中国科学院上海高等研究院
SHANGHAI ADVANCED RESEARCH INSTITUTE CHINESE ACADEMY OF SCIENCES

SSRF 上海同步辐射光源
Shanghai Synchrotron Radiation facility

Synchrotron Radiation

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Shanghai Synchrotron Facility

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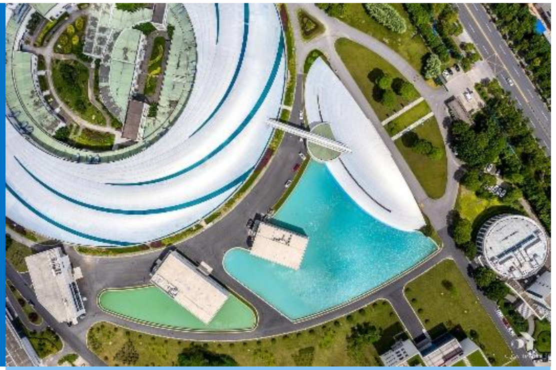
- What is synchrotron?
- X-ray and synchrotron radiation
- X-ray interaction with matter
- Synchrotron beamlines
- Shanghai Synchrotron Radiation Facility (SSRF)

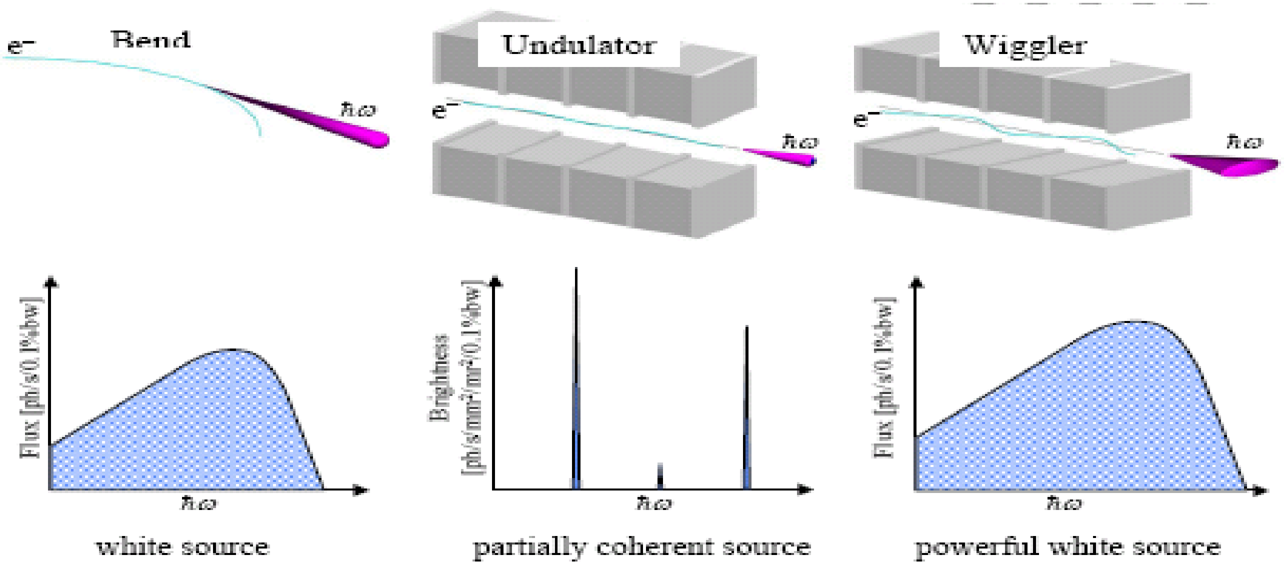
01

What is synchrotron?



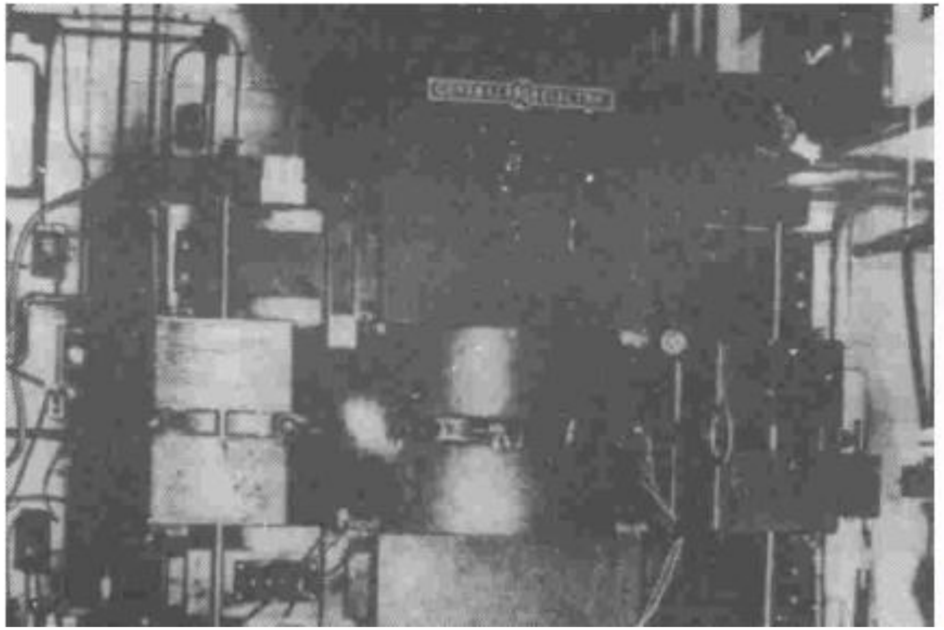
What is synchrotron?

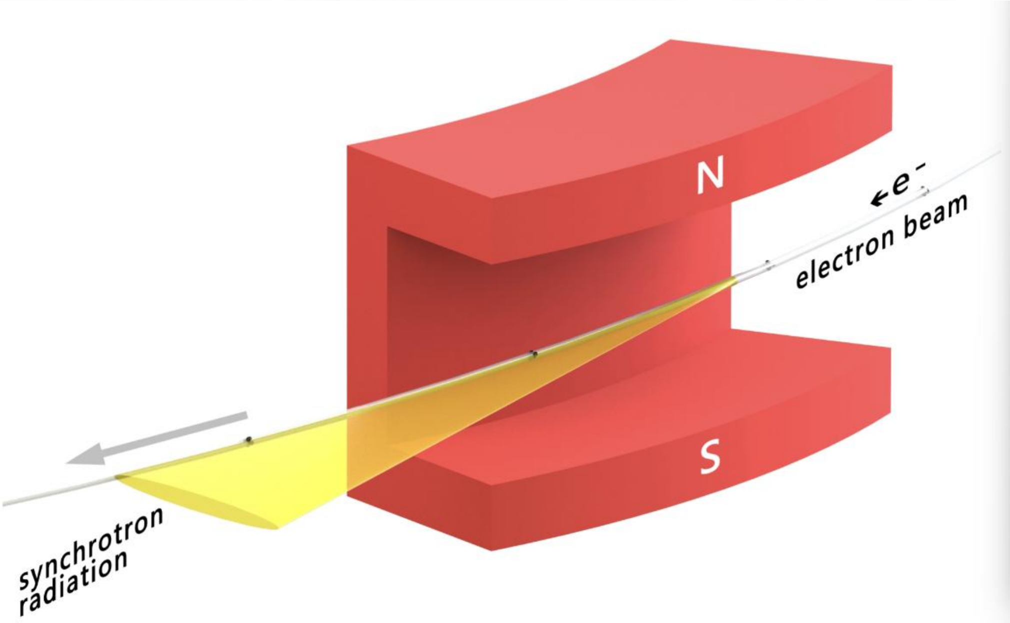
- Synchrotron radiation is the electromagnetic waves (light) radiated along the tangential direction when charged particles at a speed close to that of light change their direction of motion;
- Devices (radiation sources) used to change the direction of movement of charged particles can be bending magnets, undulator and wiggler.



History of synchrotron radiation

In April 1947, F.R. Elder team observed the electromagnetic radiation from electrons for the first time at the 70MeV electron synchrotron at General Electric Laboratories in the United States, hence the name synchrotron radiation.





1950s, after a series of explorations, people discovered that SR is a very excellent light source.

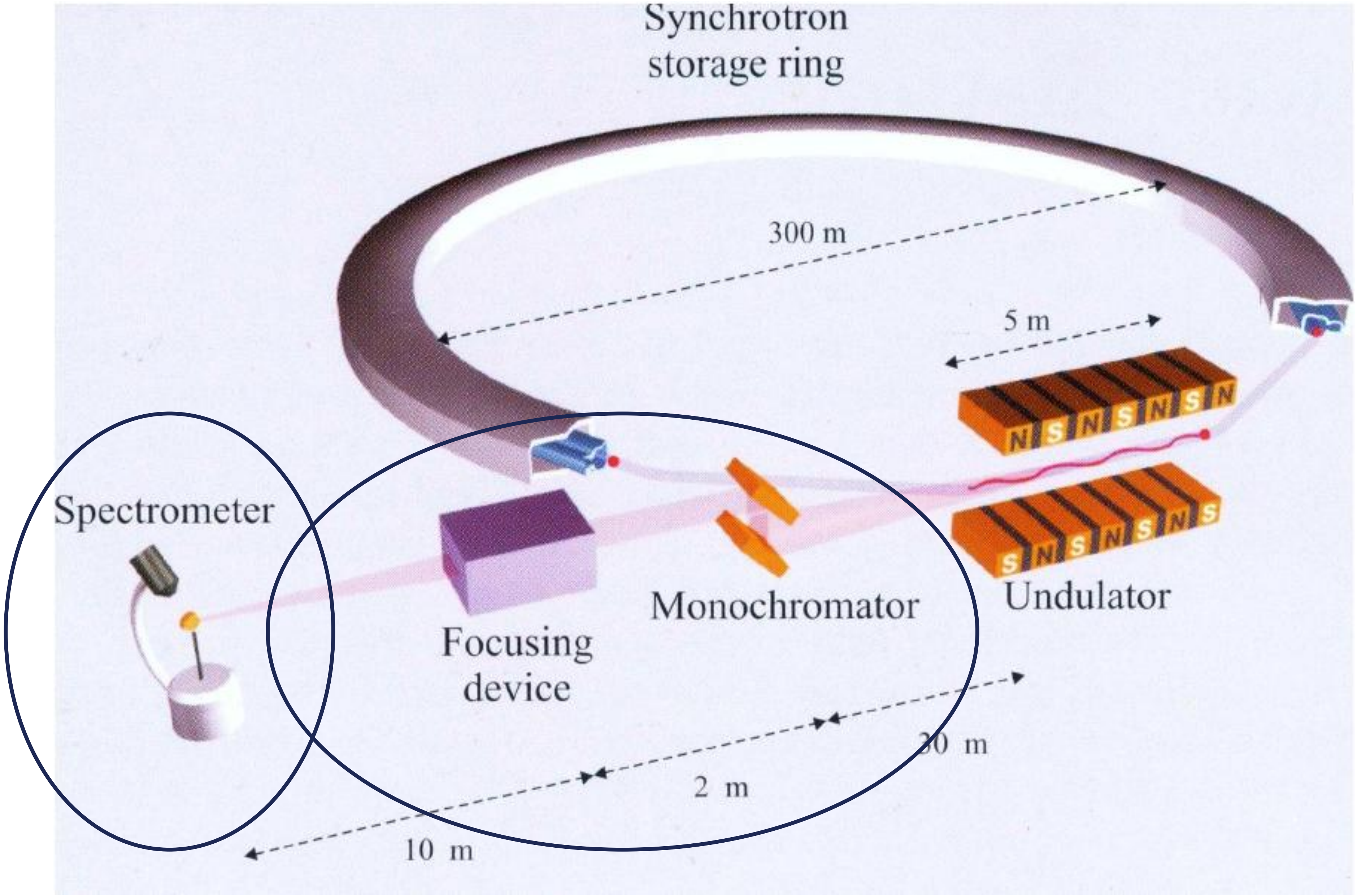
Early 1960s, the application of synchrotron radiation began.

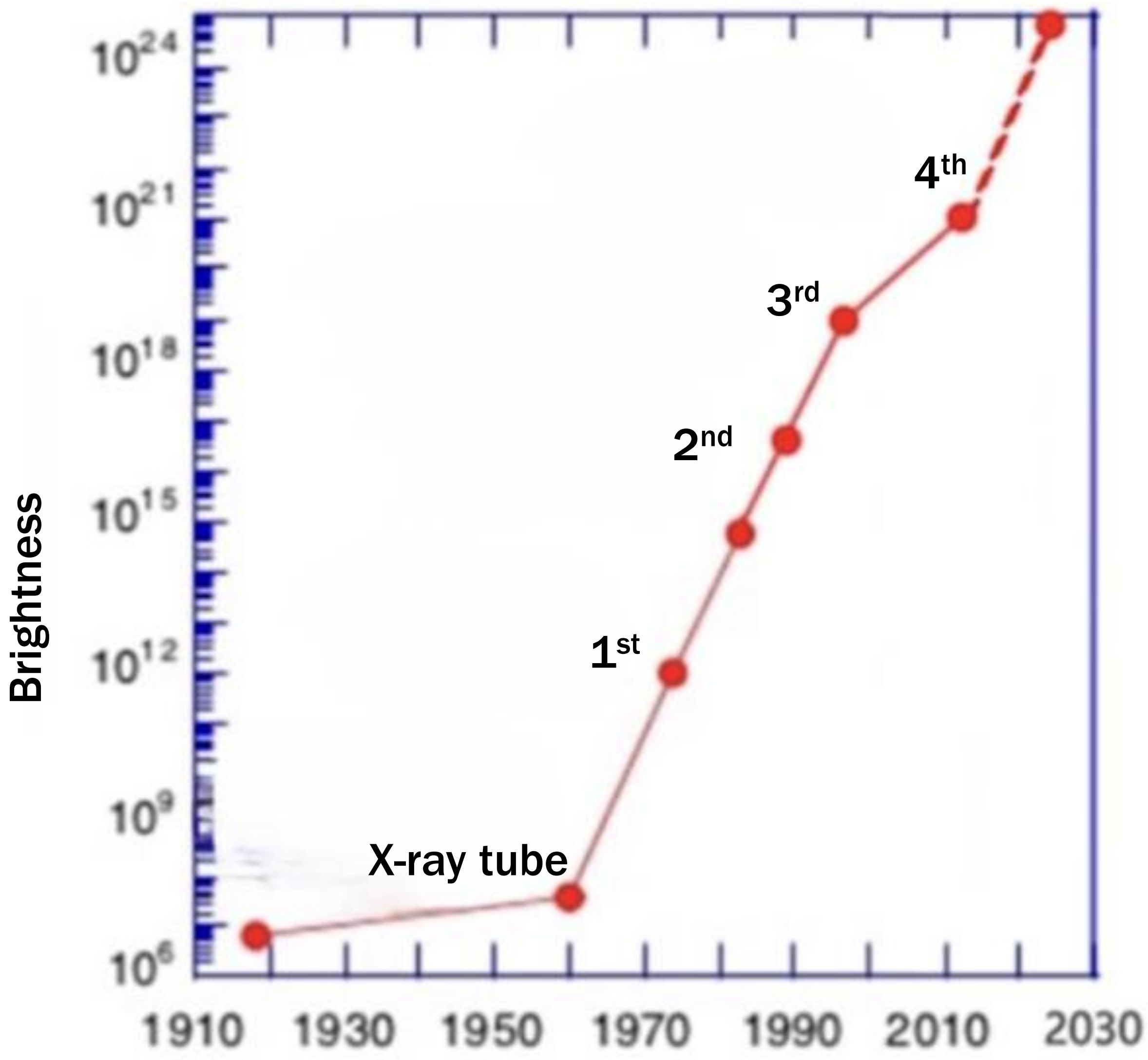
1965, first storage ring built in Frascati.

1970s ,the modern stage of synchrotron radiation application began.

The major parts

- Storage ring with radiation sources
- Beamline
- End station





第四代：北京先进光源 2025

High Energy Photon Source, HEPS
Hefei Advanced Light Facility, HALF

第三代：上海光源 2009

Shanghai Synchrotron Radiation Facility, SSRF

第二代：合肥同步辐射光源 1991

National Synchrotron Radiation Laboratory, NSRL

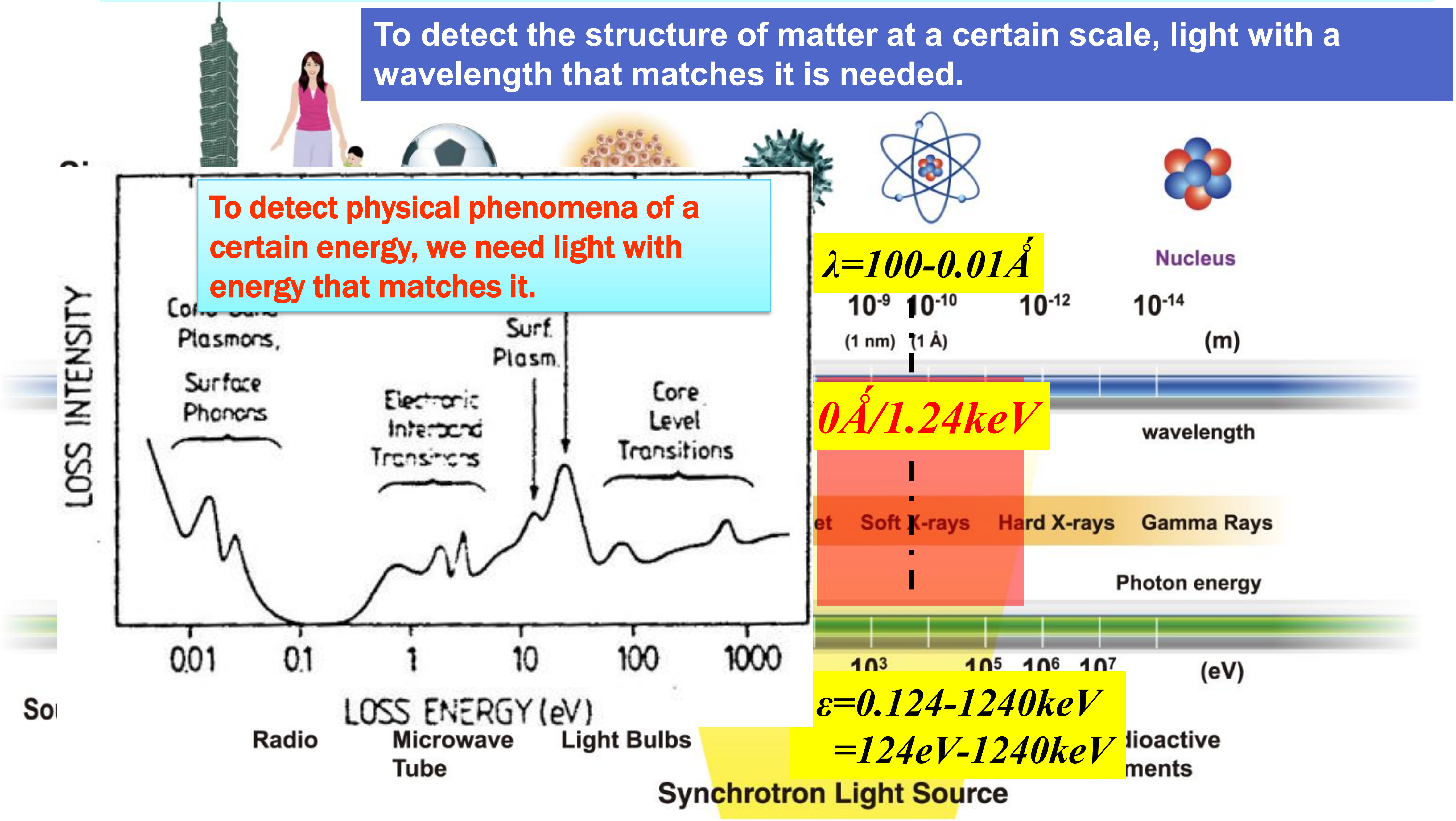
第一代：北京同步辐射装置 1990

Beijing Synchrotron Radiation Facility, BSRF

The spectrum of synchrotron radiation covers a wide range from infrared to hard X-rays

To detect the structure of matter at a certain scale, light with a wavelength that matches it is needed.

To detect physical phenomena of a certain energy, we need light with energy that matches it.



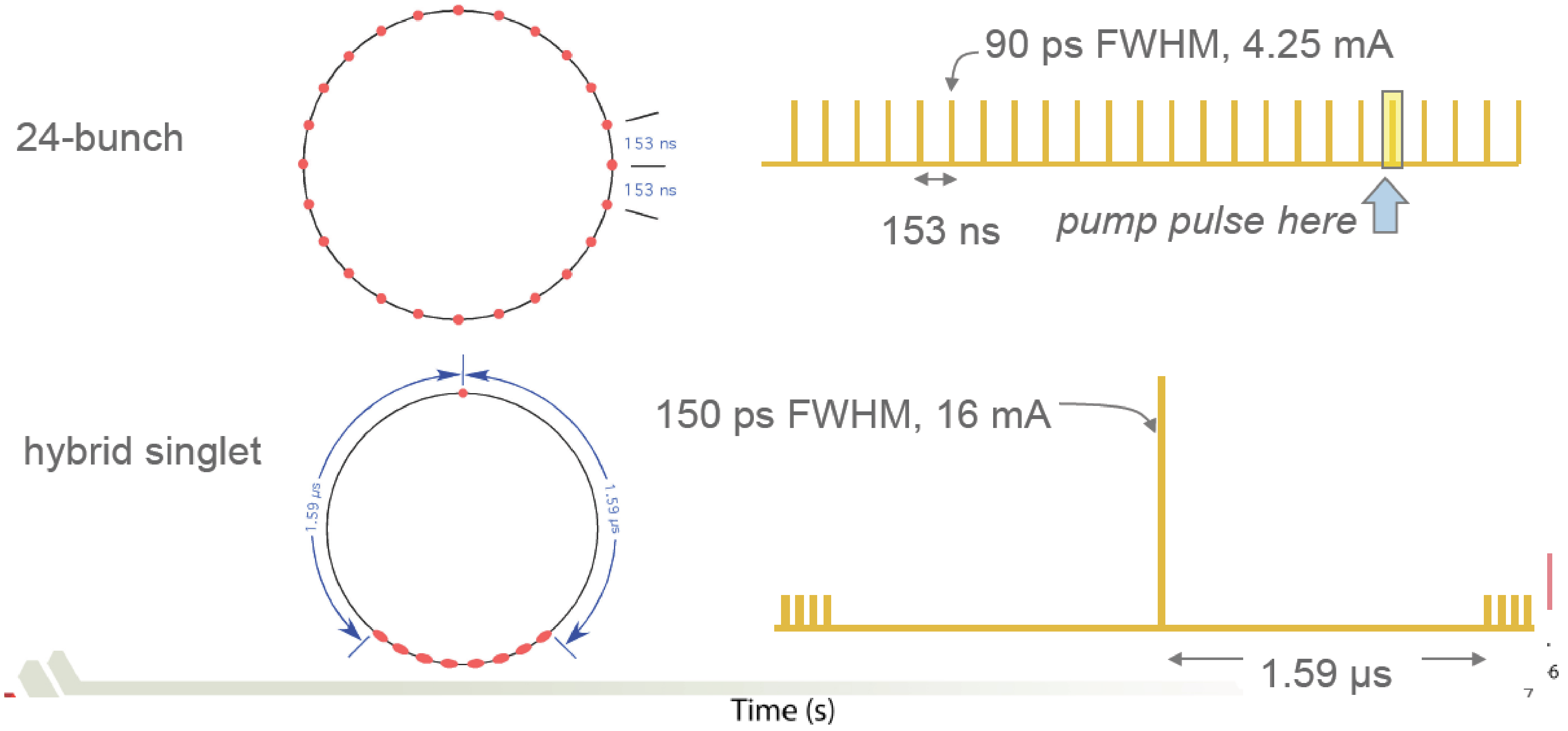
λ=100-0.01Å

0Å/1.24keV

ε=0.124-1240keV =124eV-1240keV

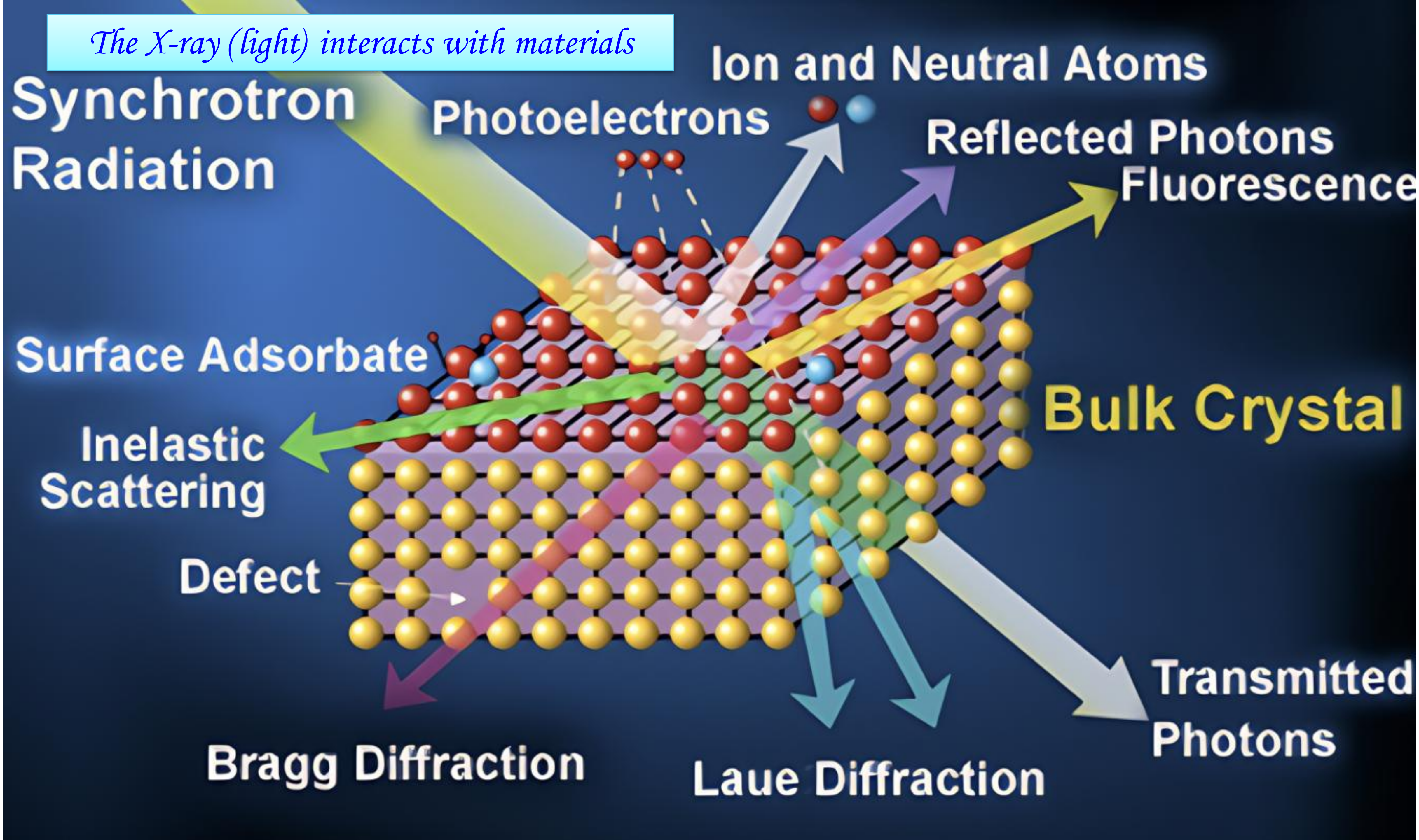
Time structure of synchrotron radiation

To detect physical processes on a certain time scale, we need light with a temporal structure that matches it.

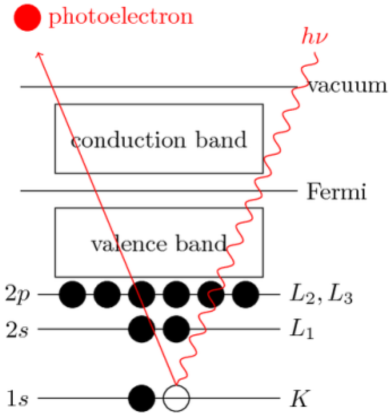


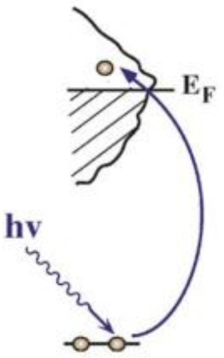
FEL or slice technology can achieve fs resolution

The X-ray (light) interacts with materials

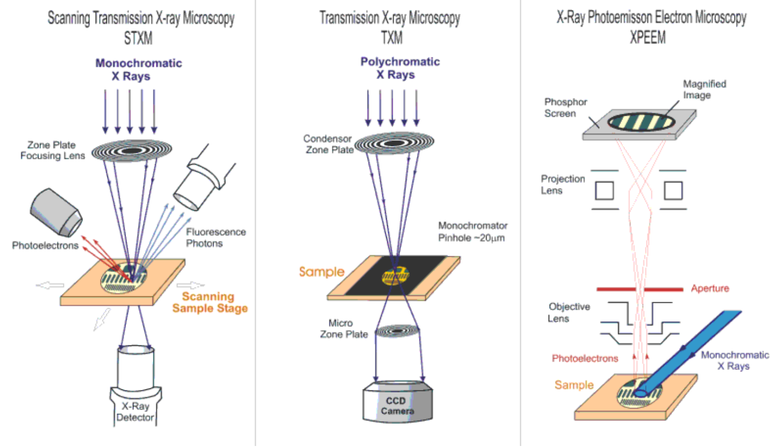


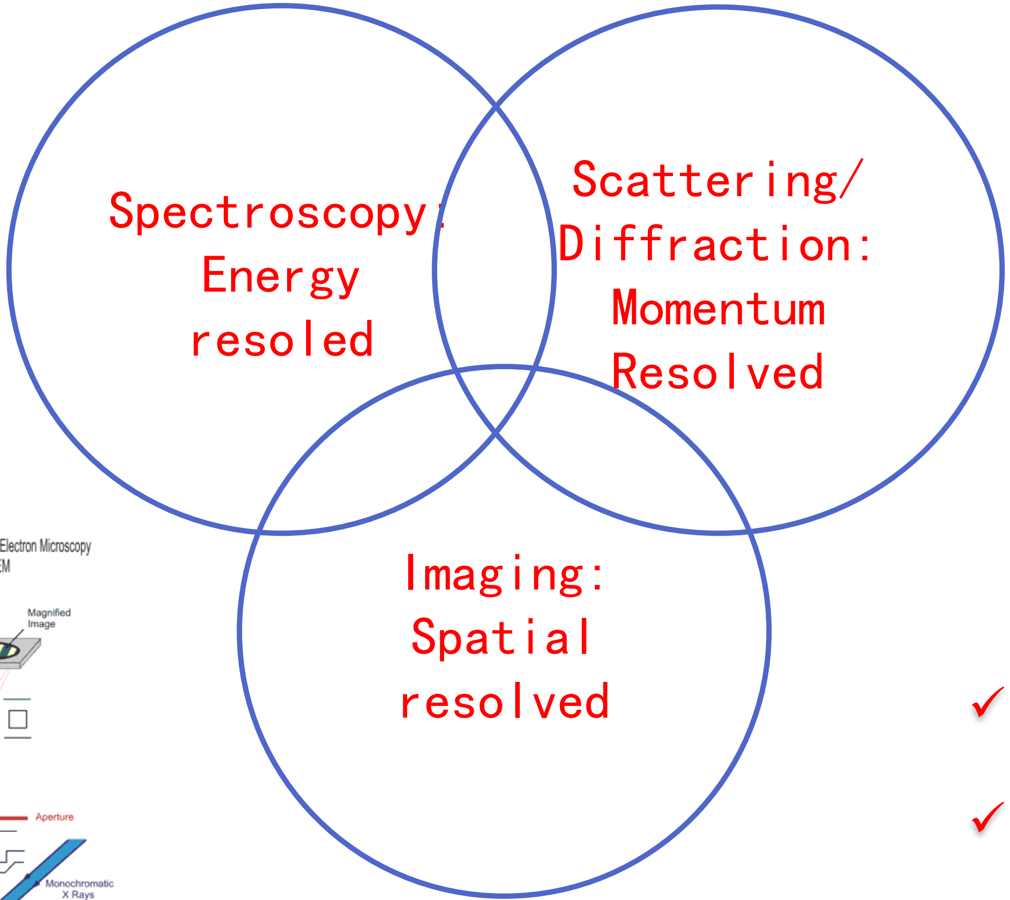
Classification of synchrotron-based characterization techniques

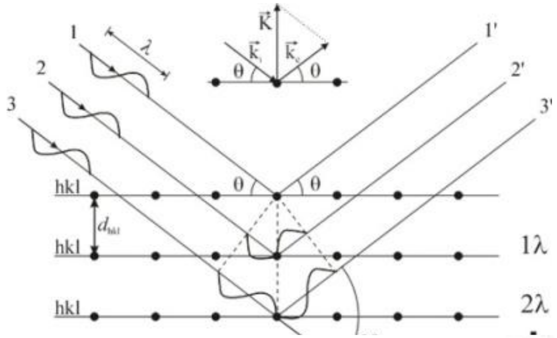


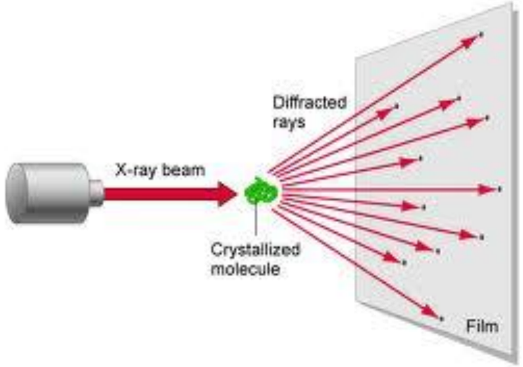


Excitation
X-ray Absorption Spectroscopy (XAS)









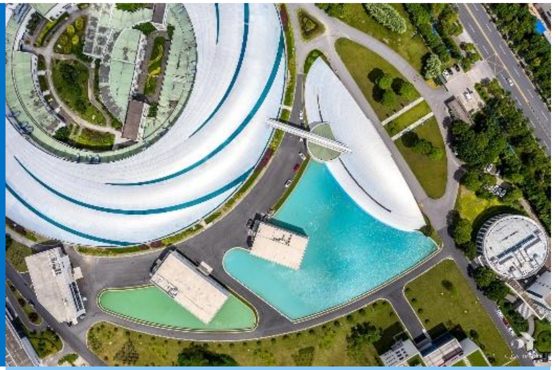
- ✓ Various techniques can be integrated
- ✓ Suitable for in-situ, dynamic, operando study
- ✓ High throughput

World wide Synchrotron Facilities

	Faciality	Electro Energy (GeV)
S	ASTRID 2	0.54
	SOLARIS	1.5
	MAX-IV	1.5
	NSRL	0.8
	BESSY-II	1.7
	ALS	1.9
	ELETTRA	2/2.4
T	SSRF	3.5
	TPS	3
	PLS-II	3
	SLS	2.4
	SOLEIL	2.75
	CLS	2.9
	ALBA	3
	DIAMOND	3
	MAX-IV	3
	NSLS-II	3
	AS	3
H	ESRF	6
	PETRA-III	6
	APS	7
	SPring-8	8

02

X-ray and synchrotron radiation

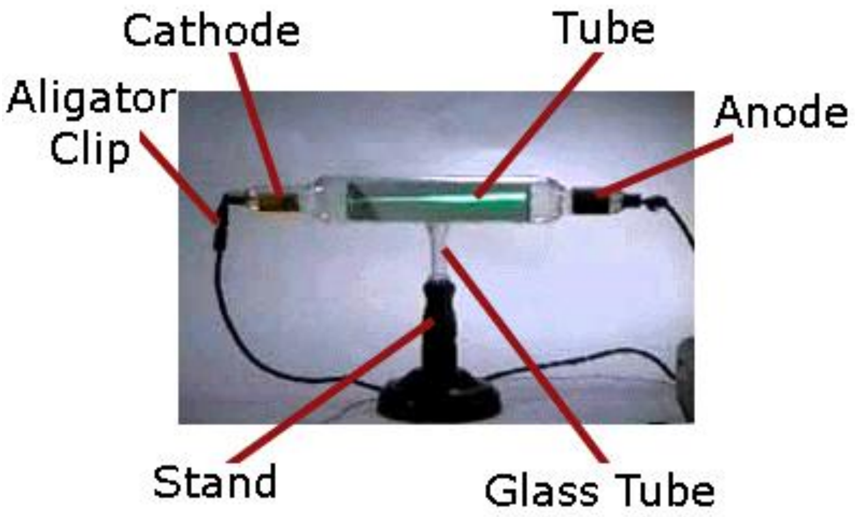


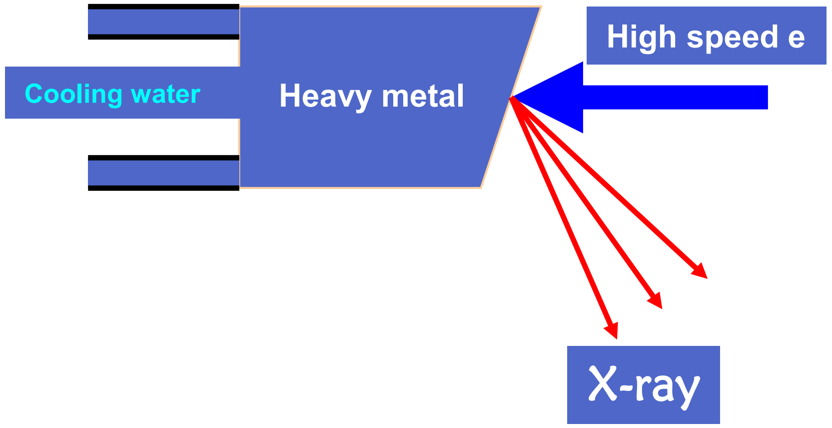
The discovery of X-ray

At the end of 1895, German scientist Wilhelm Conrad Röntgen discovered a mysterious radiation- X-ray - while studying cathode ray tubes.

- cathode ray 1858
- Electron 1897
- X-ray 1895
- Radioactivity (α、β、γ) 1896

Electromagnetic technology: high voltage electricity
Vacuum technology: obtaining vacuum





What is X-ray: its nature

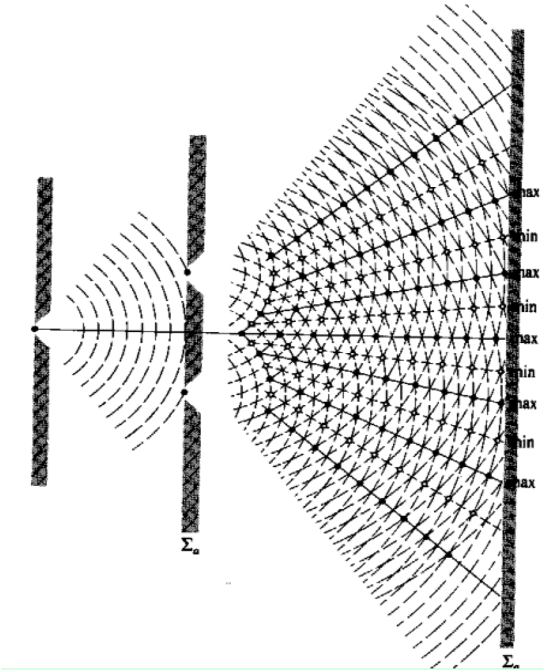
- ✓ Wave：

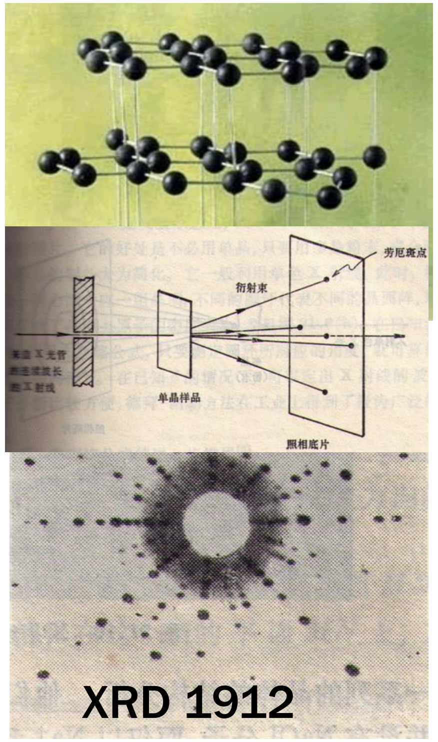
transverse wave not Longitudinal wave： double scattering experiment

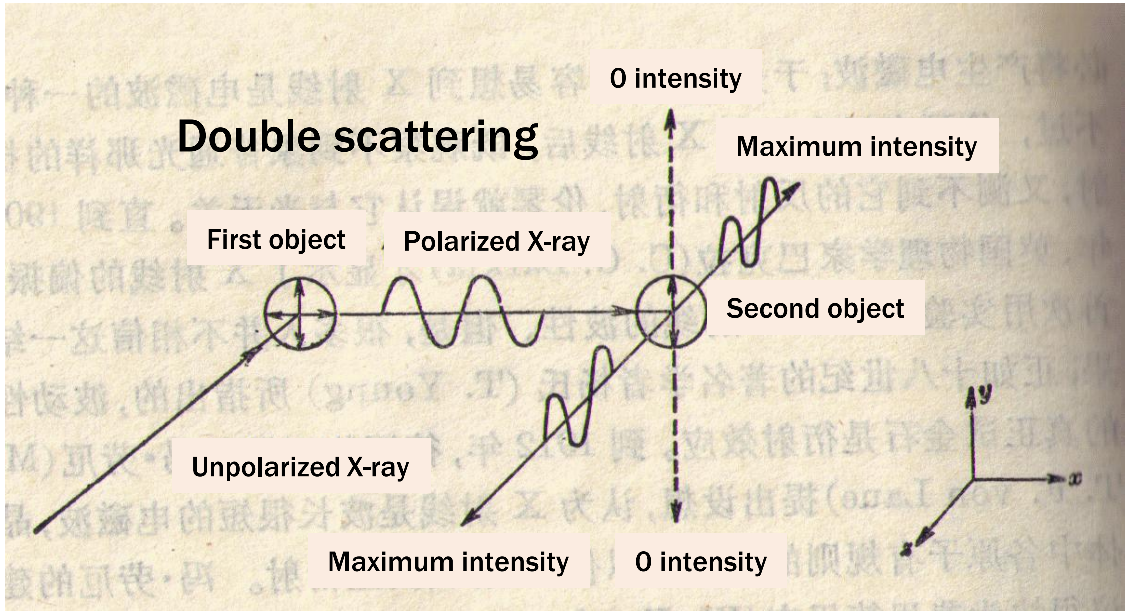
- ✓ particle：

Photoelectric effect: energy quantization

Compton scattering: energy and momentum quantization



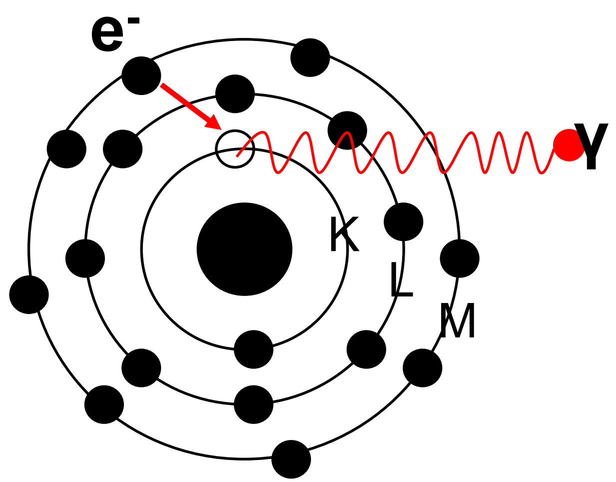


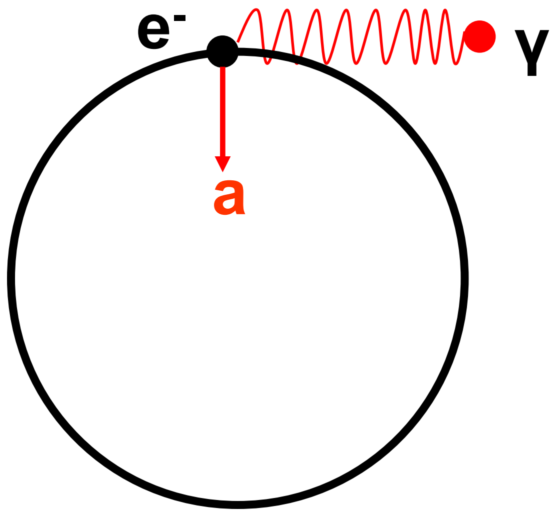


Generation of X-ray

- The electrons in the inner shell of an atom are excited to form holes, and the electrons at the higher energy level jump to the energy level with holes, emitting high energy photons (X-ray)；

- Radiation produced by accelerated charged particles (electrons).

