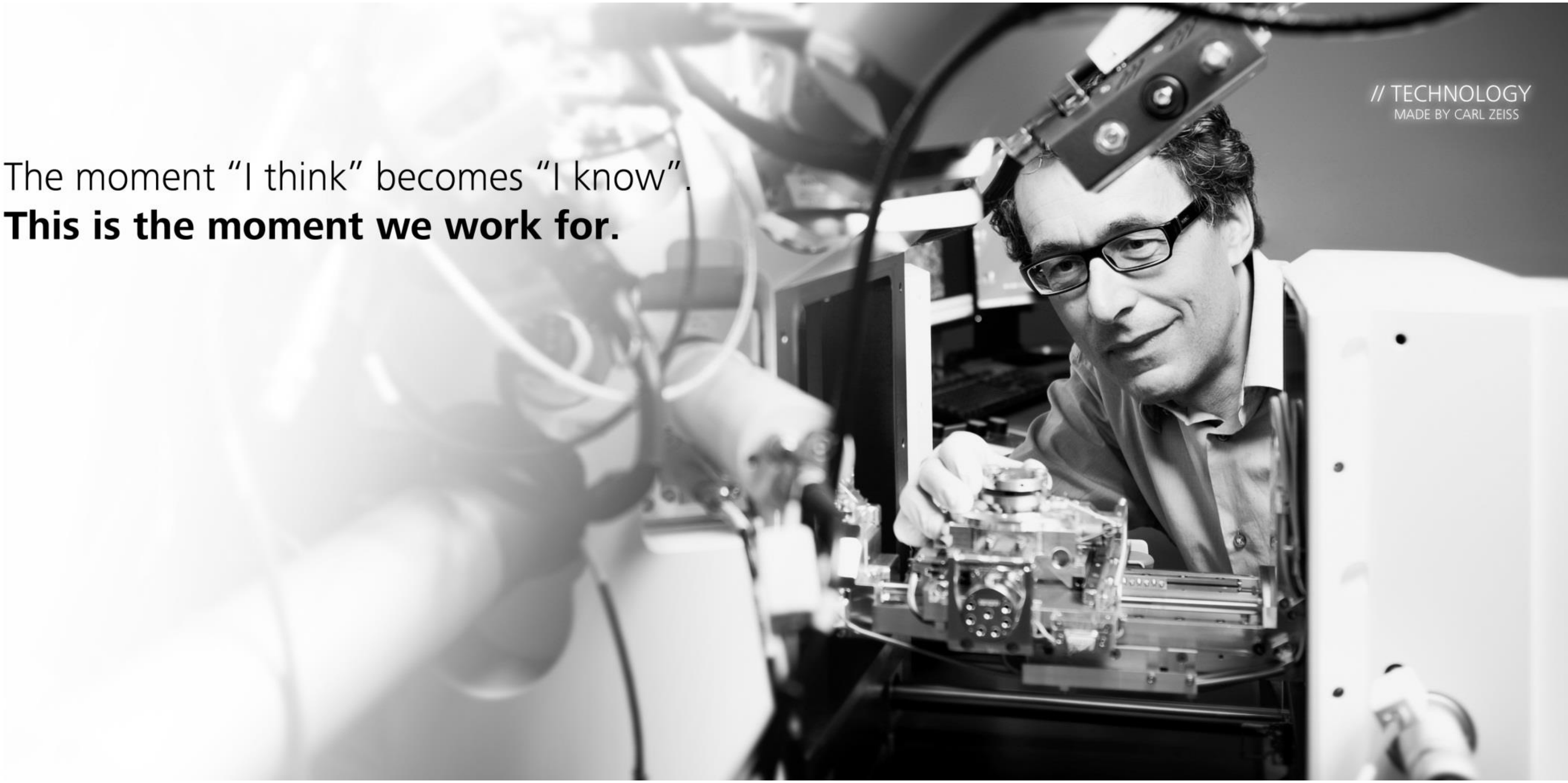
# Basics of Electron Microscopy

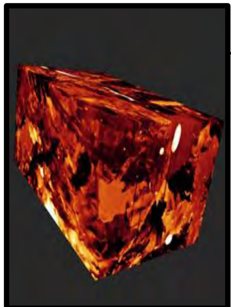



**John Kelley**
**Electron, Ion and X-ray Microscopy Specialist for Materials**
**Carl Zeiss Microscopy, LLC**

23 Jan 2019
University of Illinois, Urbana-Champaign

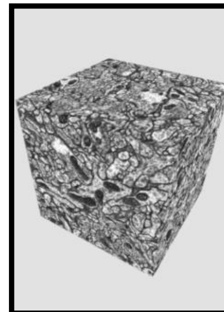
# Agenda

# Application Fields



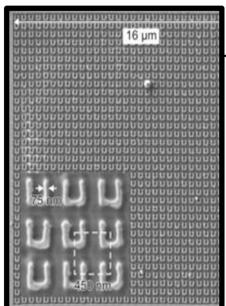
## Materials Research

- **Task:** Understand and tailor physical properties of materials. Develop new materials.
- **Examples:** Steels, Alloys, Polymers, Ceramics, Composites
- **Image:** Manganese sulfide inclusions in steel. Courtesy of Georgsmarienhütte GmbH, Germany



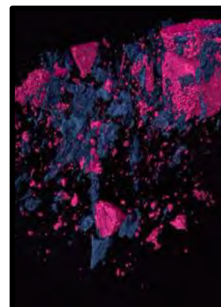
## Life Sciences

- **Task:** understand structure and function of biological material
- **Examples:** Cell biology**,** Neurobiology, Histology, Zoology, Botany
- **Image:** drosophila larval brain. Courtesy of C. Shan Xu, HHMI, USA



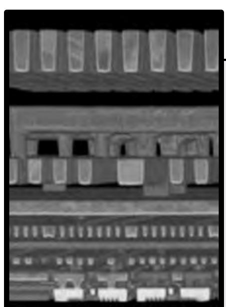

## Advanced Materials

- **Task:** Design materials and functional nanostructures with improved or new physical properties
- **Examples:** Metamaterials, MEMS, Biomaterials
- **Image:** Focused-Ion-Beam Nanofabrication of Near-Infrared Magnetic Metamaterials, Enkrich et al. Adv. Mater. 17 (2005)



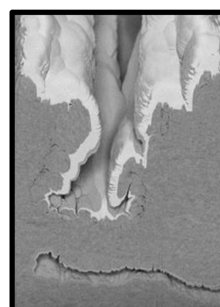
## Raw Materials

- **Task:** find new profitable deposits of natural resources
- **Examples:** Oil&Gas (sedimentary rocks, shale), Mining
- **Image:** Pyrites and voids in shale rock. Courtesy of NanoFUN, Poland



## Electronics / Semiconductors

- **Task:** Design better and more efficient electronic devices. Failure Analysis.
- **Examples:** Semiconductors, Polymer Electronics, Photonics
- **Image:** Cross-Section of IC with Intel 22nm-Tri-Gate-technology. Courtesy of UBM TechInsights, Canada



## Manufacturing

- **Task:** quality control of material systems used in different industries (e.g. automotive)
- **Examples:** Coatings, Oxidation, Corrosion, Irradiation
- **Image:** Crack in steel sheet. Courtesy of AUDI AG, Germany

# Agenda

| | |
|---|---|
| 1 | Why Electrons? |
| 2 | Interaction with Matter |
| 3 | Electron Emitter |
| 4 | Electron Column Design |
| 5 | Operating Parameters |
| 6 | Insulating Samples |

# Carl Zeiss Microscopy
## Why electrons?

- similar **optical properties**:
  - diffraction, abberation, astigmatism etc.

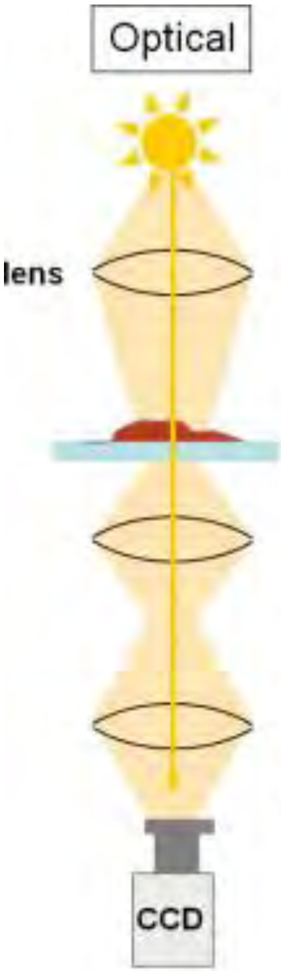
- **spatial resolution** depends on wavelength:
  - the higher the energy (of the electrons)
    - the lower the wavelength,
      - the higher the resolution

- typical **acceleration voltages** of electrons:
  - Scanning electron microscopes (SEM): 0.2 – 30 kV
  - Transmission electron microscopes (TEM): 40 – 1200 kV

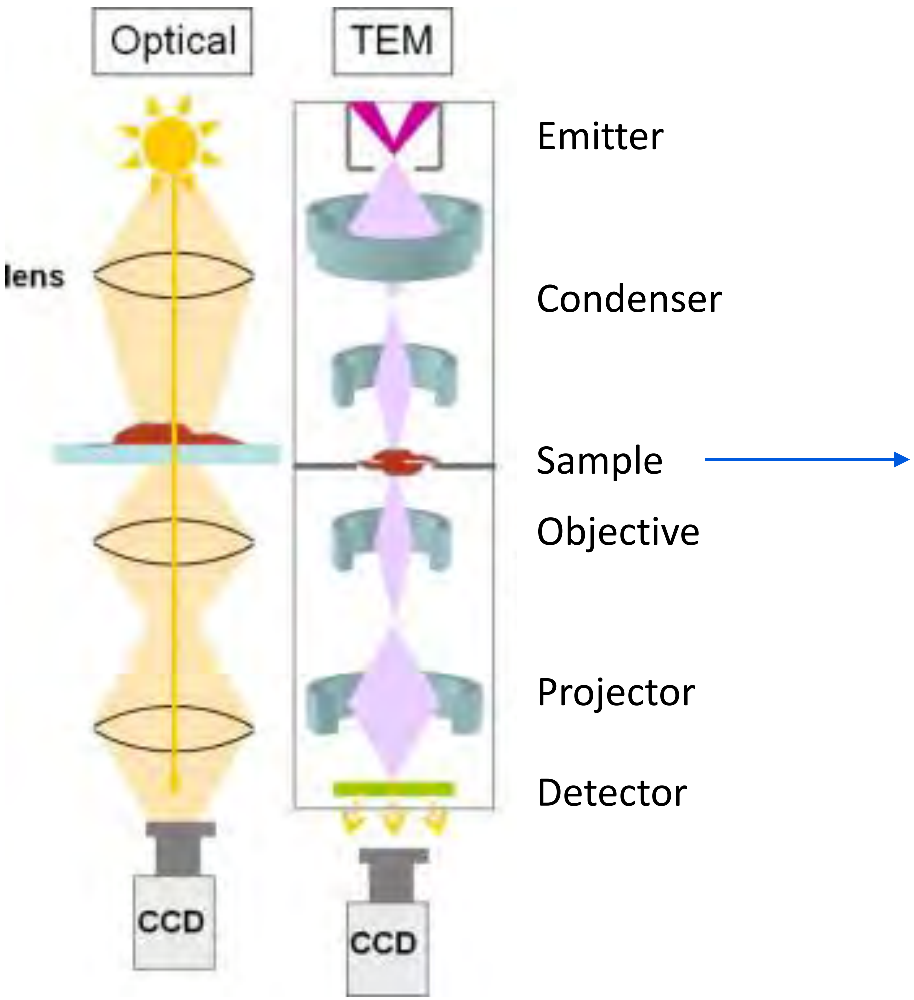
| | Light Microscopy | Electron Microscopy |
|---|---|---|
| Wavelength | 400 – 700 nm | 0.1 – 0.002 nm<br>(1 – 100 kV) |
| Spatial Resolution | ~ 1 µm | ~ 1 nm |
| Max. Magnification | 1,000 x | 1,000,000 x |
| Modes of Operation | reflected light, transmitted-light | SEM,<br>TEM |
| Samples | Unmodified, hydrated | vacuum-compatible |

# Carl Zeiss Microscopy

## How a SEM works

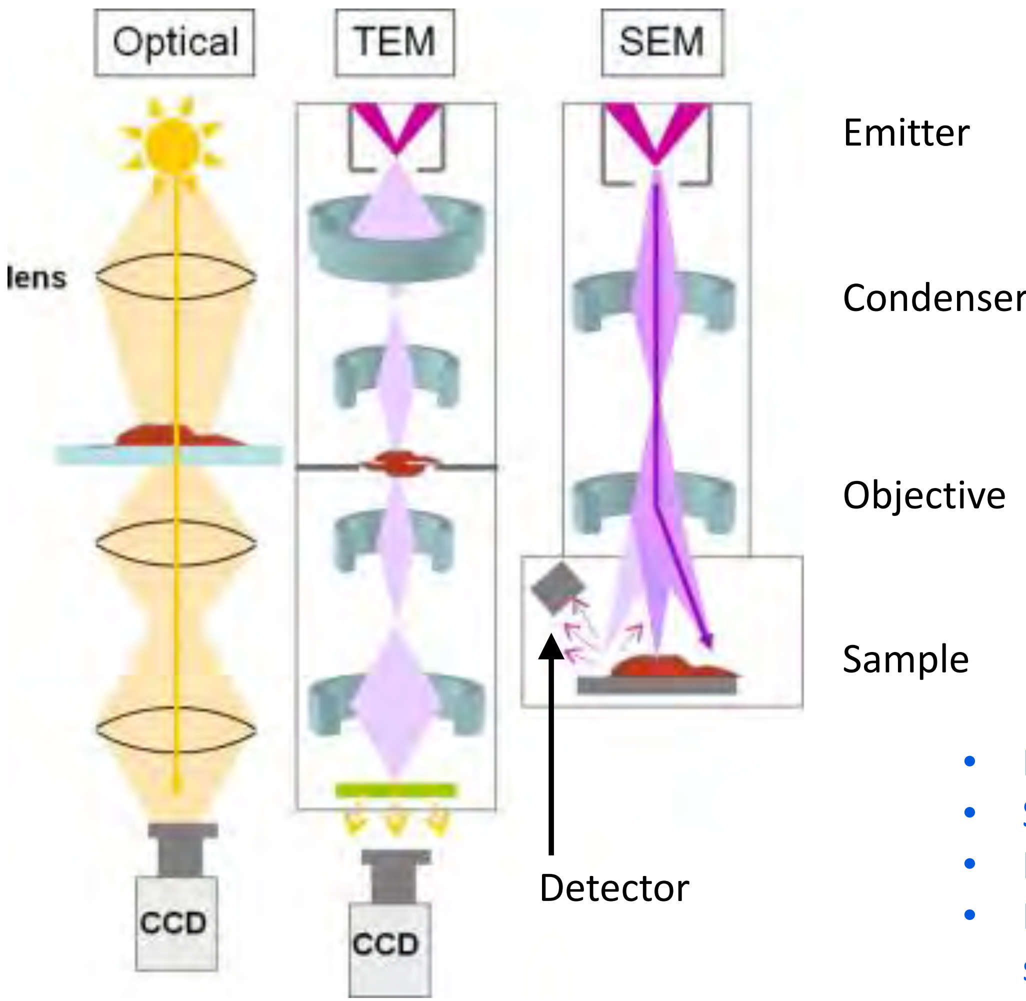


# Carl Zeiss Microscopy
## How a SEM works



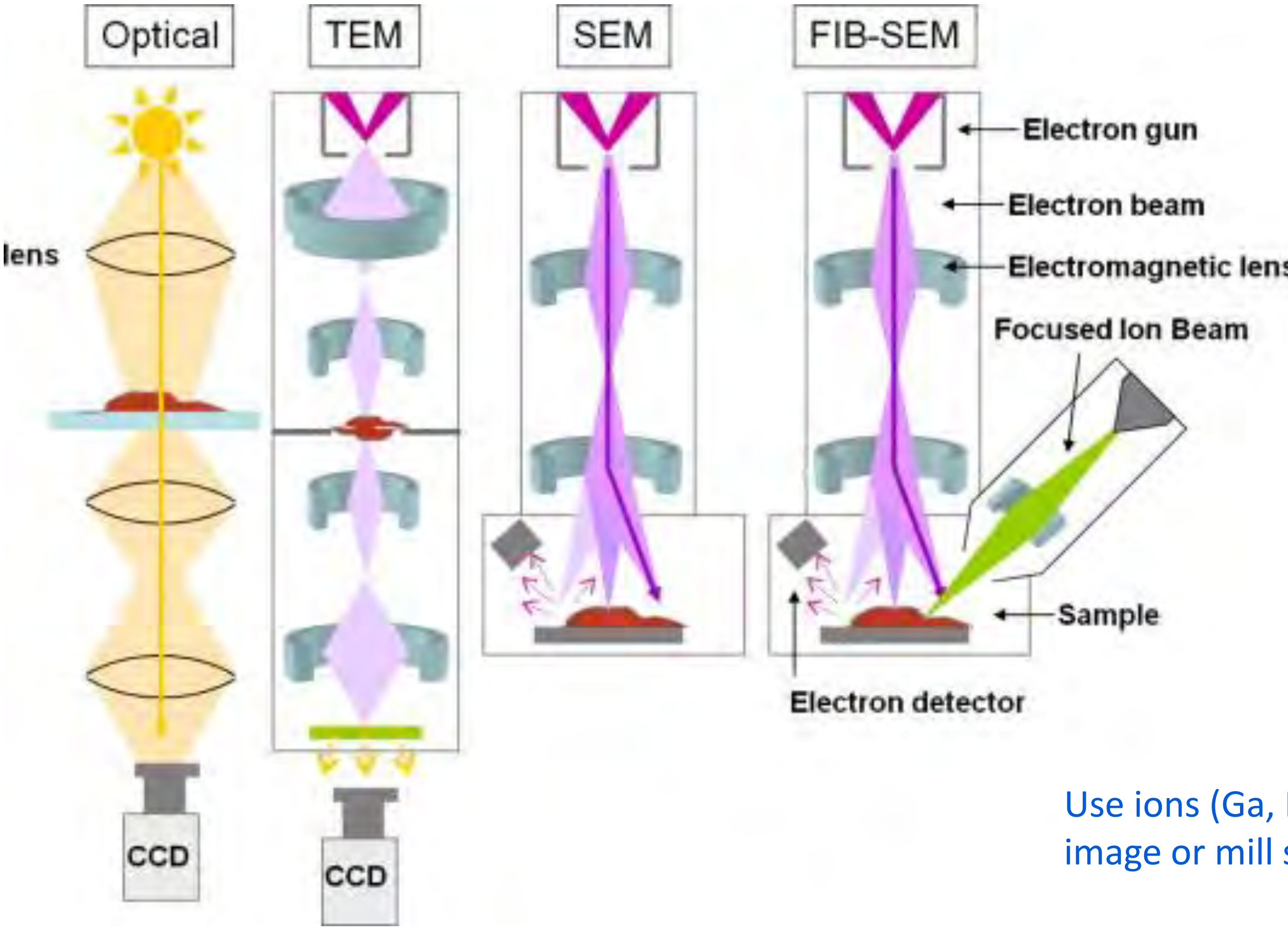

TEM samples must be very thin
(electron transparent)
~ 70 nm or less

# Carl Zeiss Microscopy
## How a SEM works



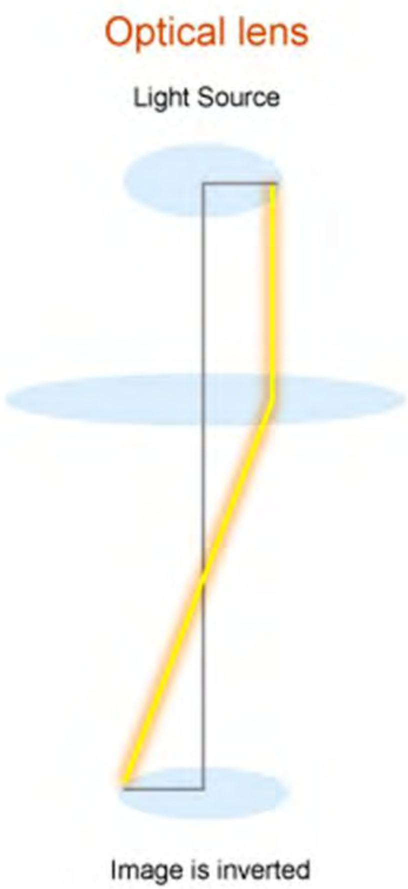

- Bulk sample
- Sub-surface (few nm or more below)
- Rastered beam
- Detect secondary and back-scattered electrons

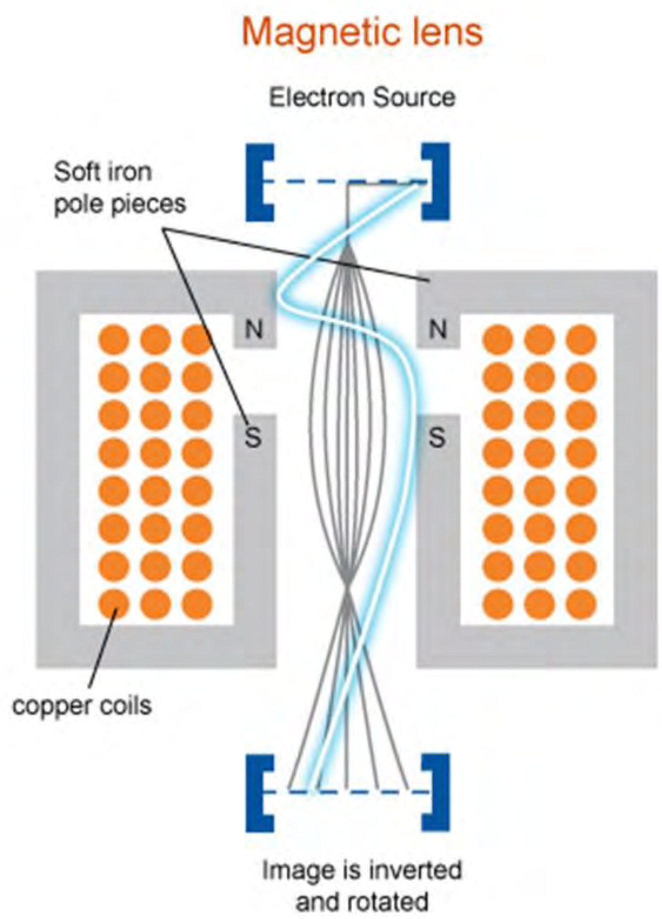
# Carl Zeiss Microscopy
## How a SEM works

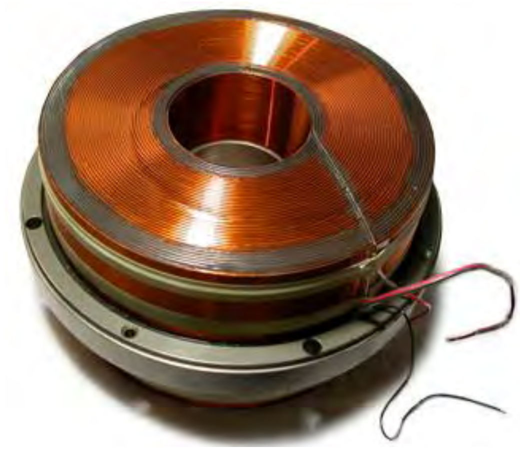



Use ions (Ga, Ne, He) to image or mill sample

# Electron Microscopes
## Electromagnetic Lenses

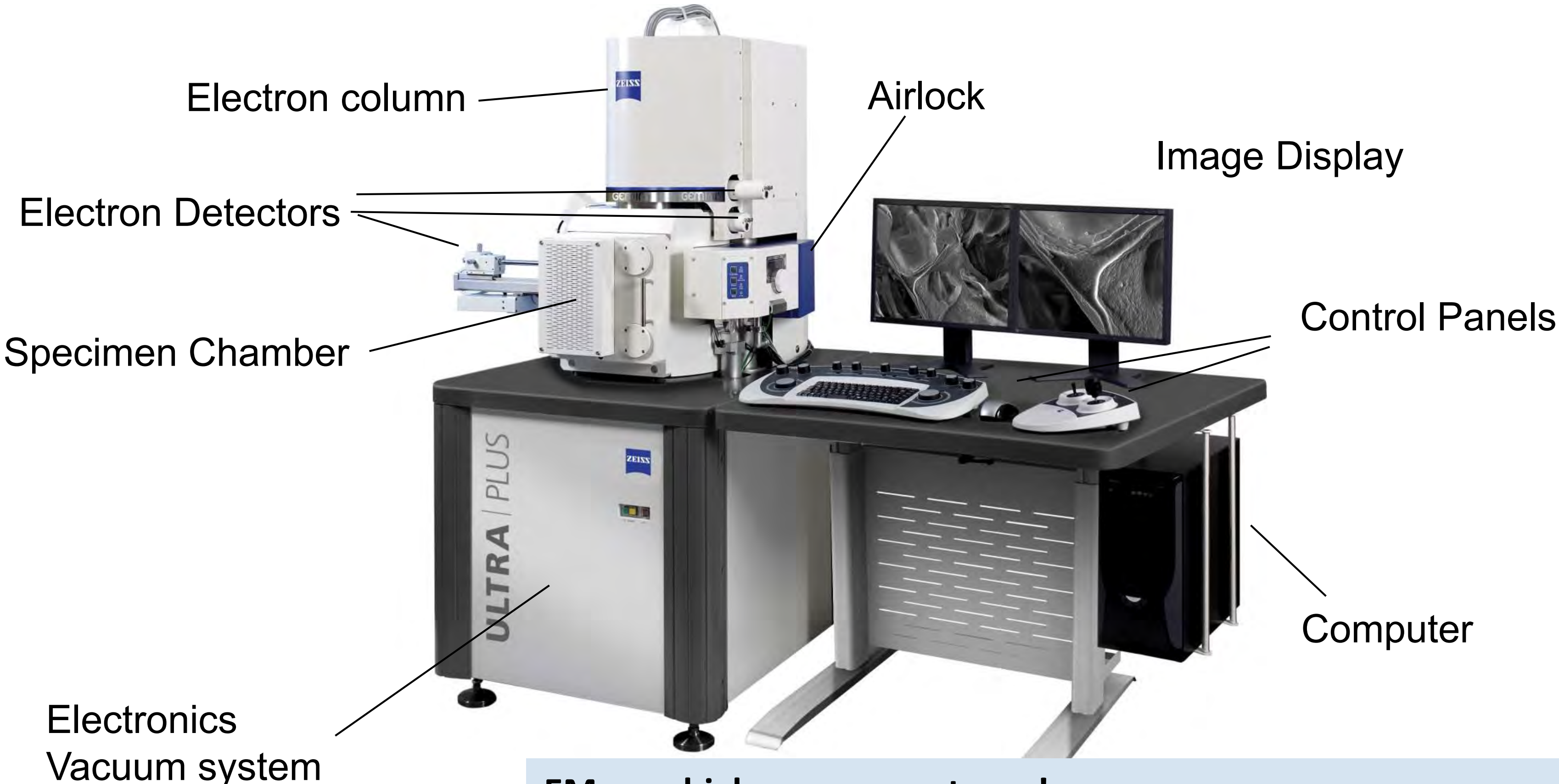


We can change the strength of the lens (i.e. the focal plane) by changing the current, but not the shape of the fields.

