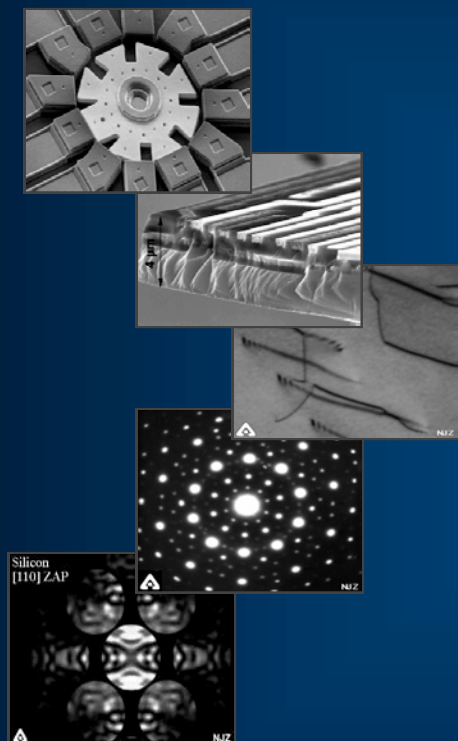
Introduction to Transmission/Scanning Transmission Electron Microscopy and Microanalysis



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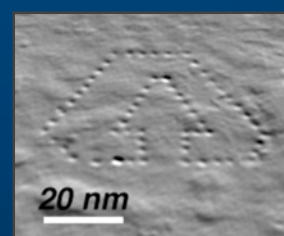

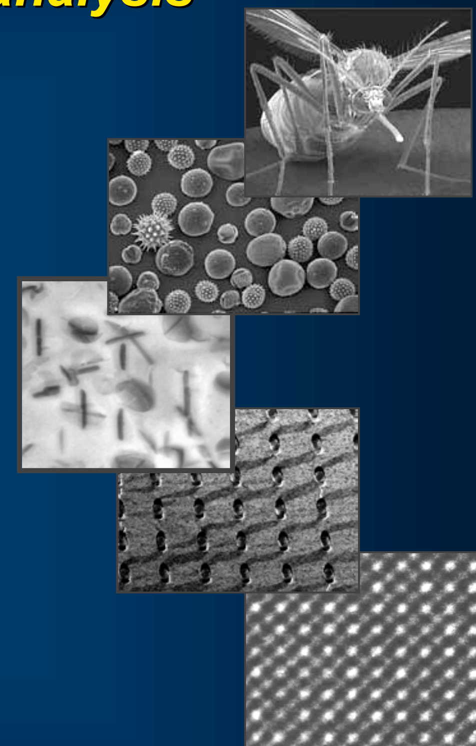

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A Few References:

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Introduction to Analytical Electron Microscopy
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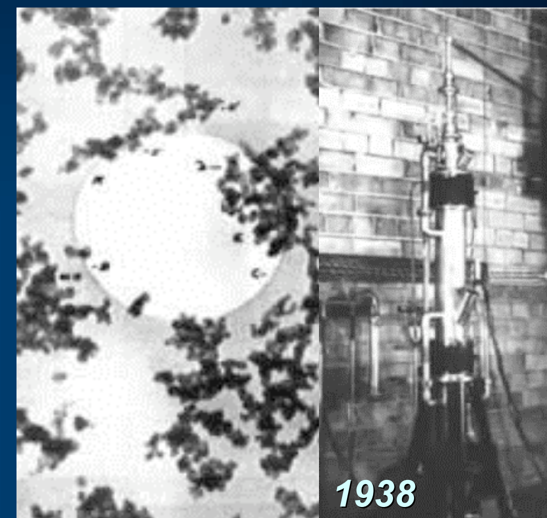
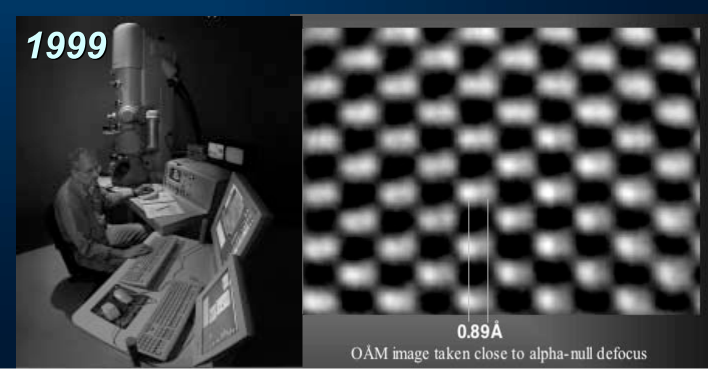
A Historical Time Line in Electron Optical Instrumentation



1897 JJ Thompson - Discovery of the Electron
1926 H. Bush Magnetic/Electric Fields as Lenses
1929 E. Ruska PhD Thesis Magnetic lenses
1931 Knoll and Ruska 1st EM built
1932 Davisson and Calbrick - Electrostatic Lenses
1934 Driest & Muller - EM surpases LM
1939 von Borries & Ruska - 1st Commerical EM
~ 10 nm resolution
1945 ~ 1.0 nm resolution (Multiple Organizations)
1965 ~ 0.2 nm resolution (Multiple Organizations)
1968 A. Crewe - U.of Chicago - Scanning Transmission Electron Microscope
~ 0.3 nm resolution probe - practical Field Emission Gun
1986 Ruska etal - Nobel Prize
1999 < 0.1 nm resolution achieved (OÅM)
2009 0.05 nm (TEAM)



Tutorial Outline

Introductory Remarks

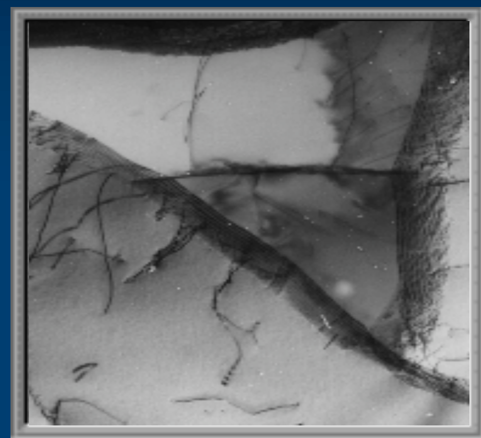
Instrumentation

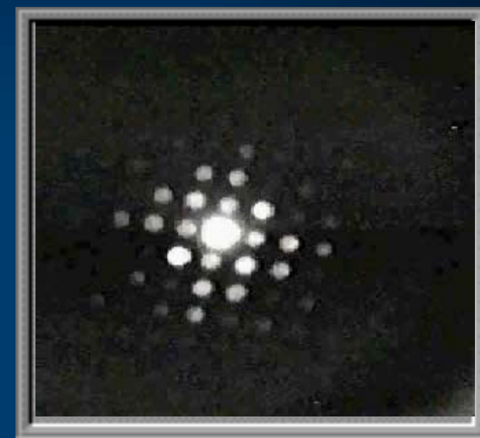
- Electron Sources
- Electron Optics
- Electron Detectors

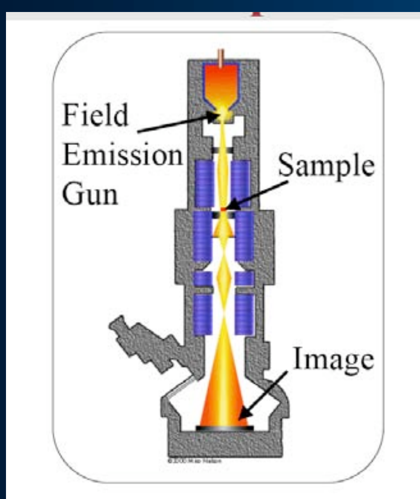
Electron Beam Interations ->Operating Modes

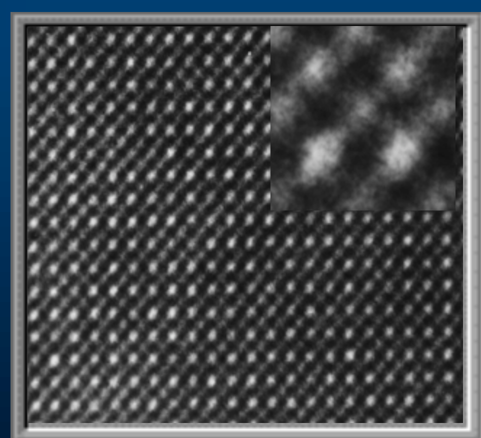
- Electron Scattering
- Diffraction
- Imaging
- Other Modes
  - STEM
  - HREM
  - ? Others ?
- X-ray Energy Dispersive Spectroscopy
- Electron Loss Spectroscopy

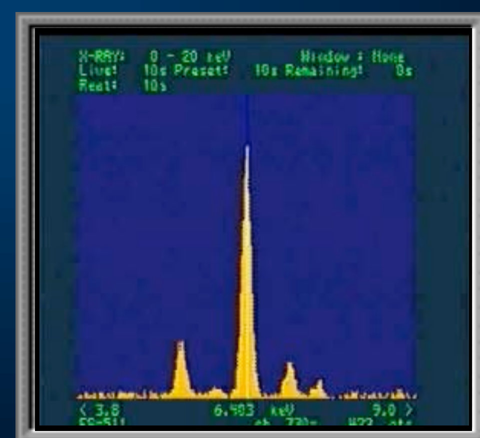
Transmission Electron Microscopy







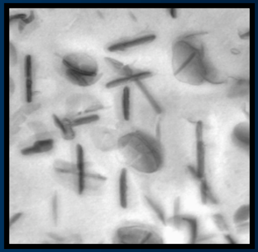




Microscopy & Microanalysis

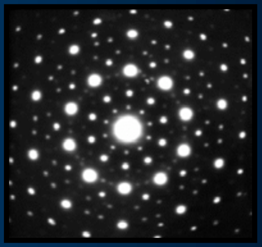
Experimental methodologies which employs (electron-optical) instrumentation to spatially characterize matter on scales which range from tenths of a millimeter to tenths of a nanometer. The principle modalities employed are:

Imaging



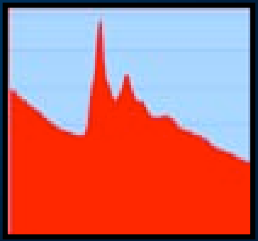
- Scanning Electron Microscopy
- Transmission Electron Microscopy
- Scanning Transmission Electron Microscopy
- Focussed Ion Beam

Diffraction



- Electron Backscattered Difrraction
- Selected Area Electron Diffraction
- Convergent Beam Electron Diffraction
- Reflection High Energy Electron Diffraction

Spectroscopy



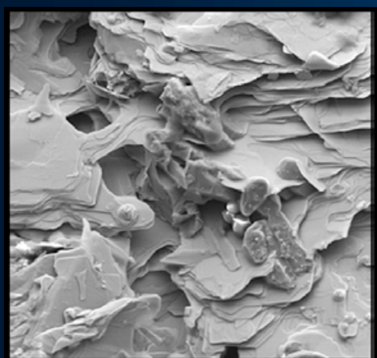
- X-ray Energy Dispersive
- Electron Energy Loss
- Auger Electron

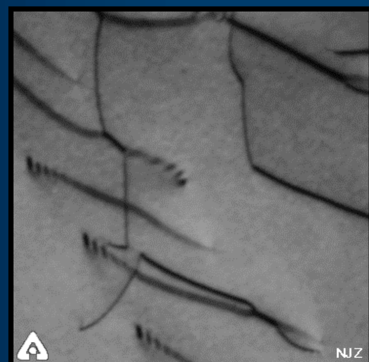
Role of Traditonal Electron Microscopy

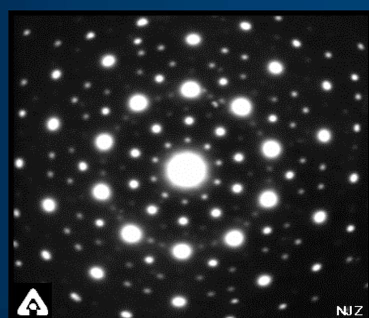
SEM
Scanning Electron Microscopy

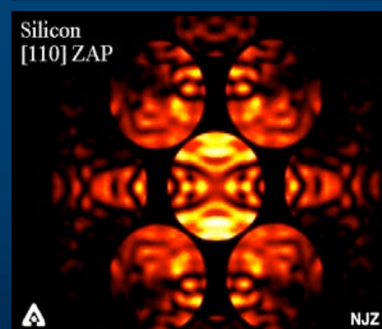
TEM - STEM - HREM
Transmission - Scanning Transmission - High Resolution Electron Microscopy

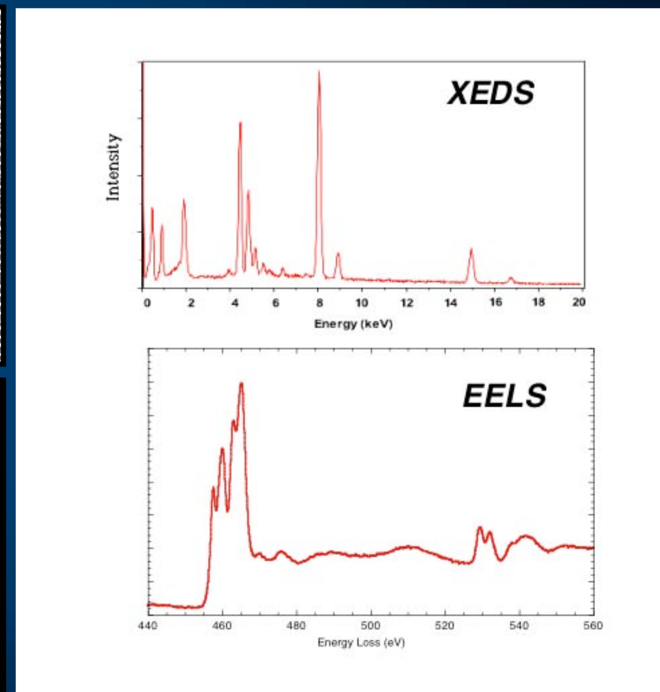
AEM
Analytical Electron Microscopy











Morphology, Crystallography, Elemental , Chemical , Electronic Structure

Elastic Scattering Spectroscopies

Electron Microscopy (EM),

Scanning Electron Microscopy (SEM),
SEM-based Electron Channeling Patterns (ECP),
Transmission Electron Microscopy (TEM),
Transmission Electron Diffraction (TED),
Convergent Beam Electron Diffraction (CBED)
Selected Area Electron Diffraction (SAED)
Scanning Transmission Electron Microscopy (STEM),
Reflection High Energy Electron Diffraction (RHEED)

Low Energy Electron Diffraction (LEED)

X-ray Diffraction (XRD),
Scanning Transmission X-ray Microscopy (STXM)
Neutron Diffraction (ND).

Inelastic Scattering Spectroscopies

	Type

Secondary Electron Imaging (SEI)
Backscattered Electron Imaging (BEI/BSI)
Auger Electron Spectroscopy (AES),
Electron Energy Loss Spectroscopy (EELS),
    EXtended Energy Loss Fine Structure (EXELFS),
    Energy Loss Near Edge Fine Structure (ELNES),
	$e^- \Rightarrow e^-$

X-ray Emission Spectroscopy (XES),
    X-ray Energy Dispersive Spectroscopy (XEDS),
    Wavelength Dispersive Spectroscopy (WDS),
Cathodoluminescence (CL)
	$e^- \Rightarrow \lambda$

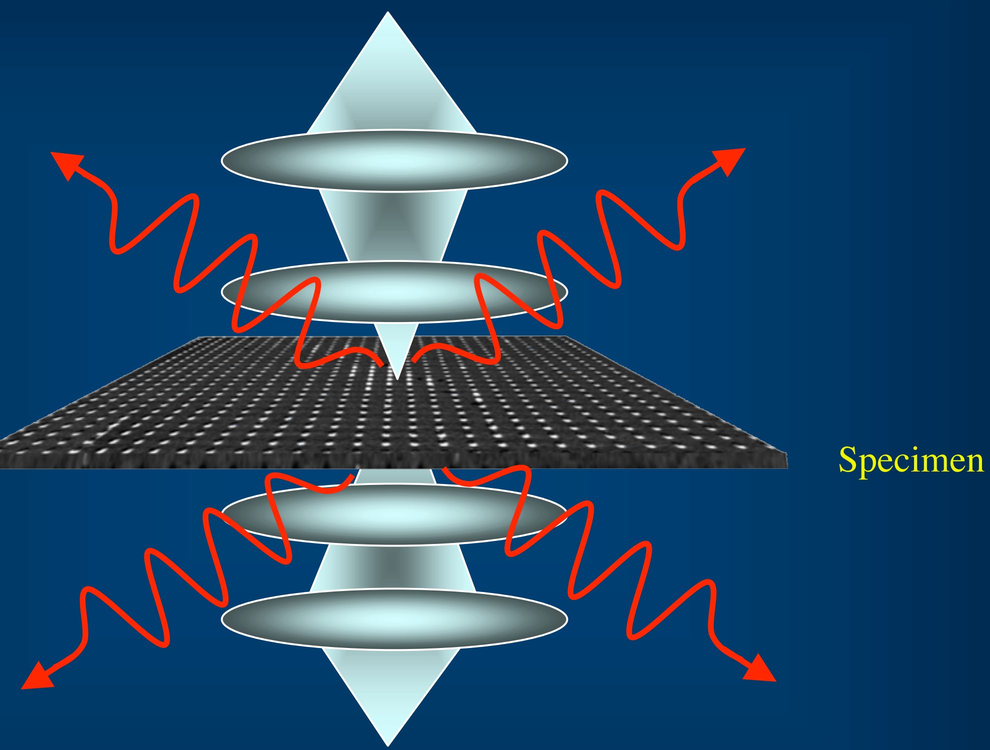
X-ray Photoelectron Spectroscopy (XPS), X-ray Photoelectron Microscopy (XPM), Ultraviolet Photoelectron Spectroscopy (UPS),	$\lambda \Rightarrow e^-$

X-ray Absorption Spectroscopy (XAS),
    EXtended X-ray Absorption Fine Structure (EXAFS),
    X-ray Absorption Near Edge Fine Structure (XANES)
X-Ray Fluorescence (XRF).
	$\lambda \Rightarrow \lambda$

Comparison Source Characteristics

Source	*Brightness (particles/cm^2/sR/eV)*	*Elastic Mean Free Path (nm)*	*Absorption Pathlength (nm)*	*Attainable Probe Size (nm)*
Neutrons	10^{14}	10^{7}	10^{8}	10^{6}
X-rays	10^{26}	10^{3}	10^{5}	~ 30
Electrons	10^{29}	10^{1}	10^{2}	< 0.1

Reflection / Scanning Microscopy
Deals Mainly with Near Surface Region



Transmission Microscopy
Deals Mainly with Internal Structure

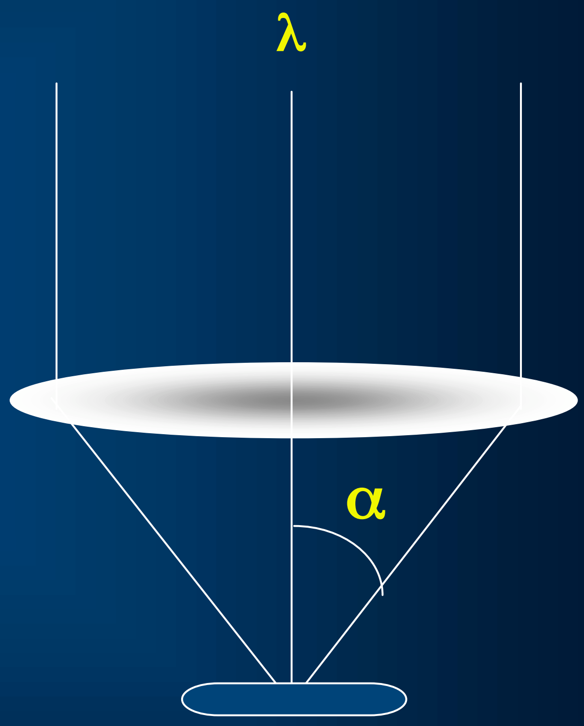
Modern EM's can depending upon the specimen operate in both modes

What are the limits of Resolution?

Abbe (Diffraction) Limit:

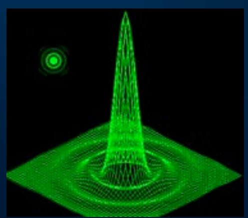
Defines the minimum resolvable distance between the image of two point objects using a perfect lens.

In any magnifying system a point object (i.e. zero dimension) cannot be imaged as a point but is imaged as a distribution of intensity having a finite width.



Resolution of an imaging system

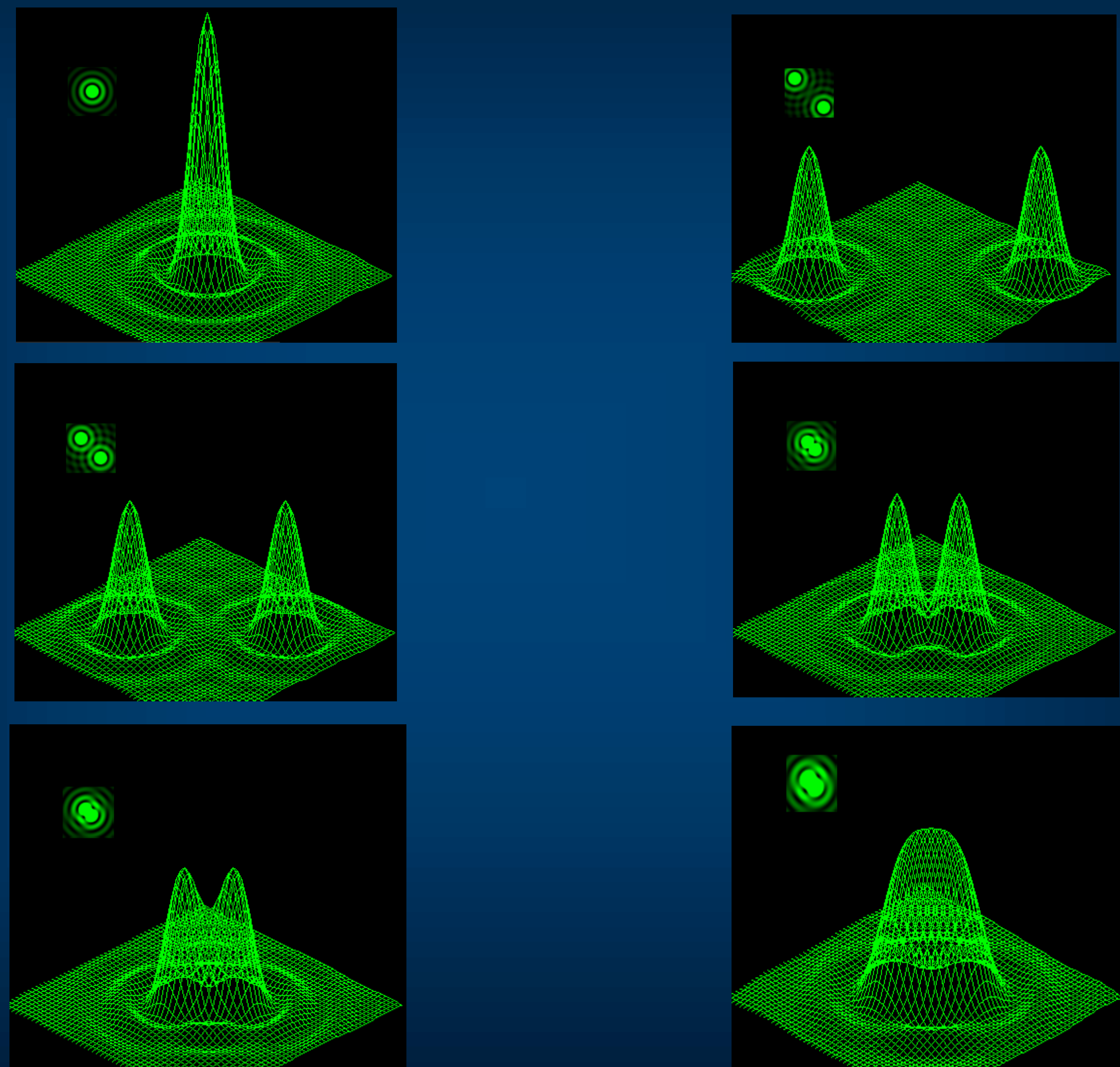
$$\rho = \frac{0.6\lambda}{\eta \sin(\alpha)}$$



λ = wavelength of the imaging radiation
η = index of refraction of the lens
α= illumination semi-angle
NA = numerical aperture = η sin (α)

Resolution vs. Magnification

$$\rho = \frac{0.6\lambda}{\eta \sin(\alpha)}$$



Magnification in these images is constant ! Do not confuse the two concepts.

Some Fundamental Properties of Electrons

- Electron wavelength: based on de Broglie's ideas of wave-particle duality we know $\lambda = h/p$, where p is the electron momentum , h is Planck's constant, and λ is corresponding wavelength of the electron.
- In the TEM we impart momentum to the electron by accelerating it through a potential drop, V, giving it a kinetic energy *eV* This potential energy must equal the kinetic energy:

$$eV = \frac{m_0 v^2}{2}$$

$$p = mv = \sqrt{2 m_0 eV}$$

For nonrelativistic electron wavelength

$$\lambda(\mathring{A}) = \frac{h}{p} = \frac{h}{\sqrt{2 m_0 eV}} \approx \frac{12.27}{\sqrt{V(volts)}}$$

- However, for electron microscopy, relativistic effect cannot be ignored at 100-keV energies and above because the velocity of the electron become greater than half the speed of light. So the corrected (relativistic effect is considered) electron wavelength is:

$$\lambda = \frac{h}{p} = \frac{h}{\sqrt{2 m_0 eV\left(1 + \frac{eV}{2 m_0 c^2}\right)}} \approx \frac{12.27}{\sqrt{V(1 + 0.978x10^{-6} V)}}$$

Electron Properties as a Function of Accelerating Voltage

Table 1.2. Electron Properties as a Function of Accelerating Voltage

Accelerating voltage (kV)	Nonrelativistic wavelength (nm)	Relativistic wavelength (nm)	Mass ($\times m_0$)	Velocity ($\times 10^8$ m/s)
100	0.00386	0.00370	1.196	1.644
120	0.00352	0.00335	1.235	1.759
200	0.00273	0.00251	1.391	2.086
300	0.00223	0.00197	1.587	2.330
400	0.00193	0.00164	1.783	2.484
1000	0.00122	0.00087	2.957	2.823

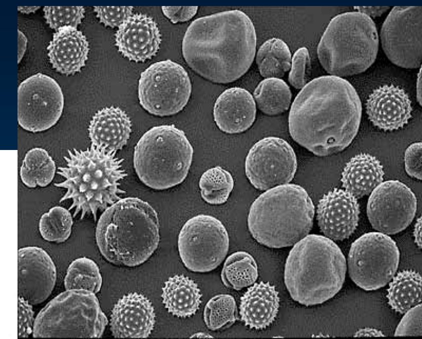
Light vs Electrons

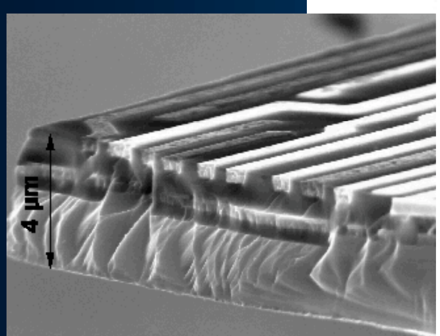
Light Microscope	Electron Microscope
$\lambda \sim 0.5\ \mu m$	$\lambda = \frac{h}{\sqrt{2m_o e V_o}} = 0.068\ Å\ (30\ kV)$
$\eta = 1.5$ (glass)	$\eta = 1.0$ (Vacuum)
$\alpha \sim 70^o$	$\alpha \leq 1^o$
$\rho \sim 0.21\ \mu m = 2100\ Å$	$\rho \sim 4.1\ Å$

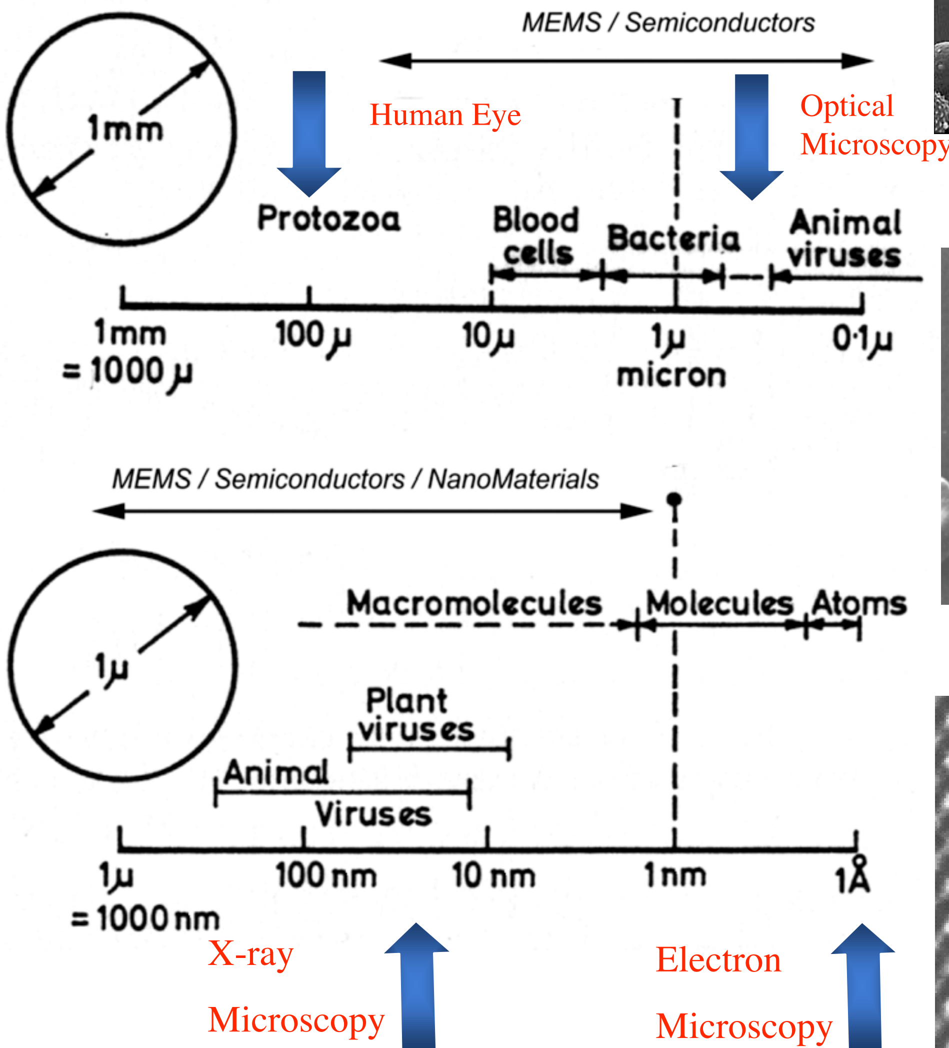
$$\rho = \frac{0.6\lambda}{\eta \sin(\alpha)}$$

