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**Lecture-12**
# Materials Characterization

## Fundamentals of Scanning Electron Microscopy

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Hello everyone welcome back to this material characterization course. In the last class we just reviewed the electron optical systems and its governing principles and electron lens design and its analogy with the light optical system and I mentioned that we will discuss the abrasions in this class and as I mentioned in the fundamentals of the optical system we have gone through all the types of aberrations which the glass lens will exhibit similar type of aberrations will also the electron optical system will encounter and then since we have already seen them in much more detailed manner about what is the each aberration and its definition.

I will just mention how this is taken care in this electron optical system and then we will take up some few examples and some of the numerical significance of a spherical and chromatic aberrations. As we all know the spherical aberration is very important and inherent to these lenses in light optical glass lenses as well as in the electromagnetic lenses and we also appreciate that this is one particular abrasion which directly influence the resolution of the microscope and we will see them in little more detail.

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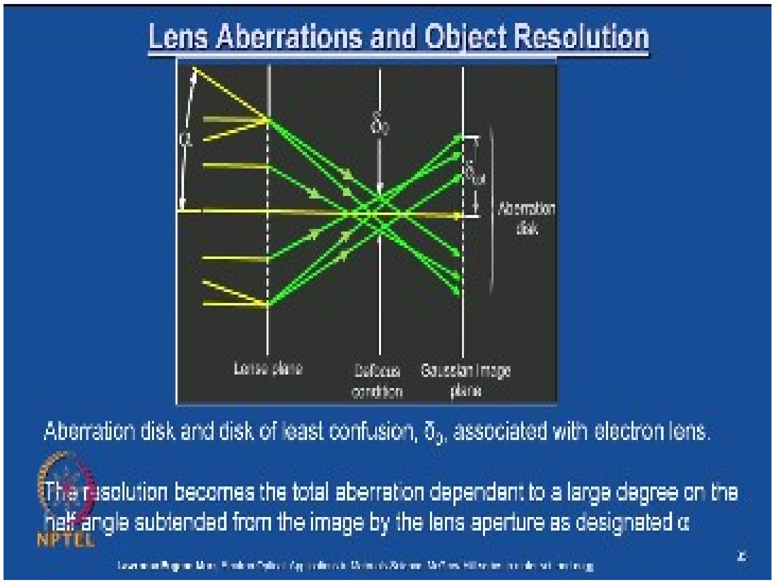


So now we'll go to this. Lens aberration & optical resolution with regard to this electron optical system you look at this schematic what you are just seeing is a lens plane and where you have the range of α that is aperture angle and then you see that look at this ray tracing path and then each ray is focusing at different - different direction and basically and this is a region we say that the disk of least confusion, and then and if you look at this all this pair of rays intersecting the image plane at the different point and then eventually you see this aberration disc in the image plane.

So the point you have to remember here is it is a general schematic which is shown here and whatever the aberration we talked about whether it would be a simple astigmatism to chromatic to spherical aberration all what all these aberrations they do to this light ray or electron beam they have they are directing this electron beam into a different focal point whether it is on axis or off axis that we have seen.

So if you just think of all the aberrations which impair the resolution of the optical system or electromagnetic lens system it is the total combination of all this aberrations put together. So you can consider this schema take a general schematic where you see this the distance $\delta_o$ is the defocusing condition and this is also considered as the disk of least confusion and then you see the aberration disk which we have already seen in the beginning and then you see that δ optimum with associated with the electron lengths in general.

So the resolution becomes the total aberration depending dependent to a large degree on the half angle subtended from the image by the lens aperture as designated α, this we have already seen so I want to emphasis again please have make sure that you understand this. So you have the it is not a completely focused condition this could be because of any aberration but this is the smallest distance that is $\delta_o$ is the least confusion and then and if you look at this δ optimum which is much larger in the image plane.

So you may see that you are at the defocusing condition your image resolution is better is that so it may be the case we will see in the coming slide.