# Carl Zeiss Microscopy
## Components of a SEM

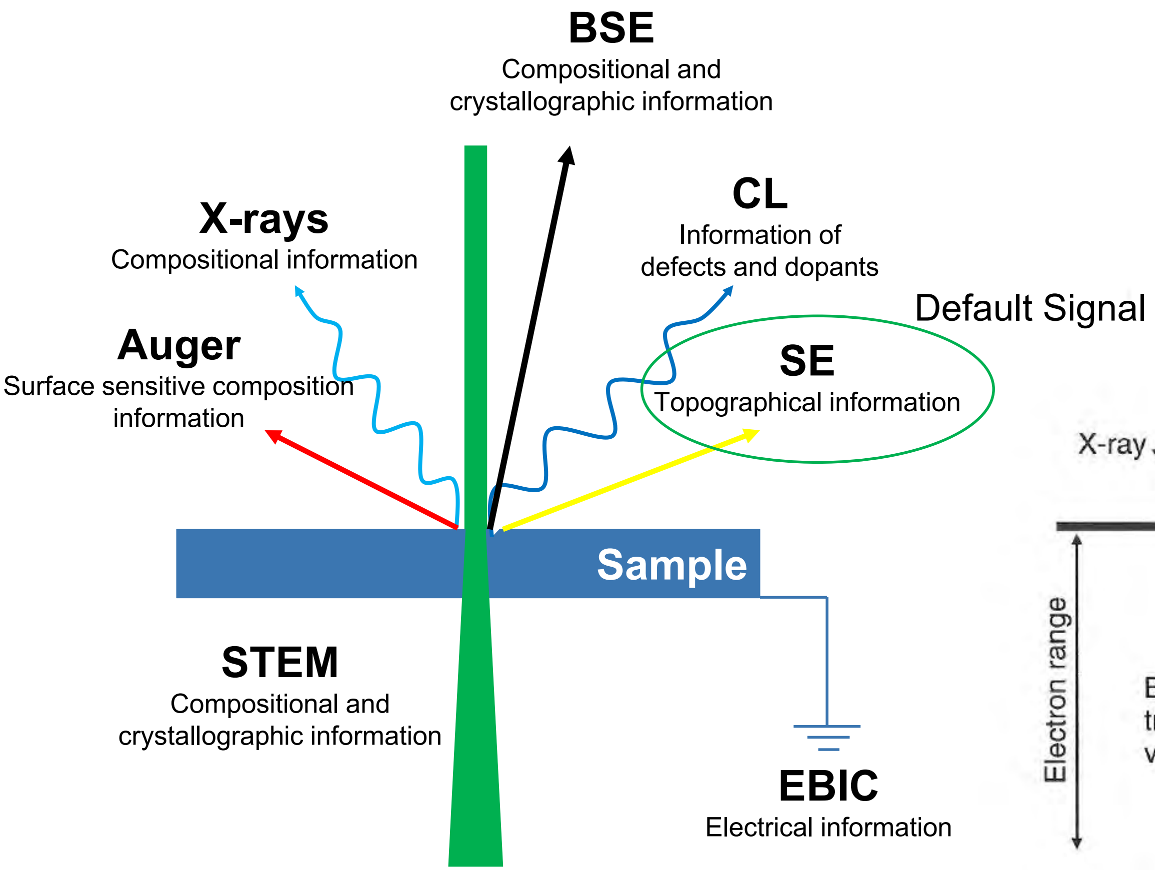


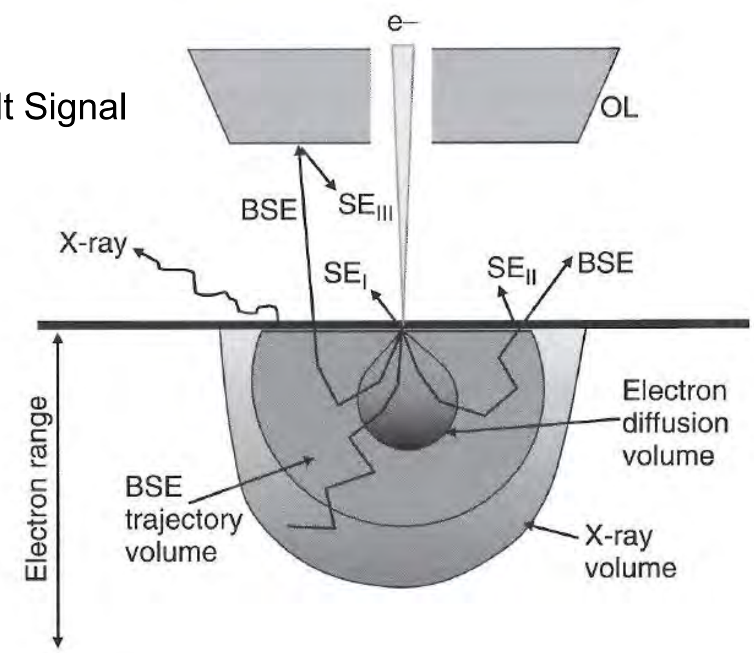

**EMs are high vacuum systems !**
→ component requirements (pumps, gauges, seals …)
→ restrictions (samples, operation time …)
→ operation procedures

# Agenda

# Electron-Induced Signals

## Plenty of Information Induced by Primary Beam



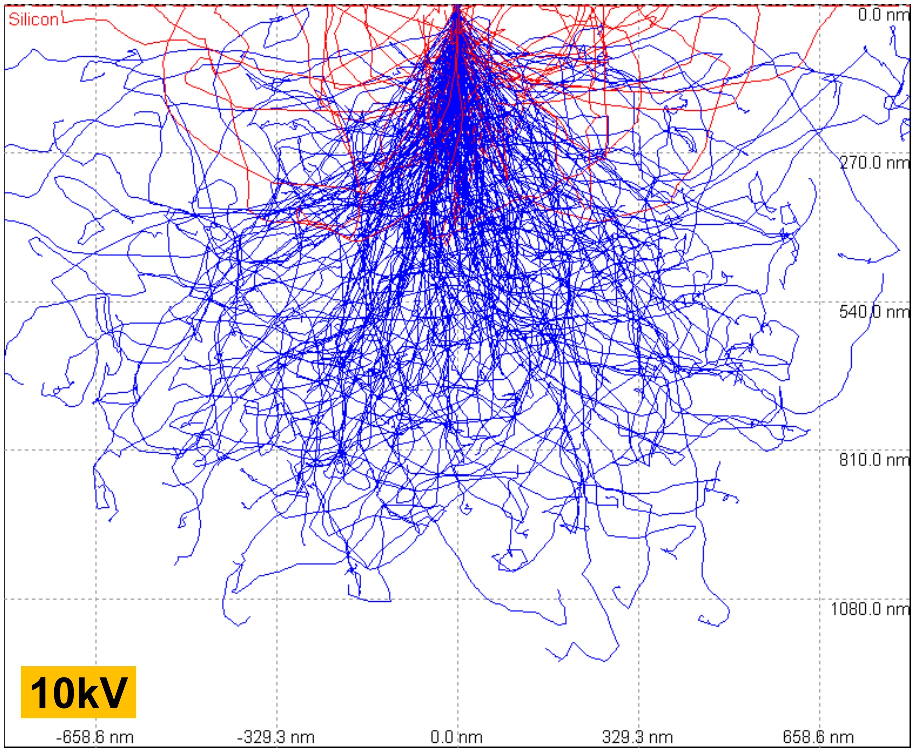




**Surface and volume information associated with the signals**

**Signals and interaction volume induced by the primary beam**

# Beam-Sample Interaction
## Influence of Beam Energy – Interaction Volume

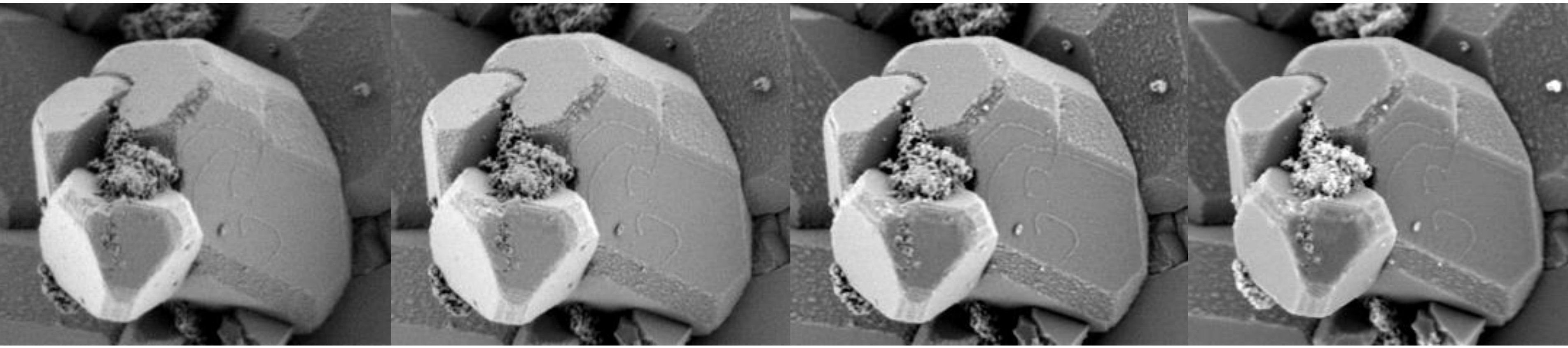
### Monte Carlo Simulations

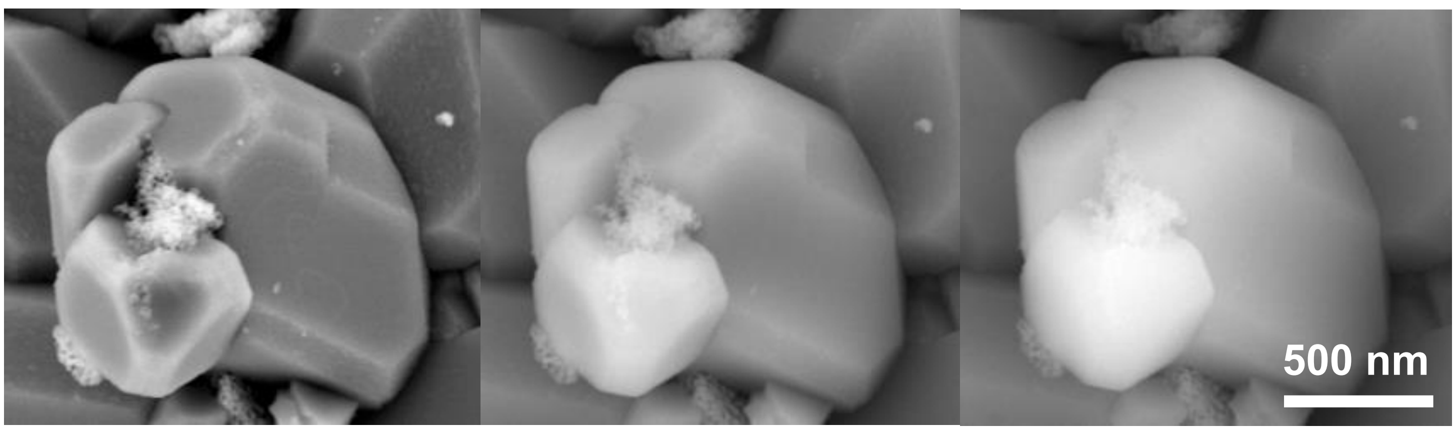

Monte Carlo simulation of the beam – sample interaction for a silicon sample at **1kV** and **10kV**.

# Beam-Sample Interaction

## Influence of Beam Energy – Image Quality



200 V 500 V 1 kV 2 kV

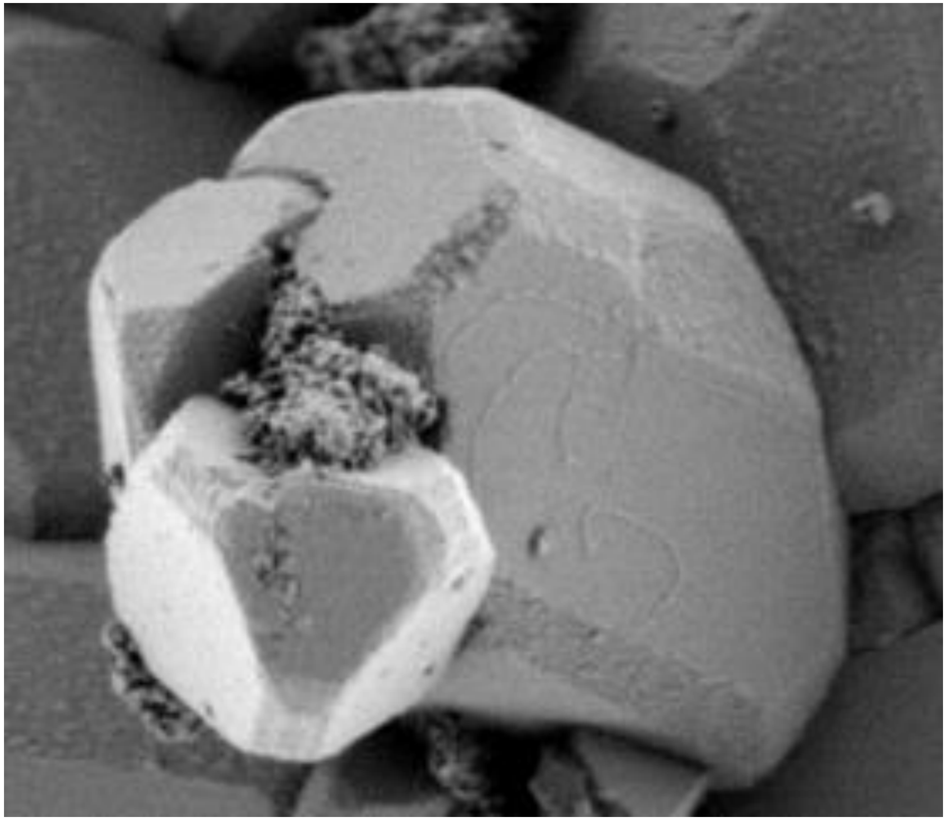



5 kV 10 kV 15 kV

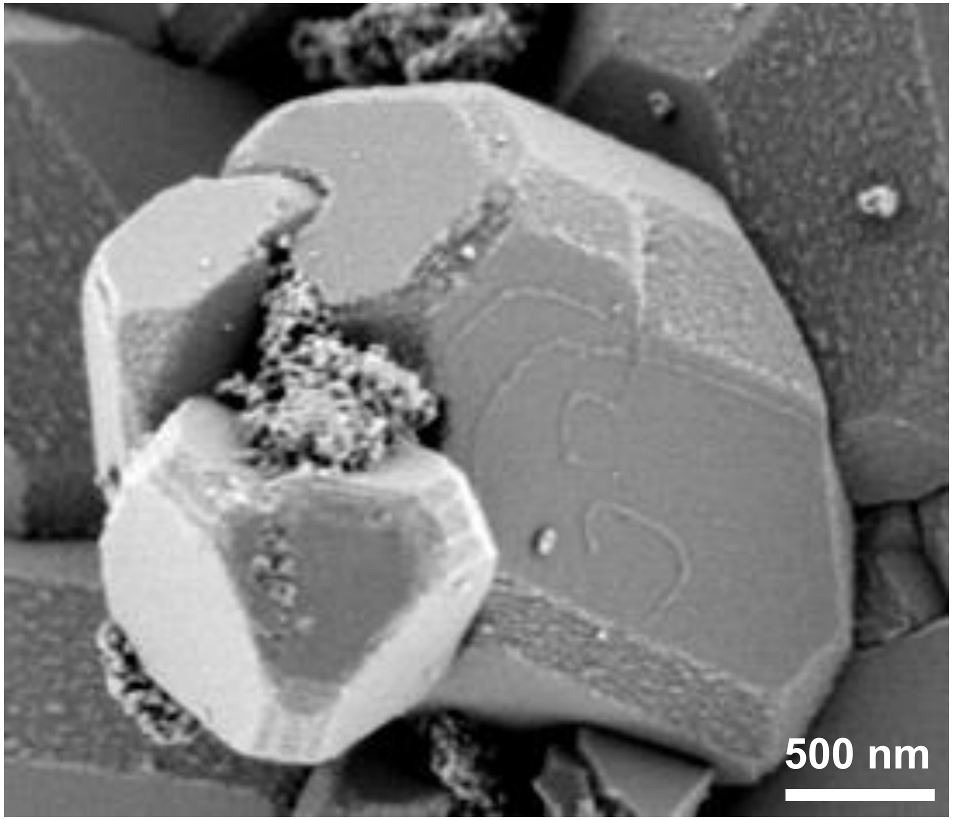
Iron oxide/ Zirconium dioxide composite

# Beam-Sample Interaction
## Influence of Beam Energy – Image Quality

Iron oxide/ Zirconium dioxide composite



200 V

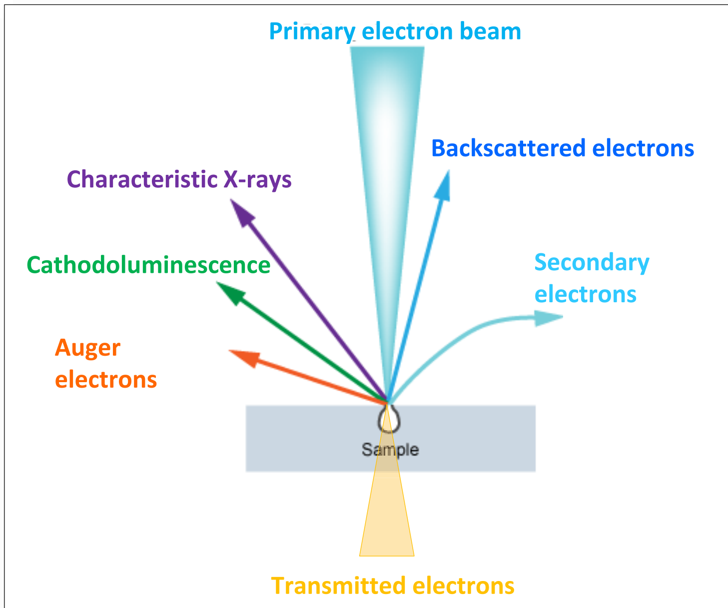



1 kV

Lower voltage provides <u>more surface detail</u>…*BUT*…with <u>loss of S/N</u> → loss of clarity!

# How a SEM Works

## How a SEM works

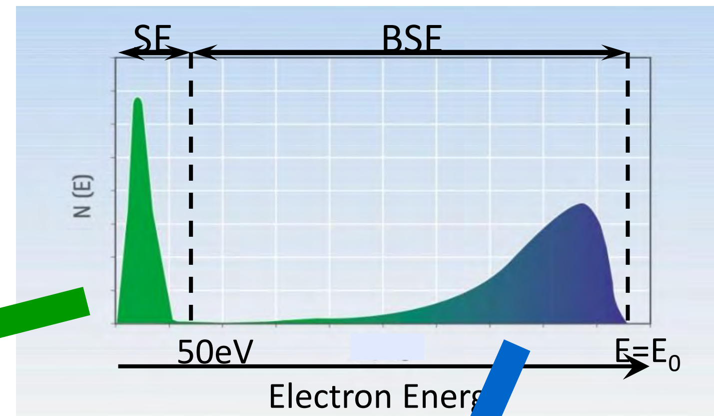


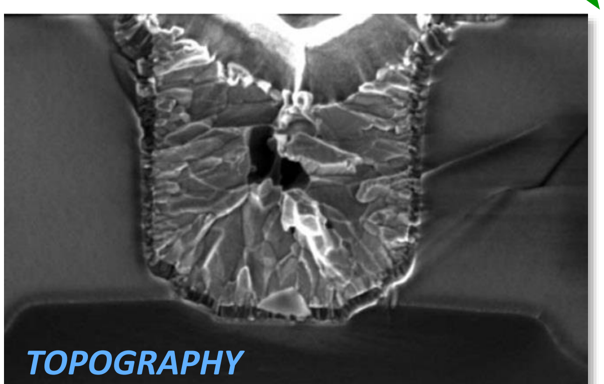

**Backscattered electrons (BSE): Compositional contrast**

**Secondary electrons (SE): Topographical contrast**

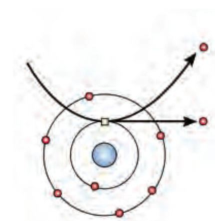
**Transmitted electrons (STEM): High-resolution, “TEM-like” contrast**

**Characteristic X-rays (EDS): Elemental information**



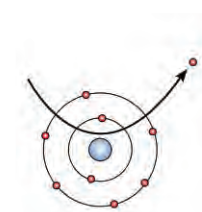




*SE image from a sectioned semiconductor.*



Secondary electrons

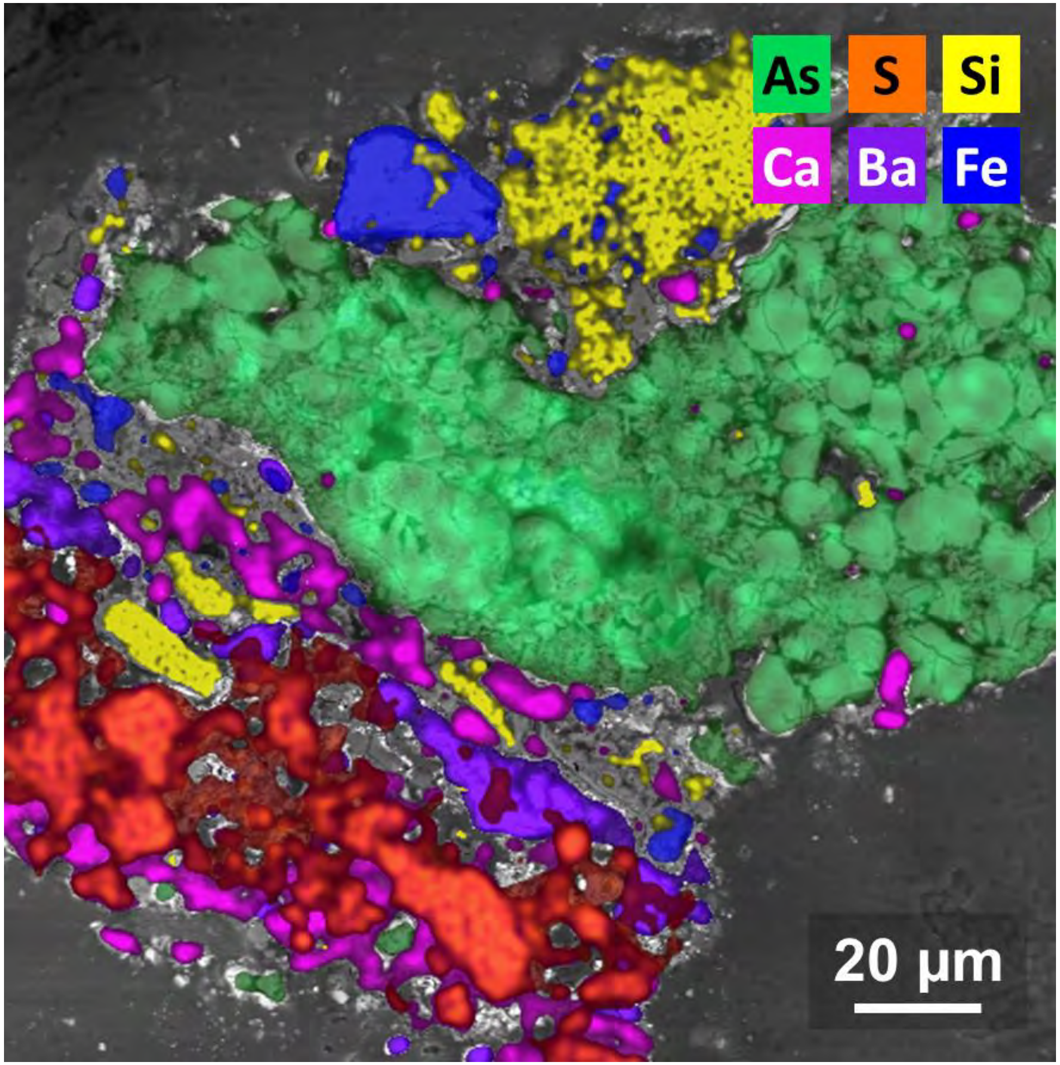

*The same section but seen with the BSE detector*



backscatter electrons

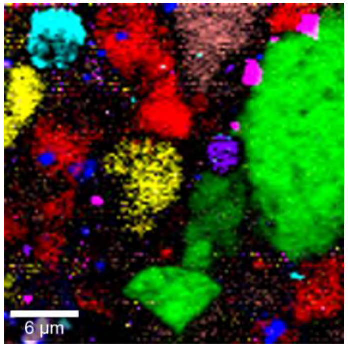
# X-ray Detection (EDS/WDS)

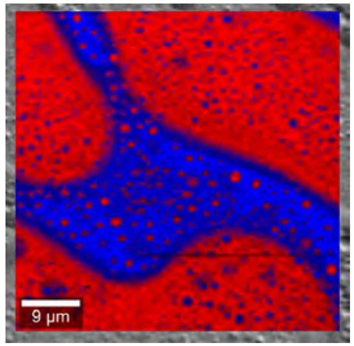
The SEM beam can excite emission of **characteristic x-rays** from the sample. Detection of these x-rays by *energy-dispersive* or *wavelength-dispersive* x-ray spectroscopy (EDS or WDS) reveals a sample's **elemental composition**.

