INSTITUTE OF SCIENTIFIC INSTRUMENTS
The Czech Academy of Sciences

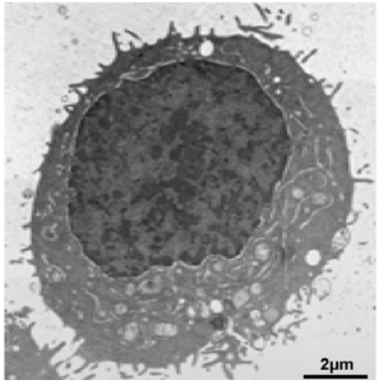
Principles of scanning electron microscopy

Vladislav Krzyžánek

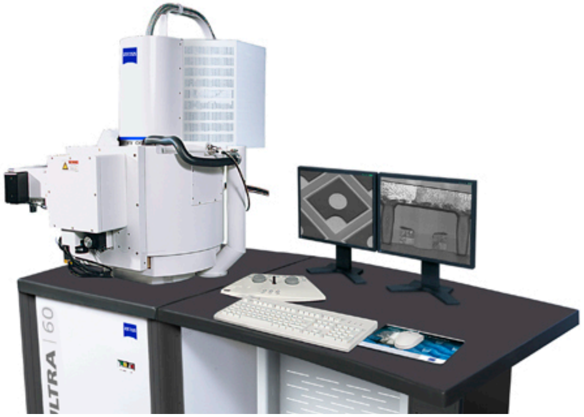
25th September 2023, Prague
course “Advanced Methods of Scanning Electron Microscopy”

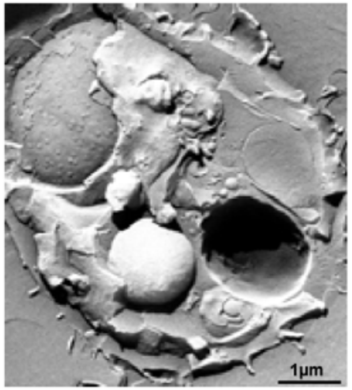
Basic types of electron microscopes

Transmission electron microscope (TEM)



Scanning electron microscope (SEM)



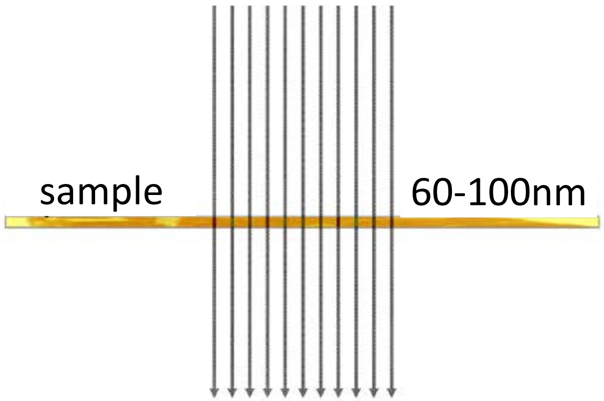


Sorry for missing photos of instruments from Czech companies

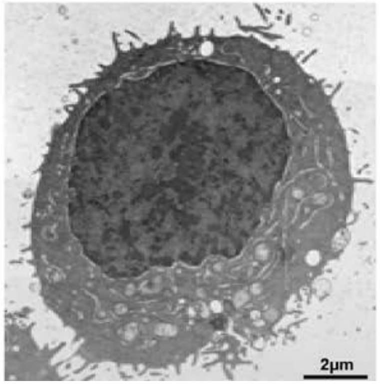
Basic types of electron microscopes

Transmission electron microscope (TEM)

Electron beam

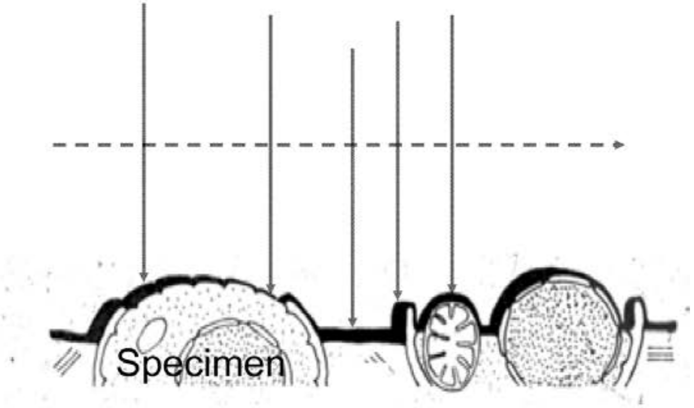


Projection

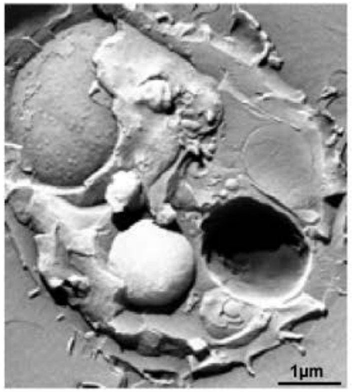


Scanning electron microscope (SEM)

Electron beam



Surface



Typical electron energies: 60 – 300 keV

≤30 keV

Content

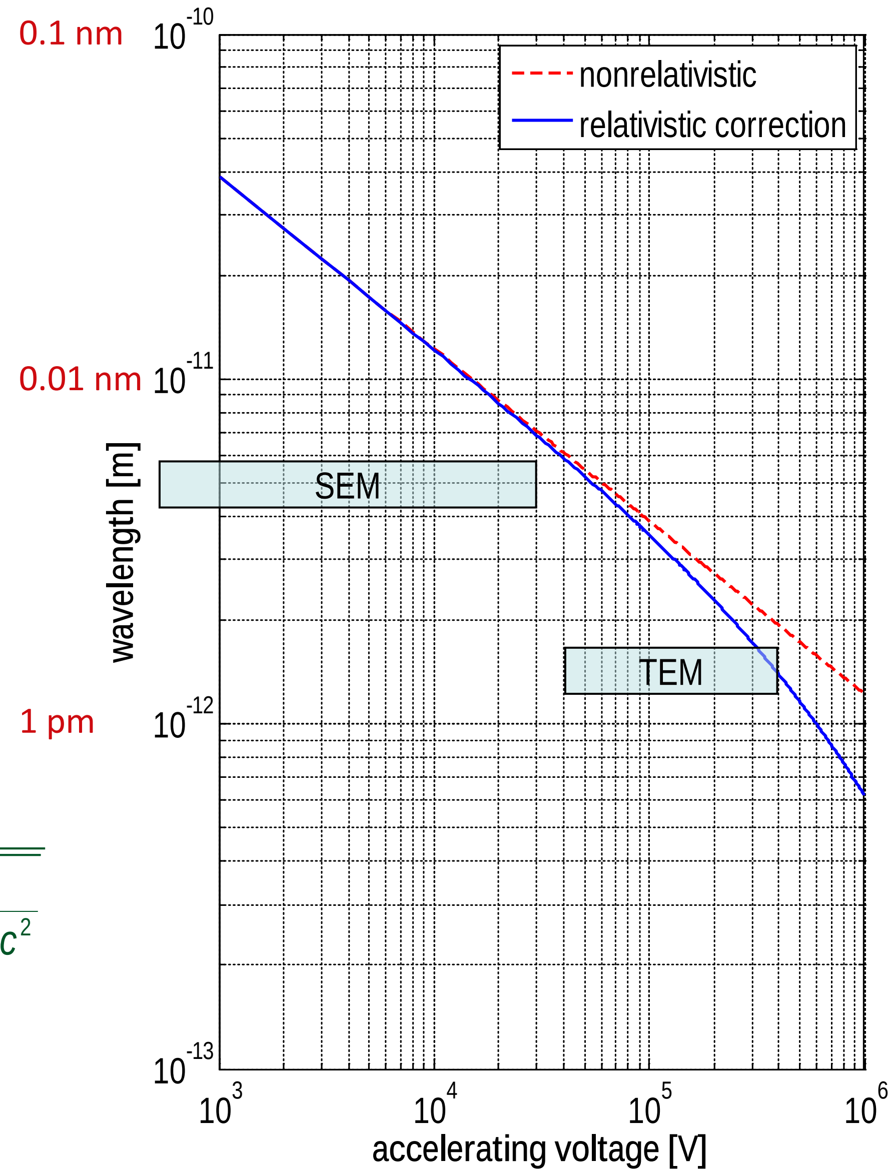
- Principle of SEM
- Electron-matter interaction
- Main parts of SEM
- Types of detectors, their usage
- Other configurations
- Multimodal imaging
- Conclusion

How SEM works

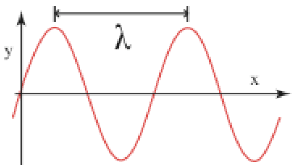
Electron gun

Electrons

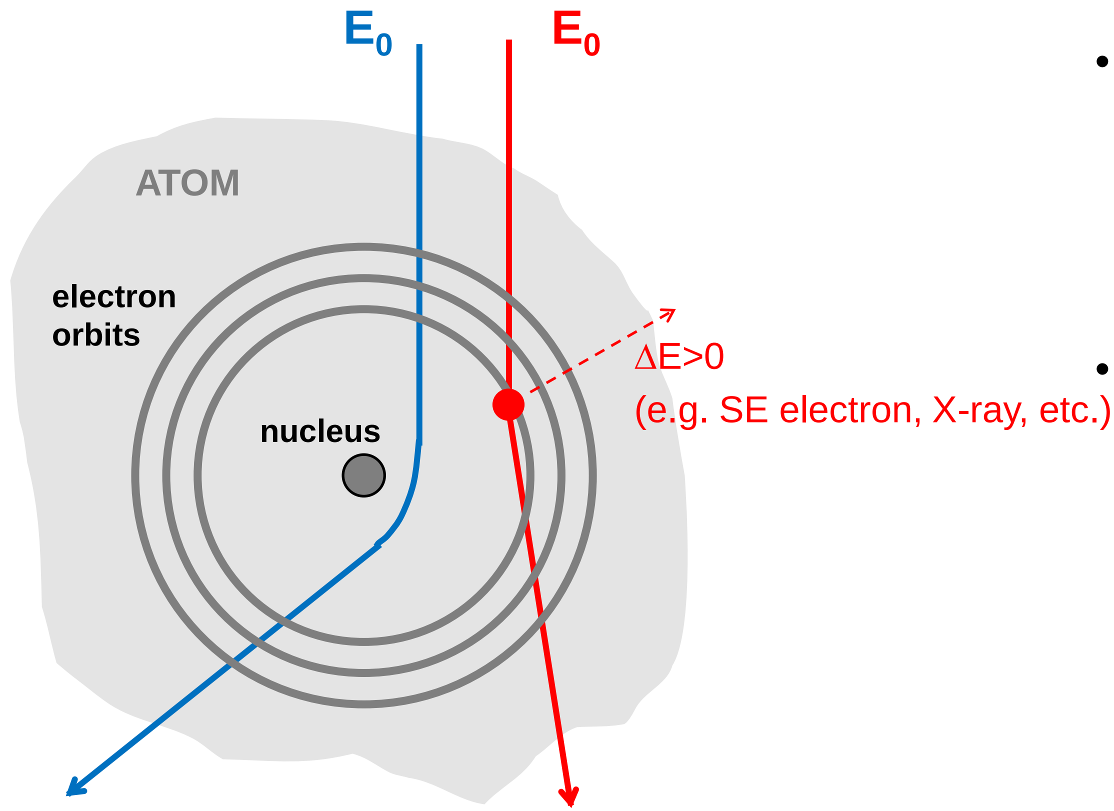
- Rest mass $m_0 = 9.1\times10^{-31}$ kg
- Charge $Q = -e = -1.602\times10^{-19}$ C
- Rest energy $E_0 = m_0c^2 = 511$ keV
- Planck constant $h = 6.6256\times10^{-34}$ Nms
- A non-relativistic approach:
  - Energy $E = eU = \frac{1}{2}m_0v^2$
  - Momentum $p = m_0v = \sqrt{2m_0E}$
  - de Broglie wavelength $\lambda = \frac{h}{p} = \frac{h}{m_0v} = \frac{h}{\sqrt{2m_0E}}$
- Wavelength including relativistic correction $\lambda = \frac{h}{\sqrt{2m_0E}}\frac{1}{\sqrt{1+\frac{E}{2m_0c^2}}}$



$$\lambda = \frac{h}{mv} \qquad f = \frac{E}{h}$$



How do electrons interact with matter



Elastic scattering

$E_{el} = E_0$

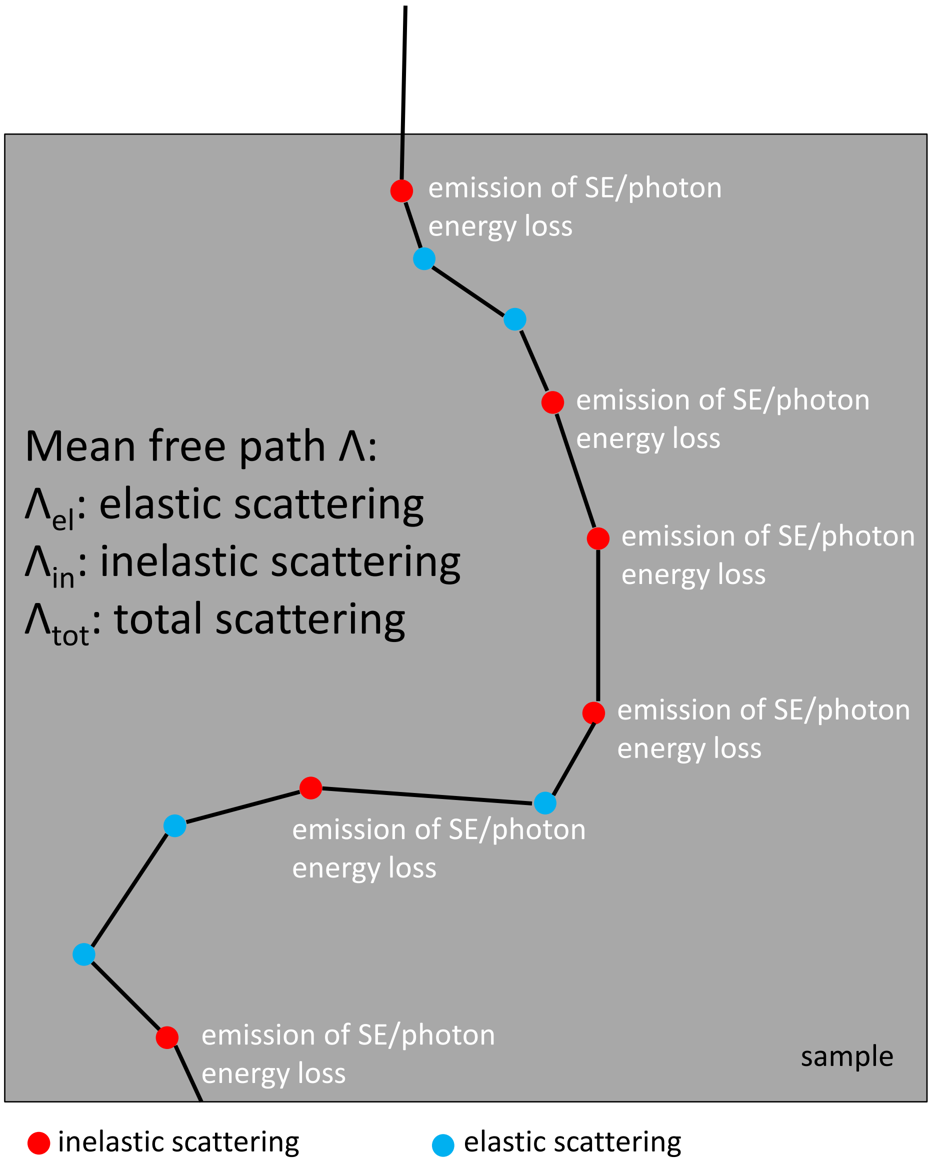
Inelastic scattering

$E_{in} = E_0 - \Delta E$

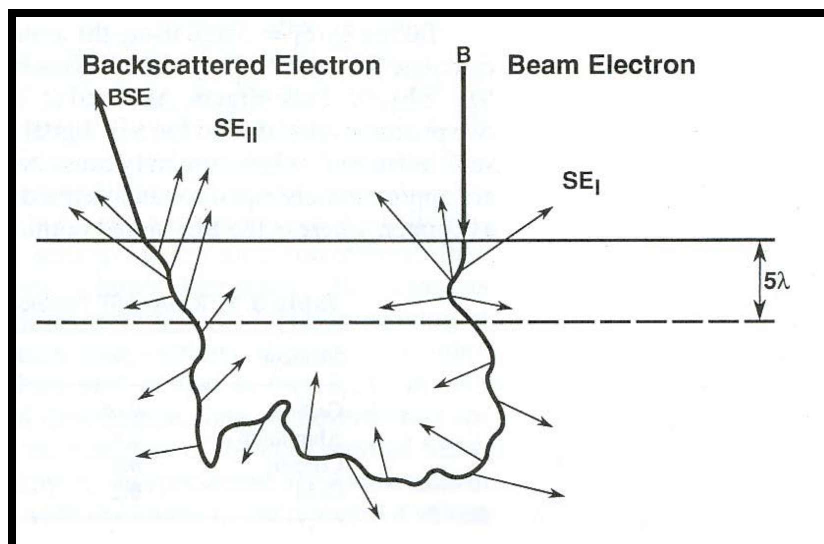
$\langle \Theta_{el} \rangle >> \langle \Theta_{in} \rangle$

