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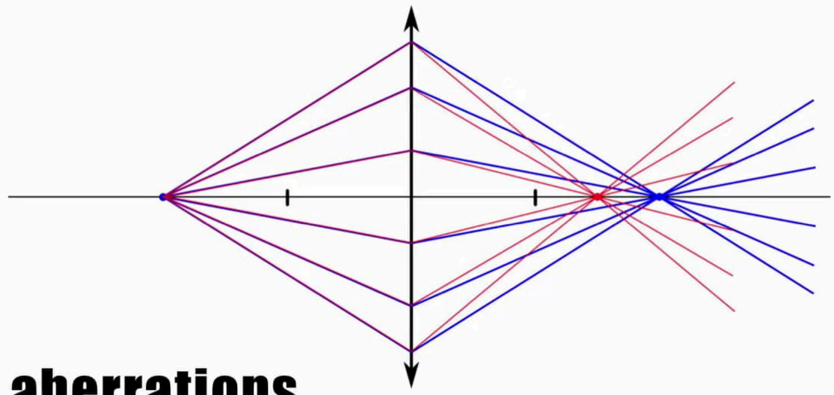
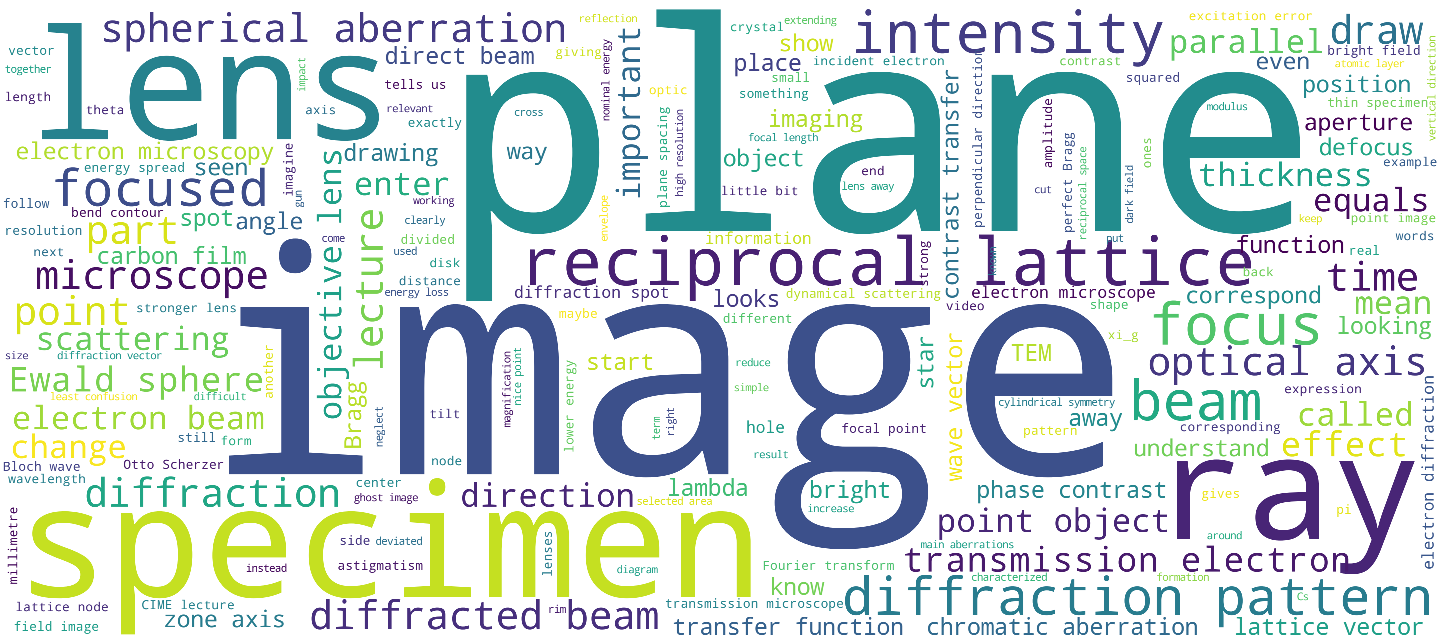