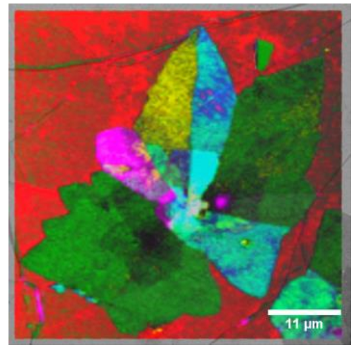



*EDS map image of a paint sample from original artwork.*

# Analysis Beyond EDS
## SEM + Raman spectroscopic imaging



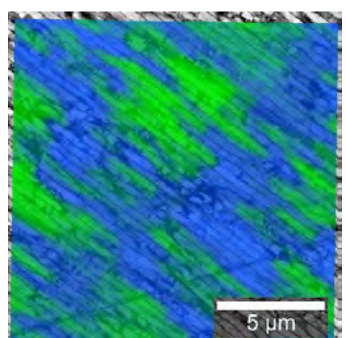



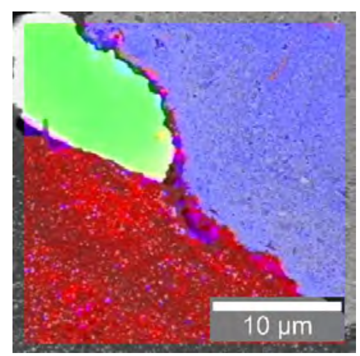

### Application fields:

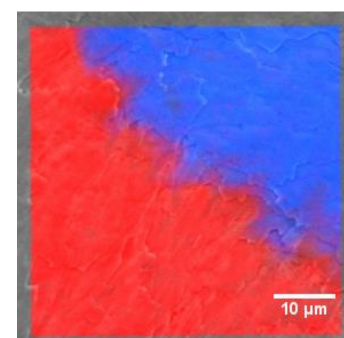
- Nanoparticles & 2D Mat.
- Polymer
- Carbon materials
- Semiconductor
- Geology/ Mineralogy
- Forensic
- Pharma
- Biomaterials
- Coatings
- Corrosion

### Nonmetallic compositions and phases:

- Polymorphs
- Molecule phases
- Polymer blends
- Crystal orientations
- Fibrillary polymer
- Degree of Crystallinity
- Kinds of Defect
- Stress and Strain
- Surface coating
- Contamination



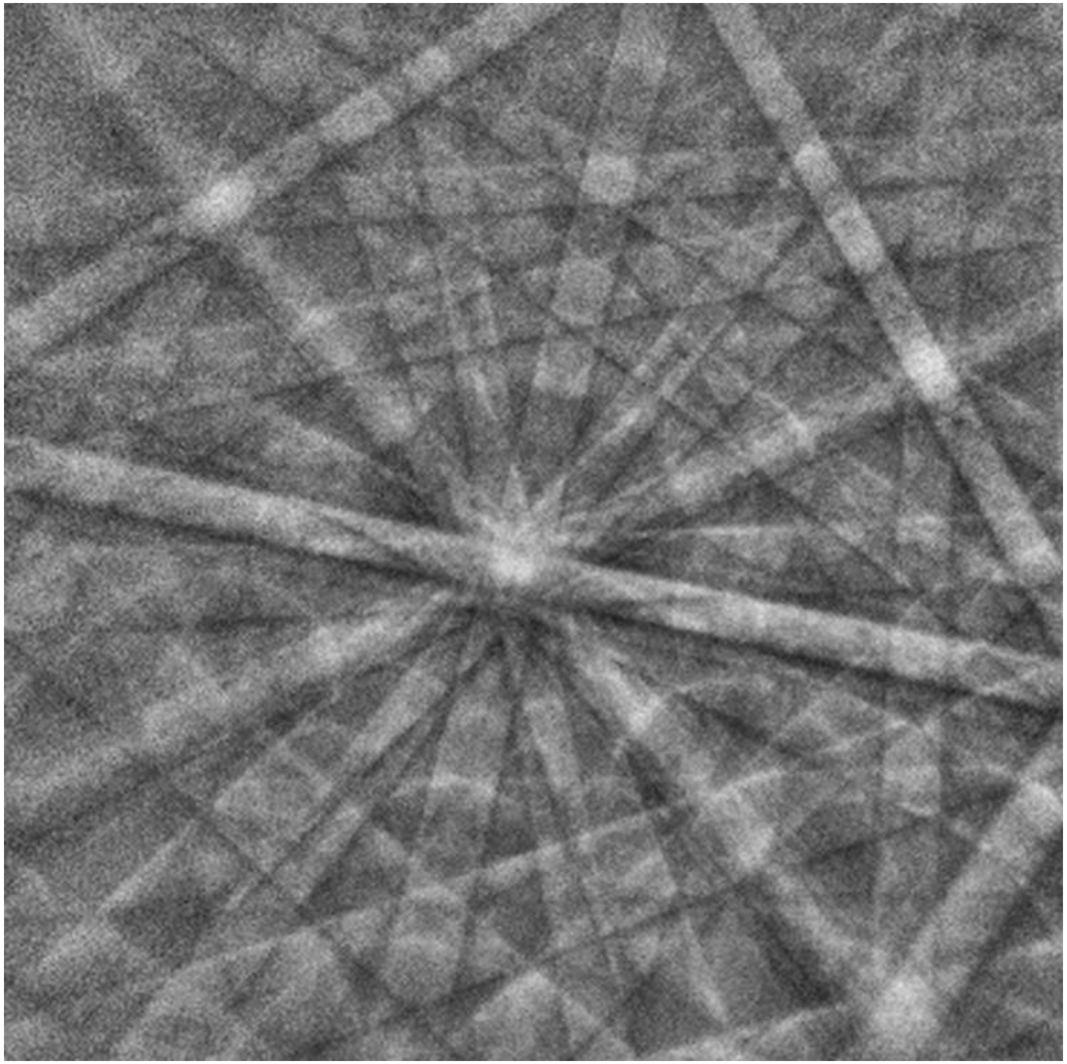



# Electron Backscatter Diffraction (EBSD)

Bragg **diffraction** occurs when the SEM beam strikes **crystalline matter**. The resulting electron backscatter diffraction (EBSD) patterns (see image) reveal the underlying **crystal structure**.

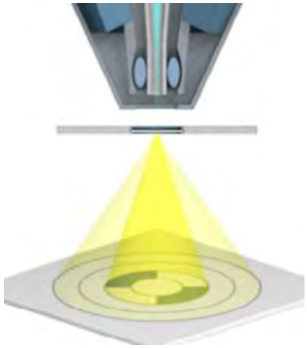
EBSD is useful for applications with metals, inorganics and ceramics.

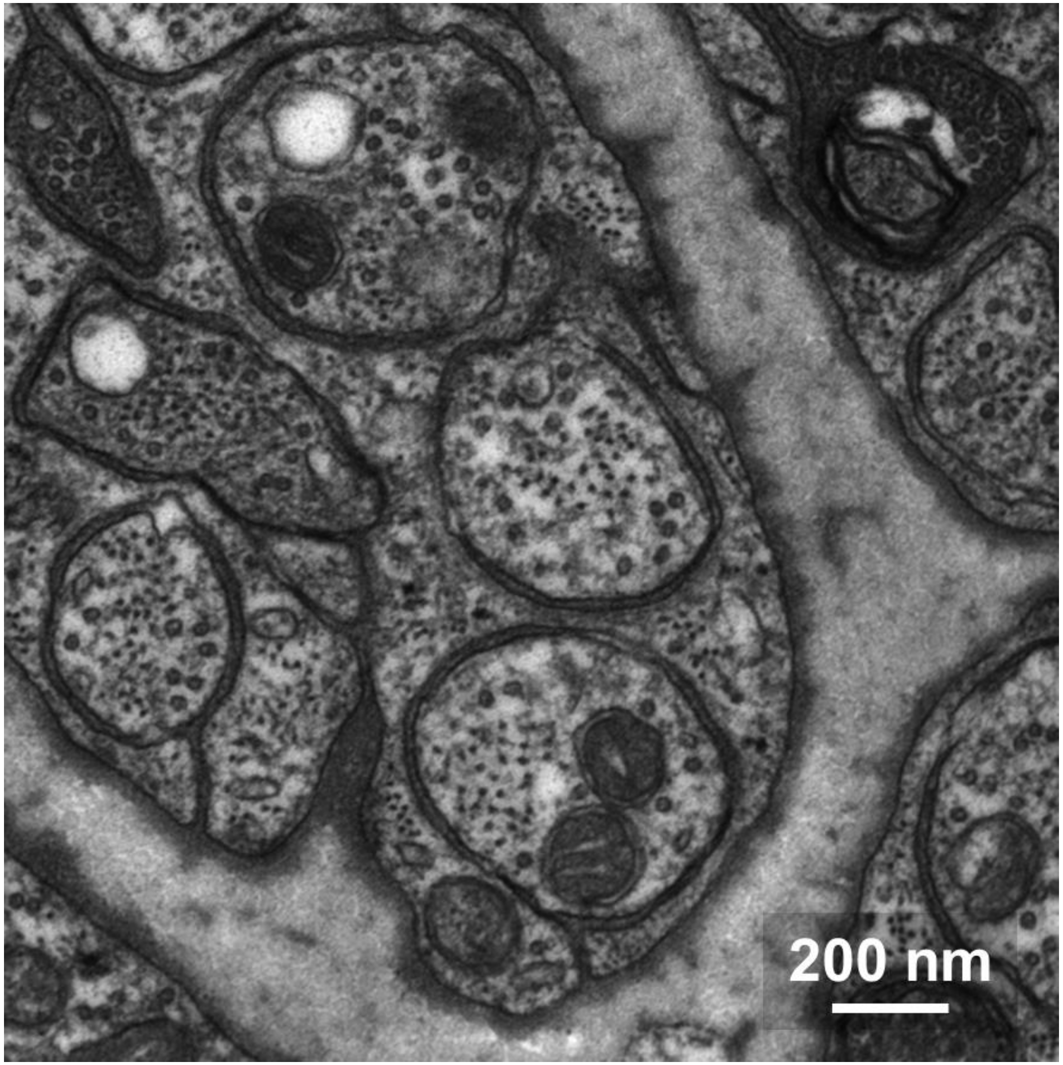


*EBSD pattern of silicon.*

# Transmitted Electrons (STEM)

When imaging very **thin samples** (<100 nm thick), electrons can pass through the sample. Detection of **transmitted electrons** yields scanning transmission electron microscopy (STEM) images of **particularly high resolution**. STEM has both materials and life sciences applications.

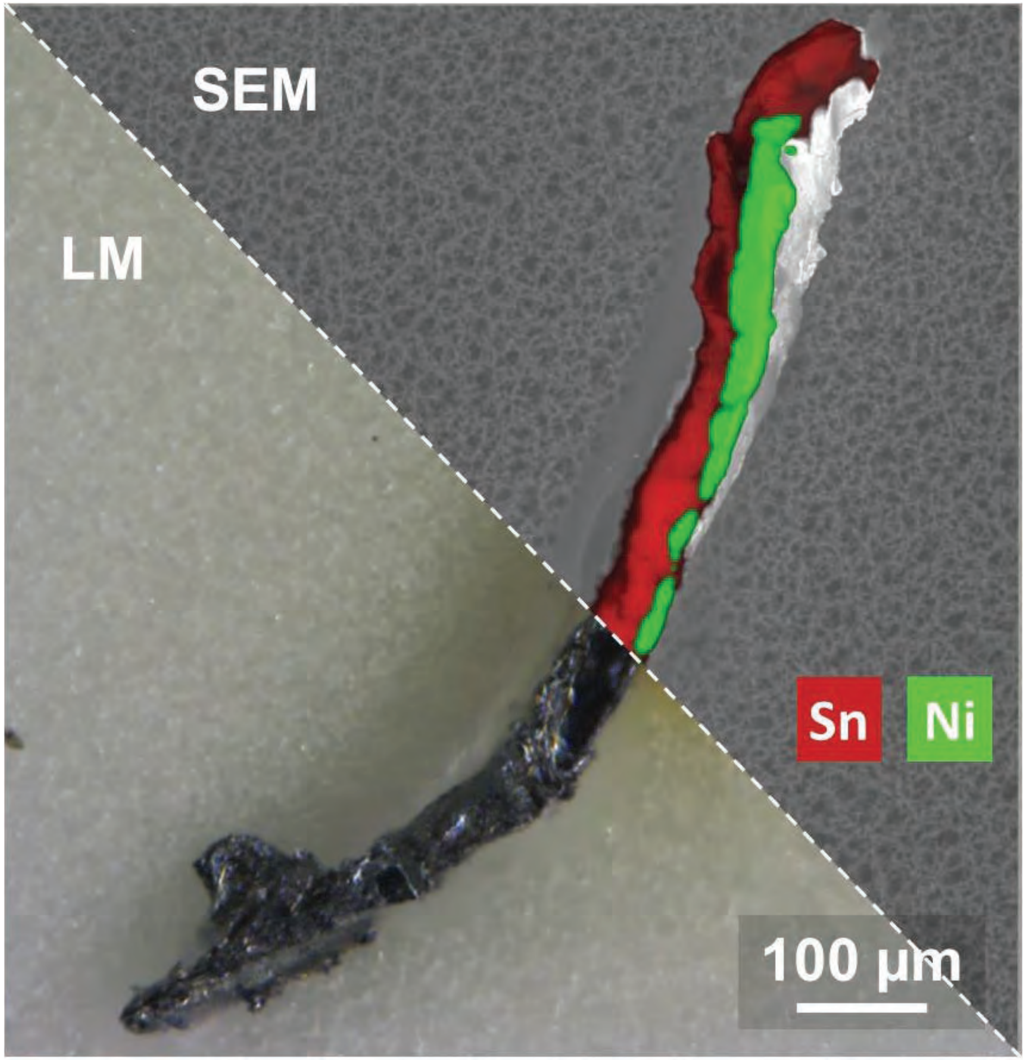





*STEM image of mouse brain.*

# Correlative Microscopy (CLEM)

Many scientific problems require the *combination* of SEM with other complementary microscopy techniques, such as light microscopy. This approach is called CLEM ("correlative light and electron microscopy").



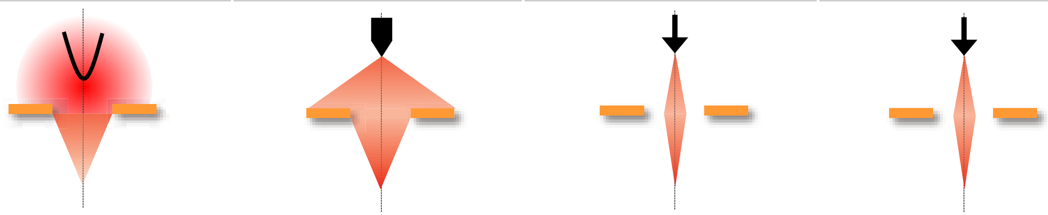

*In particle analysis applications, **light microscopy** provides the number and morphology of the particles, while **SEM** indicates elemental composition. Here, the targeted particle is metallic and rich in tin (Sn) and nickel (Ni).*

# Agenda

# Electron Emitters
## Comparison

Price ⟷ Performance

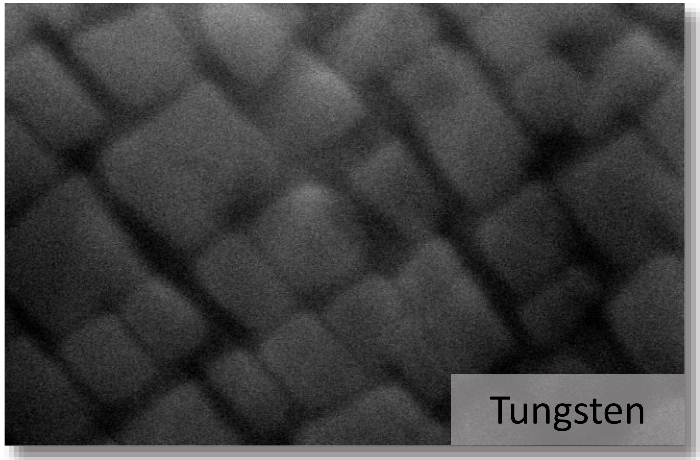
| | Tungsten | $LaB_6$ | Schottky FEG | Cold FEG |
|---|---|---|---|---|
| Source Size (nm) | > 50,000 | 5,000 | 50 | 5 |
| Energy Spread (eV) | 3 | 1 | 0.7 | 0.25 |
| Brightness ($A/cm^2/sr$) | $10^6$ | $10^7$ | > $5x10^8$ | > $5x10^8$ |
| Service Life (hours) | 100-200 | 2000 | > 2000 | > 2000 |
| Vacuum (Torr) | $10^{-5}$ | $10^{-7}$ | $10^{-11}$ | $10^{-11}$ |

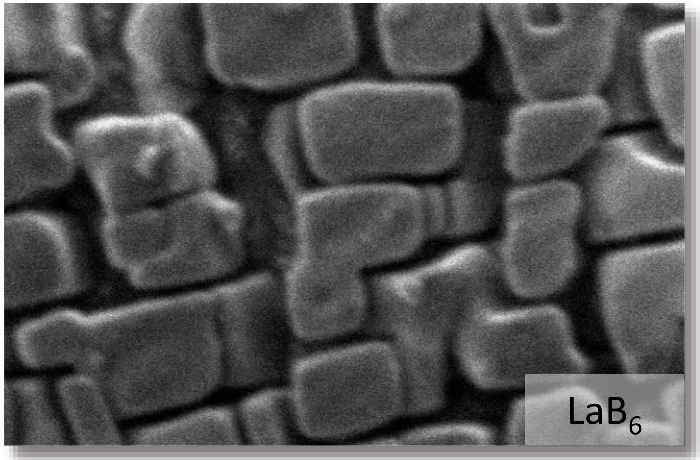


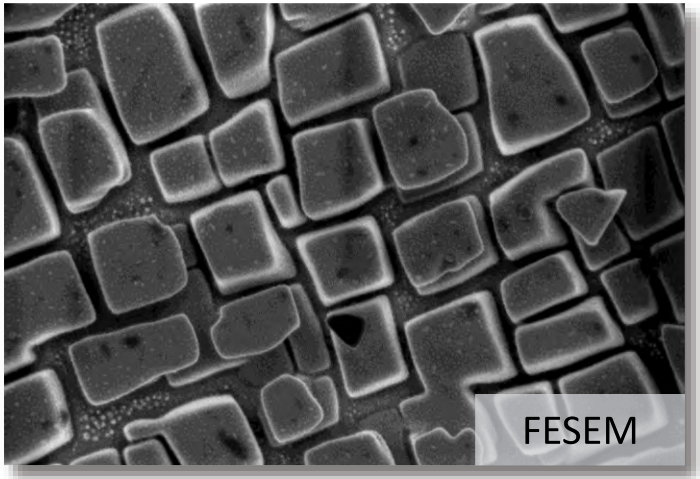
**What does this mean?**

Tungsten — "Light Bulb": High *total* emission current, but low *probe* current and large spot size.
$LaB_6$ — "Directed" thermal emission, somewhere between Tungsten and FEG
Schottky and Cold FEG — "Laser": Lower *total* emission current, but high *probe* current in a small spot.

# Electron Emitters
## Comparison




Alloy, 1kV, 35kx, SE image

# Agenda

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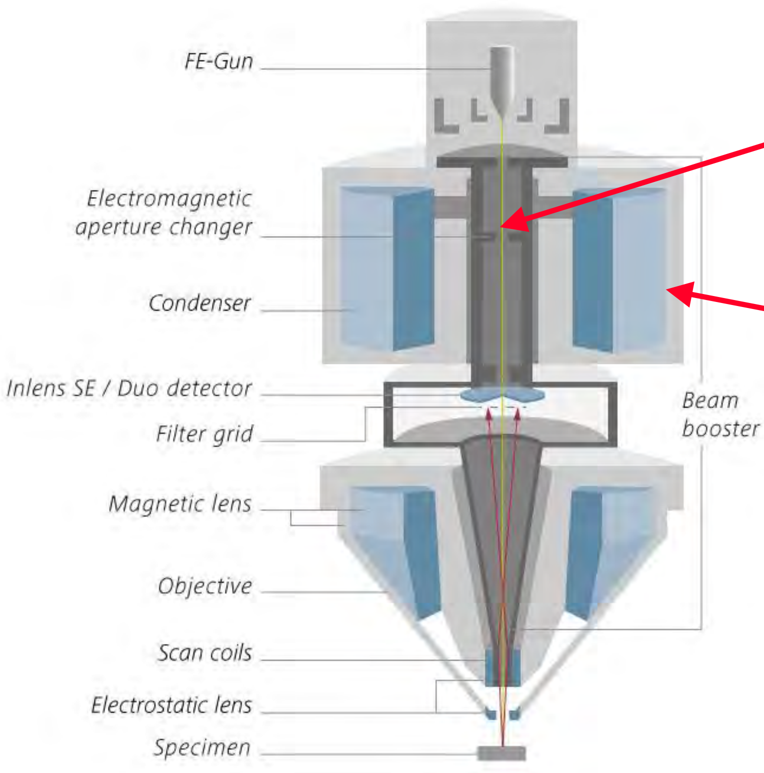
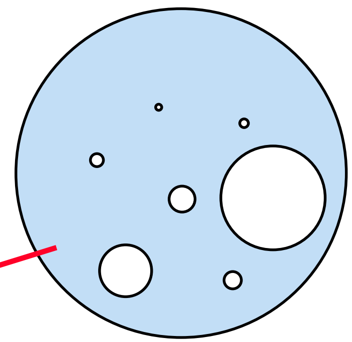
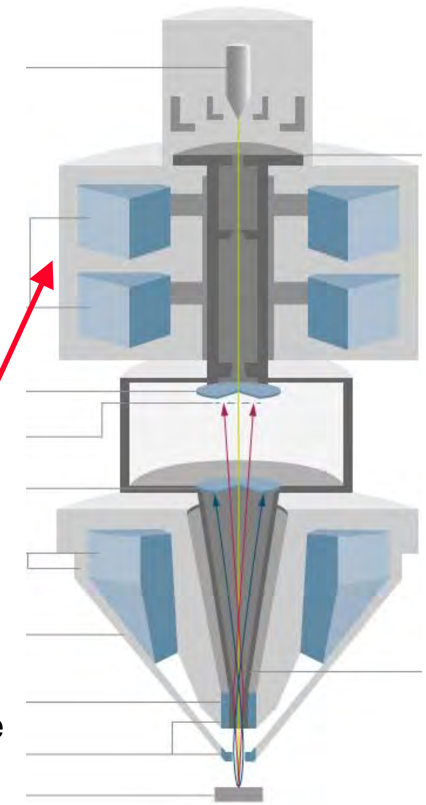
# SEM Column Design

## Single and Double Condensers





<u>Single condenser</u>

- discrete probe sizes (current)
- different size apertures

<u>Double condenser</u>

- various probe sizes
- fixed single aperture

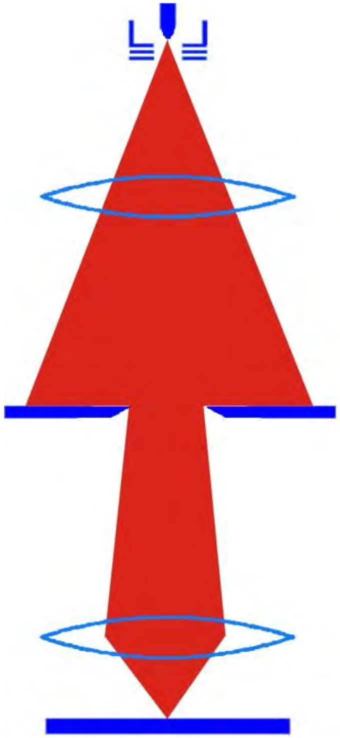
# Electron Beam Optimization
## Effects of Beam Current (Aperture Size)

**Condenser**
Used to optimize the aperture angle

**Multi-hole aperture**
Selects the beam current (6 different diameters)

**Objective lens**

**Sample**



20µm aperture
*Optimized optics*
*0.8nm @ 100pA/10kV*

# Electron Beam Optimization

## Effects of Beam Current (Aperture Size)

**Condenser**
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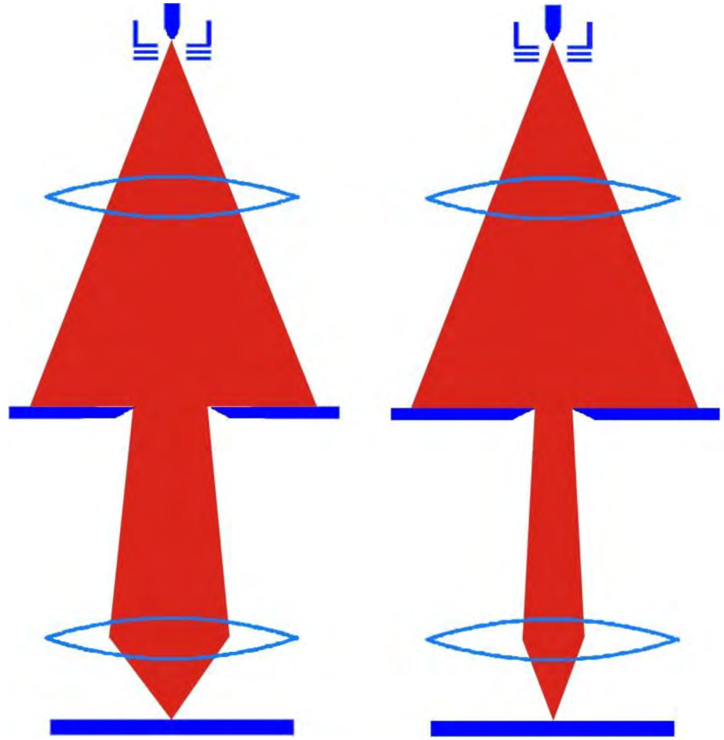


20µm aperture
*Optimized optics*
*0.8nm @ 100pA/10kV*

7µm aperture
*Limited by diffraction*
*1.7nm @ 14pA/10kV*

# Electron Beam Optimization

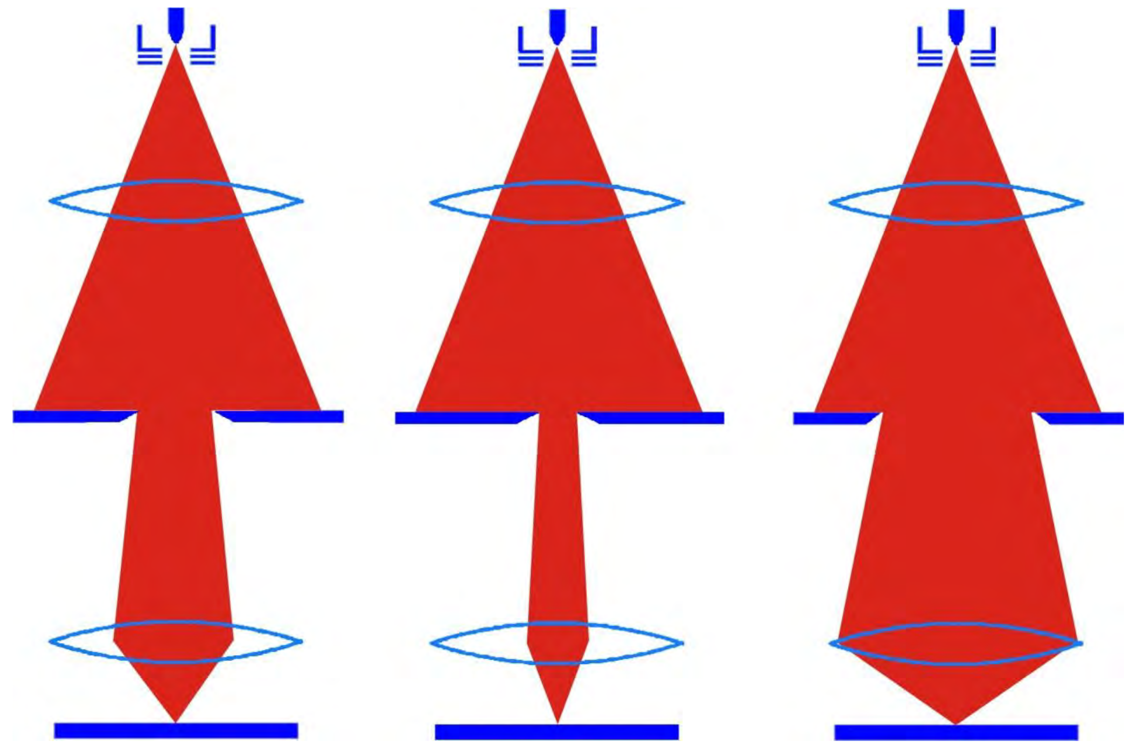
## Effects of Beam Current (Aperture Size)

**Condenser**
Used to optimize the aperture angle

**Multi-hole aperture**
Selects the beam current (6 different diameters)

**Objective lens**

**Sample**



| 20µm aperture | 7µm aperture | 120µm aperture |
|---|---|---|
| *Optimized optics* | *Limited by diffraction* | *Limited by sph. aberr.* |
| *0.8nm @ 100pA/10kV* | *1.7nm @ 14pA/10kV* | *40nm @ 3.5nA/10kV* |

**Resolution depends on the beam current!**
**Optimized imaging conditions for discrete probe currents**

# Electron Beam Optimization
## Benefit of Double Condenser

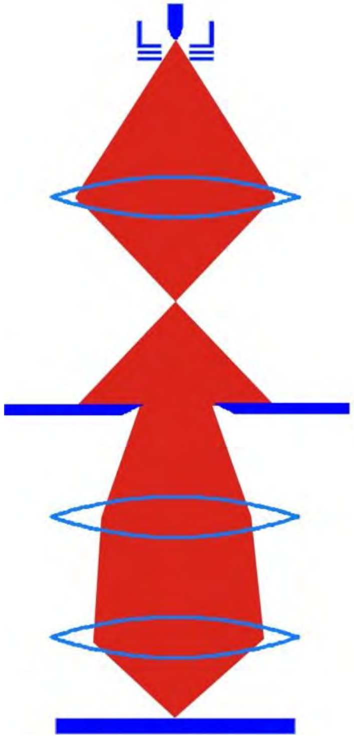
**Condenser 1**
Selects the beam current