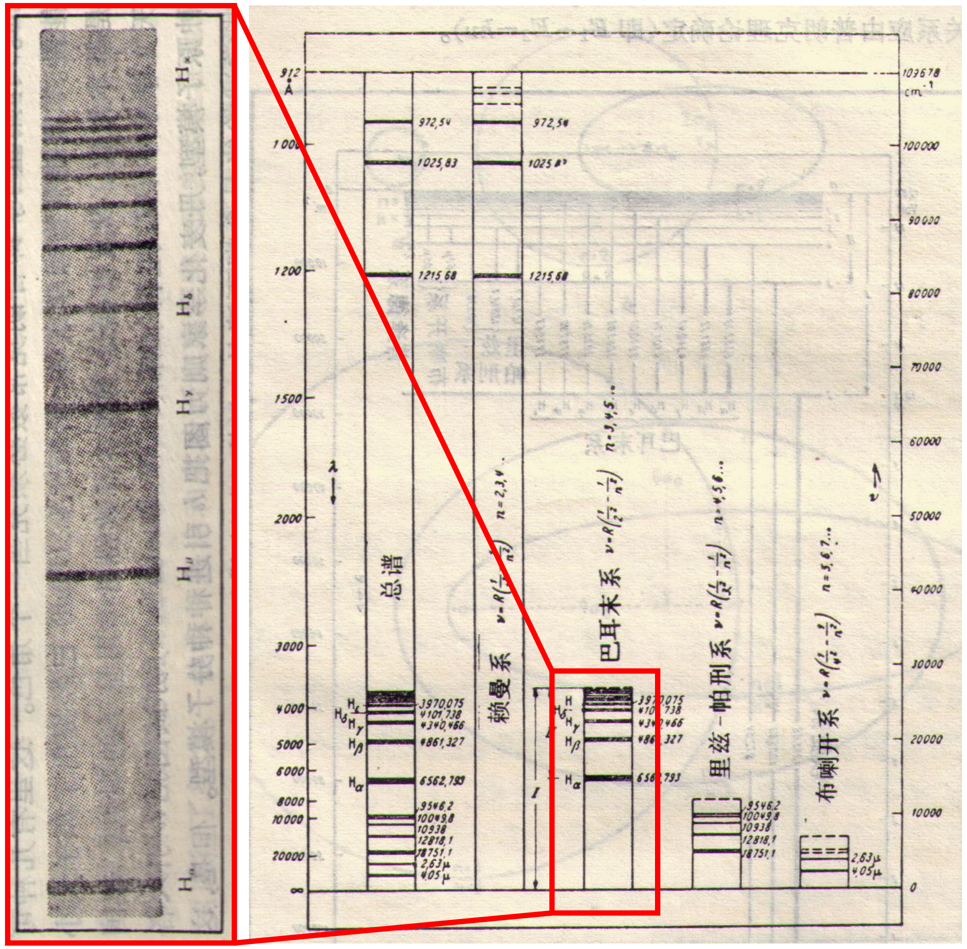




Atomic inner shell electron transition

Atomic photoemission

atomic spectrum



Hydrogen atomic spectrum

Balmer's Law：

$$\nu = \frac{1}{\lambda} = \frac{4}{B}\left(\frac{1}{2^2} - \frac{1}{n^2}\right)$$

n=3,4,5...
Balmer series

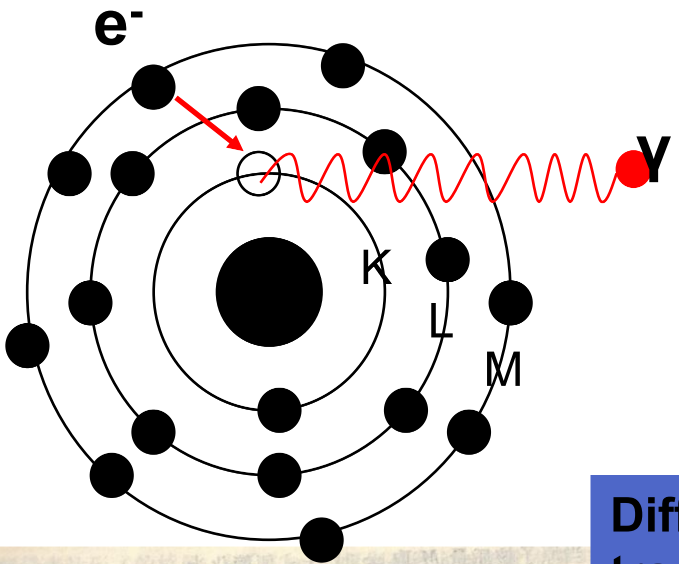
Rydberg equation：

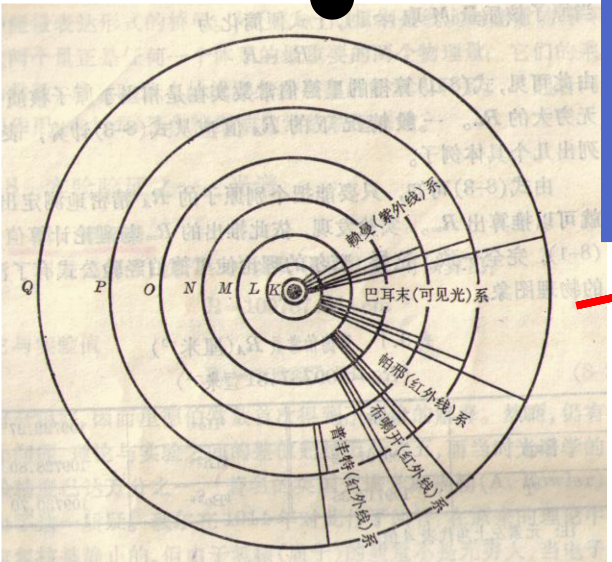
$$\nu = \frac{1}{\lambda} = R_H\left(\frac{1}{n_1^2} - \frac{1}{n_2^2}\right)$$

n_1=1,2,3…Lyman, Balmer, Paschen

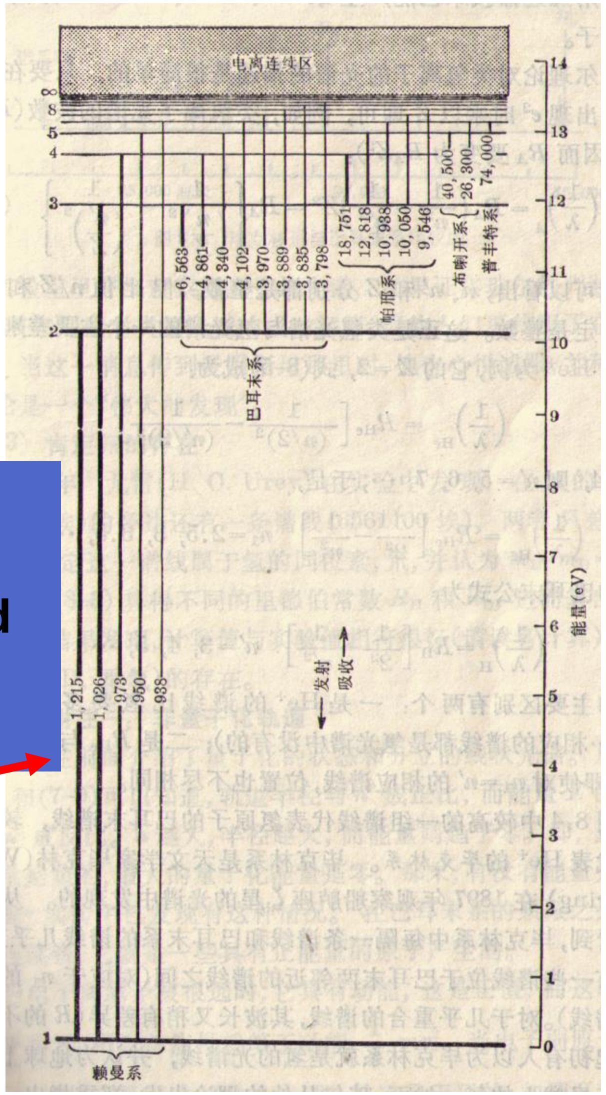
n_2=n_1+1,n_1+2,...

Electron transitions within an atom





Different transitions correspond to different *series*

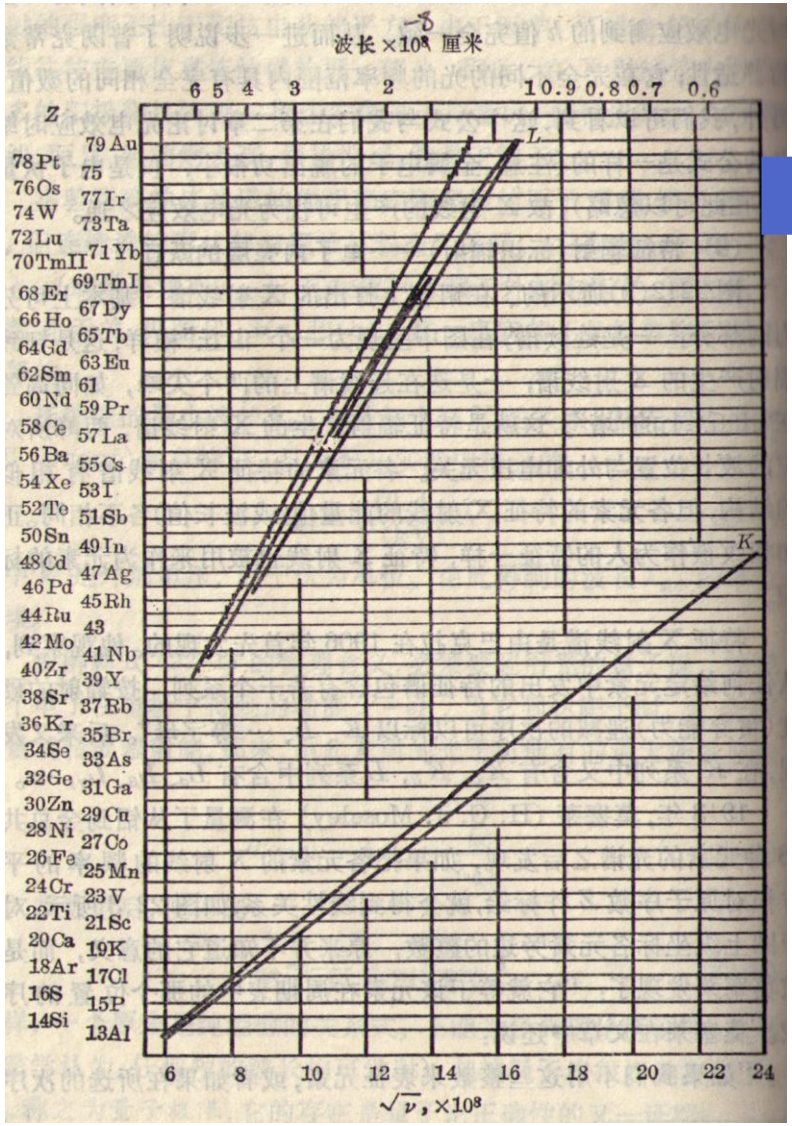


Electron transitions to the inner shells of an atom

Table 1-1. Electron binding energies, in electron volts, for the elements in their natural forms.

Element	K 1s	L_1 2s	L_2 $2p_{1/2}$	L_3 $2p_{3/2}$	M_1 3s	M_2 $3p_{1/2}$	M_3 $3p_{3/2}$	M_4 $3d_{3/2}$	M_5 $3d_{5/2}$	N_1 4s	N_2 $4p_{1/2}$	N_3 $4p_{3/2}$
1 H	13.6											
2 He	24.6*											
3 Li	54.7*											
4 Be	111.5*											
5 B	188*											
6 C	284.2*											
7 N	409.9*	37.3*										
8 O	543.1*	41.6*										
9 F	696.7*											
10 Ne	870.2*	48.5*	21.7*	21.6*								
11 Na	1070.8†	63.5†	30.65	30.81								
12 Mg	1303.0†	88.7	49.78	49.50								
13 Al	1559.6	117.8	72.95	72.55								
14 Si	1839	149.7*b	99.82	99.42								
15 P	2145.5	189*	136*	135*								
16 S	2472	230.9	163.6*	162.5*								
17 Cl	2822.4	270*	202*	200*								
18 Ar	3205.9*	326.3*	250.6†	248.4*	29.3*	15.9*	15.7*					
19 K	3608.4*	378.6*	297.3*	294.6*	34.8*	18.3*	18.3*					
20 Ca	4038.5*	438.4†	349.7†	346.2†	44.3 †	25.4†	25.4†					
21 Sc	4492	498.0*	403.6*	398.7*	51.1*	28.3*	28.3*					
22 Ti	4966	560.9†	460.2†	453.8†	58.7†	32.6†	32.6†					
23 V	5465	626.7†	519.8†	512.1†	66.3†	37.2†	37.2†					
24 Cr	5989	696.0†	583.8†	574.1†	74.1†	42.2†	42.2†					
25 Mn	6539	769.1†	649.9†	638.7†	82.3†	47.2†	47.2†					
26 Fe	7112	844.6†	719.9†	706.8†	91.3†	52.7†	52.7†					
27 Co	7709	925.1†	793.2†	778.1†	101.0†	58.9†	59.9†					
28 Ni	8333	1008.6†	870.0†	852.7†	110.8†	68.0†	66.2†					
29 Cu	8979	1096.7†	952.3†	932.7	122.5†	77.3†	75.1†					
30 Zn	9659	1196.2*	1044.9*	1021.8*	139.8*	91.4*	88.6*	10.2*	10.1*			
31 Ga	10367	1299.0*b	1143.2†	1116.4†	159.5†	103.5†	100.0†	18.7†	18.7†			
32 Ge	11103	1414.6*b	1248.1*b	1217.0*b	180.1*	124.9*	120.8*	29.8	29.2			
33 As	11867	1527.0*b	1359.1*b	1323.6*b	204.7*	146.2*	141.2*	41.7*	41.7*			
34 Se	12658	1652.0*b	1474.3*b	1433.9*b	229.6*	166.5*	160.7*	55.5*	54.6*			
35 Br	13474	1782*	1596*	1550*	257*	189*	182*	70*	69*			
36 Kr	14326	1921	1730.9*	1678.4*	292.8*	222.2*	214.4	95.0*	93.8*	27.5*	14.1*	14.1*
37 Rb	15200	2065	1864	1804	326.7*	248.7*	239.1*	113.0*	112*	30.5*	16.3*	15.3 *
38 Sr	16105	2216	2007	1940	358.7†	280.3†	270.0†	136.0†	134.2†	38.9†	21.3	20.1†
39 Y	17038	2373	2156	2080	392.0*b	310.6*	298.8*	157.7†	155.8†	43.8*	24.4*	23.1*
40 Zr	17998	2532	2307	2223	430.3†	343.5†	329.8†	181.1†	178.8†	50.6†	28.5†	27.1†
41 Nb	18986	2698	2465	2371	466.6†	376.1†	360.6†	205.0†	202.3†	56.4†	32.6†	30.8†
42 Mo	20000	2866	2625	2520	506.3†	411.6†	394.0†	231.1†	227.9†	63.2†	37.6†	35.5†
43 Tc	21044	3043	2793	2677	544*	447.6	417.7	257.6	253.9*	69.5*	42.3*	39.9*
44 Ru	22117	3224	2967	2838	586.1*	483.5†	461.4†	284.2†	280.0†	75.0†	46.3†	43.2†
45 Rh	23220	3412	3146	3004	628.1†	521.3†	496.5†	311.9†	307.2†	81.4*b	50.5†	47.3†
46 Pd	24350	3604	3330	3173	671.6†	559.9†	532.3†	340.5†	335.2†	87.1*b	55.7†a	50.9†
47 Ag	25514	3806	3524	3351	719.0†	603.8†	573.0†	374.0†	368.3	97.0†	63.7†	58.3†

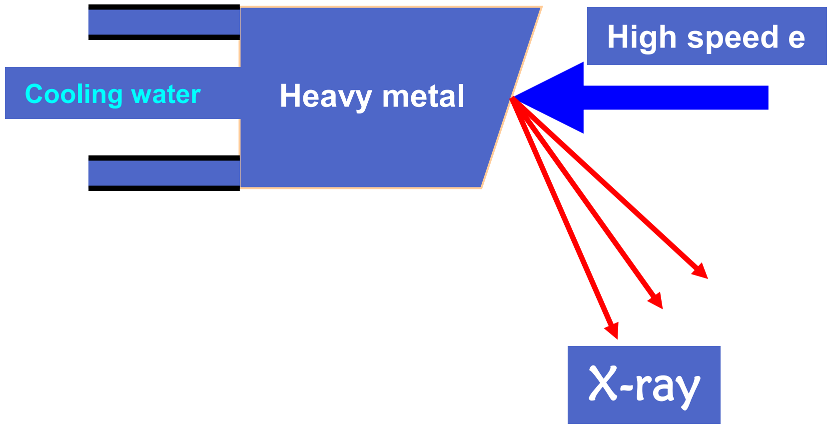
X-rays: High-energy photons released when electrons in atoms transition to holes in their inner shells.



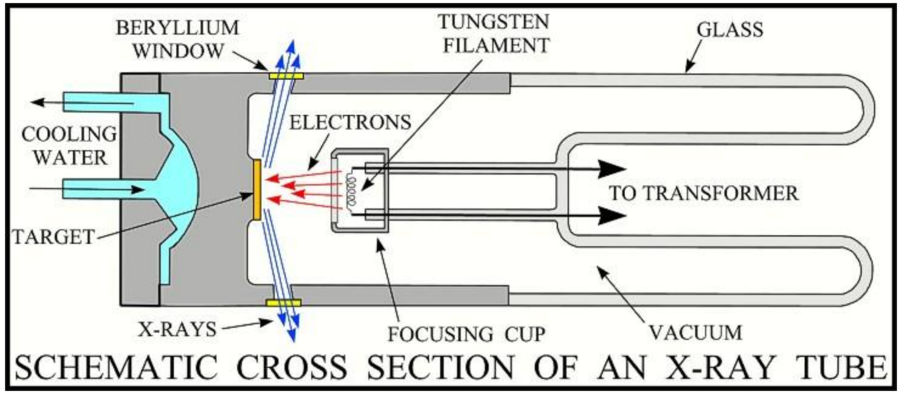
Moseley's law

$\sqrt{\nu} = a(Z - b)$, where 'ν' is the frequency of the emitted X-ray, 'Z' is the atomic number, 'a' is a constant, and 'b' is a screening constant

X-ray tube



Cooling water
Heavy metal
High speed e
X-ray



BERYLLIUM WINDOW
TUNGSTEN FILAMENT
GLASS
COOLING WATER
ELECTRONS
TO TRANSFORMER
TARGET
X-RAYS
FOCUSING CUP
VACUUM
SCHEMATIC CROSS SECTION OF AN X-RAY TUBE

X-ray characteristics generated by X-ray tubes: continuous spectrum

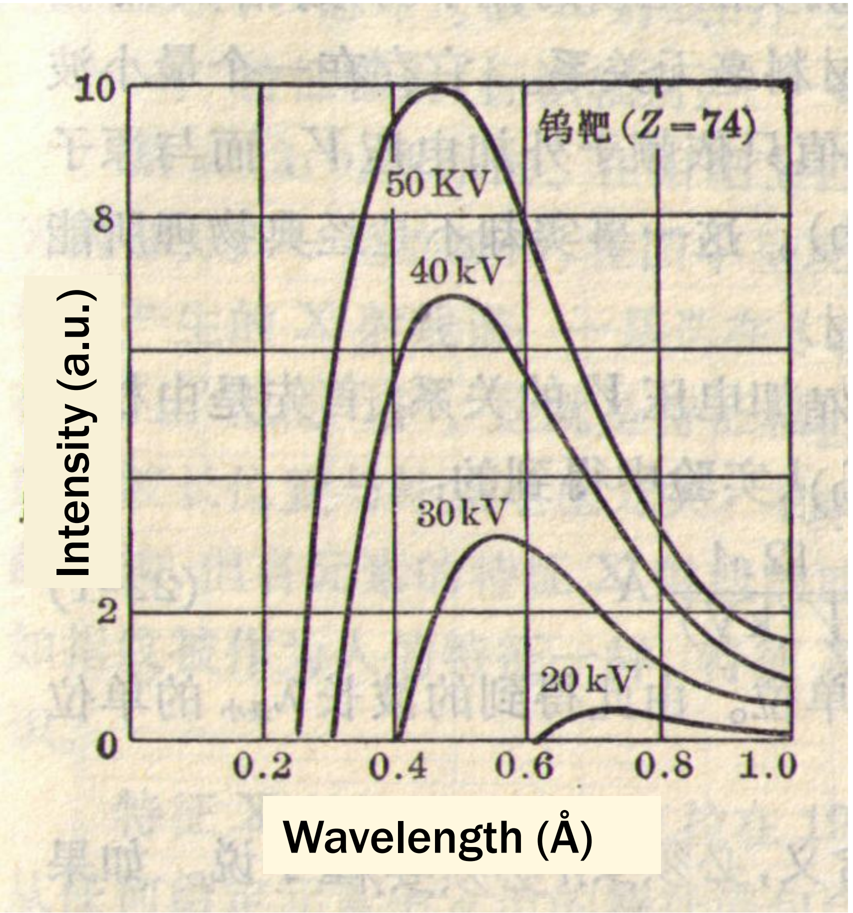
In bremsstrahlung, the energy of the X-ray photon is equal to the energy lost by the electron：

$$T = eV = h\nu_{\max} = \frac{hc}{\lambda_{\min}}$$

Due to the different collision parameters, the energy loss by electrons in different collision processes is different, which is statistically continuous, so the photon energy spectrum of bremsstrahlung is also continuous.

The maximum energy of the photon (shortest wavelength) corresponds to the maximum energy of the electron:

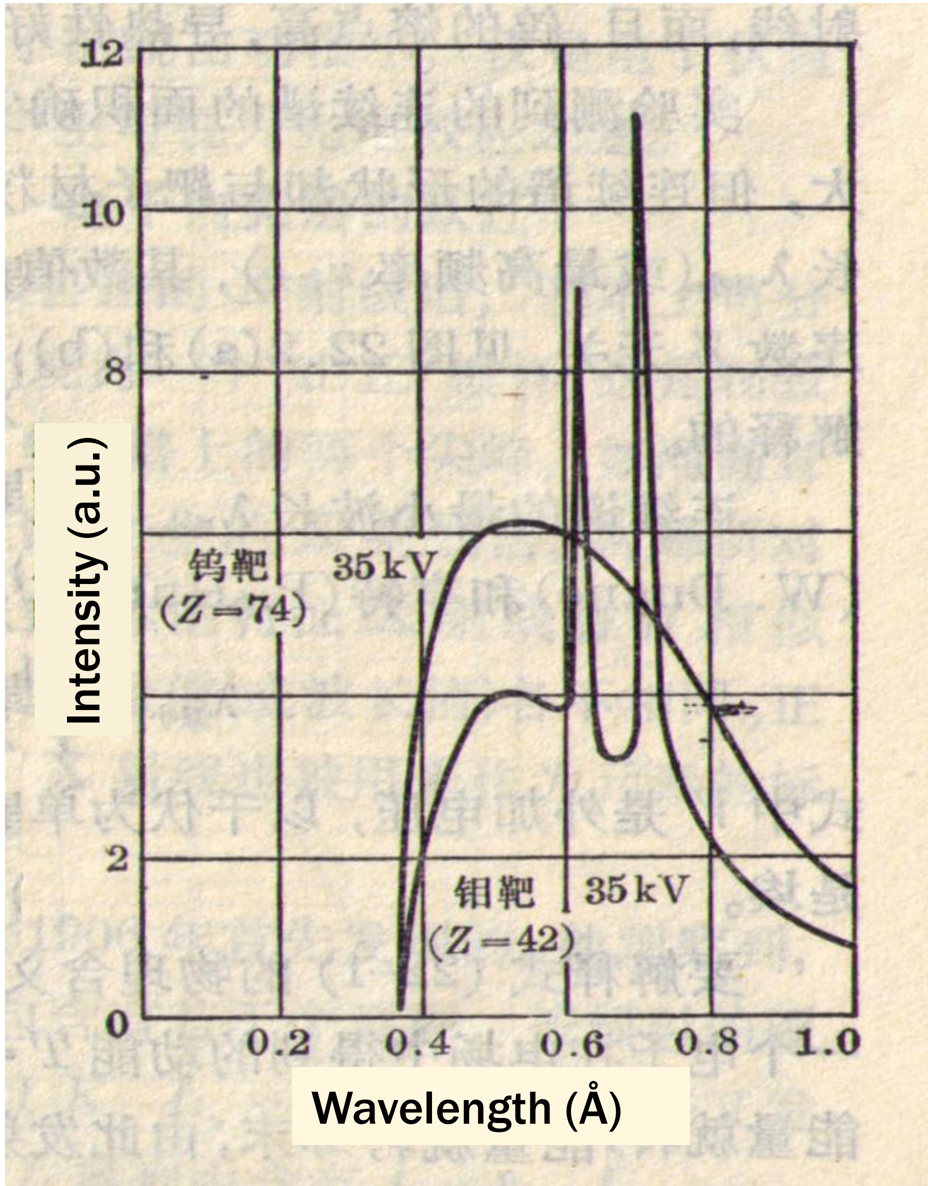
$$\lambda_{\min} = \frac{hc}{eV} = \frac{12.4}{V(kV)} \mathring{A}$$



Wavelength with maximum intensity：

$$\lambda_m \approx \frac{3}{2}\lambda_{\min}$$

X-ray characteristics produced by X-ray tubes - discrete spectra



Moseley's Law

$\nu \propto Z^2$

$\nu_{K_\alpha} = 0.248 \times 10^{16}(Z - b)^2$ $b \approx 1$

1）For X-ray tubes with the same high voltage and different target anodes, the short wavelength limit is the same；

2）The X-ray intensity produced by high-Z target anodes is higher than that produced by low-Z target anodes；

3）For the same X-ray tube, as the voltage increases, discrete spectra appear on the continuous spectrum.

X-ray fluorescence spectroscopy: The atomic number Z can be obtained from X-rays, which pioneered the X-ray analysis method.

X-ray notation

X-ray and spectroscopic notation in *j–j* coupling

Quantum numbers					
n	*l*	*j*	X-ray suffix	X-ray level	Spectroscopic level
1	0	$\frac{1}{2}$	1	K	$1s_{1/2}$
2	0	$\frac{1}{2}$	1	L_1	$2s_{1/2}$
2	1	$\frac{1}{2}$	2	L_2	$2p_{1/2}$
2	1	$\frac{3}{2}$	3	L_3	$2p_{3/2}$
3	0	$\frac{1}{2}$	1	M_1	$3s_{1/2}$
3	1	$\frac{1}{2}$	2	M_2	$3p_{1/2}$
3	1	$\frac{3}{2}$	3	M_3	$3p_{3/2}$
3	2	$\frac{3}{2}$	4	M_4	$3d_{3/2}$
3	2	$\frac{5}{2}$	5	M_5	$3d_{5/2}$
	etc.		etc.	etc.	etc.

X-ray elemental spectrum

2p3/2 → 1s and 2p1/2 → 1s

Kα1,2 (inseparable)

hν	(eV)	FWHM (eV)
Mg	1253.6	0.7
Al	1486.6	0.85

Ionized Mg or Al produces Kα3,4

Higher photon energy thanKα1,2

~9-10 eV

3p → 1s

Kβ

X-ray lines

Line	Energy, eV	Width, eV
Y *Mζ*	132.3	0.47
Zr *Mζ*	151.4	0.77
Nb *Mζ*	171.4	1.21
Mo *Mζ*	192.3	1.53
Ti *Lα*	395.3	3.0
Cr *Lα*	572.8	3.0
Ni *Lα*	851.5	2.5
Cu *Lα*	929.7	3.8
Mg *Kα*	1253.6	0.7
Al *Kα*	1486.6	0.85
Si *Kα*	1739.5	1.0
Y *Lα*	1922.6	1.5
Zr *Lα*	2042.4	1.7
Ti *Kα*	4510.0	2.0
Cr *Kα*	5417.0	2.1
Cu *Kα*	8048.0	2.6

X-ray characteristic spectral lines of different elements

Radiation produced by accelerated electrons

Radiation produced by accelerated electrons

I. The electric field of a moving charge

$$E(r_p,t)=\frac{-e}{4\pi\varepsilon_0}\left[\frac{(n-\beta)(1-\beta^2)}{r^2(1-n\cdot\beta)^3}+\frac{n\times(n-\beta)\times\dot{\beta}}{cr(1-n\cdot\beta)^3}\right]$$

electrostatic field

radiation field

II. Energy flux density of the radiation field

$$S(r_p,t)=\frac{1}{\mu_0 c}\left(\frac{e}{4\pi\varepsilon_0}\right)^2\frac{n}{c^2r^2}\frac{\left\{n\times\left[(n-\beta)\times\dot{\beta}\right]\right\}^2}{(1-n\cdot\beta)^6}$$

β = v/c

III. Radiated power distribution

$$\frac{dP}{d\Omega}=\frac{d^2W}{dtd\Omega}=r^2S(r_p,t)\cdot n$$

$$=\frac{1}{\mu_0 c^3}\left(\frac{e}{4\pi\varepsilon_0}\right)^2\frac{\left\{n\times\left[(n-\beta)\times\dot{\beta}\right]\right\}^2}{(1-n\cdot\beta)^5}$$

IV.total radiated power

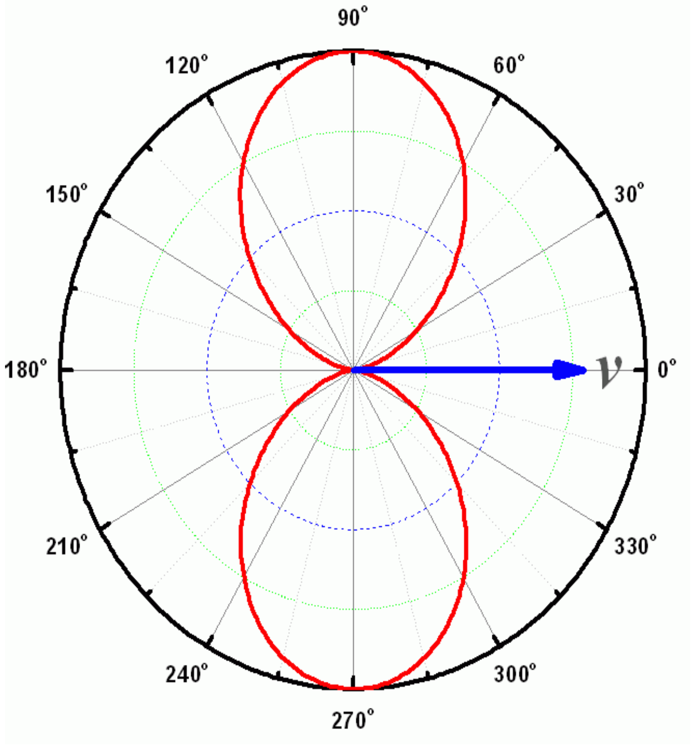
$$P=\frac{1}{\mu_0 c^3}\left(\frac{e}{4\pi\varepsilon_0}\right)^2\int\frac{\left\{n\times\left[(n-\beta)\times\dot{\beta}\right]\right\}^2}{(1-n\cdot\beta)^5}d\Omega$$

Acceleration is in the same direction as velocity (opposite direction)

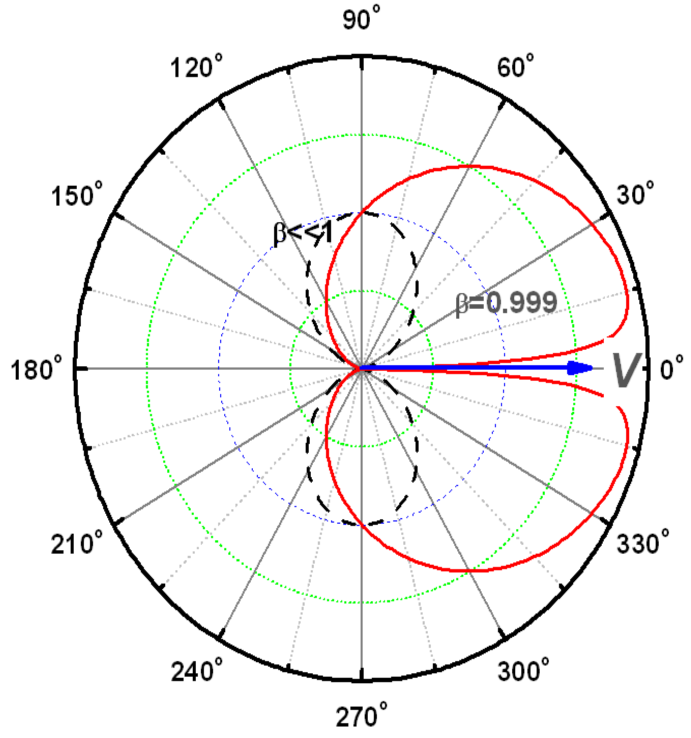
Linear motion: acceleration and velocity are in the same direction (opposite)

$$\frac{dP}{d\Omega} = \frac{e^2 \dot{v}^2}{16\pi\varepsilon_0 c^3} \frac{\sin^2\theta}{(1-\beta\cos\theta)^5}$$

Radiated power is proportional to the square of acceleration



non-relativistic： β <<1



relativistic： β →1

Radiation intensity of electrons moving in a straight line

Electron Linear Accelerator

Radiation intensity and energy gain ratio:

$$\frac{P}{dE/dt} \propto \frac{1}{\beta} \frac{dE/dx}{mc^2 \Big/ \frac{e^2}{mc^2}}$$

Electron Linear Accelerator,

$$dE/dx \approx 10\ keV/m = 10^{-17}\ MeV/fm$$

Radiation loss can be basically ignored

Bremsstrahlung

$$E_K = E_0 - \frac{e^2}{x}$$

$$E_K = 0 \qquad x_{\min} = \frac{e^2}{E_0}$$

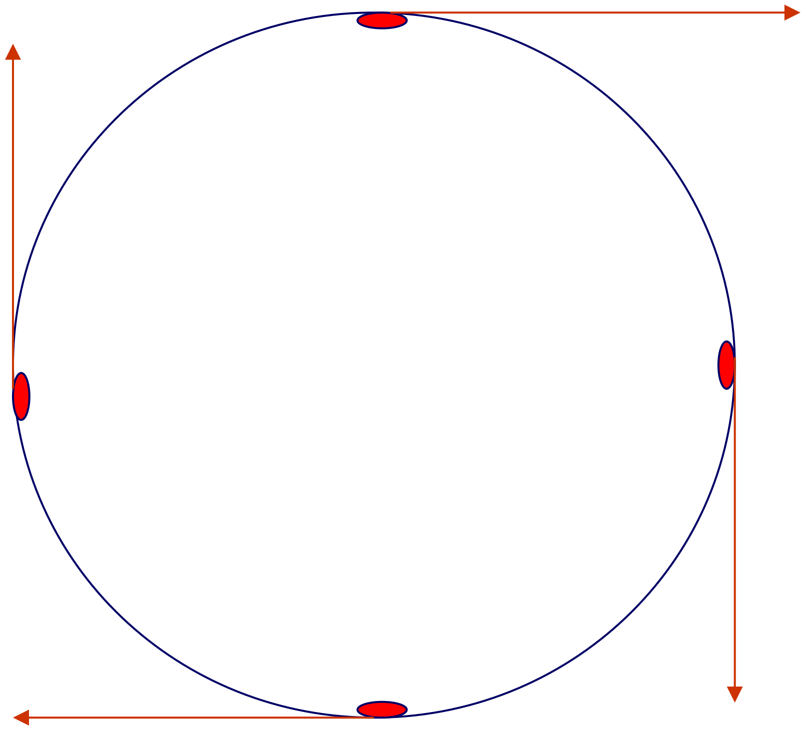
$$\frac{dE_K}{dx} = \frac{e^2}{x^2} \qquad \frac{dE_K}{dx}_{\max} = \frac{E_0^2}{e^2}$$

$$E_0 = 10keV \qquad \frac{dE_K}{dx} - 5\ MeV/fm_{\max}$$

Much larger than the radiation power and energy change ratio in the electron linear accelerator

The direction of acceleration is perpendicular to the direction of velocity: synchrotron radiation

Synchrotron radiation is an electromagnetic wave (light) emitted by charged particles (electrons) moving at close to the speed of light in an ultra-high vacuum environment when they change their direction of motion.



Discovered in 1947 on a synchrotron (70MeV), so it is called "synchrotron radiation"

Radiation from circular motion of electrons

$\dot{\beta} \perp \beta$ The angle between the observation direction n and the direction of **β**： **θ**

Distribution of radiated power：

$$\frac{dP}{d\Omega} = \frac{1}{\mu_0 c^3}\left(\frac{e}{4\pi\varepsilon_0}\right)^2 \frac{\left\{n \times \left[(n-\beta)\times\dot{\beta}\right]\right\}^2}{(1-n\cdot\beta)^5}$$

$$= \frac{e^2 \dot{v}^2}{16\pi^2\varepsilon_0 c^3}\frac{1}{(1-\beta\cos\theta)^3}\left[1-\frac{\sin^2\theta\cos^2\phi}{\gamma^2(1-\beta\cos\theta)^2}\right]$$

Radiation from the circular motion of electrons (non-relativistic)

non-relativistic， $\beta << 1 \quad \gamma \approx 1$

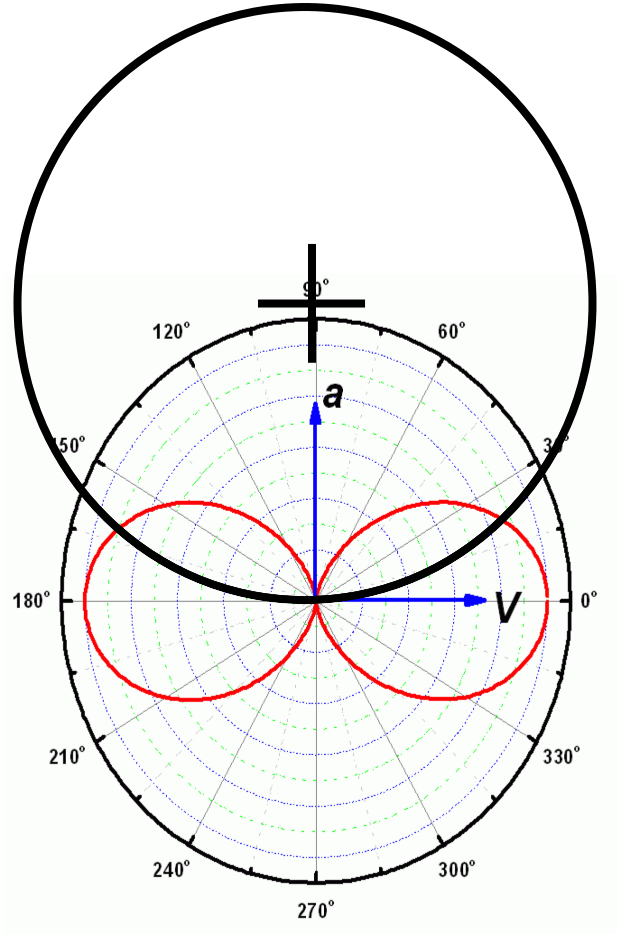
radiation power distribution：

$$\frac{dP}{d\Omega} = \frac{e^2 \dot{v}^2}{16\pi^2 \varepsilon_0 c^3}\left(1 - \sin^2\theta\cos^2\phi\right)$$

$$= \frac{e^2 \dot{v}^2}{16\pi^2 \varepsilon_0 c^3}\sin^2\chi$$

Θ is the angle between the observation direction and the acceleration direction. In the plane of electron motion，Radiated power distribution：

$$\frac{dP}{d\Omega} = \frac{e^2 \dot{v}^2}{16\pi^2 \varepsilon_0 c^3}\left(1 - \sin^2\theta\right)$$



Radiated power is proportional to the square of acceleration。

Non-relativistic Radiation power distribution of circular motion electrons

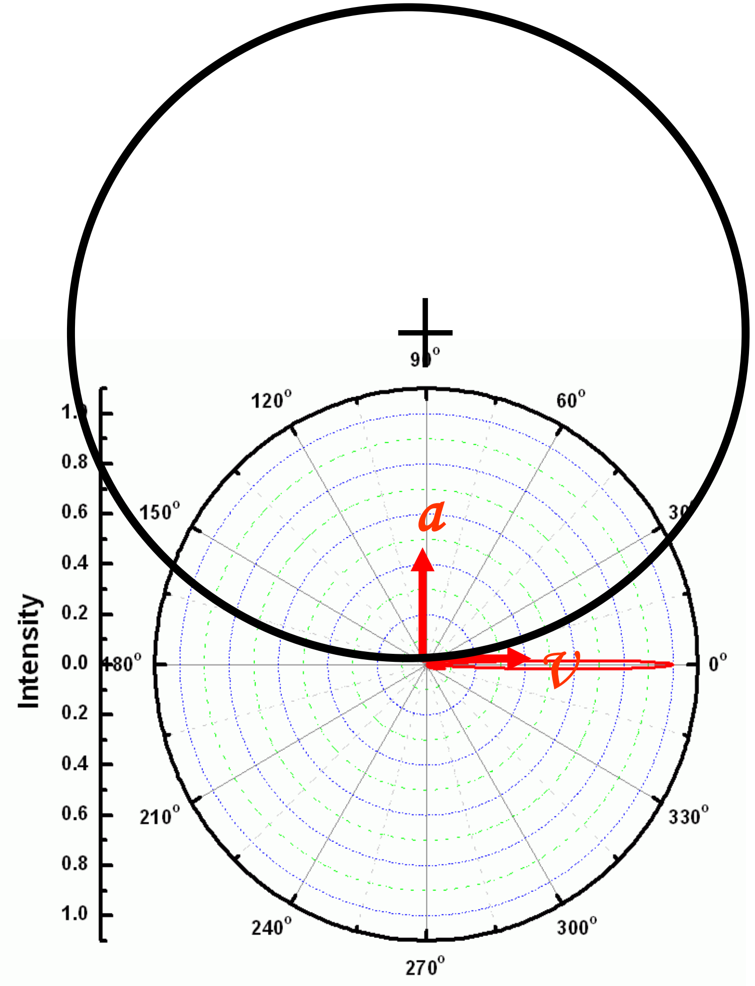
Radiation from the circular motion of electrons (relativistic)

relativistic, $\beta \to 1$, $\gamma = \frac{1}{\sqrt{1-\beta^2}}$ $\qquad 1-\beta \approx \frac{1}{2\gamma^2}$

$\theta \sim 0 \qquad \cos\theta = 1 \qquad \sin\theta = \theta$

In In the plane of the electron orbital,
Radiated power distribution：

$$\frac{dP}{d\Omega} = \frac{e^2 \dot{v}^2 \gamma^6}{2\pi^2 \varepsilon_0 c^3 \left(1+\gamma^2\theta^2\right)} \left(1 - \frac{4\gamma^2\theta^2 \cos^2\phi}{\left(1+\gamma^2\theta^2\right)^2}\right)$$



Radiated power is proportional to the square of acceleration。

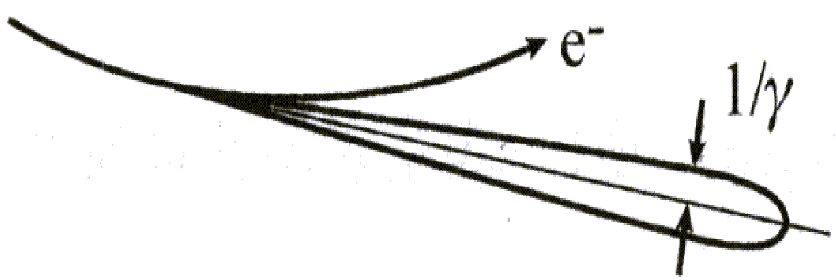
Relativistic Radiation power distribution of circular motion electrons

