Electron Diffraction and Imaging

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Lecture - 24
Lens Aberrations

Welcome you all to this course on Electron Diffraction and Imaging. In today's class, we will discuss various lens aberrations and its effect or the resolution of the microscope. The first question which arises is that why do we use lenses. It is because we know that we use lenses to magnify objects. Why do we have to magnify objects? It is because our eye has got limit on the extent to which the objects can be resolved.

If we wanted to see features which are smaller than the resolution power of the eye, then we have to magnify the image. What is the need for magnifying the image? The reason essentially is that though the light if we use for example, if we use a light as a probe, then what is going to happen is that or the ultimate resolution is given by the wavelength of the radiation lambda.

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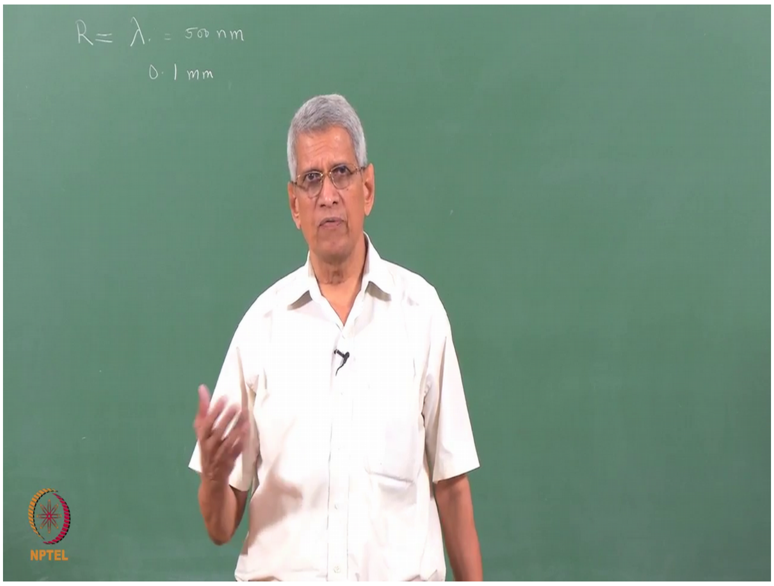

So, that means in the case of light, generally it is about something like 500 nanometers is going to be there wavelength of the radiation. That means, there are features which are of the order of 500 nanometers is resolved. Whenever light falls on the material even in this room if you look at it, when the light is falling onto this table, the features of this order are essentially resolved, but our eye is not able to see it because the resolving power of our eye is about something like roughly 0.1 millimeter.

To overcome this we have to magnify that features, so that separation between them becomes greater than the resolving power of the eye, that is why we require a lens to magnify it, but when we use a lens especially what all the features which we look for the lens, what all the characteristics which the lens should have. One of the characteristics of the lens is that you should do a faithful reproduction. What is the reality of the system the simplest case which we can take of is a magnifying lens which we normally use when we cannot read objects properly, but this is an example which is being given here. With the lens, we are trying to magnify objects. This side you can see the normal image.

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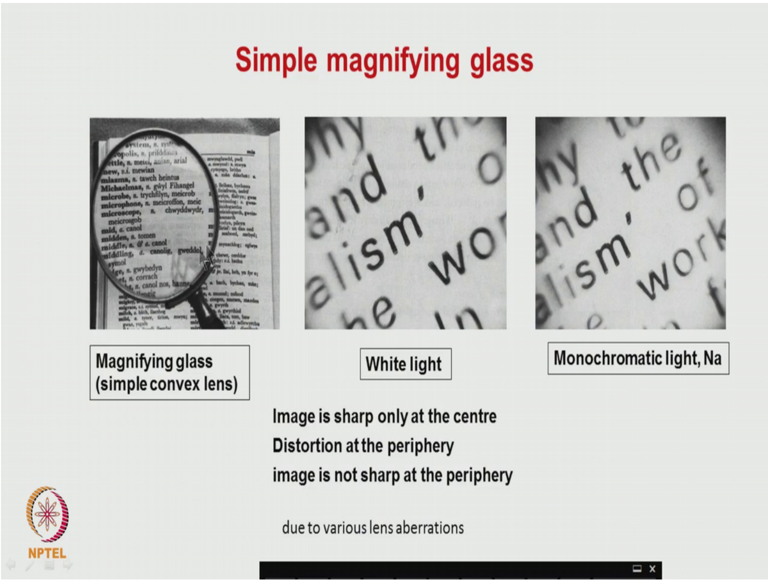

Here it is the magnified image which we can see, but if we look at it, we can immediately make out that the image is curved. It is not in a straight line. The magnification appears to be different from edge to the center and the center it is focused well. For example, in this case and the edge it is out of focus. All these problems occur because a simple lens which we use it to magnify has got lot of aberrations which are associated with it. Because of this aberration, we are not able to get a faithful reproduction of the object in the image.

In fact, one point which I want to quote at this, the statements which have been made by Maxwell in 1858. He has talked about what are the properties of an ideal image. One each point in the object, there should be an equivalent point in the image. When we form an image using a microscope, it could be an optical microscope or it could be an electron microscope and then, when we have an object, this is what essentially is given here.

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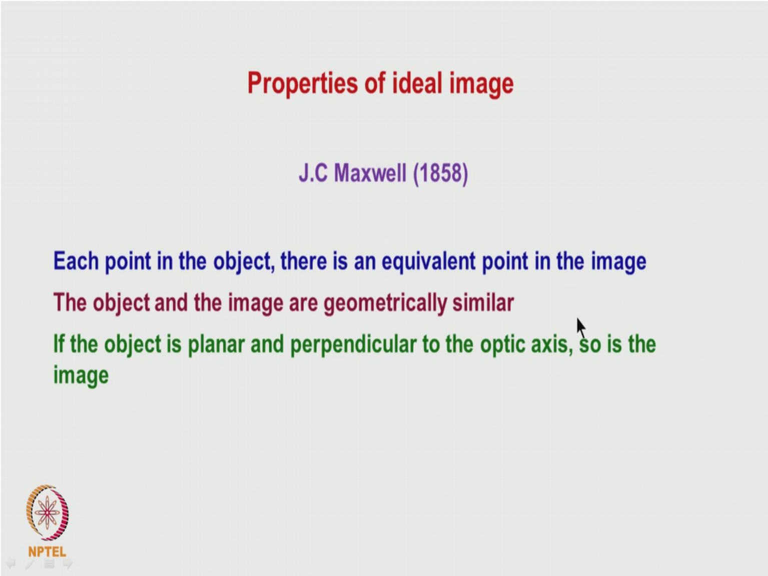

This is for example. Here if you consider a point object along the optic axis for an ideal lens, a point image should be formed.

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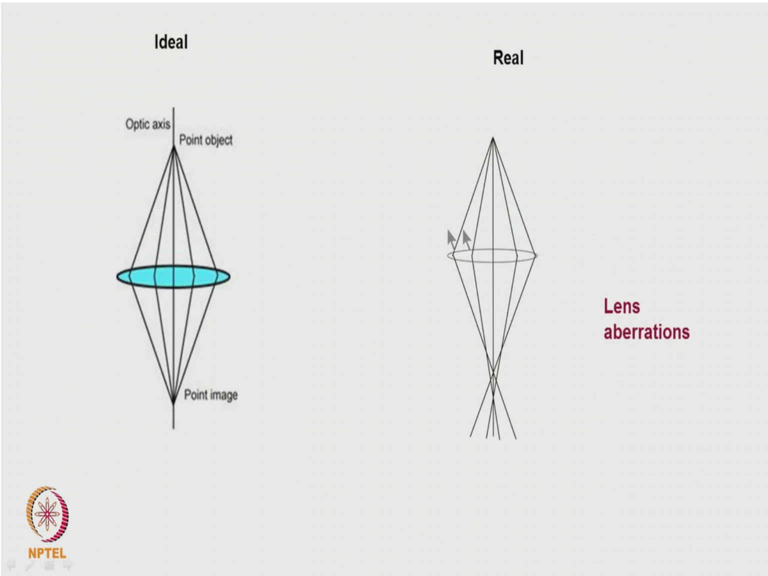

So, if the resolving power of the lens like for example, in the case of an electron microscope which is operating at it 200 kev, the wavelength of the radiation lambda is of the order of 0.0025 nanometer. That means, this is the limit of resolution. So, for an ideal lens all the atoms in the crystal should be resolved, but that is not what it happens. This is because of various lens aberrations which are associated with the lens which we will come to shortly.

The next point which he has mentioned is that object and the image are geometrically similar. What does it mean that if object has got a particular shape, the same shape should be reproduced in the image as well and the third is if the object is planar and perpendicular to the optic axis, so is the image these two points are shown in this slide here.