**Fixed aperture**

**Condenser 2**
Selects the aperture angle

**Objective lens**

**Sample**



35µm aperture
*0.8nm @ 100pA/10kV*

# Electron Beam Optimization

## Benefit of Double Condenser

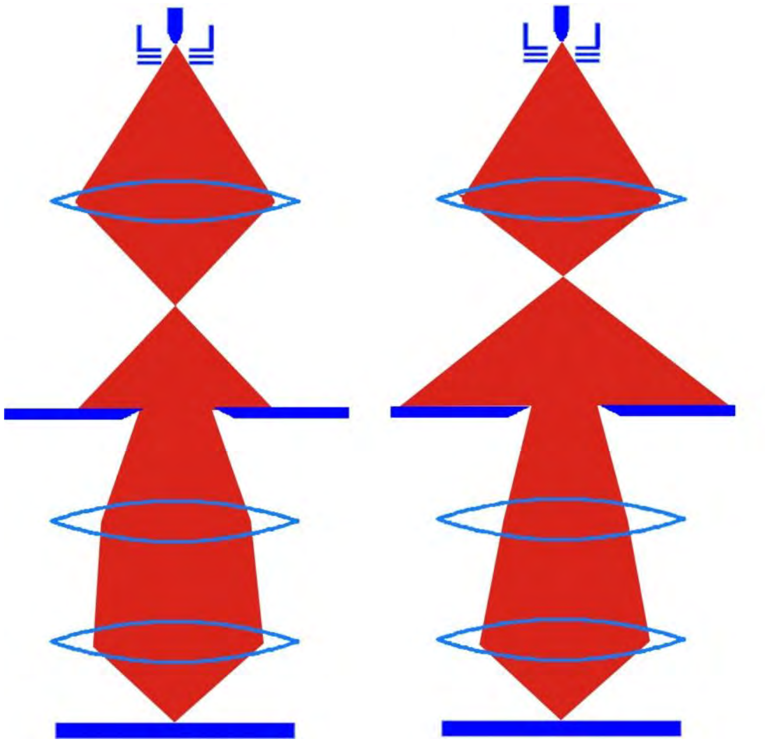
**Condenser 1**
Selects the beam current

**Fixed aperture**

**Condenser 2**
Selects the aperture angle

**Objective lens**

**Sample**



35µm aperture
*0.8nm @ 100pA/10kV*

35µm aperture
*0.7nm @ 14pA/10kV*

# Electron Beam Optimization

## Benefit of Double Condenser

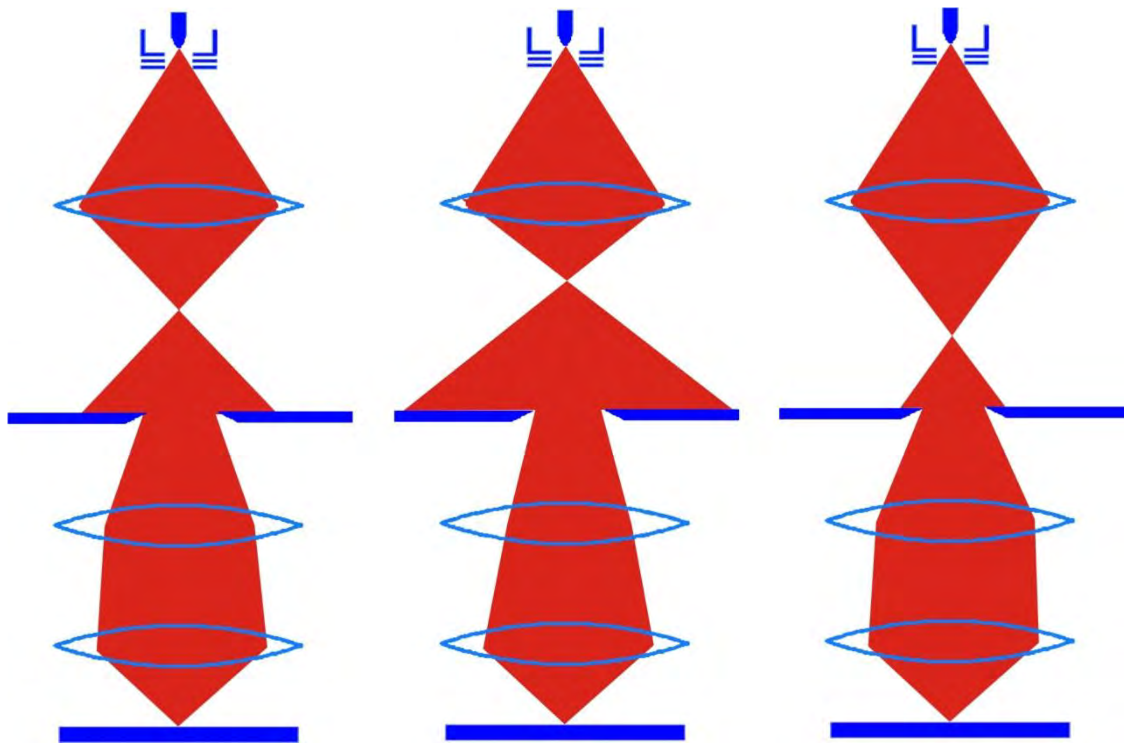
**Condenser 1**
Selects the beam current

**Fixed aperture**

**Condenser 2**
Selects the aperture angle

**Objective lens**

**Sample**

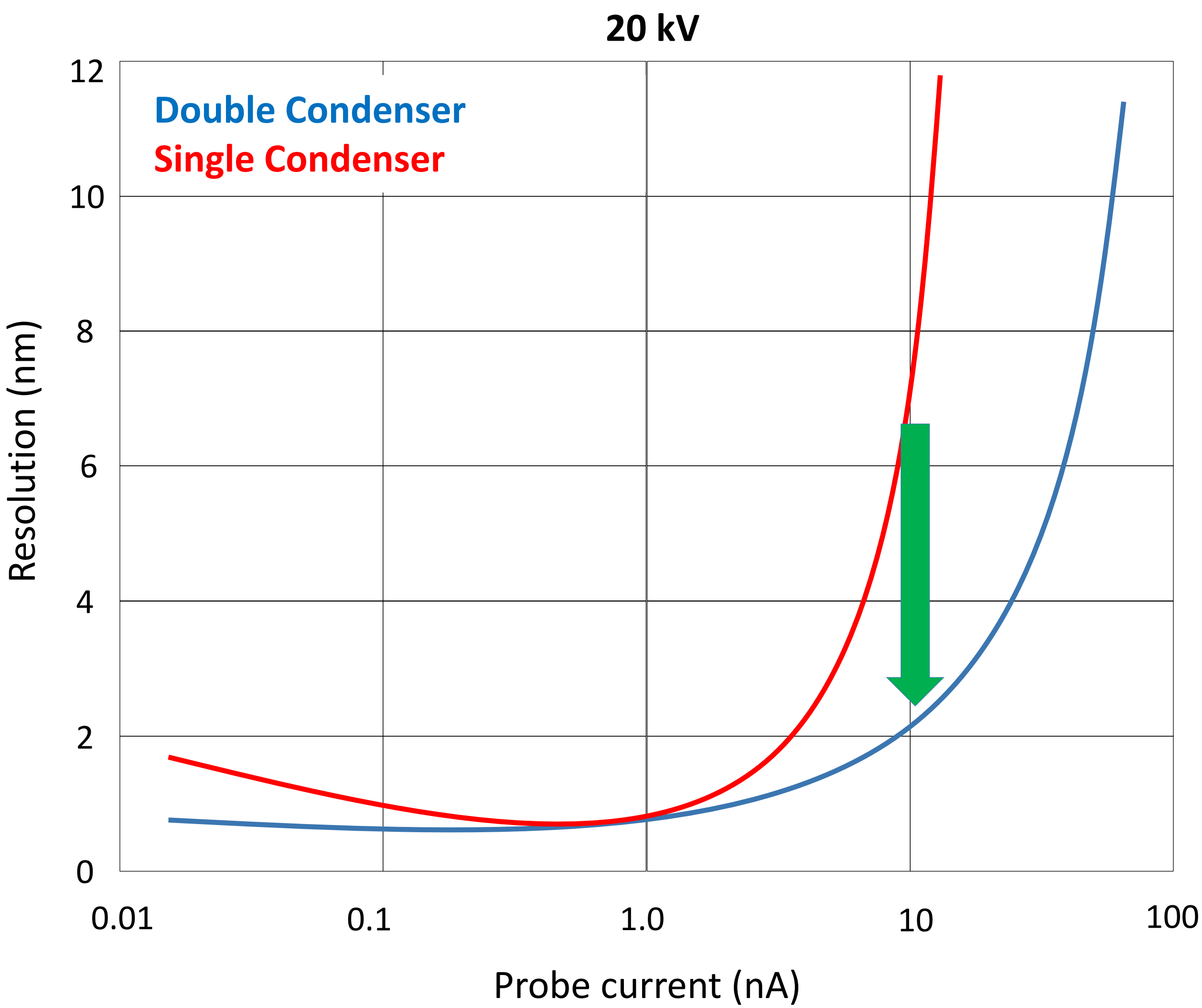


| 35µm aperture | 35µm aperture | 35µm aperture |
| --- | --- | --- |
| *0.8nm @ 100pA/10kV* | *0.7nm @ 14pA/10kV* | *1.7nm @ 3500 pA/10kV* |

**Continuous regulation of probe current and optimized imaging at any voltage**

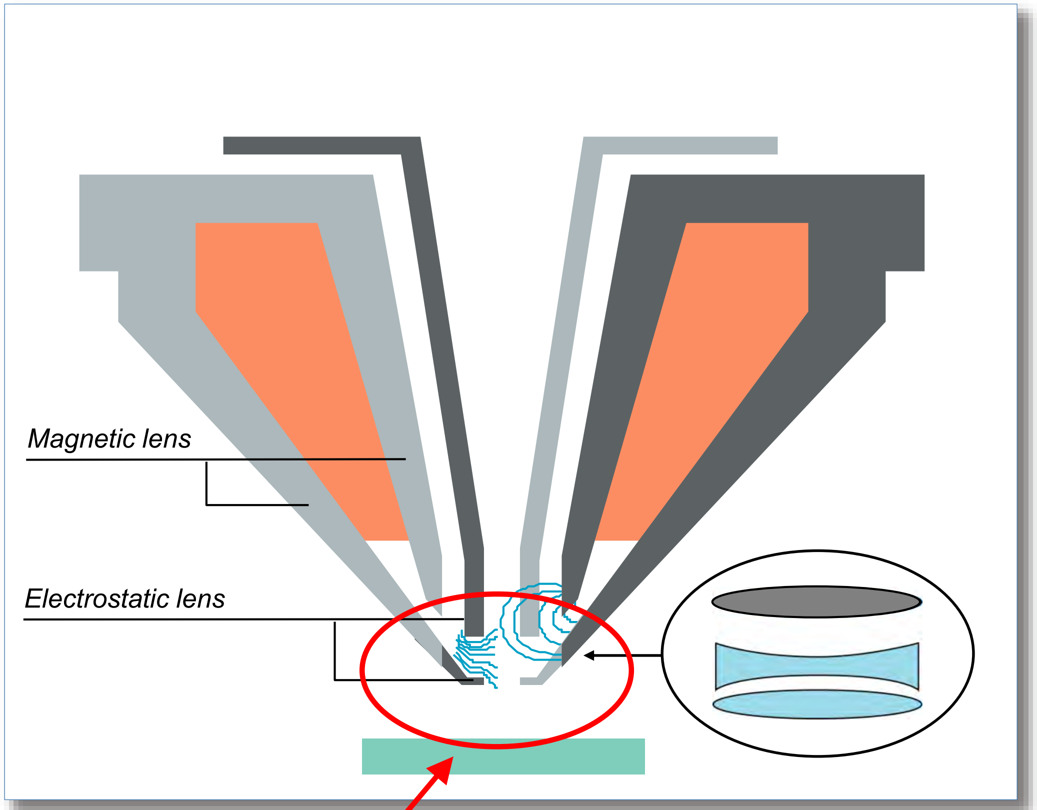
# Achieving Greater Resolution

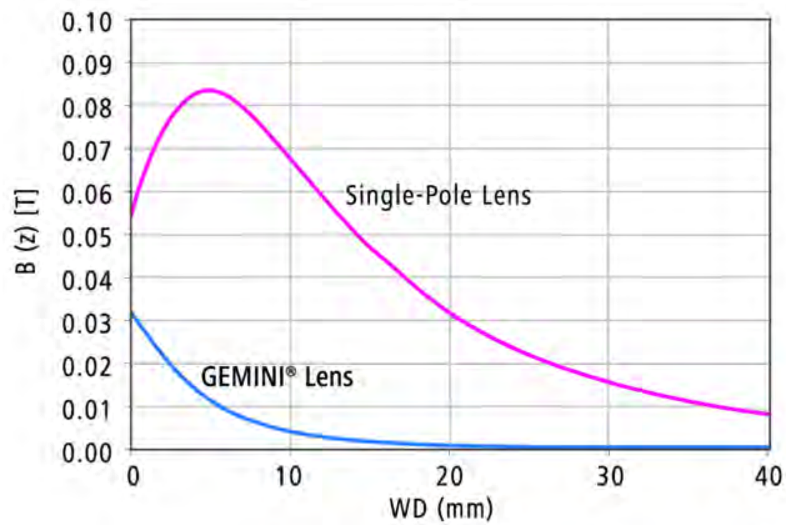
## Moving Boundaries with Column Design



# Objective Lens Design

## Magnetic + Electrostatic Hybrid

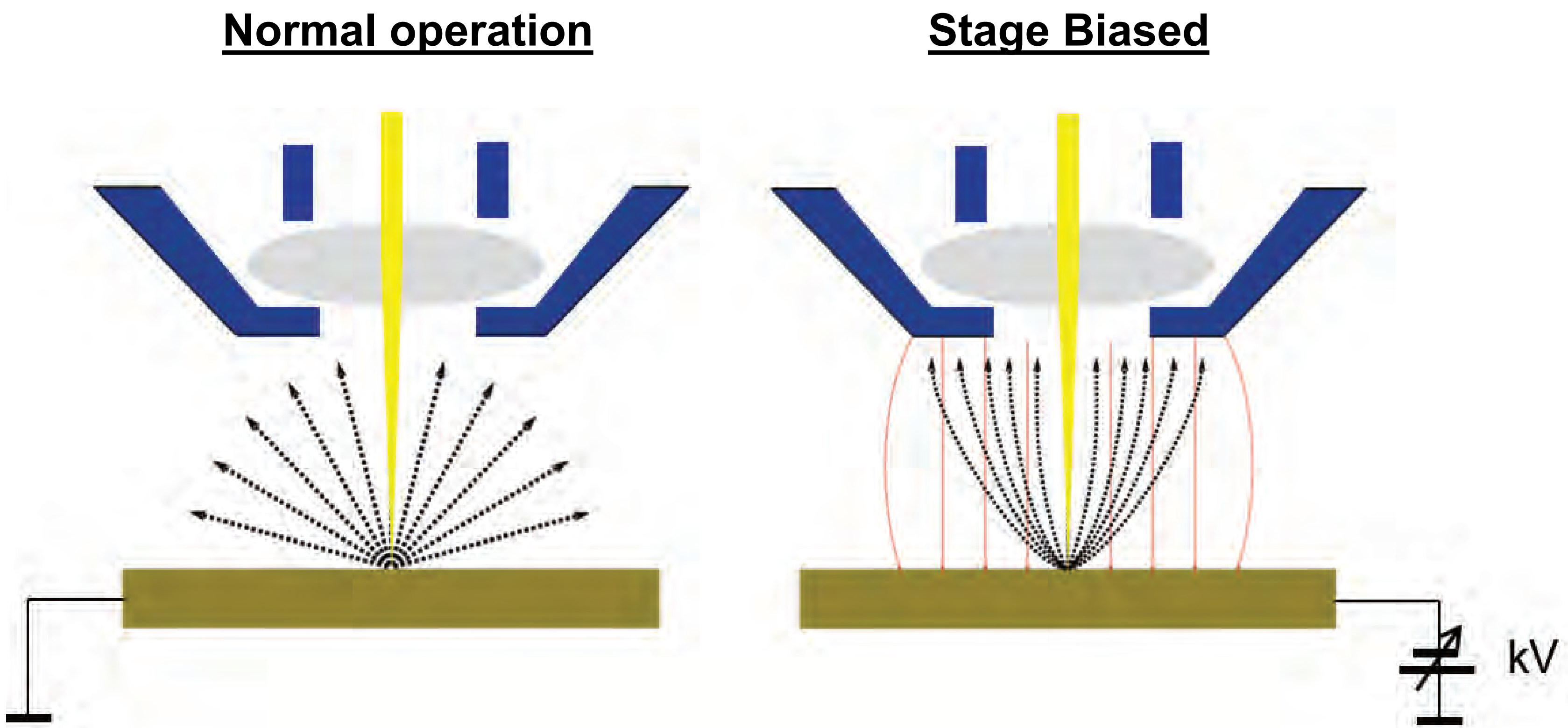



**No magnetic field at the sample**
**Imaging of ferromagnetic materials in UHR**

Electrostatic lens *eliminates magnetic fields* below the final lens to mitigate image distortion

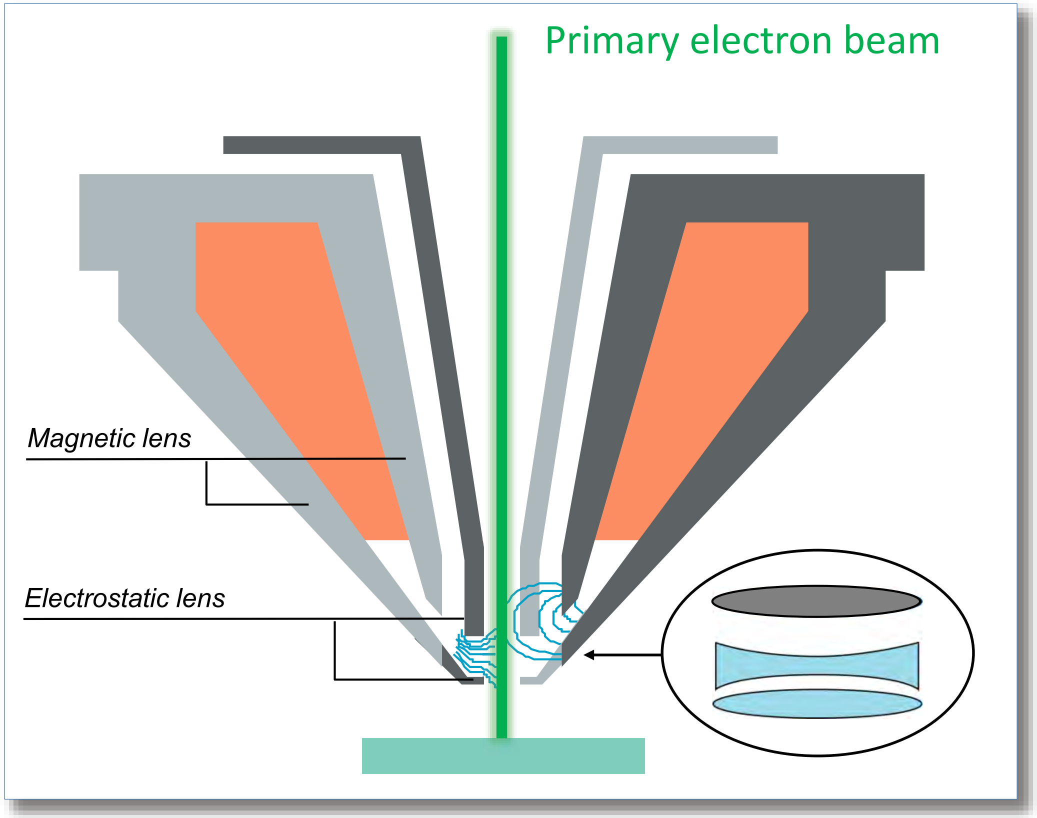
# Stage Biasing




- Improve resolution (sub-nanometer from 1 kV to 30 kV)
- Enhance contrast by tuning bias voltage
- Improve detector efficiency for inlens detection as well as BSD detection
- Suppress charging artifacts.

# GEMINI Column

## Beam Boost + Deceleration




Beam Booster technology:

Electron energy:
Landing energy **+ 8keV**

Deceleration to desired landing energy
**In the column.**

- The energy of the primary electrons in the column is kept at above 8keV at all times
- Maintains beam at high tension throughout the column preserving brightness until final deceleration at the objective lens

# Agenda

| | |
|---|---|
| 1 | Why Electrons? |
| 2 | Interaction with Matter |
| 3 | Electron Emitter |
| 4 | Electron Column Design |
| 5 | Operating Parameters |
| 6 | Insulating Samples |

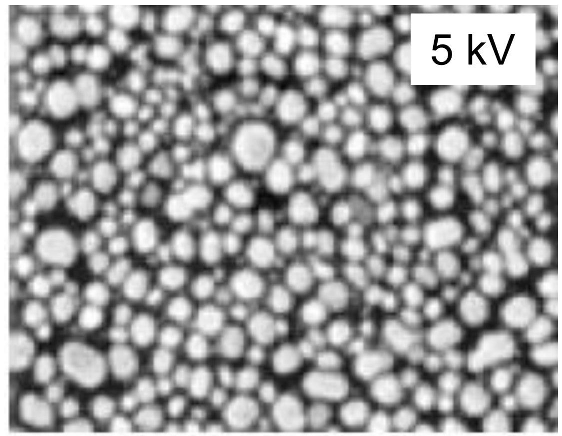
# **Optimizing Imaging Parameters**
## Accelerating Voltage

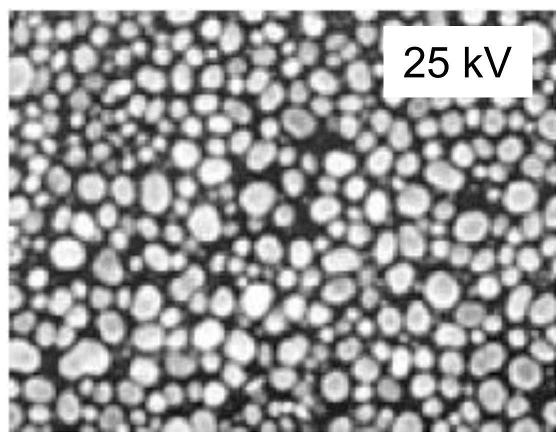
The <u>accelerating voltage</u> can typically be varied by the operator from < 1 kV to 30 kV on SEMs.

*Increasing* accelerating voltage will:

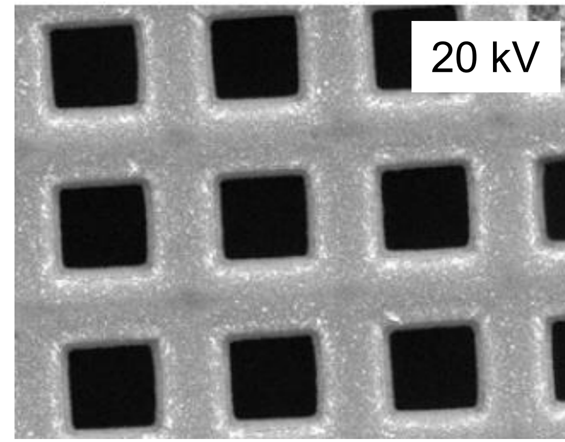
- *decrease* lens aberrations → smaller probe diameter → *better* resolution.
- *increase* the probe current at the specimen. A minimum probe current necessary for *good contrast* and a *high signal to noise ratio*
- potentially *increase* charge-up and damage in specimens that are non-conductive or beam sensitive

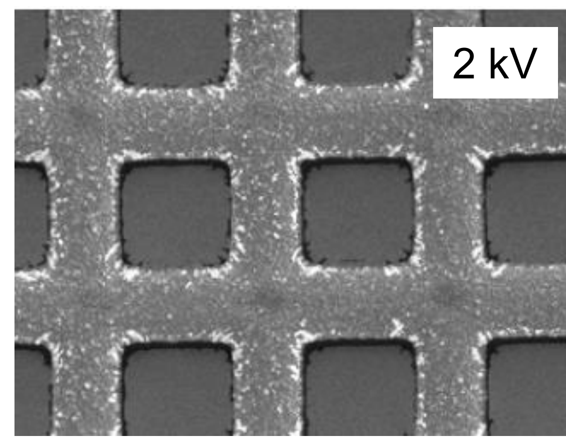
*evaporated gold particles*




*30 nm carbon film over a Cu TEM grid*



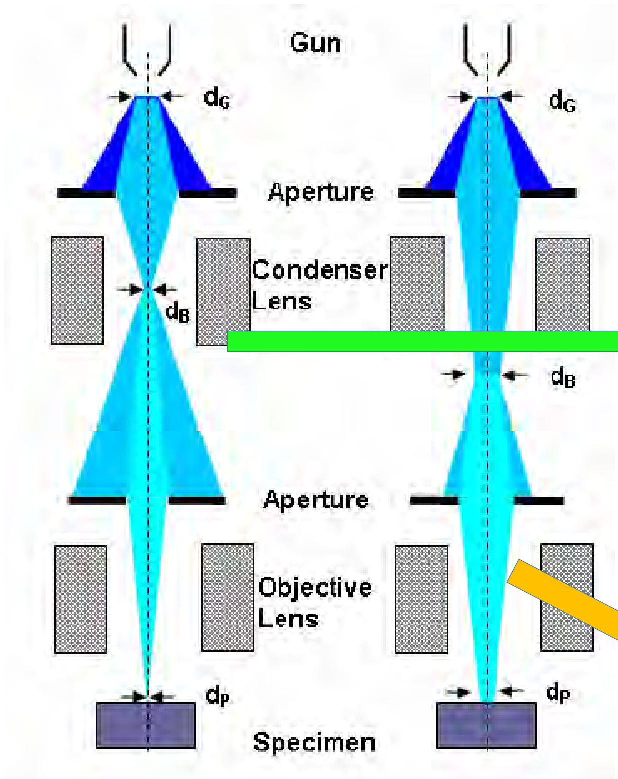

Hafner, 2007

# Optimizing Imaging Parameters
## Beam Probe Diameter

The probe diameter or spot size can be varied altering current to a condenser lens.