Radiation from the circular motion of electrons (relativistic)

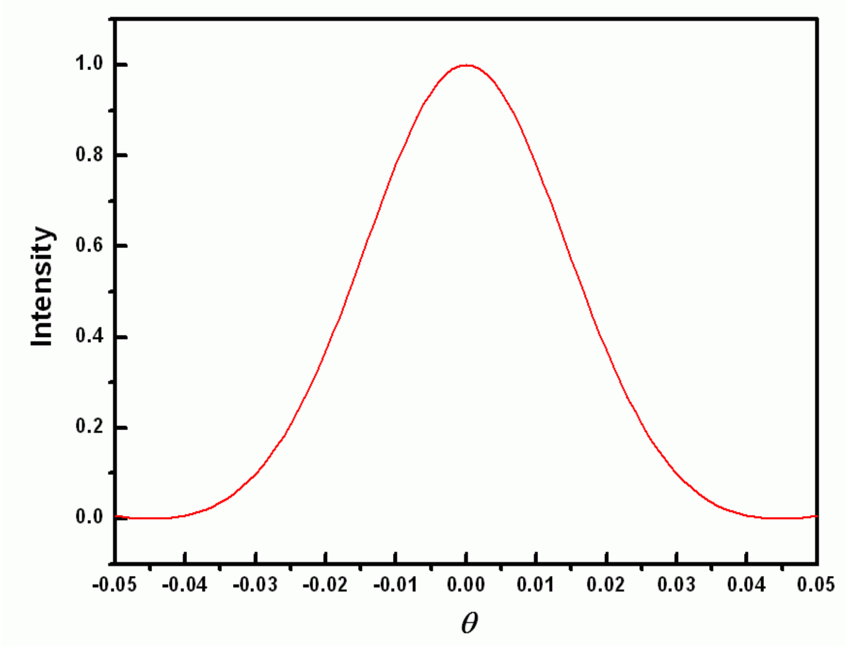
The root mean square average of θ $\quad \langle \theta^2 \rangle^{1/2}$

$$\langle \theta^2 \rangle = \frac{\int \theta^2 \frac{dP}{d\Omega} d\Omega}{\int \frac{dP}{d\Omega} d\Omega} \approx \frac{1}{\gamma^2}$$

$$\langle \theta^2 \rangle^{1/2} = \frac{1}{\gamma} = \frac{mc^2}{E} = 0.511/E_e(GeV)(mrad)$$

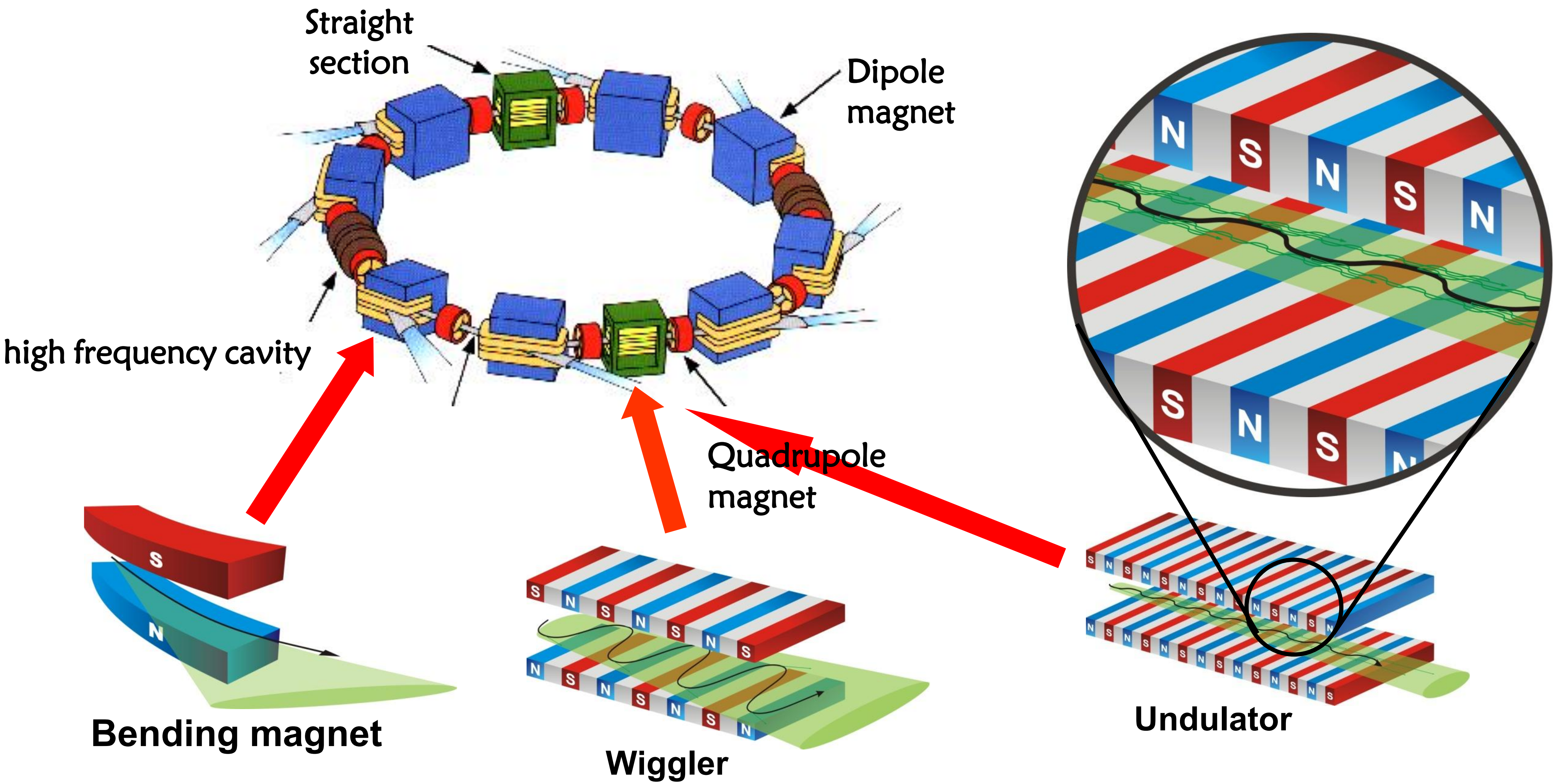


3.5 GeV



Radiation Distribution of Relativistic Electrons in Circular Motion

Synchrotron radiation sources



Bending magnet

$$\langle\theta^2\rangle^{1/2} = \frac{1}{\gamma} = \frac{mc^2}{E} = 0.511/E_e(GeV)(mrad)$$

Radiated power:

$$\frac{dP}{d\Omega} = \frac{e^2 \dot{v}^2}{16\pi^2\varepsilon_0 c^3}\frac{1}{(1-\beta\cos\theta)^3}\left[1-\frac{\sin^2\theta\cos^2\phi}{\gamma^2(1-\beta\cos\theta)^2}\right]$$

$$P = \int\frac{dP}{d\Omega}d\Omega = \frac{e^2\dot{v}^2}{16\pi^2\varepsilon_0 c^3}\int_0^{\pi/2}\frac{\sin\theta}{(1-\beta\cos\theta)^3}d\theta\int_0^{2\pi}\left\{1-\frac{\sin^2\theta\cos^2\phi}{\gamma^2(1-\beta\cos\theta)^2}\right\}d\phi$$

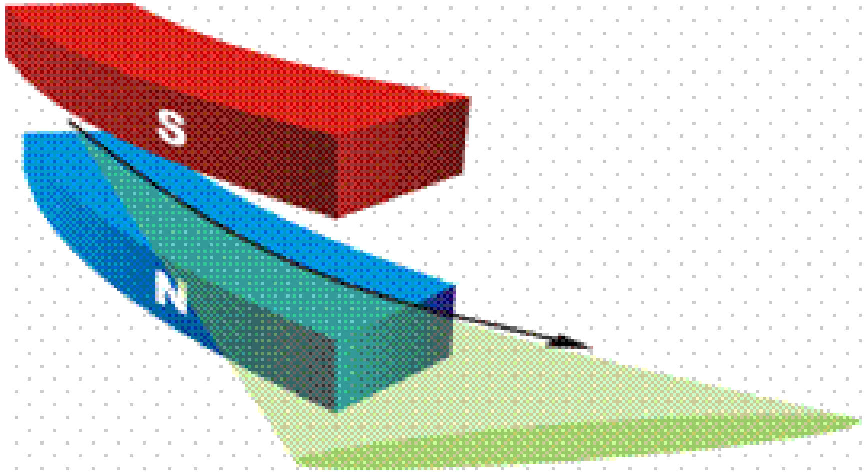
$$= \frac{e^2\dot{v}^2}{16\pi\varepsilon_0 c^3}\int_0^{\pi/2}\frac{\sin\theta d\theta}{(1-\beta\cos\theta)^3}\left\{2-\frac{\sin^2\theta}{\gamma^2(1-\beta\cos\theta)^2}\right\} \approx \frac{e^2\dot{v}^2\gamma^4}{6\pi\varepsilon_0 c^3}$$

The total energy radiated by an electron in one circle

$$E_r = \frac{e^2\gamma^4}{3R\varepsilon_0} = 88.5\frac{E_e^4(GeV)}{R(m)}(keV)$$

The total power for beam current I_e(A)

$$P = 88.5\frac{E^4(GeV)I_e(A)}{R(m)}(kW) = 26.54B(T)E_e^3(GeV)I_e(A)(kW)$$



SSRF:

Electron energy: $E_e = 3.5GeV$

BM magnetic field strength: $B = 1.27T$

Emission angle: $\langle\theta^2\rangle^{1/2} = 0.146mrad = 0.0084°$

The total energy radiated by an electron in one circle

$E_r = 1446keV$

Beam current: $I_e = 200mA$

Total power: $P = 289kW$

Bending magnet: Energy Spectrum

The time the electron takes to travel within $\langle \theta^2 \rangle^{1/2}$

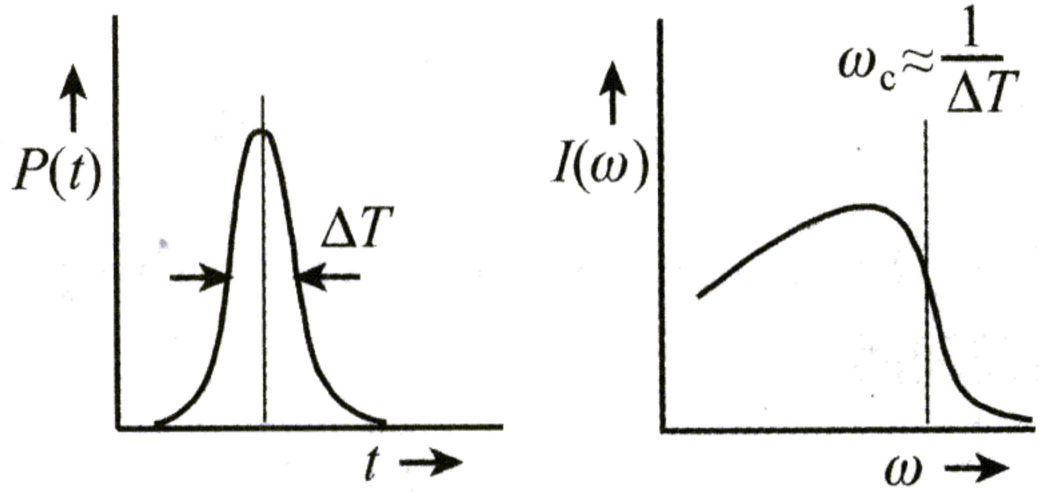
$$\Delta T = (1 - n \bullet \beta)\frac{2R}{\gamma c \beta} \approx \frac{R}{c}\frac{1}{\gamma^3}$$

SSRF

$$E_e = 3.5GeV$$

$$R = 9.186m$$

$$\Delta T = 9.63 \times 10^{-20}\ s$$



The energy spectrum can be obtained by using Fourier transform

$$I_{(\varpi)} \propto \frac{\sin^2\left(\Delta T \, \varpi/2\right)}{\left(\varpi/2\right)^2}$$

(**Paricle Accelerator Physics** Helmut Wiedemann)

Bending magnet: Energy Spectrum

$$P_{(\varpi)} = \frac{\sqrt{3}e^2\gamma}{8\pi^2\varepsilon_0 R}\frac{\varpi}{\varpi_c}\int_{\varpi/\varpi_c}^{\infty} K_{5/3}(\eta)d\eta$$

Bessel function

Critical frequency: $\varpi_c = \frac{3\gamma^3 c}{2R}$

Critical frequency, or characteristic frequency, is the frequency at which the energy (power) is the same on both sides.

Critical energy: $\varepsilon_c = \frac{h}{2\pi}\varpi_c = 2.22\frac{E^3(GeV)}{R(m)}(keV) = 0.665B(T)E_e^2(GeV)$

An electron beam with energy $E_e(GeV)$ and flux $I_e(mA)$ radiates photons per unit time and per unit energy width per unit solid angle.:

$$\frac{dN_r}{dtd\psi\left(\Delta\varpi/\varpi\right)} = 2.457\times10^7 E_e(GeV)I_e(mA)G_1\left(\varpi/\varpi_c\right)(photons/s/mrad/0.1\%BW)$$

G function: $G_1\left(\varpi/\varpi_c\right) = \frac{\varpi}{\varpi_c}\int_{\varpi/\varpi_c}^{\infty} K_{5/3}(\eta)d\eta$

The spectrum of SSRF bending magnet

Electron energy

$$E_e = 3.5GeV$$

Magnetic field strength

$$B = 1.27T$$

Emission angle

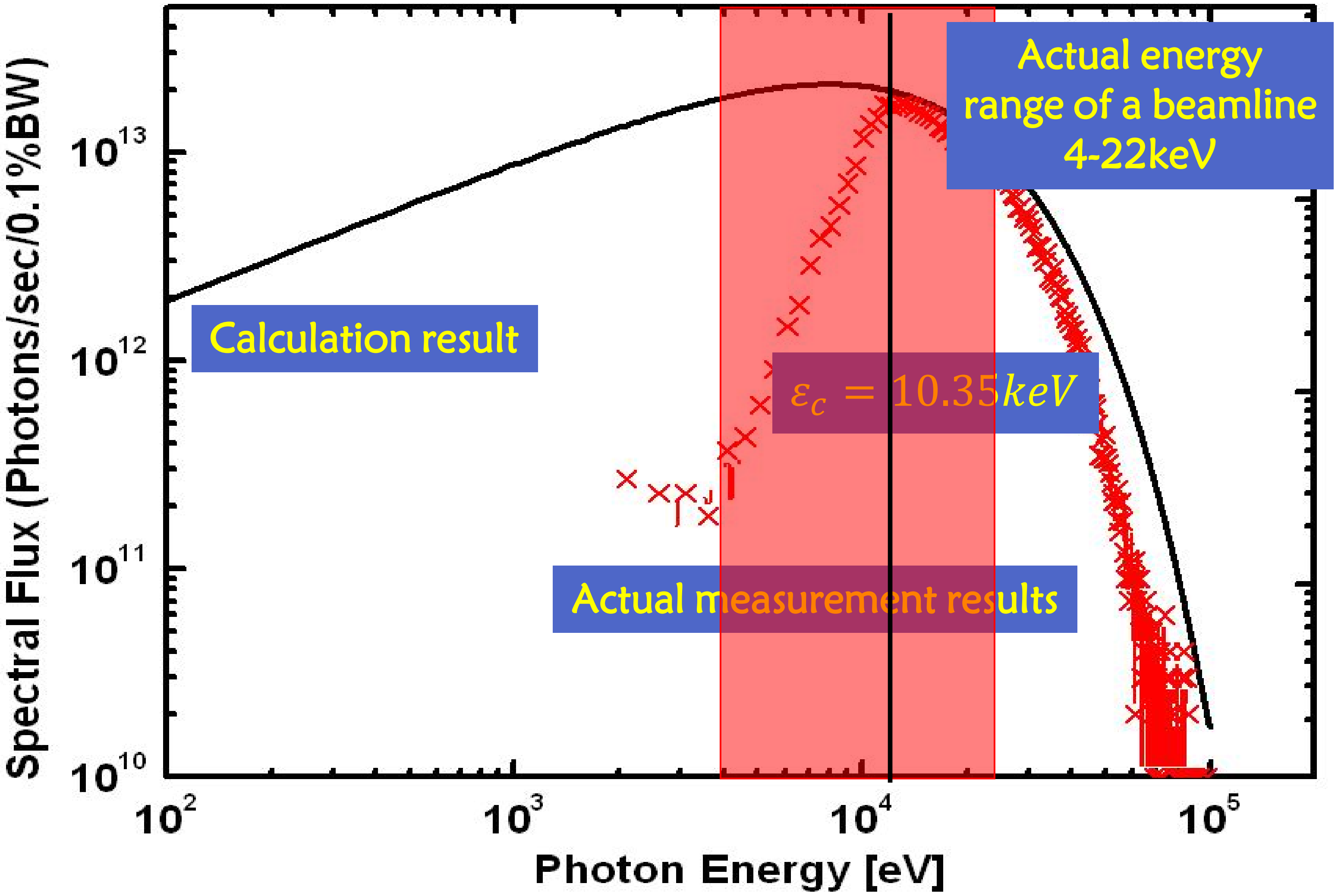
$$\langle\theta^2\rangle^{1/2} = 0.146mrad = 0.0084°$$

The total radiation energy of an electron after one circle:

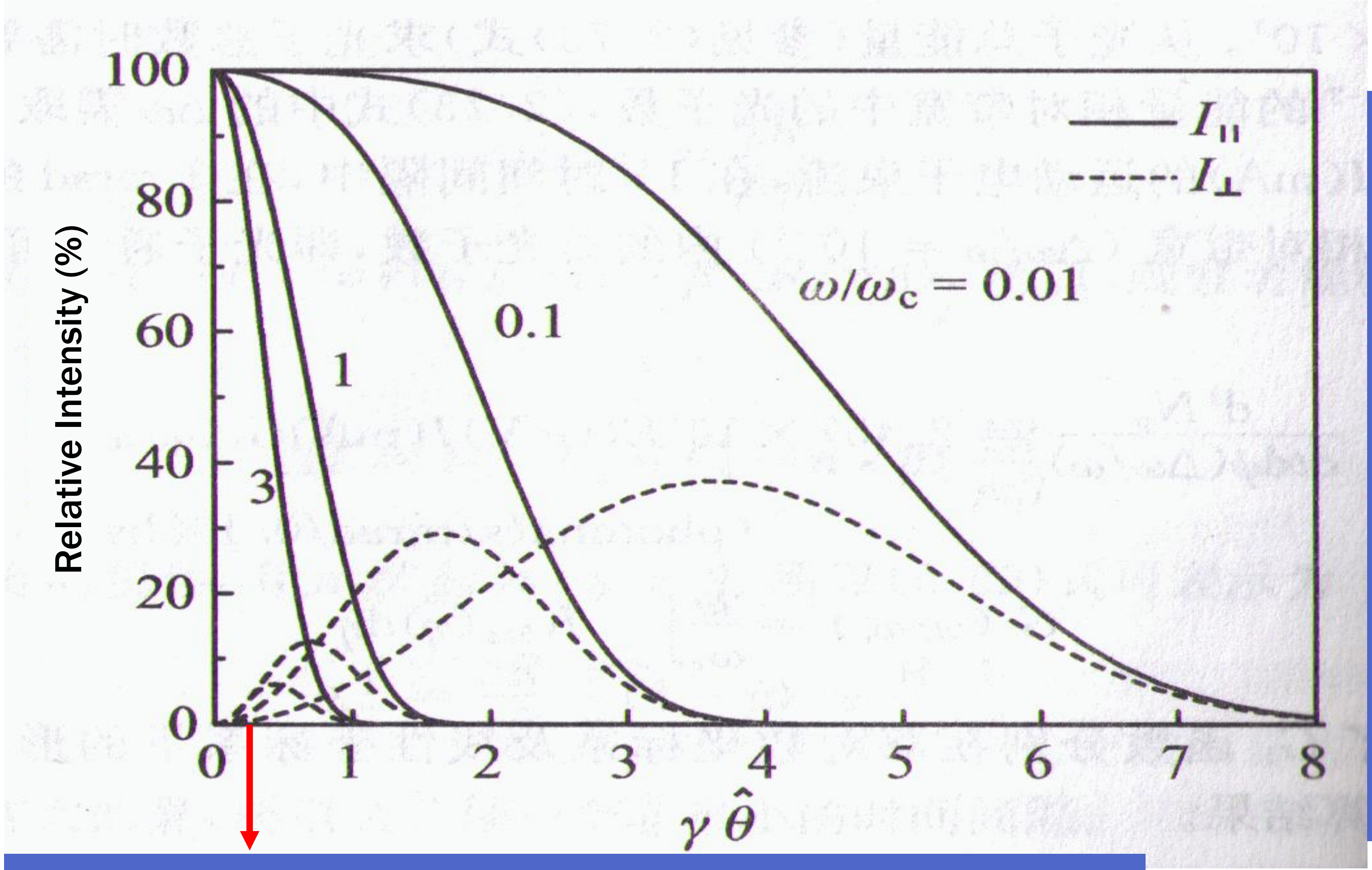
$$E_r = 1446keV$$

$$\varepsilon_c = 10.35keV$$

$I_e = 200mA$ $P = 289kW$



X-ray polarization from a bending magnet

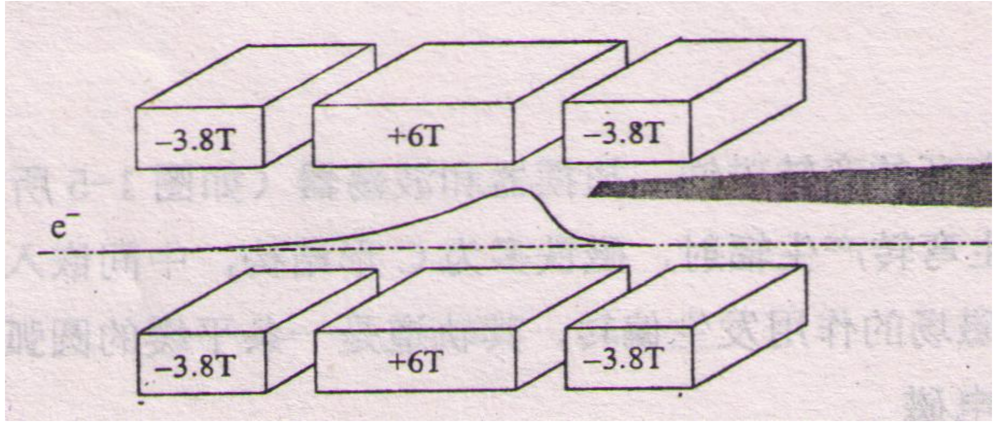


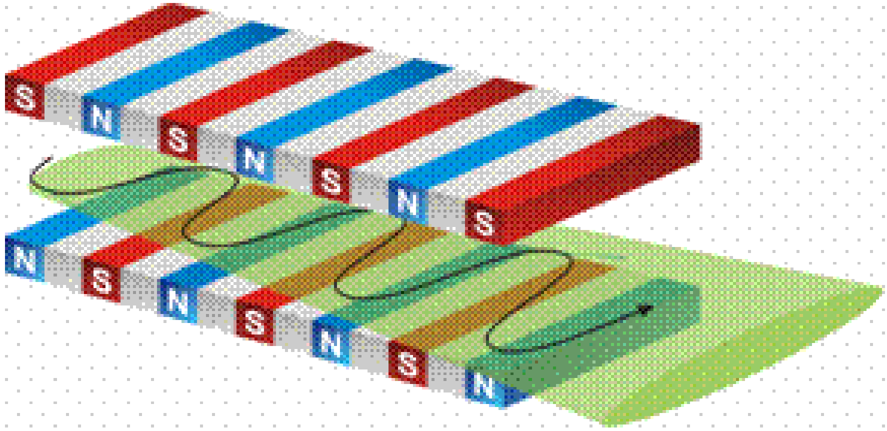
Only when θ =0 (in the XZ plane) it is linear polarization.

The degree of polarization depends on the photon energy: the higher the energy, the stronger the horizontal component.
The greater the deviation from the electron orbital plane, the stronger the vertical component.
Above this plane, linear polarization to elliptical polarization, to circular polarization.

Insertion device： Wiggler

Composed of multiple pairs of magnets with opposite directions. The period of the magnets is longer and the period number N is smaller. The electrons do not emit light once like in the bent iron, but change the direction of movement many times and emit light in the same solid angle, but the photons have no correlation with each other (incoherent).The photon energy spectrum, characteristic energy and other parameters of the wiggler are the same as those of the bent iron light source with the same magnetic field strength, but the local magnetic field strength is increased, which can increase the photon energy. The total photon intensity is 2N times that of a single magnet： $I_W = 2NI_{BM}$



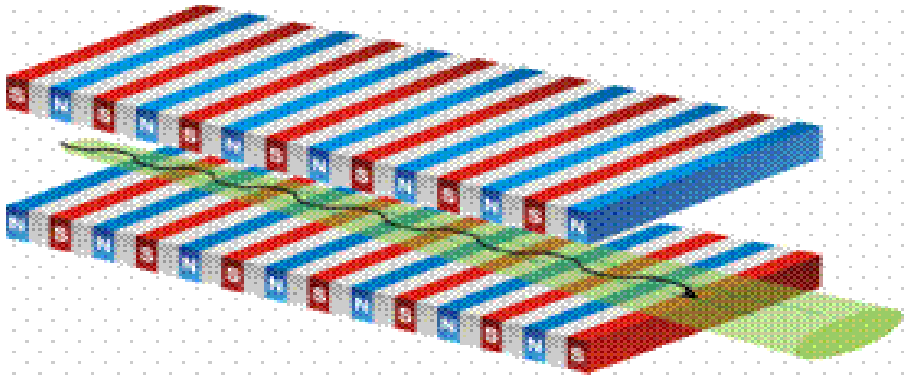


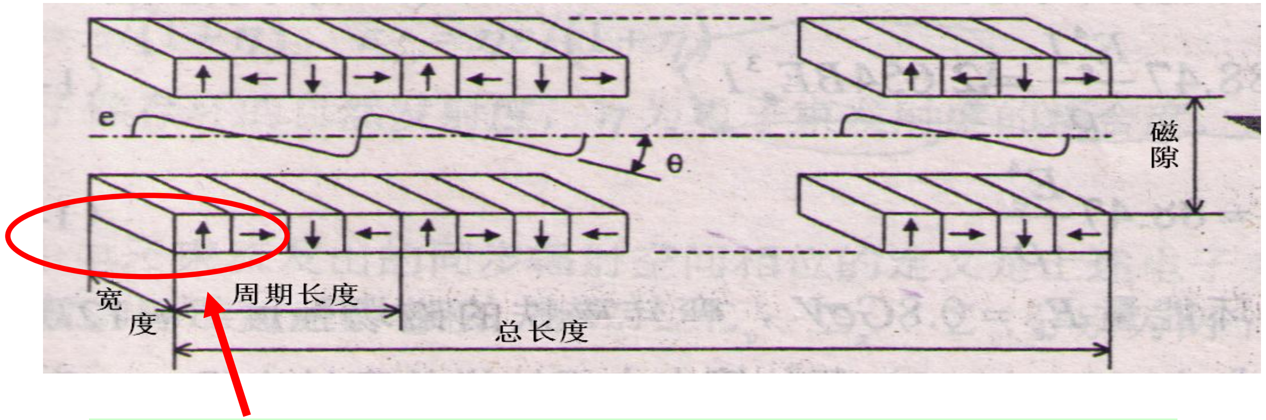
Monopole wiggler (frequency shifter):
composed of 3 dipole magnets, which enhance the local magnetic field and increase the photon energy, while the electron orbit remains unchanged at the entrance and exit.

Multipolar Wiggle: consists of N magnetic field pairs with opposite polarities. (Equivalent to 2N bent iron light sources)

Insertion device: Undulator

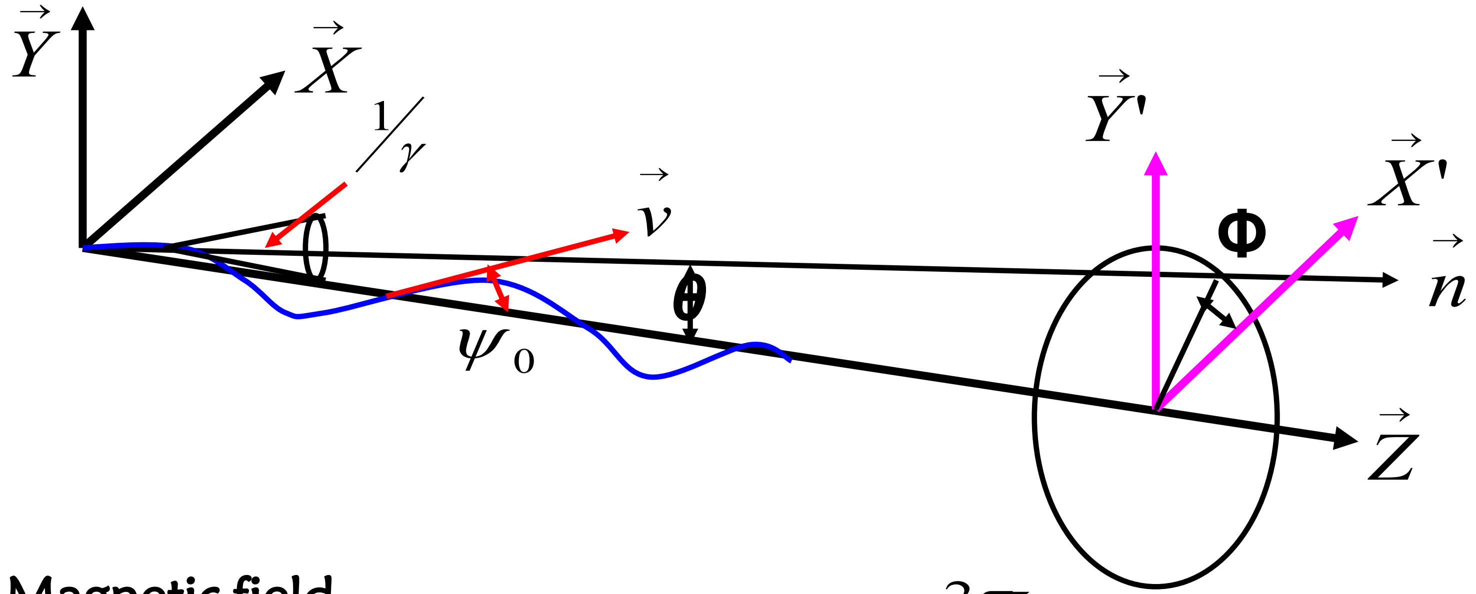
Undulator: composed of multiple magnet pairs. Its magnetic field strength is weak, but the period is short and the number of periods is large. Electrons move in a very small sine wave in a magnet group with opposite polarity. The radiation generated in each period is coherent.
In the final emitted light, the wavelength of light that meets the coherent enhancement condition will be enhanced, and its brightness is N^2 times the brightness of a single-period magnet light source. The wavelength of light that does not meet the enhancement condition is weakened, so its spectrum is discontinuous.





The polarity of the magnet is not simply NS or SN.

The spectrum of X-ray from a undulator



The magnetic field strength B_0 is weak, the period length λu is short, the electrons move in a sinusoidal motion with a smaller amplitude.

Magnetic field strength in Y direction:

$$B_y = B_0 \sin \frac{2\pi z}{\lambda_u}$$

Electron motion:

$$x(z) = \frac{\lambda_u}{2\pi} \frac{K}{\gamma} \cos\left(\frac{2\pi}{\lambda_u}\right)$$

Deflection factor:

$$K = \frac{eB_0\lambda_u}{2\pi mc} = 0.934\lambda_u(cm)B_0(T)$$

Electron energy：

$$\gamma = \frac{E_e}{mc^2} = 1957E_e(GeV)$$

$K/\gamma << 1$

K小： λu和B小
γ大： 能量高

The spectrum of X-ray from a undulator

The equation of motion of the electron in the undulator is sinusoidal, and the energy spectrum obtained from the Fourier transform is a quasi-monochromatic spectrum. The wavelength that satisfies coherent enhancement is:

$$\lambda_n = \frac{\lambda_u}{2n\gamma^2}\left[1+\frac{K^2}{2}+(\gamma\theta)^2\right]$$

When K<<1, $\lambda_1 = \frac{\lambda_u}{2\gamma^2}$ quasi-monochromatic, coherent, parallel beam

In the forward direction, there are only odd harmonics, n=1,3,5,7…

Along z axis， θ = ψ =0，When n=1, that is, the fundamental wave, the fundamental wave energy：

$$\varepsilon_1 = \frac{0.95E_e^2(GeV)}{(1+K^2/2)\lambda_u(cm)}(keV)$$

An electron beam with $E_e(GeV)$ energy and $I_e(mA)$ flux radiates photons per unit time and per unit energy width per unit solid angle.：

$$\left.\frac{dN_\gamma}{dt\,d\psi(\Delta\omega/\omega)}\right|_{\theta=0} = 1.744\times10^{11}N_u^2E_e^2(GeV)I_e(mA)F_n(K)(photons/s/mrad/0.1\%BW)$$

The radiation intensity is proportional to the square of the number of magnetic field periods Nu.

The spectrum of X-ray from a undulator

$$F_n(K) = \frac{n^2}{(1+K^2/2)^2}|E_{nx}|^2$$ n an odd number

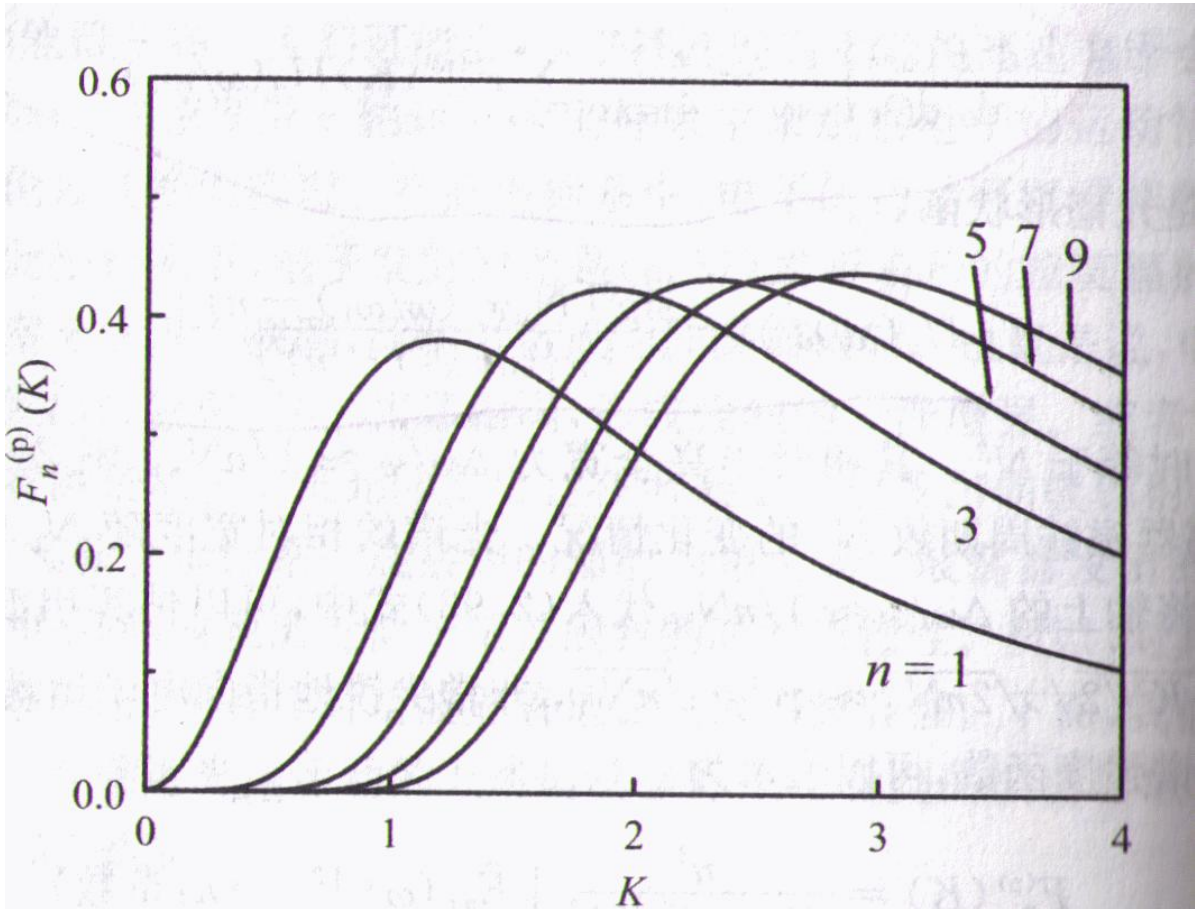
$$= 0$$ n an even number

$$|E_{nx}| = K\left|J_{(n+1)/2}(Y_0) - J_{(n-1)/2}(Y_0)\right|$$

$$Y_0 = nK^2/(4+2K^2)$$

J is Bessel function

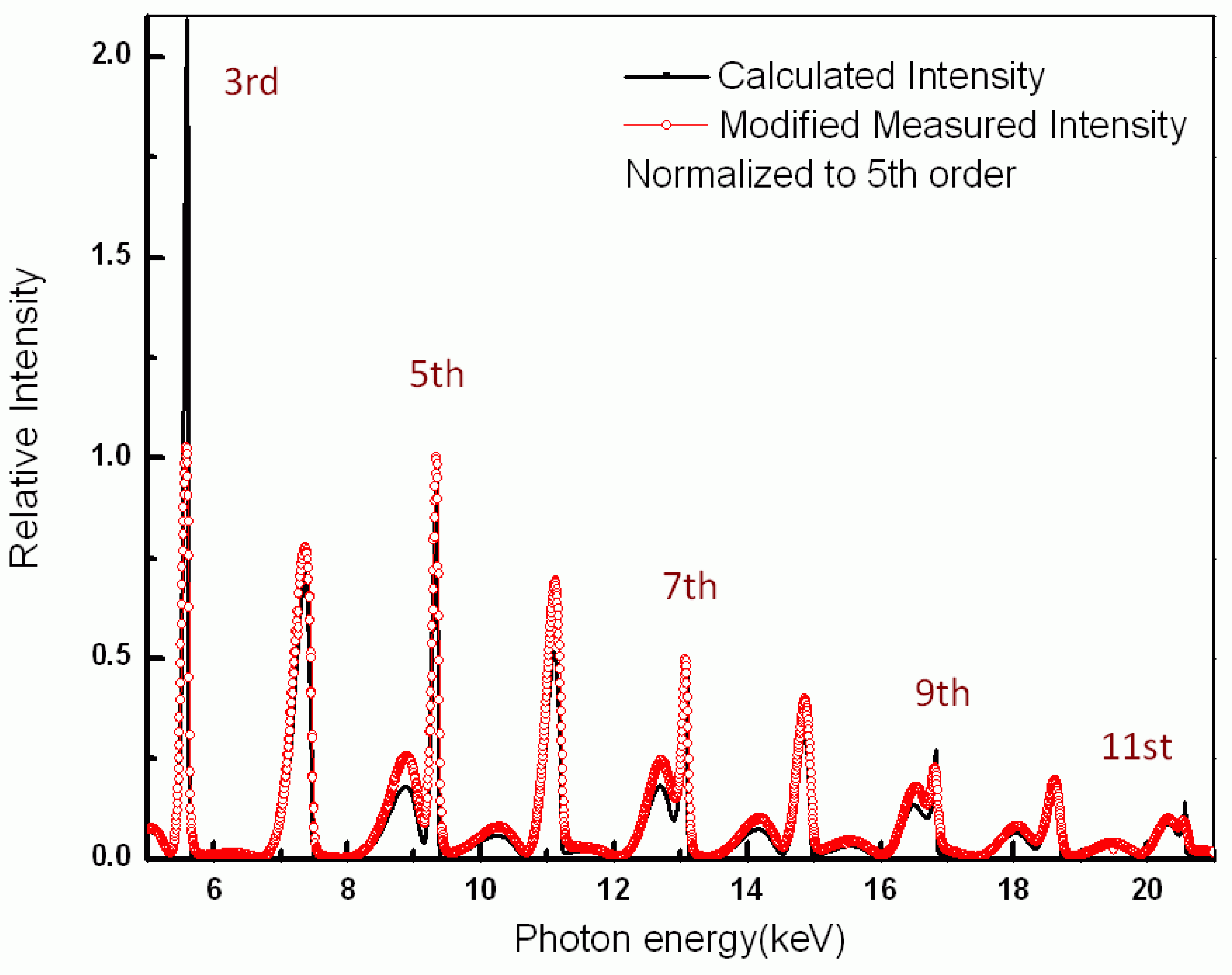
$$K = \frac{eB_0\lambda_u}{2\pi mc} = 0.934\lambda_u(cm)B_0(T)$$



Adjusting K (magnetic field strength B) can change the maximum intensity wavelength

Energy spectrum of IVU source at SSRF

IUV25：
B=0.95T@Gap=7 mm
T=25 mm
Nu=80



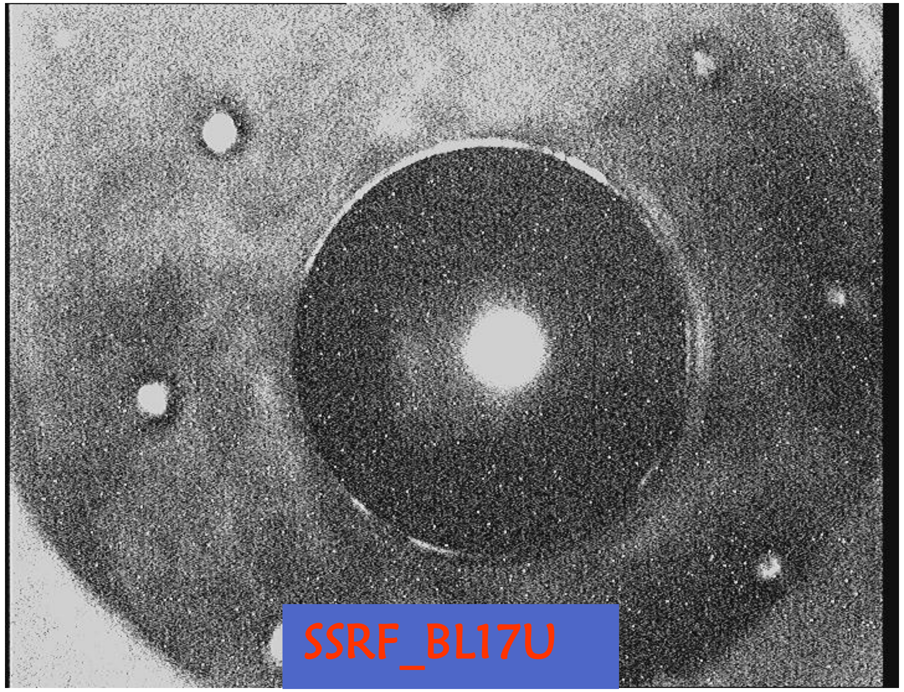
Angular distribution of the beam of an undulator source

Divergence angle of the undulator beam

$$\theta_{1/2} \approx \frac{\sqrt{1+K^2/2}}{\gamma^2\sqrt{2nN_u}} \approx \frac{1}{\gamma}\frac{1}{\sqrt{2nN_u}}$$

