Techniques of Materials Characterization
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Lecture – 13
Basic Components of Electron Microscope - Continued

Welcome everyone to this NPTEL online certification course on techniques of materials characterization. We are in week 3 and we were discussing about general concepts of electron microscopy. In the previous two lectures, we have covered some of the very basics and very common concepts of electron microscopy, which can be applicable to any kind of microscope, any kind of electron microscopy.

And there we were first discussing about various type of components. So, like in the last lecture we have discussed about the electron guns and various type of thermionic guns, field emission guns, we were making a comparison between them and so on and so forth.

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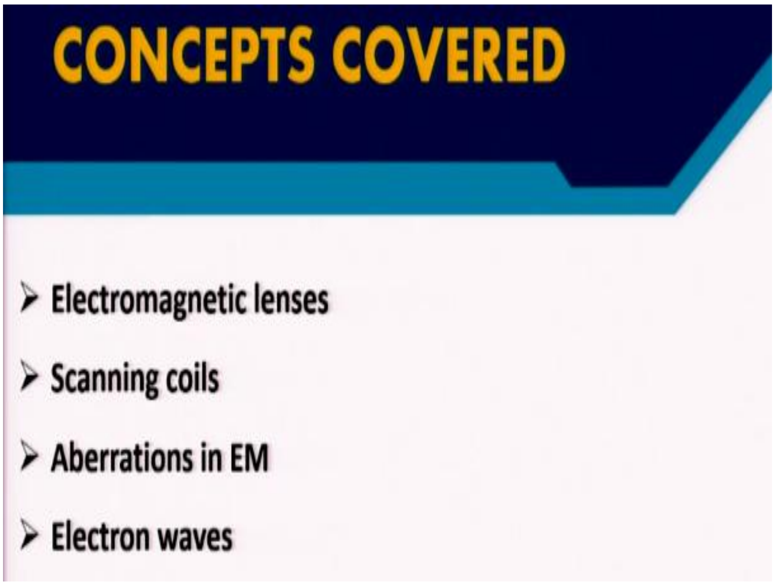

And now, in this week we will be continuing those basic components of electron microscopy discussion and here we will be discussing about the two things. Number one primarily electromagnetic lenses and then one variation of that electromagnetic lenses and that is the scanning coil. So, these are the concepts that we will be covering today electromagnetic lenses, scanning coils which construction wise almost similar to electromagnetic lenses, but yes there are certain differences.

And then we will be seeing that how these aberrations in electron microscopy, we have discussed about aberrations in earlier also as a general concept, but now we will be discussing aberrations particularly for electron microscopes. And finally, we will be discussing about electron waves and then we will be trying to see how these last two topics aberrations and electron waves how they are related to various concepts or various basic components of any electron microscopy.

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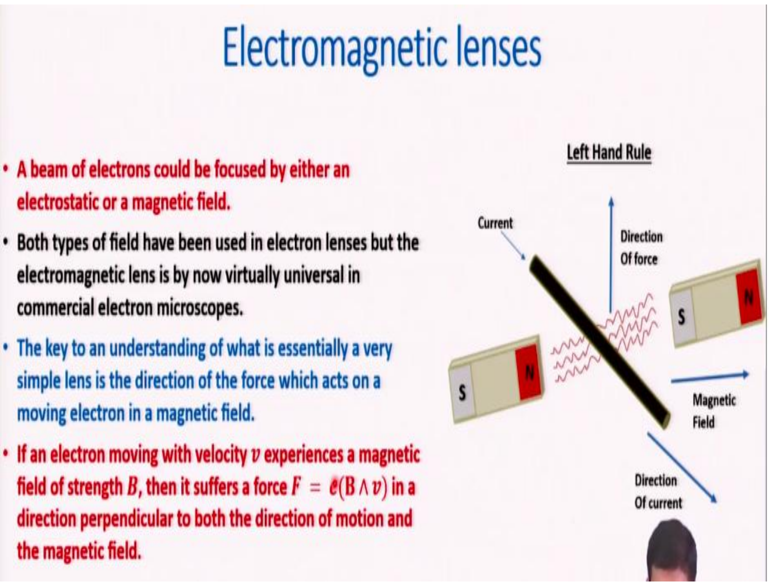

So, the first topic that we will be discussing now is the electromagnetic lenses. And electromagnetic lenses basically what does it do? Just like an optical lens, glass lens here they also focus the electrons. And I am not discussing, when we are discussing about optical microscope, we were discussing condenser lenses separately and then objective lenses separately. Here we will not do that because construction wise basically there is no difference between an objective lens and condenser lens.

Here in case of an electron microscopy, all of these are electromagnetic lenses and they are pretty much the same construction, same design, same concept. So, these are common lenses whether you put them for focusing the electrons before they reach to the specimen or after the electron passes through the specimen, you use those electrons. The electromagnetic lenses basically focus them for image formation, it does not matter.

So, as we were discussing electrons being charged particles, they have an advantage compared to light that is they can be focused or they can be worked with using electromagnetic lenses. Basically, they can be influenced by both electrostatic or magnetic lenses either of them and such lenses were used initially. As if you remember when I was discussing about the history of electron microscopy.

