Beam Line – X-Rays

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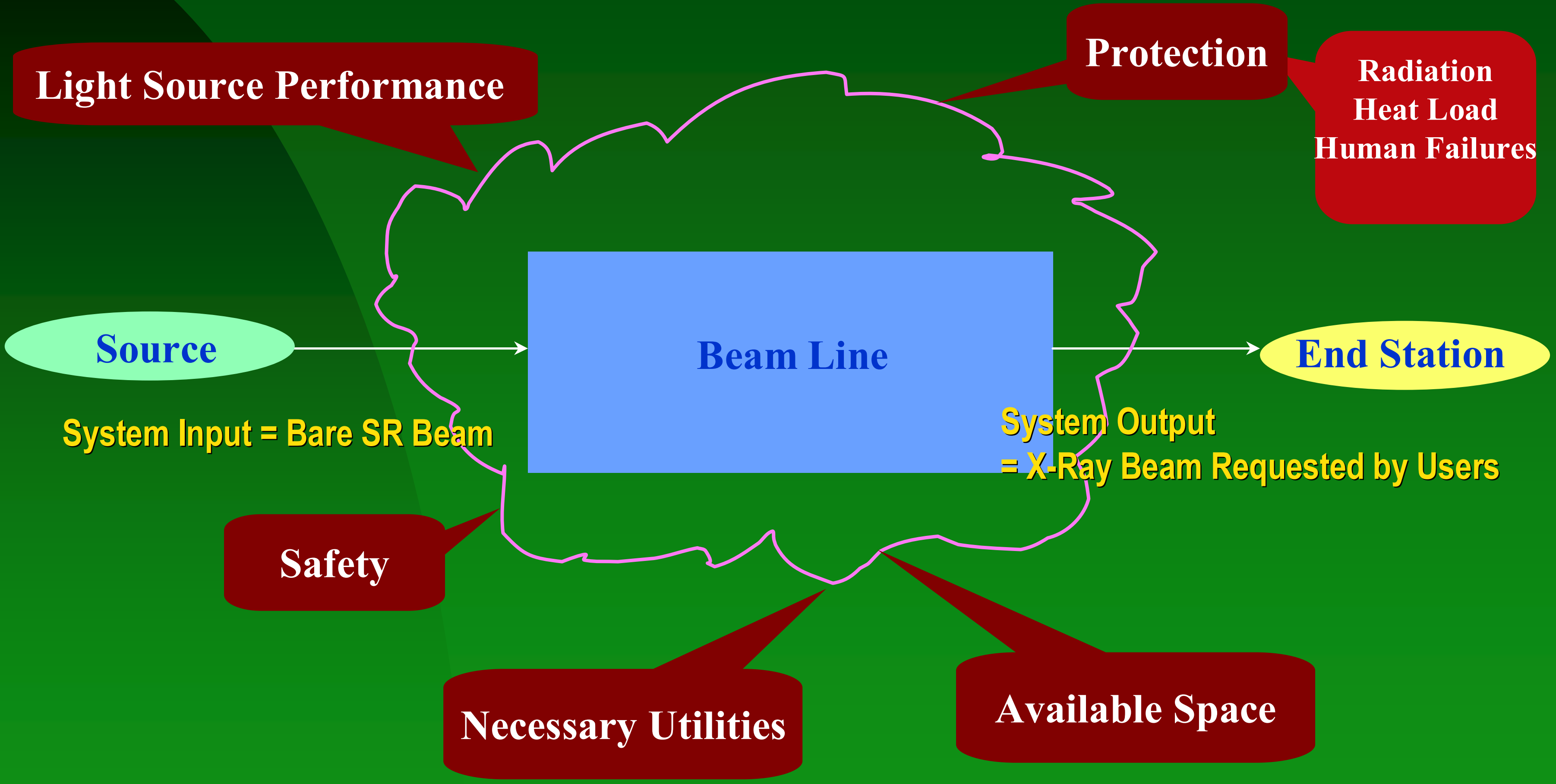
Part 1. General Discussion

Part 2. Beamline X-Ray Optics

Introduction

- In the 1st part, general aspects of x-ray beamlines are presented.
- The 2nd part is devoted to the discussion of x-ray optics for beamlines, including some detail of double-crystal x-ray monochromators.

Beamline as an Optical System



Light Source Performance

Protection

Radiation
Heat Load
Human Failures

Source

Beam Line

End Station

System Input = Bare SR Beam

System Output
= X-Ray Beam Requested by Users

Safety

Necessary Utilities

Available Space

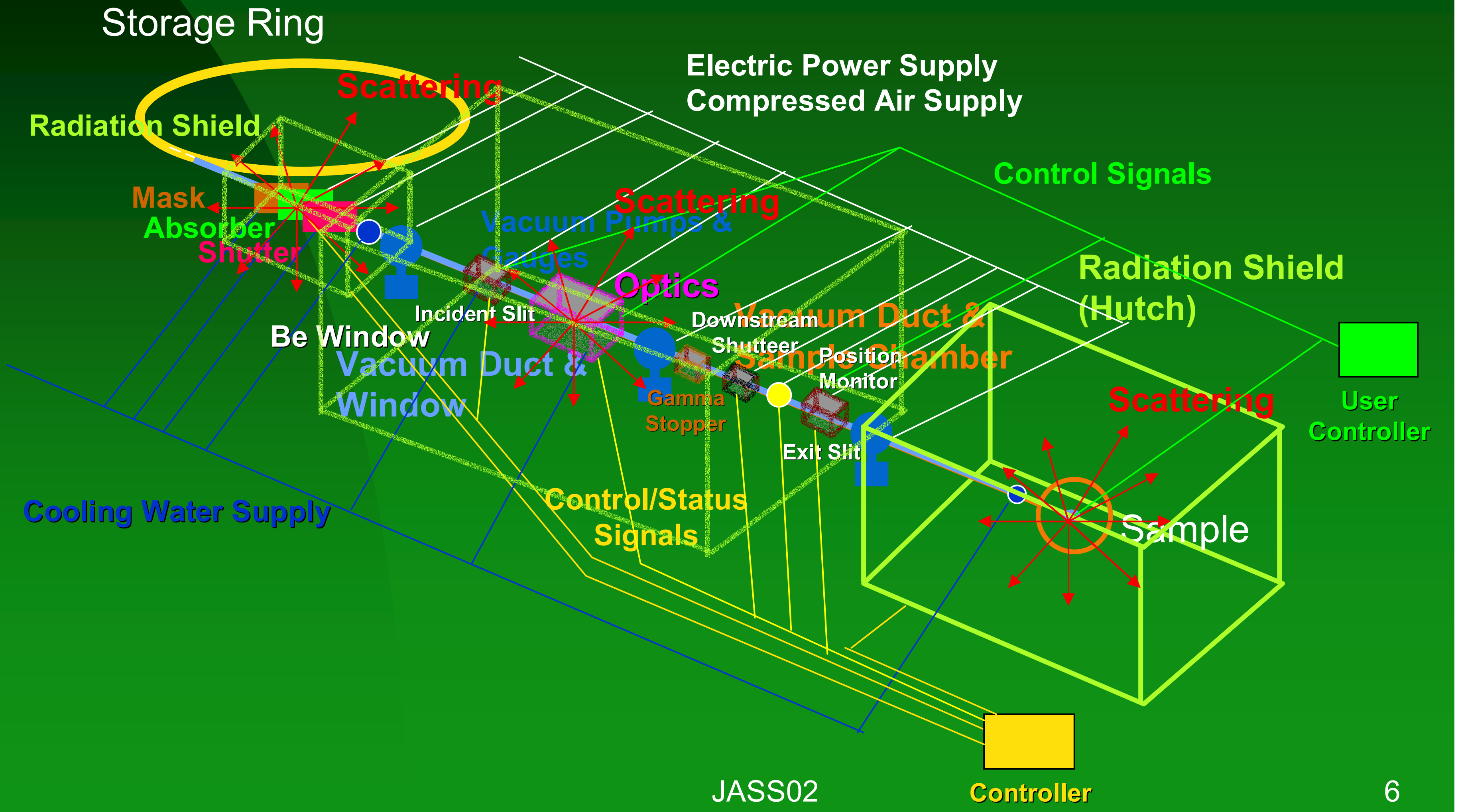
Source: System Input

- **Bending Magnet**
  - White X-Rays
  - Wide Horizontal Divergence
  - 1/Gamma Limited Vertical Divergence
  - Moderate Power
  - Moderate Power Density
- **Wiggler**
  - White X-Rays
  - Moderate Horizontal Divergence
  - 1/Gamma Limited Vertical Divergence
  - High Power
  - High Power Density
  - Elliptically Polarized/Linearly Polarized
- **Undulator**
  - Quasi-Monochromatic X-Rays
  - Small Verical and Horizontal Divergence (Central Cone)
  - High Power
  - Extremely High Power Density
  - Circularly Polarized/ Linearly Polarized

Beam: System Output

- **Spatial Size**
  - Small Beam for Small Samples
  - Wide Beam for Large Samples
- **Beam Divergence**
  - Parallel Beam for High Angular Resolution
  - Convergent Beam for Higher Photon Density
- **Energy**
  - Particular Energy for particular phenomena
  - Energy Resolution
  - Energy Purity (Higher Harmonics Contamination)
- **Polarization**
  - Linear Polarization
  - Elliptical Polarization
  - Circular Polarization
  - Polarization Switching

X-Ray Beam Line: Conceptual



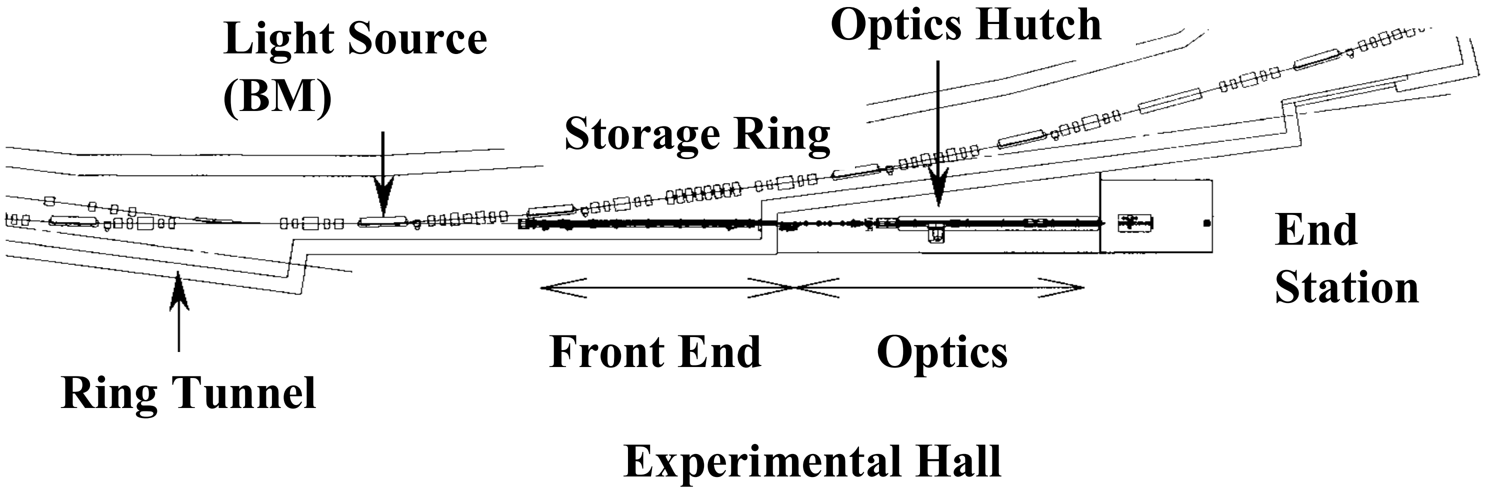
Functions of Beam Line

- **Photon Tailoring**
  - Energy, Energy Resolution, Size, Divergence, Polarization

Other Functions

- **On/Off Control**
- **Vacuum**
  - Absorption, Protection of Equipment, Protection of Storage Ring, Reduction of Scattering
- **Human Safety**
  - Radiation Shield, Safety Interlock
- **Interface**
  - Storage Ring Interface
  - User Interface

Structure of a Beam Line



SPring-8, BL01B1 (Bending Magnet Beamline)

Front End

(1) Vacuum System (Ion Pump)

Keep High Vacuum ($10^{-7} \sim 10^{-5}$ Pa)

