NANO 703-Notes

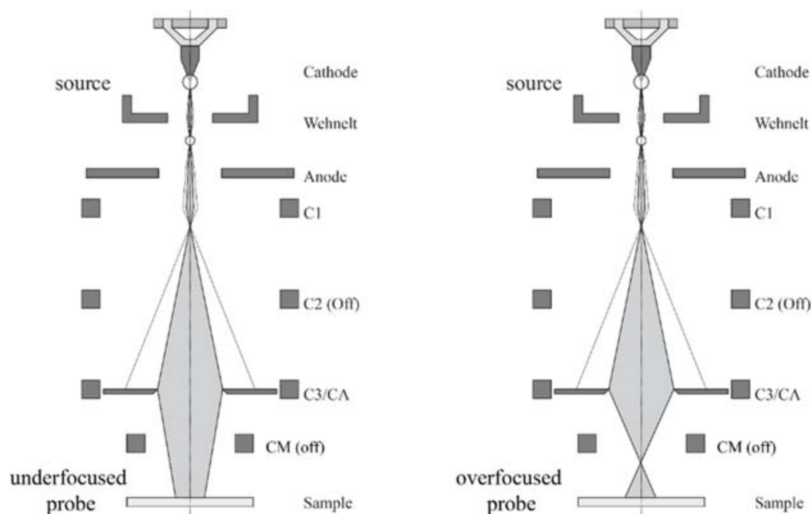
Chapter 9-The Instrument

Illumination (condenser) system

Before (above) the sample, the purpose of electron lenses is to form the beam/probe that will illuminate the sample. Our electron source is macroscopic (100's of μm to ~mm), so the probe should be a significantly demagnified image of the source. The Wehnelt cap is the first lens to demagnify the source. The condenser lenses are the more conventional type of electromagnetic lenses discussed in the previous chapter. There are usually at least two, and as many as four condenser lenses. The role of the first of these, called C1, is primarily to make a demagnified image of the source. It is usually directly associated with the "Spot Size" setting on the microscope controls. The object for the C1 lens is the probe image formed by the Wehnelt. The image of the probe produced by C1 becomes more demagnified the stronger the lens is excited. We will see how this works later.

After C1, the additional condenser lenses are needed to focus the demagnified probe on the sample (as a convergent beam), or change of the beam brightness/diameter of (as a nearly parallel beam). The last of this set (usually C3) is directly controlled by the "Brightness" setting. The C2 lens between these two enables additional optical control of the probe size and convergence angle. A condenser min-lens is often included, just slightly above the objective lens, for reasons we will see later.

Consider that we may want to keep the magnified diameter of our illuminated area roughly the same over a wide range of magnification, say from 2 Kx to 1 Mx, so that the beam current density on the viewing screen or camera is nearly constant. To achieve this, these condenser lens strengths must be continually changed over the magnification range. Often the C3 lens is controlled manually (with the "Brightness" know) to suit the users needs, and the others assume preset values.



The crossover point moves up as the C3 lens excitation is increased. When the crossover is below the sample, C3 is underfocused; when above, C3 is overfocused.

Demagnification of source

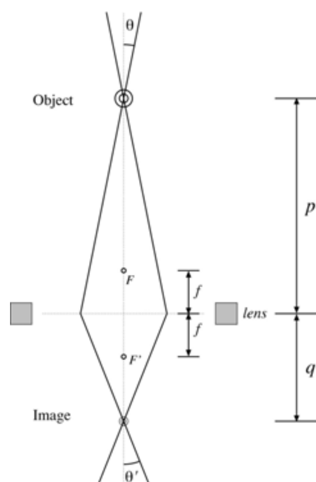
We derived the lens equation by considering an object of some lateral size. But if we draw a ray diagram where the object (such as the electron source) is indicated only by a point on the optic axis, rays on the back of the lens will also converge at a point, so how can we tell if the image is magnified or demagnified? We also found that the angular magnification is the inverse of the lateral magnification:

$$M = \frac{q}{p} = \frac{1}{M_\theta} = \frac{\theta}{\theta'}$$

Looking at such a ray diagram, we see that the angle of convergence is magnified ($M_\theta > 1$) when the image is closer to the lens plan than the object (i.e., $q < p$). So we can conclude that the lateral size is demagnified ($M < 1$) in this case.