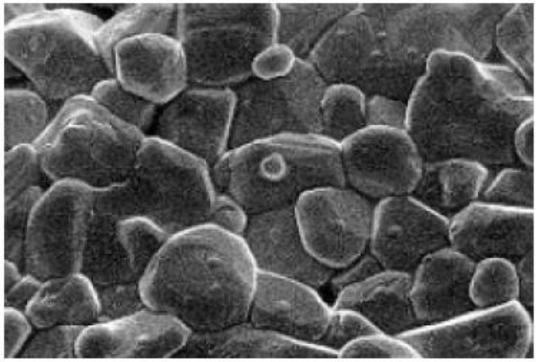
*Decreasing* the probe diameter will:

- *decrease* probe current
- enable *greater* resolution. Resolving small specimen features requires probe diameters of similar dimensions.
- *decrease* lens aberration due to a stronger lens setting

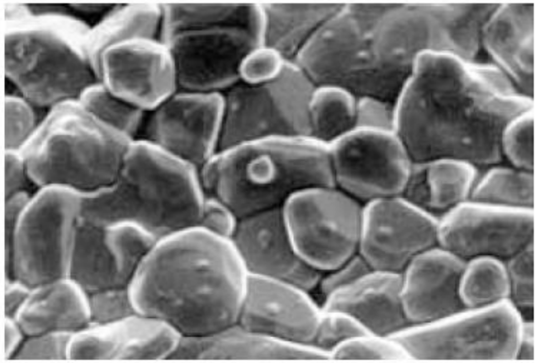



small probe large probe

Hafner, 2007



Smaller spot size: image is *sharper* but also *grainier* in appearance due to the lower signal to noise ratios associated with a lower beam current



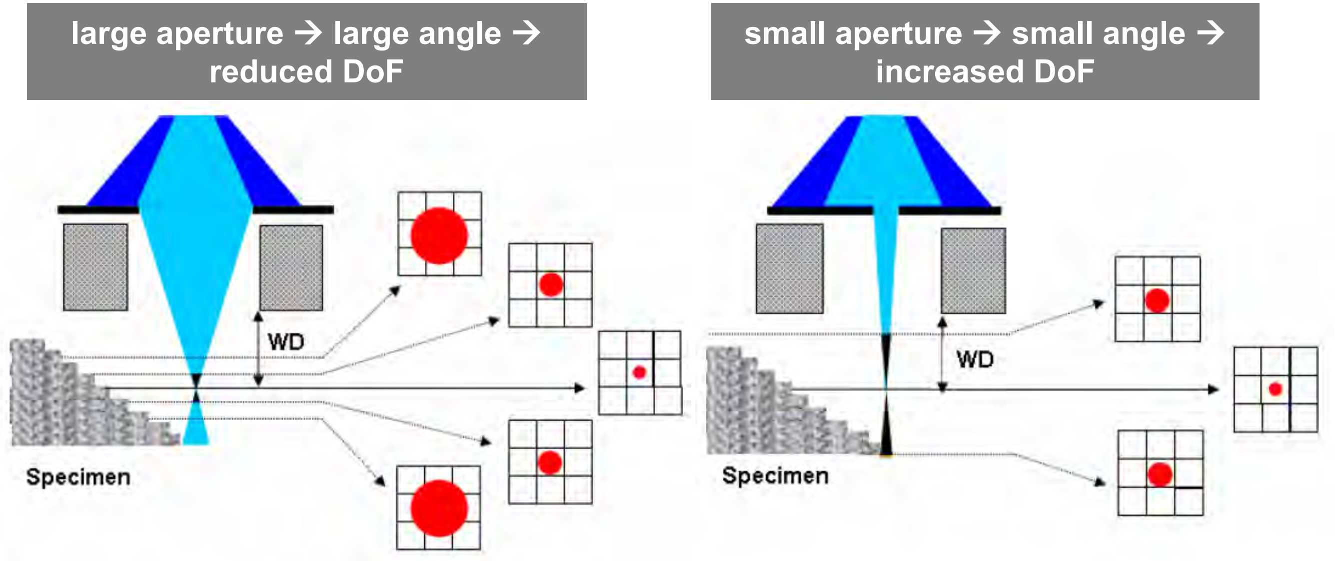
Larger probe size: results in a *less sharp* but *smoother* image in appearance.

# Optimizing Imaging Parameters
## Objective Aperture Size

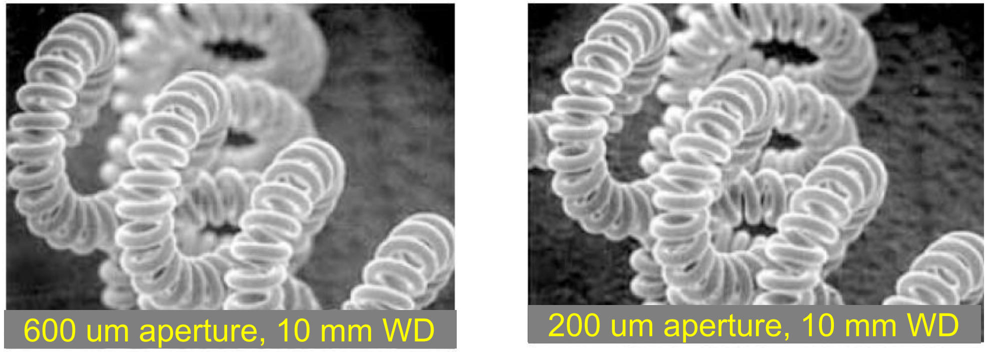
The aperture size can be selected by the user

*Decreasing* the diameter of the aperture will:

- *decrease* lens aberrations → *increase* resolution
- *decrease* the probe current
- *decrease* the convergence angle of the beam → *increase* depth of focus




*Light bulb filament*




Hafner, 2007

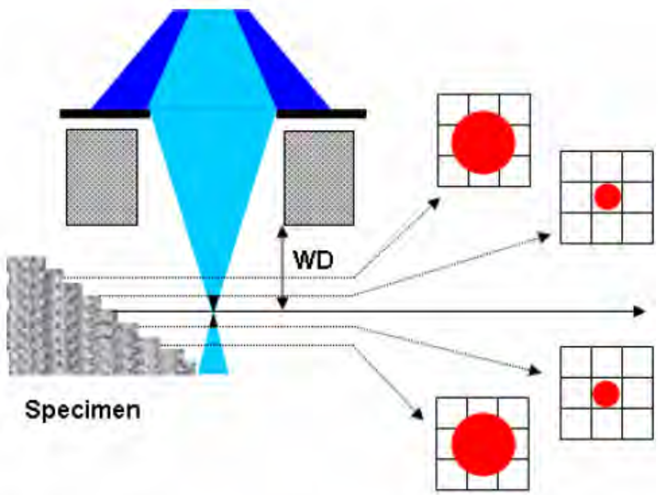
# Optimizing Imaging Parameters
## Working Distance

<u>Working Distance</u> is the distance from the final lens to the top of the sample

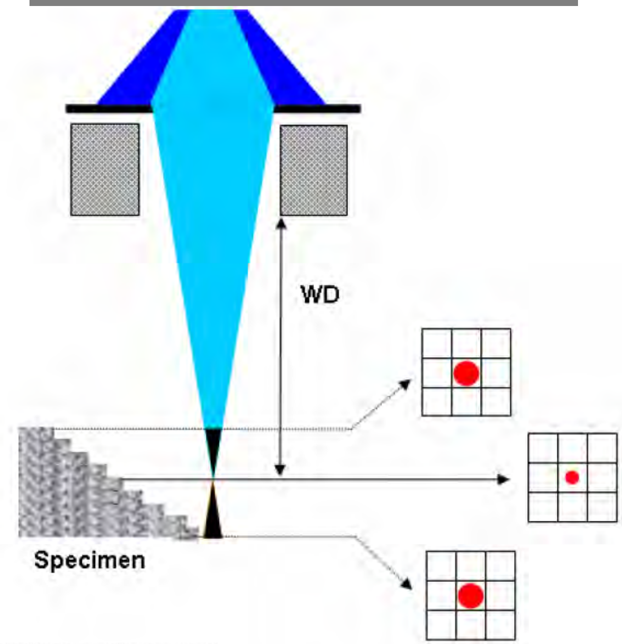
*Increasing* the working distance will:

- *increase* depth of focus increase probe size BUT *decrease* resolution
- *increase* the effects of stray magnetic fields BUT *decrease* resolution
- *increase* aberrations due to the need for a weaker lens to focus

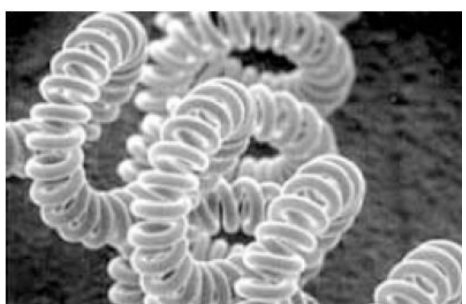
**short WD → short DoF → higher res.**



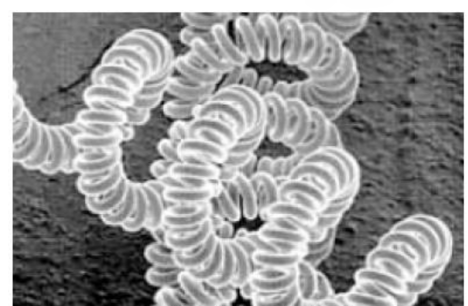

**long WD→ long DoF → lower res.**




*Light bulb filament*



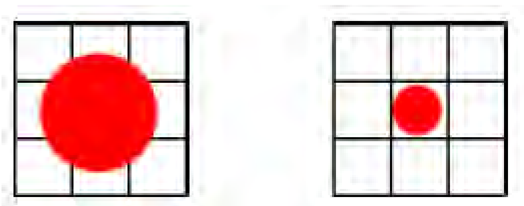
200 um aperture, 10 mm WD



200 um aperture, 38 mm WD

Hafner, 2007

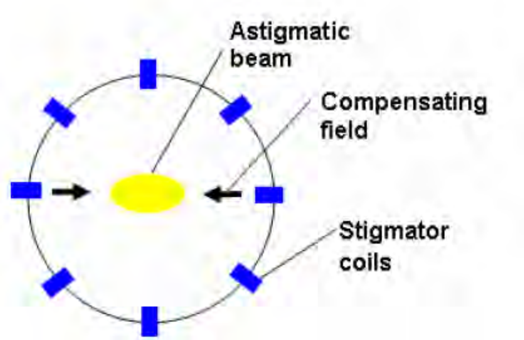
# Optimizing Imaging Parameters
## Focus and Stigmation

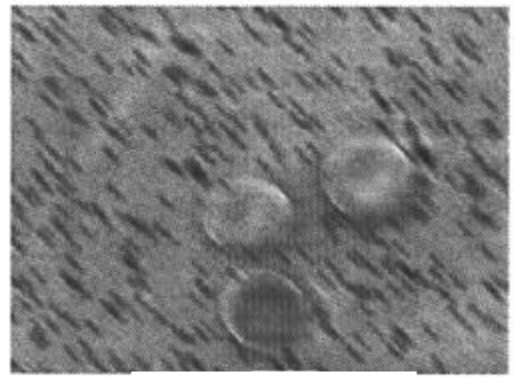


Best focus

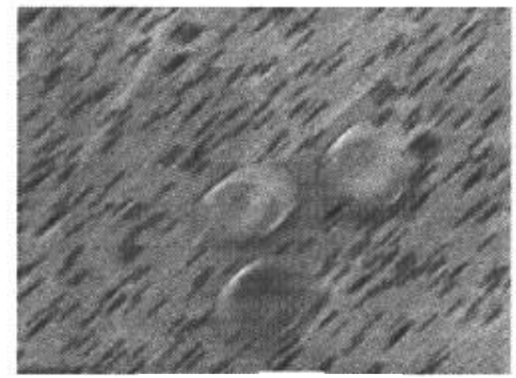
**Objective lens astigmatism**

- Revealed as streaking when going in and out of focus
- Corrected by applying current differently to a ring of stigmator coils around the objective lens
- Correct to obtain circular beam

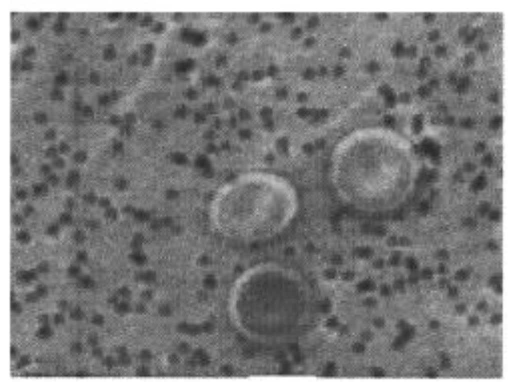


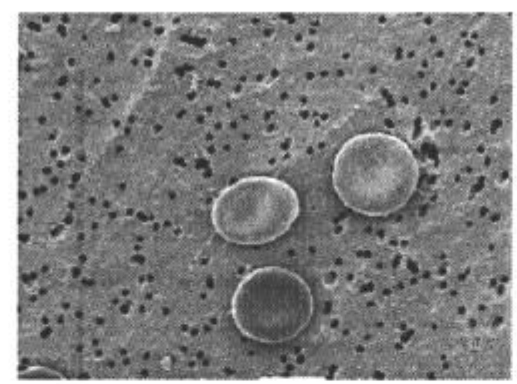
Under-focused



Over-focused



Focused, Astigmated



Focused, Stigmated

Hafner, 2007

# Agenda

| | |
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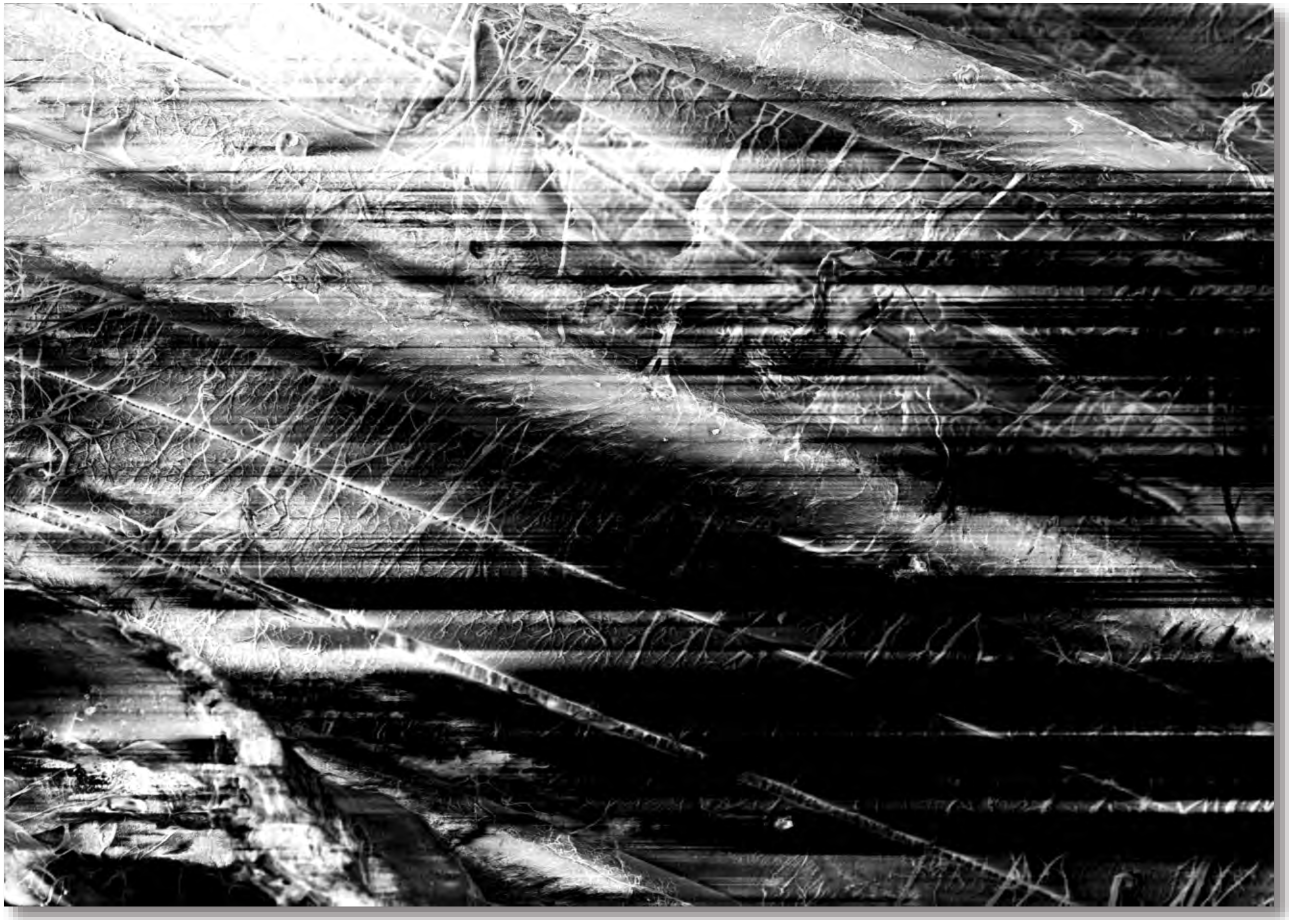
# Electron Microscopes
## Imaging difficult samples

Insulating or non-conductive samples: charging leads to artifacts and distorted images.

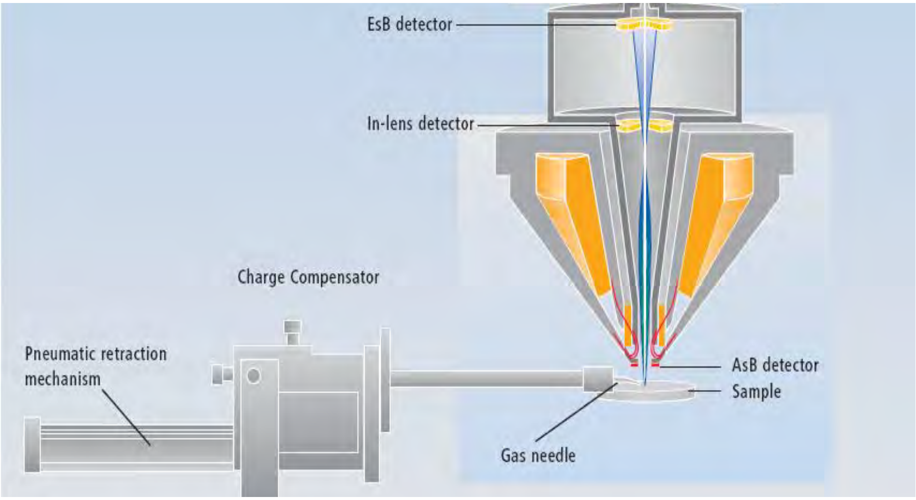


*Example: paper fibers imaged at 5keV*

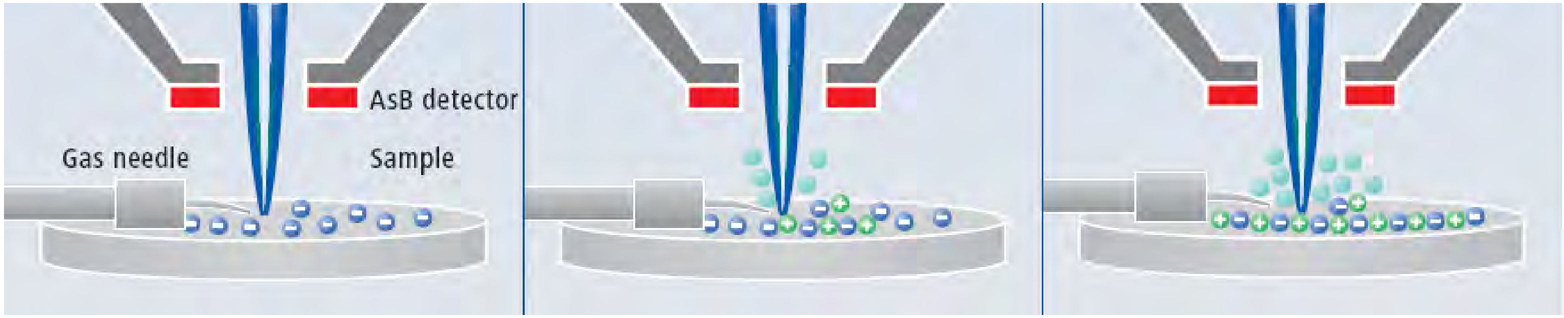
# Electron Microscopes
## Imaging difficult samples

Insulating or non-conductive samples: charging leads to artifacts and distorted images.

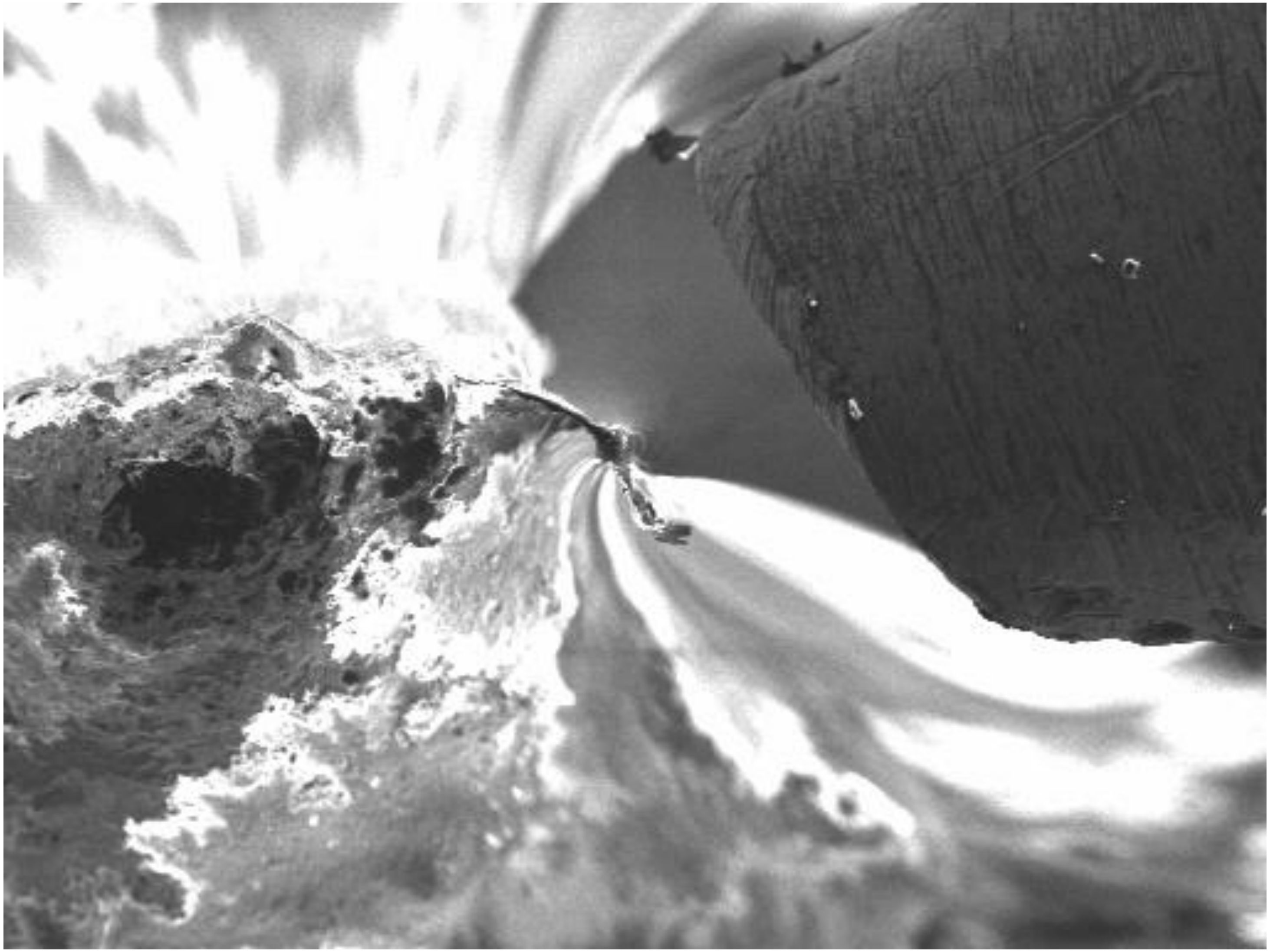
# Local Charge Compensation




- Surface discharging with nitrogen ions
- No additional high pressure detectors needed (full InLens detection)
- Fully automated, discharging within a few seconds

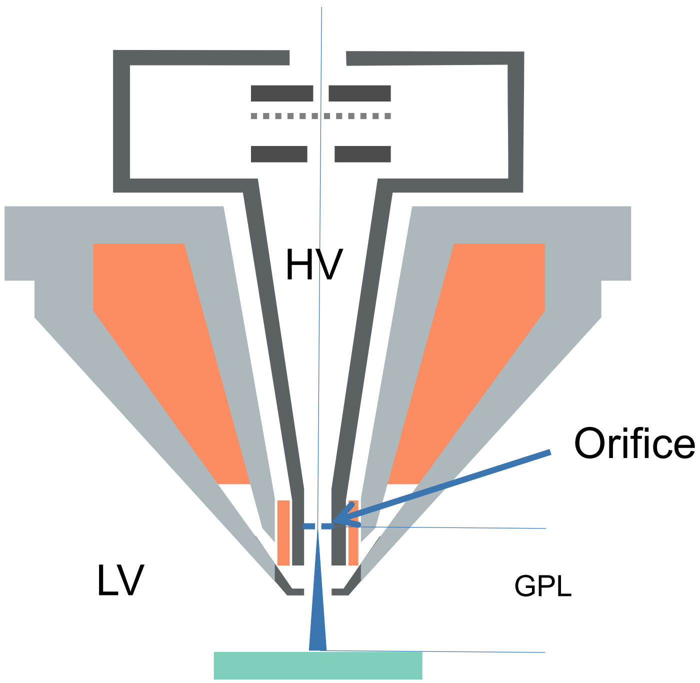


# Easily Eliminate Charging Problems
By switching on local CC



video link

# Variable Pressure (VP) Design

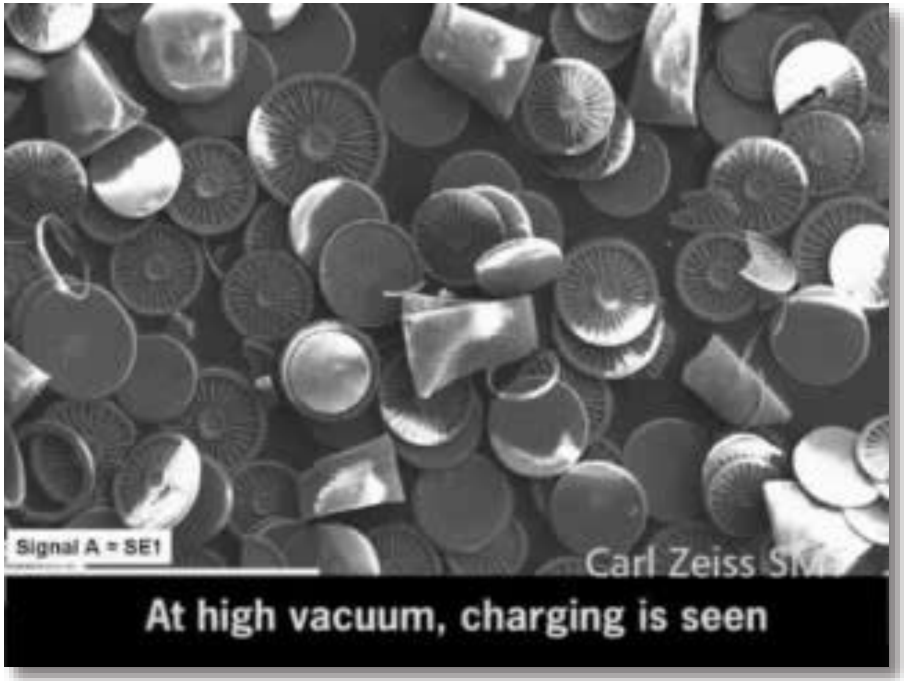


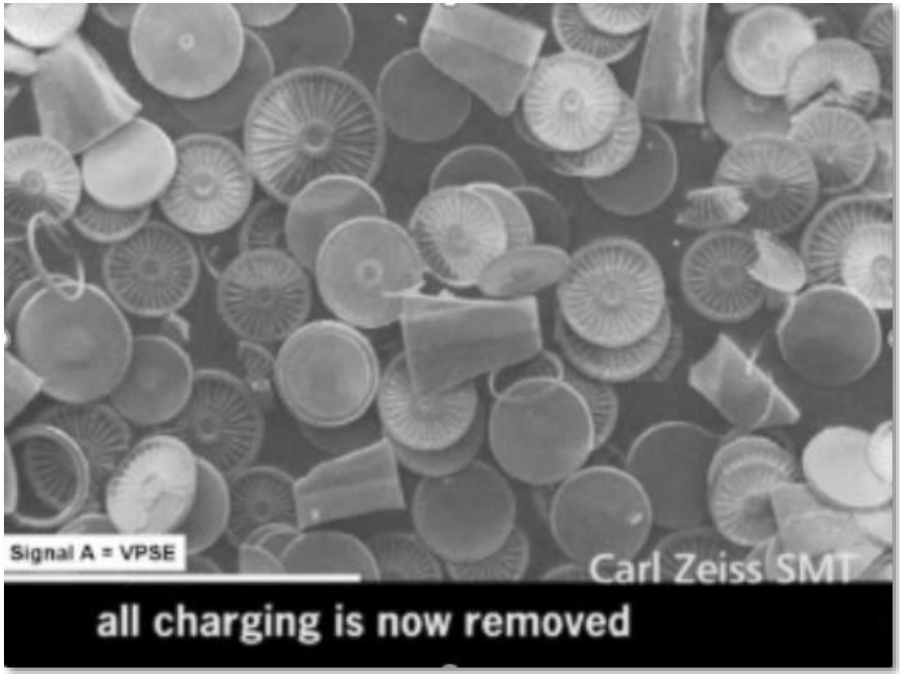

**VP design**

- Up to 133 Pa chamber pressure
- Gas molecules dissipate charge
- Loss of S/N, resolution