Introduction: lens aberrations

Transmission Electron Microscopy

Prof. C. Hébert & Dr. D. Alexander



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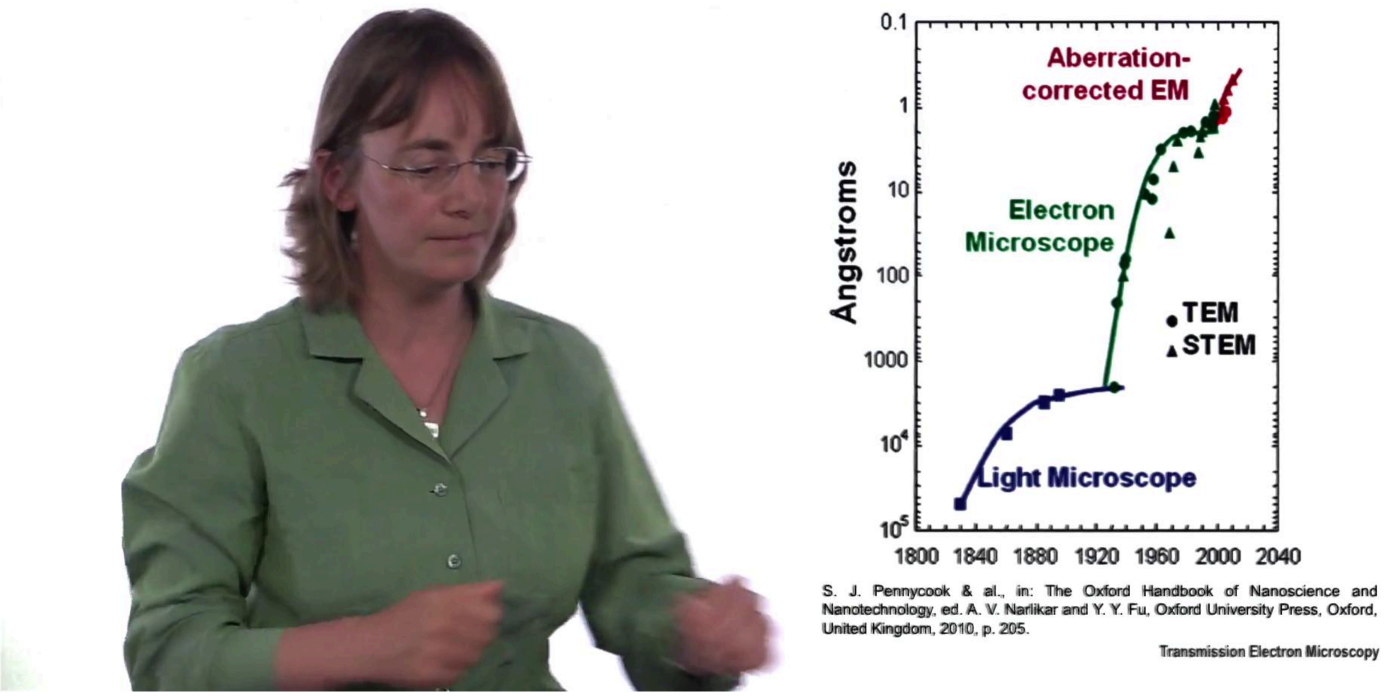


Welcome to CIME's lecture on Transmission Electron Microscopy for Material Science. In this video, we will review the main aberrations that are relevant to understand the imaging properties of a transmission electron microscope. You remember, from the last lecture, we had this graph that shows you and tells you that the microscope has its resolution limited by aberrations. Actually, the most important one is the spherical aberration, and we will start with it.

Notes

Summary

0m 04s

Lenses aberrations: spherical aberration

- Spherical aberration, characterized by its coefficient Cs, given in millimeter.
- Rays that enter the lens away from the optical axis are more focused (positive Cs)

Transmission Electron Microscopy

So, spherical aberration, you probably remember it from your lecture in optics. First of all, it is characterized by its coefficient, Cs, given in millimetre. Then, it tells us that rays that enter a lens away from the optical axis are more focused. That is the case for positive Cs. How does it look if we try to draw this information?