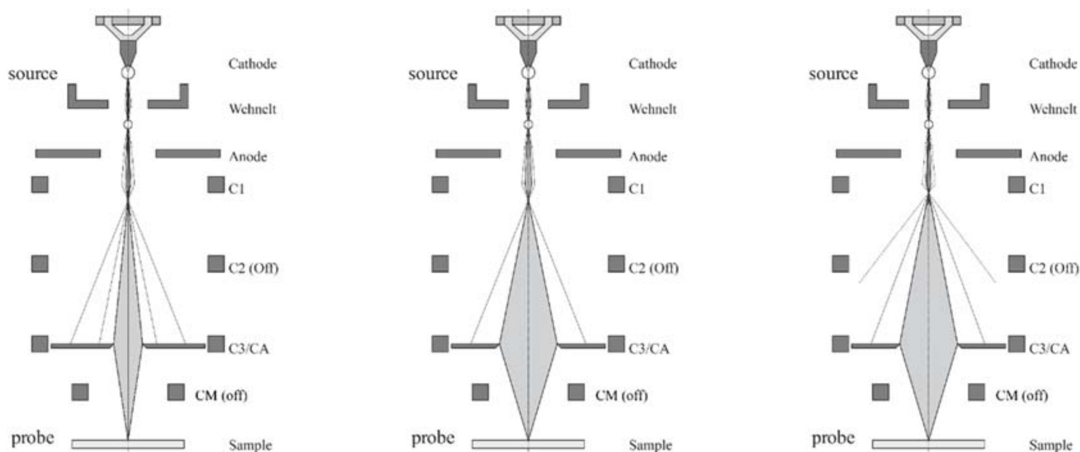
$$\theta' > \theta \Rightarrow q < p \Rightarrow M < 1$$

For the lenses before (above) the sample, we then expect the images of the electron source to be closer to the lens than the objects they are focusing on (which may be images of the source from the preceding lens). In short, lateral demagnification requires angular magnification.



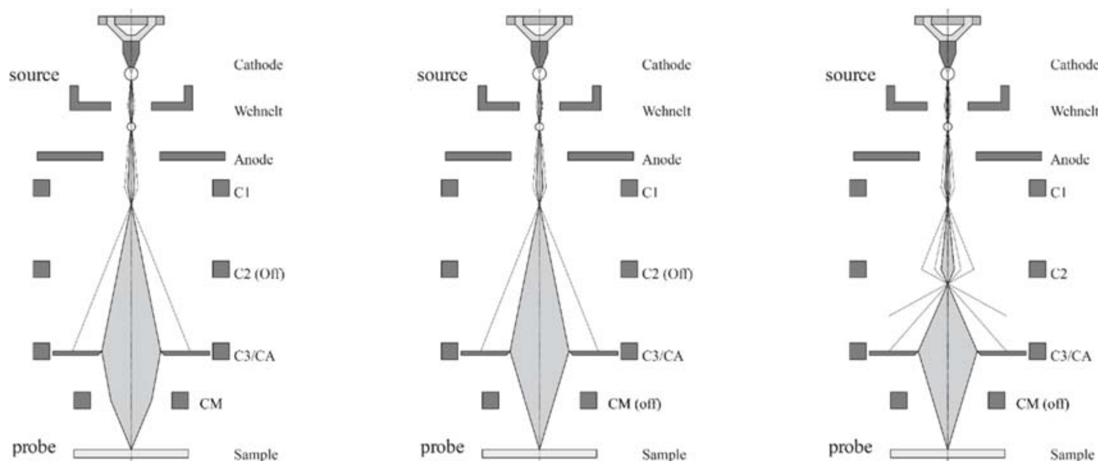
Convergence angle and probe size

Two primary characteristics of a convergent probe are the convergence angle (α), and the probe size. Let's assume the second condenser lens (C2) and the condenser mini-lens (CM) are both off. There is a moveable condenser aperture associated with C3, which we refer to as just CA. A smaller CA radius gives a smaller convergence angle. But, as stated previously, a stronger C1 excitation gives a smaller probe (or "spot") size. (With C2 off, we will need to adjust C3 slightly to keep the probe in focus when changing spot size.)



