Scanning electron microscope

6th CEMM workshop

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Outline

- The basic principle?
- What is an electron?
- Parts of the SEM
  - Electron gun
  - Electromagnetic lenses
  - Apertures
  - Chamber and detectors
- Electrons and their interactions with the specimen
- SEM settings and how we see it on the SEM image
  - Voltage
  - Current
  - WD and apertures on DOF
  - Scanning speed

Figure removed for copyright reasons.

(Image: ammrf)

Basic principle of SEM operation

Basic principle?

By using a focused beam of electrons, we can see otherwise invisible worlds on the microscale and nanoscale.

SEM advantages over LM:

- Resolution at high magnification
- Depth of focus (field, depth)
- Microanalysis (EDS, WDS, EBSD, CL)

In LM: the specimen is unchanged by observation
In EM: interaction can have more serious consequences (heated and chemical changes)

But must be vacuum compatible and conductive!

(Images: ammrf)

Figure removed for copyright reasons.

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Magnification is the enlargement of an image, or portion of an image. In a SEM this is achieved by scanning a smaller area. In the images, the beam is indicated by arrows on a sample.

Resolution? The ability to distinguish closely spaced points as separate points.

What is an electron?

Electrons are small subatomic particles (small and firm, like a ball).

In the 1920 in Bell laboratories an experiment was made were the beam of electrons passed a double slit and was observed on the screen

Figure removed for copyright reasons.

Quantum mechanics: Niels Bohr

Wave – particle duality

What do you see?

Figure removed for copyright reasons.

Image: getmedic.ru

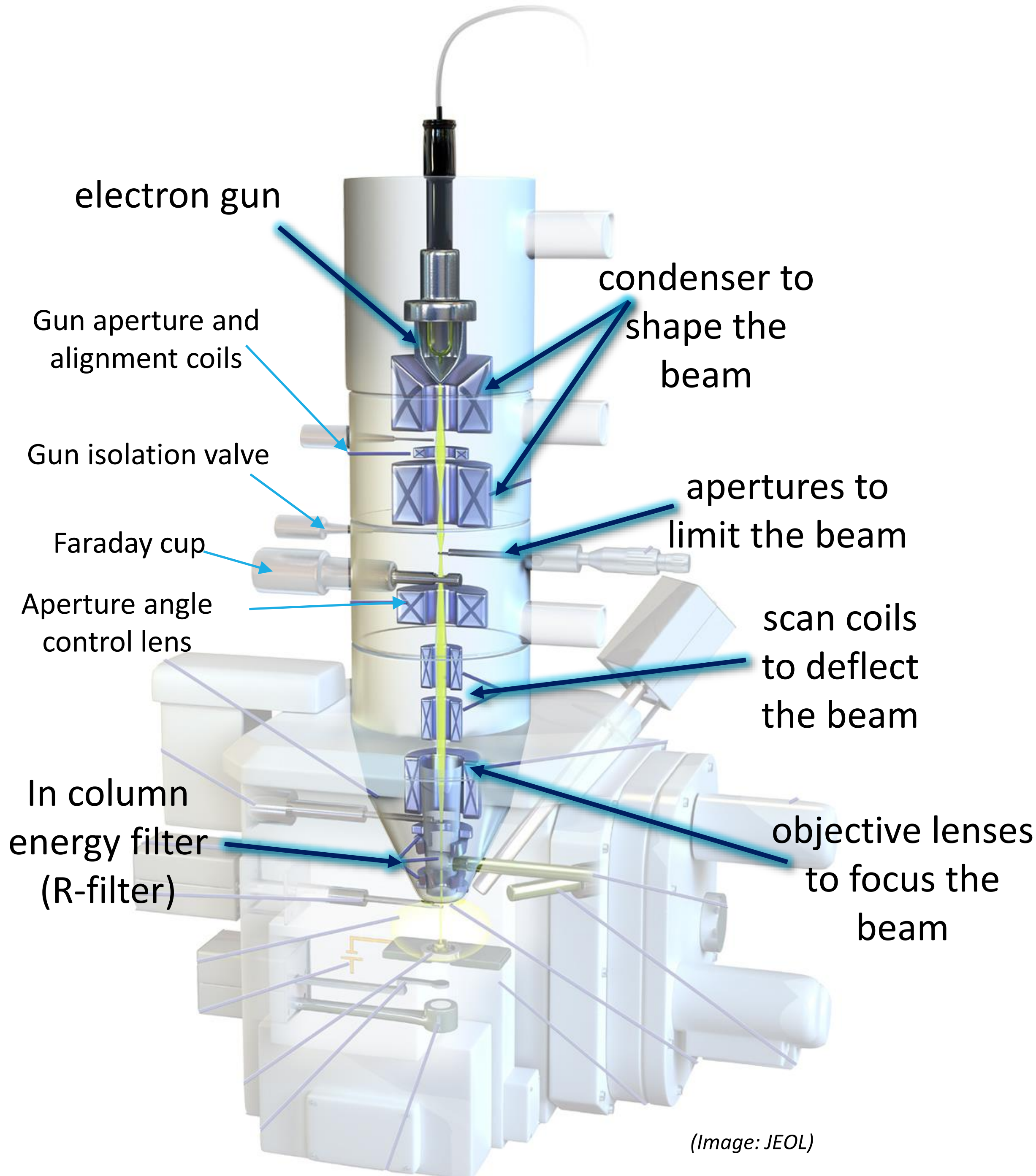
(Images: physics.stackexchange.com*)*

(Image: LEGO)

Parts of the SEM

Microscope (column and chamber), computer and other parts (vacuum system, water chilling system, microanalysis)

Microscope column



(Image: JEOL)

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Electron gun

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Thermionic emission

The components to produce an electron beam:

an **emitter** (electrode W or LaB6)

a surrounding cathode (**Wehnelt** cylinder/ grid cap)

an **anode** with a central hole.

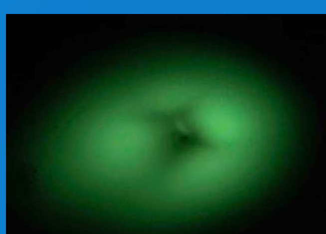
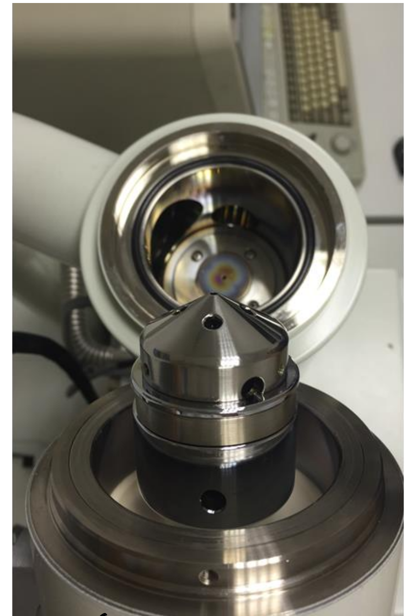
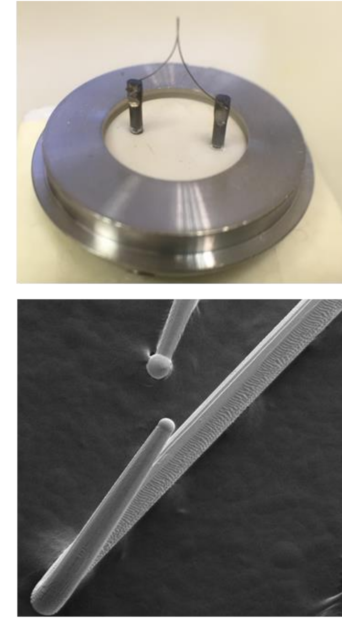


Image of the TE LaB_6





JSM-5800

Figure removed for copyright reasons.

$$E = E_W - E_F$$

Emission current density

Tungsten: J_{th} **= 3,4 A/cm²** → $J_{th} = 3{,}4\ A/cm^2$

$T = 2700\ K,\ E_w = 4{,}5\ eV$

LaB_6: $J_{th} = 40\ A/cm^2$

$T = 1800\ K,\ E_w = 2{,}5\ eV$

(Image: ammrf)

Figure removed for copyright re

(Image: Goldstein)

Field emission

The FE gun consists of:

Emitter

cathode - tungsten with a very sharp point <100nm

Suppresser anode

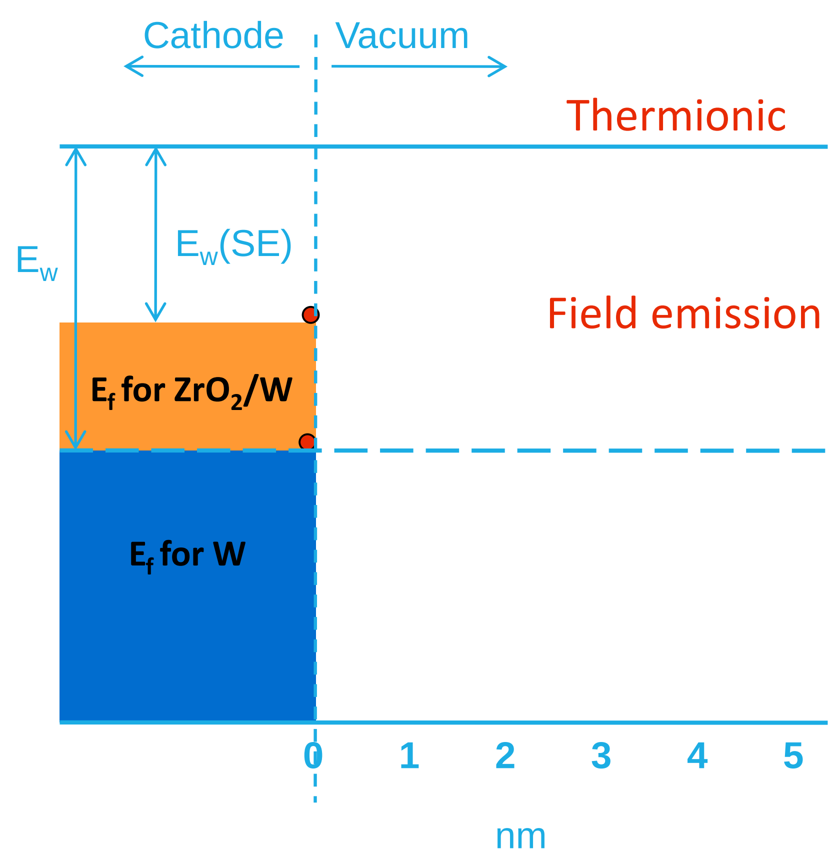
(only Schottky – field assisted thermionic emitter)