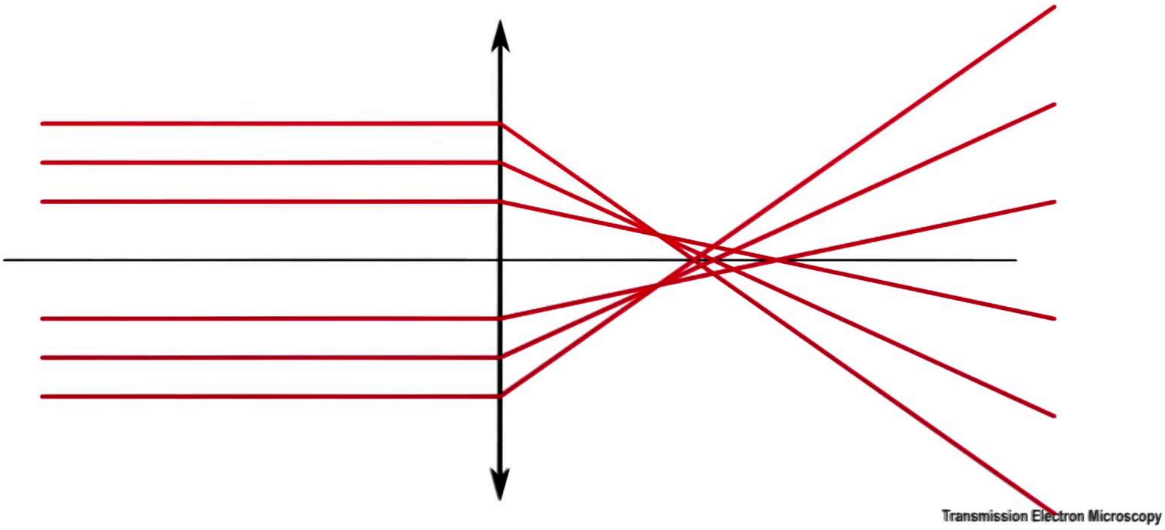
Notes

Summary

0m 39s

Lenses aberrations: spherical aberration

- Spherical aberration, characterized by its coefficient Cs, given in millimeter.
- Rays that enter the lens away from the optical axis are more focused (positive Cs)



We have here a lens and we will take some rays that will enter the lens, all parallel to the optical axis. There we have it. Normally, such rays should be focused to the focal point of the objective lens. So, something like this, and all the rays coming through the same point. But now, we say that rays that enter the lens away from the optical axis are more focused. So this one is further away. So the lens will be stronger, and the ray will be more deviated. That continues holding for the next rays, which will be even more deviated. Then, we should draw this in a symmetrical manner, and finishing the drawing, obtain something like this. That is what you are used to in optics. But now, generally, in a transmission microscope, we are working with very small specimen parts. So you can consider that everything comes from the same place on the specimen. What is the effect, now, if we take a point object?

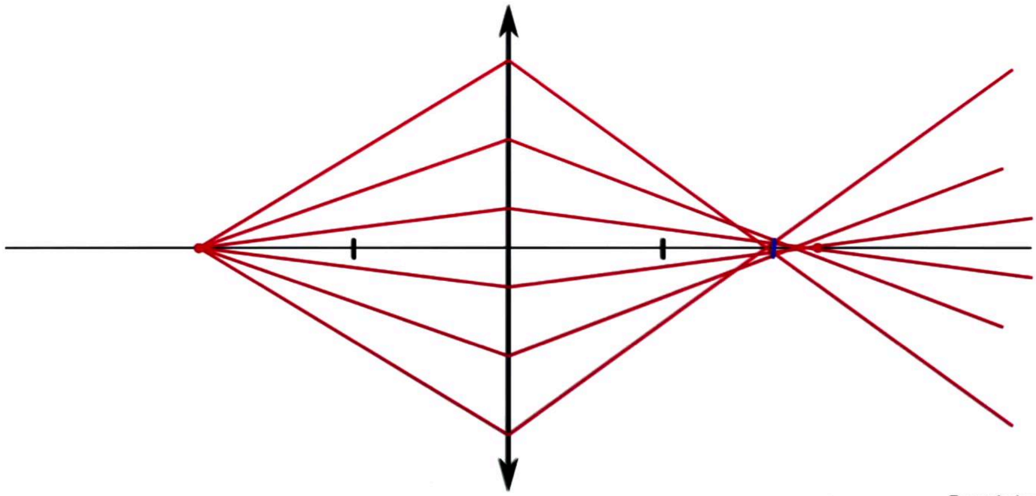
Notes

Summary

1m 09s

Lenses aberrations: spherical aberration

- Effect on a point object



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Let's take the same setup, but our object is now a point. I first need to find a place where the image will be formed. For this, I need to imagine an extended object and draw its image by the lens. This gives me the position of the image at that point on the optical axis. that is where the image of this point object should be. Now, a point object will emit rays in different directions that will hit the lens. Those rays will be focused by the lens to the object point. The problem is that rays that are further away from the optical axis will see a stronger lens and be focused closer to the lens. It is symmetrical and is even worse for the further rays. You see that the image of a point is not a point anymore, but a disk. Somewhere on the optical axis, I have the place where my disk has the smallest possible size. It is the disk of least confusion. This will blur the image and, eventually, make some kind of strange effects, like the one we will see on the next slide, which shows a real electron microscopy picture.