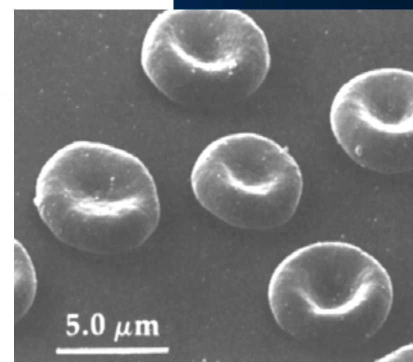
From Ants to Atoms

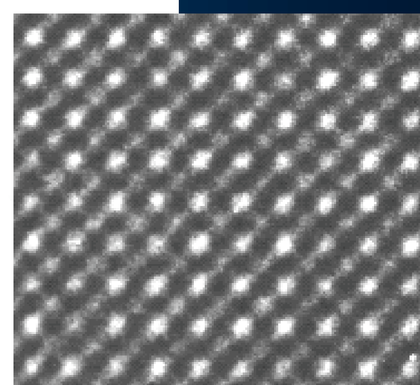
Microscopy is needed nearly everywhere



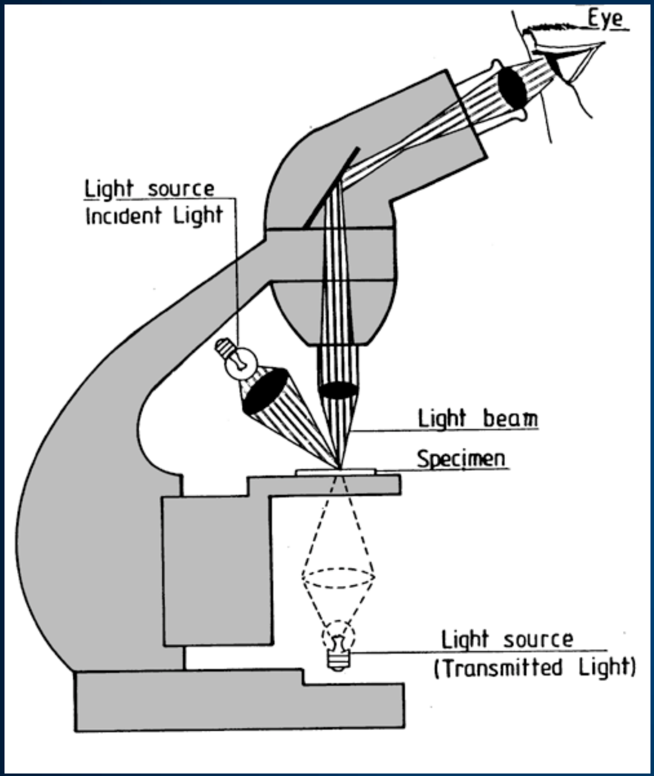


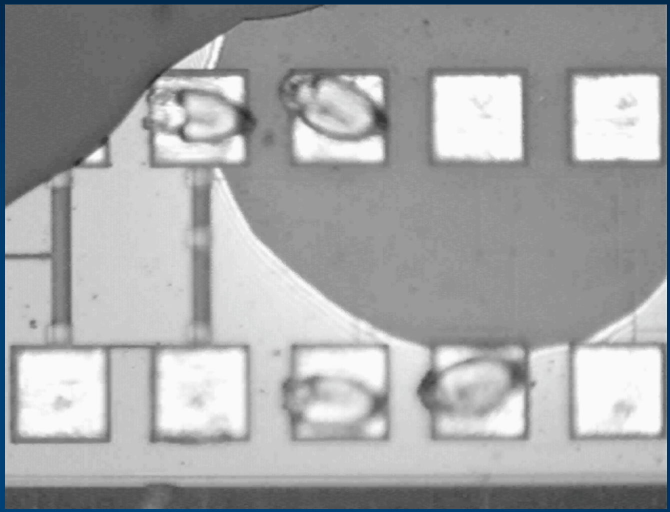


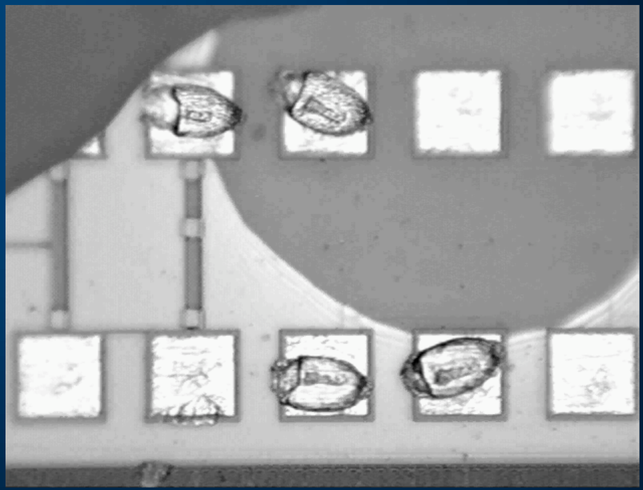




Depth of Field



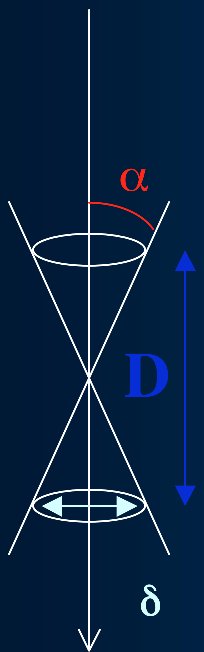




The distance parallel to the optical axis of the microscope that a feature on the specimen can be displaced without loss of resolution

Depth of Field

Varies with Magnification



Depth of Focus/Field

The distance parallel to the optical axis of the microscope that a feature on the specimen can be displaced without loss of resolution

Optical Microscope

$$d = \frac{\lambda \sqrt{\eta^2 - (NA)^2}}{(NA)^2} + \frac{250}{M^2}$$

Electron Microscope

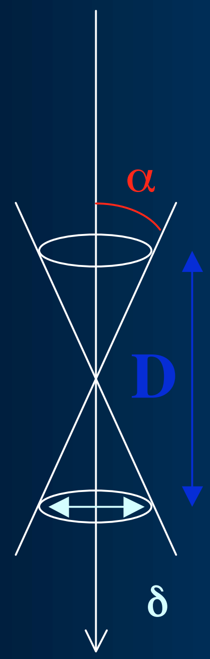
$$d = \frac{0.1 \text{ mm}}{M \alpha}$$

λ = wavelength
η = refractive index
α = semi angle
M = total magnification
NA= Numerical Aperture of lens

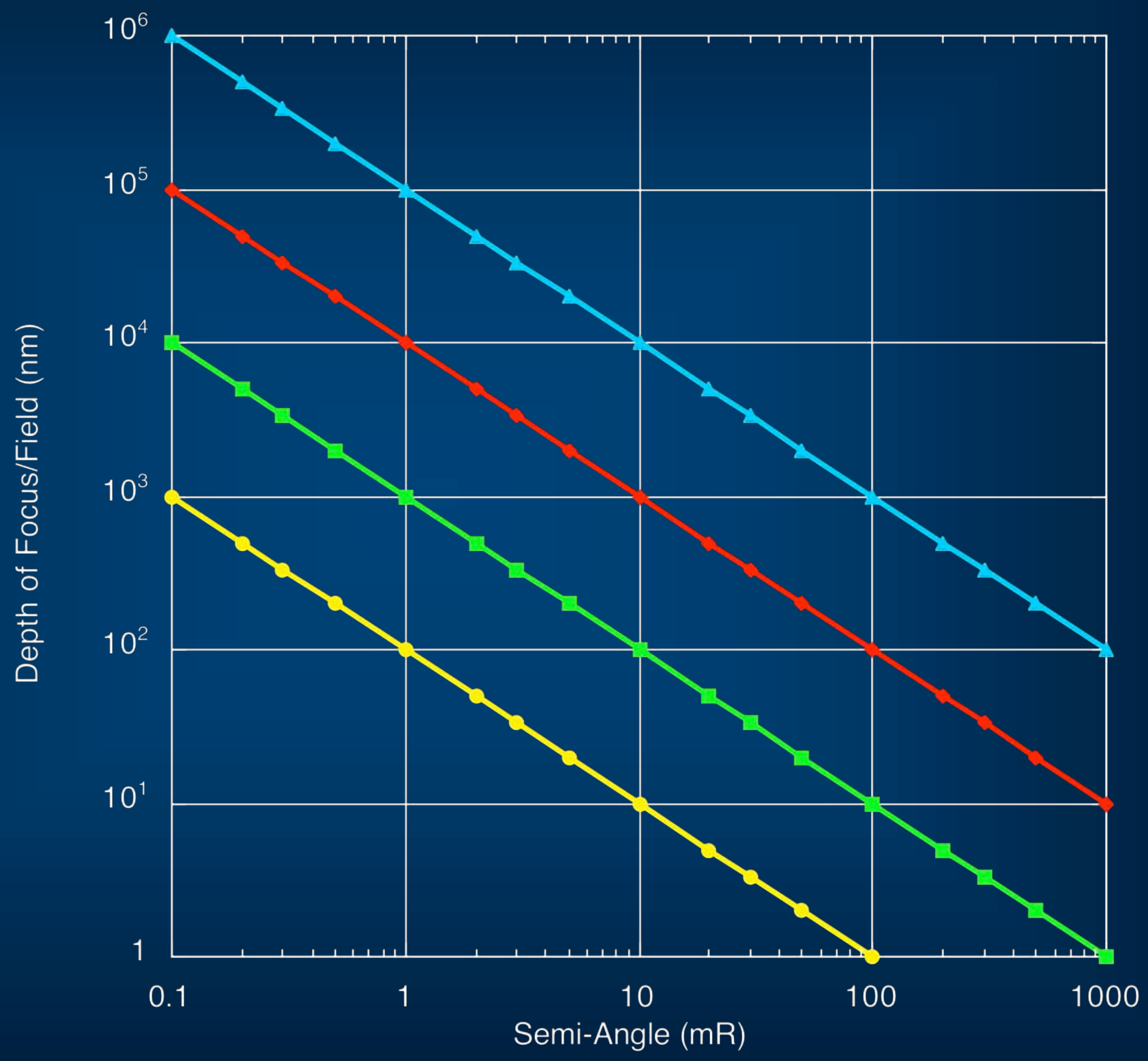
Depth of Focus

Magnification	Depth of Focus	
	Optical	SEM
10	60 μm	1000 μm
100	8 μm	100 μm
1,000	0.2 μm	10 μm
10,000	-	1 μm

Depth of Focus (Specimen Plane)
Pre Specimen Semi-Angles

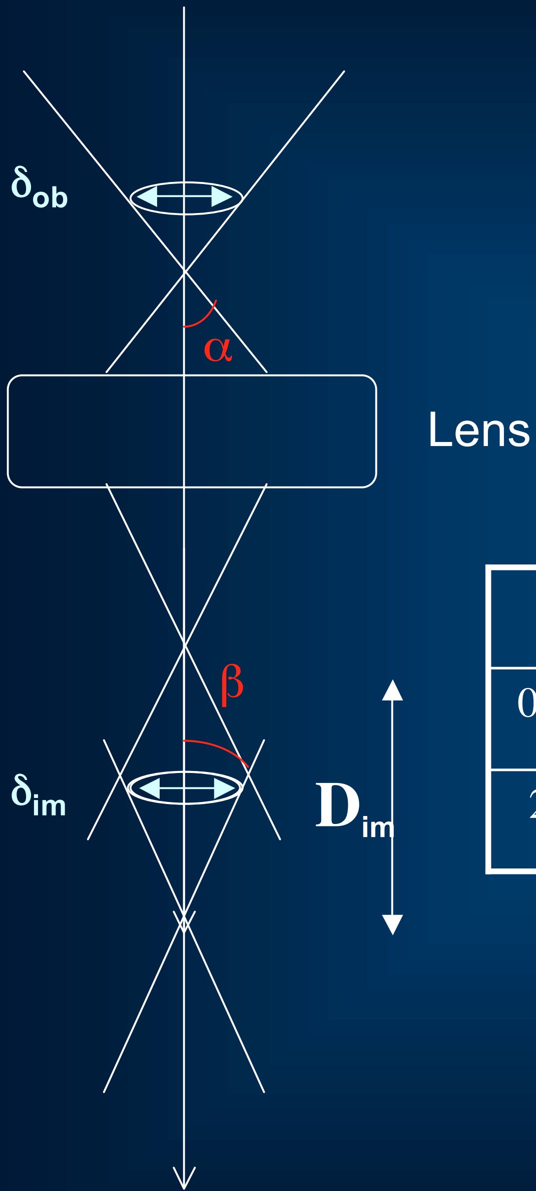


$$D = \frac{\delta}{\alpha}$$



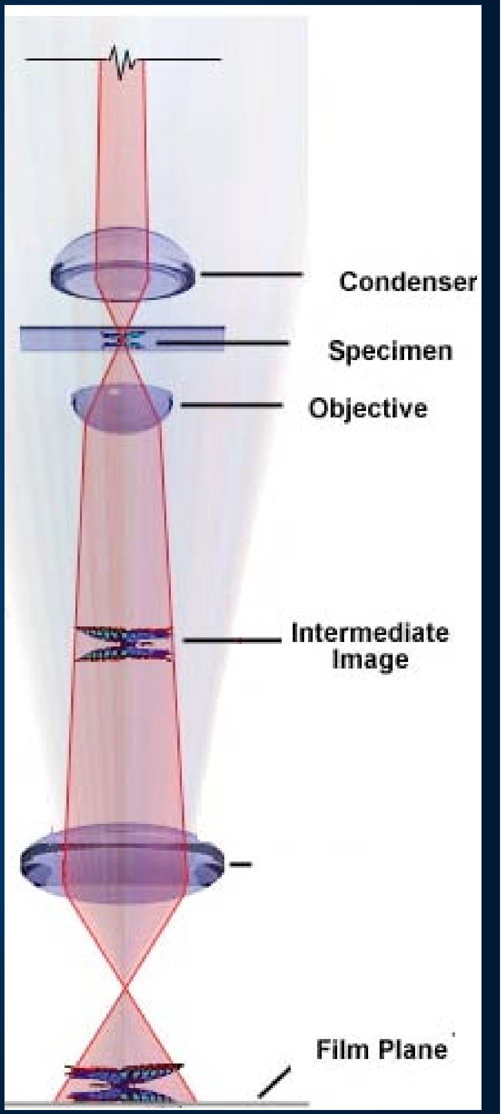
In an EM α is controlled by both Apertures & the Lens Magnification

Depth of Field (Image Plane)
Post Specimen Semi-Angles



$$D_{im} = \frac{\delta_{im}}{\beta} = \frac{\delta_{ob}}{\alpha} M^2$$

δ_{ob}	α	M	D_{im}
0.2 nm	10 mR	500kX	5 km
2 nm	10 mR	50kX	5 m



Basic Components of All Microscopes That Use Lenses

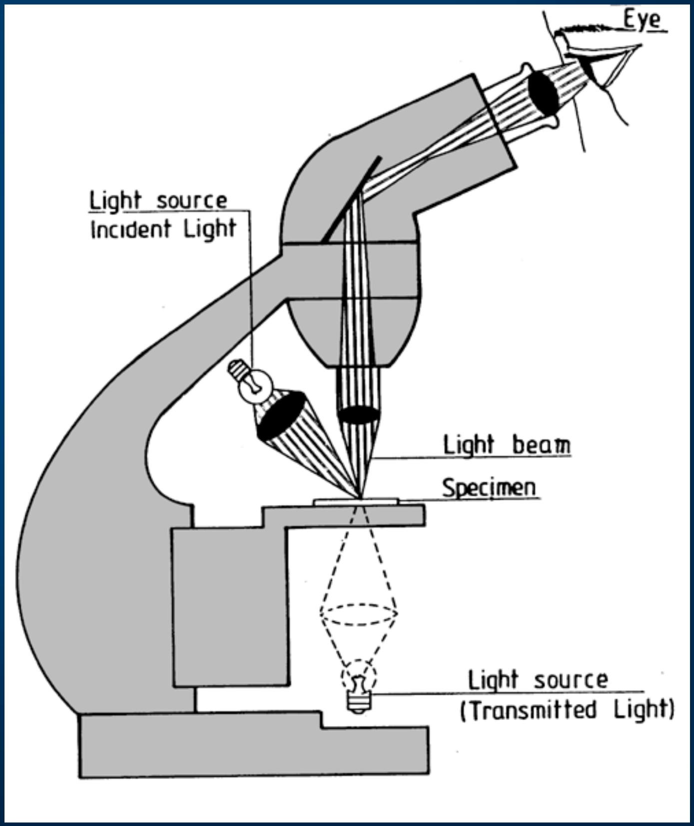
Illumination Source

Illumination Lens

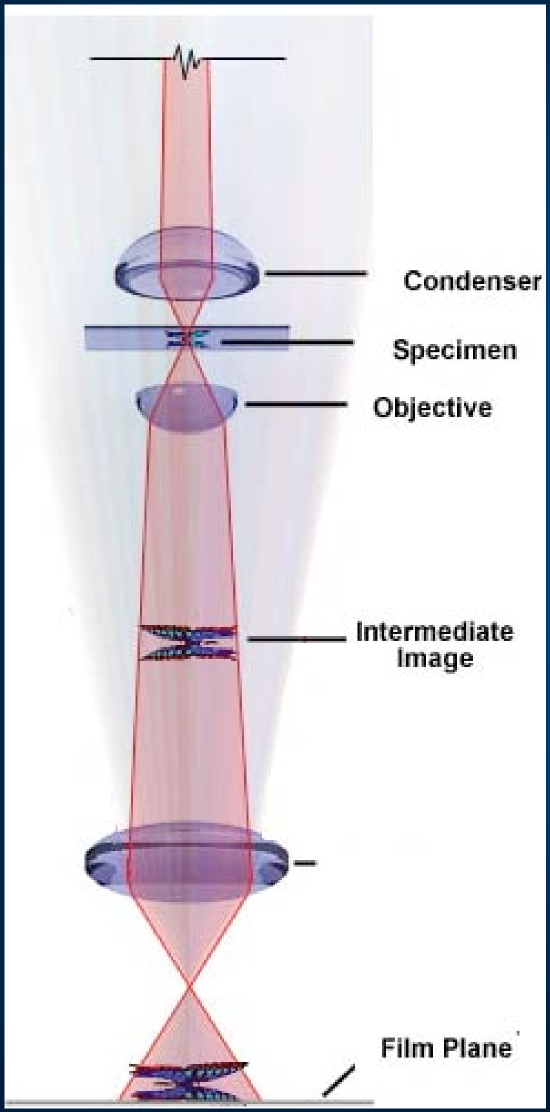
Specimen

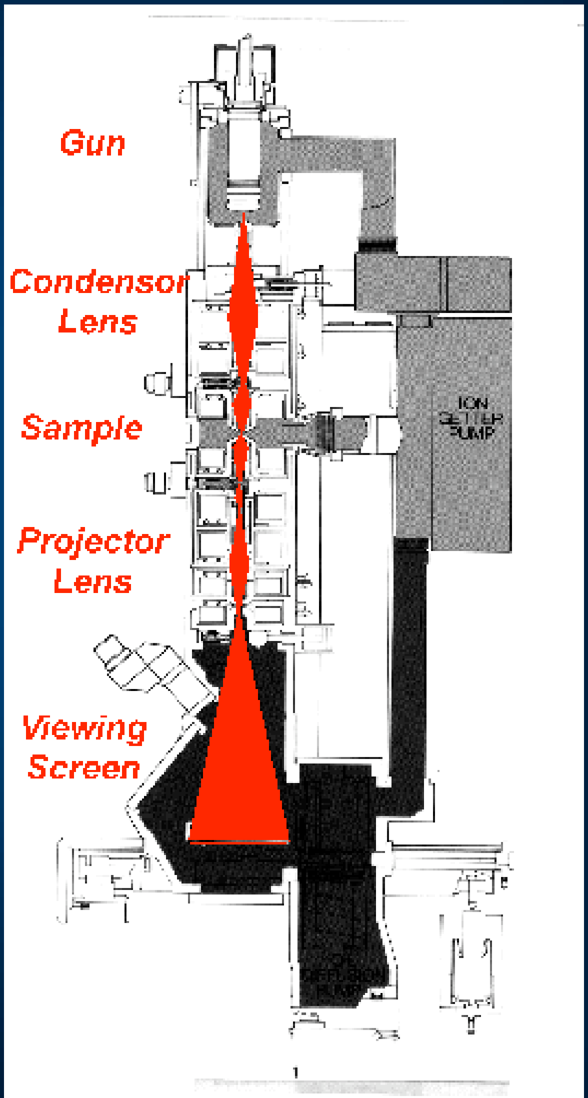
Magnifying Lens

Detector/Viewer



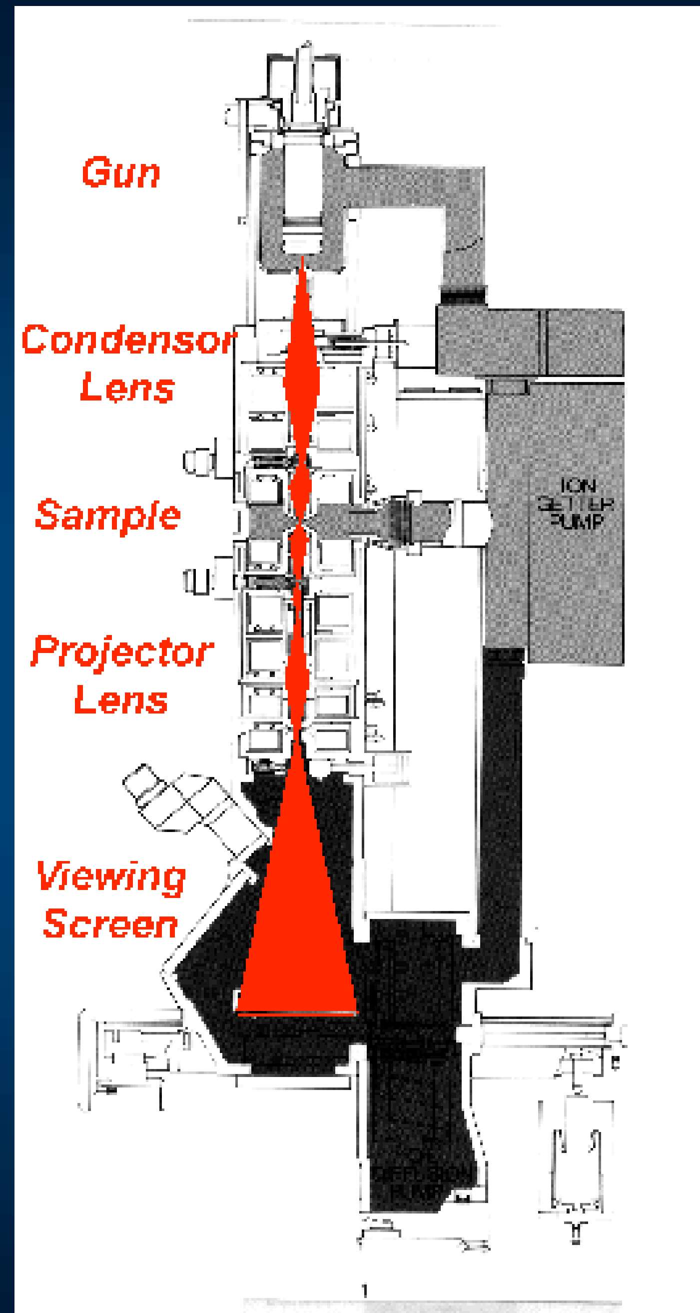
Transmission Electron Microscope





Basic Components of an Electron Microscope

Transmission Electron Microscope



Basic Components of All Microscopes That Use Lenses

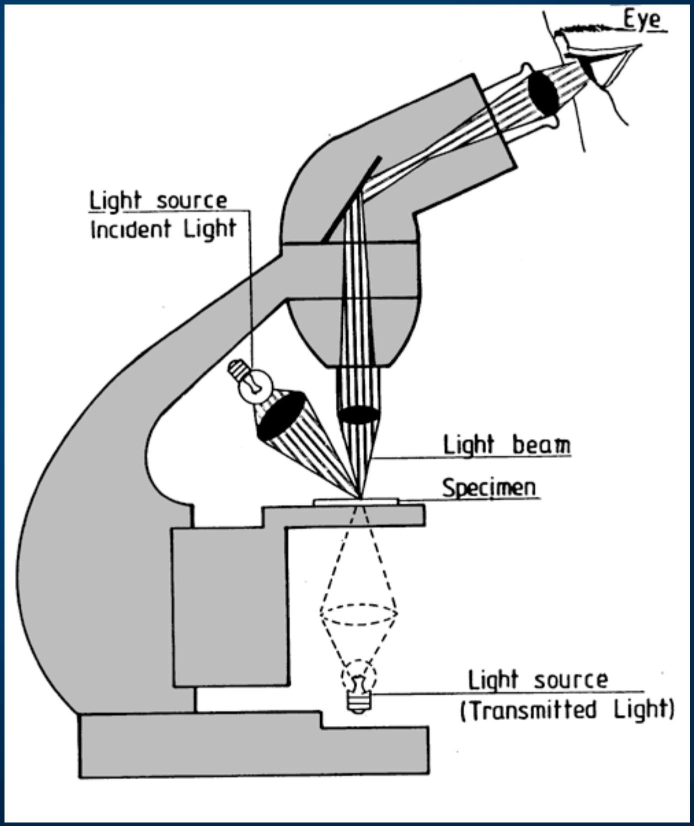
Illumination Source

Illumination Lens

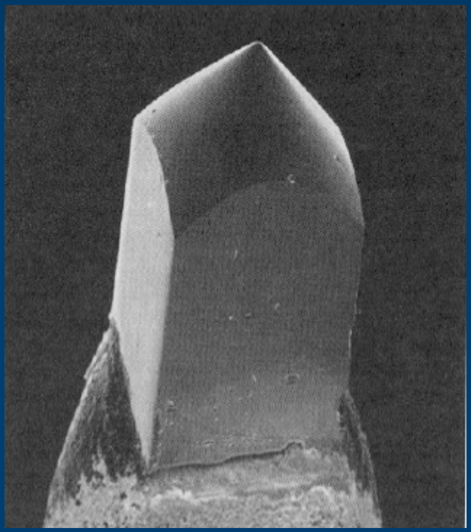
Specimen

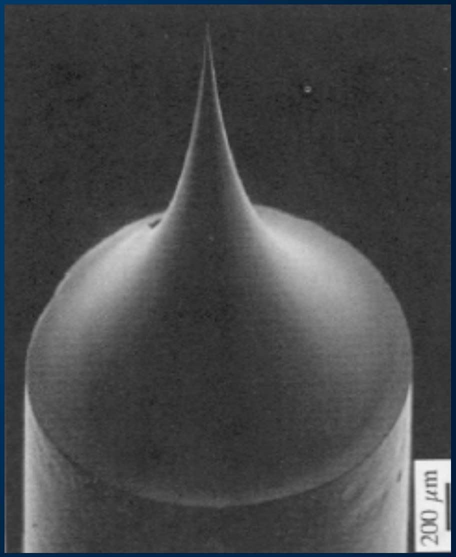
Magnifying Lens

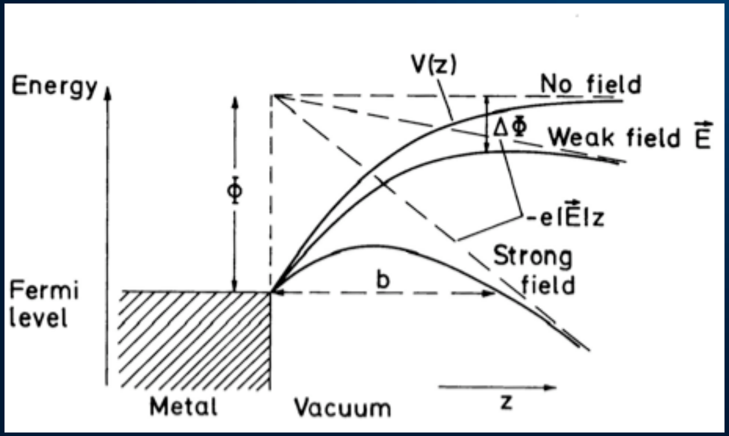
Detector/Viewer



Sources for Electron Microscopy
Thermionic, Thermally Assisted, and Field Emission







Conduction electrons must overcome the work function ϕ if they are to be emitted from the cathode into the vacuum.

Thermionic sources

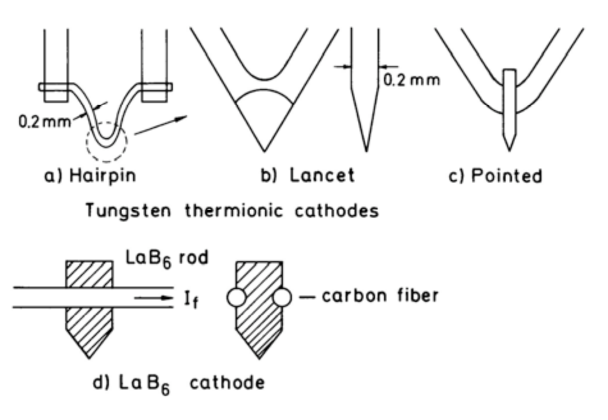
Richardson law gives the current density :

$$j_c = AT_C^2 \exp(-\phi / kT_C)$$

k is Boltzmann's constant, T_C is the cathode temperature and A and ϕ are a constants depending on material. Note that $j_c \propto T$.

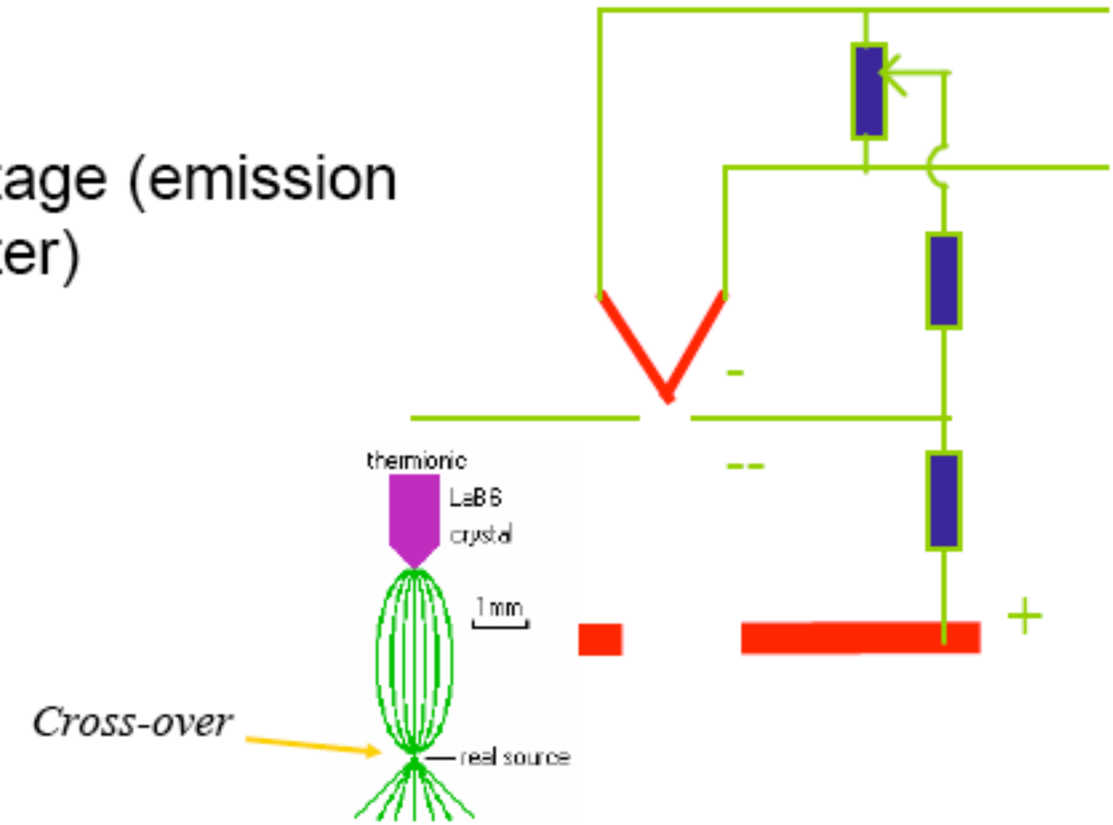
W has T_C of 2500-3000 K (melting point 3650 K)
LaB_6 has a T_C of 1400-2000 K

Heating usually produced by running a current through the material!



Electron Source
Thermionic Gun

- Filament
- Wehnelt
  - bias voltage (emission parameter)
- Anode

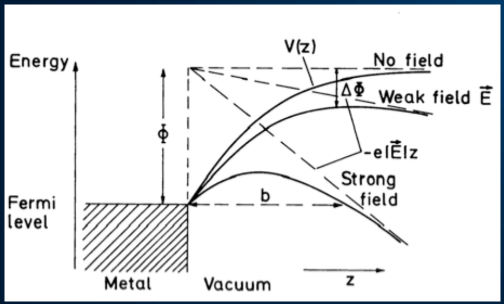


Field emission and Schottky sources

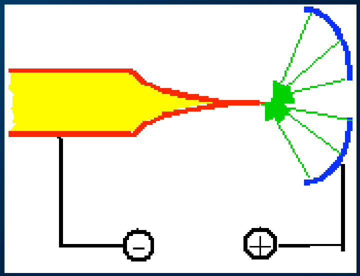
The width b of the potential barrier at the metal-vacuum boundary decreases with increasing electric field **E**.

For |**E**|>10^7 V/cm the width b < 10 nm and electrons can penetrate the potential barrier by the wave mechanical tunneling effect.

