Transmission Electron Microscopy
8. The Instrument

EMA 6518
Spring 2007

01/31/07

Outline

- The Illumination System
- The Objective Lens and Stage
- Forming Diffraction Patterns and Images
- Alignment and Stigmation
- Calibration

The purpose is to go through the principal functions of each of the three components and give you some feel for what is happening in the microscope when you "press the button". The more you understand the operation of the TEM, the better you can be sure that you are getting the most out of the instrument.

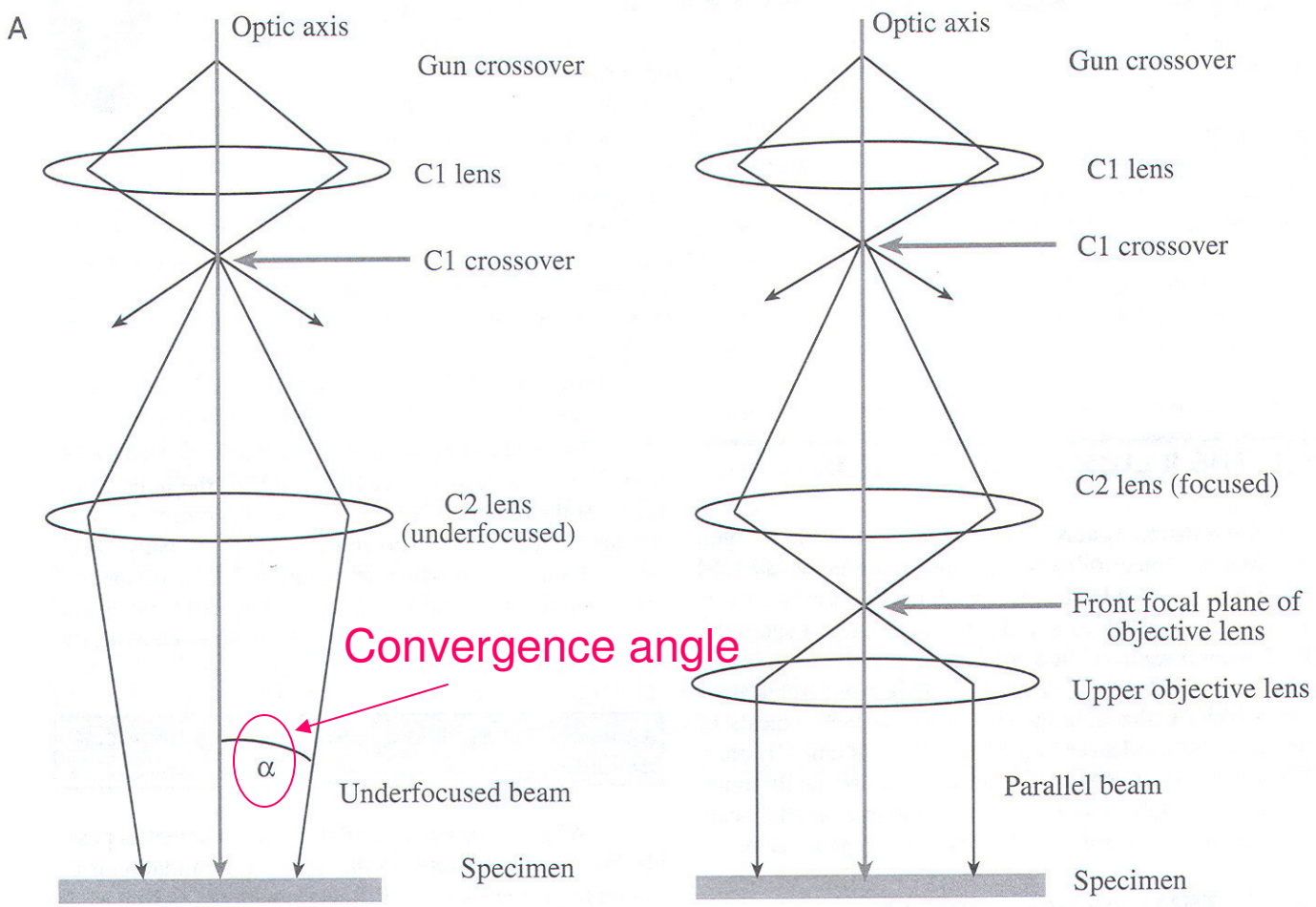
The Illumination System

- The illumination system comprises the gun and the condenser lenses.

- The illumination system takes the electrons from the gun and transfers them to the specimen giving either a broad beam (wide-field illumination) or a focused beam (spotlight).

  - Parallel Beam: TEM imaging and diffraction
  - Convergent Beam: STEM imaging, microanalysis, and microdiffraction

The Illumination System-Parallel Beam



parallel

↓

coherent

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.

The Illumination System-Convergent Beam

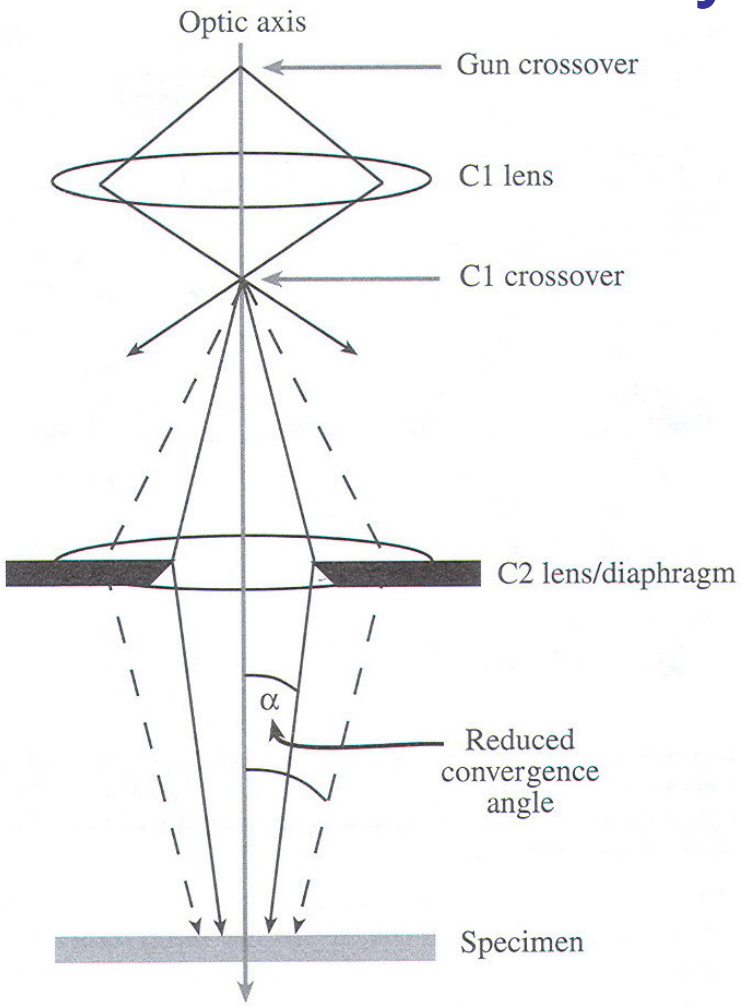


Figure 9.2. Effect of the C2 aperture on the parallel nature of the beam: a smaller aperture creates a more parallel beam.

- The convergence destroys the parallelism and the image contrast. So to see an image we have to scan the beam; the mode of operation of the illumination system is standard for STEM and AEM.

- The convergent beam is a probe. We use such a probe when we want to localize the signals coming from the specimen, as in microanalysis or convergent-beam diffraction.