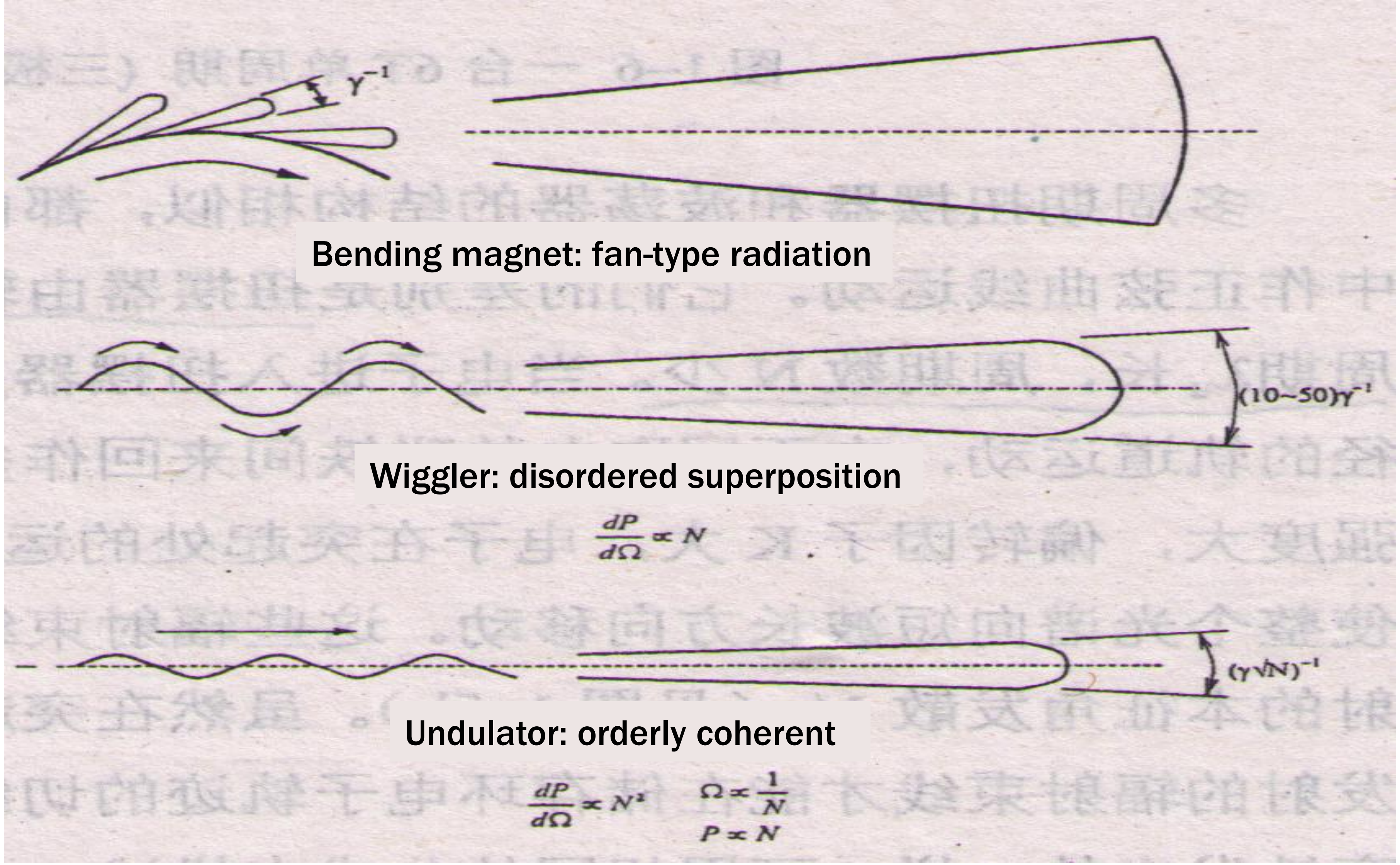
Divergence angle of bending magnet source

$\langle\theta^2\rangle^{1/2}$

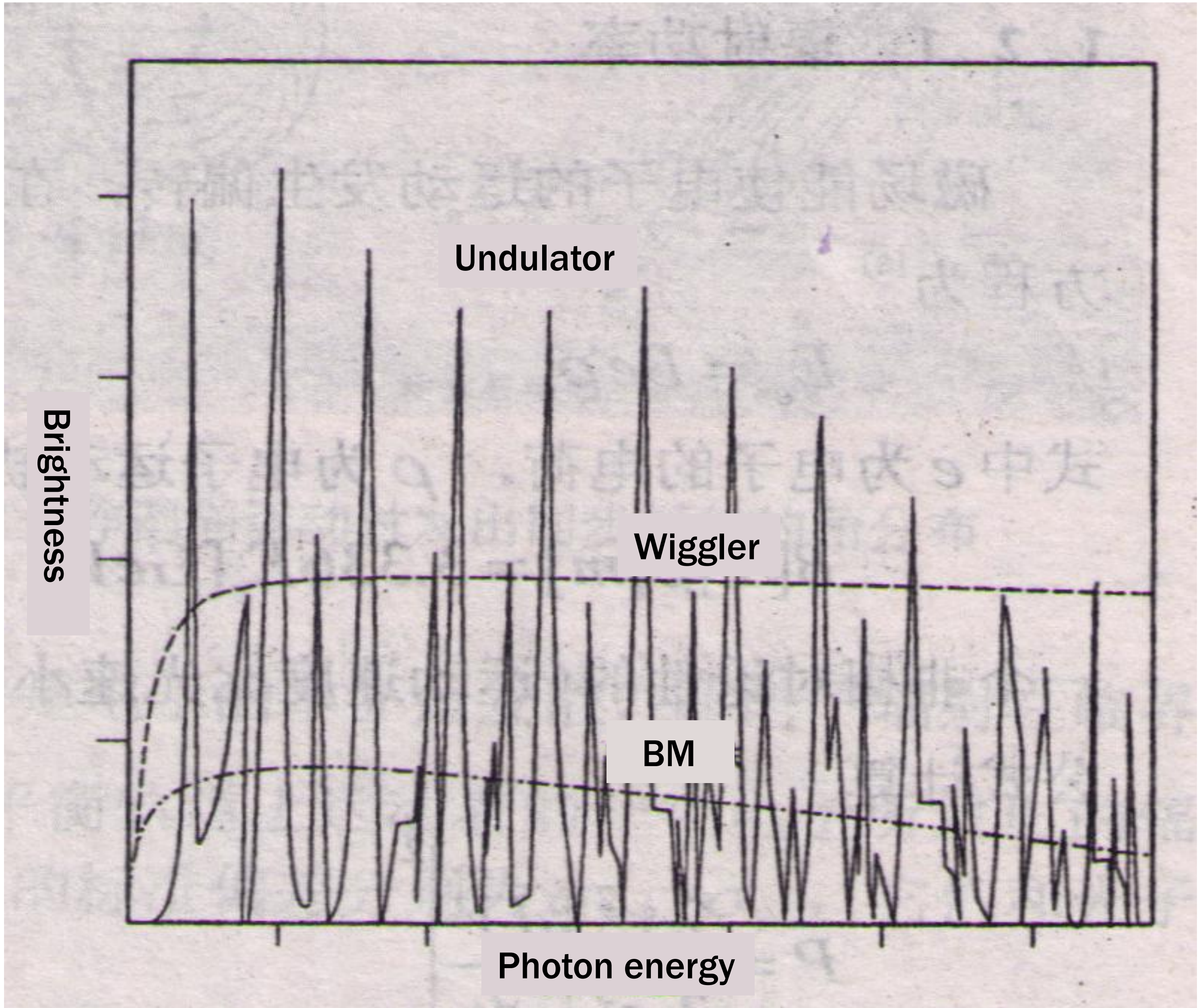


The undulator is a plane undulator, that is, the electrons move in the XZ plane, and the radiation generated is linearly polarized in the XZ plane.
If the magnetic field is a spiral distribution rotating around a certain axis, elliptically polarized radiation can be generated.

Comparison of the principles of three light sources



Comparison of the spectra of three light sources



Advantages of synchrotron light sources

Wide energy spectrum: capable of producing full-band radiation from far infrared to hard X-rays;

Monochromatic: produced by electrons in an ultra-high vacuum environment and further monochromatized by the beamline optics.

High collimated: since the divergence angle of the emitted electron beam can be controlled to be very small, the divergence angle of the emitted light is also very small, with high collimation;

High brightness and high flux: since very high-power radiation is concentrated in a very small spot, synchrotron radiation has very high power (flux) and brightness

High polarization: synchrotron radiation is the emission of electrons in a magnetic field. By controlling the structure of the magnetic field and the extraction position of the light, a beam with good polarization can be obtained.

Stable time structure: since the energy of the electron bunch running in the accelerator is very stable, synchrotron radiation has a stable pulse time structure and can be used for time process research;

Precise predictability: since synchrotron radiation is radiation caused by precise charge movement, its energy spectrum, brightness and other parameters can be accurately calculated based on electron energy, beam current, magnetic field strength and other parameters, and can be used as a standard light source;

Coherence: partial coherence, quasi-coherence.

03

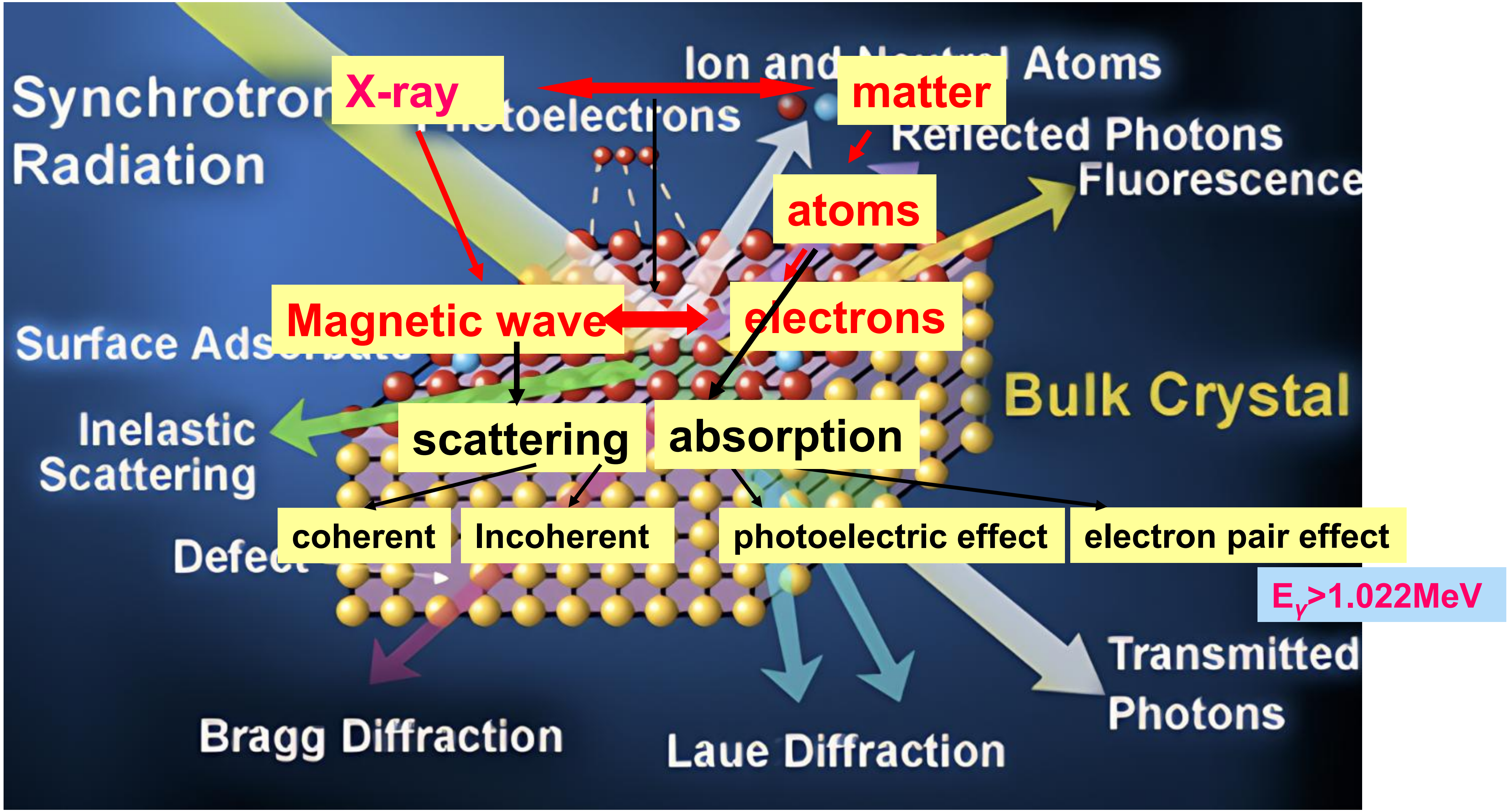
X-ray interaction with matter

X-ray interaction with matter

Photoelectric effect produce photoelectrons with a certain kinetic energy, and produces secondary characteristic fluorescence radiation or Auger electrons

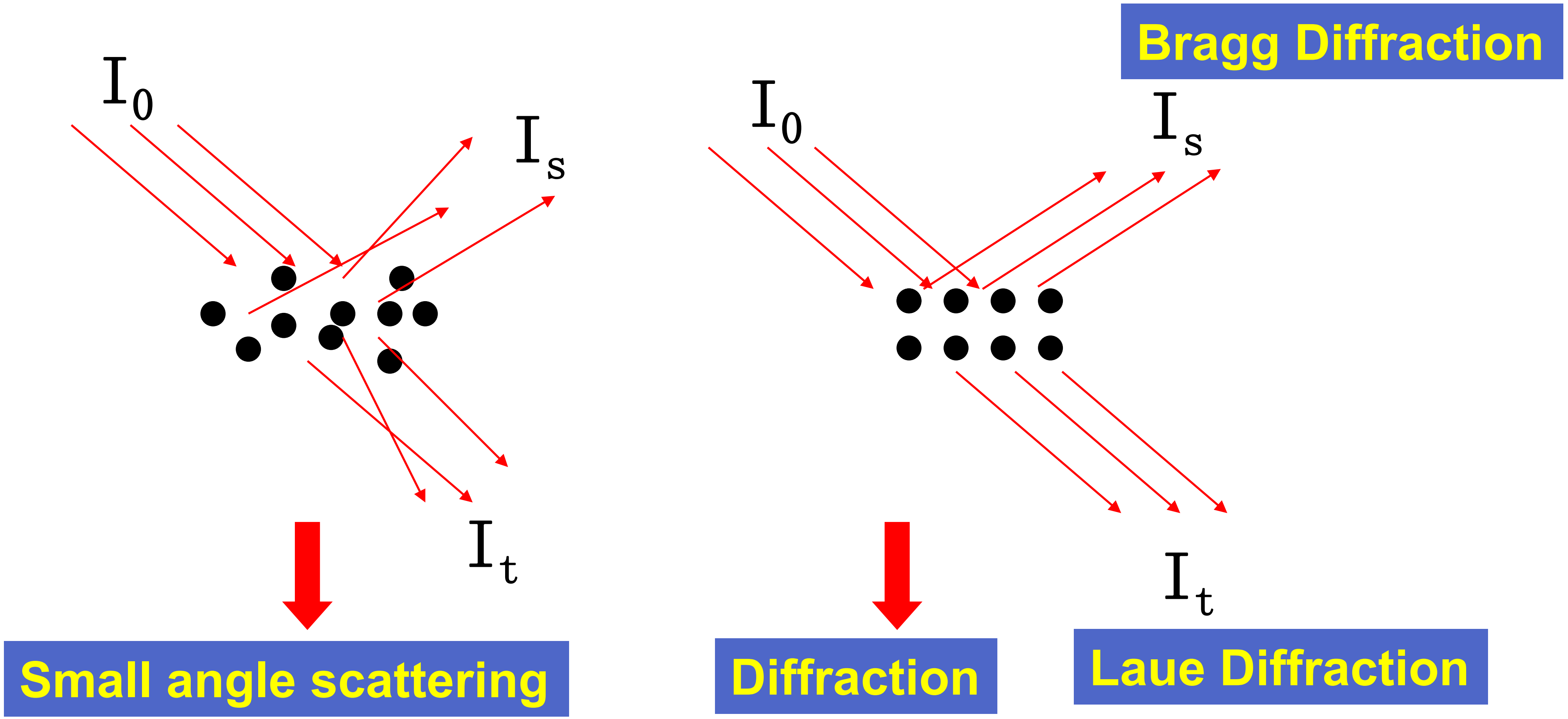
Incoherent scattering: Direction and frequency change, the electron gains a certain amount of energy and momentum

Coherent/classical /Thomson scattering: direction may be changed, the frequency unchanged.



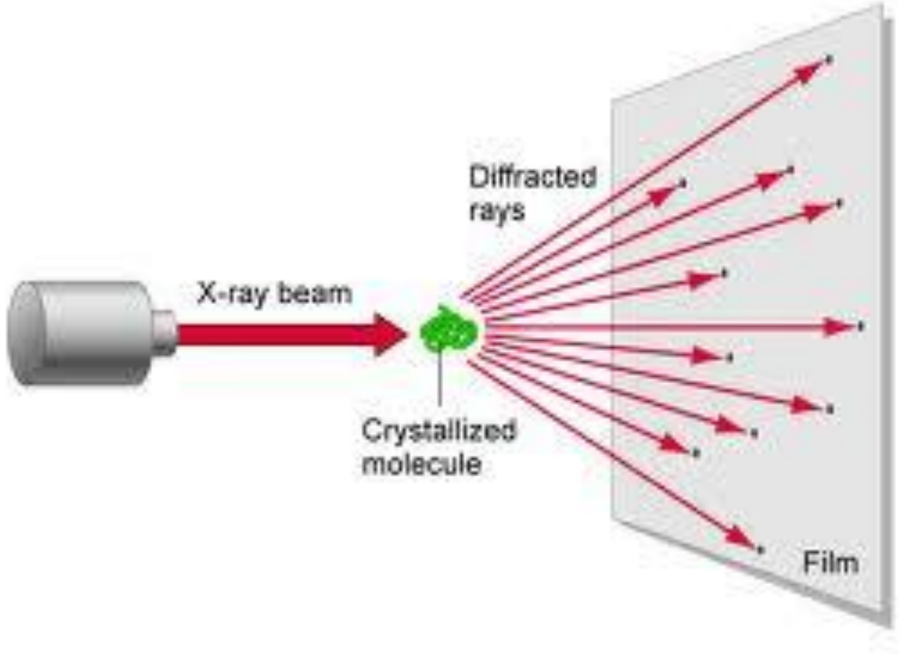
X-ray Scattering

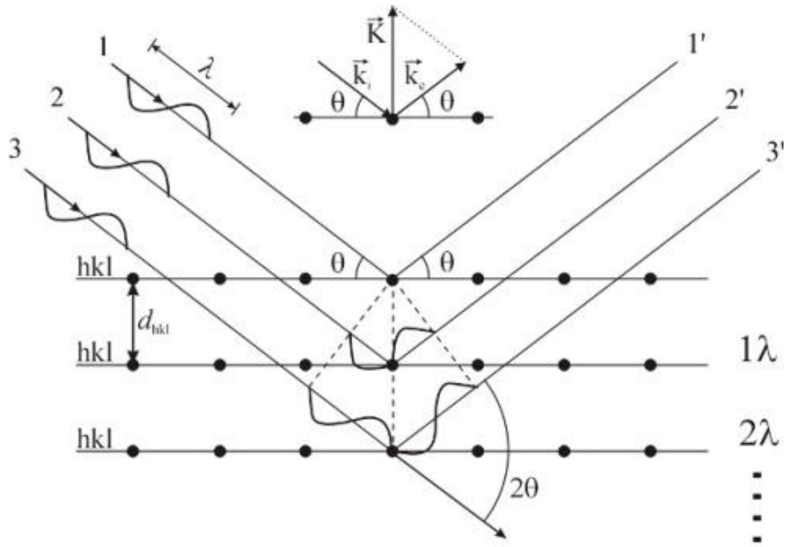
Coherent scattering (Thomson scattering)

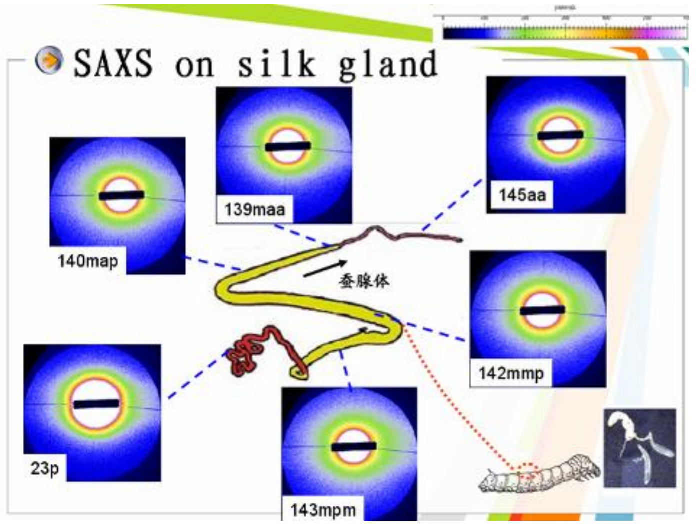


X-ray scattering/Diffraction

Diffraction: long range order





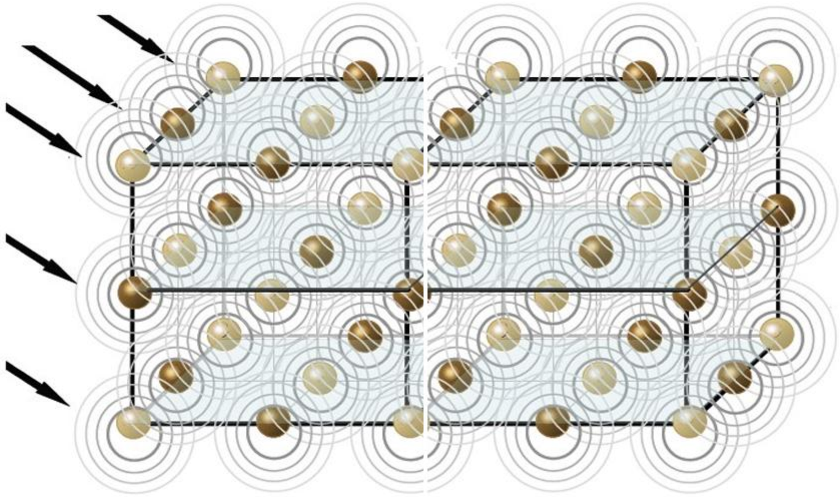


Real space ⟺ reciprocal space

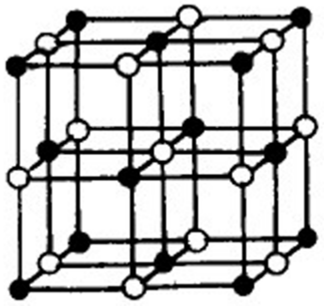
Scattering: average microscopic morphology

X-ray diffraction - interference of coherent scattering

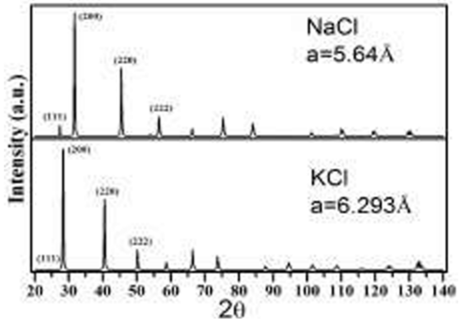
Each electron in the material is subjected to vibration under the action of the electric field of X-rays. In this way, the electrons generate electromagnetic waves of the same frequency as the incoming X-rays in all directions, and the interference between the coherent scattering from the long-range neighboring lattices causes X-ray diffraction.



X-ray Crystallographic Diffraction Structure Analysis



NaCl



Crystal structure : lattice + structural unit (basis)

Lattice parameter | atomic position

$$2d_{hkl}\sin\theta = \lambda$$

$$F(hkl) = \sum_{i=1}^{n} f_j e^{i2\pi(hx_j+ky_j+lz_j)}$$

peak position | peak intensity

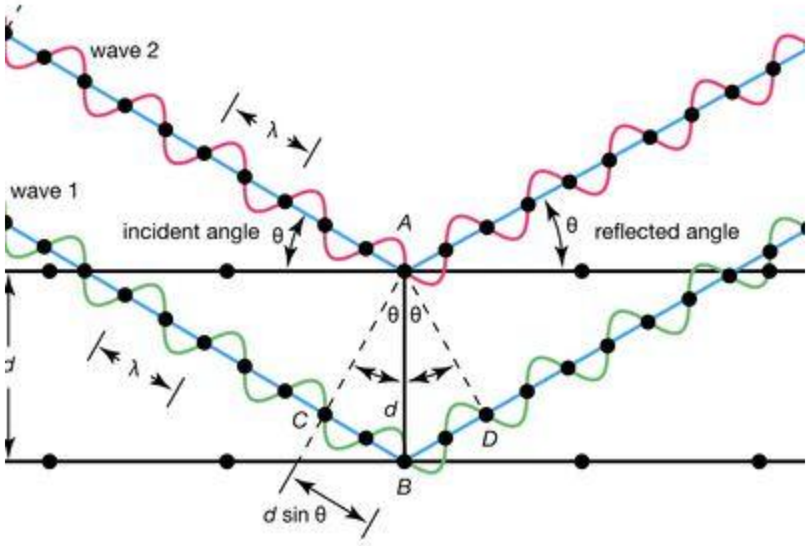
Experimental results

Bragg equation

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

•Incident beam and lattice parameters：

θ d a, b , c, α, β γ



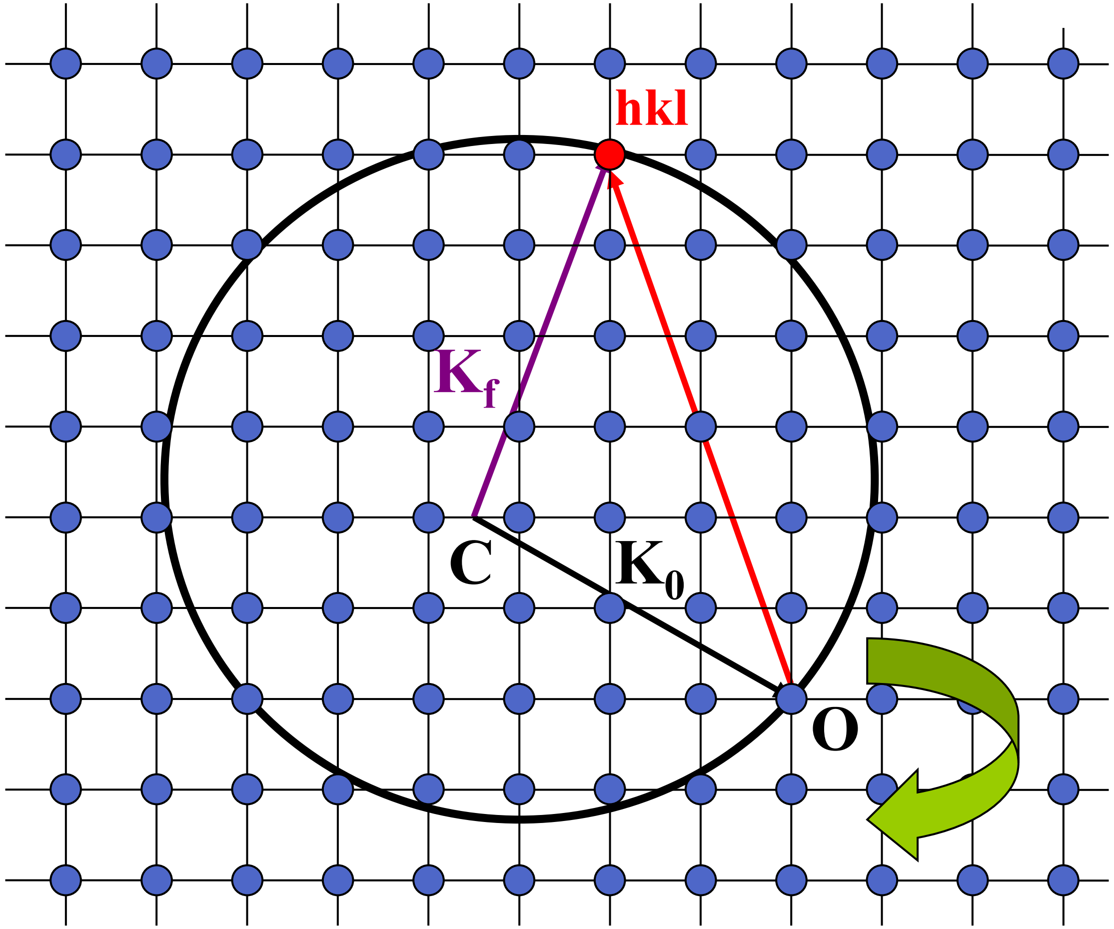
Interplanar spacing, for Orthorhombic lattice

$$\frac{1}{d_{hkl}^2} = \frac{h^2}{a^2} + \frac{k^2}{b^2} + \frac{l^2}{c^2}$$

Determine the position of the diffraction peak, the diffraction spectrum is the change of the diffraction intensity with the angle θ, or the change of the diffraction vector q, the diffraction angle and the wavelength: $q=4\pi\sin\theta/\lambda$

Ewald sphere

When a reciprocal lattice point intersects the Ewald sphere, it means the conditions defined by Bragg's law are met for that particular set of crystal planes. By rotating the crystal (and thus the reciprocal lattice) or changing the wavelength of the incident X-rays, one can bring different reciprocal lattice points into contact with the Ewald sphere, resulting in diffraction from different crystal planes.

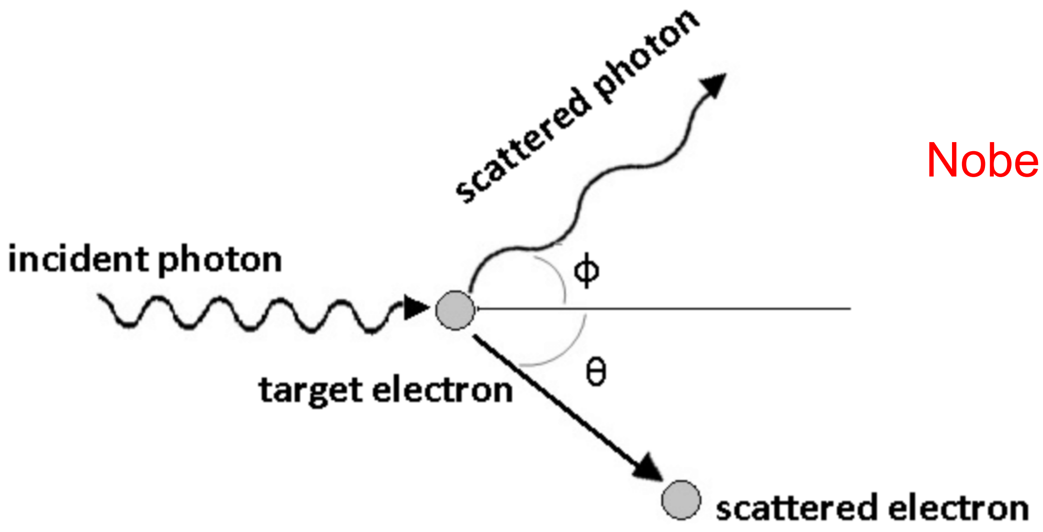


Compton scattering (incoherent scattering)

E_e
p

Nobel Prize in Physics 1927

E_γ
$E\gamma/C$



$E_{\gamma'}$
$E\gamma'/C$

Conservation of energy:

$$E_\gamma = E_{\gamma'} + E_e$$

Conservation of momentum:

$$\frac{E_\gamma}{c} = \frac{E_{\gamma'}}{c}\cos\theta + p\cos\phi$$

$$\frac{E_{\gamma'}}{c}\sin\theta = p\sin\phi$$

$$E_e^2 = E_0^2 + p^2c^2$$

$$E_0 = m_e c^2$$

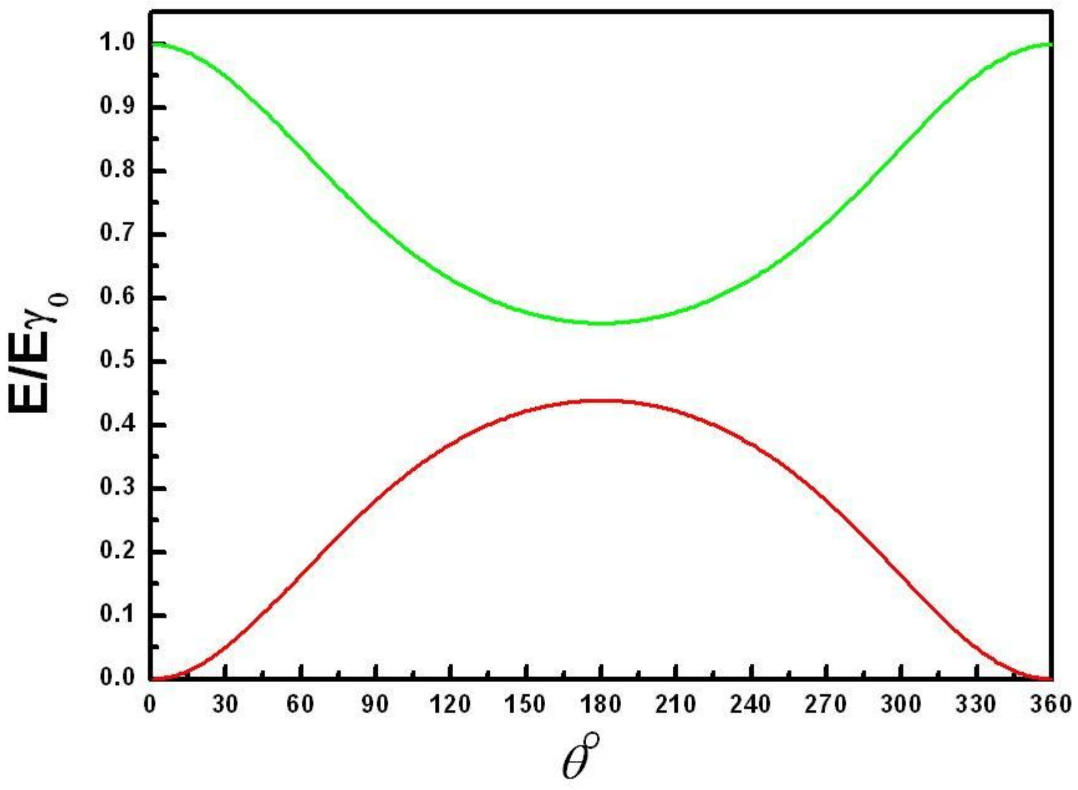
Compton scattering

Photon energy angular distribution:

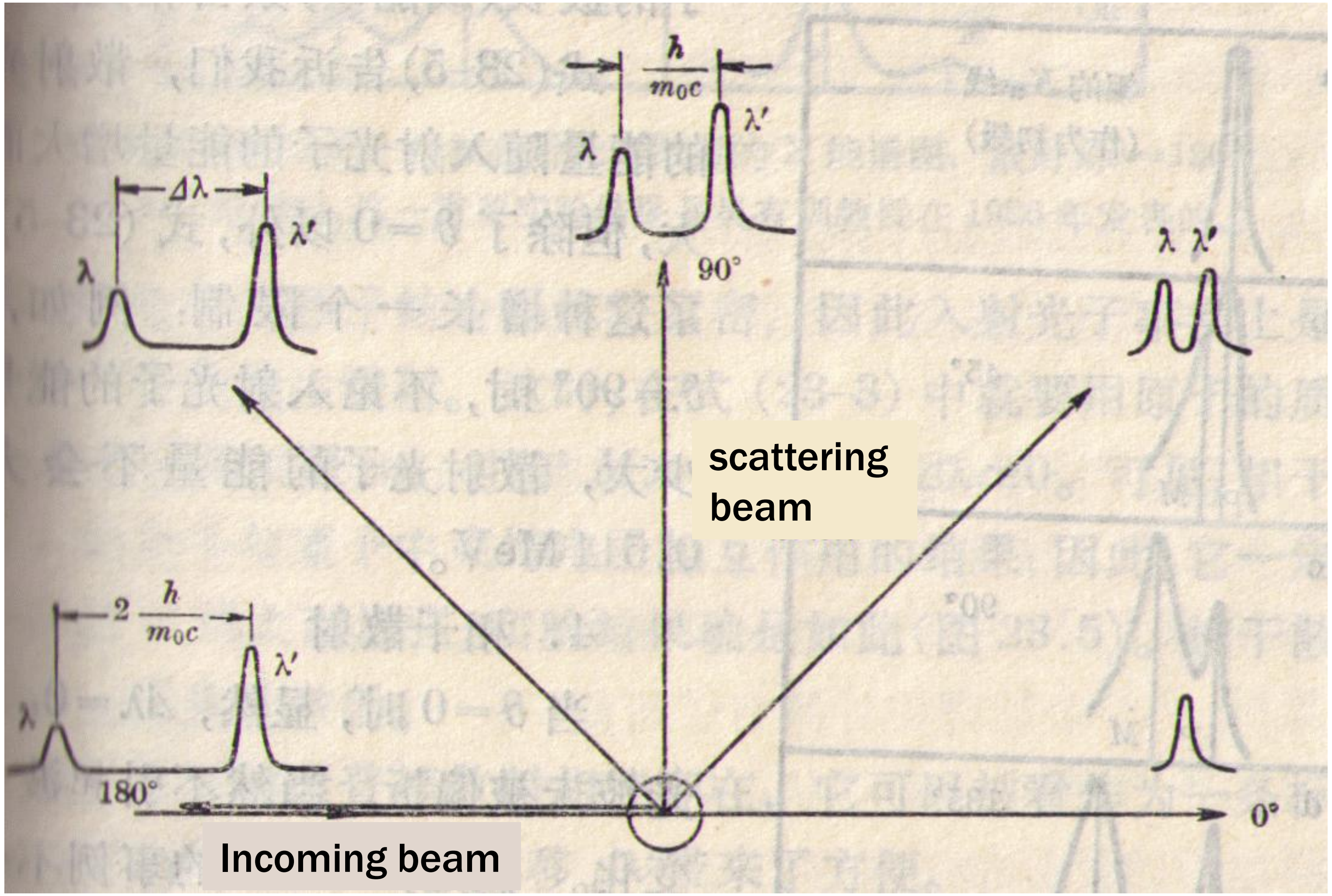
$$h\nu' = \frac{h\nu}{1 + \frac{h\nu}{mc^2}(1-\cos\theta)}$$

electron energy angular distribution:

$$E_e = \frac{h\nu(1-\cos\theta)}{\frac{m_0c^2}{h\nu} + (1-\cos\theta)}$$



Compton scattering



$$\Delta\lambda = \lambda' - \lambda = \frac{h}{m_0 c}(1-\cos\theta)$$

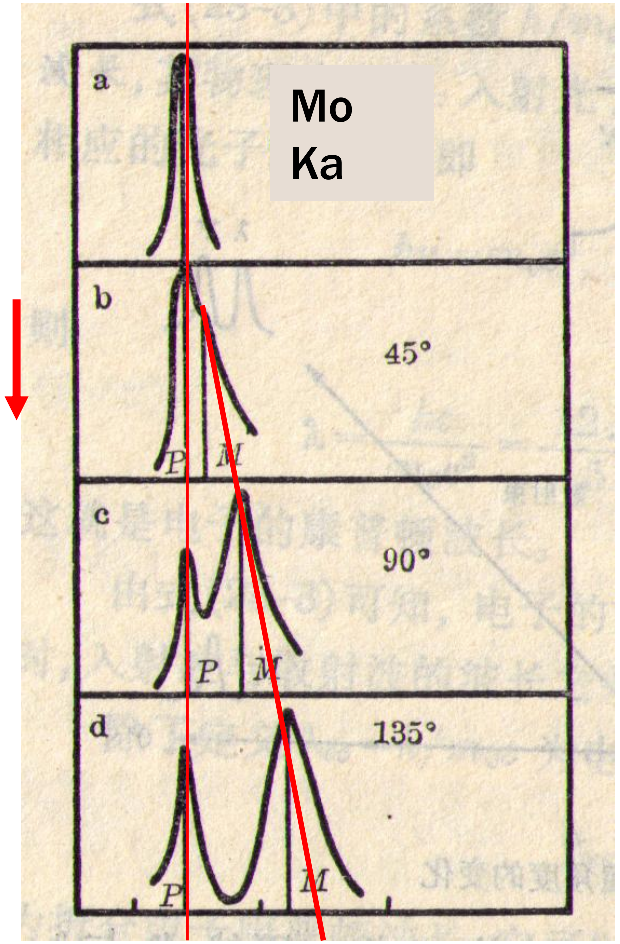
$$\theta = 180^\circ$$

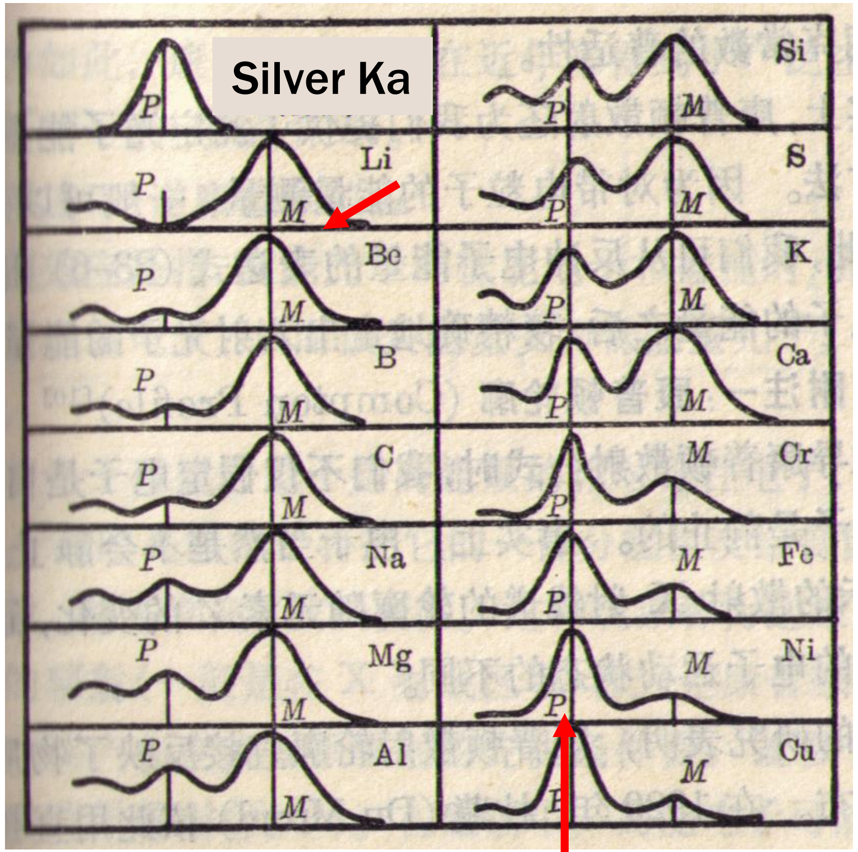
$$\Delta\lambda_{\max} = \frac{2h}{m_0 c} = 0.049\ \mathring{A}$$

$$E_{k,\max} = \frac{2\dfrac{h\nu}{m_0c^2}}{1+2\dfrac{h\nu}{m_0c^2}}h\nu$$

Compton scattering

Coherent scattering: scattering of photons by inner shell electrons.
Compton effect: scattering of photons by weakly bound electrons in the outer shell.