The current density of field emission can be estimated from the Fowler-Nordheim formula:

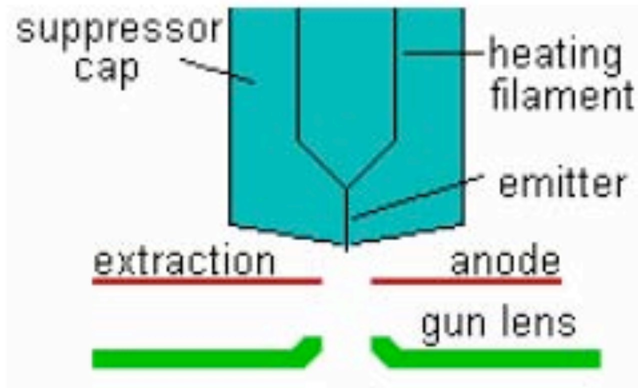


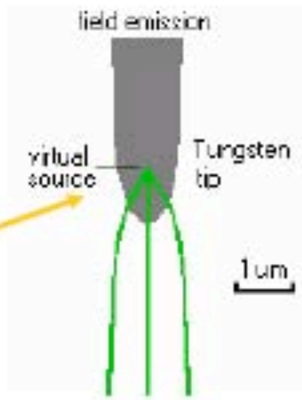
$$j = \frac{k_1 |\mathbf{E}|}{\phi} \exp\left(\frac{k_2 \phi^{3/2}}{|\mathbf{E}|} \right)$$



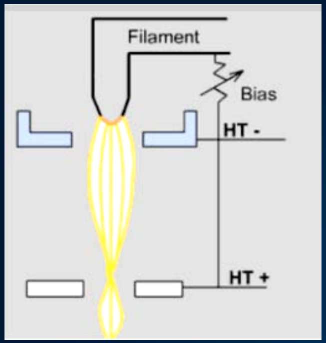
Field Emission Gun (FEG)

- Heating Filament
- Single Crystal Emitter
- Suppressor Cap
- Extraction Anode
- Electrostatic lens

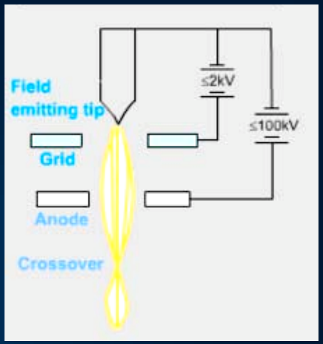




Electron seemingly originating from tip itself



Sources for Electron Microscopy: Thermionic, Thermally Assisted, and Field Emission



Comparison of Electron Sources

Type		Brightness β/Vo A/cm^2/sr/eV	Source Size (μm)	Energy Spread (eV)	Temporal Coherence (μm)	Shot Noise	Current Stability	Spatial Coherence	Vacuum (Torr)
Thermonic	Hairpin	1	50	2-3	0.4	Low	Good	Low	$<10^{-4}$
	Pointed	5	10				Fair	Moderate	$<10^{-5}$

Temporal Coherence = $2 E \lambda / \Delta E$

Spatial Coherence = $\lambda / 2\alpha$

Comparison of Electron Sources

	W	LaB_6	FEG (Schottky)
Maximum Current (nA)	1000	500	300
Normalised Brightness (-)	1	10-30	2500
Energy spread (eV)	3-4	1.5-3	0.6-1.2
Source spotsize	30-100 µm	5-50 µm	15-30 nm
Required Vacuum (Pa)	10^{-3}	10^{-5}	10^{-7}
Temperature (K)	2700	2000	1800
Life time (hr)	60-200	1000	>2000
Normalised Price (-)	1	10	100

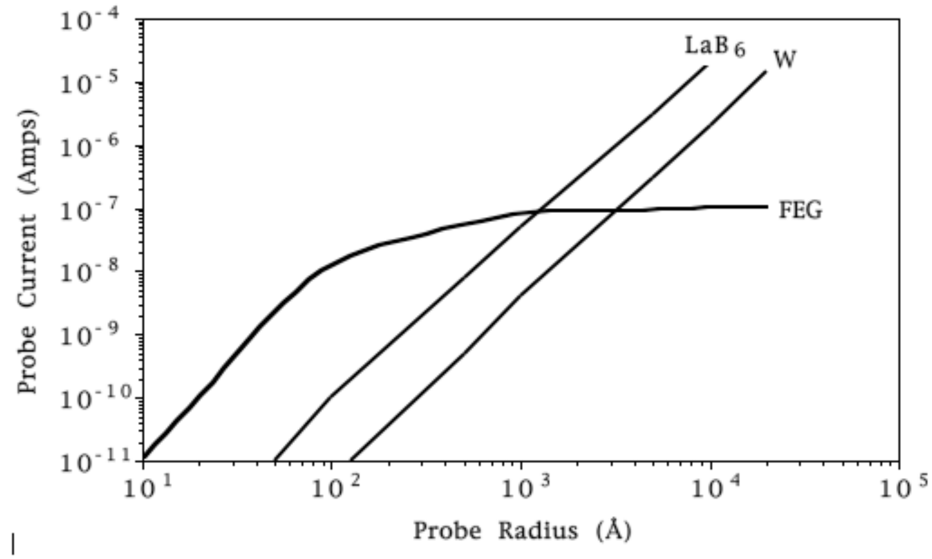
Probe Current Related Parameters

$$J = \text{Probe current} = \frac{(\pi d_o \alpha_o)^2 \mathcal{B}}{4}$$

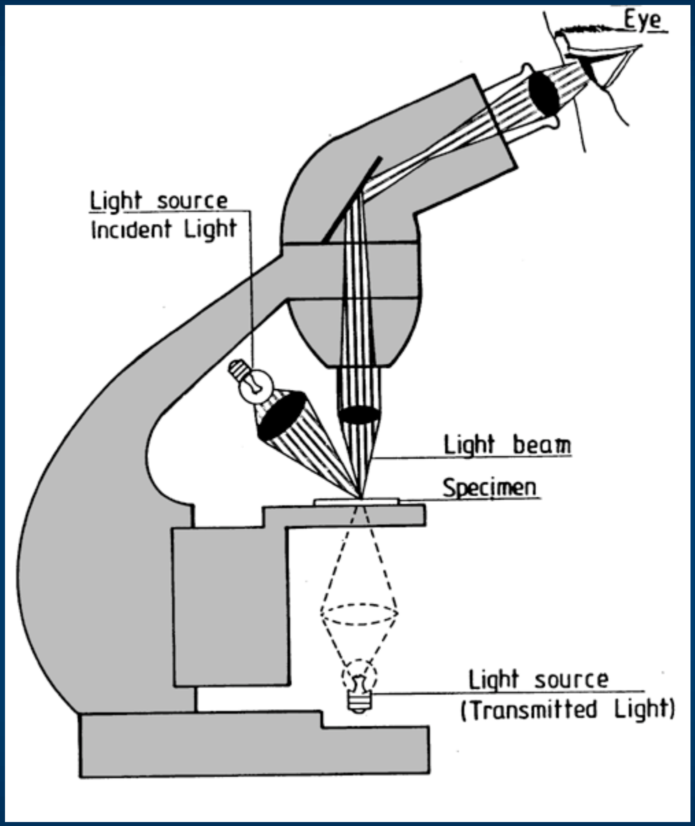
$$\mathcal{B} = \text{Brightness} = \left(\frac{J_c}{\pi k T}\right) eV_r$$

$$V_r = \text{Relativistic Voltage} = V_o\left(1 + \frac{eV_o}{[\ 2m_oc^2\ ]}\right)$$

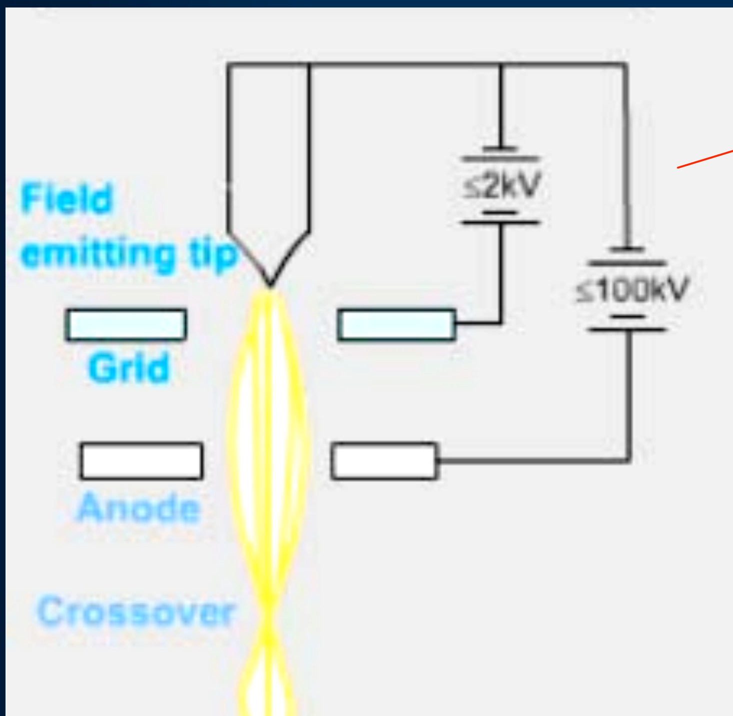
$$V_o(\ 1 + 9.785 \times 10^{-7} V_o)$$

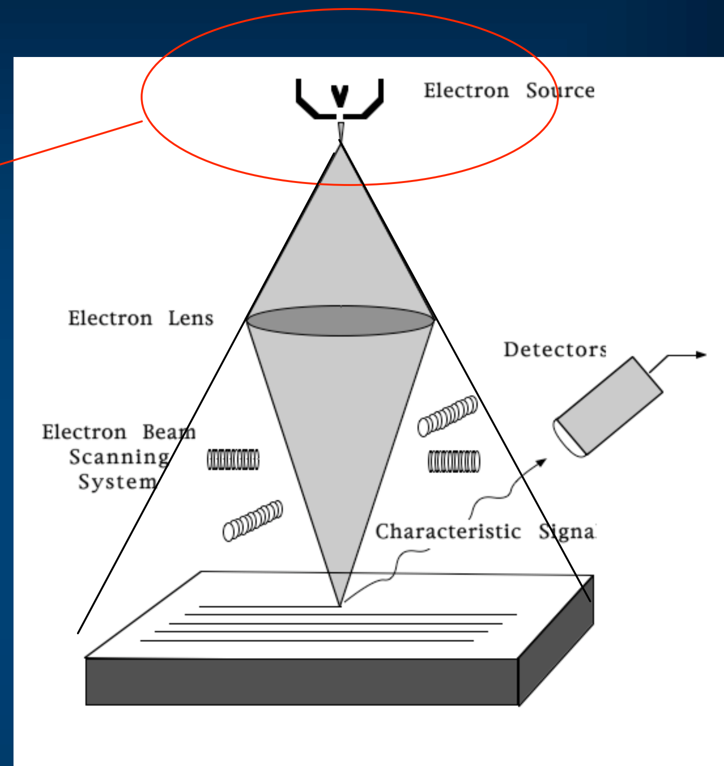


Why do we need a lens?



Why do we need a lens?





Because all electron sources generally produce a diverging beam of electrons. This beam must be "focussed" onto the specimen, to increase the intensity and thus to making the probe "smaller".

Basic Components of All Microscopes That Use Lenses

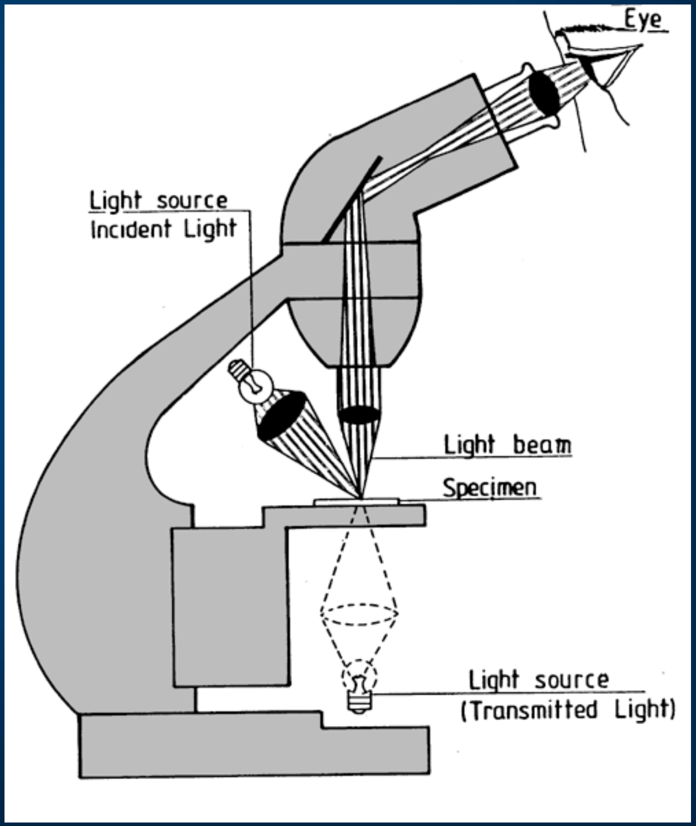
Illumination Source

Illumination Lens

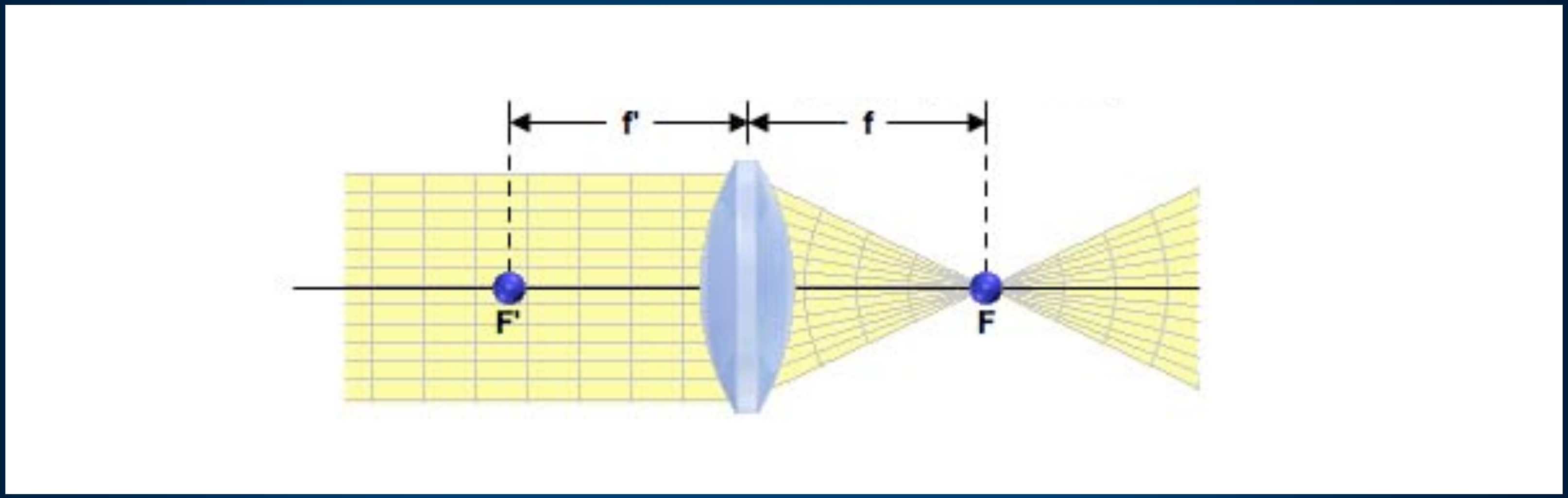
Specimen

Magnifying Lens

Detector/Viewer



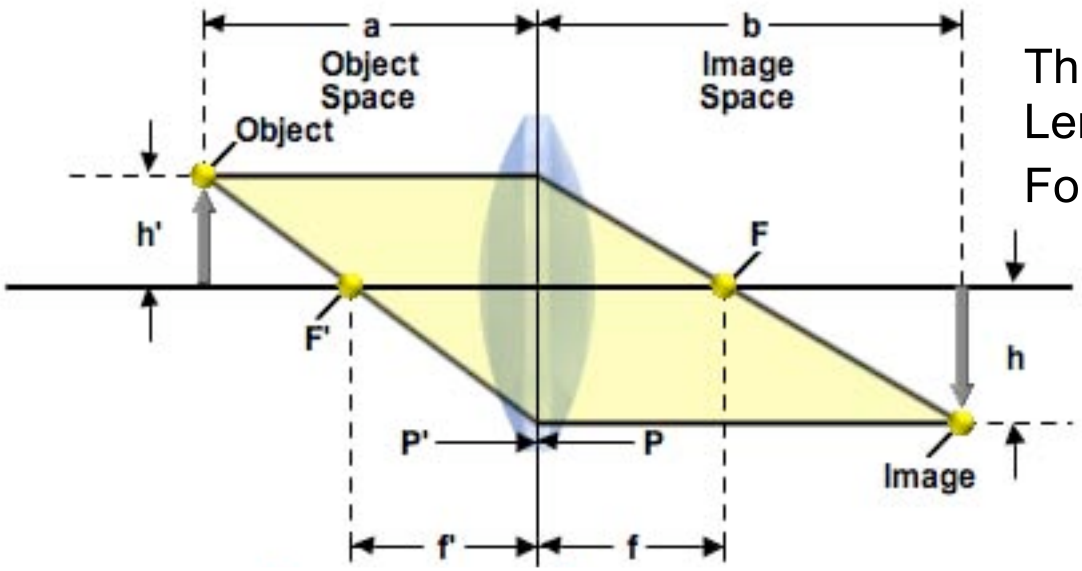
What is a Lens?



It is a device which focuses radiation.

f = focal length of the lens

How Does a Converging Lens Work as a Magnifier?



Thin
Lens
Formulae

$$\frac{1}{f} = \frac{1}{a} + \frac{1}{b}$$

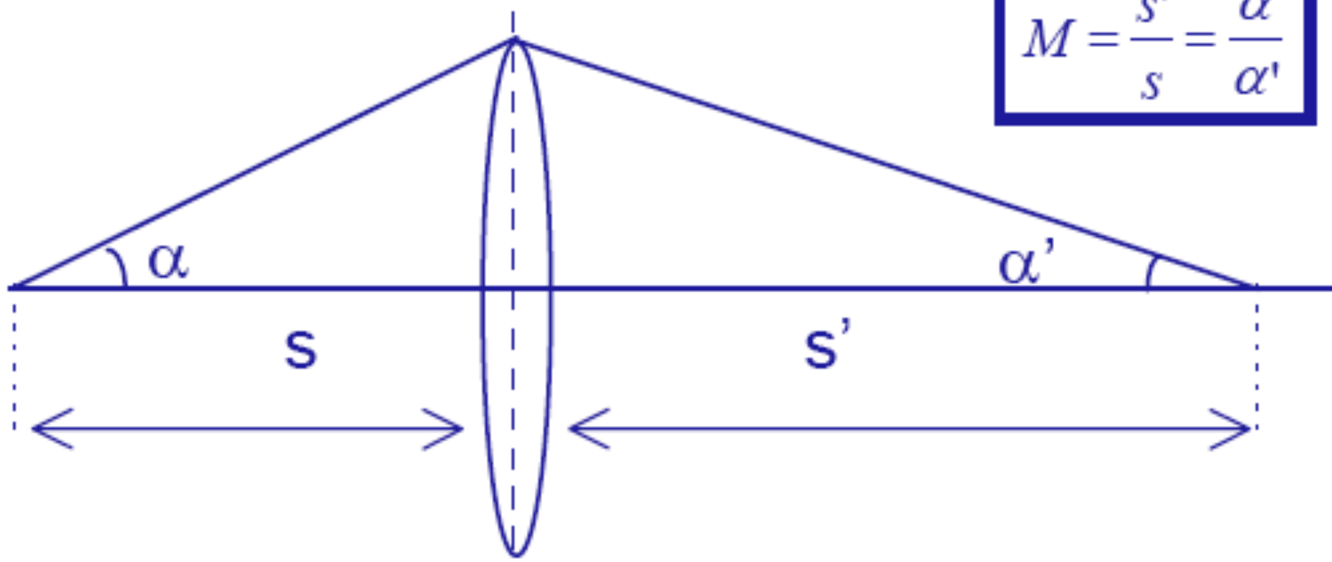
$$M = \frac{h}{h'} = -\frac{b}{a}$$

In a TEM the function of lens are to either demagnify the probe from the source point to the sample. This means that b < a resulting in a smaller electron probe. It's 2nd role as a post specimen lens is magnify an image hence b > a

Lenses

- Gaussian Law

$$M = \frac{s'}{s} = \frac{\alpha}{\alpha'}$$

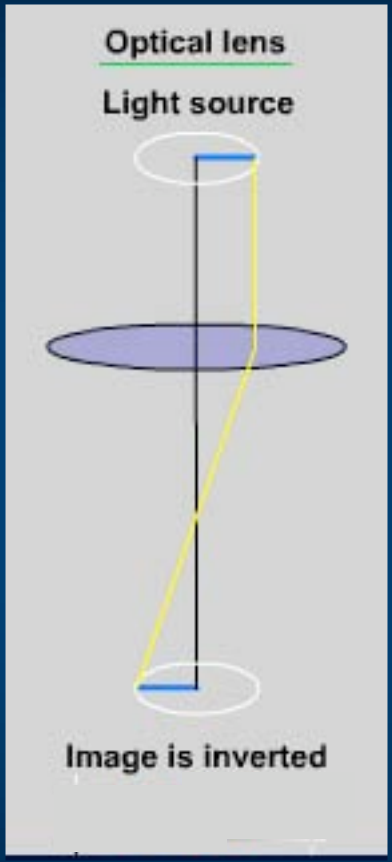


Lenses and Magnification

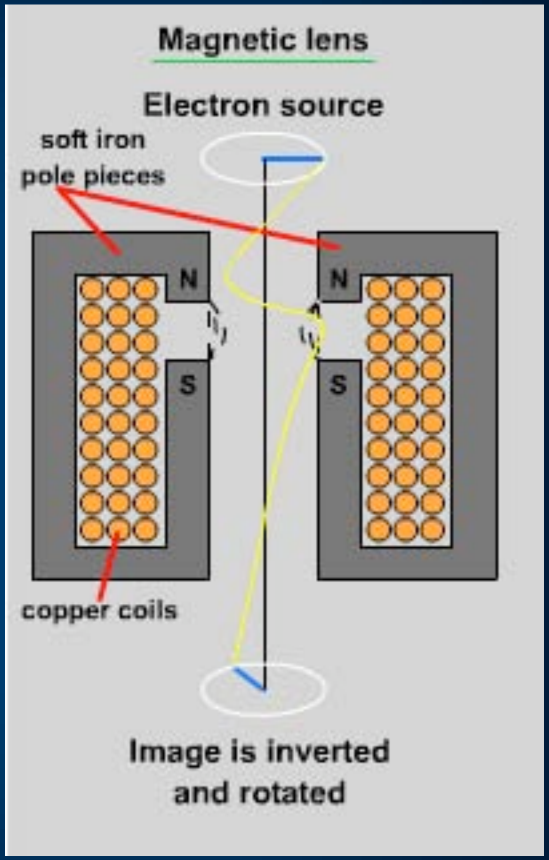
$$\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i}$$

$$M = -\frac{d_i}{d_o}$$

Thin Lens Formulae



Focus achieved using Refraction



Focus achieved using Lorentz Force

Electron Lenses

Electrons are charged particles and are influenced by Electromagnetic Fields. Lenses in an TEM/STEM utilize either or combinations of Magnetic and Electrostatic Fields to direct the beams as desired.

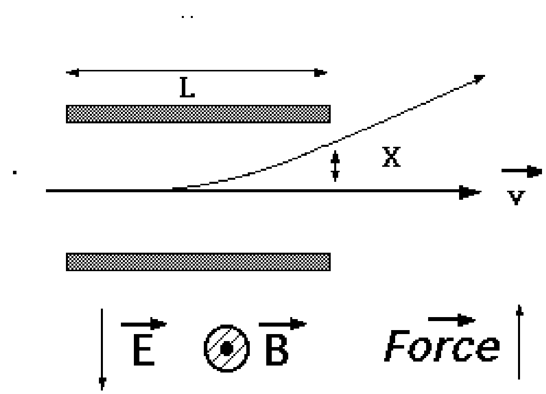
Force (F) and displacements (X) on electrons by different types of fields yields a deflection in their trajectory. In a uniform field region the electrons drift at a characteristic radius (R).

Electrostatic

$$\vec{F_E} = q\,\vec{E} \qquad X_E = \frac{1}{2}\frac{qEL^2}{m_o v^2} \qquad R_E = \frac{m_o v^2}{qE}$$

Electromagnetic

$$\vec{F_B} = q\left[\vec{v} \times \vec{B}\right] \qquad X_B = \frac{1}{2}\frac{qBL^2}{m_o v} \qquad R_B = \frac{m_o v}{qB}$$



Lenses

- the focal length is given by:

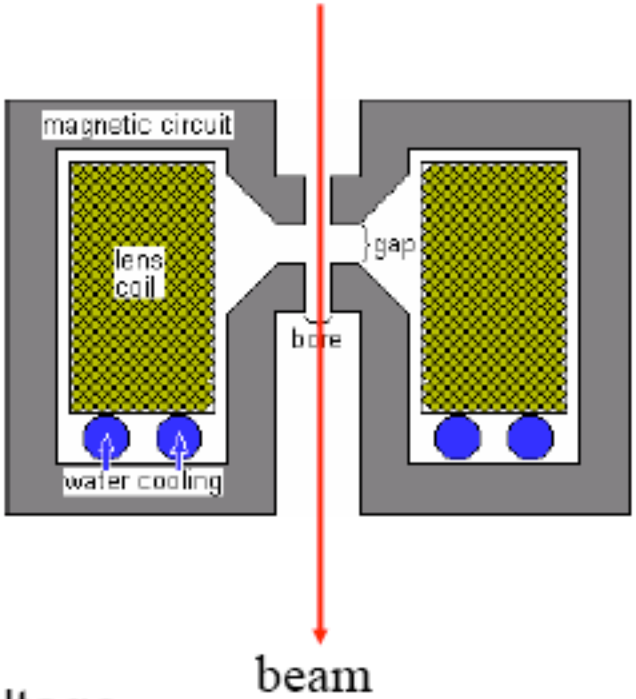
$$f = \frac{K \cdot U}{(N \cdot I)^2}$$

K : constant

U : accelerating voltage

N : windings

I : lens current



Types of Electron Lenses

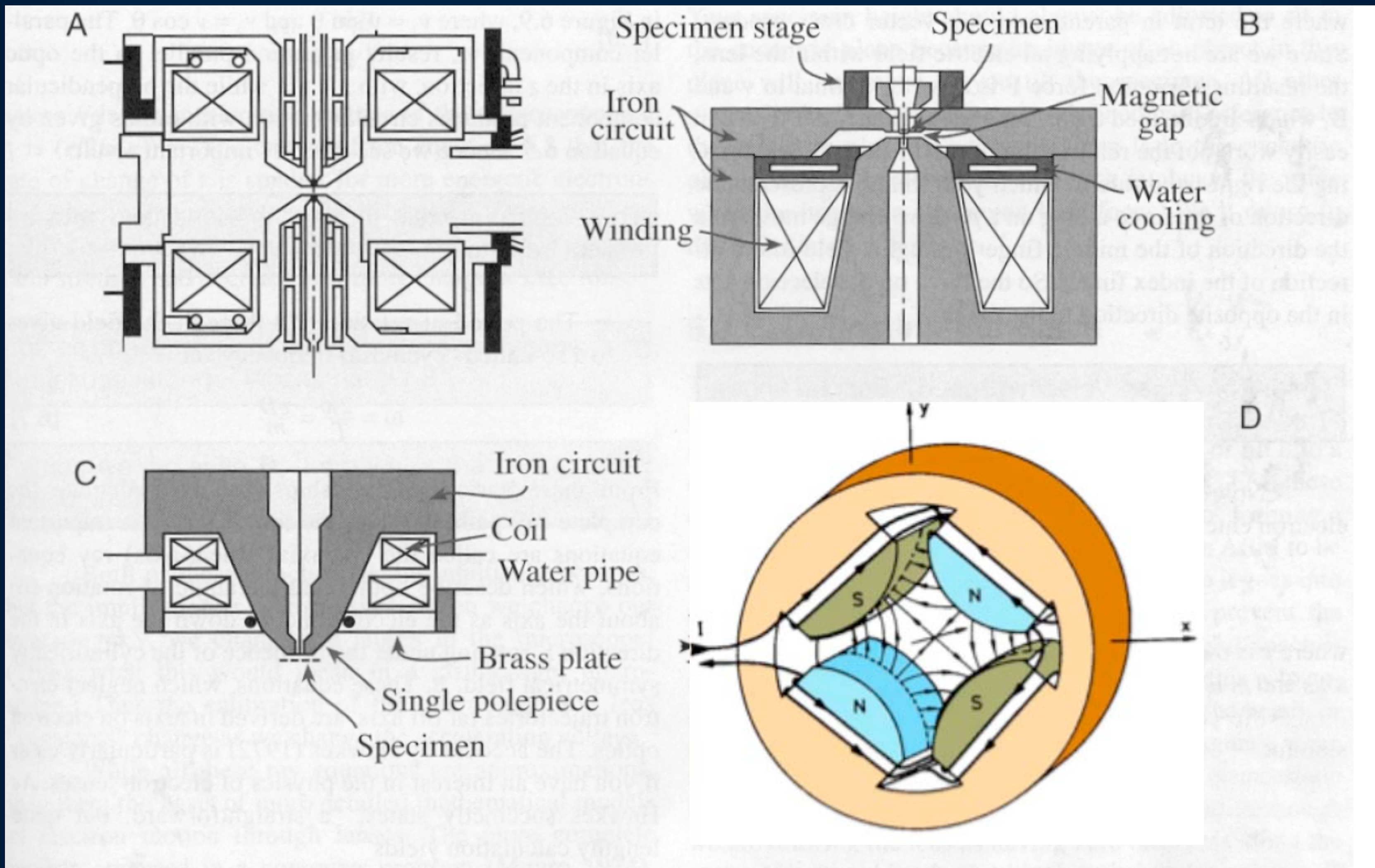
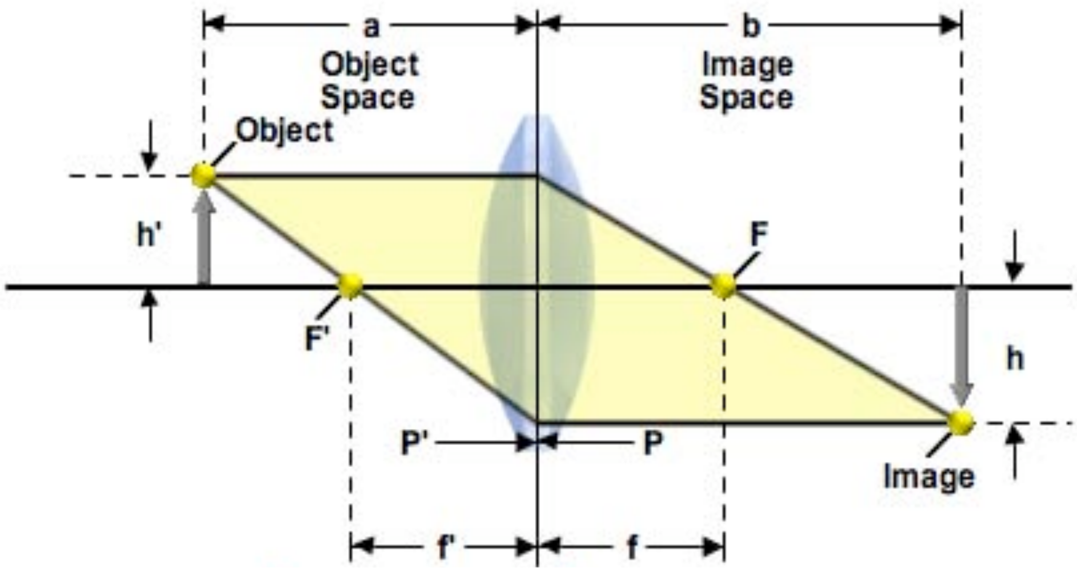


Figure 6.8. A selection of different lenses: (A) a split polepiece objective lens, (B) a top-entry immersion lens, (C) a snorkel lens, and (D) a quadrupole lens.