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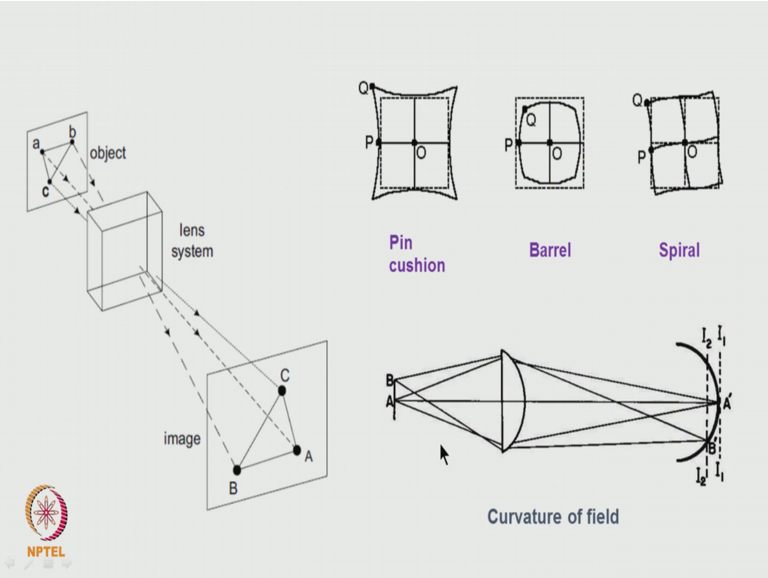

If you see it this is a b c is an object, this is a lens system which magnifies it. We are able to get a magnified image on the screen. If we measure the ratio between e a b here and a b here, b c here and b c here, and also the angle between them, they are faithfully maintained. Then only we can say that this is a true reproduction of the image. What normally happens in many of the lenses, one for an example which is shown here is as square grid is taken as the object and you find that the grid itself is distorted. This is the way it appears. When this appears, we call it a pin cushion distortion and this is another way in which a square grid can appear.

Then, we call it as a barrel distortion. There a rotation is also associated with it and then, it is called as spiral distortion. Then, there is another distortion which can come is that the image is not formed perpendicular to the optic axis for an object which is there like in this case is for a Plano convex lens. You can see that image is formed in a curved space. So, this is also another type of an aberration. So, we have seen curvature, then different types of distortions and there is another aberration which comes. Because of the curvature of the lens, the spherical lens, this aberration is normally called as the spherical aberration.

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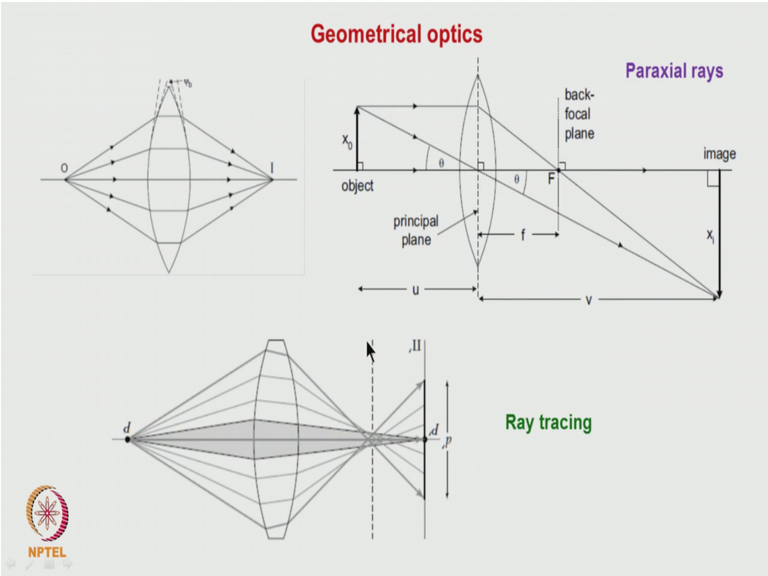

Before we go into and understand the aberration, what we should know is that why does this aberrations arise in the lens in the first place.

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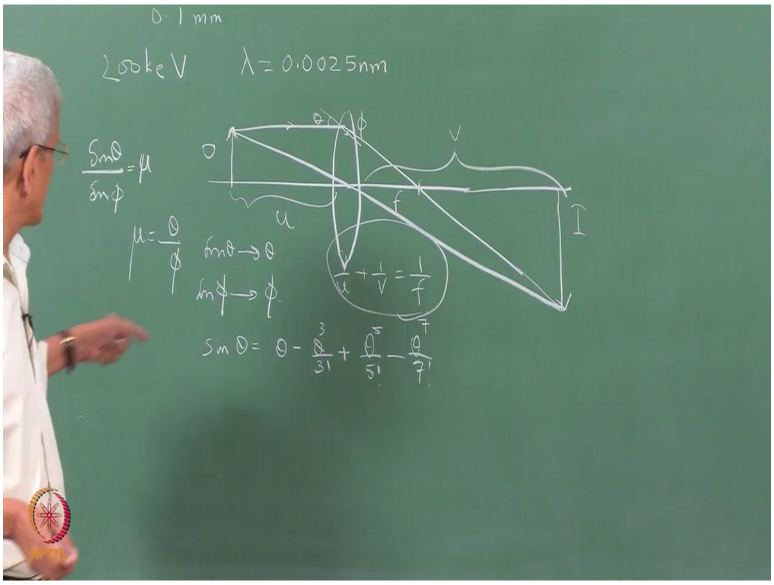

In 10th or 11th standard, everybody has studied about a geometrical optics and in this we consider that if a lens is there and if we have an object which is kept along that optic axis, then we know that the rays which are optic axis go through the focus and the ray which passes through the center of the lens, the place where they meet this is where the image comes. This is the object, this is the image and if this distance is u and this distance is v and if it is f in 1 by u plus 1 by v equals 1 by f, this is the formula which we use to construct that image, but what one should understand is that when this image is being constructed, there is one condition which is there. We call that the rays are paraxial rays.

What does paraxial rays mean? When the light from one medium which is air enters into the lens, since the refractive index is different, it has to obey the lens. What is Snell's law? Snell's law says that sin theta by sin phi equals mu, the refractive index that is if this is the normal, this is theta and this angle is phi, this Snell's has to be obeyed and this is the rule which governs how the rays are bend when it enters from one medium to another medium. If we apply this rule, then what essentially will happen for an ray from an object which is parallel to axis, but not very close to it will obey this rule or not.

This law, this formula itself, this Gaussian formula itself is derived for the condition that these are all paraxial rays. What are paraxial rays? Paraxial rays are the rays for which this value of the theta and phi becomes so small that this mu can be written as theta by phi, that is sin theta can be approximated to theta and sin, phi can be approximated to phi, but what is normally happening is that the actual expansion for sin theta is sin theta equals theta minus theta cube by three factorial plus theta to the power of 5 by 5 factorial minus theta to the power of 7 by 7 factorial. This is the way the sin has to be expanded.

So, only when the value of theta is very small that higher order tempts can be neglected and sin theta can be approximated. That means for rays which are very close to the optic axis, only this rule is valid and this Gaussian formula is valid, but that is not the case. When the rays are coming falling on the lens on all points, in such a case we have to use formula or the approximation which we can use.

This is the approximation sin theta can be if we use this approximation till which it closes to the reality, then what is going to happen is that the rays which are coming closer to the optic axis, they form image at one particular point. The ray which is coming at the edge of the lens, they are focused to a point. In all the cases, the Snell’s has been used to trace the ray which emanates from the object and forms an image in this.

So now, we can make out that the ray which is further away from the optic axis, they form an image on the Gaussian plane because this plane where the image is formed for paraxial rays, this is called as the Gaussian plane. In this the image size is very large here. So, in between there is a region where that image size is minimum. This is called as the disc of these confusion which you have all studied.

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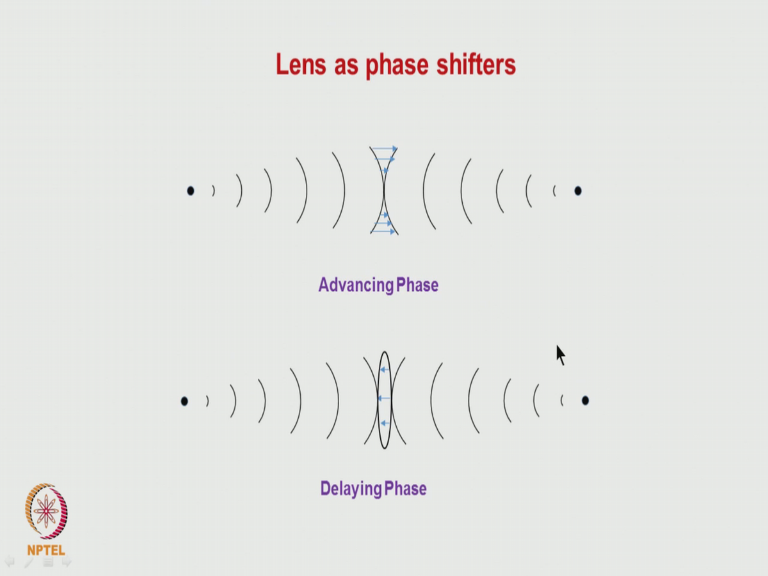

So, this same rate racing itself we can look at it in a different way. Instead of a ray if we consider the light as a way which is propagating, then we can think of from the object, from a particular point in that object on that optic axis, the spherical waves are emanated. Emanating and these waves one can make out that they come and meet at that lens. What does that lens do?