Extraction anode

(a very strong field at the tip >10^7 V/cm)

Accelerating anode

(final accelerating)



Comparison of electron guns

Emitter Type Cathode material	Thermionic W	Thermionic LaB_6	Schottky FEG ZrO/W (100)	cold FEG W(310)
Operating temperature [K]	2,800	1,900	1,800	300
Cathode radius [nm]	60,000	10,000	< 1,000	< 100
Effective source radius [nm]	15,000	5,000	15	2.5
Emission current density [A/cm^2]	**3**	30	**5,300**	17,000
Total emission current [µA]	200	80	200	5
Normalized brightness [A/cm^2.sr.kV]	**1×10^4**	1×10^5	**1×10^7**	2×10^7
Maximum probe current [nA]	1000	1000	10 - 100	0.2
Energy spread @ cathode [eV]	0.59	0.40	0.31	0.26
Energy spread @ gun exit [eV]	**1.5 - 2.5**	1.3 - 2.5	**0.35 - 0.7**	0.3 - 0.7
Beam noise [%]	1	1	1	5 - 10
Emission current drift [%/h]	**0.1**	0.2	**< 0.5**	5
Operating vacuum hPa/mbar[1]	**$< 1 \times 10^{-5}$**	$< 1 \times 10^{-6}$	**$< 1 \times 10^{-9}$**	$< 1 \times 10^{-10}$
Typical Cathode life [h]	**100**	> 1000	**> 5000**	> 2000
Cathode regeneration	not required	not required	not required	every 6 to 8 hours
Sensitivity to external influence	minimal	minimal	low	high

(Table: tedpella)

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Electromagnetic (EM) lens system

Condenser lens, objective lens and scanning coils.

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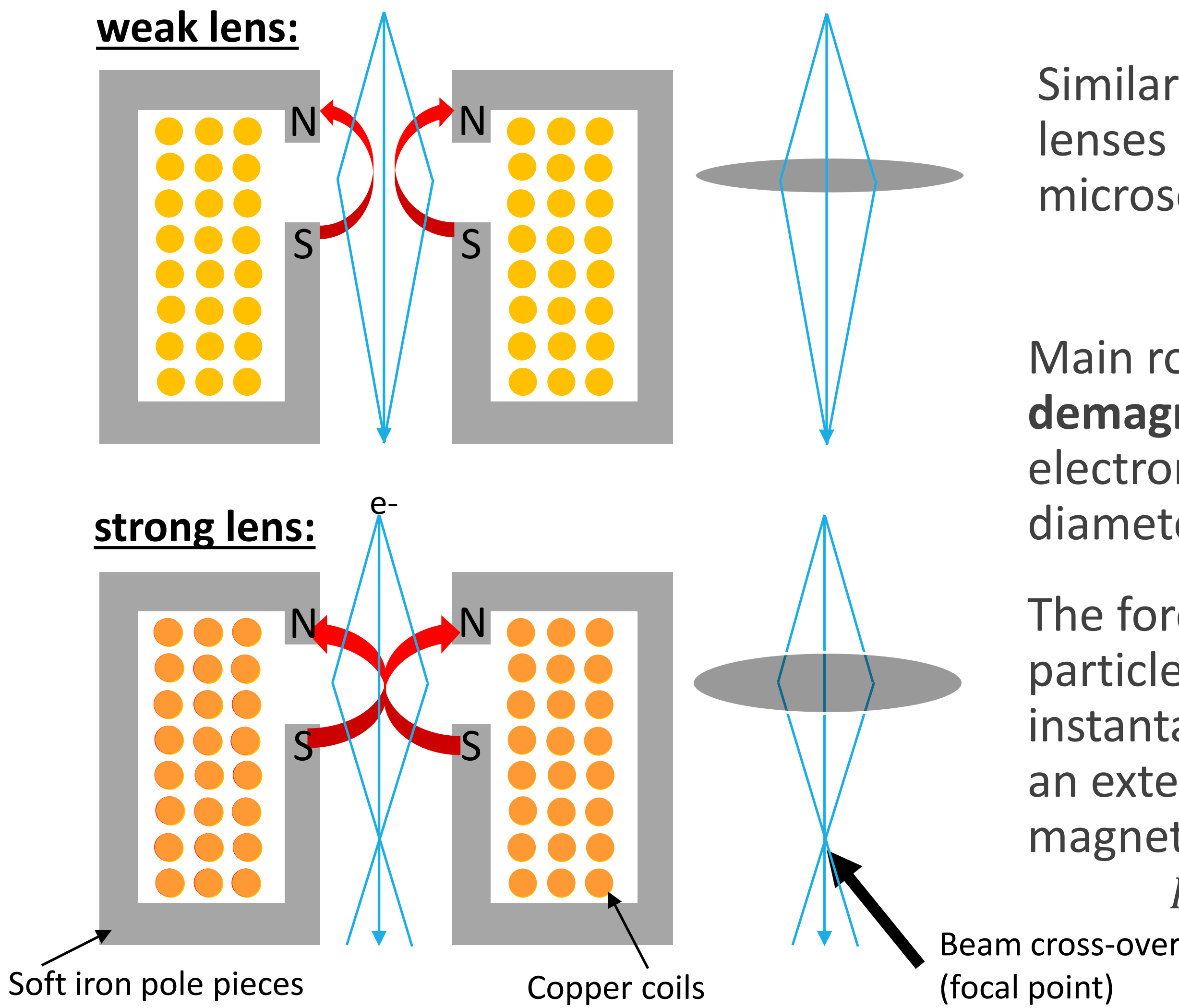
EM lenses



Similar to glass lenses in optical microscopes.

Main role of EM lenses is to **demagnify** the source of electrons to form a much smaller diameter probe.

The force F (Lorentz) acting on a particle of electric charge q with instantaneous velocity v, due to an external electric field E and magnetic field B, is given by:

$$F = q(E + v \times B)$$

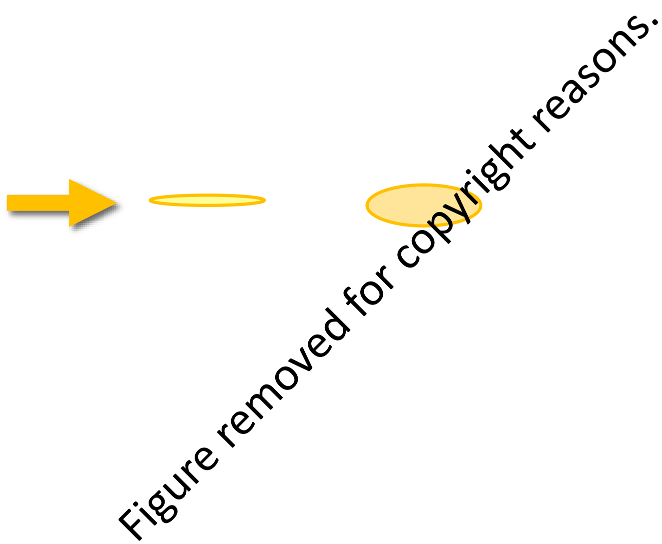
Two main lenses used in EM:

CONDENSER LENS

The main role of the condenser lens is to control **the size of the beam** and determines the number of electrons in the beam which hit the sample.

Low SPOT SIZE or PROBE CURRENT is a **STRONG** condenser lens.

High SPOT SIZE or PROBE CURRENT is a **WEAK.**



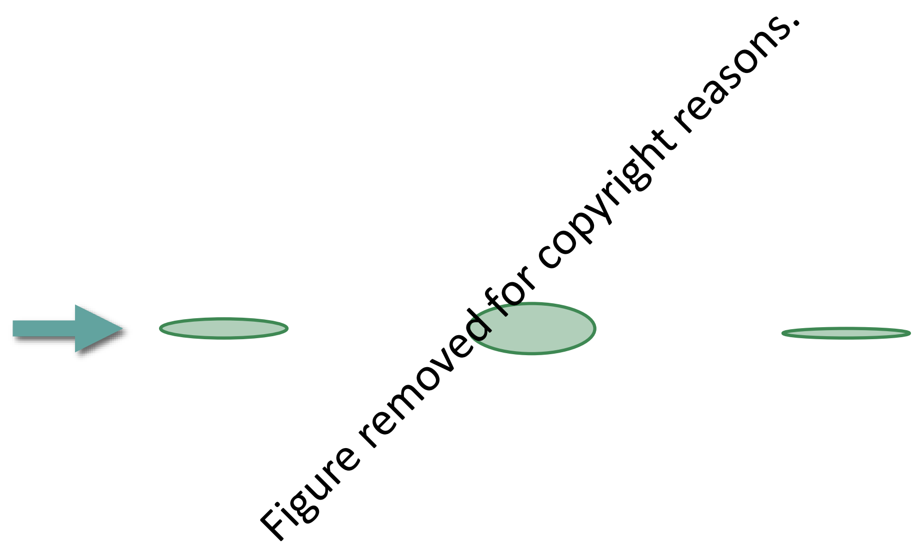
OBJECTIVE LENS

Focuses electrons on the sample at the working distance.

In SEM we have TWO objective lenses.

In TEM there are three objective lenses (mini, upper and lower OL).