Condenser Lenses ~ Type A, Objective Lenses ~ Type A B or C, Stigmators Type D

How Does a Lens Work as a Magnifier?



$$\frac{1}{f} = \frac{1}{a} + \frac{1}{b}$$

$$M = \frac{h}{h'} = -\frac{b}{a}$$

In a TEM the function of lens are to either demagnify the probe from the source point to the sample. This means that b < a resulting in a smaller electron probe. Or to Magnify an Image b > a

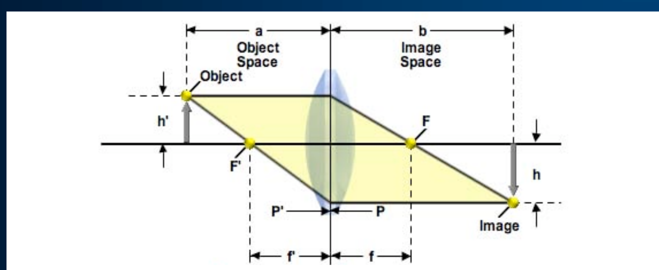
Magnification is achieved by

Stacking Lenses

$M = M_1 * M_2 * M_3$

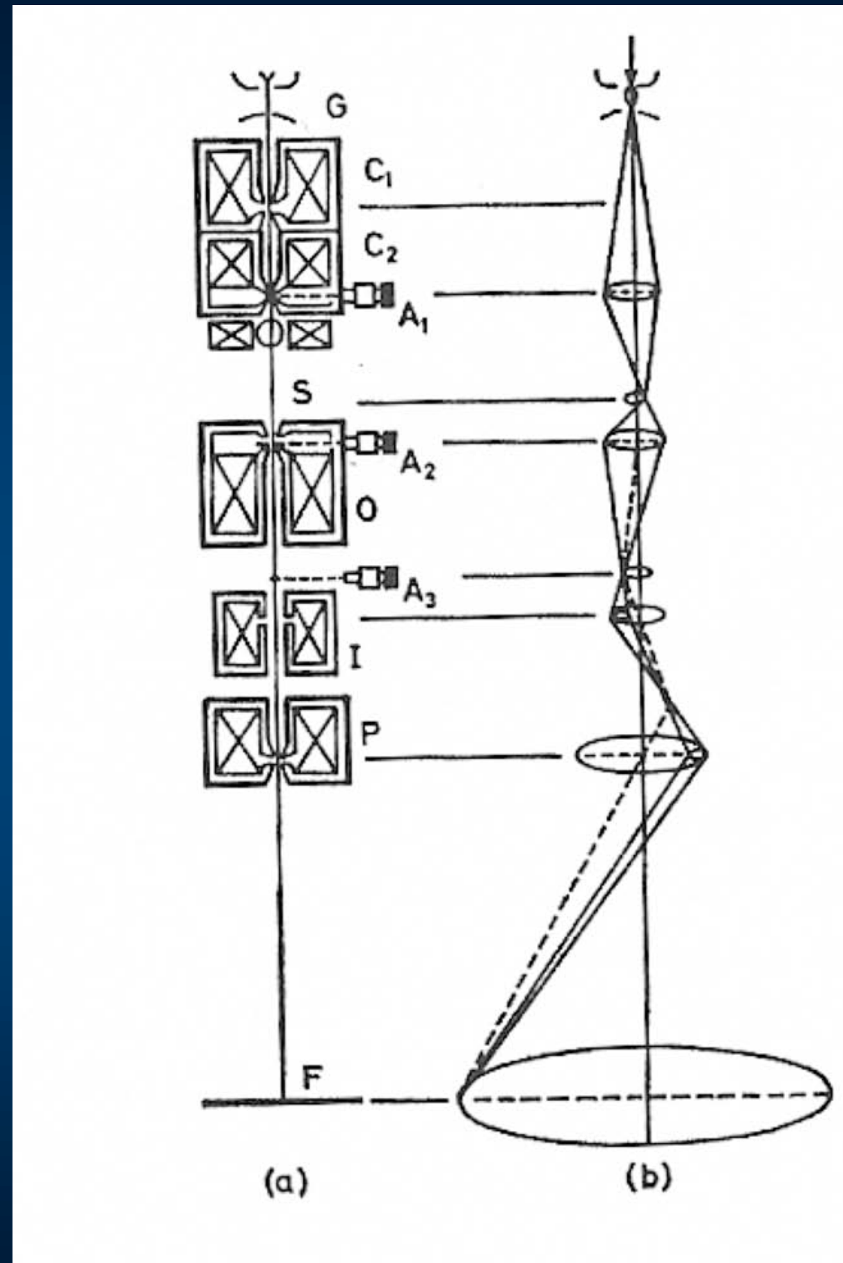
How Accurate is M ?

What are the limiting Factors?



$$\frac{1}{f} = \frac{1}{a} + \frac{1}{b}$$

$$M = \frac{h}{h'} = -\frac{b}{a}$$



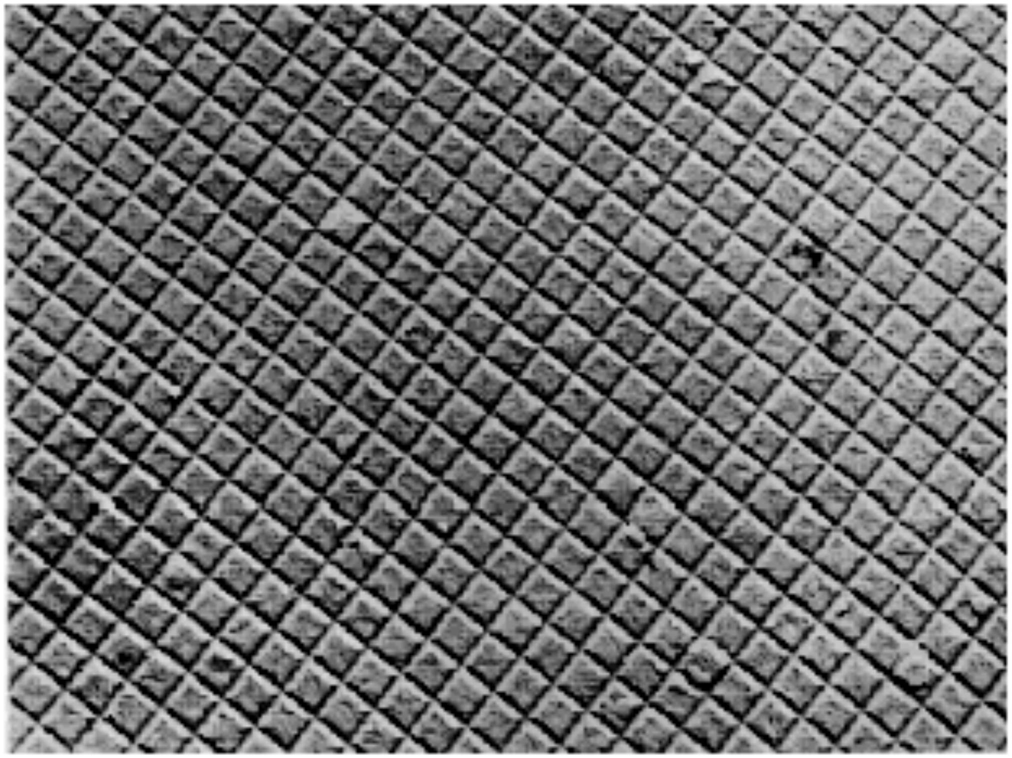
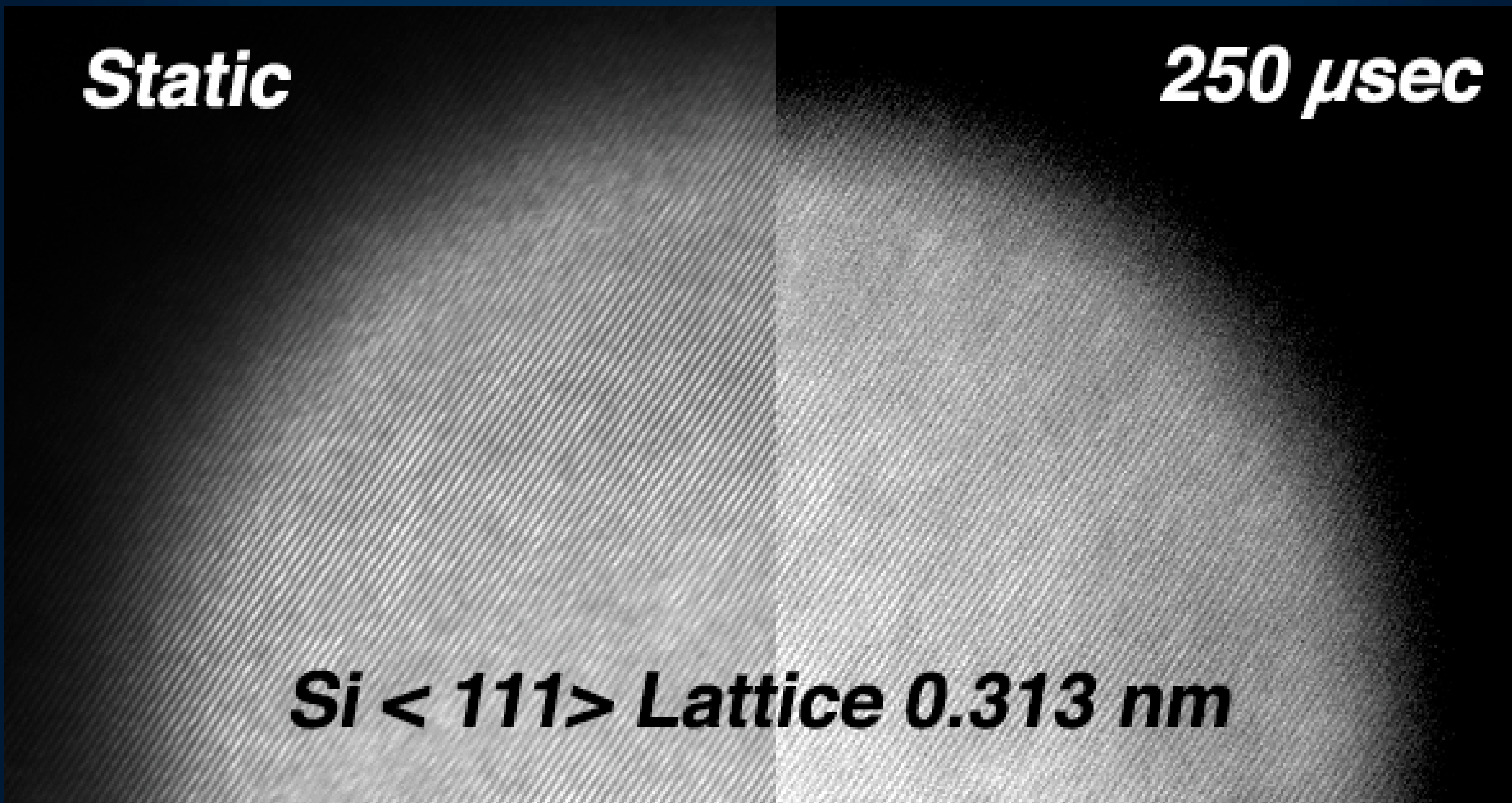
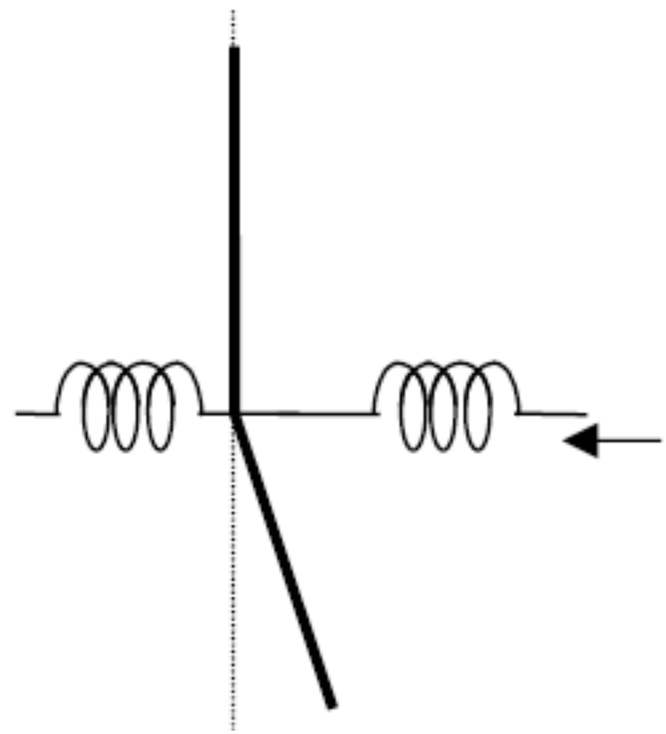


Fig. I.130. Replica of cross-ruleddiffraction grating with 2160 lines/mm used as a calibration specimen.(From Agar, p.162)


Static
250 µsec
Si < 111> Lattice 0.313 nm

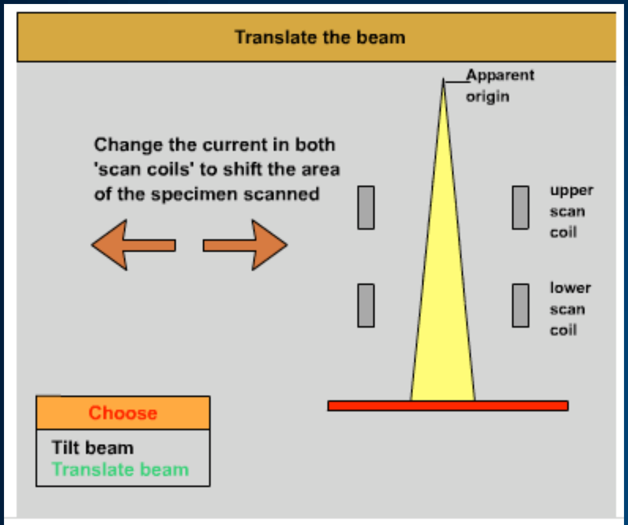
Deflection Coils

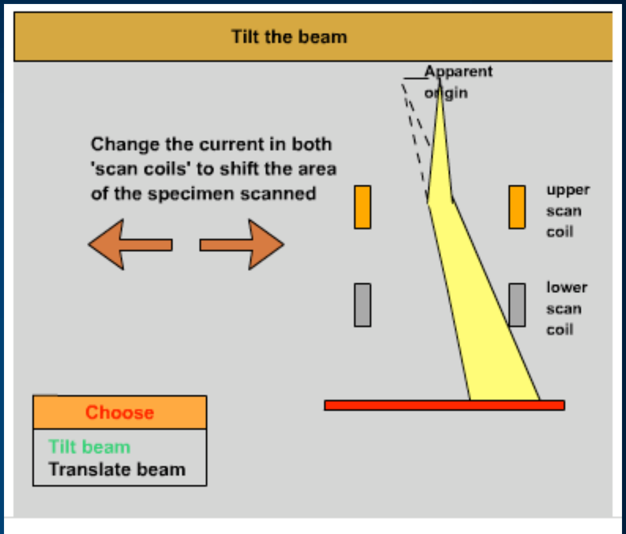
- Basic Principle
  - Gun coils
  - Beam coils
  - Image coils
  - Scanning coil
  - ....
  - ......

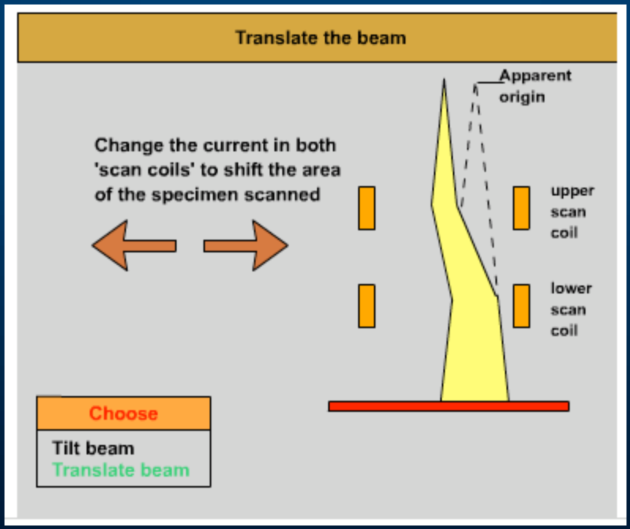


$$\vec{F}_B = q\left[\vec{v} \times \vec{B}\right] \qquad X_B = \frac{1}{2}\frac{qBL^2}{m_o v}$$

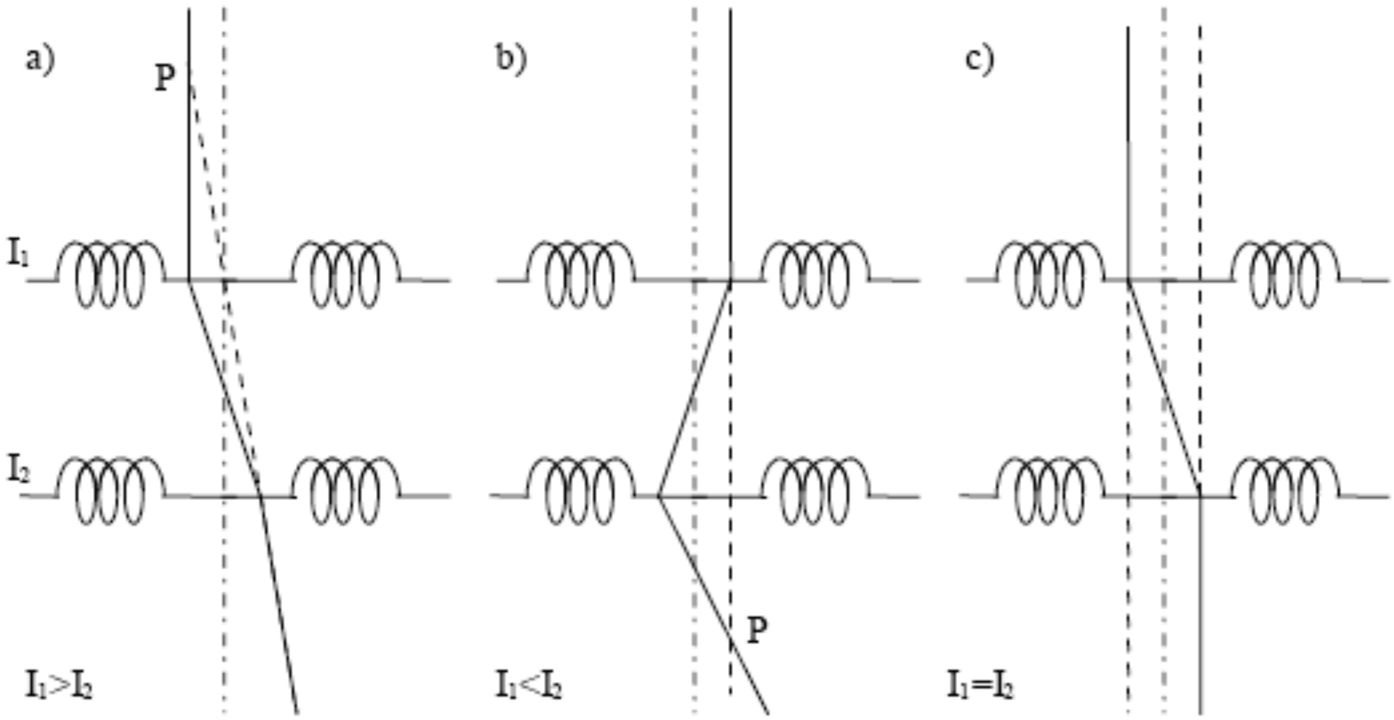
Alignment/Deflection Coils also use Lorentz Fields but they are not axially symmetric







Deflection Coils

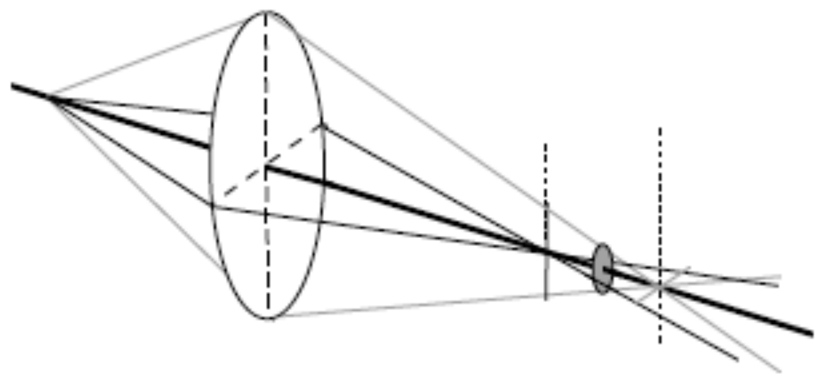


Tilting the Beam

Translating the Beam

Astigmatism

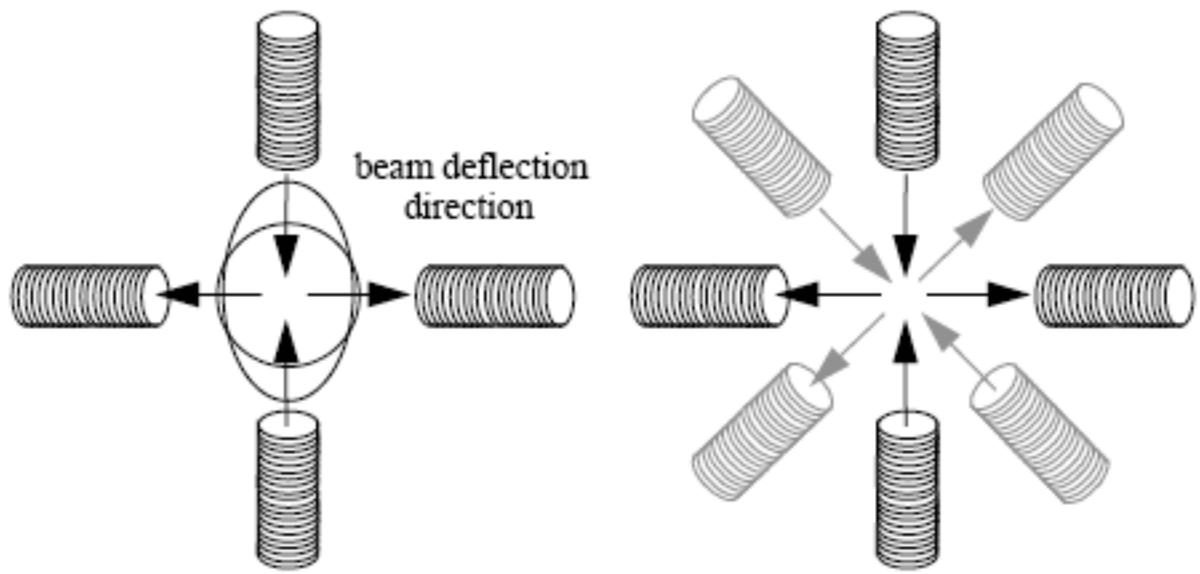
- Lens defect caused by magnetic field asymmetry

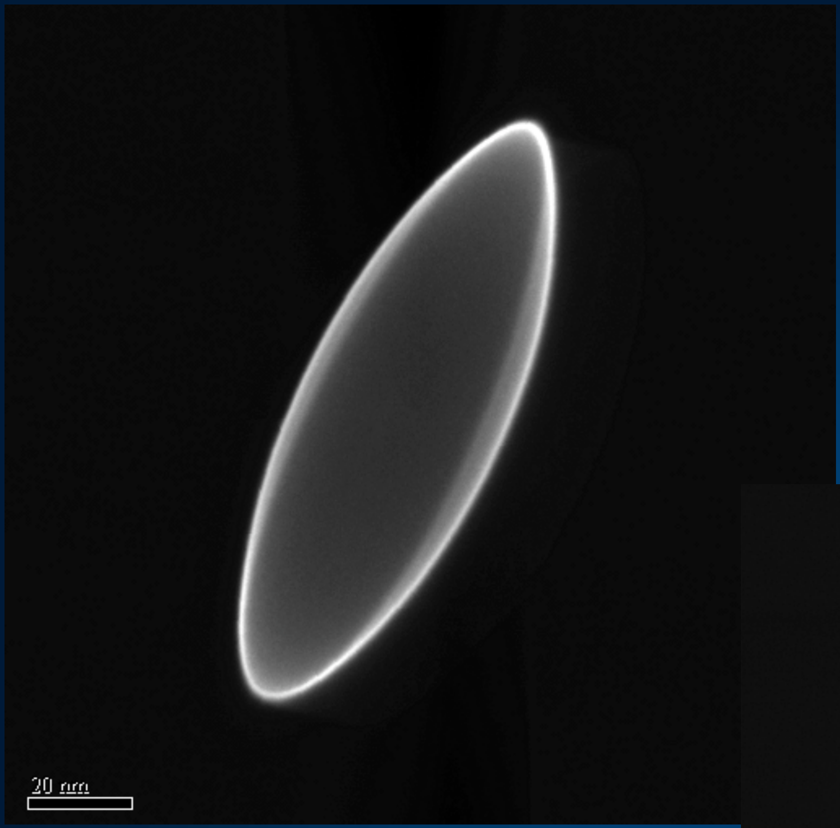


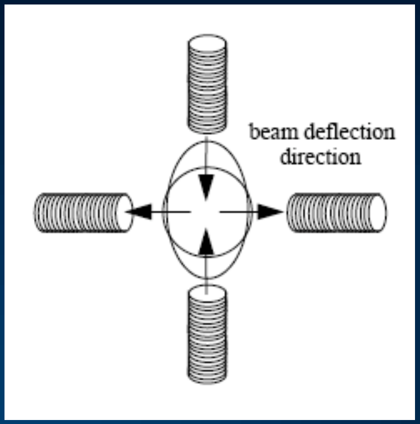
- can be corrected using stigmators!

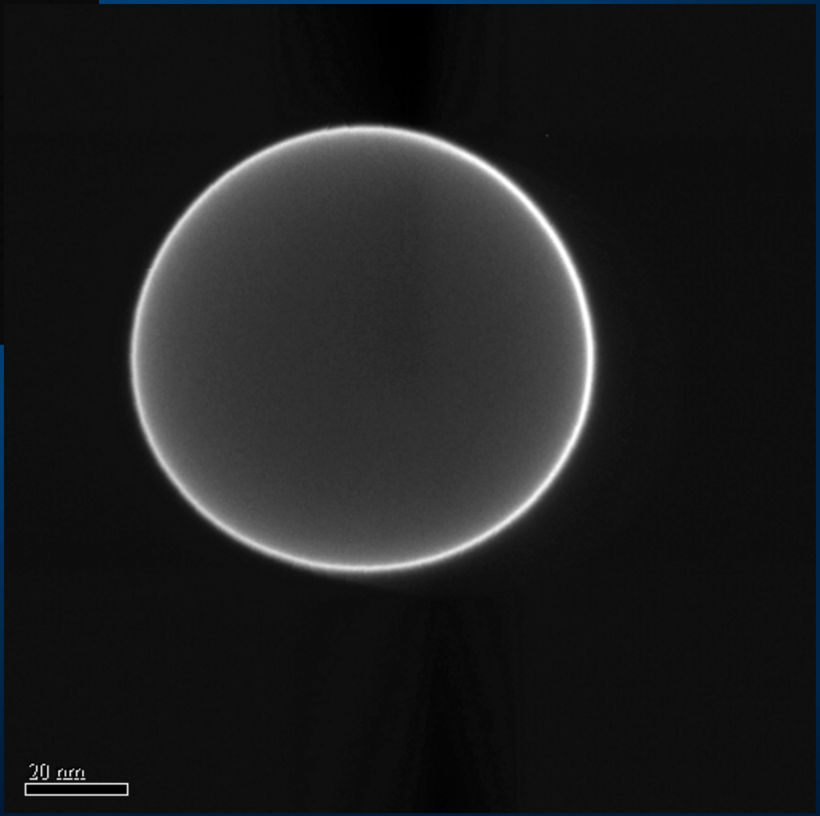
Stigmators

- Working Principle

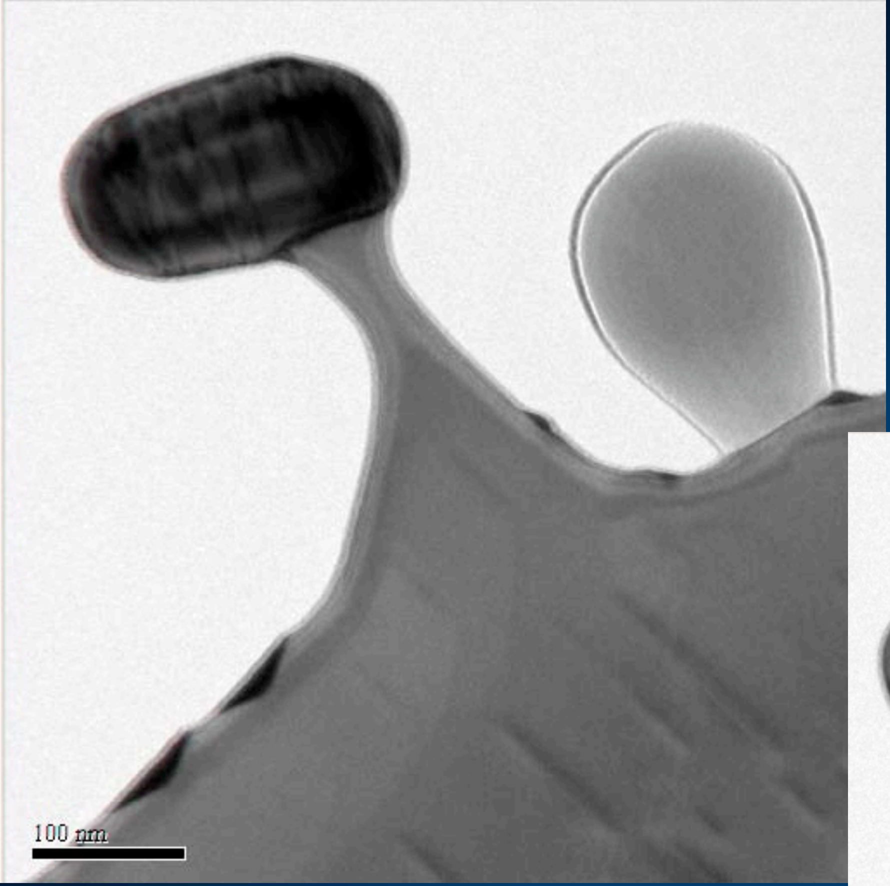


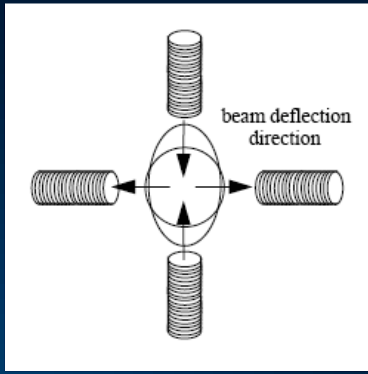






Probe Astigmatism





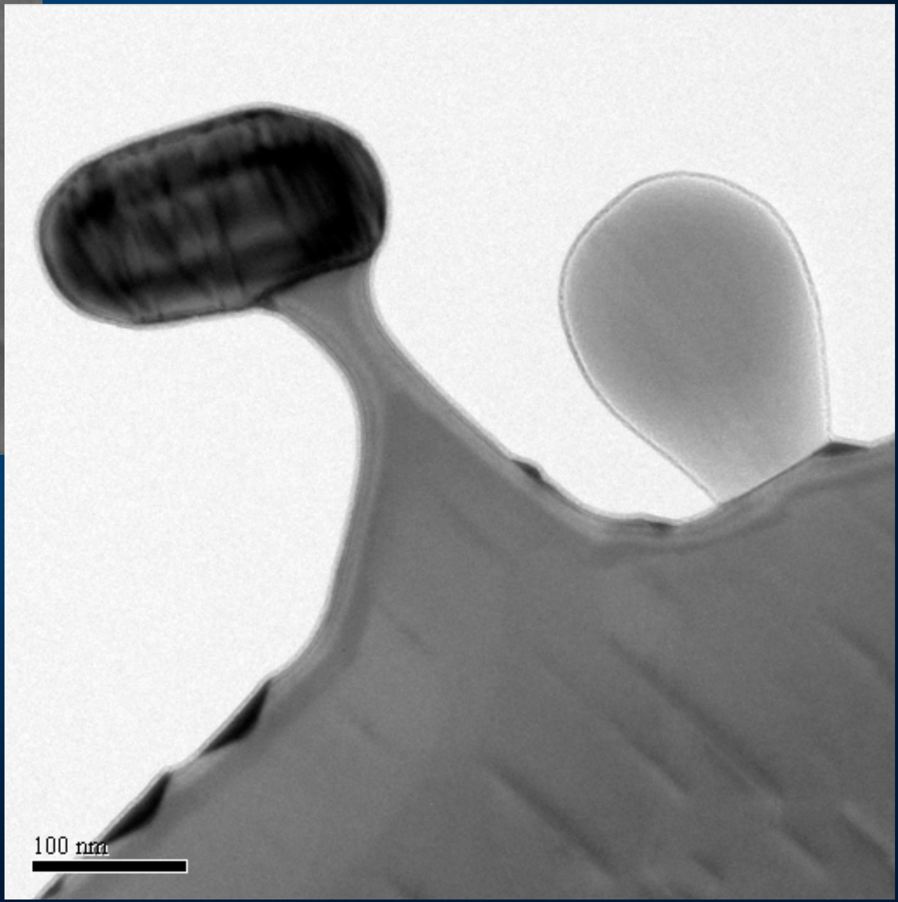


Image Astigmatism

Roles of the Lenses

Gun Lens

Helps form probe

Condenser Lens

Mainly controls:
Spot Size
hence total beam current

Objective Lens

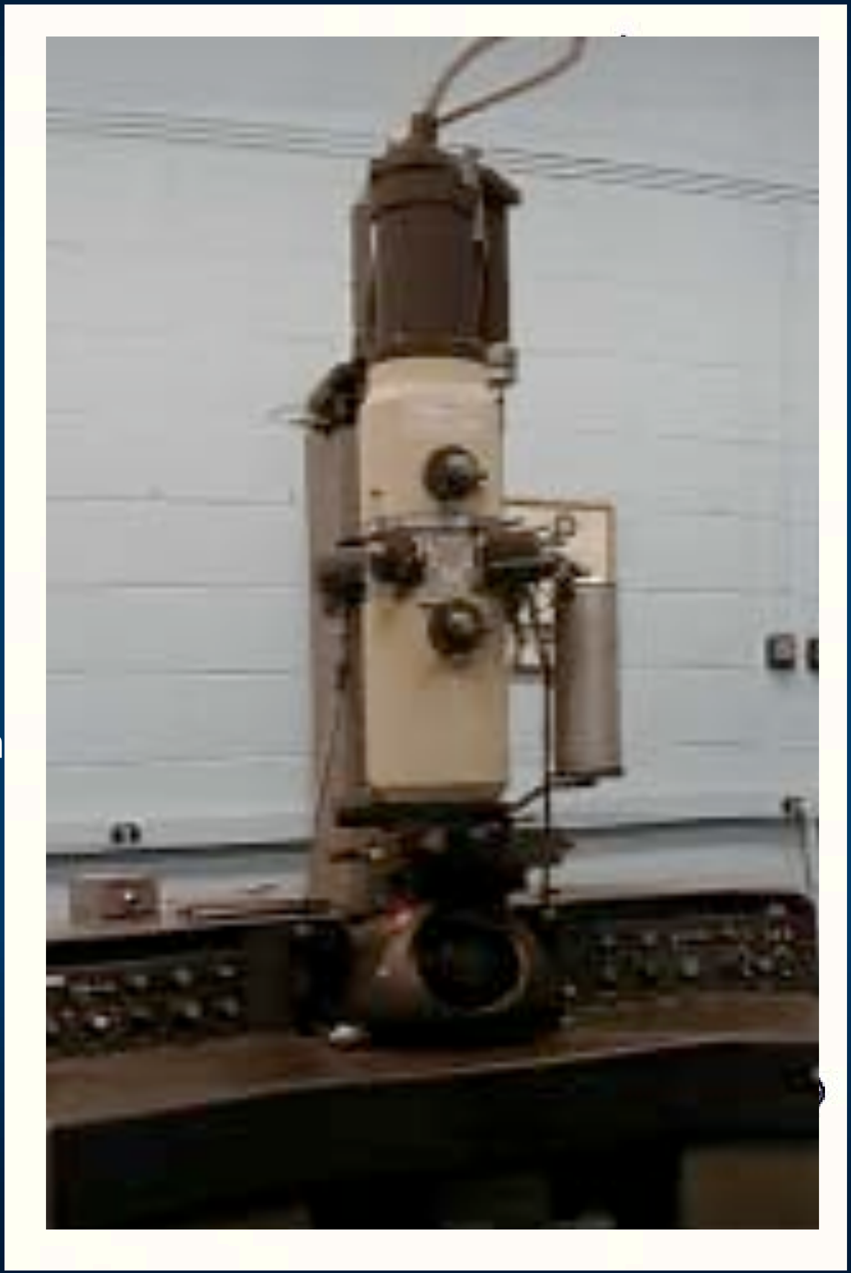
Mainly controls
Focus, 1st Magnification

Diffraction/Intermediate Lens

Controls Mode

Projector Lens

Magnification



Most TEM/STEM have 7-8 Lenses

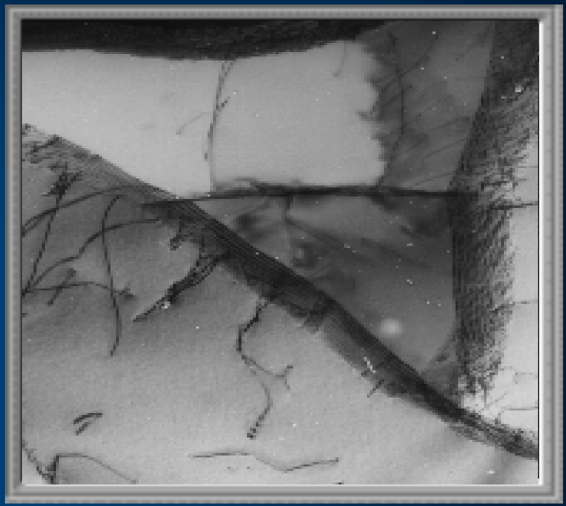
1 Gun Lens
2 Condensers
1 Objective
1-2 Intermediate
1-2 Projectors

Most instruments have only Electromagnetic Round Lenses

Note the locations of the various Apertures.