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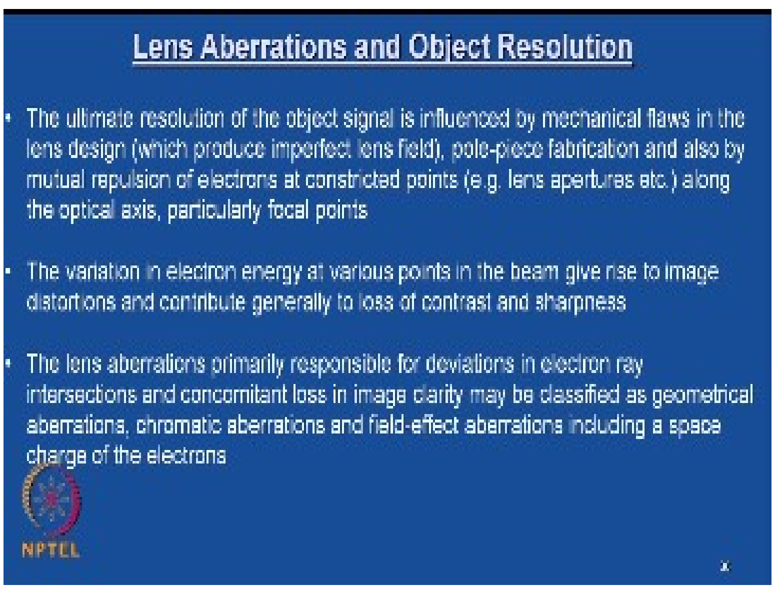


So let me read out some few introductory remarks for these aberrations of the electron optical or electromagnetic lens systems. The ultimate resolution of the object signal is influenced by mechanical flaws in the lens design which produce imperfect lens field pole piece fabrication and also by mutual repulsion of electrons are a constricted point that is a focal points lens aperture etc along the optical axis particularly the focal points. The variation in electron energy at various points in the beam gives rise to image distortion and contribute generally to loss of contrast and sharpness.

So this is the fundamental point which you have to keep in mind whatever happens in the electromagnetic lens system it is the variation in the electron energy at various points in a beam you raise to image distortion and causes the loss of contrast and sharpness. The lens operations primarily responsible for deviations in electron ray intersections and concomitant loss image clarity may be classified as geometrical aberrations, chromatic aberrations and field effect aberrations including a peak space charge of the electrons.

We will see one by one and the space charge of electrons will be we did not discuss in the light optical system we will see in this system how it is affecting the resolution.

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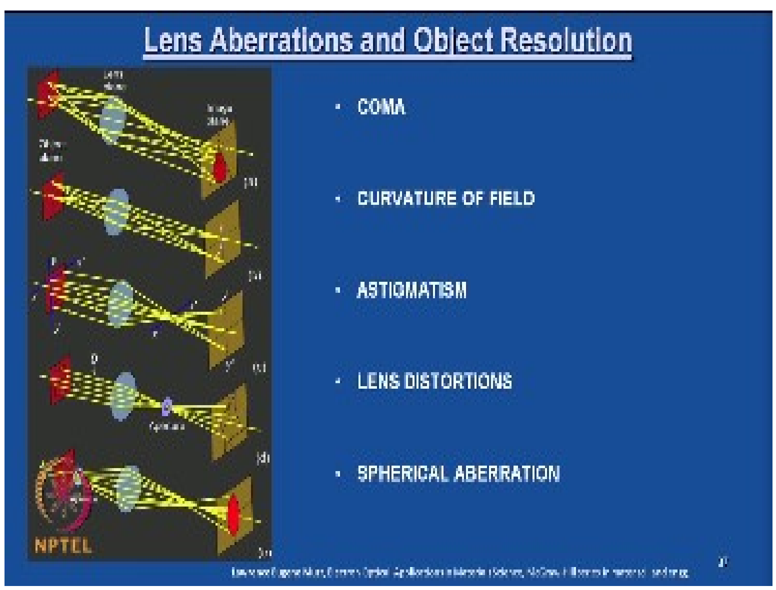


So it is just a recap of what we have seen, the type of abrasions the this the schematic I have just put it everything in one image because we have already seen them in much more detailed when we discussed in the light optical systems so the first schematic shows the coma effect and second schematic describes the curvature of field and thirds schematic shows the astigmatism and the fourth one is lens distortion and the fifth one is spherical aberration. I will not describe them in detail because you have already seen it. If you have a doubt you can go back to that lecture and then look at all this individual defects and then make yourself clear about this.

And it is the same thing I will only discuss about how these defects are taken care in this electron optical system.

