Hitachi HD-2700 – type B, Dedicated STEM

Alignment strategies

Prepared for:

HTA Customers

V1.2

Hitachi High Technologies America Inc.
Nanotechnology Systems Division

HD-2700 Overview

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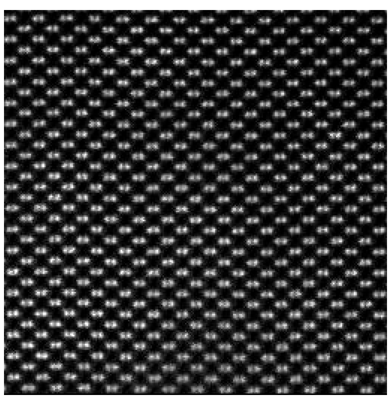
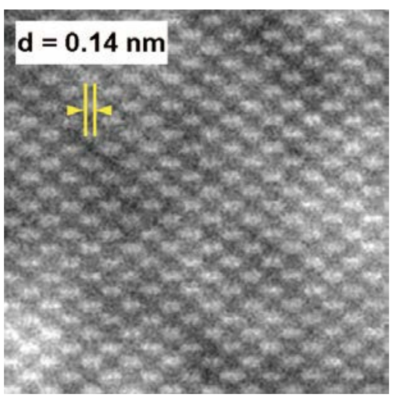


Z-contrast STEM



200kV SEM

Features

■ ***Ultrahigh performance STEM***

- **-Hitachi Cold FEG***
- **-10x increased probe current***
- **-Hitachi developed Cs corrector***

■ ***Ease of Use***

- **-SEM-like friendly GUI**
- **-Automated alignment steps**
- **-Total integrated data acquisition**

■ ***Multiple Signal detection***

- **-Secondary Electron**
- **-Bright Field**
- **-Annular Dark Field (Z/Diff-Contrast)**
- **-Live Diffraction Observation***
- **-EDXS* (dual detector compatible)**
- **-EELS***

■ ***Holders compatible with FIB***

■ ***Hitachi Reliability***

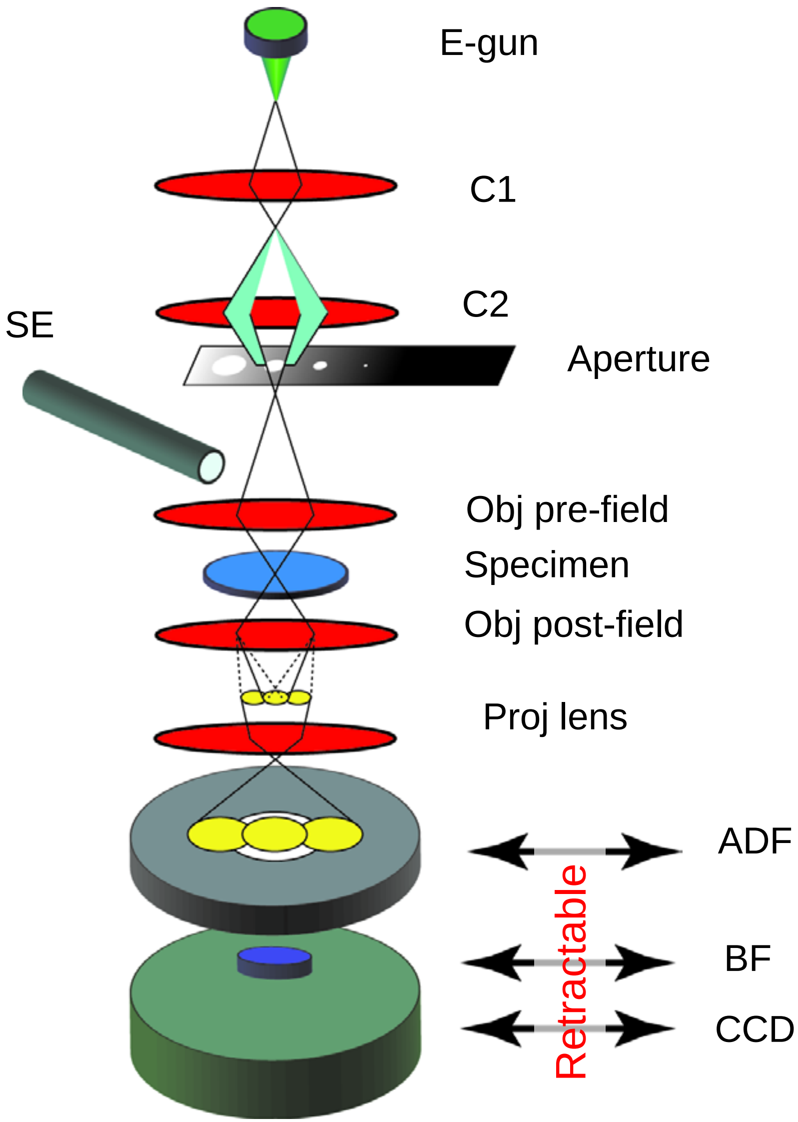
****option***

Outline

1) Lenses and detectors
2) Coils and alignments
3) Alignment procedures
4) Appendices
    1) Sample tilting
    2) Aberrations

HD-2700 Optical Elements

Optical elements overview 1



Electron Beam generation
→ Electron gun

Illumination system
→Condenser lens 1
→Condenser lens 2
→Objective Aperture
→Objective lens pre-field

Surface Detector
→Secondary Electron Detector (SE)

Projection system
→Objective lens post-field
→Projection lens

Transmission Detectors
→TE = Transmission detector (bright field)
→ZC = Z-contrast (annular dark field)
→Live Diffraction Camera (CCD)

Optical elements overview 2

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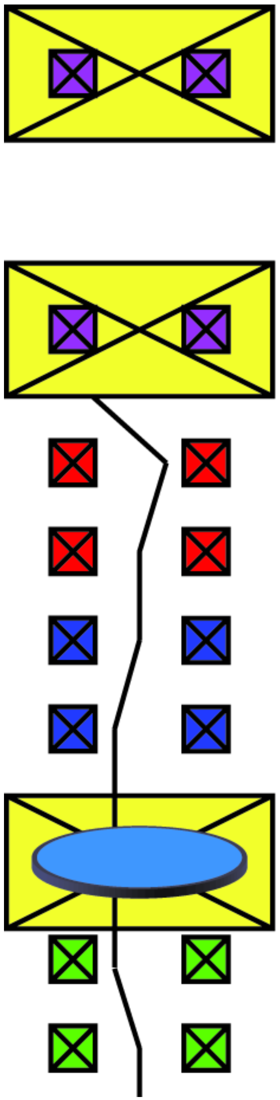


Condenser Lens 1
with x-stigmator

Condenser Lens 2
with y-stigmator

Alignment Coils

Scan Coils

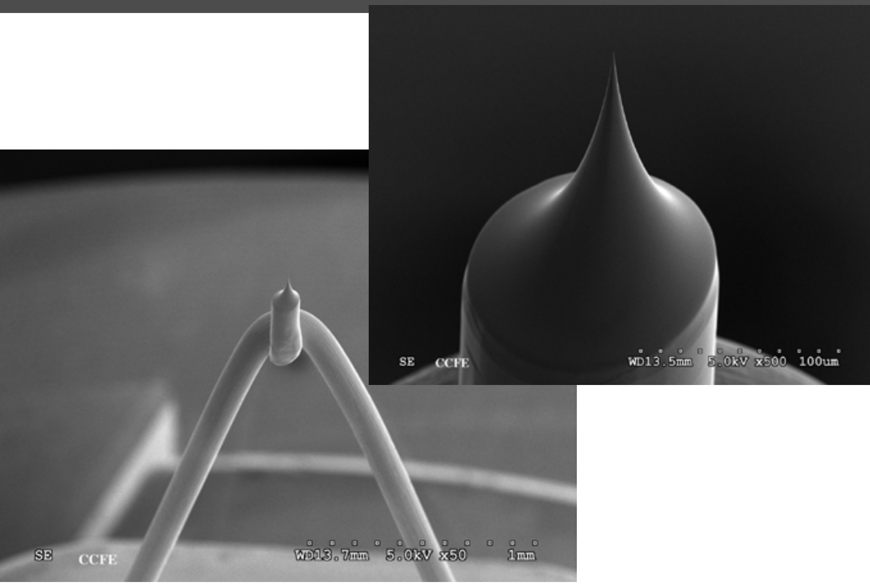
Objective Lens / Specimen

DEflection ALignment (DEAL) Coils

Detectors

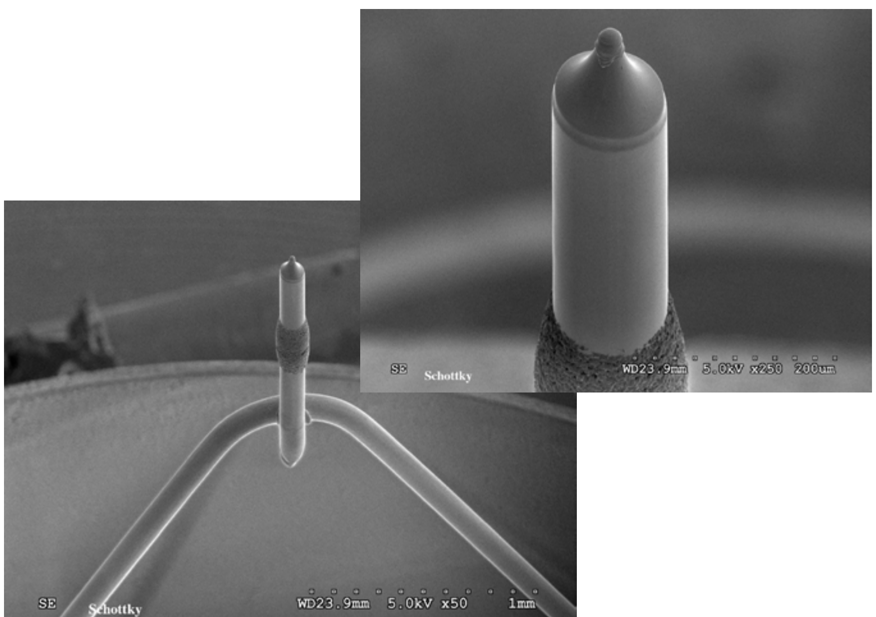
Beam Deflection
(BD) Coils

Electron Gun



The Cold Field Emission Electron Gun (C-FEG) operates at room temperature by “pulling” (tunneling) electrons out of tip due to the high voltage and tip curvature.

Energy spread ~0.3eV-0.5eV
Highest brightness



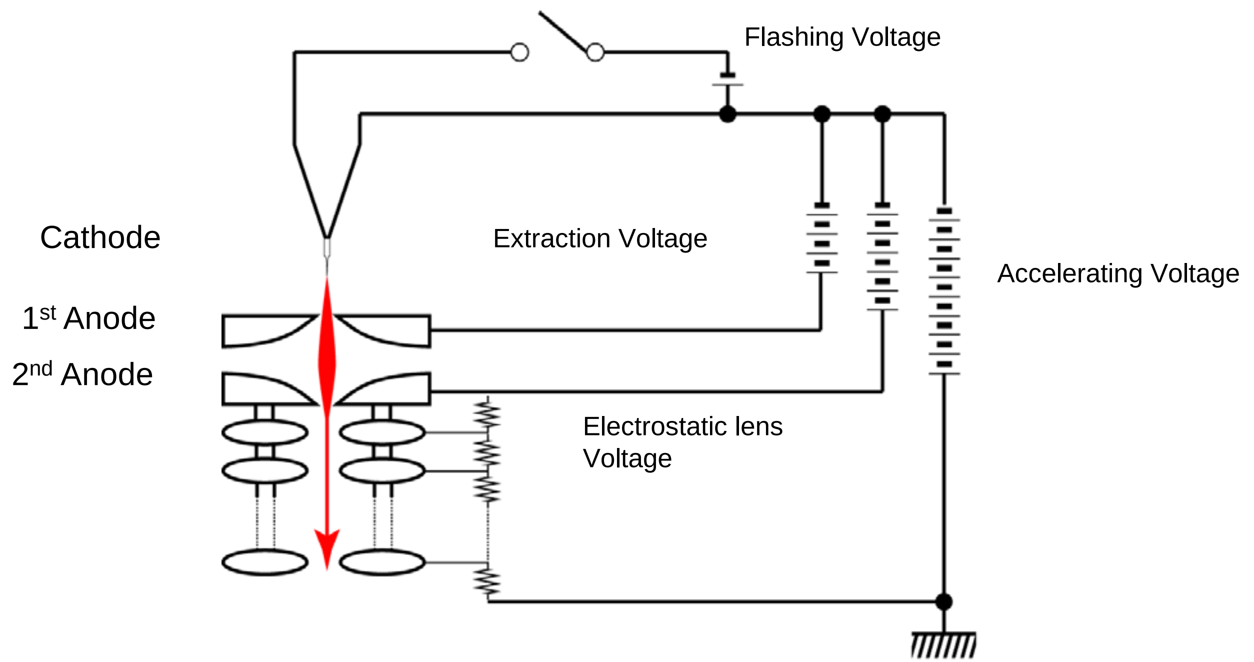
The Schottky Field Emission Electron Gun (FEG) operates at about 1700^{o}C and “boils” electrons off the tip to aid the high voltage field.

Energy spread ~0.7e – 1.0eV

Electron Gun

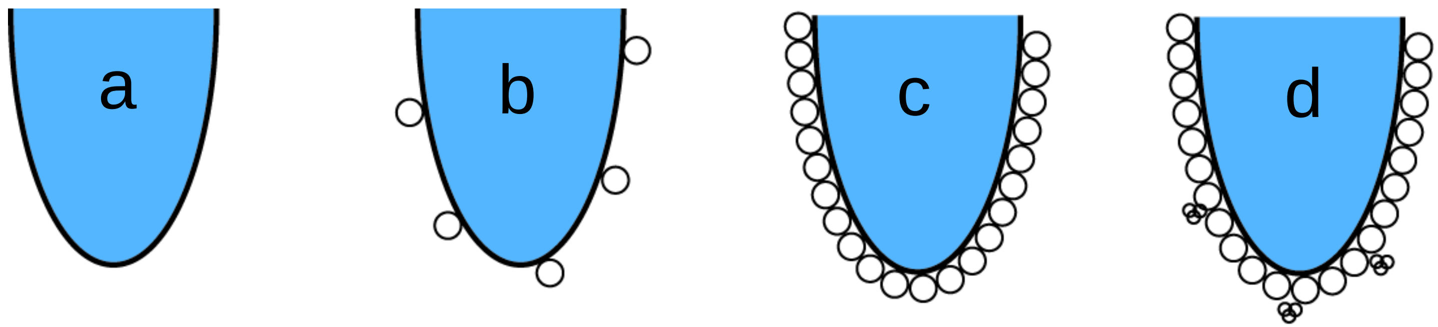
The field emission gun operates as follows:

1) A high voltage (~3-5kV) is applied between the filament (cathode) and the 1st anode.
2) A voltage applied to electrostatic lens (2nd anode) is then used to form the first cross-over.
3) A series of anodes is used to accelerate the electrons to the final voltage (i.e. 200kV).