Optimum aperture sizes are needed for various imaging functions.

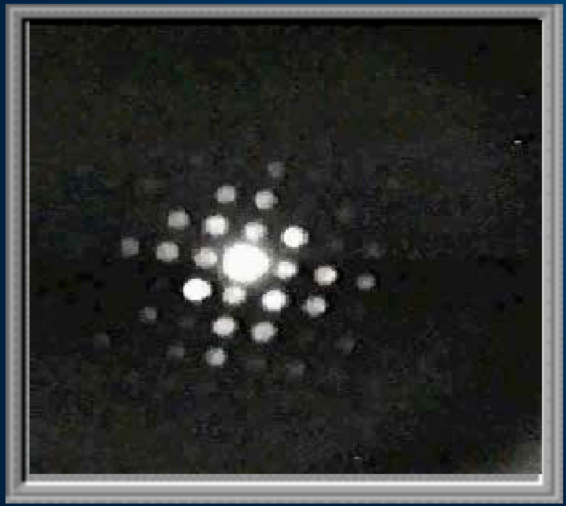
Transmission Electron Microscopy

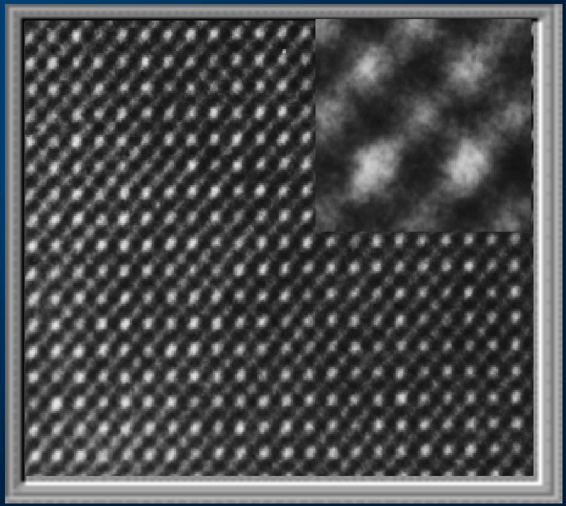


Conventional Imaging

High Resolution Imaging

Diffraction





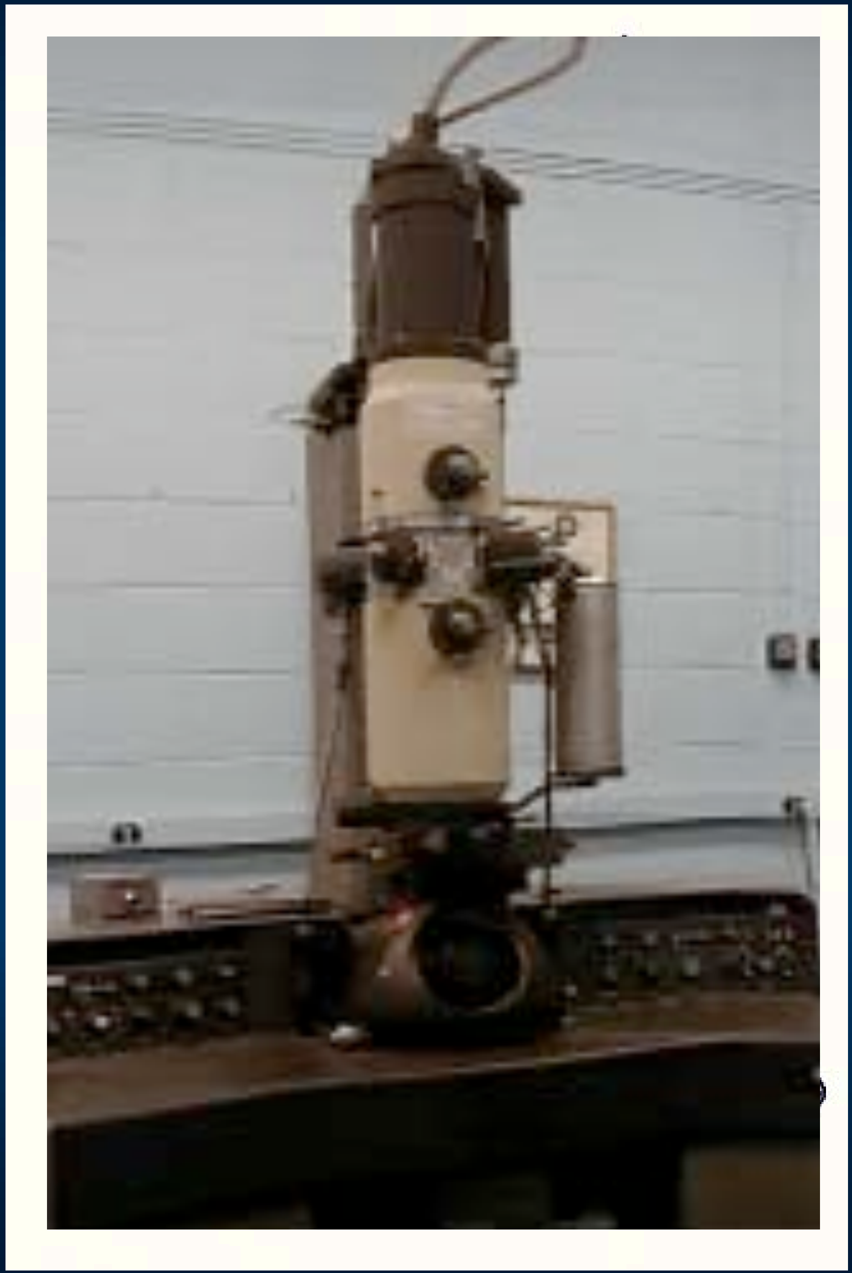
Roles of the Lenses

Gun Lens

Helps form probe

Condenser Lens

Mainly controls:
Spot Size
hence total beam current



Most TEM/STEM have 7-8 Lenses

2 Condensers
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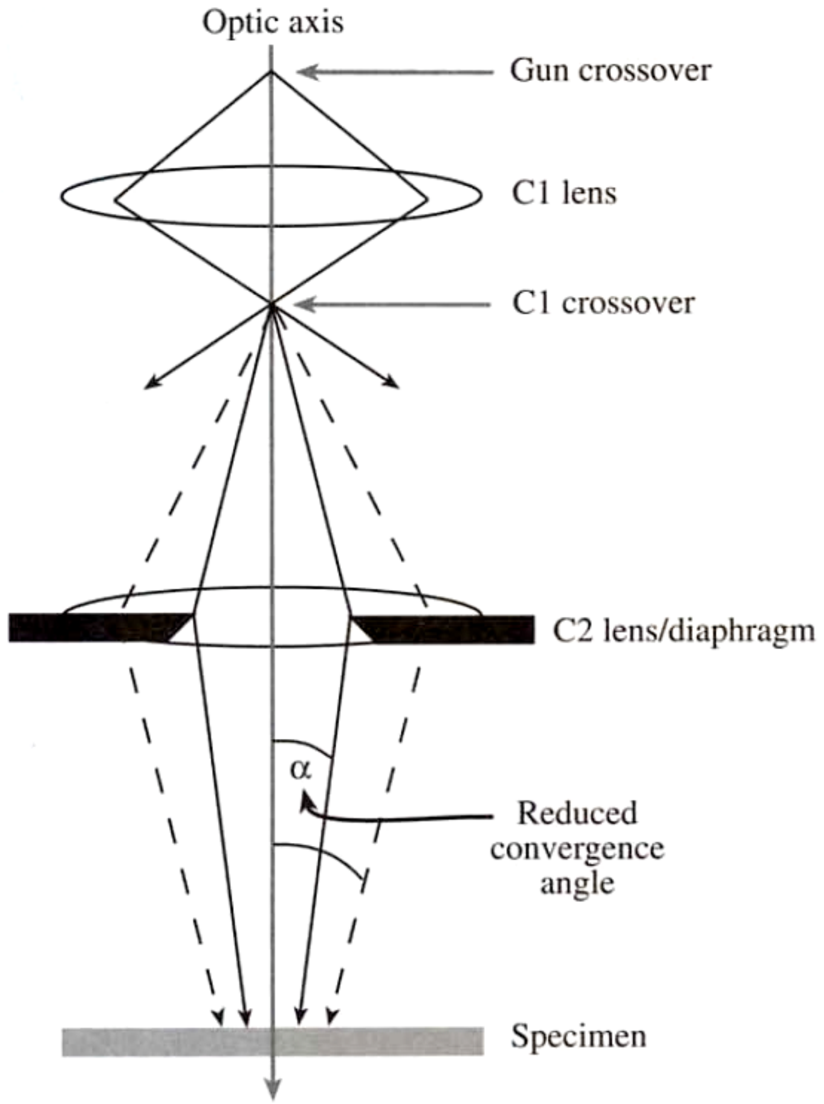


Figure 9.2. Effect of the C2 aperture on the beam coherence: a smaller aperture creates a more parallel, more coherent beam.

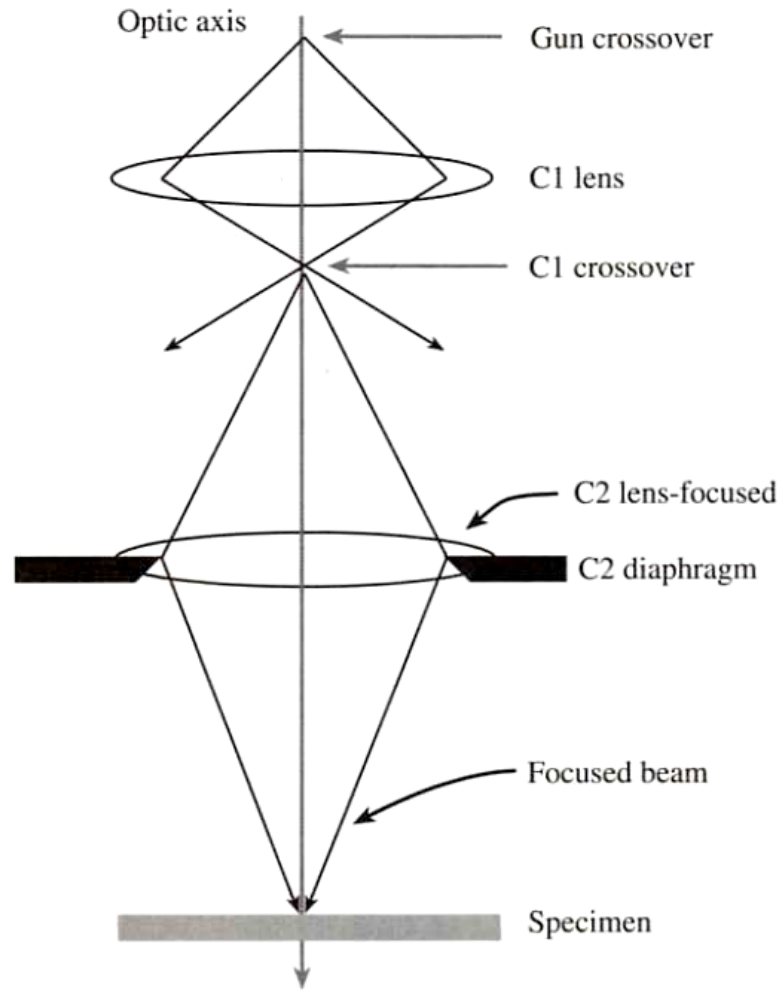


Figure 9.3. A focused C2 lens illuminates a small area of the specimen with a nonparallel beam.

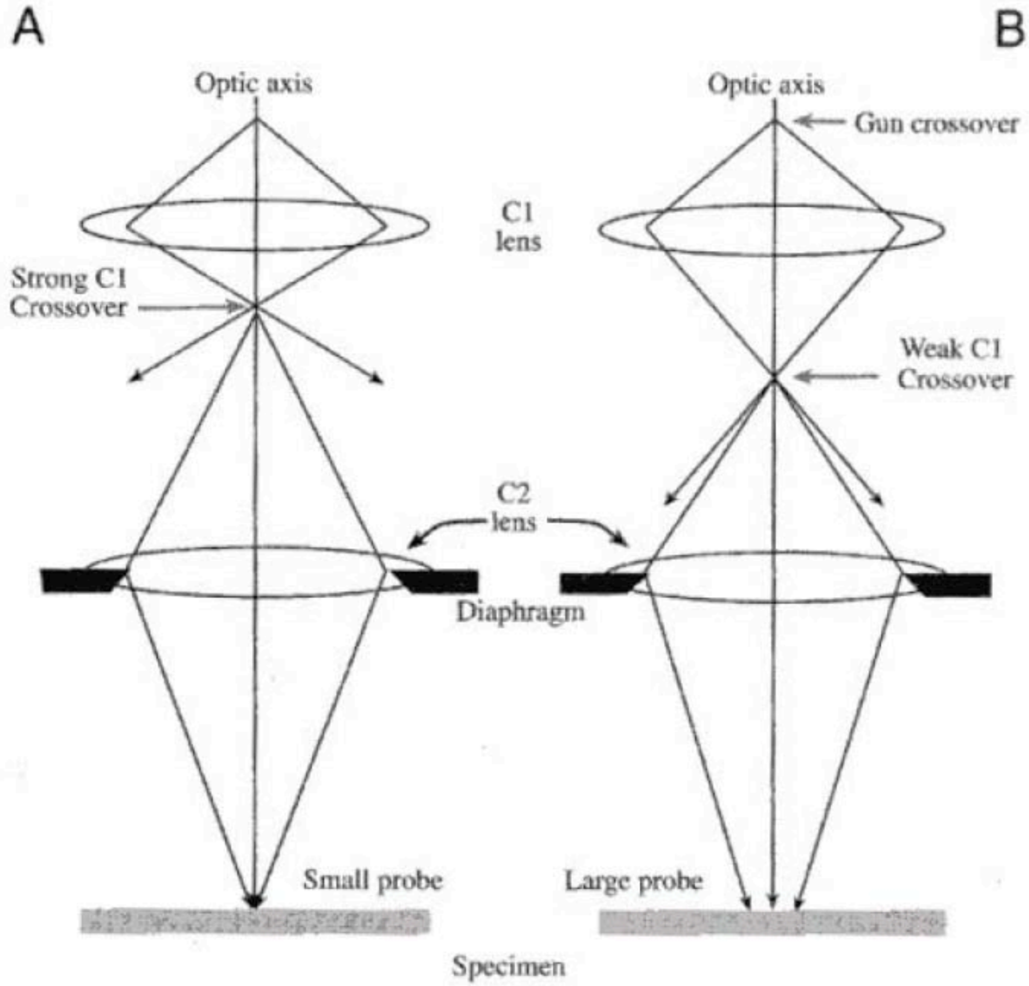


Figure 9.5. Effect of the C1 lens strength on probe size: a stronger C1 lens (A) results in greater demagnification by any subsequent lens (C2 or C3), giving a smaller electron beam at the specimen. A weaker lens (B) gives a broader probe.

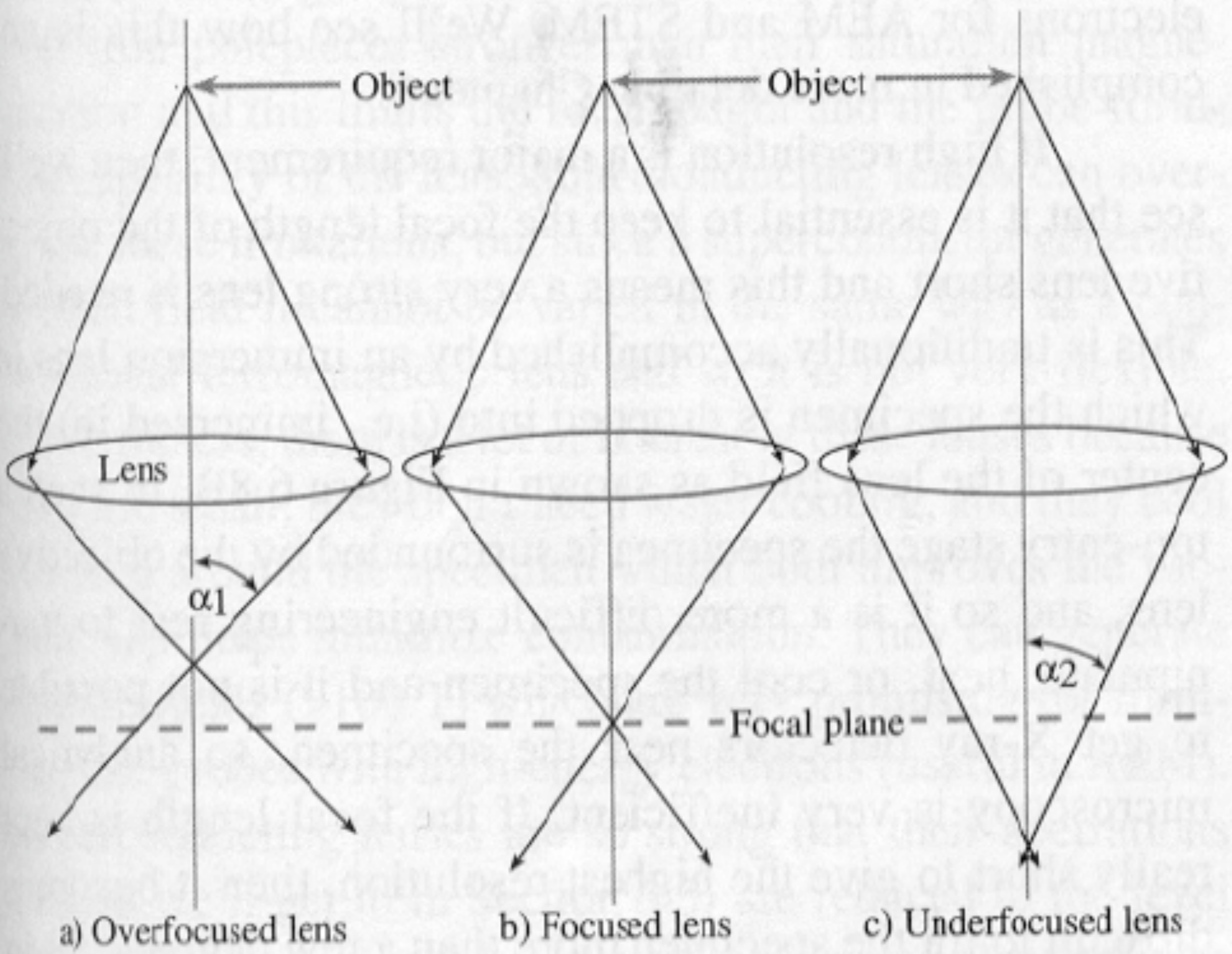
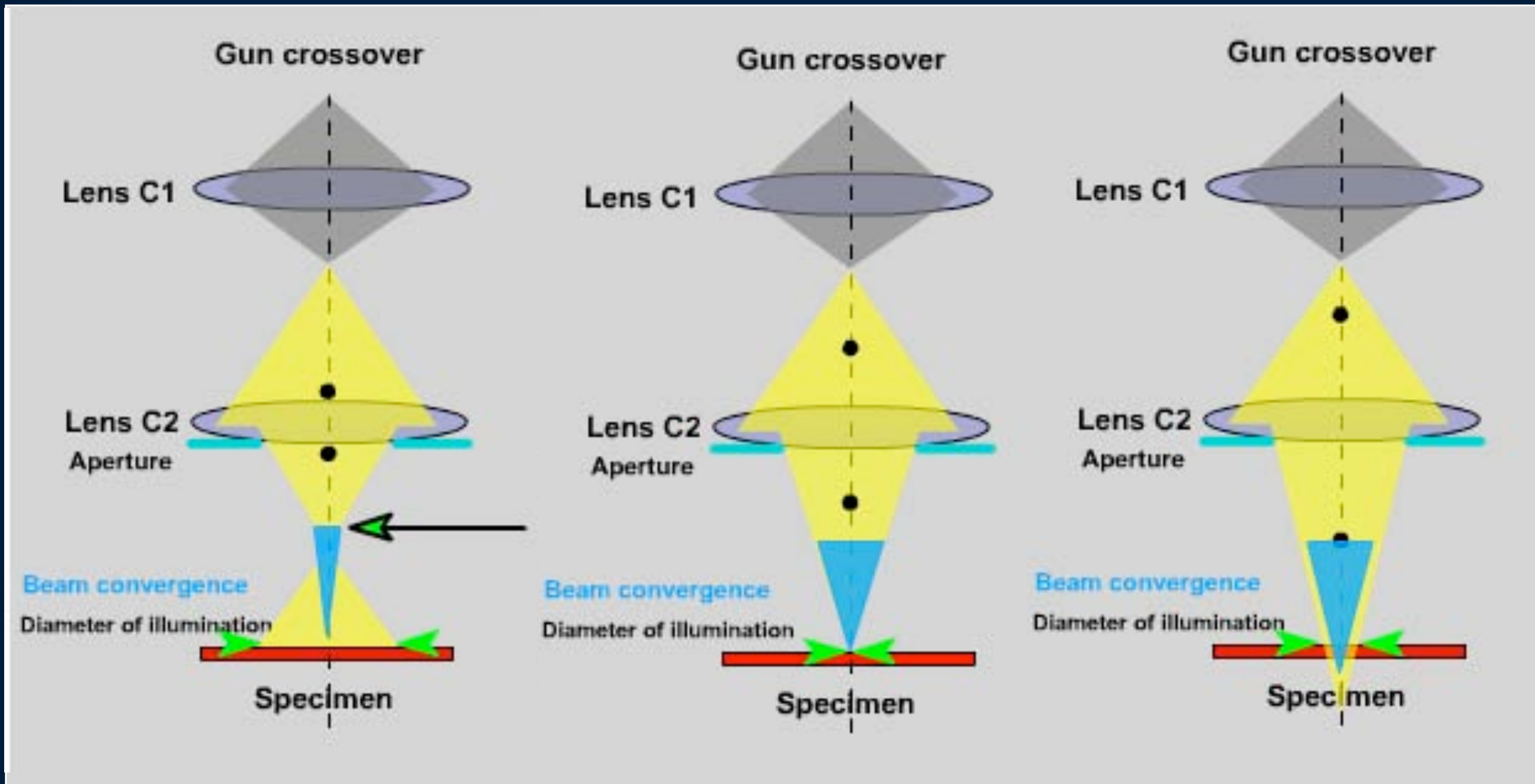


Figure 6.5. (a) Ray diagram illustrating the concepts of overfocus, in which a strong lens focuses the rays before the image plane, and (c) underfocus, where a weaker lens focuses after the image plane. It is clear from (c) that at a given underfocus the convergent rays are more parallel than the equivalent divergent rays at overfocus ($\alpha_2 < \alpha_1$).



Overfocused:
beam convergence
decreases substantially
because electrons
come from the
crossover only

Focused:
beam convergence is
at a maximum

Underfocused:
beam convergence
decreases slightly

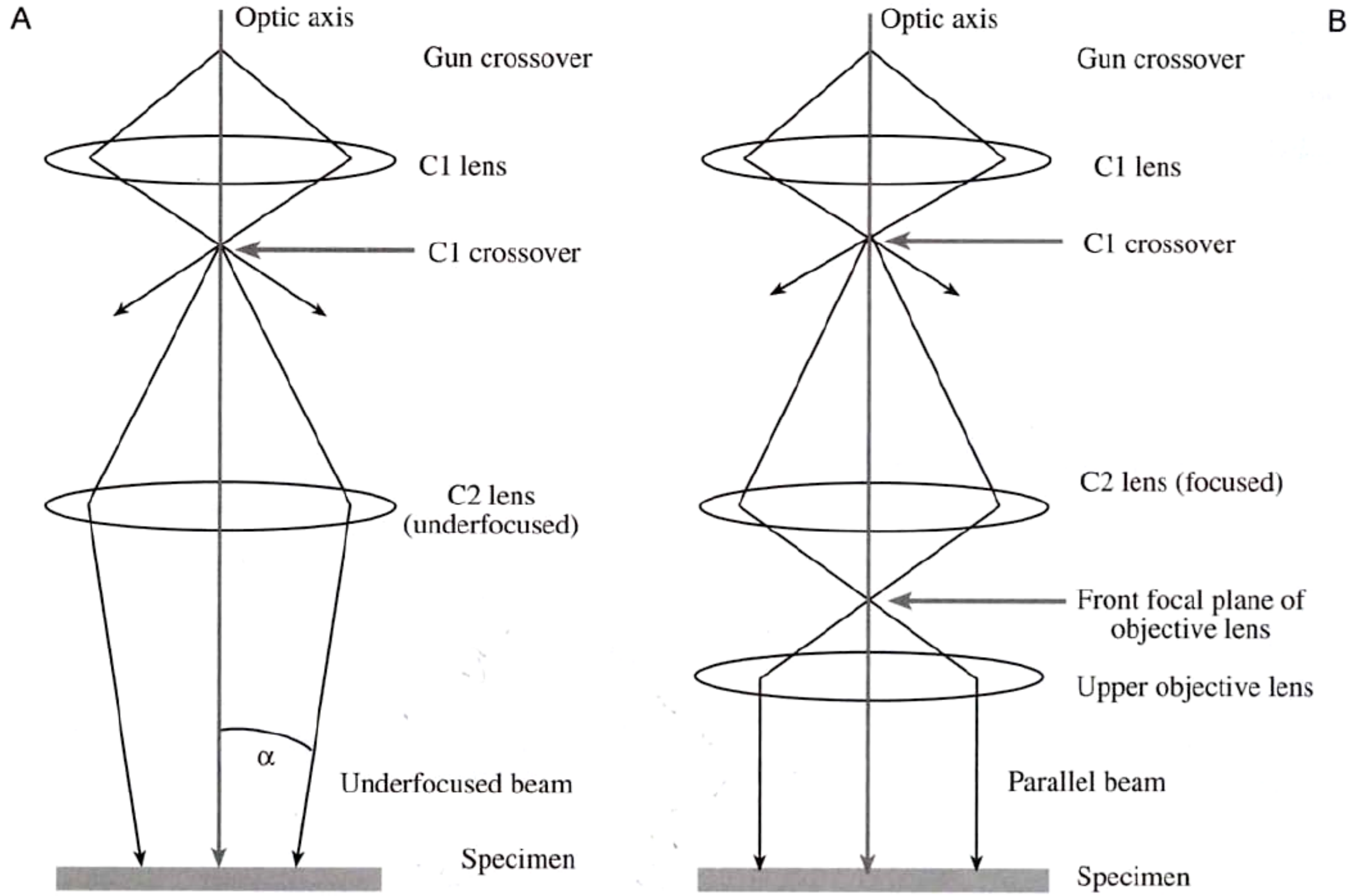
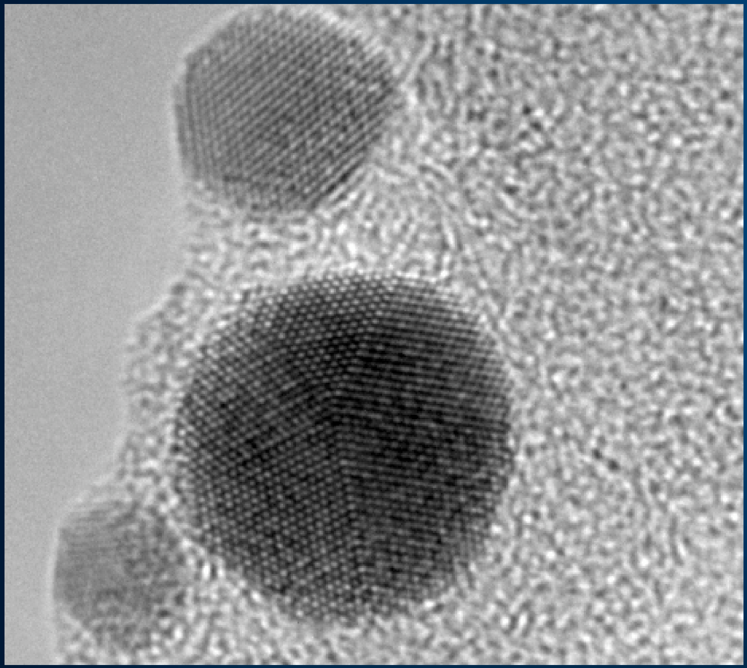
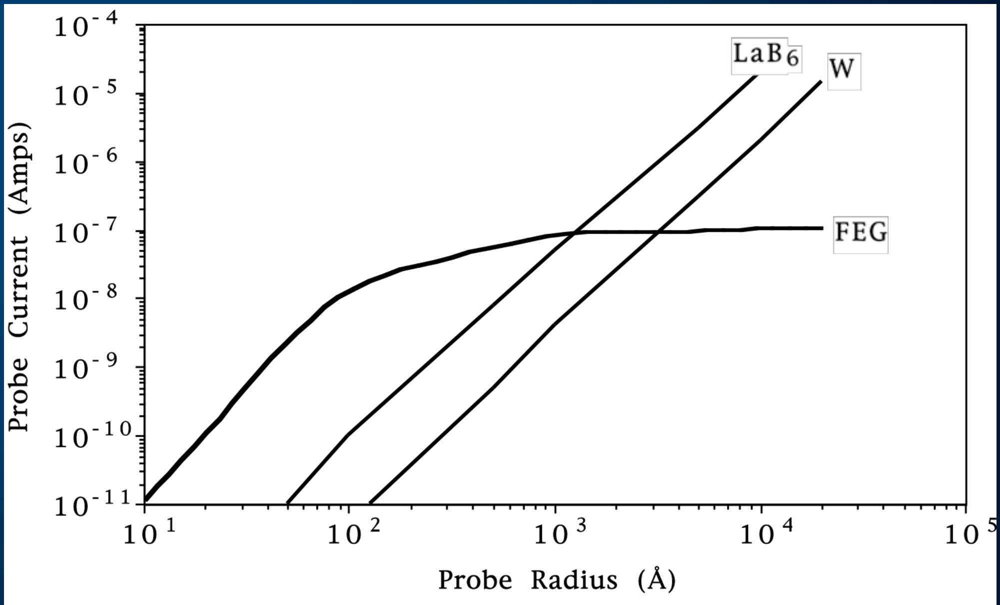


Figure 9.1. Parallel-beam operation in the TEM (A) using just the C1 and an underfocused C2 lens and (B) using the C1 and C2 lenses to image the source at the front focal plane of the upper objective lens.