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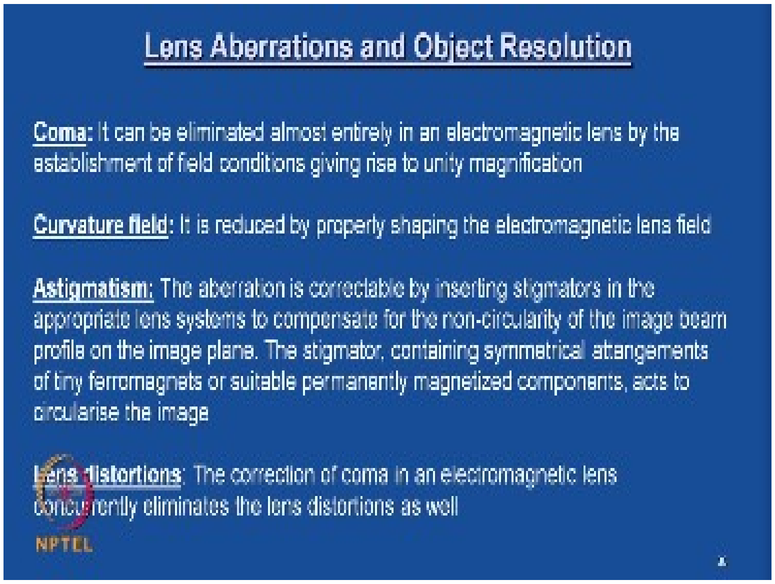


In terms of coma it can be eliminated almost entirely in electromagnetic lens by the establishment of field conditions giving rise to unity magnification and in terms of curvature field it is reduced by properly shaping the electromagnetic lens field. The astigmatism on the other hand is correctable by inserting stigmators in the appropriate lens system to compensate the non-circularity of the image beam profile on the image plane.

So what is stigmator? The stigmators containing symmetrical arrangement of tiny ferro-magnets are suitable permanently magnetized components acts to circularize the image and the lens distortion, the correction of coma in an electromagnetic lens and currently eliminates the lens distortions as well. So what you should appreciate here is in electro optical systems the most of your aberrations is controlled by the field strength and the field distribution. In an optical system we just all the aberrations were compensated with the an additional glass lens here since all the focal length everything is controlled by the field strength and your aberrations also controlled by the appropriate field strength and it is distribution in the appropriate lens system.

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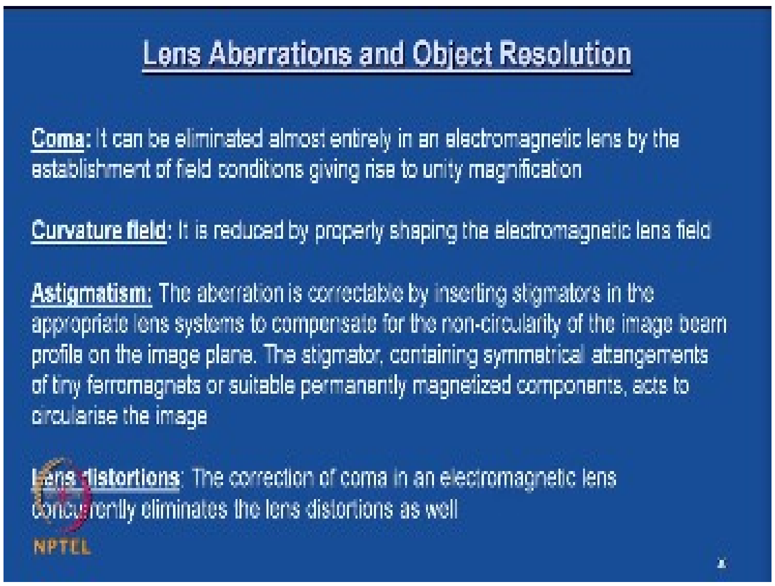


So we will see the other aberrations.