- **Unscattered electrons** (no collision)
- **Elastic scattering** on nuclei of atoms of the matter
  - primary electron changes mainly its direction by an angle Θ_{el}
  - often backscattered electrons
- **Inelastic scattering**
  - primary electron slightly changes its direction by the angle Θ_{in} and loses part of its energy ΔE
  - inner-shell ionization
  - secondary electrons (SE)
  - continuum X-rays (Bremsstrahlung)
  - phonons (lattice vibrations - heat)
  - plasmons (oscillations of loosely bound electrons)
  - cathodeluminiscence
  - …

Usually multiple scatter occurs



- Scattering occurs depending on the material of the sample and the energy of the electron
- The path of the primary electron can be reversed during the interaction with the sample (backscattered).
- Secondary electrons (SE) have very little energy and therefore only those at the surface get out of the sample
- Due to the loss of energy during inelastic scattering, the primary electron can be absorbed in the sample (electron range)



Electron scattering: atomic number and energy

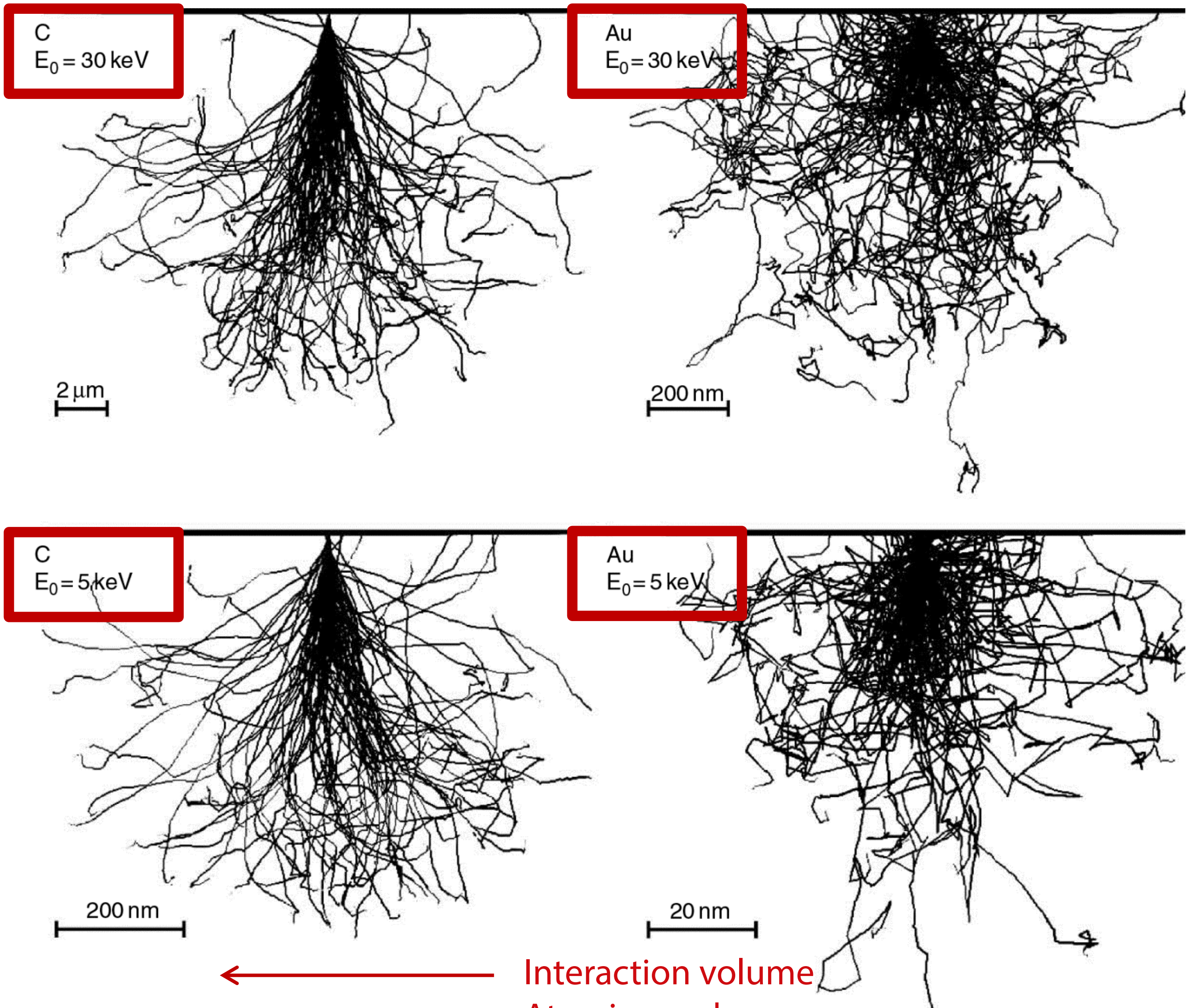
Table 3.1. Total elastic cross-sections σ_{el} in units 10^{-16} cm^2, elastic mean-free-path length $\Lambda_{el} = 1/N\sigma_{el}$ in nanometres ($N = N_A\rho/A$: Number of atoms per unit volume), total mean-free-path length $\Lambda_t = \Lambda_{el}/(\nu + 1)$ with $\nu = \sigma_{inel}/\sigma_{el}$ and the electron range R in μm for different elements and electron energies E = 1–50 keV

E [keV]		1	5	10	20	30	50	
C Z=6	σ_{el}	0.65	0.11	0.055	0.027	0.018	0.012	$\times 10^{-16}$ cm^2
ρ = 2 g/cm^3	Λ_{el}	1.5	9	18	37	55	83	nm
$\nu \simeq 3$	Λ_t	0.4	2.3	4.5	9	14	20	nm
	R	0.033	0.49	1.55	4.9	9.7	22.6	μm
Al Z=13	σ_{el}	1.26	0.31	0.16	0.08	0.053	0.034	$\times 10^{-16}$ cm^2
ρ = 2.7 g/cm^3	Λ_{el}	1.3	5	10	21	31	49	nm
$\nu \simeq 1.5$	Λ_t	0.5	2	4	8	12	20	nm
	R	0.025	0.36	1.14	3.6	7.1	16.7	μm
Cu Z=29	σ_{el}	1.84	0.64	0.37	0.21	0.15	0.11	$\times 10^{-16}$ cm^2
ρ = 8.9 g/cm^3	Λ_{el}	0.64	1.8	3.2	5.6	7.8	10.7	nm
$\nu \simeq 0.6$	Λ_t	0.4	1.1	2.0	3.5	4.9	6.70	nm
	R	0.007	0.11	0.35	1.10	2.26	5.1	μm
Ag Z=47	σ_{el}	3.09	1.15	0.71	0.43	0.32	0.22	$\times 10^{-16}$ cm^2
ρ = 10.5 g/cm^3	Λ_{el}	0.5	1.5	2.4	4.0	5.3	7.7	nm
$\nu \simeq 0.4$	Λ_t	0.4	1.0	1.7	2.8	3.8	5.5	nm
	R	0.006	0.09	0.29	0.93	1.8	4.3	μm
Au Z=79	σ_{el}	3.93	1.60	1.05	0.67	0.52	0.37	$\times 10^{-16}$ cm^2
ρ = 19.3 g/cm^3	Λ_{el}	0.43	1.0	1.6	2.5	3.3	4.6	nm
$\nu \simeq 0.2$	Λ_t	0.36	0.9	1.3	2.1	2.7	3.8	nm
	R	0.003	0.05	0.17	0.51	1.0	2.3	μm

Λ increases with decreasing Z

Λ increases with increasing E

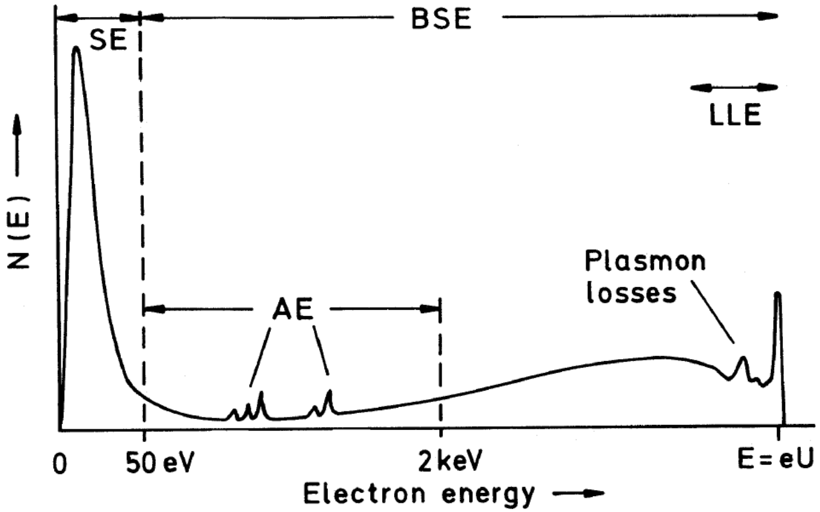
Monte Carlo simulations of electron scattering



Interaction volume ↑
Electron energy ↑

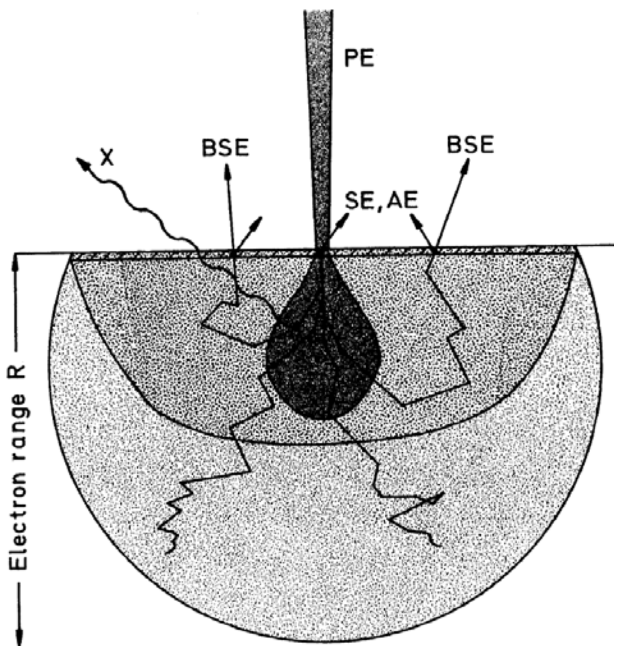
Interaction volume ←
Atomic number →

Spectrum of signal electrons



Schematic energy spectrum of emitted electrons consisting of

- secondary electrons (SE; $E_{SE} \leq 50$ eV)
- backscattered electrons (BSE; $E_{BSE} > 50$ eV)
- and more signals like Auger electrons (AE) or low-loss electrons (LLE) used mainly for material science

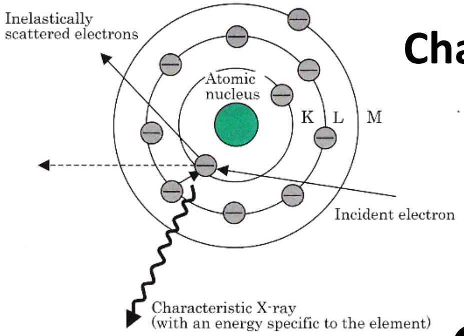


Origin and information depth of

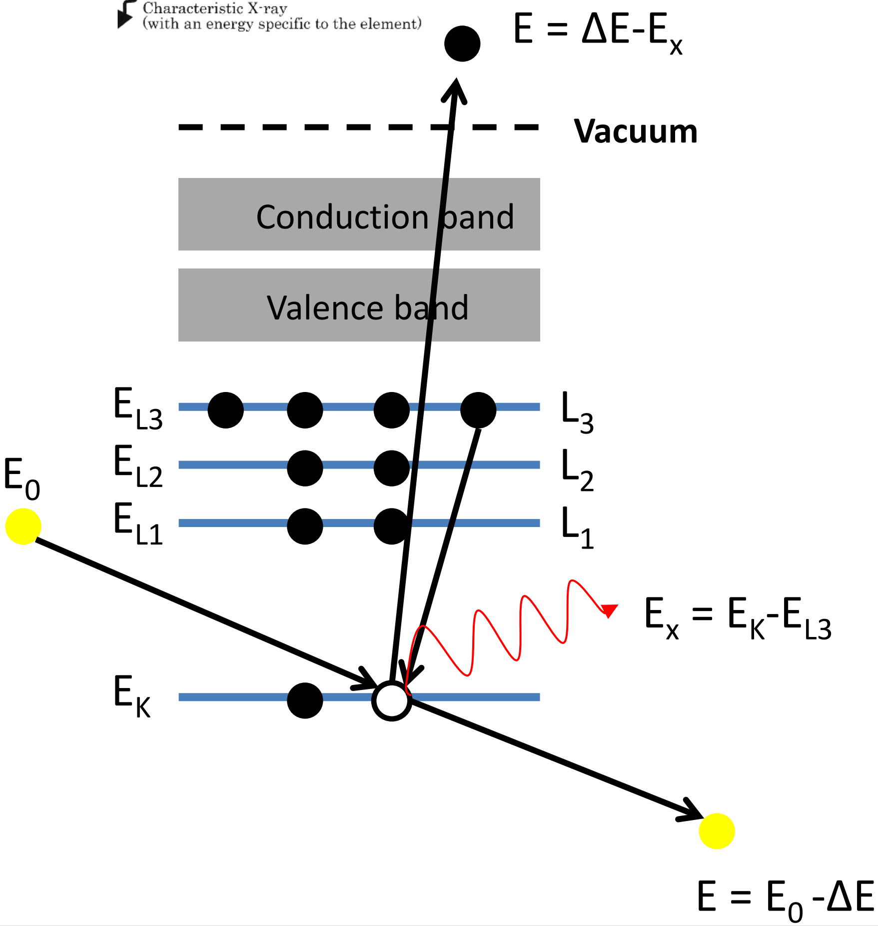
- secondary electrons (SE)
- backscattered electrons (BSE)
- Auger electrons (AE)
- X-ray quanta (X)

in the diffusion cloud of electron range R for normal incidence of the primary electrons (PE)