The lens essentially gives a phase shift, so that the crystal has changed to this particular shape and when this propagates in these directions, it will come back to a focus at a particular point which is that image point. So, here it is only an advancing the phase shift which is doing it which is varying as we go away from the optic axis in the case of a convex lens. If we consider it here, what is going to happen is essentially delaying that phase which is happening.

So, in this case also for a point object, we are able to form a point image and these lenses are considered as ideal lenses. Why I am mentioning this point is that later when we talk about high resolution microscopy, we have to consider lens as phase shifters.

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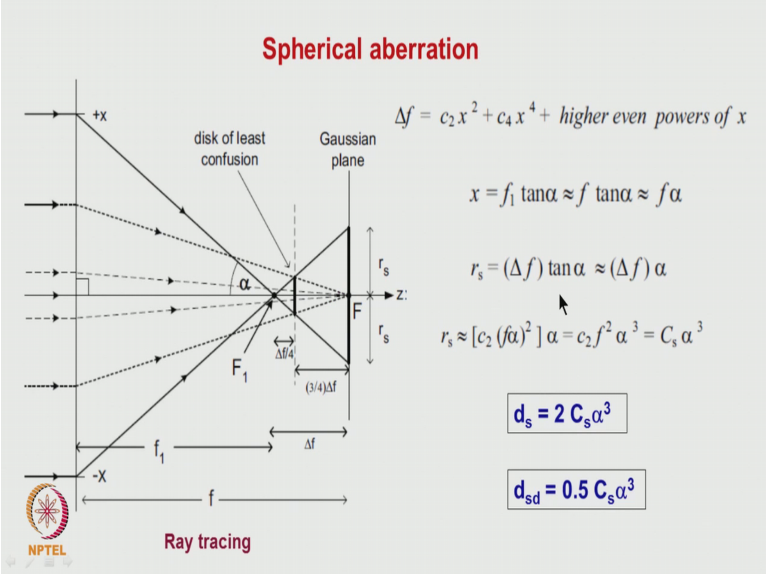

Let us come back to the spherical aberration. What is spherical aberration? The spherical aberration is nothing but when we try to draw the ray diagram for a lens, ok.

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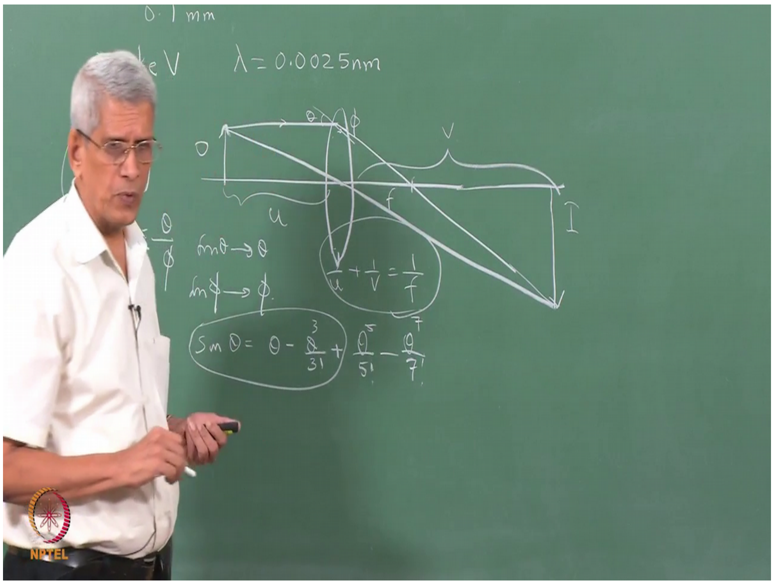

If we give the case of paraxial ray, this is the formula which we will be using to find out the position of that object and the position of that image, but when the lenses of finite dimension and the angle which submits with the ray surface is not very small, in such cases we have to use this particular formula and if we use that, then it gives rise to a situation where the lens has different focal lengths depending upon which point the ray is entering, the lens at what or that is what distance from the center of the lens the ray is entering.

This spherical aberration what is its effect which we can calculate it because what we find here is that it is not one focal length. That is for a paraxial ray. This is the focal point and we can assume that f is the focal length and the ray which is coming at the edge of that sample that is focused at this particular point. So, this delta f is the variation in focal length which is occurring. This delta f can be represented in terms of some constant to the distance from the center to the edge or it is the radius of the lens that is into x square plus C 4 into x to the power of plus per higher order terms it can be written.

Using simple geometry, we can calculate that this x itself equals if this distance is f 1 and into tan alpha, this is that angle which submits here is alpha and then, it can be written as assuming that delta f is very small, this can be written as f tan alpha and also, the assumption that the alpha is small. Similarly on the Gaussian plane, what is going to be the spread of that image that r s is equal to delta f into tan alpha. So, this is delta f into alpha. We can substitute for delta f with respect to this is the only term which is being used first time. When we submit substitute this one, the value of r s turns out to be a factor C s into alpha to the power of 3. So, that is the diameter of that image. It is going to be 2 C alpha C s into alpha to the power of 3 and the disc of least confusion, the diameter is going to be 0.5 C s into alpha to the power of 3.

So, for a point object we can make out that it is not a point image. There is a disk of least confusion is what we get. This is one aberration, ok.

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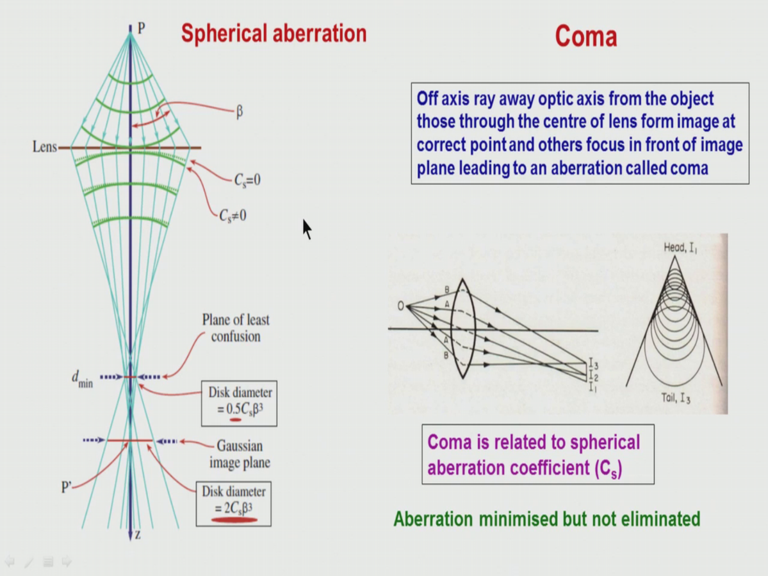

This aberration itself we have just shown it for a point object which is going there on the optic axis and we do not get point image, but it is an image which is spread out in space. If we consider it as waves which are emanating from the sample and then, propagating, then we can make out that the rays which are away from the optic axis, they are bent. The clusters have been bent a little bit more forward. Because of that only this sort of aberration which is occurring.

So far we have considered a spherical aberration for a point object which is lying on the optic axis, but normally object have a finite size like in this example. So, the rays which are coming away from the optic axis from this point on the sample, what will happen to it is, this also leads to an error or an aberration and this aberration is called as the comma. It is like a comma, the shape of the aberration looks like that of a comma.

Here one can make out that the ray which is passing through the center of the lens that goes on deviated and for this particular ray and the rays which are close to it paraxial rays, the focal point is here. So, it is a small point at which we form that image and the rays which are far away, there is going to be a spread and that is what essentially is being shown from here to here as we go that size of the image itself is becoming large.

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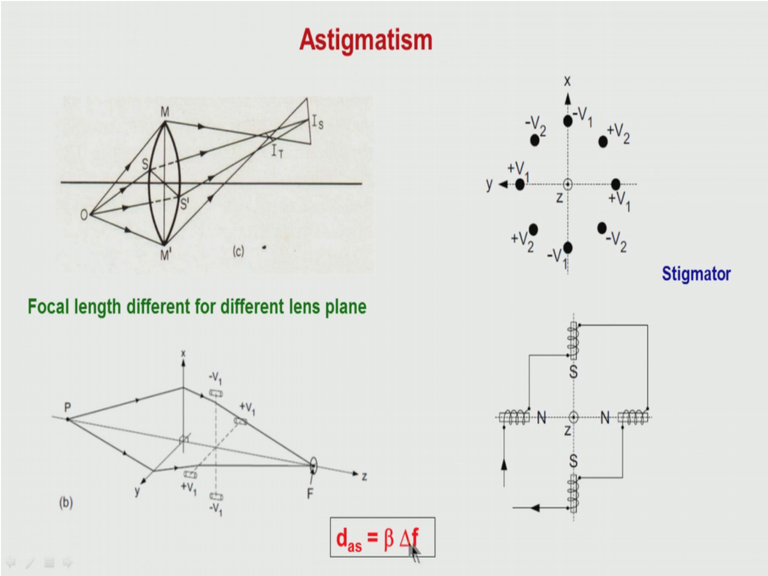

So, this is like that of a comma which you can see. This is that shape this aberration also has to be. So, these are all the two aberrations of the microscope and this is also related to the spherical aberration coefficient C s. What is the other aberration which arises in a microscope? This is called as the astigmatism that is if the lens itself is not perfectly spherical; the surface is not spherical here.