I said the first person to develop the prototype of electron microscopy in Max Knoll and Ernst Ruska, so their electron microscopes on birth or rather that generation of electron microscopes were all having electrostatic lenses, but nowadays nobody uses electrostatic or magnetic lenses because you have much better way of moving or doing these lenses in much better way of influencing electrons by using electromagnetic lenses.

You basically have much more control on this how you want to focus the electrons, what will be the focusing power and so on. If you use electrostatic or magnetic lens basically, the electric field or magnetic field that they produce is very much fixed whereas in case of electromagnetic lenses these fields can be changed just by changing the current. We will see that how and how that will influence the electromagnetic lenses and their focal points powers.

So right now, virtually almost all the commercial electron microscopes which are available in the market which you will be seeing possibly anywhere, they are all having these electromagnetic lenses and there are obviously some benefits to that. Primary benefit is because you can change that, you can change their focal power, you can you can change this magnetic force on the electrons everything you can control.

So, the key to understand how these electromagnetic lenses basically work on the electrons what you have to understand is the forces that is acting on the electrons and what is the direction of those forces that is ultimately or the direction with respect to the direction of electrons how those forces are causing or how those forces are influencing the electrons, what force they are imparting on the electrons and what is the direction of the force.

This is all we have to understand in order to understand the electromagnetic lenses. So, let us assume that we have an electron which is moving with a velocity. So here it is shown current, but already we discussed that basically an electron movement is reverse to the direction of current that is it. So, this one you have possibly familiar with. You may have seen this during your +2. This is plain and simple, Fleming's left-hand rule.

What does that rule says is that direction of current and magnetic field if these two are parallel or perpendicular to each other, then the force that this magnetic field is exerting on this current moving or in this case we can imagine this are electrons in this direction, the direction of force will be perpendicular to each of them. So basically, this direction will be perpendicular to this plane that contains that direction of current and our direction of electron movement and the magnetic field that is it.

If we do that, then what we can imagine that an electron which is moving at a velocity of v and under a magnetic field which is having a strength of B, then the force F = e*B in a direction which is perpendicular to both the direction of the motion and the magnetic field where e is basically charge of the electron, nothing. So, this is the basic force that acts in the electromagnetic lenses when an electron passes through.

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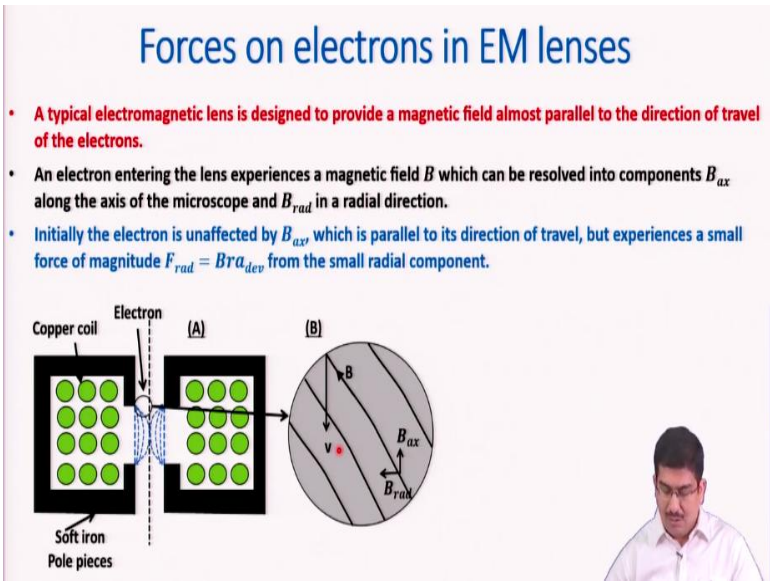

Now this is a typical electromagnetic construction of an electromagnetic lens, we will discuss more about that, what is this all about, how this electron what are the components of this like copper coils, soft iron poles, what are their functions and so on. But for the present moment just imagine that an electron is moving through this lens okay and this lens is causing a magnetic field to exist somewhere on the path of this moving electron.

And initially what happens is that the magnetic field, the magnetic lines of forces you can imagine, so this magnetic field is almost parallel to the path of the electrons and electrons are moving here along the optic axis. So, if this is the optic axis the electrons are moving parallel to the optic axis and the magnetic force is also working almost parallel to the electron movement or parallel to the optic axis here.

Now initially, so this is shown here, so this portion if you zoom up here, you can very well this what is happening. So, let us imagine that this B is almost parallel, not exactly parallel, but almost parallel to the direction of this velocity, the direction at which the electrons are moving. So, what is happening now? This B I can resolve it into two components, B_{ax} and B_{rad}. Initially, the B_{ax} component is exactly parallel to the velocity of the electrons.

So, this one will not exert any force on the moving electron the axial component. The actual component will not exert any force on the moving electron, but the electron will feel a force because of this radial component and that feel will be equal to this Frad = B_{rad}*ev, I am sorry this one is a little problem, but this will be like B_{rad}, here B_{rad}*ev exactly which is coming out of this.