The Illumination System-Convergent Beam

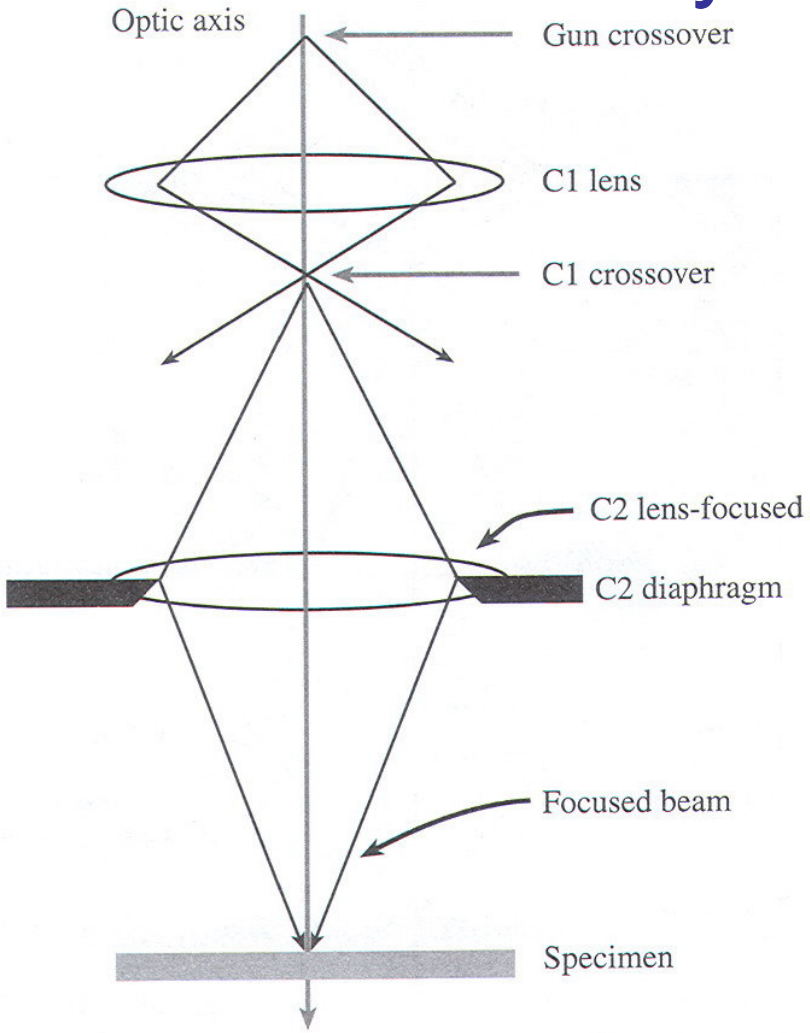
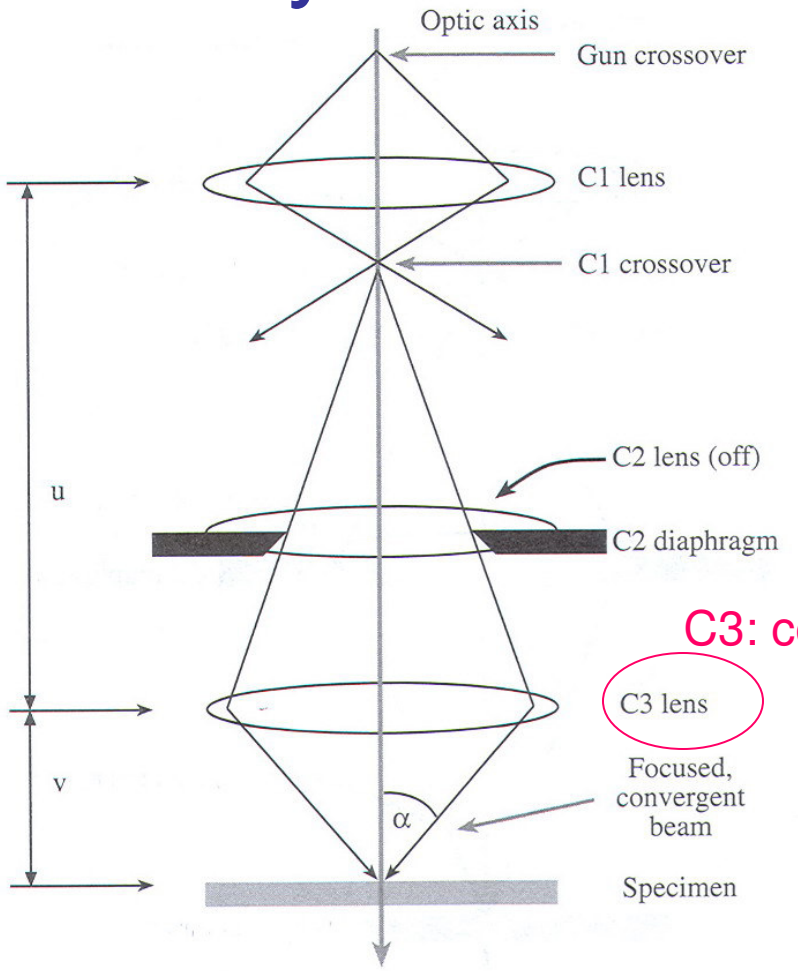


Figure 9.3. A focused C2 lens illuminates a small area of the specimen with a nonparallel beam.

- Unless you have an FEG, it isn't possible to use just the C1 and C2 lenses to converge the beam to as small as a probe (<10nm).

- C1 and C2 lenses can't demagnify the gun crossover sufficiently.

The Illumination System-Convergent Beam



C3: condenser-objective lens

Figure 9.4. Use of the objective polepiece as a third condenser lens (also called a condenser-objective, or C3, lens) gives the smallest possible probe and large convergence angles. The large *u*/*v* ratio gives the maximum demagnification of the image of the gun crossover.

The Illumination System

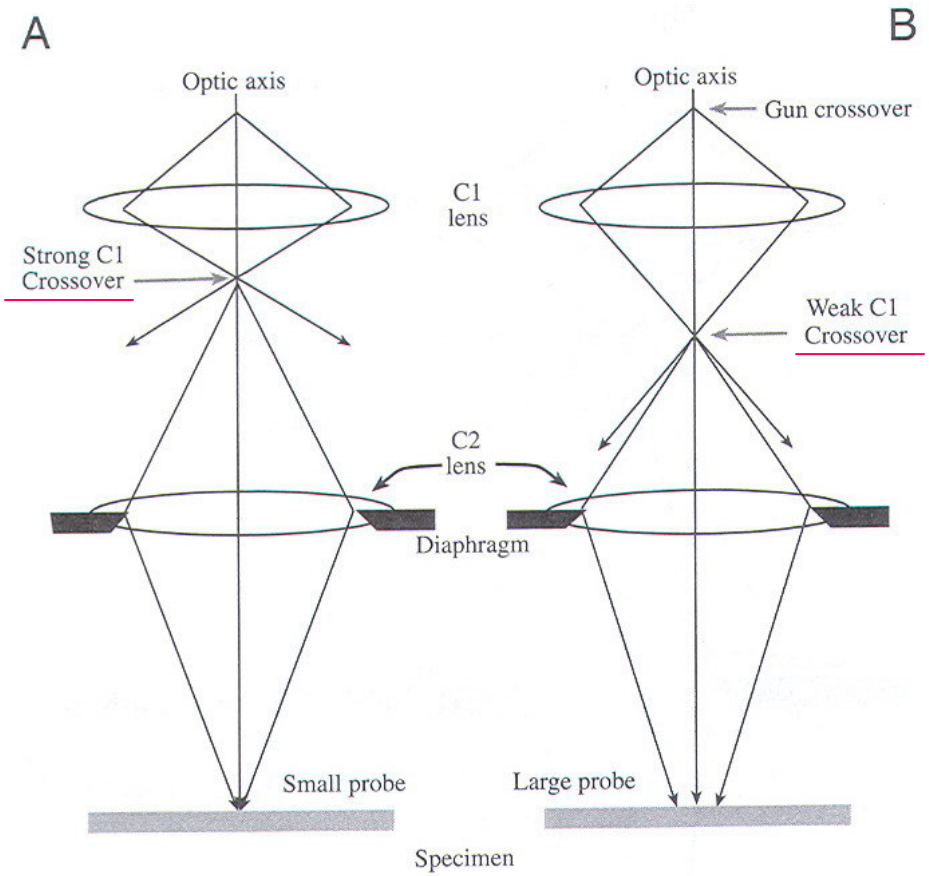


Figure 9.5. Effect of the C1 lens strength on probe size: a stronger C1 lens (A) results in greater demagnification by any subsequent lens (C2 or C3), giving a smaller electron beam at the specimen. A weaker lens (B) gives a broader probe.

The Illumination System

Translating and Tilting the Beam

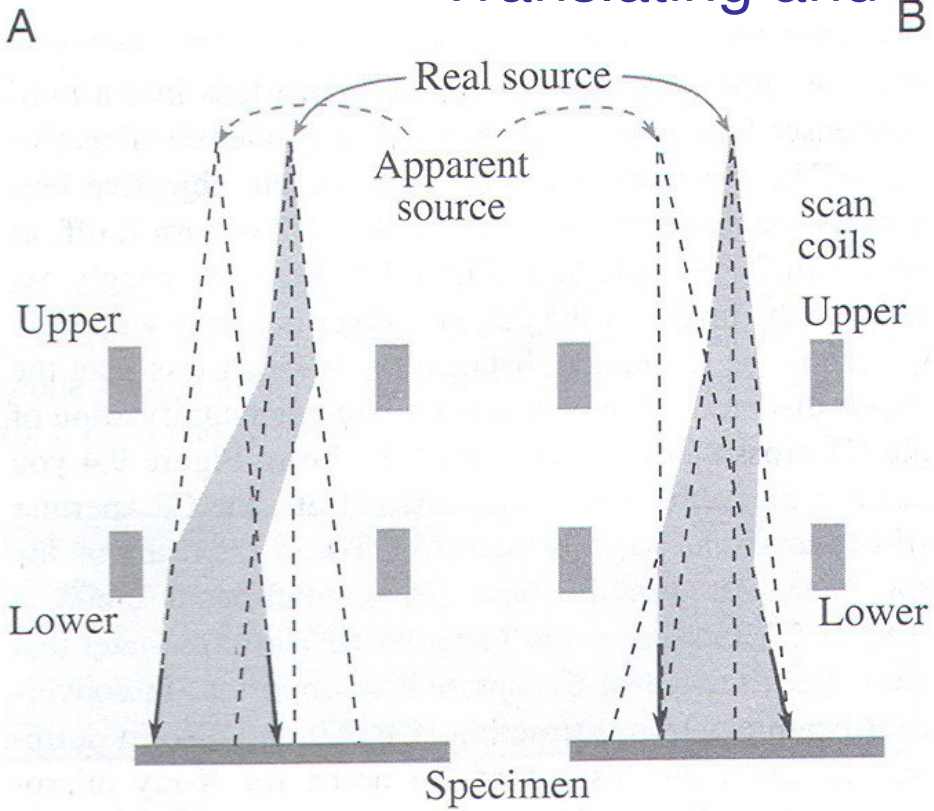
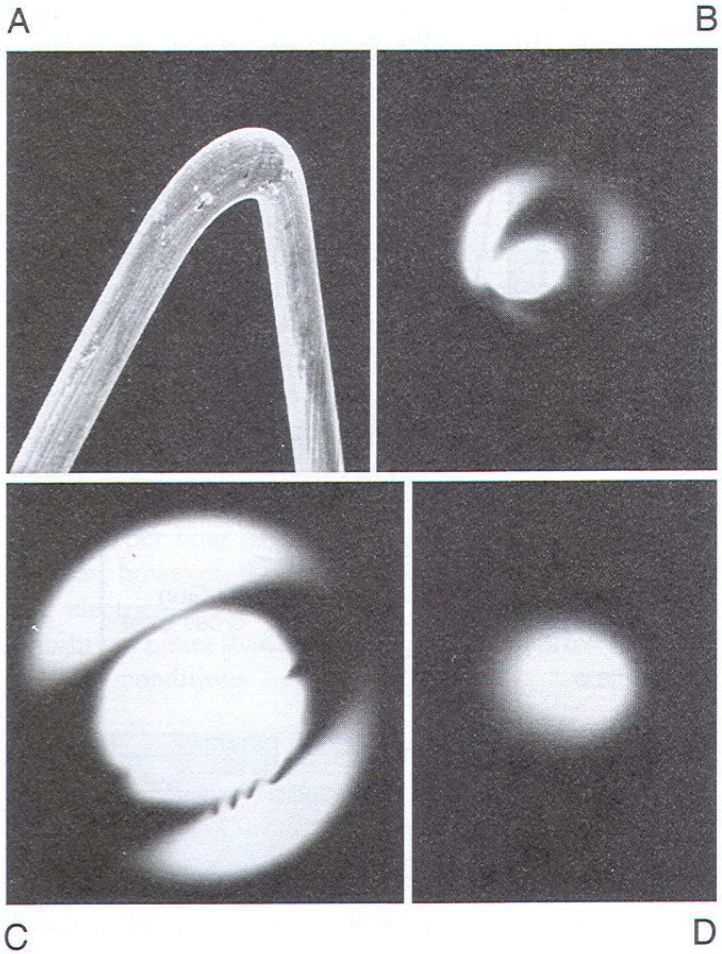


Figure 9.6. The use of pre-specimen scan coils for (A) traversing the beam and (B) tilting the beam. Traversing moves the beam to a different area of the specimen but it stays parallel to the optic axis. Conversely, tilting the beam illuminates the same area of the specimen, but from a different angle.