Coherent scattering

Compton Scattering

The larger the Z, the stronger the coherent scattering

Photoelectric effect

Photoelectric effect

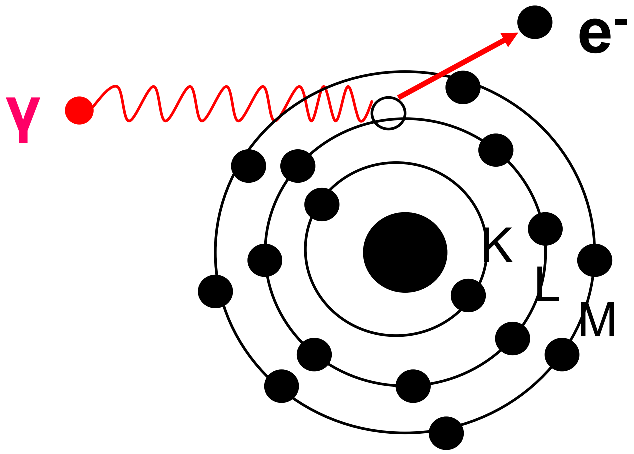
When the energy of a photon is greater than the binding energy of an electron in a certain orbit of an atom, the photon is absorbed by the electron, causing the electron of the atom to gain energy and become a free electron

Photoelectron kinetic energy：

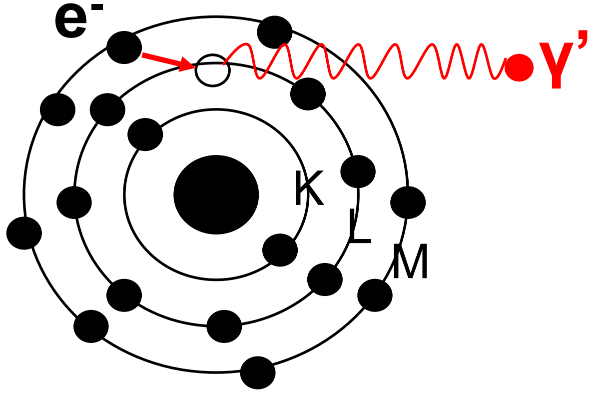
$$E_e = h\nu - E_B$$

$$E_B = R_c (Z-b)^2 \left(\frac{1}{n_i^2} - \frac{1}{n_j^2}\right)$$

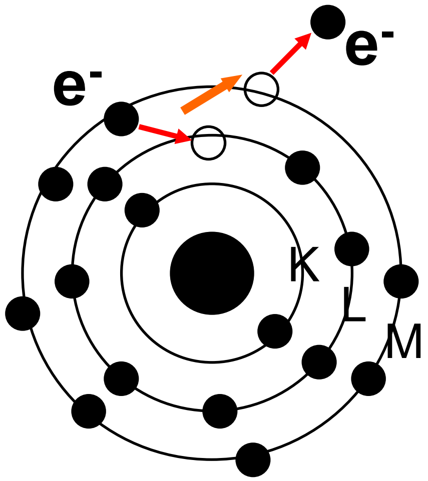
K层：n_i=1　b=1
L层：n_i=2　b=5
M层：n_i=3　b=9



XPS

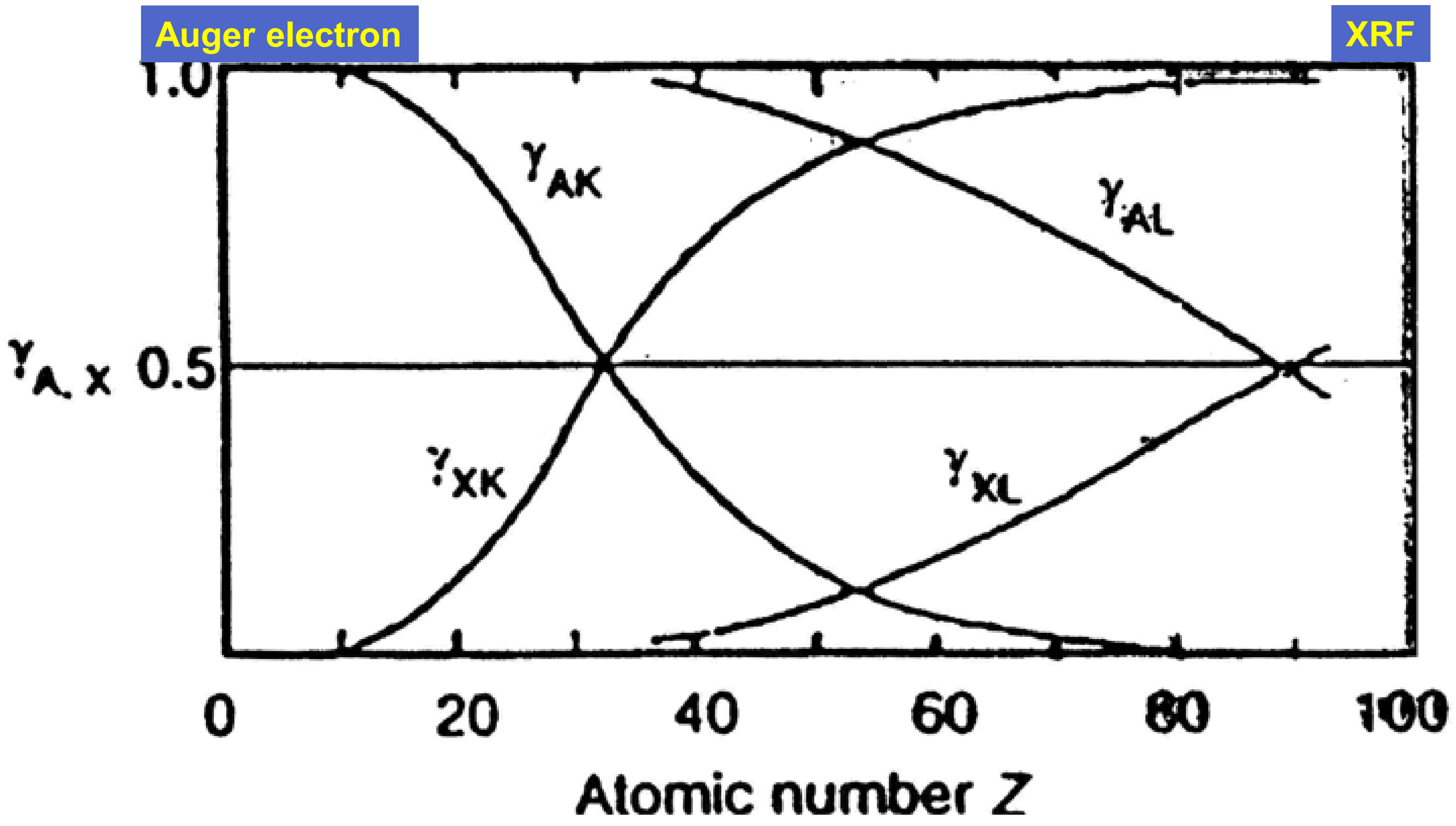


XRF



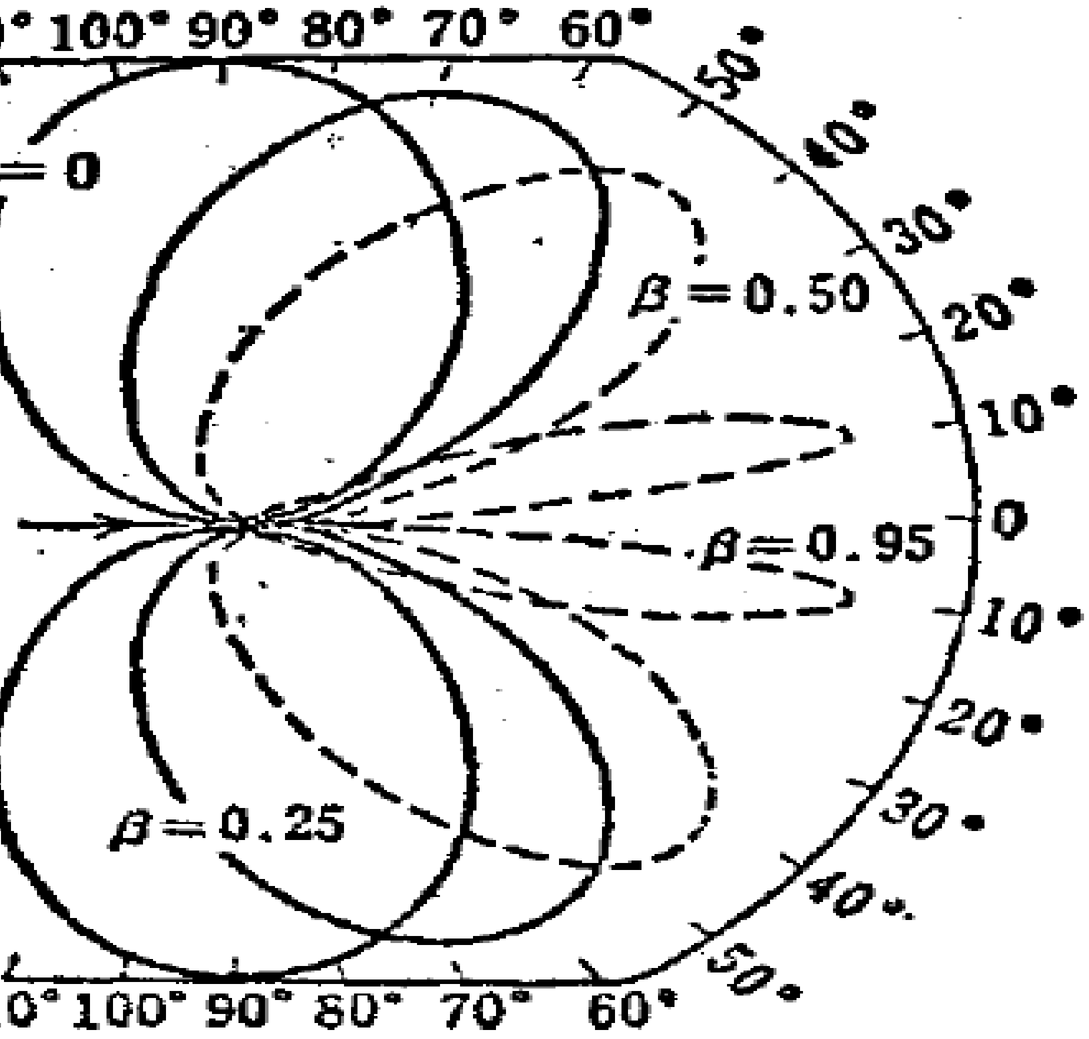
Auger electron

Competition between the two secondary effects of the photoelectric effect



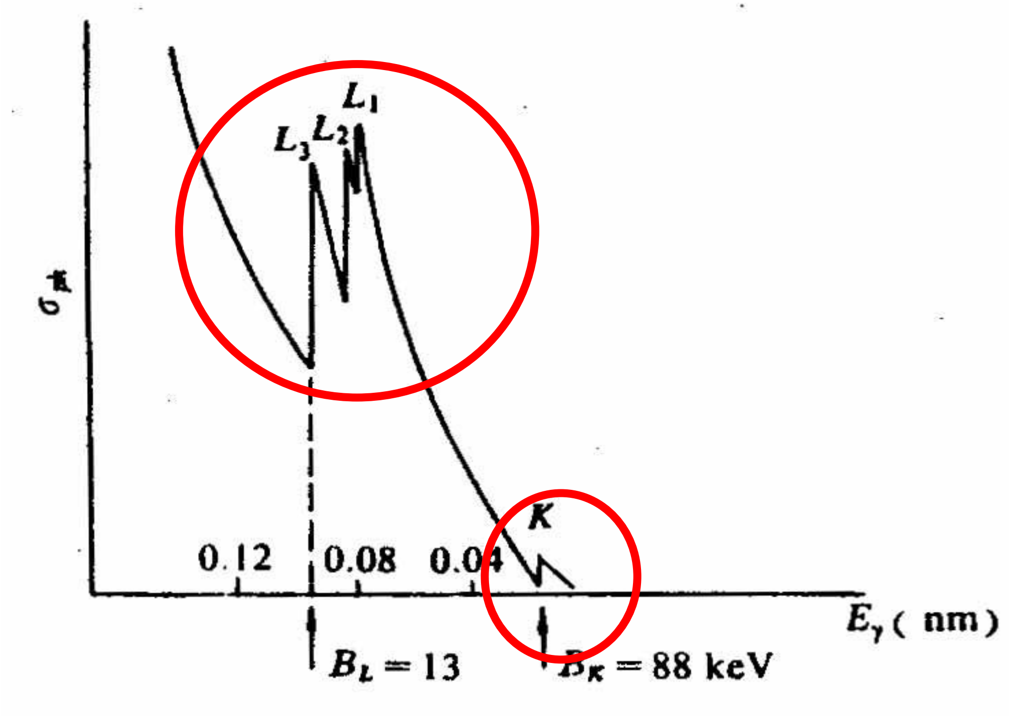
Angular distribution of photoelectrons

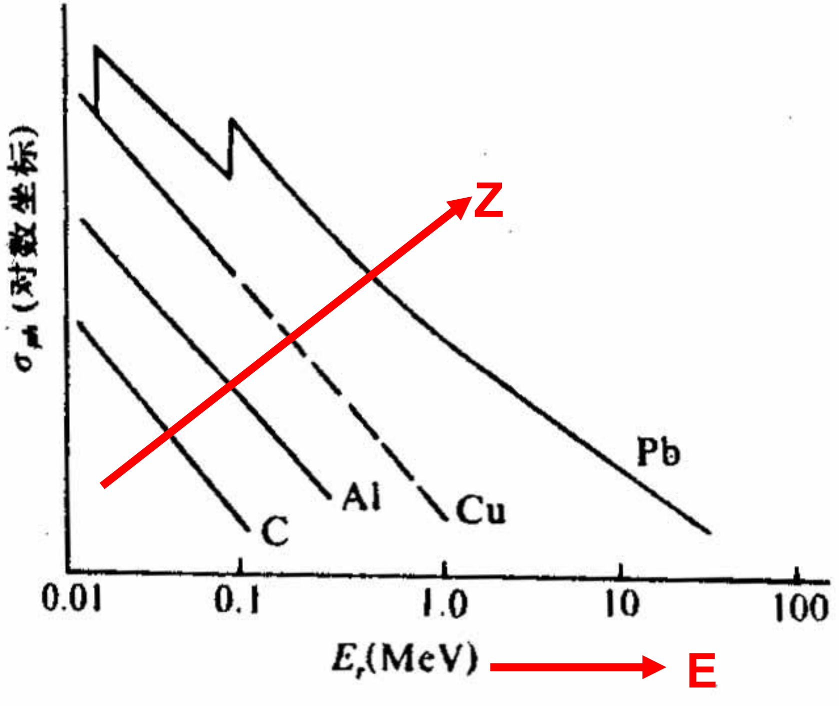
The direction of incoming photon



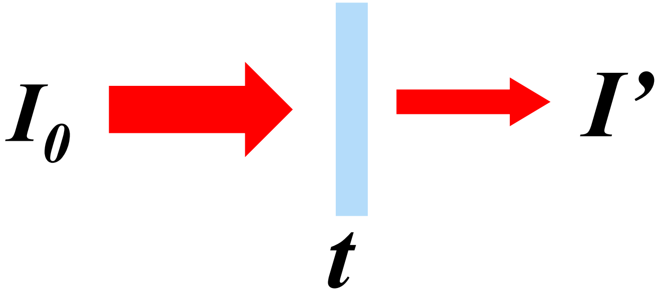
Photoelectric effect cross section

cross section: the probability of interaction between microscopic particles: the probability of a particle colliding with another particle in a unit area perpendicular to the direction of motion per unit time.
A geometric cross section equivalent to the probability of collision.





X-ray attenuation (absorption) in matter



Photoelectric effect, scattering (including Compton effect), electron pair effect…

$$\frac{I' - I_0}{I_0} = \frac{dI}{I_0} = -\mu t$$

$$I = I_0 \exp(-\mu t)$$

$$\mu = \mu_{ph} + \mu_c + \mu_p$$

Linear Absorption Coefficient and Mass Absorption Coefficient

The attenuation of X-rays (Compton scattering, photoelectric effect, electron pairs) is related to the total number of interacting atoms (electrons) and has nothing to do with their morphology (density).

$$\mu_m = \frac{\mu}{\rho}$$

$$I = I_0 \exp(-\mu t) = I_0 \exp\left(-\frac{\mu}{\rho} \cdot \rho t\right) = I_0 \exp(-\mu_m t_m)$$

Mass absorption coefficient
Mass thickness:

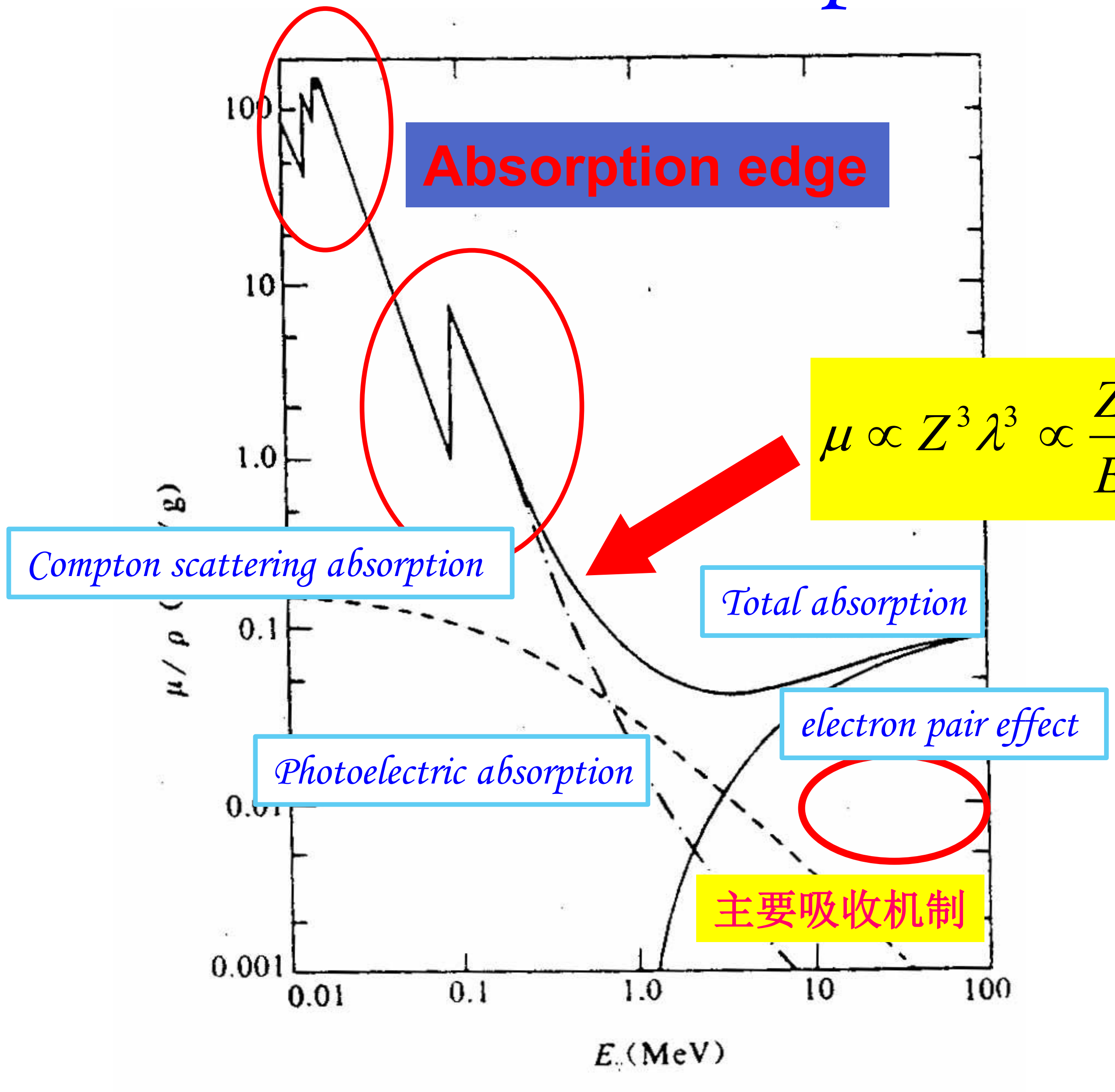
$$t_m = \rho t$$

compound or mixture

$$\mu_m = \sum_{i=1}^{n} w_i \mu_{mi}$$

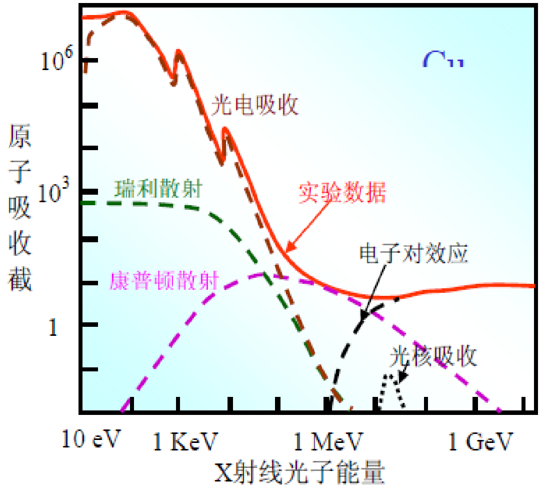
The weighted sum of each component

Absorption coefficient

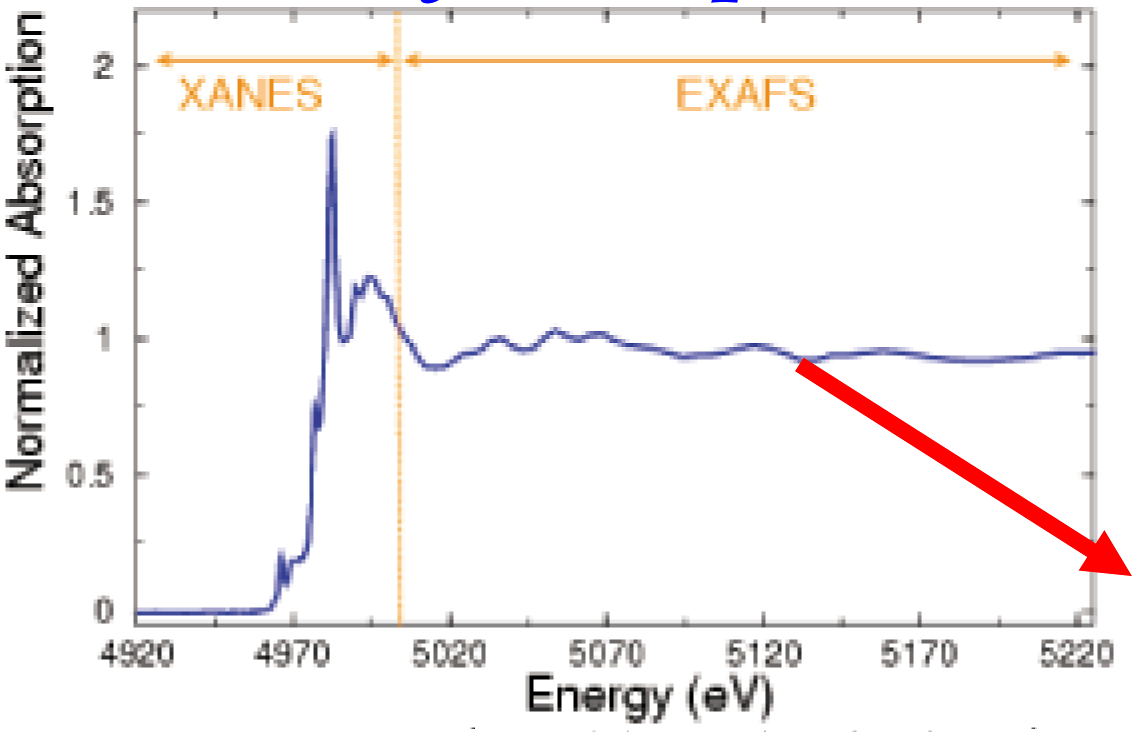


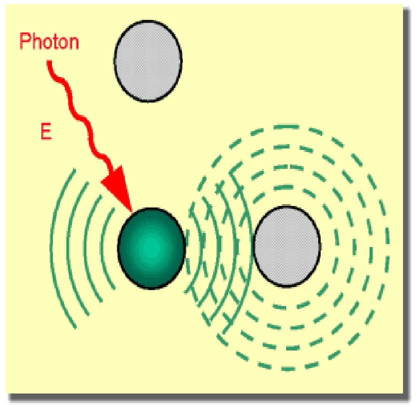
$$\mu \propto Z^3 \lambda^3 \propto \frac{Z^3}{E_\gamma^3}$$

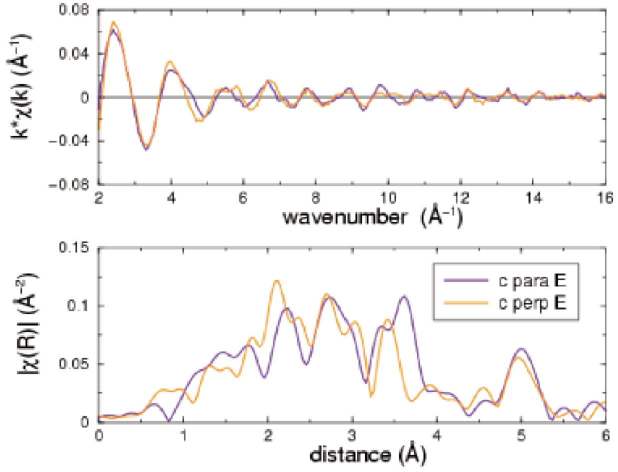
- **X-ray absorption spectroscopy: XAS**
- **Extended X-ray absorption fine spectroscopy: XAFS**
- **X-ray near-edge absorption spectroscopy: XANSE**



X-ray Absorption Near Edge Structure (XANES) and Extended X-ray Absorption Fine Structure (EXAFS)



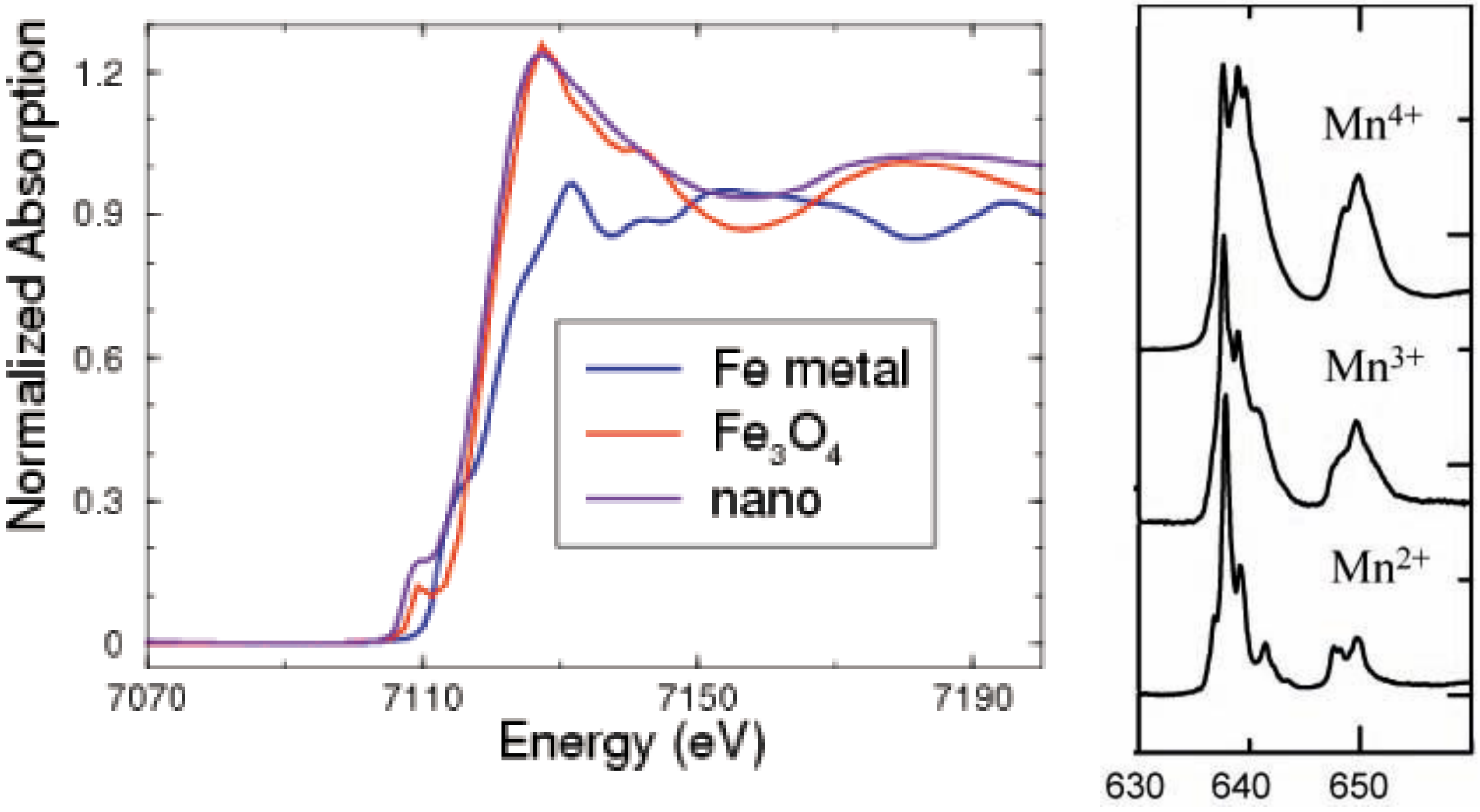




Near-edge region
0-50 eV
Valence transitions
Multiple-scattering theory
Chemical bonds
(NEXAFS or XANES)

Extended X-ray Absorption Fine Structure (EXAFS)
>50 eV to several 100's of eV
Near-neighbor geometry

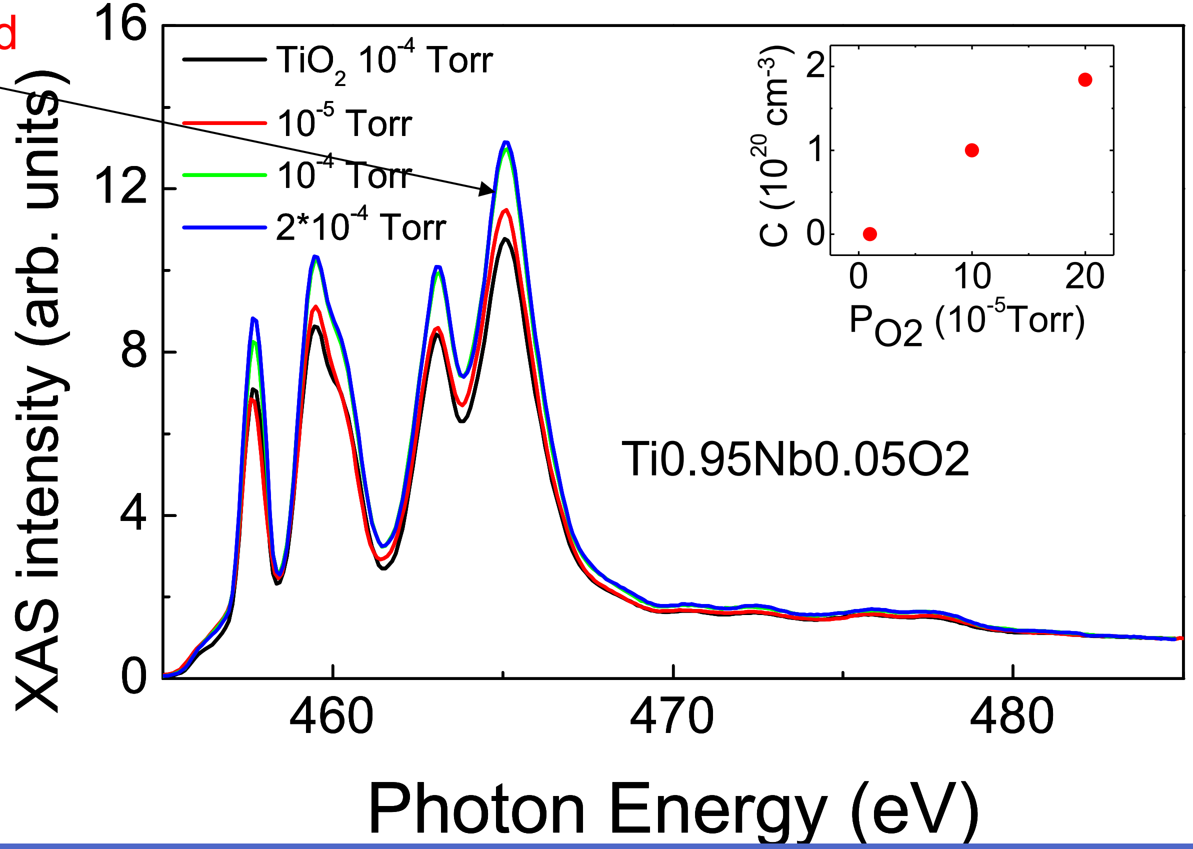
XANES



Normalized Absorption
1.2
0.9
0.6
0.3
0
7070
7110
7150
7190
Energy (eV)
Fe metal
Fe3O4
nano
Mn4+
Mn3+
Mn2+
630
640
650

XANES

More holes for Ti with higher pressure and Nb!

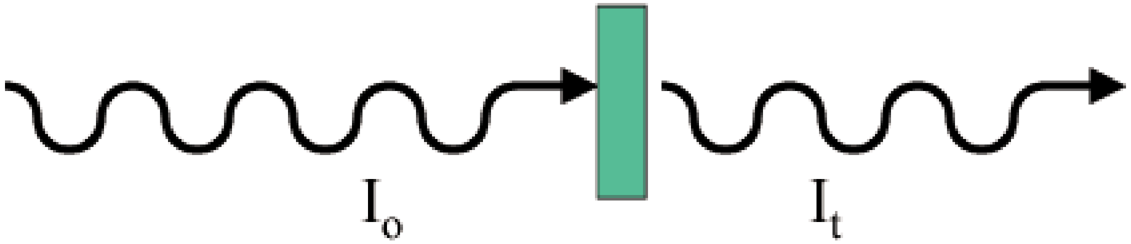


Ti L edge XAS spectra for different TiO2 films. The inset: the concentration of magnetic moment vs oxygen partial pressure.

Adv. Mater. , 21, 2282, (2009).

Different detection modes

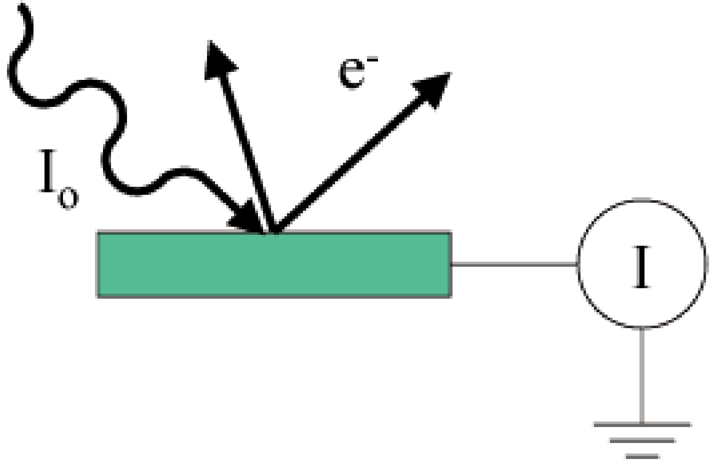
(a) Transmission—bulk properties



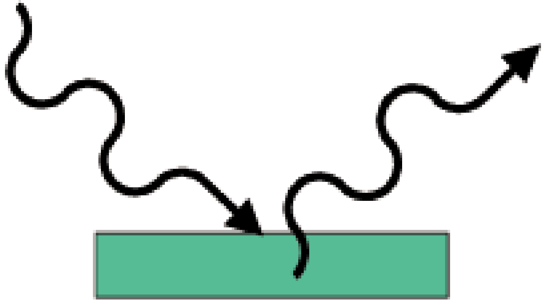
$$I_t = I_0 e^{-\mu(\hbar\omega)d}$$

$$\mu(\hbar\omega) = -\frac{1}{d}\ln\left(\frac{I_t}{I_0}\right)$$

(b) Total electron yield
—surface properties

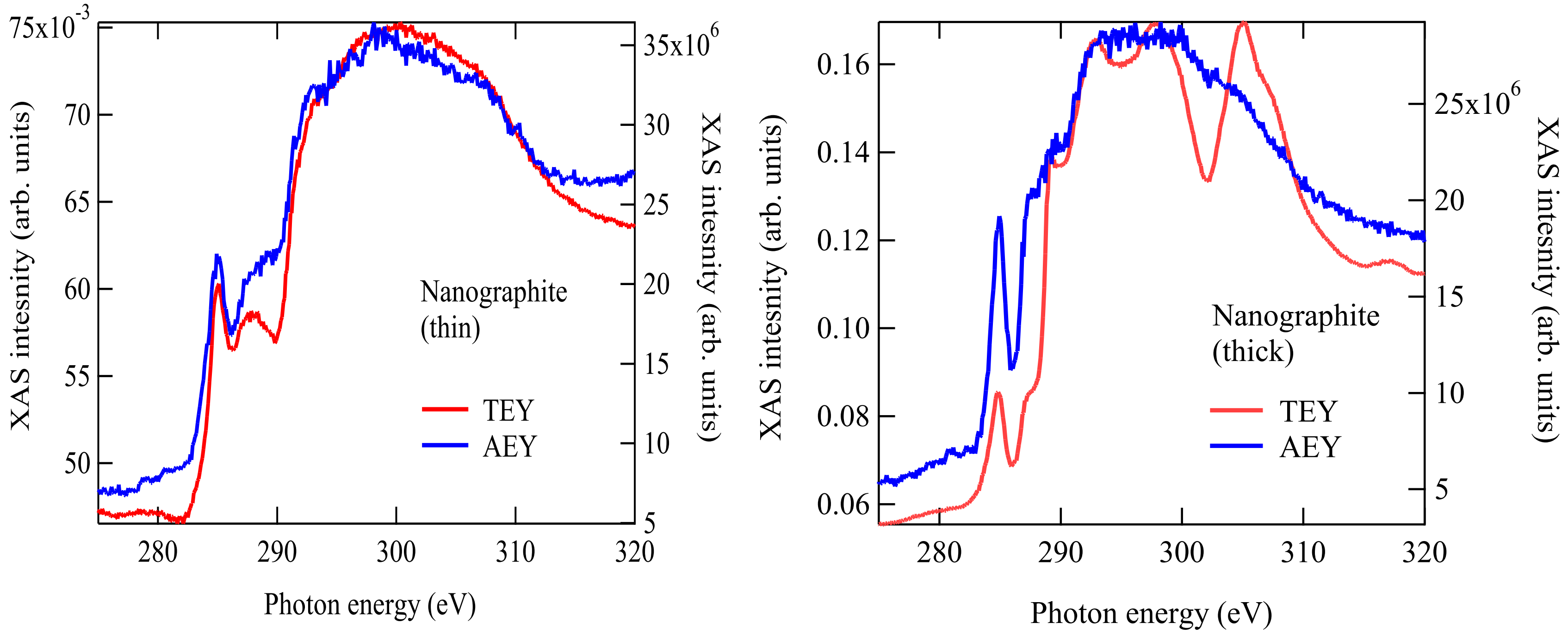


(c) Fluorescence—dilute species;
Buried interfaces



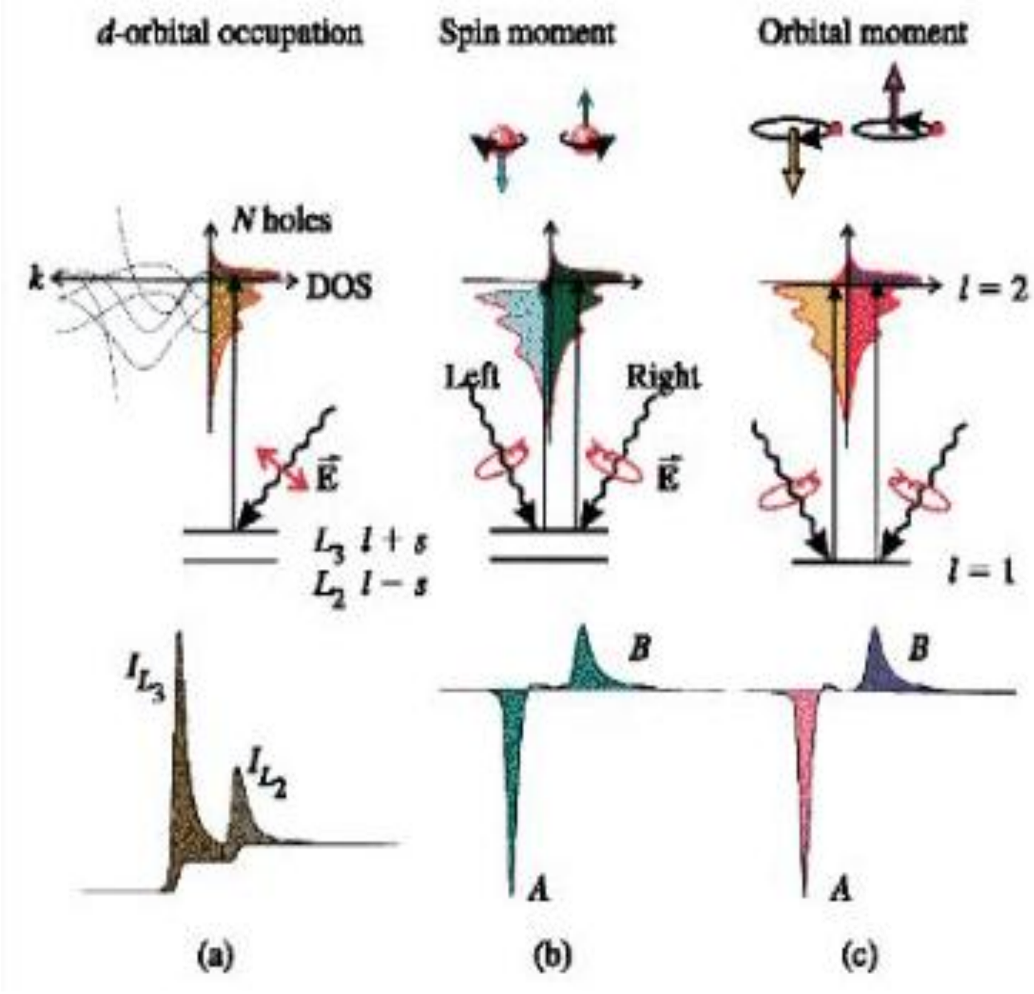
Different surface sensitivity !