So, with this force and this force of course because of Fleming's left-hand rule, the force this F radial will be perpendicular to both direction of flow current electron movement v and direction of this radial component of magnetic field. So, that direction or that force will act perpendicular to the plane of this paper imagine.

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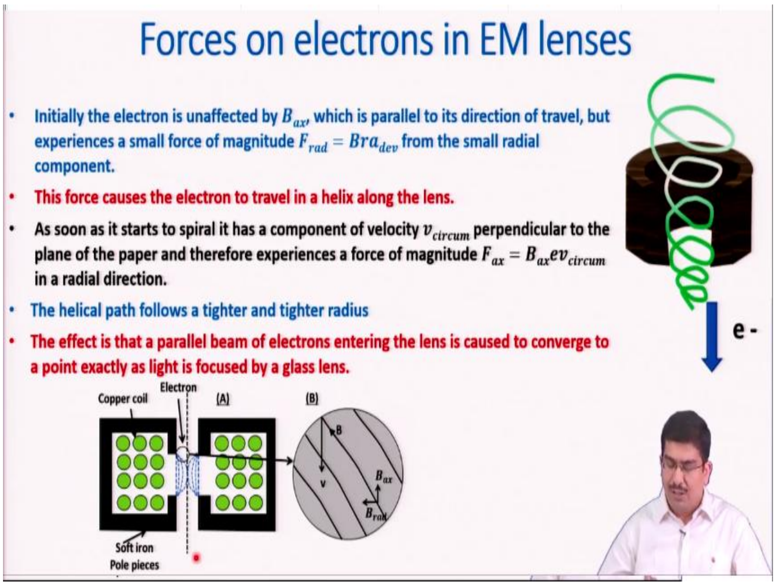

Now, what happens out of that basically because of this field now, the electrons will have a deviation from the regular path. So, earlier if the electrons were moving along this direction along this parallel to the optic axis, now there is a force acting perpendicular to this perpendicular to their motion. So, what it will do is that this force will deviate the electrons from their original path.

And as it deviates it will be experiencing different fields or different force because continuously now the direction of electron movement this v is continuously changing, the direction is continuously changing. This one is constant, but this direction is continuously changing because of this force. So, what ultimately it will happen is that this force will cause the force due to this component, the radial component.

This will make the electrons to travel in a helical path or like a spring. The electrons will have a spring kind of movement, the direction of its movement is continuously changing along in one plane if we imagine that because of this one that is one part of the story. First part of the story is this, electrons are moving like a spiral path. So as soon as it started having this spiral movement, then the electrons will have now a velocity component.

Because right now this is not the direction of electron movement, it is somewhere else, it will make some angle with the optic axis and the moment it does we can similarly just like what we did for this magnetic force we can do a similar, we can resolve this velocity of electrons into two components and one of those components that is v circumferential this direction along that will now become perpendicular to this axial component.

So, then what will happen is that this axial component will also start putting a force on the moving electron which is equal to this $F_{ax} = B_{ax} * ev_{circum}$, equal to this amount the electrons will be experiencing a force from this actual component as well. So, ultimately what will happen the B radial one is causing the electrons to move in a spiral path.

And the axial one is causing another force which is basically making the radius of the spirals shorter and shorter. So, ultimately the electrons will move like a helical path which is shown here. Because of these two forces electron will finally move like a helical path and finally, it is initially starting like a spiral path and then because of the actual force, the radius of the spiral path is getting shorter and shorter and it will follow like a helical path with a tighter and tighter radius.

So, what we can imagine ultimately is that if we consider one single electron when it enters here, it has this parallel to the optic axis that kind of velocity that can have a direction it is moving parallel to optic axis. But because of these two forces, the electron ultimately comes down to one single spot. And if we imagine the entire electron beam which is moving here, all the electrons will suffer the same fate.

All of them will move along this helical path with a shorter and shorter radius and finally all of them will meet at one place. So, ultimately what we can imagine that a parallel beam of electrons, so if the electron beam is entering parallel to the optic axis all the electrons which are entering here as a parallel beam, they will converge to a point. This process we can think of exactly as the focusing of a light by a lens.

Here also these electrons are getting focused to a point, a parallel beam of electron will finally get focused somewhere outside this lens that is it. That is how the forces on electron or forces in the electromagnetic lenses basically cause these electrons to finally focus at one point in space. This is how it happens. Of course, this is a very simplistic feature or very simplistic approach that I told you.

There are much more complex equations, complex mathematics is involved in to describe this helical path, there are different type of forces that is acting on electrons directions and so on. So, this is very complex subject. If you are interested, please refer to all those reference books that was initially given. The details of those books were initially given, please refer to that.

And that will give you much more idea about this helical movement of electrons and how these electromagnetic lenses ultimately are focusing the electrons. But for the purpose of this present course, this much of idea hopefully will be good enough.

