빔라인 구성 기본

신현준
충북대학교 물리학과

순서

(1) 방사광원 리뷰
- -방사광가속기 목적
- -방사광원 종류

(2) 방사광 활용 원리
- -X-선 및 light matter interaction

(3) 빔라인 기능 및 구성 개념

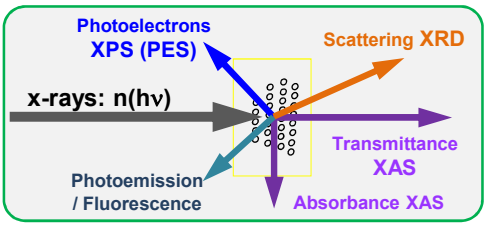
(4) 빔라인 구성 요소 디테일
- -X-선 광학계
- -빔라인 설계
- -단색분광기
- -빔라인 구성 예
- -검출장치

(1) 방사광원 리뷰

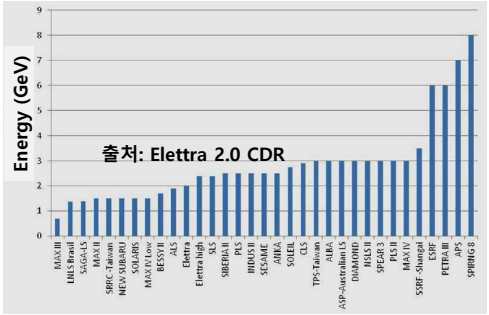
Ochang Multipurpose Synchrotron Radiation Facility

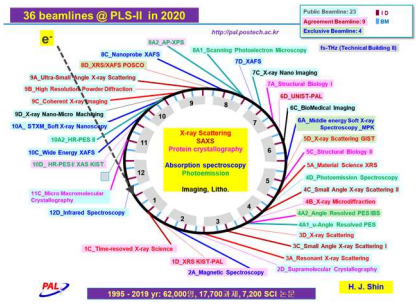
(1) 방사광원 리뷰: 방사광가속기 주목적

X-ray & mater interaction: scientific findings + material probing...
Related techniques: scattering, spectroscopy, imaging



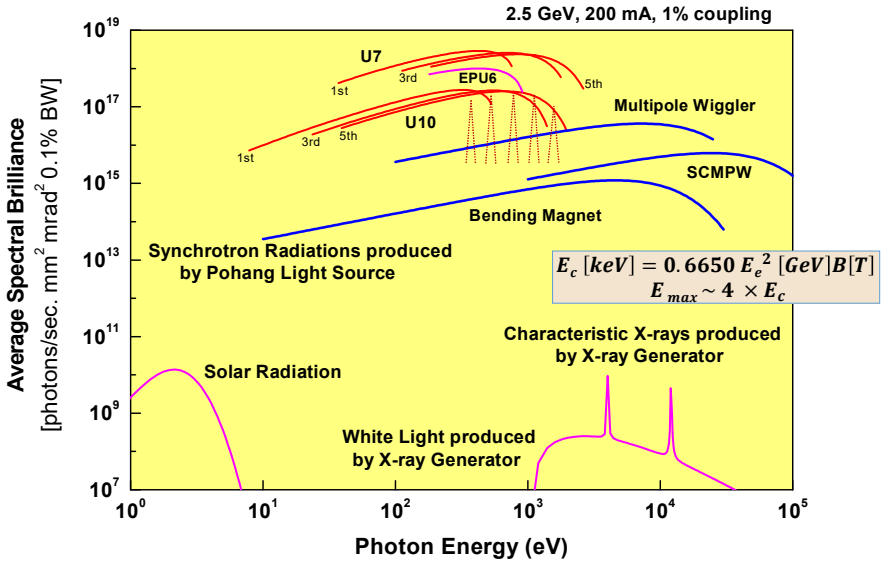
연구:
10^4~10^5 건/년





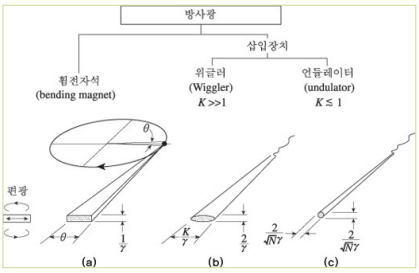
(1) 방사광원 리뷰: 방사광원 종류

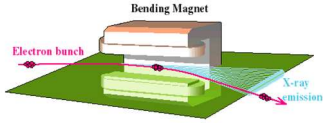
Synchrotron (x-) rays : PLS | 파장 λ [A] = 12,400 / 에너지 E [eV]

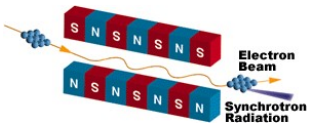


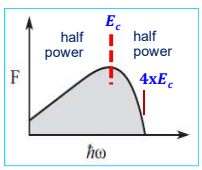
(1) 방사광원 리뷰: 방사광원 이해

Radiation sources from Synchrotron radiation facilities

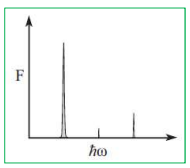






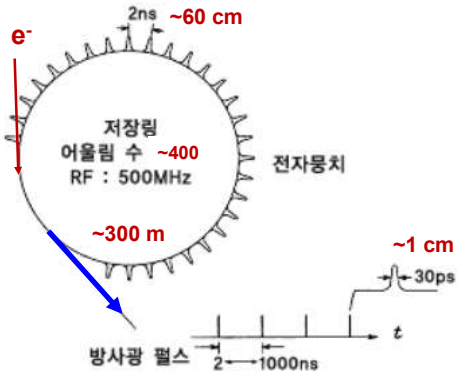


$\theta_V = 1/\gamma = 0.01°$ for 2.5 GeV



$\theta_{cen} = 0.0026°$ for 2.5 GeV, N=61

(1) 방사광원 리뷰: 방사광원 time structure



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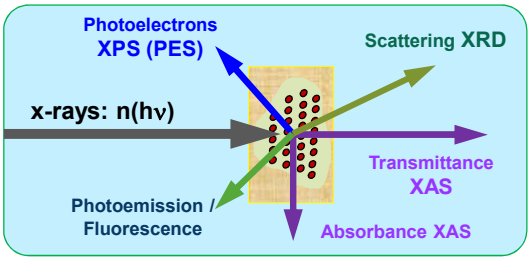
- -검출장치

(2) 방사광 활용 원리: light matter interaction

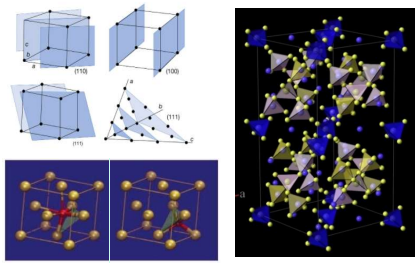
X-선 물성 분석 기법: scattering, spectroscopy, imaging



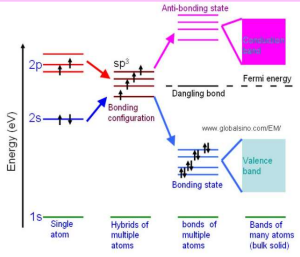
crystal structure,
atomic/ molecular structure,
local atomic structure,

electronic structure,
elemental speciation,
bonding configuration,
oxidation state,
magnetic moment, ...