The Cold-FEG operates at room temperature which allows gas atoms to readily stick to the tip surface. The tip state is characterized as having four conditions:

a) Perfectly clean without any adatoms – high fluctuating intensity
b) Adsorption of some gas atoms – reducing intensity
c) A monolayer of adatom coverage – Stable
d) Increase in emission current, but unstable

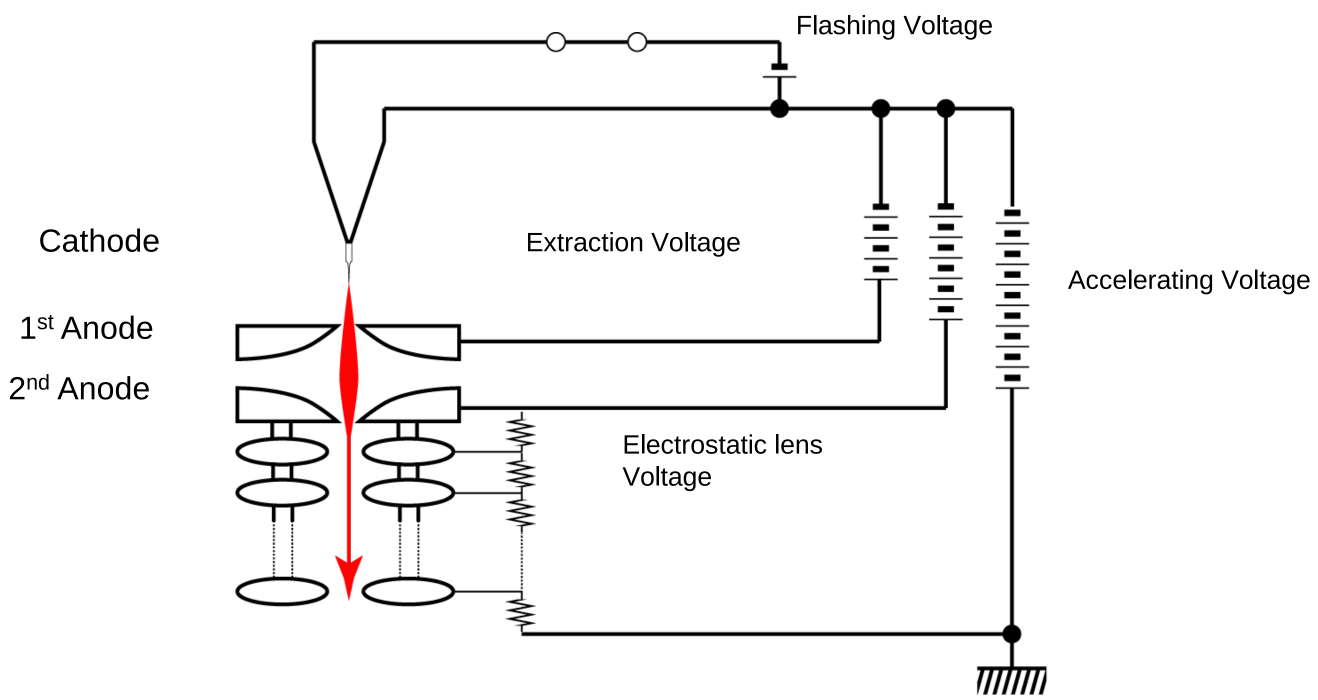


Electron Gun - flashing

The surface of the filament can be cleaned by “Flashing” whereby the filament is heated by closing a circuit to apply a “flashing” voltage through the filament support.

The HD-2700 has three levels of Flashing: “low”, “medium”, and “high.”

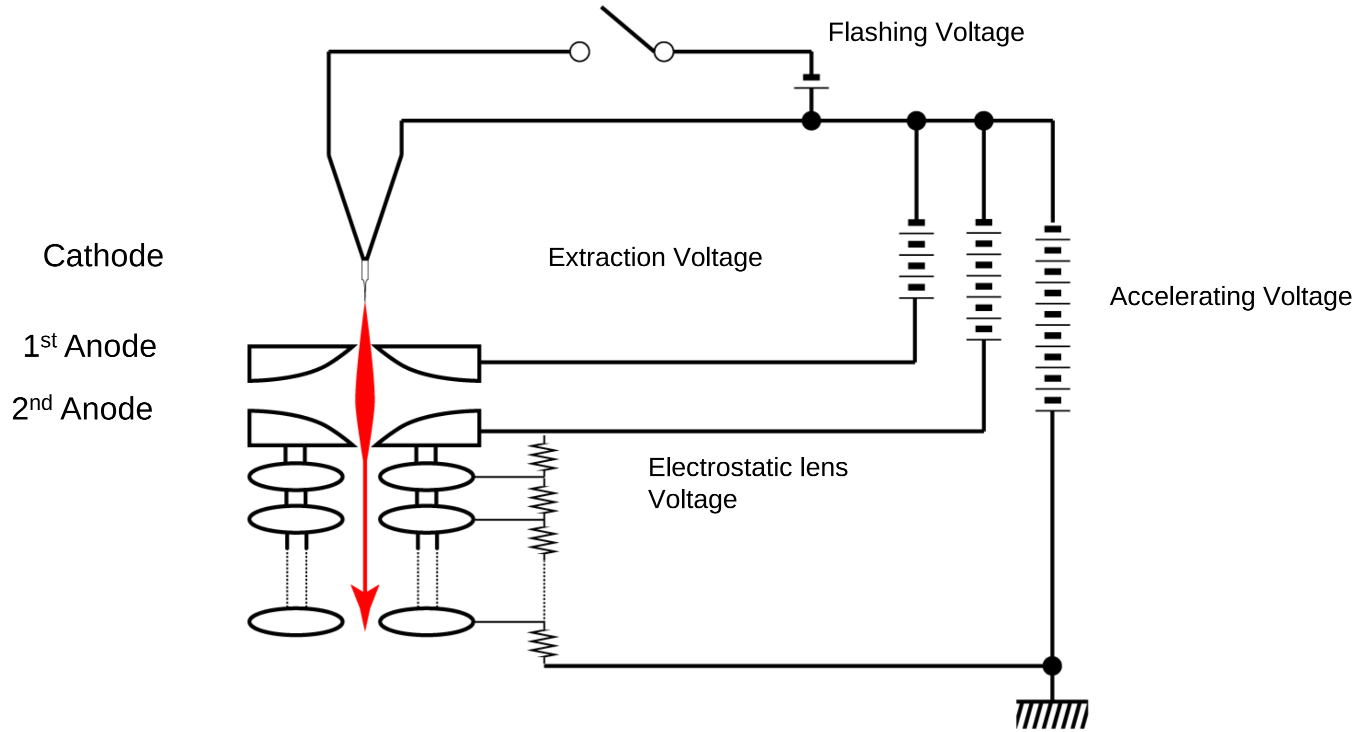
- Every 24 hours, or when the HV is started, a “High” flashing should be performed.
- During operation, a flashing is possible, however it is advisable to reframe from this as much as possible as it reforms the filament



Electron Gun

As an alternative to flashing in operation, the “Ie set” routine can be applied. This increases the extraction voltage which increases the filament current.

- The Ie Set routine does not clean the filament, but extends the current experiment
- Run the “Ie Set” routine between flashings when the emission current is ~3-5μA or to reach a more stable emission current.



Electron Gun

Advantages of C-FEG:

1) room temperature operation (no thermal shock/stability issues)
2) highest brightness (all others are compared against the C-FEG)
3) low energy spread (reduces chromatic aberration impact, improves EELS)

Disadvantages of C-FEG:

1) extreme vacuum requirements
2) gas molecules stick to and build-up on the cold surface

Important point: every microscope is different and the users will find the optimum duration between flashings and Ie settings.

Optical elements overview 2

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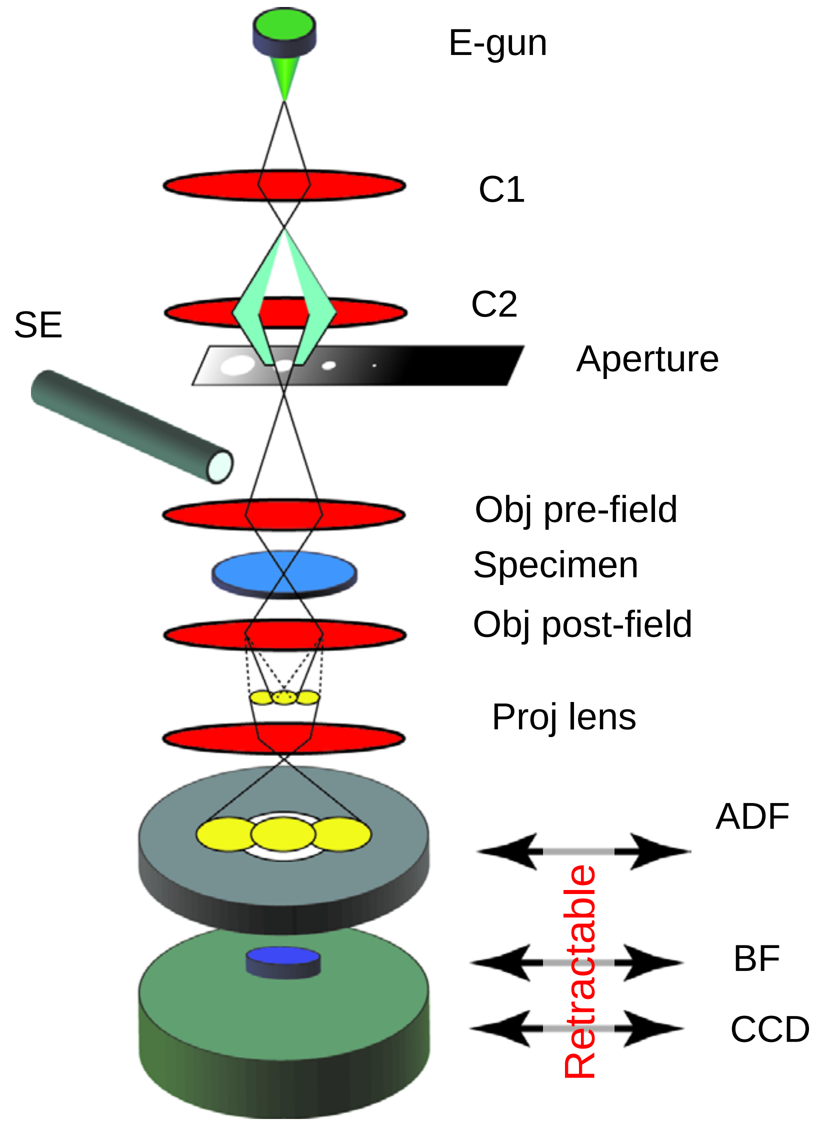

Electron Beam generation
→ Electron gun

Illumination system
→Condenser lens 1
→Condenser lens 2
→Objective Aperture
→Objective lens pre-field

Surface Detector
→Secondary Electron Detector (SE)

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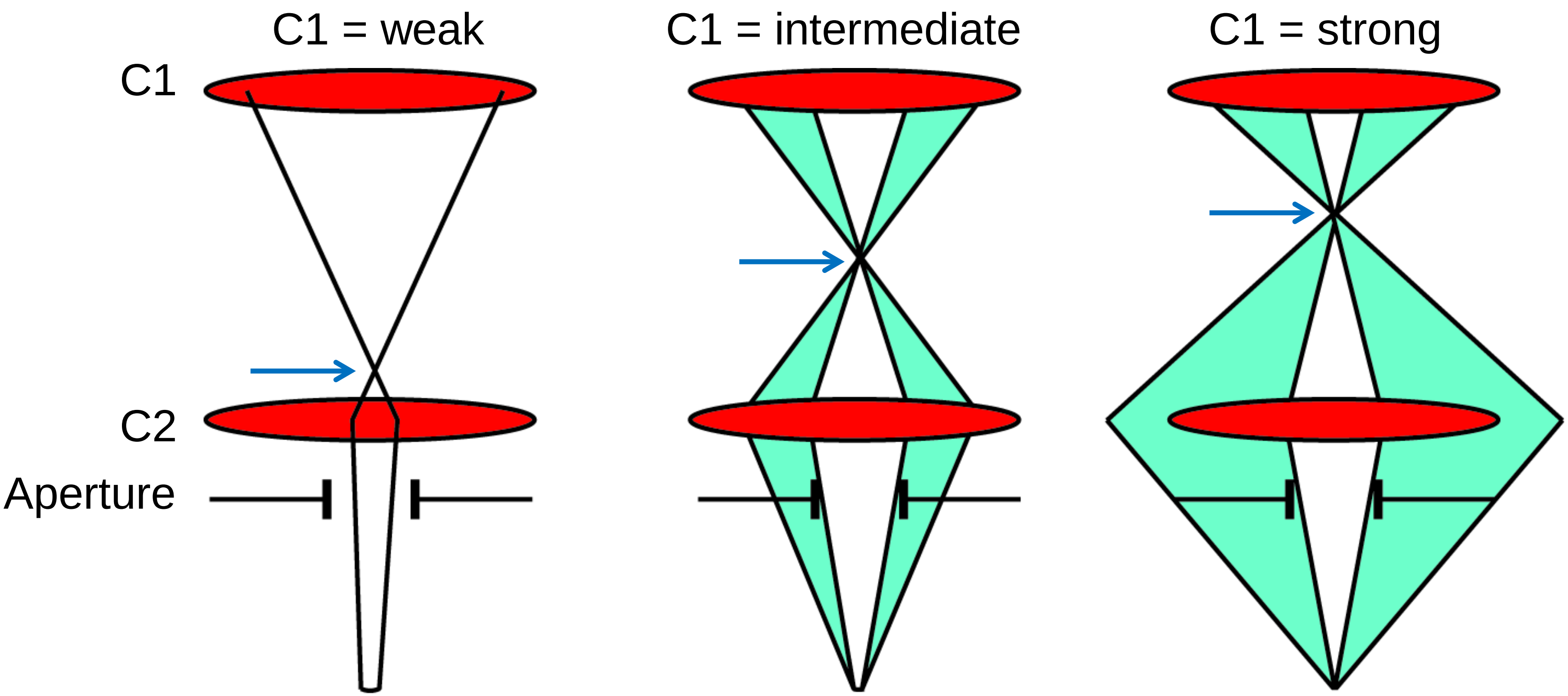
Double Condenser lens system

The first condenser lens (C1) is used to form a cross-over between the first and second (C2) condenser lenses.