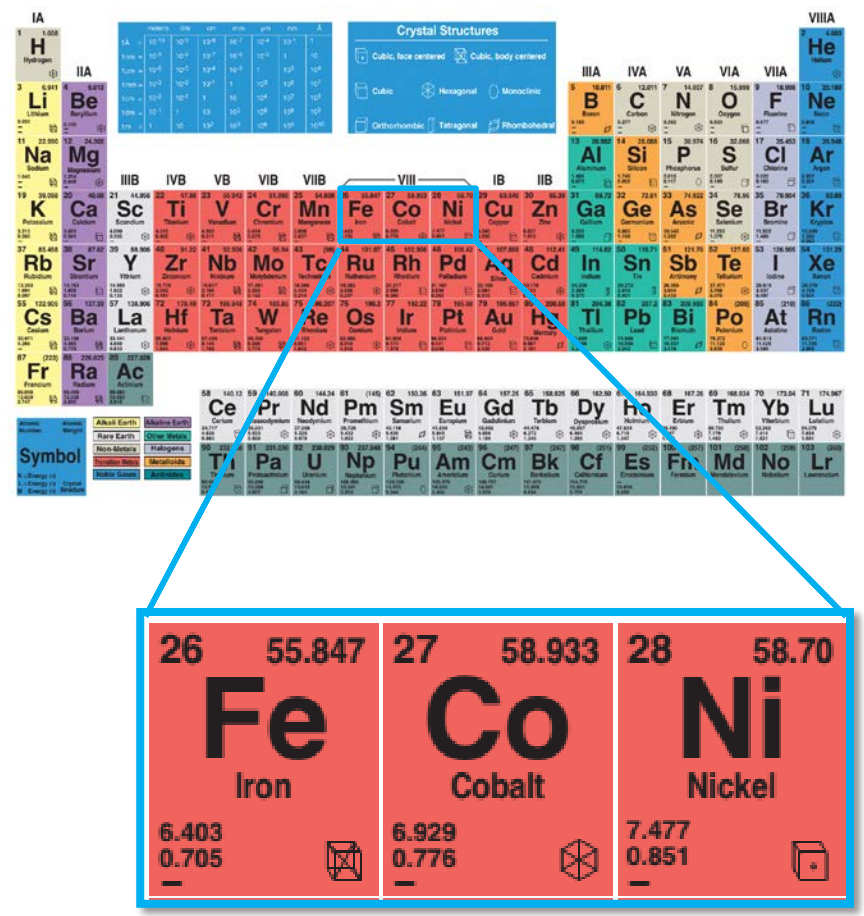
X-rays: Energy dispersive X-ray spectroscopy (EDX)



Characteristic X-rays



Values for individual elements are well known



Energy is characteristic of a given element

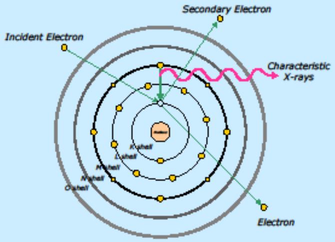
JEOL ISO 9001 Certificated ISO 14001 Certificated

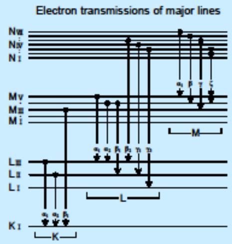
High technology for quality assurance and the environment

Energy table for EDS analysis

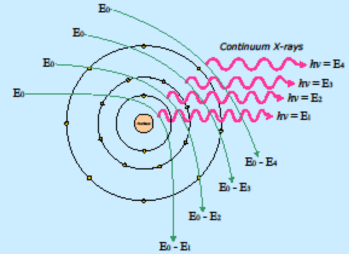
http://www.jeol.com/

Characteristic X-rays





Continuum X-rays

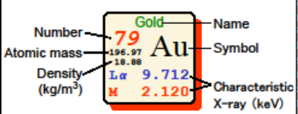


The electrons generated by the electron gun are accelerated and irradiate the sample. The electron has a kinetic energy proportional to the accelerating voltage. The kinetic energy dissipated within the sample generates characteristic signals from the specimen. The characteristic X-rays are the information used for EDS analysis.

If the incident electrons have sufficient acceleration and then have enough energy to strike an electron from the inner shell of the atom, it'll make an electron hole. An electron from the outer shell will fill up the hole and then, some characteristic X-rays will be emitted. The characteristic X-rays have different energy for each element, and the intensity will be proportional to the element concentration.

The continuum X-rays are emitted when the primary electrons are decelerated by the strong electric field existing close to atomic nucleus. The continuum X-rays have the energy of the kinetic energy lost during the deceleration. It will be observed as EDS spectrum background.

Name	Number	Symbol	Atomic mass	Density	Characteristic X-ray (keV)
Hydrogen	1	H	1.01	0.08	
Helium	2	He	4.00	0.19	
Lithium	3	Li	6.94	0.53	
Beryllium	4	Be	9.01	1.85	Kα 0.110
Boron	5	B	10.81	2.54	Kα 0.183
Carbon	6	C	12.01	2.25 *	Kα 0.277
Nitrogen	7	N	14.01	1.14	Kα 0.392
Oxygen	8	O	16.00	1.57	Kα 0.525
Fluorine	9	F	19.00	1.5	Kα 0.677
Neon	10	Ne	20.18	1.20	Kα 0.848
Sodium	11	Na	22.99	0.97	Kα 1.041
Magnesium	12	Mg	24.31	1.74	Kα 1.253
Aluminium	13	Al	26.98	2.70	Kα 1.486
Silicon	14	Si	28.09	2.42	Kα 1.739
Phosphorus	15	P	30.97	1.83 *	Kα 2.013
Sulphur	16	S	32.06	2.07 *	Kα 2.307
Chlorine	17	Cl	35.45	2.2	Kα 2.621
Argon	18	Ar	39.95	1.65	Kα 2.957
Potassium	19	K	39.10	0.87	Kα 3.312
Calcium	20	Ca	40.08	1.55	Kα 3.690
Scandium	21	Sc	44.96	2.99	Kα 4.088 / Lα 0.395
Titanium	22	Ti	47.90	4.5	Kα 4.508 / Lα 0.452
Vanadium	23	V	50.94	5.87	Kα 4.949 / Lα 0.511
Chromium	24	Cr	52.00	7.14	Kα 5.411 / Lα 0.573
Manganese	25	Mn	54.94	7.3	Kα 5.894 / Lα 0.637
Iron	26	Fe	55.85	7.86	Kα 6.398 / Lα 0.705
Cobalt	27	Co	58.93	8.71	Kα 6.924 / Lα 0.776
Nickel	28	Ni	58.70	8.8	Kα 7.471 / Lα 0.851
Copper	29	Cu	63.55	8.93	Kα 8.040 / Lα 0.930
Zinc	30	Zn	65.38	6.92	Kα 8.630 / Lα 1.012
Gallium	31	Ga	69.72	5.93	Kα 9.241 / Lα 1.098
Germanium	32	Ge	72.59	5.46	Kα 9.874 / Lα 1.188
Arsenic	33	As	74.92	5.73	Kα 10.530 / Lα 1.282
Selenium	34	Se	78.96	4.82	Kα 11.207 / Lα 1.379
Bromine	35	Br	79.90	4.2	Kα 11.907 / Lα 1.480
Krypton	36	Kr	83.80	3.4	Kα 12.631 / Lα 1.586
Rubidium	37	Rb	85.47	1.53	Kα 13.373 / Lα 1.694
Strontium	38	Sr	87.62	2.60	Kα 14.140 / Lα 1.806
Yttrium	39	Y	88.91	4.48	Kα 14.931 / Lα 1.922
Zirconium	40	Zr	91.22	6.44	Kα 15.744 / Lα 2.042
Niobium	41	Nb	92.91	8.4	Kα 16.581 / Lα 2.166
Molybdenum	42	Mo	95.94	9.01	Kα 17.441 / Lα 2.293
Technetium	43	Tc	(97)		Kα 18.325 / Lα 2.424
Ruthenium	44	Ru	101.07	12.1	Kα 19.233 / Lα 2.558
Rhodium	45	Rh	102.91	12.44	Lα 2.696
Palladium	46	Pd	106.4	12.16	Lα 2.838
Silver	47	Ag	107.87	10.49	Lα 2.984
Cadmium	48	Cd	112.40	8.65	Lα 3.133
Indium	49	In	114.82	7.28	Lα 3.286 / M 0.368
Tin	50	Sn	118.69	7.30 *	Lα 3.443 / M 0.691
Antimony	51	Sb	121.75	6.62	Lα 3.604 / M 0.733
Tellurium	52	Te	127.60	6.25	Lα 3.769 / M 0.778
Iodine	53	I	126.90	4.94	Lα 3.937
Xenon	54	Xe	131.30		Lα 4.109
Cesium	55	Cs	132.91	1.87	Lα 4.286
Barium	56	Ba	137.34	3.5	Lα 4.465 / M 0.972
Lanthanoid	57–71				
Hafnium	72	Hf	178.49	13.3	Lα 7.898 / M 1.644
Tantalum	73	Ta	180.95	16.6	Lα 8.145 / M 1.709
Tungsten	74	W	183.85	19.3	Lα 8.396 / M 1.774
Rhenium	75	Re	186.21	20.53	Lα 8.651 / M 1.842
Osmium	76	Os	190.2	22.5	Lα 8.910 / M 1.914
Iridium	77	Ir	192.22	22.42	Lα 9.174 / M 1.977
Platinum	78	Pt	195.09	21.37	Lα 9.441 / M 2.048
Gold	79	Au	196.97	18.88	Lα 9.712 / M 2.120
Mercury	80	Hg	200.59	14.19	Lα 9.987 / M 2.195
Thallium	81	Tl	204.37	11.86	Lα 10.267 / M 2.267
Lead	82	Pb	207.2	11.34	Lα 10.550 / M 2.342
Bismuth	83	Bi	208.98	9.78	Lα 10.837 / M 2.419
Polonium	84	Po	(209)		Lα 11.129
Astatine	85	At	(210)		Lα 11.425
Radon	86	Rn	(222)		Lα 11.725
Francium	87	Fr	(223)		Lα 12.029
Radium	88	Ra	226.03	5	Lα 12.340
Actinoid	89–103				
Lanthanum	57	La	138.91	6.17	Lα 4.650 / M 0.833
Cerium	58	Ce	140.12	6.66	Lα 4.839 / M 0.883
Praseodymium	59	Pr	140.91	6.77	Lα 5.033 / M 0.929
Neodymium	60	Nd	144.24	7.02	Lα 5.229 / M 0.978
Prometium	61	Pm	(145)		Lα 5.432
Samarium	62	Sm	150.4	7.54	Lα 5.635 / M 1.081
Europium	63	Eu	151.96	5.25	Lα 5.845 / M 1.131
Gadolinium	64	Gd	157.25	7.90	Lα 6.056 / M 1.185
Terbium	65	Tb	158.93	8.25	Lα 6.272 / M 1.240
Dysprosium	66	Dy	162.50	8.56	Lα 6.494 / M 1.293
Holmium	67	Ho	164.93	8.80	Lα 6.719 / M 1.347
Erbium	68	Er	167.26	9.06	Lα 6.947 / M 1.405
Thulium	69	Tm	168.93	9.32	Lα 7.179 / M 1.462
Ytterbium	70	Yb	173.04	6.96	Lα 7.414 / M 1.521
Lutetium	71	Lu	174.97	9.84	Lα 7.654 / M 1.581
Actinium	89	Ac	(227)	10.07	Lα 12.650
Thorium	90	Th	232.04	11.00	Lα 12.967 / M 2.991
Protactinium	91	Pa	231.04		Lα 13.288 / M 3.077
Uranium	92	U	238.03	18.7	Lα 13.612 / M 3.164
Neptunium	93	Np	237.05		Lα 13.942 / M 3.260
Plutonium	94	Pu	(244)		Lα 14.276 / M 3.348
Americium	95	Am	(243)		Lα 14.615 / M 3.437
Curium	96	Cm	(247)		Lα 14.953 / M 3.539
Berkelium	97	Bk	(247)		Lα 15.304 / M 3.634
Californium	98	Cf	(251)		Lα 15.652 / M 3.731
Einsteinium	99	Es	(254)		
Fermium	100	Fm	(257)		
Mendelevium	101	Md	(258)		
Nobelium	102	No	(255)		
Lawrencium	103	Lr	(262)		



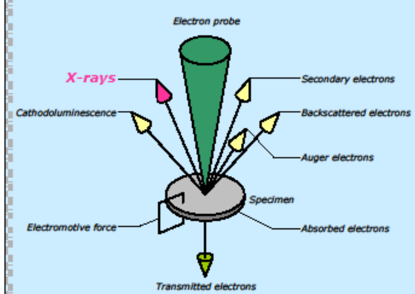
Note: Density
* 'C' as (graphite), 'P' as (white), 'S' as (alpha), 'Sn' as (white)

Minimum accelerating voltage

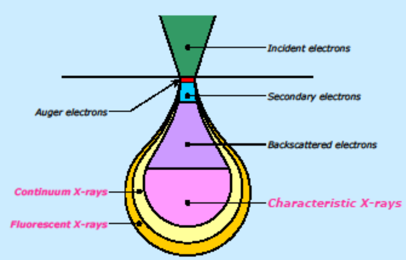
Unable to detect | 5kV or higher | 10kV or higher | 15kV or higher

The colors mean to detect the characteristic X-ray of the lowest energy for each element.

Information from specimen



Generation depth and space resolution

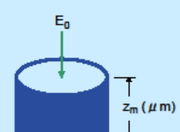


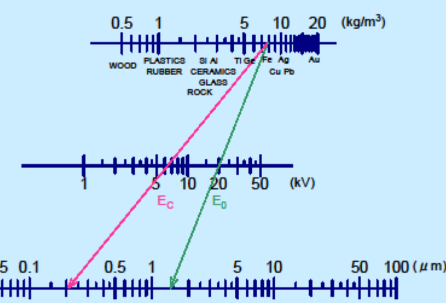
Analytical area

Castaing's formula

$$z_m = 0.033\,(E_0^{1.7} - E_c^{1.7})\frac{A}{\rho Z}$$

E_0: Accelerating voltage (kV)
E_C: Minimum emission voltage (keV)
A : Atomic mass
ρ : Density (kg/m³)
Z : Atomic number





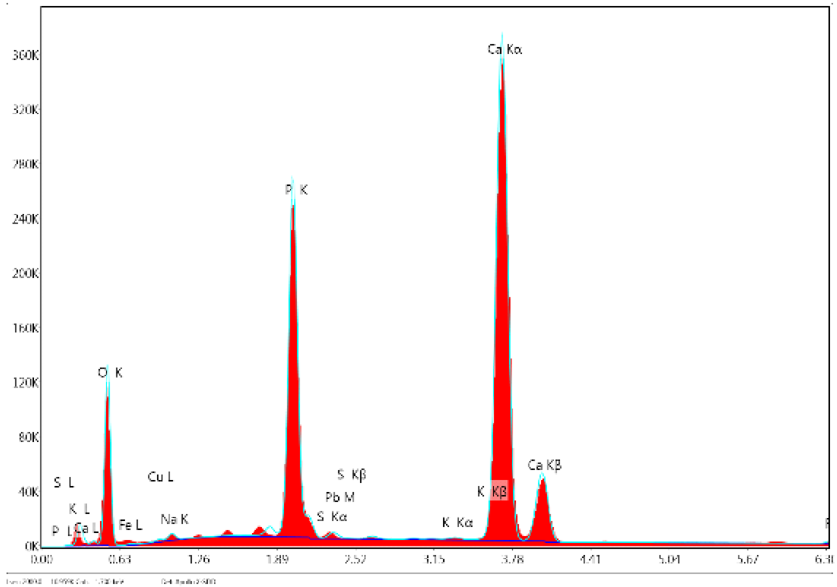
Analytical area of iron in 20kV ≒ 1.5 – 0.2 = 1.3 (μm)

JEOL
Serving Advanced Technology

JEC6101C602A Printed in Japan.