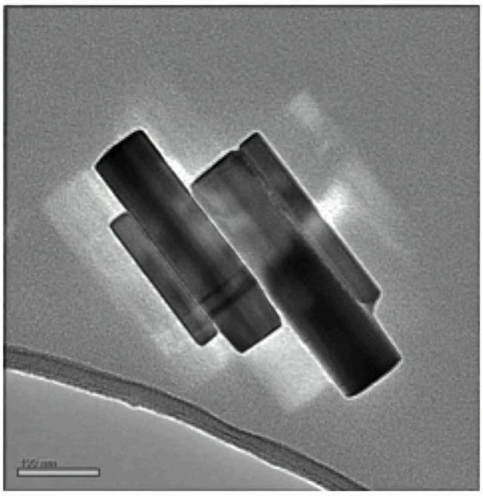
Notes

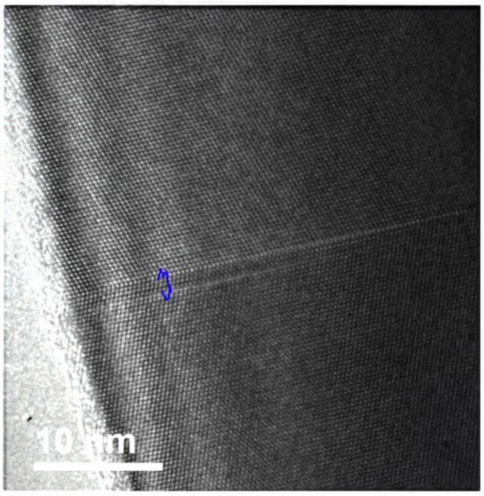
Summary

2m 26s

Lenses aberrations: spherical aberration

- Examples on TEM images





Creates ghost images

Blurs interfaces

delocalisation

Transmission Electron Microscopy

Typically, the Cs will make 2 effects. On one side, it is able to create ghost images of strongly diffracting specimen. You see, there, that you have the actual image of the small crystal but also like a bright image on each side, left and right. That is what we call ghost image and this can be obtained due to the Cs. It will also blur interfaces. Here we have defects in a crystal which should be only extending over 1 atomic layer in this high resolution image, but if you look at it you have the feeling that it is extending over 4 or more atomic layers. These 2 effects are called delocalisation. You will see this one in the lecture about imaging with diffraction contrast and this one will be discussed in the lecture about phase contrast.

Notes

Summary

4m 04s

Lenses aberrations: chromatic aberration

- Chromatic aberration, characterized by its coefficient Cc, given in millimeter.
- Electrons at lower energy (longer wavelength) are more focused.

Transmission Electron Microscopy

The next aberration I want to discuss is the so-called chromatic aberration. Again, probably you know it. It is characterized by its coefficient, Cc, given in millimetre. In that case, it tells us that electrons at lower energy, or longer wavelength, will be more focused by the lens. Again, let's try to draw this.

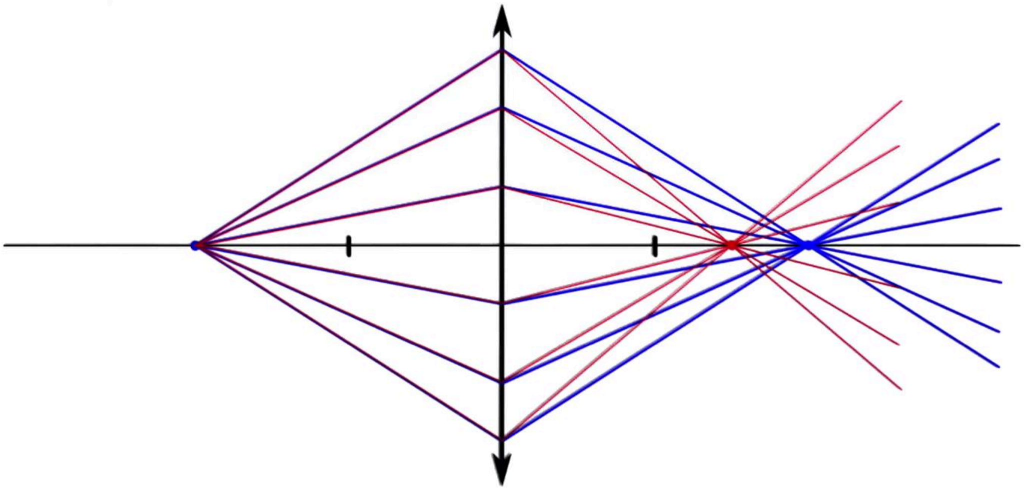
Notes

Summary

5m 13s

Lenses aberrations: chromatic aberration

- Chromatic aberration, characterized by its coefficient Cc, given in millimeter.
- Electrons at lower energy (longer wavelength) are more focused.