XRD: X-ray diffraction



XPS: X-ray photoelectron spectroscopy
XAS: X-ray absorption spectroscopy



google/ www.globalsinocom.

(3,4) 빔라인 기능 및 구성 개념

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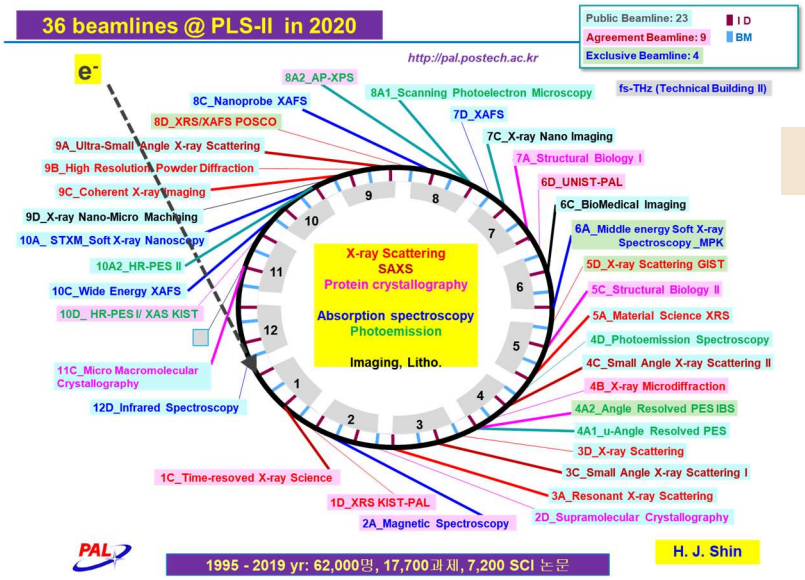
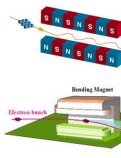
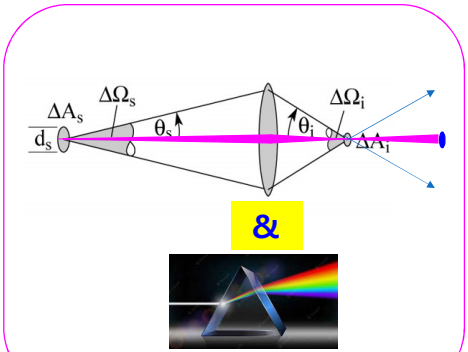
방사광 빔라인들



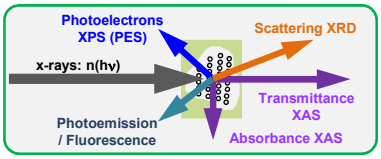
36개의 빔라인

빔라인 (beamline)



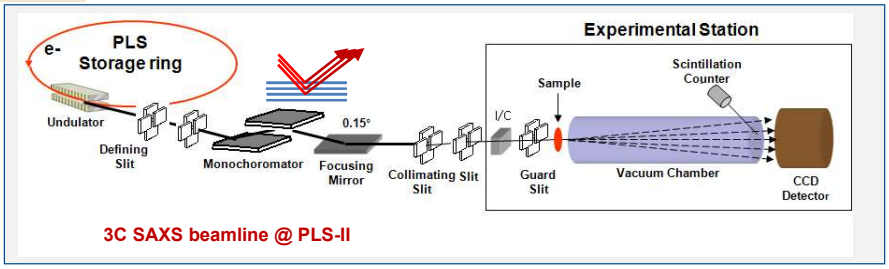


&



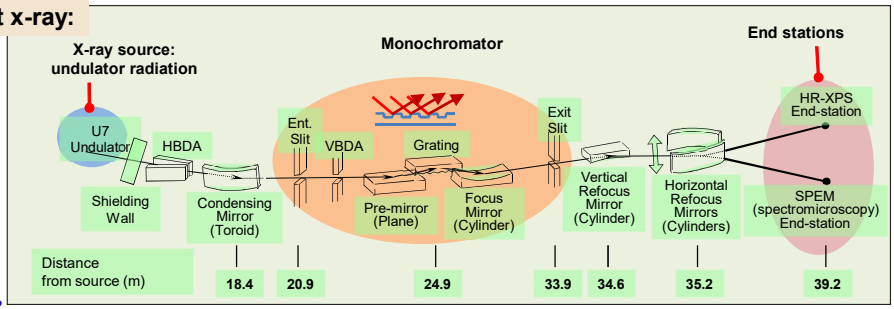
(3) 빔라인 기능 및 구성 개념

Hard x-ray:



3C SAXS beamline @ PLS-II

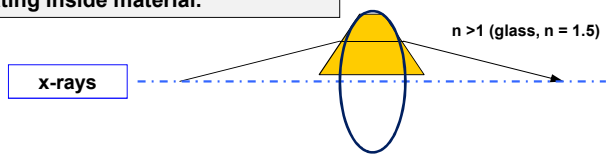
Soft x-ray:



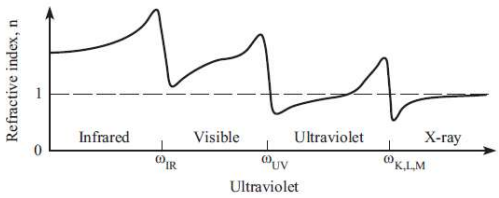
(4) 빔라인 기능요소 디테일: x-ray property in material

X-ray: transmission through material

Below ~10 keV, transmission through materials is very weak.
X-ray absorption induces heating inside material.



$n(\omega)$: refractive index is slightly less than 1
refractive index in air or in vacuum is ~1



X-rays and extreme ultraviolet radiation; 2nd ed., D. Attwood & A Sakdinawat, Cambridge Univ. Press, (2016).

(4) 빔라인 기능요소 디테일: x-ray property in material

$$\mathbf{E}(\mathbf{r},t) = \mathbf{E}_0 e^{-i(\omega t - \mathbf{k}\cdot\mathbf{r})}$$

$$\mathbf{E}(\mathbf{r},t) = \mathbf{E}_0 e^{-i[\omega t - (\omega/c)(1-\delta+i\beta)r]}$$

$$\mathbf{E}(\mathbf{r},t) = \underbrace{\mathbf{E}_0 e^{-i\omega(t-r/c)}}_{\text{vacuum propagation}} \underbrace{e^{-i(2\pi\delta/\lambda)r}}_{\phi\text{-shift}} \underbrace{e^{-(2\pi\beta/\lambda)r}}_{\text{decay}}$$

$n(\omega)$: refractive index

$$n(\omega) = 1 - \delta + i\beta$$
$$= 1 - \frac{n_a r_e}{2\pi}\lambda^2 [f_1^o(\omega) - i f_2^o(\omega)]$$