- We use scan coils to apply a local magnetic field to deflect the beam.
- To translate the beam we use deflector scan coils.
- To tilt the beam we use tilt scan coils situated between C2 and C3.

The Illumination System-Alignment



- Gun alignment: if the gun is very badly misaligned, you may have to turn the condenser lenses off, before you use the gun traverses to center the filament image. Then use the gun tilts to make the source image symmetrical and repeat the whole procedure.

The Illumination System-Alignment

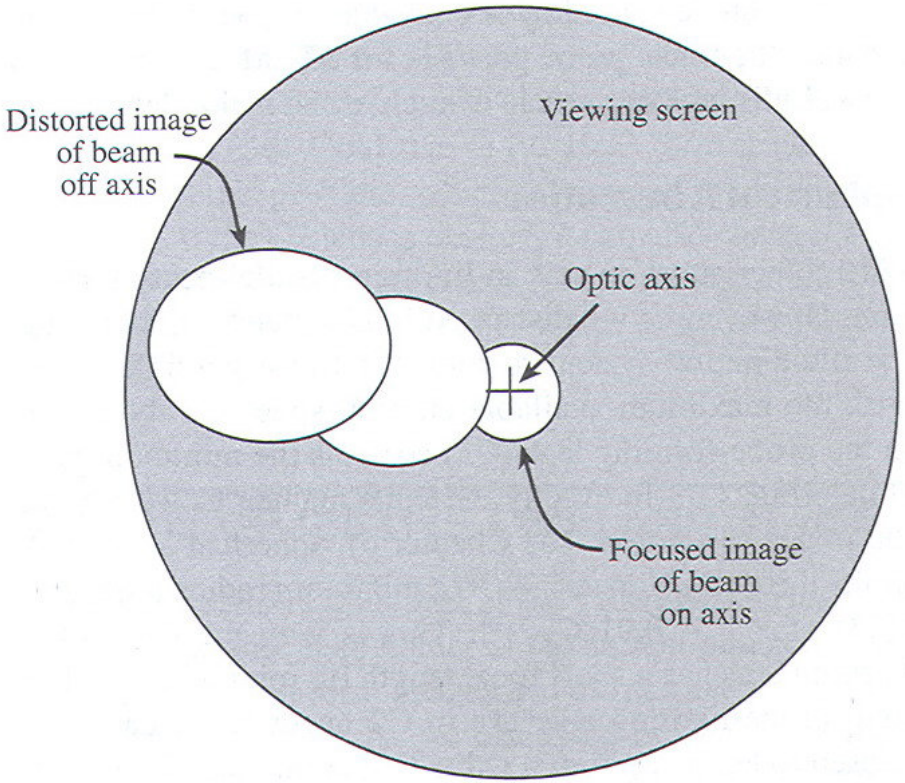


Figure 9.7. If the C2 aperture is misaligned, underfocusing or overfocusing the C2 lens causes the image of the beam to sweep off axis (i.e., across the viewing screen) and to become distorted.

- Manual centering of the C2 aperture remains a most critical step in obtaining the best performance out of the TEM.

The Illumination System-Alignment

Alignment of the C2 Aperture

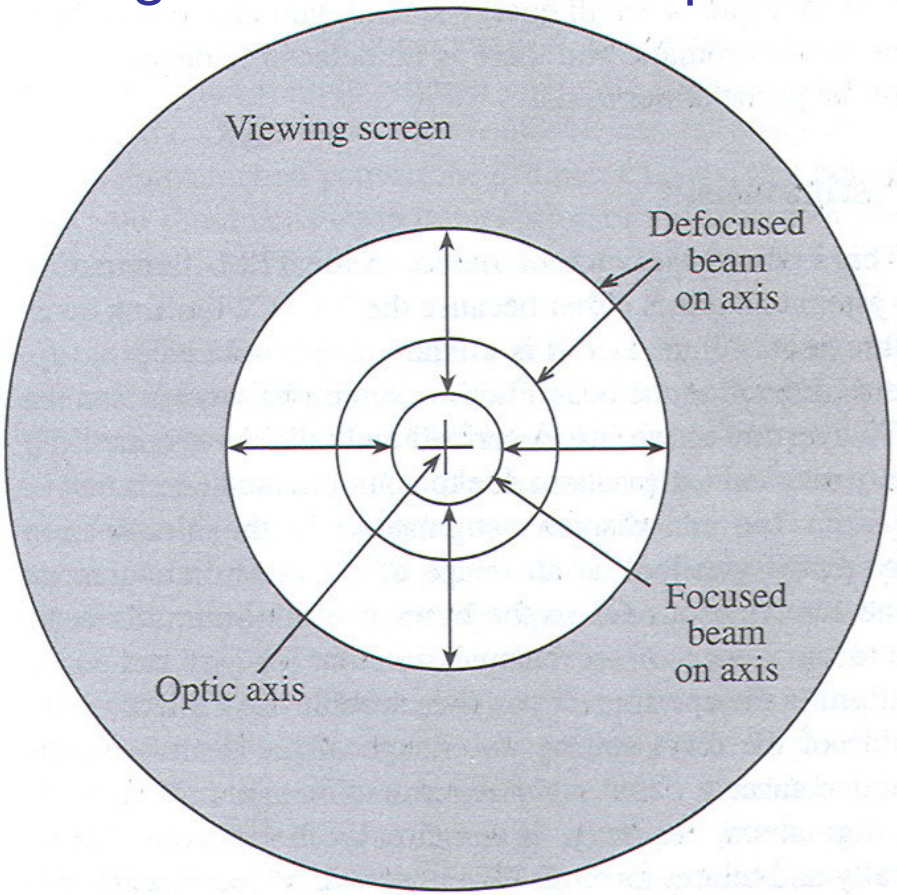


Figure 9.8. If the C2 aperture is aligned, the image of the beam remains circular and expands or contracts about the optic axis as the lens is underfocused or overfocused.

The Illumination System-Alignment

Condenser Lens Defects

• The illumination system lenses suffer from the standard lens defects, such as *aberrations* and *astigmatism.*

• These defects don't really limit the operation of the TEM in parallel-beam mode, but they are crucial if you're intent on forming the finest probe possible for STEM and analytical work.

✓Chromatic aberration: energy spread of the electrons
✓Astigmatism: C2 limiting aperture is misaligned or contaminated and charging up, thus defecting the beam.

The Illumination System-Alignment

Condenser Lens Defects

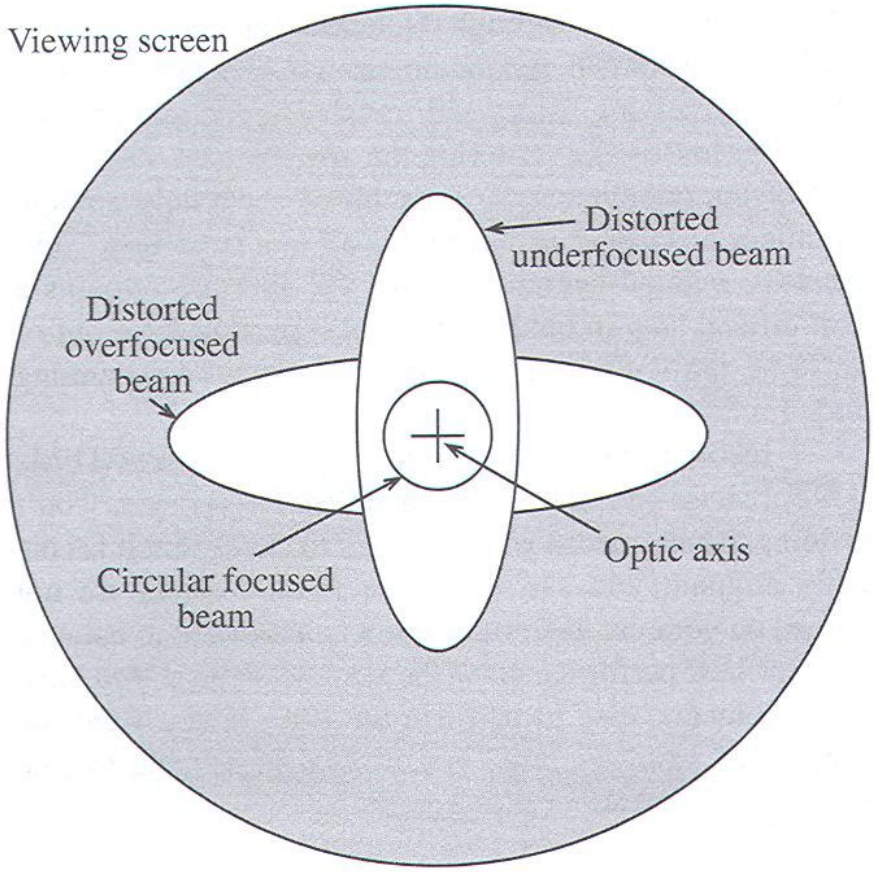


Figure 9.9. The effect of astigmatism in the illumination system is to distort the image of the beam elliptically as the C2 lens is underfocused or overfocused. Correction of this astigmatism results in an image that remains circular as the C2 lens is defocused.

