X-ray Nano Probes for Nano Materials at Taiwan Photon Source

Outline

- Synchrotron Light Source
- Application of Synchrotron Light
- X-ray nano probe at TPS

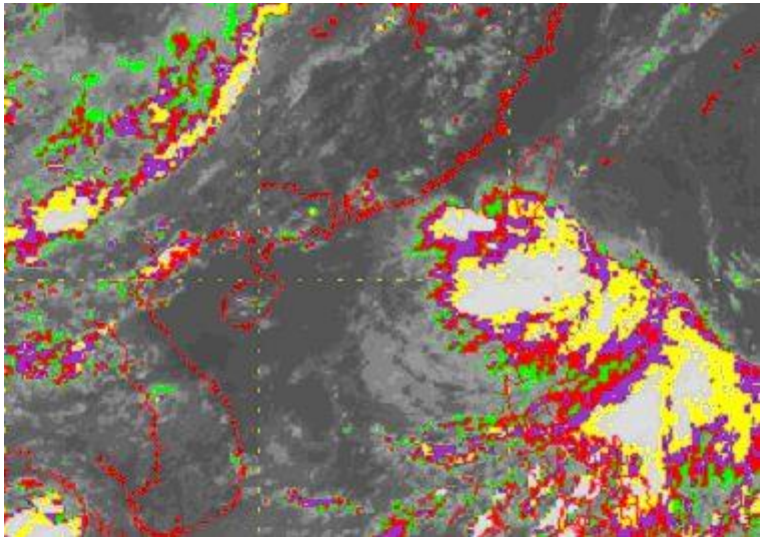
"Light" is indispensable to man's exploration of nature



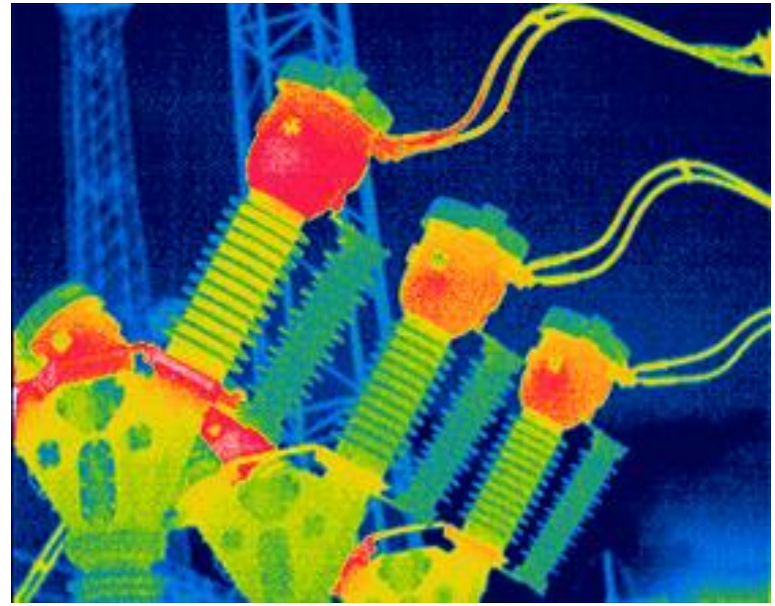




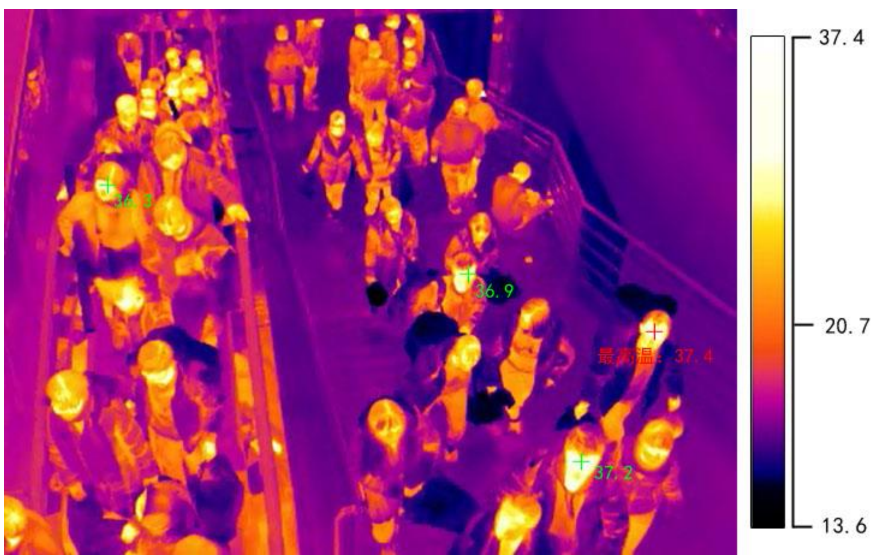
Invisible light: IR and X-ray…



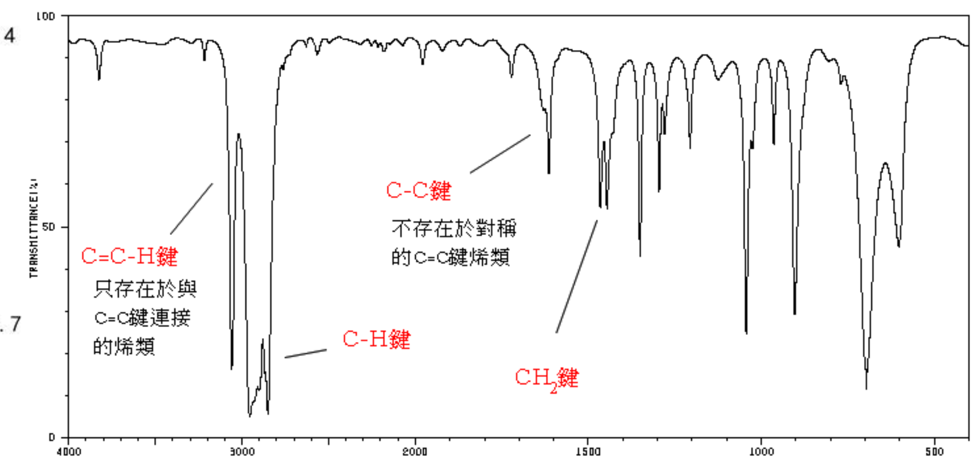
http://www.hko.gov.hk/prtver/html/docs/education/edu02rga/radiation/radiation_02-c.shtml



http://www.yingfukeji.com/appl/grid.html

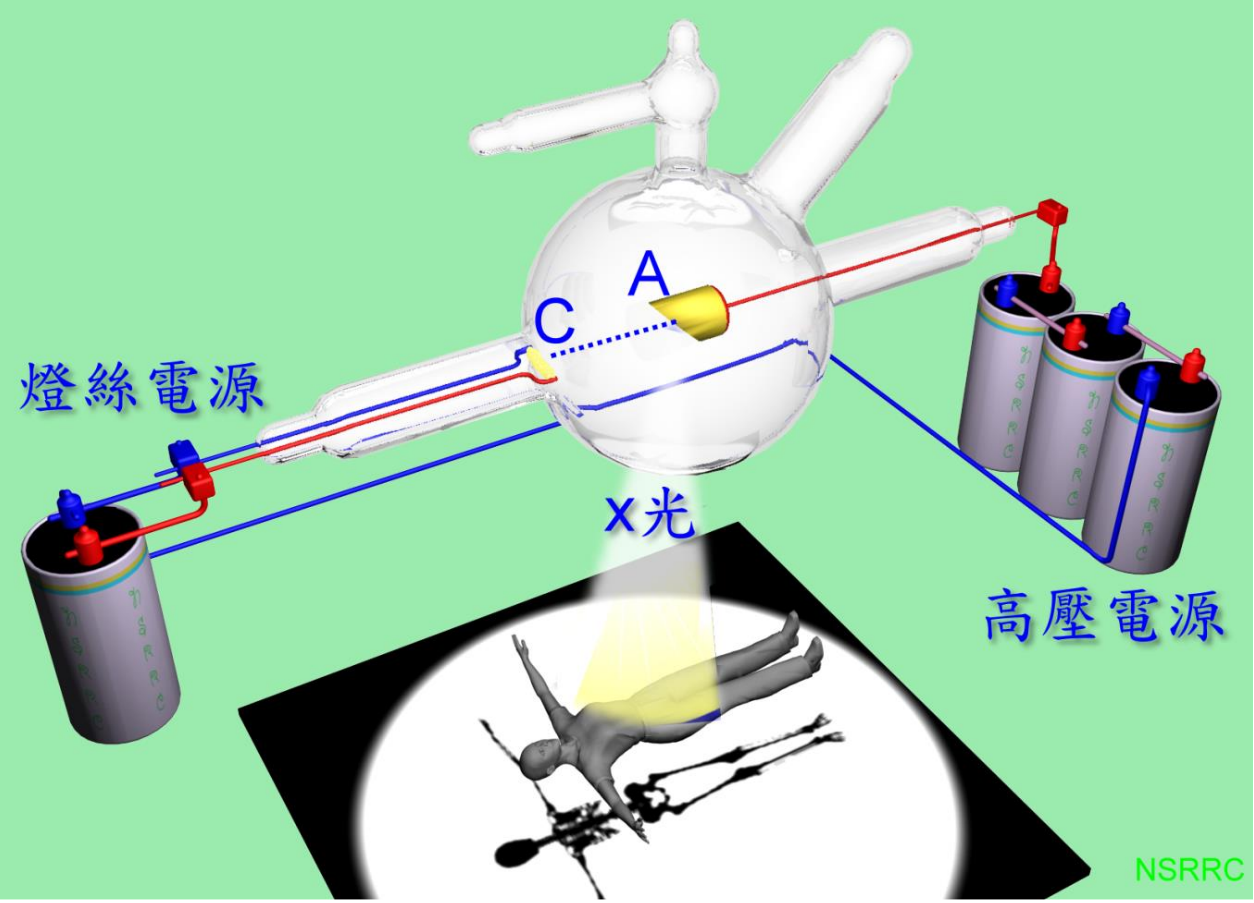


http://www.uv-teck.com/Ttwjy



http://smallcollation.blogspot.tw/2014/02/infrared-spectroscopy-of-alkanes.html#gsc.tab=0

Rontgen used a simple accelerator to discover X-rays

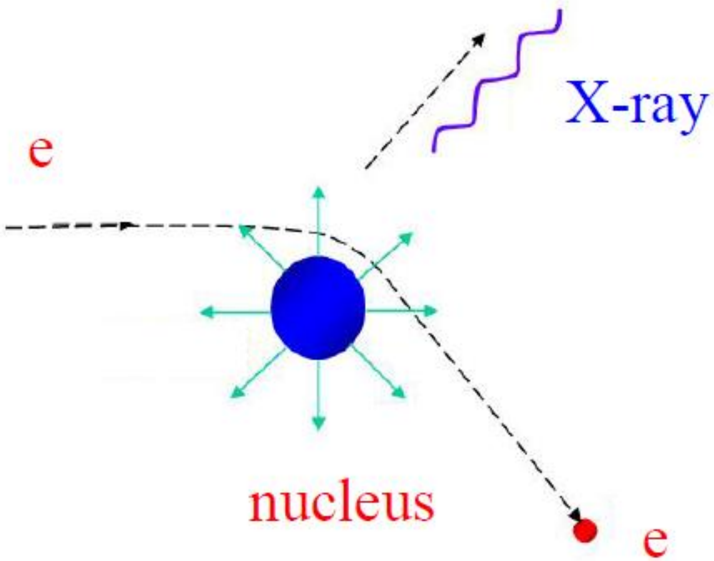


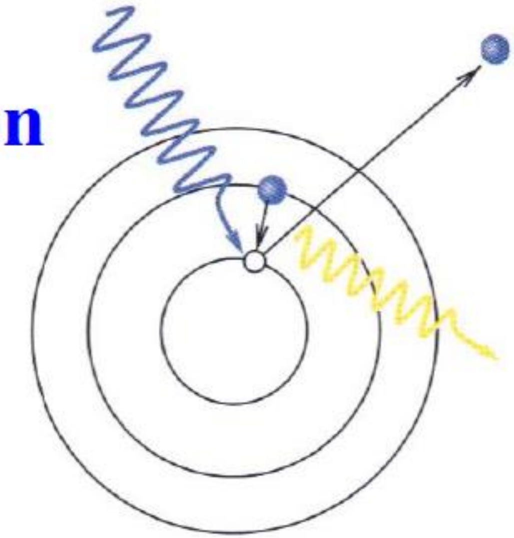
1895

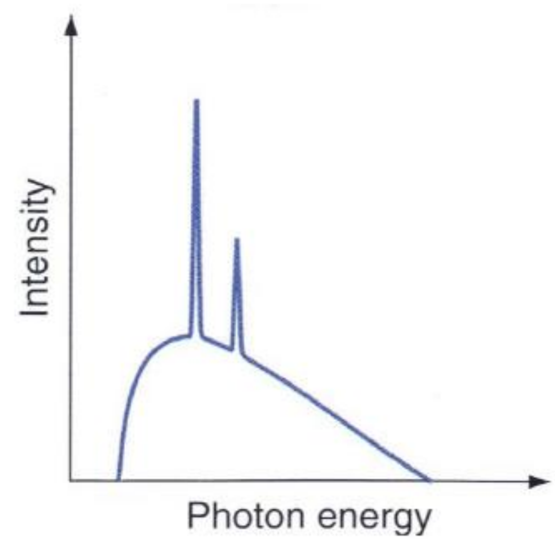
Hand mit Ringen (Hand with Rings): Wilhelm ROntgen's first "medical" X-ray, of his wife's hand, taken on 22 December 1895 and presented to Ludwig Zehnder of the Physik Institut, University of Freiburg, on 1 January 1896.

http://en.wikipedia.org/wiki/X-ray

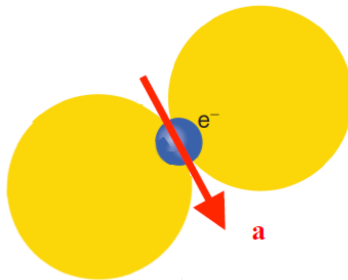
Characteristic X-ray emission



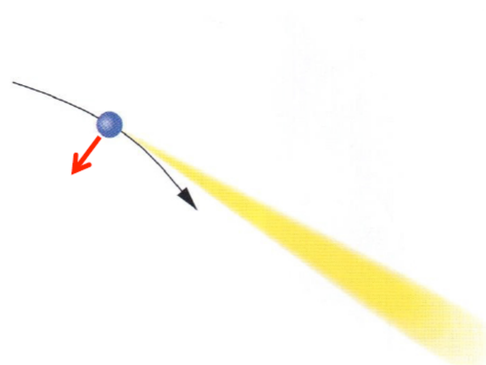




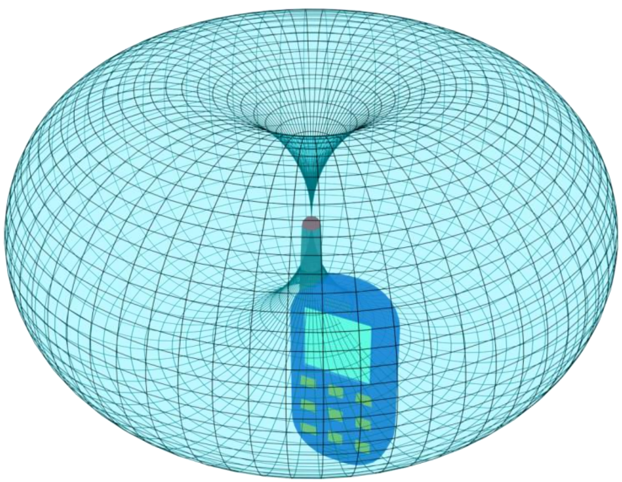
Electromagnetic wave from a moving charge

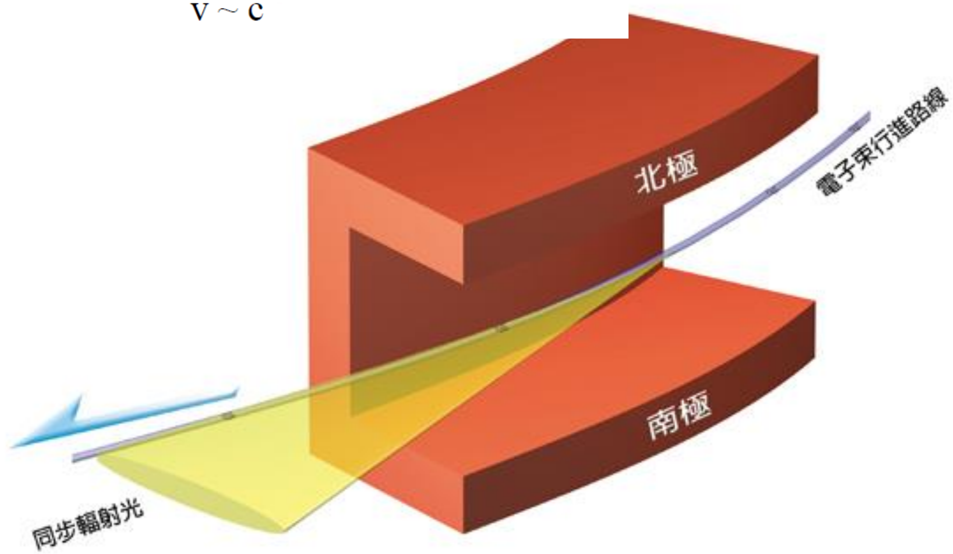


$v \ll c$



$v \sim c$

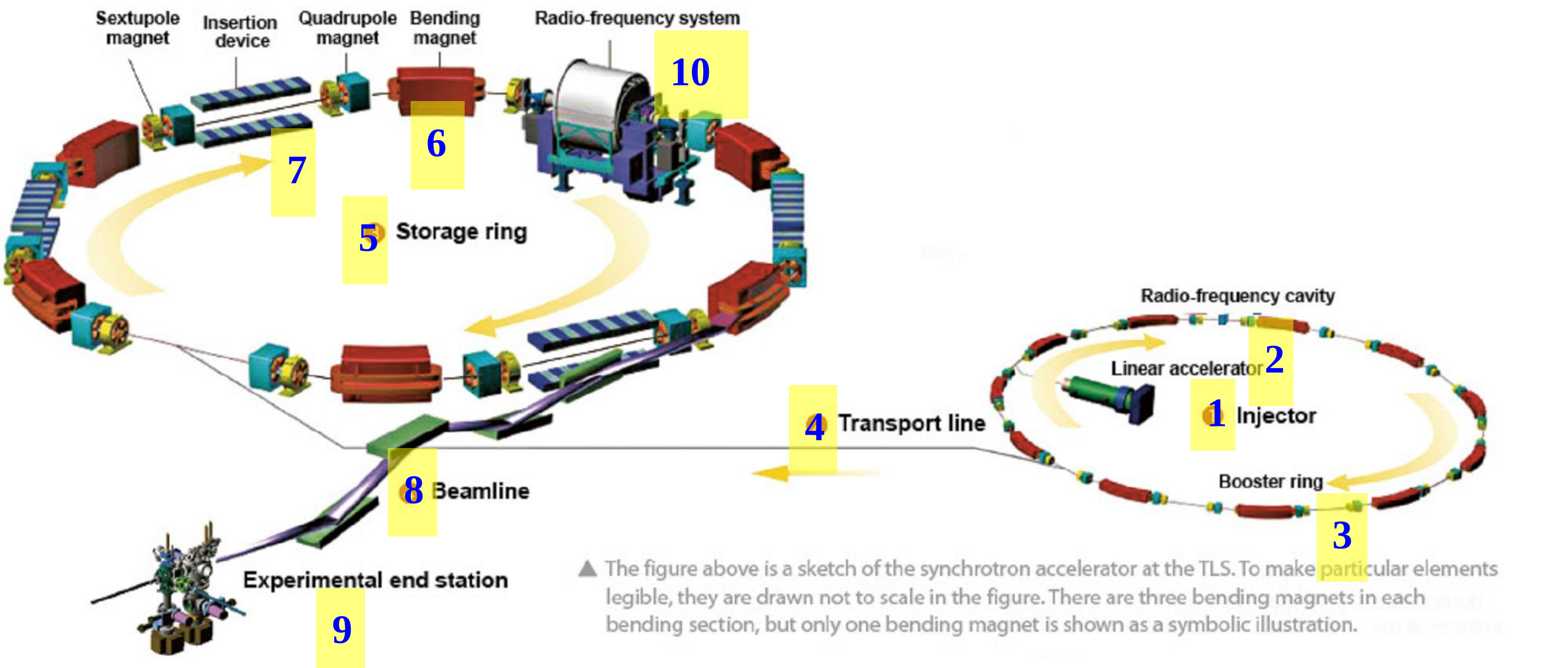




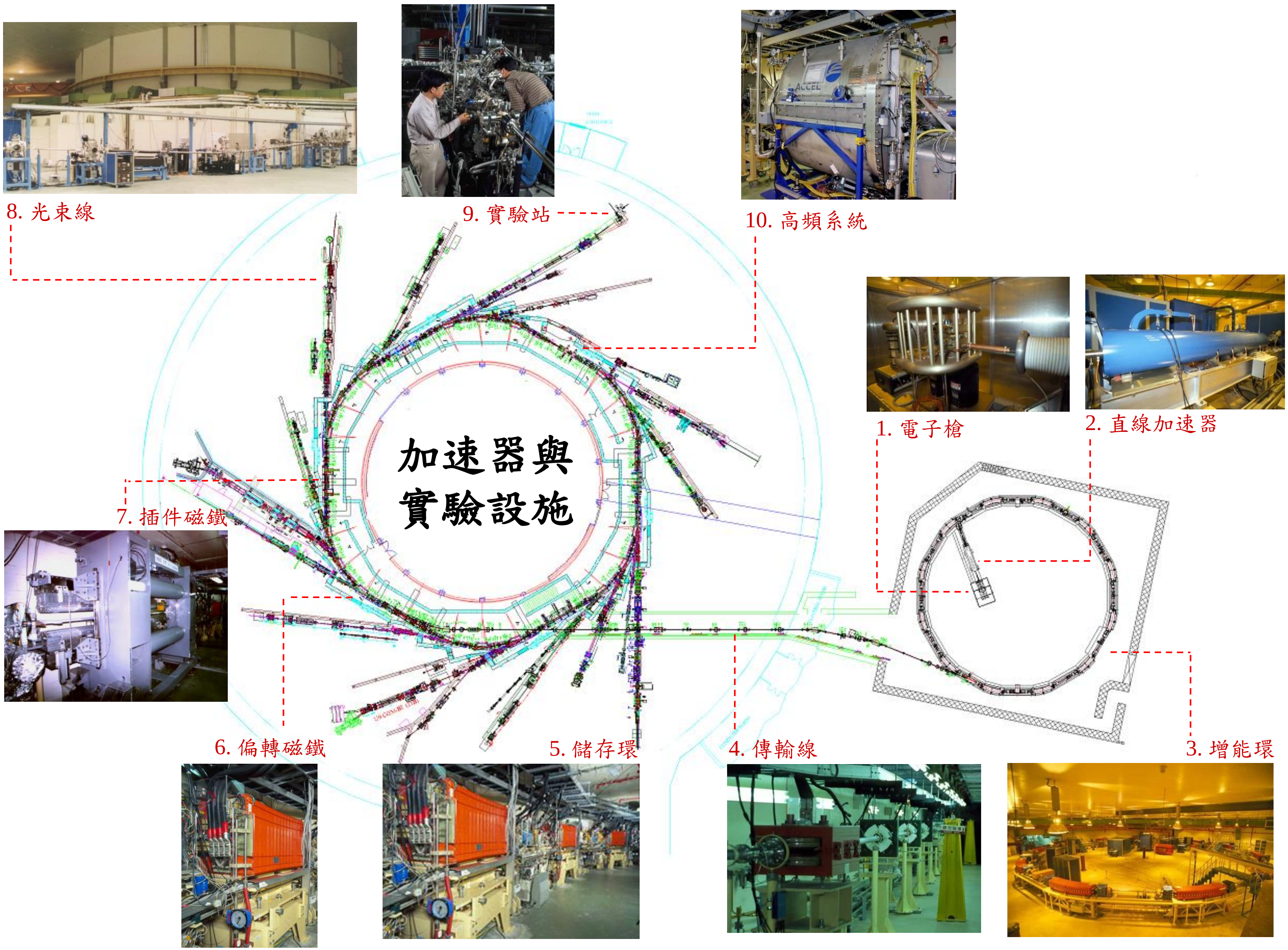
二極偏轉磁鐵

同步加速器光源的原理

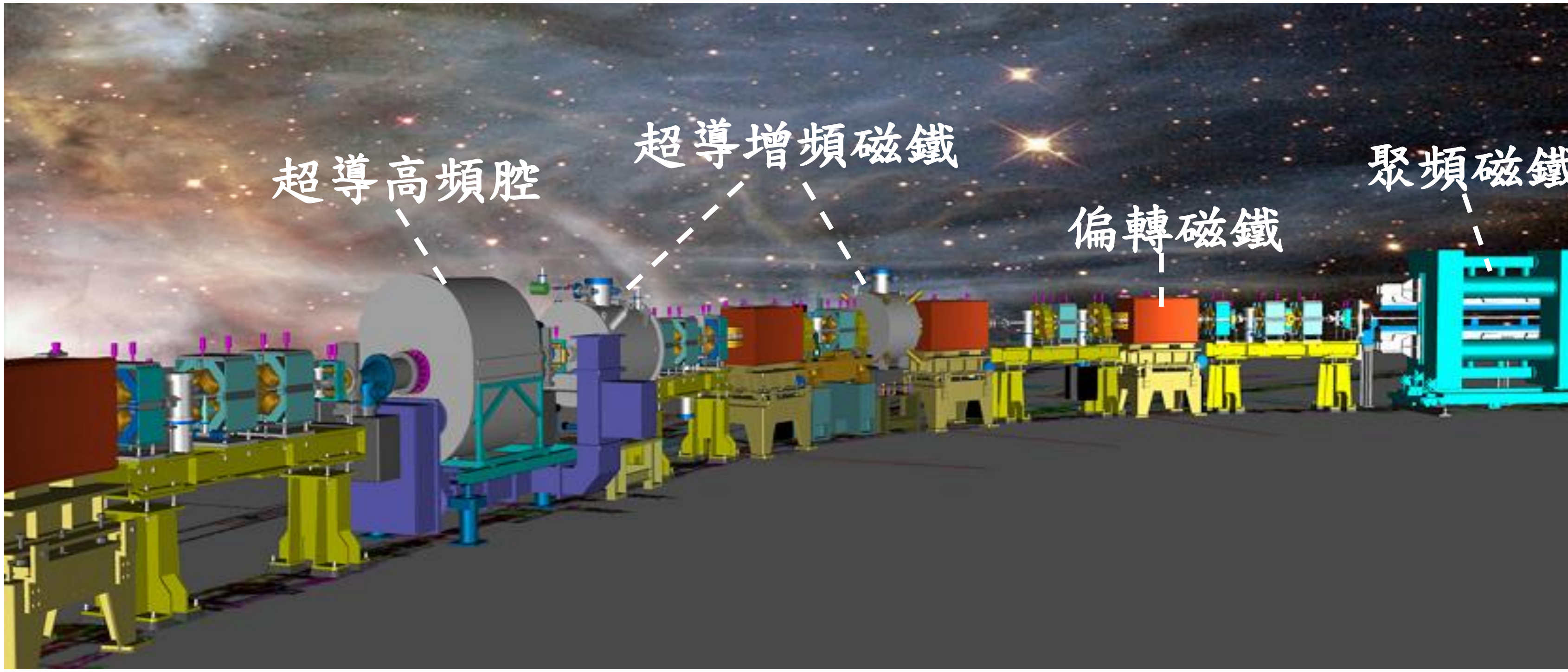
- 電子在電子槍(1)內產生，經過直線加速器(2)加速至能量為5,000萬電子伏特。
- 電子束進入增能環(3)後，繼續增加能量至15億電子伏特(1.5GeV)，速度非常接近光速(0.99999995倍)。
- 電子束經由傳輸線(4)進入儲存環(5) 。
- 當儲存環累積足夠的電子束後，經由各個磁鐵的導引與聚焦，電子束在偏轉磁鐵(6)及插件磁鐵(7)發出同步加速器光源，經由光束線(8)將光源引導至實驗站(9)進行實驗。
- 電子束在發出同步加速器光源後，要靠高頻腔(10)來補充失去的能量。

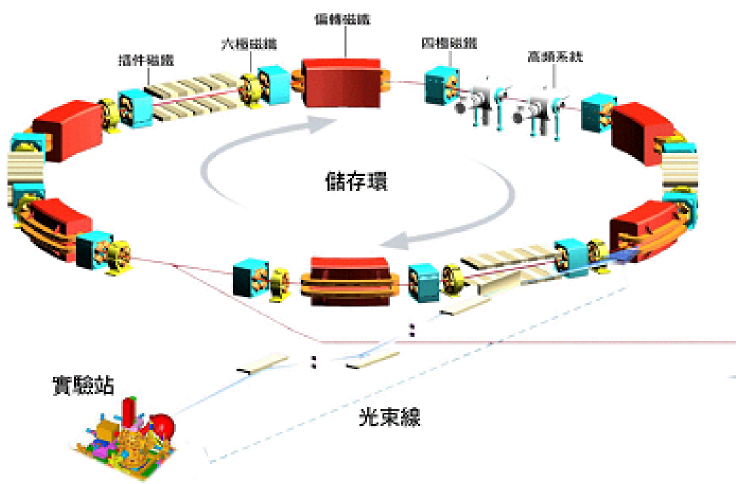


▲ The figure above is a sketch of the synchrotron accelerator at the TLS. To make particular elements legible, they are drawn not to scale in the figure. There are three bending magnets in each bending section, but only one bending magnet is shown as a symbolic illustration.