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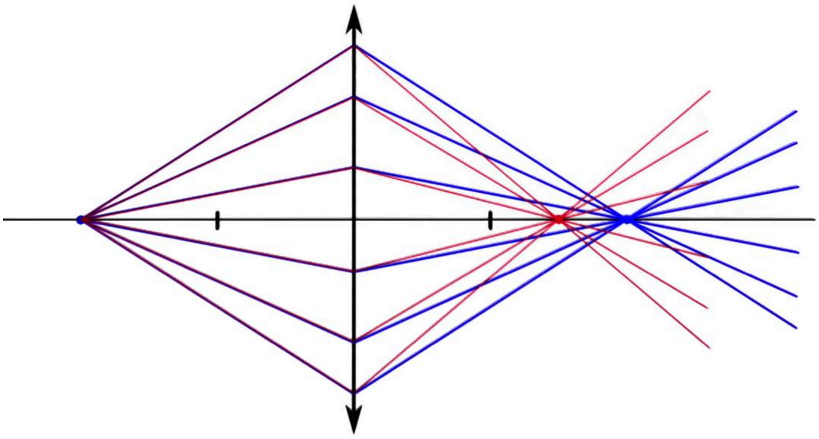
I have there my lens, and I will start this time with a simple point object and a two-focal point. Again, I should have the image of that point at the same place as I had it before. Now, I will consider electrons which have the nominal energy of the electron beam, and I will draw them in blue. They will enter the lens all with different angles and I will neglect the spherical aberration. So all those rays will be focused to the same point, properly, like it should be by a perfect lens. Finishing the drawing gives me the following: a nice point image of a nice point object. Now, I also have electrons with lower energy. I will draw them in red. They will follow the same paths between the objects and the lens, but then we say that electrons at lower energy are more focused. So those ones will see a stronger lens. The same for the ones which are there, and the ones which are at that point will also see a stronger lens. Again, I neglect the spherical aberration, which means that, still, my point object gives me a point image. Altogether, I will, again, end up with a blurred image. This also results in a disk of least confusion and, therefore, blurring of the image.

Notes

Summary

5m 42s

Lenses aberrations: chromatic aberration



- Results in a blurring of the image
- Small energy spread of the probe (monochromator) and thin specimen reduces the impact
- Correctors are developed in few labs
- To be considered at very low tension and for analytical TEM (energy loss spectrometry)

Transmission Electron Microscopy

Fortunately, the chromatic aberration is less important than the spherical aberration for several reasons. First of all, the small energy spread of the probe, especially if you use a special monochromator that will even reduce the energy spread of the electrons coming out of the gun, will reduce the impact. If you use a thin specimen, your electron beam will not interact too much with the specimen. So the electrons will not have too many events that will lead to energy loss, and they will keep the nominal energy of the beam. So, a thin specimen will also reduce the impact. Like for spherical aberrations, for chromatic aberrations, it is in principle possible to develop correctors, but they are only developed in very few labs. It is still a research area, while spherical aberration corrections exists nowadays on commercial instruments. It is important to consider it at very low tension but also if you want to analyze the energy loss by the electrons. This will be part of a later module.

Notes

Summary

7m 39s

Lenses aberrations: historical note

Über einige Fehler von Elektronenlinsen.

Von **O. Scherzer** in Darmstadt.

Mit 3 Abbildungen. (Eingegangen am 4. Juni 1936.)

Unmöglichkeit des Achromaten. Die Bildfehler dritter Ordnung. Unvermeidbarkeit der sphärischen Aberration.

Zusammenfassung. Chromatische und sphärische Aberration sind unvermeidbare Fehler der raumladungsfreien Elektronenlinse. Verzeichnung (Zerdehnung wie Zerdrehung) und (alle Arten von) Koma lassen sich prinzipiell beseitigen. Durch die Unvermeidbarkeit der sphärischen Aberration ist eine praktische, nicht aber eine prinzipielle Schranke für das Auflösungsvermögen der Elektronenmikroskope gegeben.

- 1936: Cs and Cs are always positive for lenses with cylindrical symmetry
- 1947: proposition for a solution (O. Scherzer, Optik, 1947)
- 1997: first successful correction!