The condenser stigmators introduce a compensating field which you use to correct the distortion

The Illumination System-Calibration

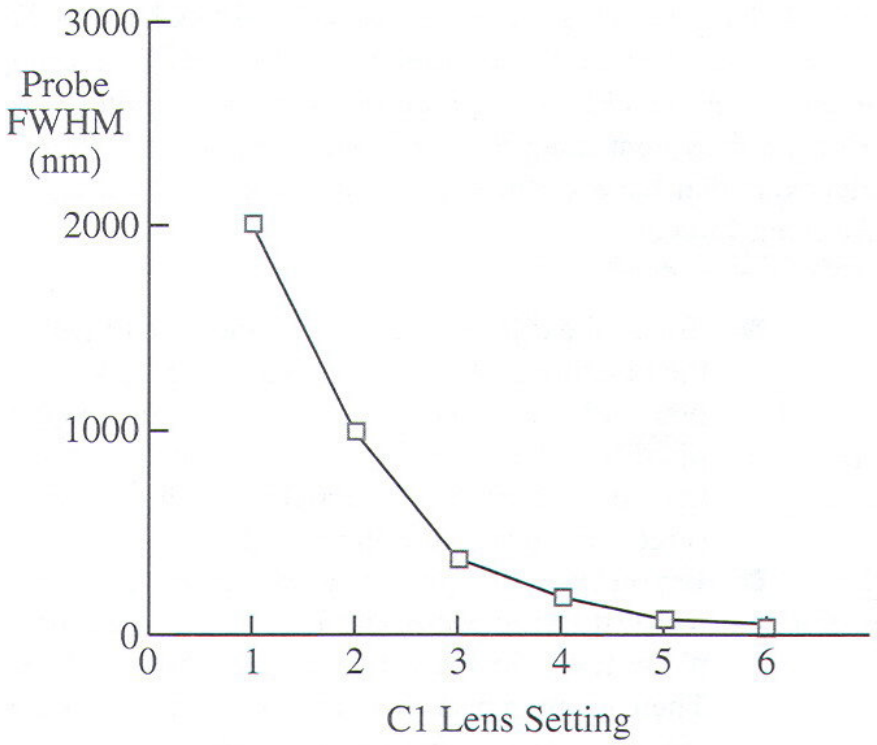


Figure 9.10. Calibration of the illumination system requires determining the variation of the probe size with C1 lens strength.

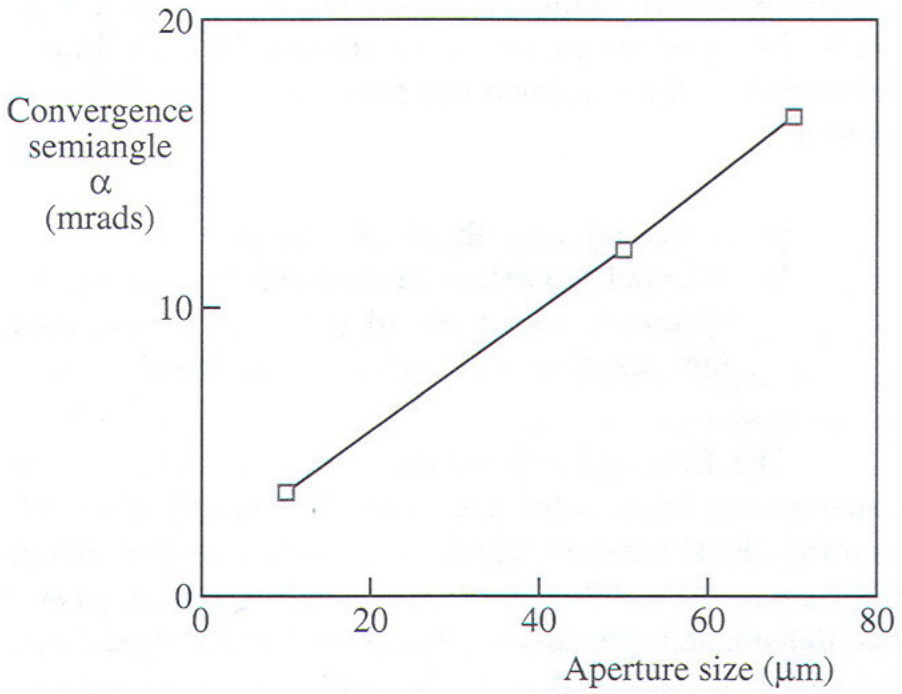


Figure 9.11. Variation of the beam-convergence semiangle, α, with the C2 aperture dimensions.

The Objective Lens and Stage

- This combination is the heart of the TEM. We use the stage to clamp the specimen holder in the correct position so the objective lens can form images and diffraction patterns in a reproducible manner.

- We need to fix the height of the specimen on the optic axis. This will allow us to work at the same objective lens current and thus at a fixed objective lens magnification.

- As a practical consideration, you would like to be able to tilt the sample without changing its height on the optic axis. Otherwise you would be continuously using the z-control when you tilt the sample.

The Objective Lens and Stage

- The central requirement is the need to define a reference plane (*eucentric plane*) so that our calibrations will be reproducible.
- The eucentric plane is normal to the optic axis and contains the axis of the specimen holder rod. When the specimen is located at this plane and the image is in focus, the objective lens current is an optimum value.
- The first thing you must always do when inserting your specimen into the TEM is to ensure that it is in the eucentric plane.
- With computer control and auto-focusing techniques becoming common, this operation can be automated.

Imaging System

Viewing the diffraction pattern:

•To see the diffraction pattern, you have to adjust the imaging system lenses so that the back focal plane of the objective lens acts as the object plane for the intermediate lens. Then the diffraction pattern is projected onto the viewing screen.

•If you want to look at an image instead, you readjust the intermediate lens so that its object plane is the image plane of the objective lens. Then an image is projected onto the viewing screen.

Imaging System

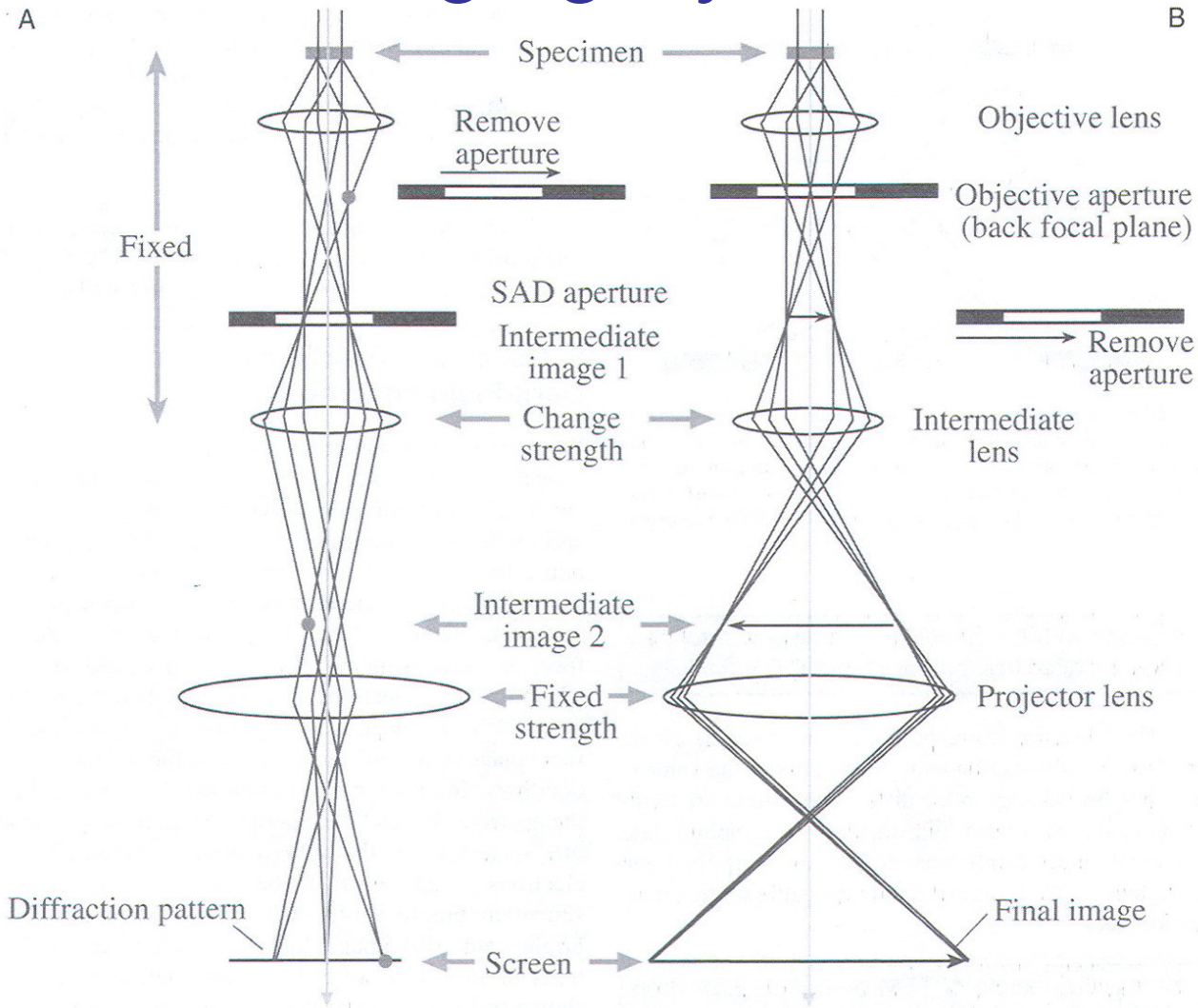


Figure 9.12. The two basic operations of the TEM imaging system involve (A) projecting the diffraction pattern on the viewing screen and (B) projecting the image onto the screen. In each case the intermediate lens selects either the back focal plane or the image plane of the objective lens as its object.