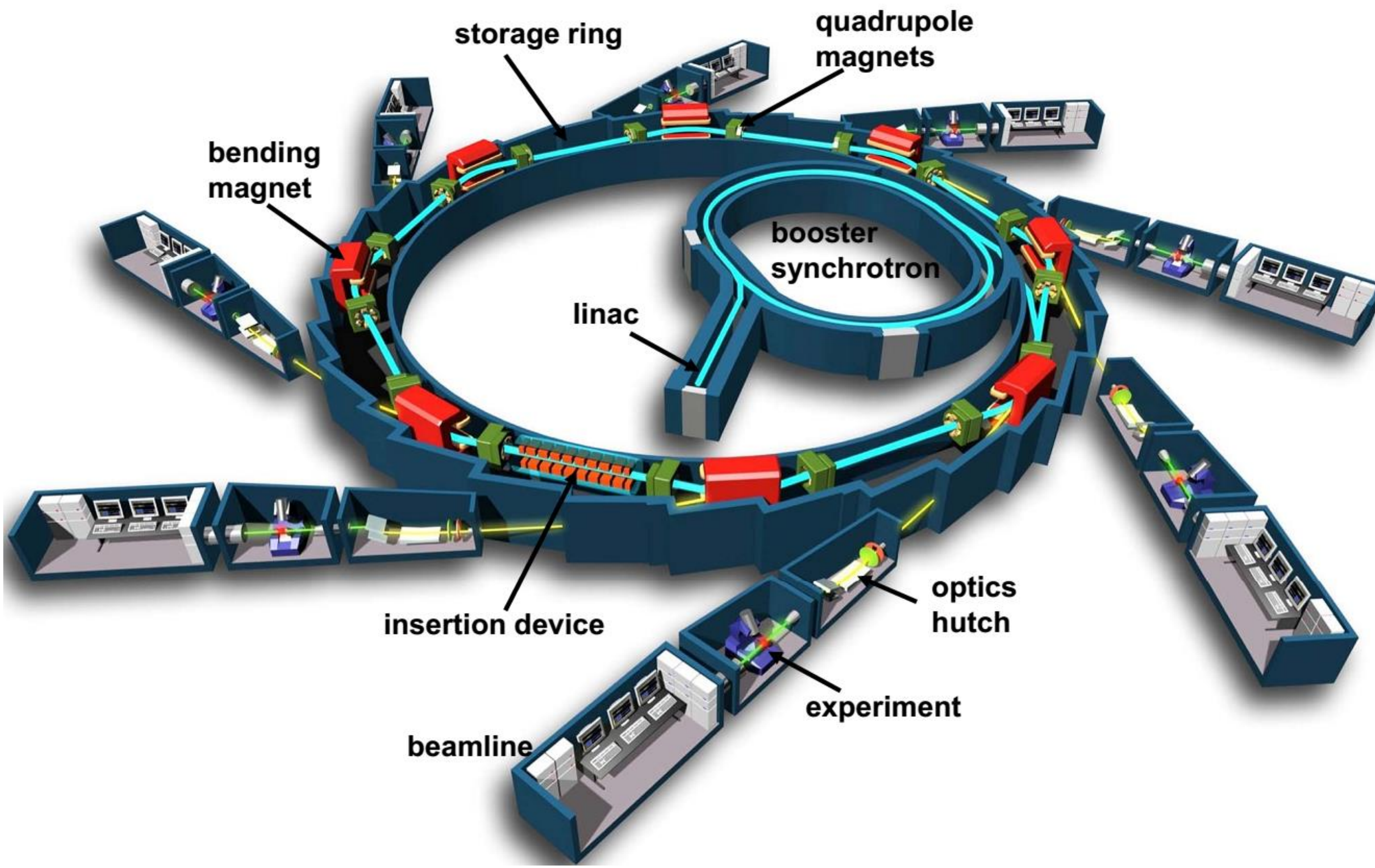

加速器與實驗設施
1. 電子槍
2. 直線加速器
3. 增能環
4. 傳輸線
5. 儲存環
6. 偏轉磁鐵
7. 插件磁鐵
8. 光束線
9. 實驗站
10. 高頻系統

儲存環 3D 圖





A Synchrotron Step by Step



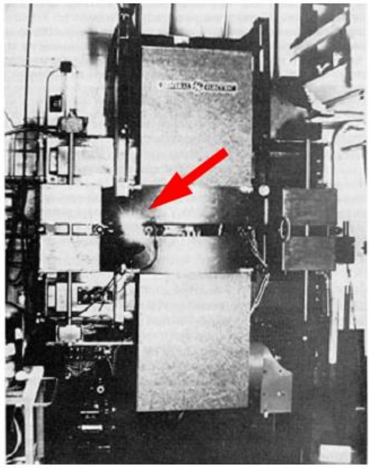
A brief history

- First observed:

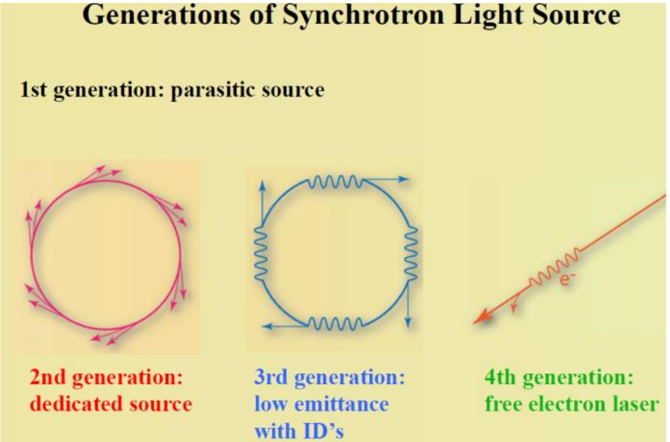
  1947, General Electric, 70 MeV synchrotron
- First user experiments:

  1956, Cornell, 320 MeV synchrotron
- First insertion Device:

  1979, 7 pole wiggler, SSRL



- 1st generation light sources: high energy physics synchrotrons and storage rings used parasitically for synchrotron radiation – eg DESY (Germany), INS-SOR (Tokyo), SPEAR (USA), (1960's, 1970's)
- 2nd generation light sources: purpose built synchrotron light sources, eg Photon Factory, NSLS, Daresbury (1980s onwards)
- 3rd generation light sources: optimised for high brilliance with low emittance and Insertion Devices; SPRing-8,ESRF, APS, Diamond, …(1990's onwards)
- Free Electron Laser sources: FLASH (Germany), LCLS (USA), SACLA (Japan), FERMI (Italy) … (2000's)
- Next??

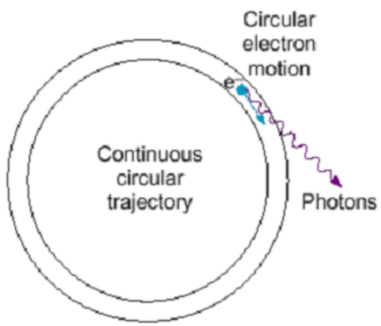


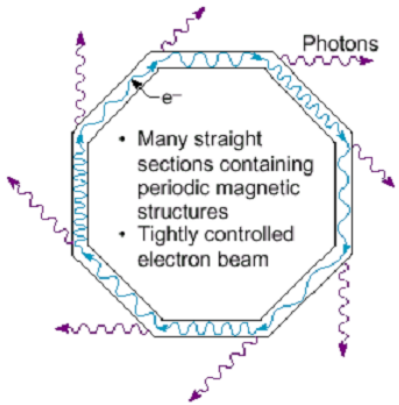
2015 Cheiron School

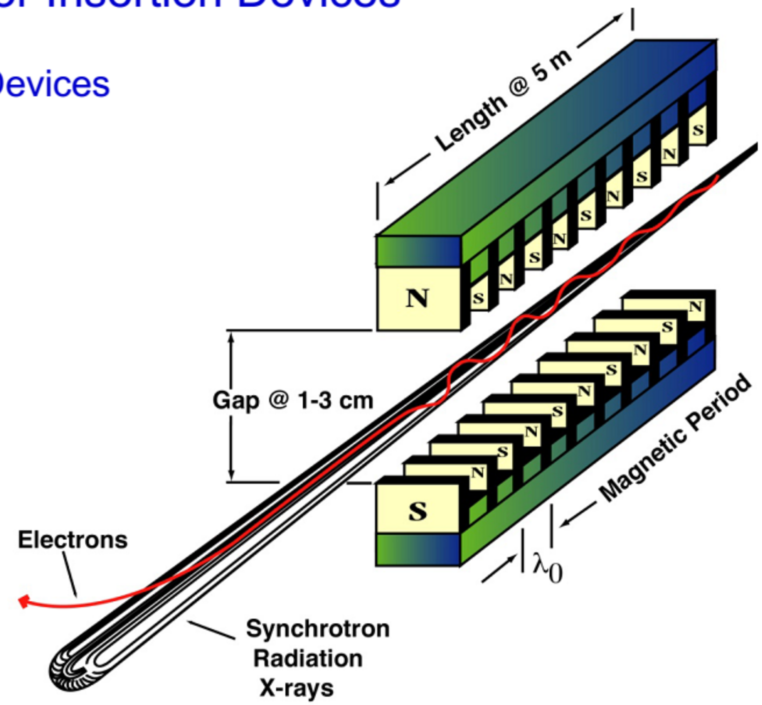
Third Generation Sources: Undulator Insertion Devices

1st, 2nd Generation

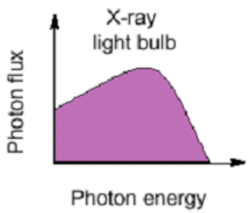
3rd Generation: Insertion Devices



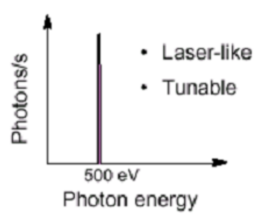


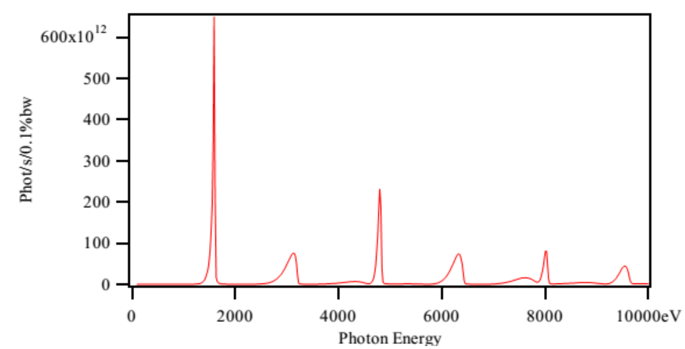


Bend Magnet Radiation



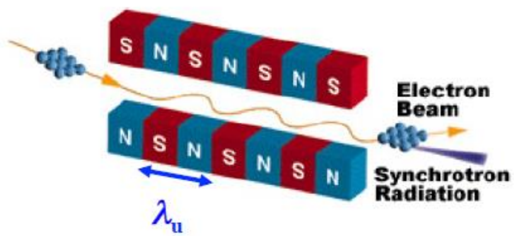
Undulator Radiation

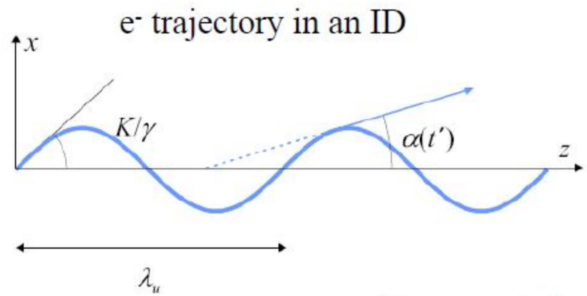




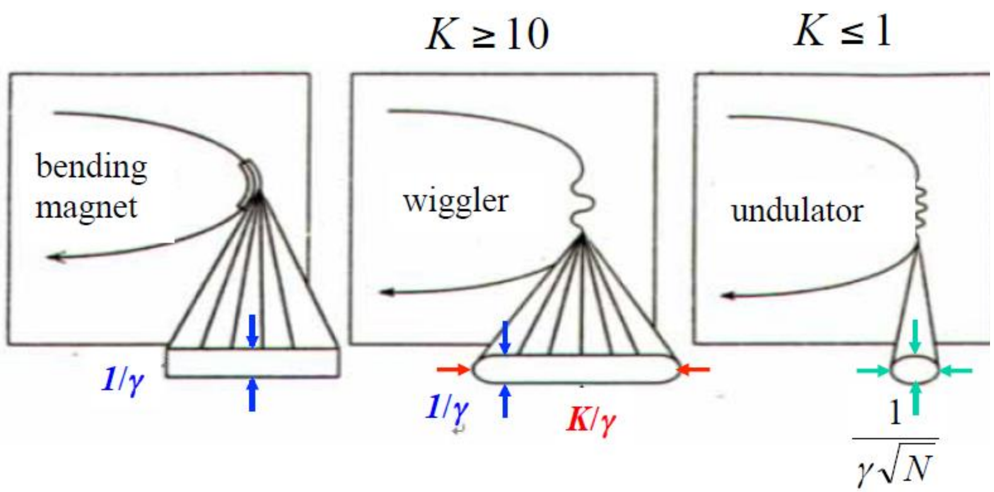
Angular distribution of synchrotron radiation emitted from various magnets

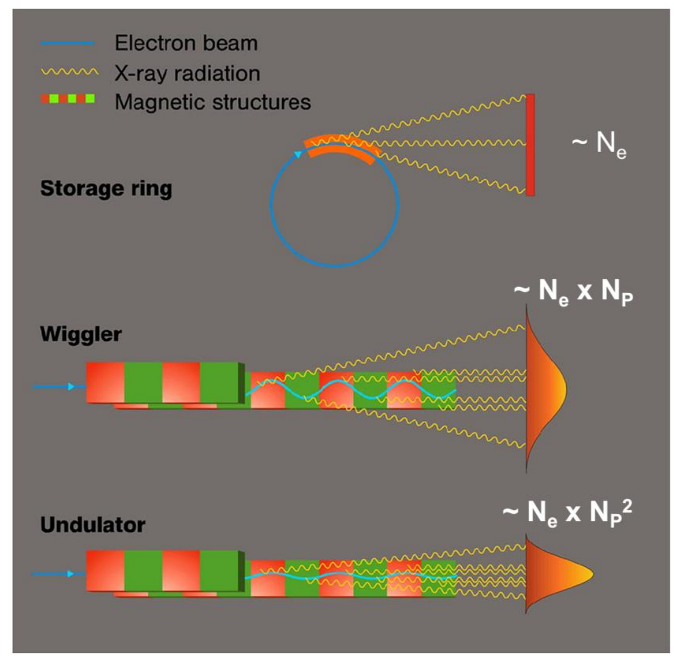
Wiggler or undulator

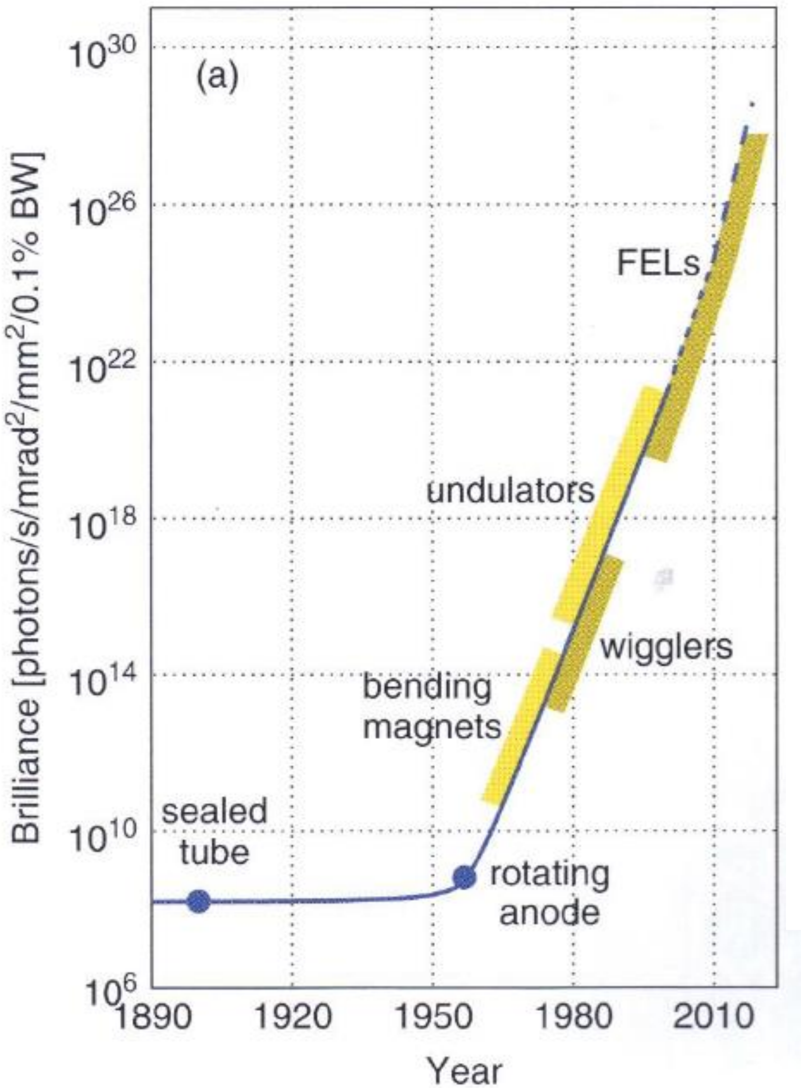




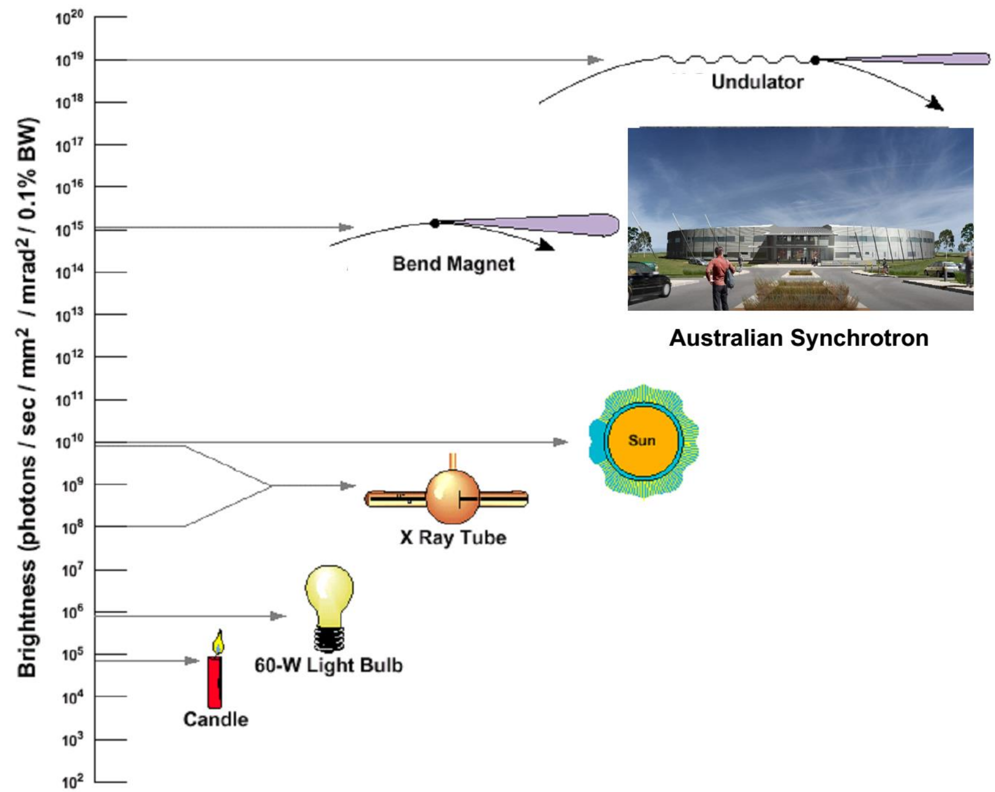
$K = \alpha_{max.} / \gamma^{-1}$







(a)
Brilliance [photons/s/mrad²/mm²/0.1% BW]
10^30
10^26
10^22
10^18
10^14
10^10
10^6
1890
1920
1950
1980
2010
Year
FELs
undulators
wigglers
bending magnets
sealed tube
rotating anode

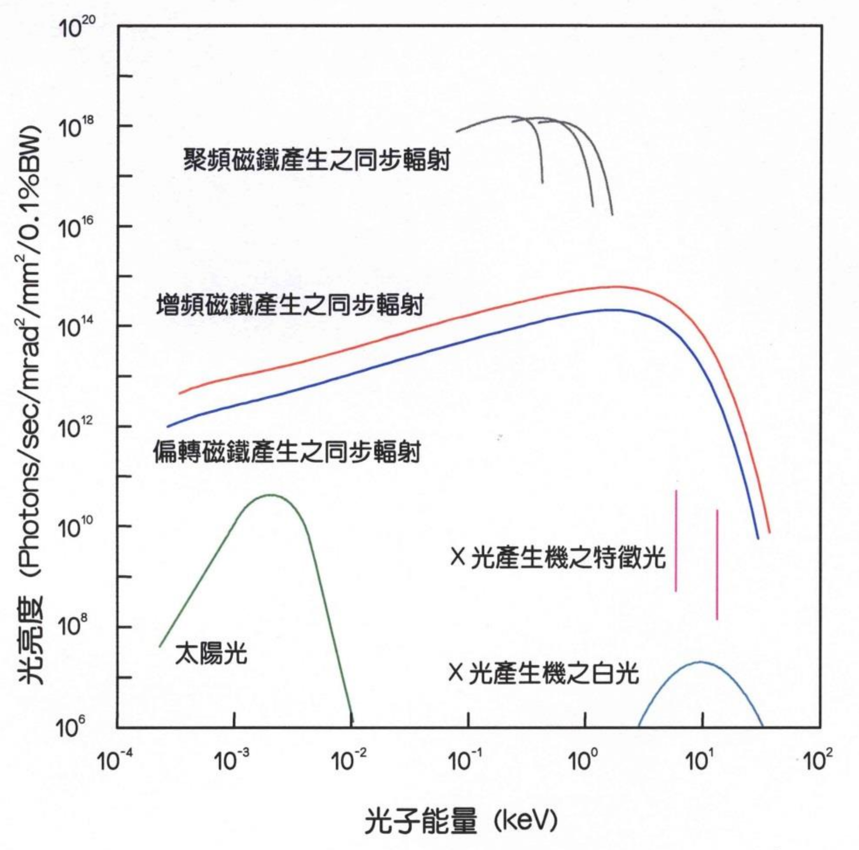


Brightness (photons / sec / mm² / mrad² / 0.1% BW)
10^20
10^19
10^18
10^17
10^16
10^15
10^14
10^13
10^12
10^11
10^10
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
Undulator
Bend Magnet
Australian Synchrotron
Sun
X Ray Tube
60-W Light Bulb
Candle

Unique Features of Synchrotron Light Source

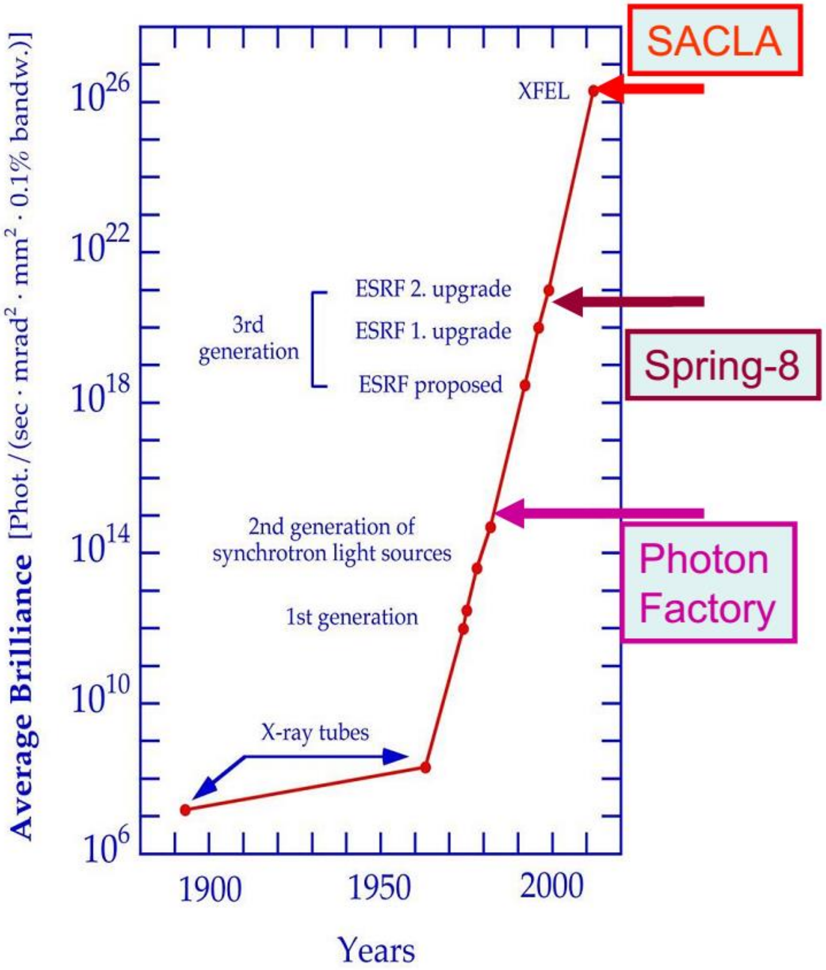
- High intensity
- Continuous spectrum
- Excellent collimation
- High polarization
- Pulsed-time structure

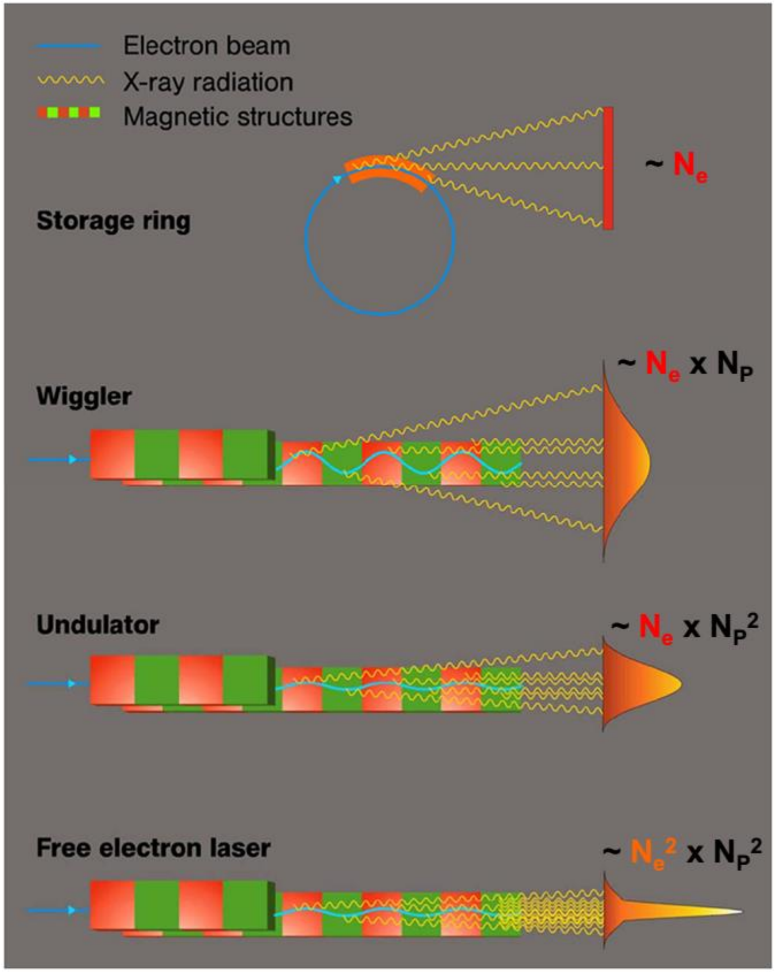
以X光為例，同步加速器光源在這個波段的亮度比傳統X光機還要強百萬倍以上！過去需要幾個月才能完成的實驗，現在只需幾分鐘便能得到結果。以往因實驗光源亮度不夠而無法探測的結構，現在藉由同步加速器光源，都可分析得一清二楚，也因此得以開發新的研究領域。



