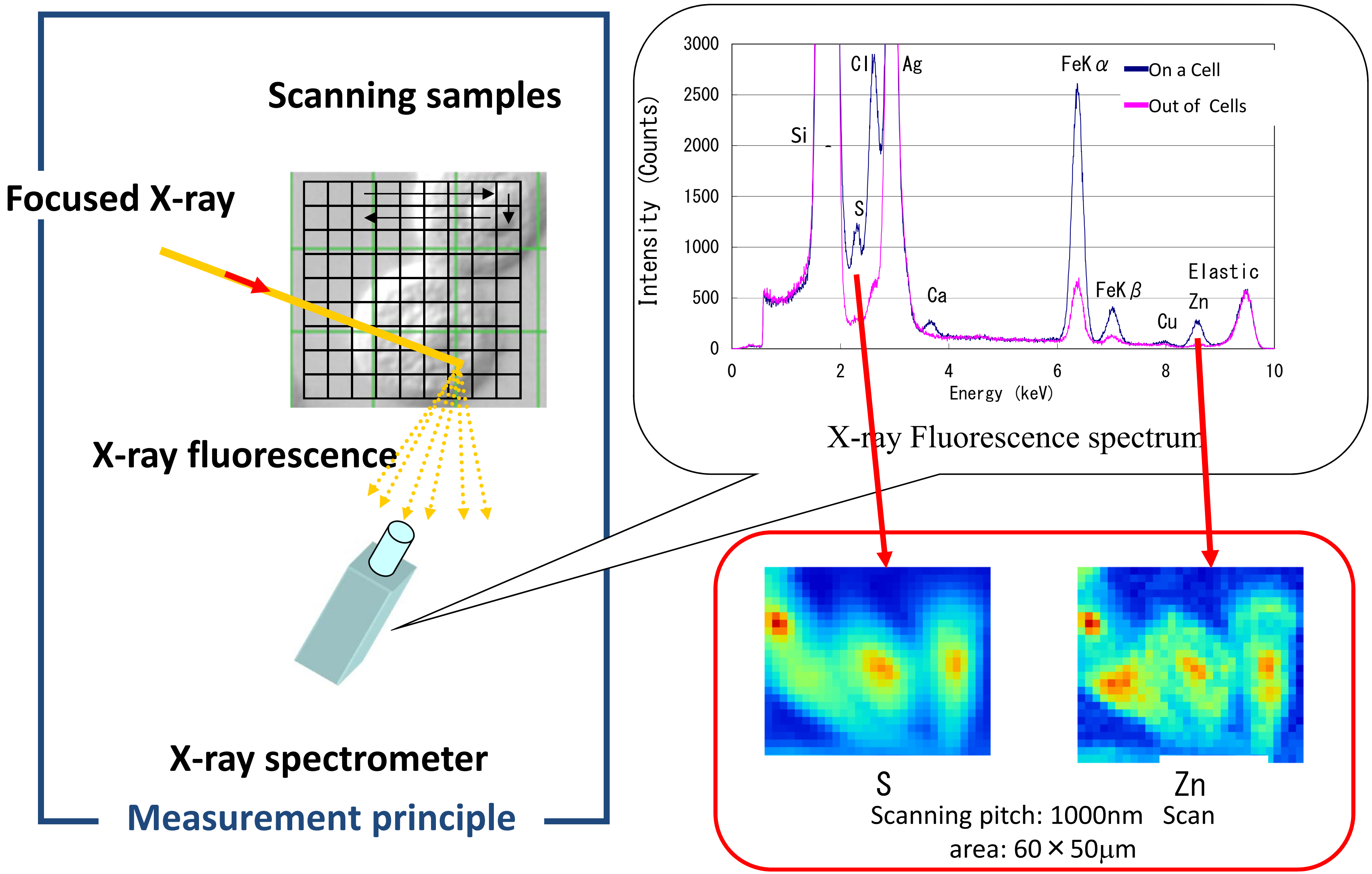


Vertical focusing

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

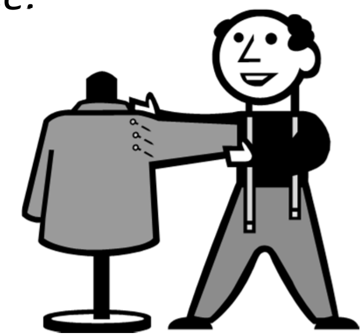
4. *To specify the tolerance of designed parameters*

   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 & applications)

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

Design components

- ✓ **End station**
- ✓ **Sample environment**
- ✓ **Detector, data processing …**

(pressure, temperature, magnetic field…)
(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 …)
- ✓ Radiation damage (cable, tube)
- ✓ Contamination on optics

- ✓ Electricity, water, air, network, control
- ✓ Environments

Management of the beamline construction

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 operated.
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 …

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(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!