(Images: ammrf)



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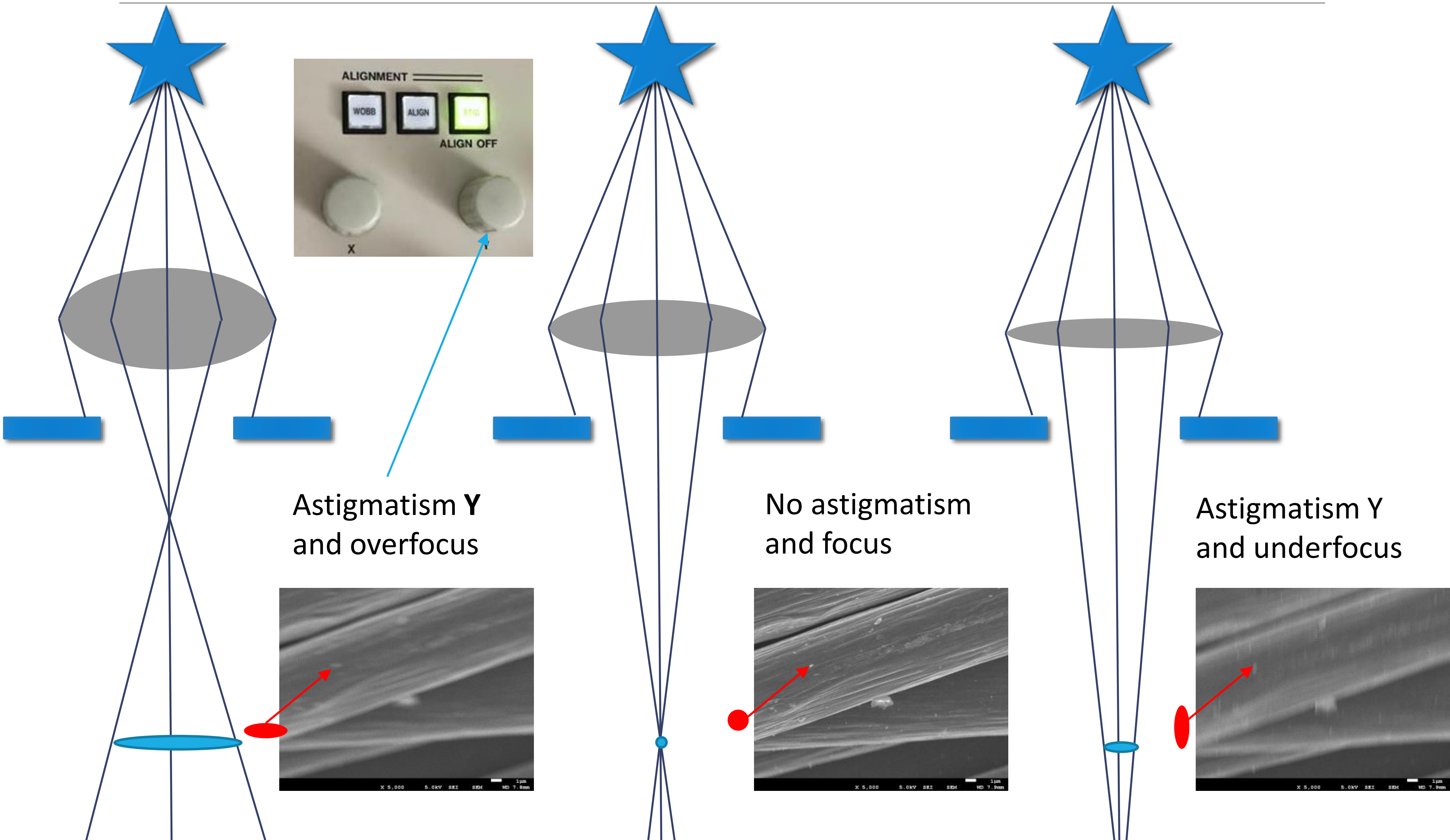
What is astigmatism?

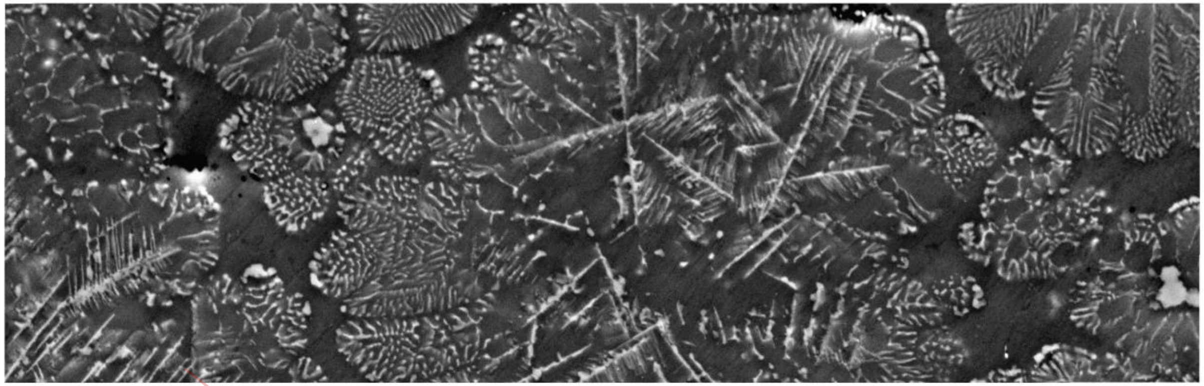
Non-spherical electron beam.

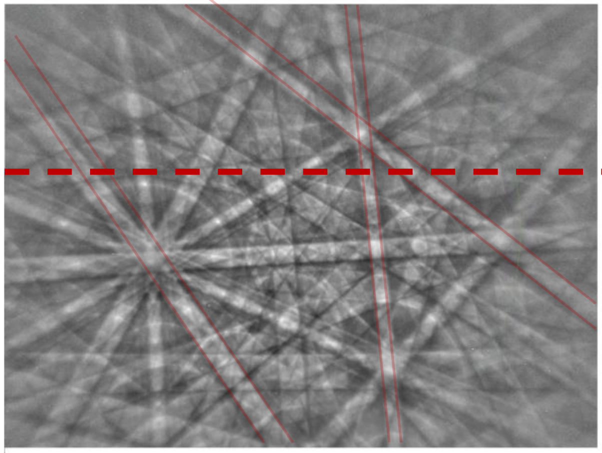


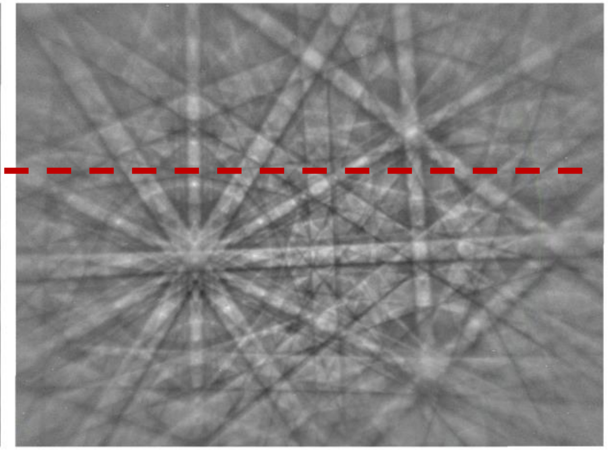
astigmatism is "easily" corrected using stigmators. These are small octupoles.

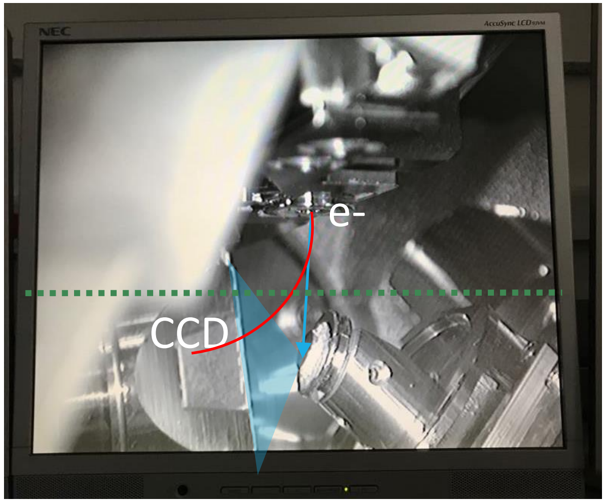
The effect of the objective lens?

By doing EBSD - Electron BackScatter Diffraction.







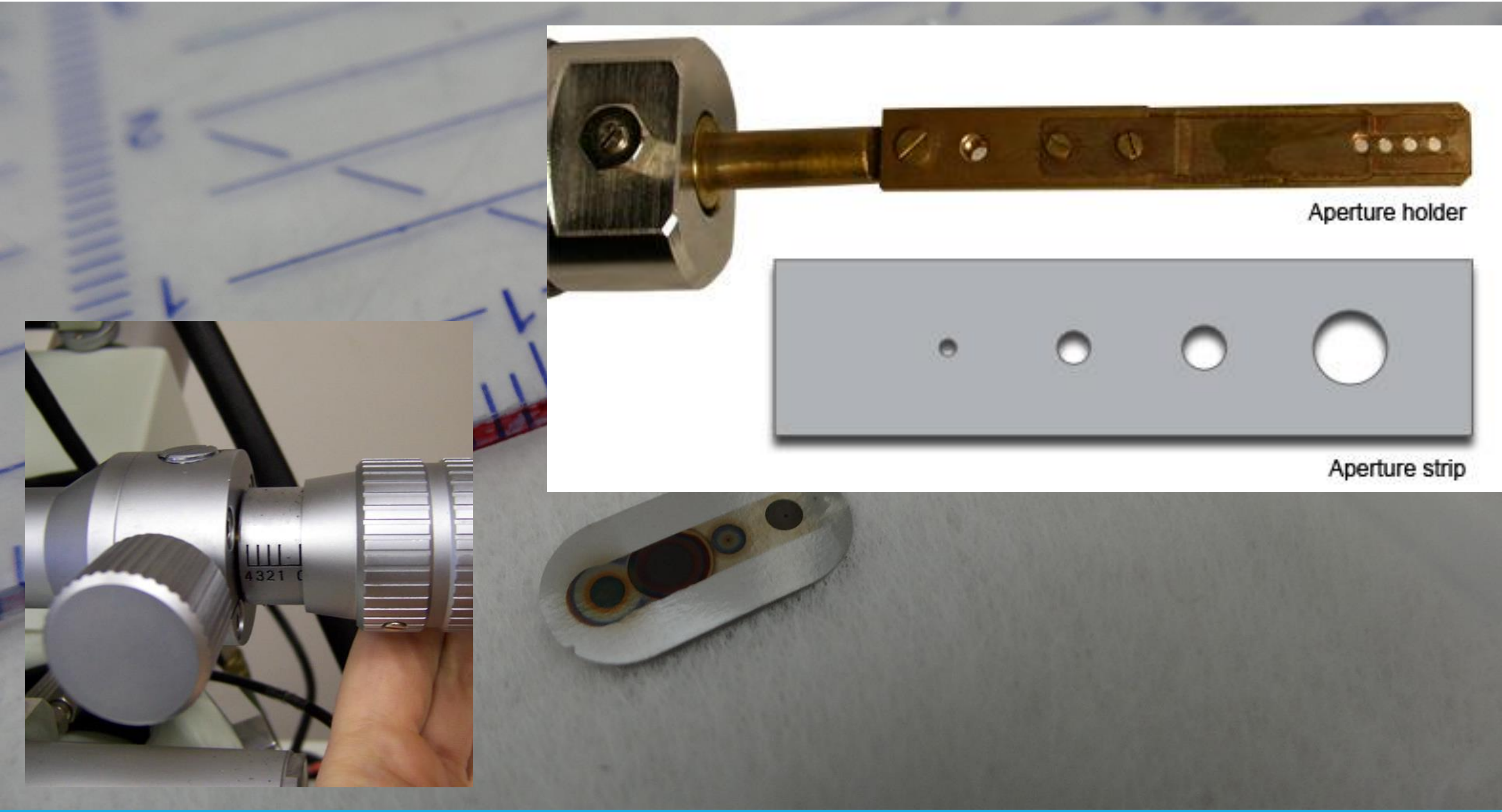


EBSP in SEM mode

EBSP in LM mode

WD 20 mm

Magnetic samples:
WD 15 mm or more.