We find that there are some distortions then this will give rise to two different focal points in two perpendicular directions that is if a ray enters that lens in this one and the ray enters in these directions, it will be focused at two different points. These gives rise to not a sharp image, but an image which is distorted. How this can be corrected?

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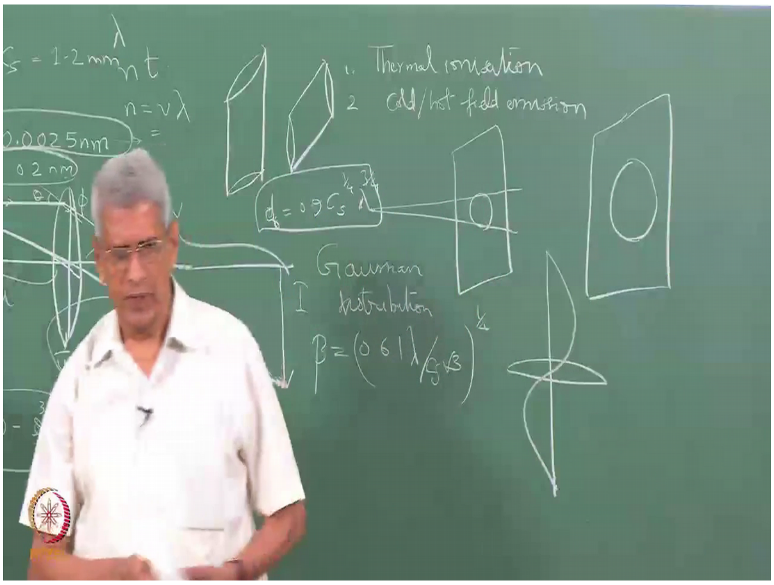

This can be corrected by putting in front of this lens; non-cylindrical lenses. That non-cylindrical lenses initially is a lens like this one. Another is in a perpendicular lens like this; this sort of lenses if we use that we can use them to compensate and correct the astigmatism, ok.

How is it done on transmission electron microscope because in an electron microscope, in all microscope we assume that lenses which are being used and in an optical microscope is the one which we are taking it is as an example and talking about all the lens aberrations, I will come to it later and mention to you that all the lenses in an electron microscope whether it is electromagnetic or electro static lenses, these are all convex lenses are the ones which form and no concave lens can be formed electromagnetic lens. Because of this the lens aberration especially the spherical aberration and comma is going to be there.

Similarly, depending upon the design of the lenses how the lenses are machined and formed, the astigmatism can come. So, how this astigmatism is corrected in the case is using what is called as stigmator. Sigmator is nothing but in plane here because that is the direction in which the ray is passing through. We have some plates are rods there to which a positive and the negative voltage is being applied. So, this will generate essentially a field like this. These fields what it is going to be the rays which are away from the optic axis, only those rays will be affected and the rays which are passing close to the optic axis or along the optic axis, they are not going to be disturbed. So, this is with an electric field we can generate a stigmator or we can keep magnets also like this. Here some magnets are there.

The North Pole in these two sides and South Pole and here again this is how the field line will be moving. So, because of this field lines, only the peripheral rays will be affected by controlling the strength of this magnetic field. We can correct for that astigmatism of the lens and what is the error which comes due to zone for a point object essentially because of the astigmatism, it turns out to be beta is into delta f. What is beta is that if this is the lens size and this is the diameter and if we keep an object at the center, what is the maximum angle which submits with the lens. This is what is called as the angle beta.

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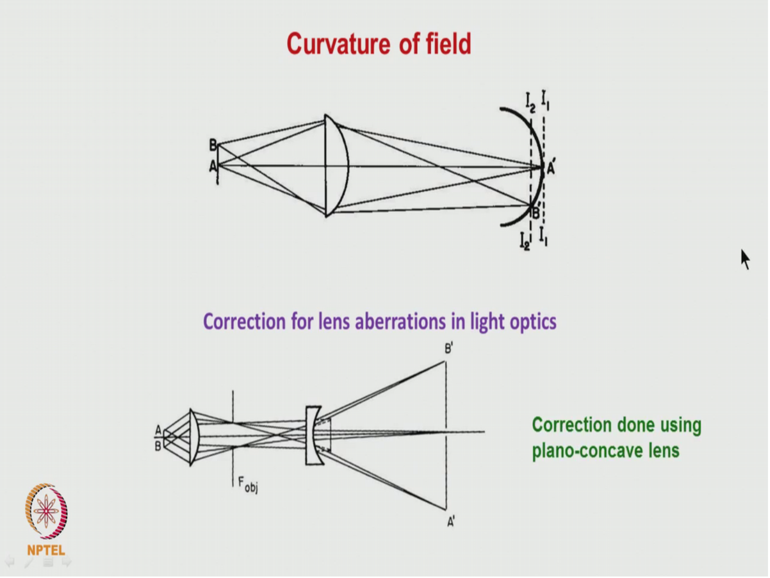

The other one as I mentioned the curvature of the field. What is the curvature of that field? For a lens which will be like a planar complex lens for an object which is perpendicular to the line, perpendicular to the optic axis, one can see that the rays which are along the optic axis, the image is formed at this particular point obeying the paraxial ray condition or the Gaussian formula and the ray which are far away from it, the image is formed at a point which is in front of the Gaussian plane.

So, because of that there is a curvature of this field. How this can be corrected? This can be corrected by using a lens which is essentially a planar convex. If we use it, this will be deviating this rise a little bit, so that they will be focused at. This way we can correct the curvature of the lens.

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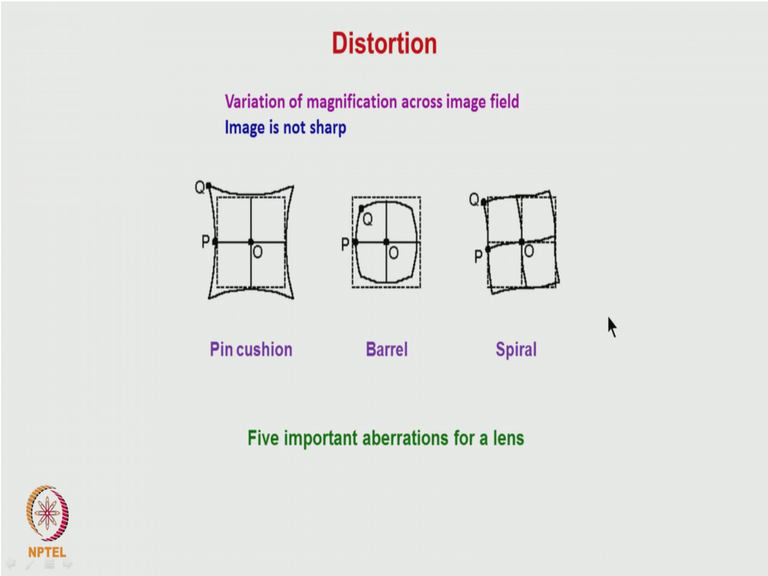

What are the other aberrations of the lens as I mentioned that is because of variation in magnification across the image field, that is a pin cushion, barrel distortion, spiral distortion, these are all the other aberrations which lens will have.

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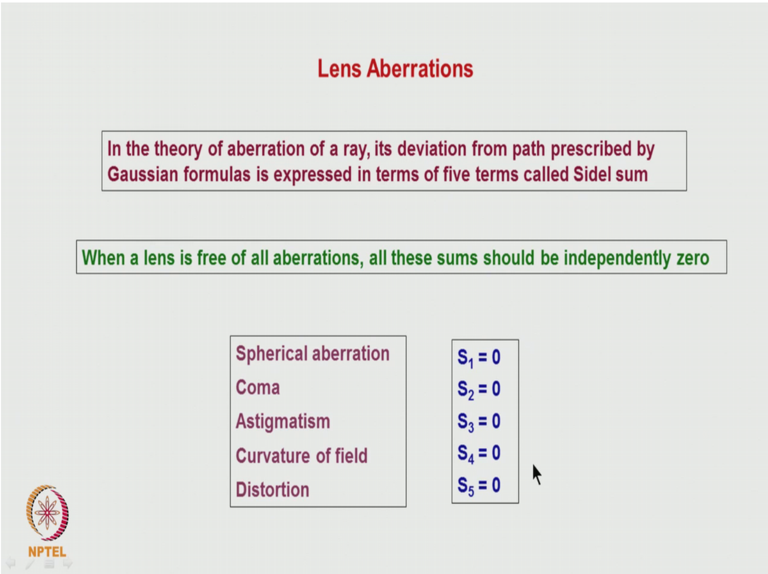

So, essentially if we look at it what we have talked about is for any lens there are five aberrations which are associated with it. What are those aberrations, spherical aberration? One comma is another astigmatism is the third curvature of the field is the other aberration distortion is the fifth aberration. When we want to compensate for the aberrations, we have to correct each of this aberrations and make it 0. This is what in if you go into the theory of lens aberrations, what is called as the sidel terms.