# Difficult Samples
## Insulating or non-conductive

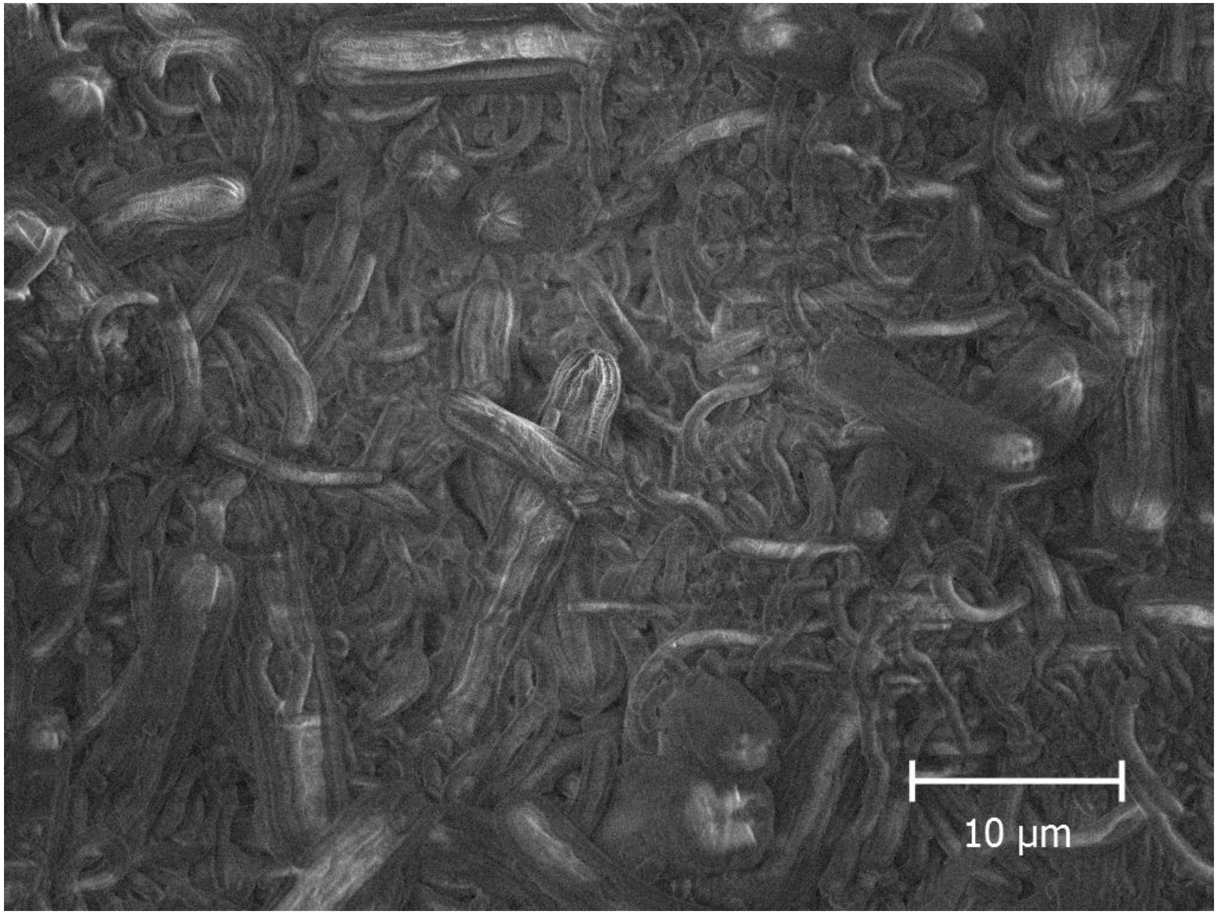
Imaging of insulating samples with Variable Pressure mode (VP)

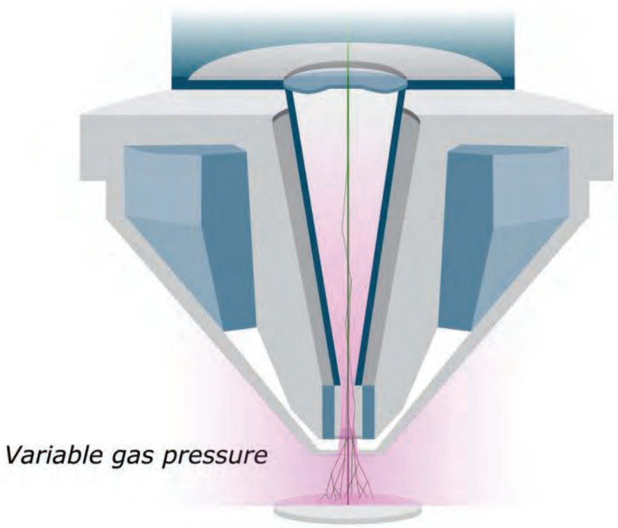


# Effective Charge Compensation in NanoVP

Fibrous polymer microstructures imaged at 3 kV in normal VP modes.



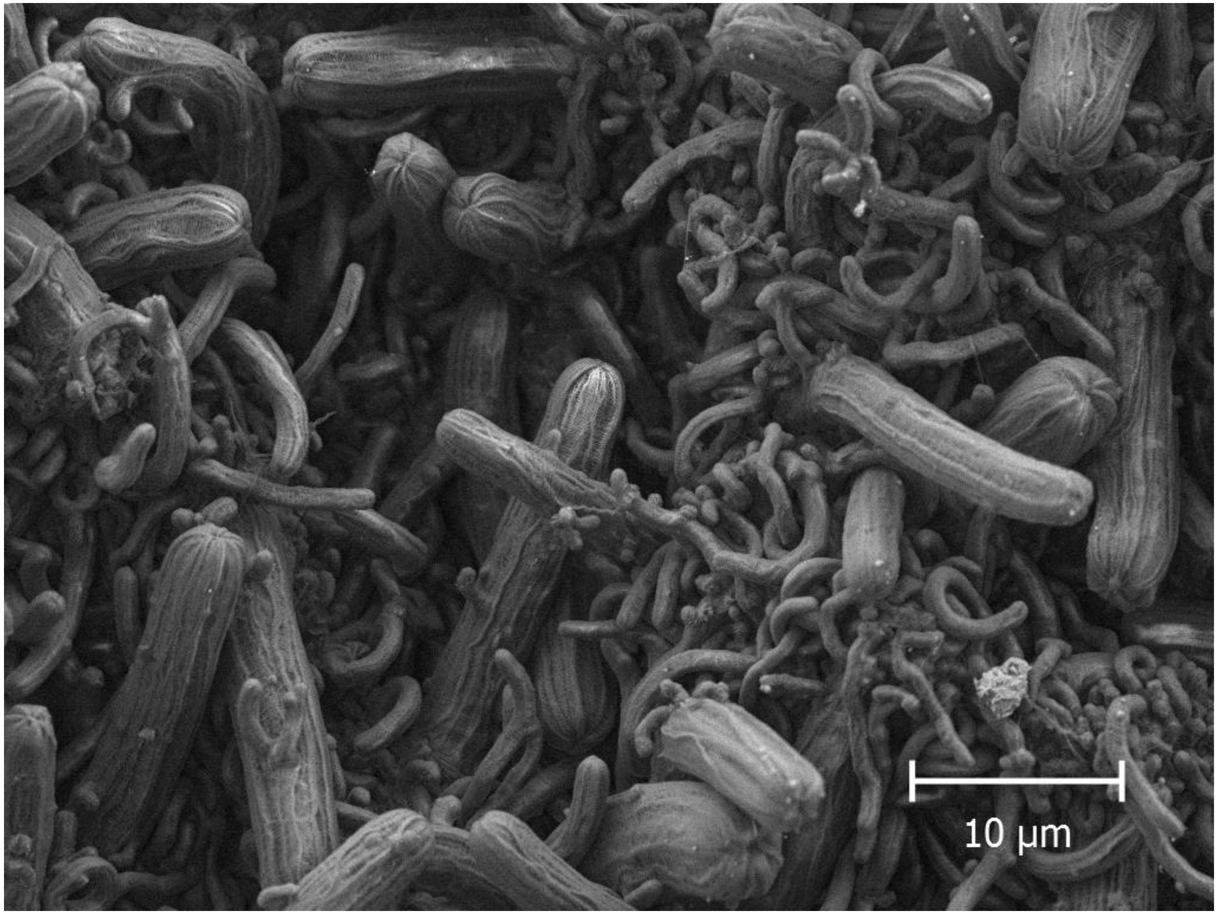



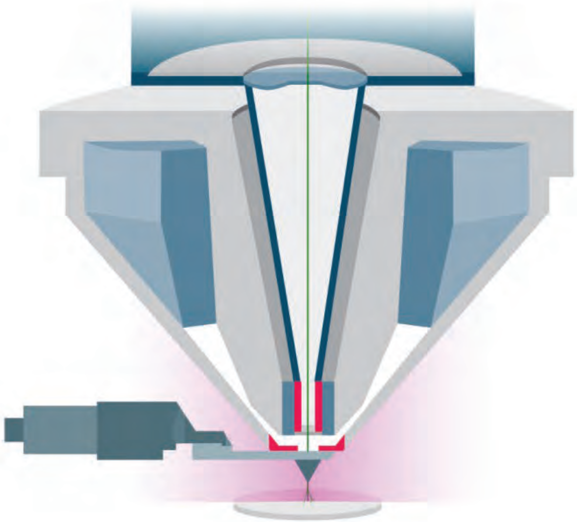

20 Pa in normal VP mode, VPSE detector

*Sample in courtesy of Dr. Hans-Georg Braun*
*Leibniz-Institute of Polymer Research Dresden*
*Max-Bergmann-Center of Biomaterials*

# Effective charge compensation in NanoVP

Fibrous polymer microstructures imaged at 3 kV in NanoVP modes.



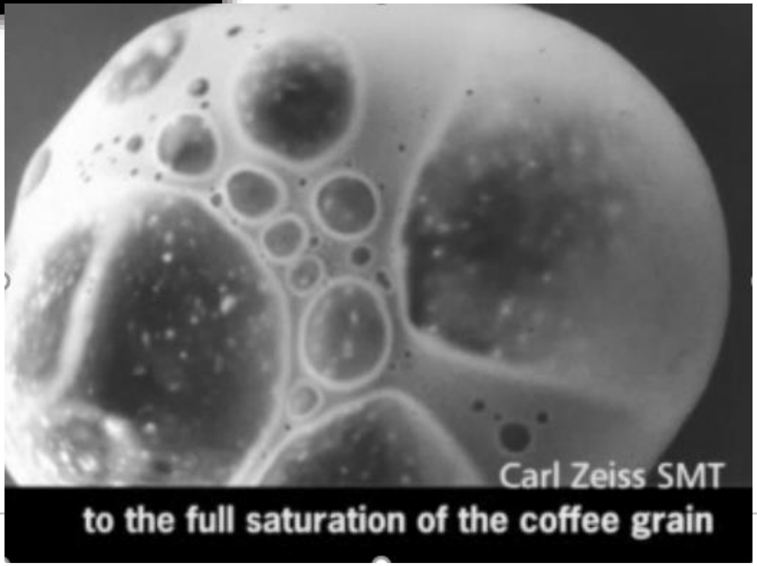
150 Pa in NanoVP mode, VPSE detector

*Sample in courtesy of Dr. Hans-Georg Braun*
*Leibniz-Institute of Polymer Research Dresden*
*Max-Bergmann-Center of Biomaterials*

# Difficult Samples
## Insulating or non-conductive



Environmental SEM – freeze dried coffee beans and water vapor



# Electron Microscopes
## In summary

**Electron Microscopes…**

… use electrons instead of photons

… can achieve much higher resolution than light microscopes. The best ones can do < 1 nm (SEM) or 0.05nm (TEM)!

… use electromagnetic lenses instead of glass lenses

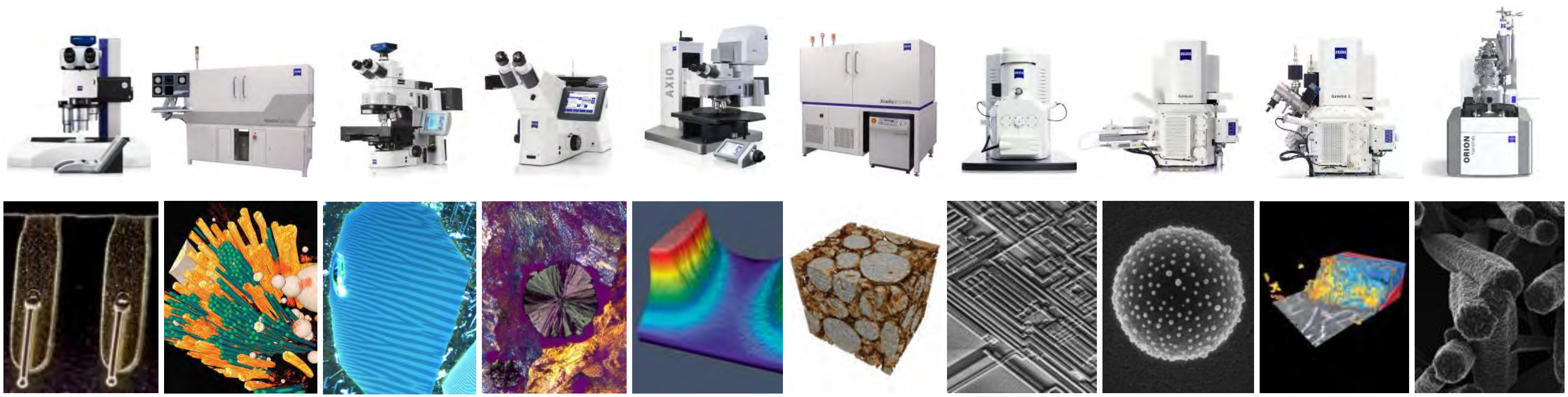
… adjust voltage, probe current, aperture size and working distance to optimize image quality and information

… have challenges imaging insulating samples, but modes to address available

… but can do more than “just” imaging

# ZEISS Microscopy Portfolio
## Multi-Scale Characterization for Multi-Scale Research

***A complete microscopy portfolio…***



| Stereo LM | Sub-micron XRM | Widefield LM | Polarized LM | Confocal LM | Nanoscale XRM | C-SEM | FE-SEM | FIB-SEM | Helium Ion Microscope |
|---|---|---|---|---|---|---|---|---|---|
| 1 µm | 700 nm | 250 nm | 200 nm | 200 nm | < 50 nm | < 2 nm | < 1 nm | < 1 nm | < 0.5 nm |

***…to address multi-scale research challenges.***

ZEISS

We make it visible.

# Backup Slides

Resources:

ZEISS – Electron / Ion Microscopy
ZEISS – EM for Life Sciences
ZEISS – EM for Materials Science
ZEISS - Correlative Microscopy
ZEISS – X-ray microscopy

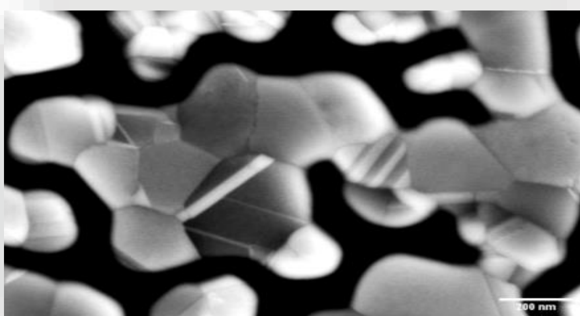
Bob Hafner; Scanning Electron Microscopy Primer; Univ of Minnesota; 2007; link

# Electron Microscopy in Various Sectors
## Serving Diverse Applications

### Materials Science

**Basic Materials,
Functional Materials,
Nanomaterials,
2D Materials**

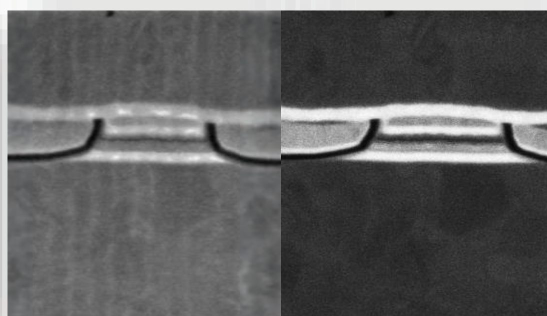
**Metals, Alloys
Ceramics, Minerals,
Polymers, Composites**



### Industry

**Semiconductor
Data Storage,
Telecom, Flat Panel
Electronics
Battery, Solar**

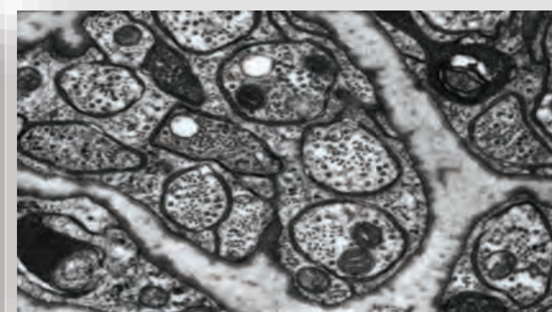
**Silicon, Resist, Metals,
Particles, Catalyst**



### Life Science

**Bio, Pharma,
Cosmetics,
Medical Diagnostics,
Brain Research**

**Nano Bio Tech
Drugs, Cells, Tissues**



# Carl Zeiss Microscopy

## Why electrons?

- similar **optical properties**:
  - diffraction, abberation, astigmatism etc.

- **spatial resolution** depends on wavelength:
  - the higher the energy (of the electrons)
    - the lower the wavelength,
      - the higher the resolution

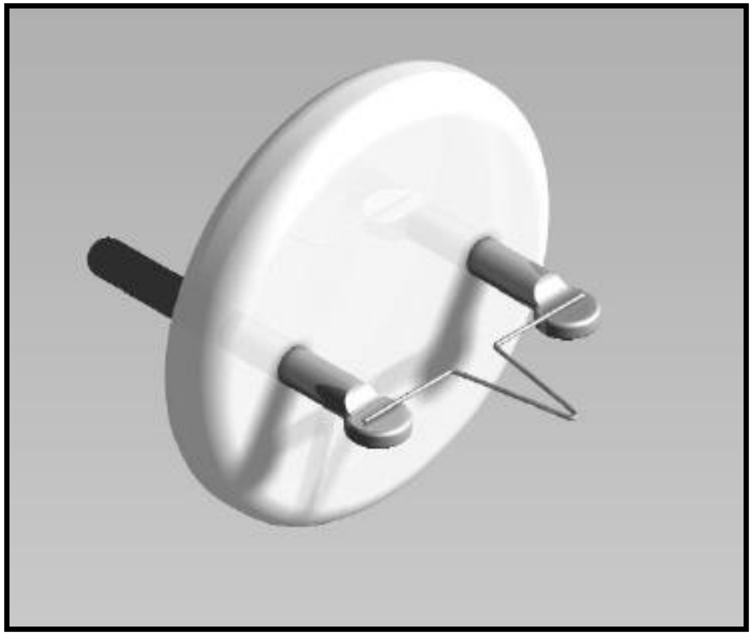
- typical **acceleration voltages** of electrons:
  - Scanning electron microscopes (SEM): 1 – 30 kV
  - Transmission electron microscopes (TEM): 40 – 1200 kV

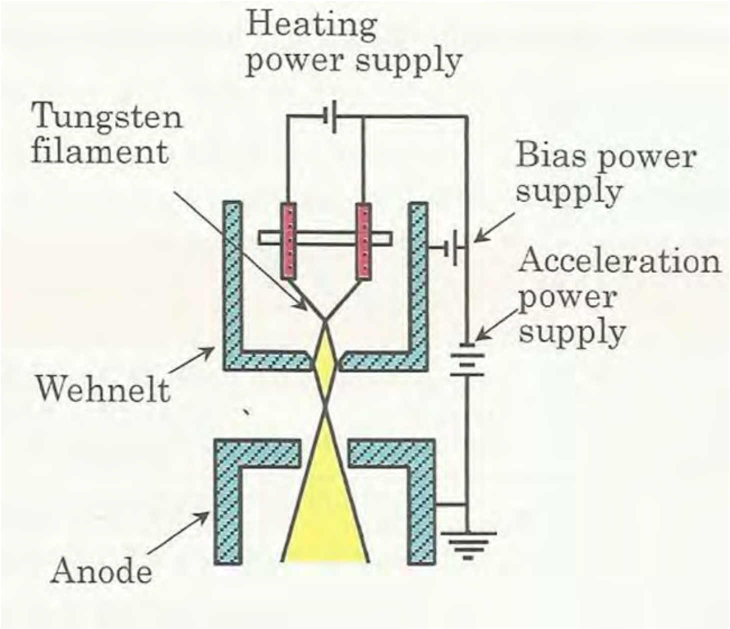
De Broglie wavelength

$$\lambda = \frac{h}{mv}$$

| | Light Microscopy | Electron Microscopy |
|---|---|---|
| Wavelength | 400 – 700 nm | λ = 0.1 – 0.002 nm<br>(1 – 100 kV) |
| Spatial Resolution | ~ 1 µm | ~ 1 nm |
| Max. Magnification | 1,000 x | 1,000,000 x |
| Modes of Operation | reflected light, transmitted-light | SEM,<br>TEM |
| Samples | Unmodified, hydrated | vacuum-compatible |

# Electron Emitters
## Tungsten

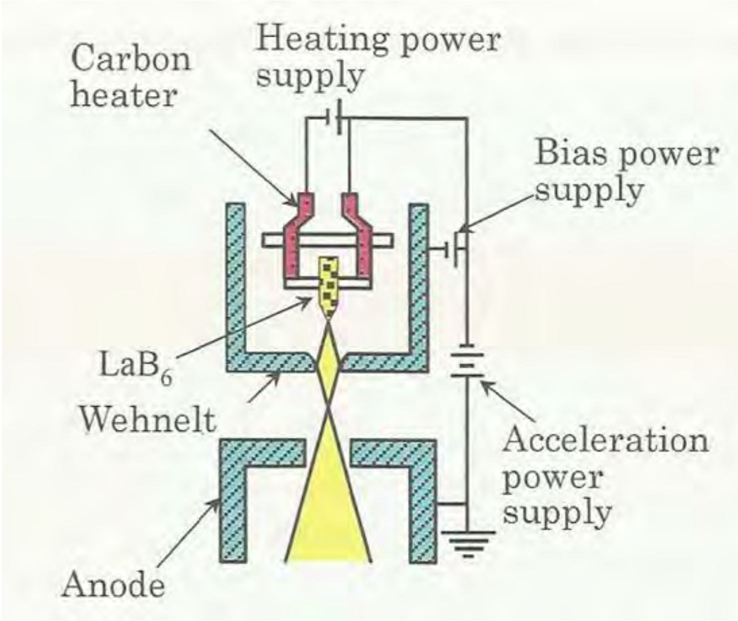





- Tungsten has the highest melting point and lowest vapor pressure of all metals, thereby allowing it to be heated for electron emission.
- V-shaped hairpin type
- Source size about 50µm
- Energy spread about 3eV
- Service life 100-200 hours
- Very cheap

Brightness $\beta = 10^6$ A/cm$^2$/sr

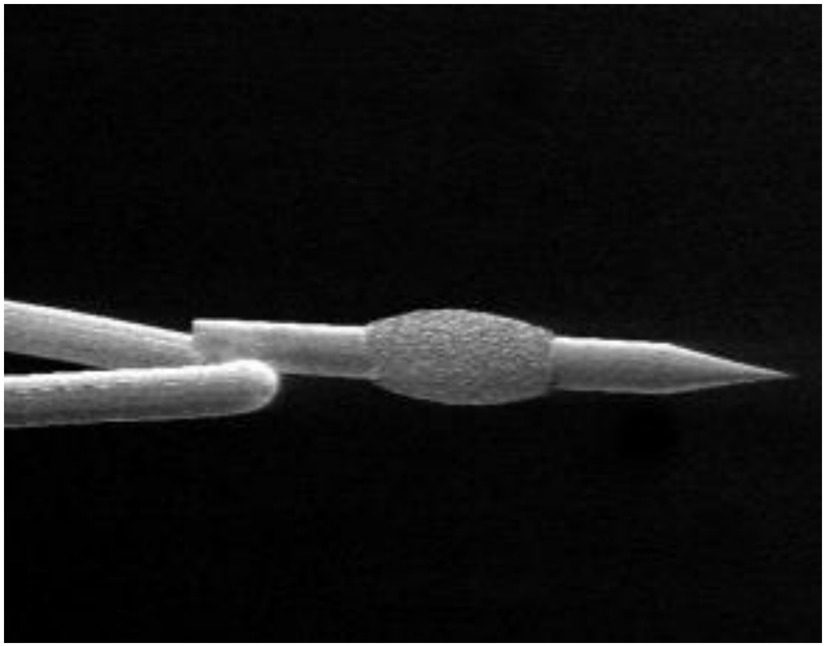
# Electron Emitters
## Lanthanum Hexaboride $LaB_6$

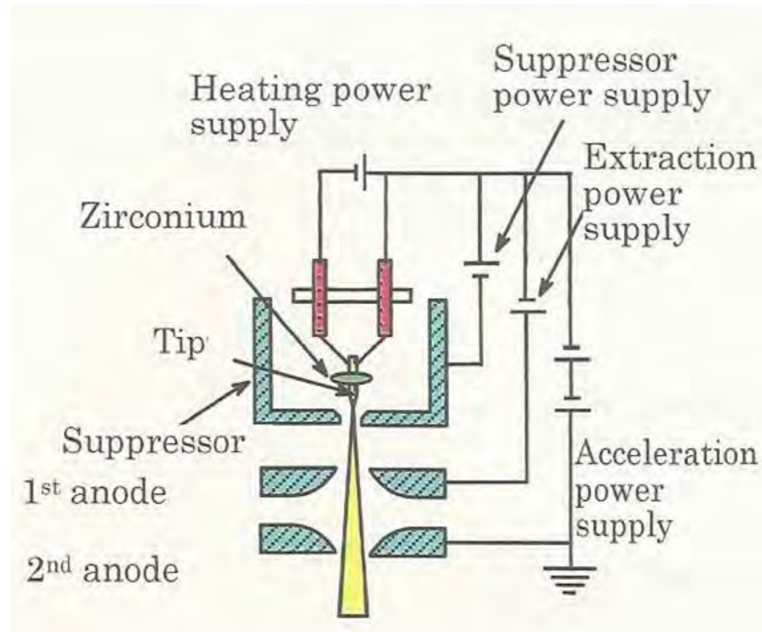



- LaB6 filaments are single Lanthanum Hexaboride crystals ground to a fine point
- Source size about 5µm
- Energy spread about 1eV
- Service life up to 2000 hours
- More expensive than tungsten (10-20x)

Brightness $\beta = 10^7$ A/cm²/sr

# Electron Emitters
## Schottky Field Emitters (FEG)






- Tungsten rod with a very sharp tip
- Tip is heated to about 1750K. Electrons are pulled out of the tip by applying an extraction voltage (tunnel effect)
- Source size about 0.05µm
- Energy spread about 0.7eV
- Service life > 2000 hours

Brightness $\beta > 10^8$ A/cm$^2$/sr

# LaB6 versus Tungsten Comparison

A comparison of the main characteristics of LaB6 and tungsten electron sources:

| Characteristic | LaB6 | Tungsten |
|---|---|---|
| Work function /eV | 2.4 | 4.5 |
| Operating temperature /K | 1700 | 2700 |
| Brightness /relative to tungsten | >50 | 1 |
| Spot diameter improvement /relative to tungsten | 1.5 | 1 |
| Gun vacuum /Pa | $10^{-4}$ | $10^{-2}$ |
| Typical lifetime in normal mode /hrs | 1000 | 50 - 100 |
| Typical lifetime in long filament life mode /hrs | 2000 | >100 |
| Resolution at 30 kV, 1pA /nm | 2 | 3 |
| Drift /% per hour | 0.5 | 1 |
| Approximate cathode cost /€ | 900 | 9 |

*Lower work function allows electrons to be more easily emitted from LaB6 source (e.g. it is more efficient)*

*Lower work function allows a lower operating temperature → longerLaB6 lifetime*

*LaB6 can be more than 50x as bright as a tungsten*

*LaB6 can produce a spot 1.5x tighter than tungsten*

*The above parameters ensure LaB6 has a lifetime of ~ 20 times that of tungsten*

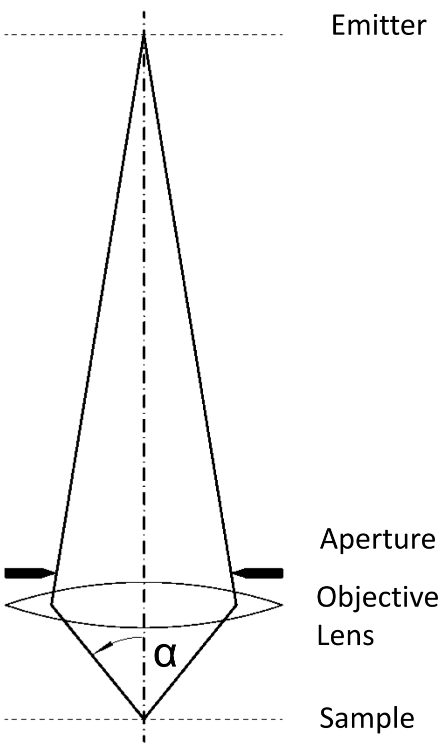
*The brightness and spot size contribute to a higher res.*

*Less drift for LaB6*

*Although the cost of the cathode is higher, downtime costs need to considered*

# Limits to Resolution
## Optical Aberrations

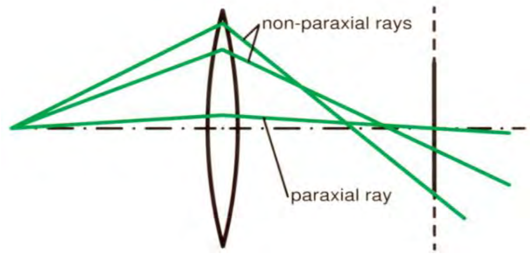
What limits the resolution in a SEM?