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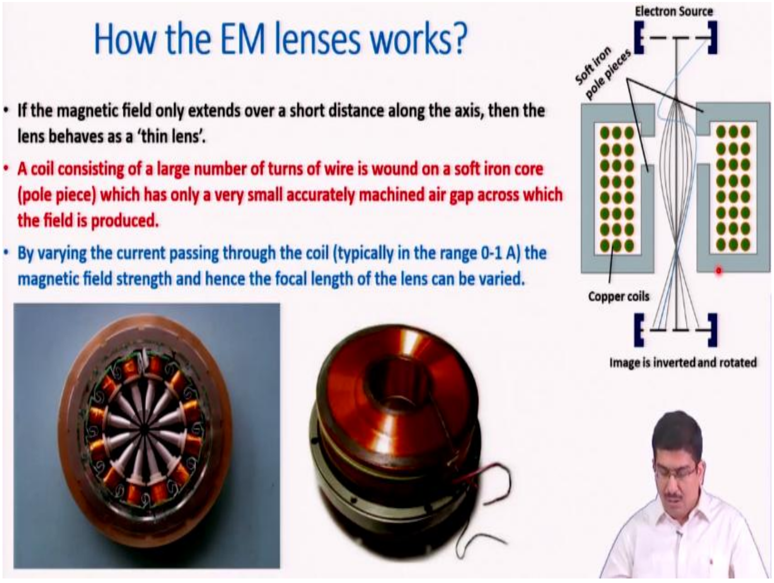

So, number one now in an actual practical in real electromagnetic lenses how these things happen? So, first of all the actual electromagnetic lenses are very small. So, they can be considered as a small or thin lens this is the first thing. So, if they are not thin lenses, the problem that will happen is that if you remember initially when we started with the thin lens equation 1/f = (1/u+ 1/v) that equation gets modified.

And they are with the focal length and with object distance, image distance with everything you have to add the thickness of the lens and that will cause a lot of problems in further calculation of resolution, aberration, depth of coil, depth of focus and so on and so forth. So, if something is not a thin lens it itself will introduce a lot of aberrations in the final image that is the first problem.

So, that is why the electron or electromagnetic lenses are purposefully kept or build in such a way that they walk like a thin lens. If one is not sufficient just like in glass, one is not sufficient a combination of different lenses is usually used so that is how the electromagnetic lenses behaves first of all. Secondly the electromagnetic lenses they are basically number of copper coils, copper coils and number of turns which is here.

So, these are basically the copper coils right and the copper coils are kept in a soft iron pole piece. So basically, this is exactly the same structure as a transformer. So, this is just like a mini transformer. Here also there are lots of or a motor for example, you can imagine this to be a motor structure or this to be an any kind of electromagnetic lens, basically the same structure here itself also, so copper wires and then a soft iron pole piece is there.

Within the iron pole piece there is a very small very carefully prepared machined hole is given and all the magnetic lines of forces are allowed to pass through this small little gap which is provided here. So, only within this, even though this one is really bigger, this lenses finally the area over which they work the magnetic lines of forces interacts with the electron direction of the electron velocity of electron that area is very thin that is why these lenses can be considered as a thin lens that is the first thing.

What is the importance and usually as I said usually in one kind of one lenses, there are many combination of these kind of wires, there are many such copper wires turned around here and this is how you can see the lenses from a top view you can imagine, this is the top view. So electrons, this is the optic axis and electrons are basically passing through here and that you can think that this is your soft iron pole piece which is having a gap, small little gap somewhere over here.

And this is one individual such copper turn which is shown here. Now like all electromagnetic lenses by varying the current passing through the coil, which is usually in the range of 0 to 1 ampere, you can change this magnetic field, the strength of this magnetic field can be varied just by changing the current. Two ways you can do that out, either you can change the wires, the turns, number of turns here that can be changed and that will also change the magnetic field.

Otherwise, you can change the current from here and that will also change the magnetic field. So you can change the magnetic field here, everything the total scenario will change, the strength of this forces will also change and you can make this helical path the way you want. So basically, you can change the focal length just by changing the magnetic field here.

Just by changing the current basically in the lenses you can change the magnetic field, you can change the forces and that will change exactly where the electrons will be focused, where this spiral helix will end. So, in electromagnetic lenses you can have variable focal length just by changing the current. This is the first and most important difference between this electromagnetic lenses and optical lenses.

If you remember in optical lenses since they are physical lenses, they are basically glass lenses, physical lenses, so there in order to change the focal length you need to change the entire lens that is why in the objective lens if you remember we were having at least 4 to 5 different types of objective lenses in one pole piece. So, if you want to change magnification by changing the focal length, the entire lens we need to change.

Compared to that here you just change the current in the electromagnetic lens, immediately it will change the magnetic field, forces will change and the electrons focal length will change that is it. So, that is what the primary difference.