(2) Main Beam Shutter

On/Off Control

・Water-Cooled Absorber

・Beam Shutter

400 mm thick W

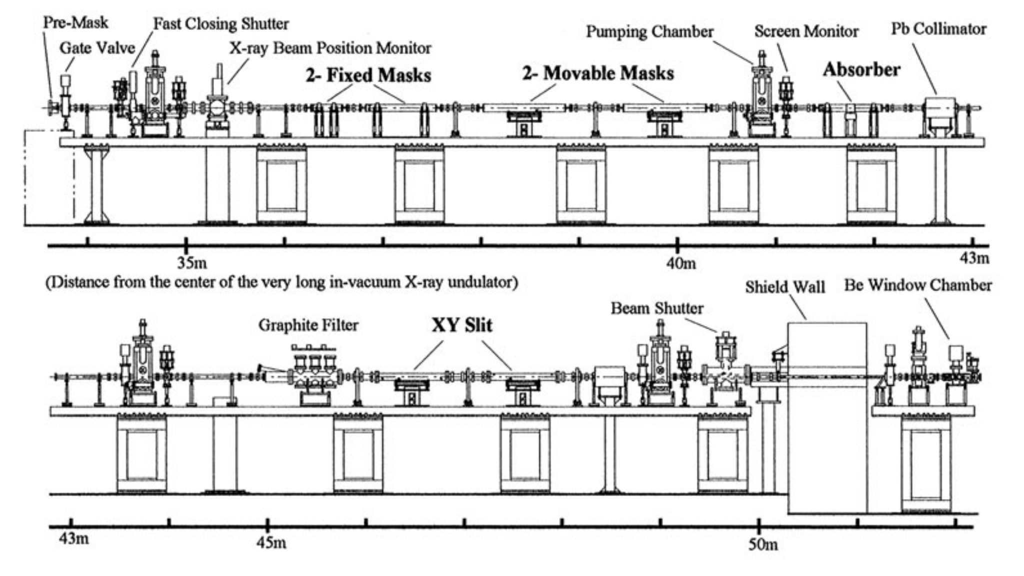
(3) Masks, XY-Slit

Spatial Power Control, Spatial Shaping

(4) Water-Cooled Be Window

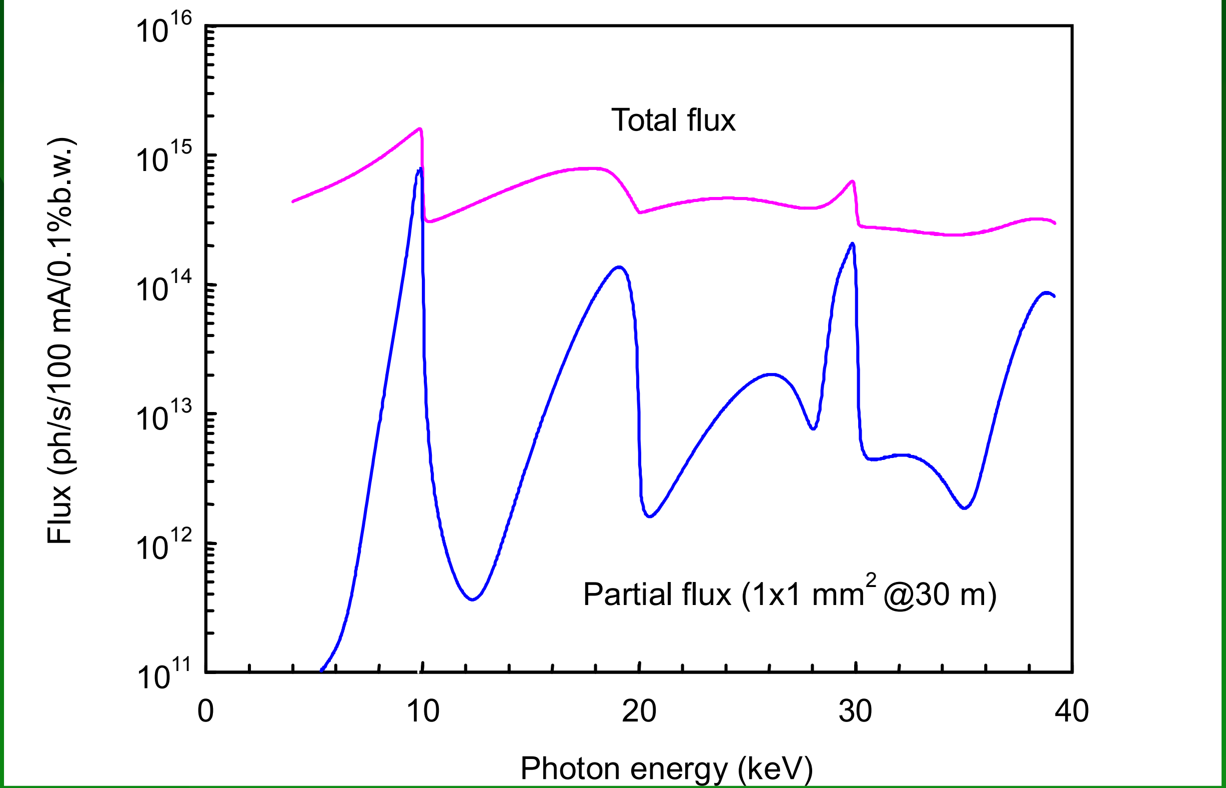
Separation of Vacuum from Optics

(5) Photon Beam Position Monitor



Example: Front End of BL19LXU at SPring-8

Radiation Spectrum of Undulator



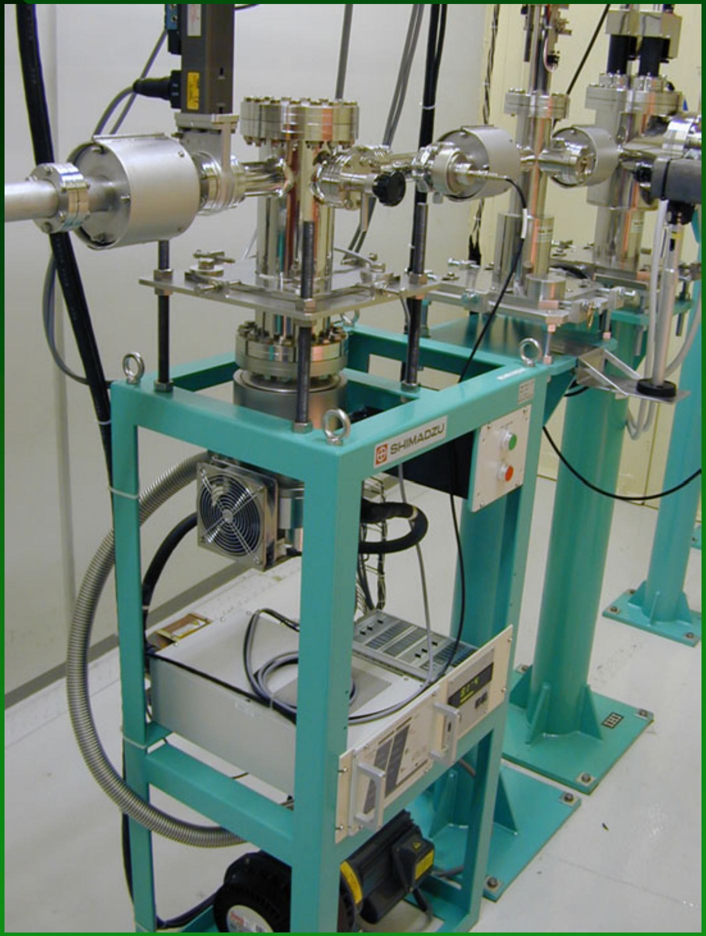
Masking off-axis radiation at front-end reduces power load on optical elements.

Vacuum

Oil-Free Vacuum

- **Protect Ring Vacuum**
  - keep long beam life time
  - suppress high energy gamma-ray
- **Avoid Absorption/Scattering**
  - transport photon intensity as high as possible
  - avoid radiation leakage due to scattering
- **Avoid Contamination and Deterioration of Optical Elements**
  - Carbon contamination, Oxidization

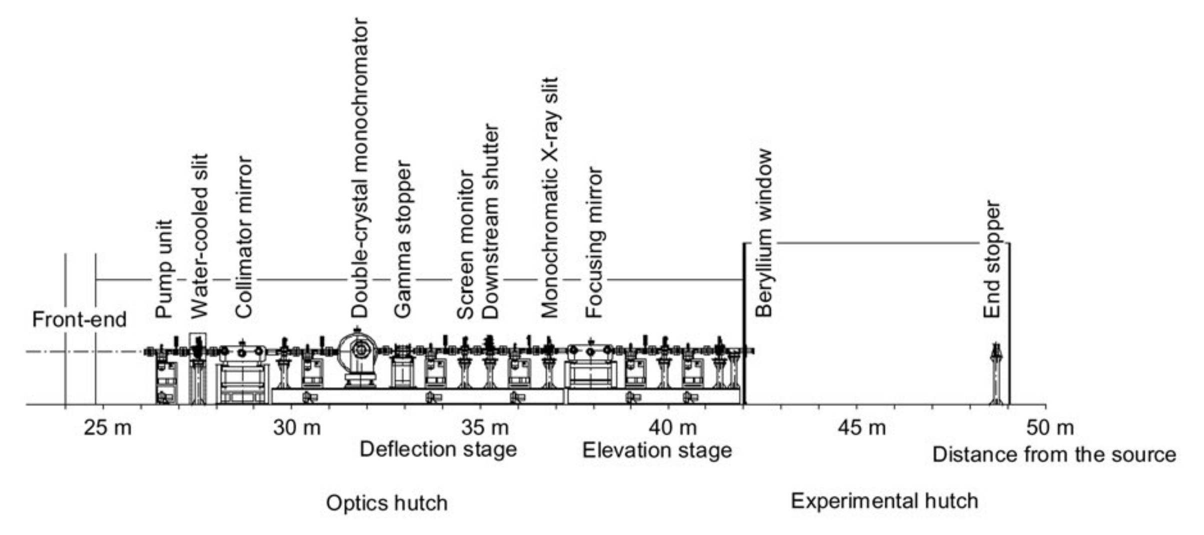
Vacuum Pumping Units



Undulator Beamline

Bending Magnet Beamline

Optics and Beam Transport



Optical Components	
Crystal Monochromators	Limit Energy Band-Pass
Total Reflection Mirrors	Focusing, Higher Harmonics Rejection
Beam Transport Components	
Exhaustion Unit	Reduction of Absorption/Scattering
Downstream Shutter	On/Off Control of Monochromatic Beam
Gamma-Ray Stopper	Stop Gamma-Ray originated by Gas-Bremsstrahlung
Beryllium Window	Separate Beam Line Vacuum from Atomosphere
Screen Monitor	Monitor Beam Position/Intensity

Major Optical Components in X-ray Beam Lines

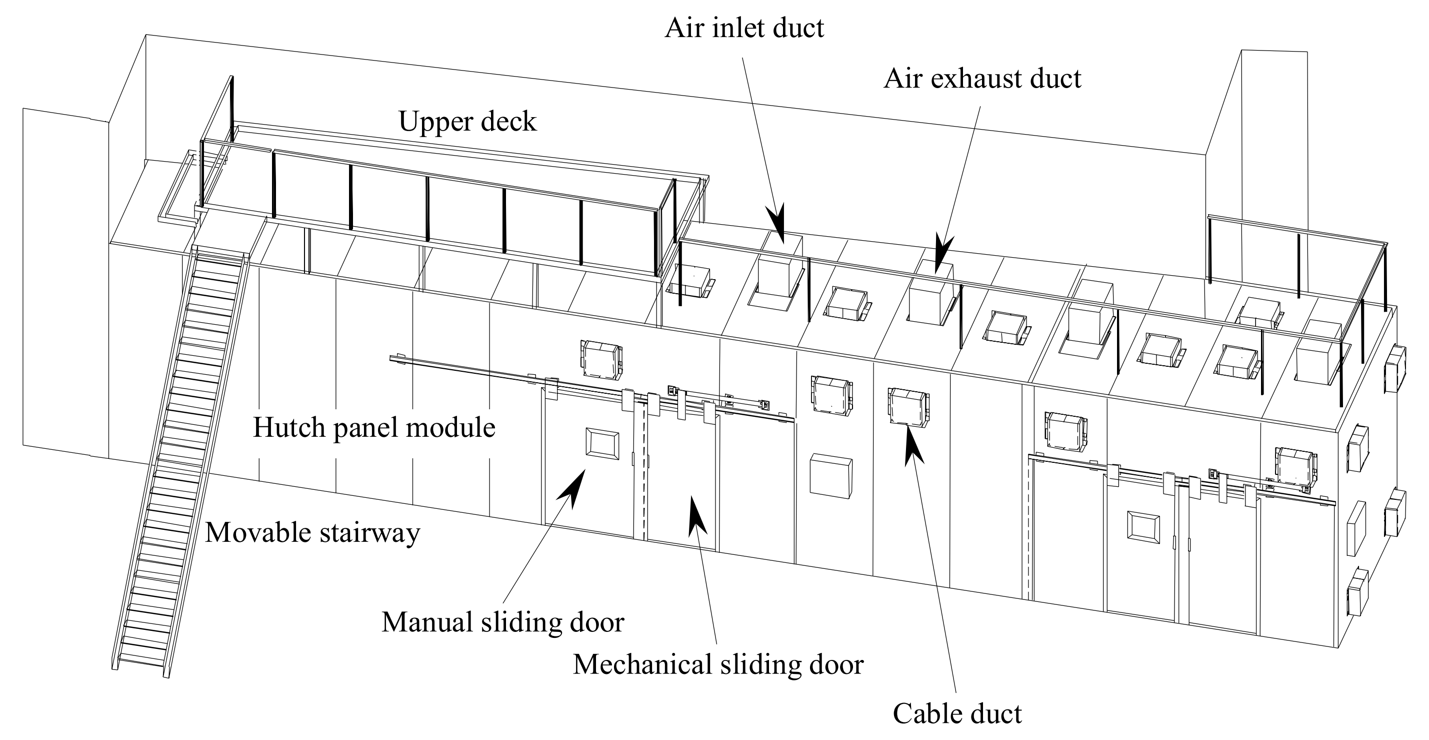
Crystal Monochromators

- Energy Selection
- Energy Bandwidth
- Focusing (Optional)