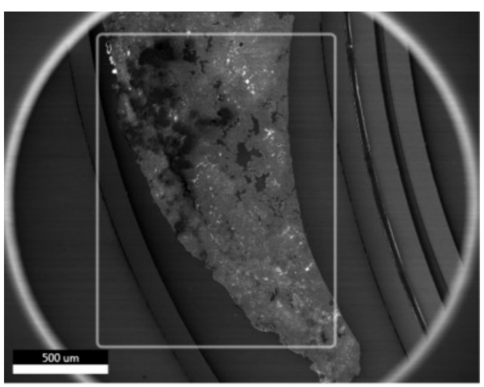
X-rays: Energy dispersive X-ray spectroscopy (EDX)

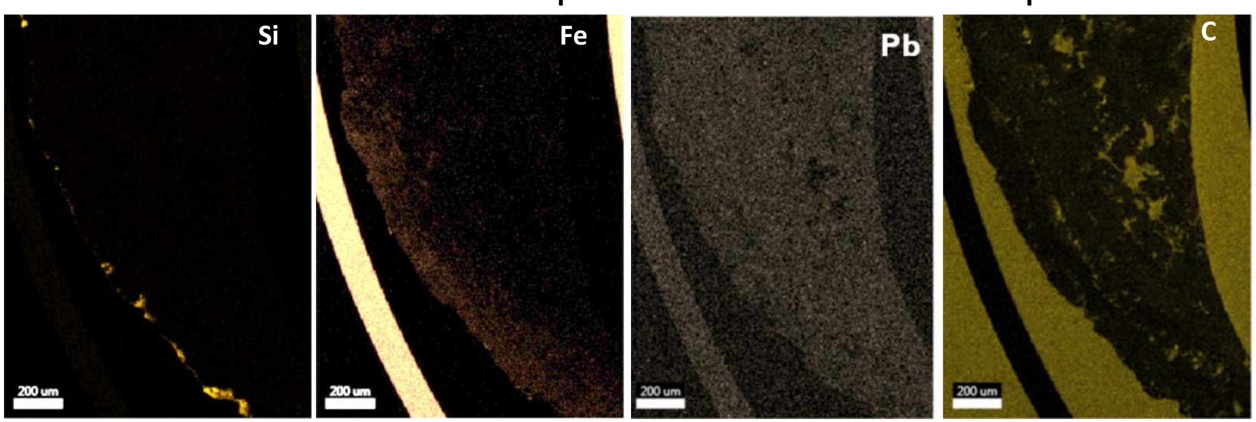
EDX spectrum recorded from an area or point = all elements in one place



Element	Wt %	Atomic %	Error %	Net Int.	Net Error %
O K	42.04	63.00	9.71	368.04	0.13
Na K	0.60	0.63	9.20	15.80	1.28
P K	15.20	11.76	2.79	1119.15	0.08
S K	0.06	0.04	10.32	3.98	7.24
Pb M	0.57	0.07	5.27	17.70	2.23
K K	0.13	0.08	7.62	8.86	5.97
Ca K	39.54	23.65	1.53	2026.68	0.05
Fe K	1.44	0.62	2.70	33.46	1.04
Cu K	0.42	0.16	6.01	6.04	4.37

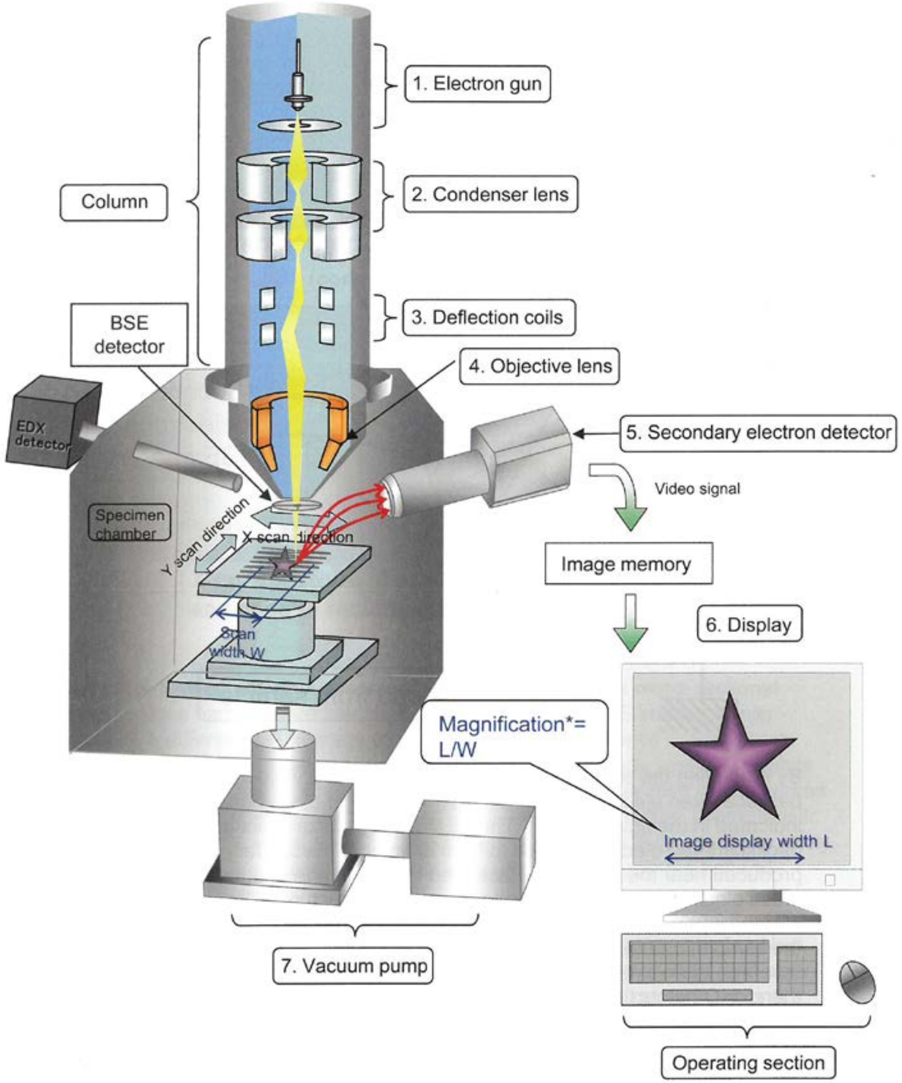
Color representation of selected elements in the sample = one element in all pixels





WDX/WDS: wavelength dispersive X-ray spectroscopy (much better energy resolution, but slow)

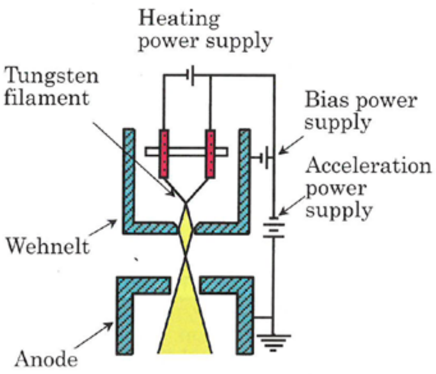
Scanning electron microscope (main parts)



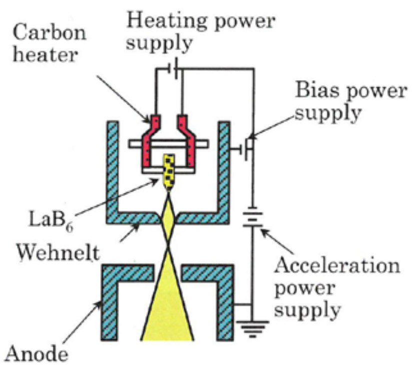
- Electron gun is source of electrons with required parameters
- Condenser lens converge the electron beam emitted from electron gun into finer beam
- Deflection coils are used to scan the electron beam in X and Y directions and change size of the area to be scanned (magnification)
- Objective lens converges electron beam into a fine beam and focus it on the sample surface.
- Detectors for capturing signal for each pixel
- Synchronization of data acquisition and scanning system to receive an 2D image

Kinds of electron guns

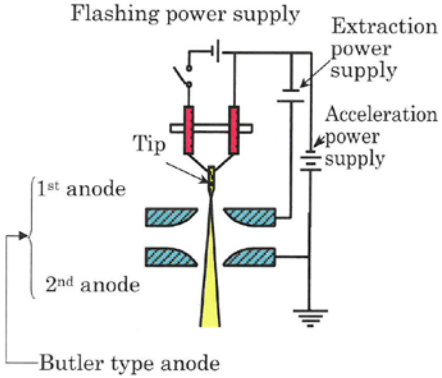
Tungsten



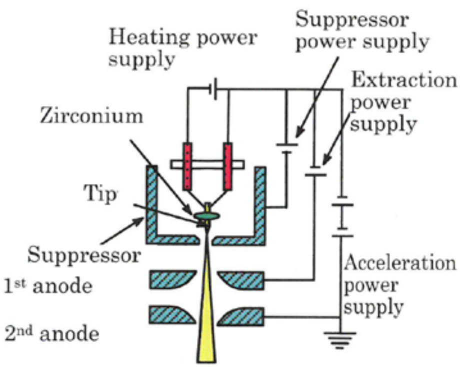
LaB_6



Cold field-emission



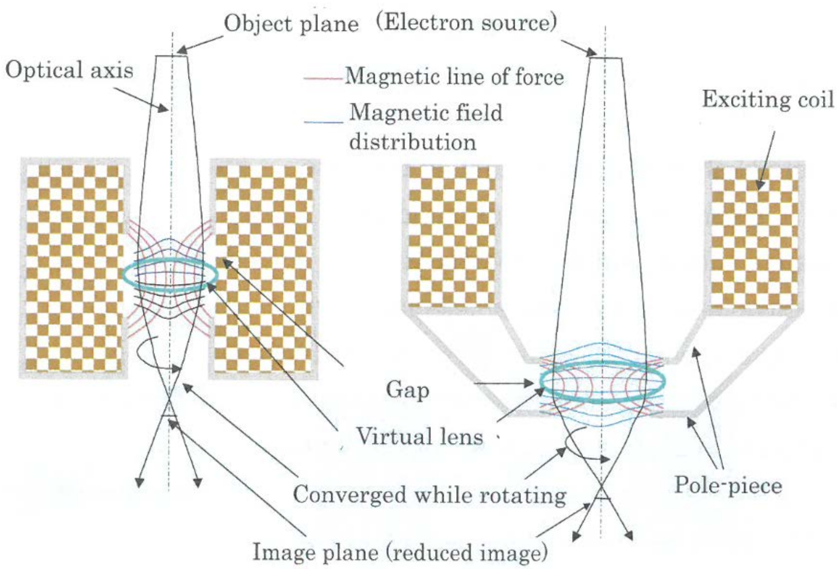
Schottky



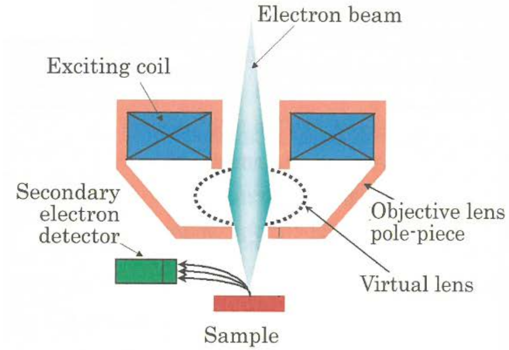
	Tungsten	LaB_6	CFE	Schottky
Material	Tungsten hairpin	Lanthanum hexaboride single crystal	Tungsten single crystal	Tungsten single crystal/ zirc. oxide
Cathode temp	~2300 °C	~1500 °C	RT °C	~1500 °C
Brightness	10^6 A/cm^2·sr	10^7 A/cm^2·sr	10^9 A/cm^2·sr	10^8 A/cm^2·sr
Energy width	~2 eV	~1.5 eV	0.2-0.3 eV	0.3-1 eV
Max. probe current	~100 nA	~100 nA	~10 µA	~100 nA
Working pressure	10^{-4} Pa	10^{-5} Pa	10^{-8} Pa	10^{-7} Pa
Lifetime	50-100 h	200-1000 h	2-4 y	2-3 y

Electron lenses

Condenser lens **Objective lens**

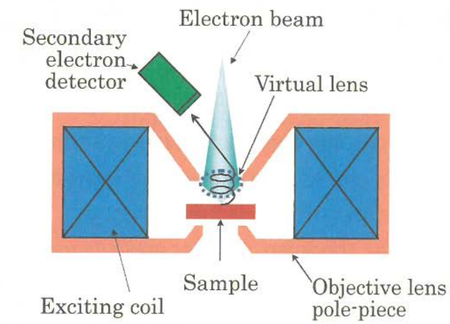


Electron lenses in SEM: magnetic/electrostatic lenses to focus the accelerated virtual electron source from electron gun into a fine probe onto the sample surface.
Condenser lens: "shaping" electron beam (responsible for its intensity)
Objective lens: focusing the electron beam into a fine probe



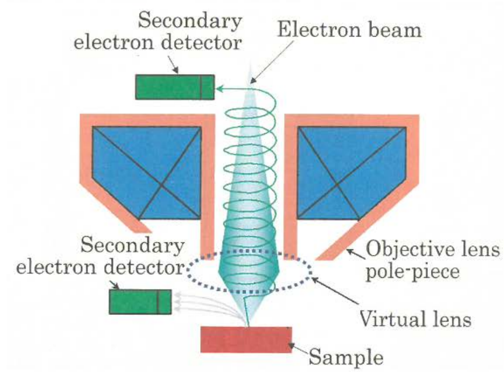
Standard type

- generally used in low-end SEM
- WD can be high (longer depth of focus)
- optionally can be set also in snorkel type