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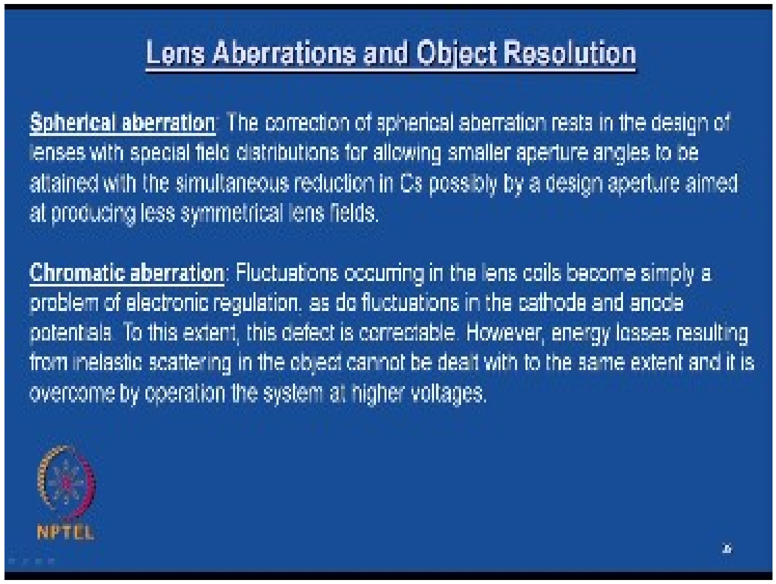


Spherical aberration the correction of the spherical aberration rest in the design of lenses with special field distributions for allowing smaller aperture angles to be attained with the simultaneous detection in CS possibly by a design aperture aimed at producing less symmetrical lens field. So as I mentioned this particular aberration is very important and how much we can reduce this will finally determine the resolution of the optical system, and then we will see them and its numerical significance in a few minutes.

And chromatic aberration which is caused by the fluctuations occurring in the lens coils becomes simply a problem of electro electronic regulation as do fluctuations in the cathode and anode potentials. To this extent this defect is correctable however the energy losses resulting from the inelastic scattering in the object cannot be dealt with to the same extent and it is overcome by operation of the system at higher voltages.

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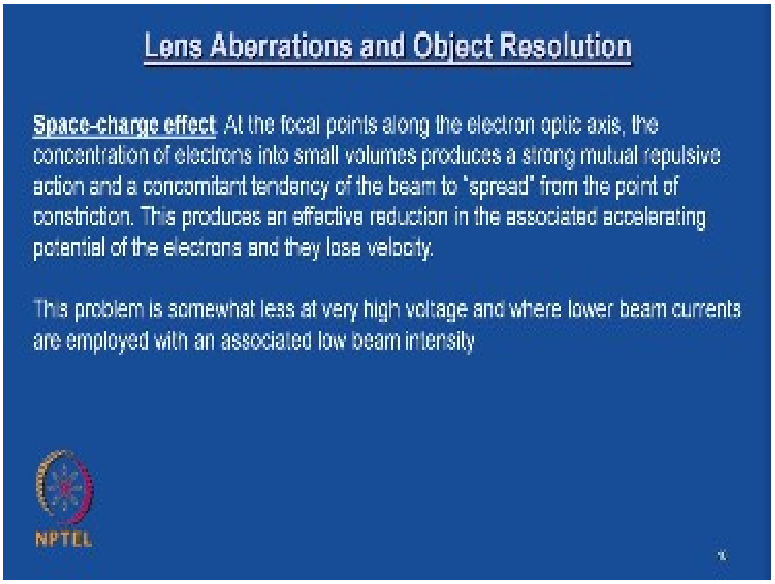


The another important aspect of this electron optical system is a space charge effect. What is this space charge effect? At the focal points along the electron optic axis, the concentration of electrons into small volumes produces a strong mutual repulsive action and a concomitant tendency of the beam to spread from the point of constriction, that is from the point of focus this produces an effective reduction in the associated accelerating potential of the electrons and they lose velocity and this problem is somewhat less at very high voltage and where lower beam currents are employed with an associated low beam intensity.

So this particular effect is specially belonged to this electron optical system and you have to remember the aberrations which we talked about and its effect on resolution we simply assume that or we simply do not consider the specimen condition, for example whatever the aberration we talked about we assume that the specimen is pure and it does not have any contaminating I mean constituents in it or it does not react with the beam and then produce its whole new product that will impair the resolution.

So all this the treatment which we are talking about are the compensating effect we talked about assuming that the specimen is in the ideal condition, okay. So in the mathematical treatment which you are going to look at is also in the similar manner that we are not taking the specimen effect that means we assume that specimen is ideally prepared and it does not have any contamination or any other reacting constituents with the electron beam. So now we will just take up this to spherical I mean two aberrations first we talked about spherical aberrations.