Nanographite: chemical states at different depths



C K-edge XANES spectra of one kind of nanographite at different thicknesses

XMCD (x-ray magnetic circular dichroism)



Dipole selection rules

For left-circular

Δ_{ml} **= -1**
Δ_{ms} **= 0**

For right-circular

Δ_{ml} **= +1**
Δ_{ms} **= 0**

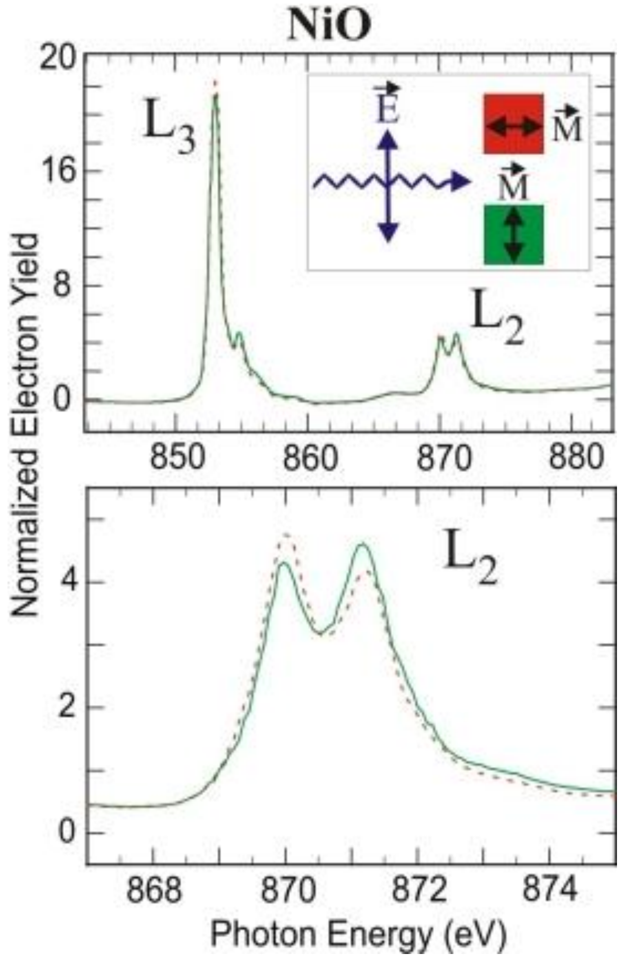
Sum Rules

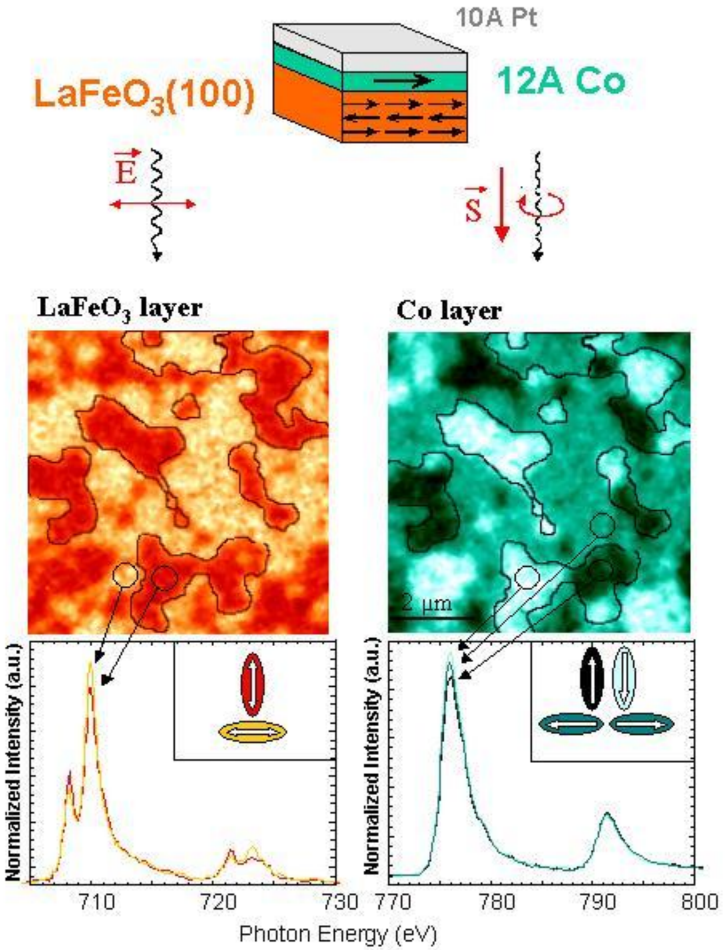
$M_{spin} = C(A - 2B)$ Spin moment

$M_{orb} = C(A + B)$ Orbital moment

C total intensity (number of d-holes)

X-ray magnetic linear dichroism (XMLD)

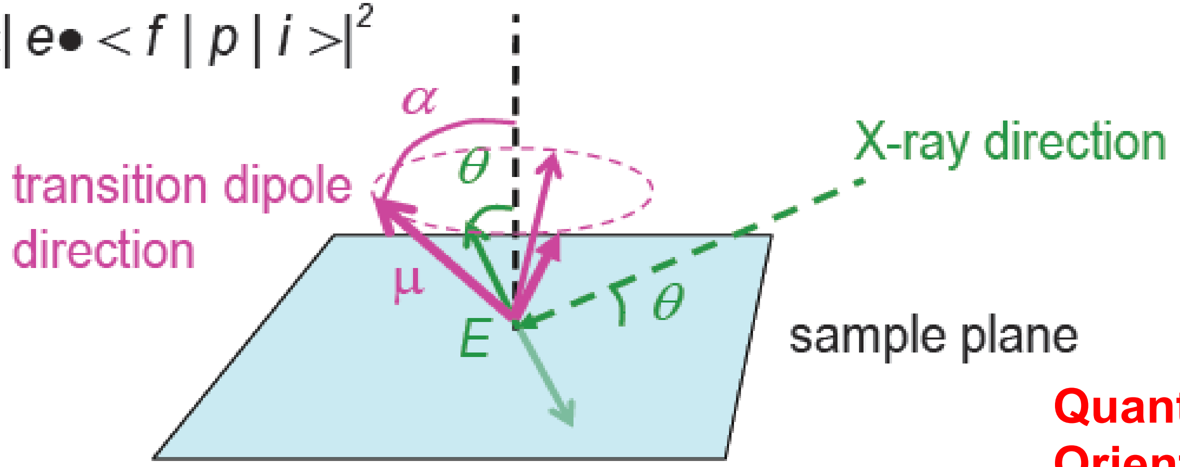




Only sensitive to spin along which axis!

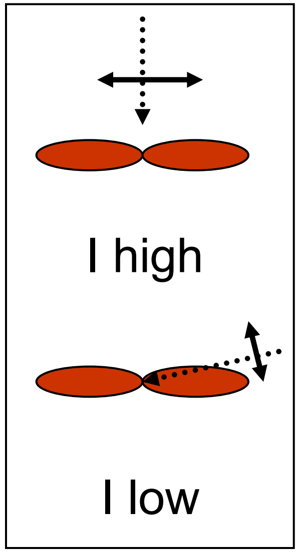
Angular dependence of XANES

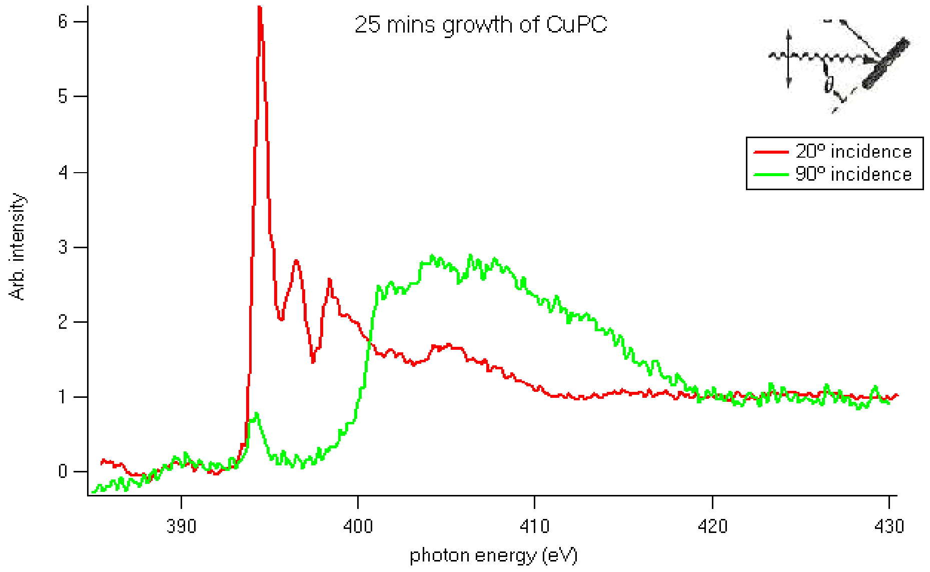
$$I(\theta) \propto | e \bullet \langle f | p | i \rangle |^2$$



Quantitative Orientation!

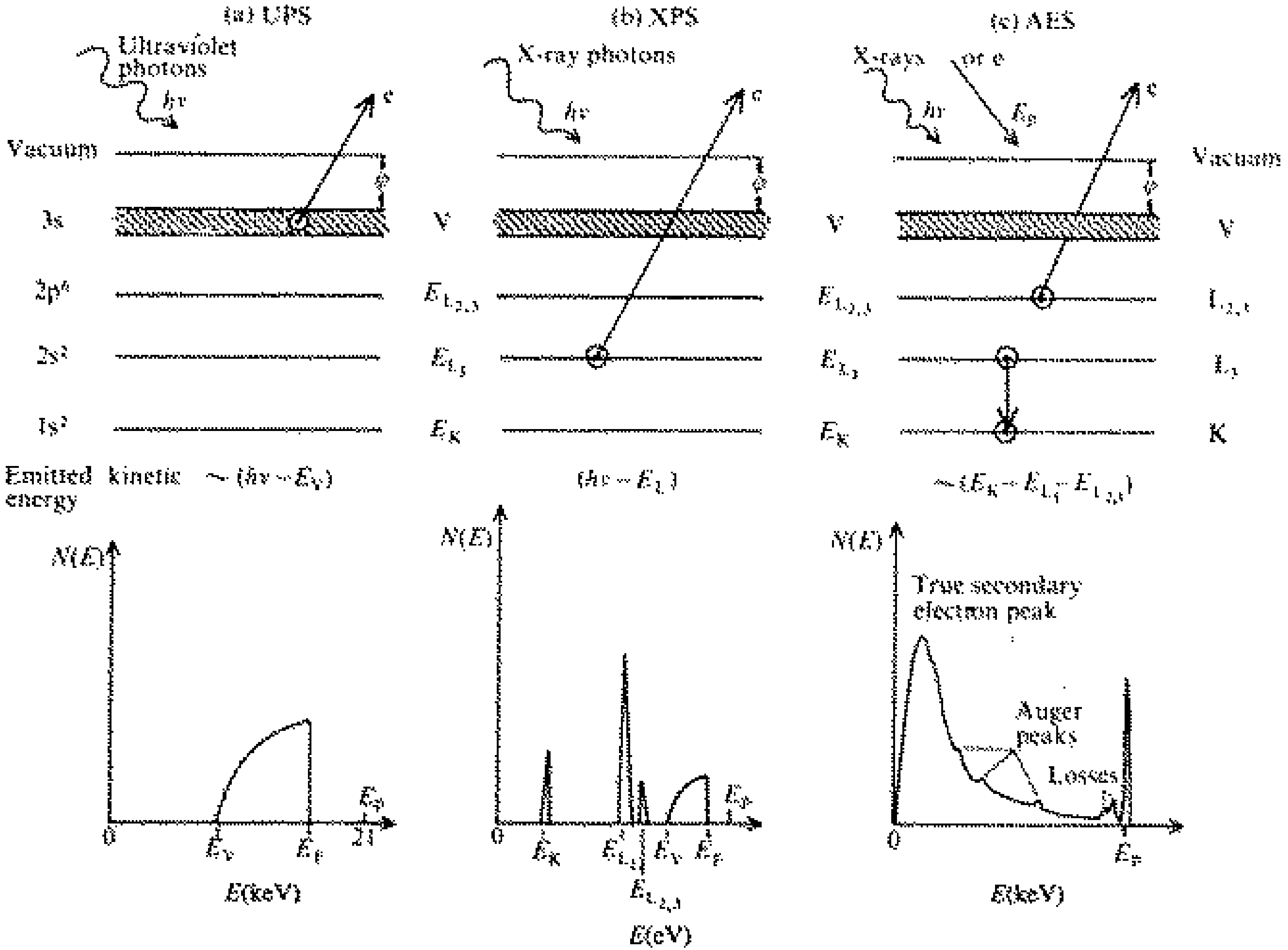
Polarized light



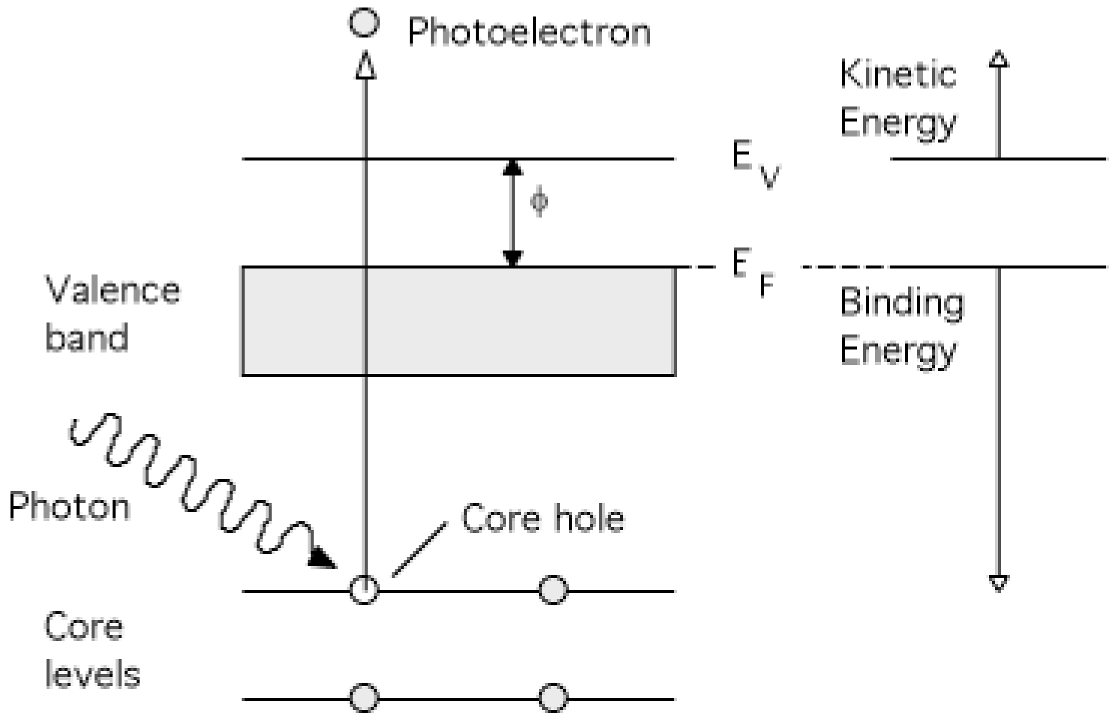


Electron spectroscopies: photoemission

- XPS (X ray photoemission spectroscopy) /ESCA (Electron Spectroscopy for Chemical Analysis)
- Ultraviolet Photoelectron Spectroscopy (UPS)
- Auger electron spectroscopy



Theoretical consideration



As photoemission is much more simple process than Auger process, conservation of energy then requires that :

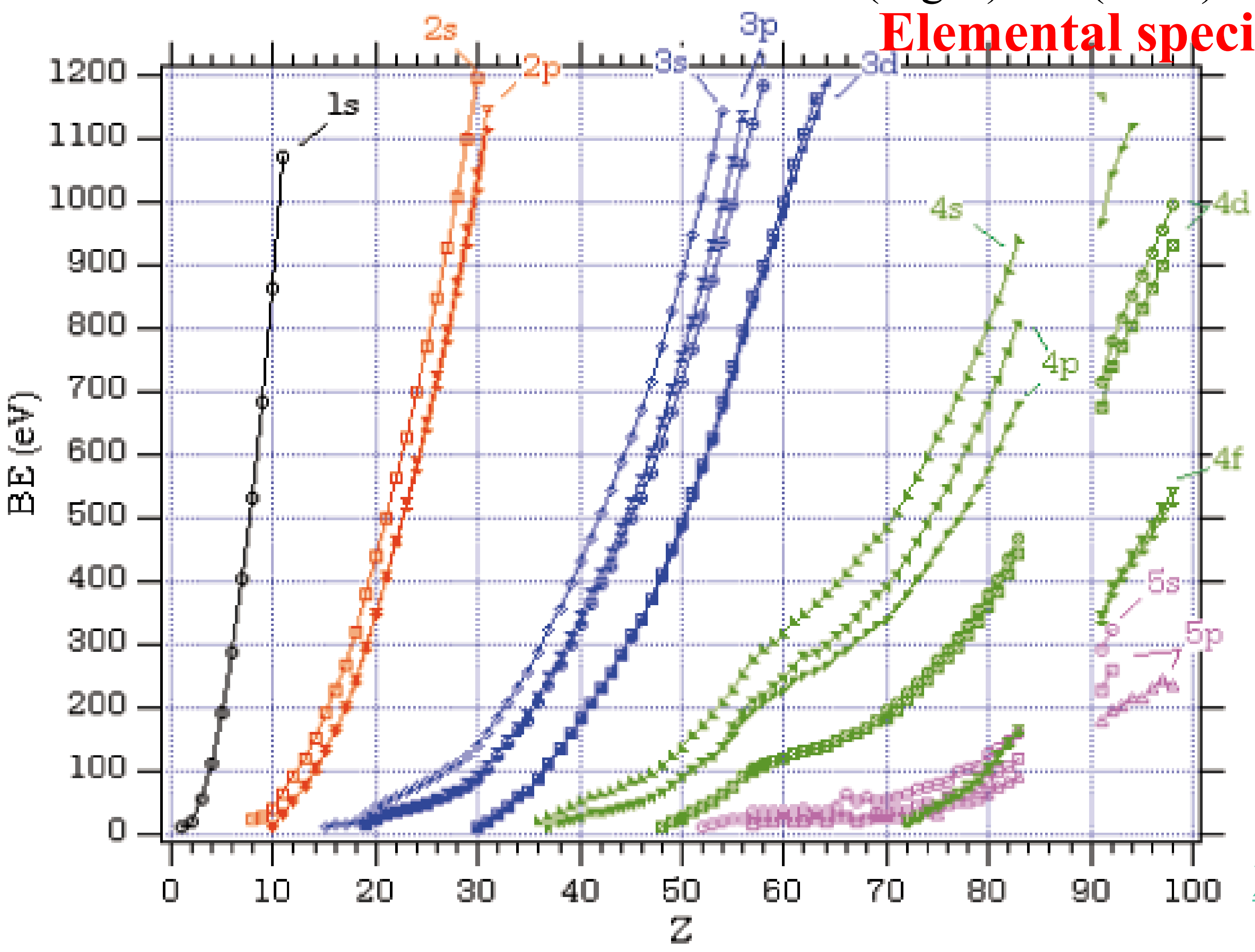
KE = hν - (E(A^+) - E(A)) - Φ

The final term in brackets, representing the difference in energy between the ionized and neutral atoms, is generally called the ***binding energy*** (BE) of the electron . (Φ is the work function of the solid when KE is counted near surface, however, KE detected by analyzer then Φ is the work function of analyzer.)

Z dependence

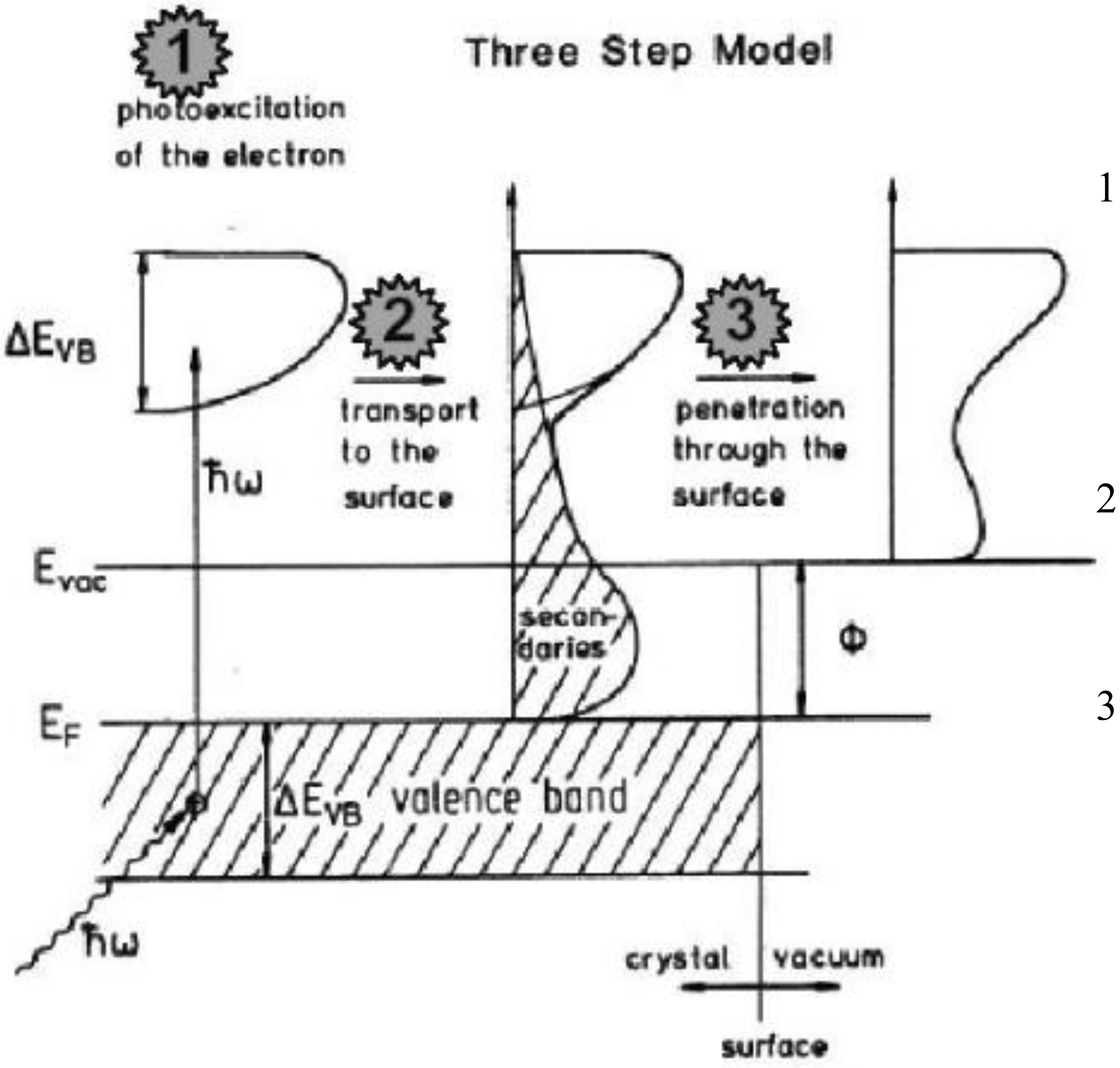
BE follows the energy levels: BE(1s)>BE(2s)>BE(2p)…
BE with same orbital increase with Z: BE(Mg1s)>BE(Na1s)

Elemental specific!



XPS data base

Three Step Model



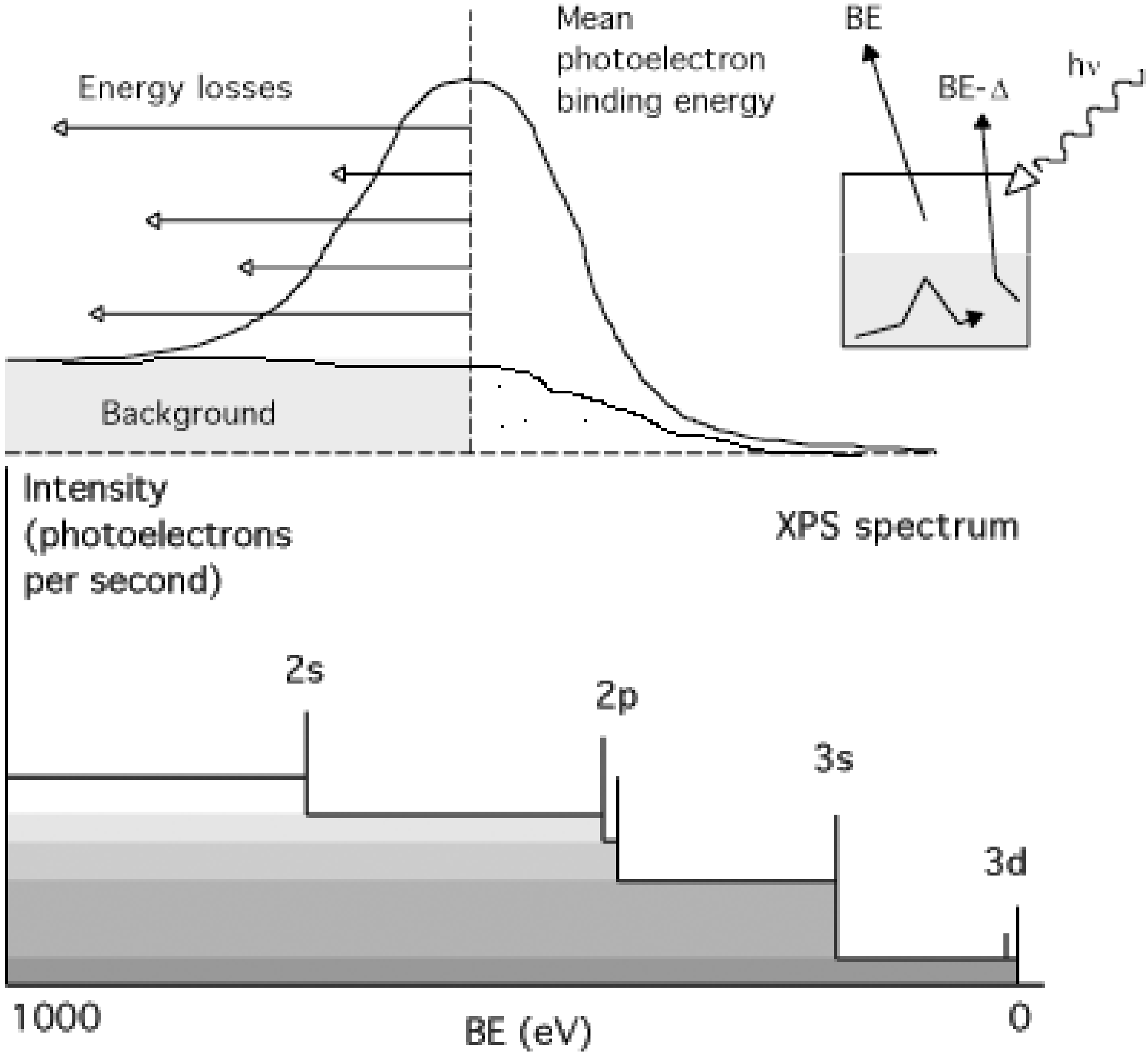
1. Absorption of the photon and excitation of electrons

2. Transport of electrons to the surface

3. The escape of the electrons from surface to the vacuum.

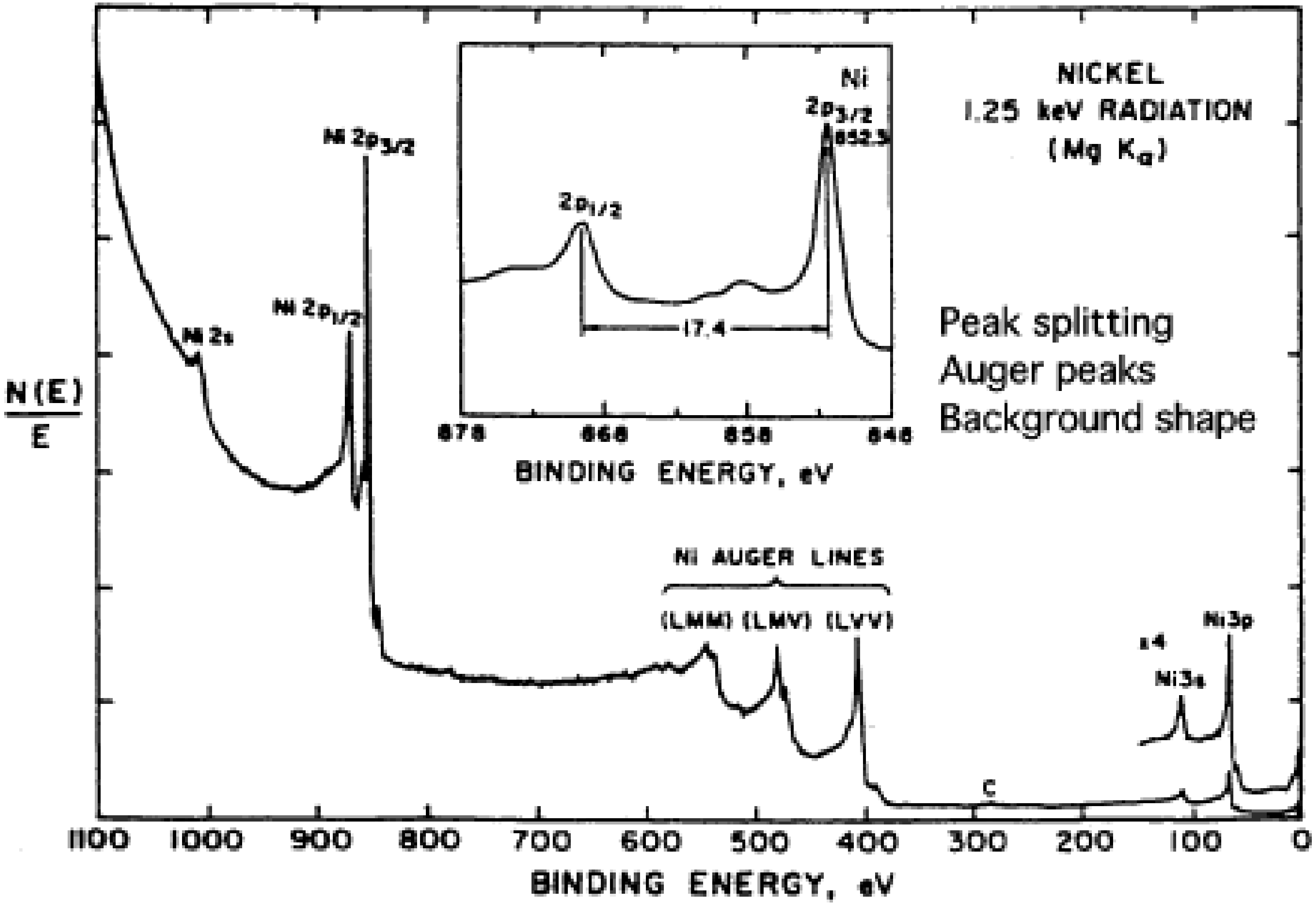
Inelastic scattering

In the step 2, inelastic scattering let XPS spectra consists of core-level photo-emission peaks imposed by a step-like structure (background) due to the various mechanism to lose kinetic energy. Besides, there are also AES processes visible.



XPS peak fit

Main features of XPS



Peak splitting
Auger peaks
Background shape

Core Level Chemical Shifts

Position of orbitals in atom is sensitive to chemical environment of atom. In solid all core levels for that atom shifted by approx. same amount (<10 eV). Chemical shift correlated with *overall charge* on atom (Reduced charge ®increased BE)

For k-shell of an atom in a compound:

$$E_B(k) = E_B(k,q_A) + V$$

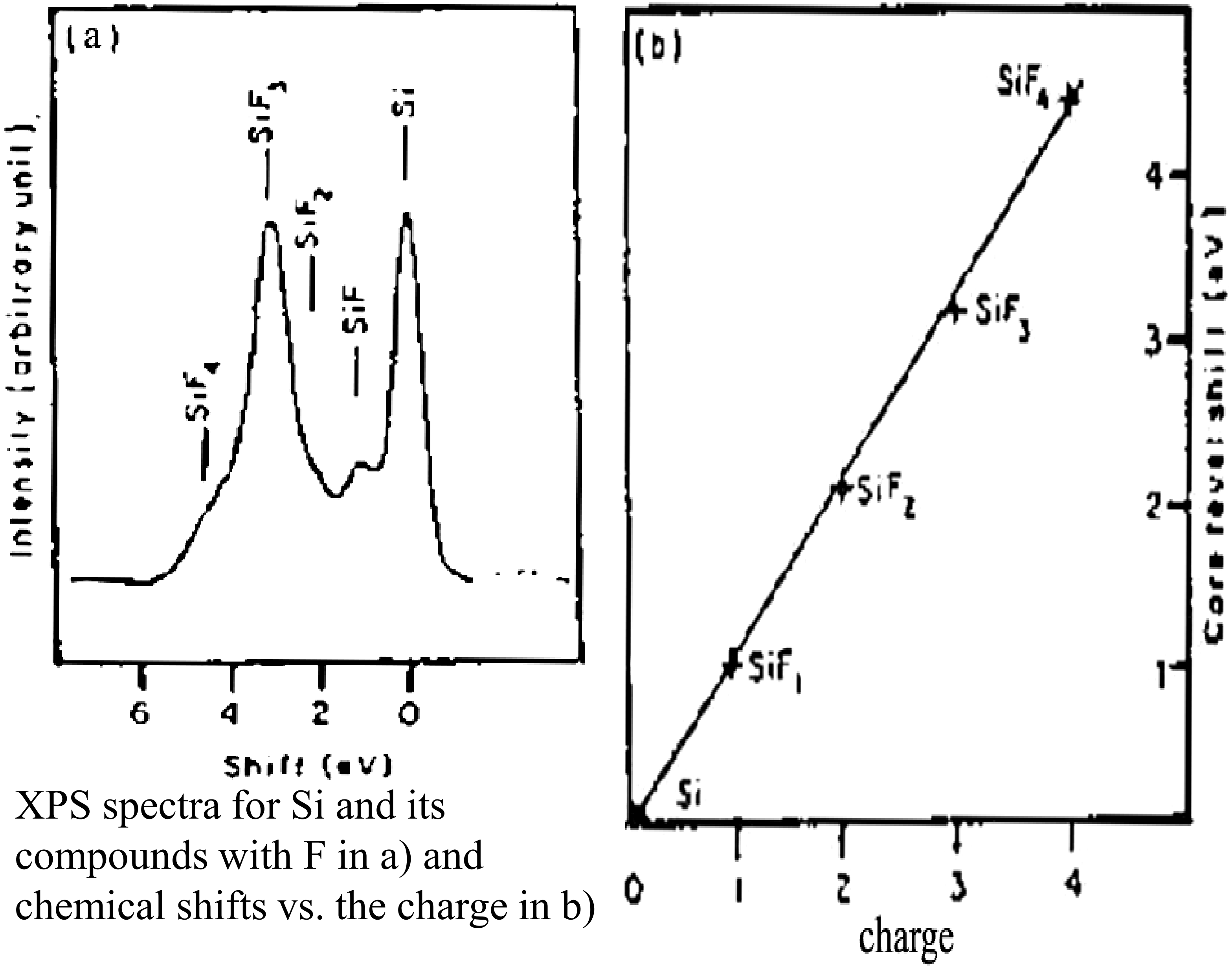
where $E_B(k,q_A)$ is the binding energy of a free ion, A, qA is the net charge of A, and V is the potential at A due to all other atoms. V can be described as:

$$V = e^2 q_A \Sigma q_i / r_{iA}$$

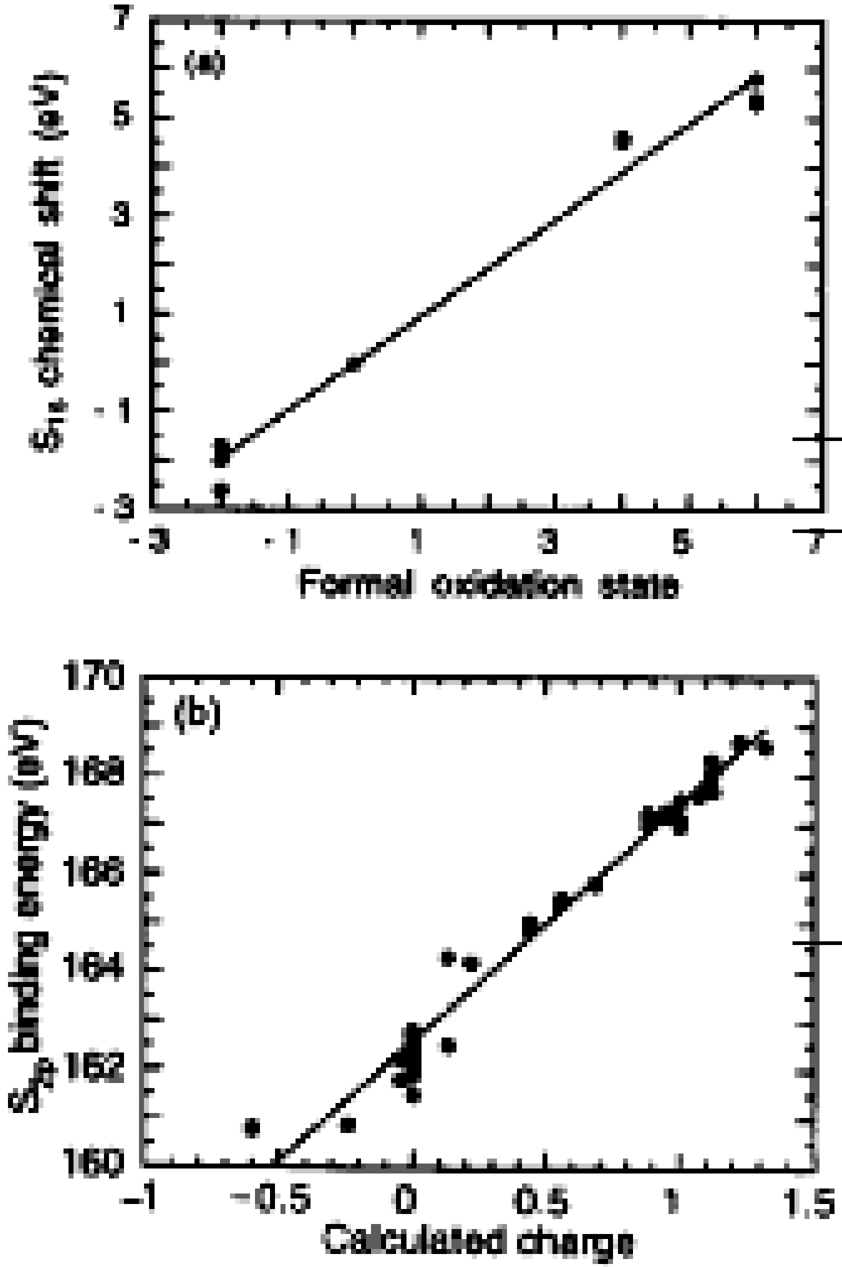
(i is any other atoms except A), r_{iA} **is the distance between i and A, therefore chemical shift is:**

$$\Delta E_B(k) = E_B(k,q_{A1}) - E_B(k,q_{A2}) + V_1 - V_2$$

q_{A1} and q_{A2} **is the difference of charge in two states.**

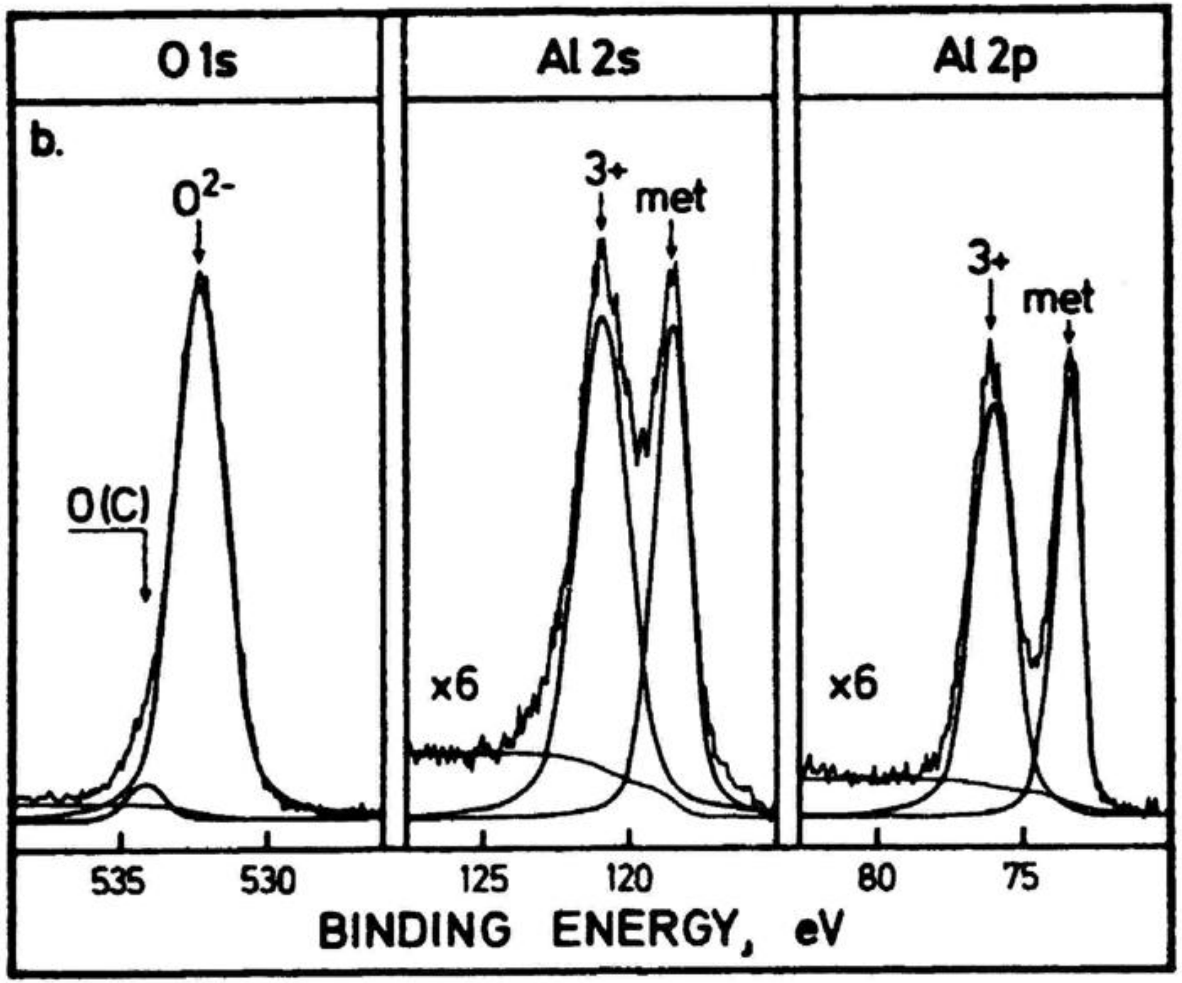


XPS spectra for Si and its compounds with F in a) and chemical shifts vs. the charge in b)



Both S and Si binding energies increase with psitive charge (the loss of negative charge of electron), and the same for C.

Functional Group		***Binding Energy (eV)***
hydrocarbon	C-H, C-C	285.0
amine	C-N	286.0
alcohol, ether	C-O-H, C-O-C	286.5
Cl bound to C	C-Cl	286.5
F bound to C	C-F	287.8
carbonyl	C=O	288.0



The **chemical shifts** due to the variation of the distribution of the charges at the atom site is the main reason for the other name of XPS:

ESCA

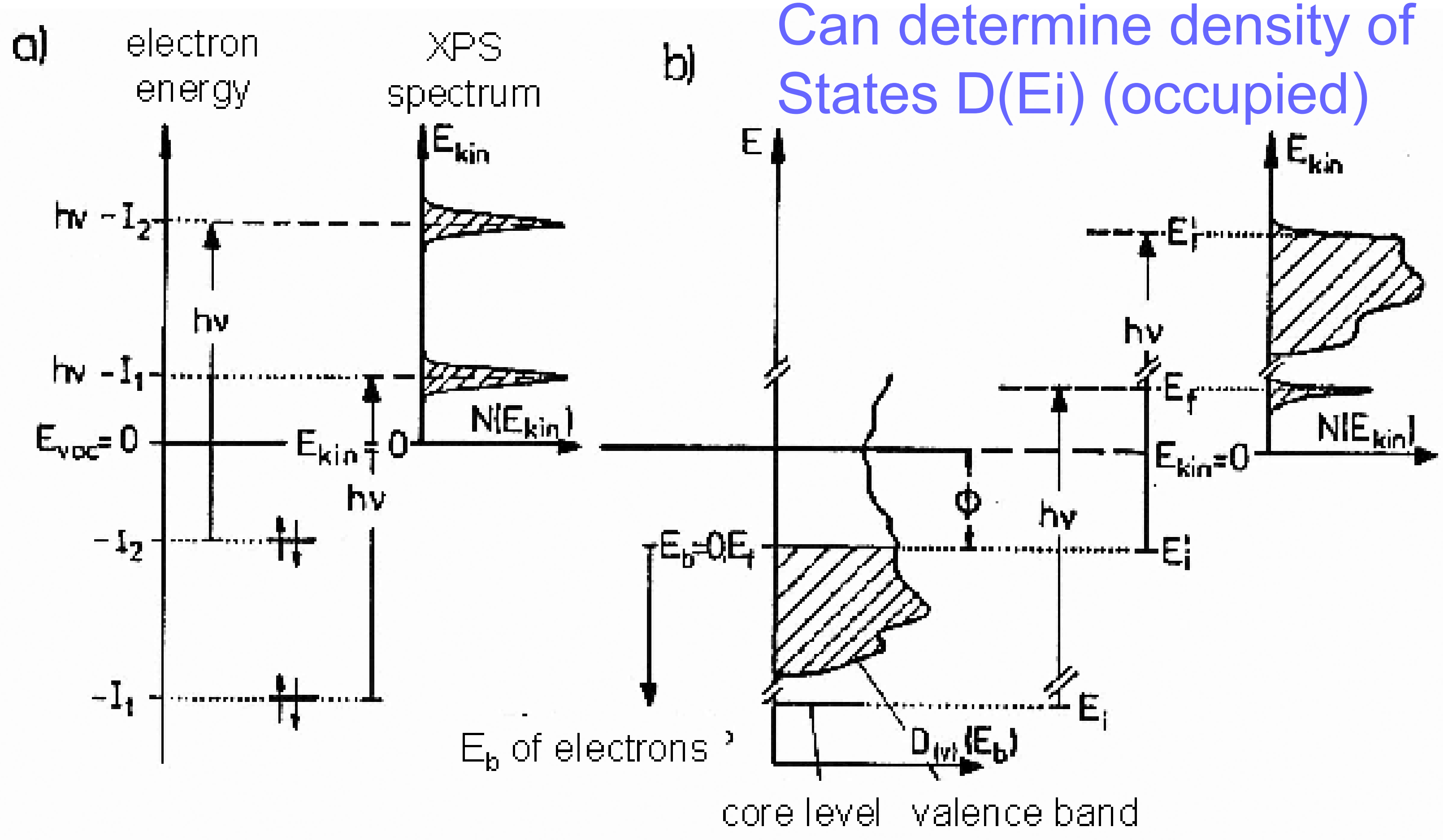
(Electron Spectroscopy for Chemical Analysis)

As the samples shown before, binding energies of Al^{3+} is higher than the metal atom, in the meanwhile, the binding energy of O atom (more positive charge) is higher than the O^{2-} ion.