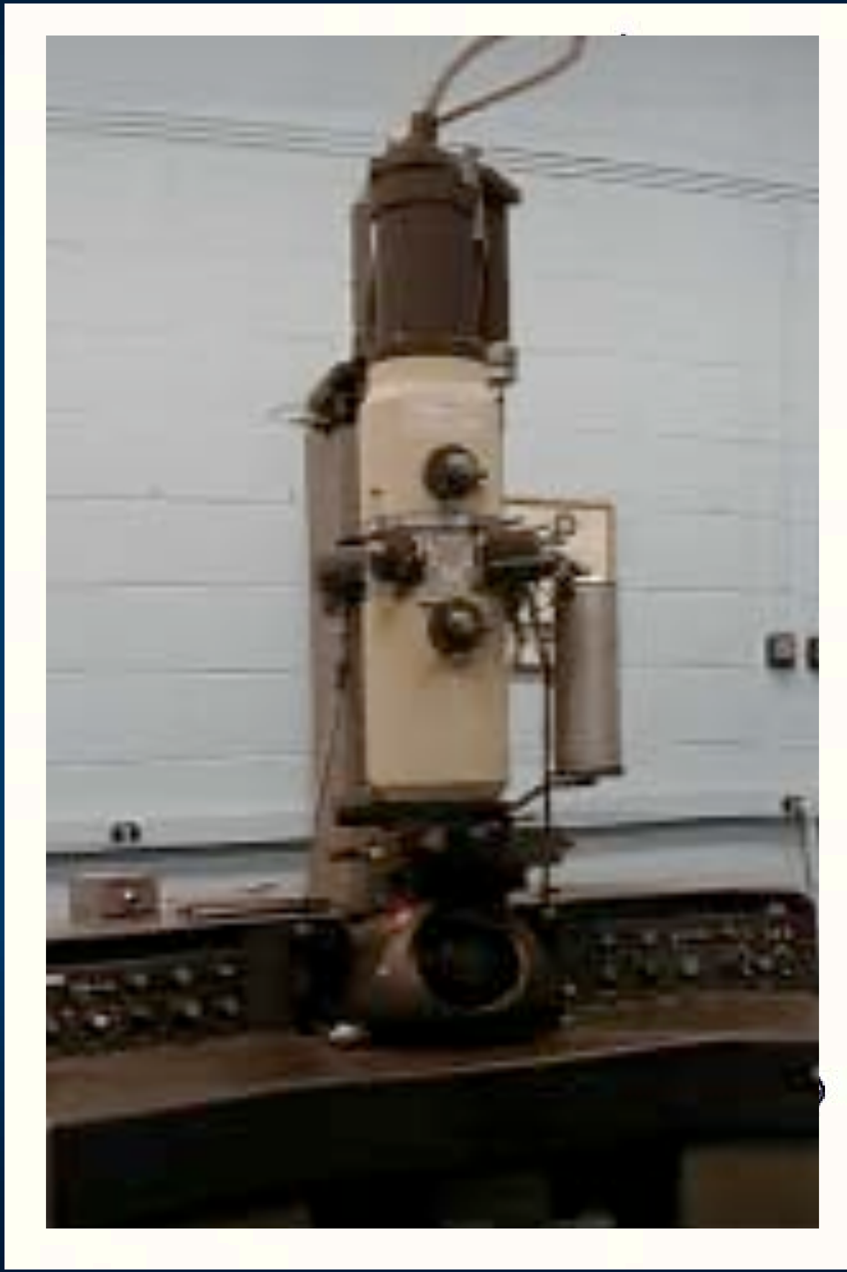
With Modern Instruments
Spectroscopy can be done at the Sub-Nanometer Scale

Selection of Probe Forming Source is Important





Roles of the Lenses



Objective Lens

Mainly control probe focus

Diffraction/Intermediate Lens

Controls Mode

Projector Lens

Magnification

Most TEM/STEM have 7-8 Lenses

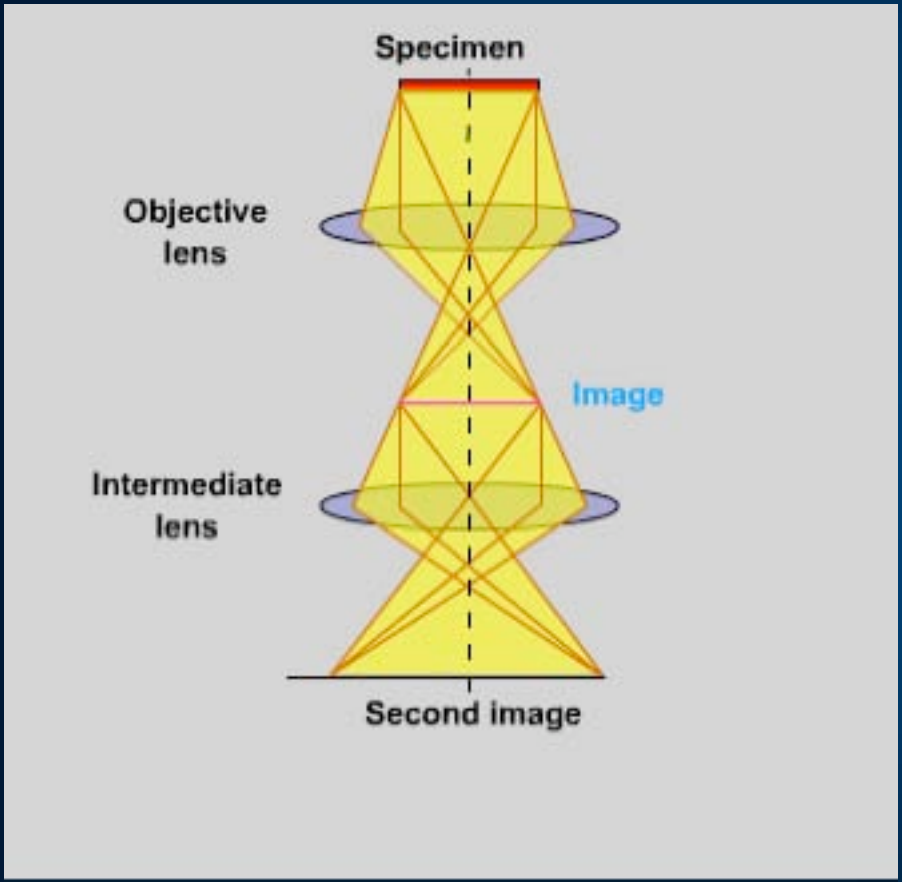
2 Condensers
1 Objective
1-2 Intermediate
2 Projectors

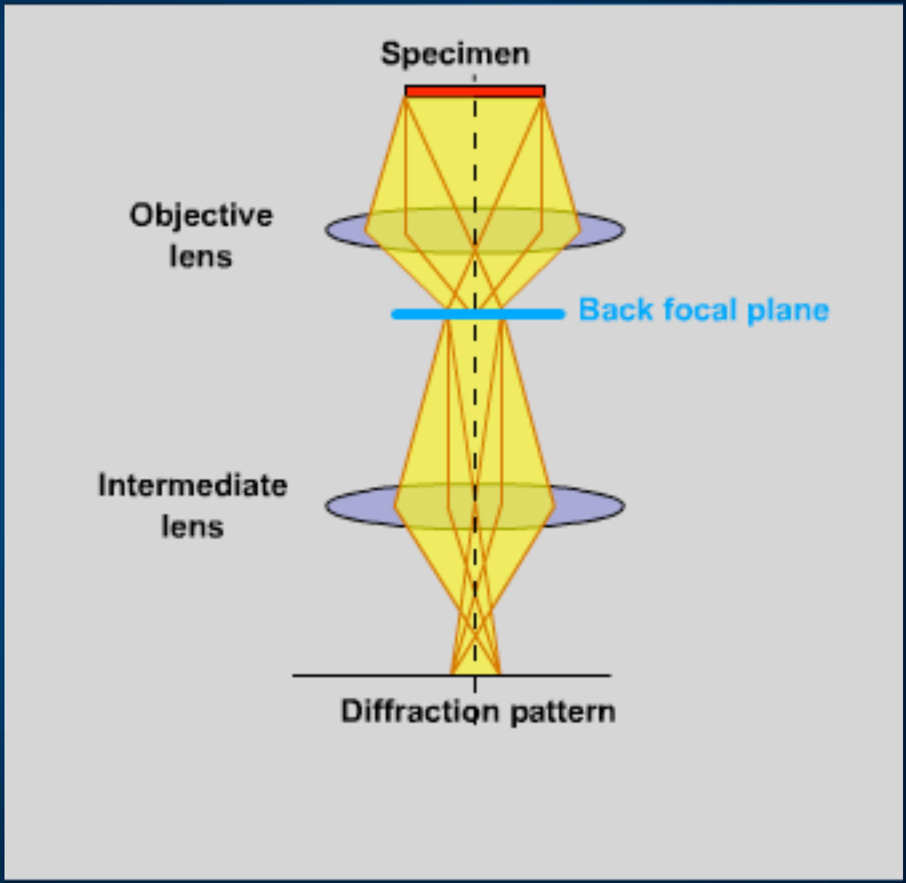
Most instruments have only Electromagnetic Round Lenses

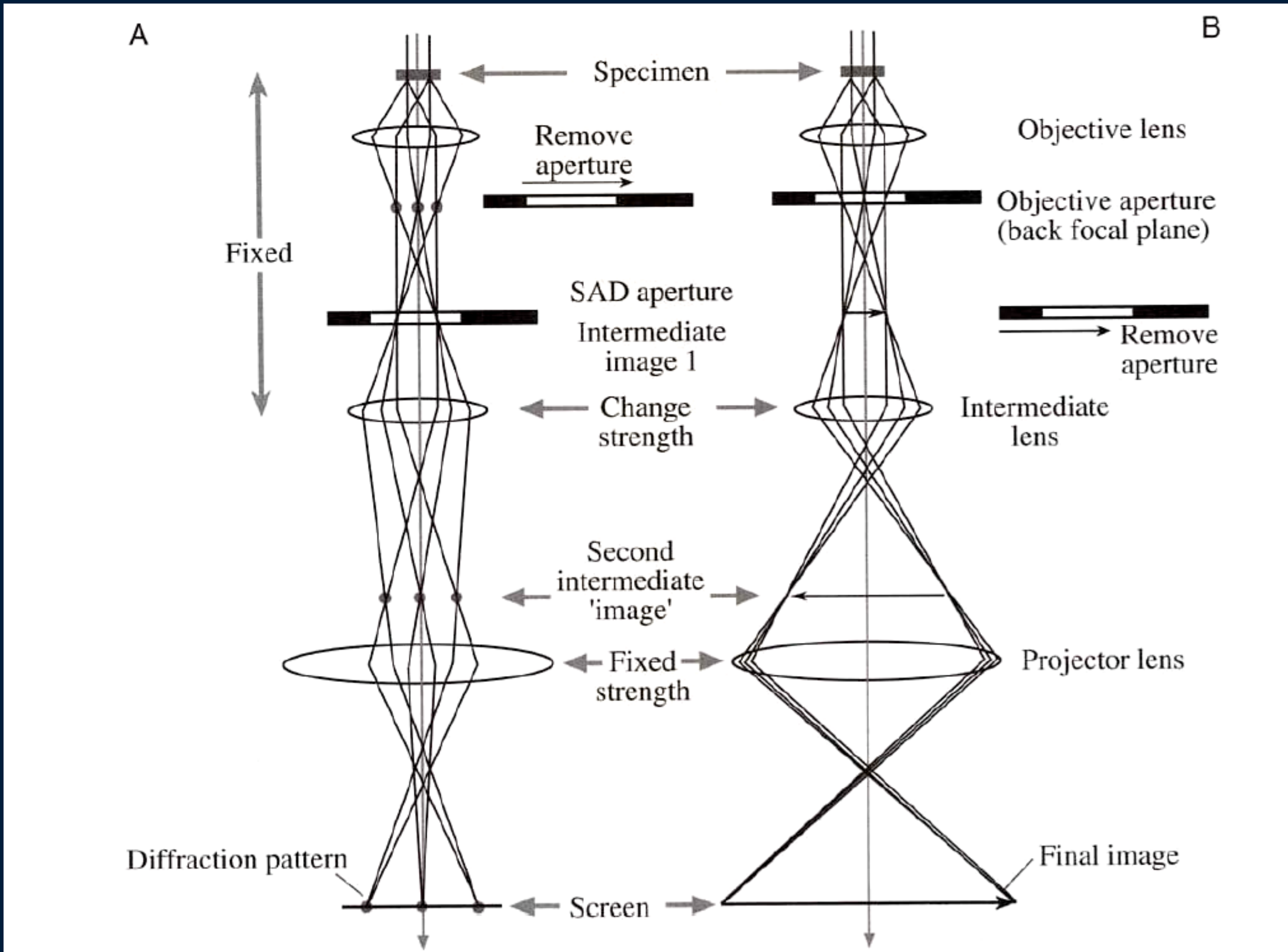
Note the locations of the various Apertures.

Optimum aperture sizes are needed for various imaging functions.

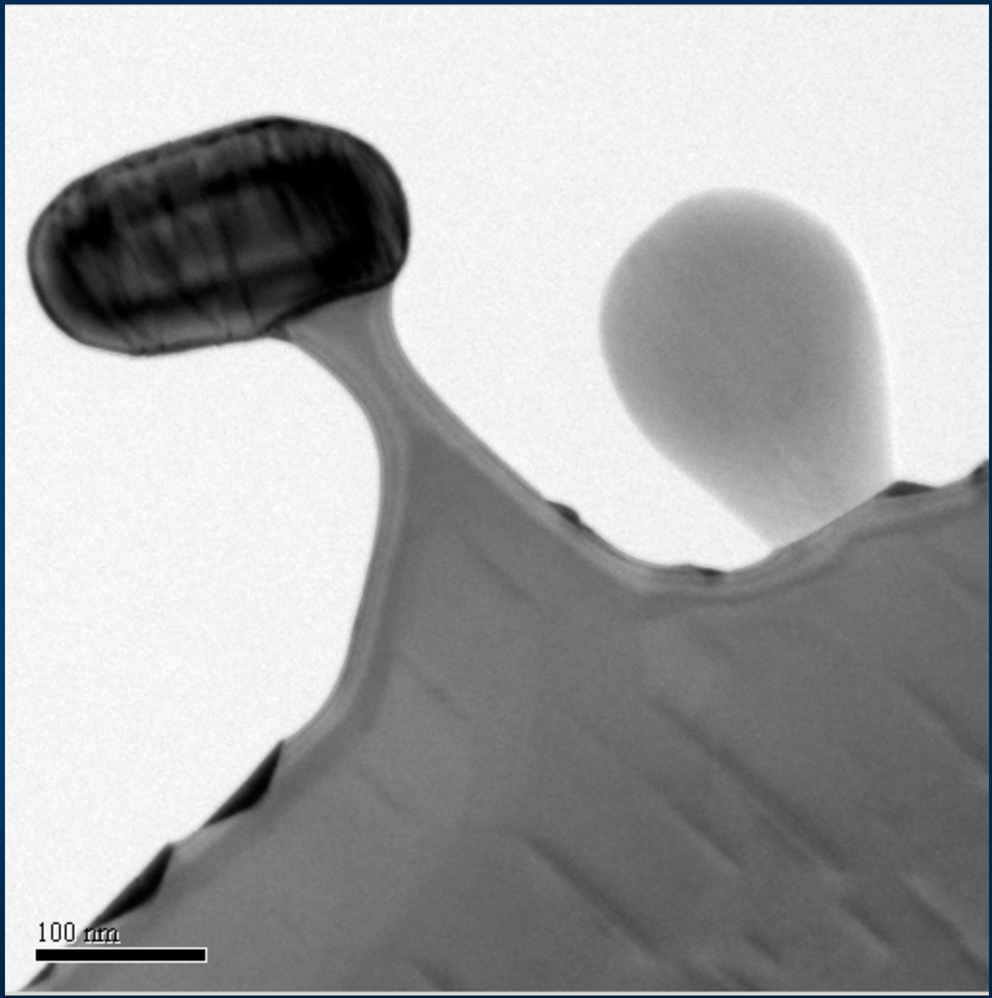
Imaging vs Diffraction:
Post Specimen Lenses determine the mode



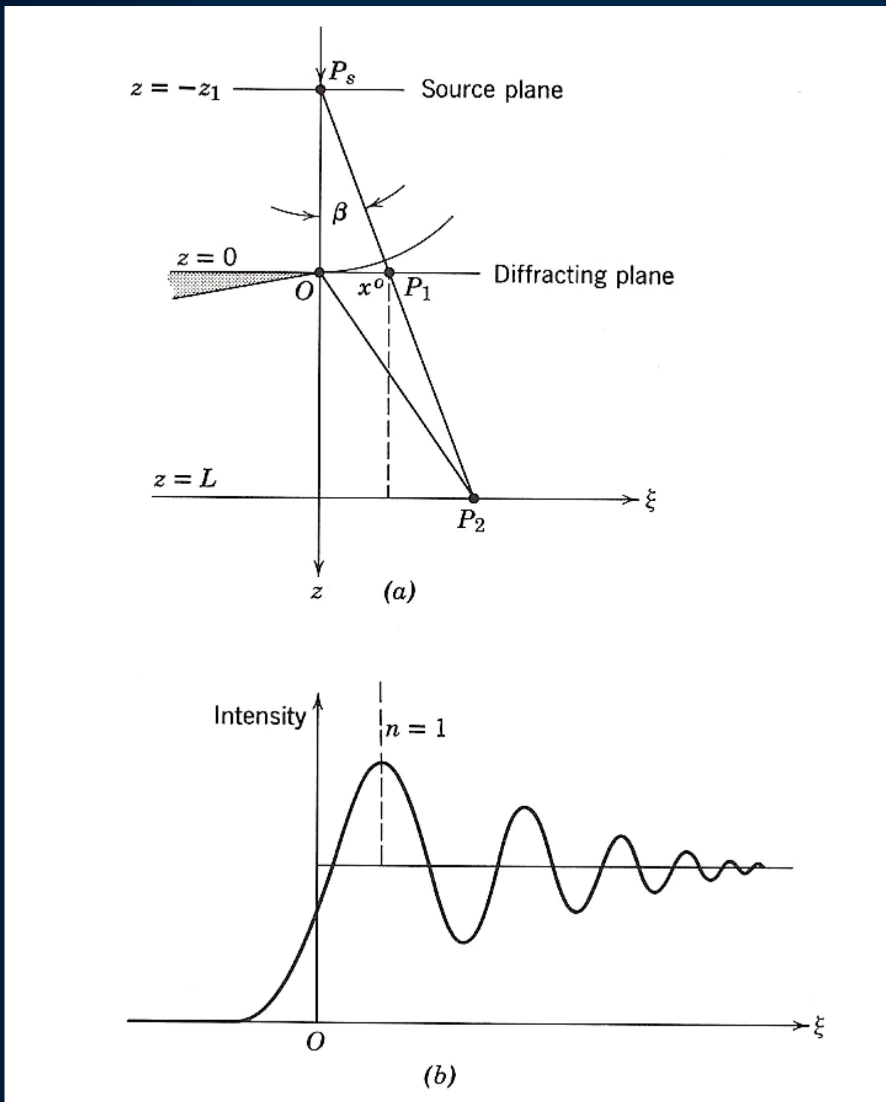


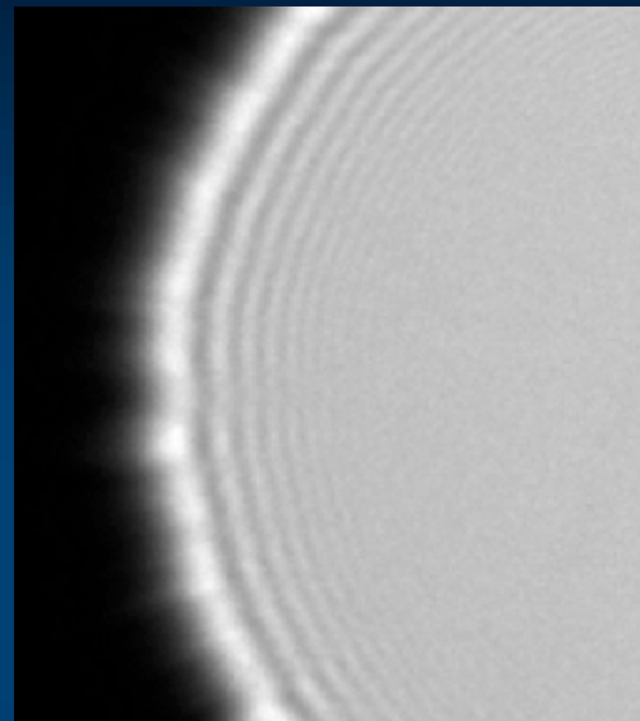

A
B
Specimen
Objective lens
Remove
aperture
Objective aperture
(back focal plane)
Fixed
SAD aperture
Intermediate
image 1
Remove
aperture
Change
strength
Intermediate
lens
Second
intermediate
'image'
Fixed
strength
Projector lens
Diffraction pattern
Final image
Screen

When is the Image in Focus?



Fresnel Fringes - Diffraction (Interference) from an Edge



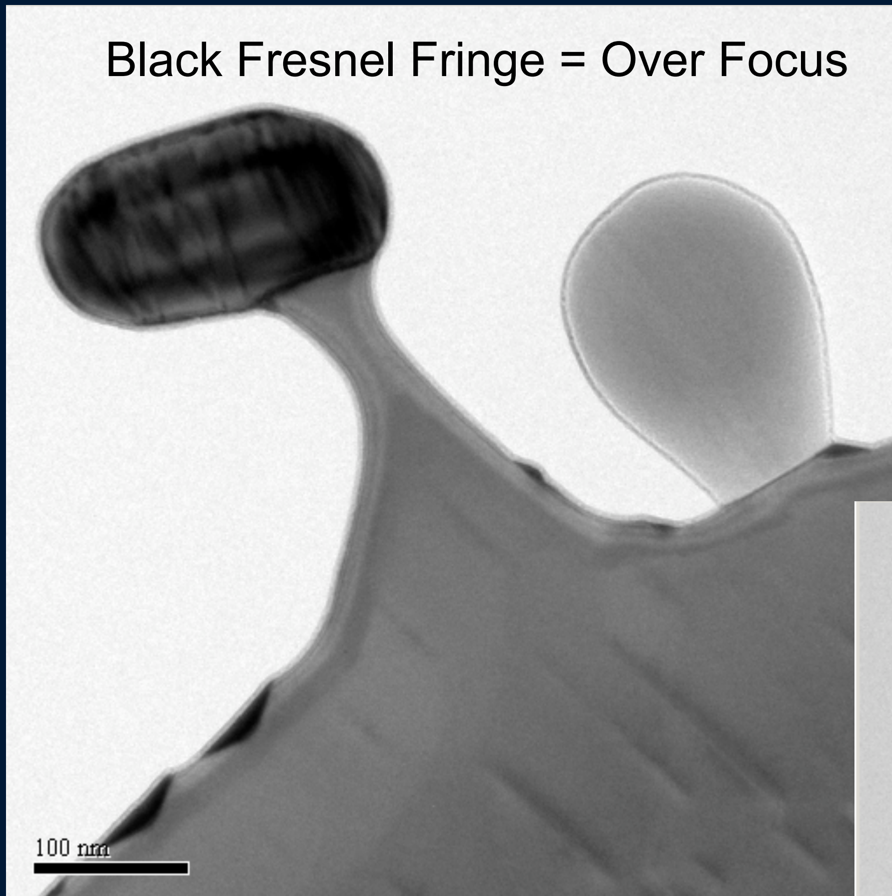


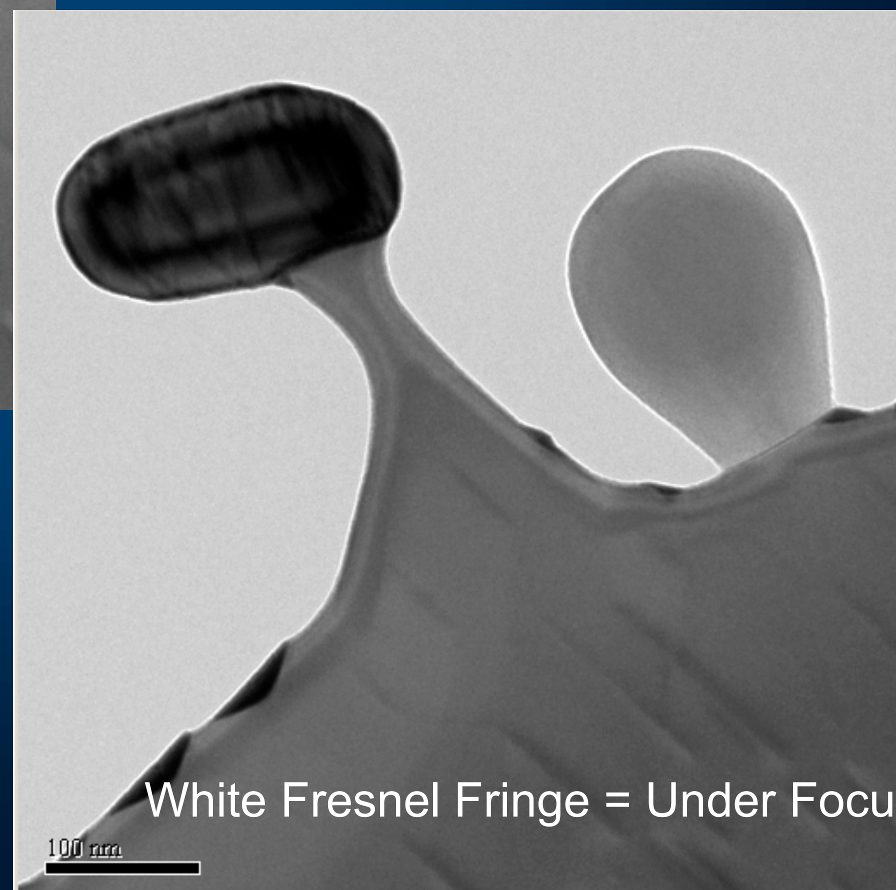
$$\nabla^2\Psi(r) + \frac{8\pi^2 me}{h^2}[E + V(r)]\Psi(r) = 0$$

$$\Psi_1(r,z) = \frac{\exp(2\pi ikr)}{r} \quad \Psi(r,z) = \sum \Psi_i(r,z)$$

$$I = \Psi(r,z)\Psi^*(r,z)$$

$$\xi_{\max} \simeq [\Delta f(2n - 1)\lambda]^{1/2}$$


Black Fresnel Fringe = Over Focus
100 nm


White Fresnel Fringe = Under Focus
100 nm

B O ↔ W U

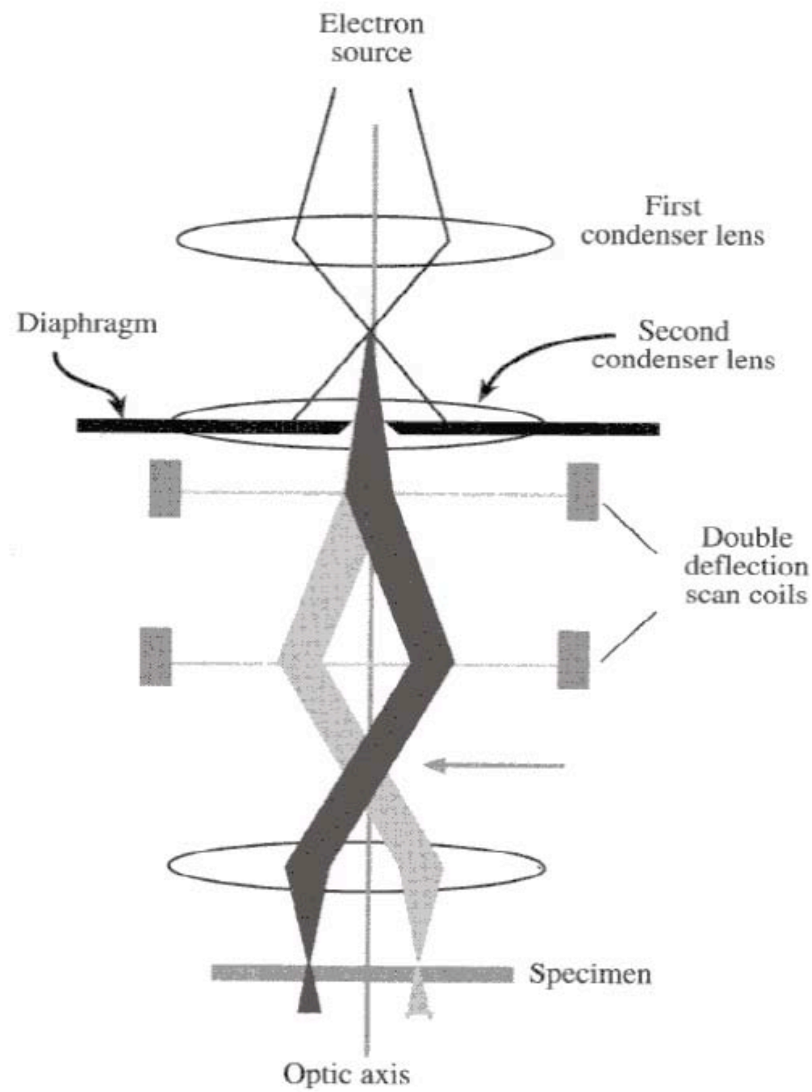
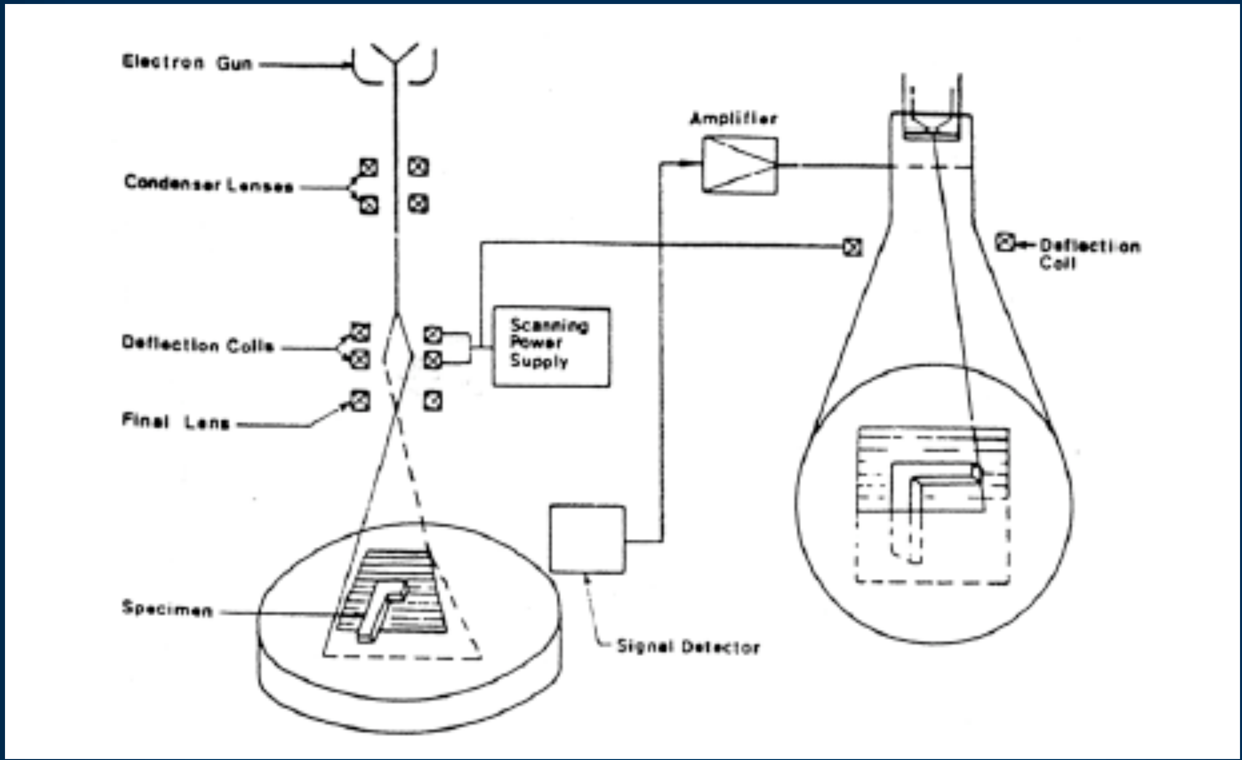


Figure 9.15. Scanning the convergent probe for STEM image formation using two pairs of scan coils between the C2 lens (usually switched off) and the upper objective polepiece. The probe remains parallel to the optic axis as it scans.