Uses of additional condenser lenses

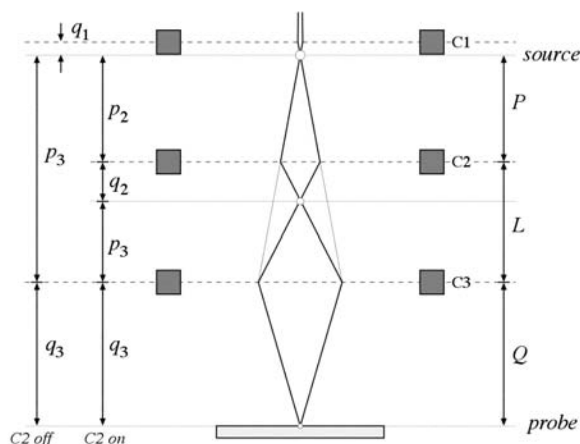
The C2 and CM give additional freedom to change α and probe size. Being so close to the sample, CM allows controlling the convergence angle electronically. We will show next that C2 allows even greater demagnification of the spot size than is possible with just C1. Since all of these lenses work in concert to produce the final probe, we usually just change them all in concert to reach desired settings of α and probe size.



Demagnification with C2 off vs. C2 on

We now compare the size of the probe on the sample with C2 on vs. C2 off. Say we have C1, C2, and C3 equally spaced by a distance L. If the C1 current is fixed, an image of the source is formed at a distance P above C2. The sample is at a distance Q below C3. For each of these lenses (if they are on), we can identify a particular object and image location on axis.

First assume C2 is off. The object for C3 is the image formed at q_1 below C1, which is P above C2, so $p_3 = P + L$. Its image is formed on the specimen at $q_3 = Q$ below C3.



Next assume C2 is on: Its object is the image formed at q_1 below C1, so $p_2 = L - q_1 = P$. Its image is q_2 below C2, which is the object for C3, which again produces an image at $q_3 = Q$. In the diagram shown, the rays diverging from the source and converging at the probe do not change between the two cases, so these must be settings for which the probe size is the same for the two case.

Comparison: C2 off vs. C2 on

Using the preceding construction, we can find the C2 excitation (i.e., its focal length f_2) when the net effect is a greater demagnification of the probe. With C2 off, if the size of the source is d, the probe size is

$$d' = M_3 \cdot d = \frac{q_3}{p_3} \cdot d = \frac{Q}{P+L} \cdot d$$

So the magnification with C2 off is

$$M_{C2\ \mathrm{off}} = \frac{Q}{P+L}$$

With C2 on, we use the lens equation to find its focal length:

$$\frac{1}{f_2} = \frac{1}{p_2} + \frac{1}{q_2} = \frac{1}{P} + \frac{1}{q_2}$$

So the magnification produced by C2 is:

$$M_2 = \frac{q_2}{p_2} = \frac{q_2}{P} = \frac{1}{\frac{P}{f_2} - 1}$$

With C2 on, the magnification produced by C3 is:

$$M_3 = \frac{q_3}{p_3} = \frac{Q}{L - q_2} = \frac{Q}{L - \left(\frac{1}{\frac{1}{f_2} - \frac{1}{P}} \right)}$$

The final probe size depends on the product of these magnifications:

$$d' = M_3 \cdot M_2 \cdot d = \frac{Q}{L \cdot P} \cdot \frac{1}{\frac{1}{f_2} - \frac{1}{L} - \frac{1}{P}} \cdot d$$

Thus, the magnification in this case is

$$M_{C2\ on} = \frac{Q}{L \cdot P} \cdot \frac{1}{\frac{1}{f_2} - \frac{1}{L} - \frac{1}{P}}$$

So when is $M_{C2\ \mathrm{on}} < M_{C2\ \mathrm{off}}$? We have

$$\frac{\not{Q}}{L \cdot P} \cdot \frac{1}{\frac{1}{f_2} - \frac{1}{L} - \frac{1}{P}} < \frac{\not{Q}}{P+L}$$

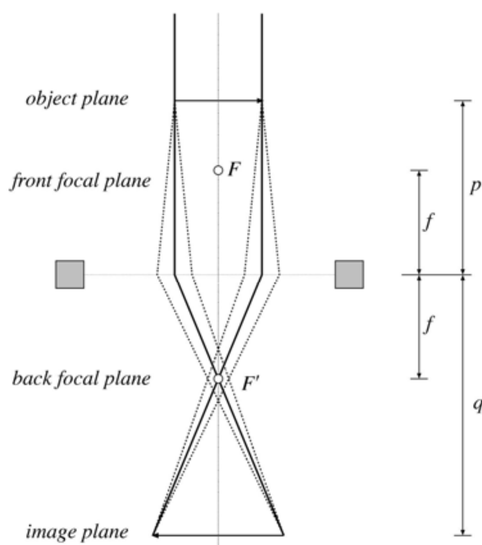
or

$$\frac{1}{P}+\frac{1}{L}<\frac{1}{f_2}-\frac{1}{L}-\frac{1}{P}\Rightarrow f_2<\frac{1}{2}\cdot\left(\frac{1}{\frac{1}{P}+\frac{1}{L}}\right)$$

A shorter focal length corresponds to a stronger lens,. So when f_2 is less than the expression above, the size of a focused probe with C2 on will be less than with C2 off. (Notice that we also have to adjust C3 to keep the probe focused on the sample.)