Total Reflection Mirrors

- Higher Harmonics Rejection
- Beam Focusing/Collimation
- Beam Deflection

Radiation Shielding Hutch



Beam Line Interlock System (X-rays)

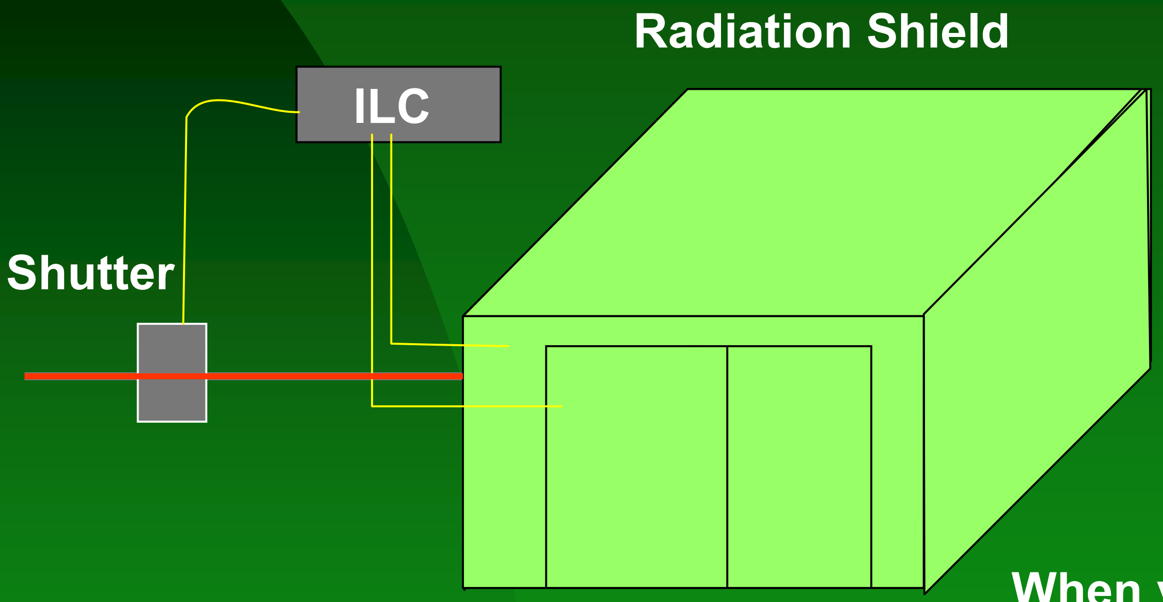
Good thing for x-ray beam lines (as compared with VUV and SX BLs) is:

You can access your sample easily (not in UHV).

But you should be very careful to protect yourself from radiation environment.

Unfortunately, not all the users are very careful, facilities must take care of them by equipping interlock systems.

Beam Line Interlock System (X-rays)



When your work in the shield is done,

Confirm no one remaining in the shield,

Close the shield door, (Some sensors tell the status of the shield door to ILC system)

Ready for shutter operation

Open the shutter

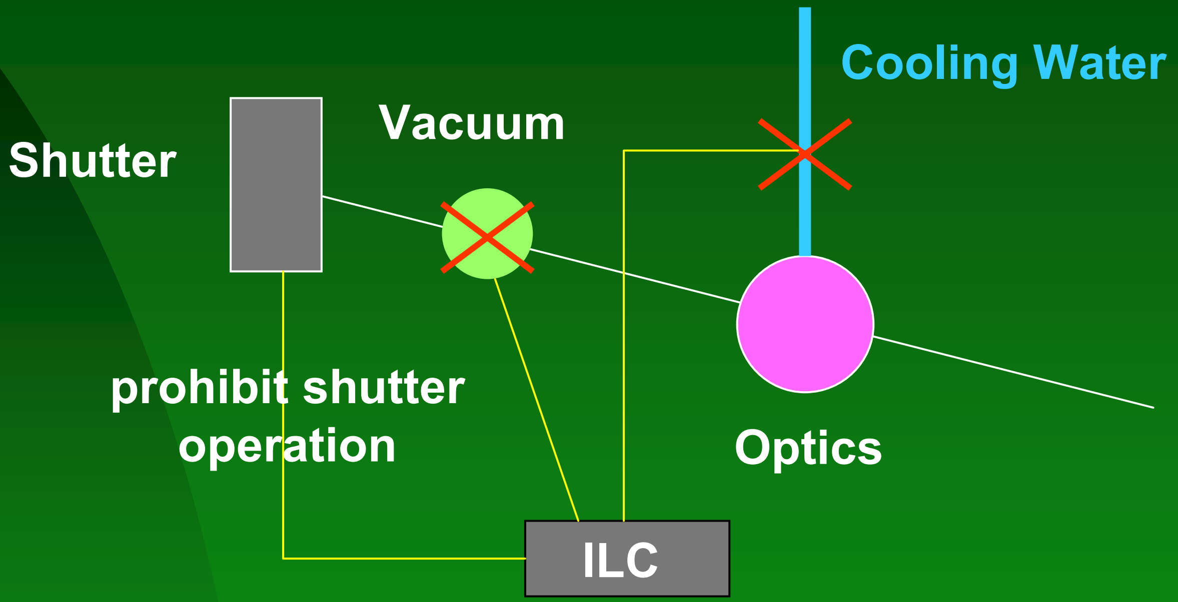
When you enter the shield for work,

Close the shutter

Ready for door operation

Open the shield door

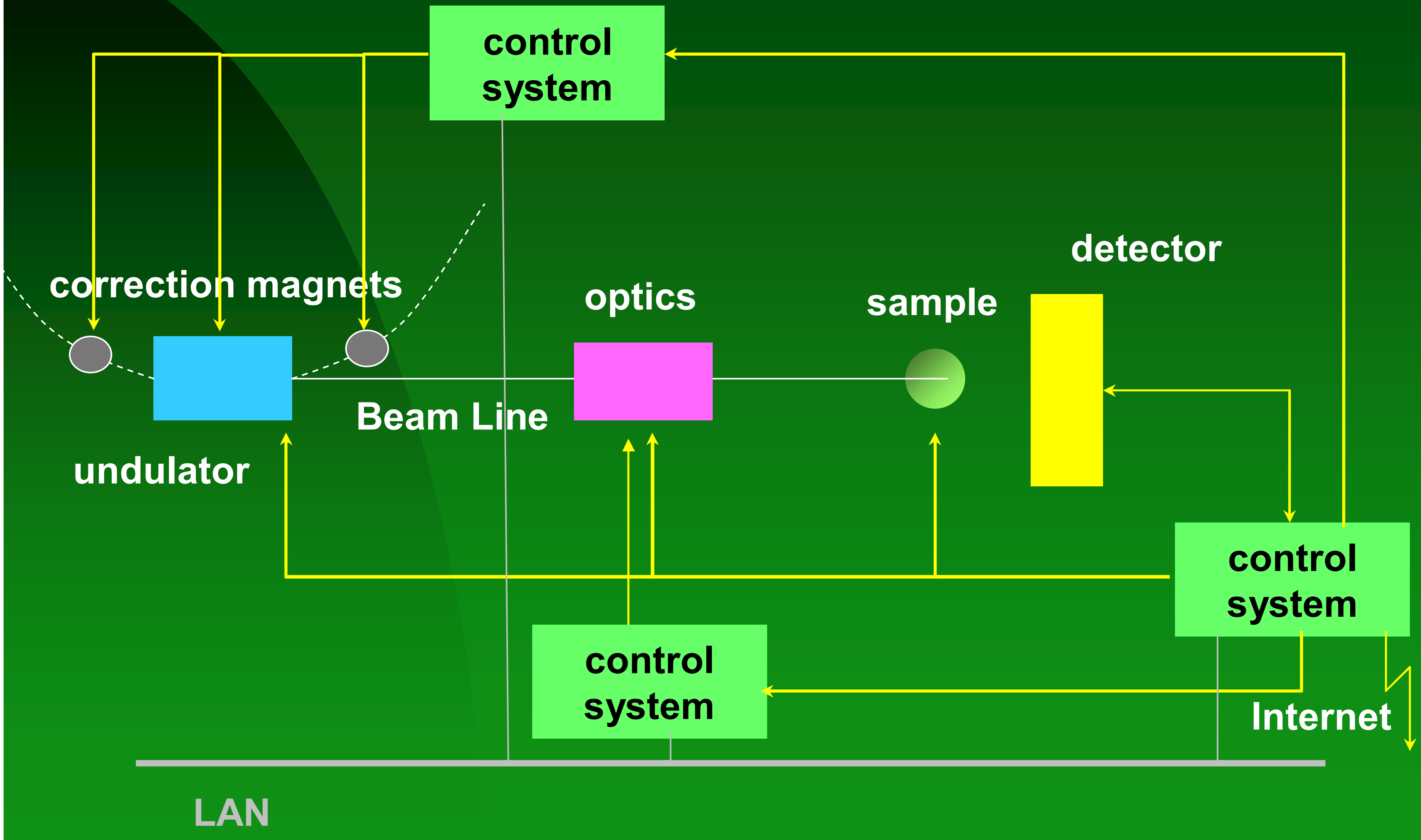
ILC system also look around equipments to protect the beam line



ILC: Human safety

Equipment Protection

Control System/Data Acquisition



Beamline Control System

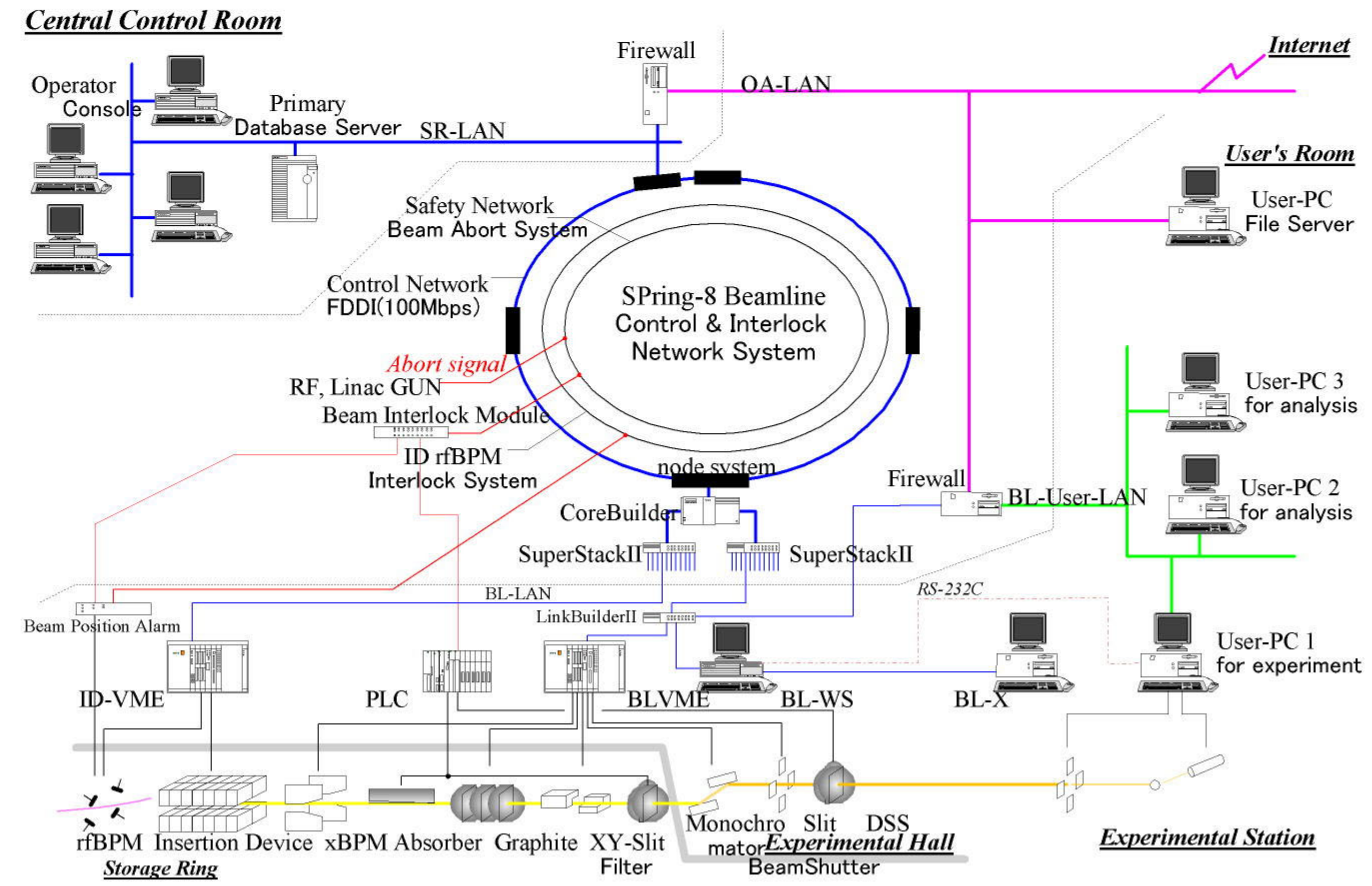


Figure 1. Schematic diagram of the beamline control system and network with firewall

Design & Construction of Beam Lines

- Most Beamline Components are Commercially Available.
- Some Companies can Make Total Design and Construction.