Imaging System

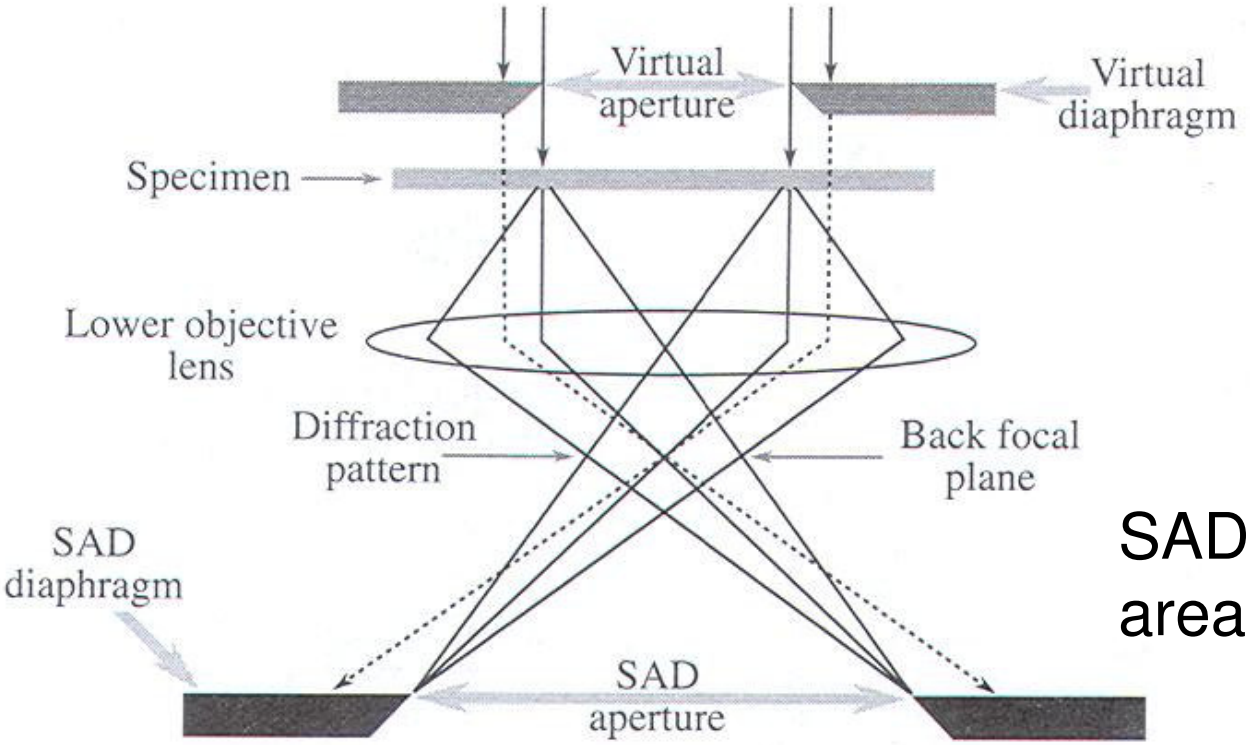
- The diffraction pattern contains electrons from the whole area of the specimen that we illuminate with the beam.
- The direct beam is so intense that it will damage the viewing screen.

•Select a specific area of the specimen to contribute to the diffraction pattern

•Reduce the intensity of the pattern falling on the screen

- We could make the beam smaller
- We could insert an aperture in a plane conjugate with the specimen, i.e., in one of the image planes.

Imaging System



SAD: selected-area diffraction

Figure 9.13. Ray diagram showing SAD pattern formation: the insertion of an aperture in the image plane results in the creation of a virtual aperture in the plane of the specimen. Only electrons falling inside the dimensions of the virtual aperture at the specimen will be allowed through into the imaging system. All other electrons will hit the SAD diaphragm.

Imaging System

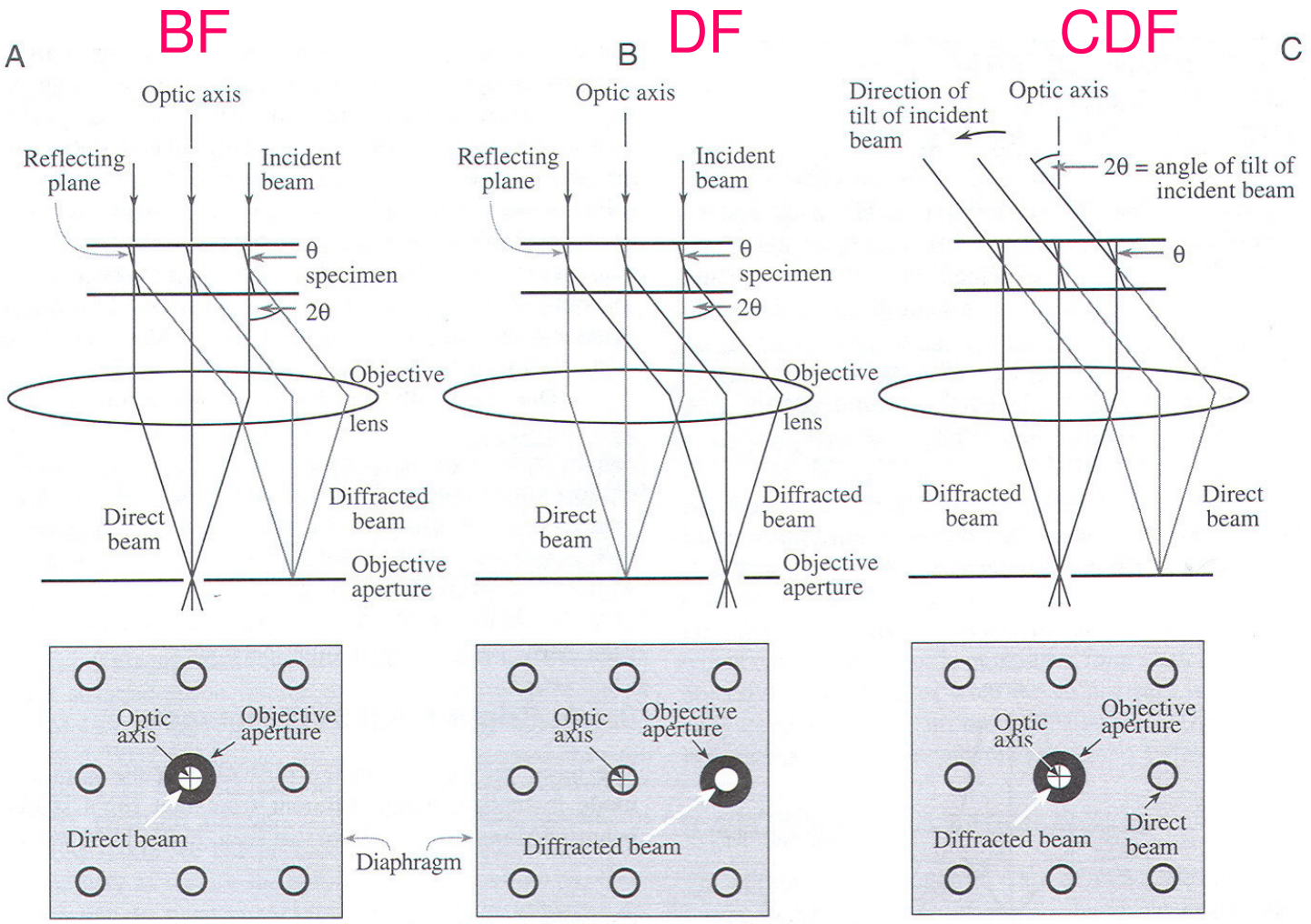


Figure 9.14. Ray diagrams showing how the objective lens/aperture are used in combination to produce (A) a BF image formed from the direct beam, (B) a displaced-aperture DF image formed with a specific off-axis scattered beam, and (C) a CDF image where the incident beam is tilted so that the scattered beam remains on axis. The area selected by the objective aperture, as seen on the viewing screen, is shown below each ray diagram.

Imaging System

Principles of TEM Operation:

1. When you want to look at the diffraction pattern (i.e., the *back focal plane* of the objective lens), you put an SAD aperture into the image plane of the objective lens.

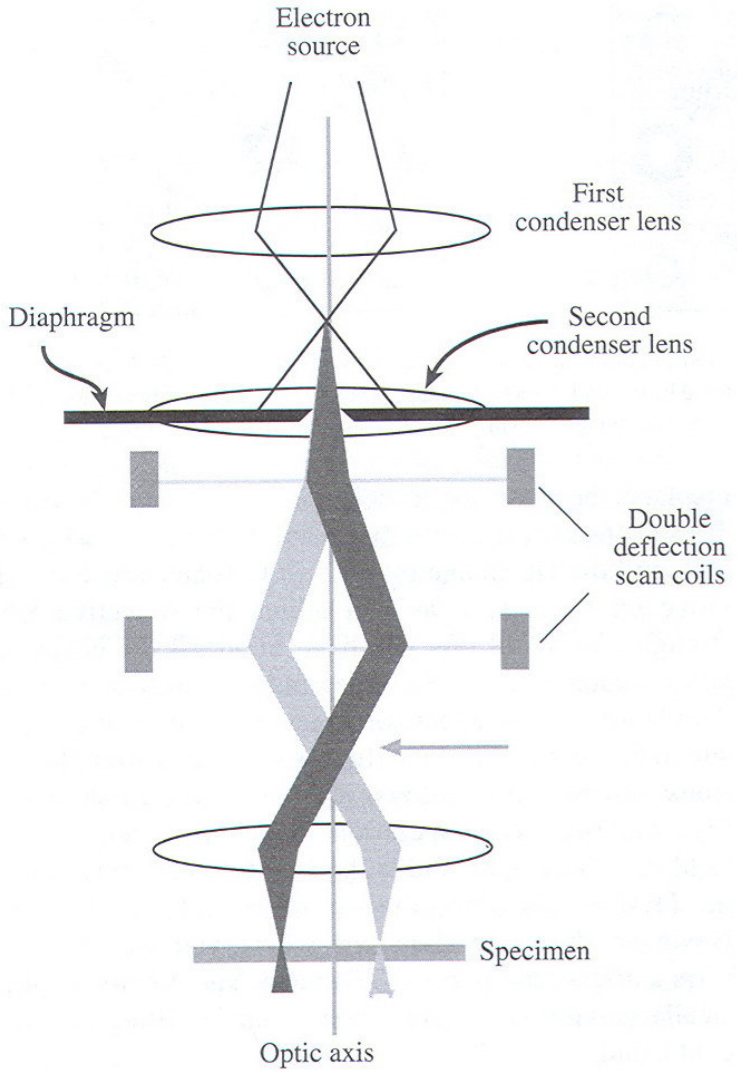
2. When you want to view an image (i.e., the *image plane* of the objective lens), you insert an aperture into the back focal plane of the objective lens. This is called the *objective aperture* and is most important in the TEM, since its size controls the collection angle and hence determines the effect of all the aberrations and resolution of the most important lens in the instrument.