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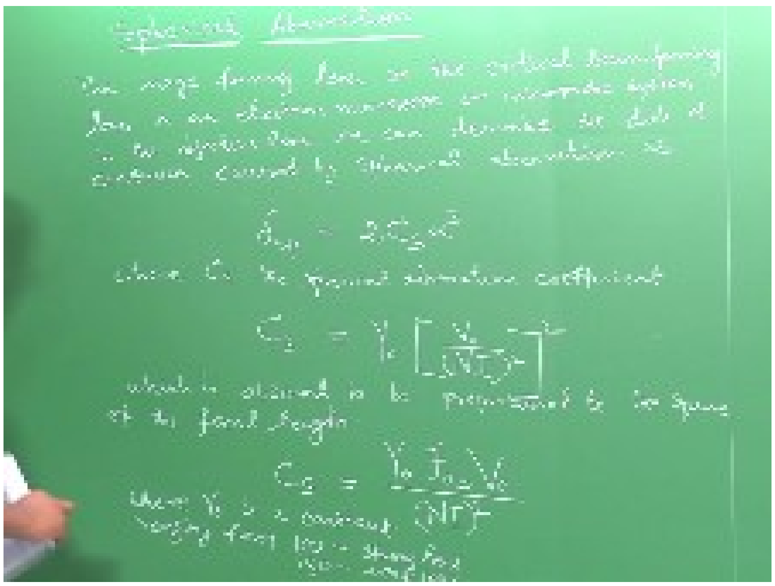

So what I am trying to write here is the image-forming lens or the critical beam forming lens in an electron microscope or microprobe system in the objective lens, we always talk about objective lens whether it could be a any image forming lens or it could be an electron forming then I mean you know electron microscope critical beam forming lens or it could be electron microprobe analyzer we always concerned about the aberrations of objective lens.

We can describe the disk of confusion caused by the spherical aberration as that is $\delta_{SP}$, $\delta_0$ is general notation for disk of least confusion here, $\delta_{SP}$ is it is exclusively caused by the spherical aberration can be represented as **$\delta_{SP} = 2.\ C_S.\alpha^3$** where $C_S$, the spherical aberration coefficient which is also given by **$C_s = \gamma_o * [V_o / (N.I)^2]^2$**.

So this expression you are familiar with already this is potential, this is number of coil, this is current which is which is which is observed to be proportional to the square of the focal length, so this can be written as $\mathbf{C_s = [(\gamma_o.f_{ob}.V_o)/(N.I)^2]}$, where $\gamma$ is a constant ranging from hundred for strong lens and 150 for weak lens. So, $\gamma$ is a constant ranging from 100 for a strong lens 150 for weak lens. So similarly we will see this chromatic aberration.

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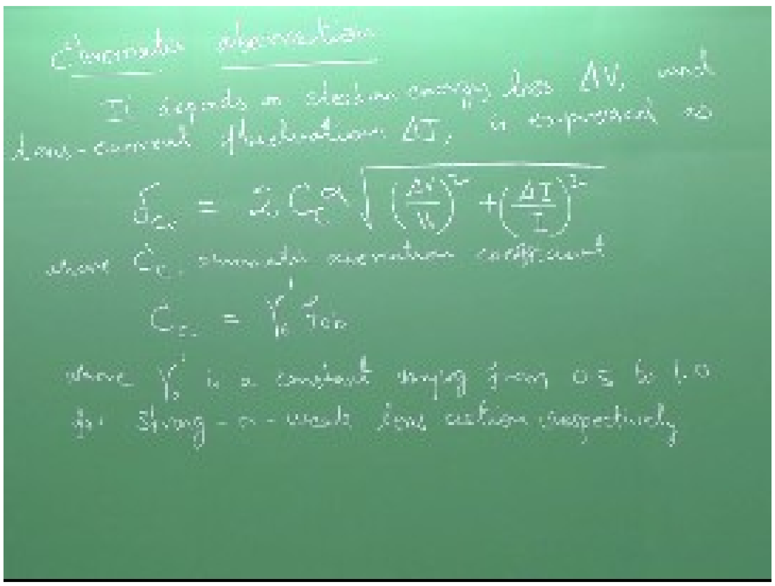


So as we discussed earlier it depends on electron energy loss and lens current fluctuation $\Delta I$ and is express as $\delta$ chromatic disc of confusion created by chromatic aberration can be related $\mathbf{\delta_{Cr} = 2.C_c.\alpha.\sqrt{[(\Delta V/V_o)^2 + (\Delta I/I)^2]}}$.