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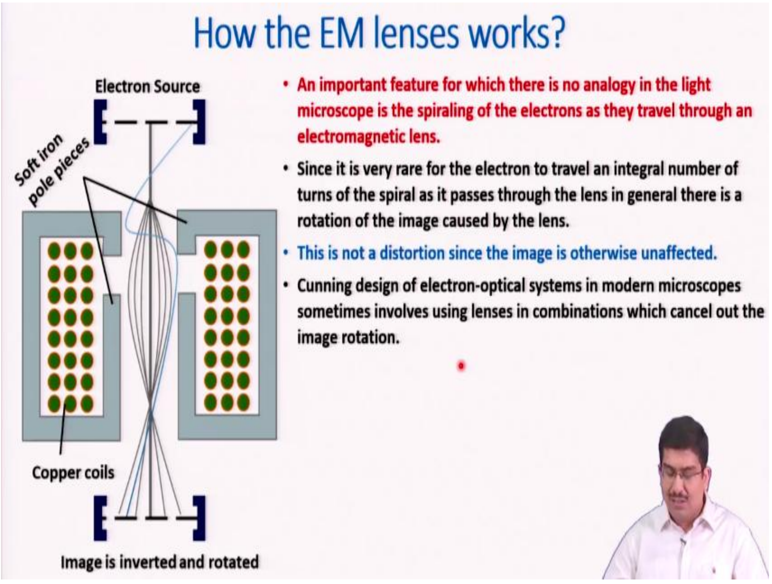

Now but these electromagnetic lenses will introduce one important error which is not there in optical lens again. What is that error? Since these electrons are moving in this spiral path here in this helical path here, so there is no guarantee that electrons will move an integer number of turns, integer number of paths or spiral path here. So, they may or may not travel an integral number of turns in this spiral path as it passes through the electrons as it passes through the lens.

It completely depends on the focal length of that lens; what focal length you are working on so completely depends on that how many such number of turns the electrons will have in their spiral helical path. So, this basically introduce a problem in the final image that is seen, the final image is rotated. Because of this in accordance to the rotation of electrons in the spiral path, the final image also gets rotated with respect to the specimen.

So, certain features in the specimen if they are not spherical, then in the image they will be appearing like rotated. This is not distortion, this has nothing to do with the distortions that we discussed previously; barrel distortion and pincushion distortion are not because the image is unaffected. There is no blurring, there is no such change in magnification nothing, only the image gets rotated.

So, this when we do an electron microscopy when we see an image, this we need to consider that depending on the focal length, depending on the magnification the image gets rotated and obviously these days there are multiple lenses. So, we use multiple lenses so that finally we rectify and correct this image rotation. So, finally we try to make the number of turns or number of turns in the spiral path of these electrons to be an integer number that corrects the entire image rotation problem.

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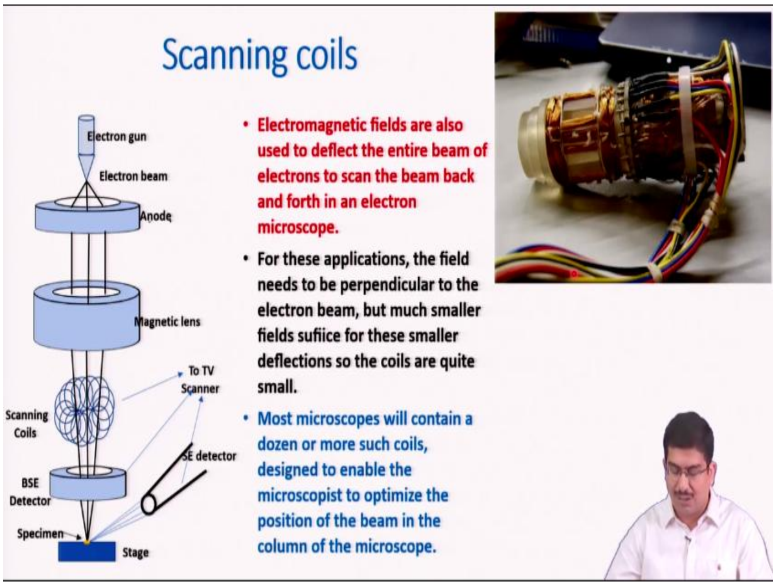

So, the next thing to discuss is about the scanning coils. Scanning coils again are just like electromagnetic lenses. These are also electromagnetic lenses only, but their primary purpose is not to focus the electrons rather to deflect the electron beam just by the same method, same helical moment, same spherical path it follows, but basically these are not getting focused at one point. They do not do the complete focusing.

They are of a much lesser strength compared to the electromagnetic lens. Their purpose is just to deflect the entire beam from its path. So parallel beam enters and they get deflected by certain amount by this scanning coils, which are also electromagnetic lenses here. And this scanning coils is basically useful if you are operating the electron microscope in a scanning mode and that can be in transmission electron microscope, that can be in scanning electron microscope.

Scanning electron microscopy is more common, more general because as the name itself suggests it works on a scanning method. The beam basically raster over the specimen; point by point the beam raster over the specimen and this entire rastering is done by this scanning coil. So, the scanning coils are basically kept just before the beam reaches to the final specimen.