In-lens type

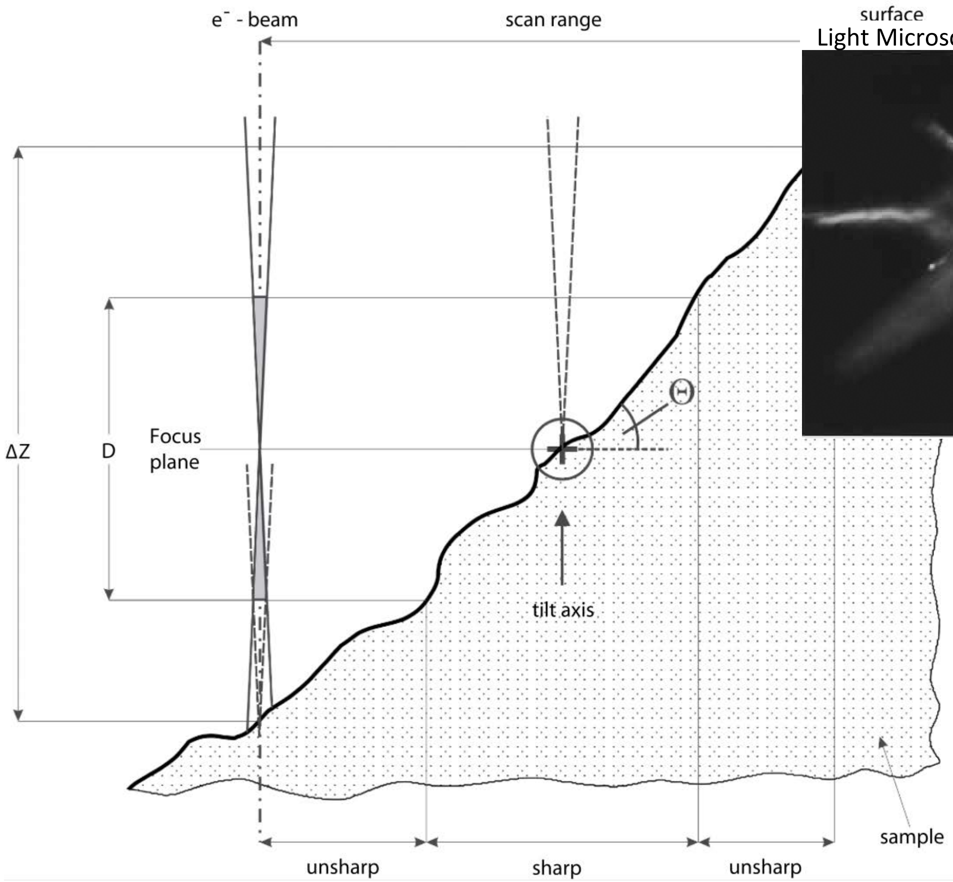
- best resolution SEM
- only short WD
- limited sample size



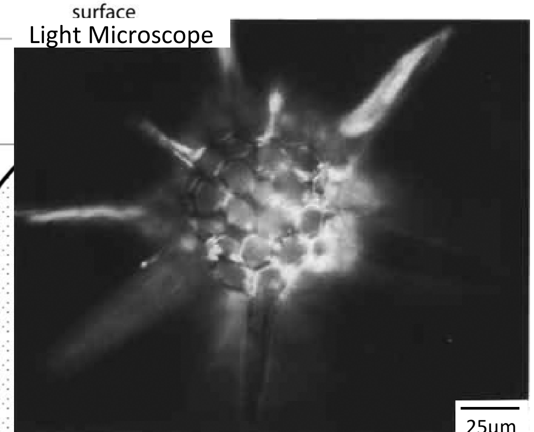
Semi in-lens (snorkel) type

- high-end SEM
- virtual lens close to sample (sample in EM field)

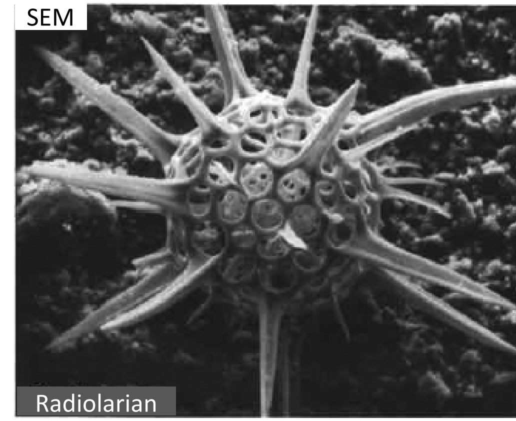
Depth of focus in SEM



Light Microscope

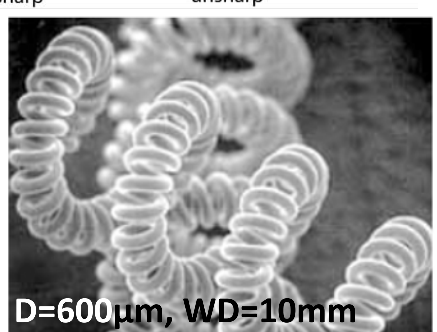


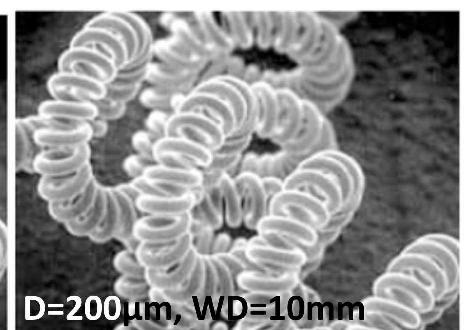
SEM

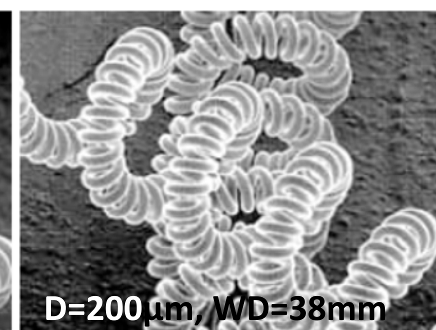


Magnification	Depth of focus (example)	
	Light microscope	SEM
10	60 µm	1000 µm
100	8 µm	100 µm
1,000	0.2 µm	10 µm
10,000	---	1 µm

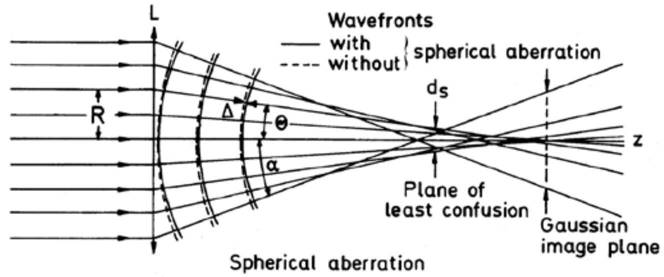
Effect of aperture diameter (D) and working distance (WD) of depth of focus
(Light bulb coil)

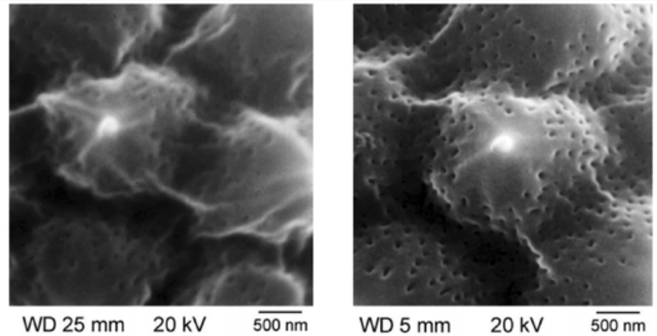






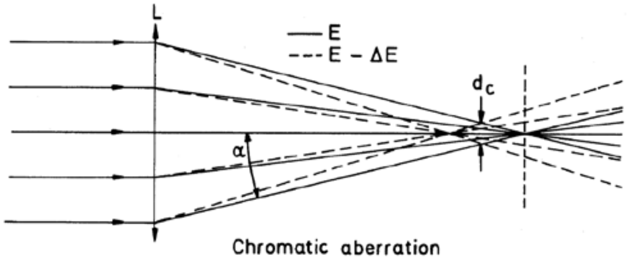
Lens aberrations

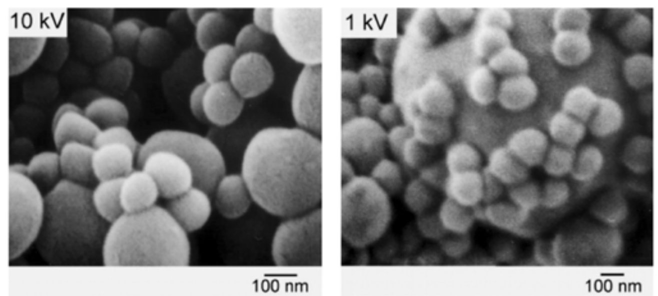




$d_S \sim ½ \, C_S \, \alpha^3$

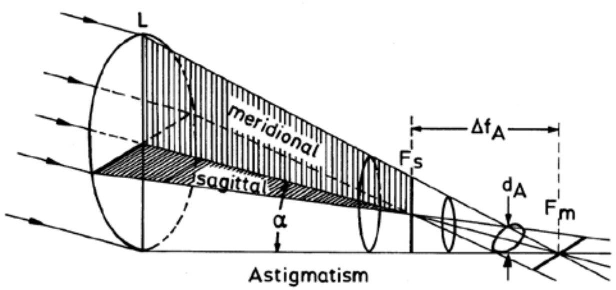
C_S … spherical aber. coef.

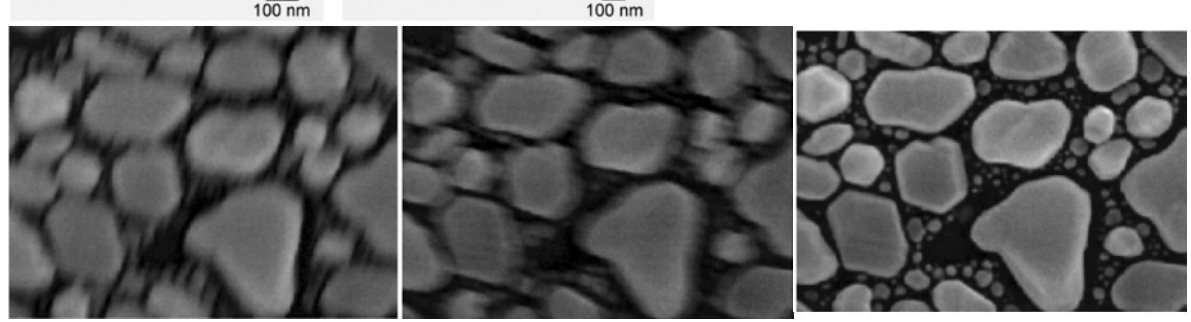


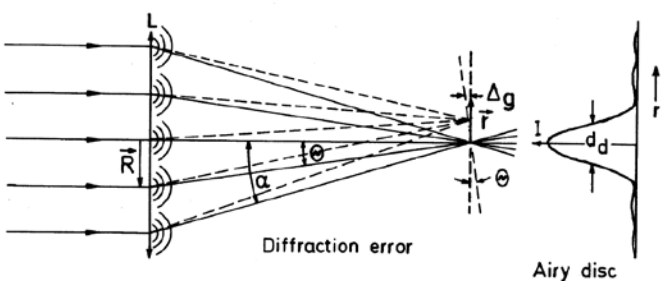


$d_C \sim C_C \, (\Delta E/E_0)\alpha$

C_C … chromatic aber. coef.



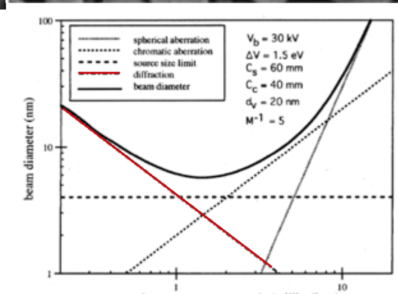




$d_d = 1.22 \, \lambda/\alpha$

λ … wavelength of electrons

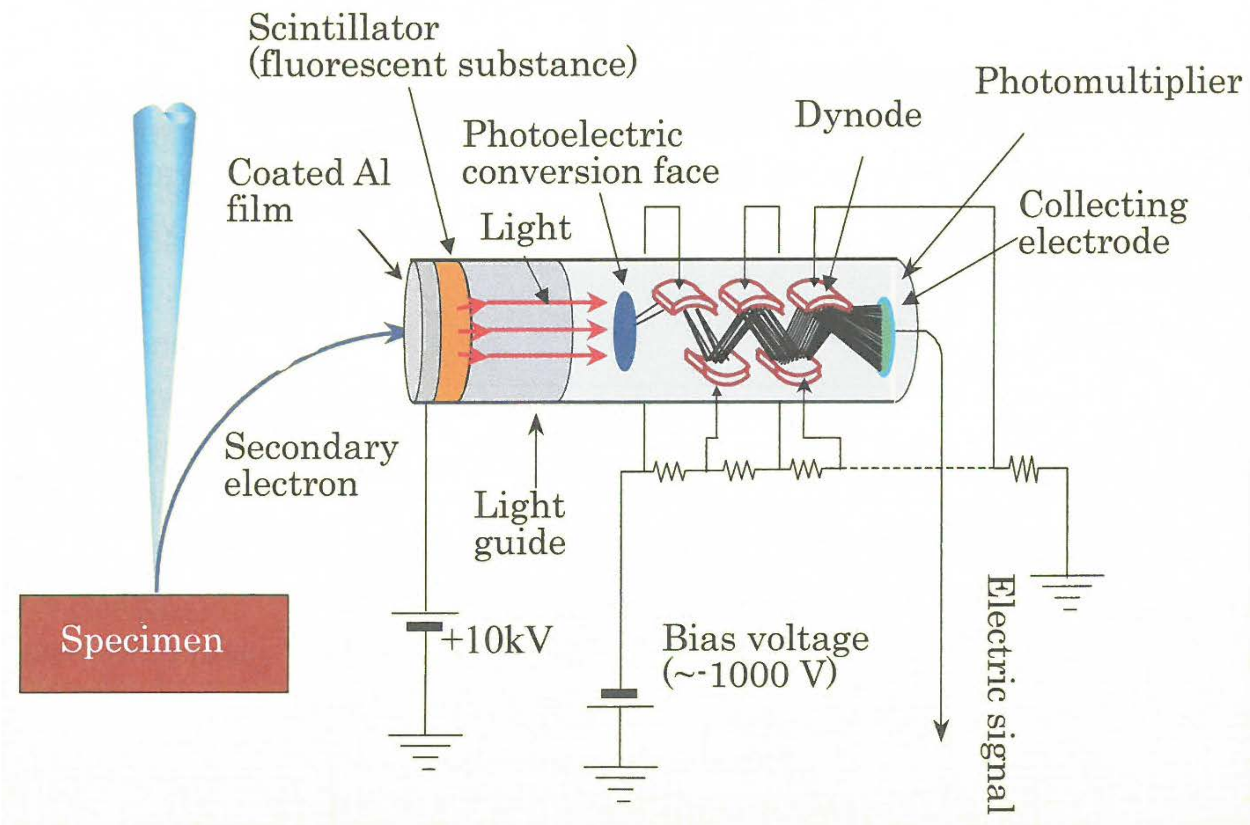
Increasing α effects spherical and chromatic aberrations being higher



Detector of secondary electrons (SE)

Everhart-Thornley (ET) detector

- SE electrons (very low energy <50 eV) are accelerated towards 10 kV electric field and hit against the scintillator for conversion into the light signal which leads to the photomultiplier tube (PMT) through a light pipe