- When the C1 lens current is weak, the cross-over is close to C2 and more electrons make it through the aperture.
- When the C2 lens current is strong, the cross-over is closer to C1 and fewer electrons make it through the aperture.
- More electrons = higher brightness = more repulsion = larger probe size.



Double Condenser lens system + aperture

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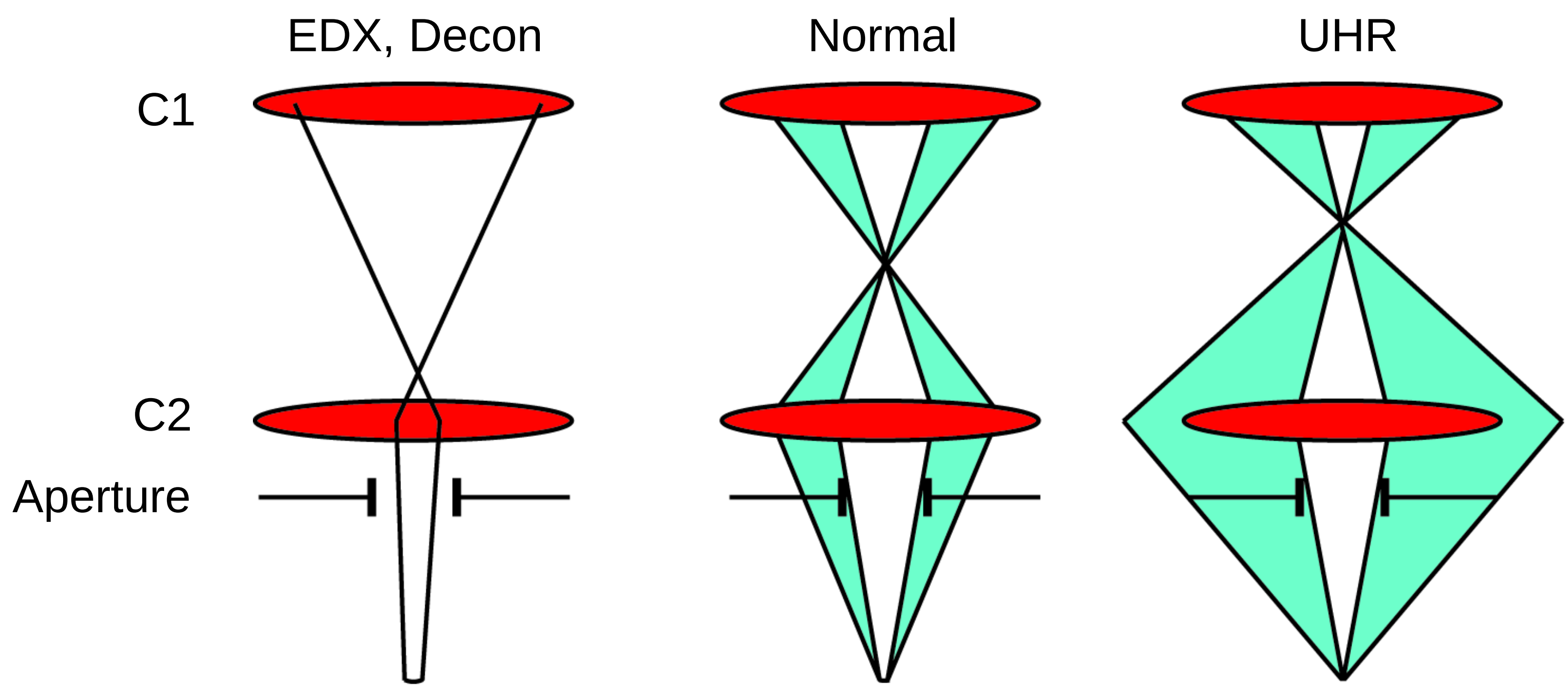
Spot Size	Operation Mode	Aperture
large ↑	EDX, DeCon	1
	Normal	1
	High Resolution	2
small	Ultra High Resolution	3



Standard imaging mode:
High Resolution with #2 aperture.

Optical elements overview 3

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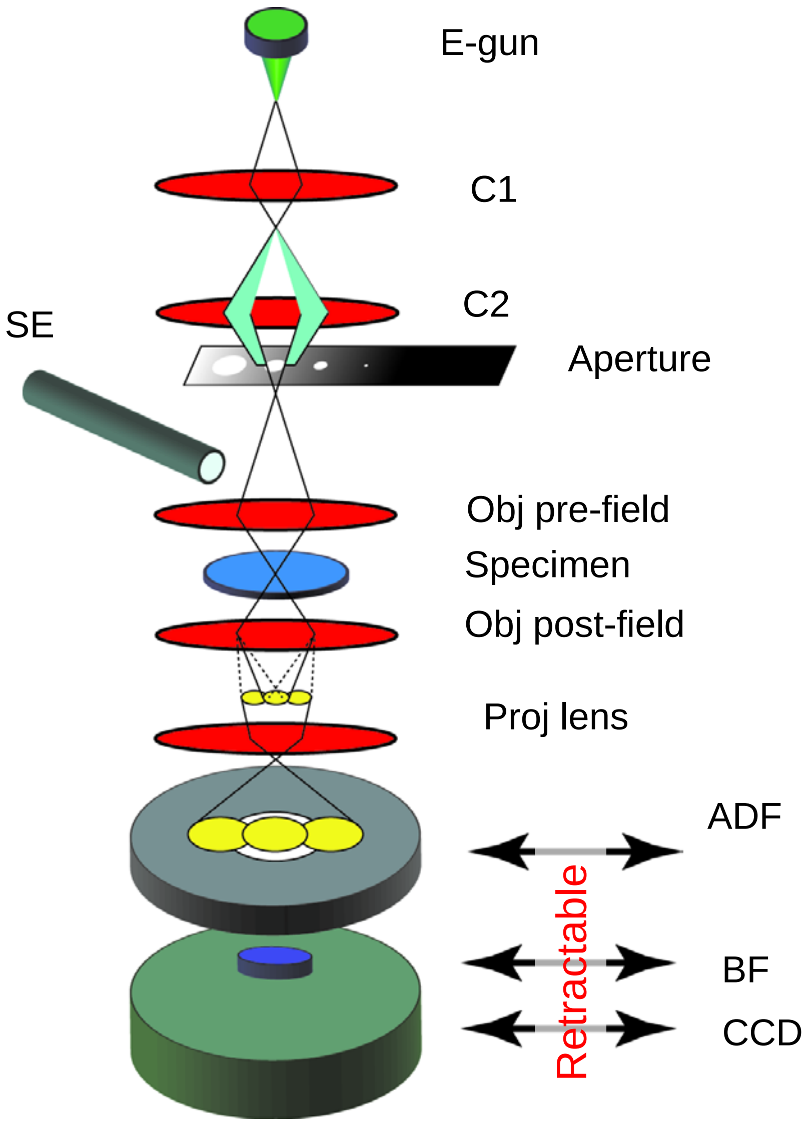

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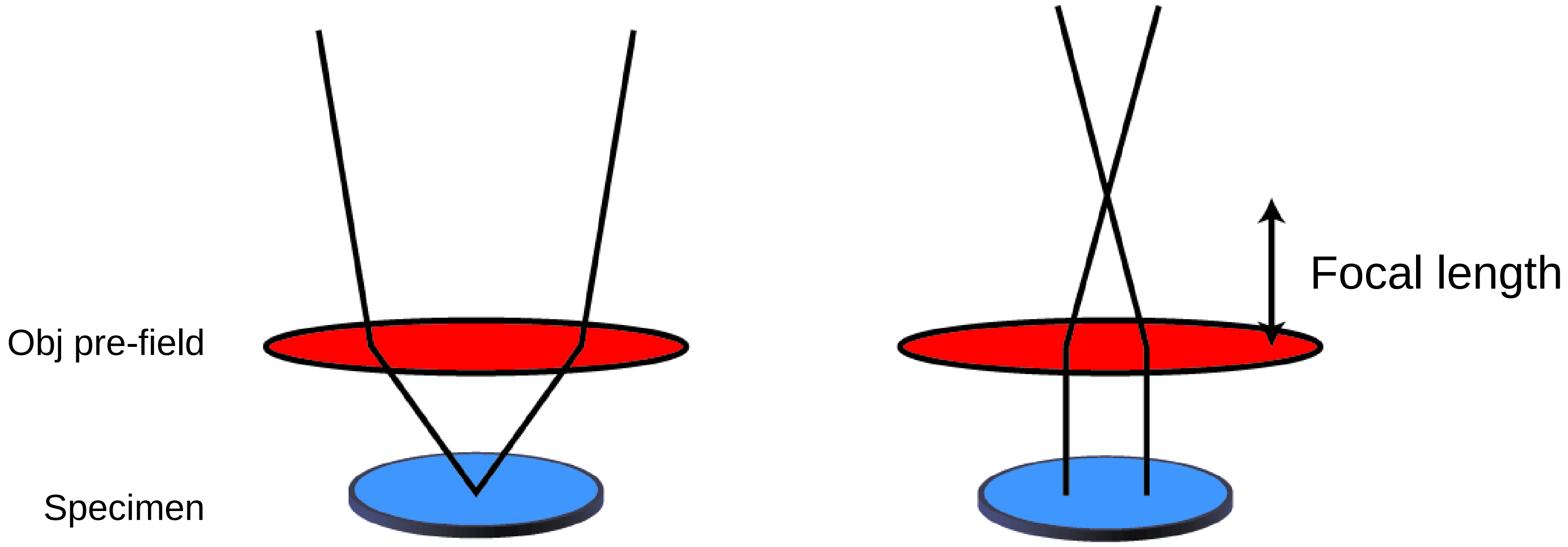
Objective lens Pre-field

The specimen is located within a gap between two pole pieces which focus the magnetic flux creating a pre-field and a post-field.

- In standard STEM mode, the objective lens pre-field is the final focusing lens in the illumination system. This lens is also the strongest and most critical lens in the system. **Always operate very near the pre-set current displayed as defocus=0nm.**
- (Near) Parallel illumination is used to obtain spot diffraction patterns. In this situation, C2 is more strongly excited and a cross-over is located at the objective lens focal length in front of the pre-field. This is the configuration for the Nano-Diff mode with Apt #4 (smallest).



Probe mode

Parallel illumination

SE Detector

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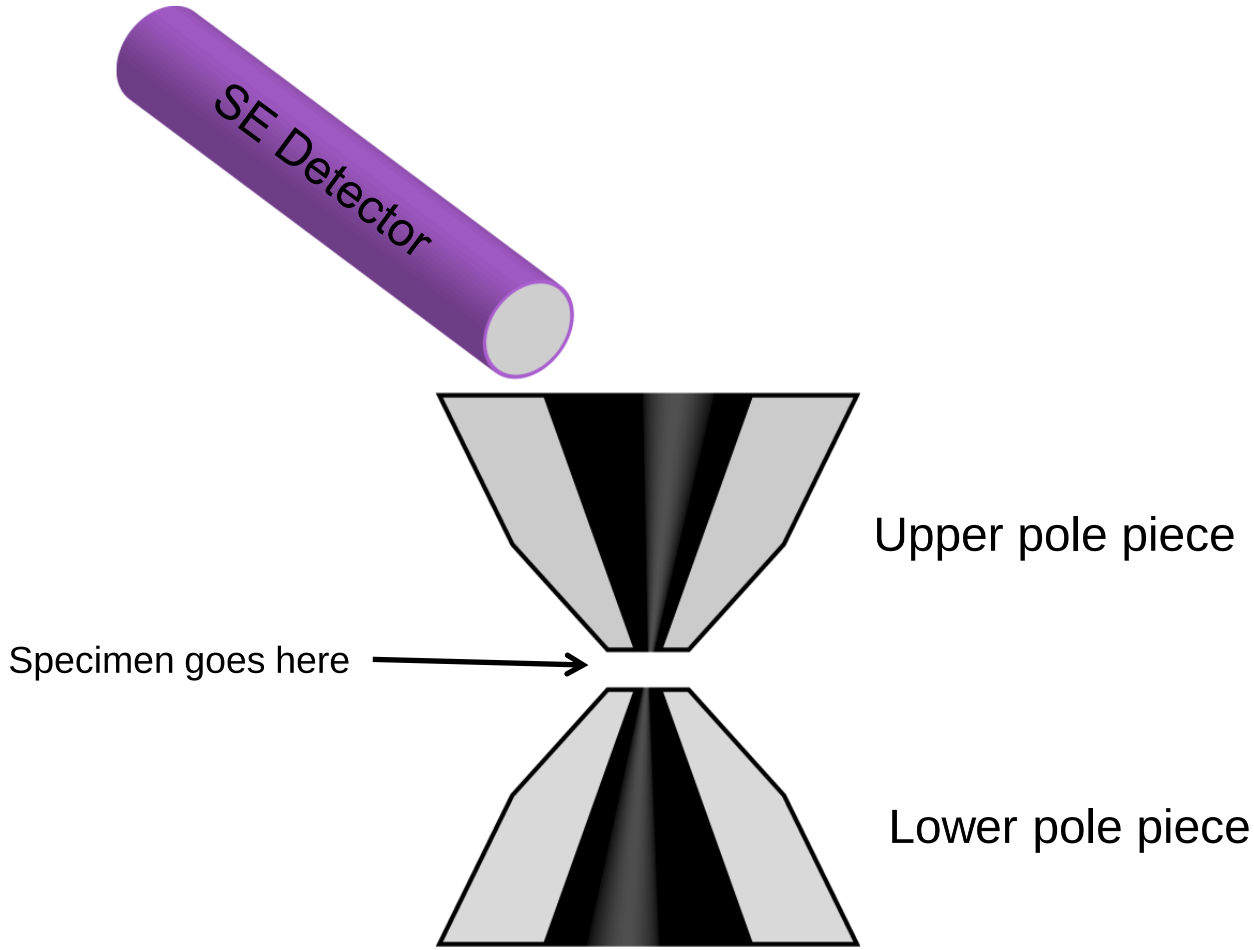
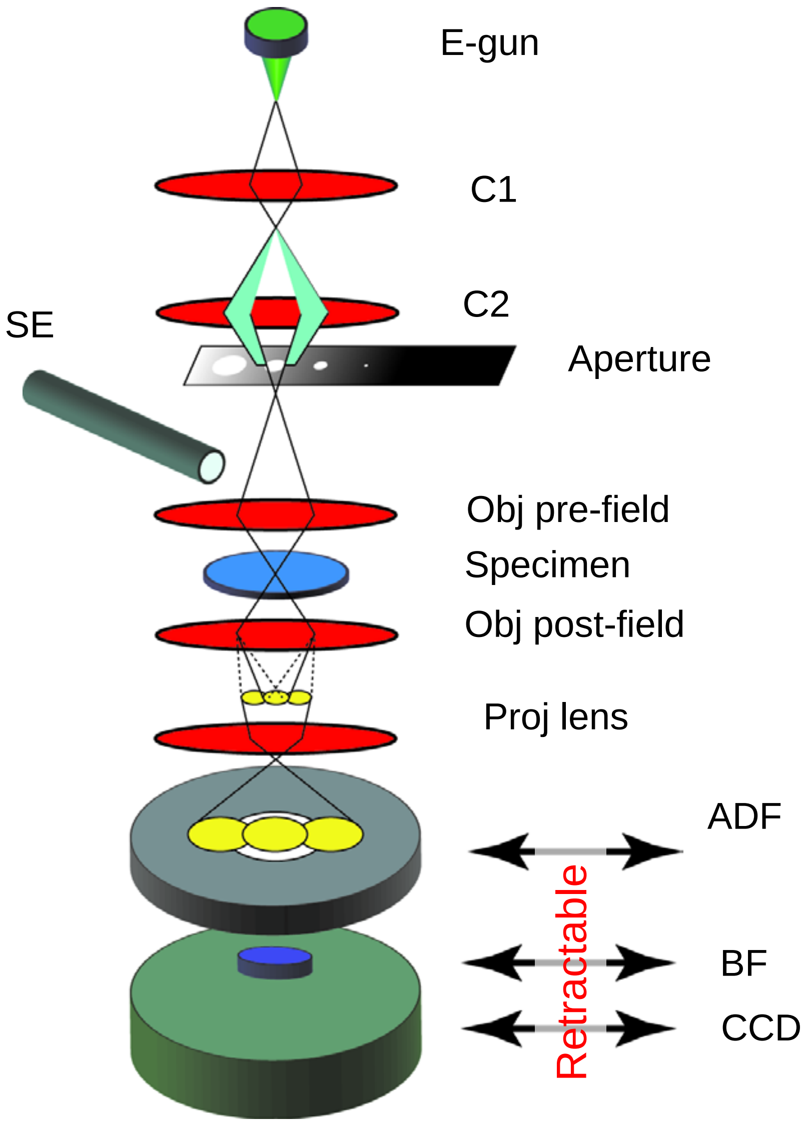
The objective lens region is composed of a coil and two pole pieces which focus a magnetic field analogous to an optical lens. The Hitachi design allows the secondary electron detector to be inserted just above the upper pole piece to maximize the collection efficiency.