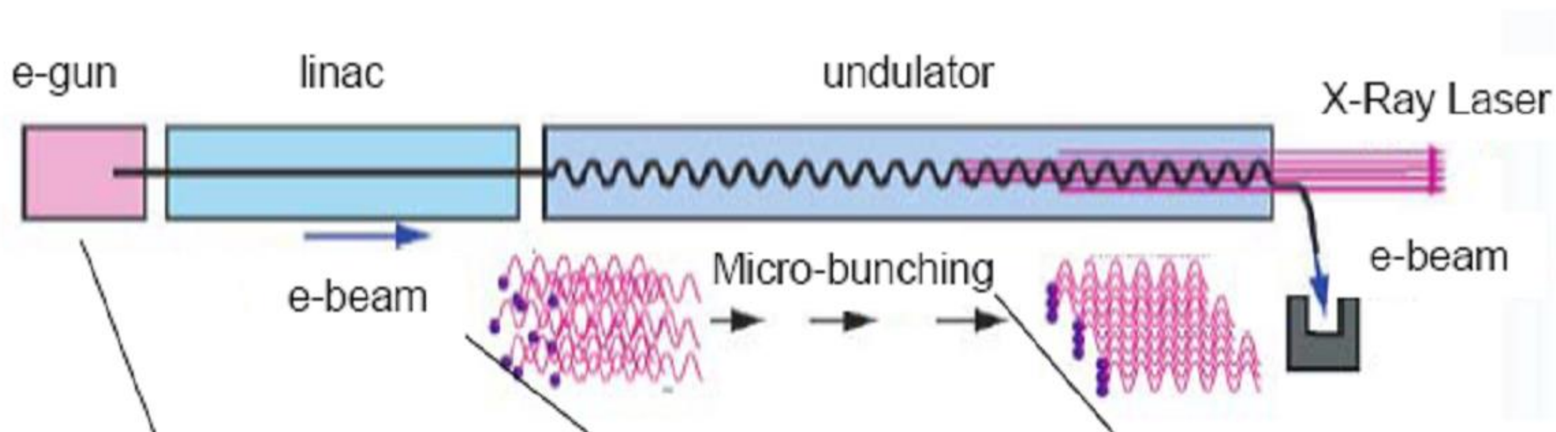
光子能量：一般單位為電子伏特(eV)，一電子伏特為電子在真空中通過一伏特電位差所獲得的能量。
光亮度：指單位時間內通過單位立體角的單位頻寬光子數。

Next Step - X-ray Lasers?   Yes ➔ FELs

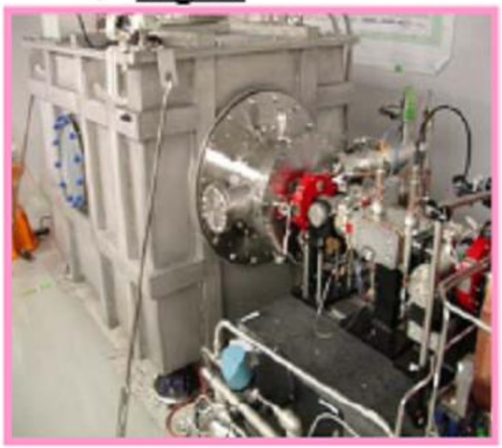




Linac-Based Free Electron Laser
Self-Amplified Spontaneous Emission (SASE)



- **e-gun**

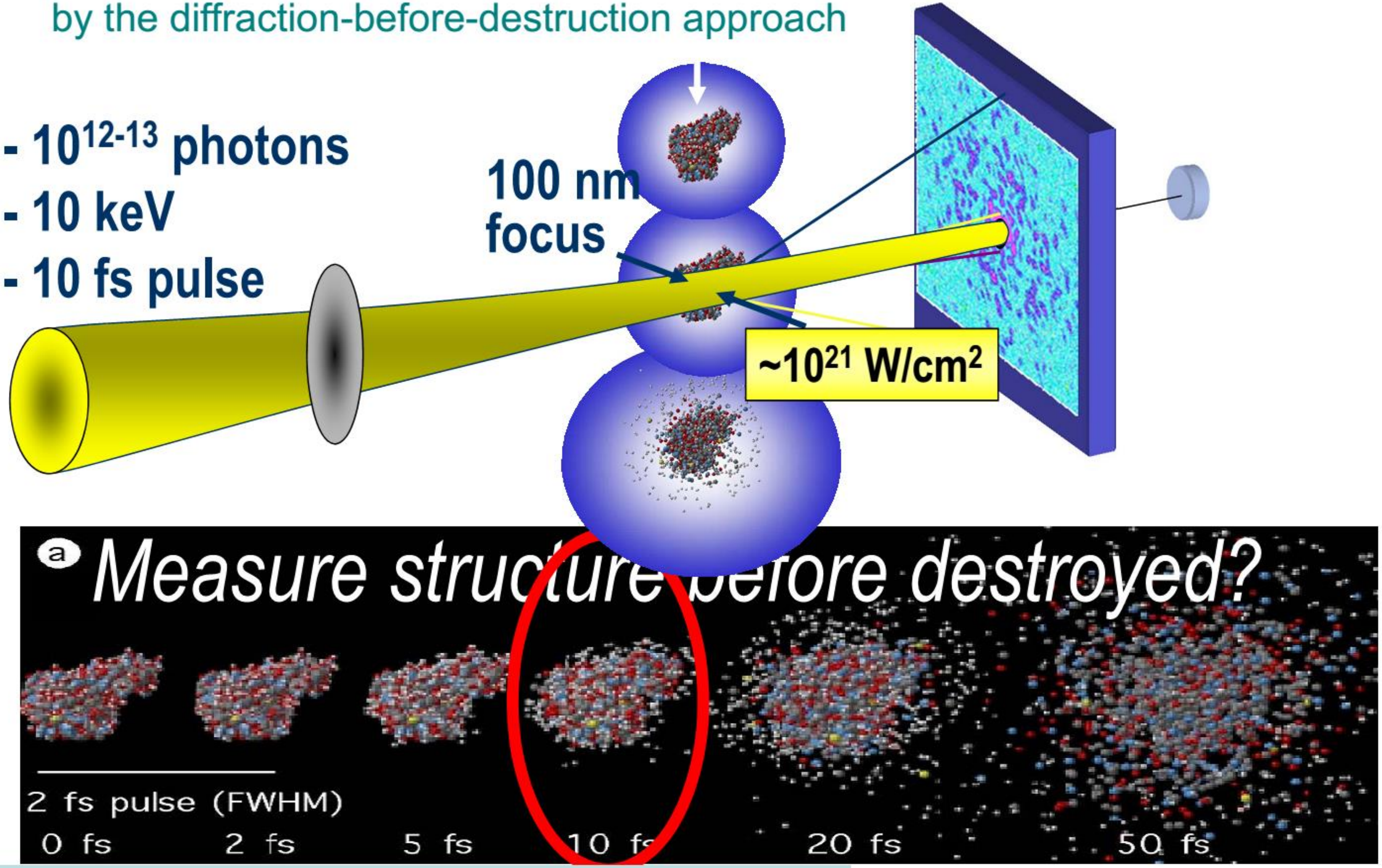


- **linac**

- **undulator**

Coherent diffractive imaging of single particles

by the diffraction-before-destruction approach



Calculations. in vacuum Neutze et al., Nature 2000

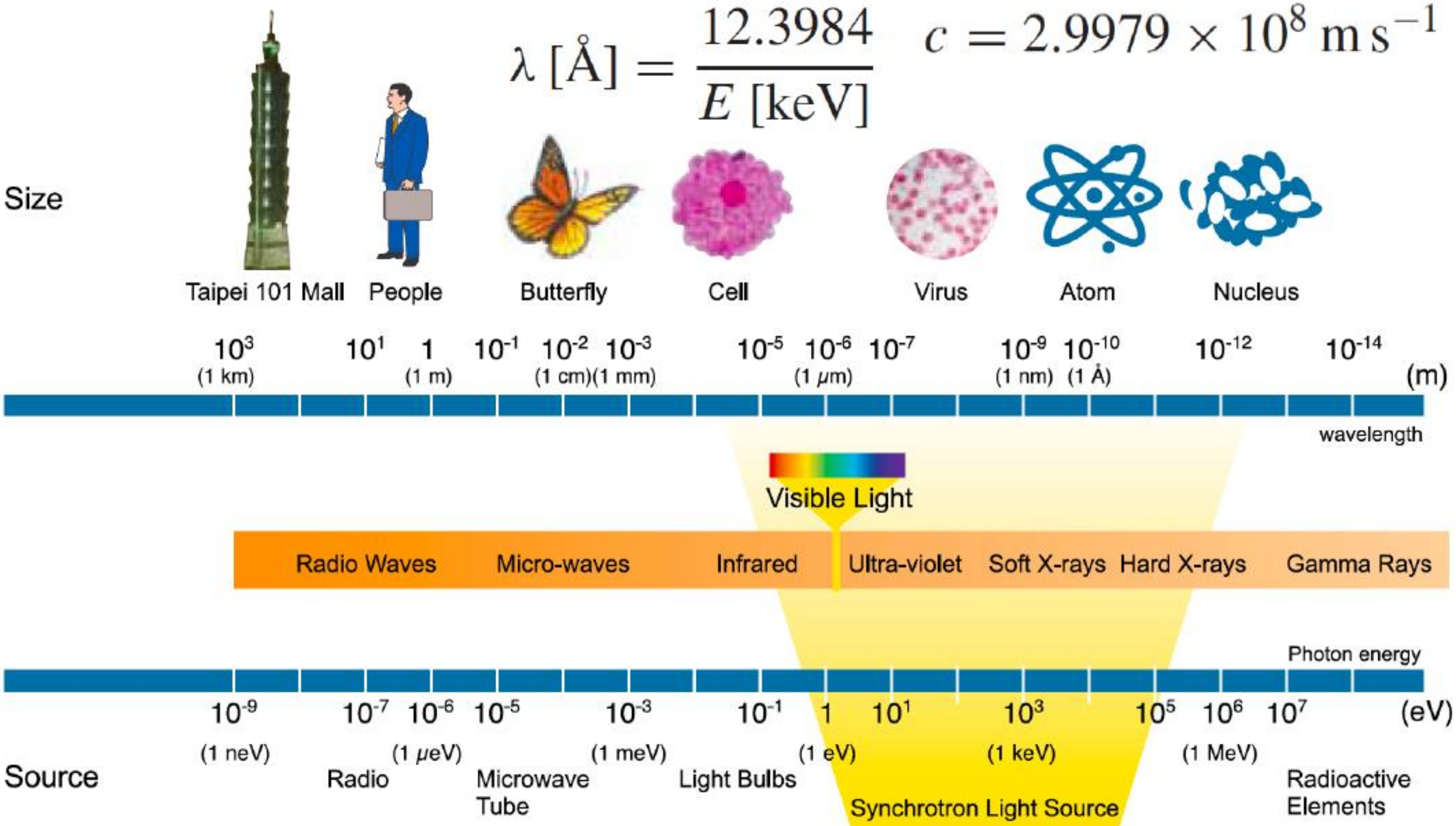
$$E = h\nu = hc/\lambda,$$

$$h = 6.626 \times 10^{-34}\,\mathrm{J\,s}$$

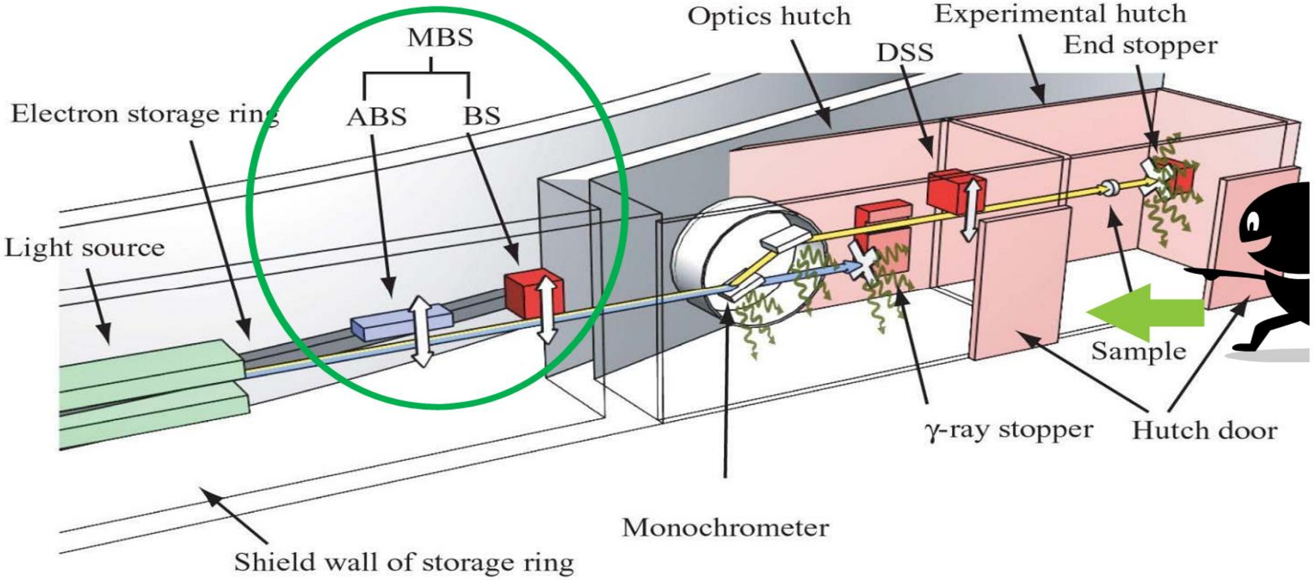
Electromagnetic Spectrum

$$c = 2.9979 \times 10^{8}\,\mathrm{m\,s^{-1}}$$

$$\lambda\,[\text{Å}] = \frac{12.3984}{E\,[\text{keV}]}$$



Beamline



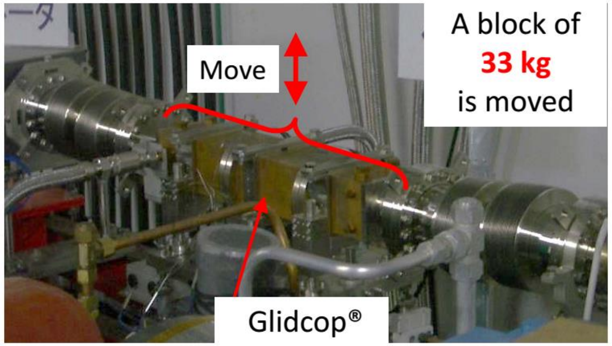
For safety

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

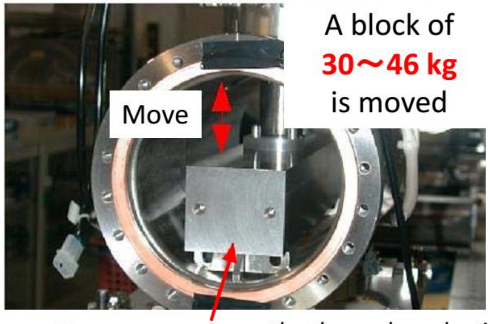
X-ray → Absorber (Abs) → Beam shutter (BS)

to protect BS from heat load

to shield you against radiation



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



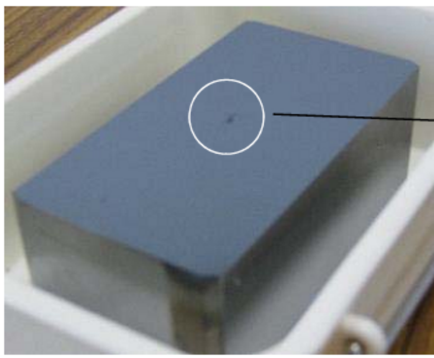
Heavy metal
(alloy of tungsten)

the thermal conductivity not so high

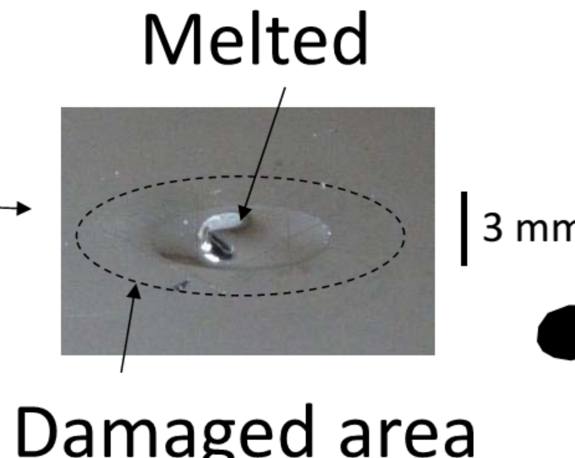
If an optical component is irradiated by too much power ....

One user opened FE slit excessively.

2kW

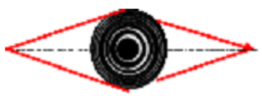
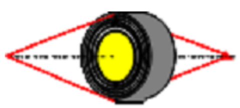


LN2-cooled
Si crystal



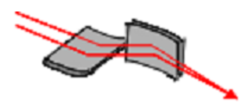
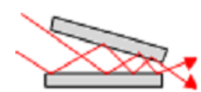
Slit : *“Too much is as bad as too little”*

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

Outline

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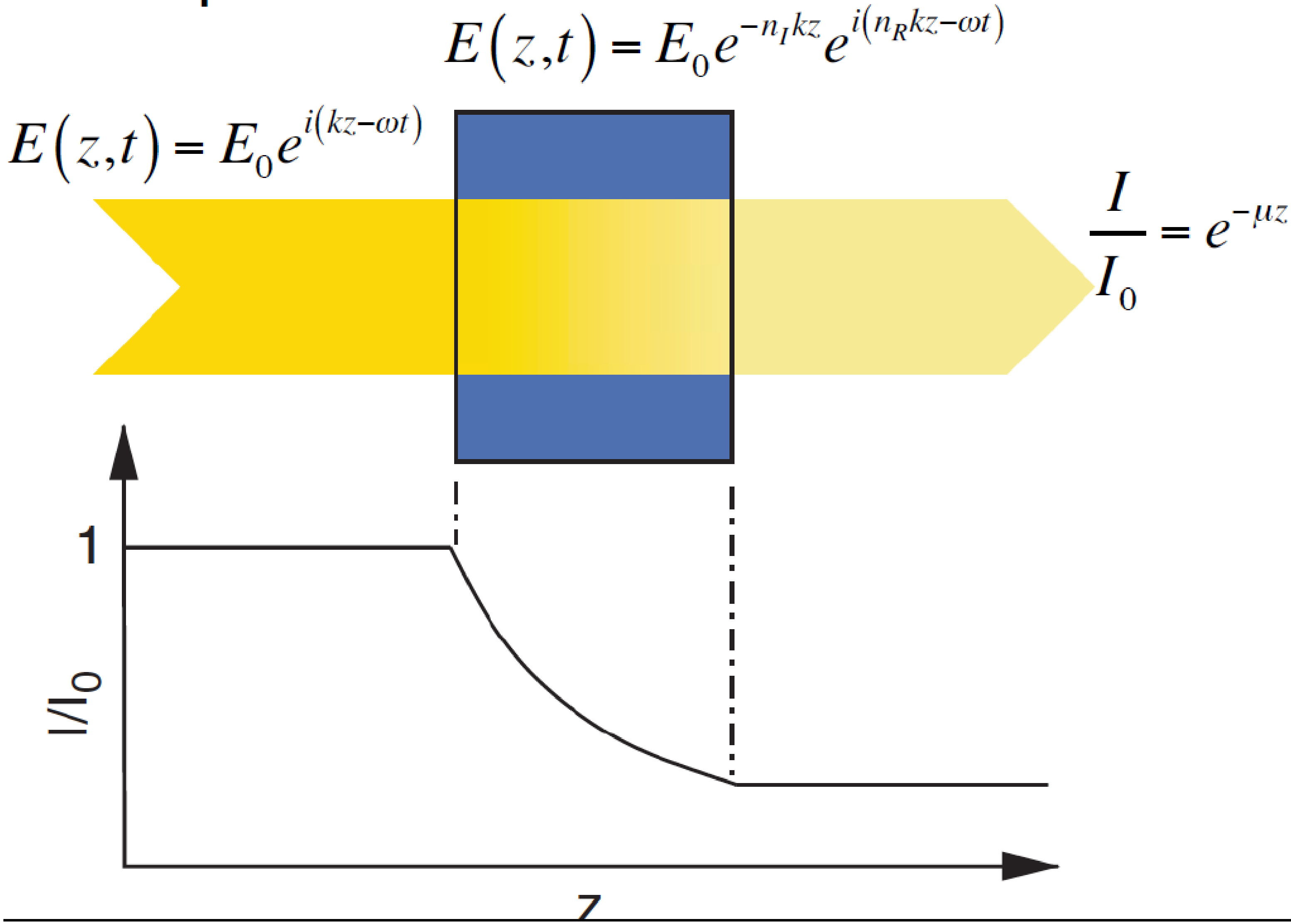
- Application of Synchrotron Light
- X-ray nano probe at TPS

Absorption


$E(z,t) = E_0 e^{-n_I kz} e^{i(n_R kz - \omega t)}$
$E(z,t) = E_0 e^{i(kz - \omega t)}$
$\frac{I}{I_0} = e^{-\mu z}$
1
I/I_0
z

absorption coefficient

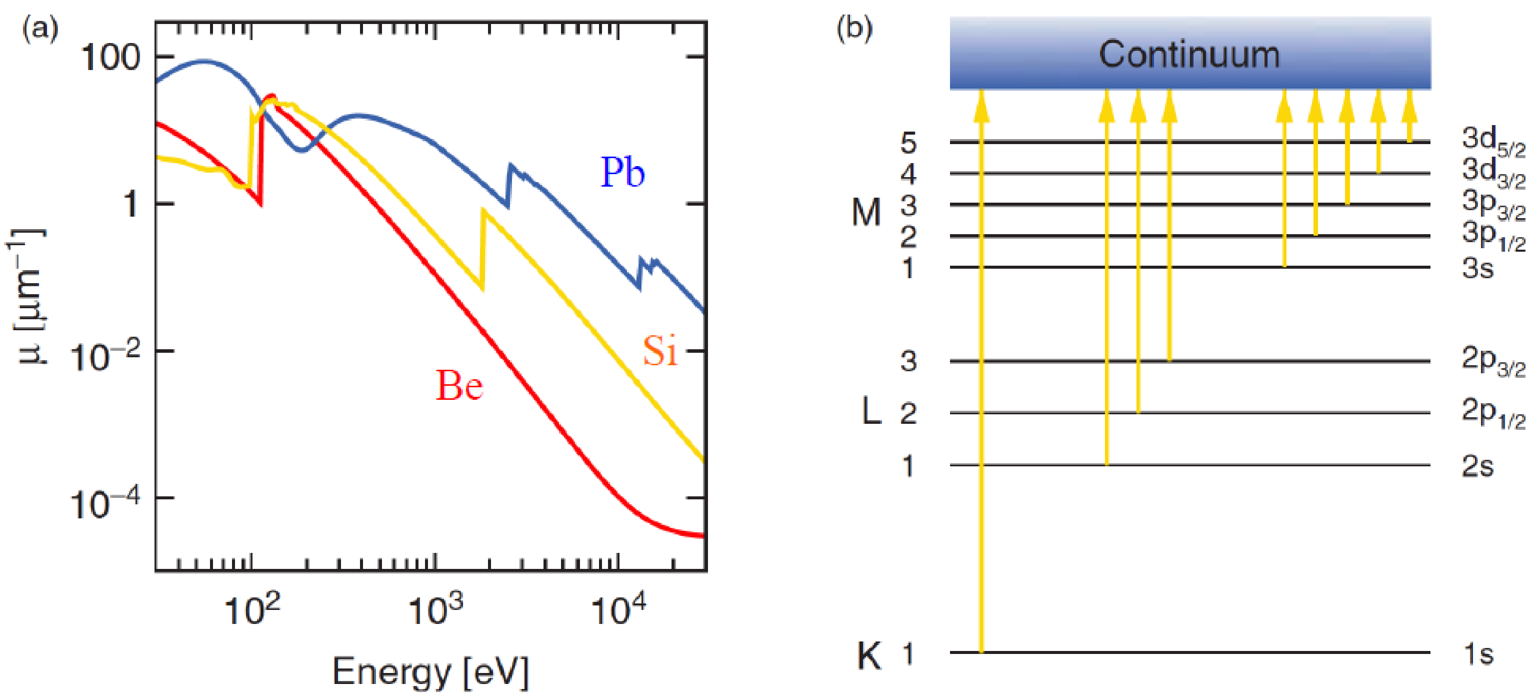
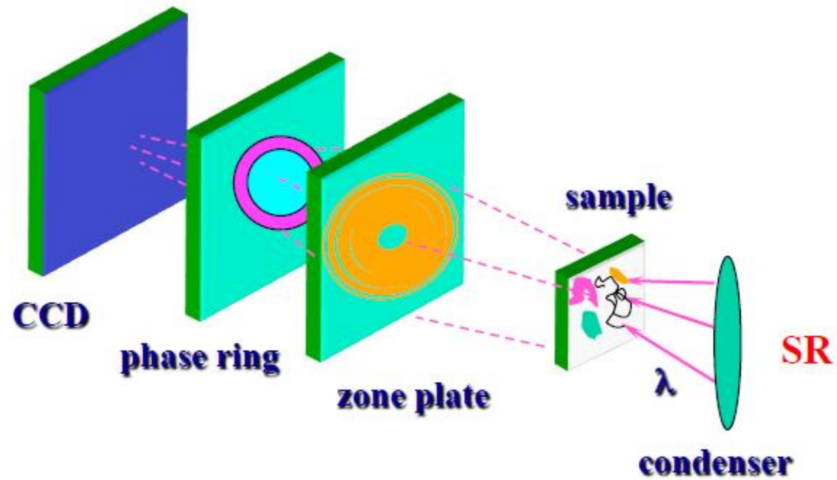


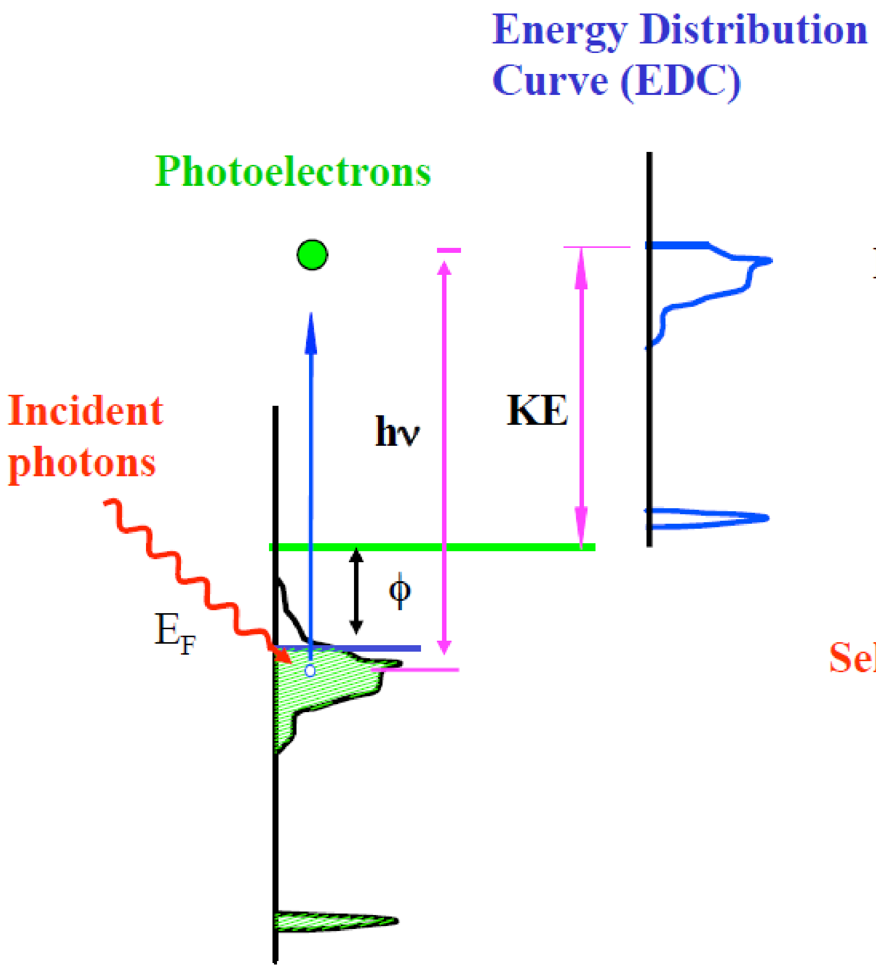
Figure 2.16 *(a) The x-ray absorption coefficient μ for beryllium (red curve), silicon (yellow) and lead (blue) as a function of the photon energy. (b) Sharp increases in the absorption occur when the photon energy is just sufficient to eject the electron from the electronic orbital to the continuum. The x-ray absorption (left) and atomic orbital labellings (right) are shown.*