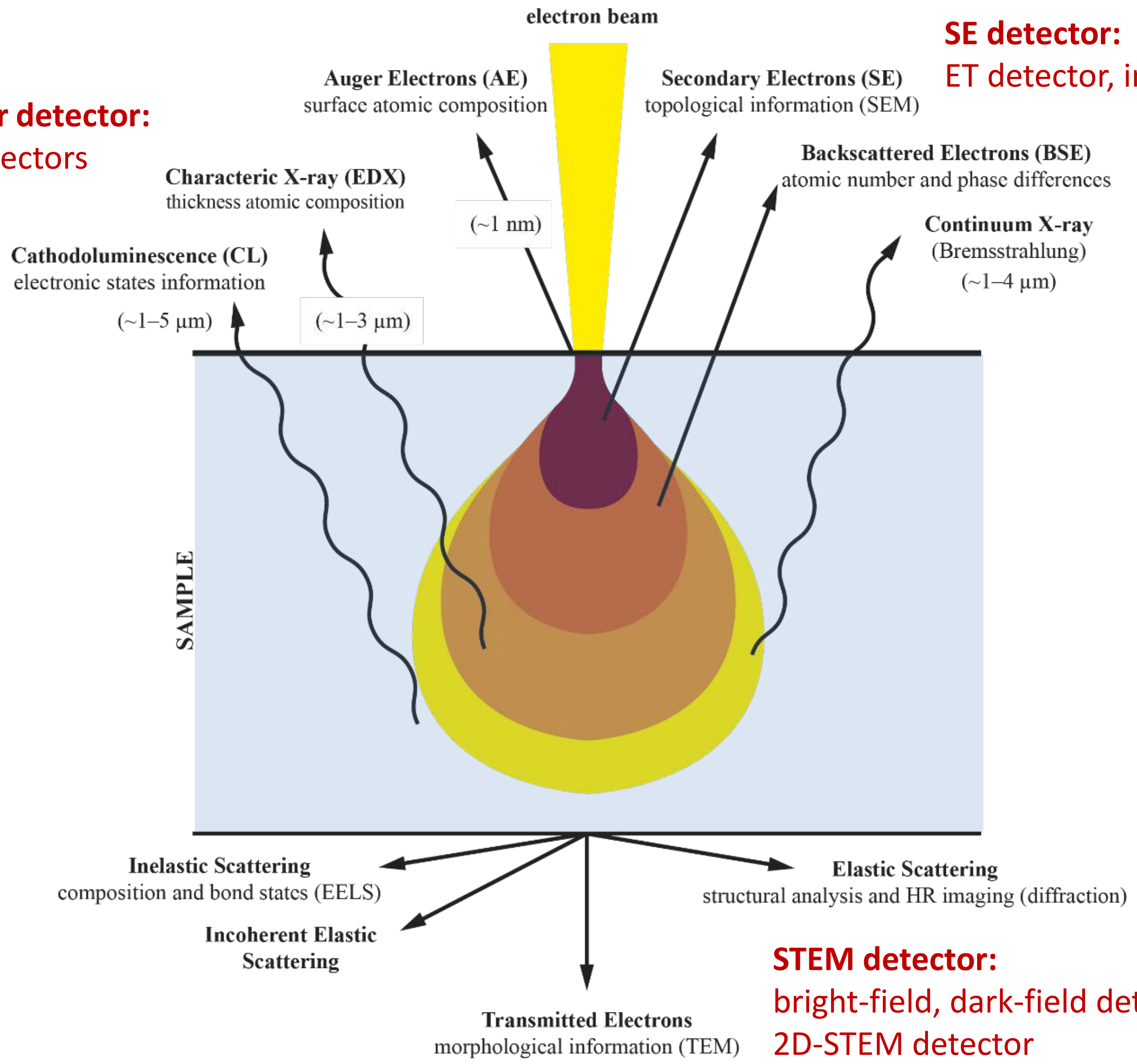
Signals in SEM and their detection

SE detector:
ET detector, in-lens (TLD) detector

X-ray detector detector:
EDX, WDX detectors

BSE detector:
retractable BSE detector,
in-lens detektor

CL detector

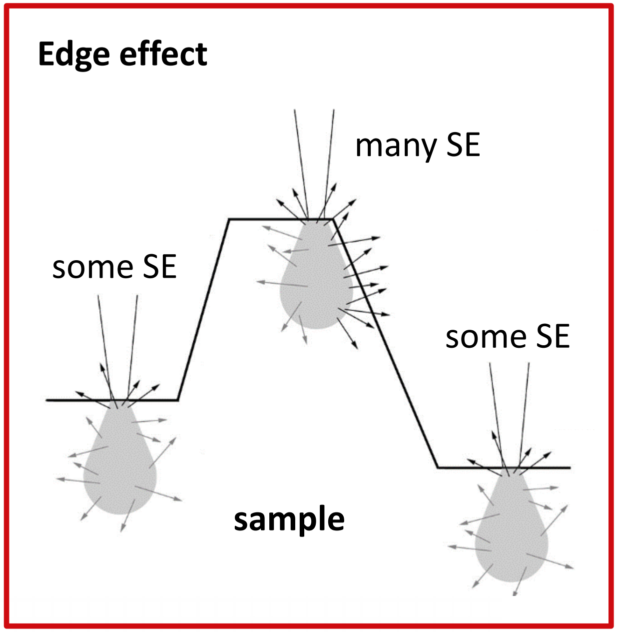


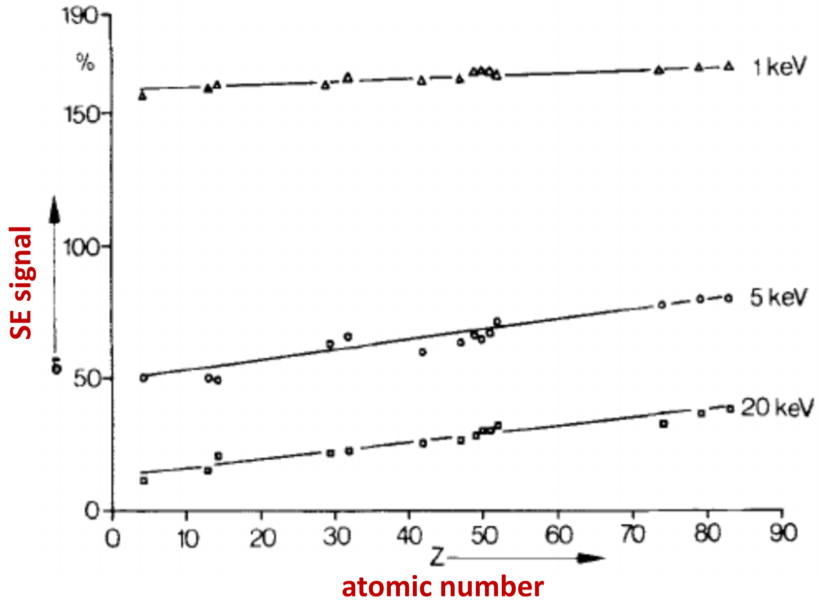
STEM detector:
bright-field, dark-field detectors,
2D-STEM detector

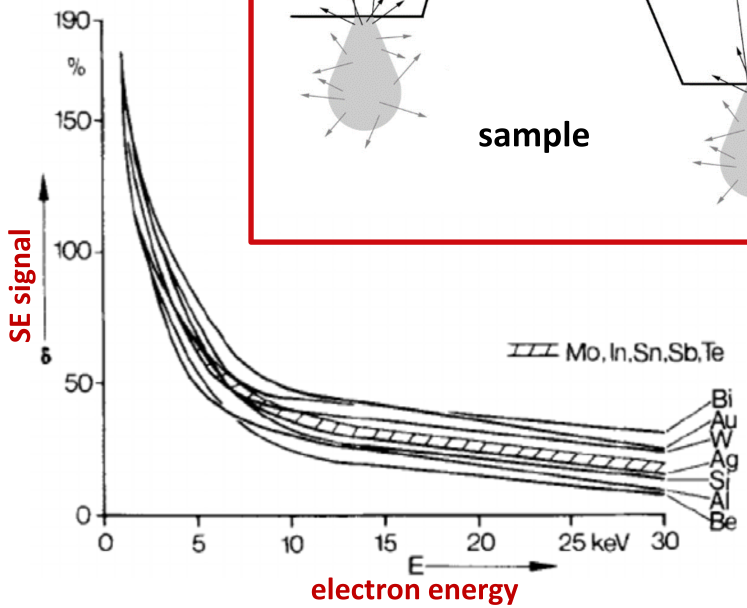
Secondary electrons (SE)

SE signal:

- is formed by very low energy of secondary electrons (≤ 50 eV) generated from the collision between the primary electrons and loosely bound outer electrons
- gives **mainly information about topography (topographic contrast)**, less about composition
- **increases with decreasing electron energy**
- **weaker dependence on atomic number Z**
- is **strongly dependent on tilt of the sample (edge effect)**

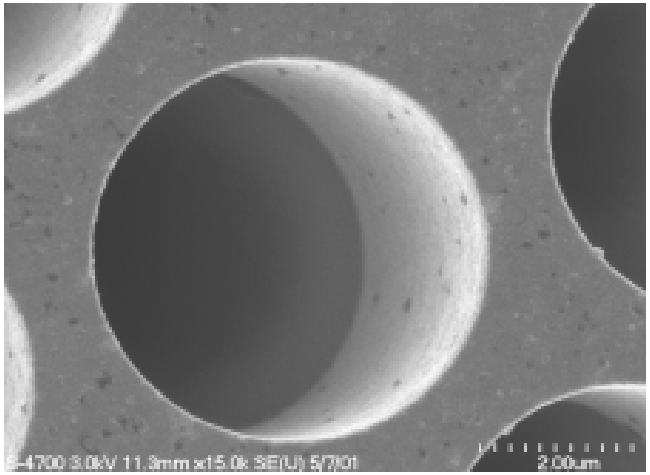




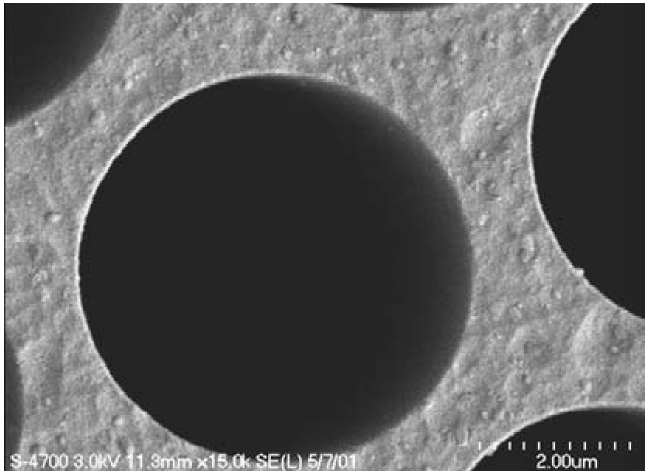


Secondary electrons (SE)

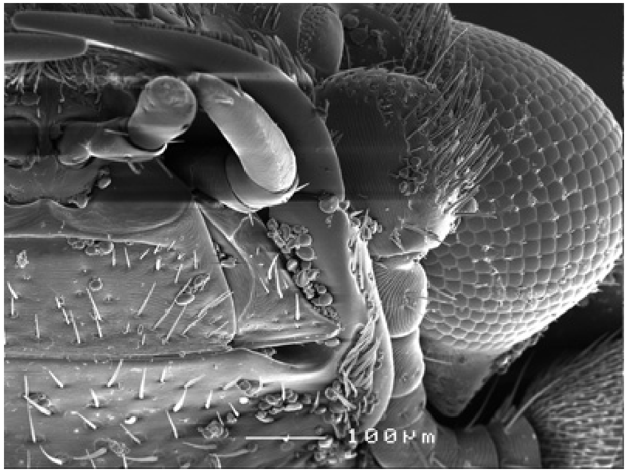
- **SE detector type**
- upper “in lens” detector



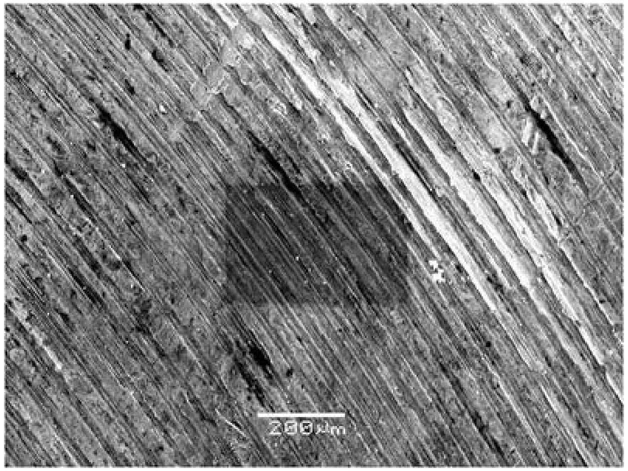
- lower “ET” detector



- **Artefacts**
- charging



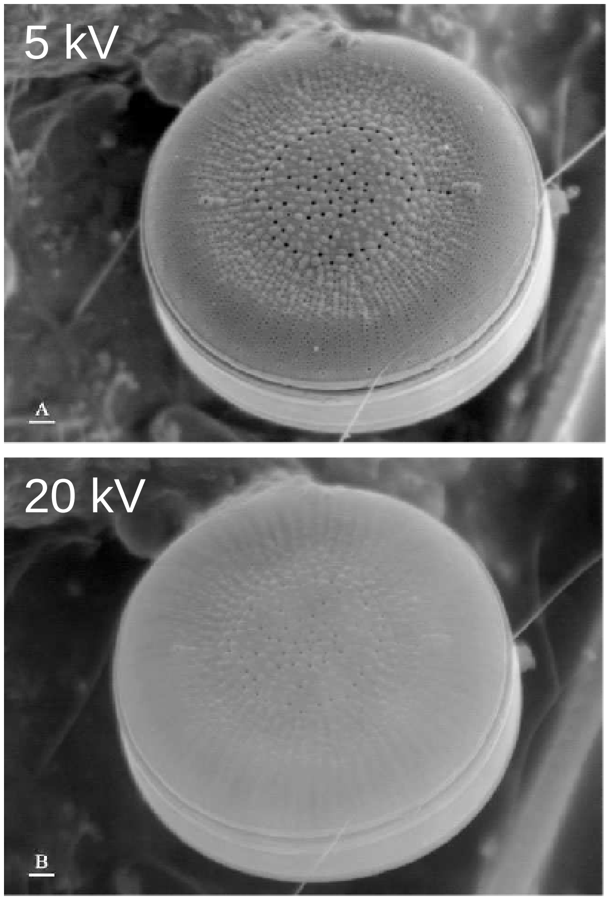
- contamination



- In non-conducting samples the electron probe current remains in sample → accumulation of charge → artefacts mainly for SE *(reducing probe current, lowering E_0, imaging with BSE, metal coating,…)*
- Result of interaction of electron beam with residual gasses and hydrocarbons on the sample surface *(ensure cleanliness, decrease probe current, use plasma cleaner,…)*