• *Bright-field (BF) image, dark-field (DF) image, and centered dark field (CDF) image*

STEM Imaging System

•STEM: the beam has to scan parallel to the optic axis at all times so that it mimics the parallel beam in a TEM even though it's scanning.

•We use two pairs of scan coils to pivot the beam about the front focal plane of the upper C3 lens



STEM Imaging System

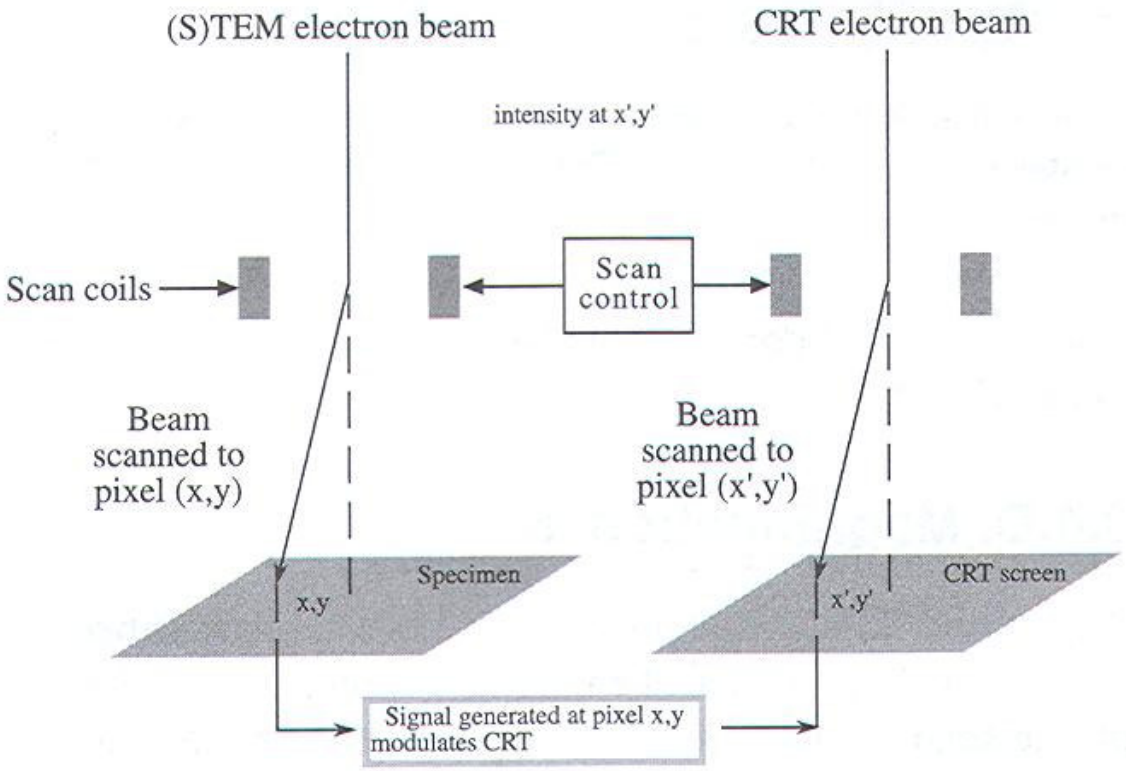


Figure 9.17. The principle of forming a scanning image, showing how the same scan coils in the microscope control the beam-scan on the specimen and the beam-scan on the CRT. Thus no lenses are required to form the image.

STEM Imaging System

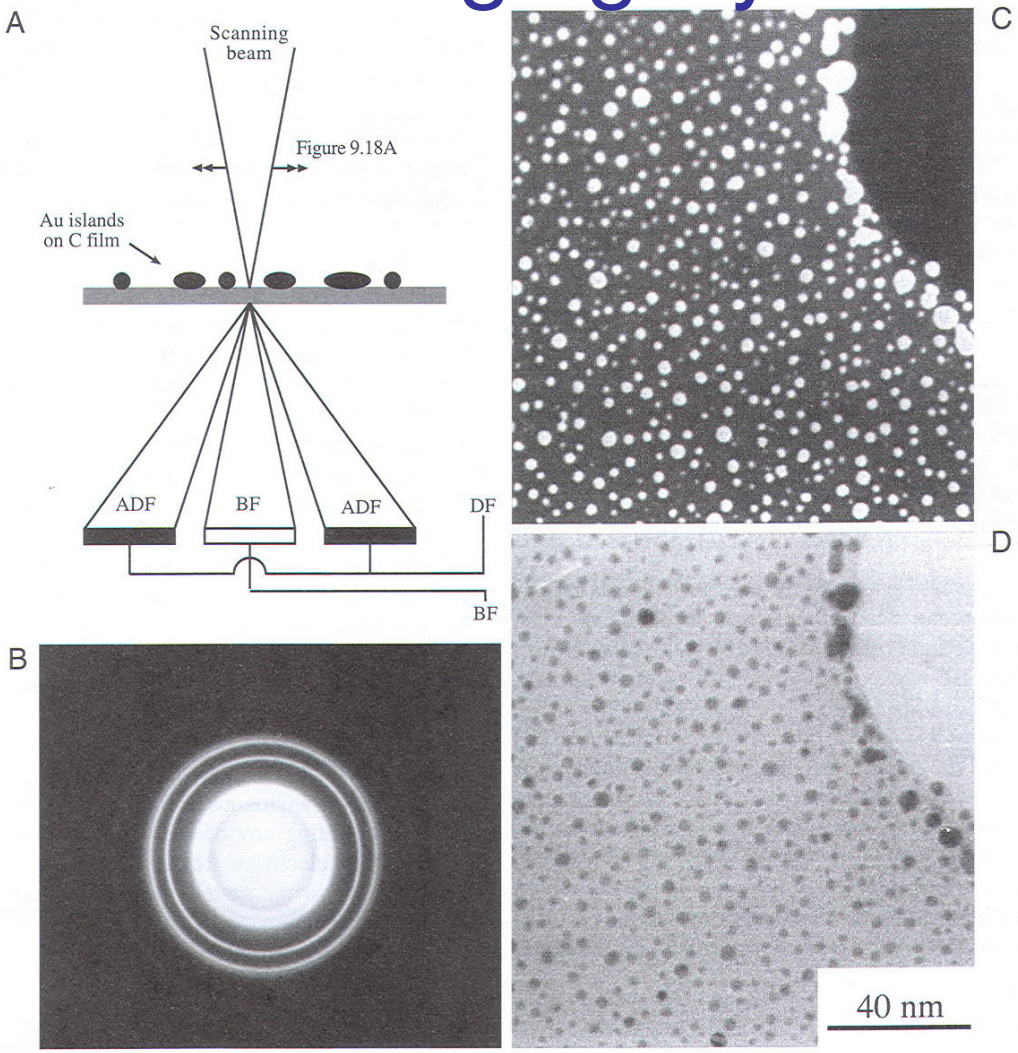


Figure 9.18. STEM image formation: A BF detector is placed in a conjugate plane to the back focal plane to intercept the direct beam (A) and a concentric annular DF detector intercepts the diffracted electrons (B). The signals from either detector are amplified and modulate the STEM CRT. The specimen (Au islands on a C film) gives complementary ADF (C) and BF (D) images.