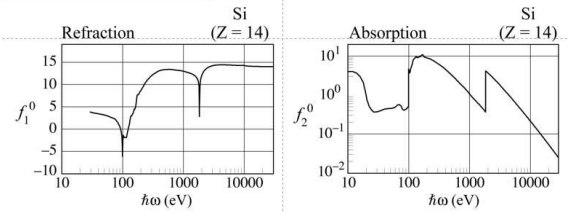
r_e : classical electron radius
ω_s : x-ray resonance
n_a : number density
γ: dissipation factor

complex atomic scattering factor

$$f^o(\omega) = \sum_s \frac{-gs\omega^2}{\omega^2 - \omega_s^2 + i\gamma\omega}$$

$$f^o(\omega) = f_1^o(\omega) - i f_2^o(\omega)$$

Atomic scattering factors



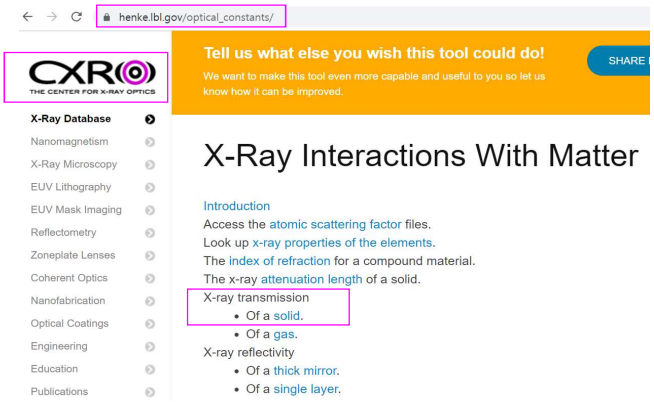
Courtesy of E. Gullikson, LBNL

X-rays and extreme ultraviolet radiation; 2nd ed., D. Attwood & A Sakdinawat, Cambridge Univ. Press, (2016).

(4) 빔라인 기능요소 디테일: x-ray property in material

CXRO homepage

transmission through a thin film



(4) 빔라인 기능요소 디테일: x-ray property in material

henke.lbl.gov/optical_constants/filter2.html

Filter Transmission

- Choose from a list of common materials: Enter Formula
- Chemical Formula: Si3N4
- Density: -1 gm/cm^3 (enter negative number to use tabulated values.)
- Thickness: .1 microns
- Photon Energy (eV) Range from 10 to 1000 in 100 steps (< 500).

(NOTE: Photon Energy must be in the range 10 eV < E < 30,000 eV and Wavelengths in th < 124 nm).

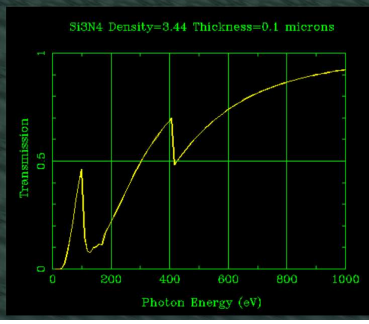
To request a Linear Plot press this button: Submit Request

To reset to default values, press this button: Reset.

henke.lbl.gov/cgi-bin/filter.pl

Filter Transmission: data file here

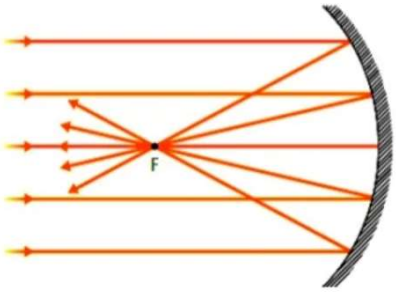
Print



(4) 빔라인 기능요소 디테일: x-ray property in material

Normal 입사 광학계 만들기 어려움 !!!

X-ray: reflectivity at surface of material



Reflectivity

$$Rs\,(90^0) \simeq \frac{\delta^2 + \beta^2}{4}$$

C @ 0.4nm,
δ = 4.9 x 10^{-5}, β = 5.71 x 10^{-7}

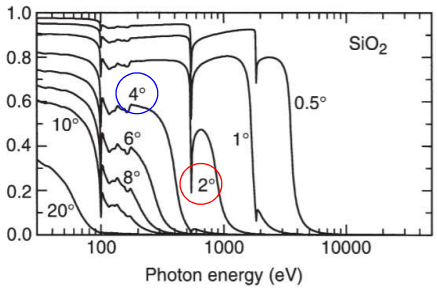
Ni @ 4.13 nm (f_1^0=17.8 f_2^0=7.70)
δ = 0.0124, β = 0.00538

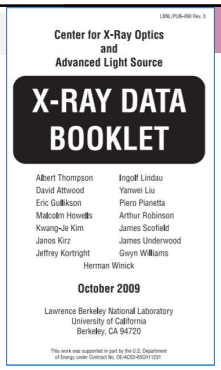
Au @ 1keV
δ = 0.0021

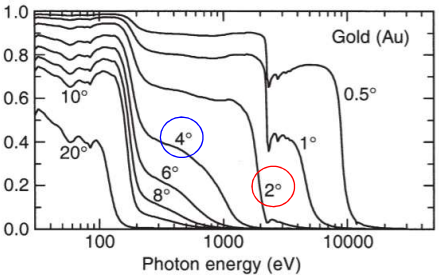
X-rays and extreme ultraviolet radiation; 2nd ed., D. Attwood & A Sakdinawat, Cambridge Univ. Press, (2016).

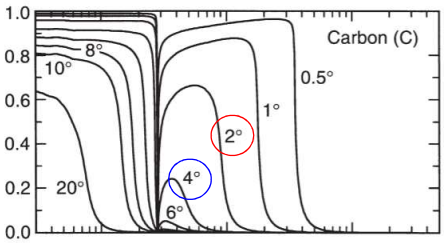
(4) 빔라인 기능요소 디테일: x-ray property in material

표면에서의 (grazing incidence) 입사각과 에너지에 따른 반사율



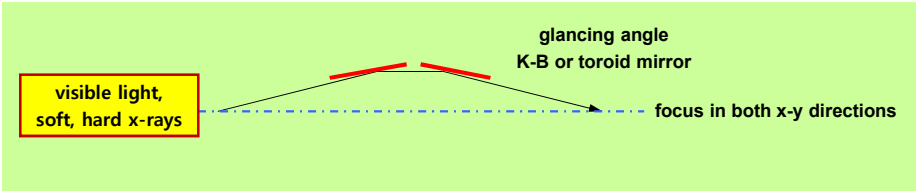






(4) 빔라인 기능요소 디테일: x-선 광학계

Practical optics scheme for x-ray beamlines ...