Apertures to limit the beam

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Apertures

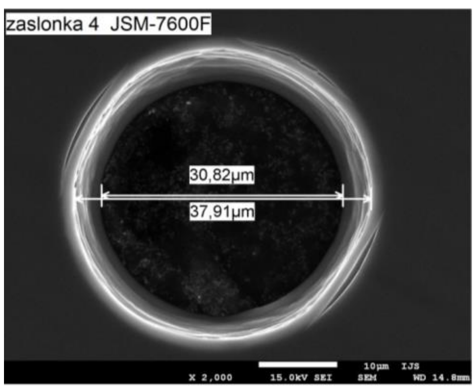
For ultra high resolution – use the smallest 30 µm (smaller probe, low current, large depth of focus).

For microanalysis – use the largest 110 µm (observation at high currents, shallow depth of focus, higher statistics).

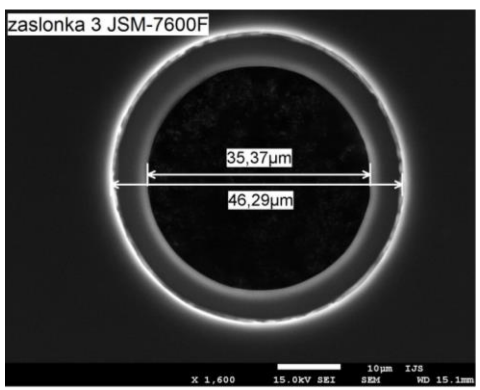
For usual observation – use 50 µm.

To work with high probe current, but still good resolution – use 70 µm.

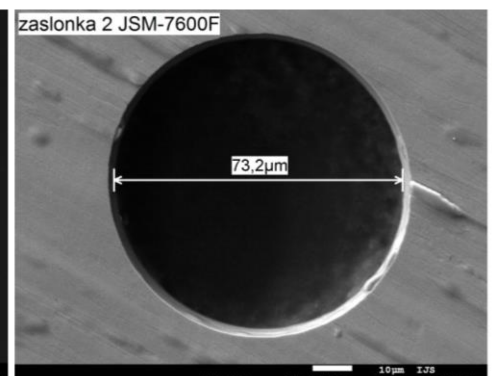
Needs to be changed regularly.



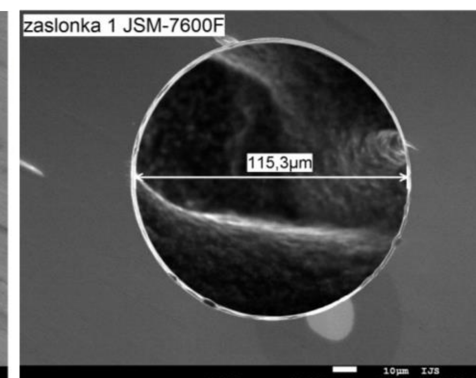
30 µm



50 µm



70 µm



110 µm

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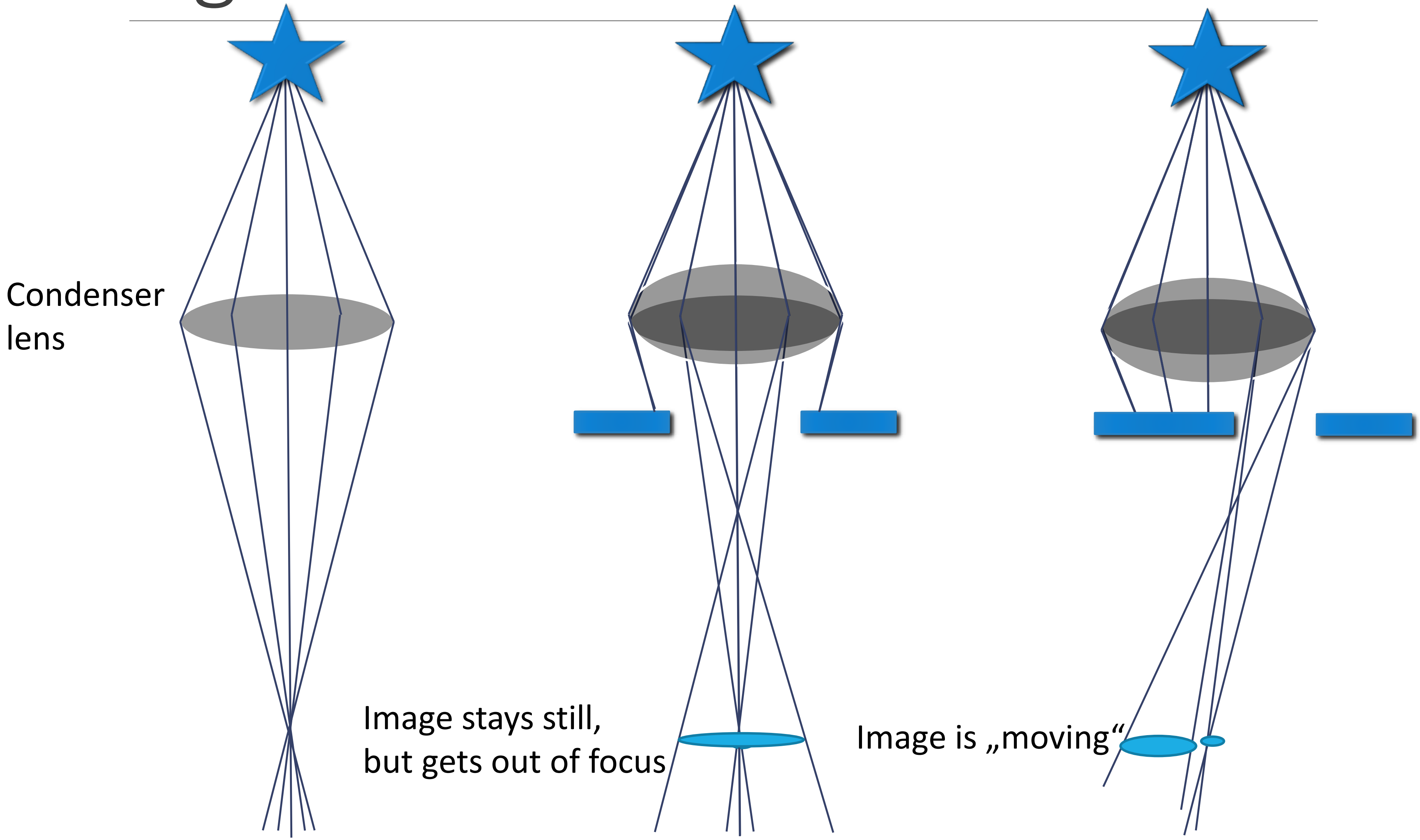
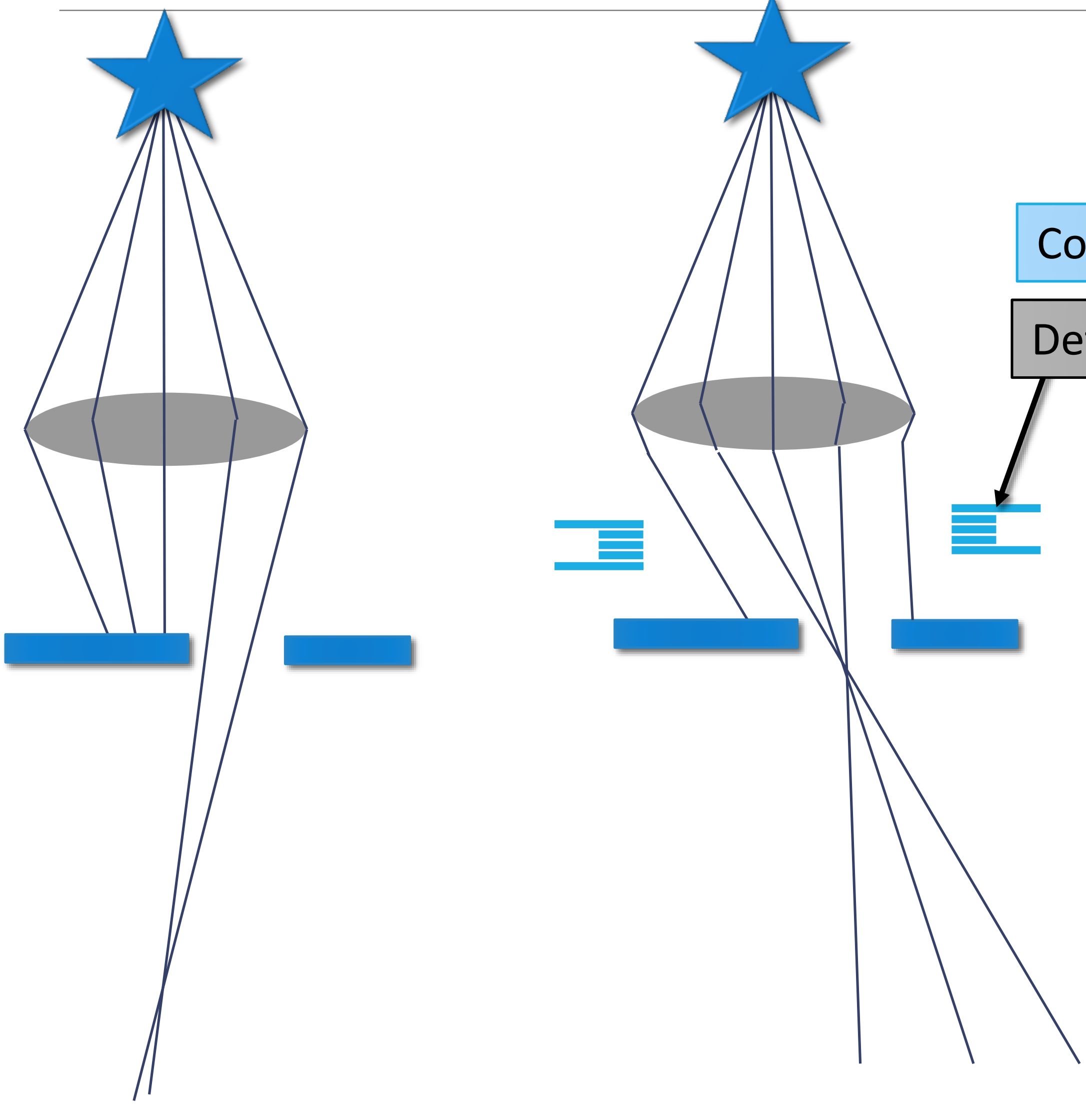
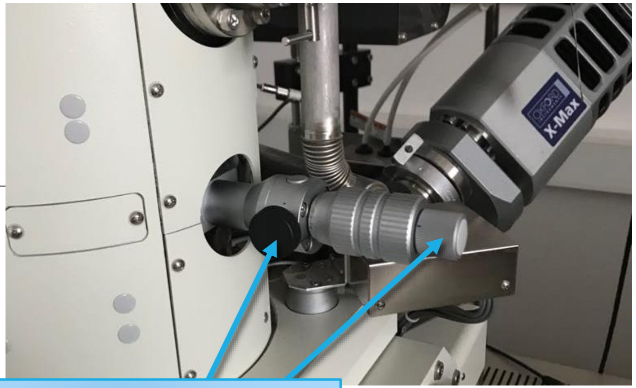
Alignment: Δ condeser lens