The scanning process is the mechanism which allows us to use small probes to form images of large areas.



Magnification = CRT Display Size / Area Swept by Beam on Sample

Electron Detectors

- TEM
  - phosphor screen, Film, CCD, Image Plate…
- SEM
  - SE detector, BE detector….
- STEM
  - BF detector, DF detector, ………

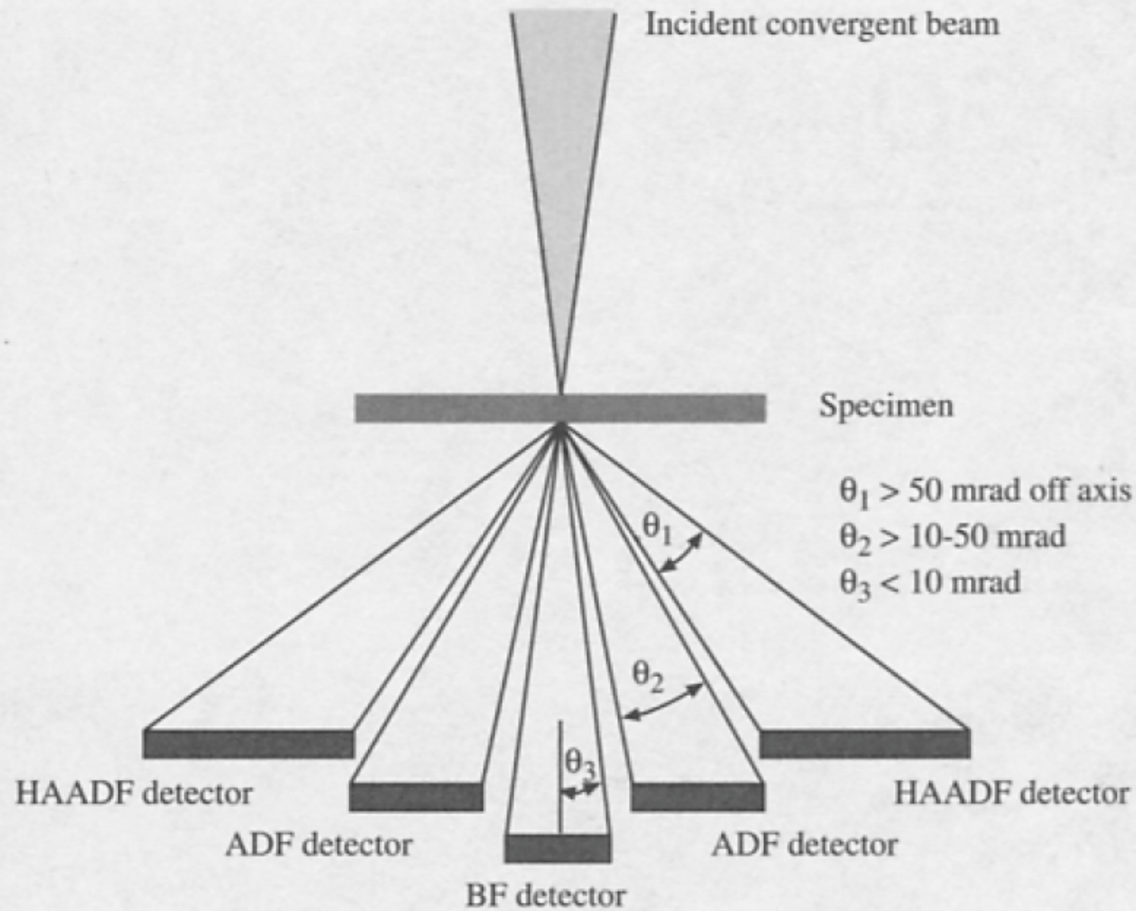
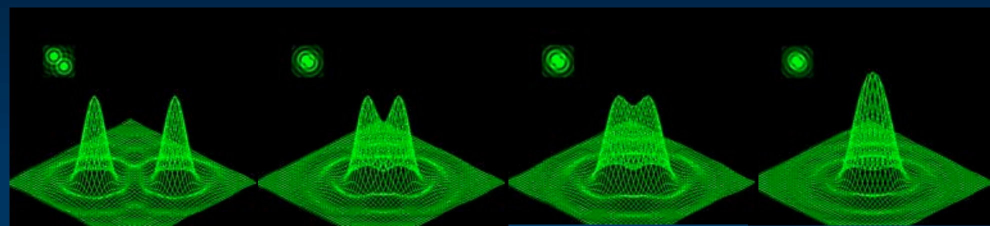


Figure 22.13. Schematic of the HAADF detector set-up for Z-contrast imaging in a STEM. The conventional ADF and BF detectors are also shown along with the range of electron scattering angles gathered by each detector.

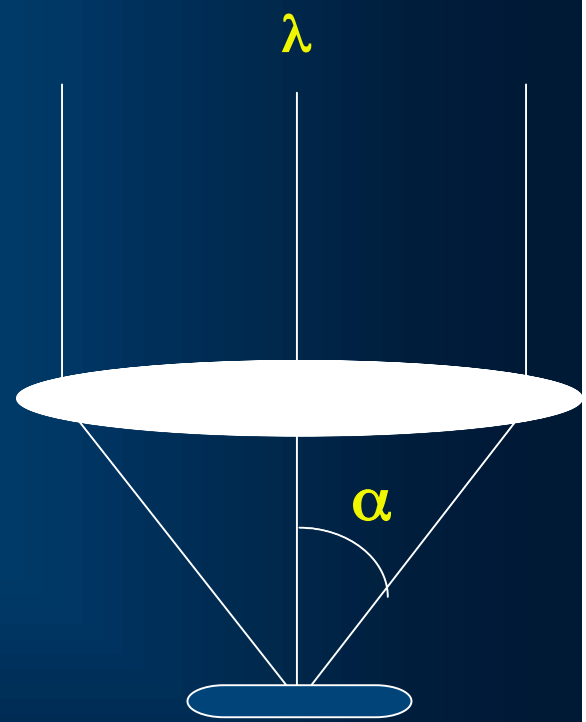
What Limits Resolution?



Abbe (Diffraction) Limit:

Defines the minimum resolvable distance between the image of two point objects using a perfect lens.

In any magnifying system a point object (i.e. zero dimension) cannot be imaged as a point but is imaged as a distribution of intensity having a finite width.



R esolution of an imaging system $= \rho = \dfrac{0.61\lambda}{\eta \sin(\alpha)}$

λ = wavelength of the imaging radiation
η = index of refraction of the lens
α = illumination semi-angle

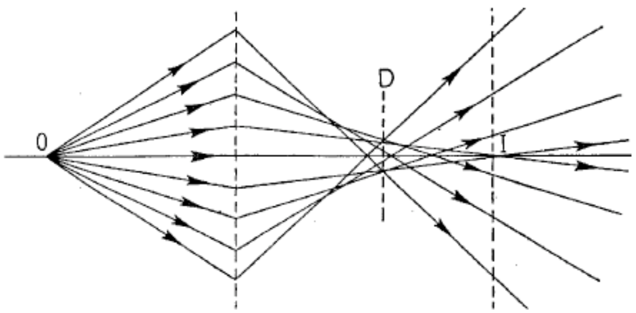
This ASSUMES a "Perfect Lens"

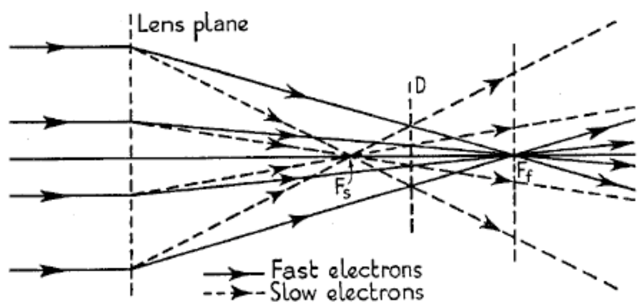
Ex: 100 kV electrons $\alpha \sim 100$ mR => $\rho = 0.23$ Å

What limits our ability to perfectly focus?

Aberrations

- Spherical
- Chromatic





$$r_{sph} = C_s \beta^3$$

$$r_{chr} = C_c \frac{\Delta E}{E} \beta$$

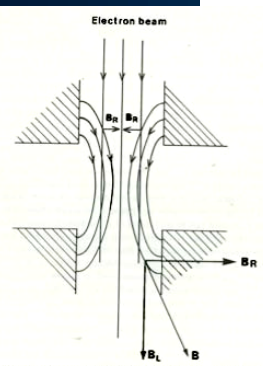
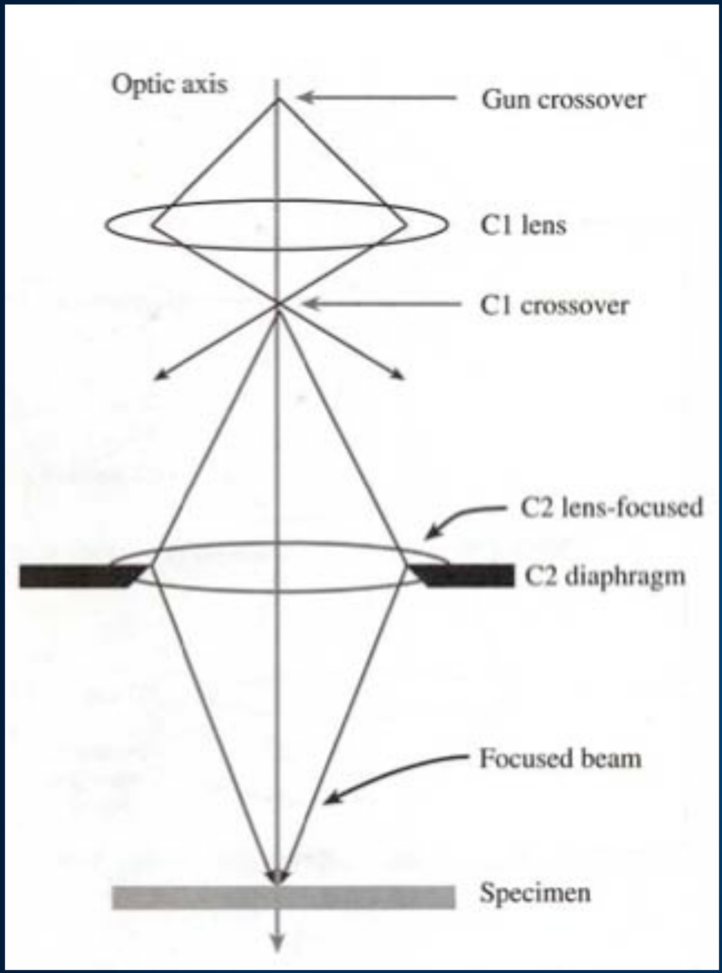
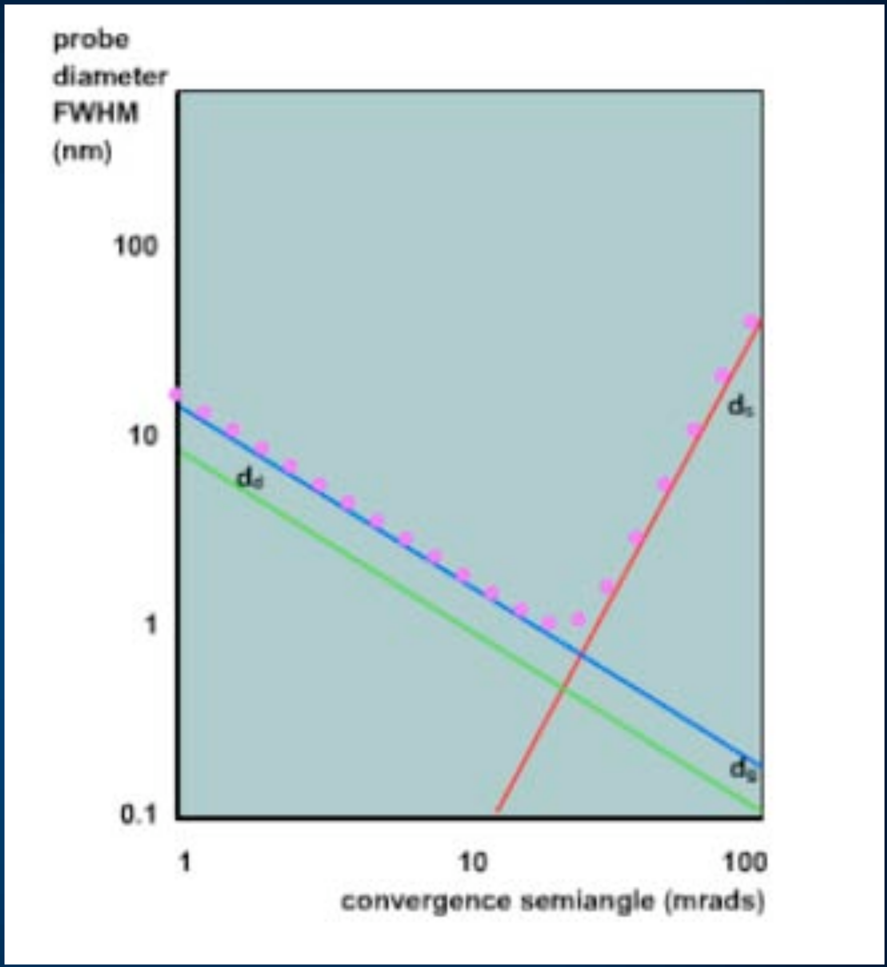


Fig. 1.2 Schematic diagram of the action of a cylindrical magnetic lens on the path of non-axial electrons. B_R is the radial component and B_L the longitudinal component of the field.

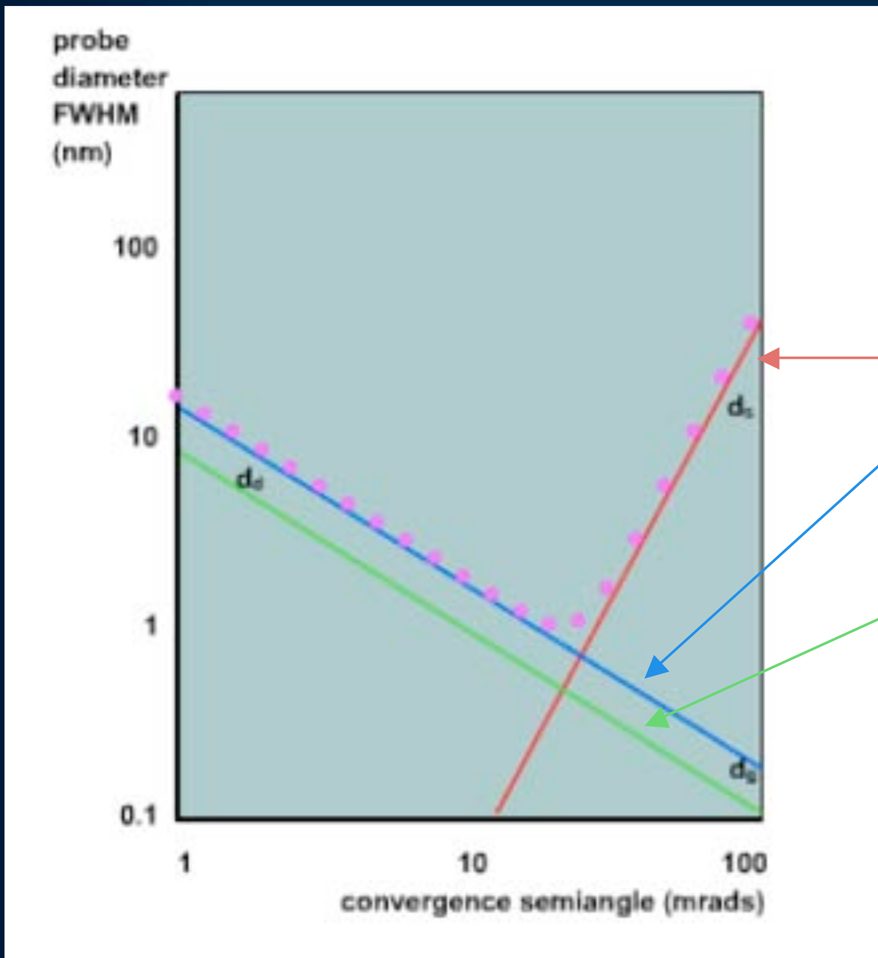
Lens Aberrations

Prespecimen Aberrations





Aberrations and Probe Size Related Parameters



$$d_g = \frac{2}{\pi}\sqrt{\frac{i}{\beta}}\frac{1}{\alpha}$$

$$d_s = 0.5 C_s \alpha^3$$

$$d_d = 1.22\frac{\lambda}{\alpha}$$

The total beam diameter is found by adding these three effects in quadrature i.e.

$$d_t = \sqrt{d_s^2 + d_g^2 + d_d^2}$$

Aberration Correction also increases *usable* probe current

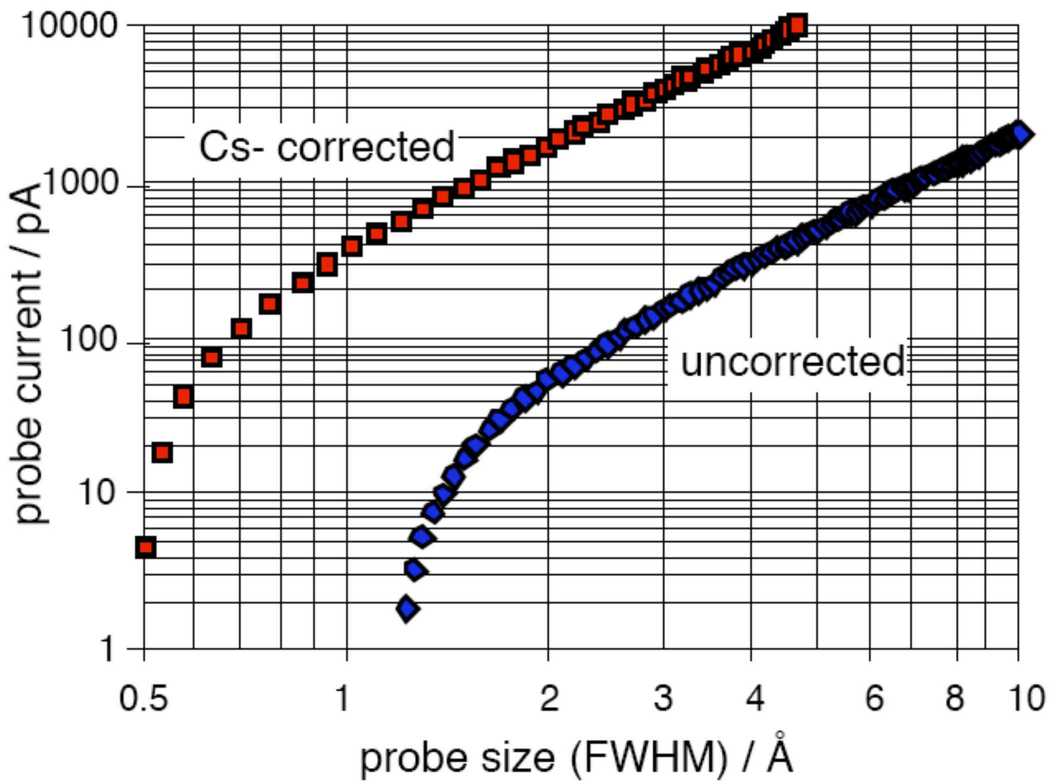
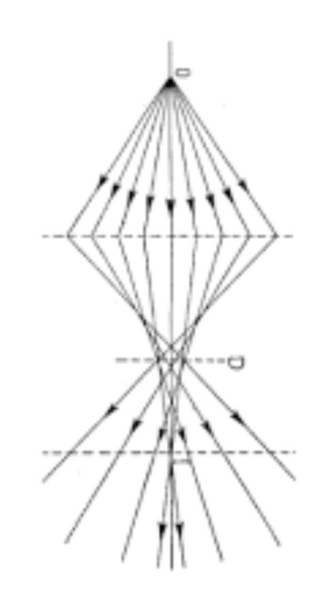


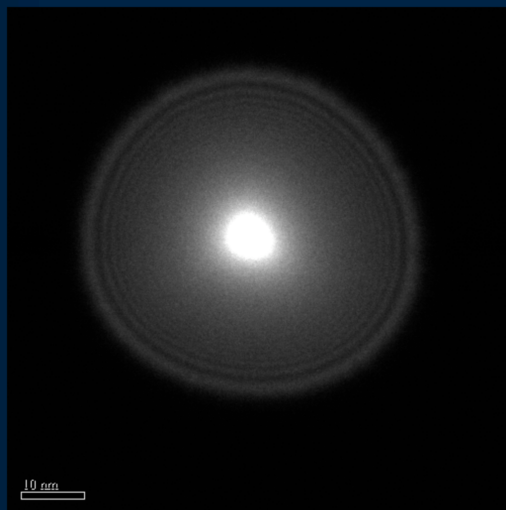
Fig. 1. Probe current vs. probe size. C_s-corrected: 200 keV, C_3/C_5 corrected, $C_{7,8}$ = 10 cm, cold field emission gun. Uncorrected: C_s = 0.5 mm, Schottky gun.



Aberration-Corrected STEM for Elemental Mapping

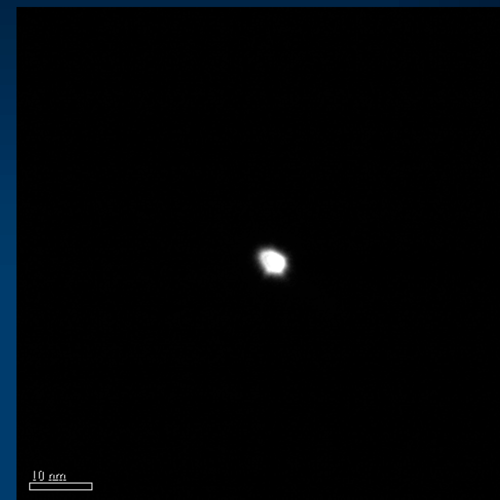
N. Dellby, O.L. Krivanek, M. Murfitt, P.D. Nellist and Z.S. Szilagyi

Can we see aberrations ? Yes if you look for them.

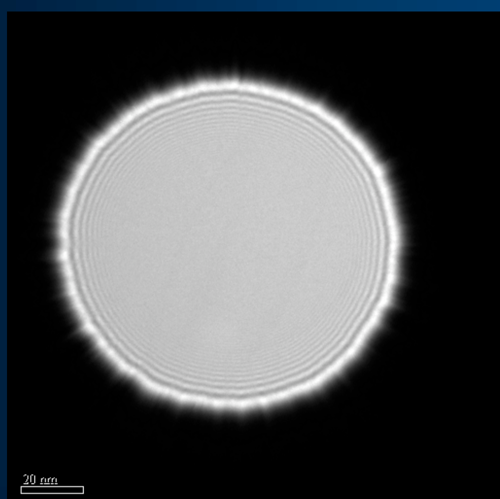


150 µm

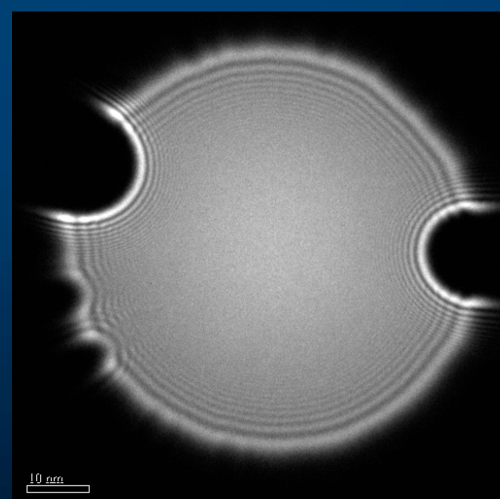
70 µm



30 µm

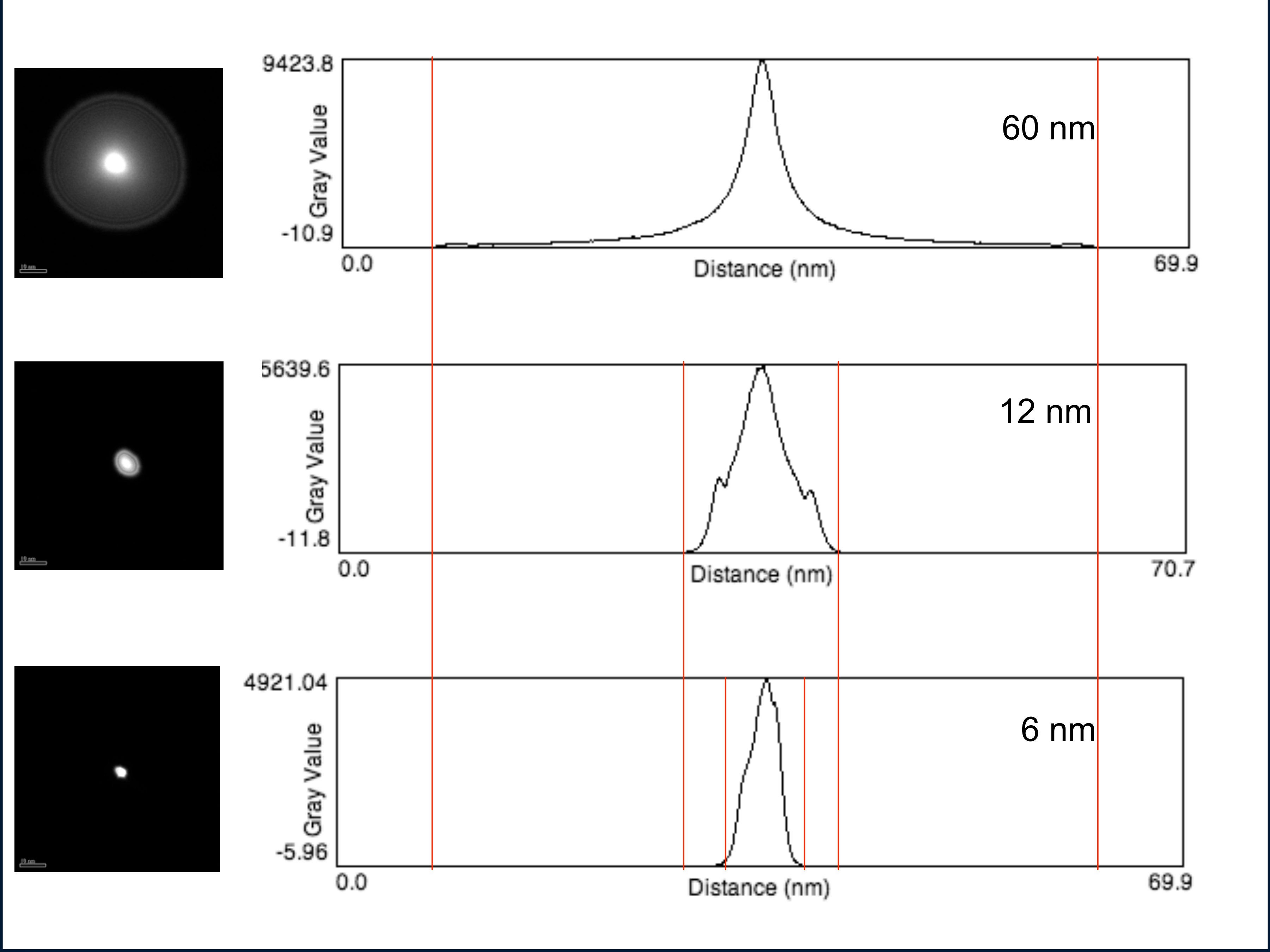


70 µm Clean

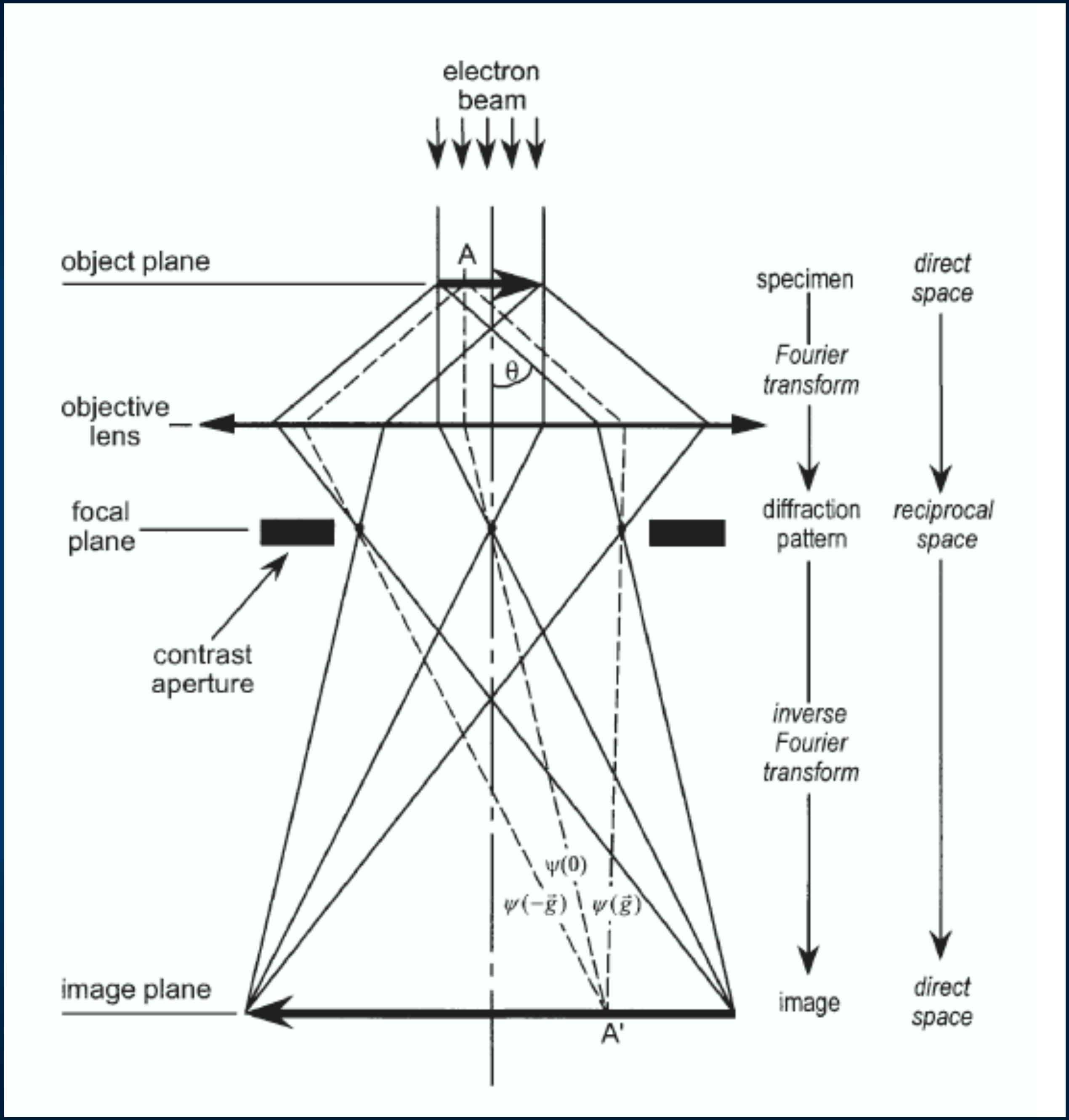


100 µm Dirty

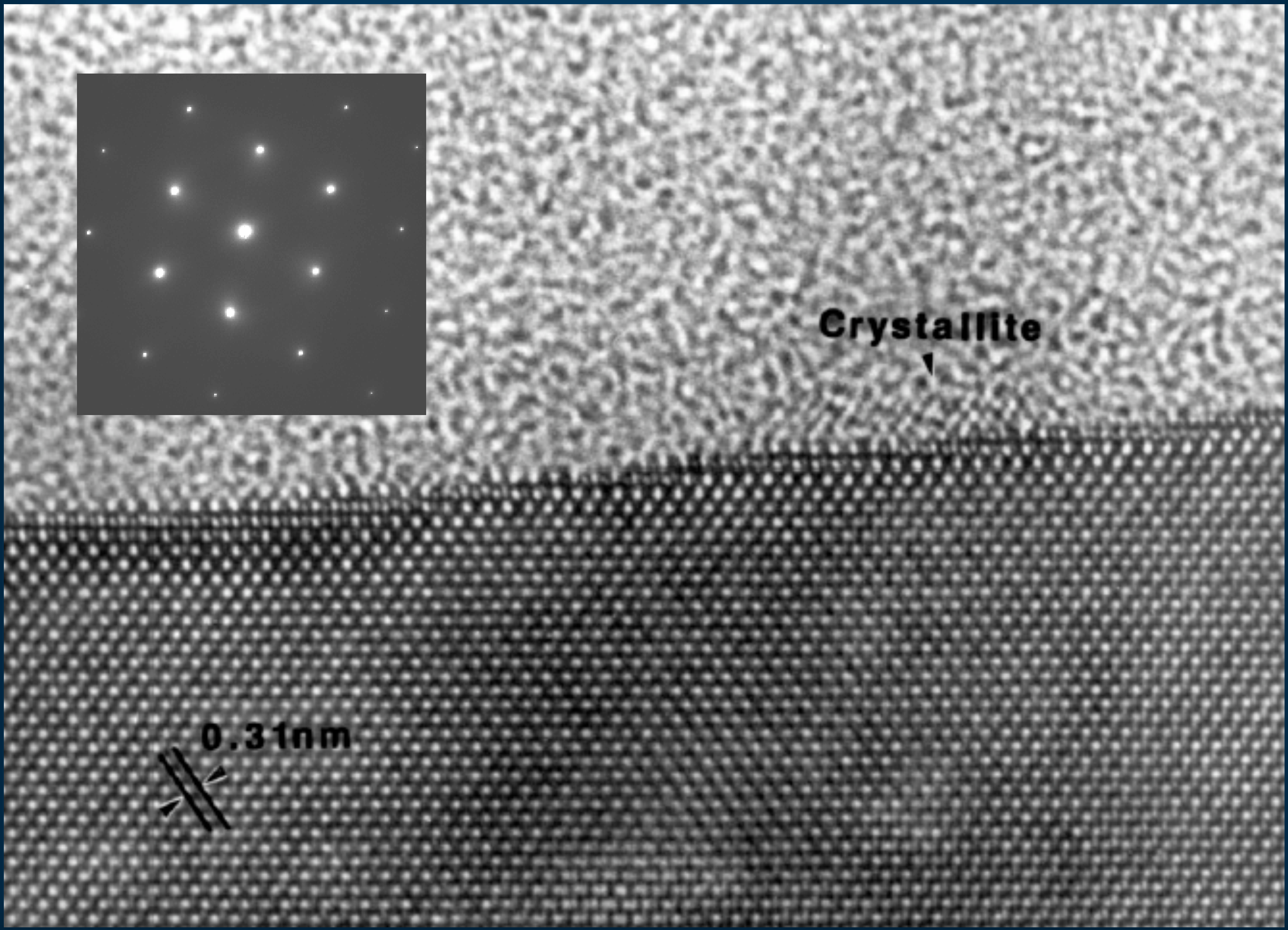
100 µm Dirty


9423.8
Gray Value
-10.9
0.0
Distance (nm)
69.9
60 nm
5639.6
Gray Value
-11.8
0.0
Distance (nm)
70.7
12 nm
4921.04
Gray Value
-5.96
0.0
Distance (nm)
69.9
6 nm