Alignment and Stigmation

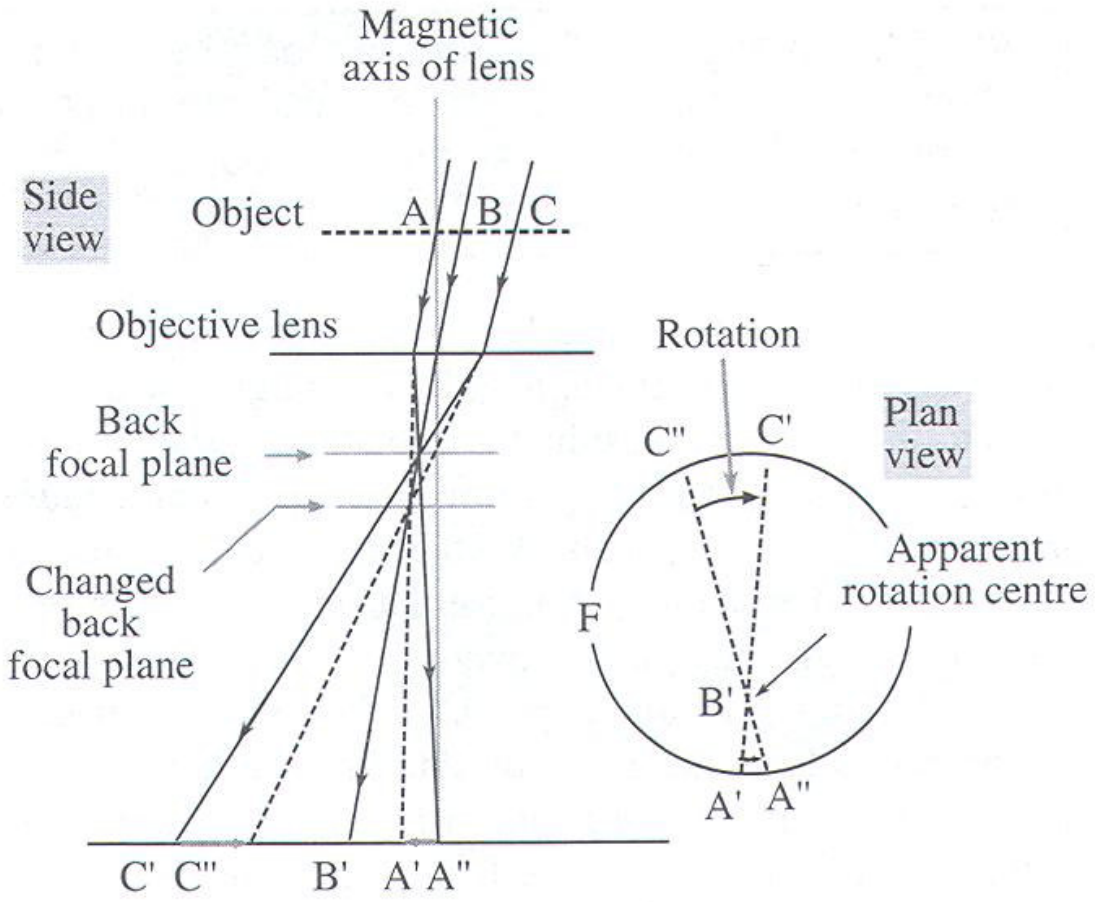


Figure 9.19. When the objective lens center of rotation is misaligned, the image appears to rotate about a point away from the center of the viewing screen when the lens is wobbled about focus.

Alignment and Stigmation

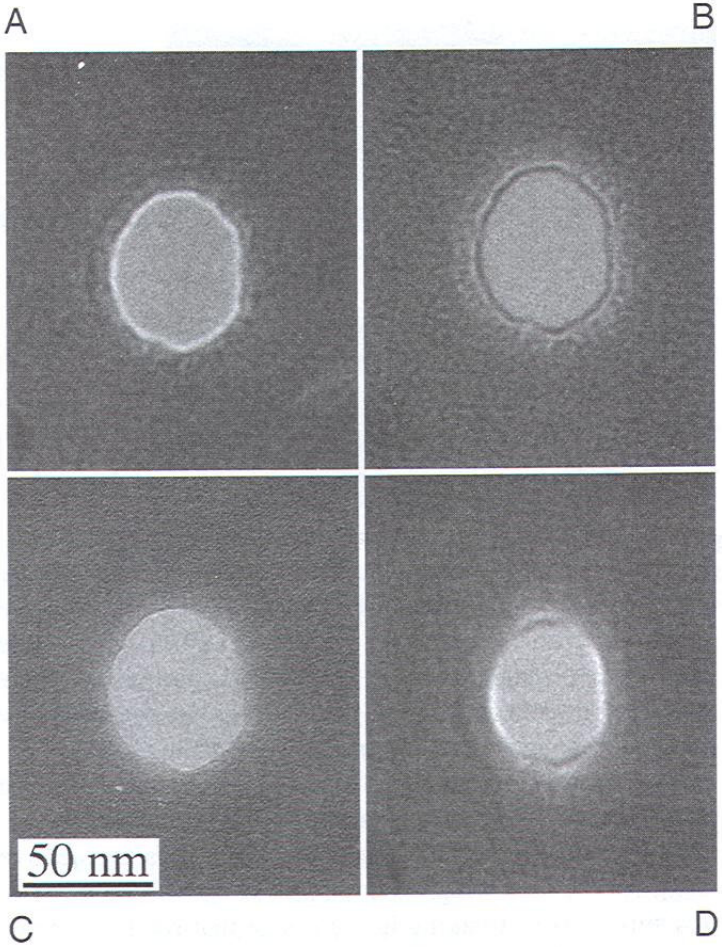
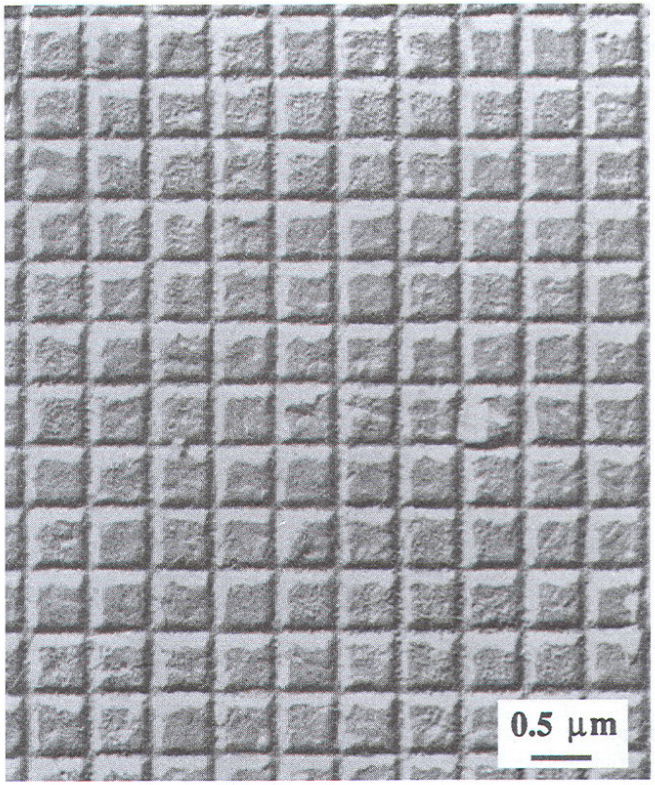


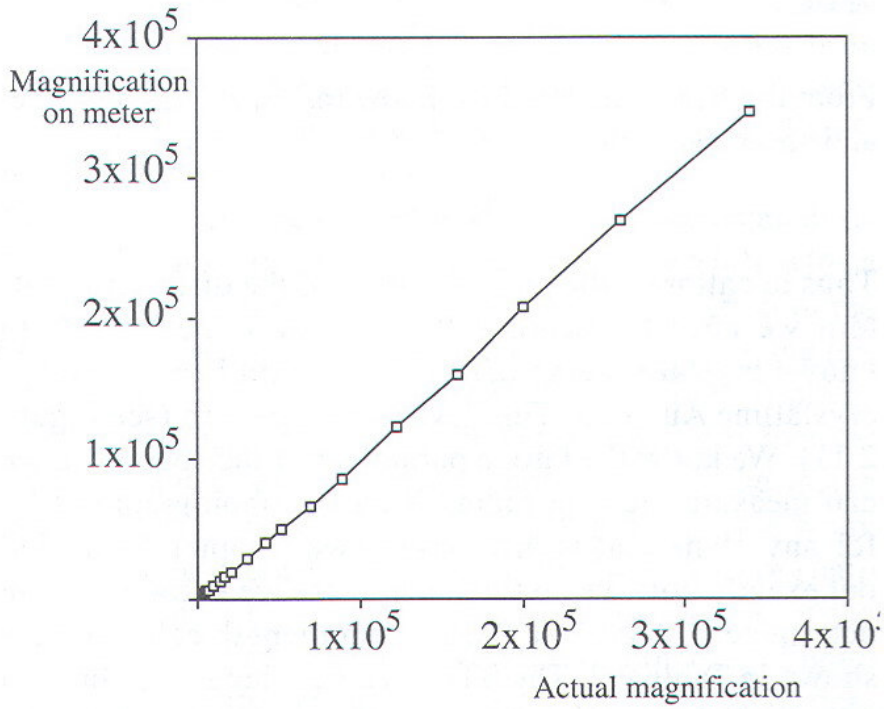
Figure 9.20. The image of a hole in an amorphous carbon film illuminated with a parallel beam showing that (A) with the beam underfocused, a bright Fresnel fringe is visible; (B) with the beam overfocused a dark fringe is visible; (C) at exact focus there is no fringe; and (D) residual astigmatism distorts the fringe.