Lens Planes

Certain planes normal to the optic axis of a lens play particularly important roles. We already mentioned the plane containing the object (assuming it is thin and flat), called the object plane. For the image, there is a corresponding image plane. The plane containing the focal point in front of the lens is the front focal plane; not a lot usually happens there. But the plane containing the focal plane behind the lens – the front focal point – is extremely important for TEM image and diffraction. That is because a diffraction pattern is formed there. In a sense, diffraction patterns are formed in any plane below the specimen, but the BFP is special, because all parallel rays incident on the front of the lens are focused into sharp spots in the BFP. So in the case of Bragg diffraction from a crystal, the scattering by a particular set of lattice planes appears as a sharp spot in the BFP. If we want to view an image of our sample, we focus the subsequent lens on the image plane. But if we want to view the diffraction pattern, we focus that lens on the BFP.

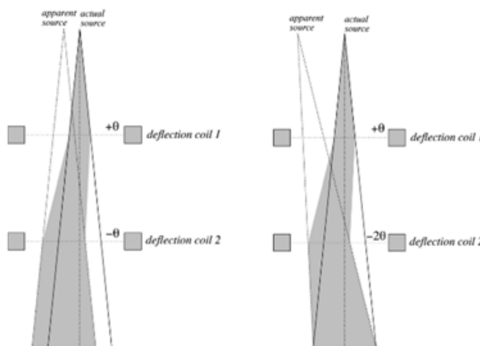


Beam deflection/tilt

So far, the types of lenses we have discussed primarily create magnetic fields that can be described as dipole fields. There are other types of lenses for alignment that affect higher-order magnetic poles. Deflecting or tilting the electron beam requires redirecting the beam asymmetrically about the optic axis. The types of lenses for this are generically called “deflection” coils. Each set of deflection coils has one opposing pair, one with the coil axis oriented along x and another pair with the axis along y. The x and y pairs each have their own currents that we can control. The primary result of changing these lenses is tilting the beam about x or y. But if we tilt the beam, somewhere lower in the column the beam will have been shifted, too. So to achieve either a pure tilt or a pure tilt, we need two sets of pairs of deflection coils.

Consider two sets, called deflection coil 1 and 2. It we want to deflect (shift) the beam, we need to tilt by some angle $+\theta$, with coil 1, then tilt back by angle $-\theta$ with coil 2. So the beam sort of jogs to one side or the other between the two coils. Now it looks like the source still points in the same direction but is off to one side or the other. The exact amount of shift will depend on several factors, like the distance between the coils.

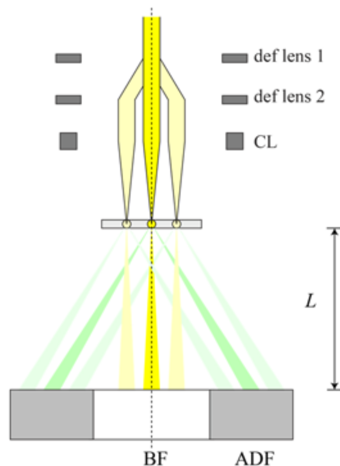
If we want to tilt the beam, but keep it in the same spot on the sample, we need to tilt by angle $+\theta$ with coil 1, then tilt back by -2θ with coil 2. The apparent source seems to have been tilted by the angle $-\theta$.



The balancing of these currents for the condenser lens deflectors is a standard alignment procedure. Basically, “wobble” the beam tilt in imaging mode and adjust the tilt balance so there is no beam shift. Then wobble the beam shift in diffraction mode and adjust the shift balance so there is no shifting of the beam image (because a shift in the diffraction corresponds to a tilt of the incident beam.)