Post Specimen Aberrations

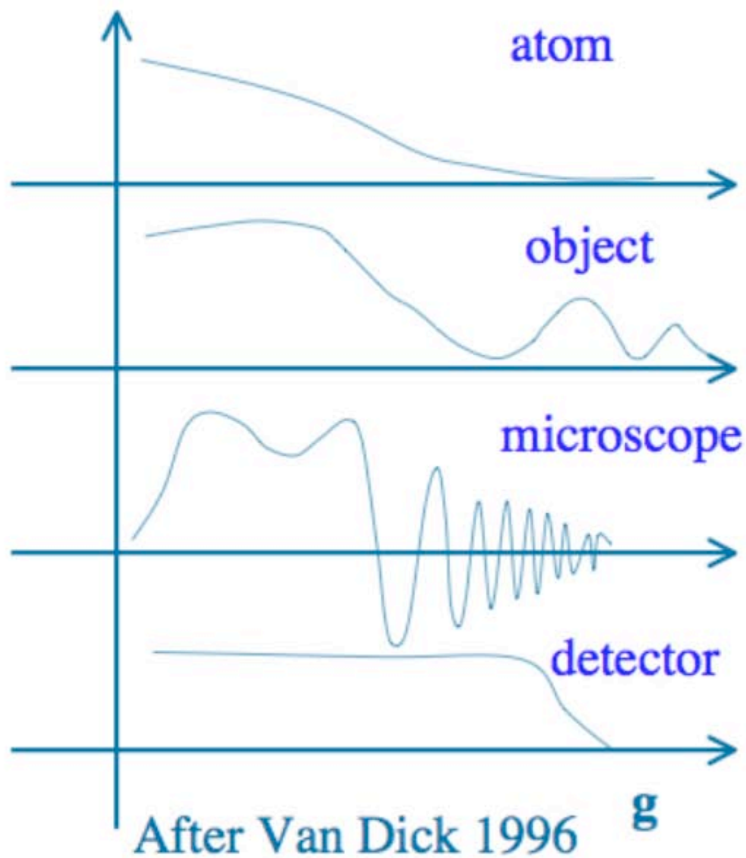


TEM-High Spatial Resolution Imaging



Resolution limiting factors

- The atom:
  - the Fourier transform of the atomic electrostatic potential is the scattering factor
- The 3D object:
  - 3D electron object interaction into a 2D imaging system, especially for thick samples
- The electron microscope
- The recording device



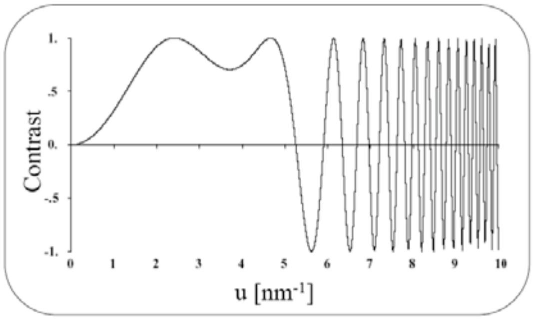
Lens System & Microscope Resolution

- Microscope resolution is governed by: (for TEM)
  - wavelength of electrons
  - C_s of objective lens
  - other lenses are less crucial (α/M)

$$\delta = 0.66 \times C_s^{1/4} \lambda^{3/4}$$

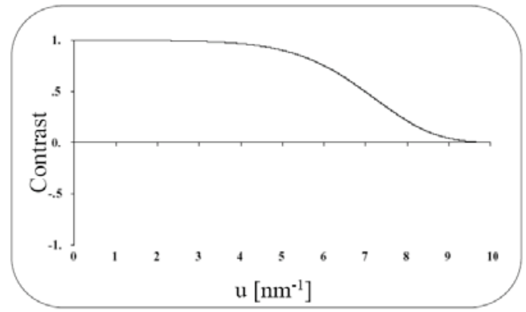
Aberrations and Image Resolution

$H(\mathbf{u}) \sim \sin(\pi \cdot \Delta f \cdot u^2 + \tfrac{1}{2} \cdot C_s \cdot \pi \cdot \lambda^3 \cdot u^4)$

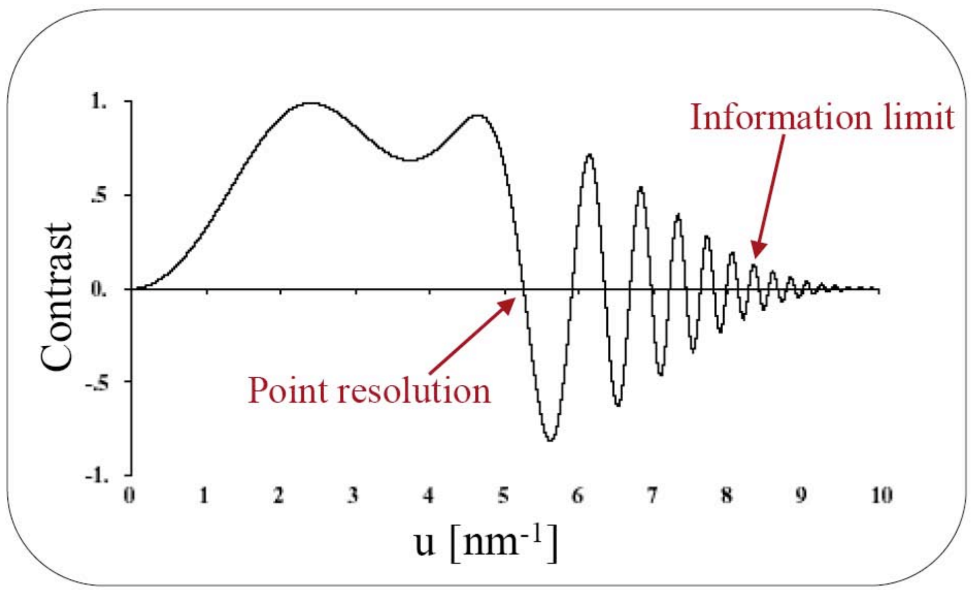


- Depends on spherical aberration (C_s) and defocus (Δf).

Bounding envelope



- Depends on chromatic aberration (C_c), coherence of electrons and stability of sample.

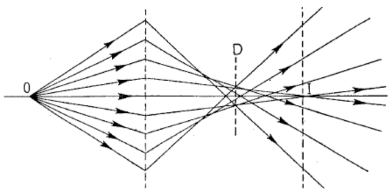


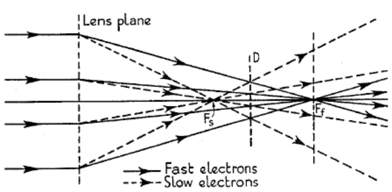
B. Kabius - ANL

What are the limitations in EM ?

Aberrations

- Spherical
- Chromatic

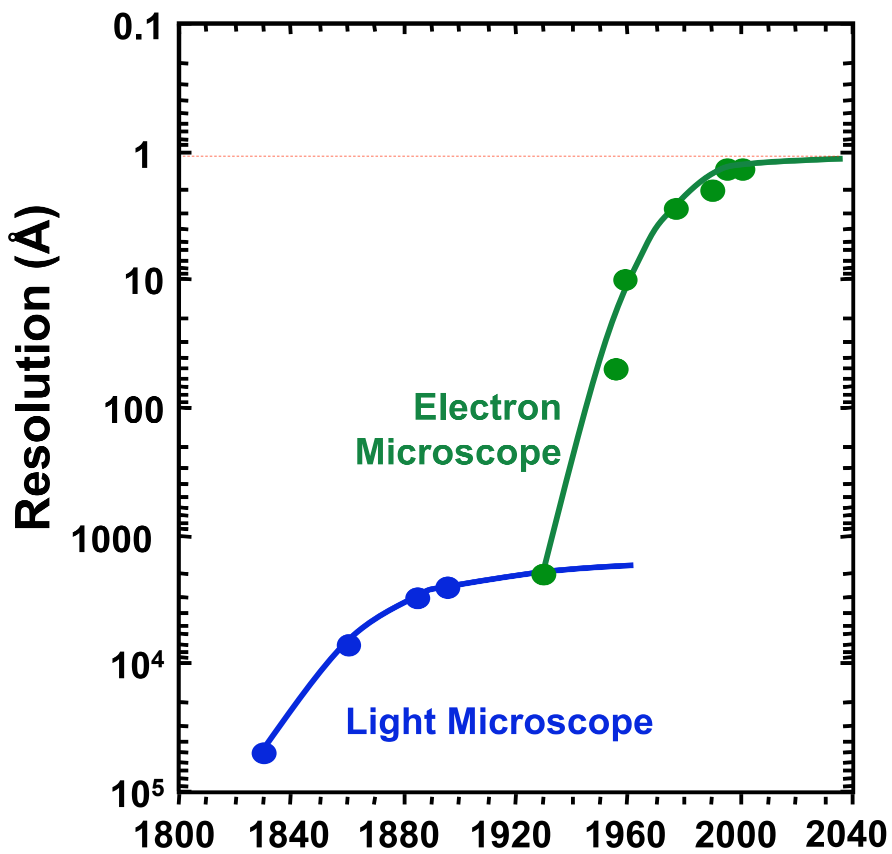




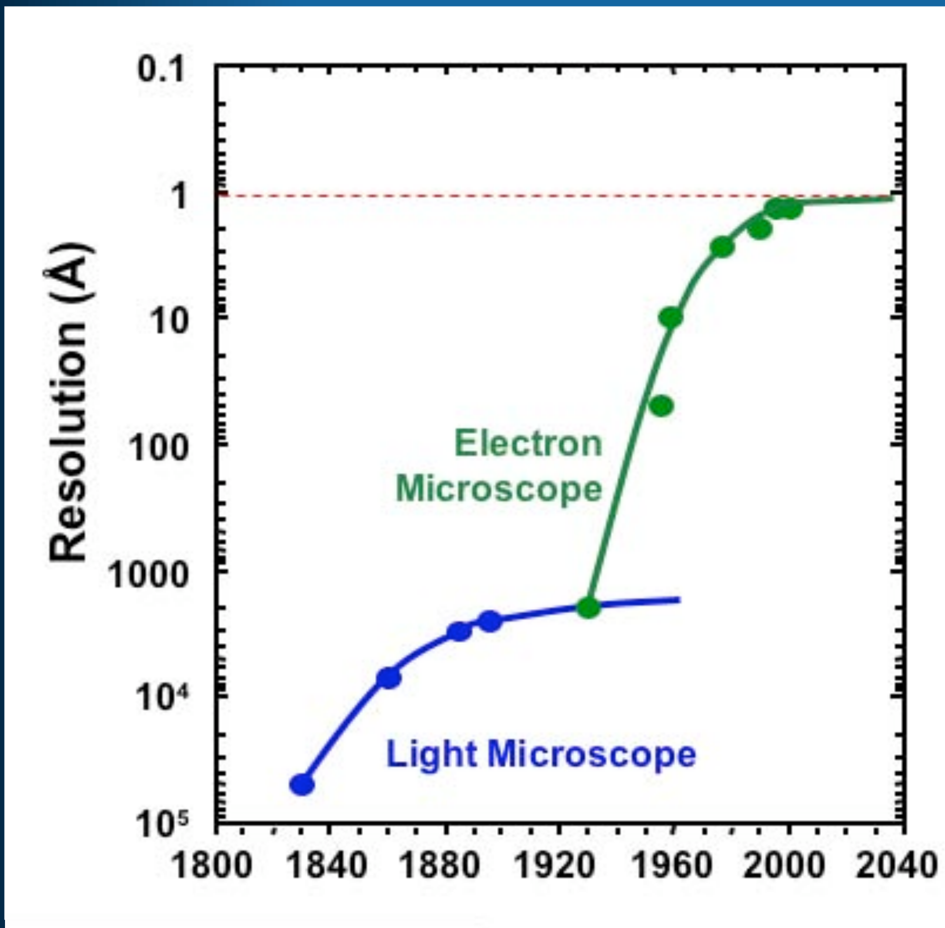
$$r_{sph} = C_s \beta^3$$

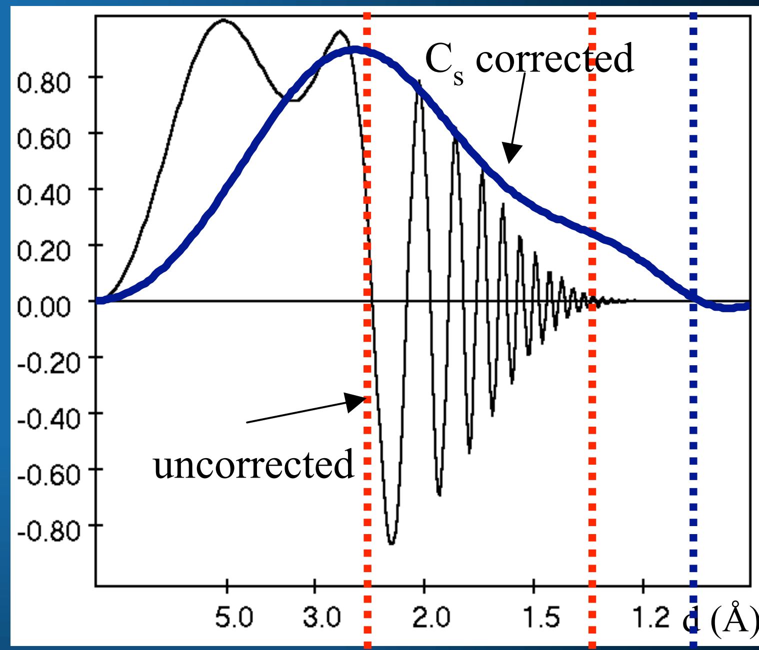
$$r_{chr} = C_c \frac{\Delta E}{E} \beta$$

The source and solution to "resolution limitations" has been known for nearly 50 years



TEAM Project Phase 1 : Ultra High Resolution Imaging
Requirements: <0.05 nm, 0.1 na , 0.1 eV





point res.

First Generation Corrected Instruments

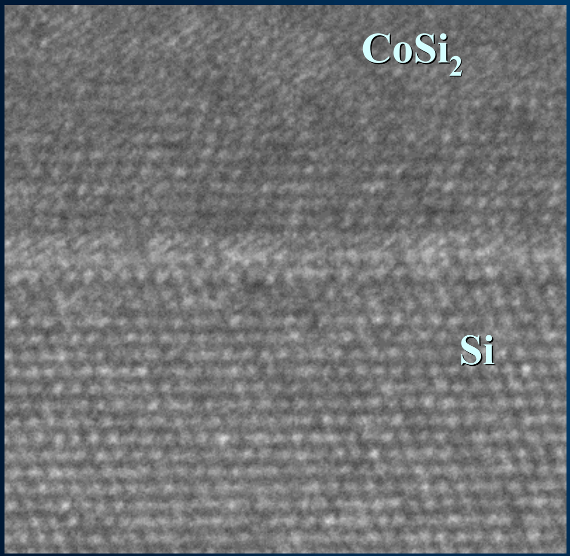
Aberration Free Imaging

Influence of Contrast Delocalization

Uncorrected : $C_s = 1.2$ mm

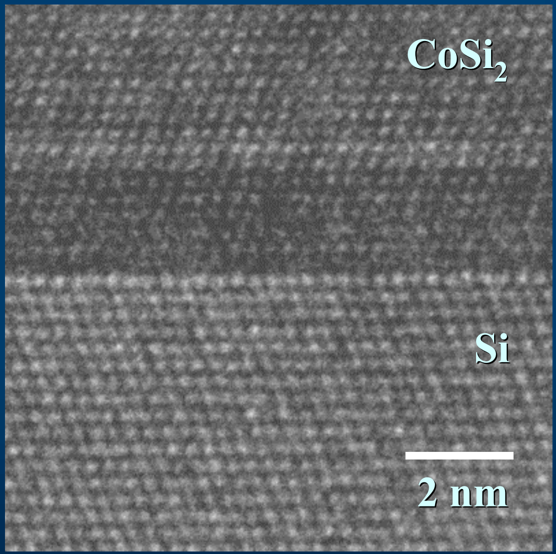
Corrected : $C_s = 0.05$ mm

$\Delta f = -257$ nm; R = 1.4 nm



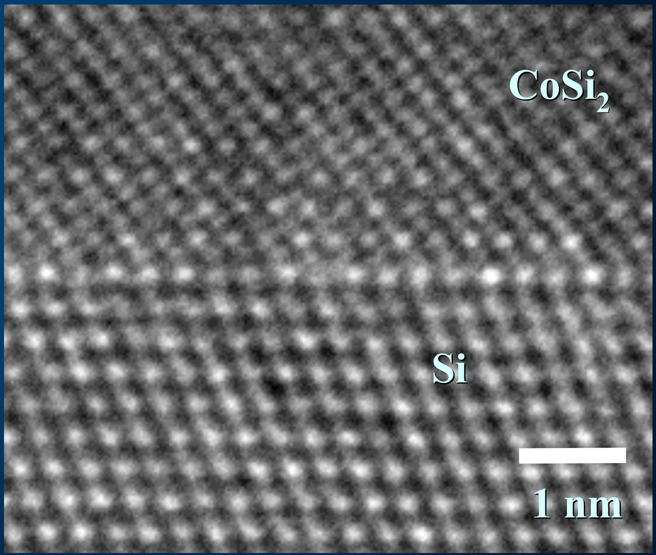
focus of least confusion

$\Delta f = -68$ nm; R = 4.4 nm



Scherzer defocus

$\Delta f = -12$ nm; R = 0.1 nm



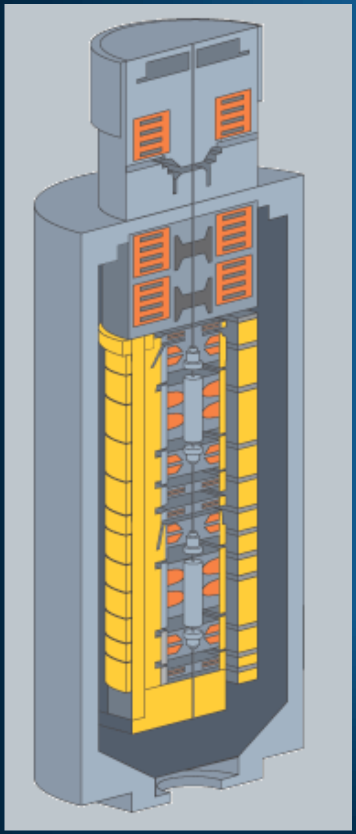
Scherzer defocus (AFI)

B. Kabius, S. Mantl
Argonne, Juelich: ~1997
CM200

Delocalization : $R = | C_5 \lambda^5 g^5 + C_3 \lambda^3 g^3 + \lambda C_1 g |_{max}$

Fig. 1: *a) The Cc/Cs-corrector (C-COR) after construction showing the total length (83 cm) without filter boxes and vacuum lines and b) the Titan with the C-COR incorporated.*

THE **TEAM** PROJECT



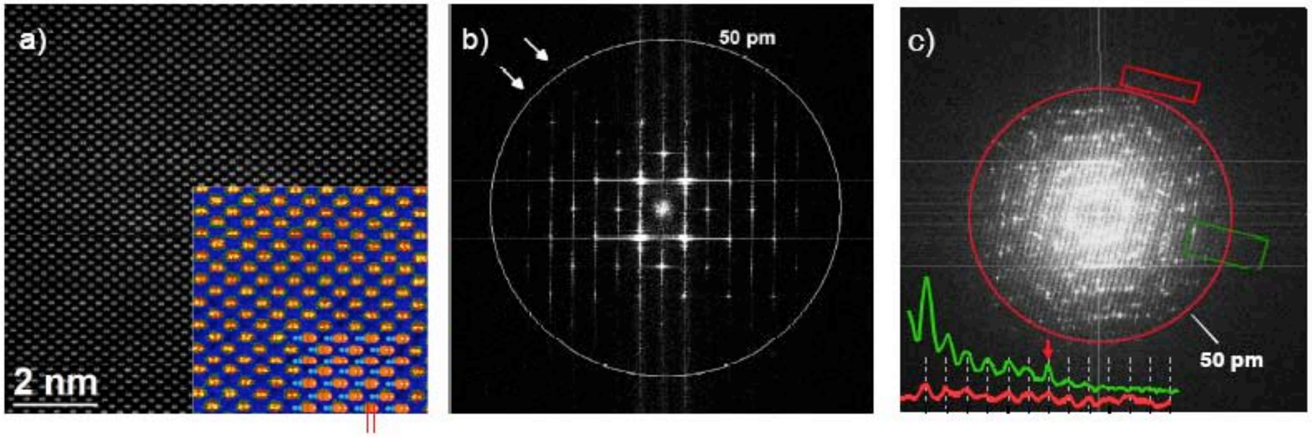


Figure 1. Performance of TEAM 0.5 microscope in STEM and TEM. Aberration-corrected high-resolution STEM image of GaN in [211] orientation (a), showing the 0.63Å distance between Ga dumbbells clearly resolved (see inset model). The corresponding diffractogram in (b) shows Fourier components beyond the 50 pm marker indicated by the circle. The Fourier diffractogram from high resolution TEM images in (c) shows Young's fringes extending beyond the 50 pm mark indicated by the circle.

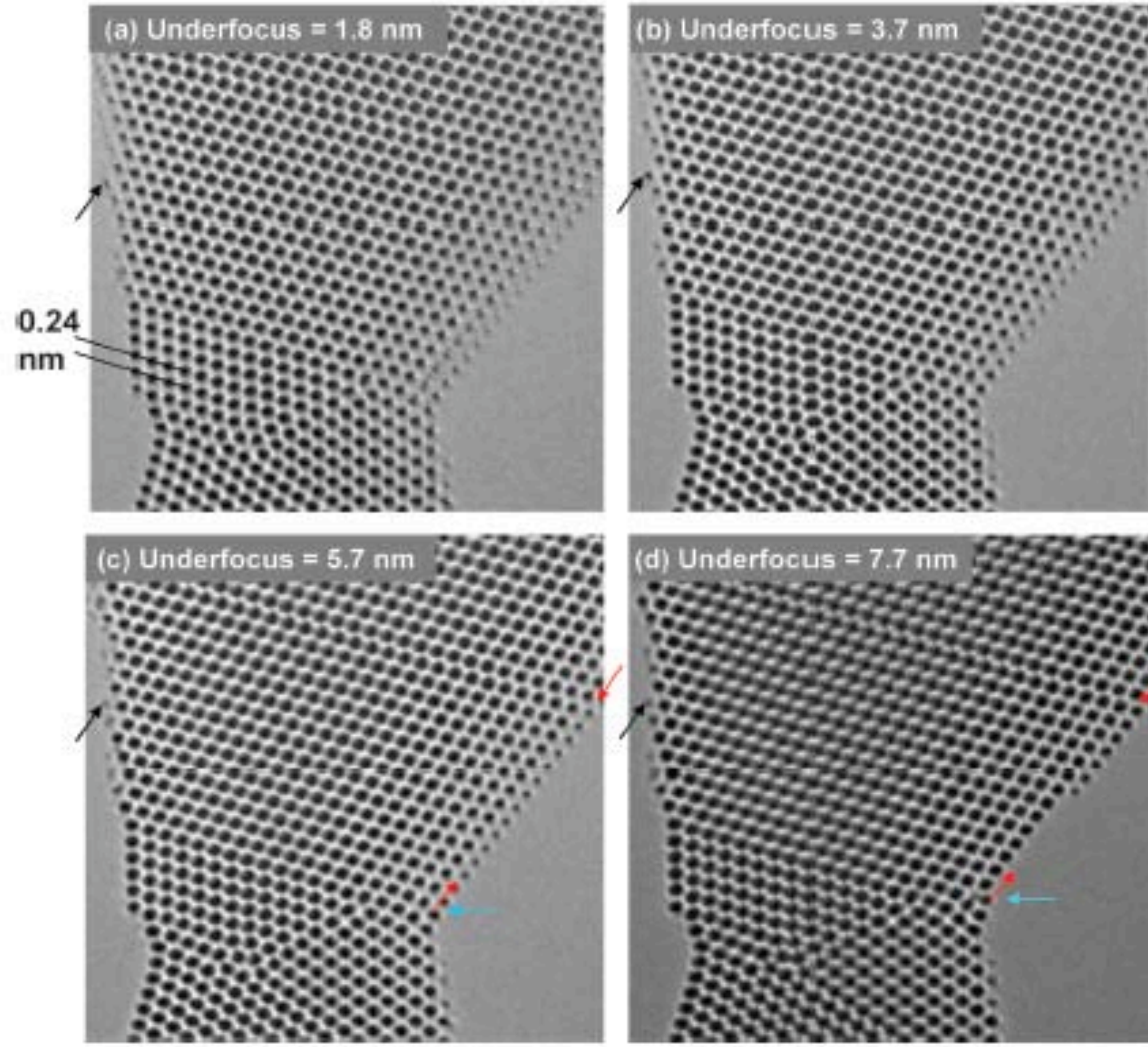
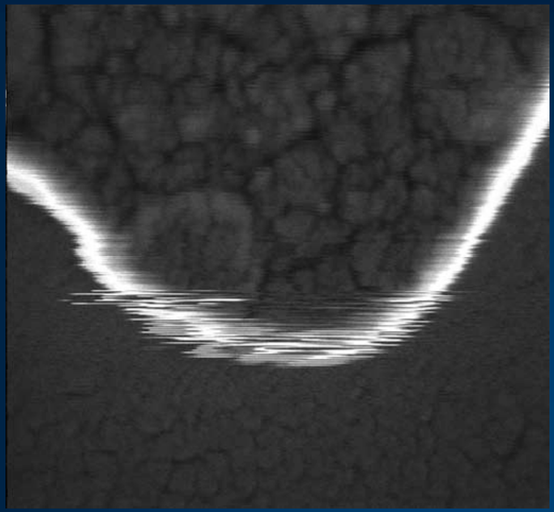


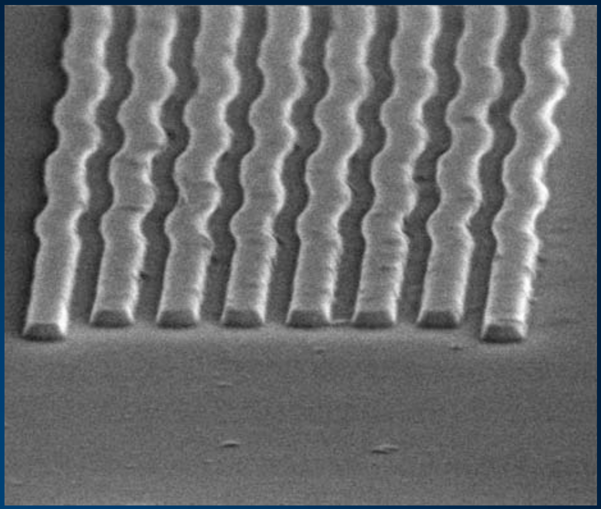
Figure 6. Four sequentially recorded TEM lattice images of gold [110] nanobridge connecting two grains that are rotated relative to each other by 90° around [110] axis. The four images shown are part of a 15-member focal series, recorded in time intervals of 1.5 s. Black arrows: (a,b) 2-atom column and (c,d) single atom. Red arrows: thirteen 2-atom columns, some of which disappear in d. Turquoise arrows: Rearrangement of atom columns at the intersection of a dissociated grain boundary with the surface. The focus difference on both sides of the bridge is negligible because the film was grown onto a flat single crystal substrate.

TEAM 0.5

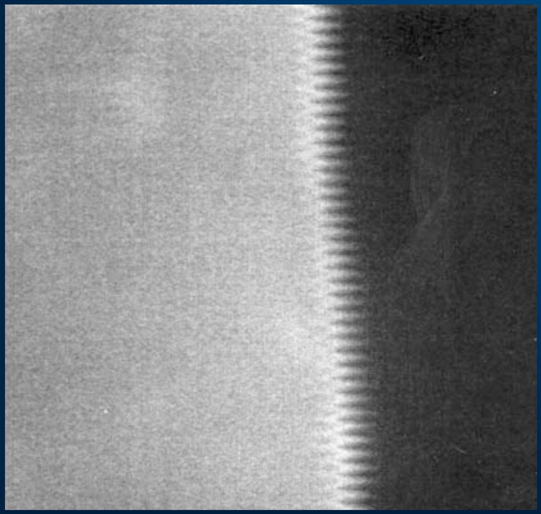
Examples of Environmental "Artifacts"



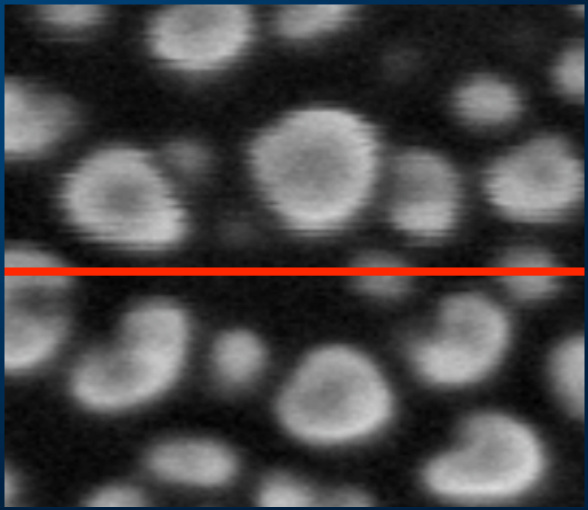
Aperiodic - Vibrational



User-Mechanical

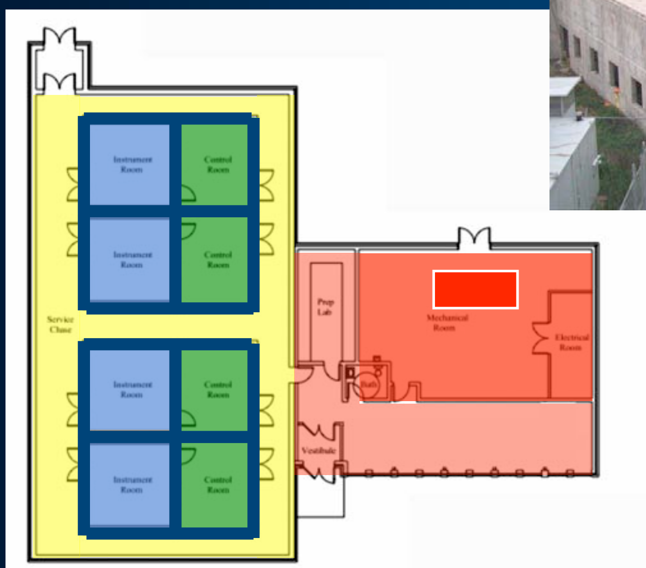


Periodic - EM Fields



User-Acoustic

Sub-Ångstrom Microscopy and Microanalysis Laboratory



Temp: ± 0.1 F

EMF: < 0.01mG

Acoustics: < 40 dB

Air Flow: < 1 cm/min

Vibrations: < 0.25 μm Pk

Environmental Conditions

Best -> Worse