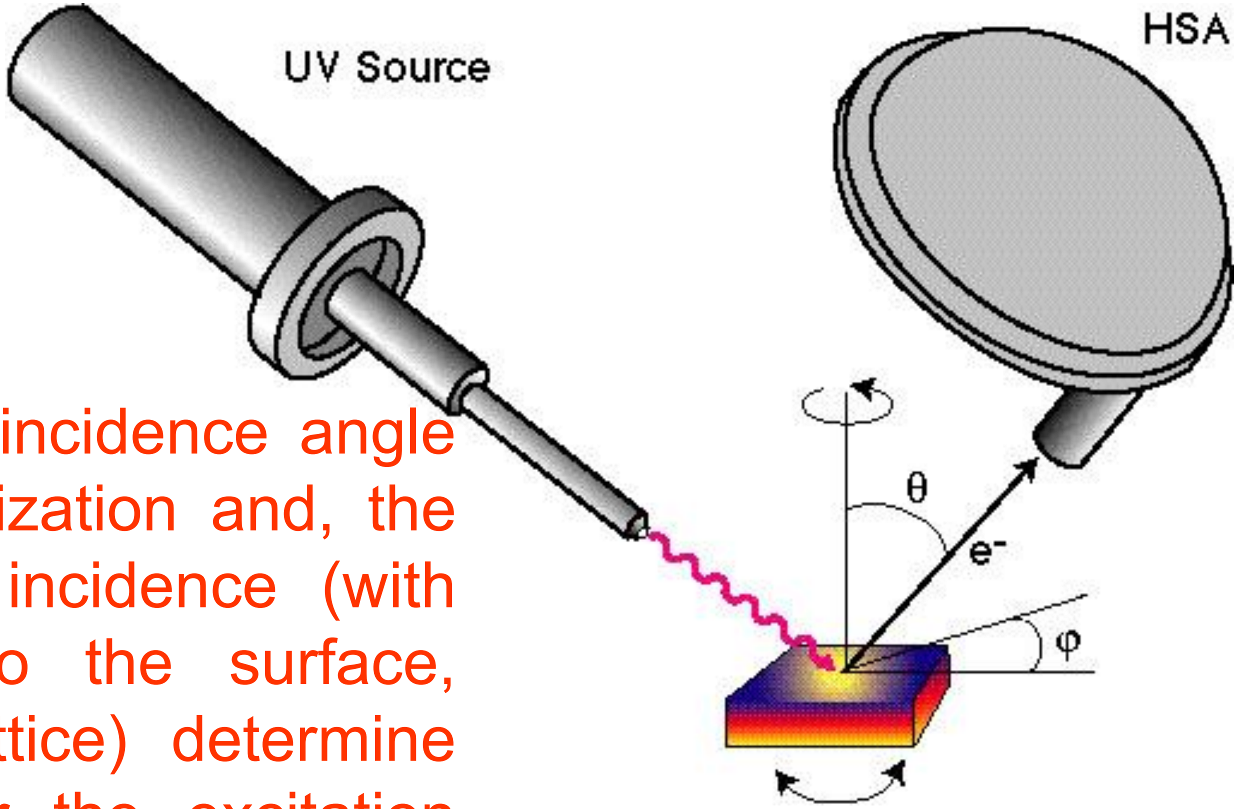
Ultraviolet Photoelectron Spectroscopy (UPS)

UV light (hν = **5 to 100** eV) to excite photoelectron. From an analysis of the kinetic energy and angular distribution of the photoelectrons, information on the **electronic structure** (band structure) of the material under investigation can be extracted with surface sensitivity.

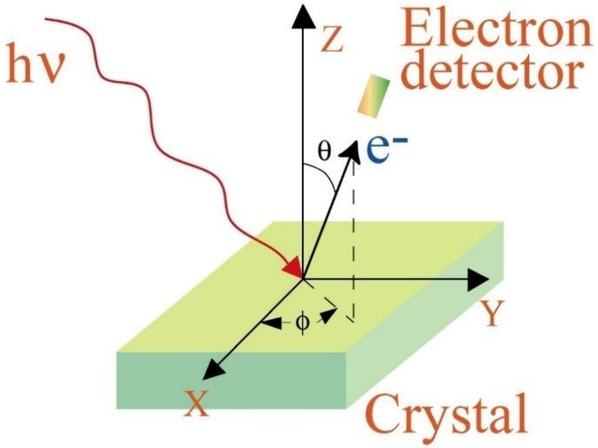
Can determine density of States D(Ei) (occupied)



Angular Resolved UPS (ARUPS)



The light incidence angle and polarization and, the plane of incidence (with respect to the surface, crystal lattice) determine the **A** for the excitation process.



Energy conservation

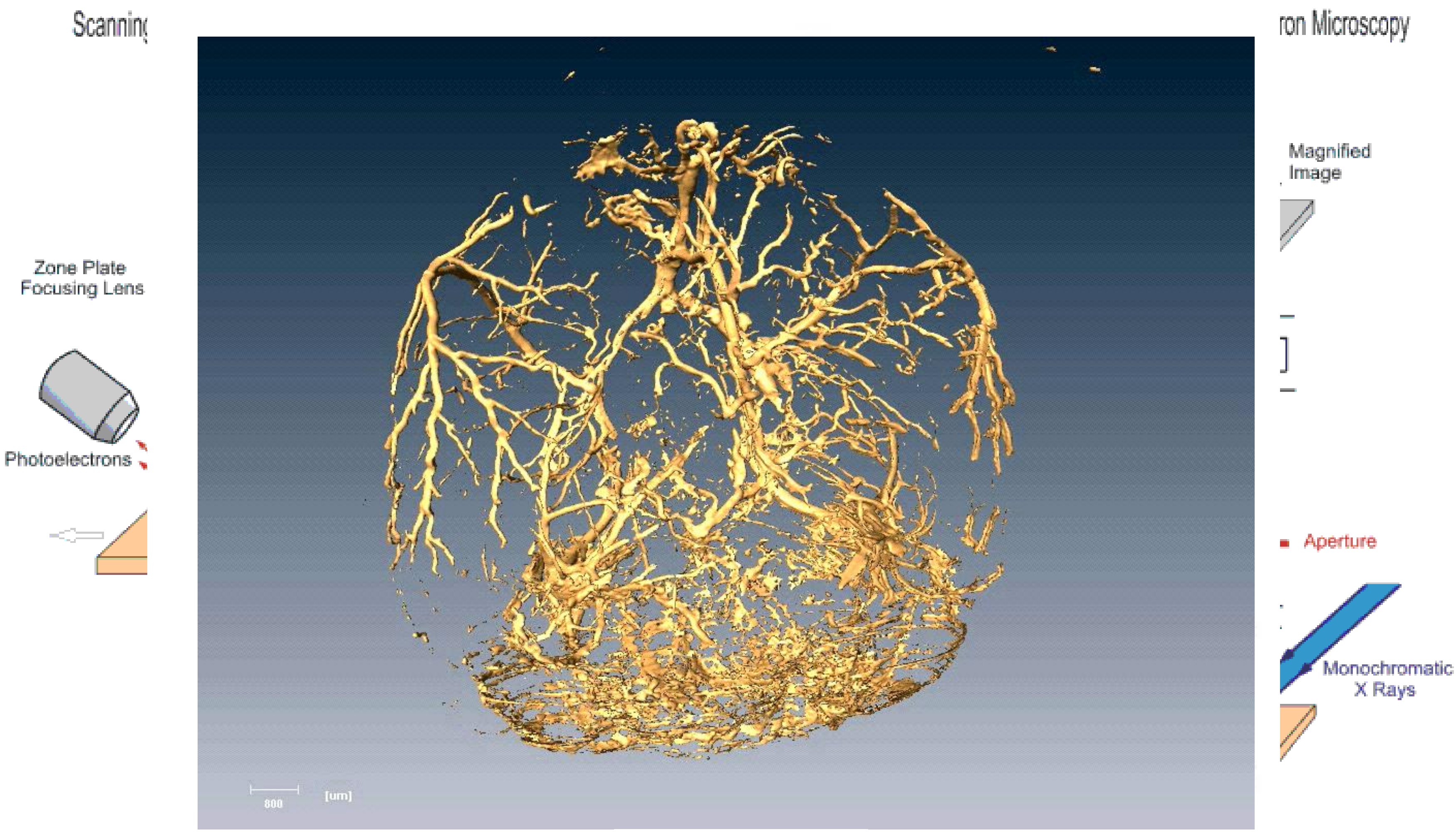
$E_B = h\nu - E_k - \Phi$

Momentum conservation

$K_{||} = k_{||} + G_{||}$

UPS spectra also have strong angular dependence for the excited electron, which can give information about band structure in the k space.

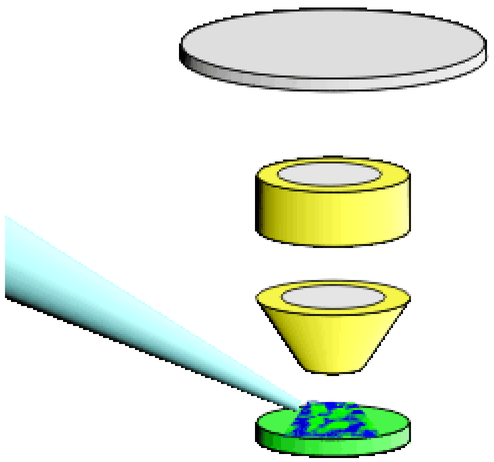
Imaging



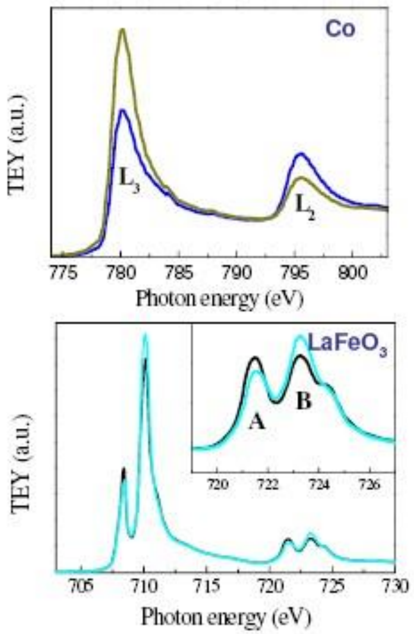
MicroCT

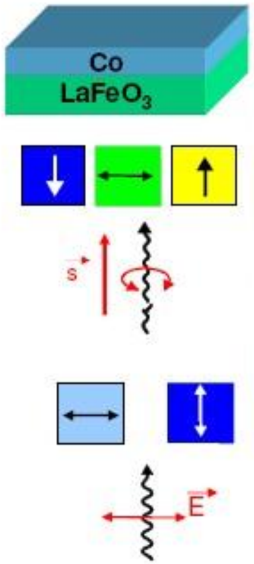
Different contrasts

PEEM

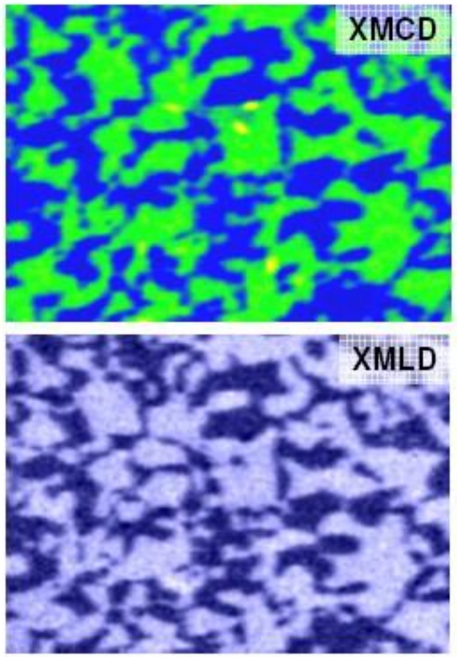


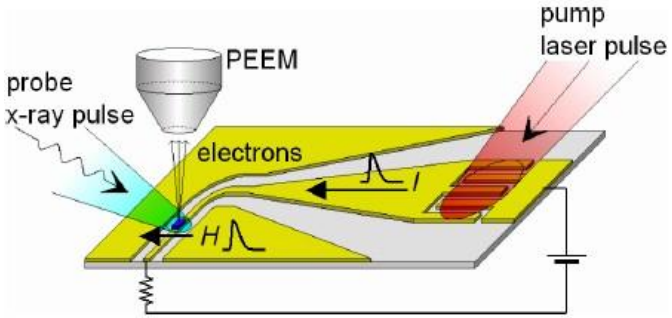
Spectroscopy

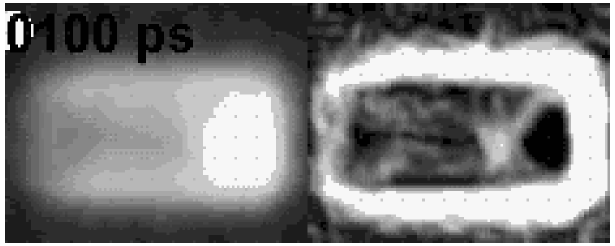




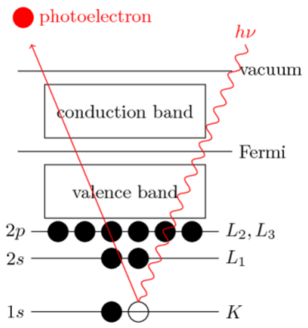
Microscopy

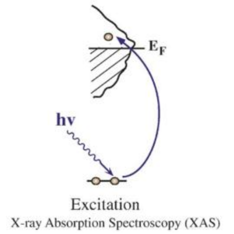


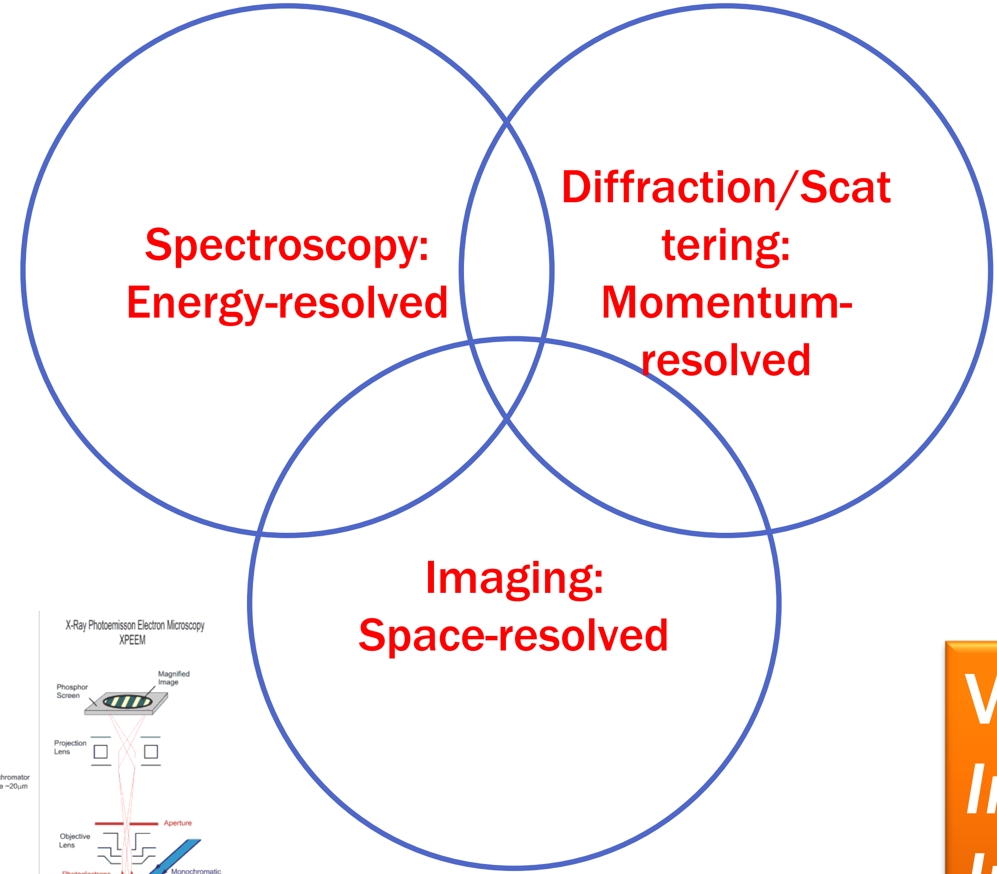


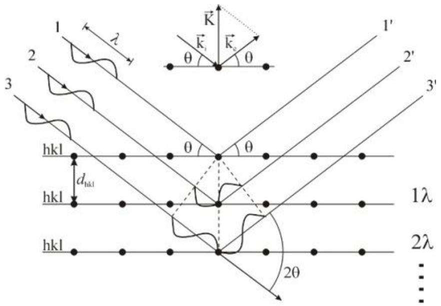


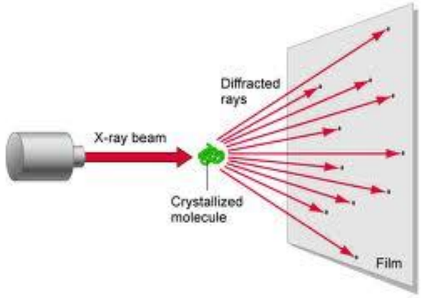
Synchrotron-based techniques

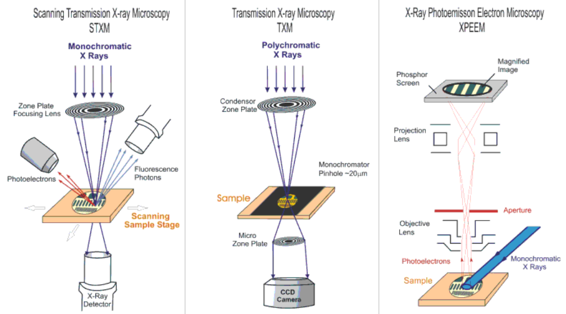








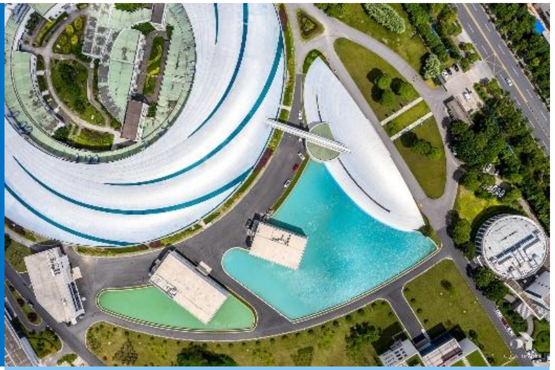




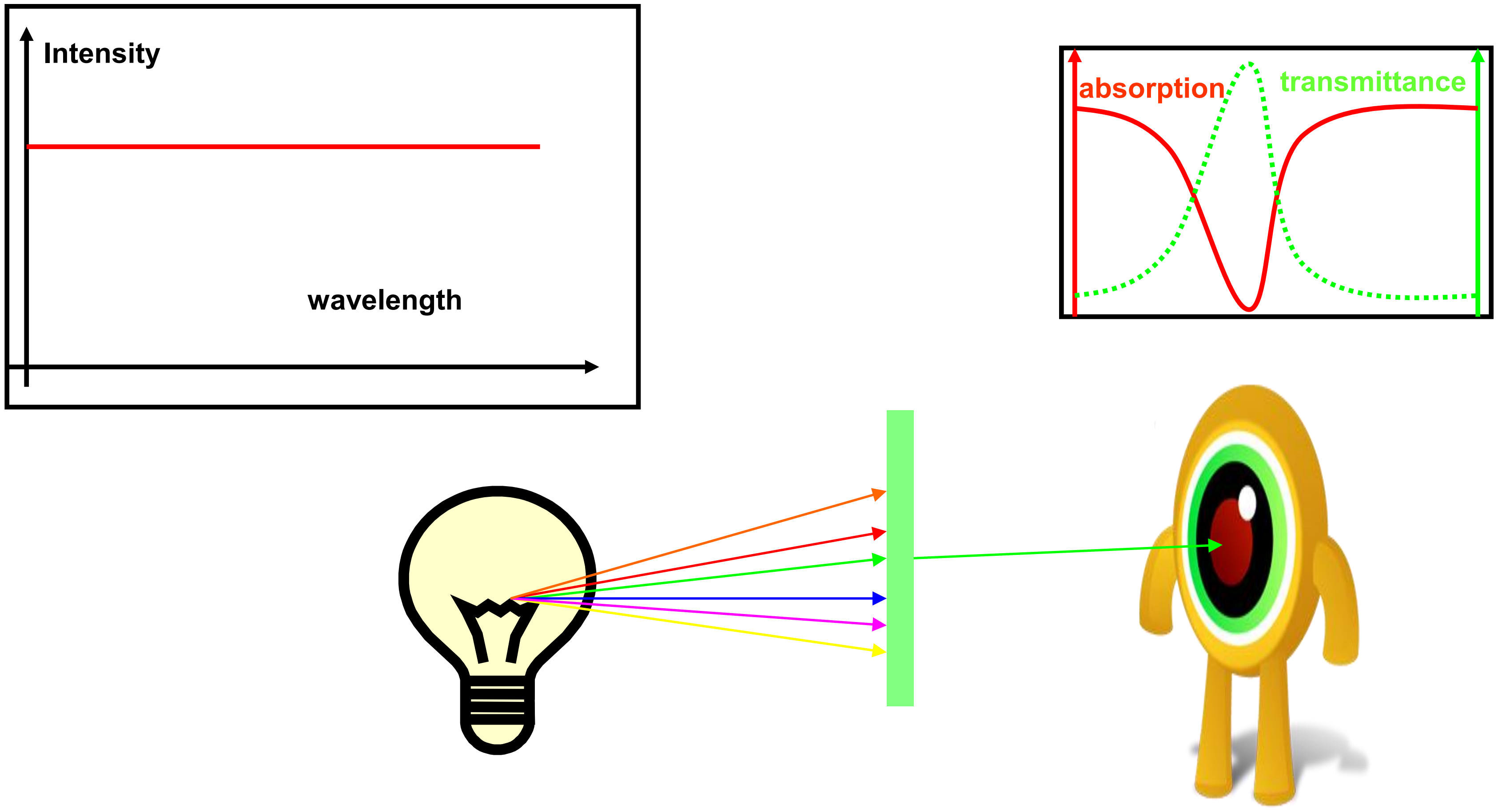
Versatile
In-situ
In-operando

03

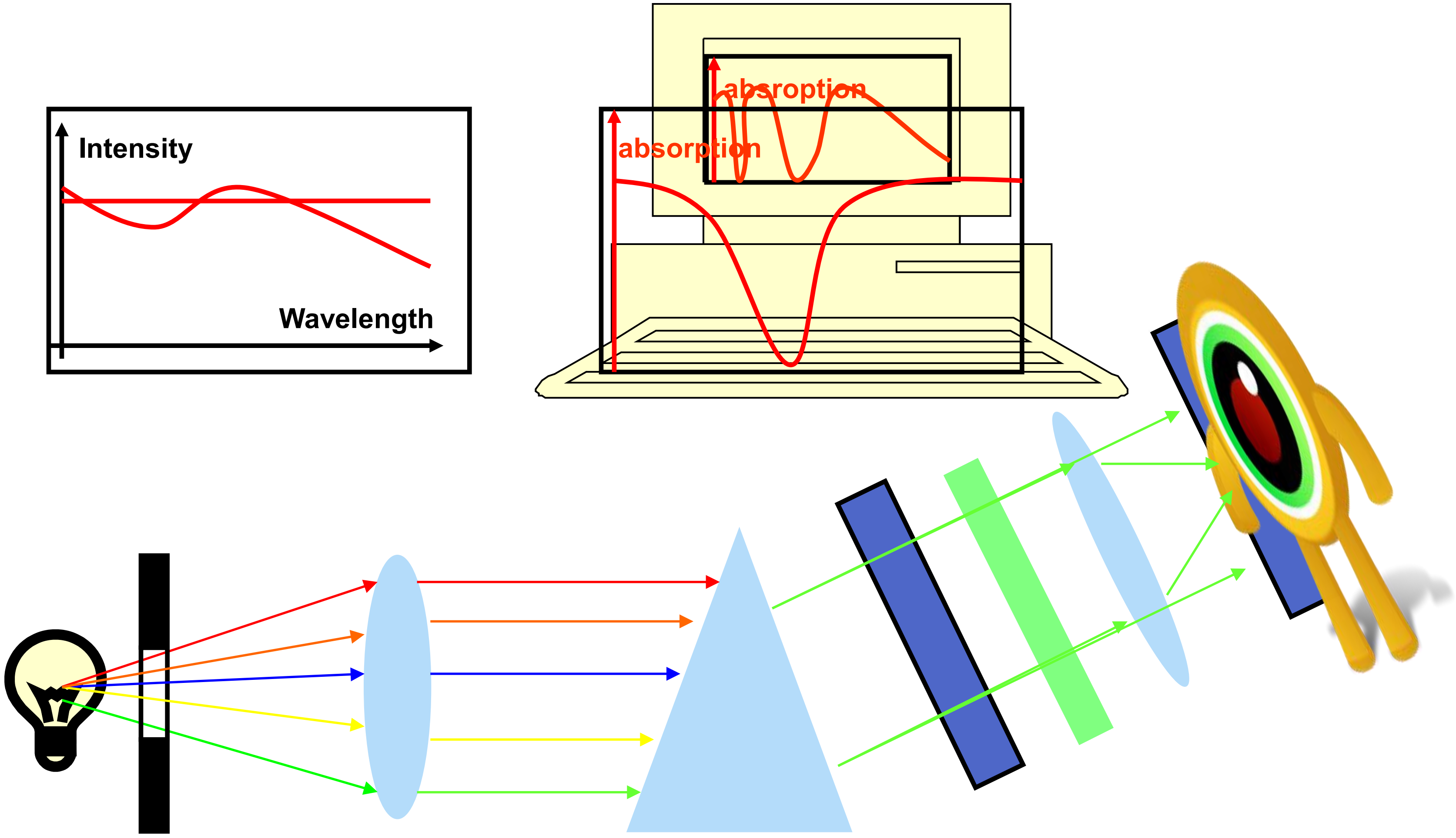
Synchrotron beamlines



Functions of the beamlines



Functions of the beamlines



Key information about beamlines

The study objects/ scientific goals

single crystals, polycrystalline powders, surfaces and interfaces of thin films/ultra-thin films, microstructures of nanomaterials

Crystal structure analysis: crystal structure, crystal constant determination; Phase analysis: qualitative and quantitative analysis of phase (intensity ratio); Grain size; Crystallinity analysis; Stress analysis;Thin film thickness; Reflectivity; Preferred orientation and texture analysis;

Experimental techniques

- Conventional single crystal or powder X-ray diffraction (XRD)
- Grazing incidence X-ray (anomalous) diffraction (GIXRD/GIXAD)
- X-ray reflectivity measurement (XRR)
- Reciprocal space intensity distribution measurement (RSM)
- Diffraction anomalous fine structure (DAFS)
- Multi-wavelength anomalous diffraction (MAD)

Specifications

Energy range
4-10 keV

Energy resolution
$\Delta E/E \sim 1.5\times10^{-4}$@ 10keV

Spot size
~ 0.35 (H) ×2.5 (V) mm^2

Photon flux
~ 1.0×10^{12} phs/s @ 10 keV

Divergence angle
~ 2.5 (H) ×0.02 (V) $mrad^2$

Design and construction of beamlines

Physical Design:

X-ray Optics

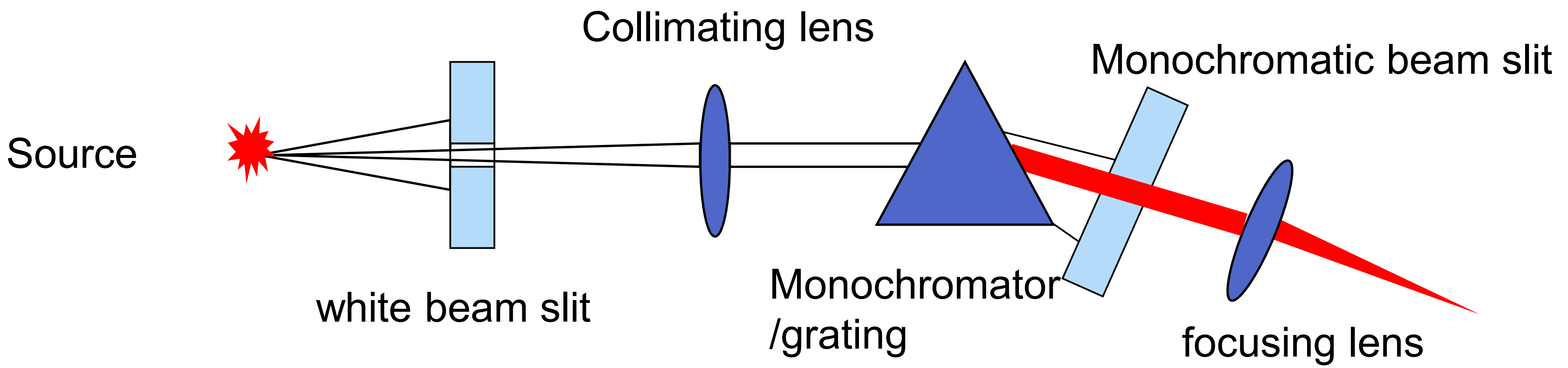
- Mirrors, monochromators
- Bending mechanisms
- Ultra-high vacuum
- Mechanical motion vacuum feed-in
- Remote control
- Signal detection
- Radiation protection

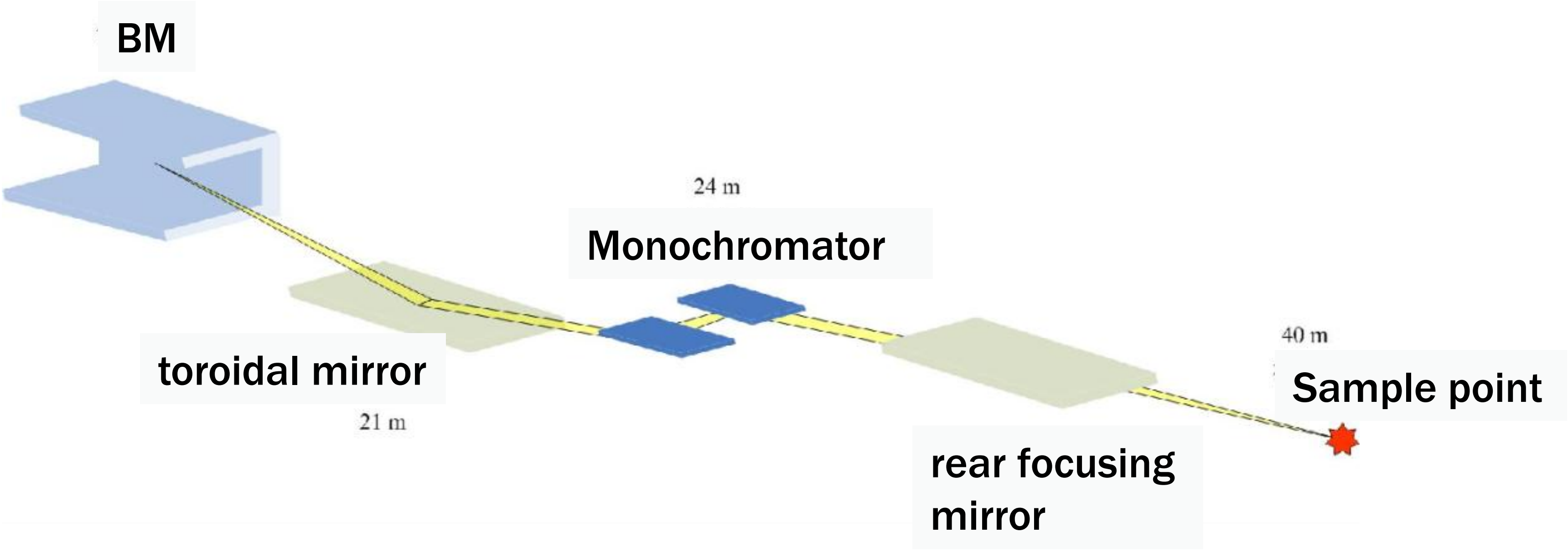
High Heat Loads

- Thermal analysis
- Optical properties
- Cooling
- Flow and temperature monitoring

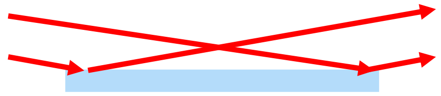
- Optical
- Vacuum
- Mechanical
- Control
- Signal Detection

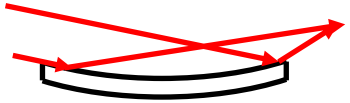
Optical layout of a beamline

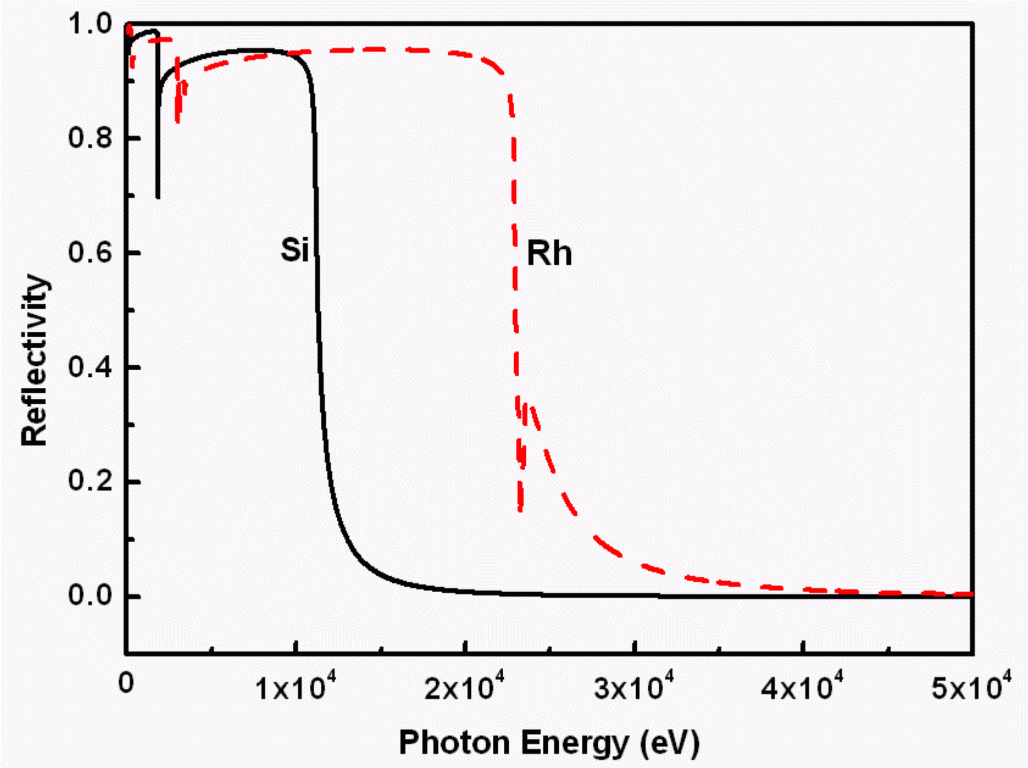


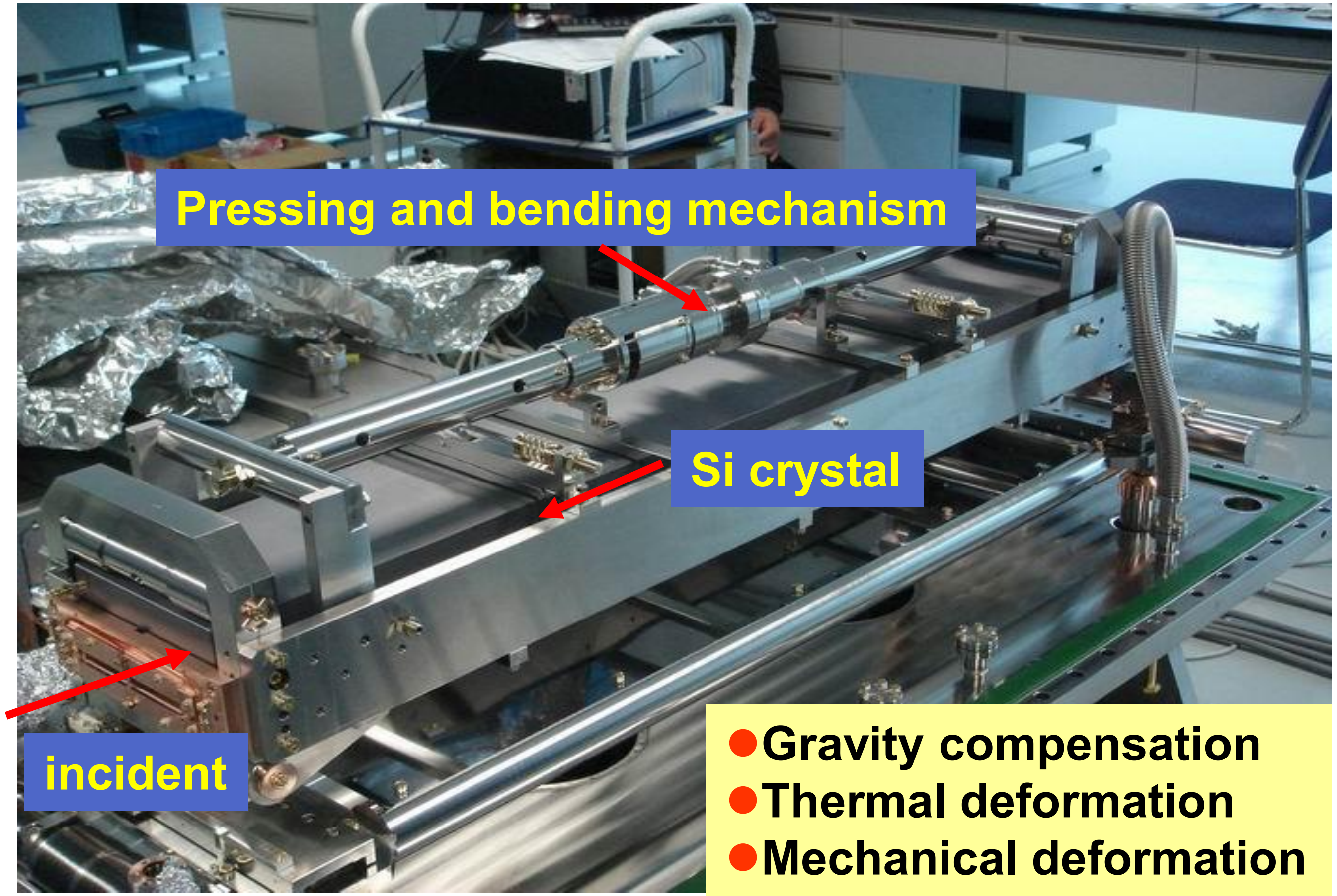


Reflection and focus



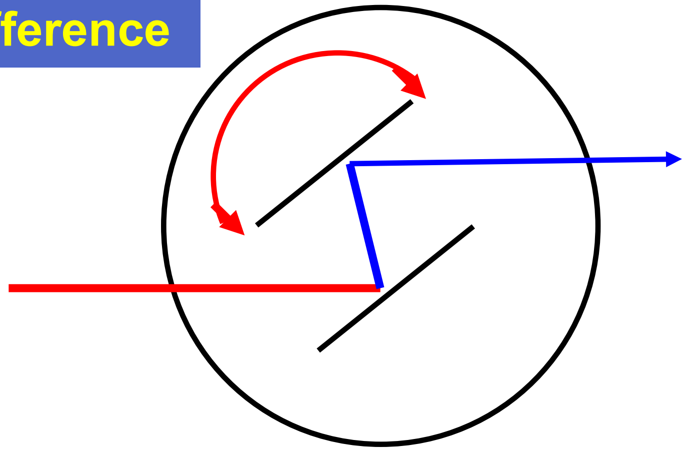


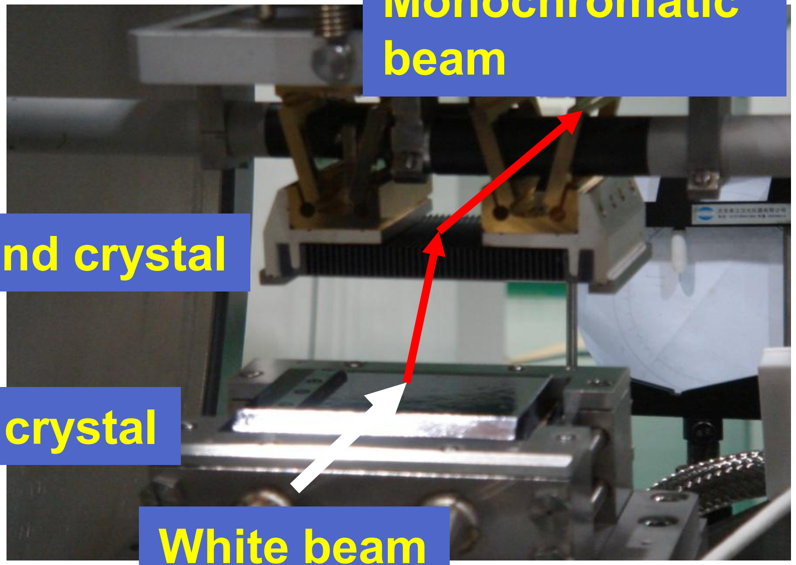


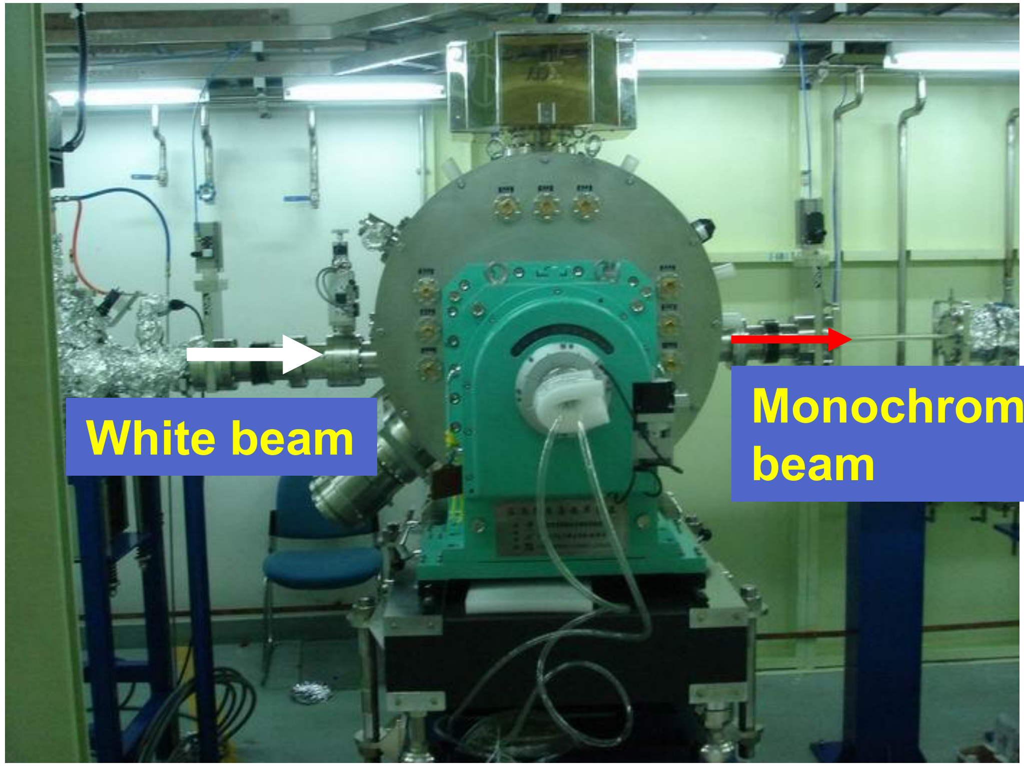


Monochromator

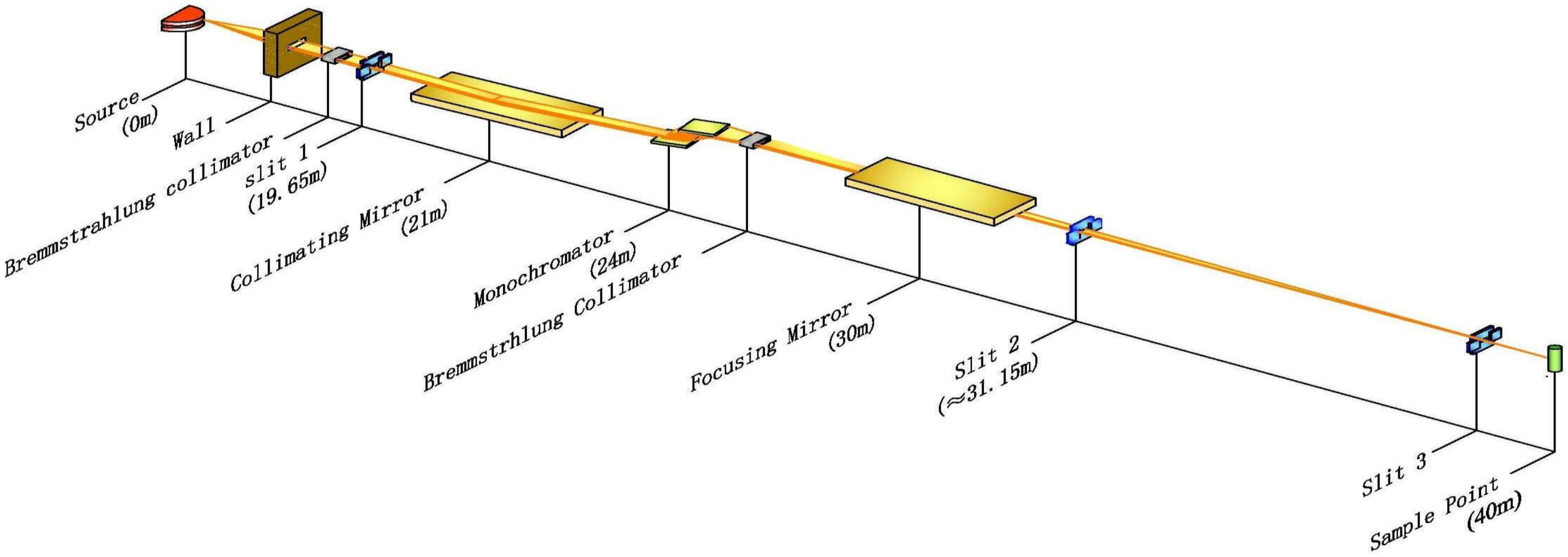
Monochromator with fixed height difference