They do not interfere much with the other electromagnetic lenses and their focal power; they are of much more I would say lower magnetic field and forces are applied on the electron movement of low velocity of electron by this scanning coils. So, there are many such scanning coils are usually kept and all of these scanning coils they primarily cause the beam to deflect over the specimen.

They make the beam to fall at certain place and then again on certain other place and so on and so forth and sometimes they can also be used in order to select certain part of the image. So, you are seeing an image and now you want to go back to certain part or zoom certain area, you can do this by using the scanning coils. The scanning coil will make the beam to go back to that position or just to select certain particular region.

So, these all things are done by scanning coils and scanning coils again construction wise they are exactly the same as the electromagnetic lenses, only thing is that the power of the scanning coils is much less; the focal power if you consider is much less and their purpose is just to deflect the beams and not to do anything with the focusing.

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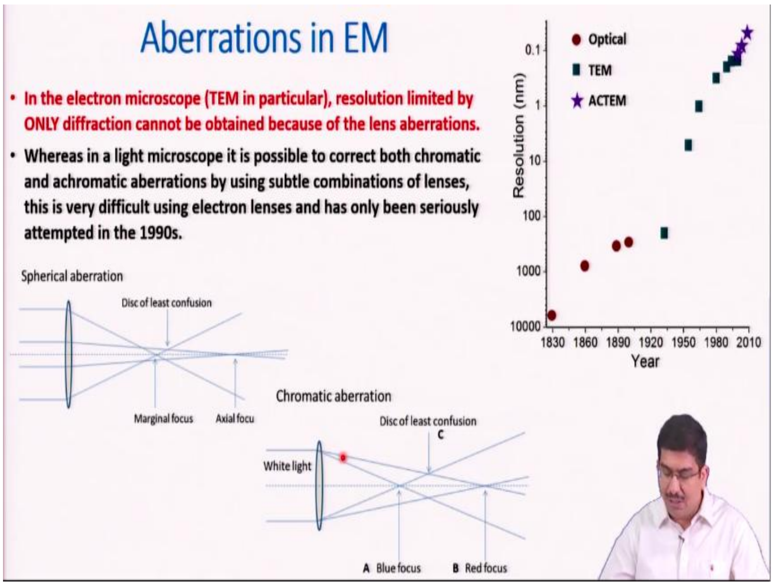

Now, let us discuss from whatever we have discussed so far about the electron gun and then the electromagnetic lenses and so on from that perspective that point of view, let us discuss the aberrations in electron microscopes once again. So as we already know that in electron microscope, aberrations exist. The resolution that we obtain from pure diffraction related criteria, Rayleigh criteria and so on that we cannot obtain because of the aberrations in lenses.

And correction of this lens aberration in electron microscopy was very difficult and much difficult compared to optical microscopes. So, we were not able to take the full advantage of electron microscope I would say. The advantage in diffraction related resolution if you remember because of the very low lambda value diffraction related resolution itself was very low for electron.

We were supposed to get almost atomic resolution on a regular basis, but lens aberration was killing it. Unfortunately, correction of those lens aberrations was very difficult and that is why only if you look at this year wise development in the resolution of various microscope, you can see that only towards recent years after 2000 and so on, this aberration correction in transmission electron microscopes is seriously attempted.

And these are now giving us almost atomic resolution 0.1 nm almost in the angstrom level we are getting resolution. So, most important resolutions again as you know spherical aberrations and chromatic aberration.

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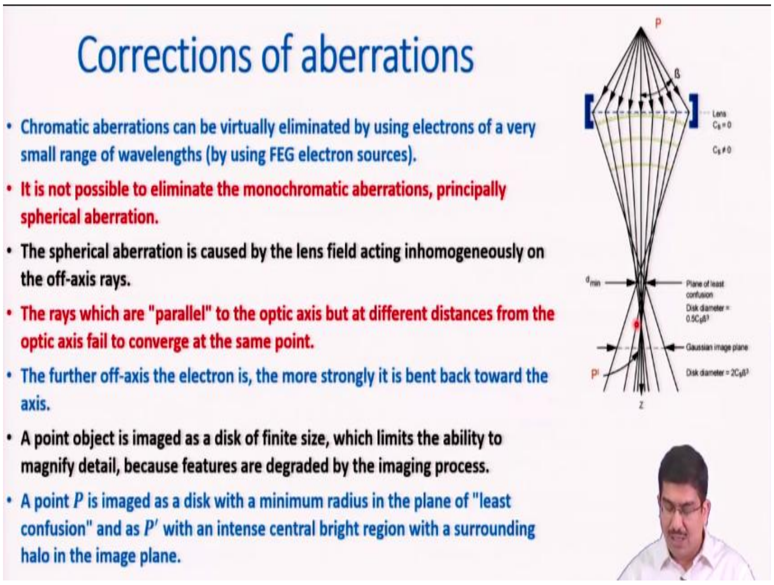

Now chromatic aberration means which is forming because of the light because of a range of wavelength or range of difference in wavelength of various electrons which are present electron or if it is light for the white light different wavelength of light or in case of an electron beam different wavelength of electron beam, which are present after it generates from the source. So, that is what is causing the chromatic aberrations.