Transmission X-ray Microscope (TXM)



energy: 8 keV
3D tomography
spatial resolution = 60 nm

Photoemission Spectroscopy



KE = hν-BE-ϕ

$$\frac{d\sigma}{d\Omega} \propto \sum \left| \left\langle \Psi_f \right| A \cdot P \left| \Psi_i \right\rangle \right|^2 \cdot \delta\left(E_f - E_i - h\nu\right)$$

Selection rule: $\Delta l = \pm 1$

$\Delta m_l = 0$ (linearly polarized)

$\Delta m_l = +1$ (L. circularly polarized)

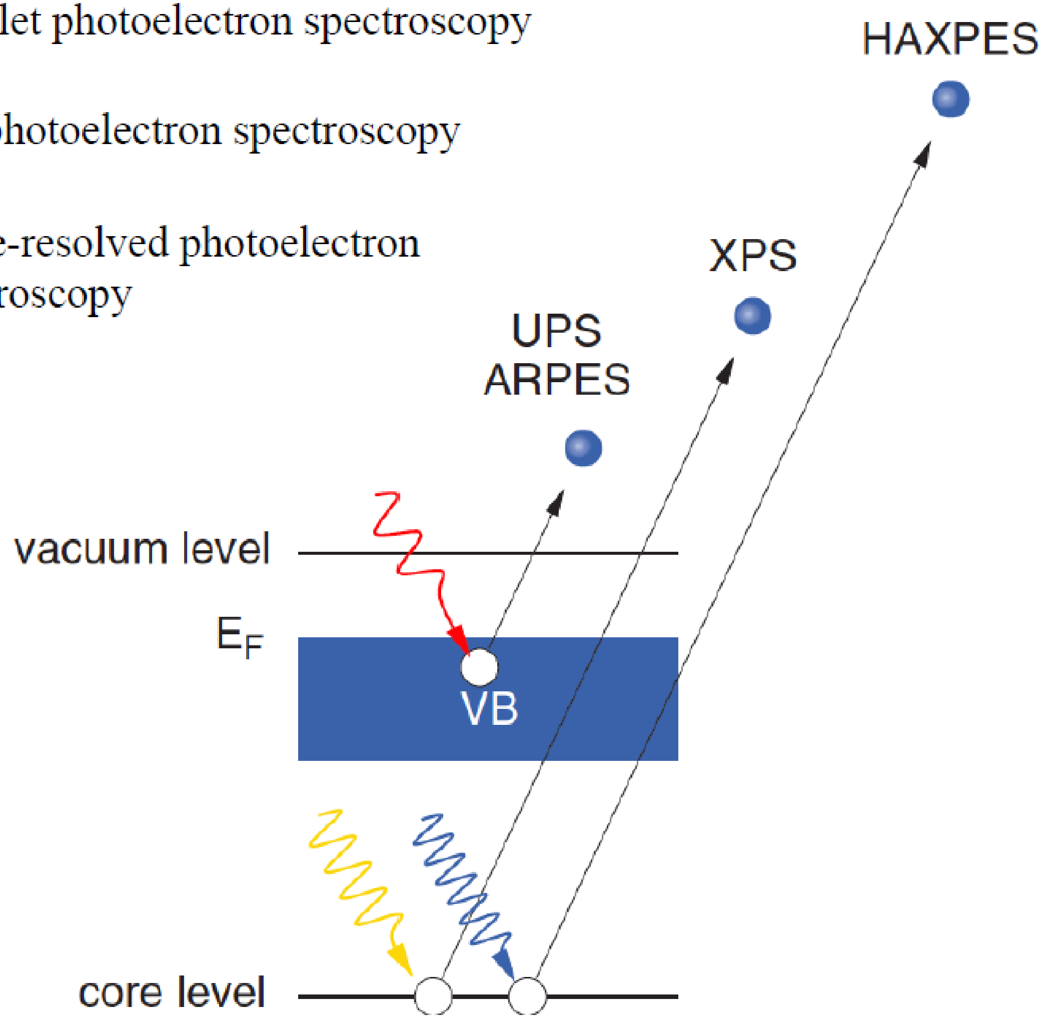
$\Delta m_l = -1$ (R. circularly polarized)

HAXPES = Hard X-ray photoelectron spectroscopy

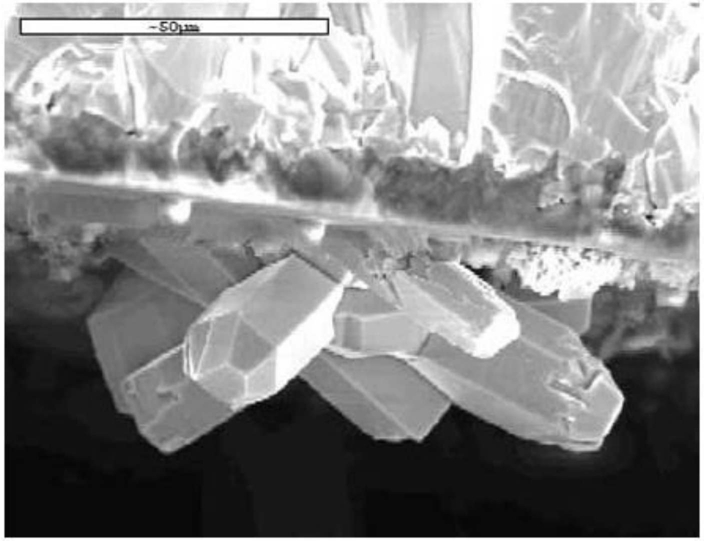
UPS = ultraviolet photoelectron spectroscopy

XPS = X-ray photoelectron spectroscopy

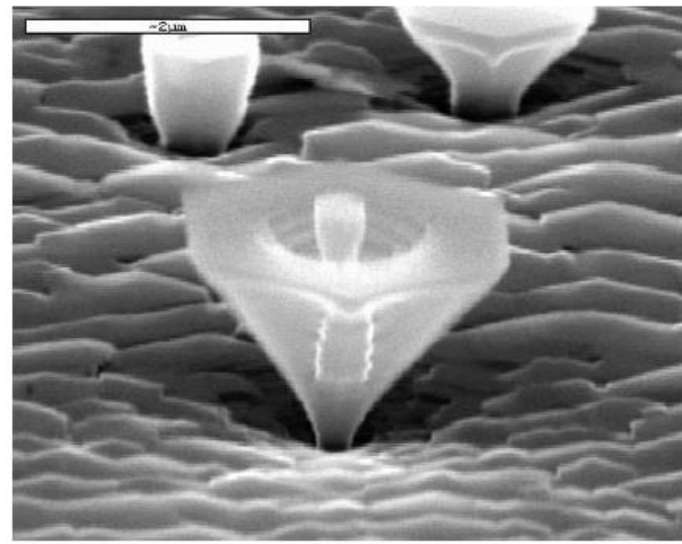
ARPES = angle-resolved photoelectron spectroscopy

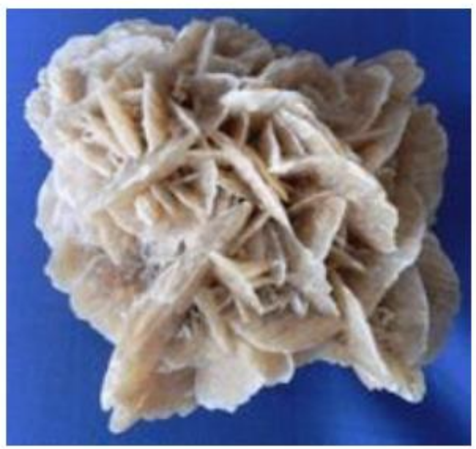


“Crystals”



GaN (hexagonal) crystal cluster grown by hydride vapor phase epitaxy





Sand Rose of gypsum (石膏) crystals

AlN pyramids grown by MBE

Bragg Law - X-ray reflected by the (hkl) planes

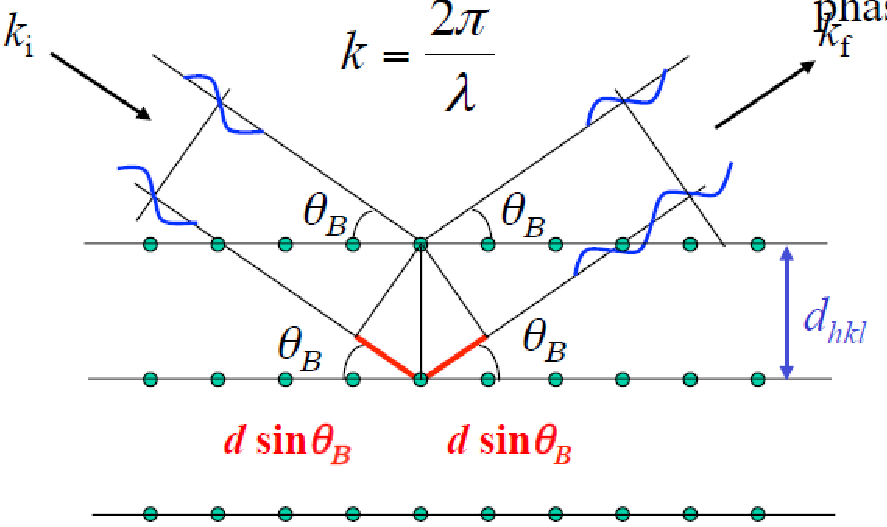
Path Difference $L = 2d_{hkl}\, sin\theta_B$

Constructive interference: $L = n\lambda$

phase difference $\phi = k\,L$

$$\vec{E} = E_0 e^{i(\vec{k}\cdot\vec{r} - \omega t)}$$

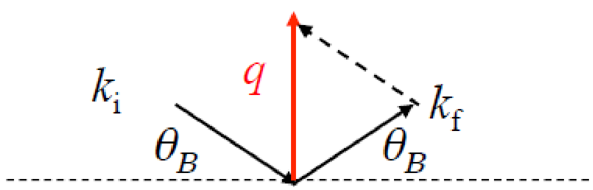
$$k = \frac{2\pi}{\lambda}$$



Bragg Law: $2d_{hkl}\, sin\theta_B = n\lambda$

$$2\pi \frac{2}{\lambda} \sin\theta_B = 2\pi \frac{1}{d_{hkl}} = G_{hkl}$$

scattering vector $\vec{q} = \vec{k}_f - \vec{k}_i \quad q = 2\frac{2\pi}{\lambda}\sin\theta_B$



$$q = G_{hkl}$$

In terms of diffraction, two key characteristics of a set of crystal planes :
$1/d$ and orientation

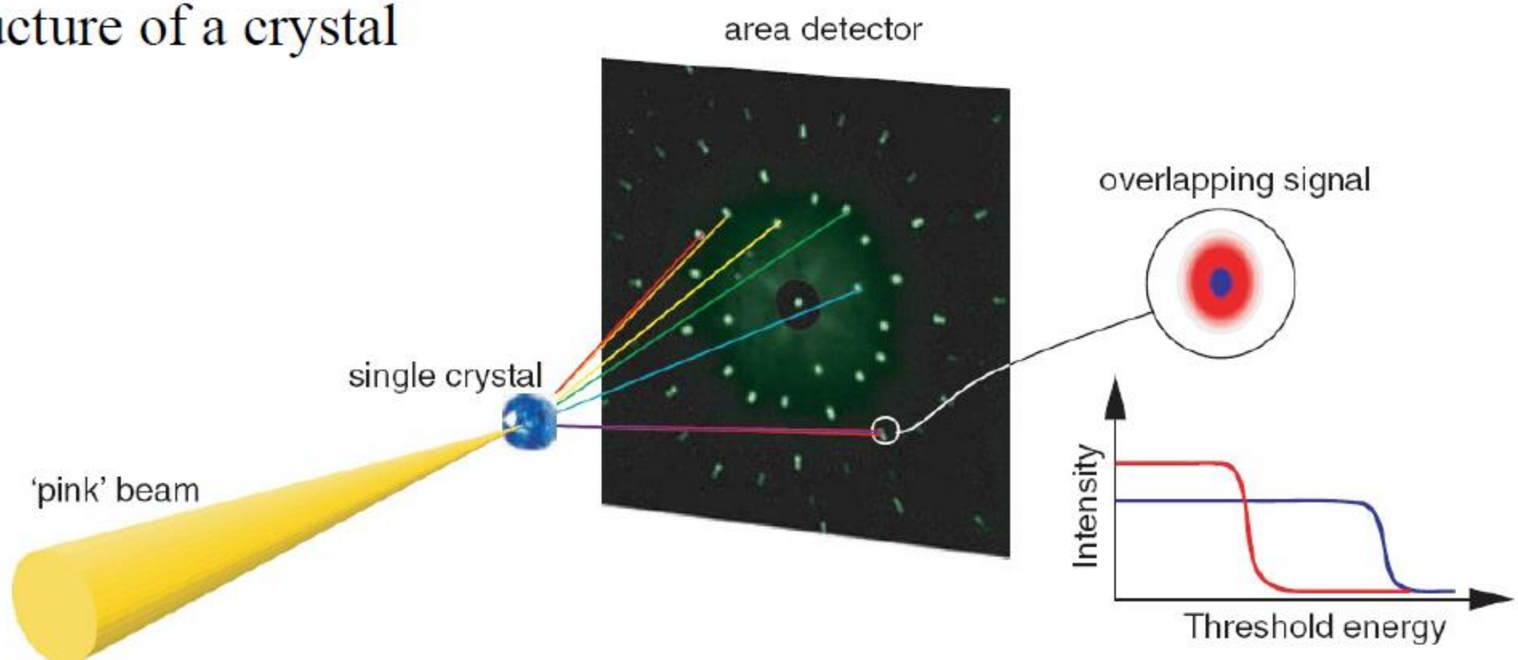
Single Crystal Diffraction - Laue Diffraction

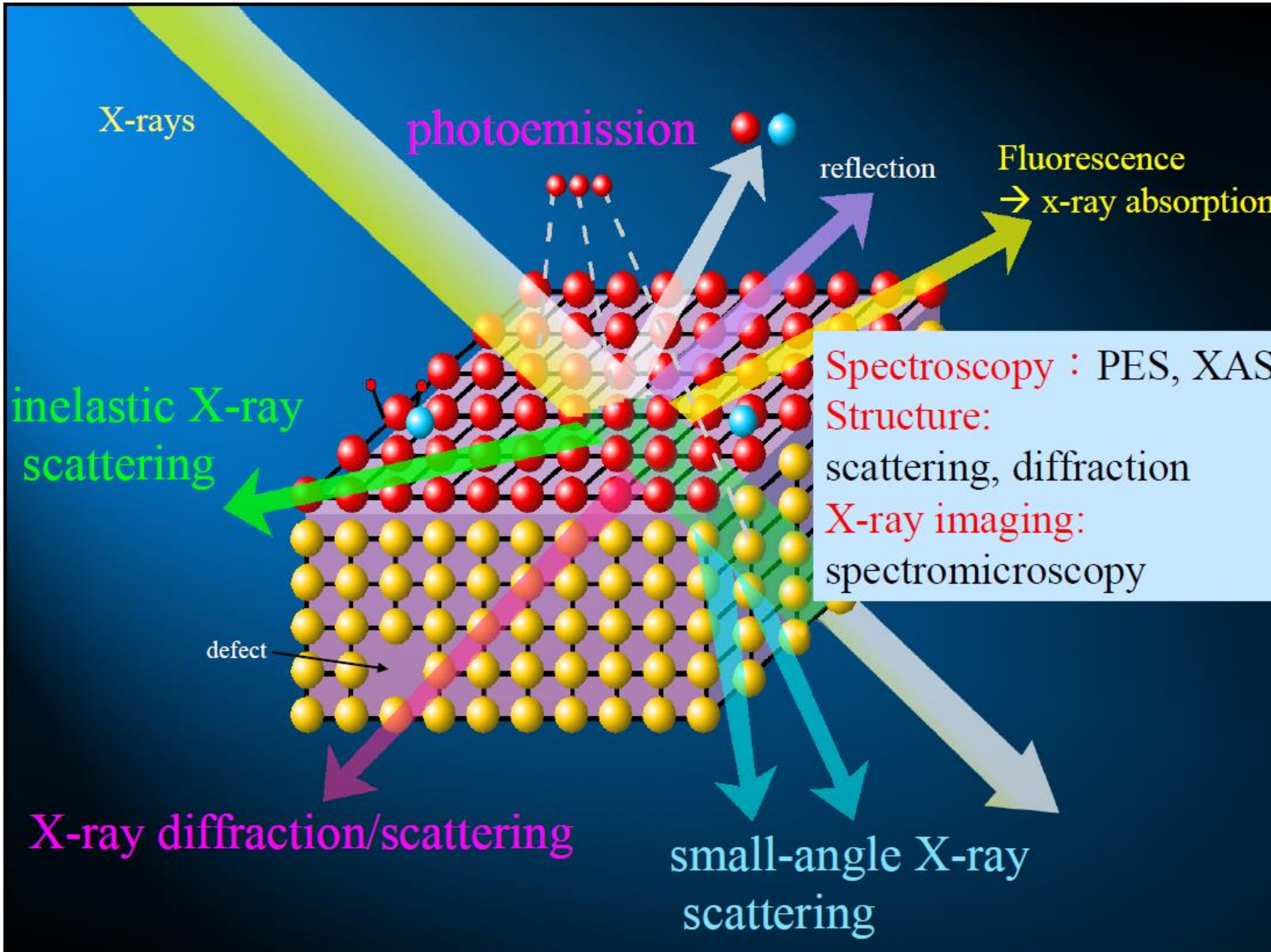
•Method: stationary

•Light source: a polychromatic 'pink' beam (e.g. ΔE <1 keV @ 10 keV)

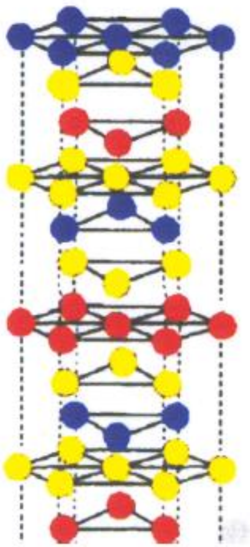
•Applications: orient single crystals, determine their crystal quality, dynamical studies of transient crystalline states (time-resolved study)

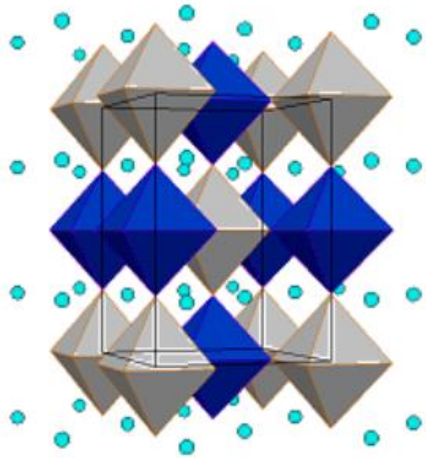
•Disadvantage: not well-suited for determining the full atomic structure of a crystal

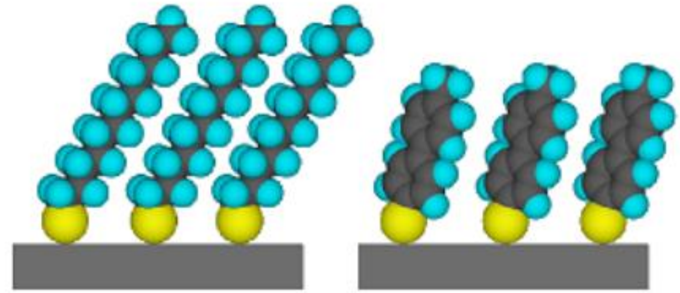


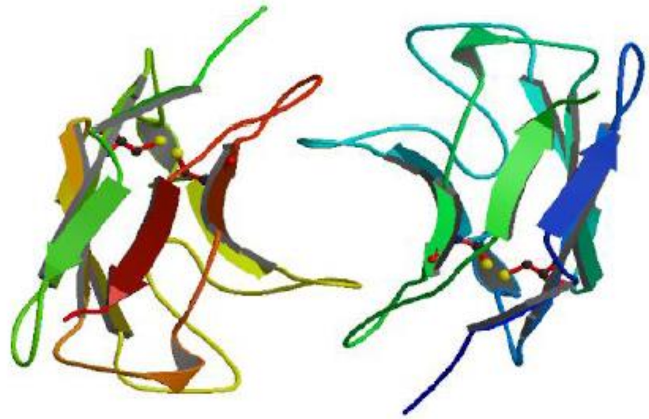


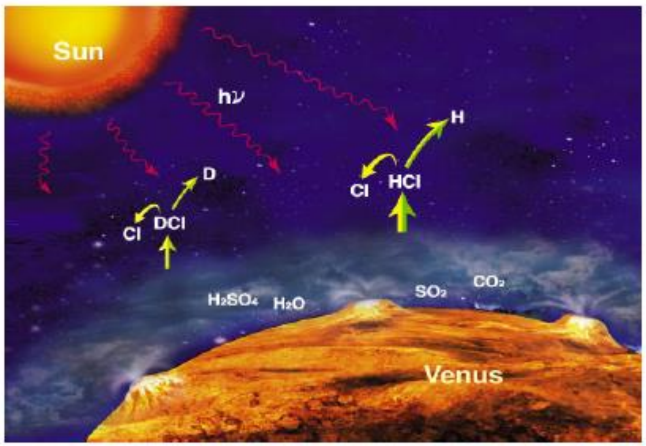
X-rays
photoemission
reflection
Fluorescence
→ x-ray absorption
inelastic X-ray
scattering
Spectroscopy：PES, XAS
Structure:
scattering, diffraction
X-ray imaging:
spectromicroscopy
defect
X-ray diffraction/scattering
small-angle X-ray
scattering

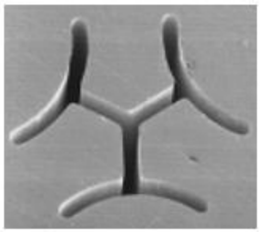


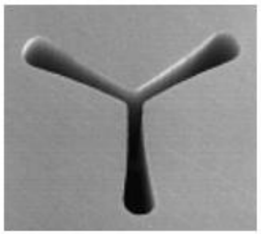






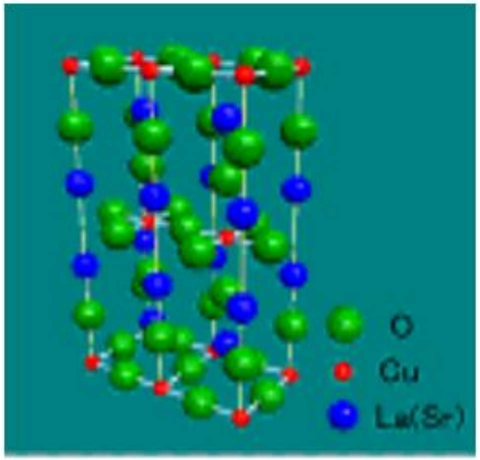




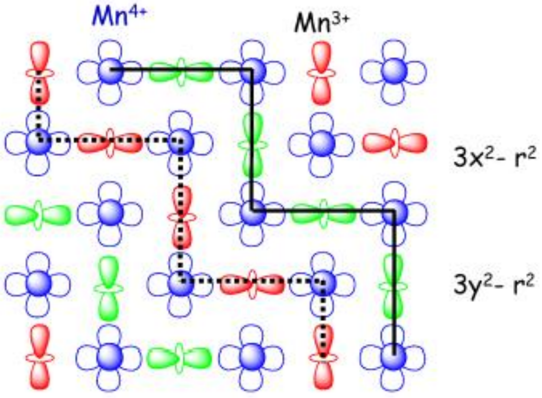


Synchrotron light source is a powerful tool for basic and applied studies in physics, chemistry, materials, biology and medicine, and their many subfields.

Condensed-Matter Physics



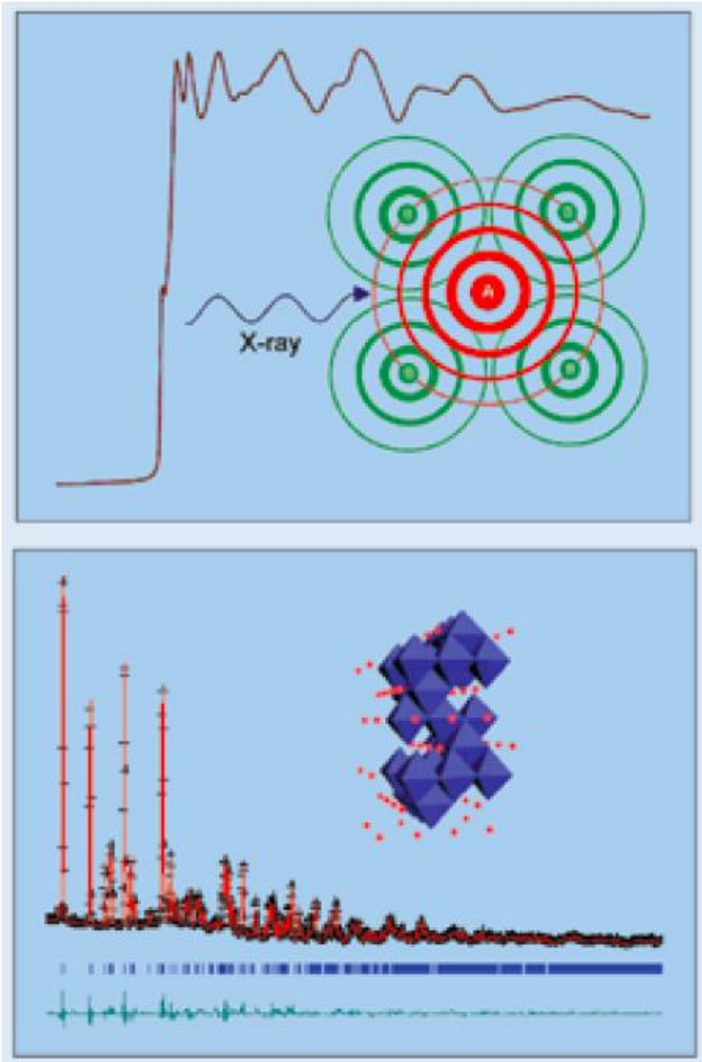
Electronic properties of novel materials can be revealed with X-ray scattering.