These terms have to be independently made equal to 0. That means, that every aberration has to be that is we cannot use one aberration to correct for another, so that at a particular point it looks like as if the aberration is corrected in some region. Each of the aberration has to be independently corrected. That is what it means. These are all the aberrations which are connected with the lens.

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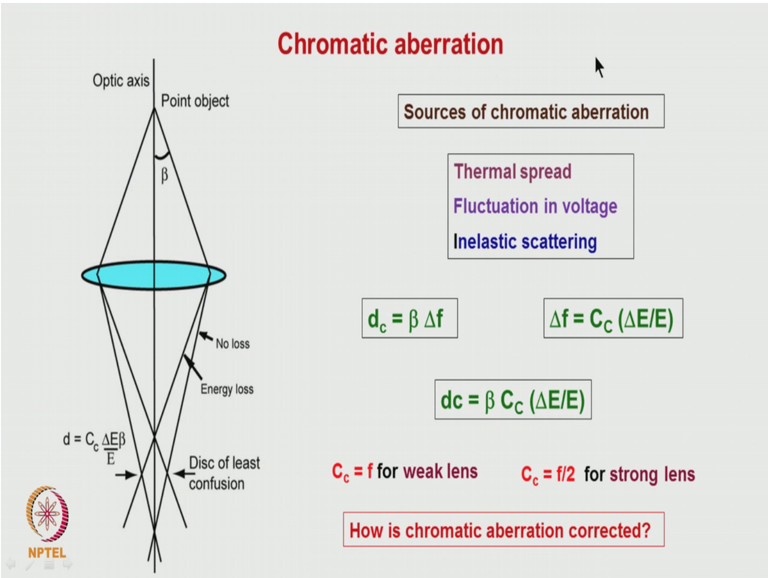

In addition to it, there is another aberration which comes that aberration which is called as a chromatic aberration. This also you might have studied, but for the sake of completeness, I wanted to mention that this is also one of the important aberration which has to be corrected, that is this aberration arises not because of any problem with the lens but this aberration comes because of non-monochromaticity of the wavelength of the radiation. That is the wavelength lambda. When we talk about it, this value is not a particular value.

There is some line with which is associated with it. When there is a width which is associated with the radiation as I mentioned earlier, the lens acts as a phase shift. That means, that depending upon the thickness of the lens and the wavelength of the radiation, that is the phase shift which it introduces is then the refractive index into t the thickness. So, depending upon different medium, the same even if the wavelength, depending upon different wavelength, the phase which it introduces is going to change that is what essentially is the reason for chromatic aberration.

In the case of a light radiation, it is essentially the spread is arising because of the finite width of the monochromatic source. In the case of an electromagnetic radiation, how do you produce monochromatic electrons? There are many ways which are done. One is thermal ionization is used to produce electrons two or cold or hot field emission, that is in thermal ionization. What is being done is that filament is taken, it is rise to a very high at temperature, so that the electrons are emitted and the electrons are coming out of the sample. They have a finite spread and these electrons are accelerated to some particular energy. So, this spread inherently in the electron energy initially that itself gives rise to a spread in the overall total energy and that will be reflected in the wavelength of the radiation.

Similarly, the voltage which we use, high voltage this is also generated from converting DC into AC. In this case also, there are some ripples which are associated with it and that can also give rise to some fluctuations in the voltage. The third point which happens is inelastic scattering that is as the light radiation passes through the sample, it interacts with the material and sometimes some energy of the radiation is lost as it passes through the sample. This gives raise to electrons with different energy which is coming out of the sample surface. So, that means that when the beam which is initially entering is monochromatic, but the beam which comes out, there spread has increased in that energy and this also will give rise to chromatic aberration.

So, here also what we can make out is that since the phase shift is going to be different for the rays which are having different wavelength, we will find that depending upon that energy, either they can be focused at this particular point or they can be focused at this point and finally, gives rise to as in the case of a spherical aberration. This gives rise to disc of least confusion which is coming. So, the diameter of this disc of least confusion is generating related to beta the angle which it submits with that lens multiplied by delta f and this delta f depends upon the spherical aberration coefficient c c of the lens into delta e by e. The energy spread for a weak lens that c c is f and for a strong lens, the c c is f by 2.

How is this chromatic aberration corrected? In the case of an optical microscope, we can use lenses with different refractive index or a combination of them. They are called as chromatic lenses with which for some particular range of wavelength, the chromatic aberrations could be corrected. The electrons, the only way we can do it is that we can make the power supplies the fluctuation in the voltages are so small, so that it is highly stable supply, the thermal spread.

Essentially we can reduce it by going for a field emission gun and then, we can make the sample as thin as possible, so that the influence of an inelastic scattering on the chromatic aberration could be reduced. Another is the lenses which we use are electromagnetic lenses, where we apply current by changing the current. The focal length of the lens itself changes by making the lens supply, the power supply highly stable. We can bring about reduction in chromatic aberration. These are all the ways the chromatic aberration is corrected.

So, essentially any microscope if we look at it, the aberrations comes one from the lens which we are using it. The other aberration comes from like a chromatic aberration which comes from the source of the radiation itself.

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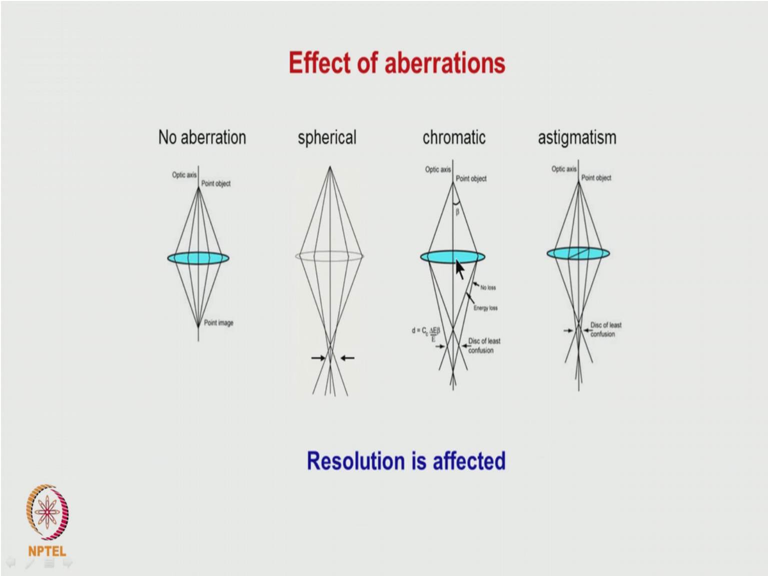

Whether the radiation is highly monochromatic or not, both these facts together decide all the aberrations going to be there. All this can affect the resolution of the instrument. This is what we will discuss it shortly how these variations aberrations have affected the resolution.

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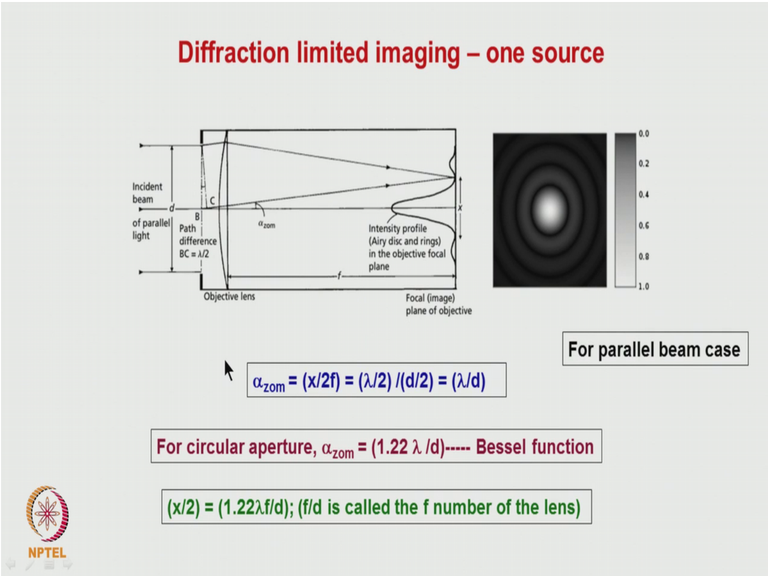

Before we go into it, let us look at how this resolution itself is defined. We know that if we have screened on which there is a hole is going to be there, there is a light source from which the light is coming. This will be forming on the screen. The image of this hole if we make the size of this hole small and small and the size become nearer to that of the wavelength of the radiation which we are using in it. Then, what happens is that normally it has been observed that you do not see a sharp image. There are some rings could be seen beyond the geometrical image and this is called an airy disc.