α: Aperture angle

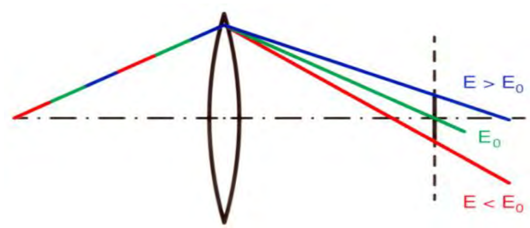
Probe size: $d_P = \sqrt{d_S^2 + d_C^2 + d_d^2 + (M \cdot d_g)^2}$

Spherical aberration:



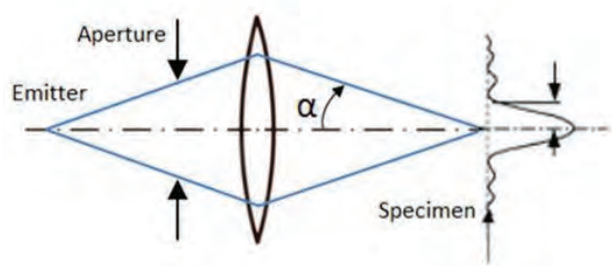

$$d_S = 0.5 C_S \alpha^3$$

Chromatic aberration:




$$d_C = C_C \frac{\Delta U}{U} \alpha$$

Diffraction:

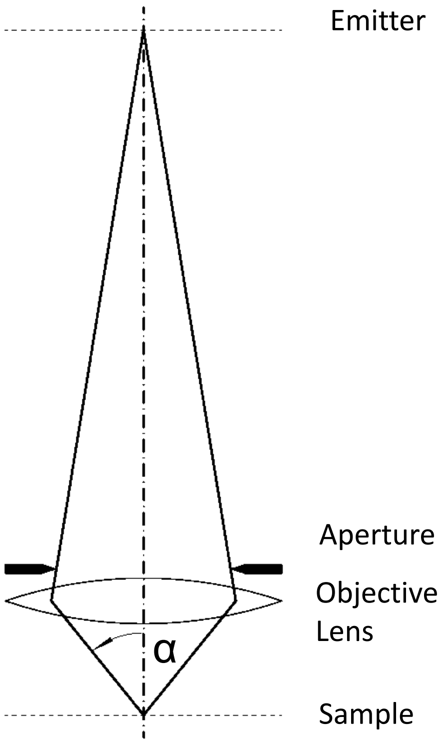



$$d_d \propto \frac{\lambda}{\alpha}$$

# Limits to Resolution

## Optical Aberrations

What limits the resolution in a SEM?



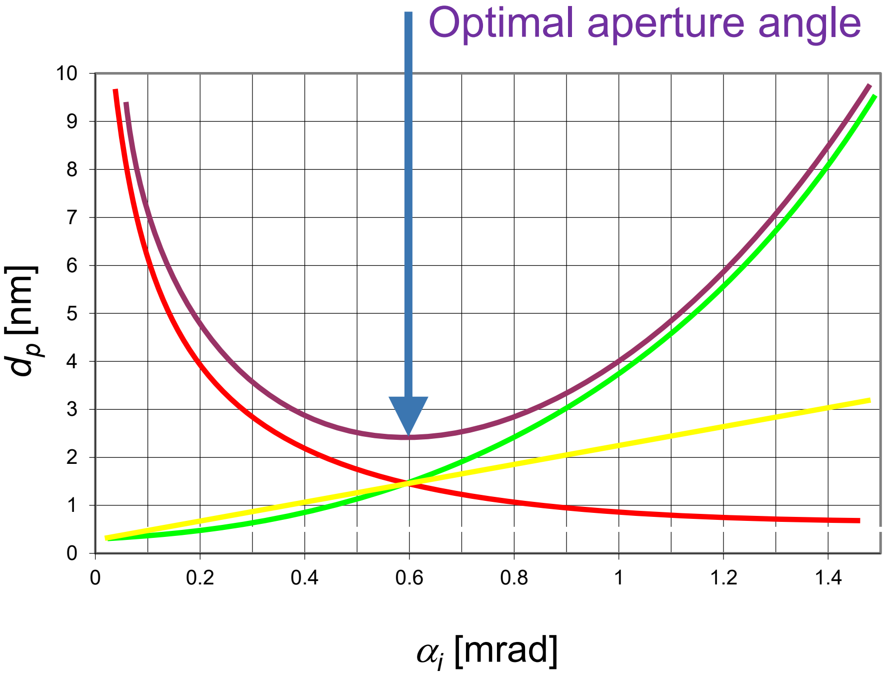

α: Aperture angle

Probe size: $d_P = \sqrt{d_S^2 + d_C^2 + d_d^2 + (M \cdot d_g)^2}$

Spherical aberration: $d_S = 0.5 C_S \alpha^3$

Chromatic aberration: $d_C = C_C \frac{\Delta U}{U} \alpha$

Diffraction: $d_d \propto \frac{\lambda}{\alpha}$

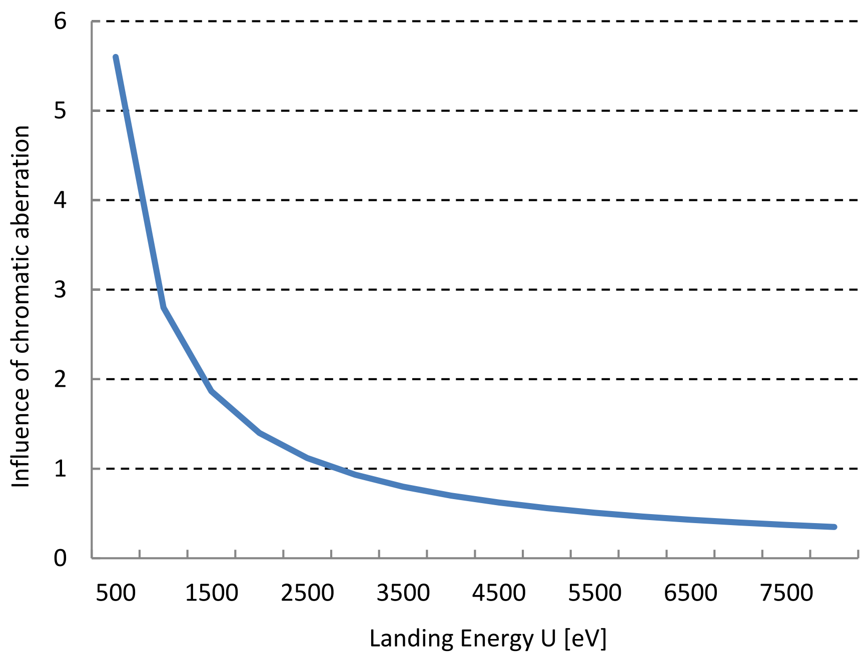


# Chromatic Aberrations

## Effects on Probe Size

*Probe Size:* $$d_P = \sqrt{d_S^2 + d_C^2 + d_d^2 + (M \cdot d_g)^2}$$

*Chromatic aberration:* $$d_C = C_C \frac{\Delta U}{U} \alpha$$




At low voltages the dominating effect that increases probe size is **chromatic aberration.**

There are 2 strategies to reduce the effect of chromatic aberration:

# Chromatic Aberrations

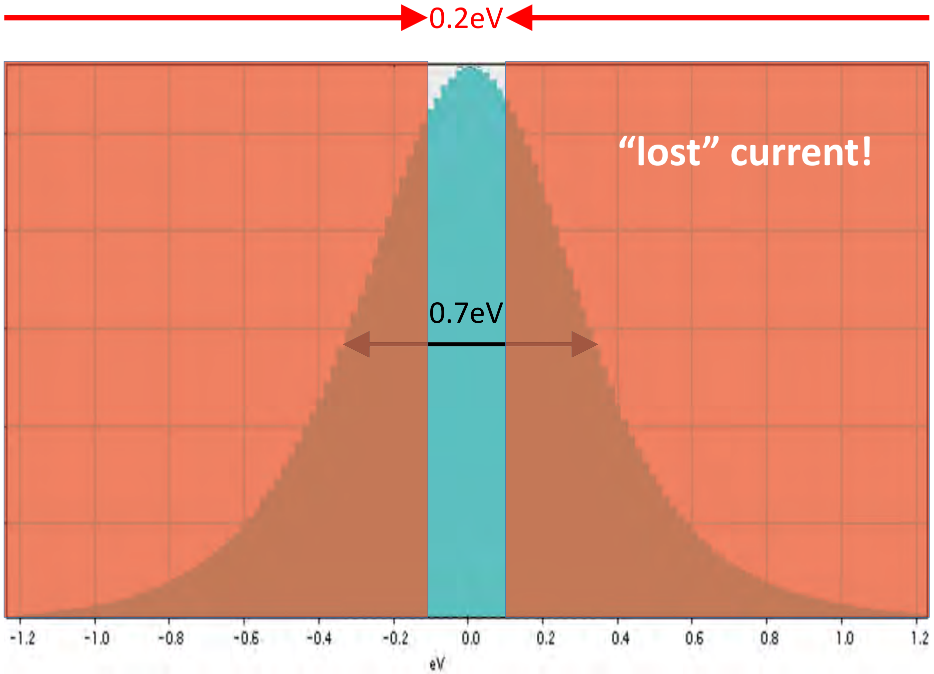
## Effects on Probe Size

*Probe Size:* $d_P = \sqrt{d_S^2 + d_C^2 + d_d^2 + (M \cdot d_g)^2}$

*Chromatic aberration:* $d_C = C_C \frac{\Delta U}{U} \alpha$

At low voltages the dominating effect that increases probe size is **chromatic aberration.**

There are 2 strategies to reduce the effect of chromatic aberration:



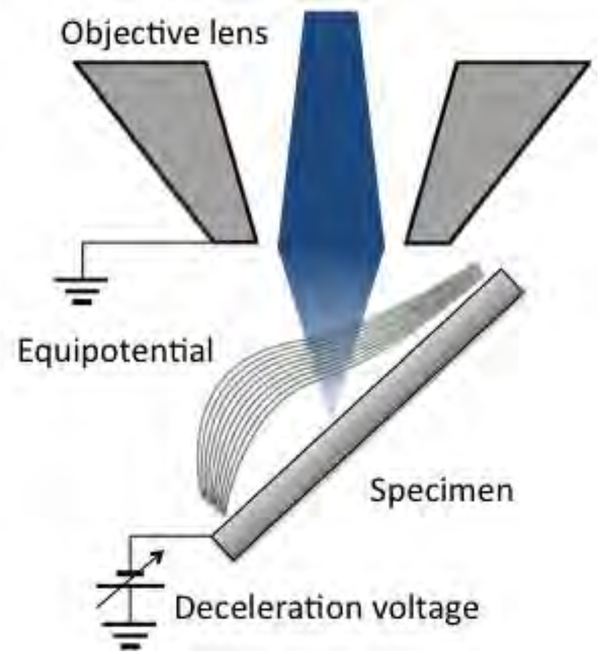

Energy width of a Schottky field emitter.

1. Reduce the energy spread *dU* (monochromator, filter)
   → usually accompanied by a huge loss of beam current!

# Chromatic Aberrations
## Effects on Probe Size

*Probe Size:* $d_P = \sqrt{d_S^2 + d_C^2 + d_d^2 + (M \cdot d_g)^2}$

*Chromatic aberration:* $d_C = C_C \frac{\Delta U}{U} \alpha$




At low voltages the dominating effect that increases probe size is **chromatic aberration.**

There are 2 strategies to reduce the effect of chromatic aberration:

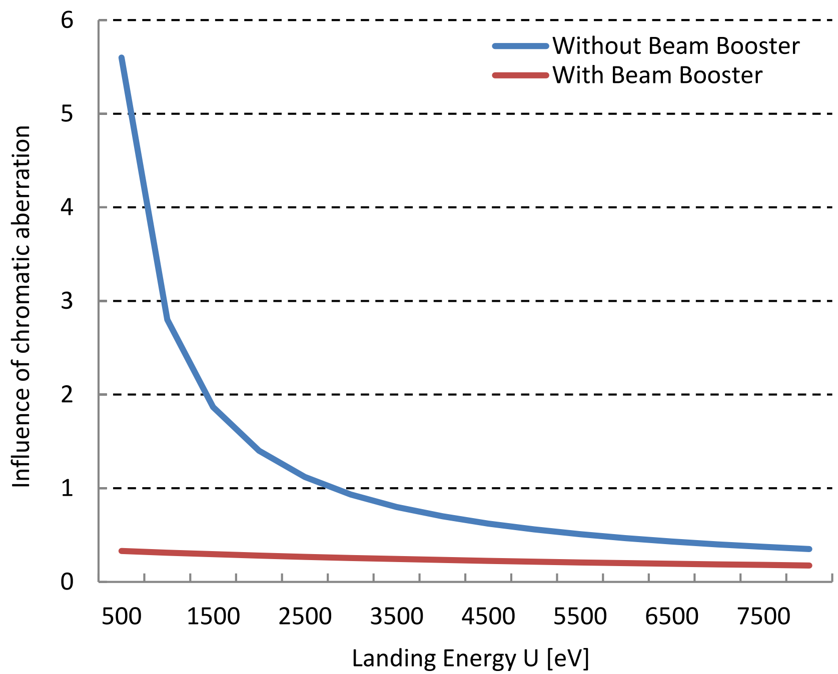
2. Keep the electron energy *U* has high as possible and then decelerate the beam to the desired landing energy. One technique is stage biasing ("Beam Deceleration"), **but**
   - Sample must be flat
   - Sample cannot be tilted
   - Sample must not be rough
   - Conductivity must be homogenous
   - Discharging can happen

# Chromatic Aberrations

## Benefit of Beam Booster

*Probe Size:* $d_P = \sqrt{d_S^2 + d_C^2 + d_d^2 + (M \cdot d_g)^2}$

*Chromatic aberration:* $d_C = C_C \frac{\Delta U}{U} \alpha$

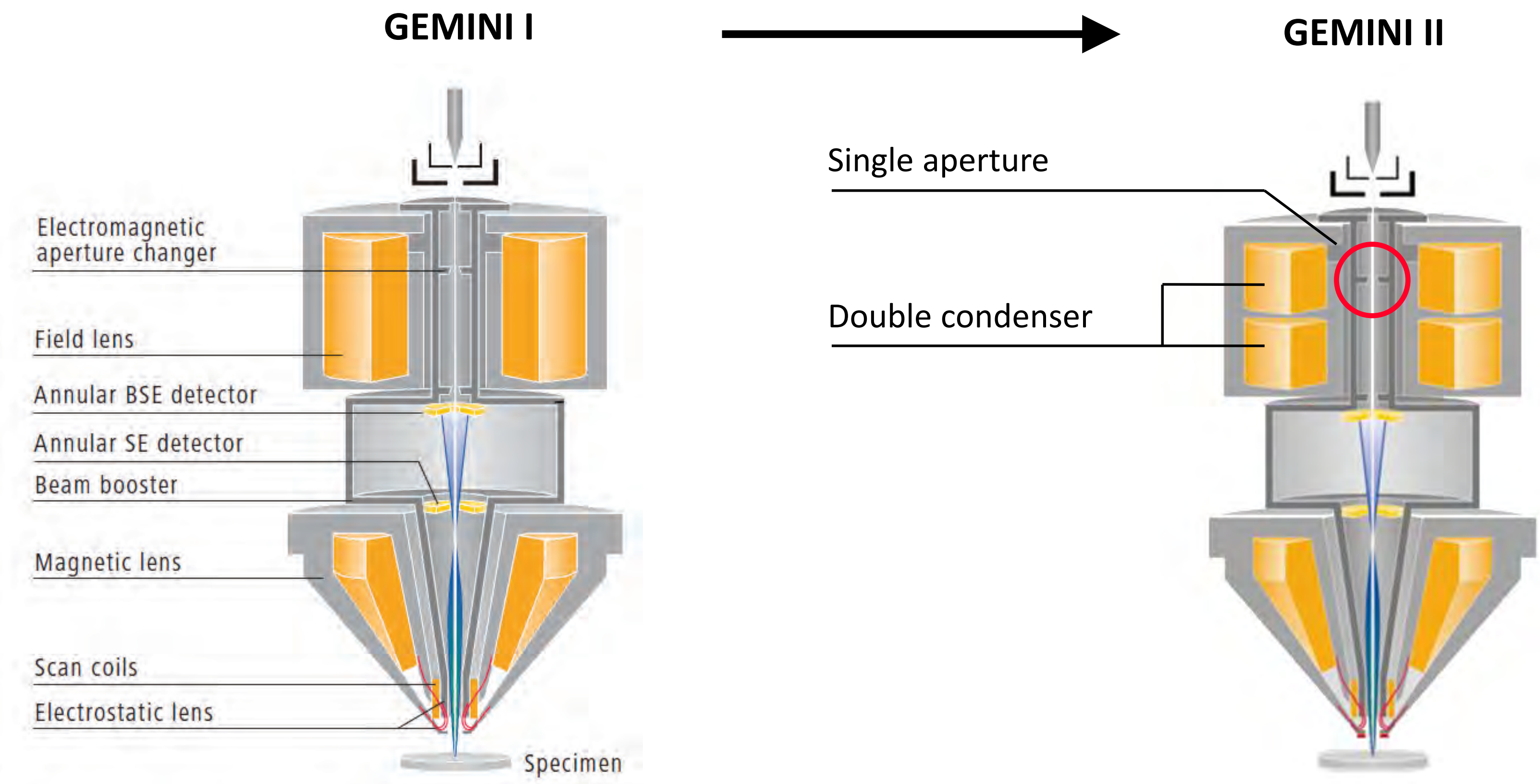



The GEMINI Beam booster advantage:

- The electron energy *U* is kept at above 8keV followed by *deceleration in the column*.
- No stage biasing is required
- No energy filtering needed
- Very high resolution even at (ultra) low voltages
- No loss of brightness and probe current at low voltages
- No alignment needed when switching from high to low voltages
- Does not influence the focused ion beam

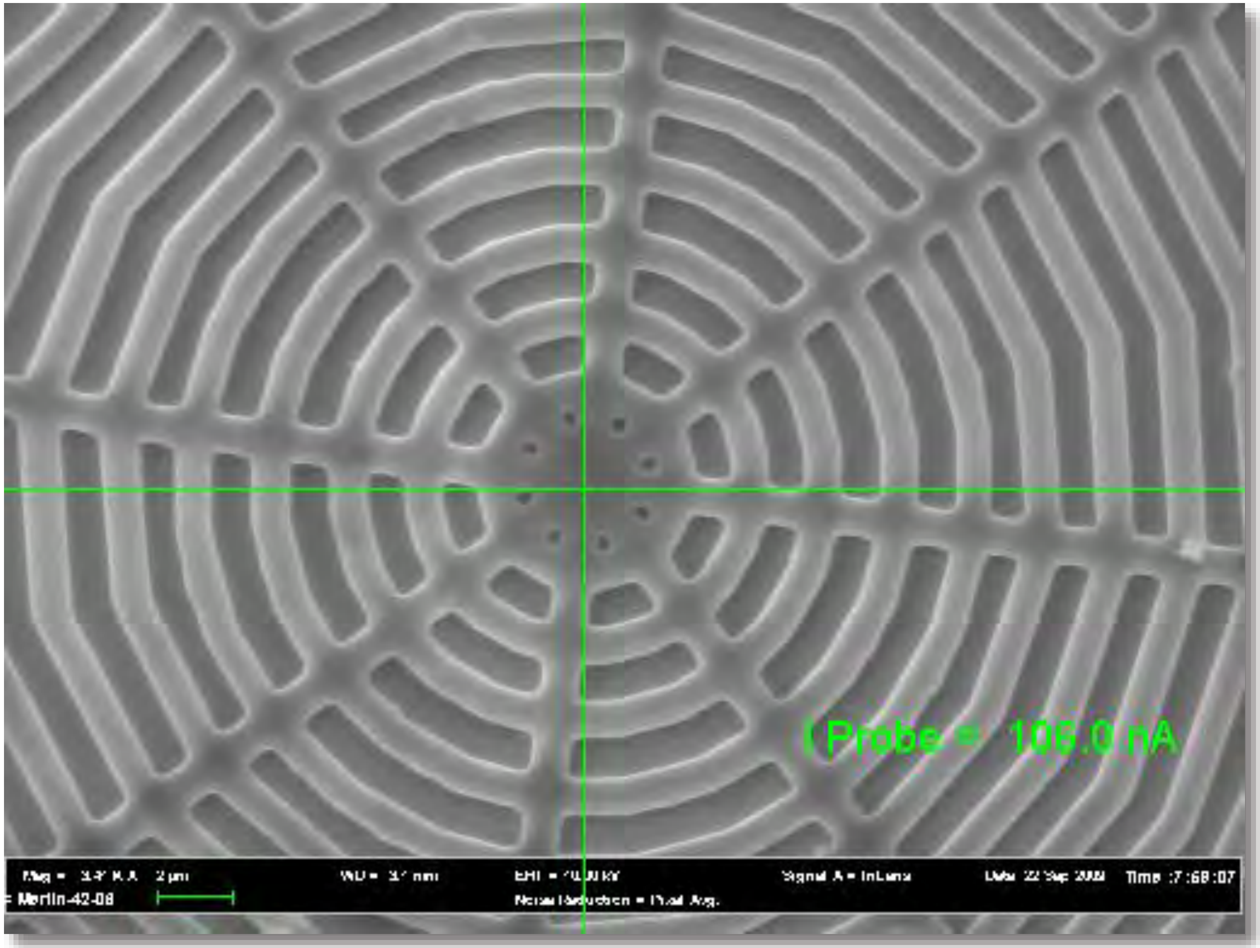
# GEMINI Column

## Improvements in GEMINI Technology - GEMINI II column



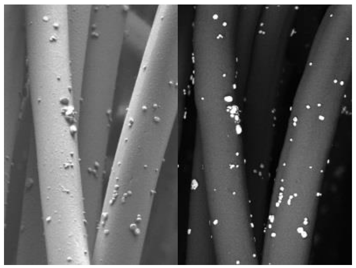
# GEMINI Column

## Improvements in GEMINI Technology - GEMINI II column

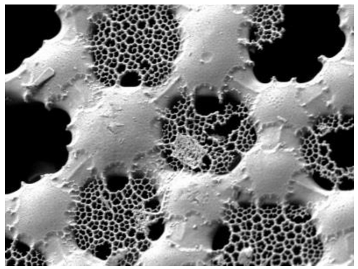



Continuous variation of beam current and acceleration voltage. No realignment needed.

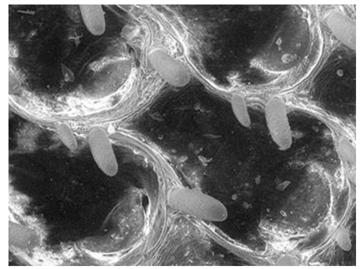
# Comprehensive Signal Detection



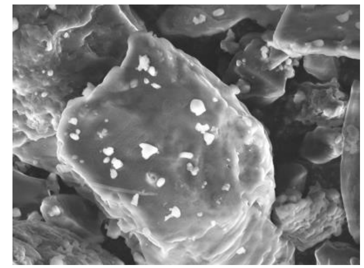
**Inlens Duo**: Inlens SE and BSE detector for high resolution topographical and compositional imaging of surfaces, thin films and nano particles.