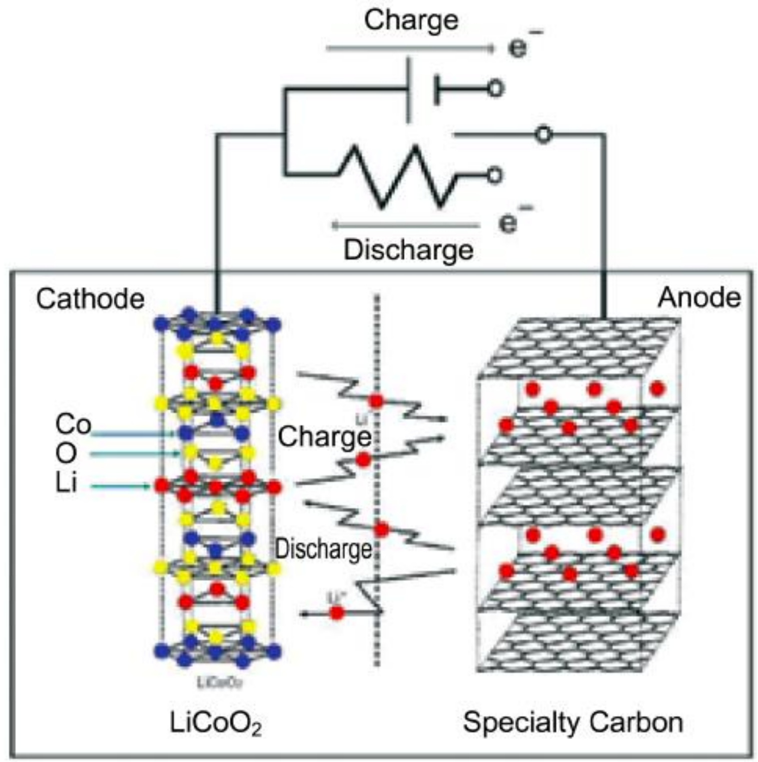


$La_{0.5}Sr_{1.5}MnO_4$

(Source: website of Railway Technical Research Institute, Japan)

Energy Science

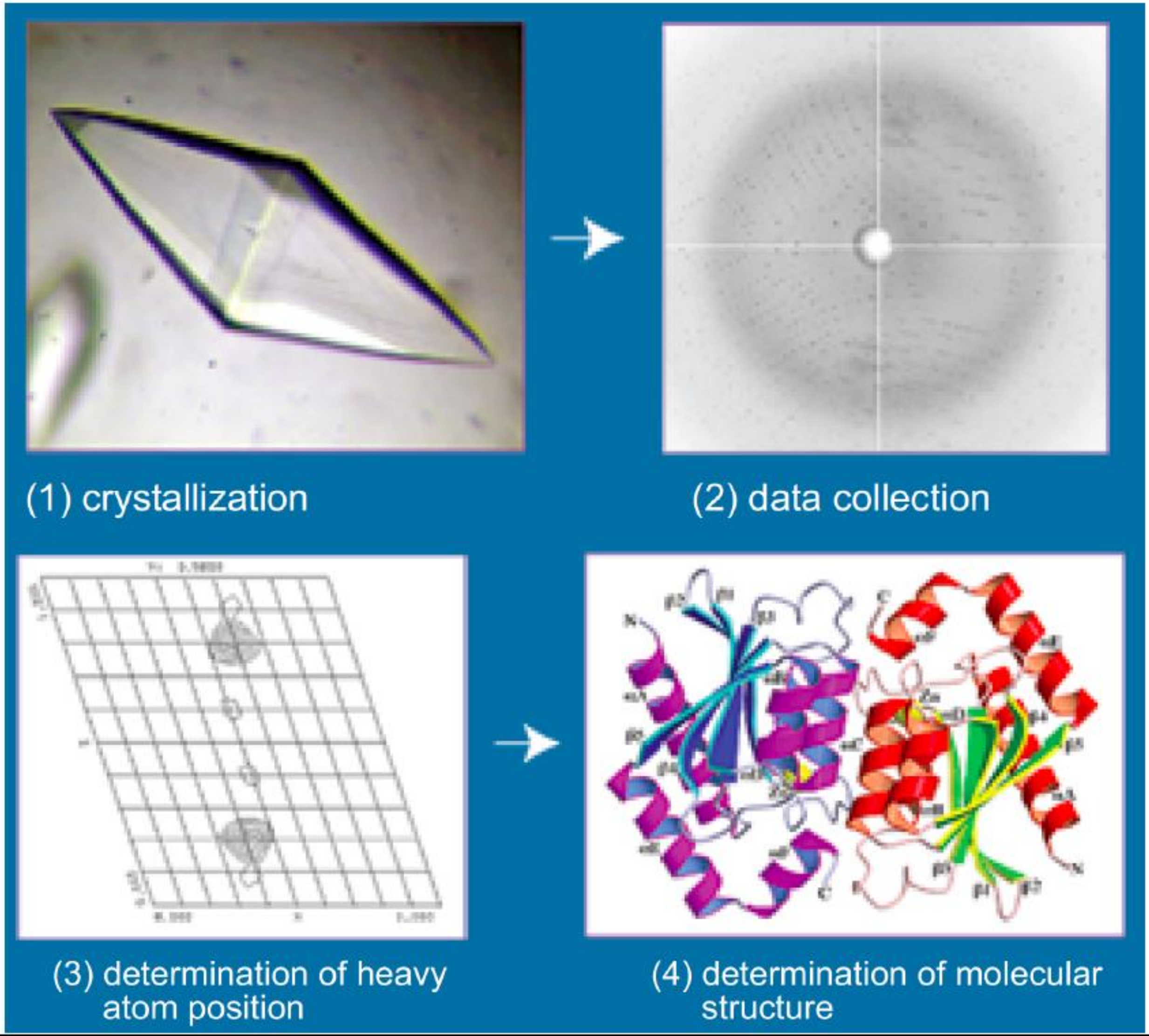


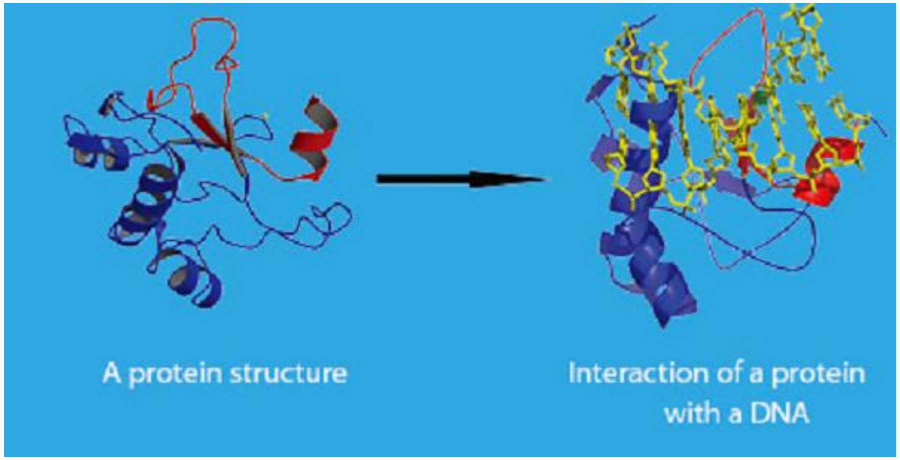


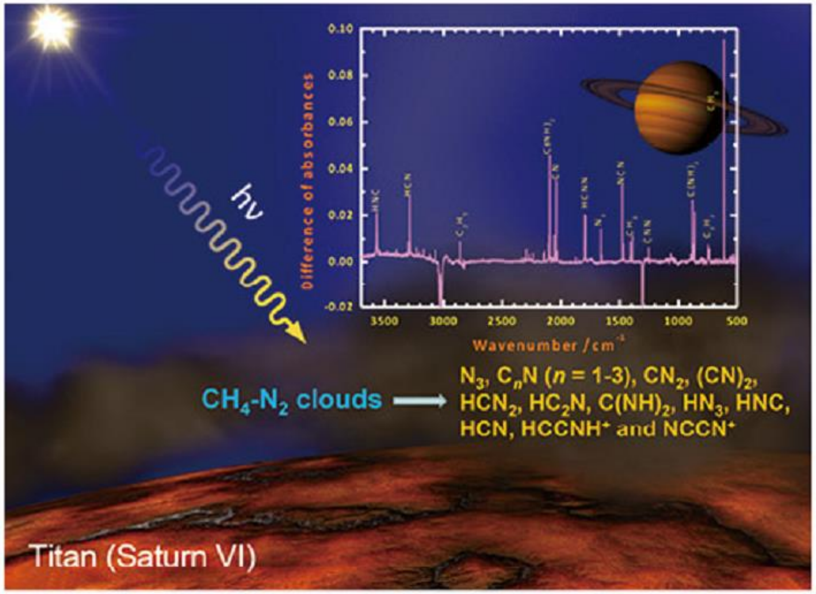
structure ←→ electrochemical properties of electrode

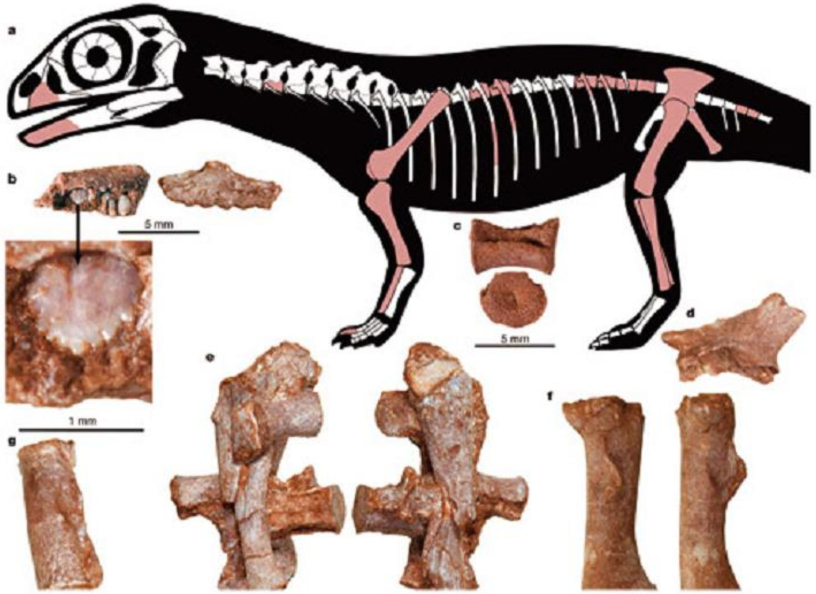
➡ develop novel electrode materials.

Biological structure: protein crystallography



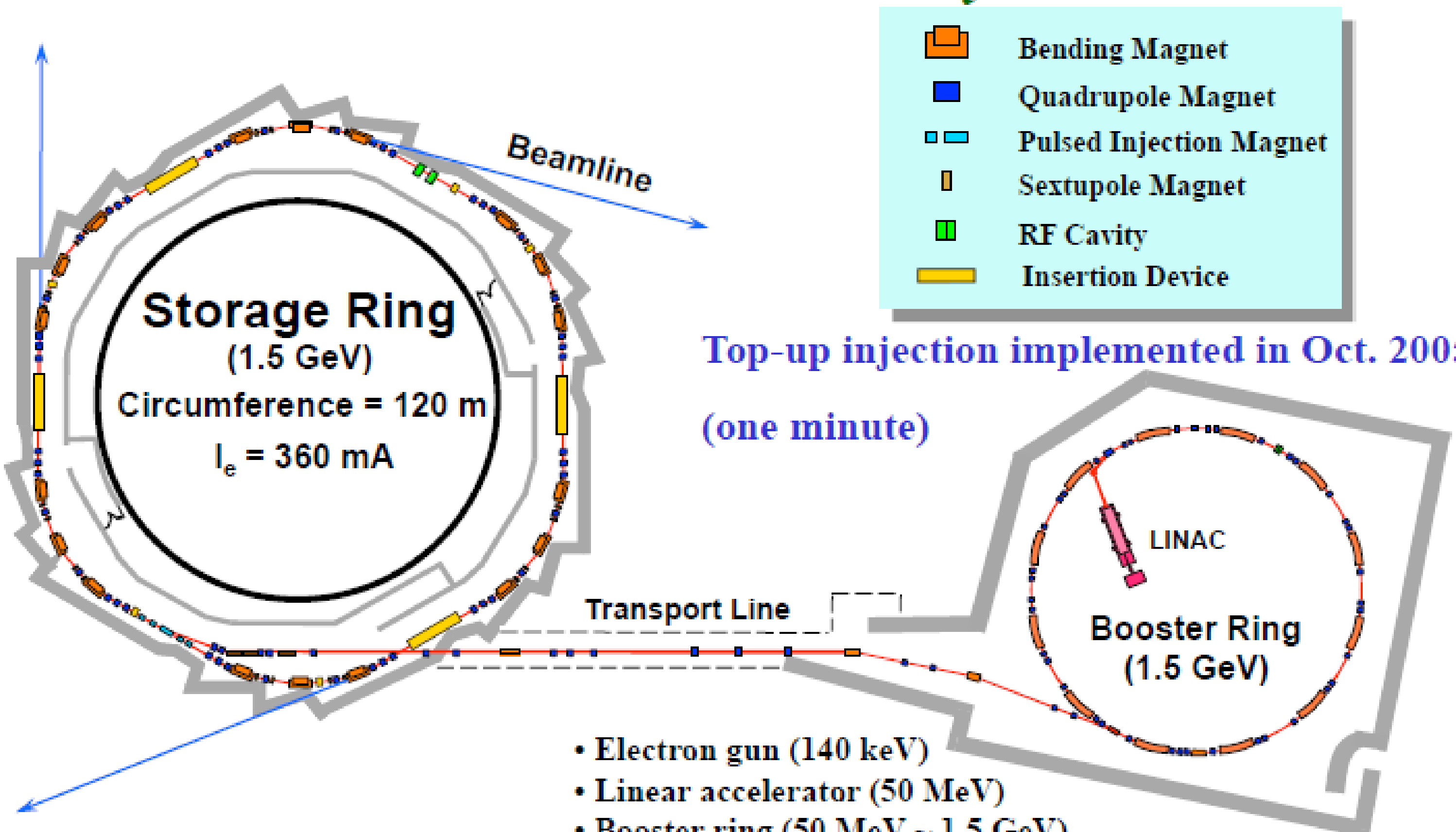

A protein structure
Interaction of a protein
with a DNA


Difference of absorbances
Wavenumber / cm^{-1}
$h\nu$
CH_4-N_2 clouds
N_3, C_nN (n = 1-3), CN_2, $(CN)_2$,
HCN_2, HC_2N, $C(NH)_2$, HN_3, HNC,
HCN, $HCCNH^+$ and $NCCN^+$
Titan (Saturn VI)


5 mm
1 mm
5 mm

Taiwan Light Source (TLS)

Accelerator Facility

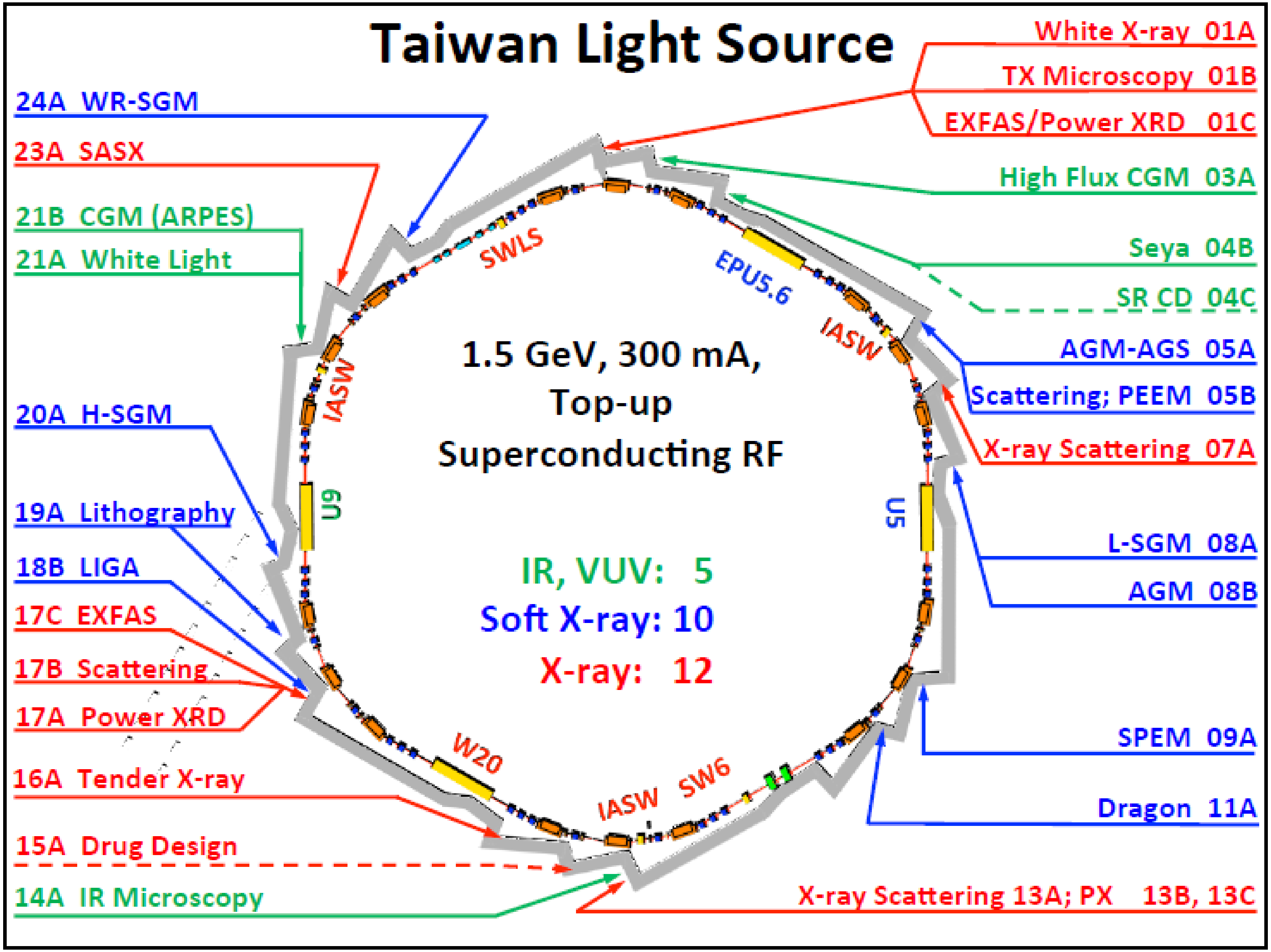


Top-up injection implemented in Oct. 2005

(one minute)

- Electron gun (140 keV)
- Linear accelerator (50 MeV)
- Booster ring (50 MeV ~ 1.5 GeV)

TLS Experimental Hall



Taiwan Light Source
White X-ray 01A
TX Microscopy 01B
EXFAS/Power XRD 01C
High Flux CGM 03A
Seya 04B
SR CD 04C
AGM-AGS 05A
Scattering; PEEM 05B
X-ray Scattering 07A
L-SGM 08A
AGM 08B
SPEM 09A
Dragon 11A
X-ray Scattering 13A; PX 13B, 13C
24A WR-SGM
23A SASX
21B CGM (ARPES)
21A White Light
20A H-SGM
19A Lithography
18B LIGA
17C EXFAS
17B Scattering
17A Power XRD
16A Tender X-ray
15A Drug Design
14A IR Microscopy
SWLS
EPU5.6
IASW
IASW
IASW
U9
U5
W20
SW6
1.5 GeV, 300 mA,
Top-up
Superconducting RF
IR, VUV: 5
Soft X-ray: 10
X-ray: 12

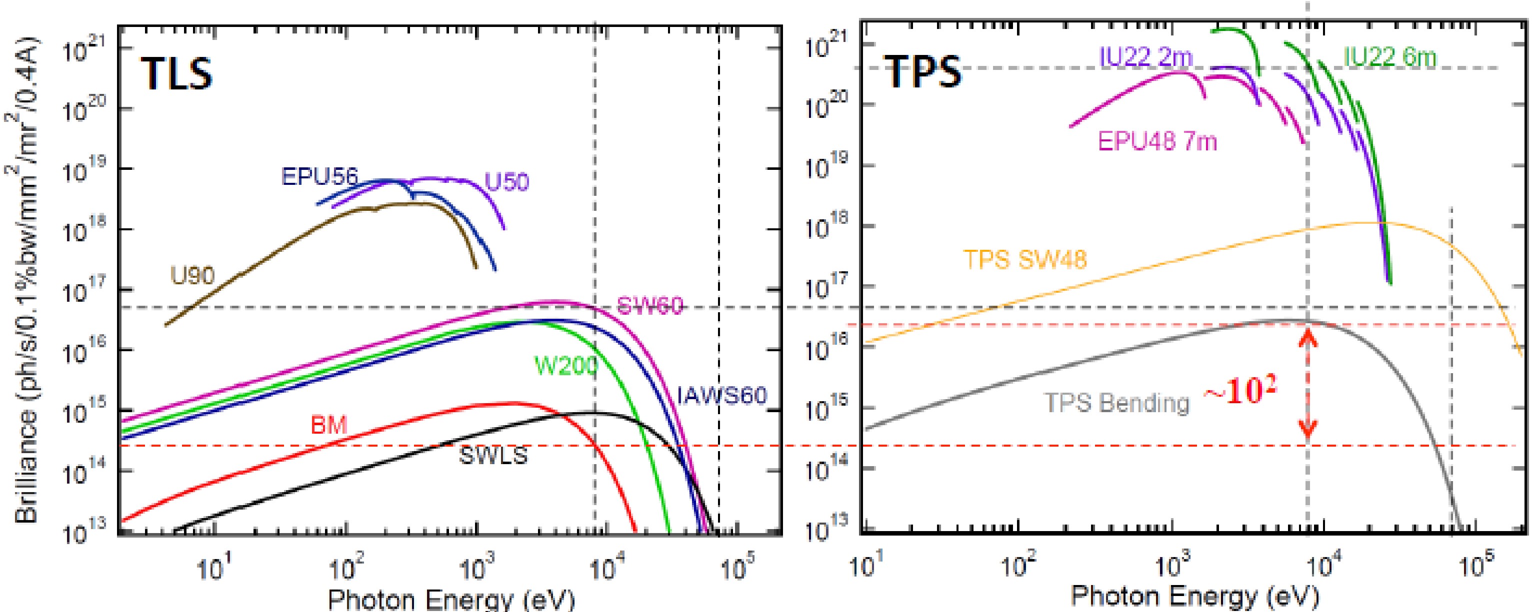
NSRRC is constructing a low-emittance synchrotron-based light source, Taiwan Photon Source (TPS)

Comparison of Brilliance between TLS and TPS

The X-ray spectrum (photon energy 8 keV - 70 keV):

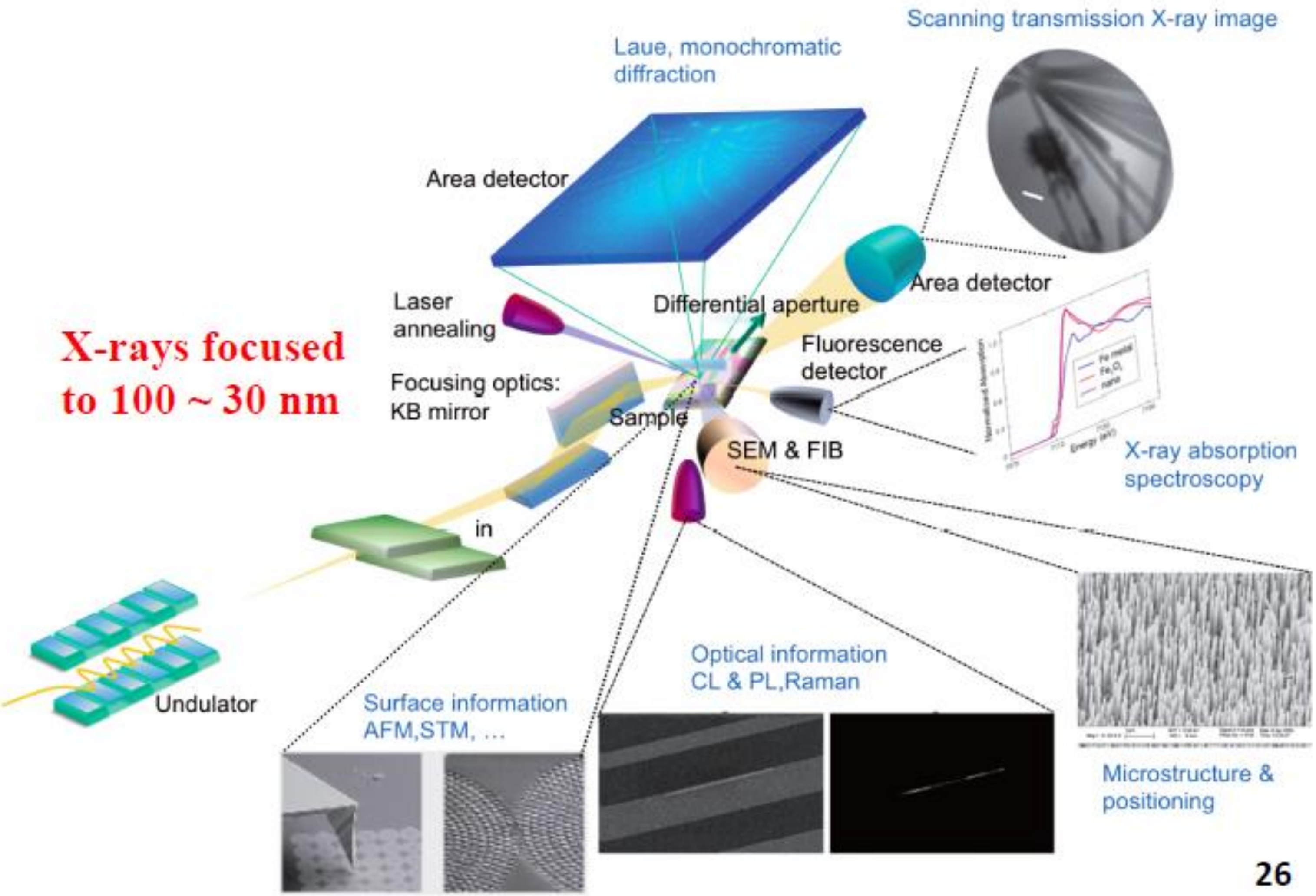
the brightness of bending magnet >10^2.

the brightness of IDs: 4～6 orders of mag.

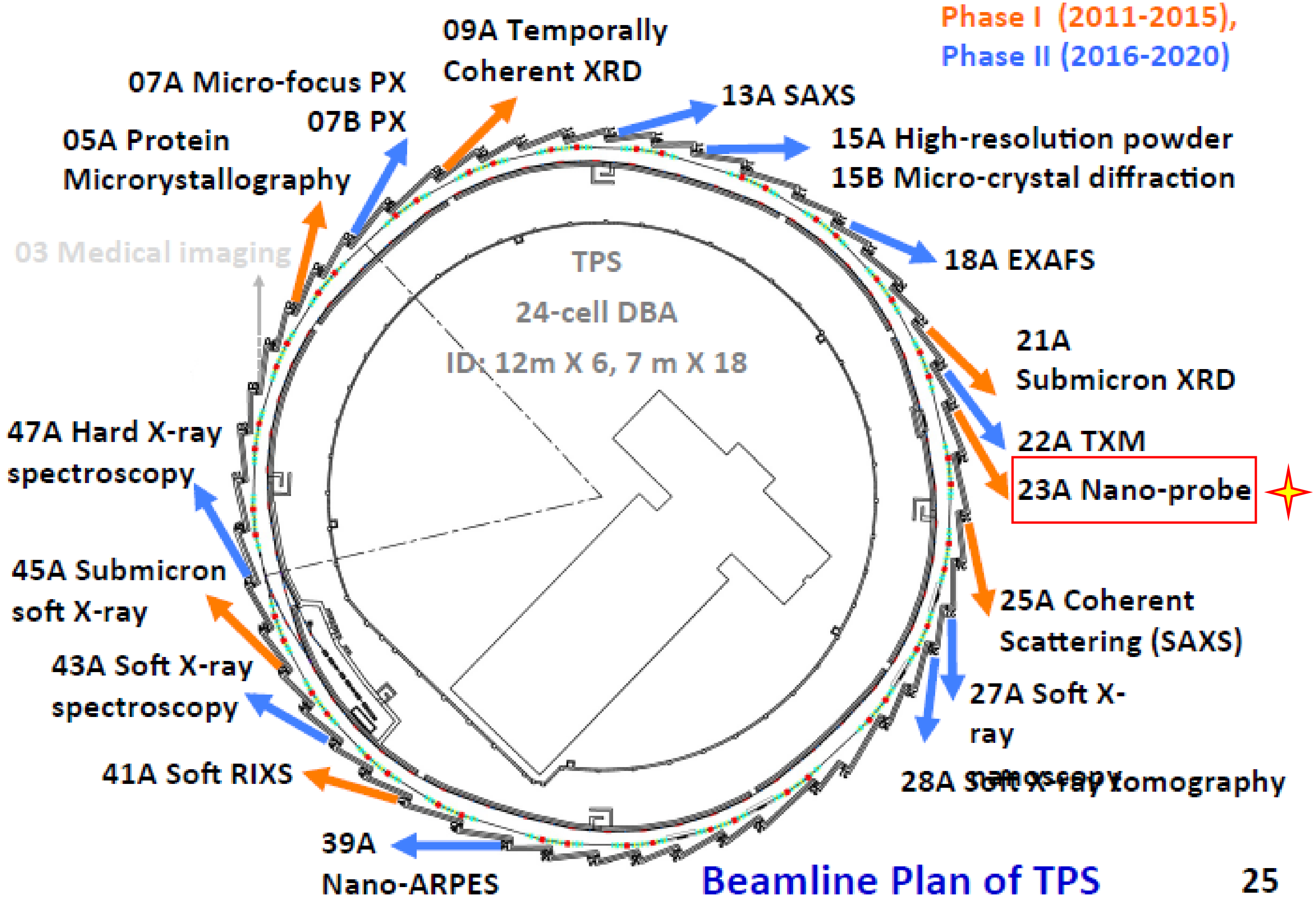


TPS will brighten the future of scientific discovery.

X-rays focused to 100 ~ 30 nm



The user operation of the TPS will begin in 2015.



Beamline Plan of TPS

Outline

- Synchrotron Light Source
- Application of Synchrotron Light
- X-ray nano probe at TPS

X-ray Methods:
With tens-nm resolution (incoherent)

TAIWAN TPS 23A

- nano-XRF (x-ray fluorescence)
  - Element-specific nanoimaging
- nano-XAFS (x-ray absorption fine structures)
  - Local electronic structure
  - Local chemical environments
  - Element-specific, averaged over nano-size area
- nano-XEOL (x-ray excited optical luminescence)
  - X-ray-to-visible down-conversion efficiency in nano phosphor
- nano-PXM (projection x-ray microscopy)
  - Absorption and phase contrast x-ray images

Beyond sub-ten-nm resolution (coherent)

- nano-CXDI (coherent x-ray diffraction imaging)
- Bragg-ptychograpgy
  - strain dynamics in nano-devices

Beamline specification

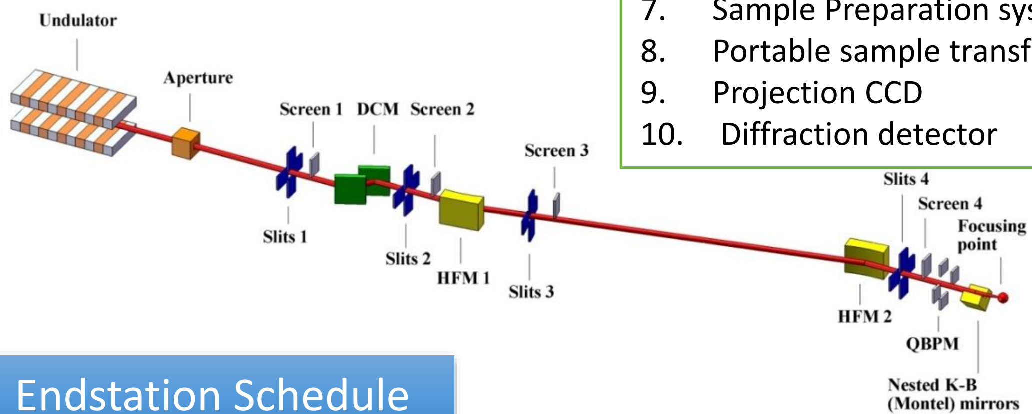
- Energy range：4 - 15 keV
- Photon flux：$10^{10} \sim 10^{11}$ photons/sec
- Energy resolution：$< 2\times10^{-4}$ with Si(111) crystals
- Beam size：$\sim$ 40 nm at 10 keV (H $\times$ V, FWHM)
- High-order harmonic contamination：$\leqq 1 \times 10^{-4}$
- Energy scanning capabilities.