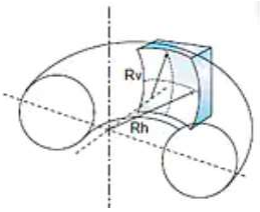


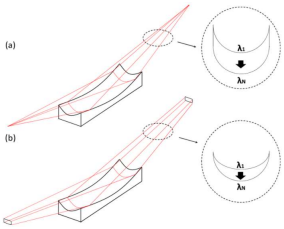
(4) 빔라인 기능요소 디테일: x-선 광학계

Toroidal shape mirrors: tangential and sagittal directional curvature

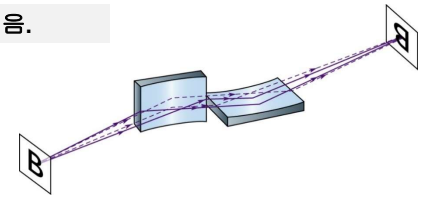
$$\frac{1}{A_t}+\frac{1}{B_t}=\frac{2}{R_t\ \cos\phi}$$

$$\frac{1}{A_s}+\frac{1}{B_s}=\frac{2\ \cos\phi}{R_s}$$





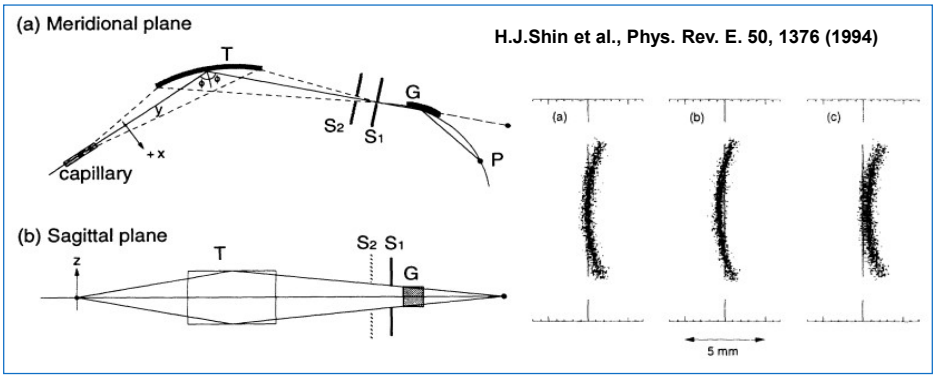
K-B mirror set이 많은 경우 선호 되고 있음.



(4) 빔라인 기능요소 디테일: x-선 광학계

- **Glancing angle optics**에 의한 집속 모양은 구형의 모양이 아님.
- **Ray tracing**을 통하여 집속 모양 이해 필요. (비 집속 현상의 이해 필요).

Capillary (discharge plasma) 에서 발생한 광원이 분광기 앞 slit에 도달할 때의 모양.

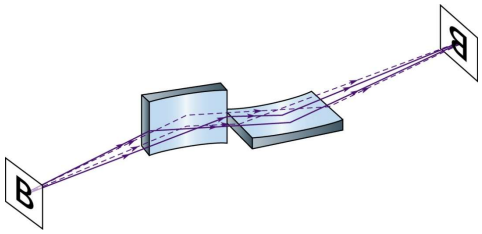


(4) 빔라인 기능요소 디테일: x-선 광학계

빔라인 **Kirkpatrick Baez (K-B mirror)**미러에 **ray tracing** 적용하는 예

Source

	Parameter	size	unit
1	Number of Random rays	10000	-
2	Sigma X	0.001	cm
3	Sigma Z	0.001	cm
4	Sigma Y	0.1	cm
5	Horizontal Sigma	50	μrad
6	Vertical Sigma	50	μrad
7	Energy	10000	eV



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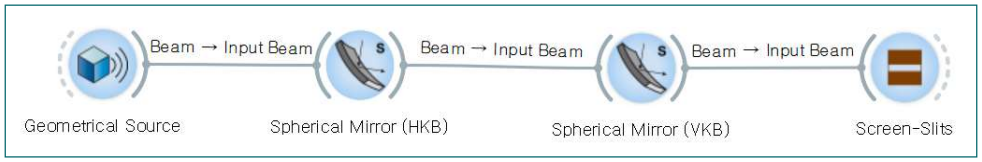
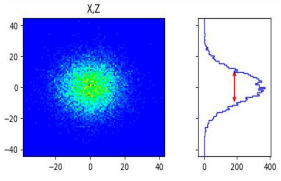
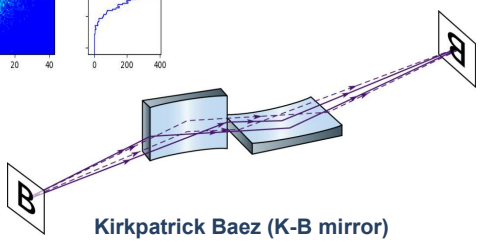
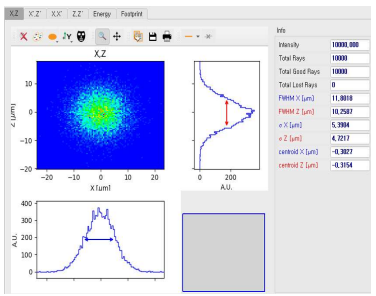




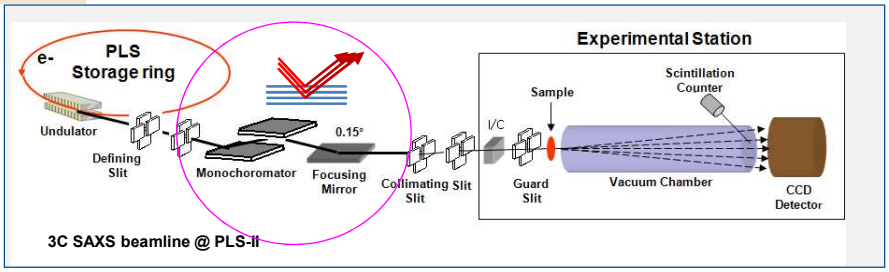


Kirkpatrick Baez (K-B mirror)

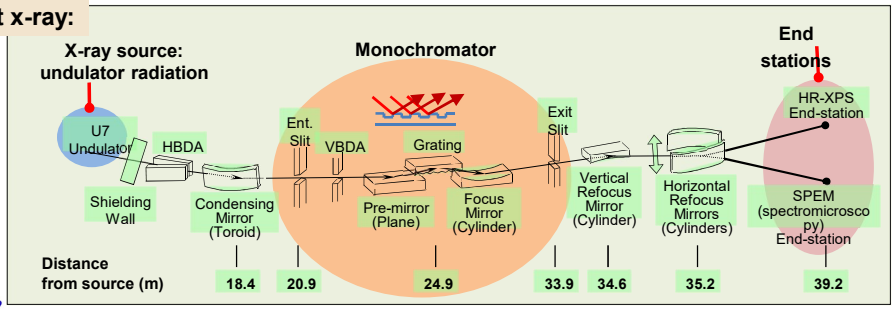


Monochromator: 단색화장치

Hard x-ray:



Soft x-ray:



PAL

Monochromator elements for hard & soft x-rays

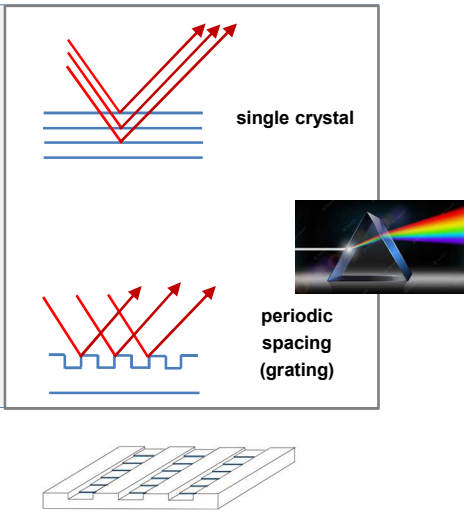
wavelength λ [A] = 12,400 / energy E [eV]

Hard x-ray:

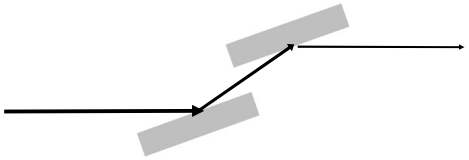
- energy > ~ 4 keV
- monochromator: single crystal
- less absorption in air

Soft x-ray:

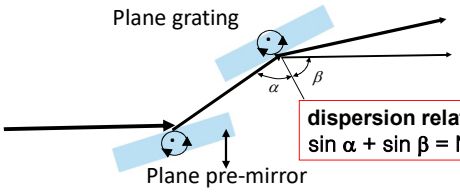
- energy < ~ 2 (3) keV
- monochromator: grating
- strong absorption in air



Monochromator type: double crystal vs. grating



Double crystal monochromator in x-ray beamline.