Custom Made v.s. Order Made

Depends on Facility Strategy, Budget, Man-power and Term

- Order Made
  - **Best Optimization**
  - **More Man-Power**
  - **More Budget**
  - **More Operating Staff**
- Custom Made
  - **Moderate Optimization**
  - **Less Man-Power**
  - **Less Budget**
  - **Less Operating Staff**

End of Part 1

Introduction for Part 2: X-Ray Optics

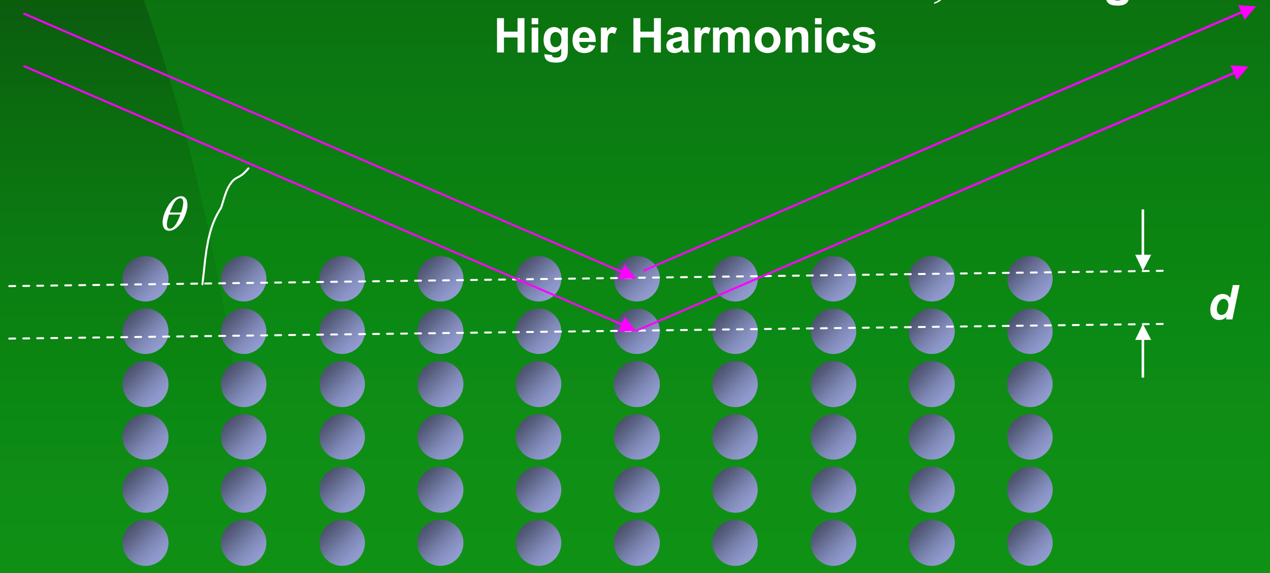
- **X-Ray Monochromator**
  - Basic Consideration
  - Various Double-Bounce Monochromator
  - Cooling Issue
- **X-Ray Mirrors**
  - Basic Consideration
  - Current Status and Problems
- **Combined Optics**

X-Ray Monochromatization: Principle

Perfect Crystal = 3D Grating

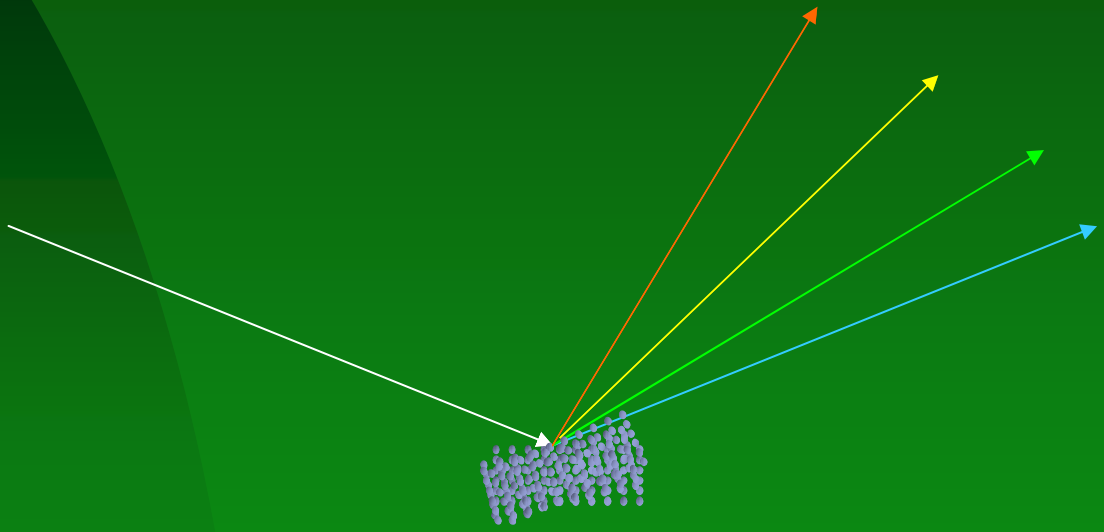
Bragg Reflection from netplanes with spacings of *d* at glancing angle θ monochromate x-rays at a wavelength $\lambda=2d\sin\theta$

Diffraction Condition: $n\lambda=2d\sin\theta$, n: integer
Higer Harmonics



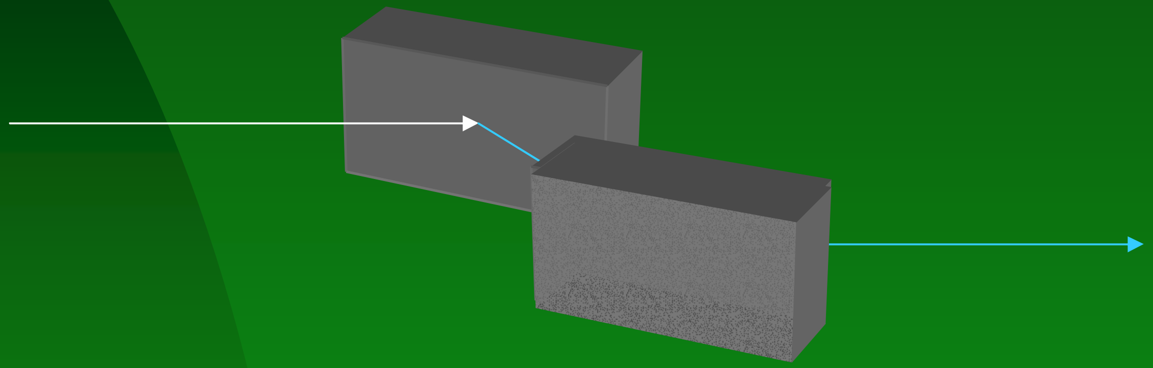
Simplest Crystal Monochromator

Rotate Single Bounce Crystal



Different Beam Direction for Different Energies

Double Crystal Monochromator

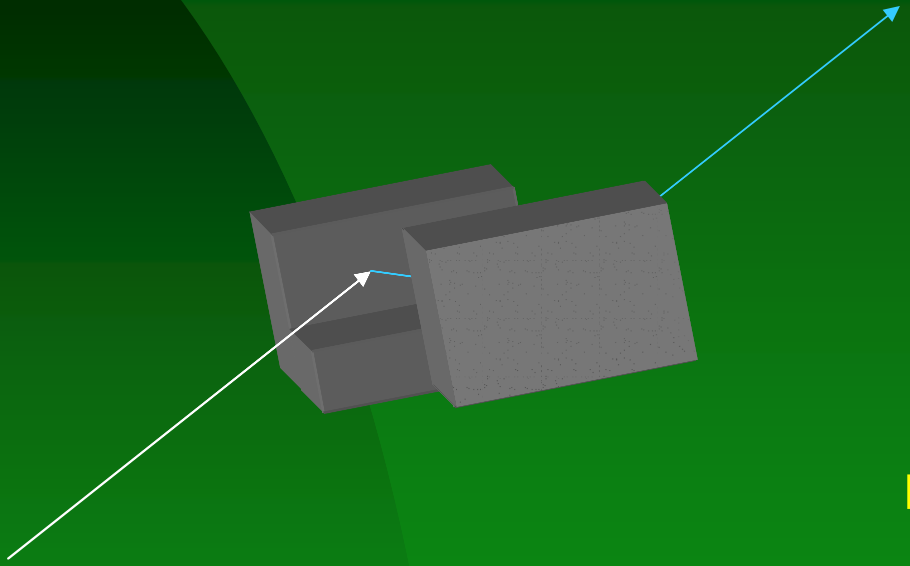


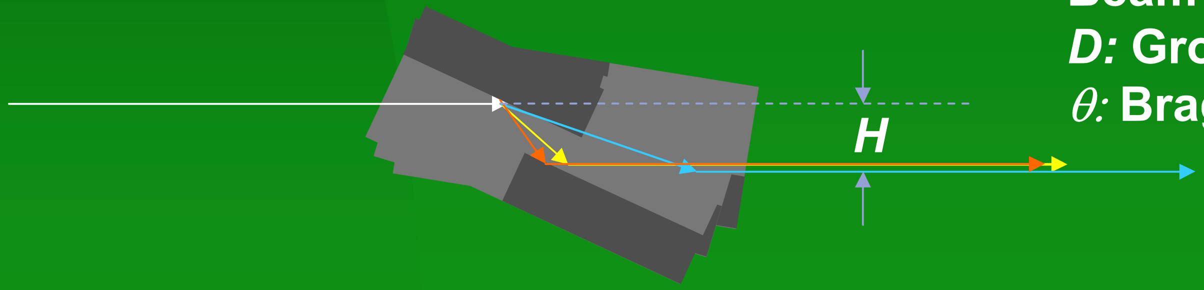
Double Bounce Reflection with the Same Netplanes.

Monochromatic Beam is Parallel to the Incident Beam.

Netplanes of Two Crystals Should be Parallel within Sub-Microradian Angular Precision.

Channel-Cut Monochromator





Channel-Cut Monochromator

Groove a Channel in
a Monolith of Crystal

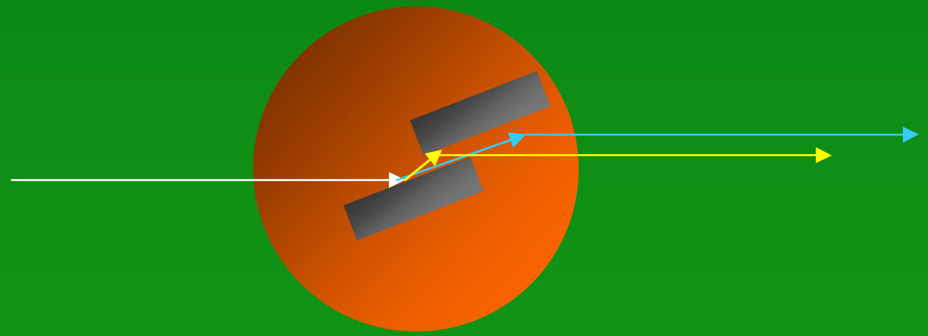
Double Bounce
Reflection on the
Channel Walls

Fixed Beam Direction

Beam Offset $H=2D\cos\theta$
D: Groove Width
θ: Bragg Angle

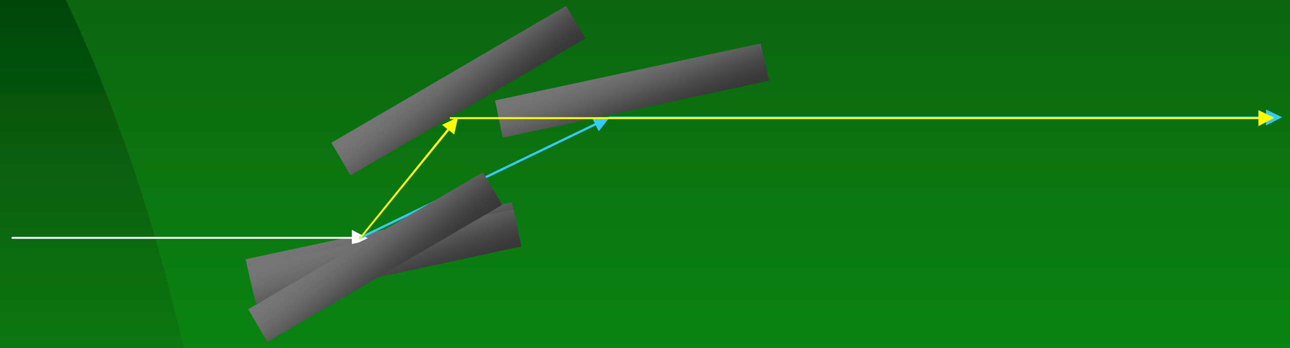
Separated Double Crystal Monochromator

- Channel-Cut Monochromator
  - Automatically Fulfill Parallel Setting
  - Less Perfect Surface Finish of Groove Walls
- Mechanically Aligned Two Flat Crystals
  - Better Surface Finish
  - Detuning capability
  - More Complicated Mechanism



Fixed-Exit Double-Crystal Monochromator

For most experiments, it is desirable to use different energies with the same beam path.