So, this has been observed long time back itself when people are been observing at it stars. So, essentially what we can make out is that at the center, there is a maximum intensity here. The same thing which is shown with respect to a telescope which is being used a lens which in front of it at the center maximum intensity and the first minimum intensity occurs at a particular point. The separation between this x that is what essentially turns out to be this angle alpha which this submits. This turns out to be is equal to lambda by d.

These derivations, from the geometry one can work out. So, essentially what is going to happen is that this x by 2 equals this is the sort of a formula which takes place, this formula is that if we use a spherical aperture because the lens itself all can be considered as a spherical aperture and in that case, that Bessel function has to be used.

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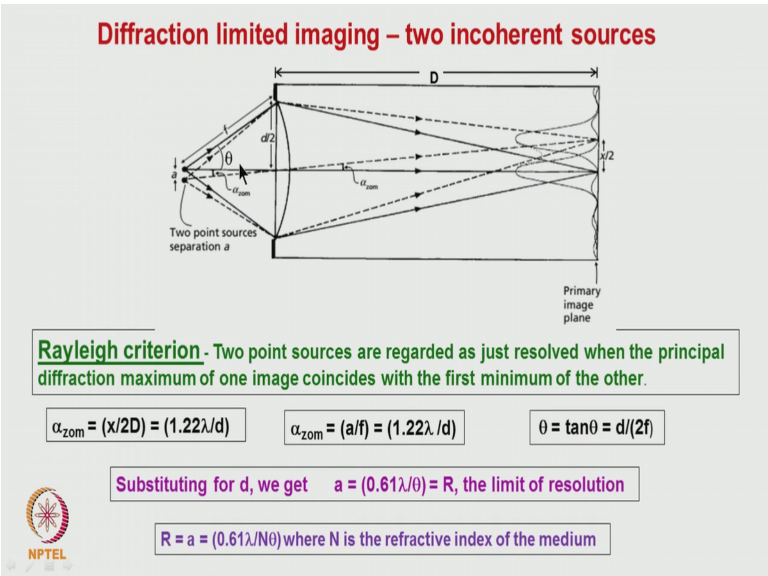

Then, this factor alpha, the angle which submits this turns out to be 1.22 lambda by d, ok where d is the diameter of the aperture. So, if this diffraction limited for what we have considered earlier is for one point source, what is the sort of an image which is formed.

The image itself we can make out there is a central disc and there is a varying intensity which comes. So, some rings could be seen outside.

Suppose we have two coherent sources, one and another source which is close by, then depending upon the separation between them it can so happen that the airy disc corresponding to one of them and the airy disc corresponding to quiet far away, they can be seen separately, but what is the minimum separation at which they could be seen is a criterion which has been put forward by Rayleigh and this criterion essentially is that if two points sources are regarded as just resolved when the principle diffraction maximum of one image coincides with the first minimum of the other, then using this geometry one can derive it and then, the formula what we get is that the separation between that object if is equal to 0.61 lambda by theta, where theta is the angle or earlier we have used that term beta to represent it by beta that represents the limit of resolution.

So, this is the best image which we can achieve when we use a lens or when we use an aperture and in the case, as an optical microscope here, we use another term that denominator n which we call it as the numerical aperture.

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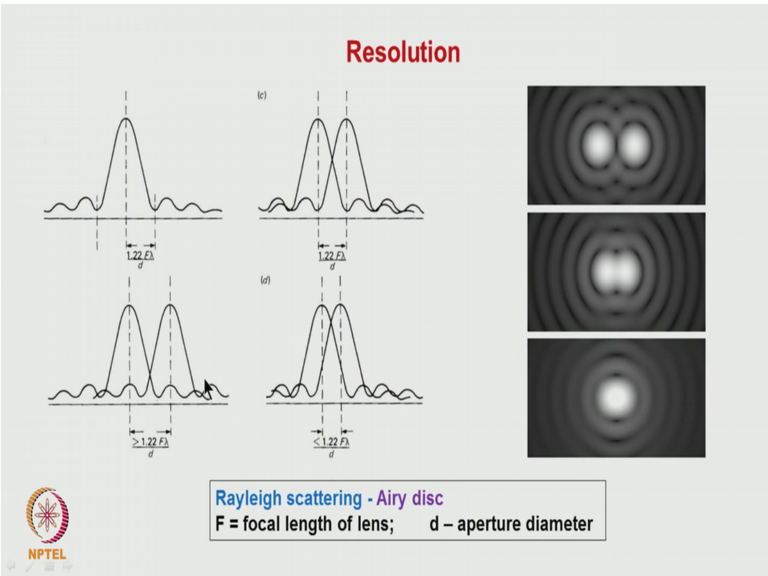

Here what I had shown it is that the same when only one object which is considered that is one light source which is being considered which is an incoherent source. Then, this is the way that image appears for a aperture whose size is of the same order as the wavelength of the radiation are closed to it and when the separation between them is very large, this is how both the sources will give rise to individual images and we can resolve them very clearly at some particular distance, where the minimum of one matches with the maximum of the other. They are just resolved and in this case, our eye will not be able to resolve it.

So, this is what essentially the images which are being shown corresponding to these three cases here, we can see the images which are resolved here. It is just resolved here. It is very difficult to make out. This is one image other two images. So, this is the criterion which has been put forward by Rayleigh to say that this is the resolution of equipment.

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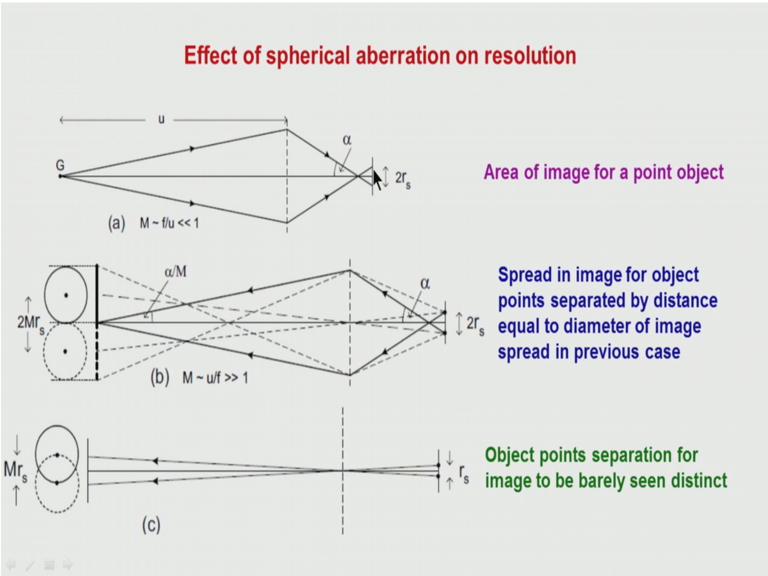

Now, having considered this Rayleigh criterion, let us now look at what is the effect of spherical aberration on the resolution. What does the spherical aberration do for a point object? We do not get a point image. We get a disc of least confusion or in the Gaussian image plane, if this is going to be twice the diameter of instead of a point image, we get a disc with a diameter. Suppose we have the same, we can continue the two source are there, point sources are separated by a distance which is larger than this. If they are there, each one of them will give rise to a disc of least confusion or on the Gaussian plane, we will be getting a disc. We will be getting it if they are well separated. We will be able to see them as two different objects.

Now, for some particular distance and this will be actually a magnified image which we get it and here for some particular separation that is the disc starts overlapping and then, we find that only for some particular separation between these objects, we are able to see them as separate one. That means, the resolution now compared to Rayleigh criterion, the lens aberration has such since it is increasing for a point object, it is not giving a point image. There is a spread. The resolution is becoming poorer and poorer and the objects which are separated by larger distance only could be seen very clearly because of the spherical aberration.

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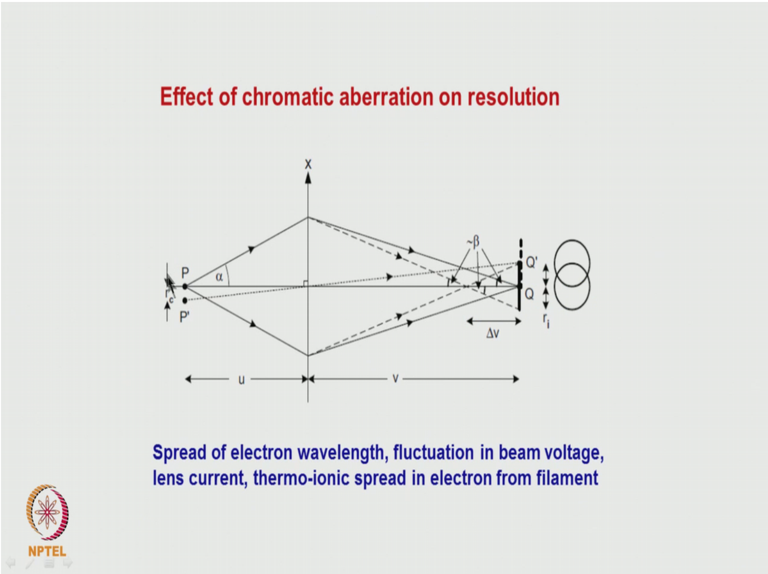

The same thing happens with the chromatic aberration also because you know that for a point object, we get a disc of least confusion at some pattern particular separation between them. The overlap is such that still we are able to resolve them as two individual ones. So far we have considered with respect to lens aberrations both spherical aberration and chromatic aberration how it is effecting the resolution, ok.