Alignment for 7600F





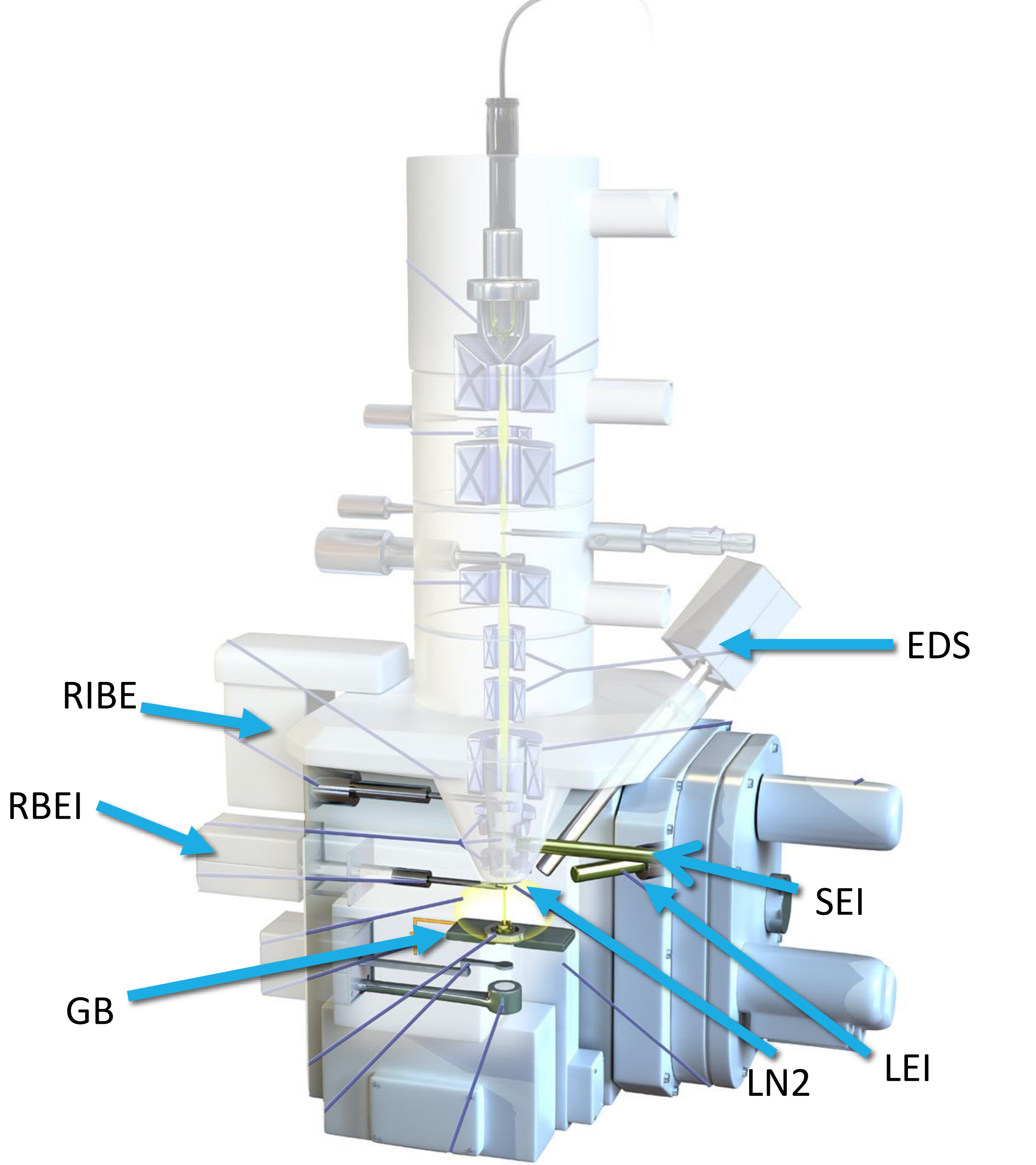
Contact CEMM staff

Deflection (alignment) coils

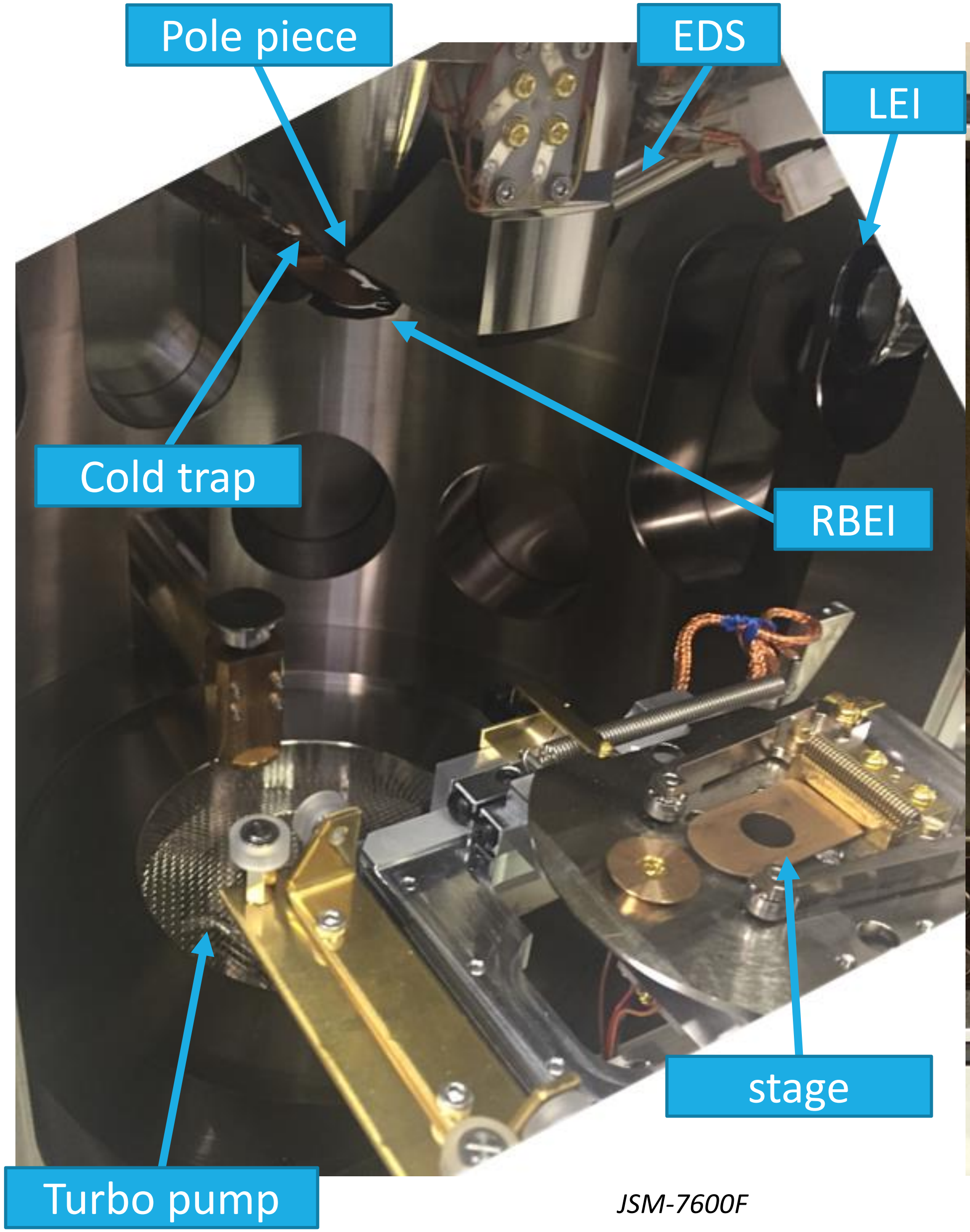
Sample chamber

motorized stage (x,y,z,t,r)