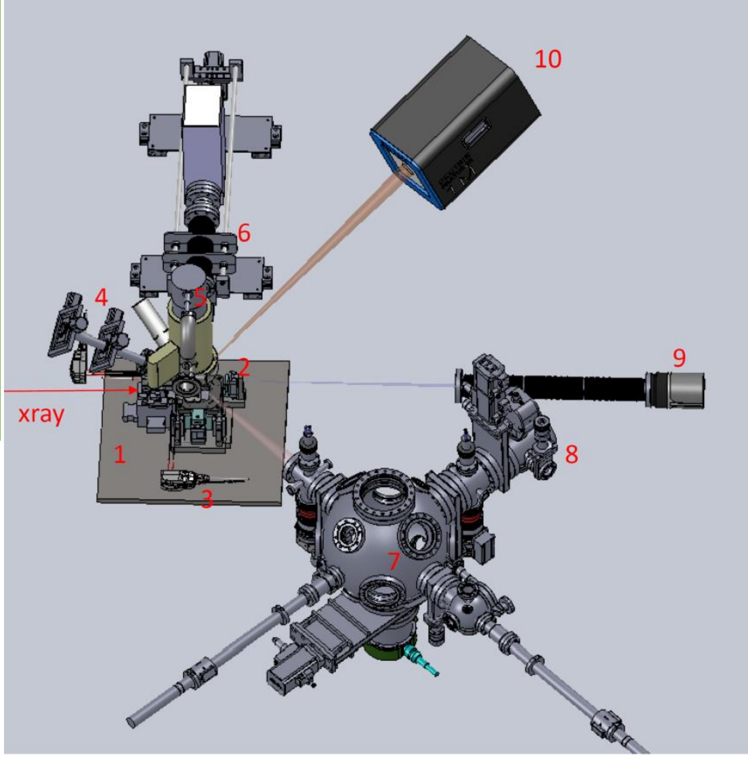
Other than X-rays

- SEM (SE, EDS, CL with high spatial resolution)
- Fly scanning
- Nanomotors (optional)
- Sample environment -heat, electric, L-He (optional)

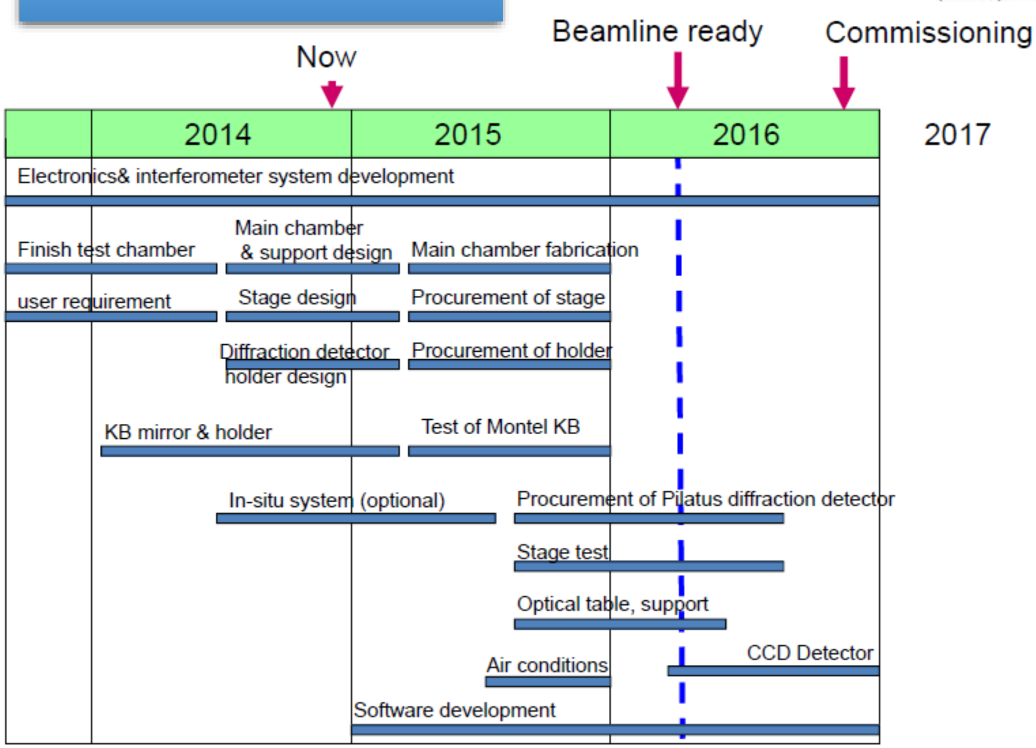
TPS 23A XNP

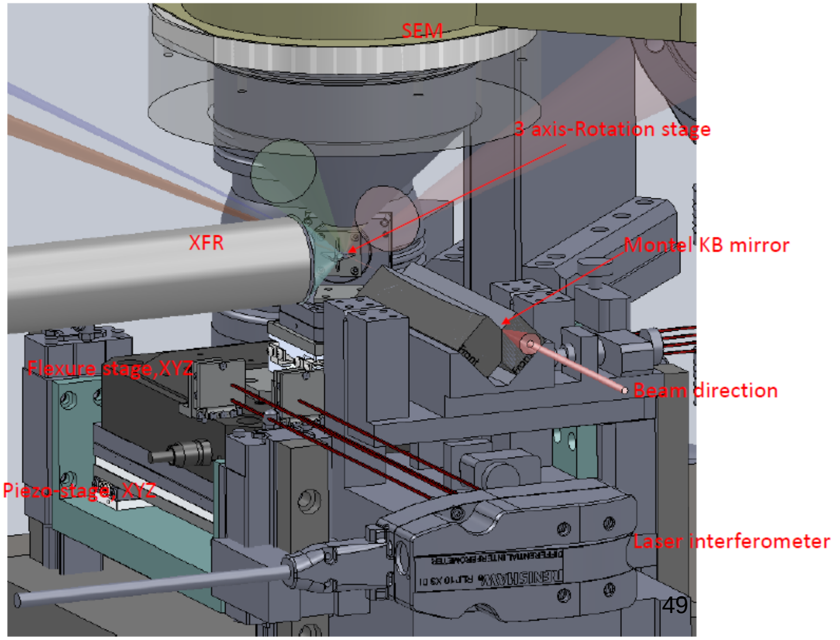
1. Montel mirror
2. Sample Stage
3. Laser interferometer
4. XEOL
5. SEM
6. EDS
7. Sample Preparation system
8. Portable sample transfer
9. Projection CCD
10. Diffraction detector





Endstation Schedule

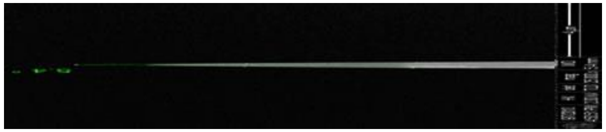




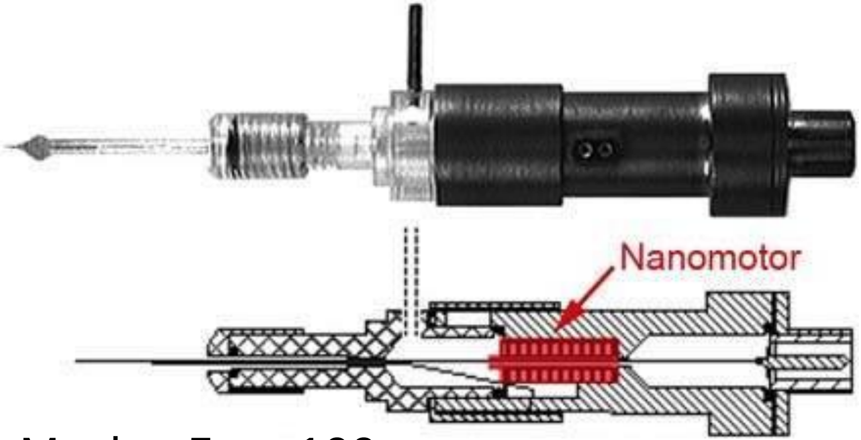
Nanomotor probe

Cone Angle: 16.5° , Diameter: 25nm

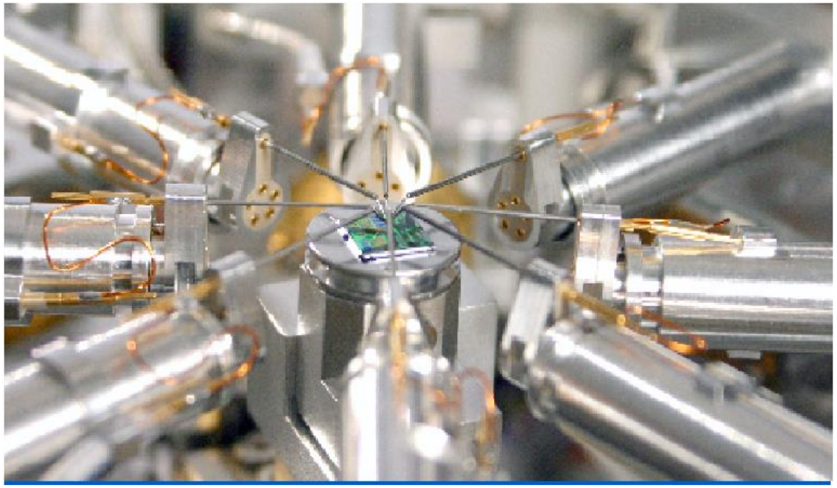
Cone Angle: 5.4° , Diameter: 6nm

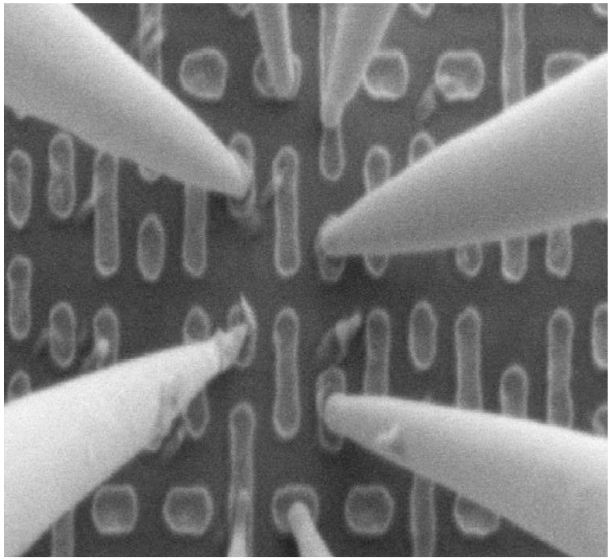


NT:600,000

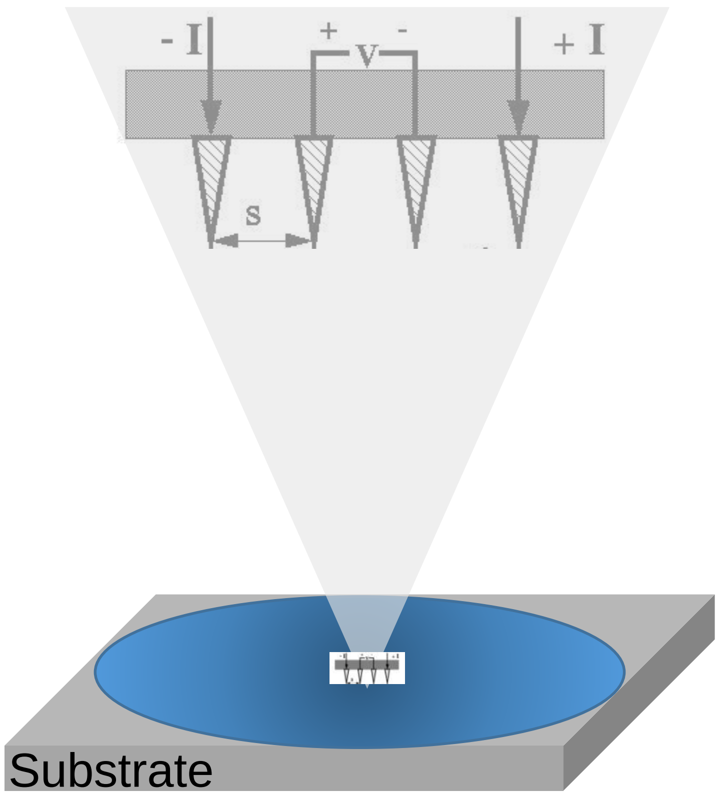


Moving 5nm-100um

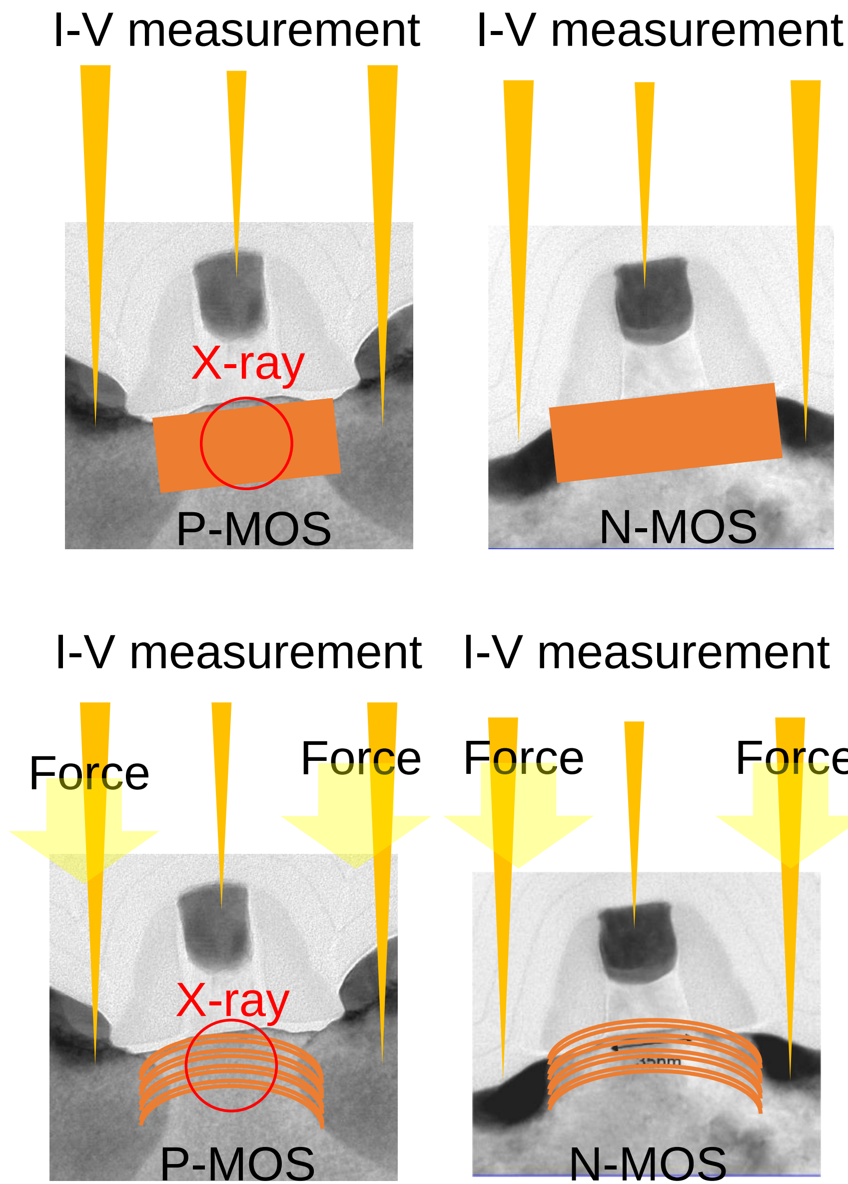


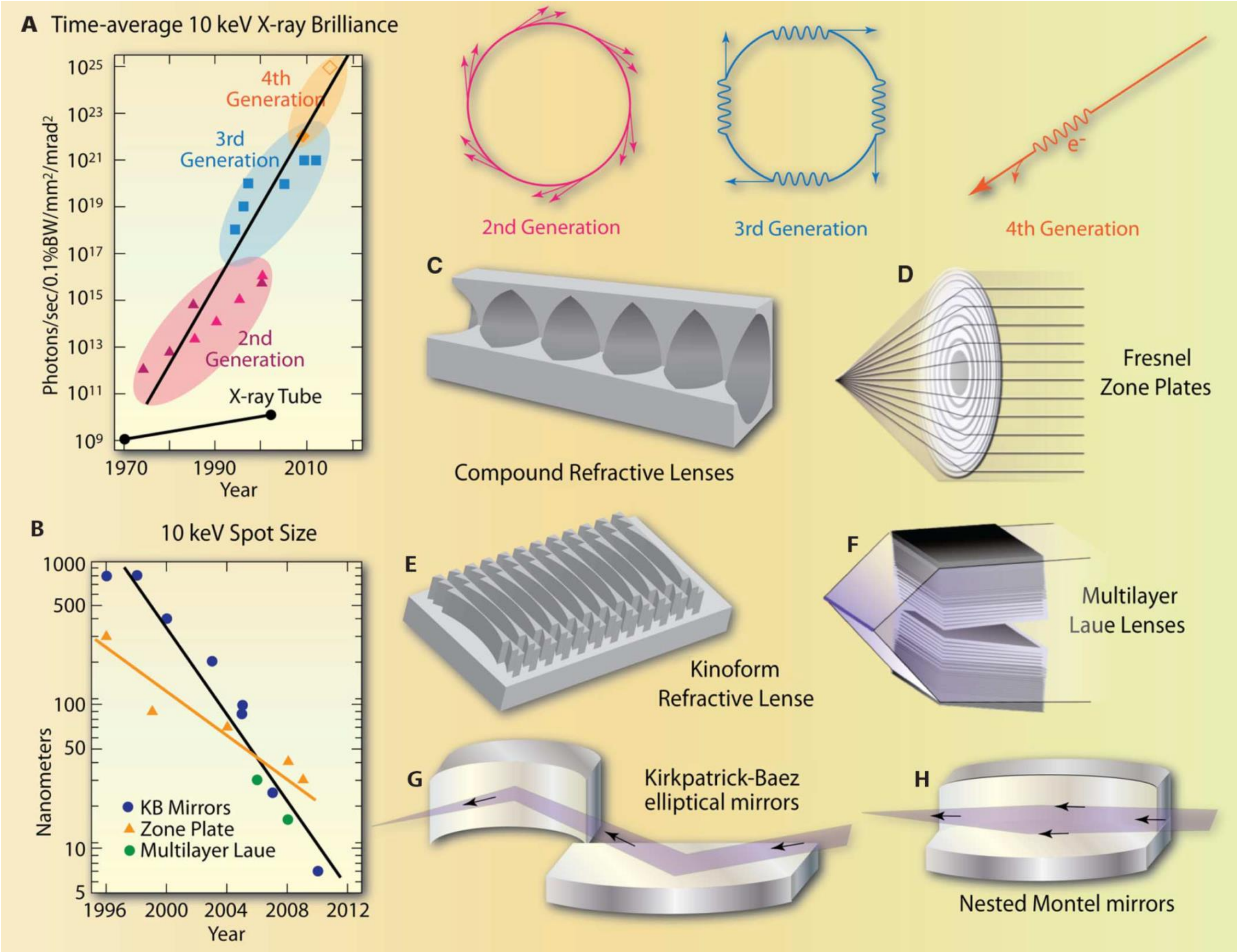


Nanomotor Probe Application



Nanometer can construct
the 4-point probe



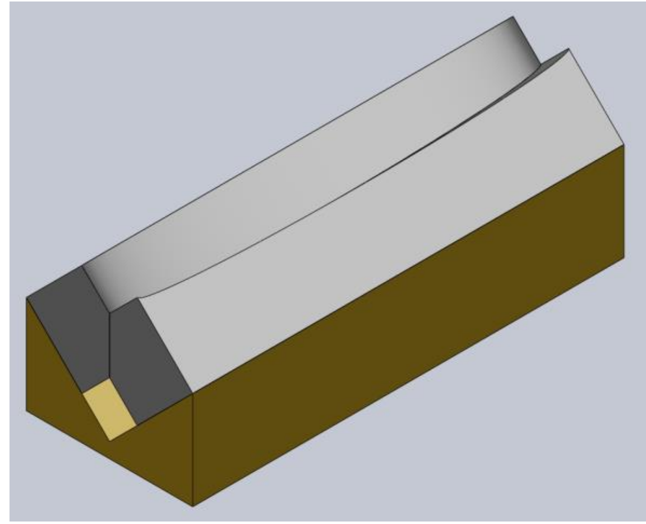

A Time-average 10 keV X-ray Brilliance
Photons/sec/0.1%BW/mm²/mrad²
4th Generation
3rd Generation
2nd Generation
X-ray Tube
1970 1990 2010
Year
2nd Generation
3rd Generation
4th Generation
e-
C
Compound Refractive Lenses
D
Fresnel Zone Plates
B
10 keV Spot Size
Nanometers
KB Mirrors
Zone Plate
Multilayer Laue
1996 2000 2004 2008 2012
Year
E
Kinoform Refractive Lense
F
Multilayer Laue Lenses
G
Kirkpatrick-Baez elliptical mirrors
H
Nested Montel mirrors

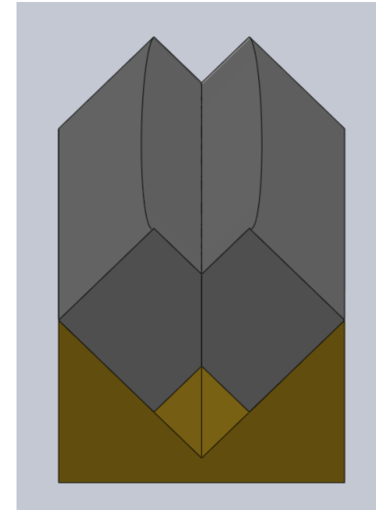
Montel Nested KB Mirror @TPS-23A

- **Montel nested KB mirror @ APS**:
  - Focal spot: 100 nm

- **Challenges**:
  - Gap between mirrors
  - Slope error

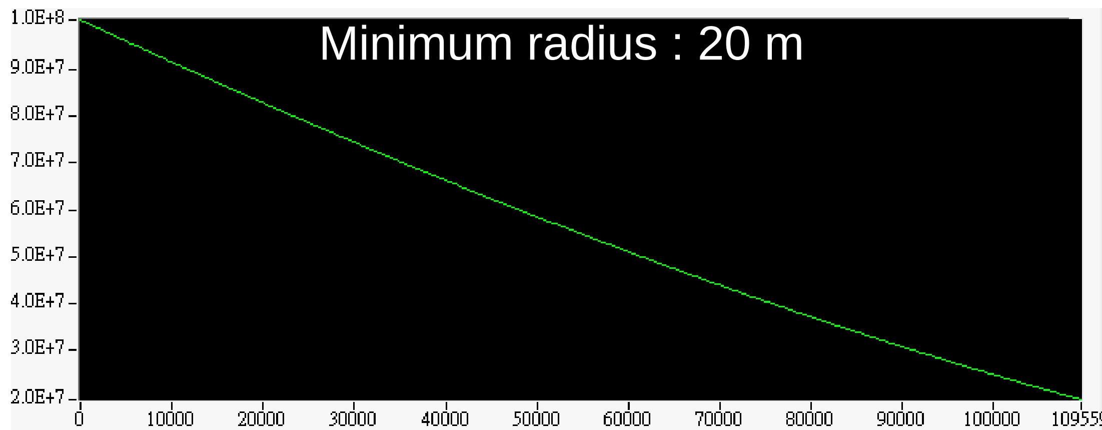
➔ Overcome by **Elastic Emission Machining (EEM)**

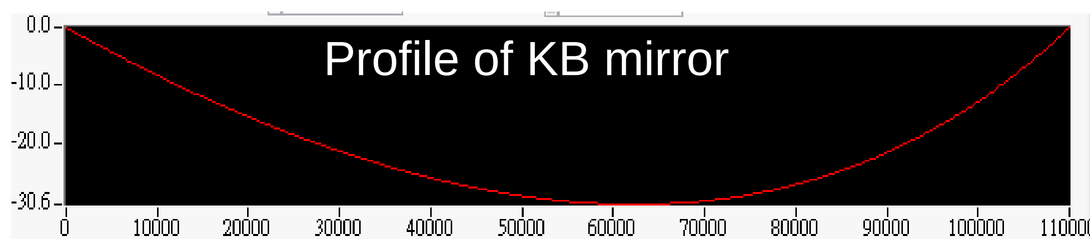




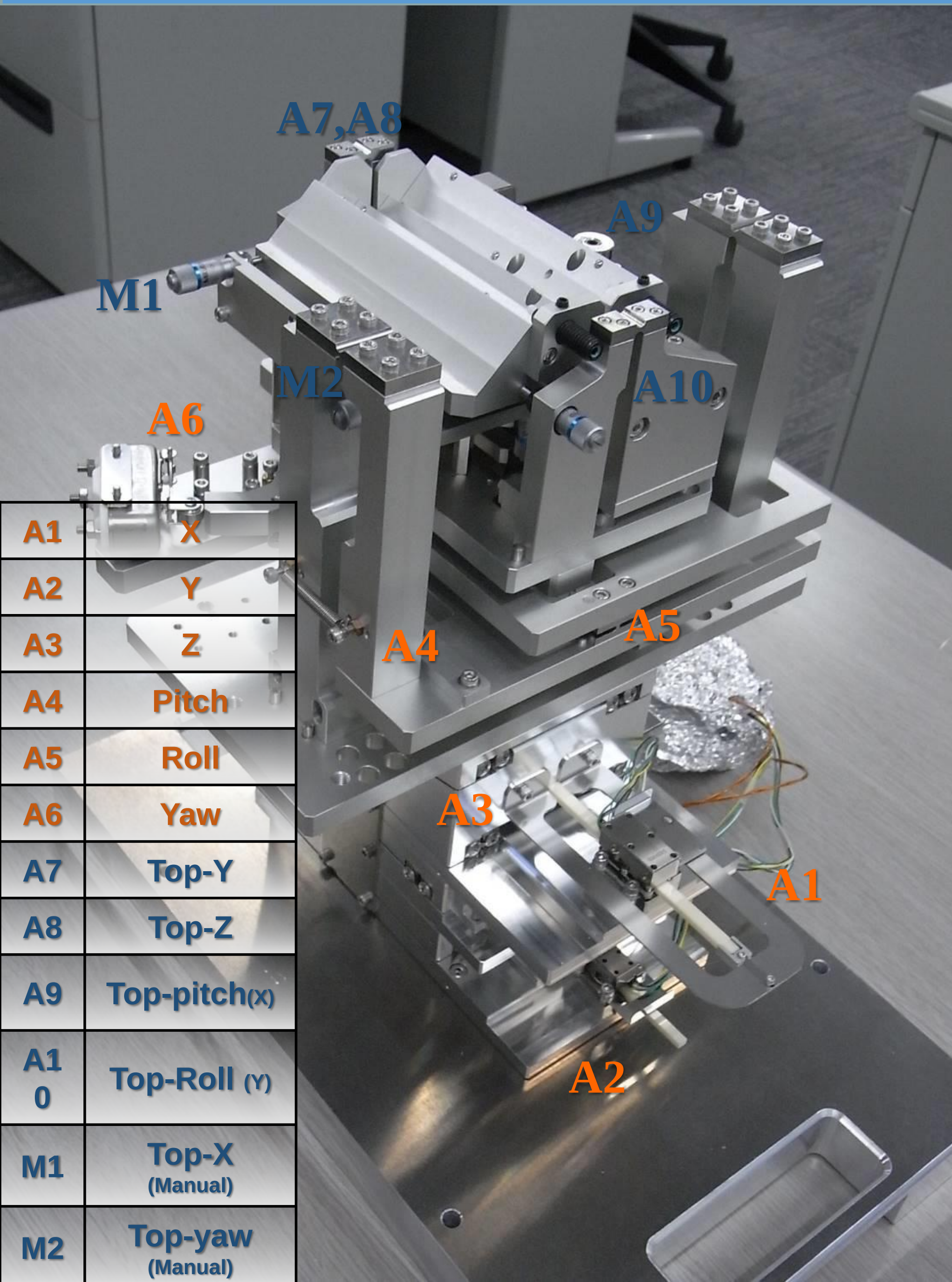
- **Montel nested KB mirror @ TPS**:

Objective distance	**69 m**
Focus length	**11 cm**
Mirror length	**11 cm**
Slope error (RMS)	**< 0.05 µrad**
Incident angle	**4 mrad**
Coating	**Rh**
Material	**silica**
Working Distance	**5.5 cm**

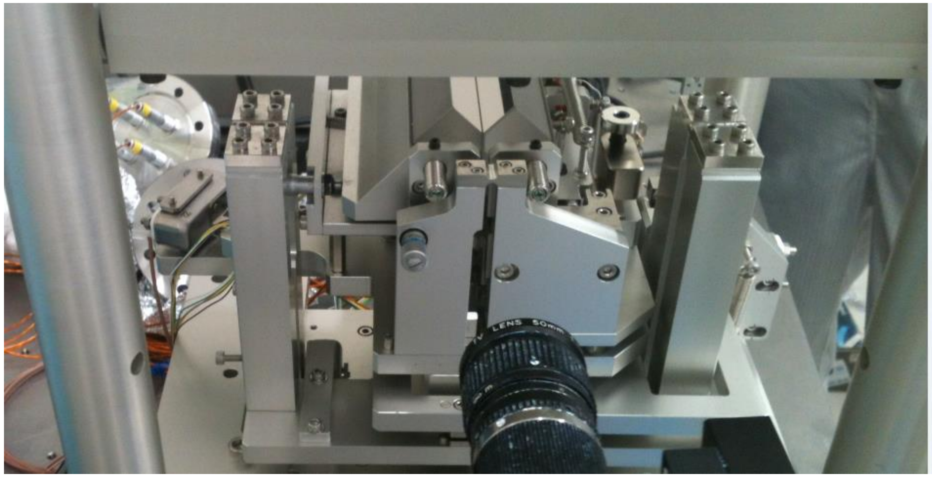




Montel KB Montel Mirror and Holders



A1	X
A2	Y
A3	Z
A4	Pitch
A5	Roll
A6	Yaw
A7	Top-Y
A8	Top-Z
A9	Top-pitch(x)
A10	Top-Roll (Y)
M1	Top-X (Manual)
M2	Top-yaw (Manual)



Montel Mirror on the holder

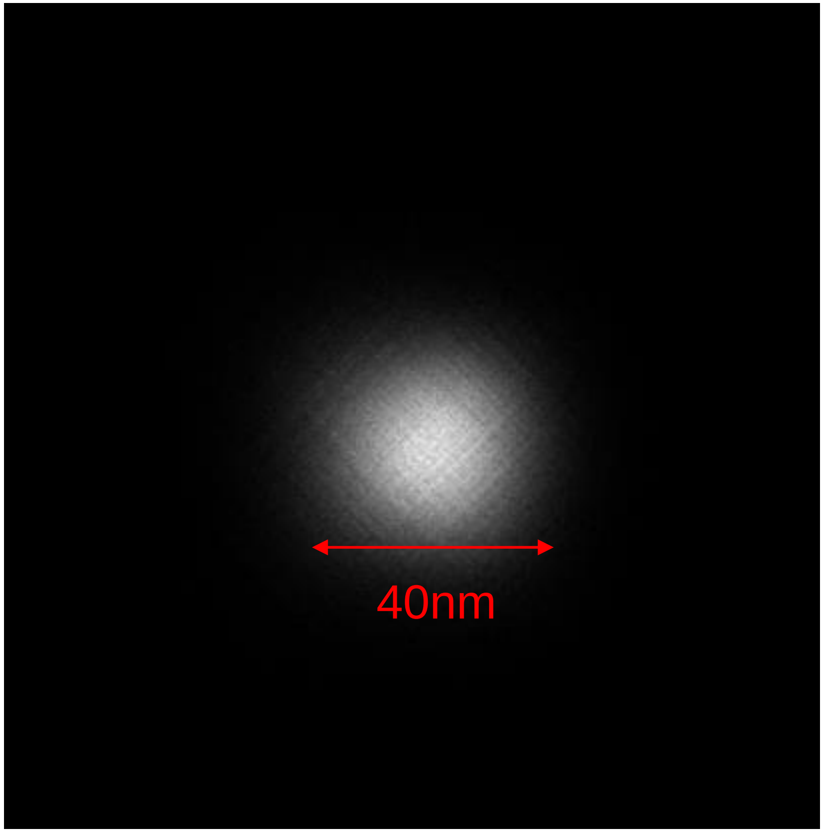
Gap imaged by microscope

June 2015, at JTEC

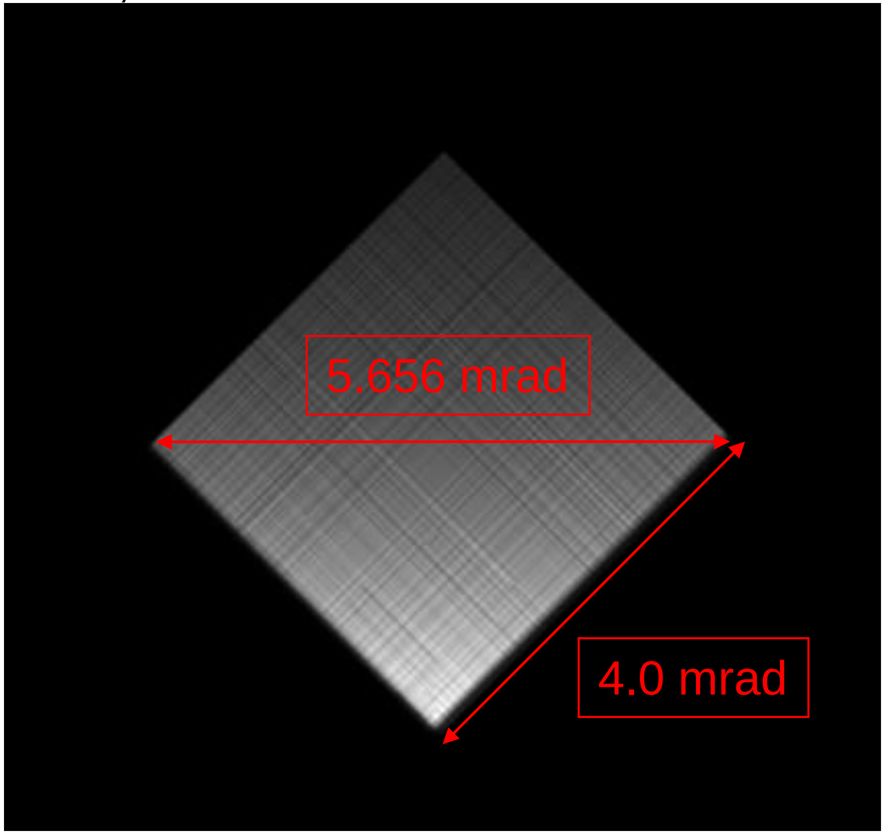
Simulation of Focus Spot

Simulation at 10 keV, average reflection=0.802, by ray tracing

Source size	12.5 μm x 12.5 μm
Source divergence	6μrad x 6μrad
FHWM	32nm x 32nm,



Simulated
Focus spot size



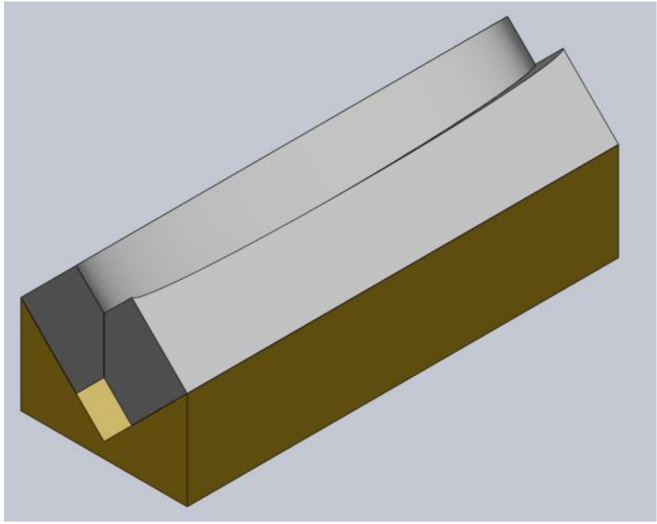
Simulated
Divergence

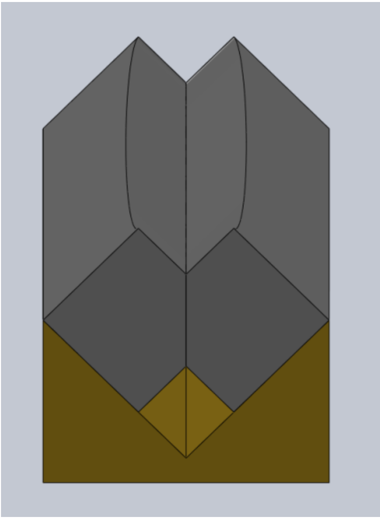
By Gung-Chian Yin

Montel Nested KB Mirror @TPS-23A

- **Montel nested KB mirror @ APS**:
  - Focal spot: 100 nm
- **Challenges**:
  - Gap between mirrors
  - Slope error

➔ Overcome by **Elastic Emission Machining (EEM)**





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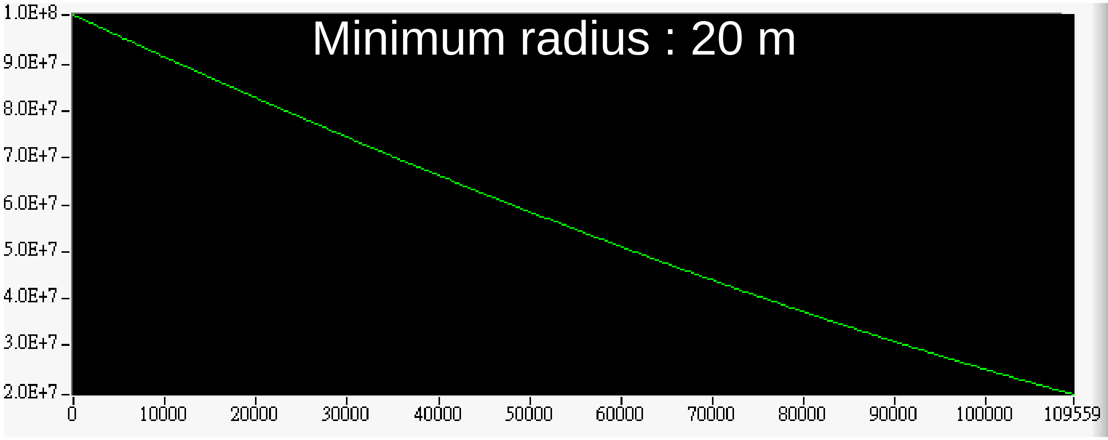
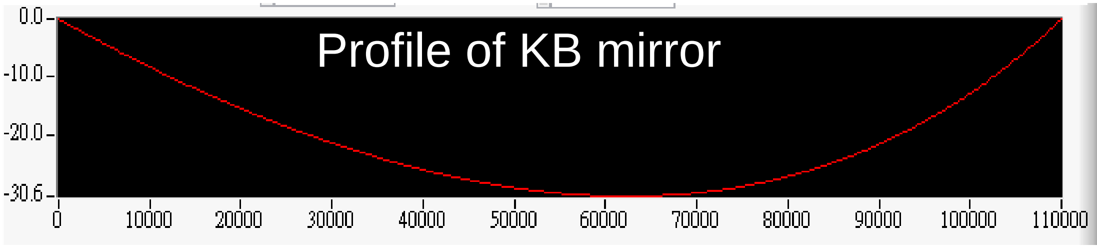
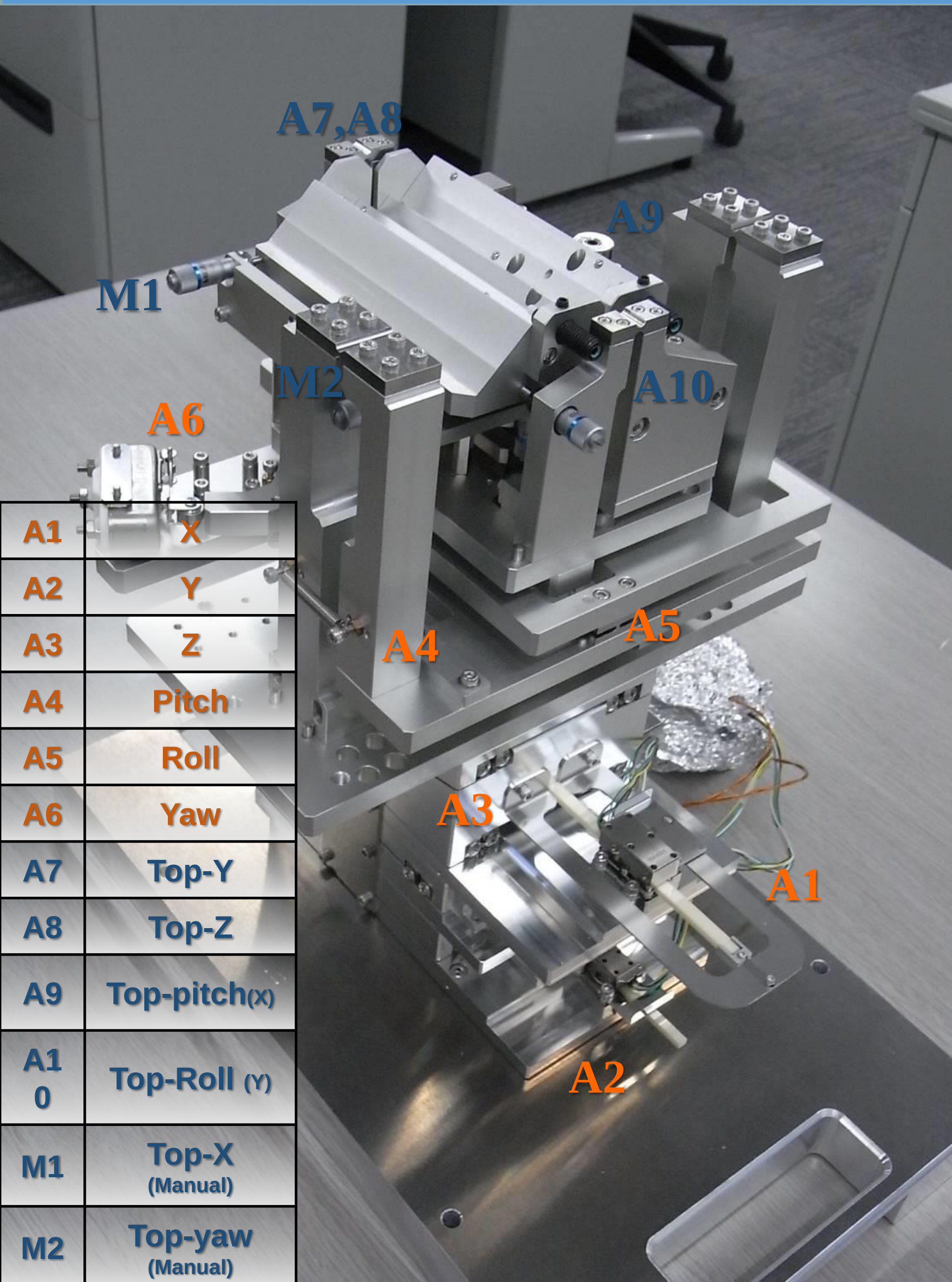
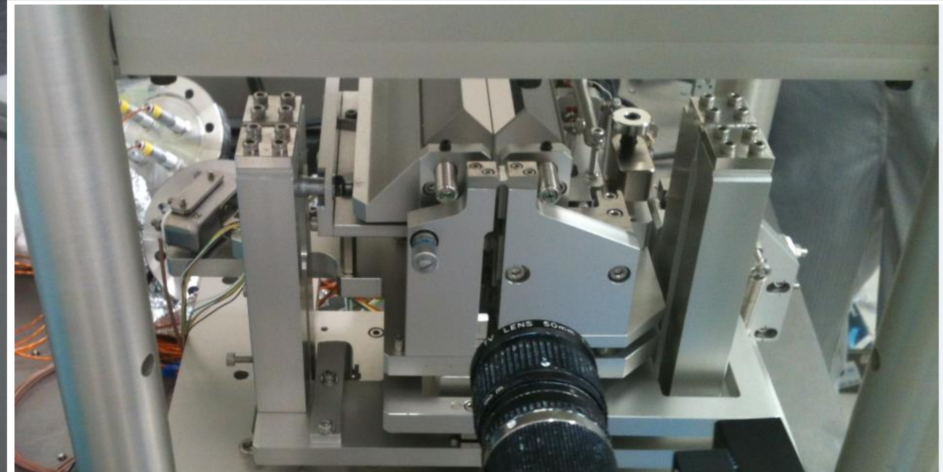




Montel KB Montel Mirror and Holders



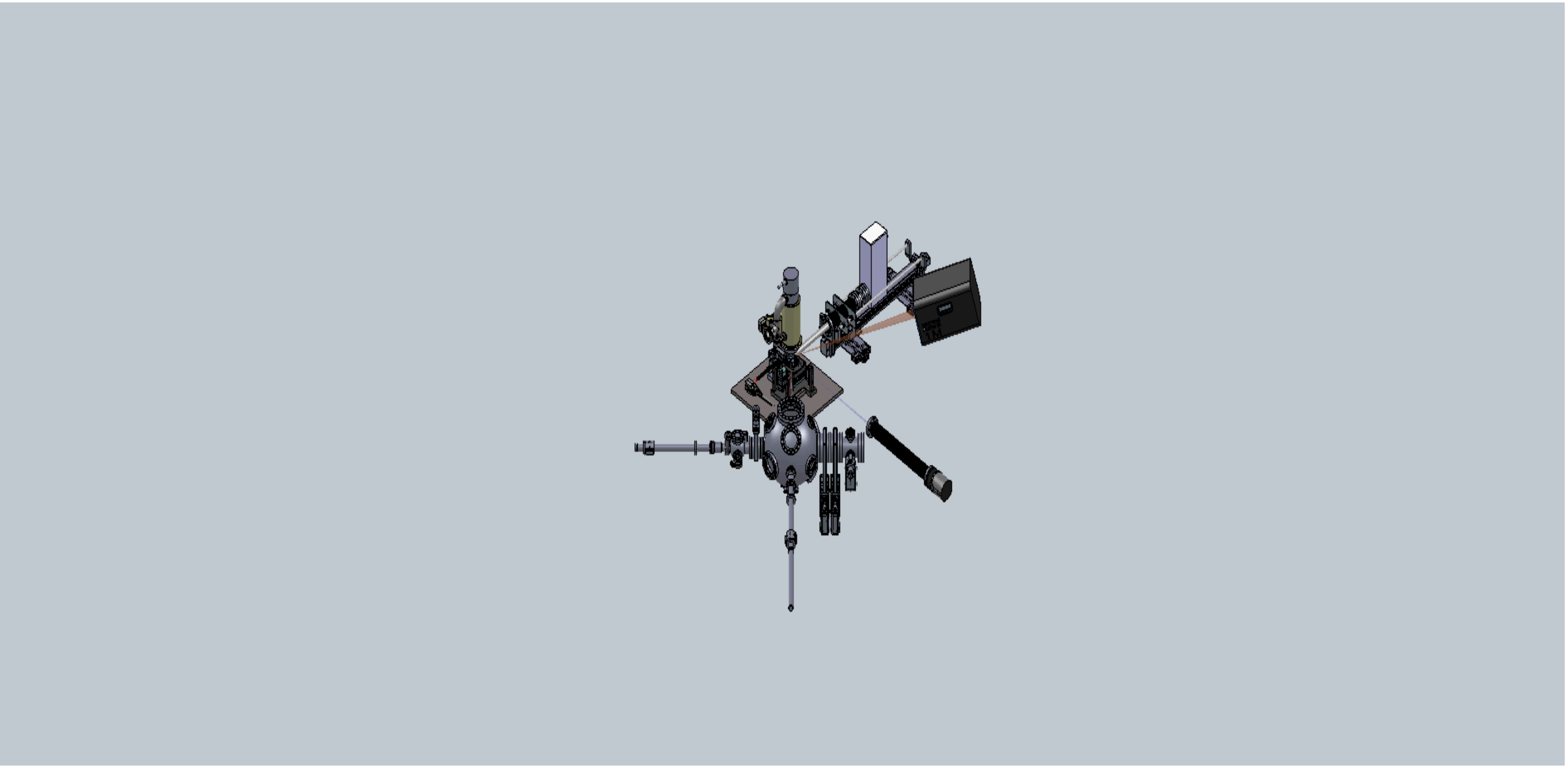
A1	X
A2	Y
A3	Z
A4	Pitch
A5	Roll
A6	Yaw
A7	Top-Y
A8	Top-Z
A9	Top-pitch(x)
A10	Top-Roll (Y)
M1	Top-X (Manual)
M2	Top-yaw (Manual)



Montel Mirror on the holder

Gap imaged by microscope

June 2015, at JTEC



nano-XRF (x-ray fluorescence)

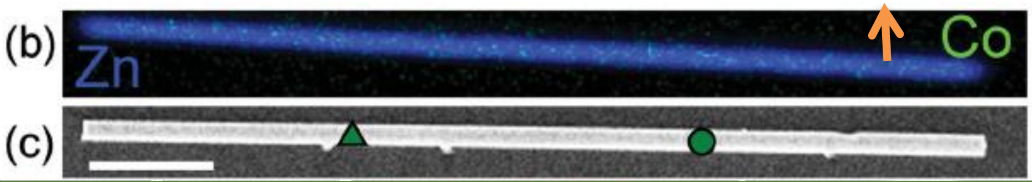
Element-specific nano-imaging

Doping of ZnO NWs by transition metal Co.
Application : Spintronic device
Want to know:

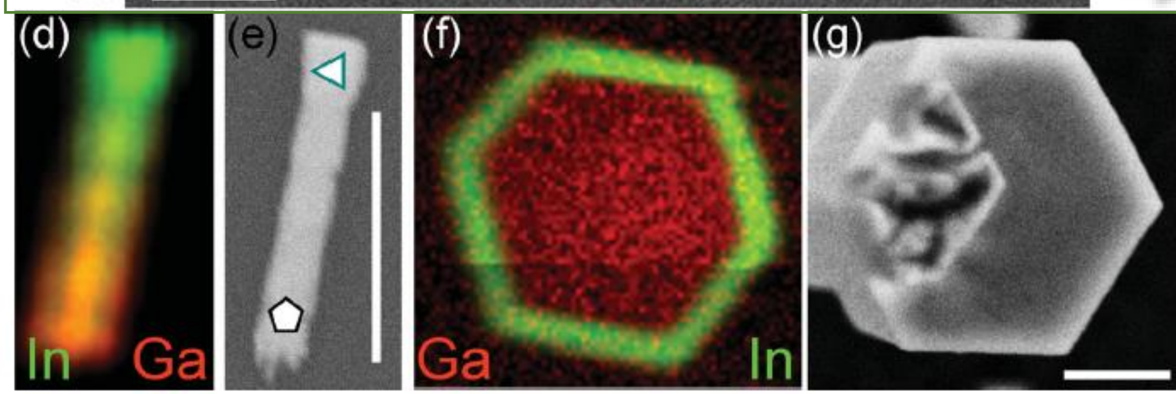
- Distribution
- Short structure order
- Elemental composition

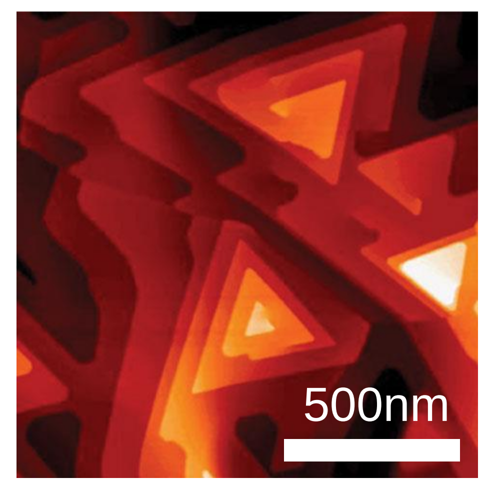
- ➢ Pink beam mode at 12 KeV
- ➢ Pixel size : 25 x 25 nm^2
- ➢ Accumulation time : 0.5 sec/point
- ➢ beam size : 60 x 60 nm^2 (V x H)

Vapour-liguid-solid process
Nano Lett. 2011, 11, 5322–5326



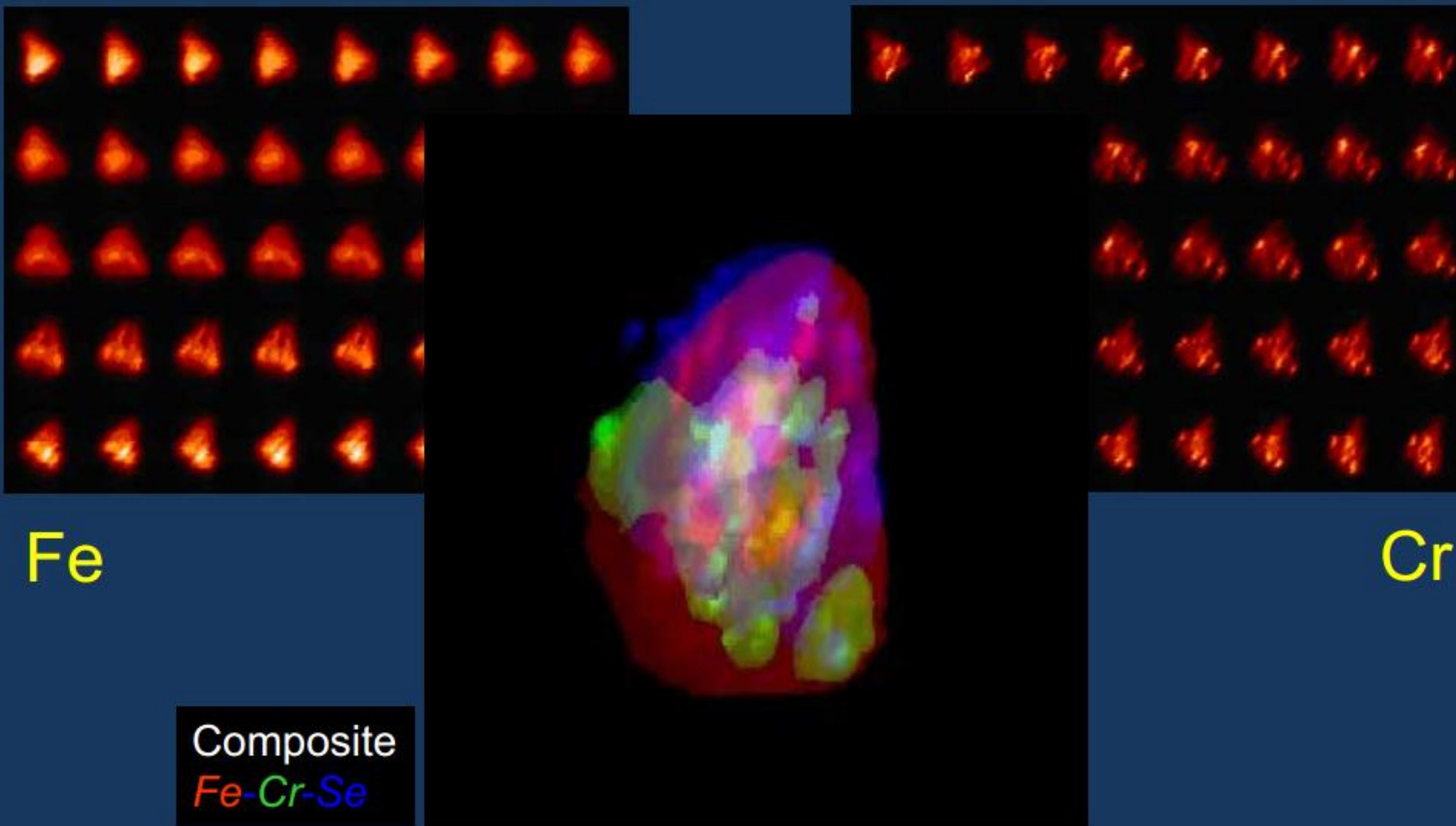
Doping method:
Ion implantation
and thermal annealing
Elemental map of XRF
SEM





High resolution XRF tomography

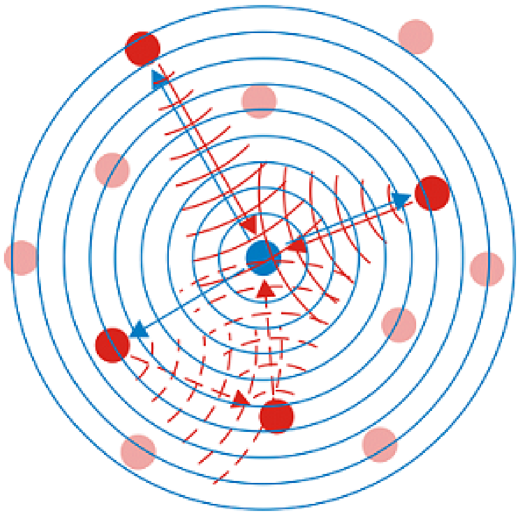
Pixel size: 100 nm, sample rotation 0-180° (4.5° / image)