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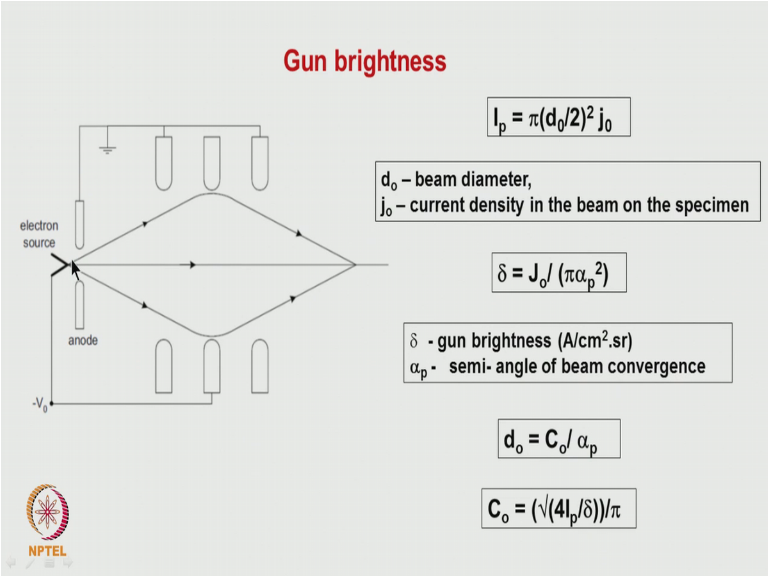

Now, if we take a light source itself if the light source is thermionin source, then what is going to happen is, the electron emission is taking place from a finite area of that sample. So, the current density is one that matters and this also gives rise to some practical limit and the size of the source which we can use it, this size of the source also has an effect on the resolution.

So, this size of the source is given by this formula which you can go through it and understand it essentially the brighter the source. That means, it is from a point region the electrons are emitted with very high intensity, then this value of d 0 becomes small. That is what essentially one should understand.

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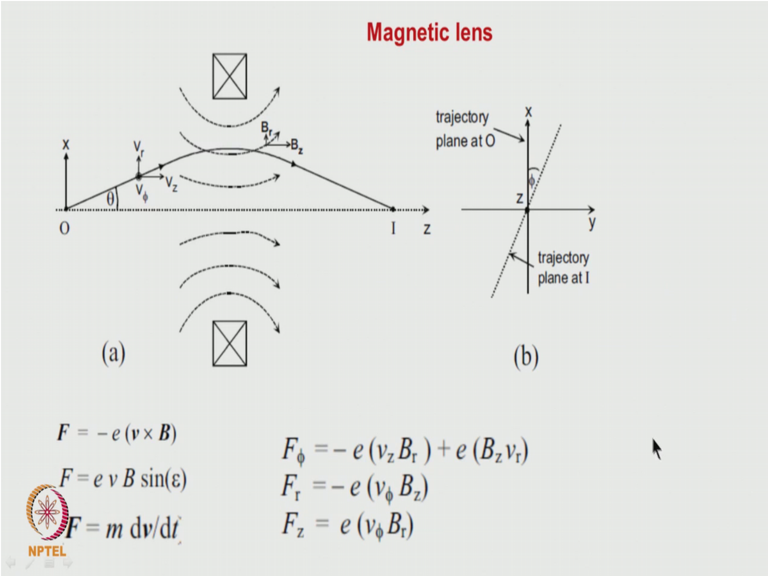

Finally, when we consider the resolution, we have to consider the total resolution. That is what is called as the point to point.

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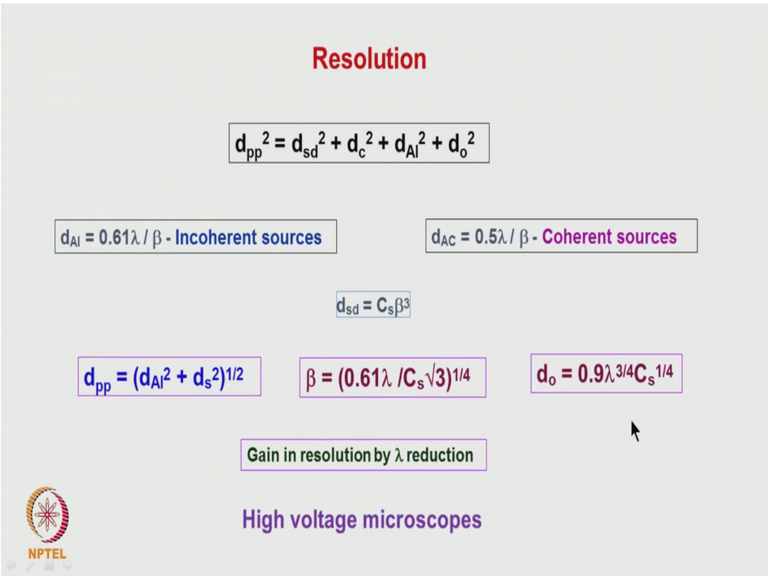

What is the spread which is going to cross for two point which are separated by a finite distance? It is decided by the spherical aberration, chromatic aberration and then due a inherent property of the source, this is Rayleigh criterion and then, another due to a finite size of the source itself. In this we have just taken the square of all the terms are added, but this can be done only when we assume that all these errors are coming due to essentially a Gaussian distribution.

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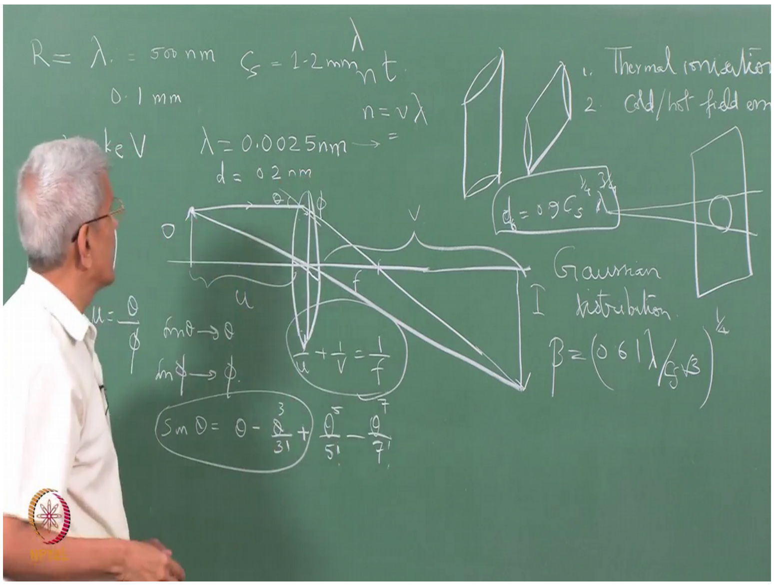

If it is non-Gaussian for Lorentzian, then this has to be just a linear addition say we know that as far as the lens is concerned, this is what essentially the spherical aberrations which it comes assuming that the beam is monochromatic. Then, this term can be assumed to be 0. We assume that the source is a point source, and then this term also can be taken to be 0. Then, these are all two terms which are going to affect the resolution and these are all the formulas which has been derived earlier for Rayleigh criterion for the point source.

If we use an aperture or lens of a particular size, what is the spread which is going to cause to the image and another is that spherical aberration for a point source what is the spread which is going to cause. What one should remember is that here it is 1 by beta dependence and in this case, it is beta to a power of two dependence. If we substitute this value and then, try to optimize it, we will find that the value of beta is 0.61. This is the optimum lambda by C s into root 3 the whole to the power of I think 1 by 4. This is the optimum angle at which we get the best resolution and what is the best resolution which is possible is this d 0 turns out to be 0.9 C s to the power of 1 by 4 and lambda to the power of 3 by 4, ok.

So, essentially from this expression we can make out that a small variation in lambda reduction in lambda can bring about large difference in the resolution that the resolution can become better whereas, for C s there is a large variation in the spherical aberration coefficient is required. So, with this concept in fact a lot of high voltage microscopes have been constructed. In these microscopes, the voltage has been increased up to present day microscopes are available where one can go upto 3 million volt energy, so that resolution can be improved considerably.