Transmission Electron Microscopy

A short historical note on these aberrations, chromatic aberrations and spherical aberrations. Actually, they were recognized to be very important in limiting the resolution of the TEM, already in the 30's by Otto Scherzer. If you look at this paper, published in 1936, what Otto Scherzer tells us is that you cannot avoid spherical and chromatic aberrations for lenses with cylindrical symmetry. They will limit the resolution of the microscope. The same Otto Scherzer proposed, only 11 years later, some solutions for this. One of them is to break the cylindrical symmetry. Building such a piece of equipment was so challenging and so difficult that the 1st successful correction of a TEM came only in 1997.

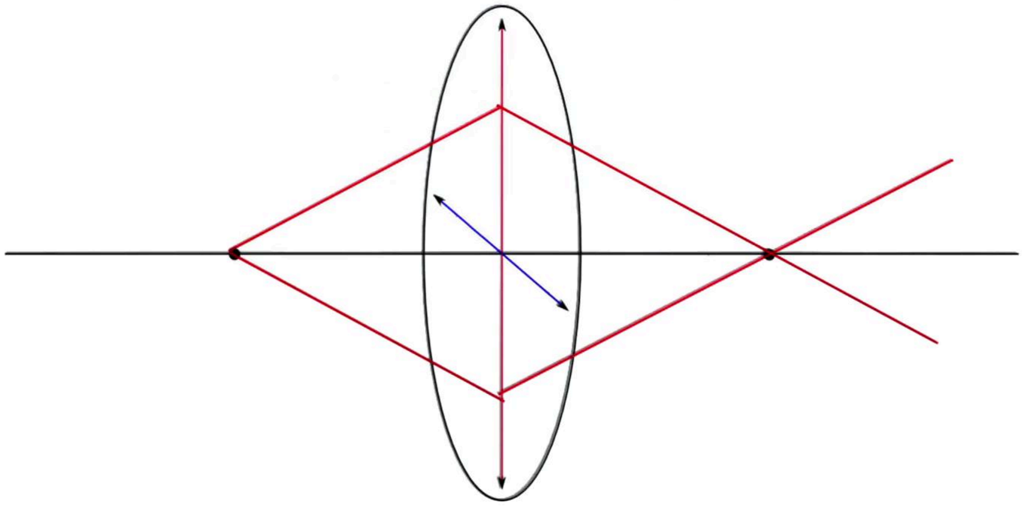
Notes

Summary

8m 58s

Lenses aberrations: astigmatism

- Astigmatism is when the focal length is not the same for two perpendicular directions of the lens
- Affects all electron lenses (inhomogeneity of the material or machining)



Transmission Electron Microscopy

So now we remain with only 1 aberration, and this one has a slightly different position. It is called astigmatism. Astigmatism is when the focal length is not the same for 2 perpendicular directions of the lens. Therefore, we need to represent astigmatism in a 3-D drawing, which will make the drawing a little bit more challenging. Astigmatism affects all electron lenses because of inhomogeneities in the material or machining, but also because of dust particles that escape the specimen, contamination on aperture or pole pieces, or even because of the specimen itself, if it is magnetic. But I have very good news. It is that astigmatism can be corrected. That is even one of the important steps that you are doing when aligning a transmission microscope. Let’s look at it in more details. First of all, I have my three dimensional lens with the vertical direction and 1 horizontal direction. So I really have to enter the third dimension. This is the optical axis. I will, again, take a point object, which has, as an image, a point image. Let's start with imaging that we have there. The image obtained when I have rays that enter the lens on the vertical axis.