Optical elements overview 4



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Diffraction concept

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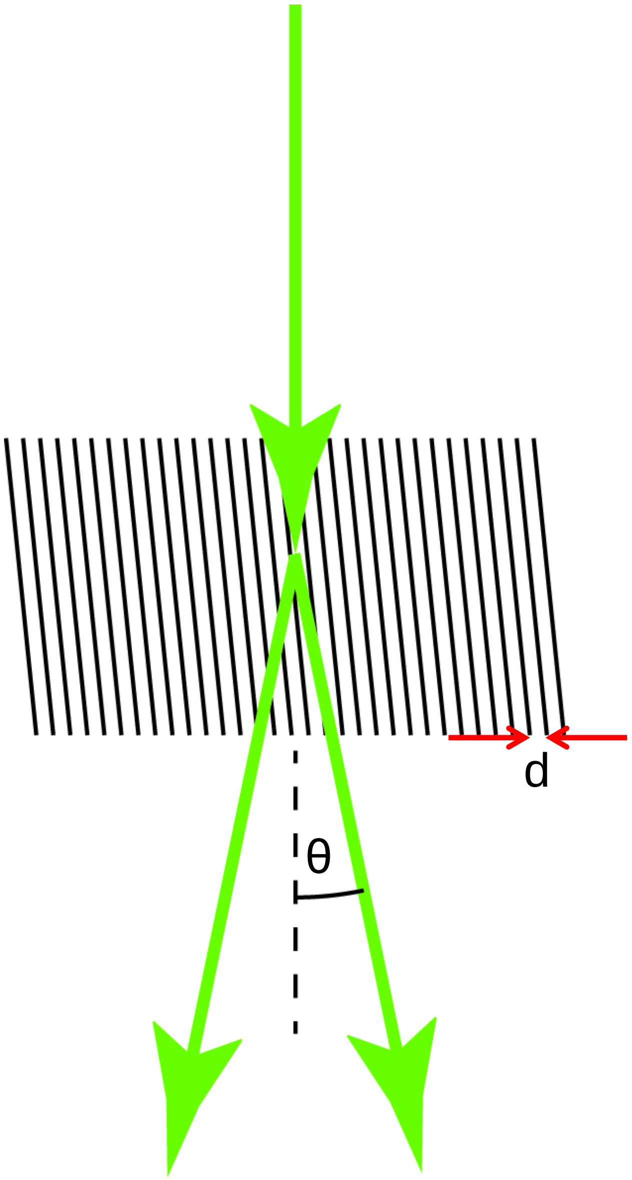


Diffraction occurs when the wavelength of an incident beam is similar to the spacing between objects.

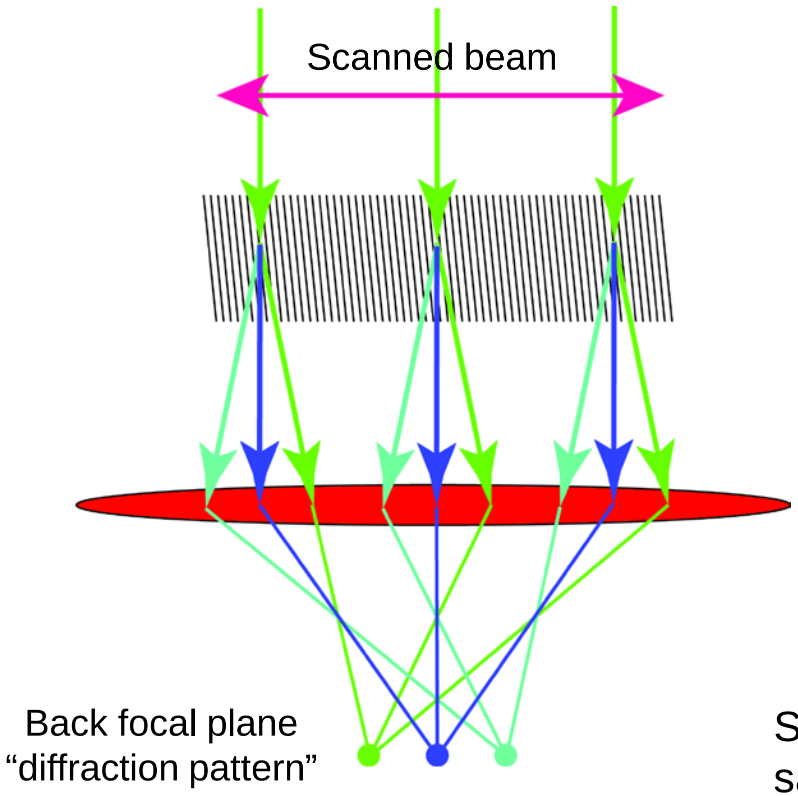
- Light scattering off water vapor in the air around a night-post
- Laser light scattering off ruler or grating
- Electrons or X-rays scattering from the spacing between atoms

$$\theta_B \sim \frac{\lambda}{d}$$

Bragg's law says that the scattering angle, θ, gets bigger as the inter-planer spacing, d, gets smaller for a particular wavelength of incident radiation.

Atomic spacing: ~100pm
Electron wavelength (200keV): 2.51pm
Cu Kα X-Ray wavelength: 15.4pm
Green light wavelength: 532nm

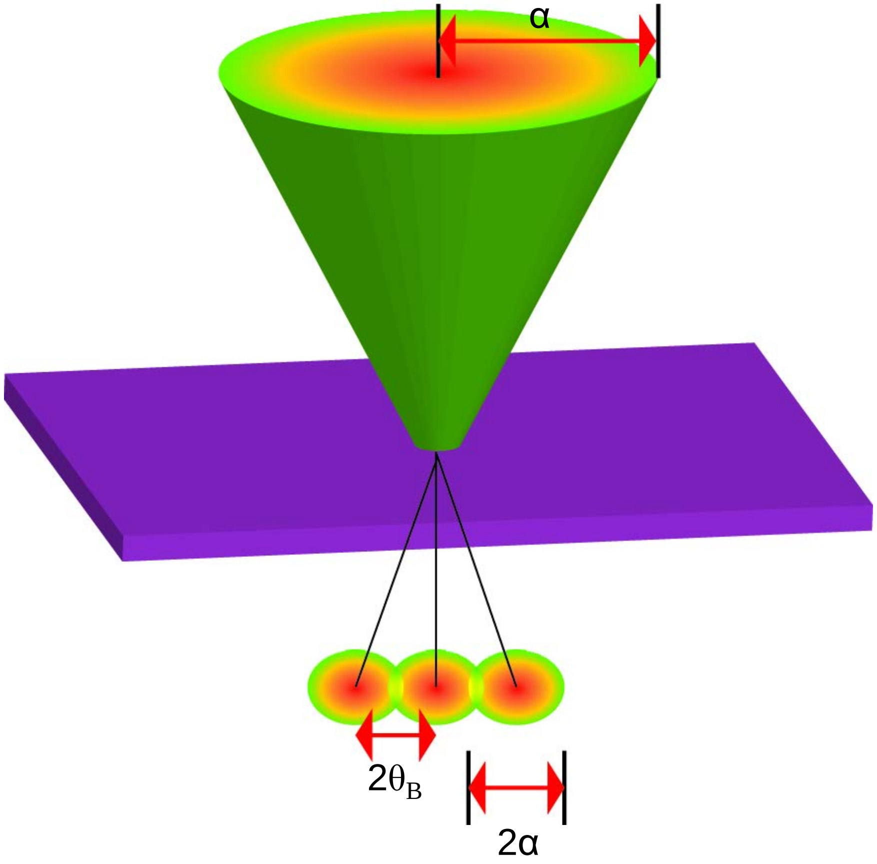
Objective post-field



As the beam is scanned, a diffraction pattern is formed at each point. The objective post-field projects each diffraction pattern onto the back-focal plane forming a diffraction pattern to be projected by the projection lens.

Spot pattern occurs when the beam incident to the sample is parallel and not converged.

Real diffraction pattern



In STEM, the beam is converged. The sharp spots expand into disks reflecting the range of incident angles to the sample.

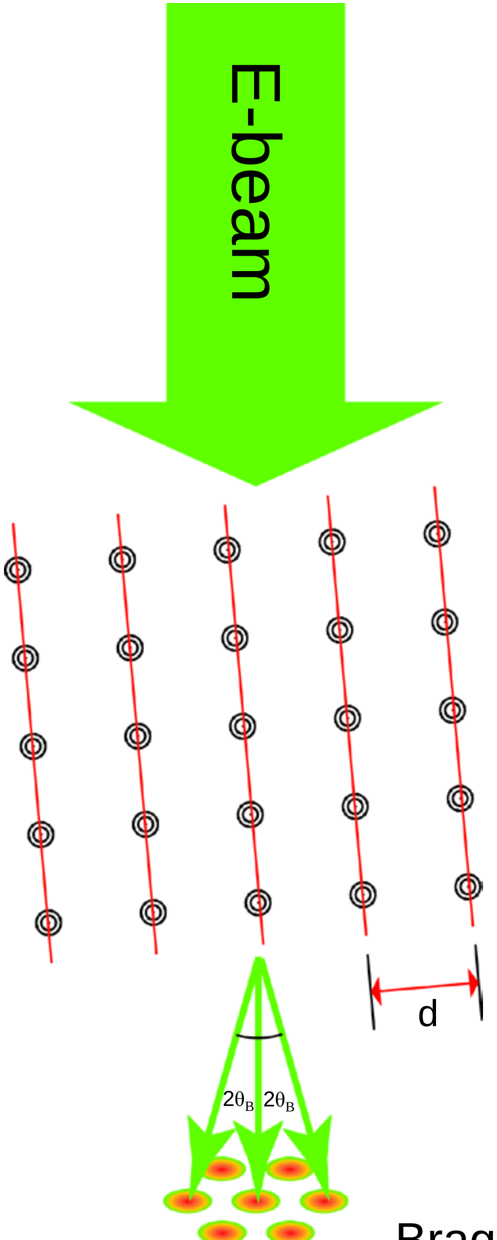
The diameter of the spots (2α) is directly related to the probe convergence semi-angle α. The distance between spots is directly related to the Bragg angle (θ_B) of the scattering planes.

Note that the scattering angle is the same as with parallel beam illumination.

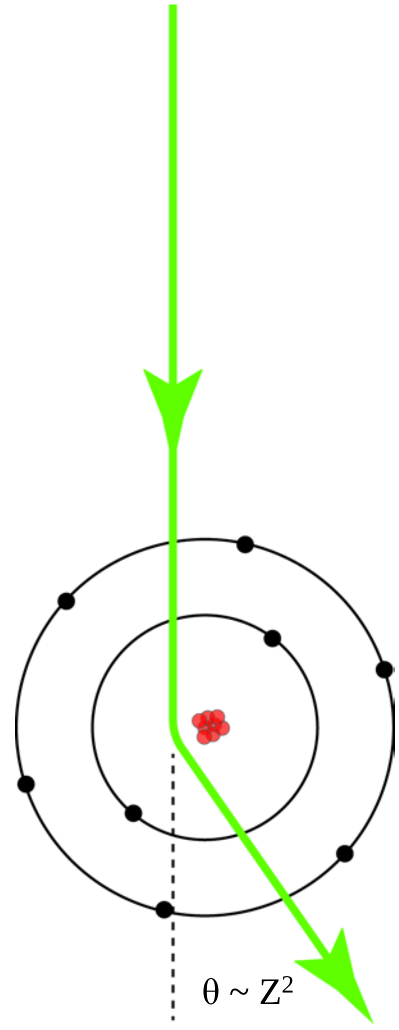
The convergence angle is determined mostly by the aperture used.