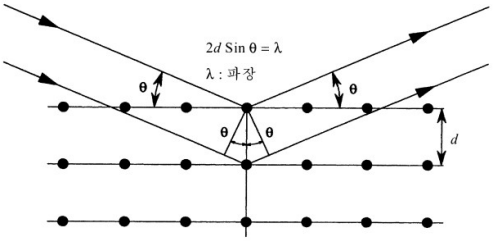


$$\frac{\cos\beta}{\cos\alpha} = 2.24$$ (U7 beamline)

Modified plane Grating Monochromator.

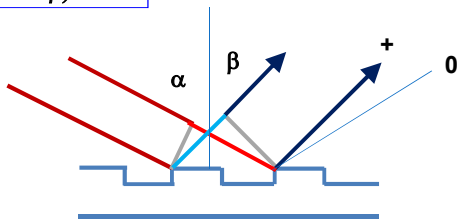
Entrance and Exit slits → can be in fixed position

Crystal monochromator in x-ray beamline.



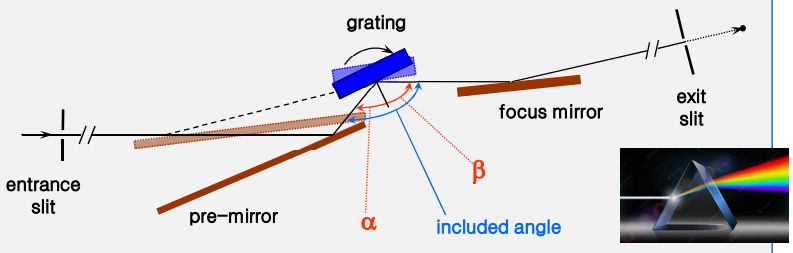
$$n\lambda = 2d\sin\theta$$

dispersion relation:
$d (\sin \alpha - \sin \beta) = k \lambda$



d: period = 1/N

VIA-PGM
(Variable Included Angle Plane Grating Monochromator)



defocus term: $1/2 (\cos \alpha^2 / r + \cos \beta^2 / r') = 0$

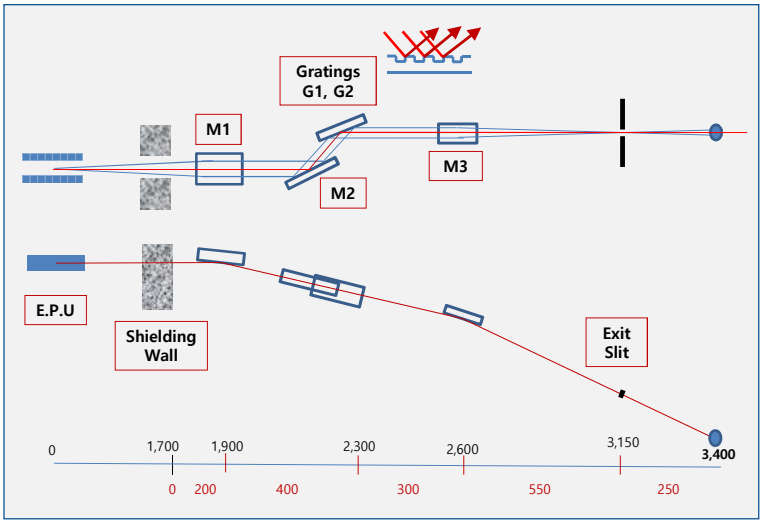
$\cos \alpha / \cos \beta = C$

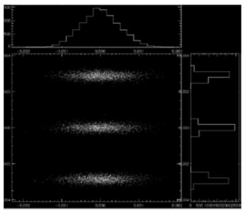
$r' = - r C^2$

$C = 2.24$

dispersion relation: $\sin \alpha + \sin \beta = N k \lambda$

10A 빔라인 구축 당시 사례: 빔라인 설계에 있어 ray tracing을 적용한 예

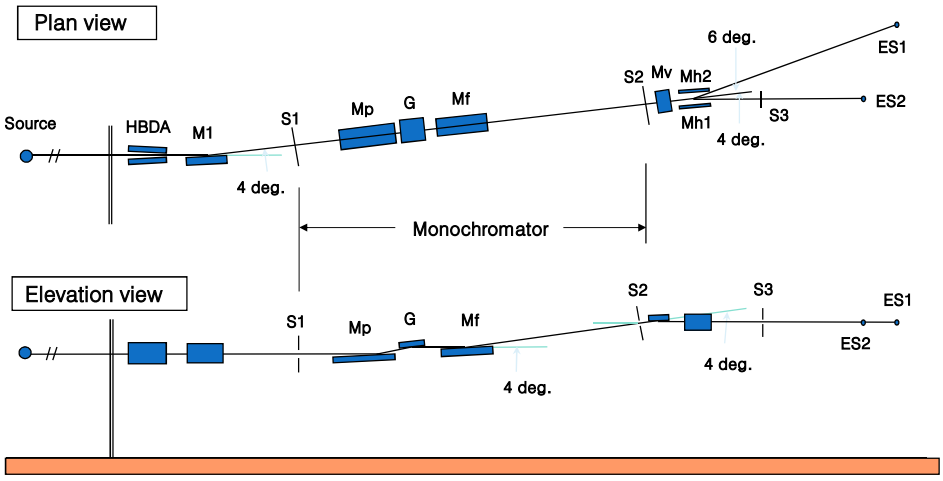




빔라인 에너지 분해능 확인

Soft x-ray beamline 구성 사례: 8A U7 undulator beamline

Schematic of U7 undulator beamline



unit; meter

HBDA: Horizontal beam defining aperture, M1: toroidal condensing mirror, S1: entrance slit, Mp: pre-mirror, G: grating, Mf: focus mirror, S2: exit slit, Mv: vertical refocusing mirror, Mh1,2: horizontal refocusing mirrors, S3: pinhole, ES1: endstation for high-resolution spectroscopy, ES2: endstation for spectromicroscopy.