We write where $C_c$ chromatic aberration coefficient which is also given by $\mathbf{C_c = \gamma_o'.f_{ob}}$, where $\gamma_o$ prime coefficient is a constant varying from 0.5 to 1.0 for strong or weak lens action separately, so you have this chromatic aberration constant is equal to $\gamma_o$ prime times focal length of objective and $\gamma_o$ prime is the constant varying from 0.5 to 1.0 for a strong or a weak lens action respectively.

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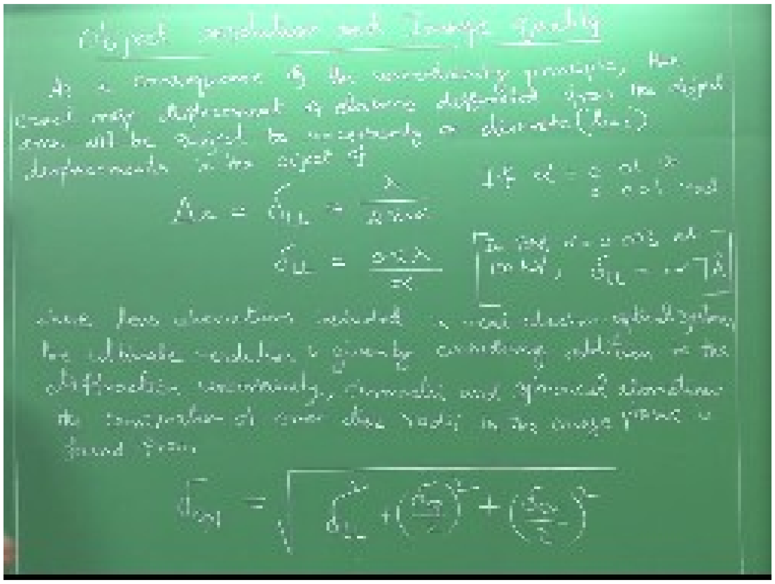

So now what we will do is we will see that how all this aberrations. We will now try to write some expressions for object resolution and then image quality involving all this aberrations which we talked about. So we see that so what I have written is as a consequence of the uncertainty principle, the exact image displacement of electrons diffracted from the object area will be subjected to uncertainty of discrete line displacement in the object of the order $\Delta$ x which is equal to L.

So this least confusion line to line extend the written as **$\Delta x = \delta_{LL} = (\lambda / 2.\text{Sin } \alpha)$**, we are familiar with this expression and it can be assumed like this. So I read out again because of the uncertainty principle the electrons diffracted from the object area will be subject to uncertainty of discrete line displacements in the object. So if $\alpha$ is 0.01 to 0.001 radian then we can write **$\delta_{LL} = (0.5*\lambda)/\alpha$**. For example you can write in a typical electron microscope $\alpha$ is 0.003 at 100 KV your $\delta_{LL}$ could be roughly about 7A°.

This will give you an idea a typical case where you see that to $\delta_{LL}$ is how to appreciate this. So now we will include the lens aberrations and see how this expression is modified. Where so what I have done is where the lens aberrations included in the real electron optical system the ultimate resolution is given by considering in addition to the diffraction uncertainty, chromatic and spherical aberrations, the combination of the error disk radii that is $\delta$ optimum in the image plane is found from $\delta_{OP} = \sqrt{[(\delta_{LL})^2 + (\delta_{SP}/2)^2 + (\delta_{Cr}/2)^2]}$.

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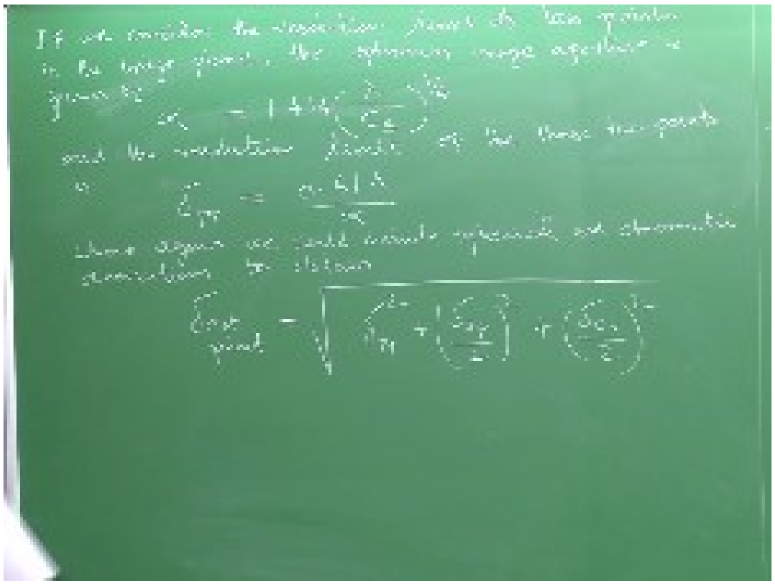