Scanning TEM

We mentioned scanning TEM (STEM) before. This makes heavy use of the CL deflectors, primarily for shifting the beam very quickly across the specimen in a “raster” pattern. In fact, the optics below the specimen can be very minimal, if needed. If we do have the post-specimen lenses on, they should be focused on the diffraction pattern in the back focal plane of the objective lens. This pattern is directed onto one or more detectors, roughly in the same location as any TEM camera. Different geometries of detectors, such as on-axis or annular, will give different types of image contrast. The (apparent) distance to the detectors is the camera length, which is used to calibrate diffraction patterns.

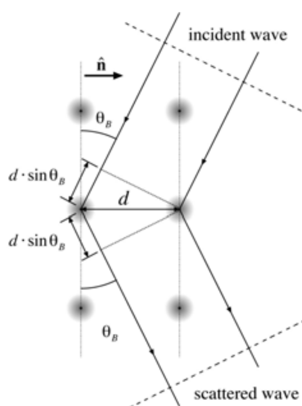


Bragg's law and lattice vectors
We should take another look at Bragg's law. Diffraction really results from the presence of multiple paths for an electron to travel from a particular starting point to a particular ending point. With a parallel incident beam, an electron scattering off atoms on adjacent lattice planes will interfere constructively with itself if the path length difference is an integer multiple of the wavelengths. A simple construction then gives Bragg's law

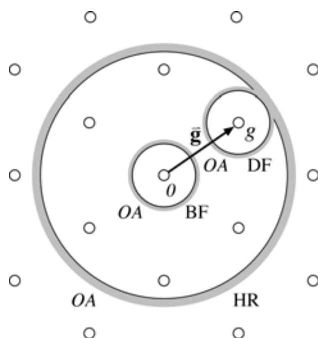
$$2d \sin\theta_B = n\lambda$$

But there is another thing worth noting here: The incident and diffracted beams have to make the angle θ_B w.r.t. the planes. This is called the Bragg condition. We define the reciprocal lattice vector (RLV) $\mathbf{g}$ for these planes as having length $1/d$ and pointing normal to the planes, for reasons that will become evident later.

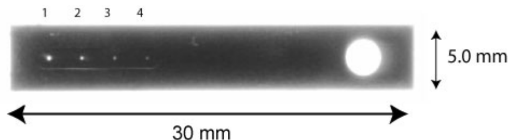
$$\mathbf{g} = \left(\frac{1}{d}\right)\hat{\mathbf{n}}$$



Objective aperture placement
The objective aperture (OA) is mounted very close to the BFP of the objective lens. This allows us to include or exclude particular features of the diffraction pattern in or from the image. For a crystal, the features are sharp diffraction spots. The RLV $\mathbf{g}$ points from the reciprocal space origin, which corresponds to the undiffracted, or direct, beam, indicated by *0*, to its corresponding diffraction spot, indicated by g. If we add a small OA that only allows *0*, the image is called a "bright-field" (BF) image. If the OA excludes *0*, the image is called a "dark-field" DF image. If we allow *0* and several different beams (also called reflections), and we use very high magnification, the image is called a "high-resolution lattice" (HR) image. If someone mentions high-resolution TEM, this is what they are talking about.



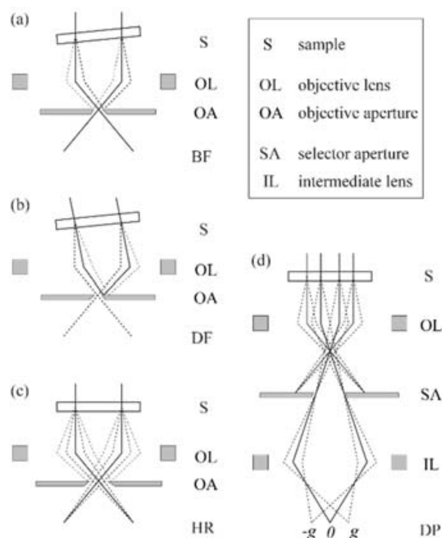
Object aperture strip for Hitachi TEM
OAs come in an many sizes and styles, but usually in sets of four or eight. Hitachi uses four holes in a thin Mo foil mounted on a metal strip. The strip moves in or out to select one of the four, or no, aperture. Other manufacturers allow changing the individual OAs separately. Non-circular OAs are not common, but also have certain applications.



TEM operational modes
Forget all the details about the condenser system and even the OL. Let's say our OA is an ideal lens slightly below the sample. Assume our sample is a crystal. In a cross-sectional view, we see that the sample may have to be tilted to reach the Bragg condition. In BF, we may let only the direct beam pass through the OA, which is centered on the optic axis, but we probably want to tilt our sample near the Bragg condition for some reflection g to get good contrast. This is called a t*wo-beam condition*. In this case, strongly diffracting features will appear darker; the vacuum (no sample) will appear bright.