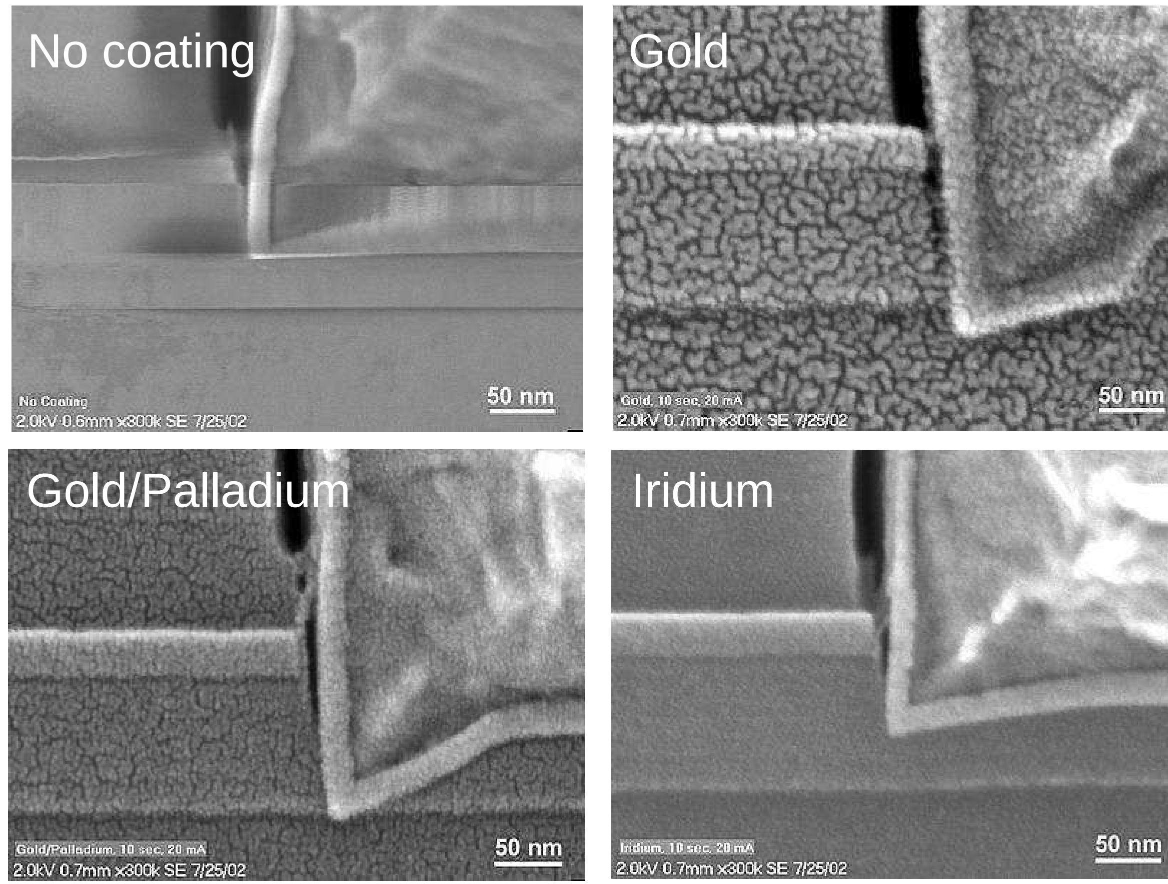
Secondary electrons (SE)

- **Effect of penetration depth**



Bar: 1 µm (Sample: Diatom)

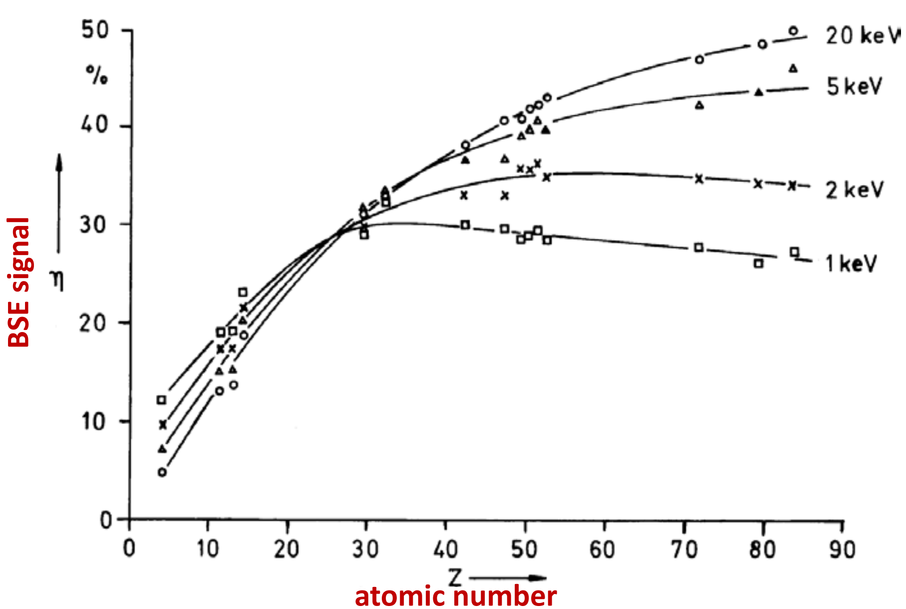
- **Enhancement of contrast by metal coating to reduce**
  - Interaction volume
  - Charging effect
  - Beam damage

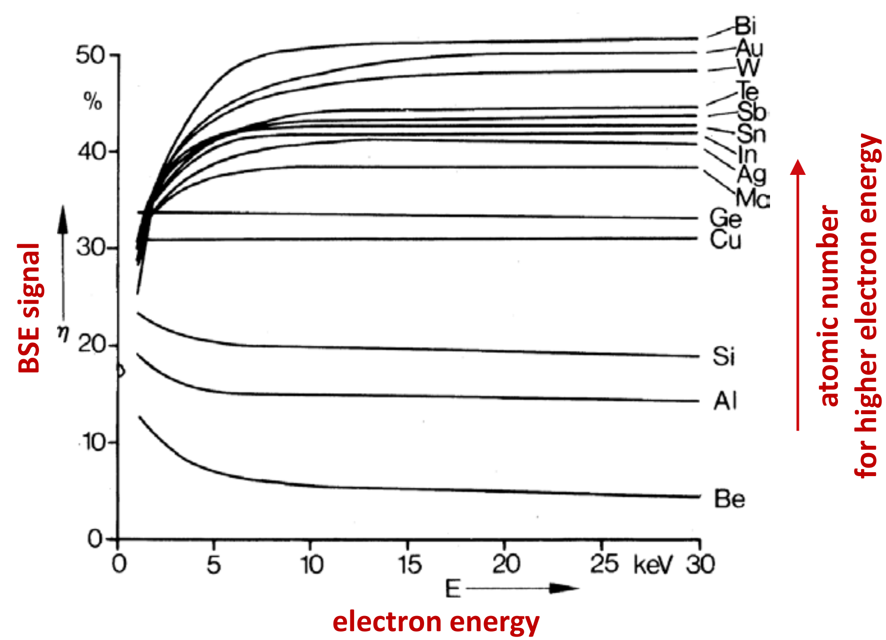


Backscattered electrons (BSE)

BSE signal:

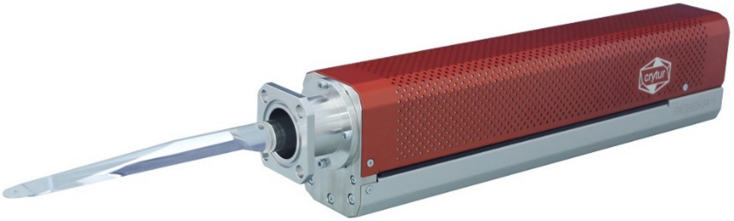
- is formed by primary electrons which are backscattered (all electrons in the energy range from 50 eV to E_0)
- in general number of BSEs is much lower than SEs
- gives **mainly information about material (material contrast)**, less about topography
- **increases with increasing atomic number Z** up to E_0~30 keV
- increases with increasing tilt of the sample
- is **almost independent on energy for E_0 >10 keV**

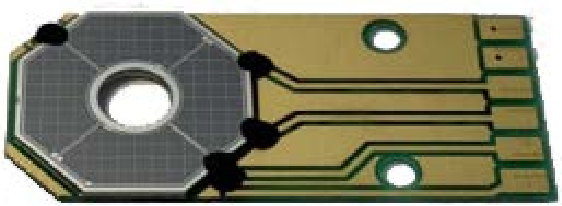




Backscattered electrons (BSE)

- **BSE detector type**
- **retractable BSE detector** (standard BSE like ET for SE)
- annular active area (well defined)
- very effective
- basic types
    - scintillator based (usually YAG detector)
        - usually 1 segment
    - semiconductor detector
        - usually multi-segment

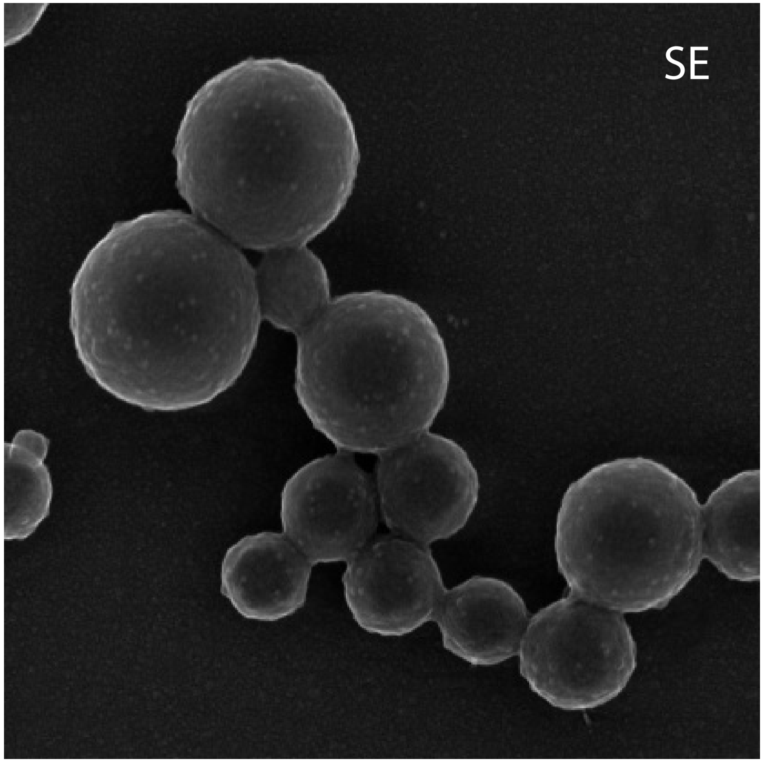


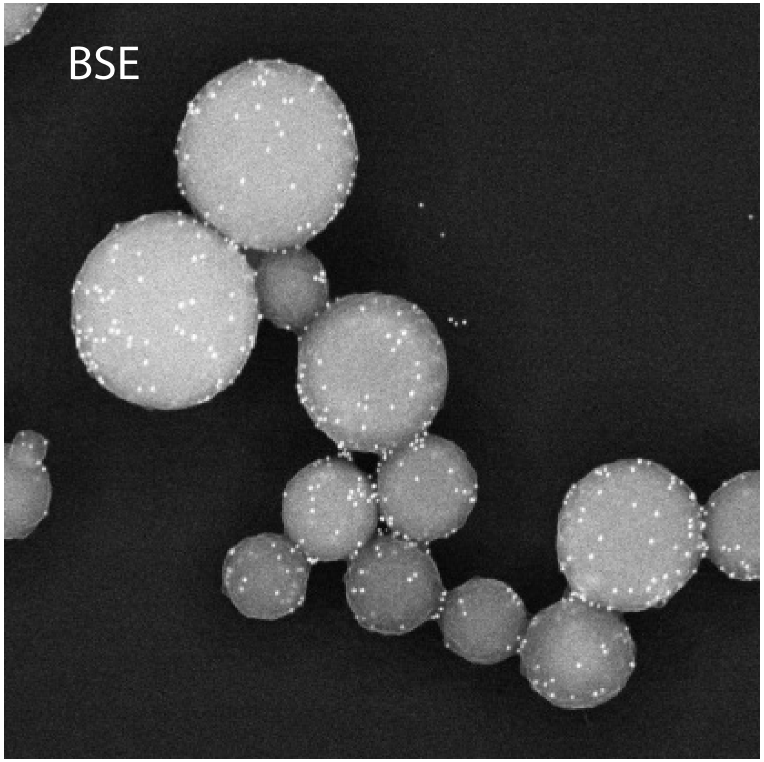


- **in-lens detector** (only for snorchel type objective)
    - various possibilities depending on SEM producer and SEM type

SE vs. BSE imaging

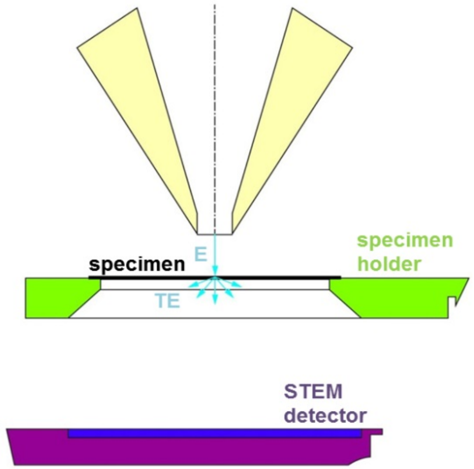
- Immunogold labeling of surface proteins (rubber nanoparticles isolated from *Taraxacum*)



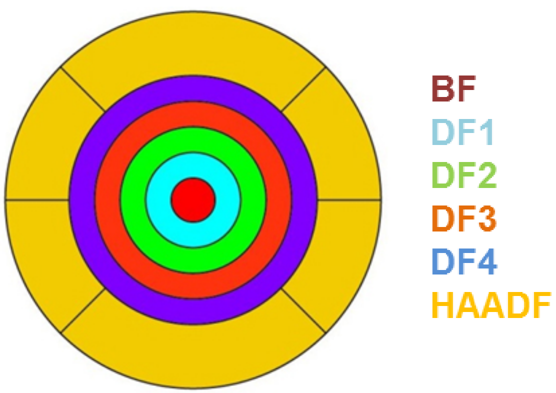


SE: sample surface information (topography)
BSE: due to targeted immunolabeling (gold nanoparticles bound to immunoglobulin) the possibility to identify specific parts on the sample (bright Au nanoparticles)

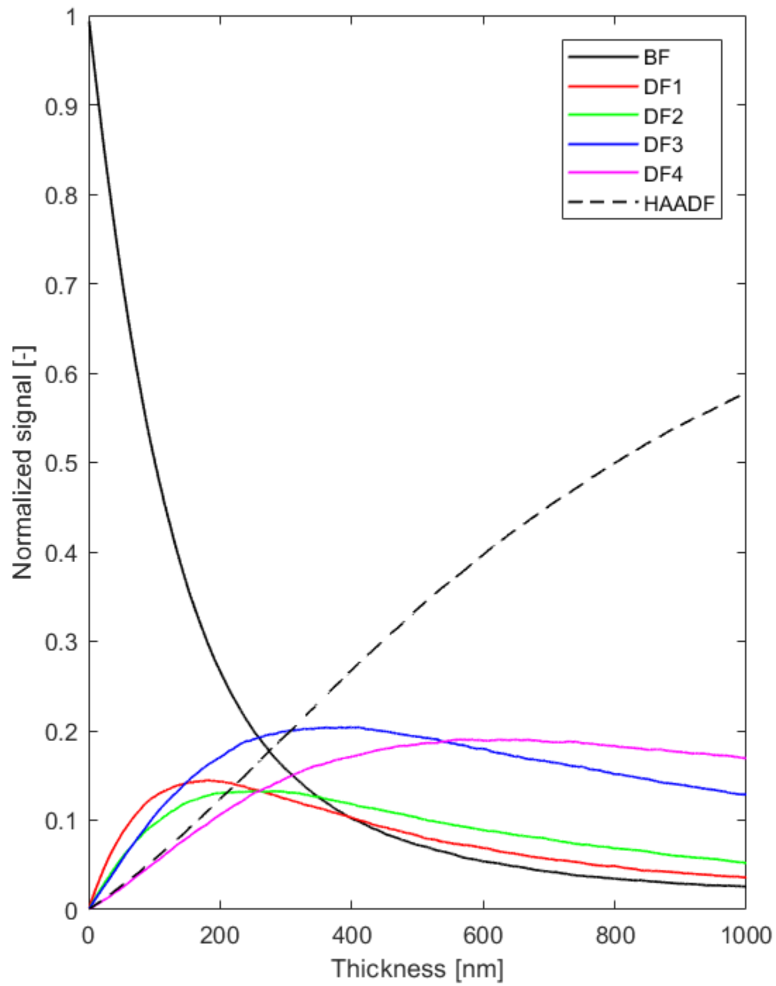
STEM: Scanning Transmission Electron Microsc.