If we consider limit of two points, we always talk about point resolution as well as line solution. You can consider these two if, you consider two points in the image plane the optimum is given by and the resolution limit of these two points is $\delta_{PP}$ that is point to point disc of confusion, this also you are familiar with already seen this where again include spherical and chromatic aberration. So if you include this the spherical and chromatic aberration expression into this, the point-to-point disk of least confusion, then you obtain $\delta_{OP} = \sqrt{[(\delta_{PP})^2 + (\delta_{SP}/2)^2 + (\delta_{Cr}/2)^2]}$.

So these basic expressions are further modified by several researchers and then we can write one more general expression for disk of least confusion, I mean we will talk about all this much more detail out this is really going to affect the practical resolution when we look at the actual microscopic operation but you should appreciate that the importance of this two spherical and chromatic aberrations how it really influence the resolution limit of the optical system.

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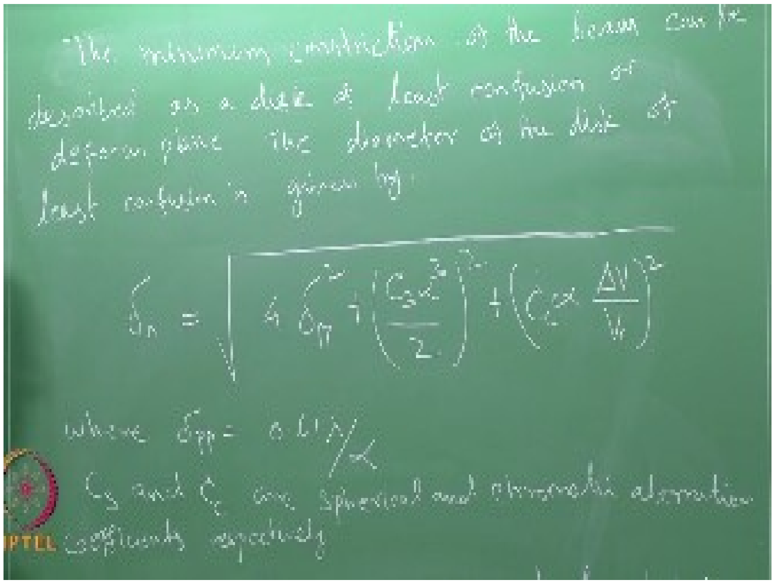


So what before we just look at this expression if you recall this the ray diagram which I showed in the beginning of this class where you see that the $\delta_o$ was defined as disk of least confusion in a defocused plain and then if you look at the image plane where δ optimal read on the image plane which is much larger than the $V_0$, δ optimum was much larger than in the array discreet described which is larger than the $V_{0.}$

So that clearly implies that if you reduce the field strength then you will automatically get the better resolution, so to emphasis this point these you get an expression for $\delta_0$ itself that is what we have trying to show here the minimum constriction of the beam described as the disk of least confusion on the defocus plain on the optical axis the diameter of the disk of least confusion is given by $\boldsymbol{\delta_0 = \sqrt{[4.(\delta_{PP})^2 + (C_s.\alpha^3/2)^2 + (C_c.\alpha.\{ \Delta V/V_o\})^2]}}$.

Where $\boldsymbol{\delta_{PP} = 0.61.(\lambda/\alpha)}$ and where $C_s$ and $C_c$ are the spherical and chromatic aberration coefficient respectively, ΔV is voltage change for a acceleration potential $V_0$ and α is an objective aperture angle. So in this class I hope you have at least have some basic idea about how this aberrations in an electron optical system is considered and its influence on the resolution of the image and the microscope. So now we will now go on to the actual electron optical system especially we will start with a scanning electron microscopy and its working principle and its application from the next class. Thank you.

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