H.J.Shin, J. Korean Phys. Soc. 34, 350-358 (1999)

U7 design parameters

electron energy (e)	2.5 GeV
period length (λ_u)	7 cm
number of period (N)	61
horizontal emittance (ε_x)	18.9 nm rad
vertical emittance (ε_y)	0.189 nm rad
β_x	10 m
β_y	4 m
beam current (I)	0.2 A
number of bunch	250
repetition rate	1 MHz
pulse width of each bunch	17 ps

	M1	Mp	G	Mf	Mv	Mh1	Mh2
shape	toroid	plane	plane	cylinder	cylinder	cylinder	cylinder
coating material	Au	Au	Au	Au	Au	Au	Au
substrate	Glidcop	Si	Si	Glidcop	Glidcop	Glidcop	Glidcop
incidence angle (degrees)	2	variable	variable	2	2	3	2
tangential radius of curvature (m)	1054.47	infinite	infinite	341.2	26-37	190-3000	55-100
sagittal radius of curvature (m)	1.1536						
tangential slope error (μrad)	15	0.5	0.5	0.5	3	5.5	14
sagittal slope error (μrad)	6						
surface roughness (nm)	1.6	0.5	0.5	0.5	0.6	0.5	0.6
clear aperture (mm x mm)	320 x 50	756 x 35	150 x 55	700 x 50	70 x 20	200 x 20	200 x 20

Line density (lines/mm)	Groove depth (nm)	Photon energy (eV)
60	150	30-75
120	50	70-190
400	17	190-500
1100	6.5	500-1400
2000	4	1000-2000

H.J.Shin, J. Korean Phys. Soc. 34, 350-358 (1999)

$S = 3d^2 [\mathrm{Sin}\theta_i\, r'_m (\mathrm{Cos}\theta_i / r_m - 1 / R_m) / r_m - \mathrm{Sin}\theta_i (\mathrm{Cos}\theta_i / r'_m - 1 / R_m)] / 2$: Spherical aberration

$\mathrm{Cos}^2\beta / \mathrm{Cos}^2\alpha = -r'/r = K_g^2$

α and β are incidence and diffraction angles at the grating

r is the distance between the entrance slit and the grating;

r' is the distance between the grating and the virtual image

Spectral resolution

Entrance slit size
Diffraction limit effect at grating
Slope error of the grating
Slope error of the premirror
Coma aberration of the grating
Coma aberration of the focusing mirror
Exit slit size

$R_{entrance} = Nk\lambda r / (\mathrm{Cos}\alpha\, w_{entrance})$

$w_{entrance}$ is width of an entrance slits

N is the groove density and k is the harmonic

$R_{diff} = N\, k\, w$

w: illuminated width of the beam at the grating

$R_{slope} = N\, k\, \lambda / (\mathrm{Cos}\theta\, 4\gamma)$

γ is the slope error at each optic

$R_{coma} = (2Nk\lambda) / [3d^2 (\mathrm{Cos}^2\alpha\, \mathrm{Sin}\alpha / r^2 + \mathrm{Cos}^2\beta\, \mathrm{Sin}\beta / r'^2)]$

d is the half size of the footprint

$R_{comaMf} = Nk\lambda r' / (\mathrm{Cos}\,\beta\, S_{comaMf})$,

S_{comaMf} is the size of the coma induced by the focusing mirror

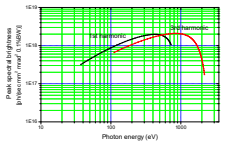
$R_{exit} = Nk\lambda r' / (\mathrm{Cos}\beta\, w_{exit})$

w_{exit} is width of an exit slit

Simulated specification of the U7 beamline

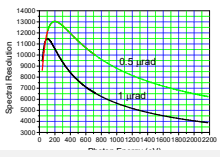
Spectral brightness of the X-rays from the undulator.

Electron energy = 2.5 GeV, beam current = 200 mA.
Magnet period length = 7 cm, number of periods = 61.
Magnet field = 1 Tesla (max.)
Repetition rate = 1 MHz.
Number of bunches = 250, pulse width of each bunch = 17.



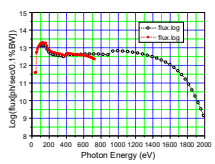
Spectral resolving power of the monochromator.

Diffraction limit caused by the illuminated width at the grating.
Slope error effects at the grating, premirror, and focus mirror.
Coma effect from the grating surface.
Coma effect from the focus mirror.
Effect of the entrance and exit slit sizes.



Total flux at endstatoin.

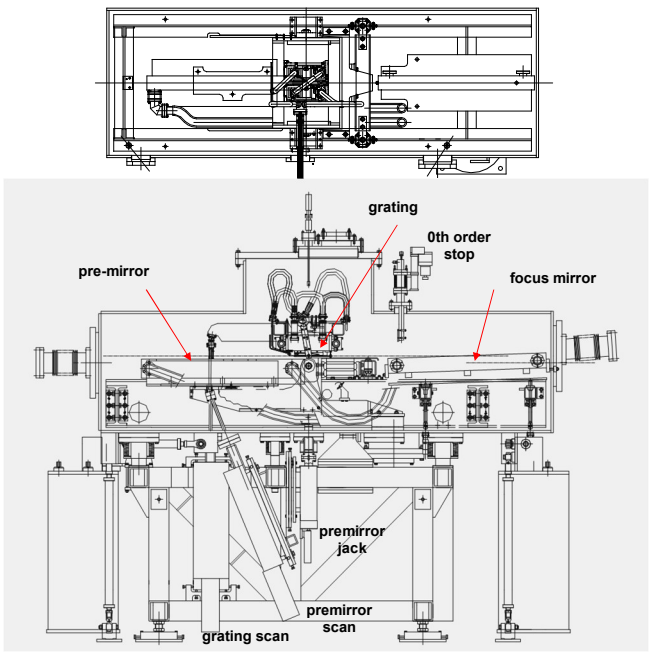
Reflectivity at each mirror.
Throughput through the entrance slit.
Throughput of the monochromator.
Reflectivity of the pre-mirror, grating, focus mirror.
Diffraction efficiency at the grating.
Throughput through the exit slit.

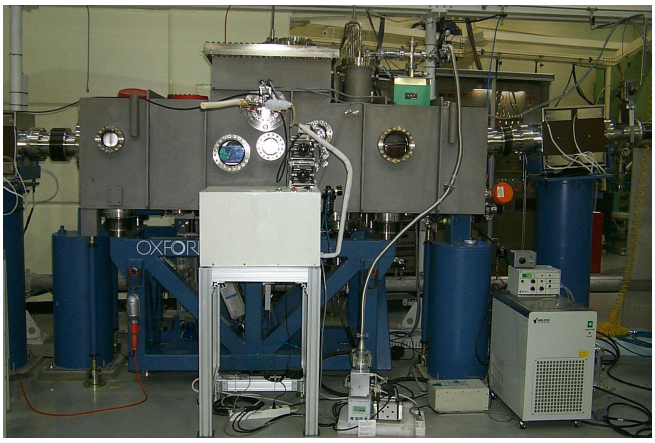


H.J.Shin, J. Korean Phys. Soc. 34, 350-358 (1999)

Soft x-ray beamline 모양 사례: 8A U7 undulator beamline

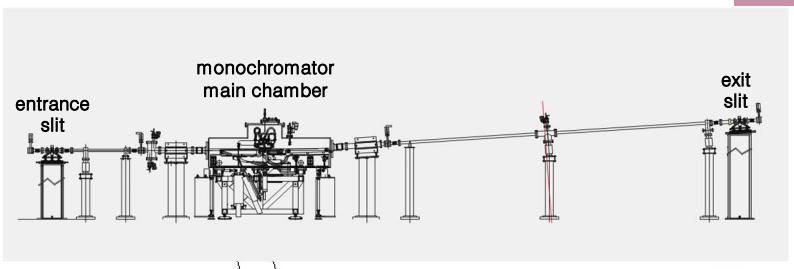
Assembly drawing of a VIA-PGM monochromator main chamber