Calibration

A



B



Calibration

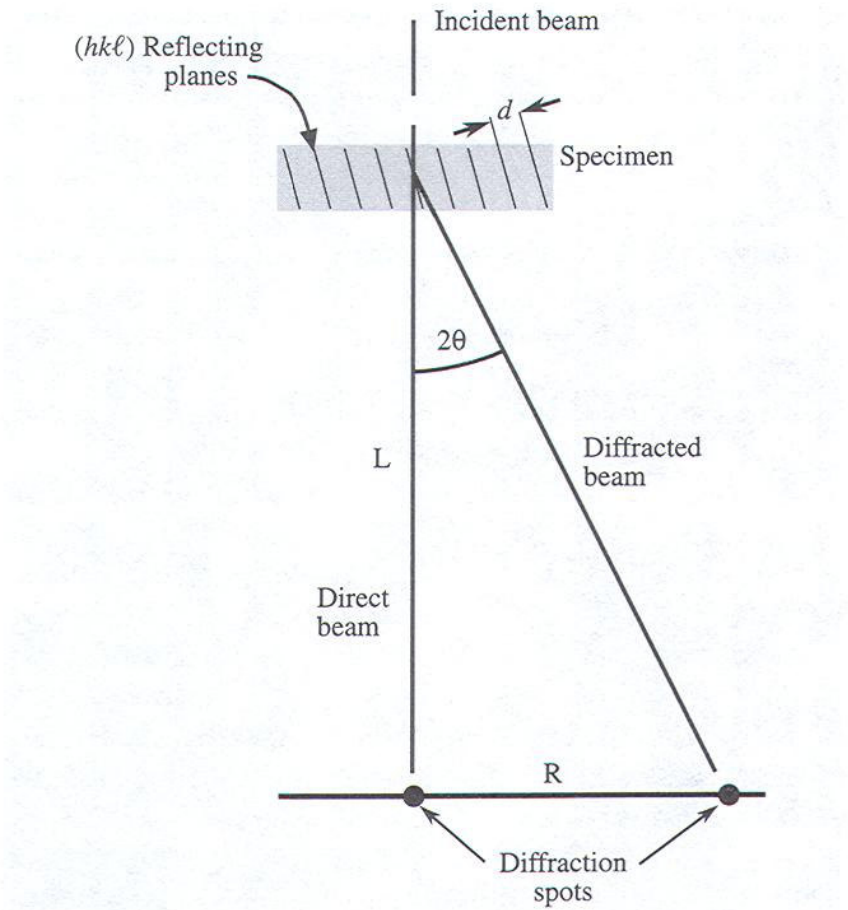
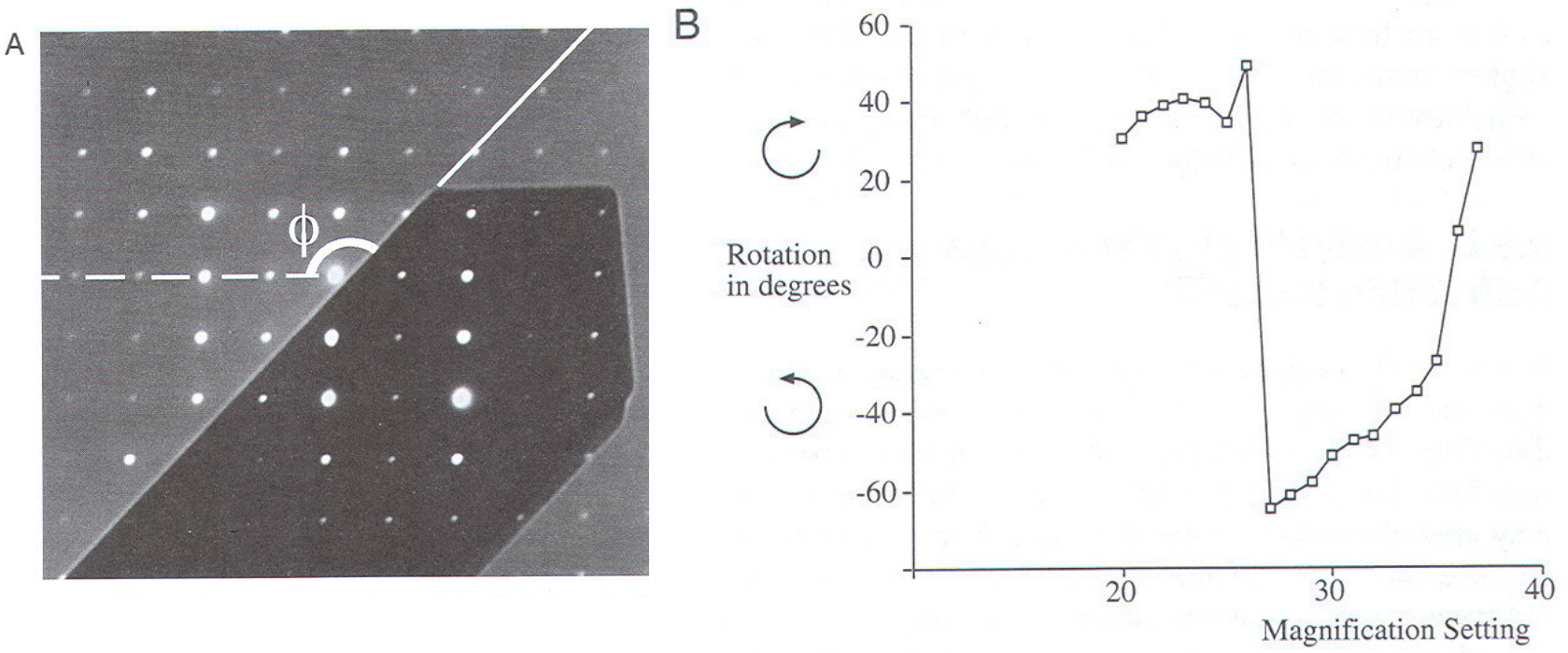


Figure 9.22. The relationship between the spacing R of diffraction maxima and the camera length, L. Increased magnification corresponds to effectively increasing L, although in practice this is accomplished with lenses.

Calibration



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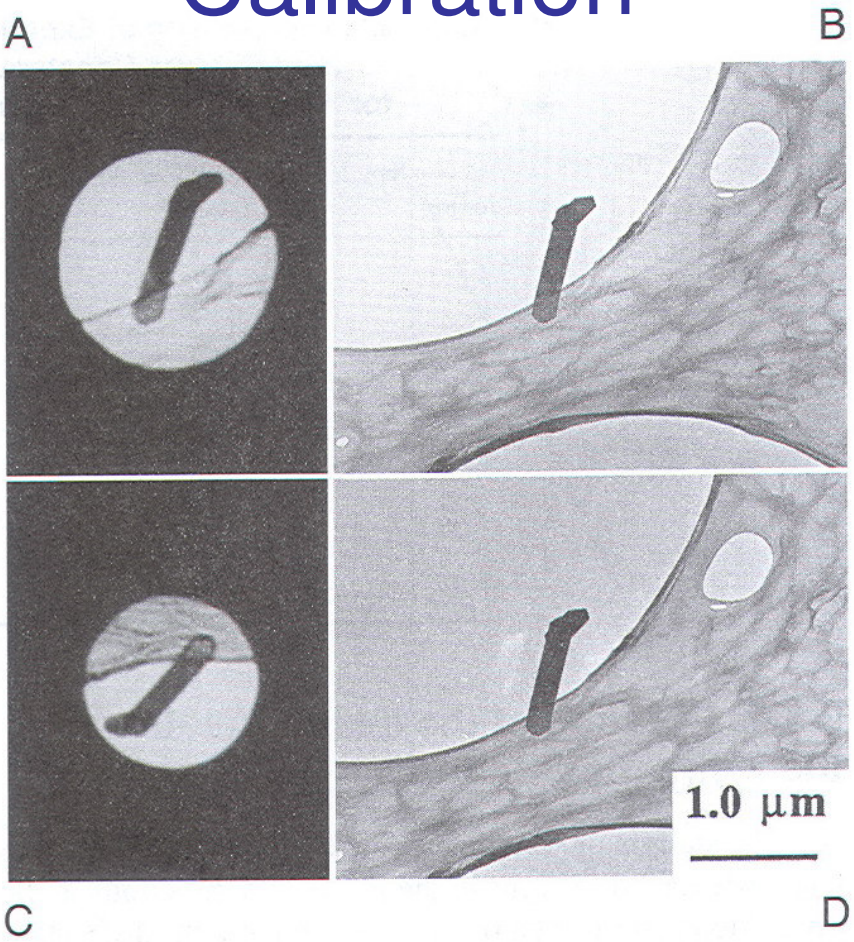

Figure 9.24. Defocused direct beam in a diffraction pattern from MoO_3 compared with a BF image, showing how to determine if a 180° inversion exists or not. If the image in the spot is rotated with respect to the image on the screen, as in (C) and (D), then the 180° inversion is required. In (A) and (B), no rotation occurs between the DP and BF image.

Calibration

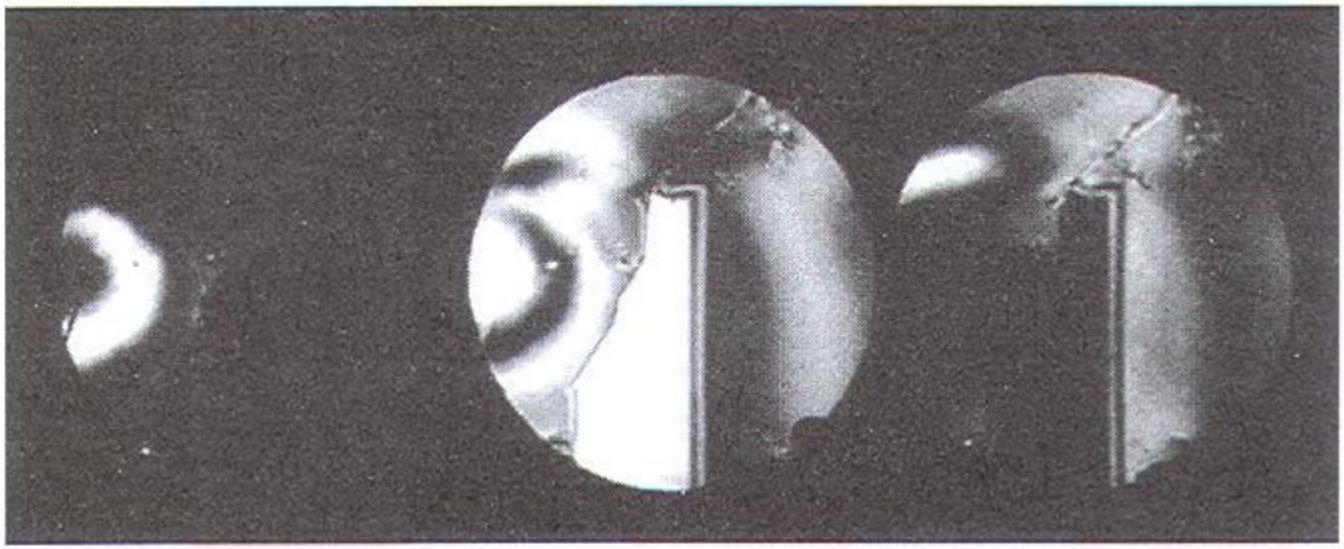

Figure 9.25. Defocused multiple DF image showing how it is possible to determine simultaneously the direction of features in the image (e.g., the vertical twin boundary) and directions in the DP (e.g., the horizontal vector between the diffraction disks). If the specimen holder is moved in the direction of the principal tilt axis, the image will move and identify the relationship between that tilt axis and the DP.