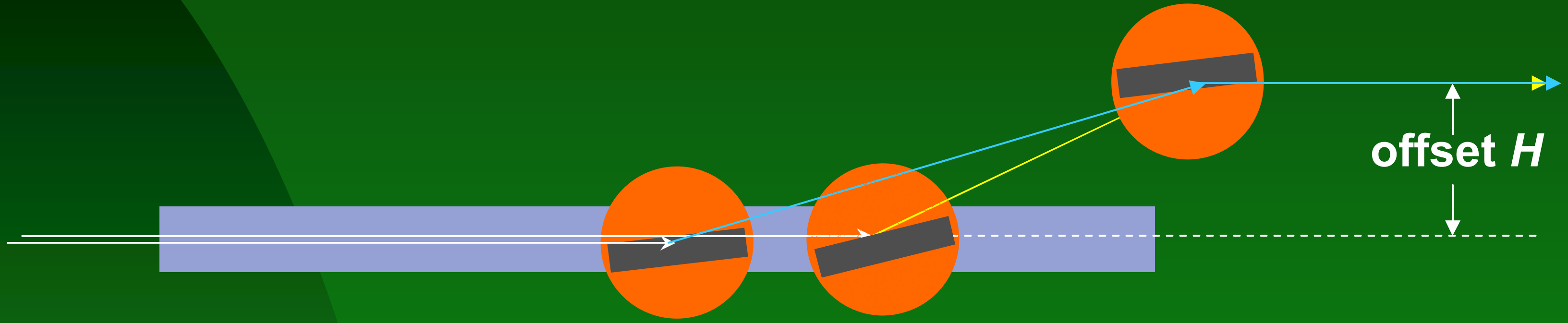


Rotation of both crystals + translation are needed.

Sub-microradian parallelity should be kept during translation.

High precision rotation and translation without yawing or pitching.

Fix-Exit DCM: Computer Linked



Independent rotation stages for 1st and 2nd crystals.

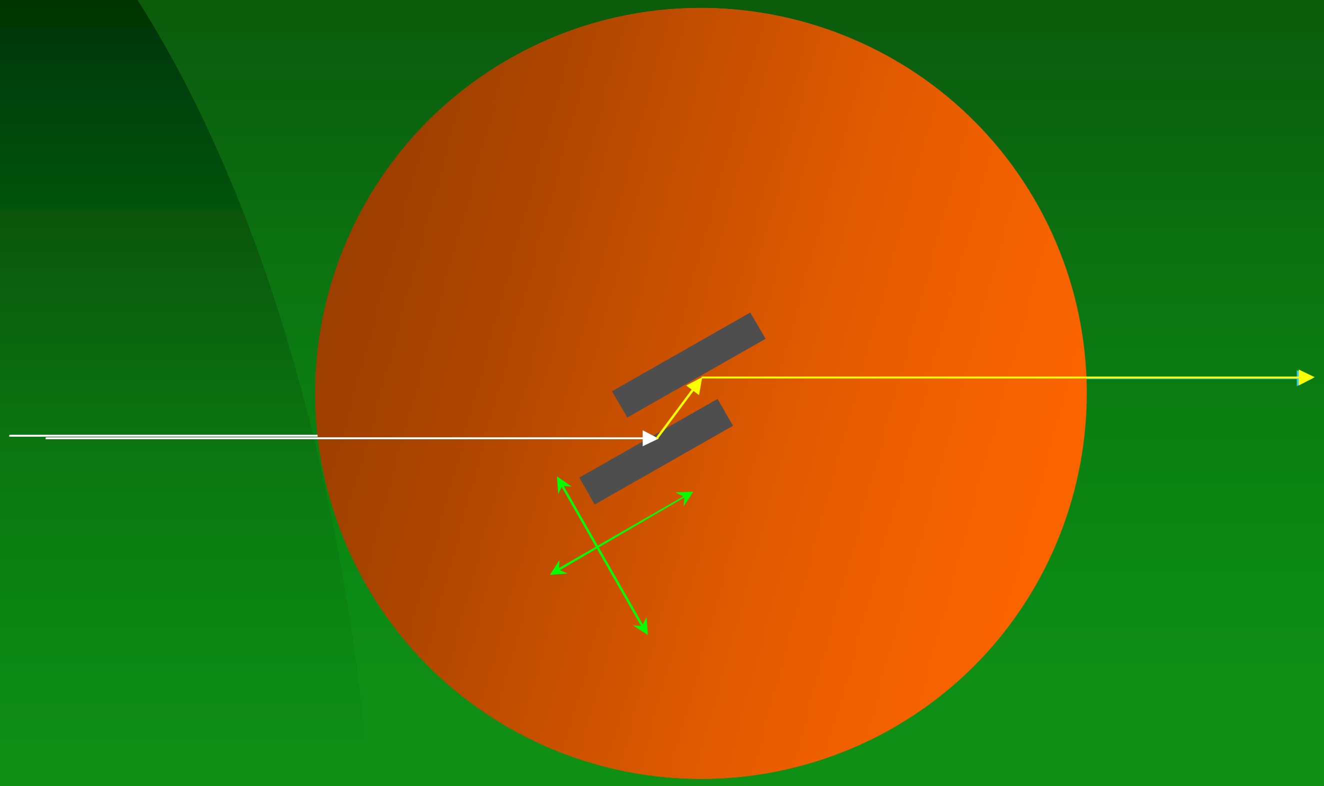
The rotation stage for 1st crystal is mounted on a translation stage along the incident beam axis.

The two rotations and translation are computer linked.

Translation, ΔL, for the change of Bragg angle from θ_1 to θ_2:

$$\Delta L = H(\cot 2\theta_1 - \cot 2\theta_2)$$

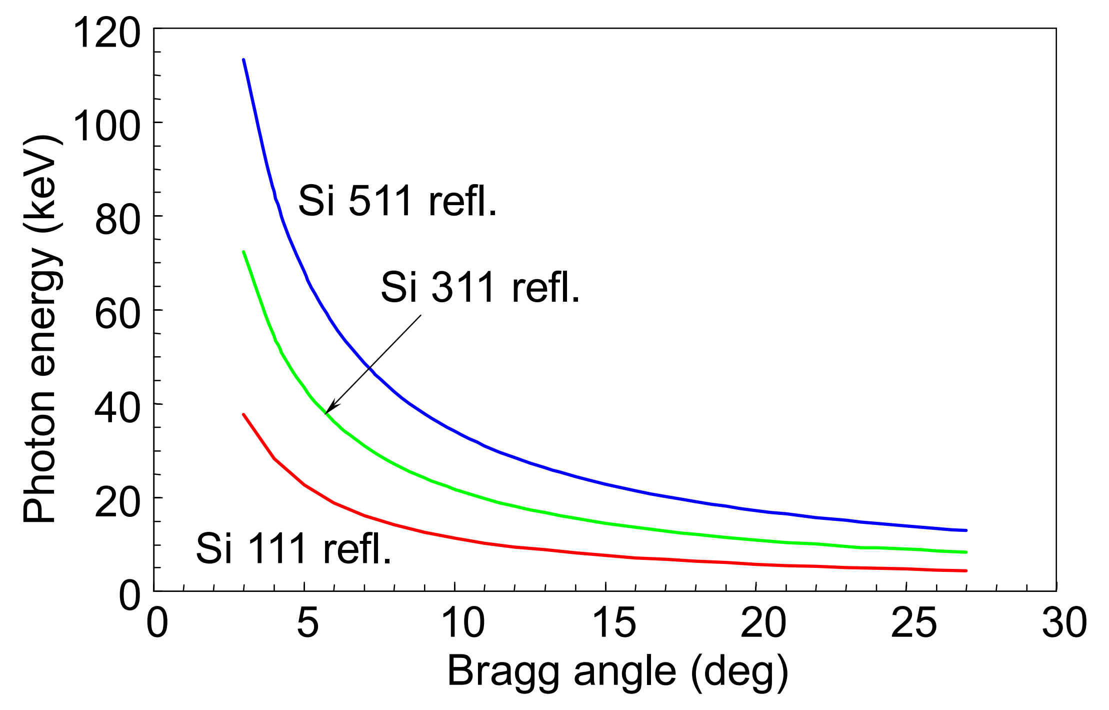
Fixed-Exit DCM: Mechanical Link



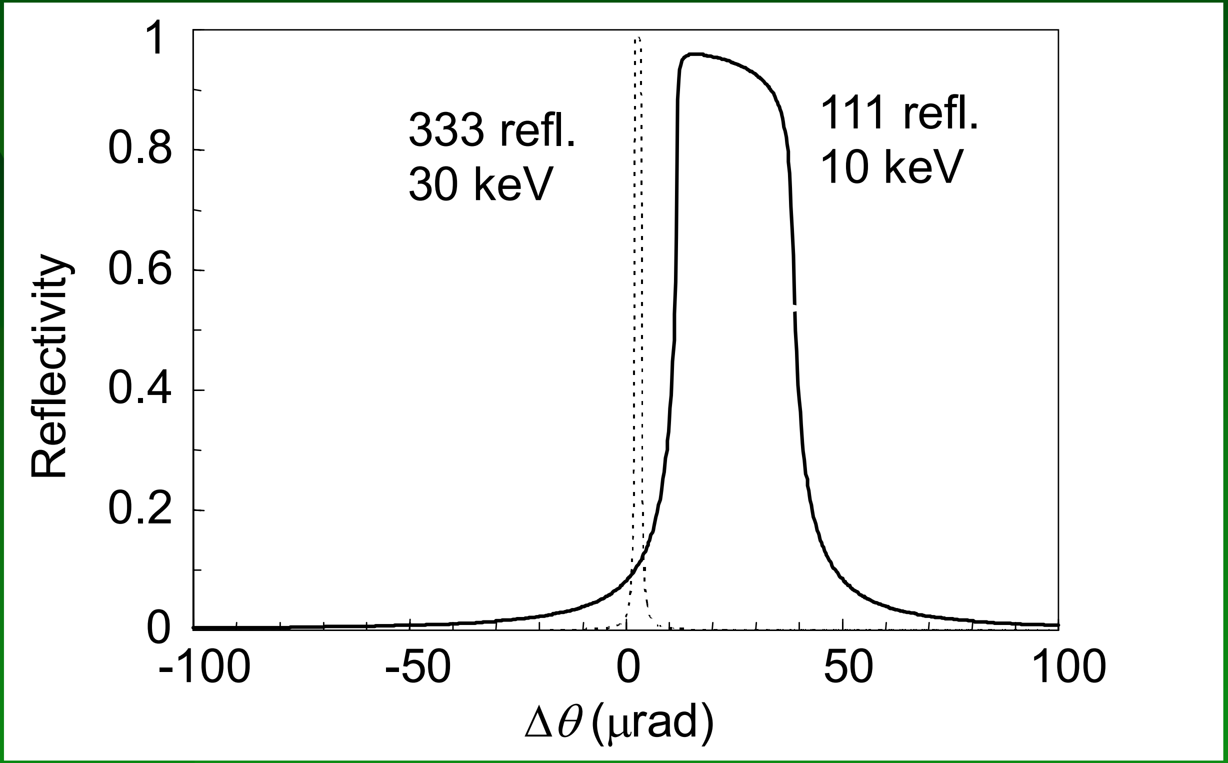
Energy Range

SPring-8 Standard DCM

- ❑ Reflection
  - Si 111
  - Si 311
  - Si 511
- ❑ Bragg Angle
  - 3～27°
- ❑ Energy Range
  - 4.4～110 keV