Aperture	Diameter (µm)	Convergence Semi-angle (mRad)
1	100	~25
2	60	~15
3	40	~10
4	10	~2.5

Scattering mechanisms



Bragg diffraction



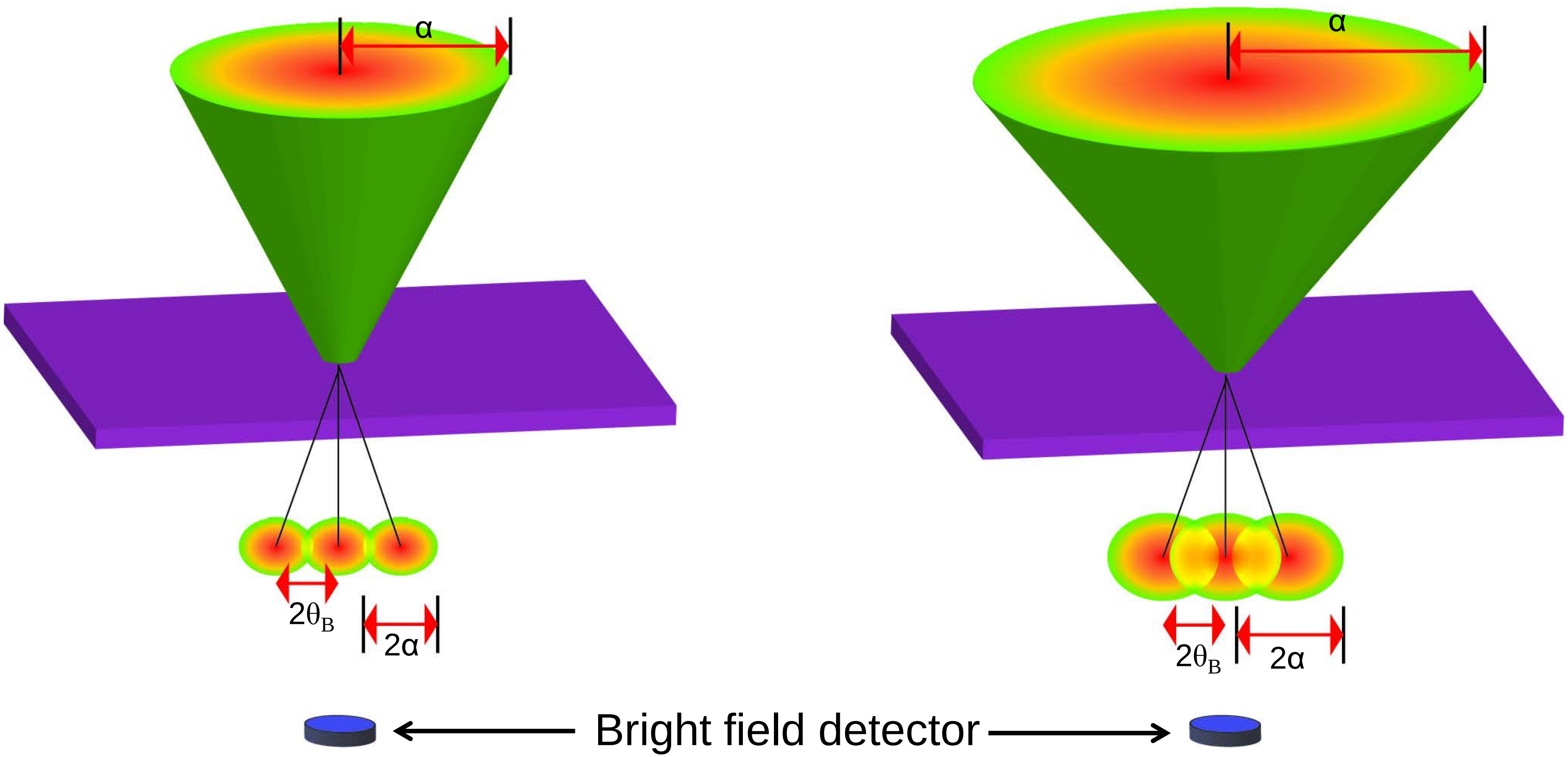
Bragg diffraction: ~10-30mRad
Z-contrast: ~50 mRad – ∞ mRad

Z positively charged protons in atomic nucleus

Z power = 2 if screening is ignored

Rutherford scattering
“Z-contrast”

Bright Field + Phase contrast lattice imaging

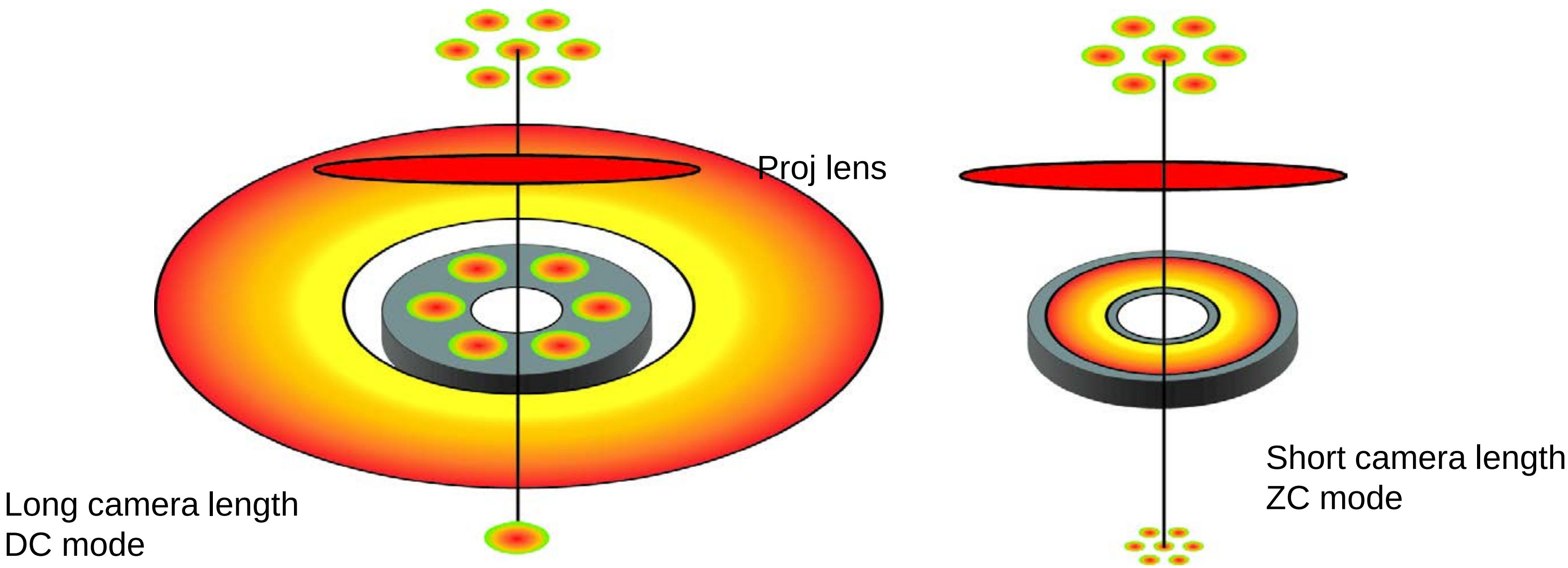


In bright field imaging, the transmitted beam is used to form an image. To obtain lattice resolution in the BF mode, at least two beams must interfere to form the constructive interference pattern showing the lattice planes. The left image above shows a convergence angle leading to little overlap and no lattice fringes. The right image has significant overlap on the BF detector and will lead to lattice fringes.

Projector lens

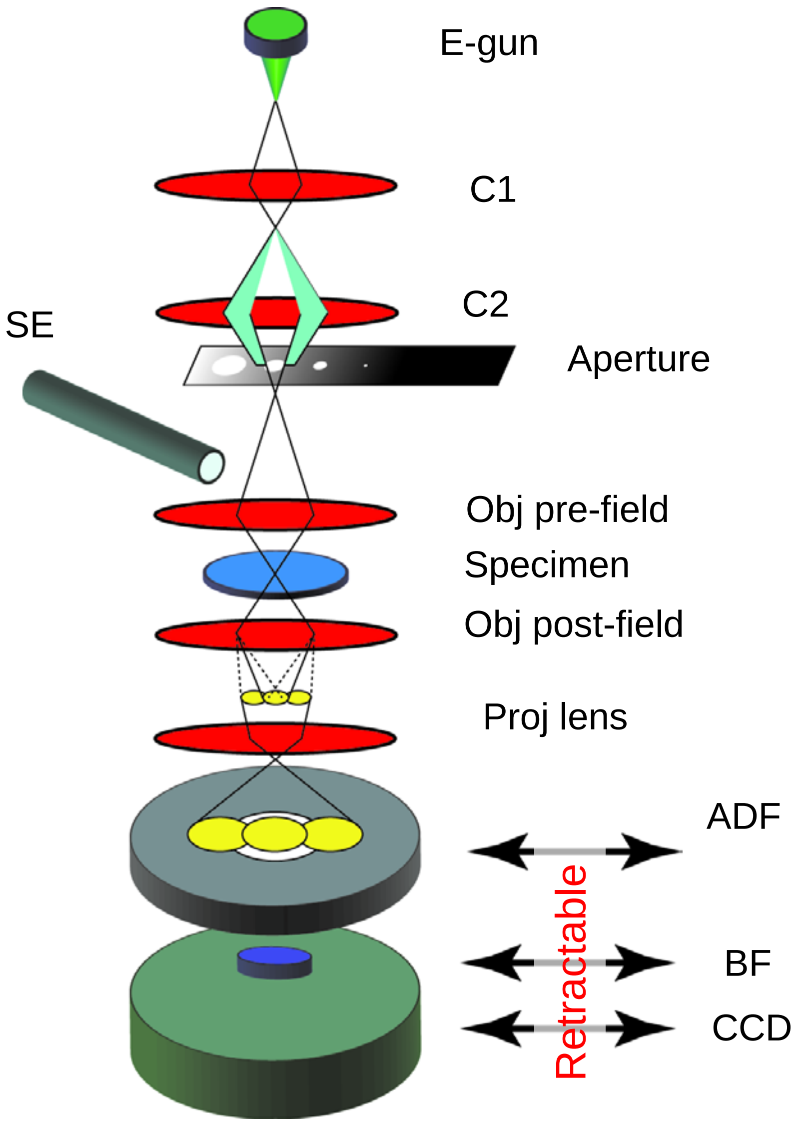
Pure diffraction contrast

Pure Z contrast



The projector lens serves to magnify the diffraction pattern (at the back focal plane of the objective lens) on the detectors. At higher magnifications (longer camera length), diffracted beams are intercepted by the ADF detector while the much less intense Z-contrast beams either miss the detector or contribute a negligible signal compared to the diffracted beams. At lower magnifications (shorter camera length), the diffraction pattern is projected through the hole in the detector and only the Rutherford scattered electrons are intercepted by the detector.

Optical elements overview 5



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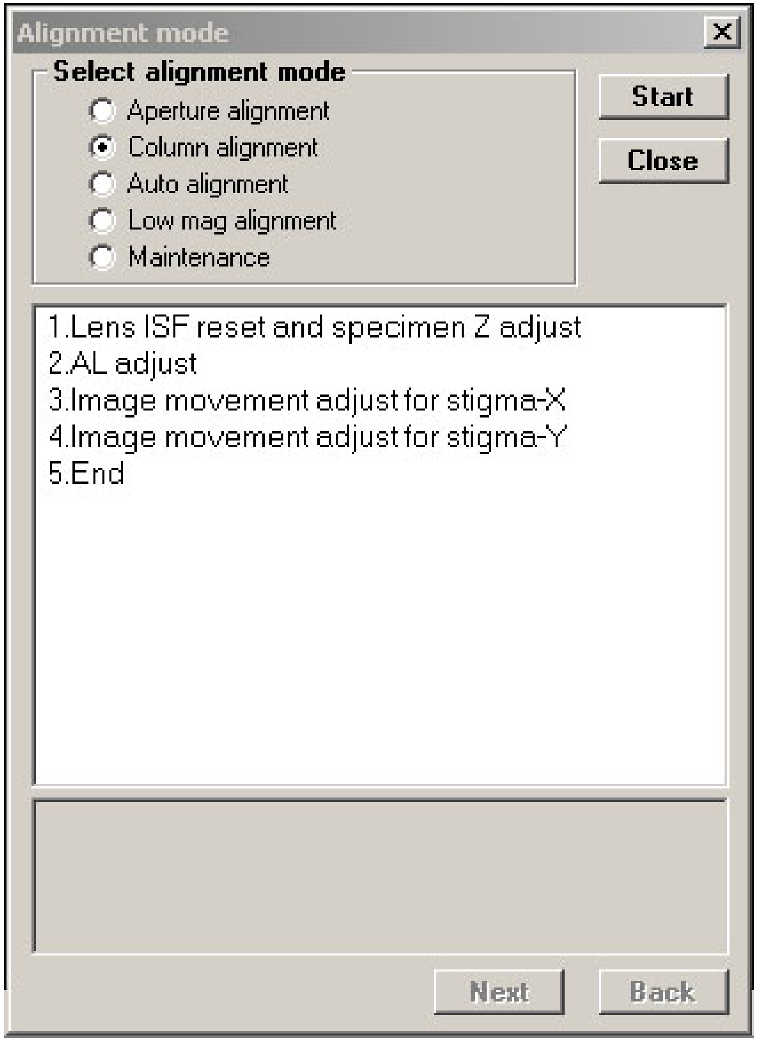
Alignments