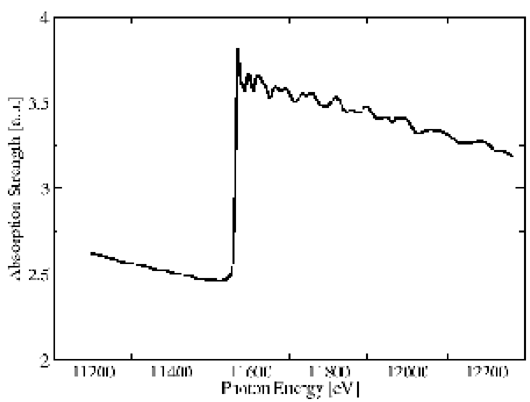


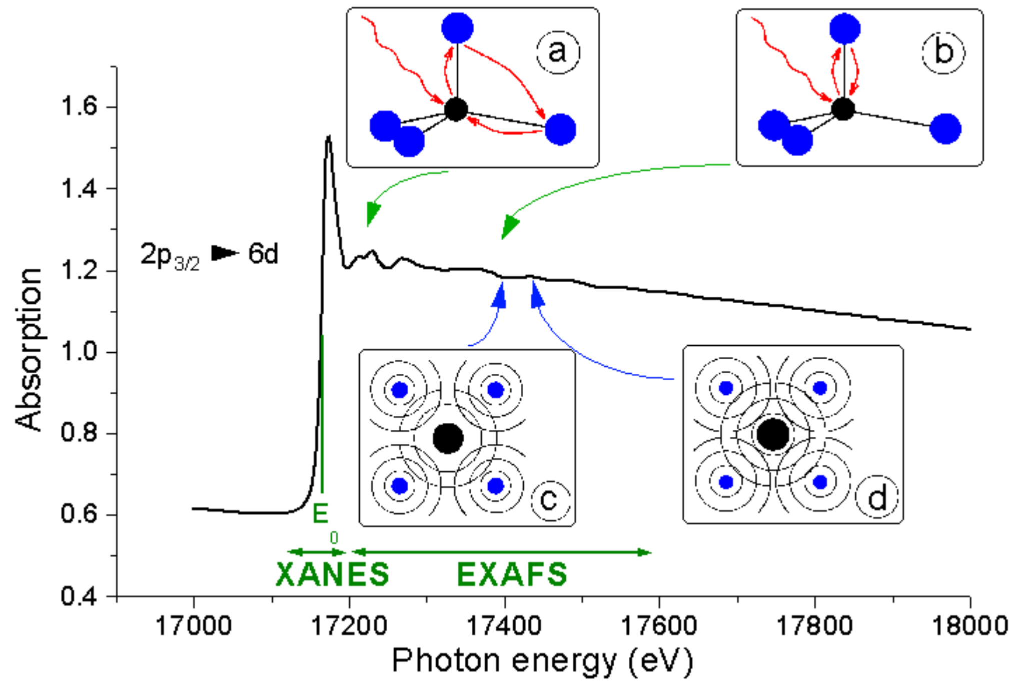
Silversmit *et al., Anal. Chem.* 81 (2009)

nano-XAFS (x-ray absorption fine structures)

- Local electronic structure
- Local chemical environments
- Element-specific, averaged over nano-area

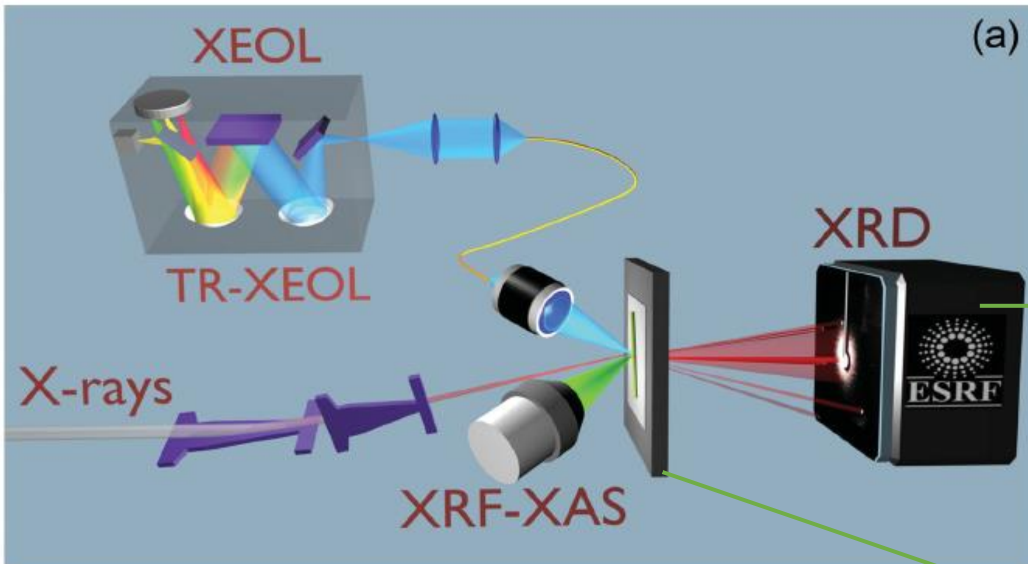






ESRF ID16B methods

XEOL
- Multimode optical fiber
- UV-VIS : linear CCD Si detector
- Si avalanche photodiode (id100 from id-Quantique)



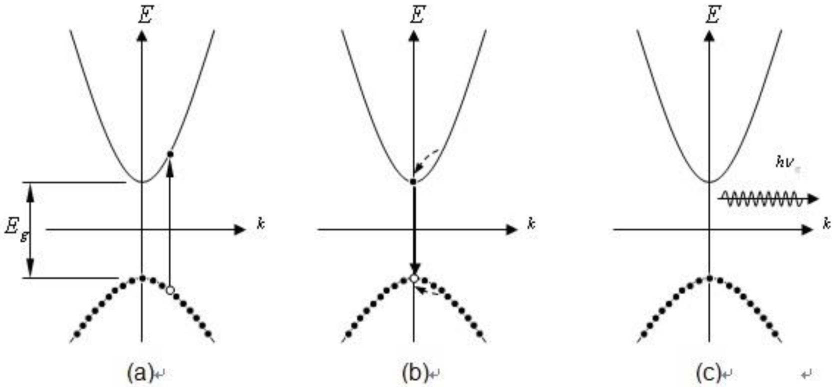
XRD
- The XRD signal was measured using a fast readout low noise (FReLoN) CCD detector.
- The CCD images were processed using Fit2D software to generate the standard diffractograms.
- Using the experimental parameters derived from the measurement of an Al2O3 reference sample.

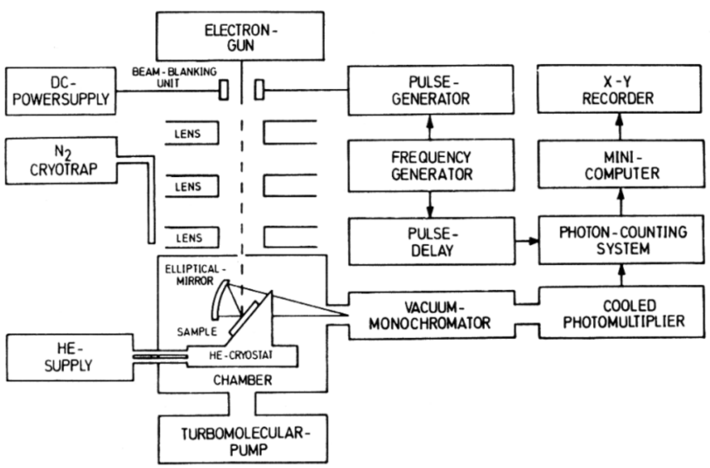
XRF
- XRF signal was collected at 15°
- The elemental composition of the NWs was estimated by fitting the XRF spectra using the PyMca program.
- XANES spectra were recorded in X-ray fluorescence mode with a step size of 1 eV and integration times determined by the counting statistics.
- The data analysis was performed using the IFEFFIT package.

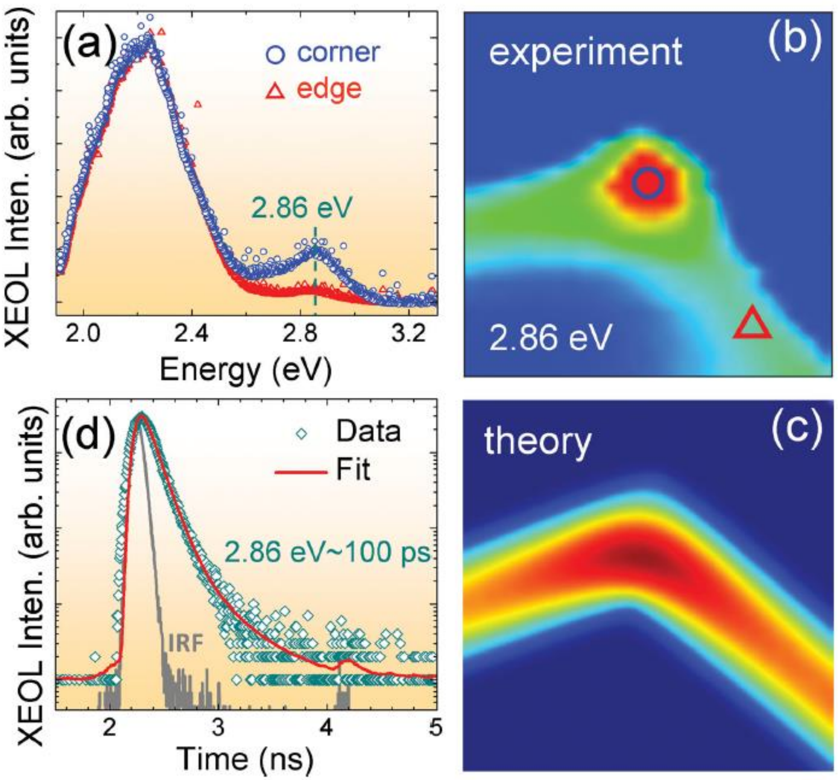
- 200 nm thick SiN membranes.
- Without XRF background signal
- X-ray diffraction can be transmitted

Adv. Mater. **2014**,
DOI: 10.1002/adma.201304345

nano-XEOL (x-ray excited optical luminescence) & CL (cathodoluminescsnce)







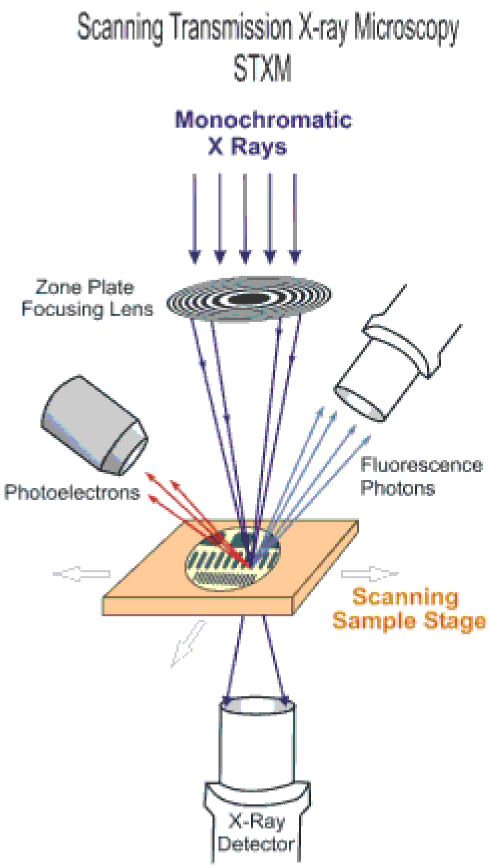
XEOL: 1.nano-area

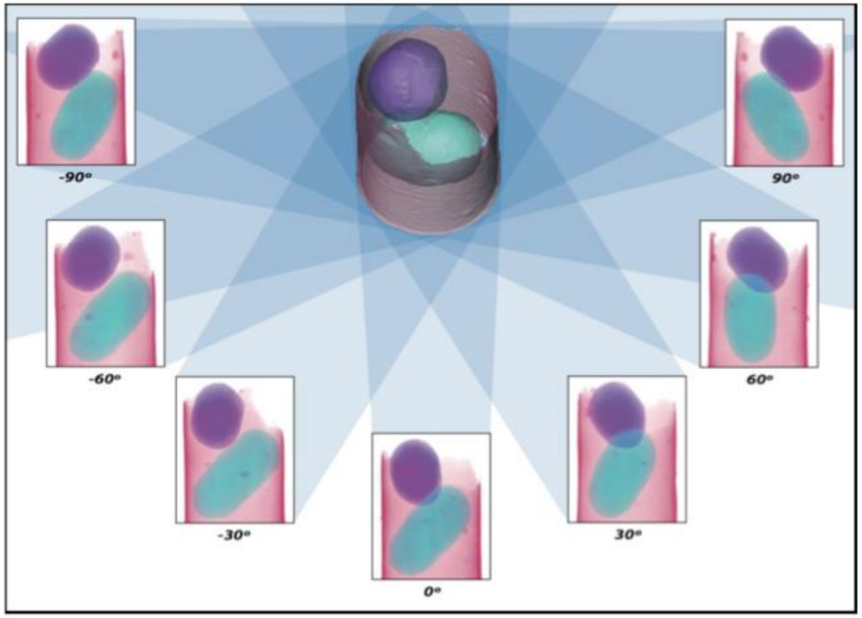
2.multi-layer, buried layer

Doping species, Band gap, Defect band, Charge transport

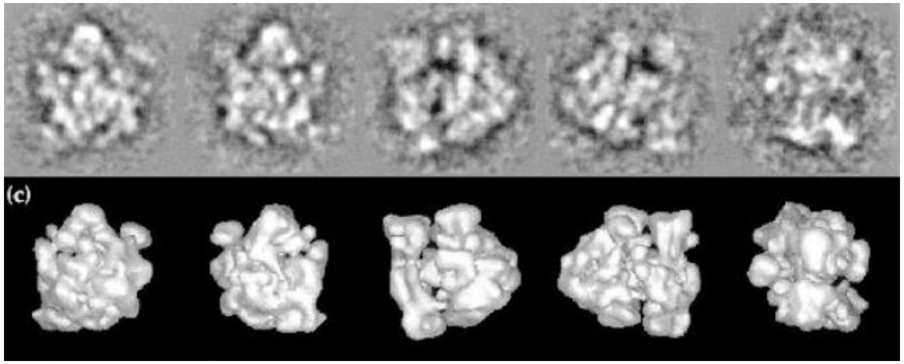
nano-PXM (projection x-ray microscopy)

– Absorption and phase contrast x-ray images

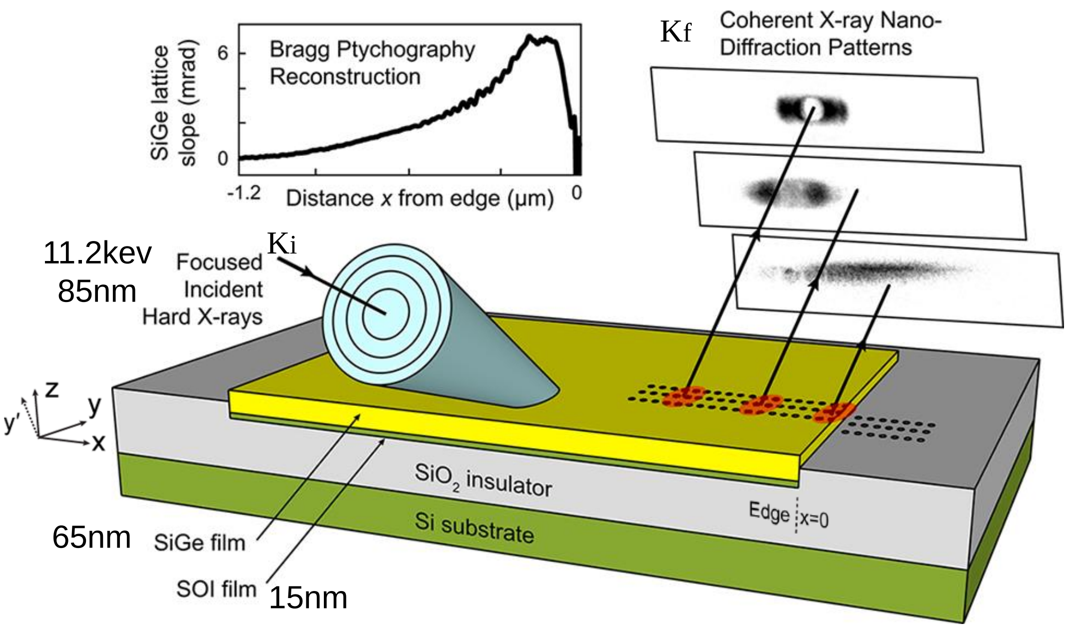


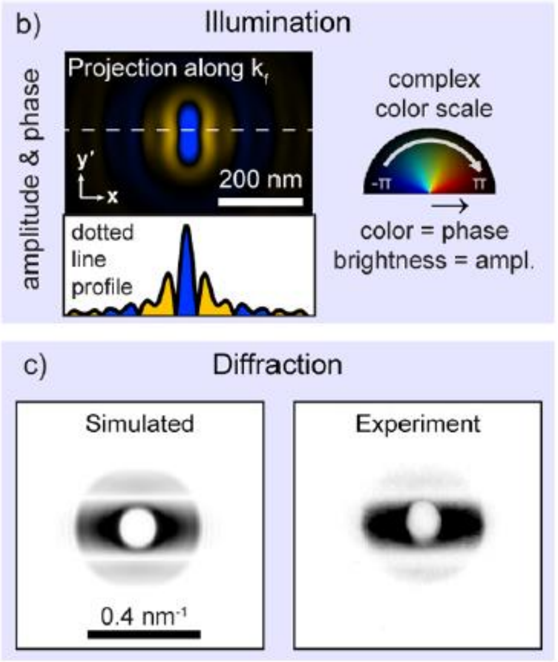


TRENDS in Cell Biology

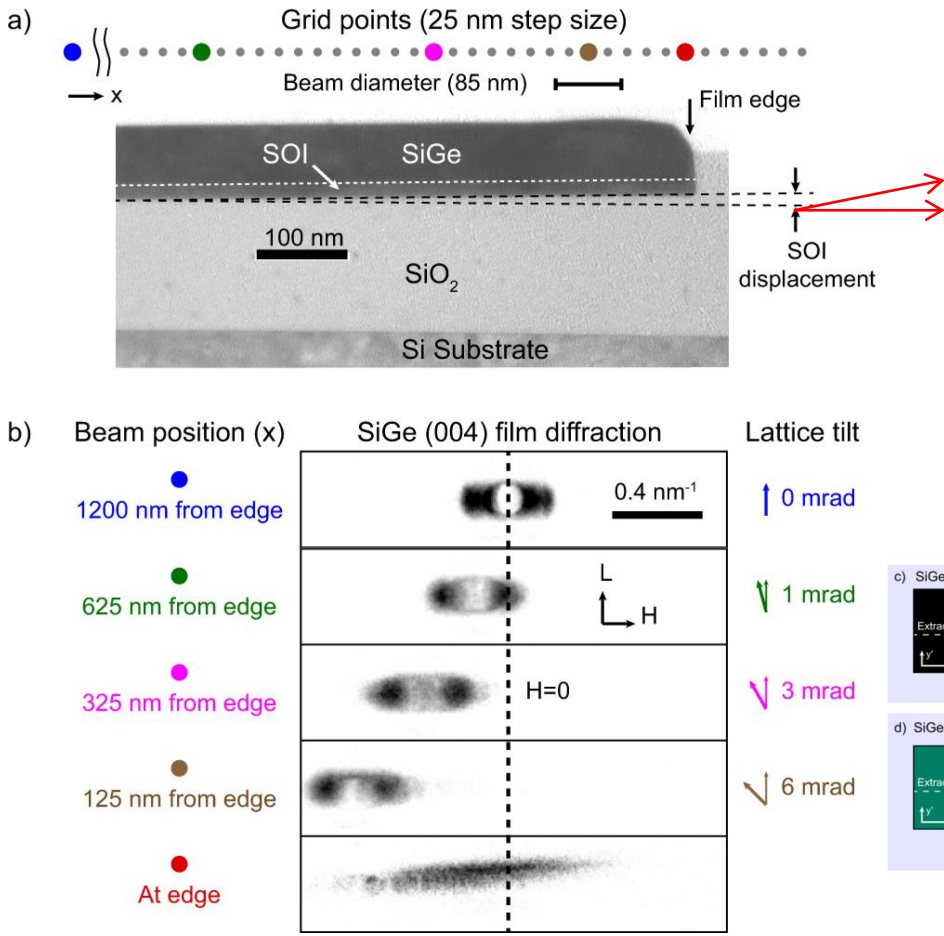


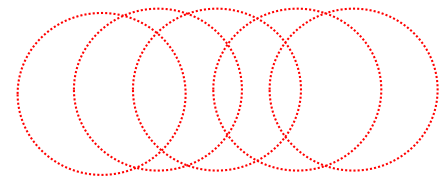
X-ray Bragg projection ptychography from thin film heterostructures



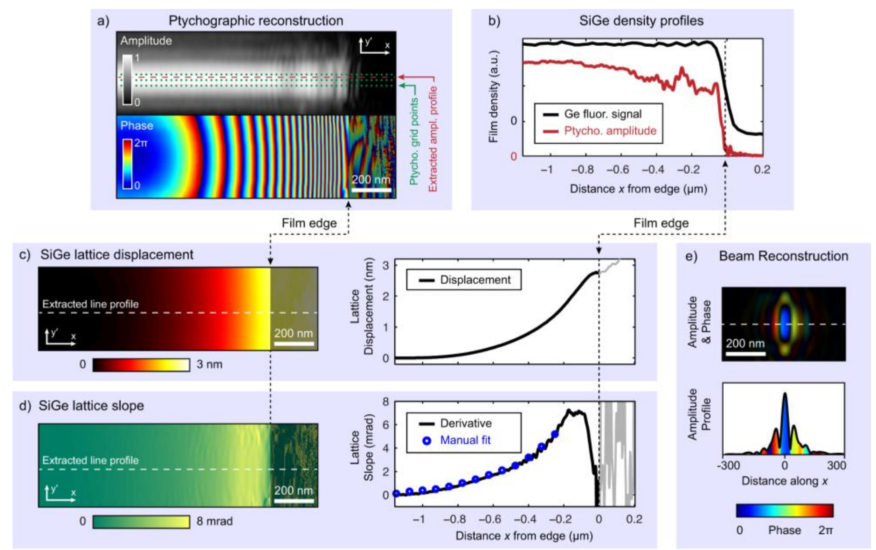


Focused beam Bragg diffraction near the device edge

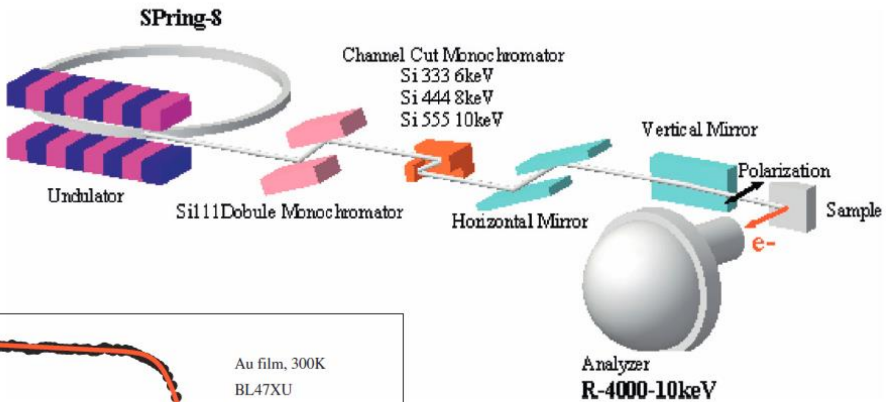




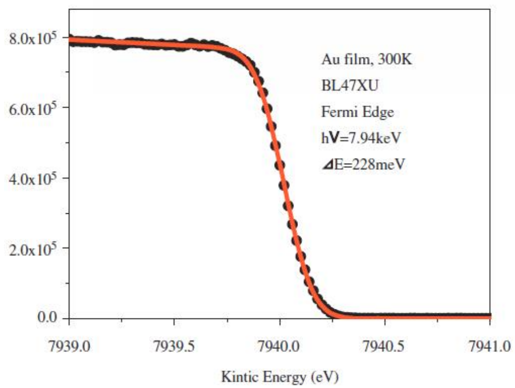
70% spatial overlap

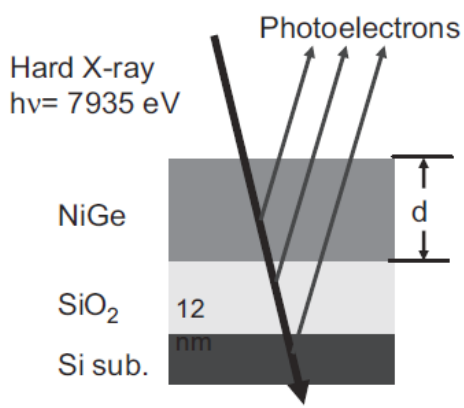


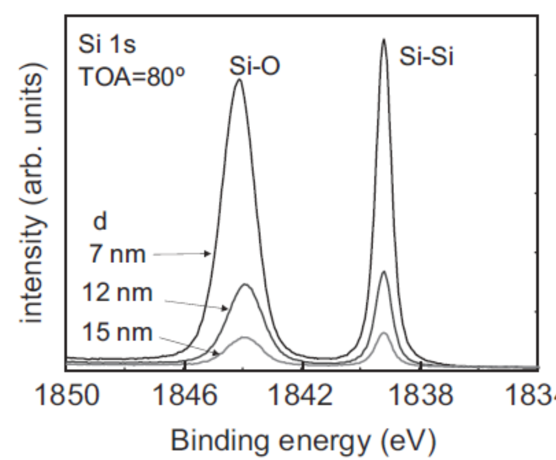
Upgrade: Hard X-ray photoelectron spectroscope(HXPS) at XNP



HXPS: Several keV to 15 keV to increase bulk sensitivity for bulk electronic structure and buried interface.







K. Kobayashi, *Nuclear Instruments and Methods in Physics Research* A 601 (2009) 32–47

Applications

Solid state physics

- Strongly correlated electron systems

YbAl3, YbInCu4, YbCu2Si2

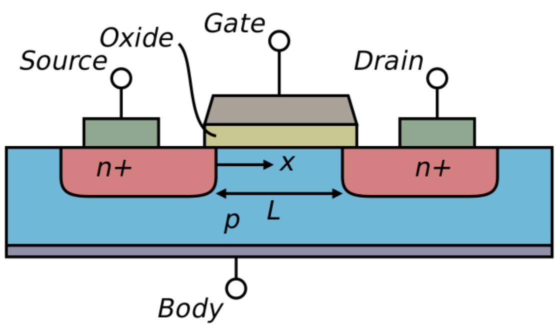
La1-xSrxMnO3 (LSMO)

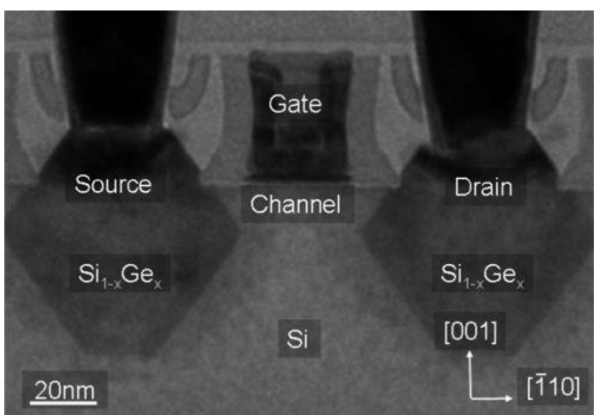
- Spintronics

LaVO3, LaAlO3, Fe3-xMxO4(M=Mn, Zn)

- Compound semiconductors

InGaZnO, GaCrN, InN, ZnMgO





M. Chu, *et al.*, Annu. *Rev. Mater. Res.* 39 (2009) 203-229

High-k gate stacks

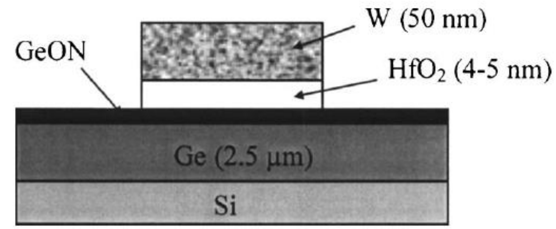


FIG. 1. Diagram of the W/HfO_2/GeON/Ge stack.