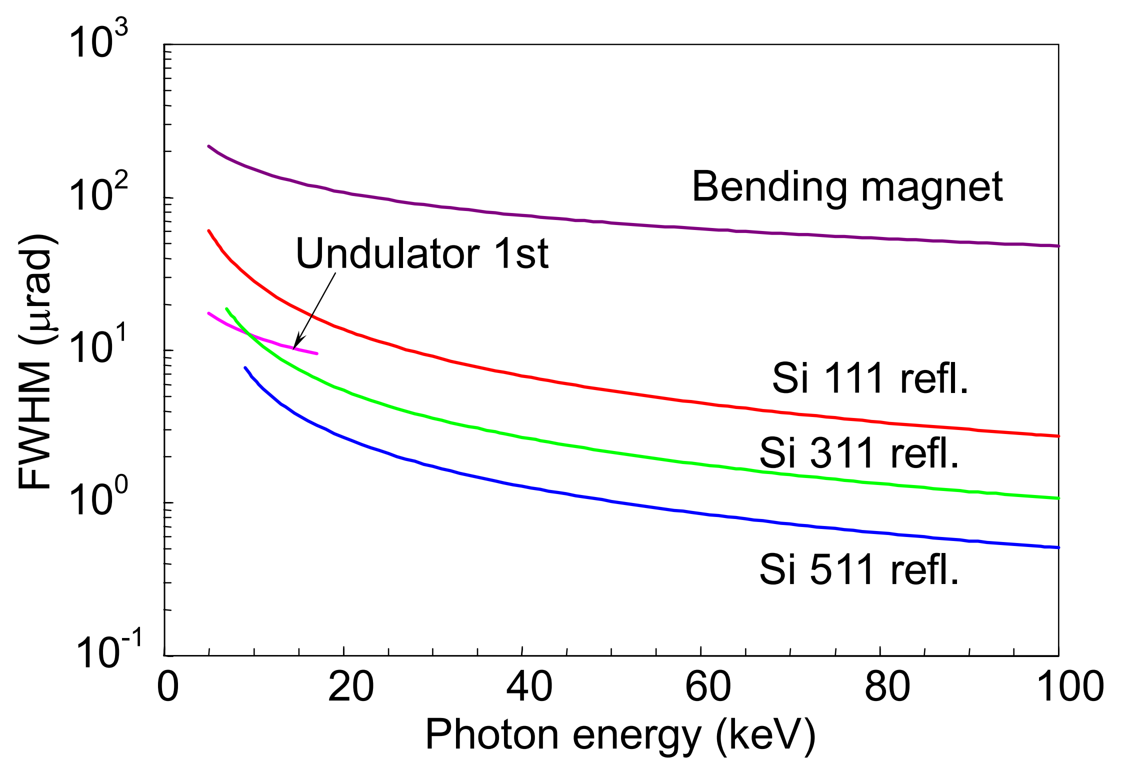
Rocking Curve



Dynamical Theory of Diffraction

- Diffraction Width: 0.1~100 μrad
- Peak Reflectivity ~ 1

Diffraction Width & Divergence of Incident Beam



Bending Magnet

$$\sigma_{\mathrm{r}} \approx \frac{1}{\gamma} \approx 60 \quad \mu\mathrm{rad}$$

Undulator (*N*= 140)

$$\sigma_{\mathrm{r}} \approx \frac{1}{\gamma\sqrt{N}} \approx 5 \quad \mu\mathrm{rad}$$

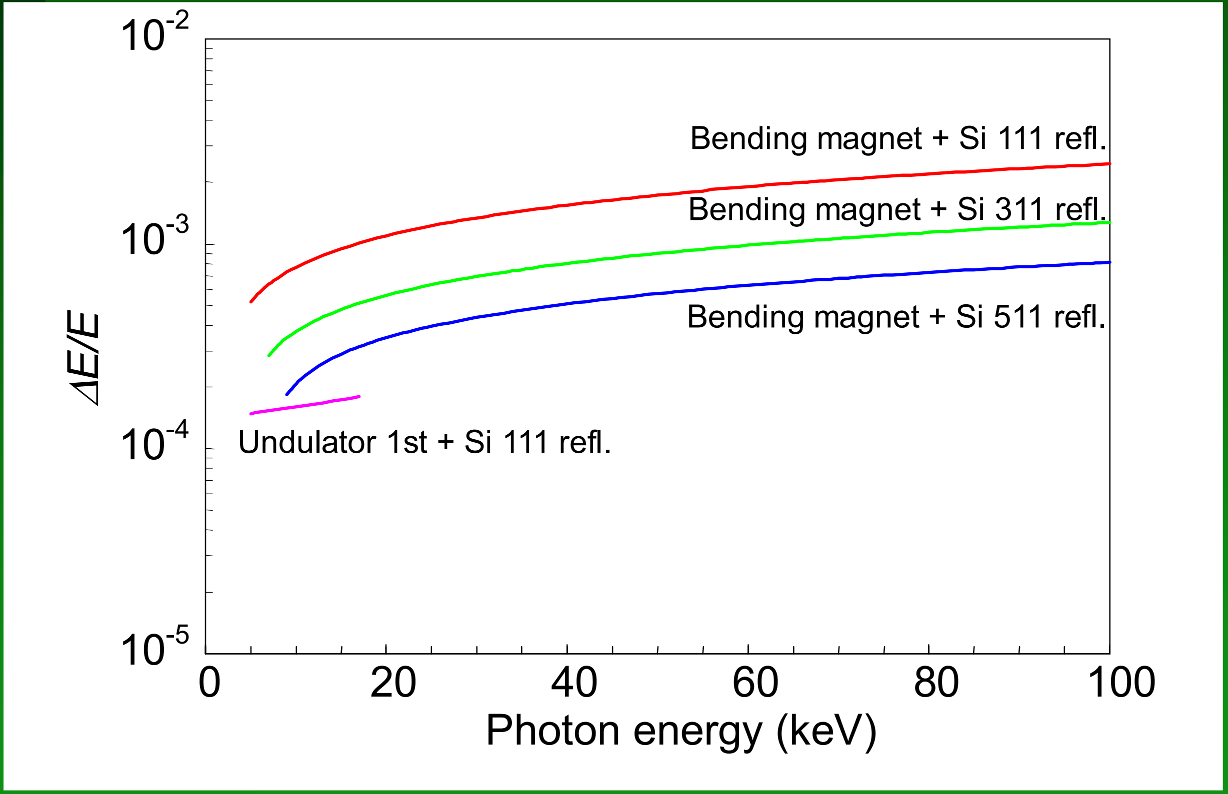
@ SPring-8

Angular divergence of undulator light ~ Diffraction width

Energy Resolution

$$\frac{\Delta E}{E} = \cot\theta_B \sqrt{\Omega^2 + \omega^2}$$

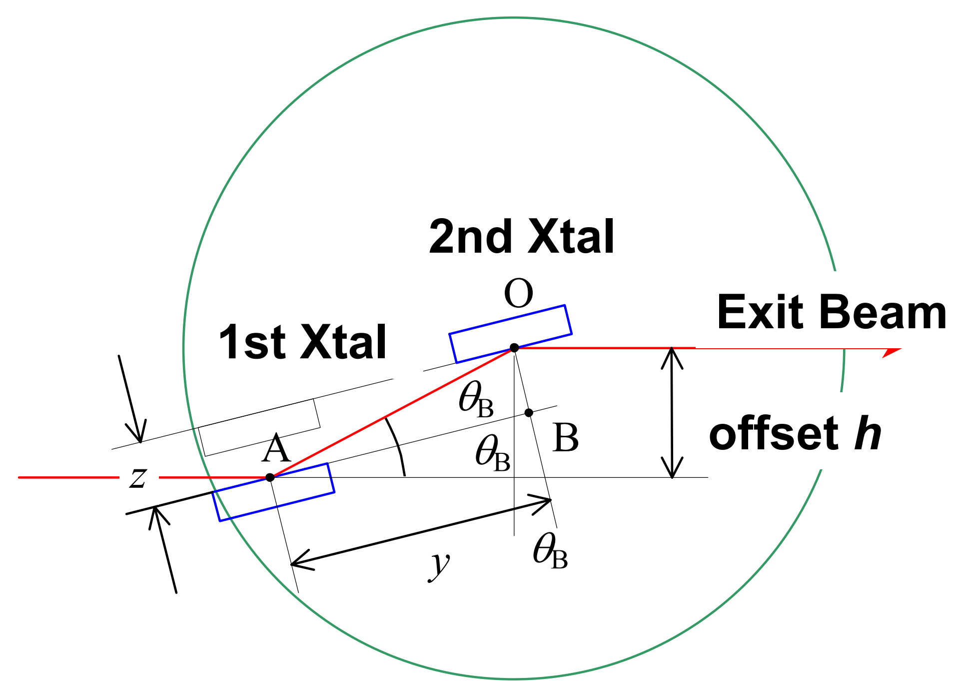
Ω: beam divergence,
ω: Diffraction width



Fixed-Exit DCM: Quantitative Consideration

$$y = \mathrm{AB} = \frac{h}{2\sin\theta_B}$$

$$z = \mathrm{OB} = \frac{h}{2\cos\theta_B}$$



$$(y^2 - h^2/4)(z^2 - h^2/4) = h^4/16$$

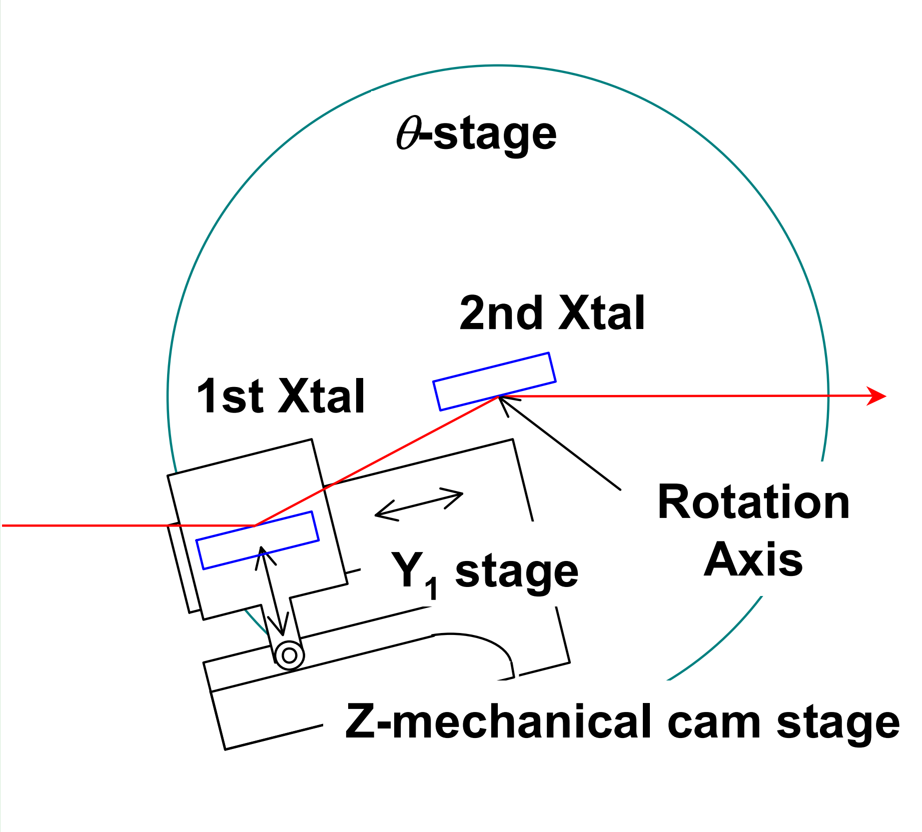
θ-y-z Mechanical Link

θ–y: Computer Control

y-z: Mechanical Cam

Figure of Mechanical Cam

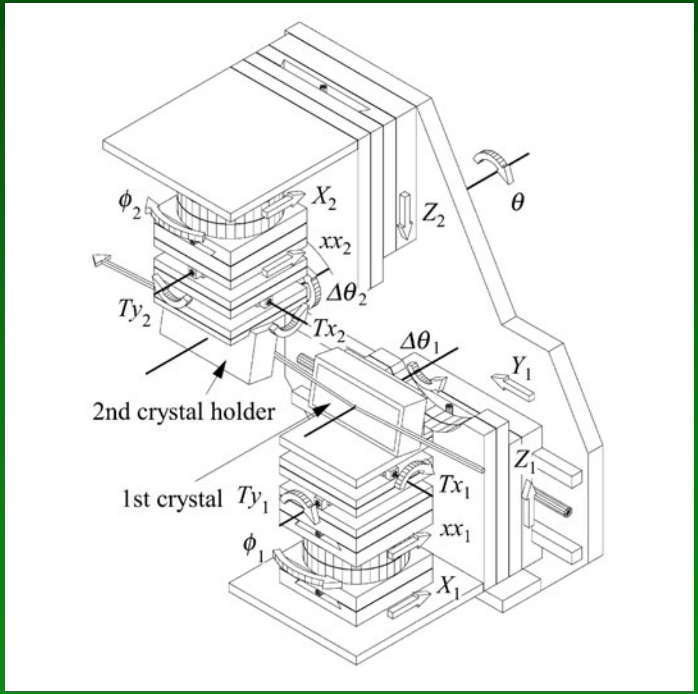
$$(y^2 - h^2/4)(z^2 - h^2/4) = h^4/16$$



SPring-8 Standard Double Crystal Monochromator

Angle Range: 3° $< \theta_B < 27°$

Offset: $h = 30$ mm



Crystal Mounts for Undulator DCM

Alignment Stages for SPring-8 Standard DCM

Axis	abbr.	finest step	range
Main Axis	θ	1 μrad	0～30°
1st Xtal Translation	Y_1	1 μm	270 mm
Hight	Z_1, Z_2	0.1 μm	15 mm
Fine Tuning of Bragg Angle	$\Delta\theta_1$, $\Delta\theta_2$	0.05 μrad	±3° 9 nrad (piezo)
Translation-1	X_1, X_2	0.05 μm	±5 mm
Azimuthal Angle	ϕ_1, ϕ_2	2.2 μrad	±5°
Translation-2	xx_1, xx_2	0.1 μm	±5 mm
Tilt-y (for Undulator Type)	Ty_1, Ty_2	0.1 μrad	±2°
Tilt-x (For Undulator Type)	Tx_1, Tx_2	0.1 μrad	±2°
Tilt (for BM Type)	α_1, α_2	0.87 μrad	15° ～+30°