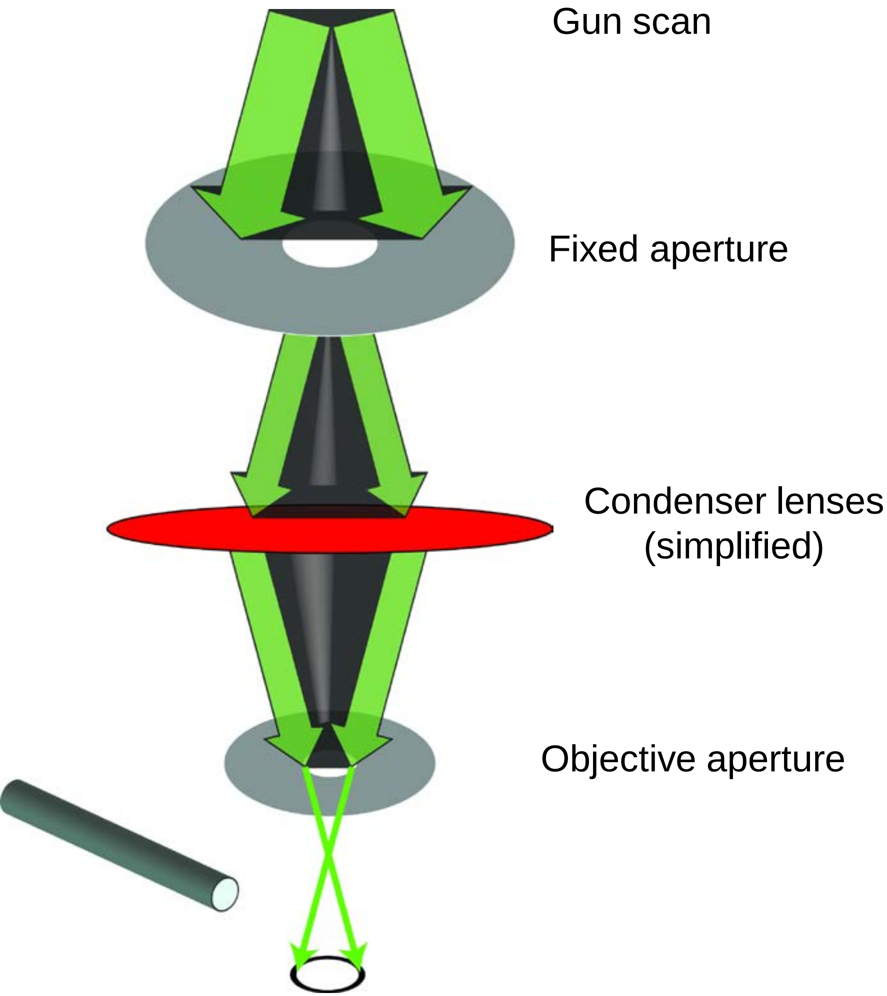
The optical elements of the dedicated STEM have been described for an idealized microscope.
Real microscopes need alignments, tweaks of the beam, apertures, and repositioning of the projected beam.

Only 4 steps

- Aperture alignment
- Eucentric height
- Current Center alignment
- Condenser astigmatism

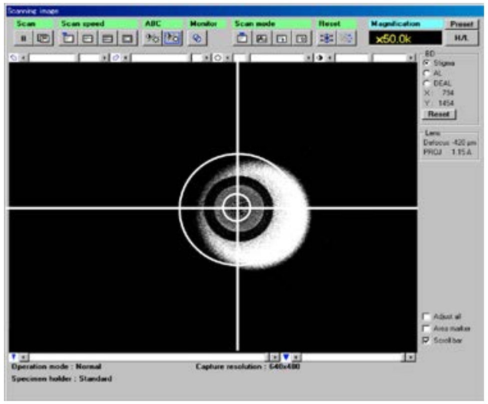


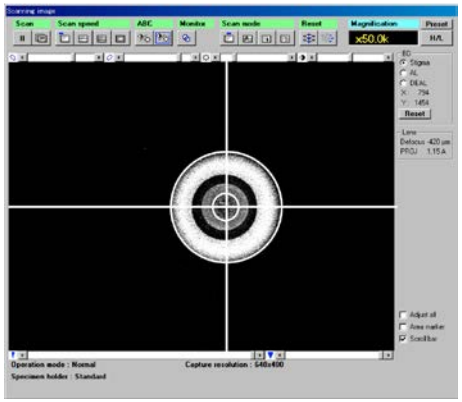
Aperture alignment



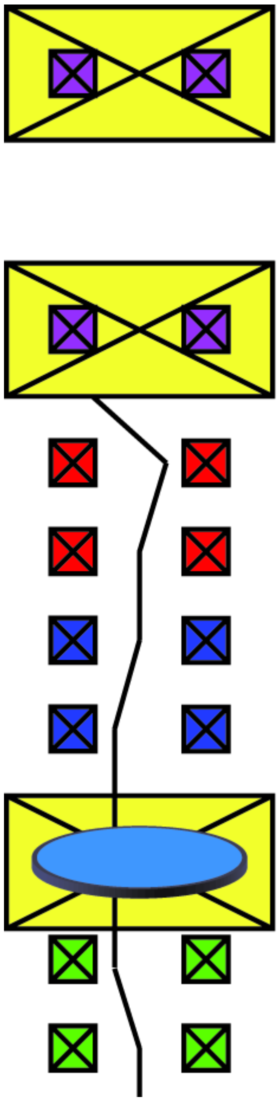
The aperture alignment function makes use of the unique Hitachi column incorporating the SE detector.

A special scan coil is built into the electron gun assembly to tilt the beam going through the objective aperture. This results in an annulus of intensity cut off by the moveable aperture. Aperture alignment is achieved by centering the annulus.





Alignment coils



Condenser Lens 1
Astigma coil 1

Condenser Lens 2
Astigma coil 2

Alignment Coils

Scan Coils

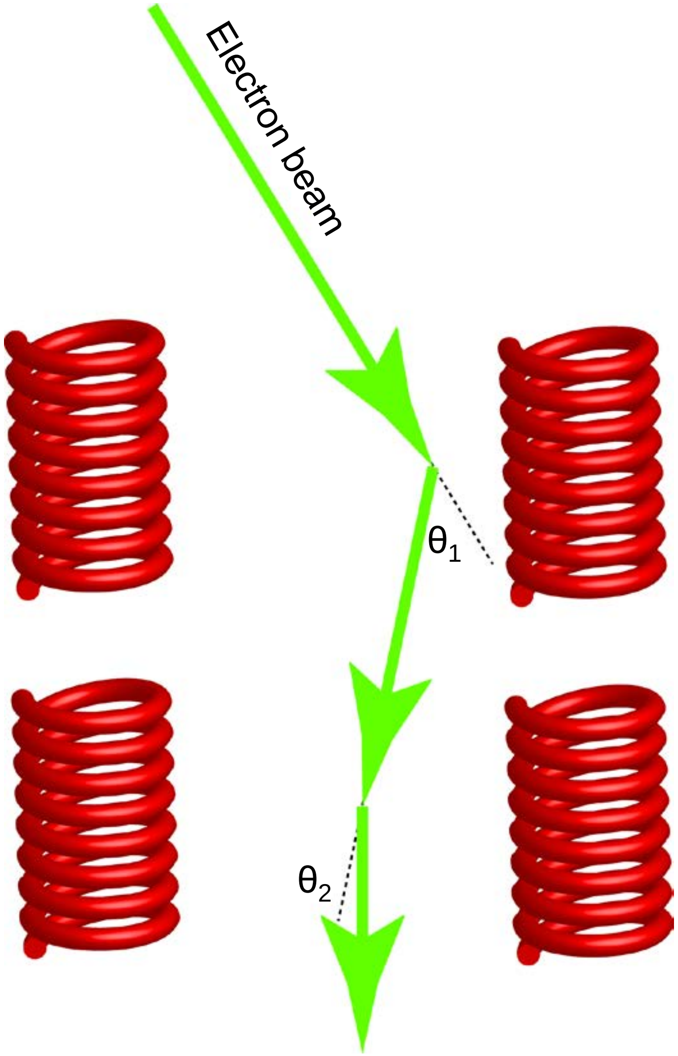
Objective Lens / Specimen

DEflection ALignment (DEAL) Coils

Detectors

Beam Deflection (BD) Coils

Deflection Coils

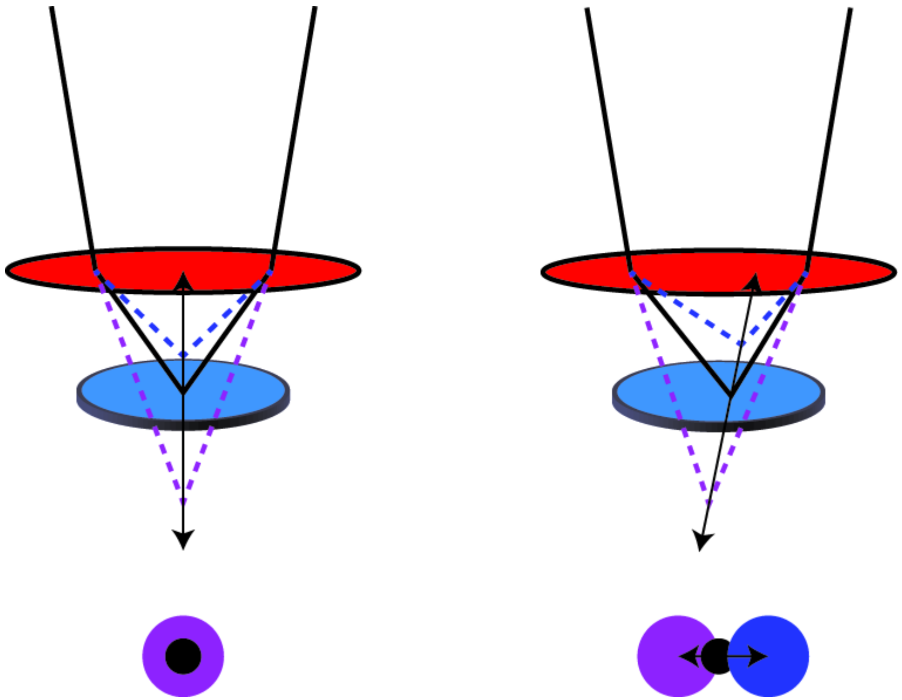


Deflection coils come in pairs with a “North” side and a “South” side to create a magnetic field to align or steer the beam.

Shown here is an alignment where the beam comes in to the top coils and is bent by θ_1 degrees into the lower coils which bend the beam θ_2 degrees onto and parallel to the optic axis.

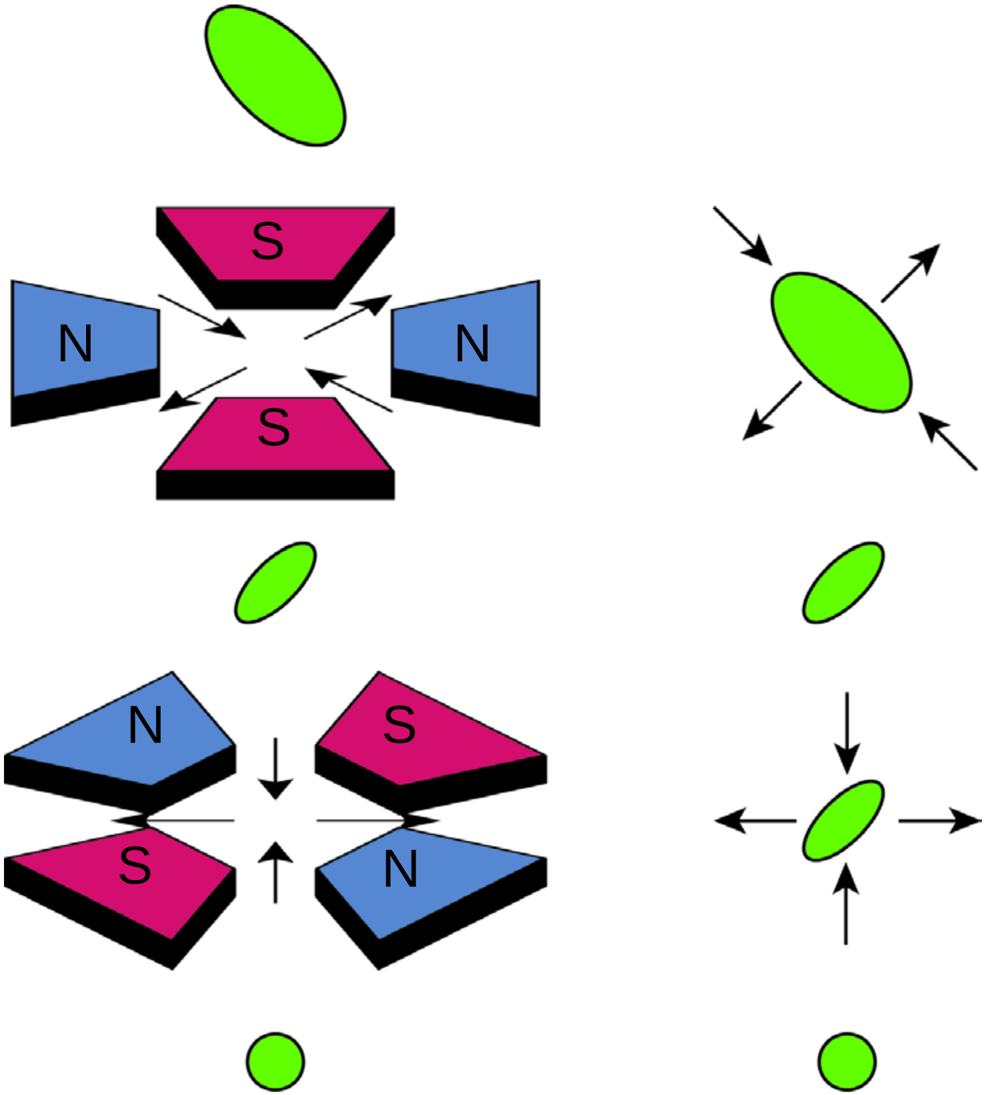
Typically, there is a second set of four coils in a plane perpendicular those shown which deflect in the “Y” direction.

Current Center Alignment



Current centering modulates the current through the objective lens resulting in a change to the focal length, which causes the beam cross-over to move up-and-down. If the alignment coils correct the beam tilt, the image will pulse symmetrically (left image). If the cross-over moves along the skewed arrow (right image), the image will pulse from side-to-side and the balance of the alignment coils can be adjusted.

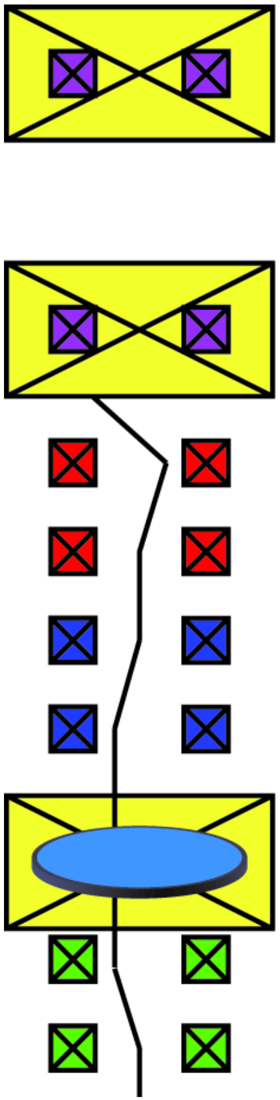
Astigmatism correction



Non-round lenses can be used to correct various aberrations, including astigmatism. 2-fold astigmatism correction is achieved by stacking quadrupole lenses rotated 45°, to shape the beam into a circular spot.