And this problem is very severe if you use thermionic guns because there itself that electrons which are coming out from the thermionic gun that itself will have a very large range of energy because of the thermionic effect itself. And after acceleration by the anodes, they will also produce a large energy spread. So, finally they will have a very large wavelength spread in that electron beam.

Compared to that the way FEG effect works, the way field emission effect works that itself will produce very small range or very small scatter in the energy of the electrons. And finally, the electrons which will be accelerated towards the specimen they will also have a very I would say tighter range of wavelength in this. So that is what at least in chromatic aberrations you can remove it just by replacing the thermionic guns with a field emission guns.

Spherical aberration, we discussed it. It is very difficult to correct because spherical aberration the way it happens is the spread of these electrons here if considered in for electron microscopy, it is basically caused by this spread of the electron here. So compared to the optic axis the electrons which are farther away from the optic axis they will get focused nearer to the lens compared to the electrons which are closer to the optic axis they will get focused at farther distance.

So, that is what will cause two different focal points for the same electron beam and then there will be a disc of least confusion which will give you; even with the disc of least confusion the problem which will happen here is that a small spot will become like a disc. So, this spot here will become if you look at this in a disc of least confusion even in that position it will become like a small spot.

So, that is what the main problem of spherical aberration. And right now the aberration correction in any kind of electron microscopy simply works on this problem, spherical aberration correction. Chromatic aberration correction I would say nearly is done, so we have the FEG source and just by making better and better FEG source cool FEG sources, we are able to remove almost everything from the chromatic aberration.

Spherical aberration is still a problem. Again, FEG sources are useful because you can use an aperture as small as possible and try to restrict this only using these rays close to the optic axis so that finally your size of the disk of least confusion will be minimum, there also FEG sources will help you.

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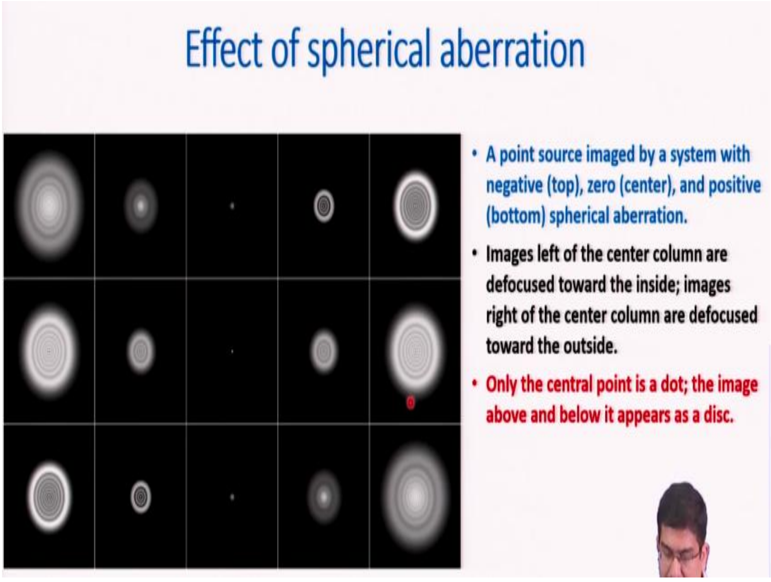

And this is how the effect of spherical aberration can be seen in case of an electron microscope, the small spot here in otherwise becomes this kind of disk in every condition whether you have negative or positive spherical aberration, whether you are in the under focused or over focused condition in all conditions this will be causing this small spot to become like a disk here.

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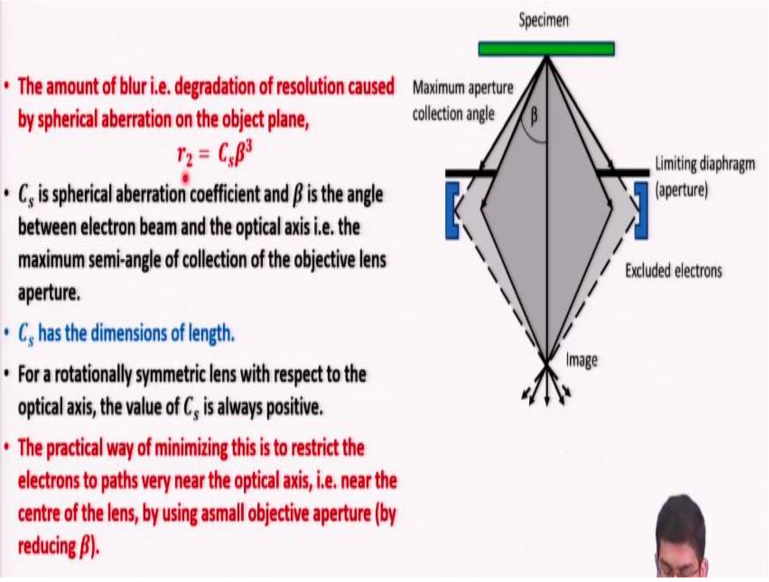

Obviously, we have discussed again this entire thing when we were discussing about aberration in microscopes that how this aberration related resolution here that is governed by this angle, semi angle of this apertures and that semi angle of the aperture basically controls the aberration related resolution here. And there is another term at the time we were discussing that is the coefficient of aberration correction.