Crystal Cooling

Power Load by SR

→ **Deformation of Optical Elements**

Themal Drift of Optical Elements and Mechanical Components

→ **Loss of Available Flux**

Effective Cooling of Optical Elements

Crystal Cooling (Examples at SPring-8)

(1) Bending Magnet Beamlines

Incident Power Density: ～1 W/mm^2 @40 m

Cooling Scheme: Indirect (Si/InGa/Water Cooled Cu), or Direct Fin-Cooling

(2) X-Ray Undulator Beamlines

(Planar Undulator, N= 140, λu= 32mm)

Incident Power Density: ～300 W/mm^2 @40 m

Cooling Scheme:

Pin-Post Water Cooling+Rotated Inclined Geometry (→1～10 W/mm^2),
or Indirect Cryogenic Cooling with Liquid Nitrogen

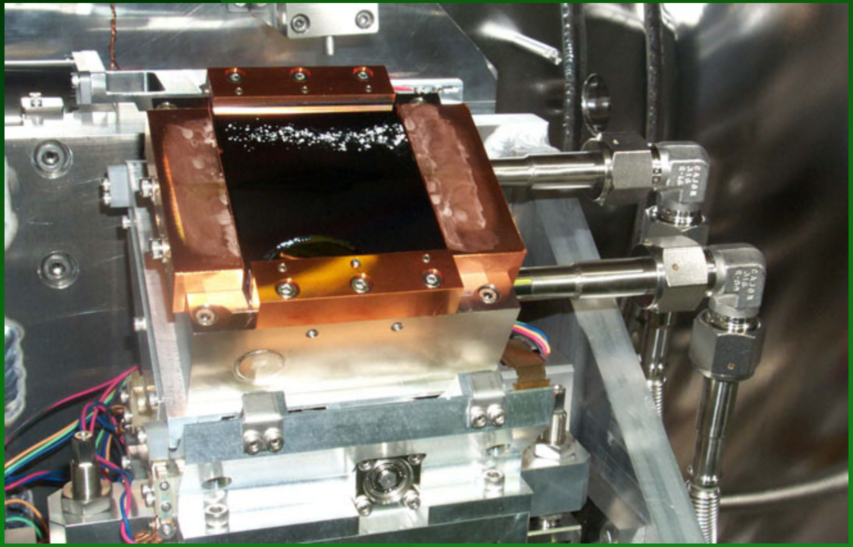
(3) 27 m Long Undulator Beamline

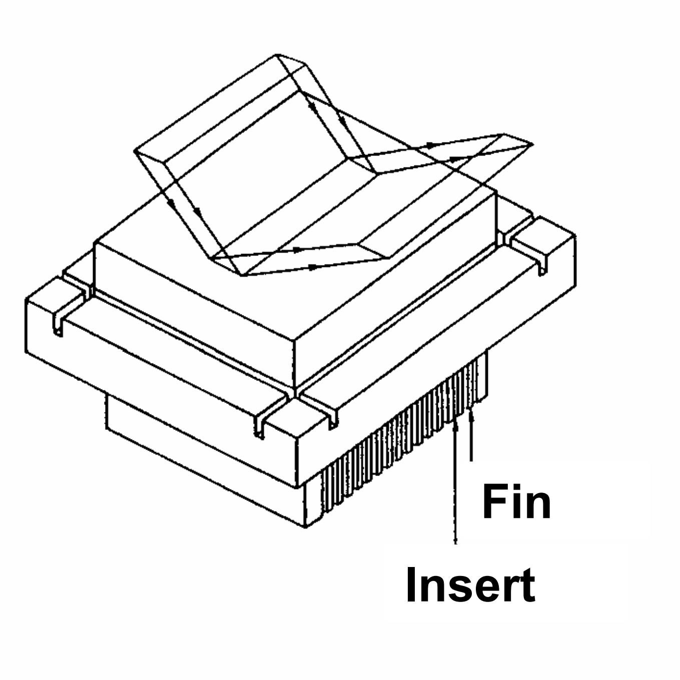
(Planar Undulator, N= 781, λu= 32 mm)

Incident Power Density: 580 W/mm^2 @58 m

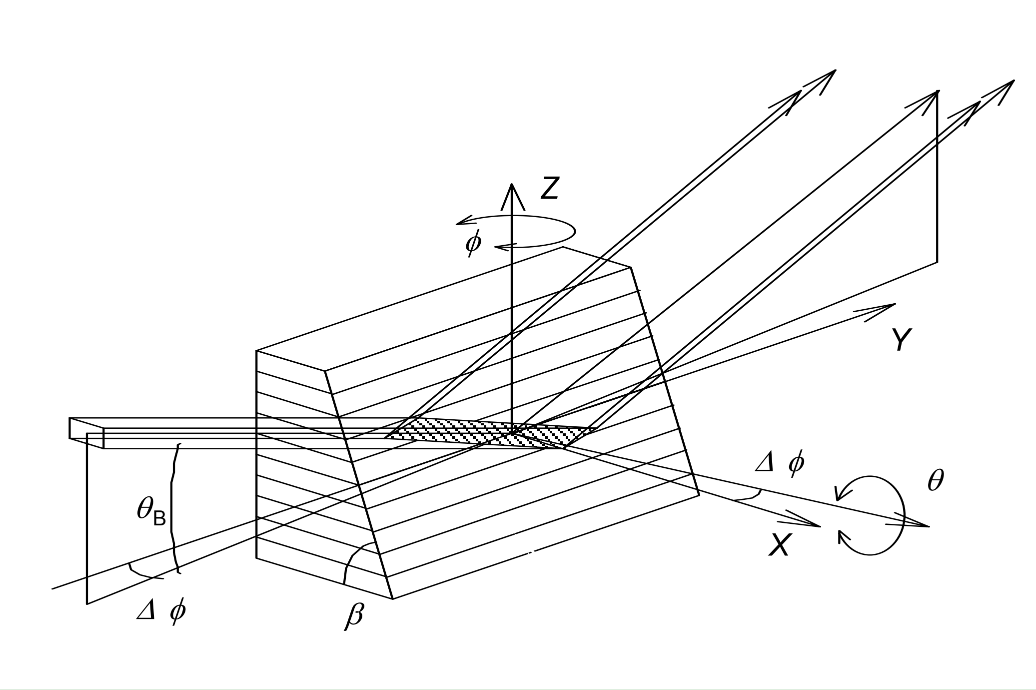
Cooling Scheme: Indirect Cryogenic Cooling with Liquid Nitrogen

Direct Water Cooling for SPring-8 BM Monochromator





Rotated-Inclined Geometry + Pin-Post Water Cooling

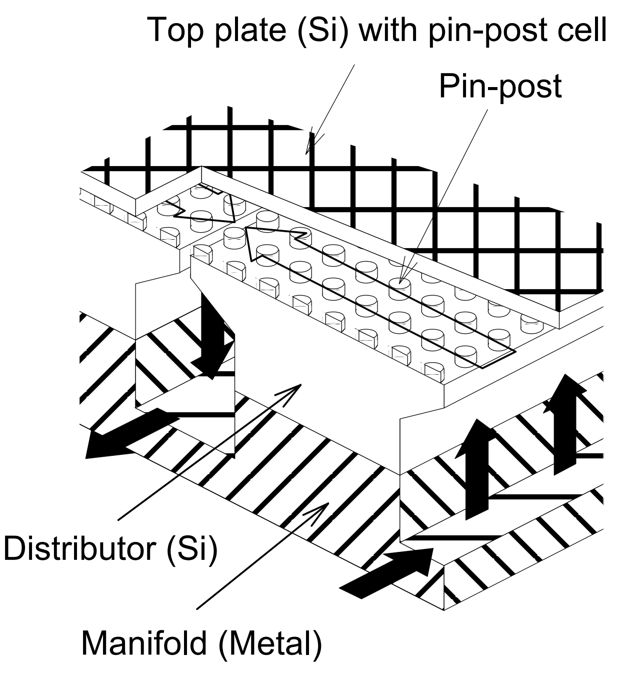


Rotated-Inclined Geometry

β= 80° for standard type

Glancing angle is set to 1 degree through ϕ-rotation

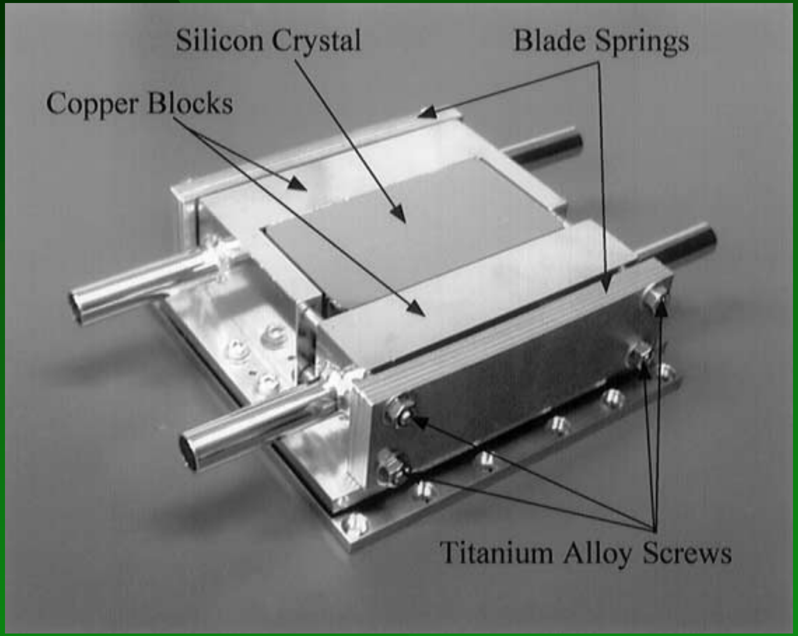
Reduction of power density to be ~1/60



Pin-Post Cooling

Cryogenic Cooling

Indirect Cooling with Liquid Nitrogen



Liquid Nitrogen Circulator with He Refrigirator

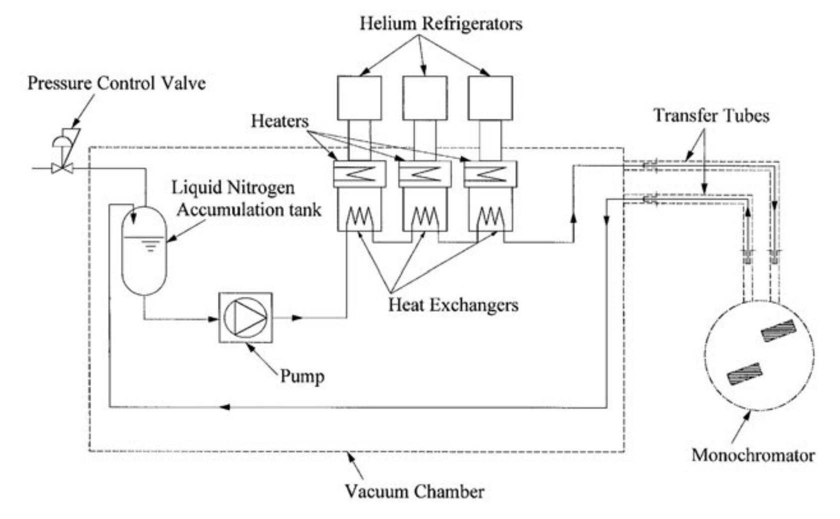


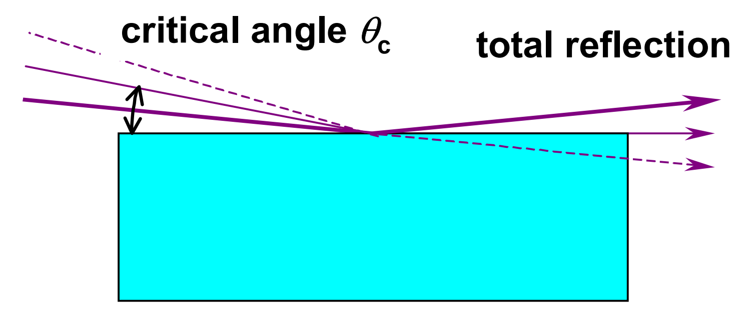
Figure of merit= Thermal Conductivity/Thermal Expansion Coefficient
~x100 compared with Room Temperature

Total Reflection Mirrors: Principle

Refractive index for x-rays is slightly less than 1;

$$n = 1 - \delta \quad (\delta << 1)$$

Glancing angle below a critical angle θ_c, total external reflection occurs



$$\frac{\cos\theta_c}{\cos 0} = \frac{n}{1}$$

Snell's Law

$$1 - \frac{\theta_c{}^2}{2} = 1 - \delta$$

$$\theta_c = \sqrt{2\delta}$$

Typical value of δ~10^{-5} at l~0.1 nm for Pt, Rh...