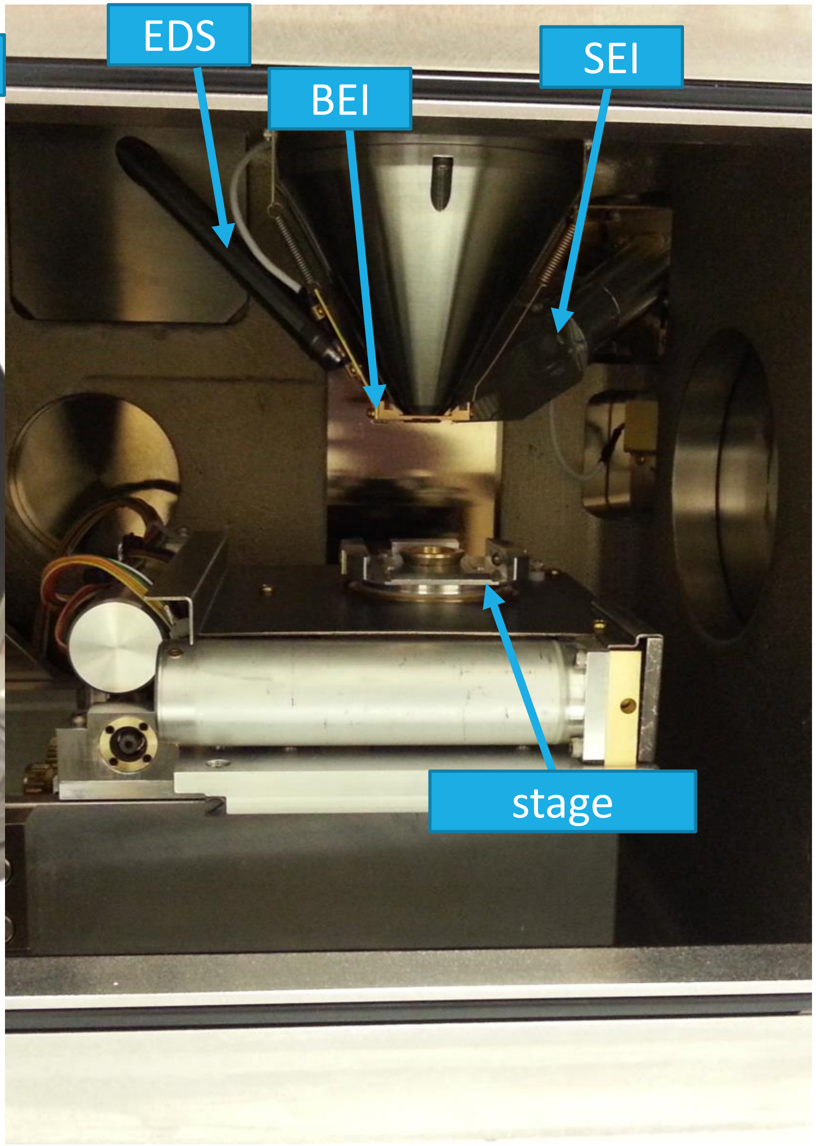
detectors



(Image: JEOL)



JSM-7600F



JSM-5800

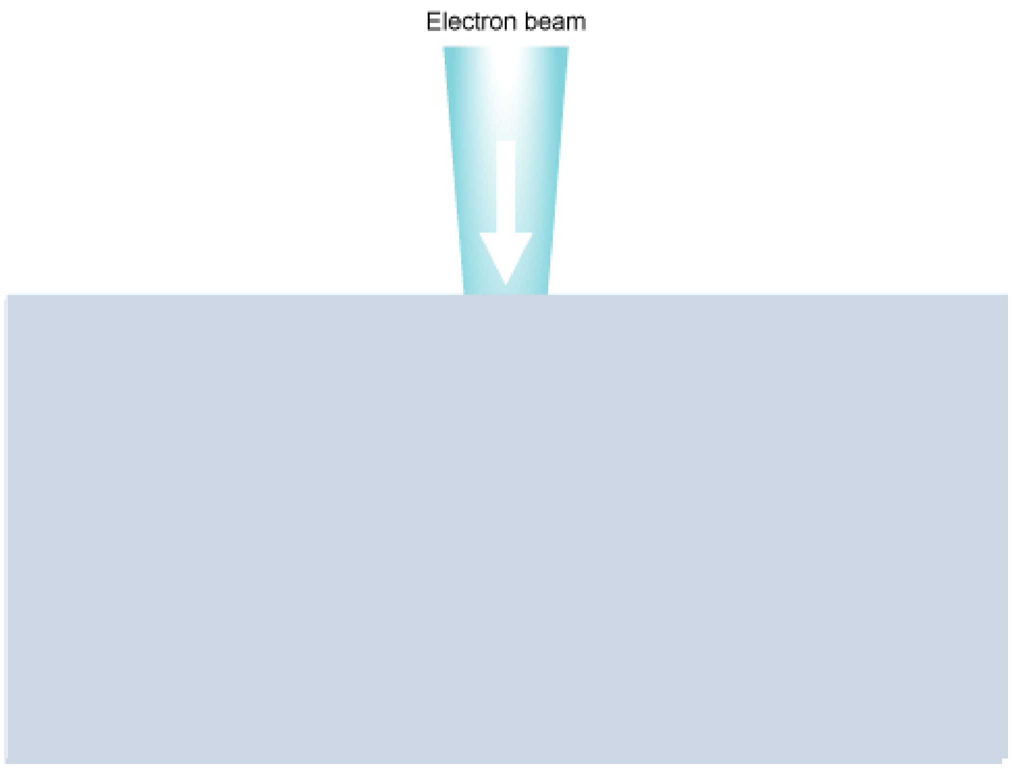
Electrons and their interactions with the specimen

Electrons:

- Secondary (low energy)
- Backscattered (high energy)
- Auger electrons
- Beam current

Photons

- X-rays
- cathodoluminescence

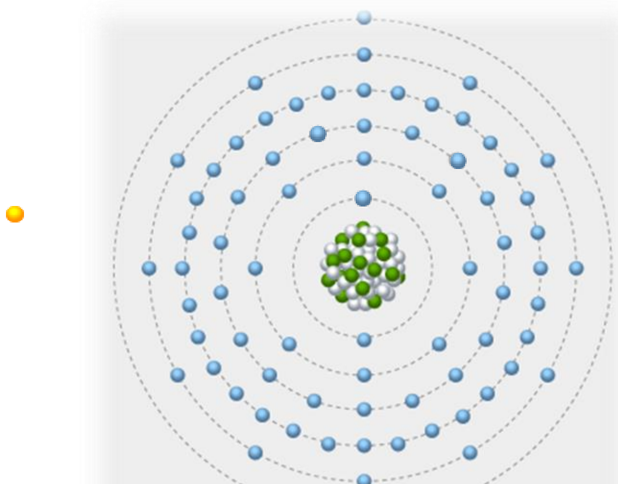


(Image: ammrf)

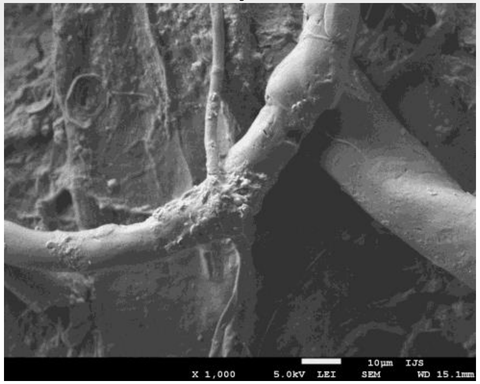
Two types of SEM image

(Images: ammrf)

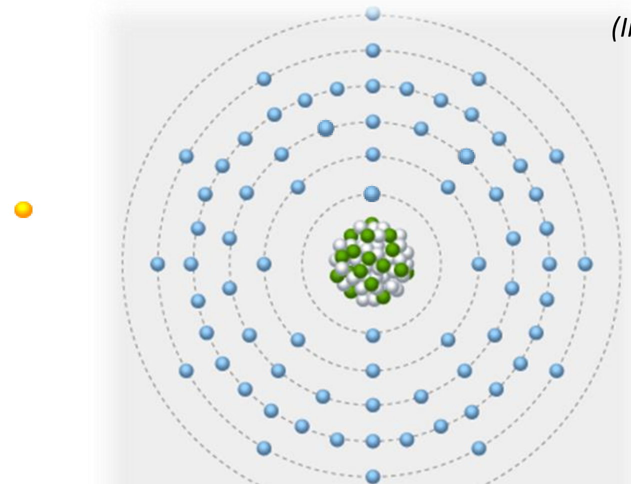
Secondary electrons (SE)



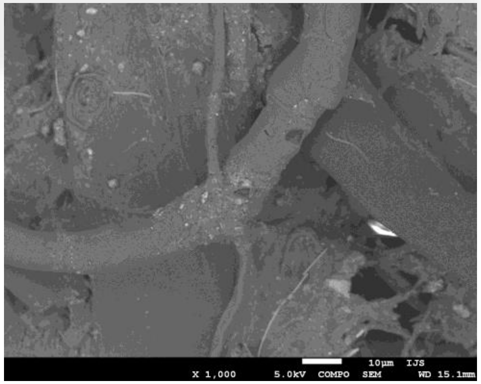
SEI - Secondary electron image



Backscattered electrons (BSE)



BEI - Backscattered electron image



Total electron yield: $\sigma = \delta + \eta$

SE yield (δ)

the number of secondary electrons emitted per incident particle is called secondary emission yield

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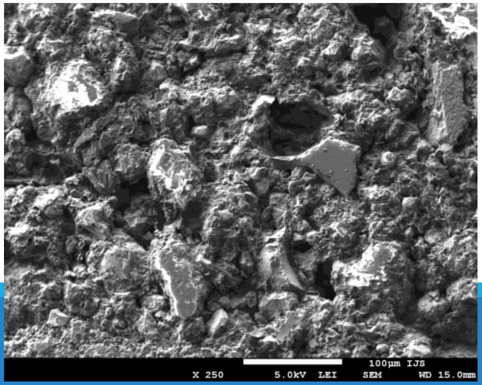

BSE yield (η)

the number of backscattered electrons emitted per incident particle is called backscattered emission yield

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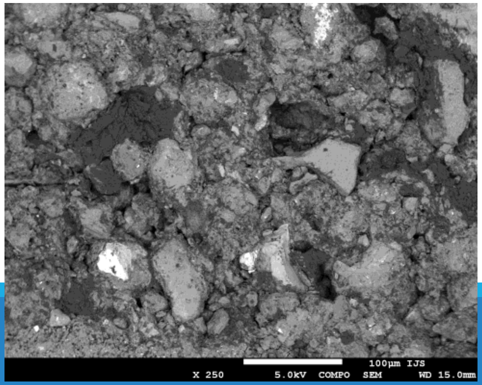