So, this coefficient of aberration correction spherical aberration is for an optical microscope where we have a physical lens, this one is pretty much constant. This we cannot change that much that is true even for electromagnetic lenses to some extent, but this can be also worked with electromagnetic lenses to some extent and that can also cause resolution and improvement in the resolution that is because of the spherical aberration.

So, other than using the aperture that is another way of improving or making this one smaller and that is what when you do.

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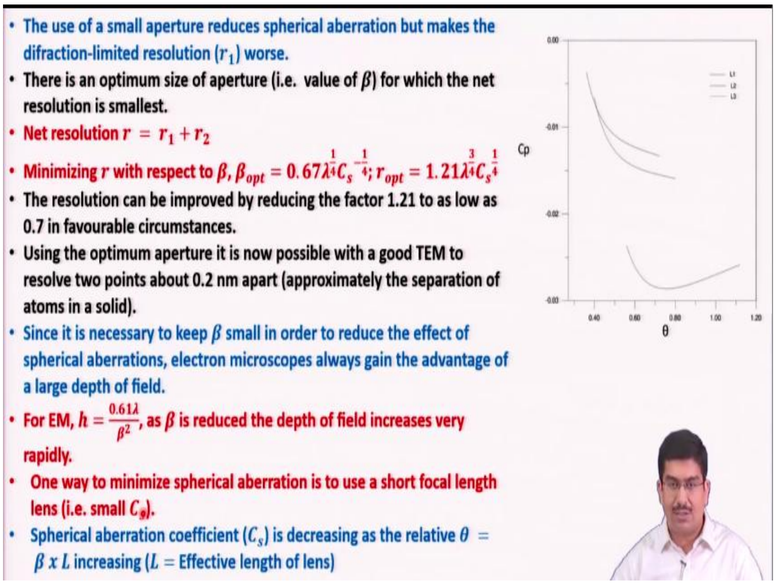

This one is again shown it here that when you try to use a very small aperture to reduce the spherical aberration, the diffraction related aberration consequently goes higher. So, finally you optimize these two and you get an optimized value for this aperture. So, you cannot do anything more with this after this. There is an optimized aperture length or aperture size that you have to have for getting the best resolution out of spherical aberration as well as diffraction related aberration.

But what you can do as I said extra here in electron microscopy is that because you have this variable focal length here, you can use short focal length lenses which will have, I am not going the entire expression, if you are interested again, please refer to those reference books. But basically what happens if the focal length is decreased, then the coefficient of spherical aberration is also reduced.

So, that means shorter focal length will give you a smaller coefficient of spherical aberration and that will obviously lead to something an improvement in the final resolution. So that is another way of doing this. And this is also shown here that when you use a very small aberration coefficient and this is a term called θ and that θ = βxL, L is effective length of the lens, effective focal length, so this theta angle here.

With increase in θ this coefficient, when we decrease the theta coefficient of spherical aberration also decreases. Of course, this is a very complex function, so after a while you will again get this one increased. So, basically what you have to do is that you have to find out an optimum angle, optimum value of theta which is given by this, both the semi angle as well as focal length and then that will optimize the coefficient of spherical aberration as well. It is another way you can remove aberration from this material.

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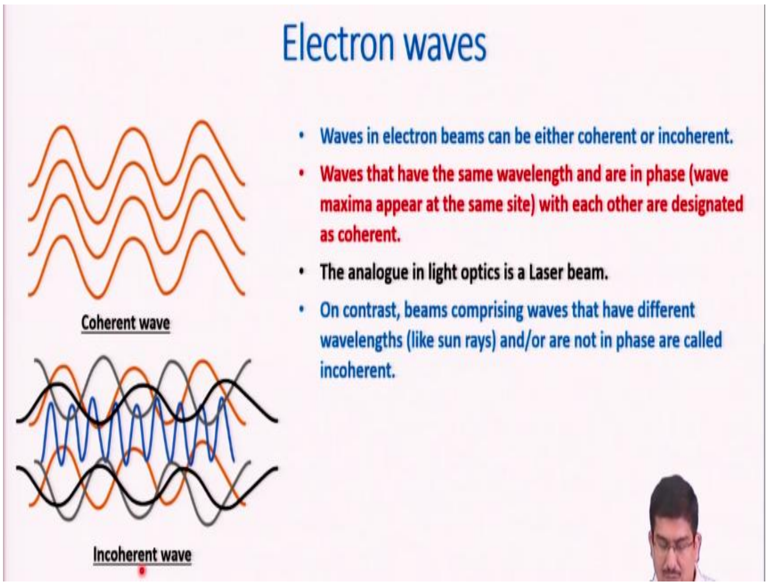

And then finally we can discuss about this, but I think we will discuss this part we will continue with this electron waves in the next class. Thank you.