⇓

θ_c ~ several mrad

Total Reflection Mirrors: Functions

(1) Higher Harmonics Rejection

cut higher harmonics from crystal monochromators

(2) Beam Focusing/Collimation with Figured Mirrors

sagittal focusing with cylindrical mirrors

meridional focusing with cylindrical/elliptical mirrors

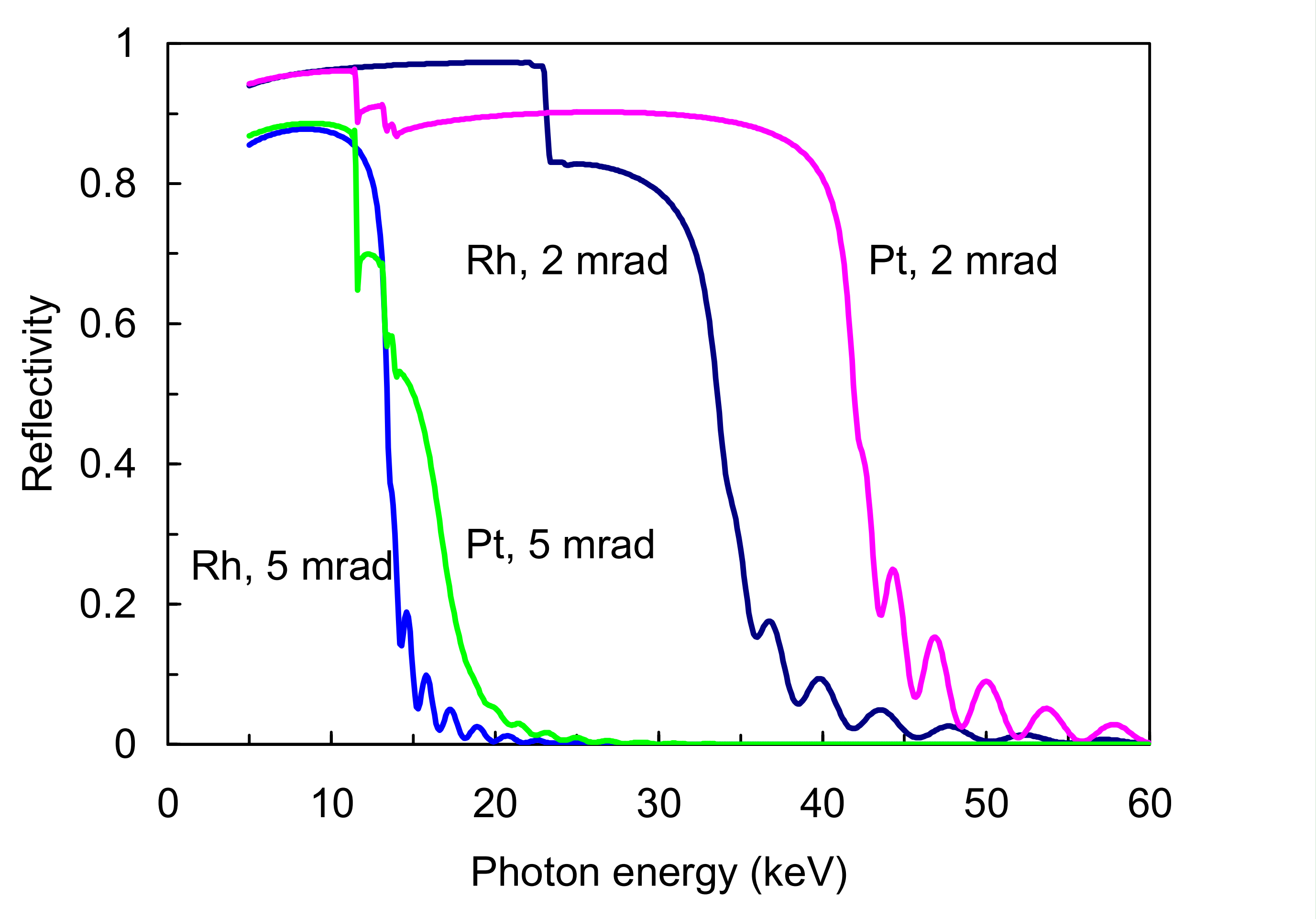
point focusing with troidal/ellipsoidal mirrors

beam collimation with parabolla mirrors

(3) Beam Deflection

switching of branch beamlines

Reflectivity (Calculation)



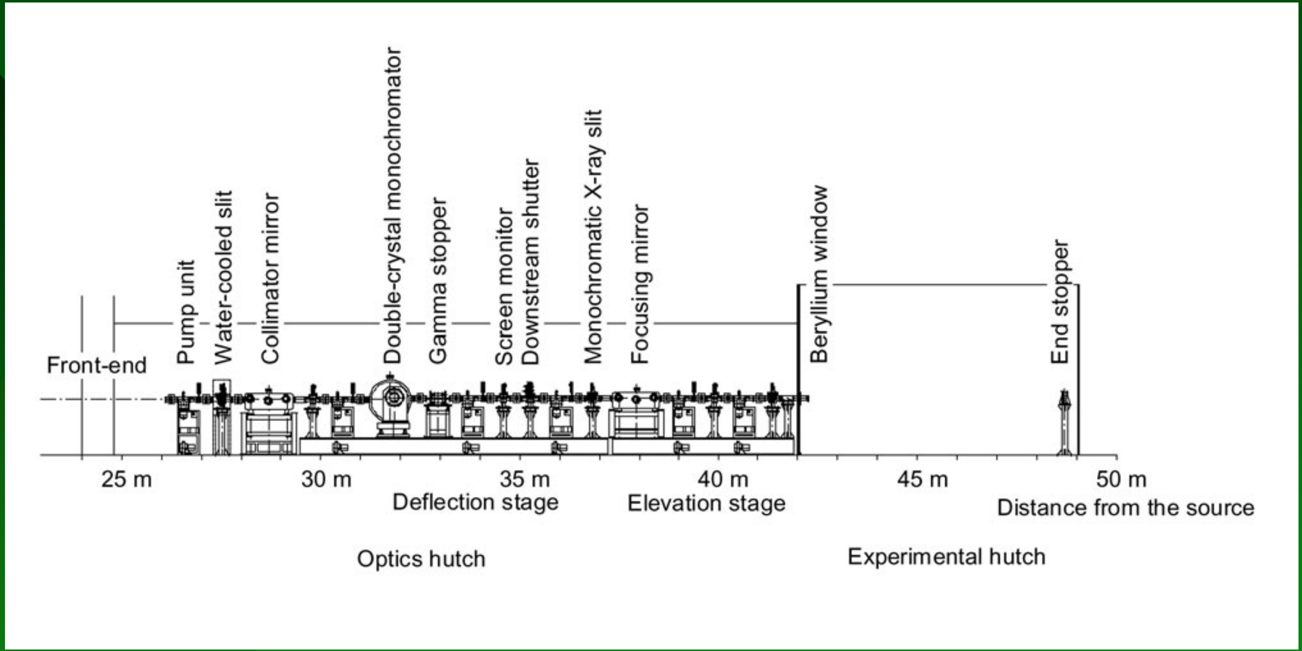
coating thickness = 50 nm, RMS surface roughness = 1nm

Mirror Support

For 1m mirror in Bending Magnet Beamline;

Vertical Deflection, Indirect Cooling, Meridional Bending

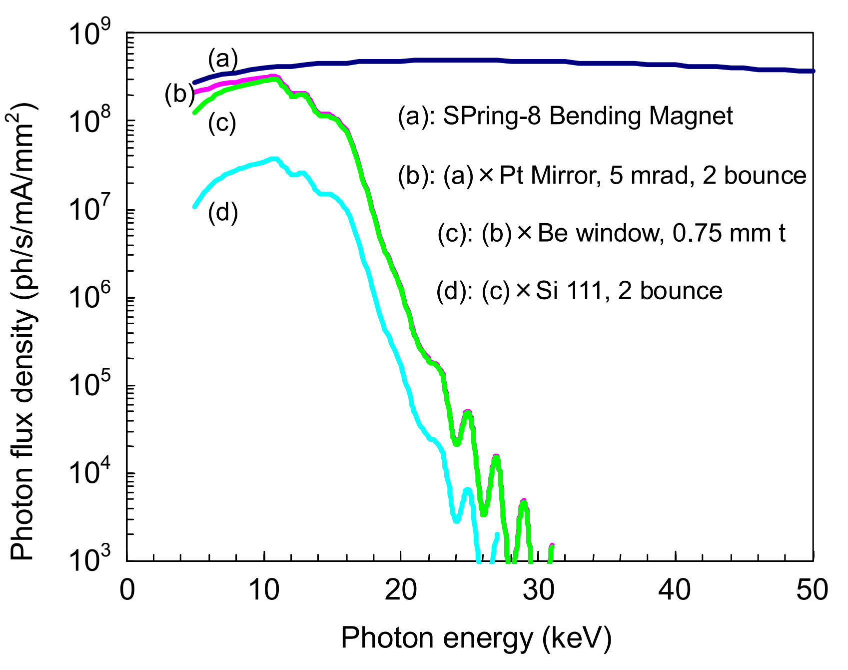
Example: SPring-8 Standard BM Beam Line

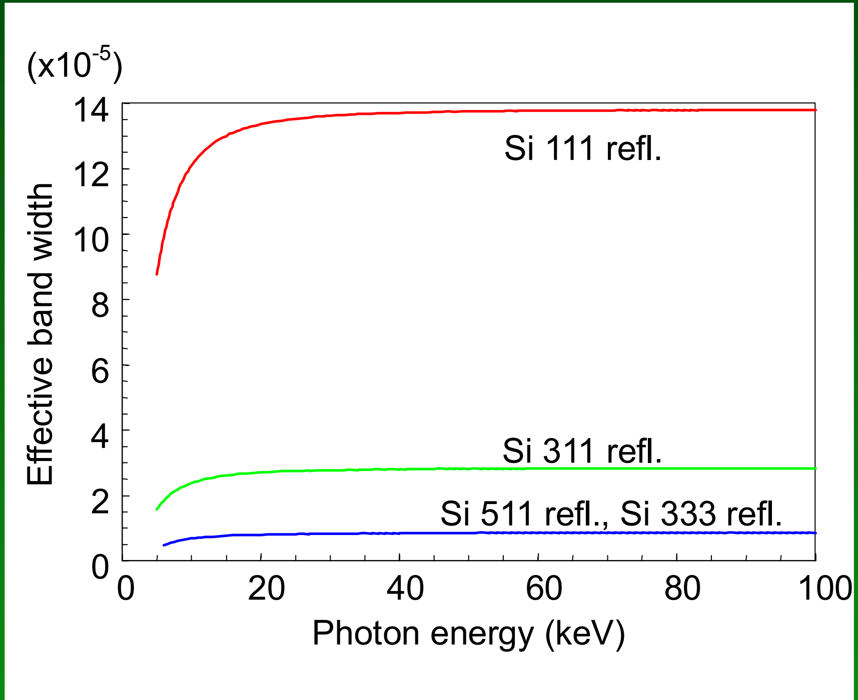


Optics

Collimator Mirror:	vertical upward deflection, 1 m long, Si, Pt-coated flat mirror, indirect water cooling, bending support beam collimation to make parallel incident beam on crystal mono
DCM:	standard BM type, Direct water cooling with fin-crystal
Focusing Mirror:	vertical downward deflection, 1 m long, Quartz, Pt-coated flat mirror, vertical beam focusing at sample position
Inclination/Elevation stage:	to follow beam path

Estimation of Available Flux





Effective Bandwidth ΔE/E

Photon Flux Estimation for BM Beam Line
Photon Flux Density @50 m from the source
(a)～(c) 0.1% bandwidth
(d) Effective Bandwidth is included

Thank you for your attention.

Acknowledgement

We would like to thank to Dr. Shunji Goto to prepare some ppt materials for this presentation. Discussion with Drs. Shunji Goto, Kenji Tamasaku and Makina Yabashi is highly appreciated.