Signal

Secondary electrons

- High resolution
- Strongly topography sensitive
- Little element sensitive
- Sensitive to charging

Backscattered electrons

- Lower resolution
- Atomic number contrast in particular strong signal to heavy atoms
- Less sensitive to charging

(Images: oxford)

SEM settings

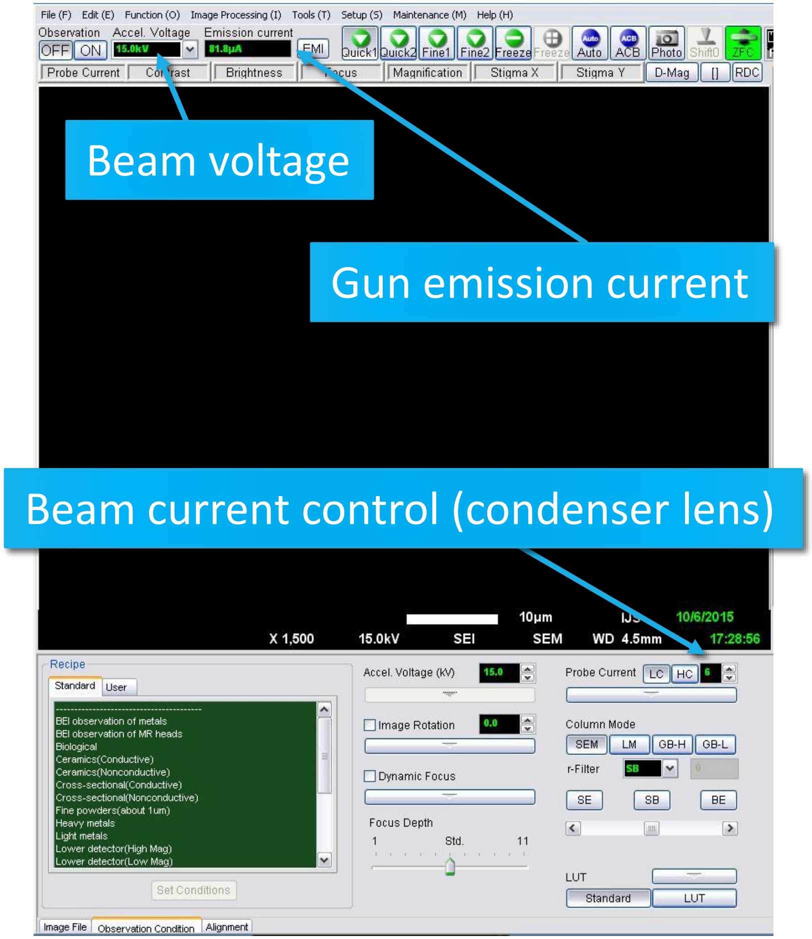
Voltage (electrical potential)

- Consider as the spread or energy of electrons
- Typically 1-30 kV or keV

Current (number of electrons/unit time (amps))

- 1 coulomb ~ 6 x 10^{18} electrons
- 1 A = 1 C/s
- Typically from 10^{-12} A to 10^{-9} A
- So 1 nA~ 9 x 10^{9} electrons/sec

WD and apertures



Voltage and SE image

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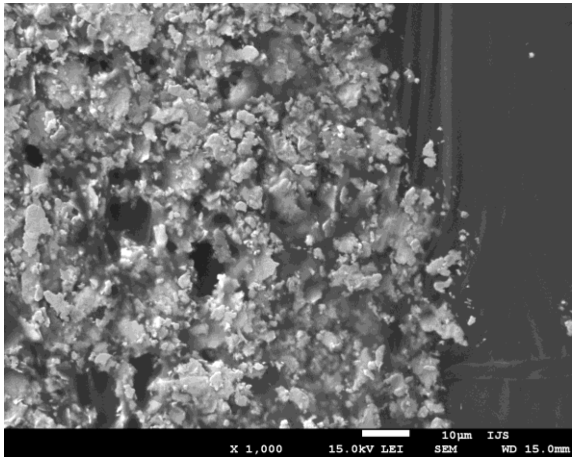
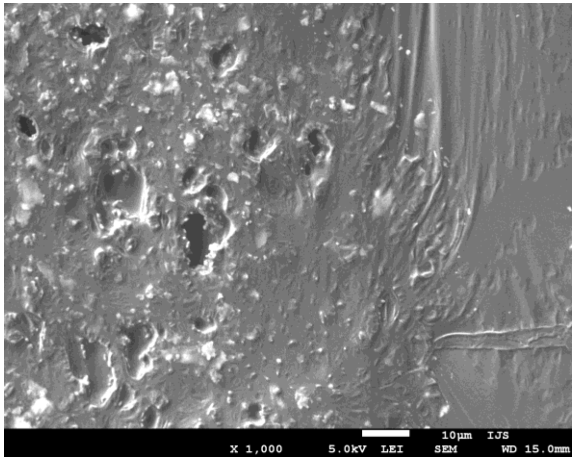
(Images: ammrf)

15 kV



5 kV



Probe current and SE image

(Images: ammrf)

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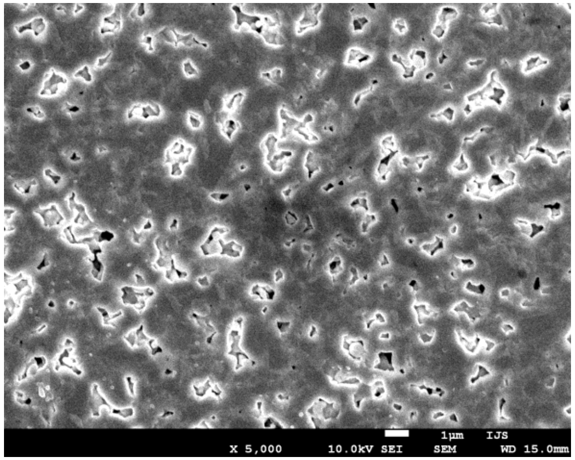
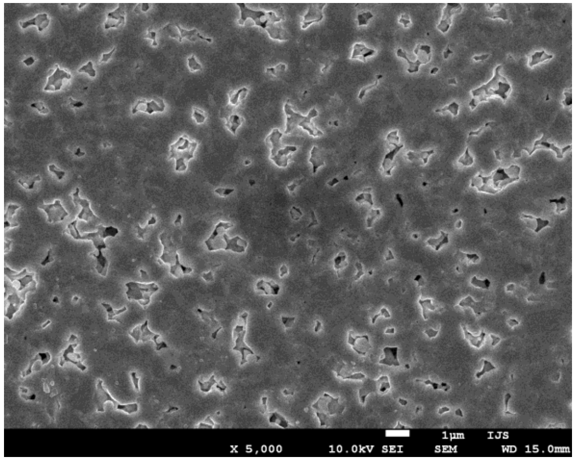
PC 8 → 0,35 nA

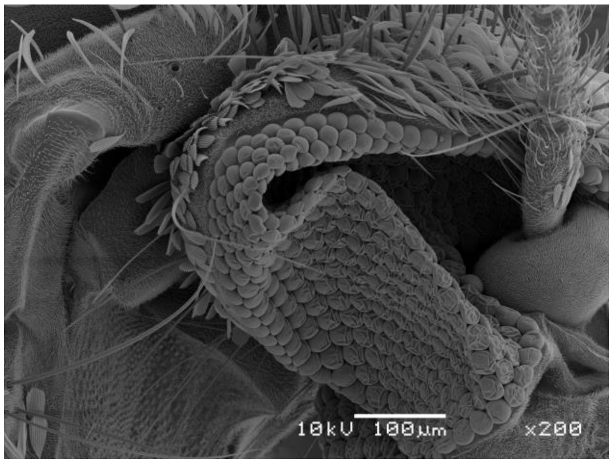


PC 6 → 0,08 nA

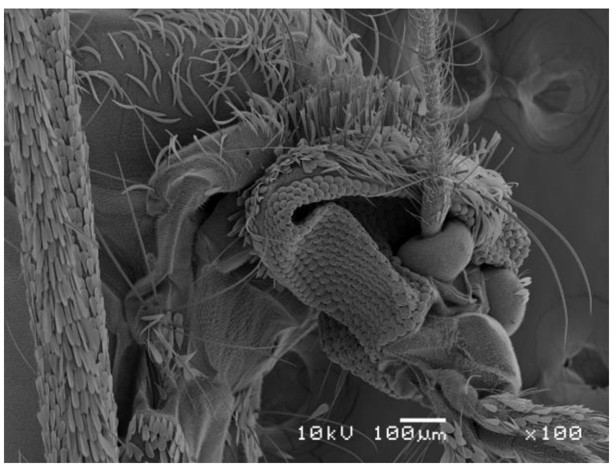


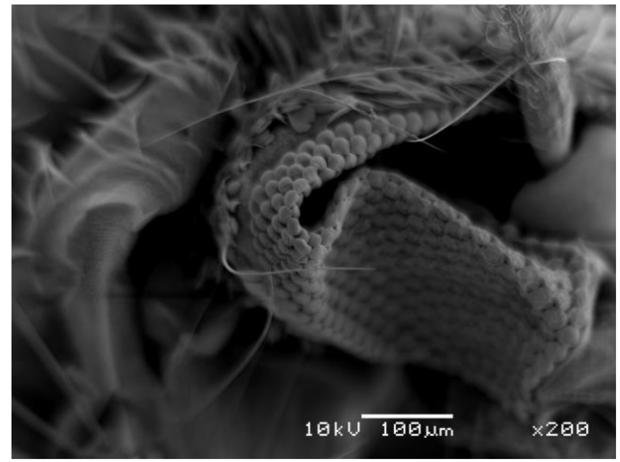
Depth of focus

The WD and the aperture impacts on the **depth of field** and **resolution** of the SEM image