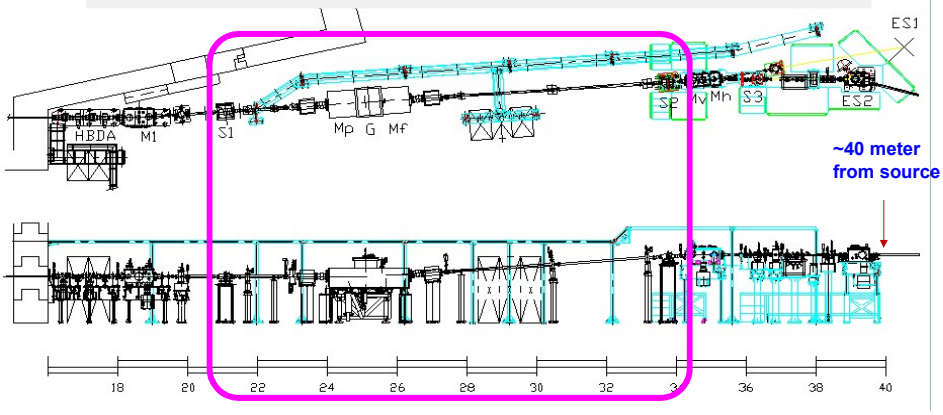




Monochromator chamber의 외부 모습

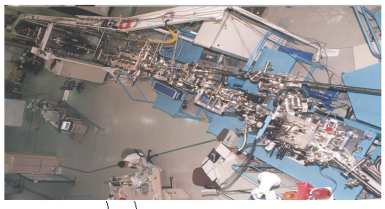
Assembly drawing of a monochromator

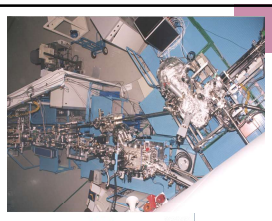


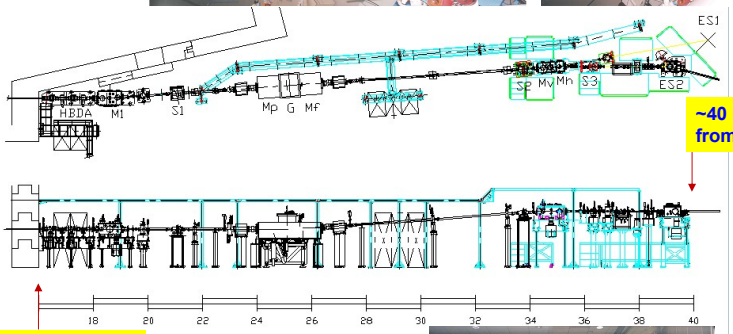


8A, U7 beamline

SPEM endstation
+ XPS endstation

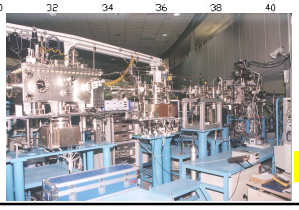






~40 meter
from a source

~16 meter
from a source



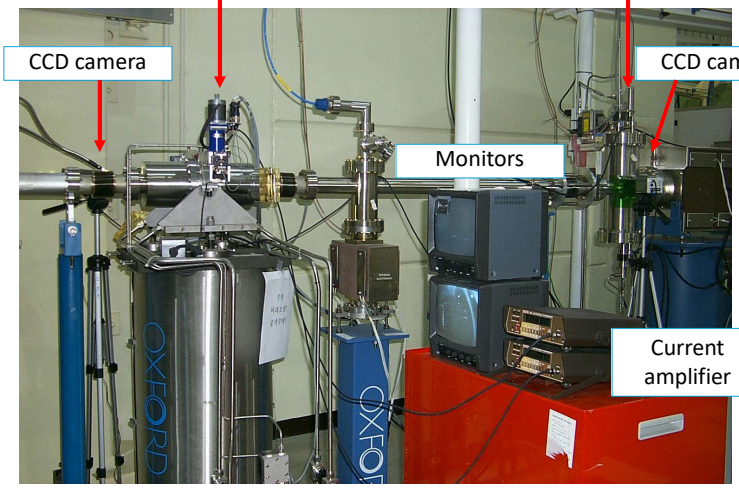
H. J. Shin

Diagnostic paddle

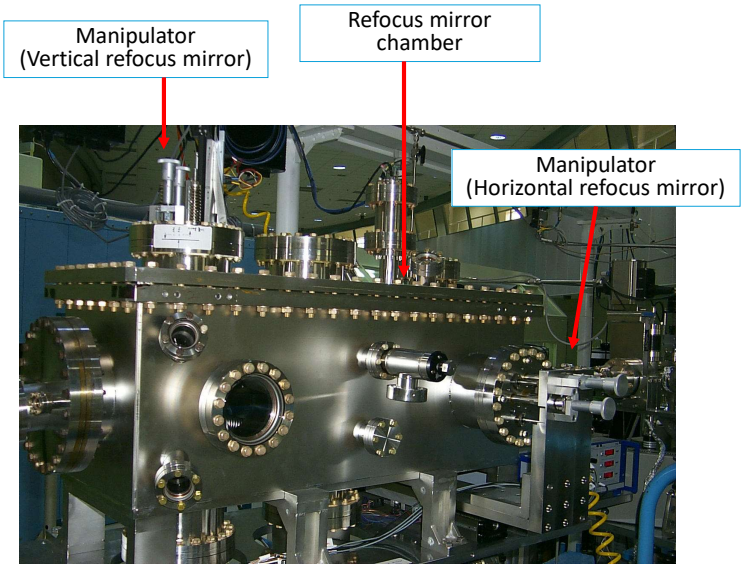
Entrance slit

CCD camera

CCD camera

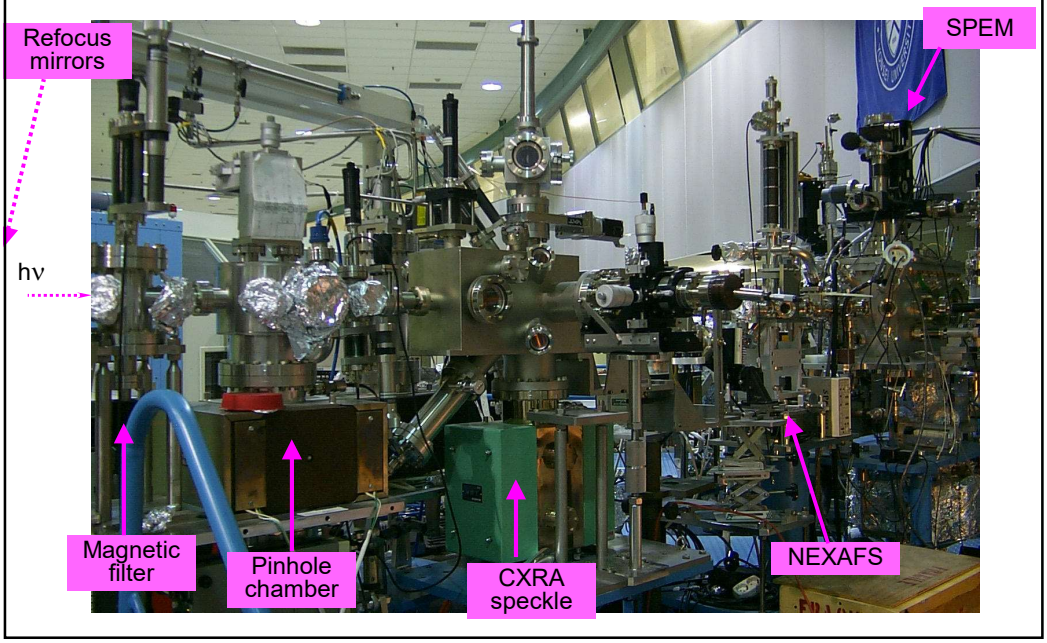


CCD camera, monitor 및 전류 증폭장치가 빔라인 정렬을 가시화하기 위한 부위에 장착된 모습