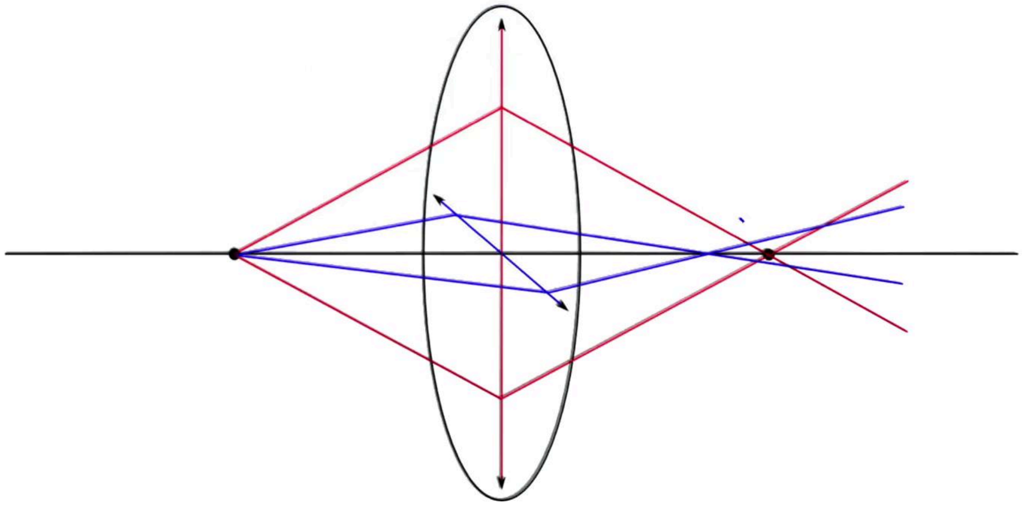
Notes

Summary

10m 04s

Lenses aberrations: astigmatism

- Astigmatism is when the focal length is not the same for two perpendicular directions of the lens
- Affects all electron lenses (inhomogeneity of the material or machining)



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Now, we say that the focal length is not the same for 2 perpendicular directions. If I take rays that enter the lens on this perpendicular direction, they will not focus at the same point. So maybe after, maybe before, depending on how the astigmatism is going, but not at the position where it should go. It will look a little bit like this. It is more difficult to imagine what is really going on there because that means that my image, if I look at this plane, is sharp in the vertical direction but completely unsharp in a horizontal direction. So let's try to see what is going on on a real transmission electron microscopy image.

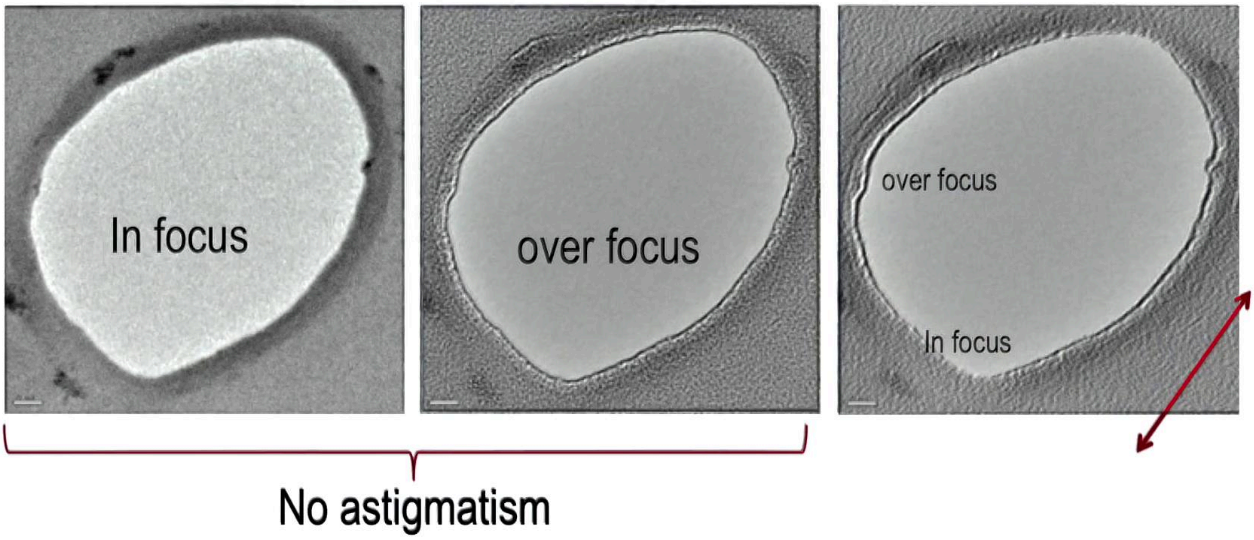
Notes

Summary

11m 48s

Lenses aberrations: astigmatism

- Astigmatism is when the focal length is not the same for two perpendicular directions of the lens