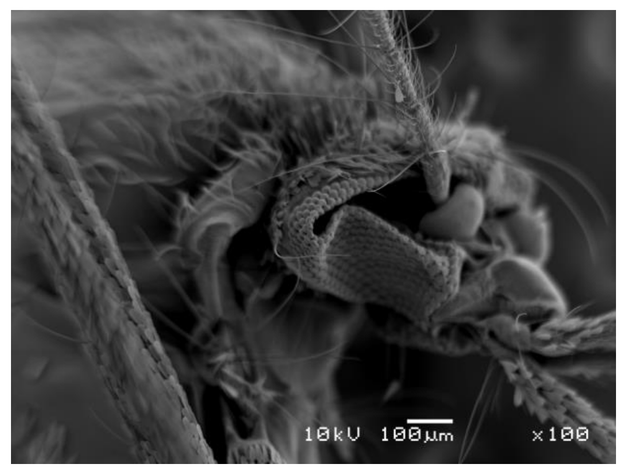


JSM-5800:
#1 and
WD 29





JSM-5800:
#3 and
WD10

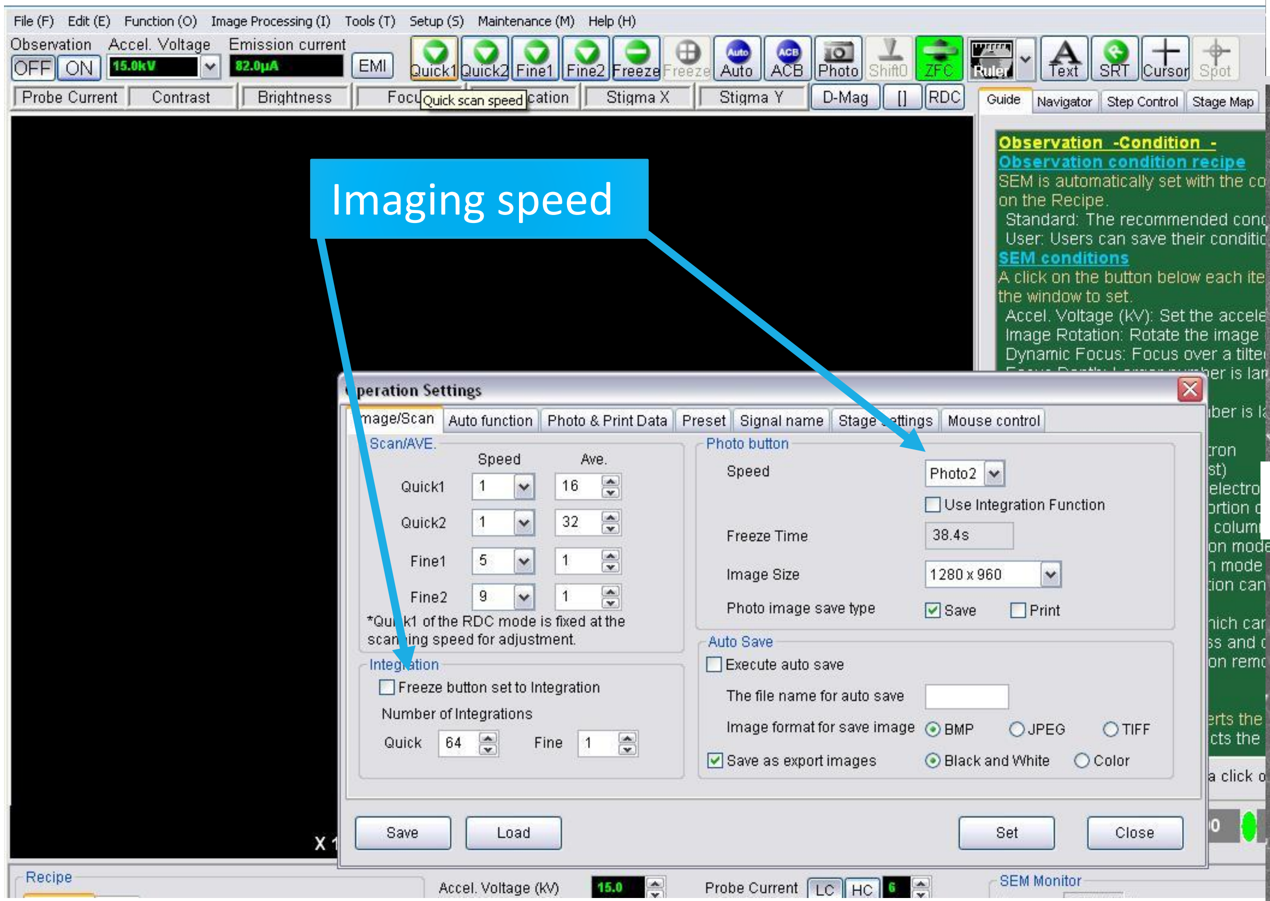


High DOF: use **smaller** aperture (#) and **larger** WD

Low DOF: use **bigger** aperture (#) and **smaller** WD

Changing the speed

If we have charging problems…



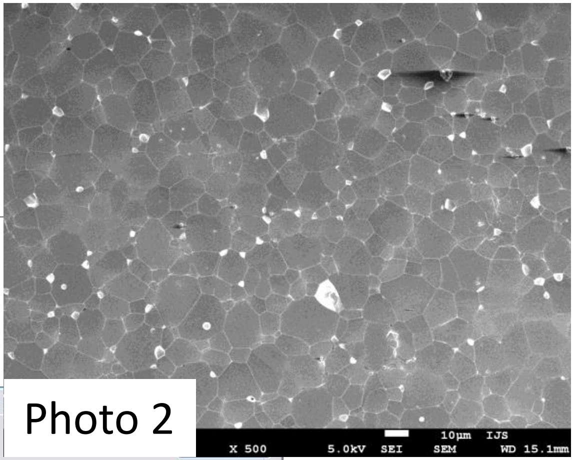
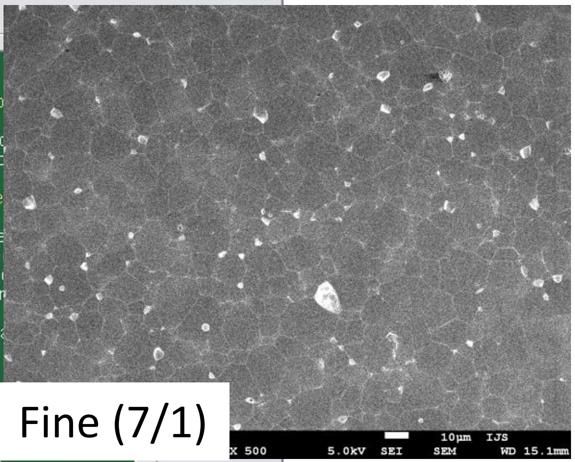
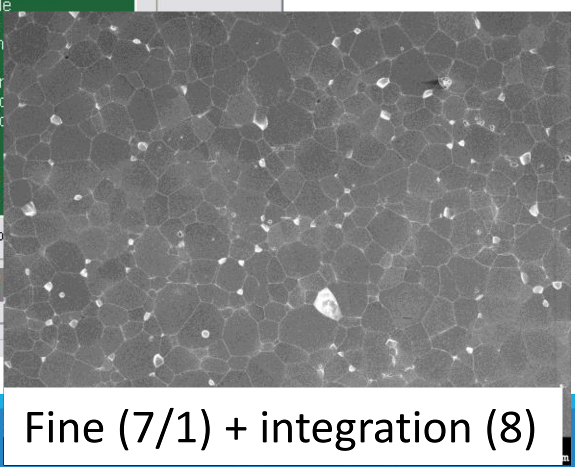


Photo 2



Fine (7/1)


Fine (7/1) + integration (8)

To finish the course?

- To understand the **WD**

  To determine the offset.

- **No damage** to the machine

  Is the sample vacuum compatible?

  How to check if the sample is magnetic?

  etc.

- Acquire a **good photo**

- To know what is a magnetic sample

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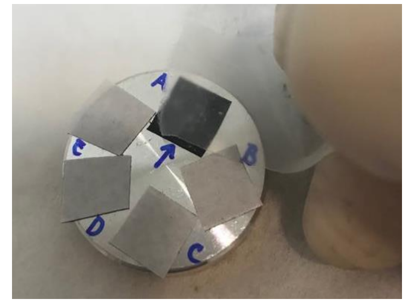
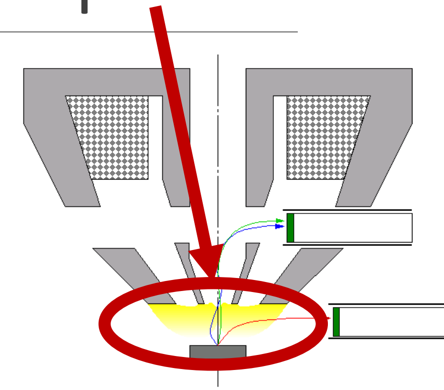
How to work with magnetic samples





A) **minimal amount** as possible!
- Bulk - less force
- Powder – to avoid flying of the holder

B) **mount it very good**! Use special holder.

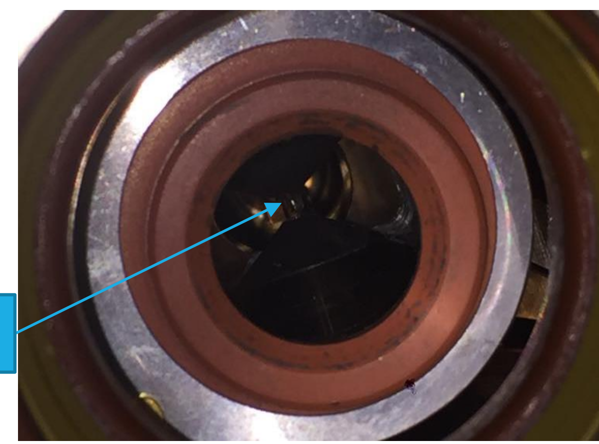
C) in TEM when inserting the sample **turn on LM**!

D) for JSM-7600F the distance is **WD 15mm or more**!

E) use **slow** movement (x, y and z) under the objective lens - ΔB!

F) **focus**, stigmatizm … very **slowly**! - ΔB!

Sample is „floating“ inside TEM



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Take home information

- Why is it possible to image with electrons
  - The wave particle duality and the scanning mode makes it possible
- Different parts of the SEM and what is the difference between them
  - Why we have different types of electron gun (W, FE)
  - How the electromagnetic lenses work and why magnetic samples are a problem
  - Why we need apertures
  - Detectors and SEM images
- Electrons and their interactions with the specimen and what kind of information we get from SE and BSE image
  - SE yield
  - BSE yield
- SEM settings and how we observe it on the image
  - What is the difference in image depending on the
    - Voltage
    - Current
    - WD and apertures and DOF
    - Scanning speed

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CEMM

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