The beam is shaped into a nearly circular disk with the first quadrupole and fully corrected by the second quadrupole.

Alignment coils



Detectors

Condenser Lens 1
Astigma coil 1

Condenser Lens 2
Astigma coil 2

} Correct 2-fold astigmatism

Alignment Coils } Correct rotation center

Scan Coils } Scans the beam

Objective Lens / Specimen

DEflection ALignment (DEAL) Coils } Moves the diff pattern

SE Alignment strategies

- Pure SE alignment
  - Aperture alignment (method previously shown)
  - Eucentric height adjustment
    - Reset defocus
    - Adjust height to focus image
  - Current Center alignment (obj current wobble)
  - Condenser astigmatism
    - Focus image with stigmators and Obj lens current

TE Alignment strategies

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TE alignment

- Adjust sample tilt if appropriate.
- Aperture alignment (method previously shown)
- Eucentric height adjustment
  - Reset defocus
  - Adjust height to focus image (TE mode)
- Current Center alignment (obj current wobble – TE mode)
- Condenser astigmatism
  - Focus image with stigmators and Obj lens current
- Use DEAL to put TE spot through TE aperture (may have to remove TE detector to see spot on Diffraction camera.

ADF Alignment strategies

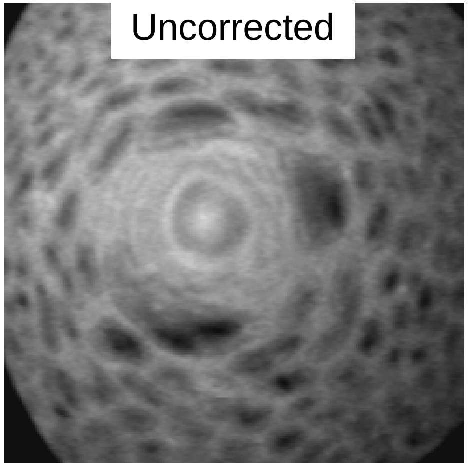
ADF alignment

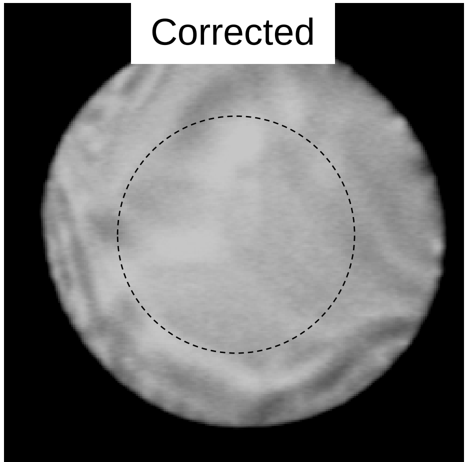
Procedure 1) Same as TE alignment

Procedure 2) Ronchigram method

Use Aperture #4 in UHR, Z-contrast mode, and beam stopped on amorphous location. Observe the Diffraction disk.

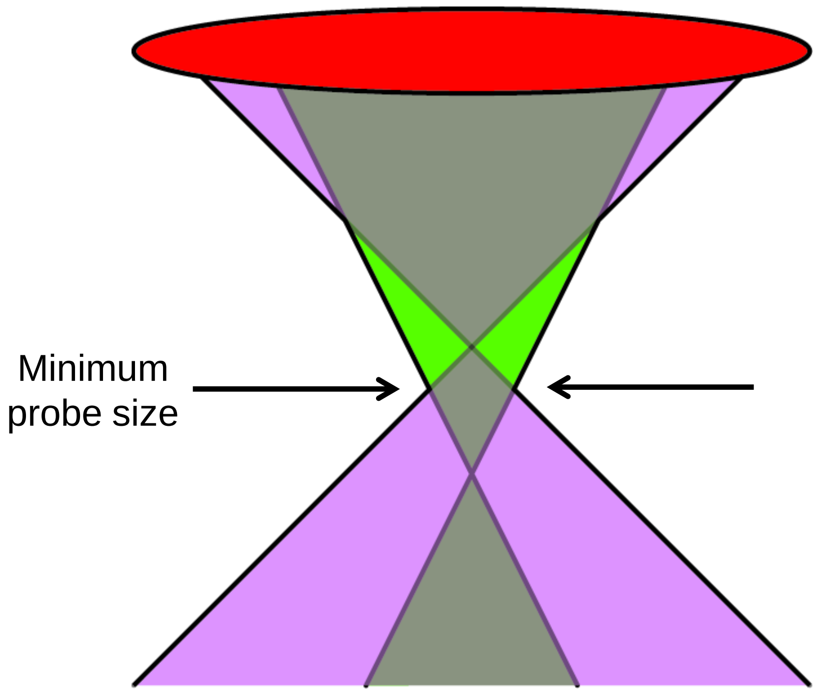
a) Use ALN to bring "sweet spot" to center of disk
b) Use DEAL to bring disk to center of diffraction camera
c) Use stigmators to make "sweet spot" circular.
d) Use focus to bring "sweet spot" to infinite magnification/flat.
e) Change to aperture #2 and center over "sweet spot"
f) Chose between DCM or ZCM





Ronchigram alignment strategy

Spherical Aberration



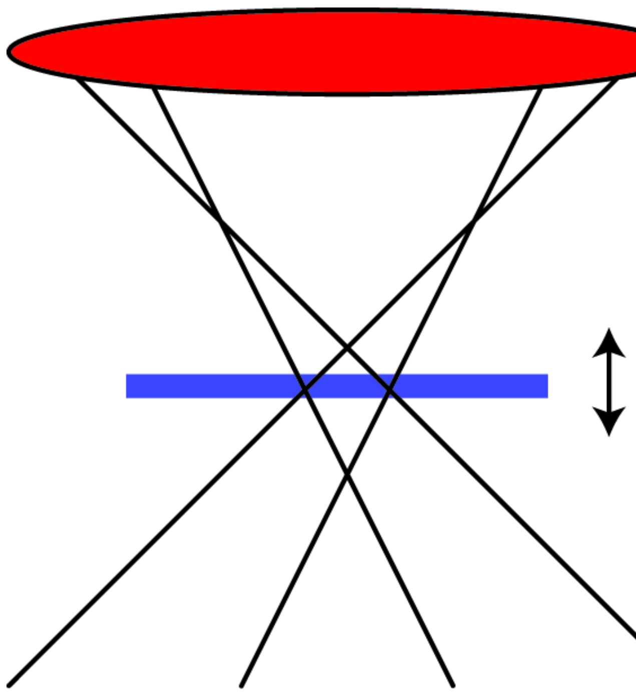
Spherical aberration of a lens causes rays at the center to be focused lower in the column than those on the edges of the lens bore.

Result: minimum diameter waist rather than point that forms the scanning probe.

Waist is called the “disk of least confusion”

Some rays are focused above specimen, some focused below specimen.
→ Use the range of cross-over heights to reveal non-symmetries of the beam.

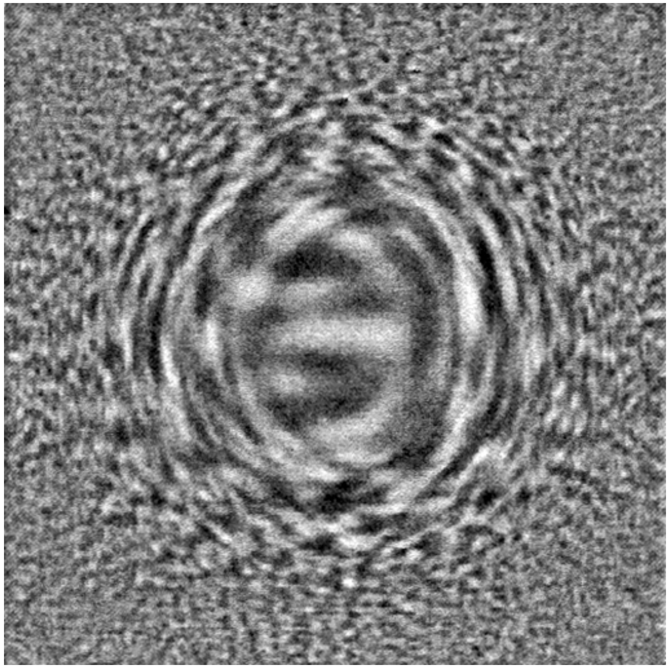
Z-height adjustment



Goal is to move sample vertically (Z-height) to being sample and disk of least confusion into the same plane. Then do fine adjustments with the lens to move the disk vertically onto the sample.

Course adjustment: Z-height
Fine adjustment: focus

Shadow image of amorphous region of sample →



Z-height/focus

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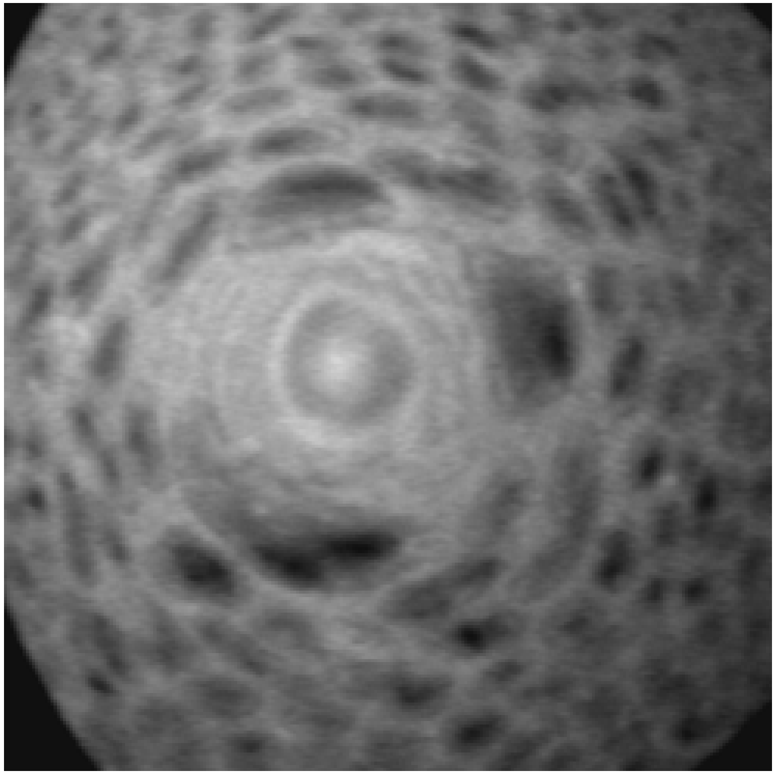
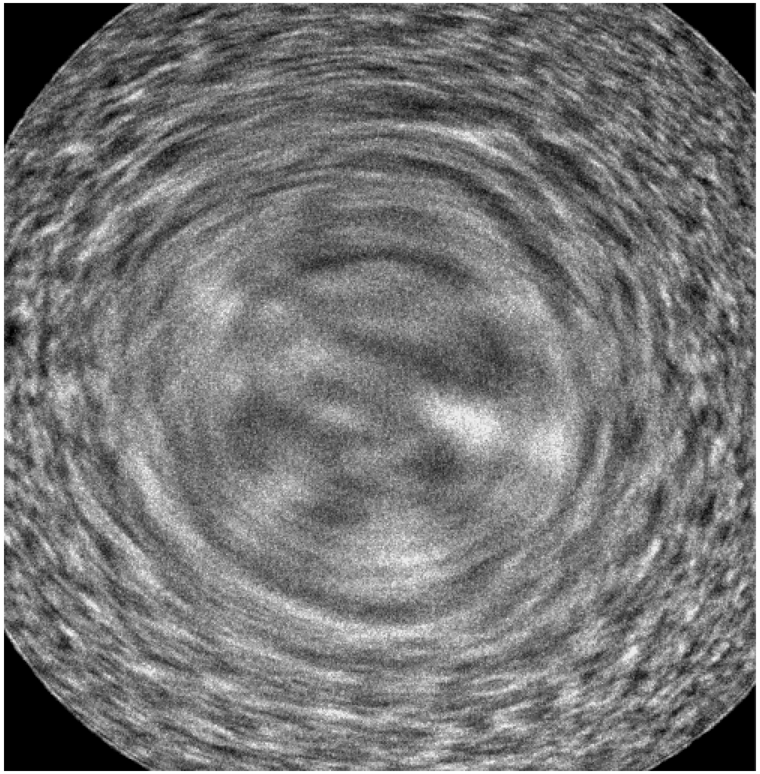


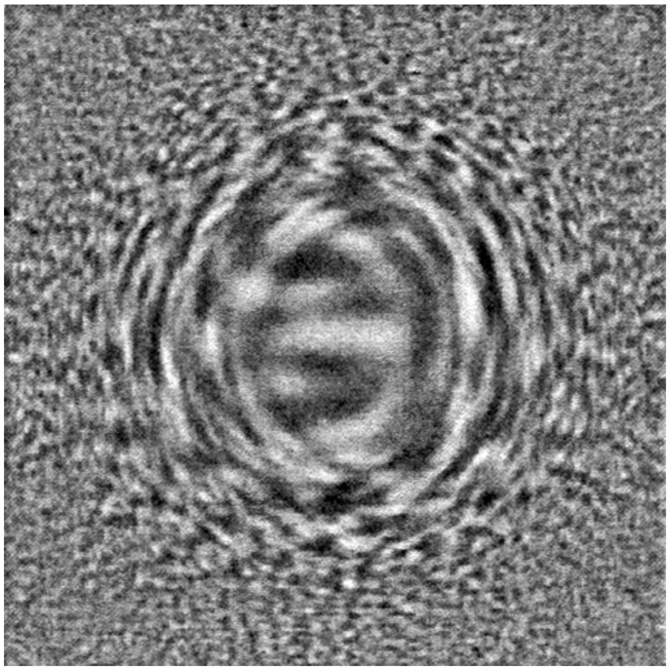
“sweet spot” off center and not at infinite magnification