Let's say we want to use the same reflection g to form a DF image. In fact, it is best to keep the OA on the optic axis, but to tilt the beam so that $-g$ (instead of g) passes through the OA to form the image. This is achieved by tilting the beam by $2\theta_B$ to reach the Bragg condition for $-g$. We still have a two-beam condition, and the image is formed with rays centered on the optic axis. (More on this later.)

An HR lattice image is really an interference pattern of two or more beams that reveal intensity arising from the planes within a crystal. The intersection of non-parallel planes is sometimes interpreted as atomic resolution, but this is somewhat misleading. Nonetheless, HR lattice imaging is one of the most powerful and exciting modes of operation of the TEM. Usually, the image formation is closely related to BF imaging, with no beam tilt and *0* centered in the OA, with contributions from several low-angle diffracted beams, which suggests a high-symmetry, low-index zone axis specifying the orientation. But there are many variations possible on this approach.



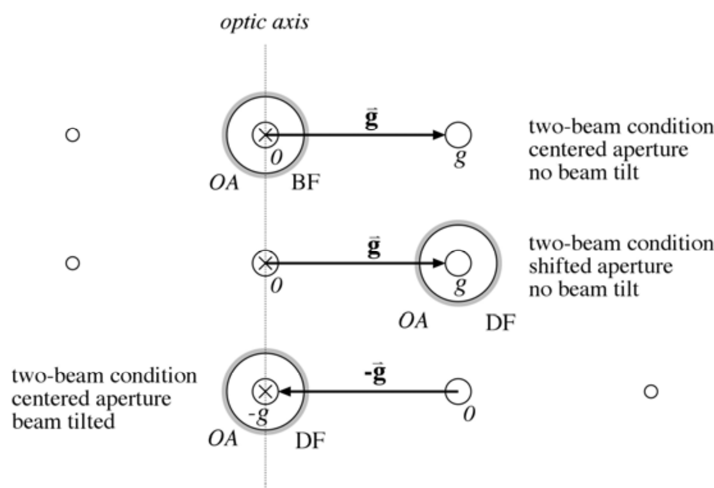
The standard mode of diffraction in the TEM is selected-area diffraction. A trick is used in selected-area diffraction patterns (DP) to actually select the area: Instead of trying to put an aperture very close to the sample, we put the SA aperture in the first image plane of the objective lens. For all intents and purposes, this accomplishes the same goal, and also allows us to use bigger apertures than we would otherwise, since the image is magnified. To really see how the pattern is generated, we should notice that, in diffraction mode, the next lens in the TEM - usually called the intermediate lens (IL) - most be focused on the BFP of the OL.

Bright-/dark-field methods

The exact placement of the OA in the BFP of the OL determines the type of image formed. It is a fairly tight space, and fine corrections can make a big difference. The SADP displays the OL BFP, so we usually do any adjusting in SA mode. Say we initially have 0 on the optic axis, with g at the Bragg condition. It is a general principal that, for every g, there must be a $-g$, only in this orientation, $-g$ is not at the Bragg condition, so it is fairly faint. Let's assume the beam is initially oriented parallel to the optic axis.

To form the g-BF image, we place a small OA around *0*. Without changing any beam tilt, switch to imaging mode. Then take out the SA to view the image. Shifting the beam, focusing C3, or focusing the OL a little are all fine now.

Again looking at the SADP, a quick way to form the g-DF image is evident: Just slide the OA over to g, then switch to imaging mode. We will have the same two-beam condition as in BF. The problem is that we are imaging with a beam that is off of the optic axis. When we try to focus the OL, the image will swing back and forth. Further the lens suffers aberrations at these higher angles.



The best way to form a g-DF image is actually form a $-g$-DF, which is essentially the same thing. Having set up a g-BF image, we tilt the beam to bring $-g$ onto the optic axis, where we have already centered our OA. (Fortunately, the TEM can save different beam tilt settings, so we don't have to mess up our existing alignment.) Switch to imaging mode to view the centered DF image. The image should be fairly high quality and stay stationary when focusing.

Centered dark-field imaging

Let's take one more look at how to form a centered DF image for a crystal sample. Here the beam is tilted so that the scattered beam used for imaging is on axis. The nice thing is, if we set up a g-BF image, we

can form a $-g$ -DF with little effort, and the difference between g and $-g$ in this context is usually not important.