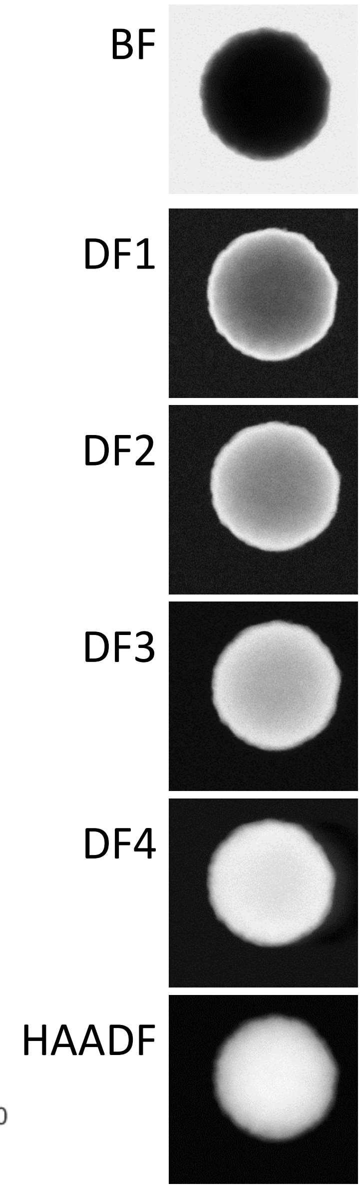


Multisegment STEM detector



Monte Carlo simulations for STEM signals

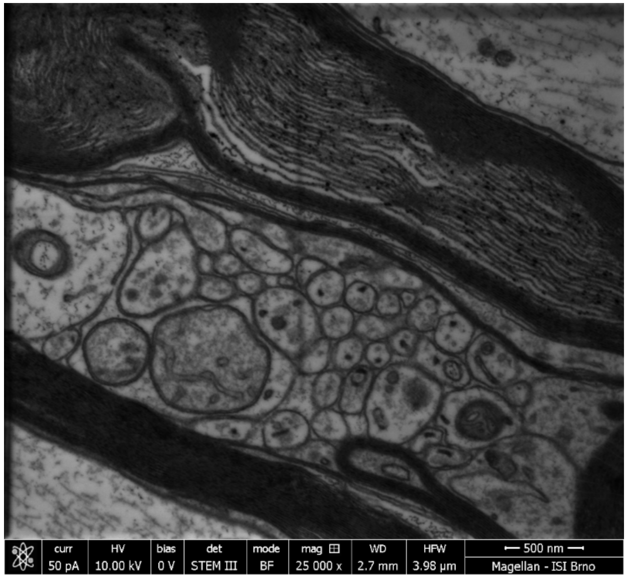




STEM (various segments) and BSE

10 kV, 50 pA

STEM BF



BSE

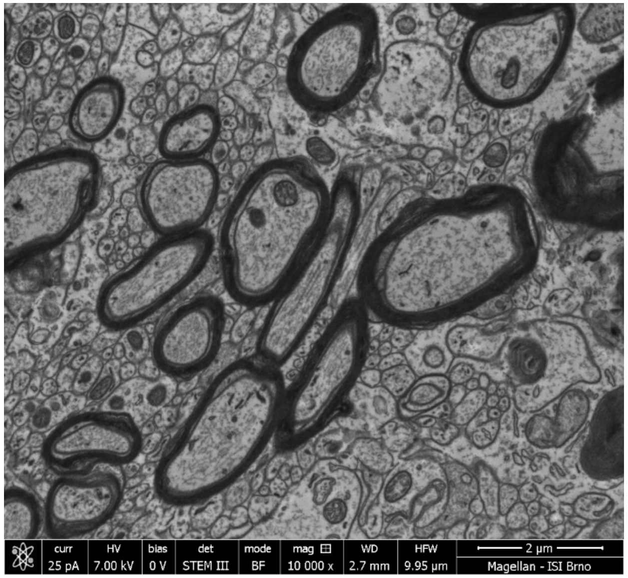
STEM DF1

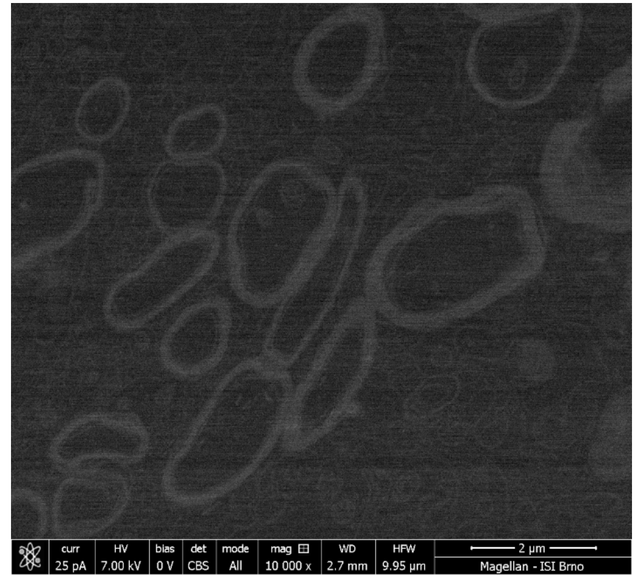
STEM HAADF

STEM vs. BSE

7 kV, 25 pA

STEM BF

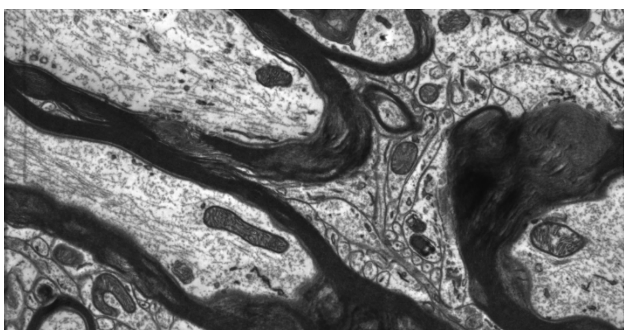


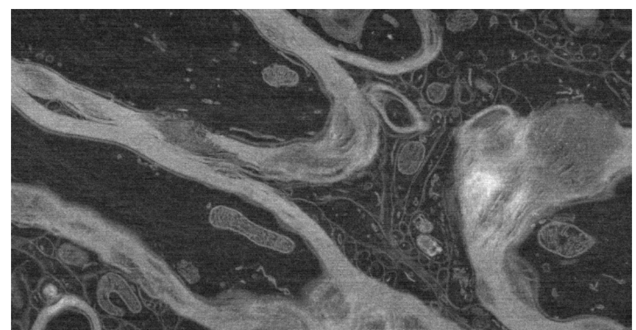


BSE

7 kV, 100 pA

STEM BF





BSE

STEM-in-SEM

- can be used for imaging of ultrathin sections like TEM (less comfortable)
- can be used as imaging without need of staining, see *Microorganisms* **11** (2023), 888

Some other configurations

ESEM (Environmental SEM)

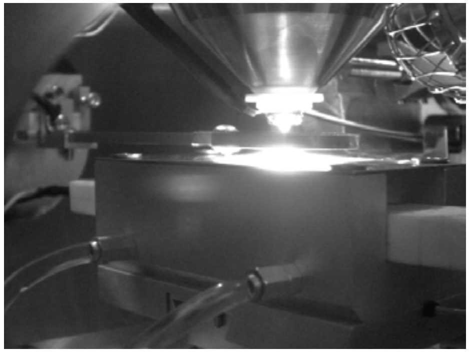
- specimen chamber pressure up to 3000 Pa (various gasses possible)
- different detectors required
- convenient for insulating samples, vacuum sensitive samples (biological),…

FIB-SEM, SBF-SEM

- focused ion-beam implemented into SEM
- ultramicrotome implemented into SEM
- → see another lecture

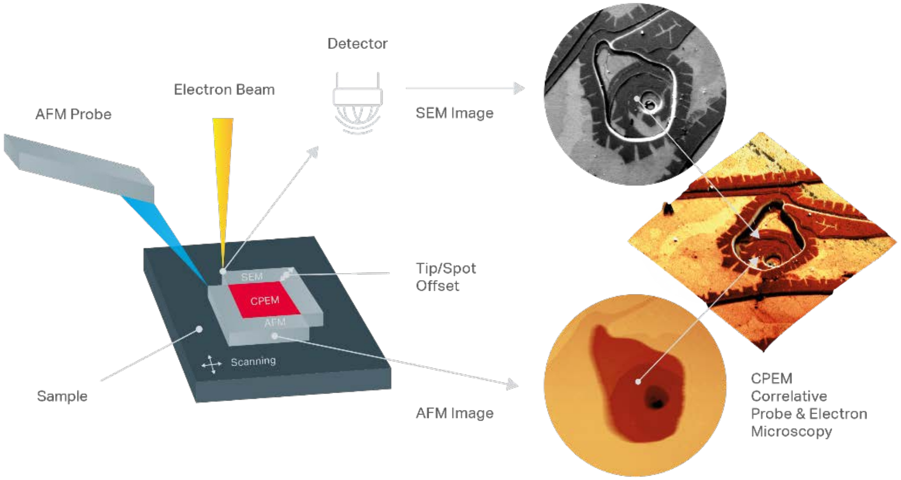
in-situ SEM, cryo-SEM

- hot stage / mainly for material sci.
- cryo-stage / mainly for life science



Combination with AFM

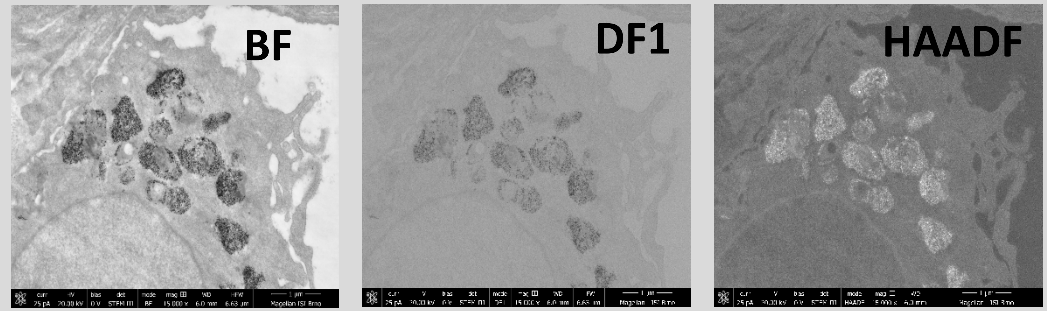
- integration of AFM into SEM



Multimodal imaging (correlative imaging)

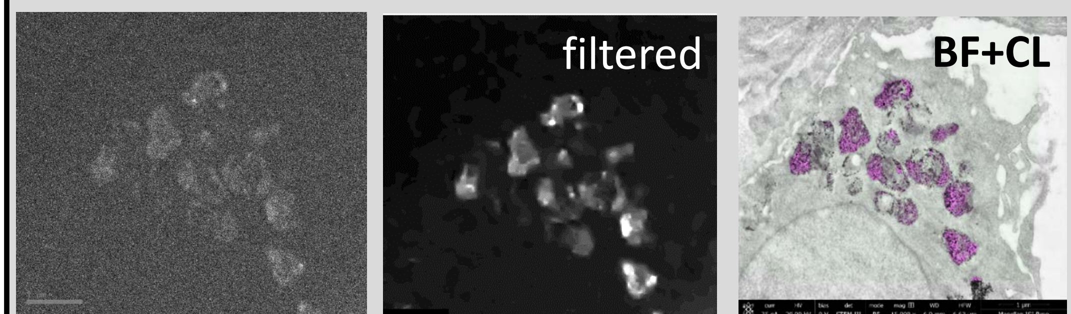
Cooling of the sample to cryo temperatures - reduction of surface contamination together with higher resistance to the electron beam

STEM



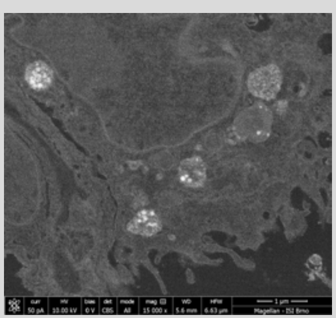
SAMPLE
Titanium particles in lung cells

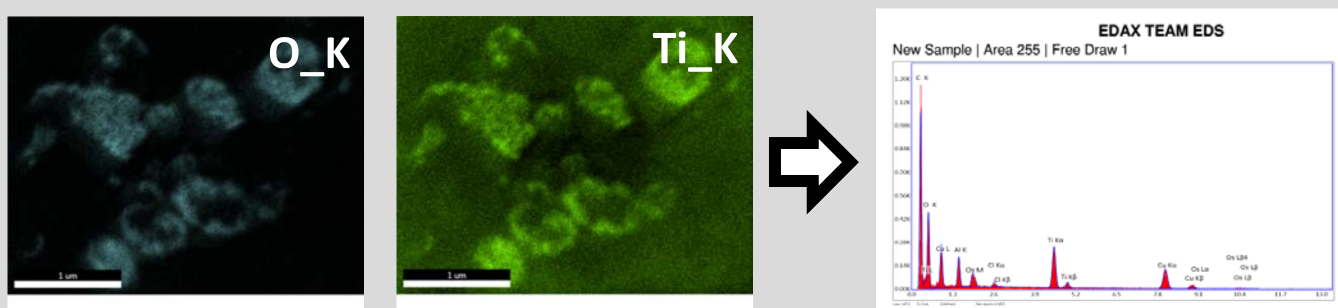
CL



EDX

BSE





Conclusions

- SEM is a versatile instrument that can be used for many purposes and can be equipped with various accessories
- Secondary electrons (SE): mainly topography
- Backscattered electrons (BSE): mainly material contrast
- Transmitted electrons (STEM): mass-density contrast
- X-ray: chemistry (composition)
- **Use the full power of your SEM - play around with the settings (modern SEMs offer many options)**

- EM manufactures:

delong instruments ®

TESCAN PERFORMANCE IN NANOSPACE

HITACHI Inspire the Next

ThermoFisher SCIENTIFIC

JEOL Solutions for Innovation

ZEISS

Thank you for your attention

INSTITUTE OF SCIENTIFIC INSTRUMENTS
The Czech Academy of Sciences

Vladislav Krzyžánek
krzyzanek@isibrno.cz

Monte Carlo simulations

- There are more free programs, e.g.
- CASINO "monte CArlo SImulation of electroN trajectory in sOlids" https://www.gegi.usherbrooke.ca/casino/
  - Version 2 is simple for users (only films) … *recommended for beginners*
  - Version 3 works in 3D (user-defined shapes) … *more complicated*

- Movie in Czech: Kukátko do nanosvěta z cyklu NEZkreslená věda https://youtu.be/2vYquoVWLqQ