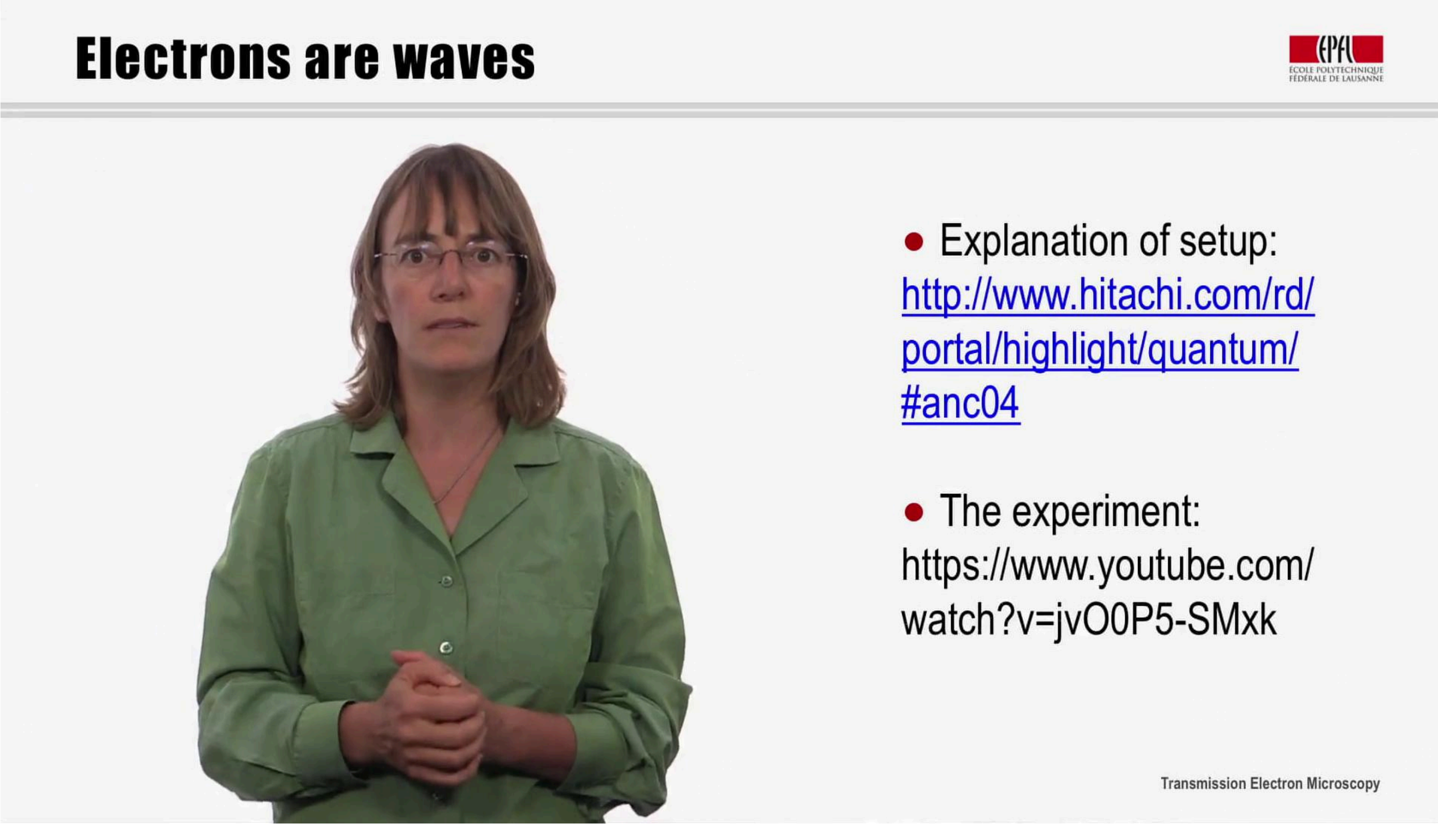
Transmission Electron Microscopy

I've taken the simplest case of a hole that is there, so I have no specimen on the inside, and which is in a carbon film. So that is amorphous carbon. If everything works well, and if my image is in focus, you see, very well, the rim of the hole with no particular contrast. If I now over focus the lens, I will see some strange contrast there, which looks like grains appearing in the carbon film, and this dark rim on the side of the hole. In this case, the rim is the same everywhere. I have no astigmatism in those 2 images. It is perfectly corrected. But this one is a bit strange, right? It looks like it is in focus there and completely over focused at that position. Indeed, this image has a strong astigmatism. So this image is in focus, over focus, and this has some parts over focused and some parts in focus. If you look carefully, you will also see that the carbon film is not homogenous anymore. It looks like maybe it has been stretched, or whatever. You see elongated structures in this direction, which correspond to the direction of the astigmatism. Again, it is because I'm in focus in that direction and not in focus in the other direction.

Notes

Summary

12m 47s



Okay. With this, we have seen the main aberrations that are relevant to understand a transmission electron microscope. In the next video, you will see how we can take groups of lenses, put them together, and build a complete transmission microscope. Before jumping to this, I would like you to have a look at these links. They will explain to you and show you that electrons are also waves.

Notes

Summary

14m 35s