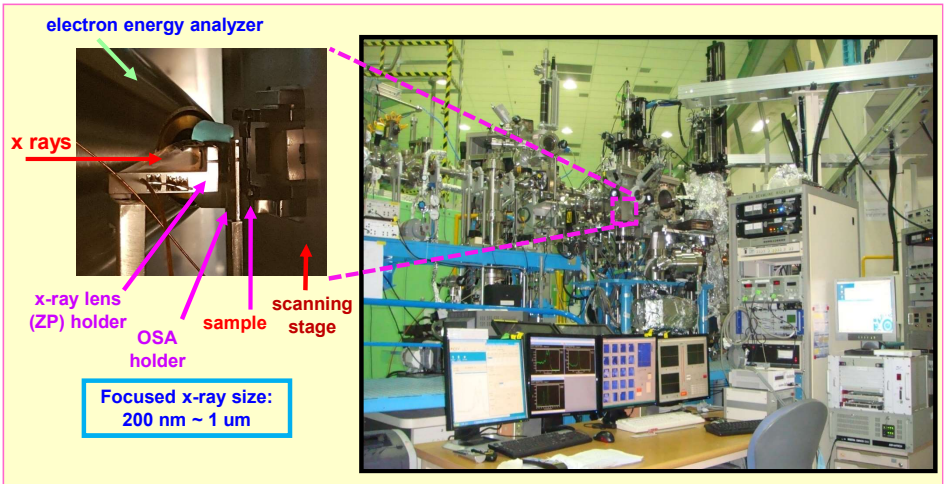
Micrometer를 이용한 mirror manipulator가 refocus mirror 조절장치에 장착된 모습

Photo of SPEM branch



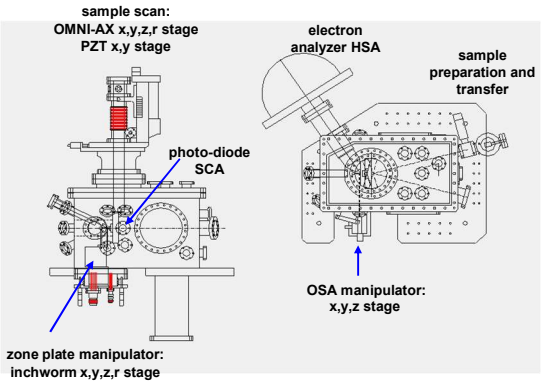
SPEM

operational since ~1998 yr. at the PLS

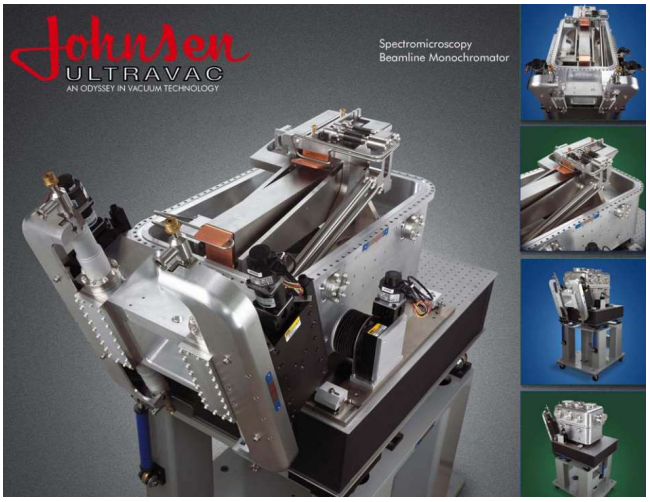


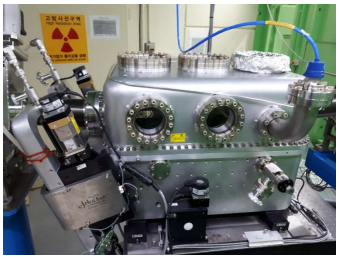
8A1 beamline, PLS

초기 8A1 SPEM main chamber assembly drawing



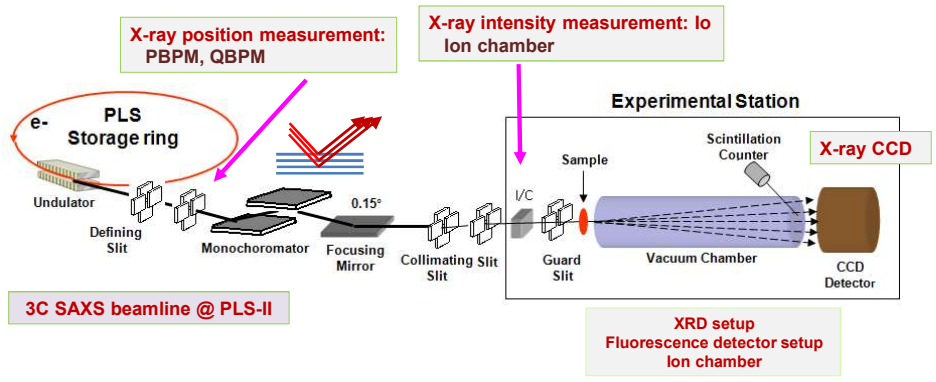
Recent shape of VIA-PGM monochromator main chamber

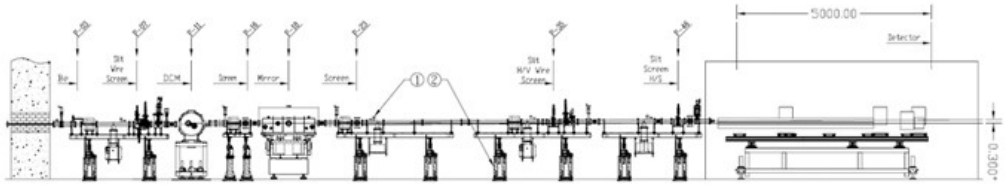




Crystal monochromator for hard x-ray beamlines.

Hard x-ray beamline components: schematic





-The end-

Thank you for your kind attention !