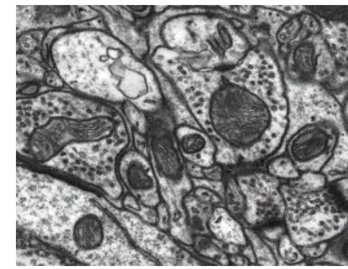
**ETSE Detector:** High resolution topographic imaging with 50% more signal to noise and reduced charging at low kV in high vacuum mode



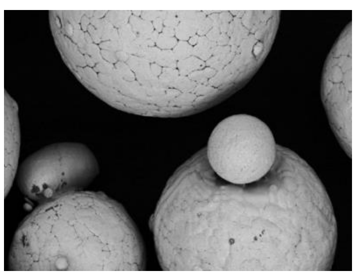
**VPSE-G4:** Fourth generation Variable Pressure SE detector provides 85% more contrast



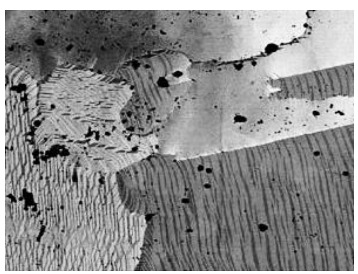
**C2D**: Cascade Detector for the ultimate performance in VP mode even at higher pressures.



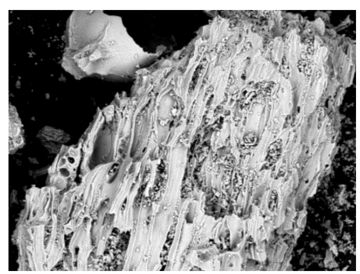
**aSTEM:** Annular STEM detector provides HAADF modes for “TEM-like” imaging of thin films or biological sections



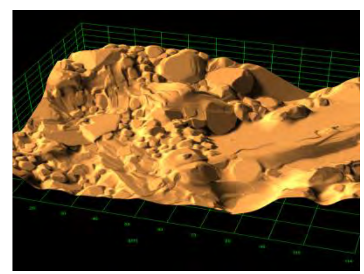
**HDBSD:** High definition BSE-detector for excellent low kV compositional imaging of all samples in all vacuum modes



**AsB Detector:** Angular selective BSE-detector enables crystallographic & channelling contrast imaging of metals and minerals mounted in the final lens.



**YAG-BSD**: YAG crystal based scintillator BSE-detector provides fast, easy compositional imaging

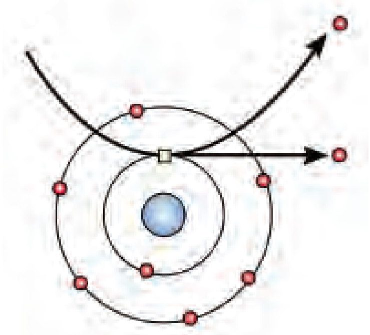


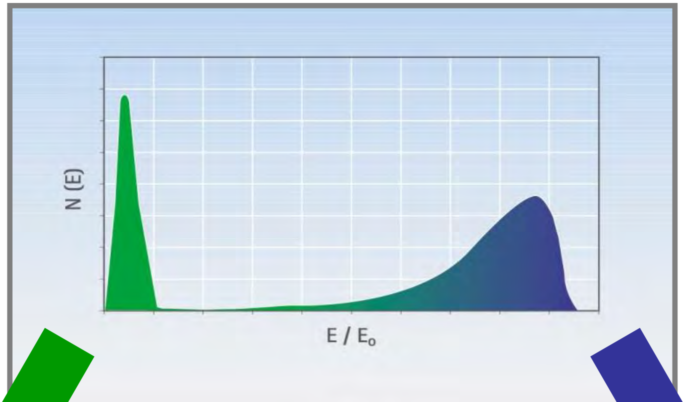
**BSD4**: 4 parallel output BSE-detector provides “real-time” 3D imaging and surface metrology.

**Dual EDS**: Diametrically opposed EDS detectors at 8.5 mm working distance & 35 degree take-off angle delivers highest analytical productivity with results delivered twice as fast.

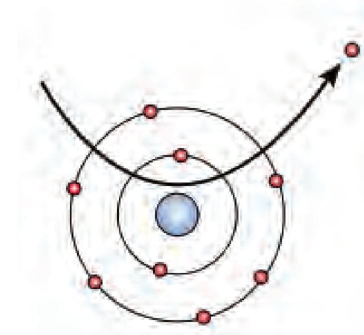
# On-Axis In Column Detection System
## Different electrons carry different information

Secondary electrons

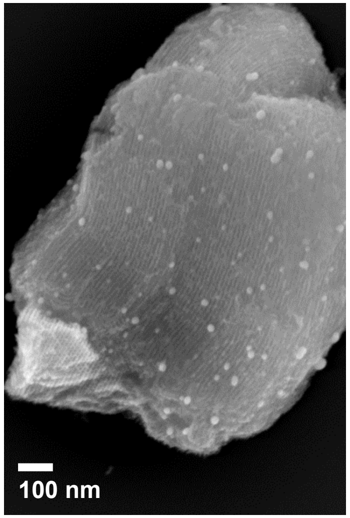


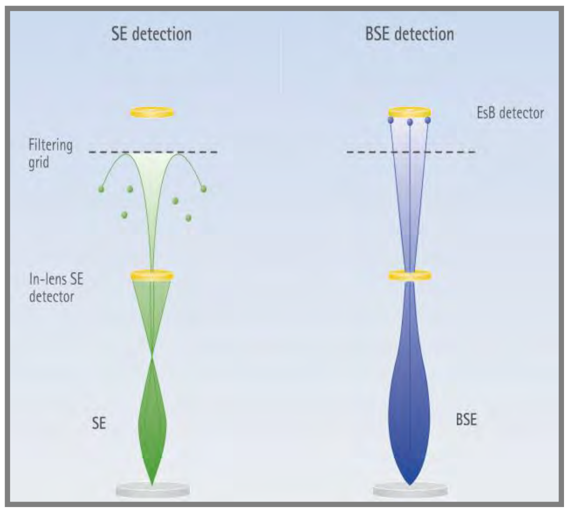



Backscattered electrons



**Topographical information**




Combined detection for maximum information!

**Compositional contrast**

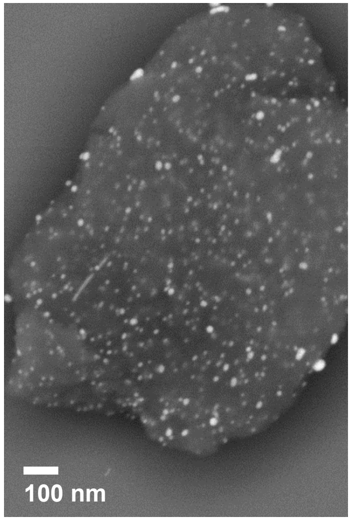
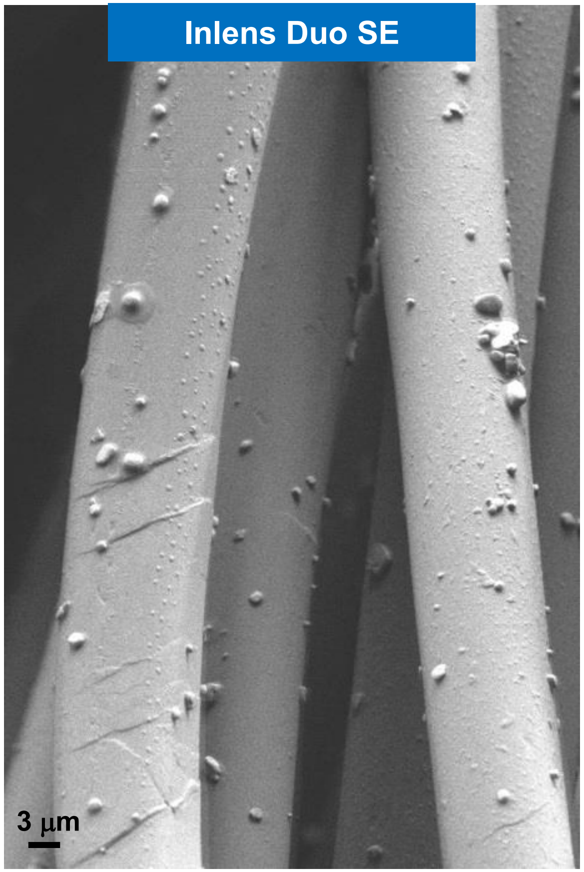



*Image: Zeolite with Ag nanoparticles, 5kV. Sample curtesy of Fritz-Haber-Institute Berlin*

# Comprehensive Signal Detection
## Inlens Duo

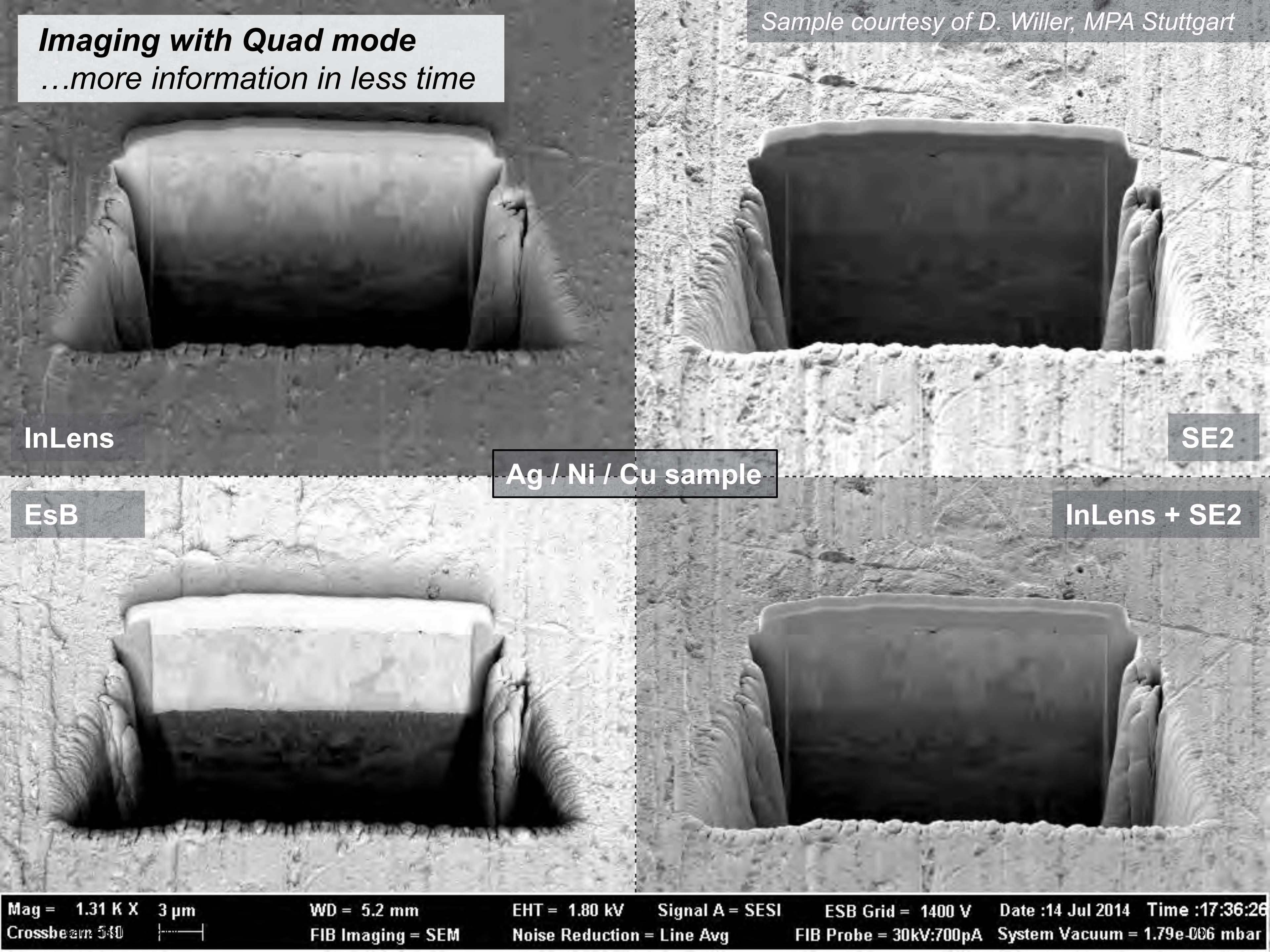
## Inlens Duo:

- Affordable in-column SE & BSE detection - **two detectors in one**
- Sequential compositional and topographic imaging of layers, coatings, thin films and nano-particles




**Topographic imaging**
with on-axis in-lens SE detection

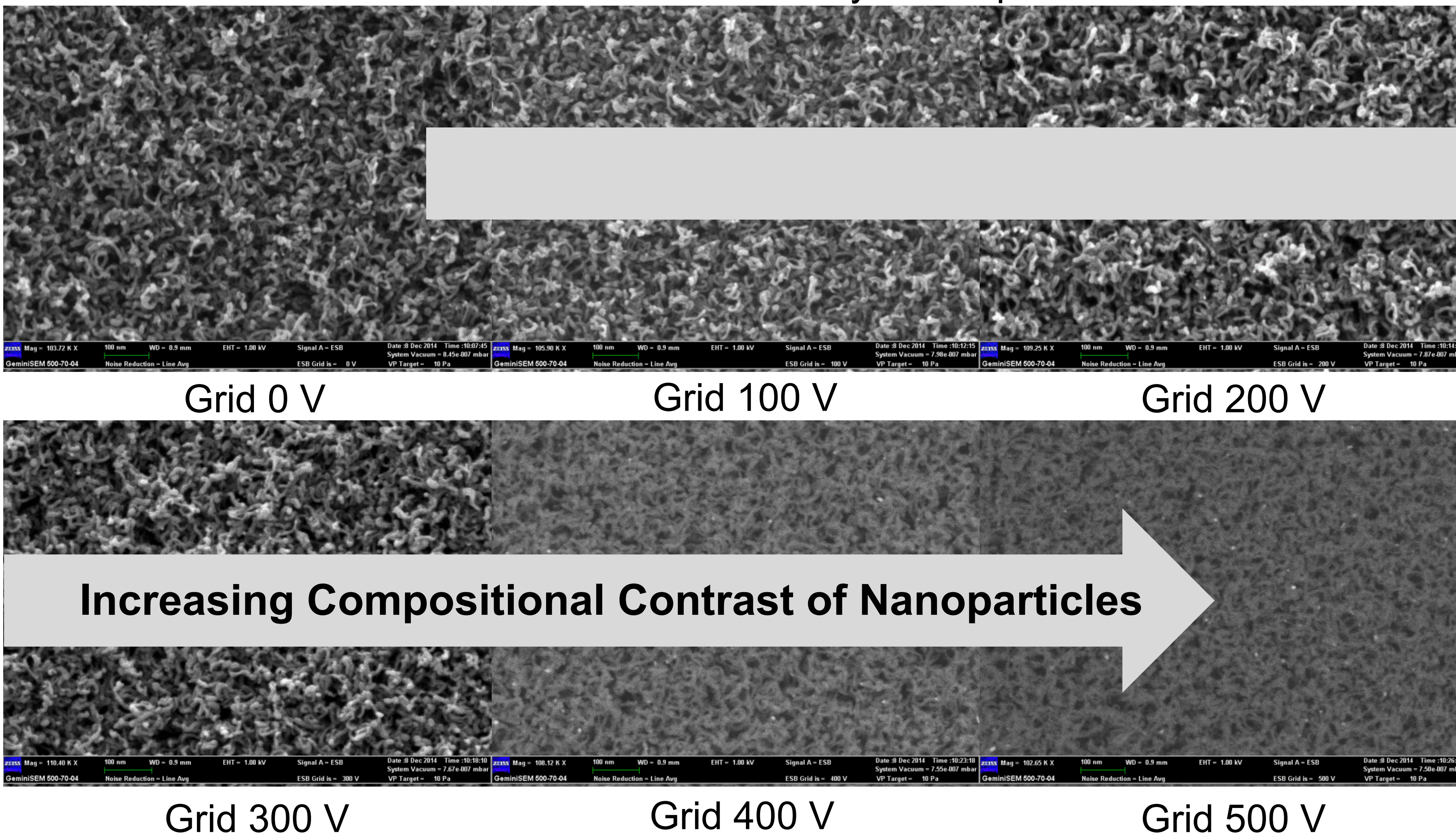

**Compositional imaging**
with on-axis in-lens BSE detection



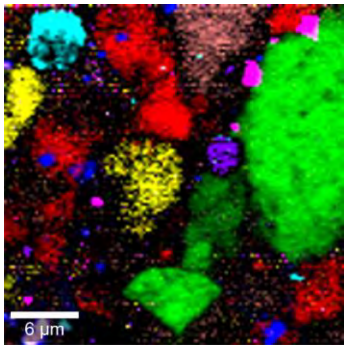
Imaging with Quad mode
…more information in less time
Sample courtesy of D. Willer, MPA Stuttgart
InLens
SE2
Ag / Ni / Cu sample
EsB
InLens + SE2
Mag = 1.31 K X
3 µm
Crossbeam 540
WD = 5.2 mm
FIB Imaging = SEM
EHT = 1.80 kV
Noise Reduction = Line Avg
Signal A = SESI
ESB Grid = 1400 V
FIB Probe = 30kV:700pA
Date :14 Jul 2014
Time :17:36:26
System Vacuum = 1.79e-006 mbar

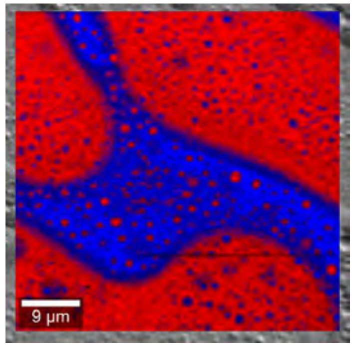
# In-lens EsB Detection
## Tunable energy selective backscatter

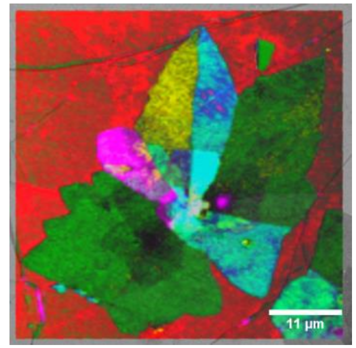
EsB detector on CNT with catalyst nanoparticles



# Analysis Beyond EDS
ZEISS FESEM + Raman spectroscopic imaging



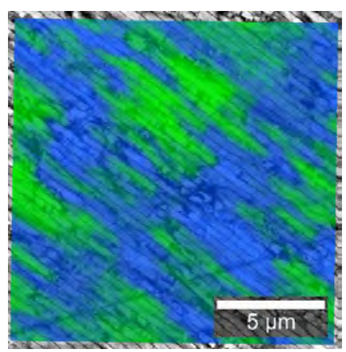



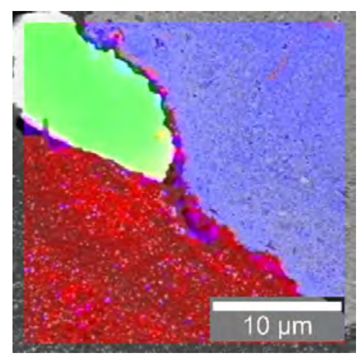

## Nonmetallic compositions and phases:

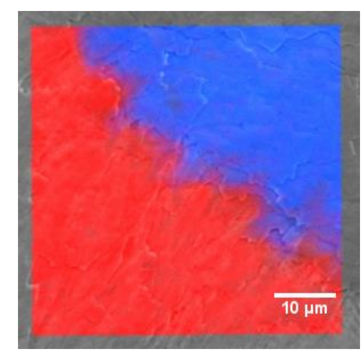
- Polymorphs
- Molecule phases
- Polymer blends
- Crystal orientations
- Fibrillary polymer
- Degree of Crystallinity
- Kinds of Defect
- Stress and Strain
- Surface coating
- Contamination

## Application fields:

- Nanoparticles & 2D Mat.
- Polymer
- Carbon materials
- Semiconductor
- Geology/ Mineralogy
- Forensic
- Pharma
- Biomaterials
- Coatings
- Corrosion



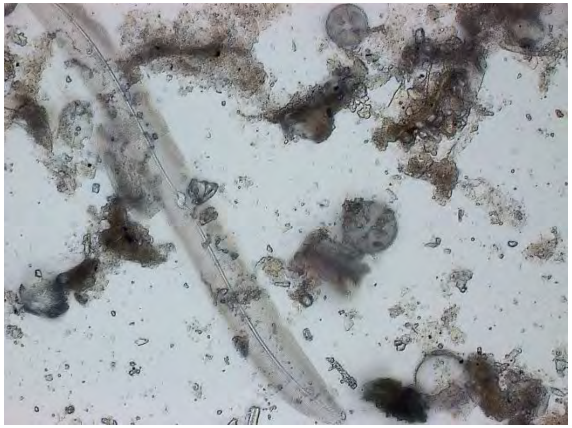



# Why Correlative Microscopy?
Zoom in from micro to nano

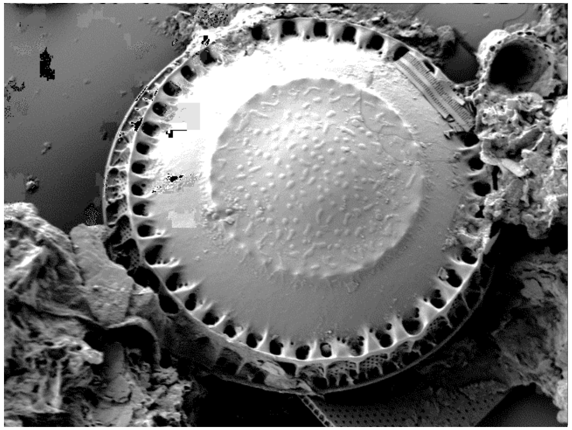
ZEISS Correlative Microscopy

Light microscope (LM)

Electron microscope (EM)



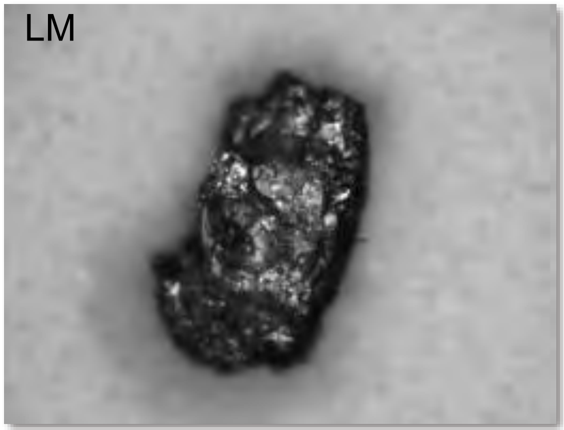
Rapid light microscopy overview – low resolution

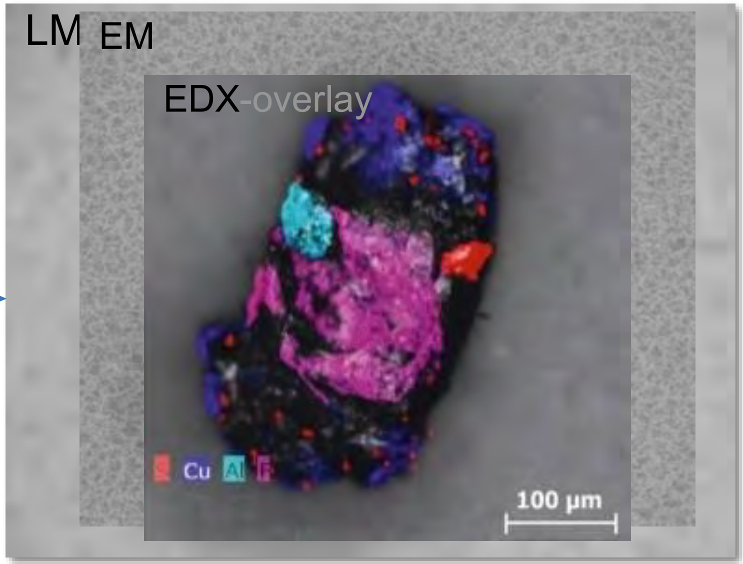


Targeted SEM imaging– high resolution

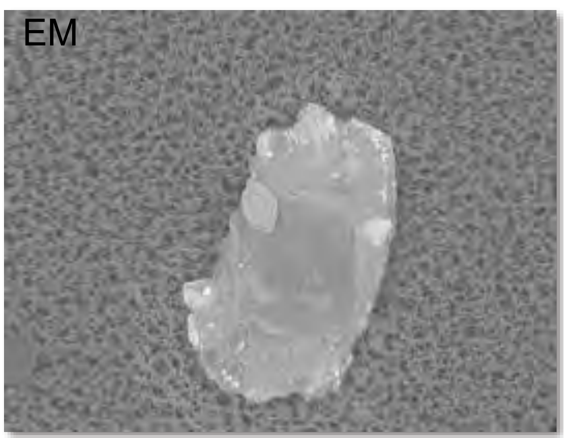
# **Correlative Microscopy**
## Correlation of functional and structural information

[ZEISS Correlative Microscopy]





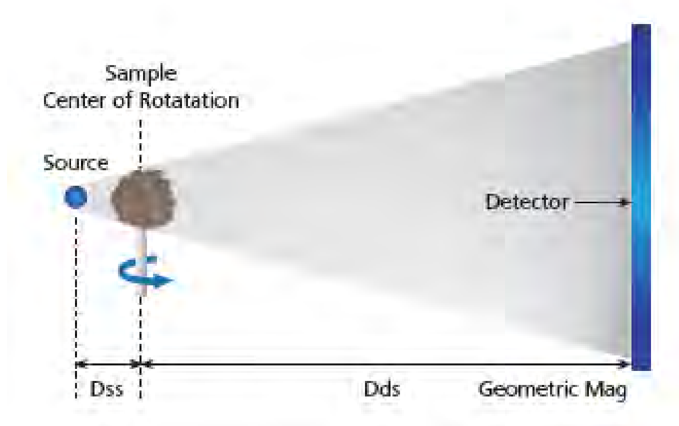


# **X-ray Tomography**

## MicroCT and X-ray Microscopy

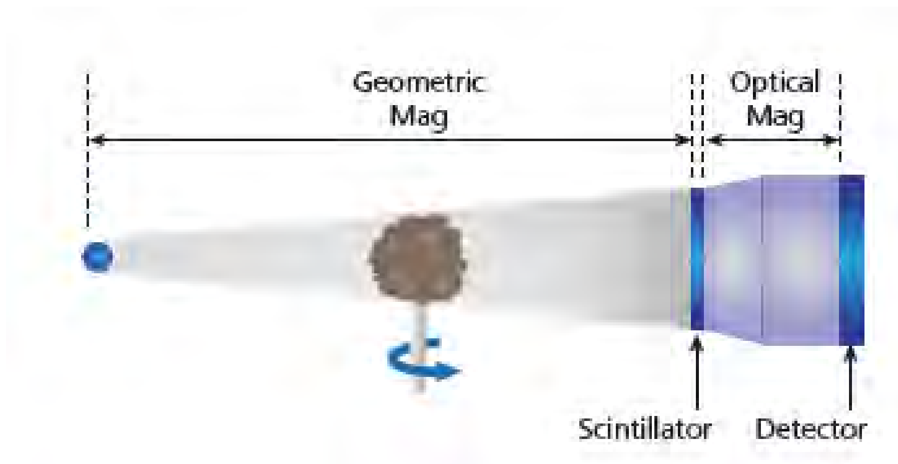
ZEISS x-ray microscopy

### Conventional MicroCT




- **Projection** based architecture
- **Resolution degrades substantially** as the sample moves away from the source

### Xradia Versa Family




- **Two-Stage Magnification** for unprecedented resolution and contrast
- **High resolution is maintained** as the sample moves away from the source