The optical layout



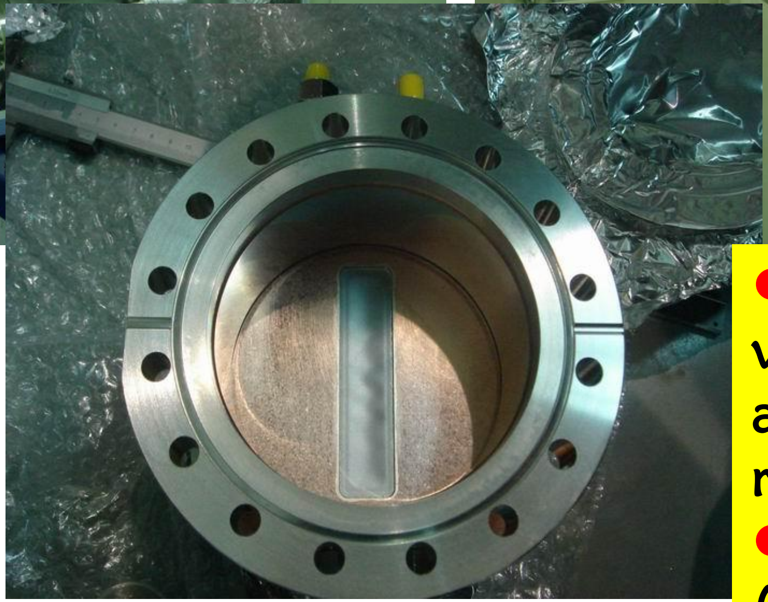
White beam slit

Two pairs of blades along vertical and horizontal directions

Control incident beam size

Beryllium Window

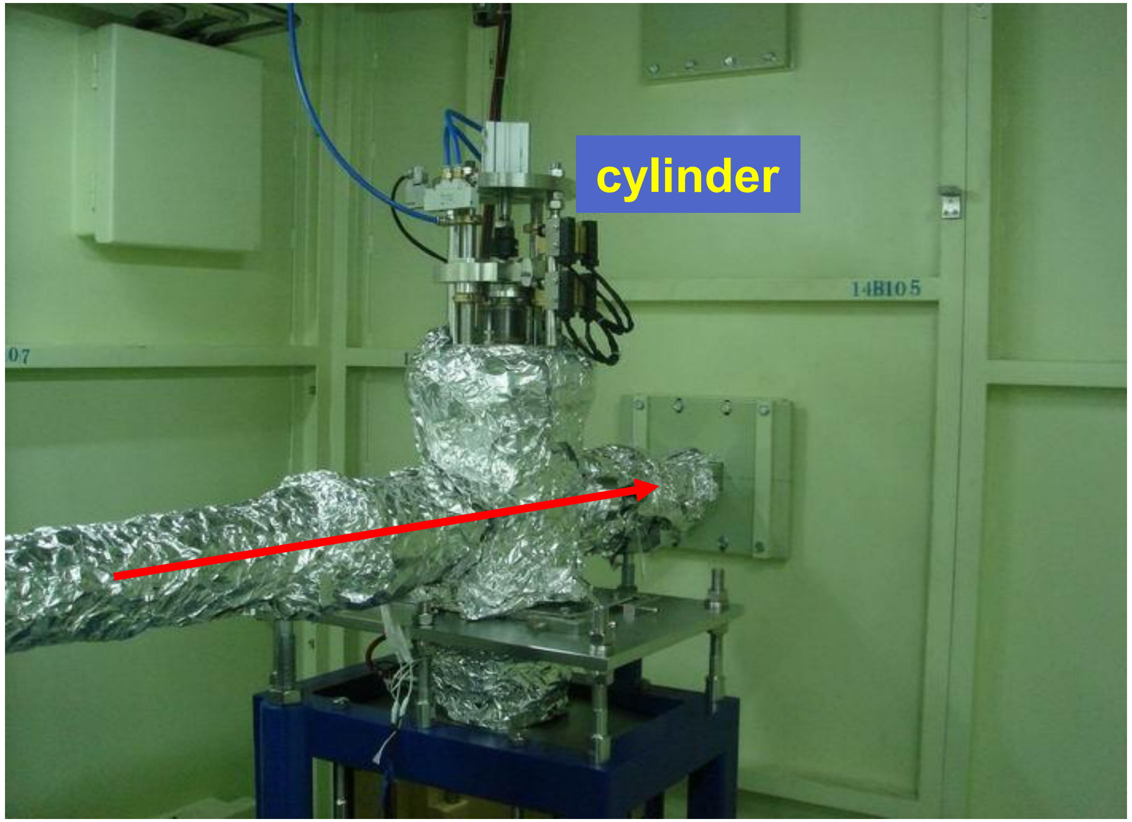
Water-cooled white light beryllium window

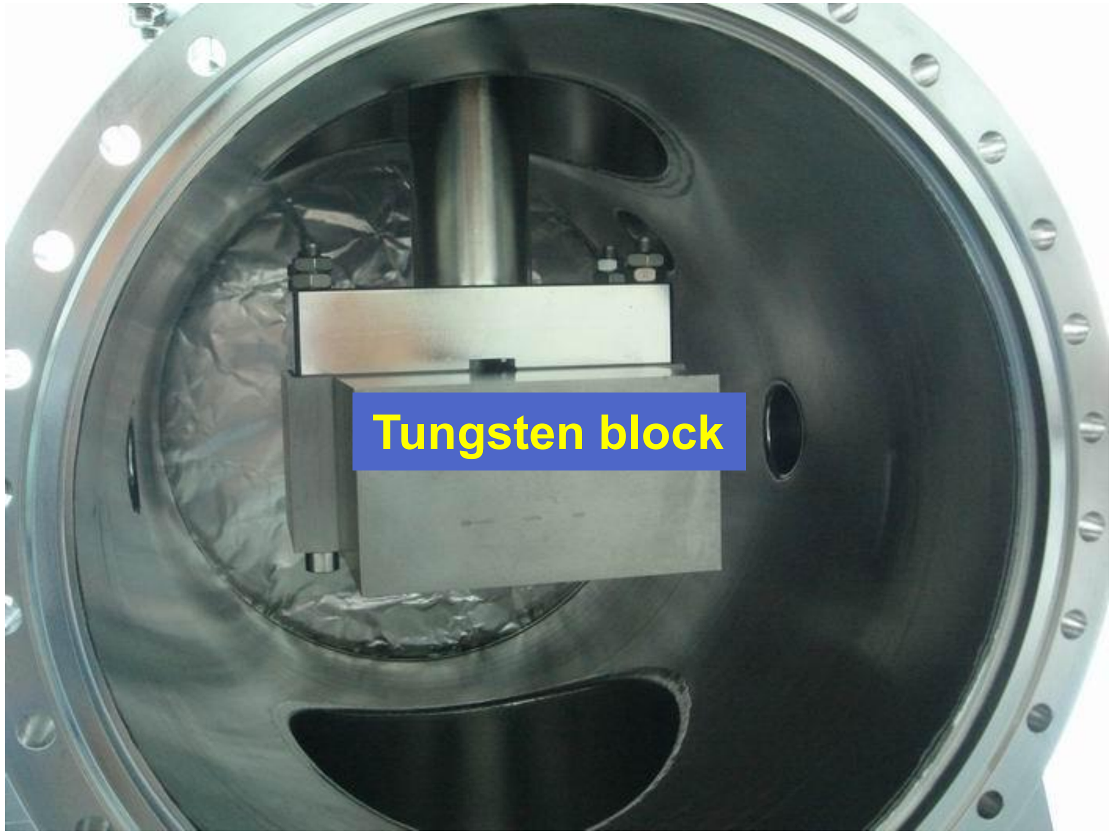


Beryllium exit window

- Separate different vacuum or vacuum-atmosphere to allow X-rays to pass through
- Block low-energy light (soft X-rays, visible light)

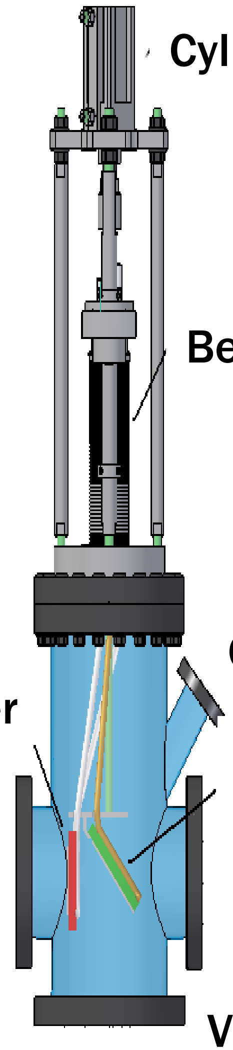
Safety shutter



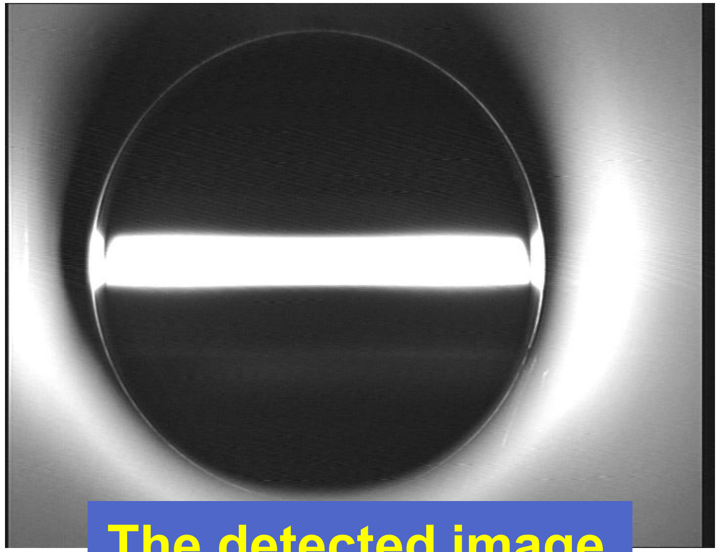


Blocking synchrotron radiation

Fluorescent target detector



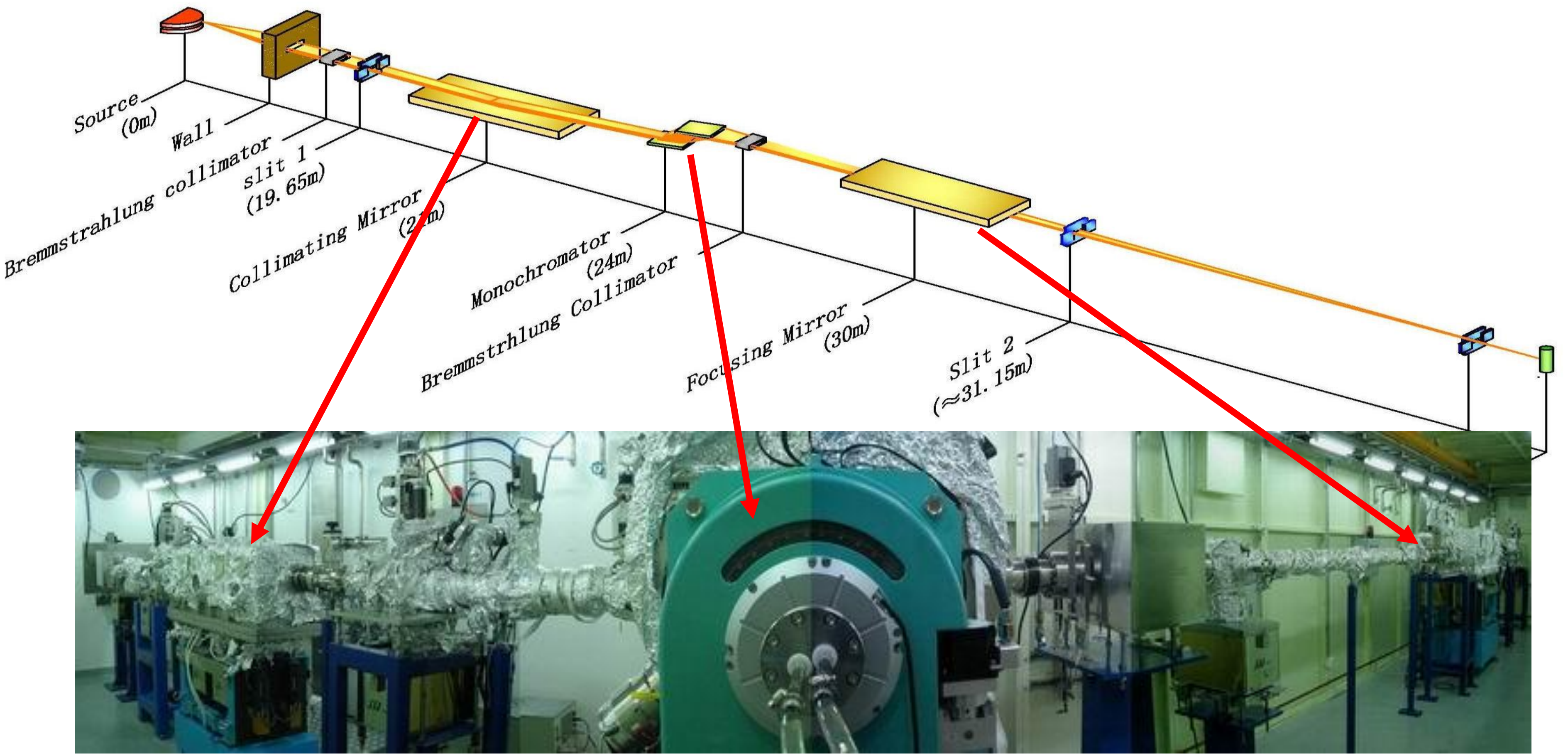
Schematic diagram



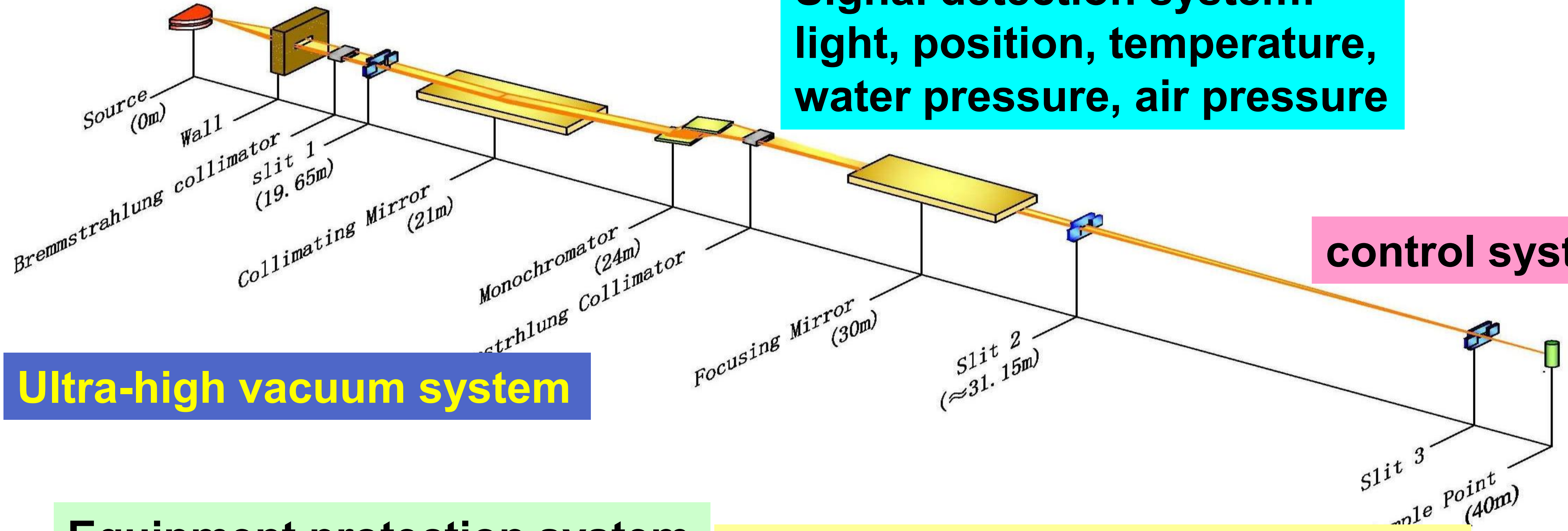
The detected image

- **Observing the beam shape**
- **Estimating the beam position**

Photo of the beamline



Beamline configuration



Signal detection system: light, position, temperature, water pressure, air pressure

control system

Ultra-high vacuum system

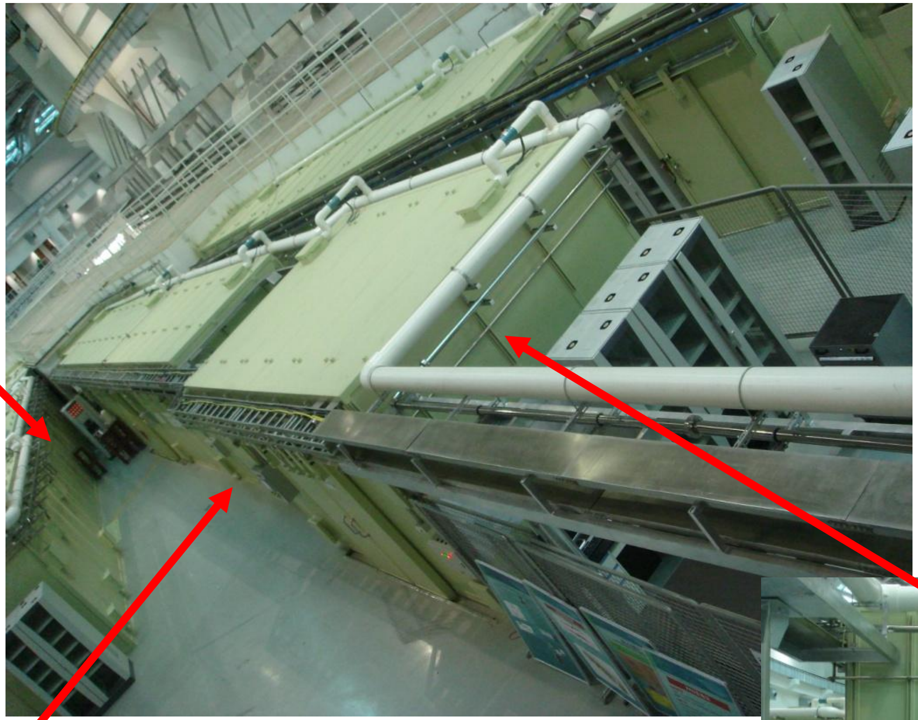
Equipment protection system

Radiation protection system
Personal safety protection system

Beamline control system

Front-end control system

Beamline control system

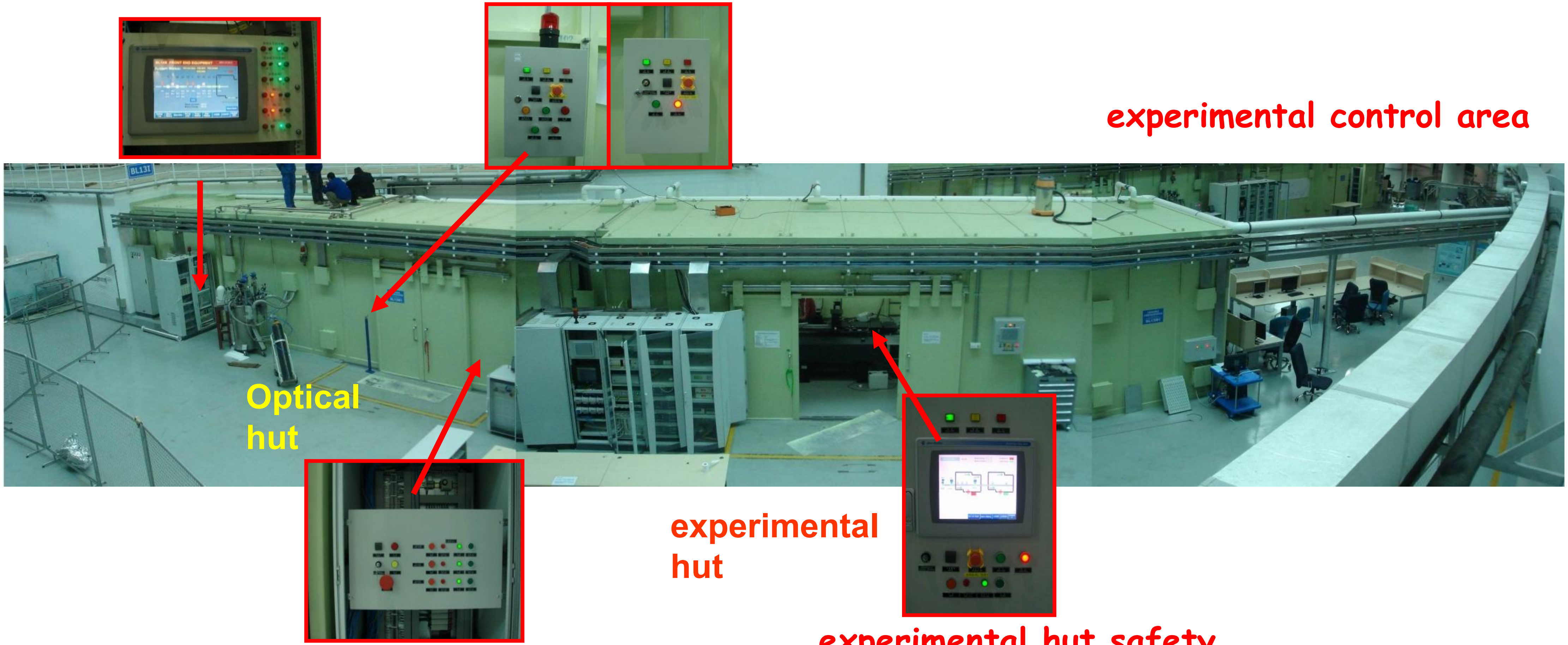


Experimental area
End station

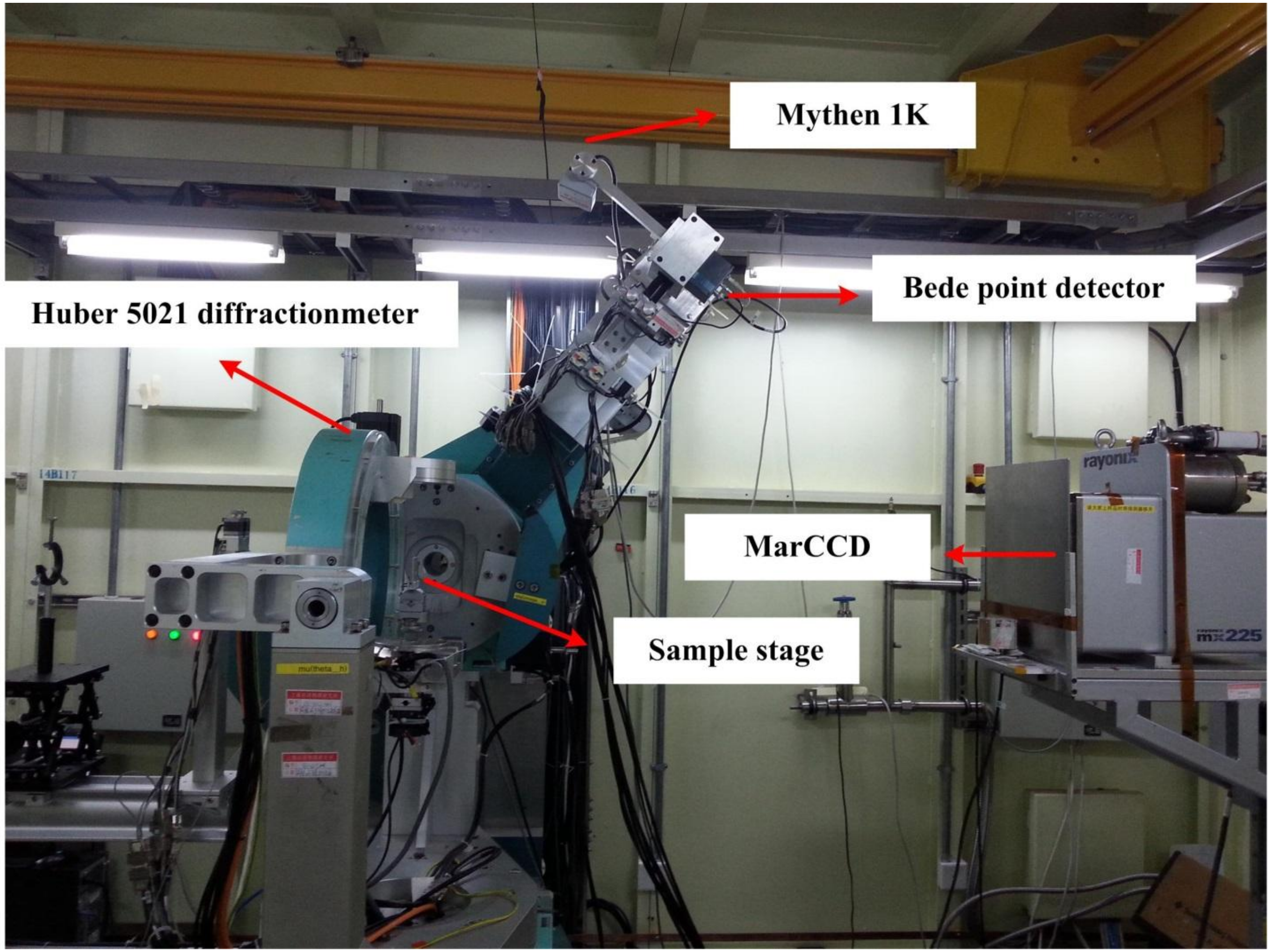
Beamline Control Terminal

Experimental station cabinet

Personal safety protection system



End station： diffractometer··.



Beamline commission

Spot size:

X-ray CCD

wire scanning

Energy range:

Monochromator scanning + ionization chamber measurement

Absorption edge

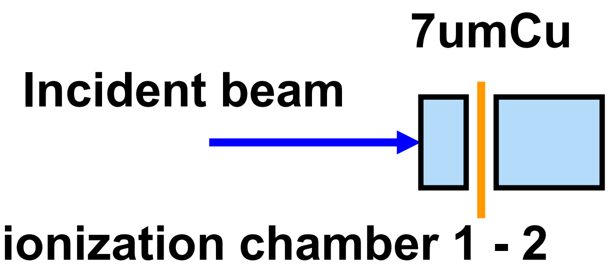
Light flux:

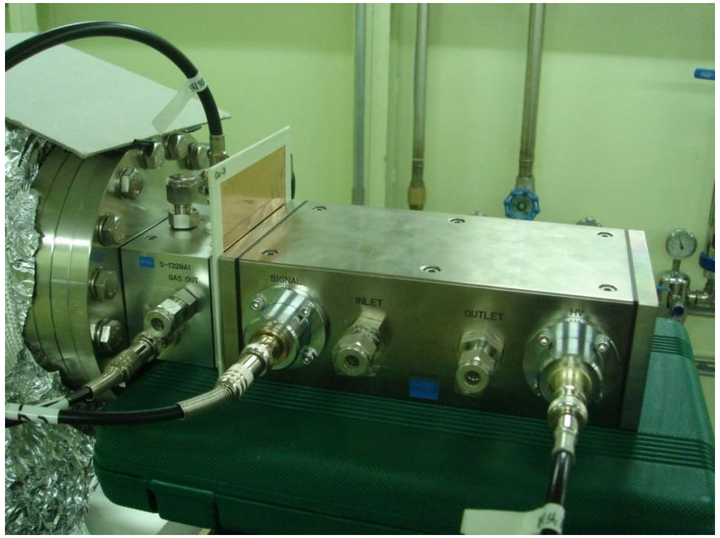
ionization chamber

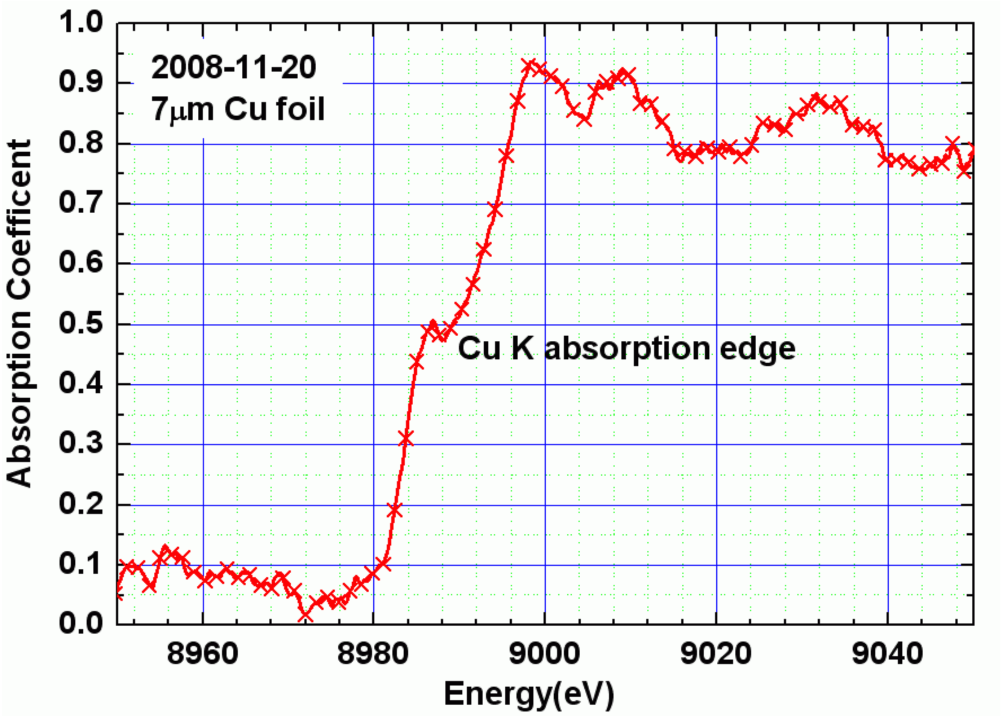
Energy resolution:

Absorption edge resolution

Diffraction peak width







Clearly resolve the pre-peak: energy resolution <2.5eV

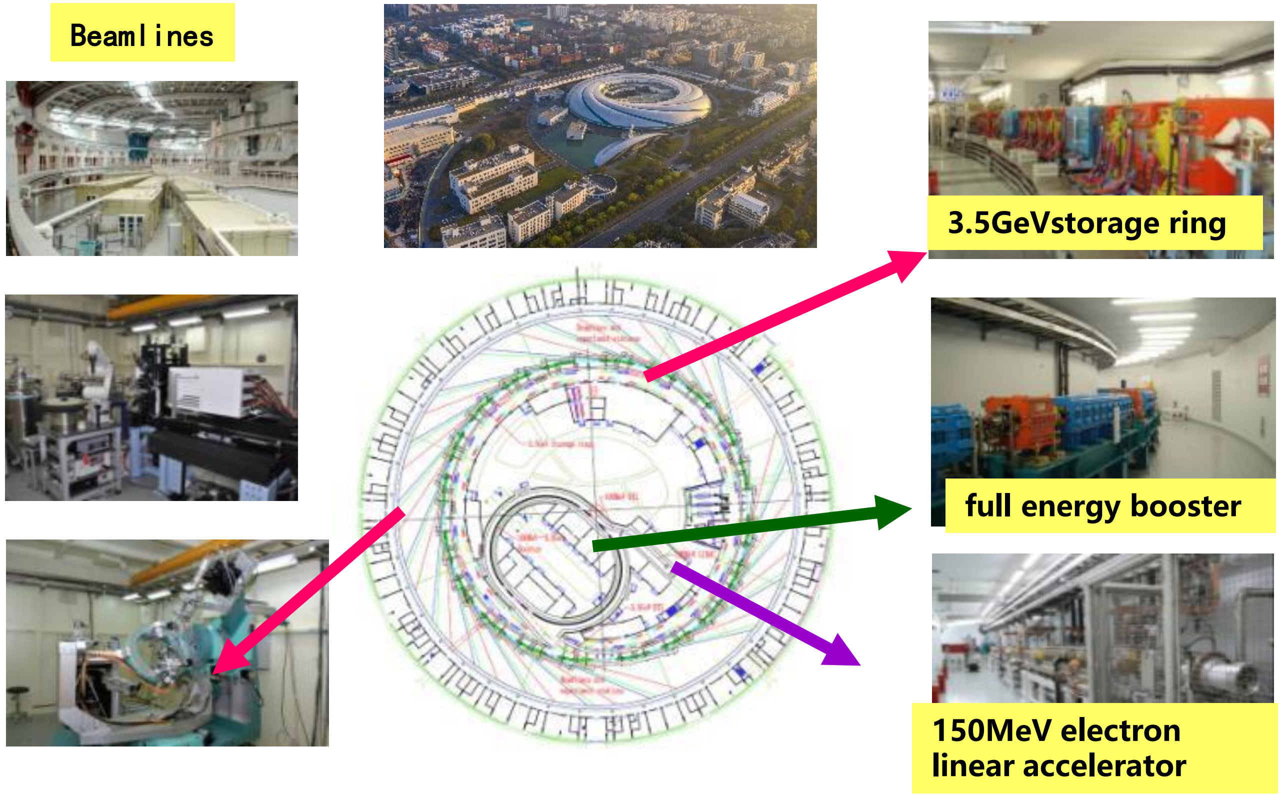
05

Shanghai Synchrotron Radiation Facility (SSRF)

SSRF overview

A third generation synchrotron radiation light source, its overall performance ranks among the advanced levels of similar devices in the world.

A 150MeV electron linear accelerator, a full energy booster, a 3.5GeV storage ring and 34 beamlines with 46 end stations in operation。



Electron energy： **3.5 GeV**

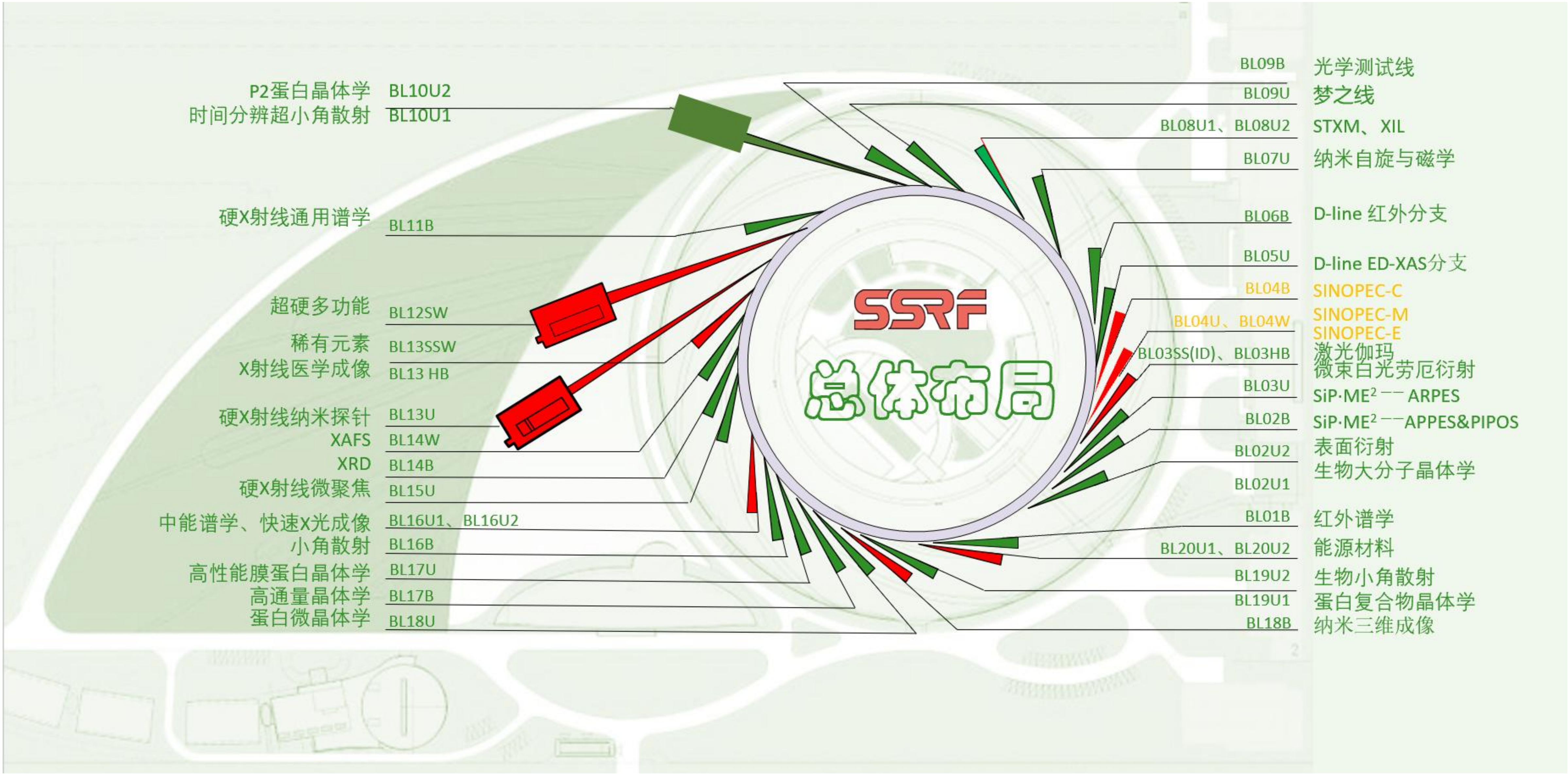
Perimeter： **432 m**

Current： **200~300mA (Top up)**

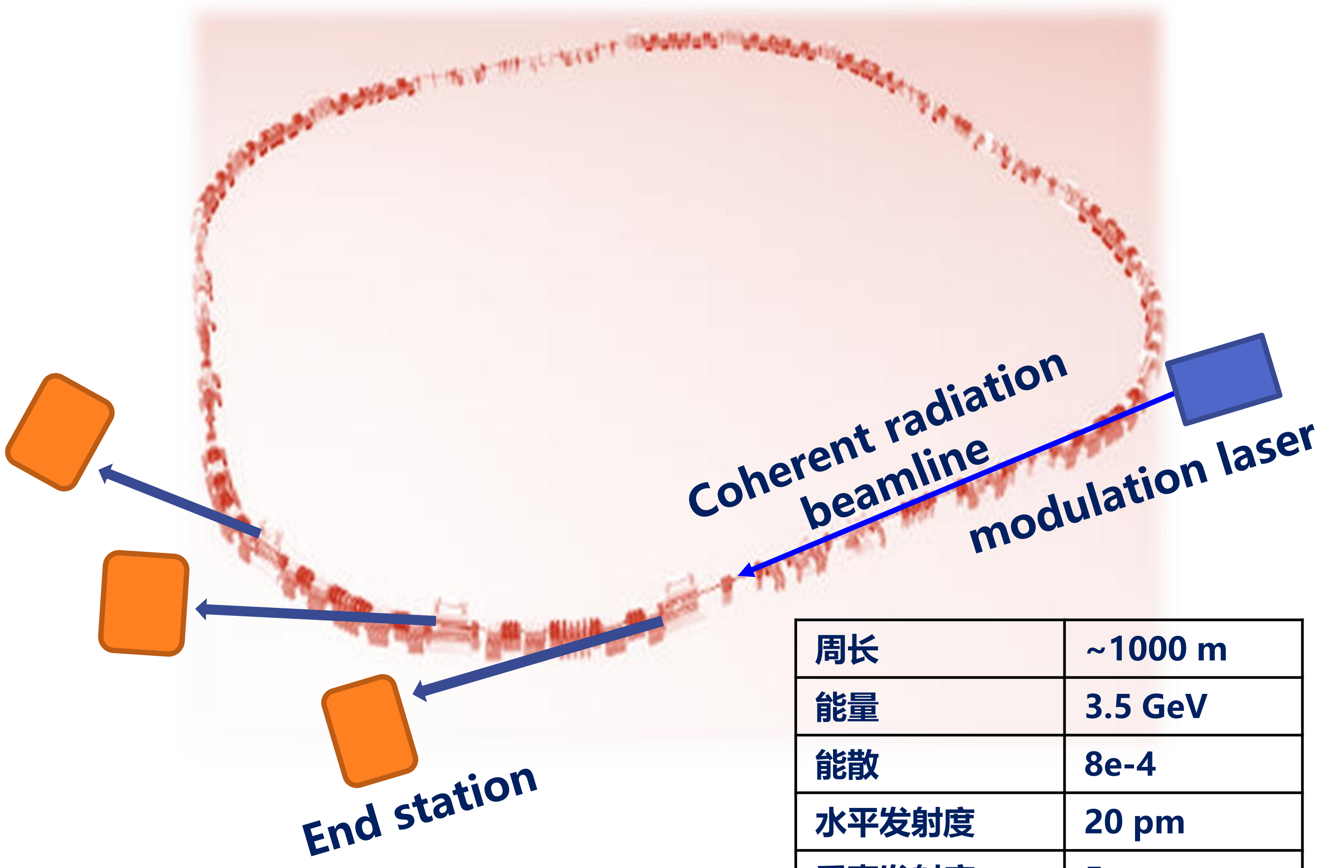
Emittence： **4.2 nm-rad**

Life time： **~20 hrs**

34 beamlines with 46 end stations in operation



Design of the new generation synchrotron radiation source in Shanghai



周长	~1000 m
能量	3.5 GeV
能散	8e-4
水平发射度	20 pm
垂直发射度	5 pm
峰值流强	100 A

	4th	5th
repetition frequency	100~500MHz	1~100MHz
Orbital stability	亚微米	亚微米
radiation stability	<1%	~1%
energy resolution	~100 meV	~0.1meV
time resolution	~10ps	0.1fs~10ps
average brightness	$\sim 10^{22}$	$>10^{24}$
Coherent photon flux	$\sim 10^{12}$	$>10^{14}$

The new generation of light sources combines the advantages of synchrotron radiation and free electron lasers to form a fully coherent light source with higher brightness and flux, wider pulse width regulation range, stable orbit and radiation, and richer experimental methods