Also, when the resolution becomes high or also when the energy becomes high, the thickness of the sample which be can useful, thickness of the sample which we can examine also increases. Both are an advantage, but the disadvantage essentially is that when the energy increases, lot of radiation damage is produced in that sample, so that the microstructure of the sample could be altered during examination of the sample. That is one of the disadvantages. Microscope can substitute values and calculate what normally happens is that here we considered the wavelength which is this order with C s for a normal lenses which are of the order of about 1 to 2 millimeter spherical aberration coefficient, then the value of d turns out to be close to around 0.2 nanometer.

Essentially what it means is that the limit of the resolution of the microscope is about 0.25 nanometer, but actual resolution which we can practically achieve is hundred times worsen with almost all the lens aberrations which has been optimized. Present day microscopes are there where the spherical aberration can be made 0. These aspects I will talk about it at a later class.

So far we have considered various types of lens aberrations and all these lens aberrations because of which the resolution which in principle, we should be able to achieve has come down to this particular value in an electron microscope. The magnification is that is in conventional optical microscope. We use optical lenses convex or concave lenses or a combination of these lenses to achieve magnification in the case of an electromagnetic lens, in the case of a transmission electron microscopes.

Since electron is the beam, they are affected by either electric field or a magnetic field. They can be reflected by an electric field or an magnetic field. So, both these fields could be used as lenses to magnify, but normally represent a microscope is essentially the magnetic lenses which are used and these are nothing but like a solenoid or coils are bound around this. Then, this is the north and the South Pole and this is how the flux lines are going to be there. An electron beam which is parallel to the optic axis passing through the optic axis that will go on diffracted, but the electron beam which is slightly away from the optic axis that will come under the action of the magnetic lines and it is they will feel some different forces.

These forces are one is that velocity will be changed in different directions, there is going to be a field lines which are perpendicular to the plane of the length and the field line along the plane of the lens. We can take this components and one can find out what is going to be the trajectory. What is essentially going to happen is that the one which is deviated from here, it will be moving around like this in a helical path and finally, it is being focused to a point that is lens. What it does is the ray which is coming from here it will be in a helical path. It is broad when it comes here.

What one should understand that in a convectional optical microscope, the image is inverted here? It is not an inversion, but there is a rotation which is taking place and the rotation depends upon, rotation of the image depends upon the strength of the magnetic field.

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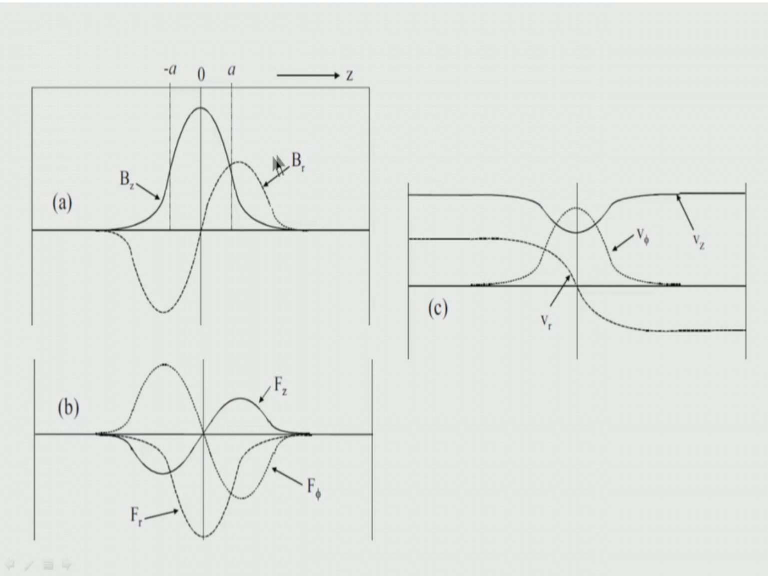

Here is how the forces on electrons as well as the magnetic flux field lengths and how the velocities are affected, this is being shown and in this particular case, one can immediately make out that if we look at it, it looks like a cylindrical geometry like a solenoide.

So, essentially a cylindrical coordinate system which is being used, then if we use a cylindrical coordinate system, then r theta phi are the coordinates which are there. So, for that velocity vector as well as the flux vector, we can take these coordinates and the force which is acting on the electron will be given by minus e into v cross b.

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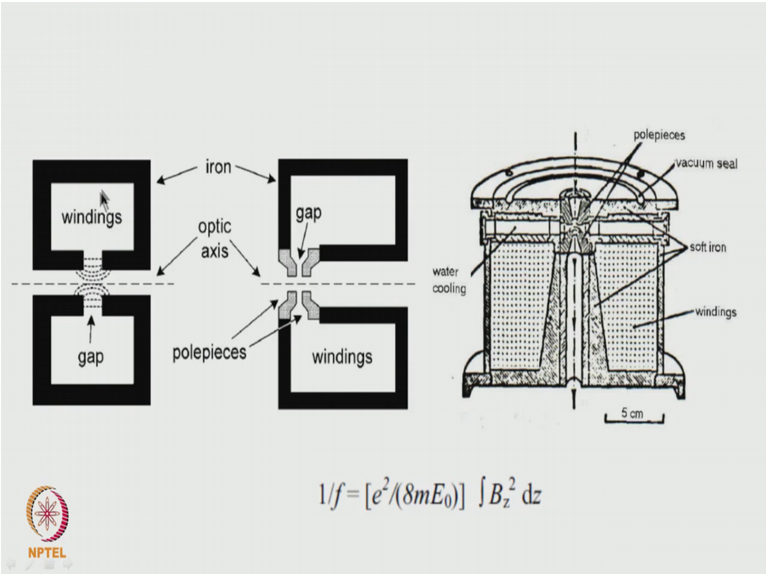

So, this is how these calculations are done. This is what it is being plotted. So, the net effect essentially is that an electron which is deviating from here is brought back to a focus. So, this solenoide acts like a lens. So, this solenoide coil itself can be surrounded with a soft ion piece, so that they capture all and with that we can have lenses with different types of shapes.

This is one pole, this gap which can be generated and another is a soft ion piece which can be attached, so that we can have a pole piece with a different type of a gap and to control the current one using a circuit which gives a stabilized power supply which has to be used and another is that since the current are very high, it is the lens itself are cooled with water, so that the magnetic field is highly stable. This is the formula which one can use to find out the focal length of the lens.

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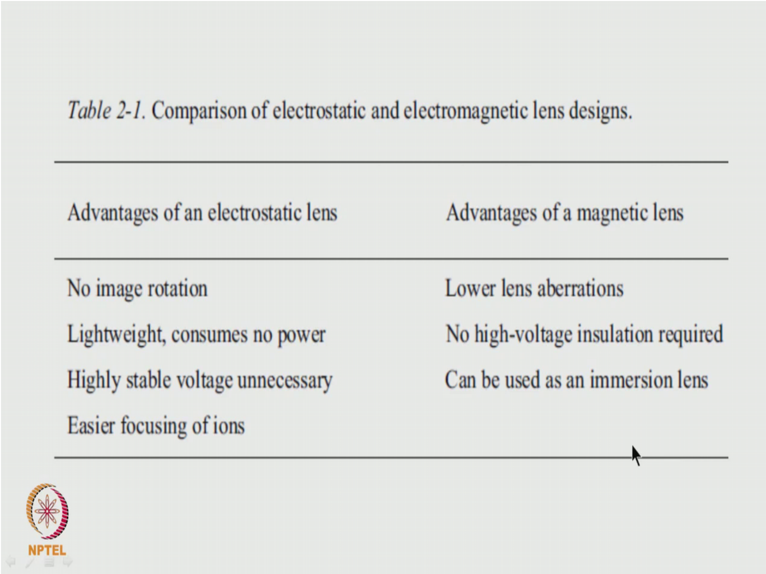

Table 2-1. Comparison of electrostatic and electromagnetic lens designs.

Advantages of an electrostatic lens	Advantages of a magnetic lens
No image rotation	Lower lens aberrations
Lightweight, consumes no power	No high-voltage insulation required
Highly stable voltage unnecessary	Can be used as an immersion lens
Easier focusing of ions	

NPTEL

Generally in the case of electromagnetic lenses, the focal lenses are of the order of 1 or 2 millimeters. When you know in optical lenses, the focal lengths are of the order of tens of centimeters, whereas here it is 1 or 2 millimeters. Here in this particular table, I had just given a comparison of electrostatic and electromagnetic lenses design because instead of electromagnetic lenses, we can use an electrostatic lens also, but the advantage with an electrostatic lens is that there is no image rotation and it is light weight and power consumption is less, but the voltage has to be highly stable and is necessary and easier is to focus ions, but the problem here what happens is that the physical dimension of the lens turns out to be very high.

When the beam energy is very high here in this case, the magnetic carved lenses are smaller dimension which we can use it. The aberrations can be lowered considerably that is one advantage here. The aberrations are high, no high voltage insulation is required whereas, when the power supply becomes very high, for high energy electrons, then the insulations and all it becomes massive in size and another is it can be used as an immersion lens, where the sample itself can be inserted into the lens.

These are all the advantages. We will stop here now.

Thank you.