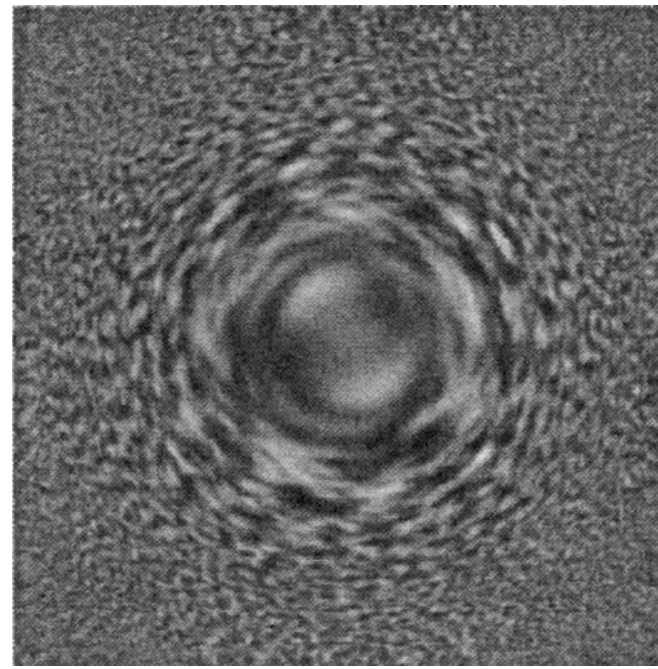
“sweet spot” centered and at infinite magnification

1) Use largest aperture (#1)
2) Position the beam on an amorphous location
3) Center the sweet spot with AL
4) Set “sweet spot” to infinite magnification with Z-height or focus (near 0nm defocus)

Condenser astigmatism (beam shaping)



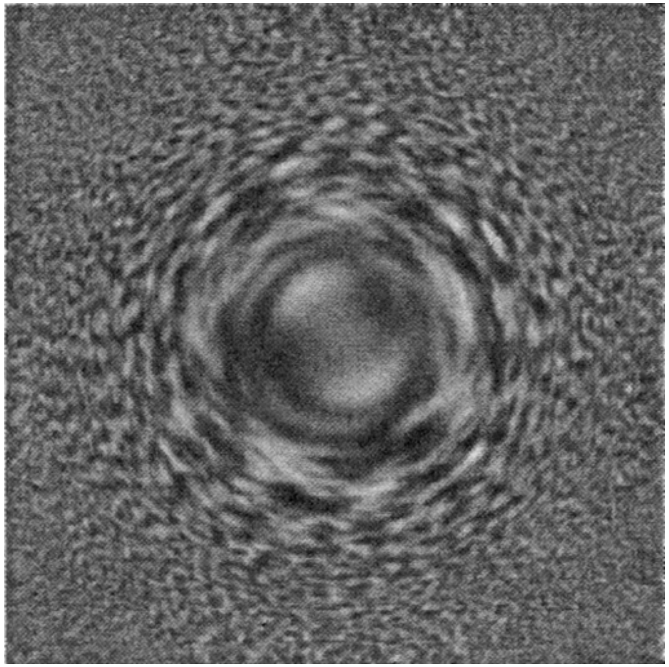
Condenser astigmatism evident (elliptical shape)



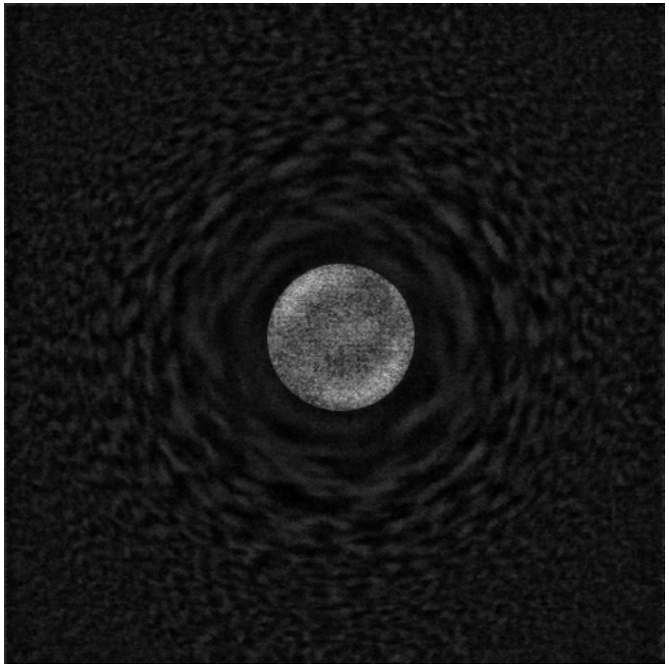
Condenser astigmatism correct (circular shape)

5) Correct condenser astigmatism to make Ronchigram circular

Filter out high angled rays



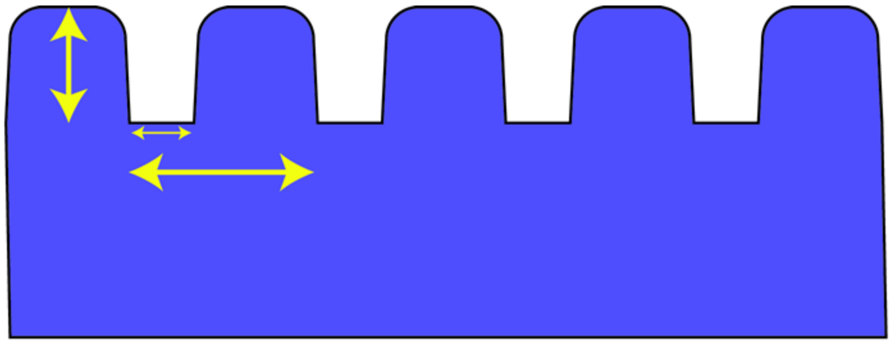
Optimized beam with aperture #1

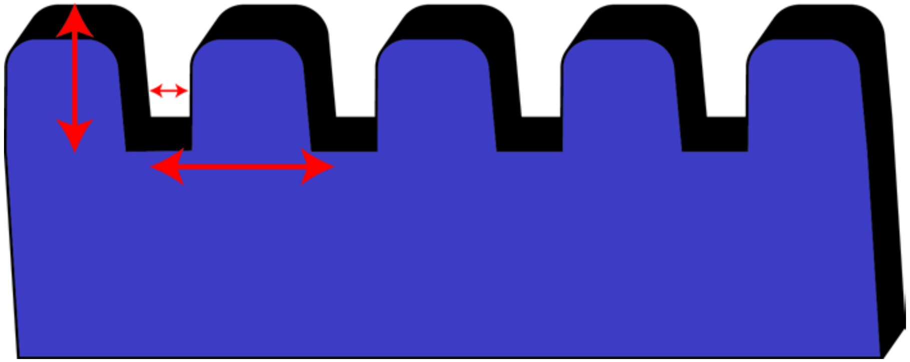


Insert aperture #3 and center on “sweet spot”

6) Use DEAL to shift Ronchigram to center on cross-hairs
7) Insert aperture #3 and center on cross-hairs.
→ remove mis-focused beams from contributing to image

Appendix 1: Sample tilt considerations

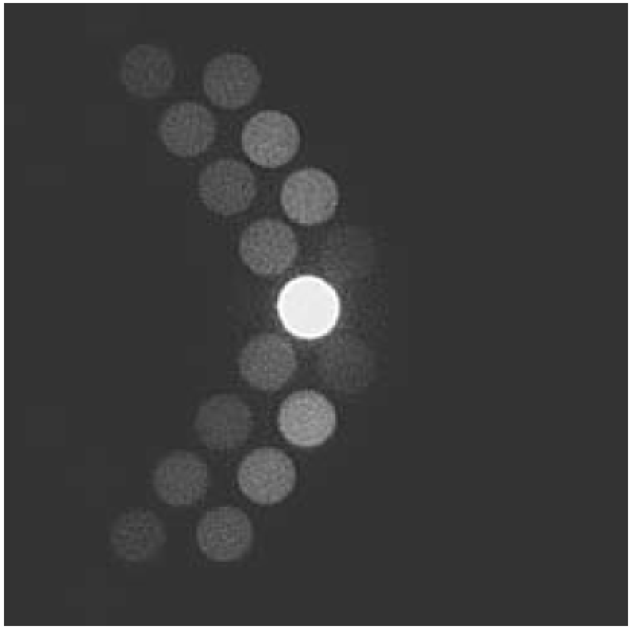


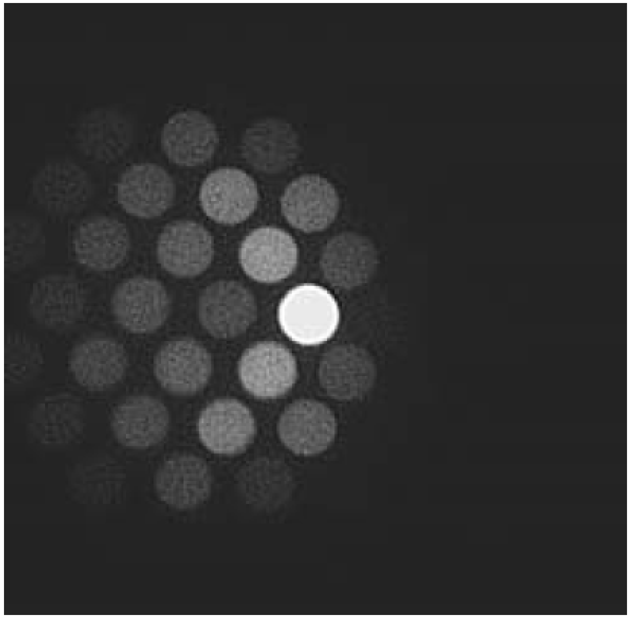


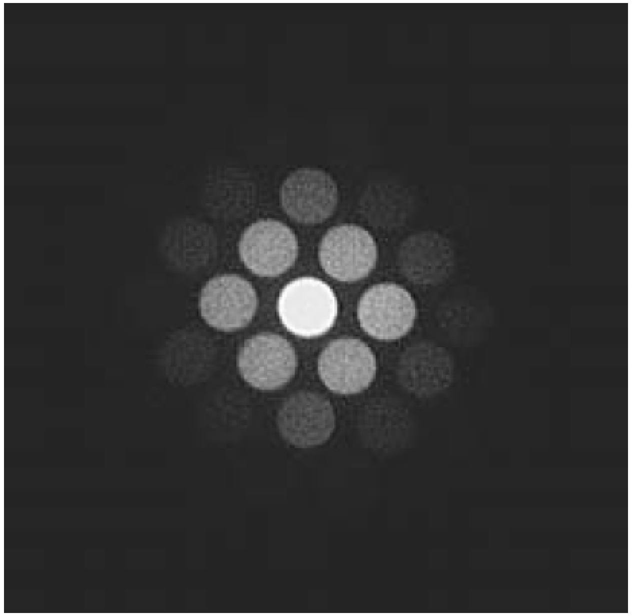
If the sample is tilted such that the edges of features are not parallel to the electron beam, CD measurements can be off significantly.

Here, the height measurement is off by 28% and the width measurement is off by -38%. Note that pitch measurements are not affected.

Appendix 1: Sample tilting



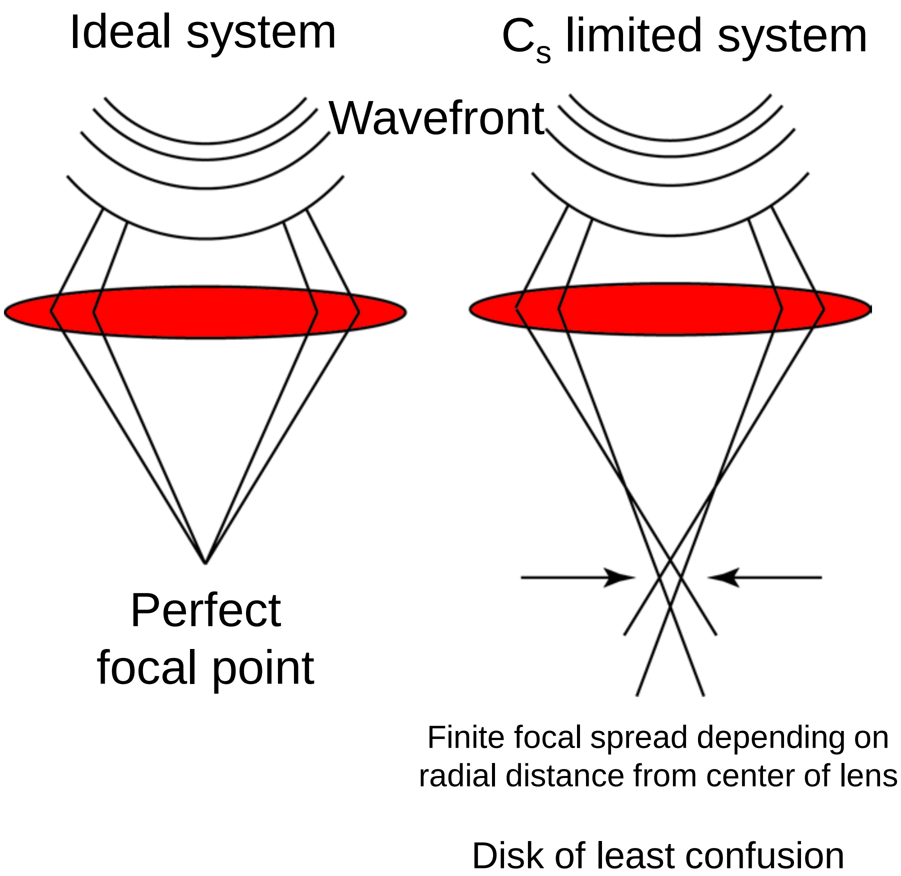




For [001] Si wafers, with TEM samples prepared parallel to a cleave plane - {110} – the viewing direction in cross-section is a <110>. The diffraction pattern is a characteristic “stretched hexagonal” structure. When tilted to the <110> zone axis, the devices built along <110> directions will be perfectly aligned to the beam.

To tilt to the zone axis, use the α and β tilts to bring the “circle of intensity” to be symmetric around the transmitted spot. Use Nano-Diff mode with aperture #1. Alternatively, use Nano-Diff mode with aperture #2 and follow the Kukuchi bands to the zone axis.

Appendix 2: Comments on spherical aberration correction



Since spherical aberration and defocus are both radially symmetric, we can partially offset spherical aberration with change in focus.

Conventional microscopes are Cs limited, but correct for defocus (C1) and twofold astigmatism (A1)

There are many aberrations, but the limiting aberration is the largest.

END

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