Fundamentals of optical and scanning electron microscopy
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Module – 03
Unit-6 Introduction to scanning electron microscopy
Lecture - 12
Lens aberrations
Object resolution
Image quality

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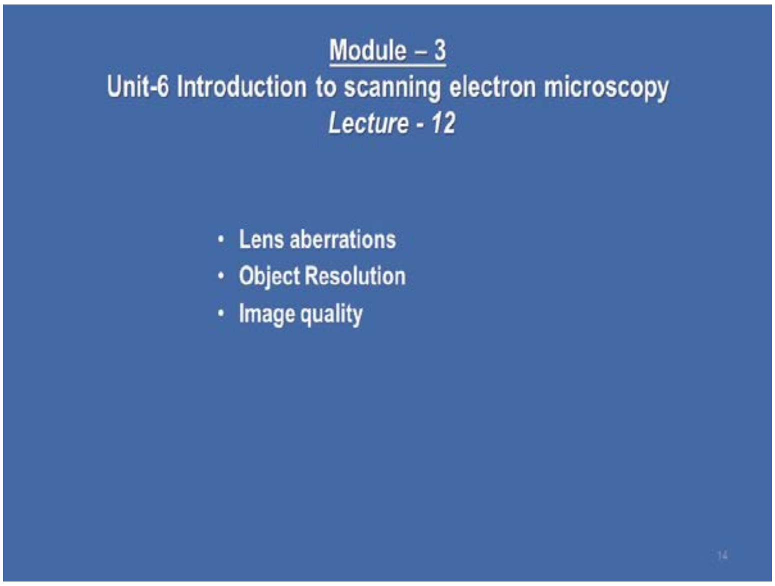

Hello everyone, welcome back to this material characterization course. In the last class, we just reviewed the electron optical systems and its governing principles, and electron lens design and its analogy with the light optical system. I mentioned that we will discuss the aberrations in this class 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 types 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 spherical and chromatic aberrations. As we all know, this spherical aberration is very important and inherent to this lenses in like optical glass lenses as well as in the electromagnetic lenses. We also appreciate that this is one particular aberration, which directly influence the resolution of the microscope and we will see them little more in detail.

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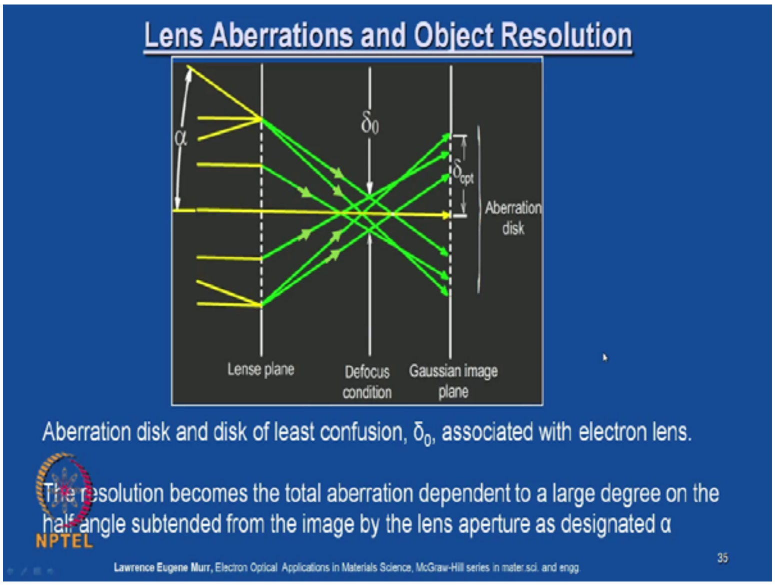

Now, we will go to this lens aberration and optical resolution with regard to this electron optical system. You look at this schematic. What you are just seeing is a lens plane and where you have the range of alpha that is aperture angle and then you see that, look at this rays tracing path and then each rays focusing at different, different direction and basically this is a region we say that the disc of a least confusion. Then and if you look at this all this pair of rays intersecting the image plane at different point and then eventually you see this aberration disk 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 talk about whether it could be a simple astigmatism to chromatic to spherical aberration, what all this aberrations they do to this light ray are electron beam they are directing this electron beam into different focal point whether it is on axis or off axis that we have seen.

If you just think of all the aberrations which impact the resolution of the optical system or electromagnetic lens system, it is the total combination of all these aberrations put together. So, you can consider this schematic, a general schematic where you see this, the distance delta naught is defocusing condition, and this is also considered as the disk of least confusion. Then you see the aberration disk which we have already seen in the beginning and then you see that delta optima associated with the electron lens 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 alpha. This we have already seen.

I want to emphasis again, please make sure that you understand this. So, it is not a completely focused condition this could be because of any aberration, but this is the smallest distance that is delta naught is the least confusion. Then if you look at this delta optimum which is much larger in the image plane, you may say that at the defocusing condition your image resolution is better is that so, it may be that case we will see in the coming slide.

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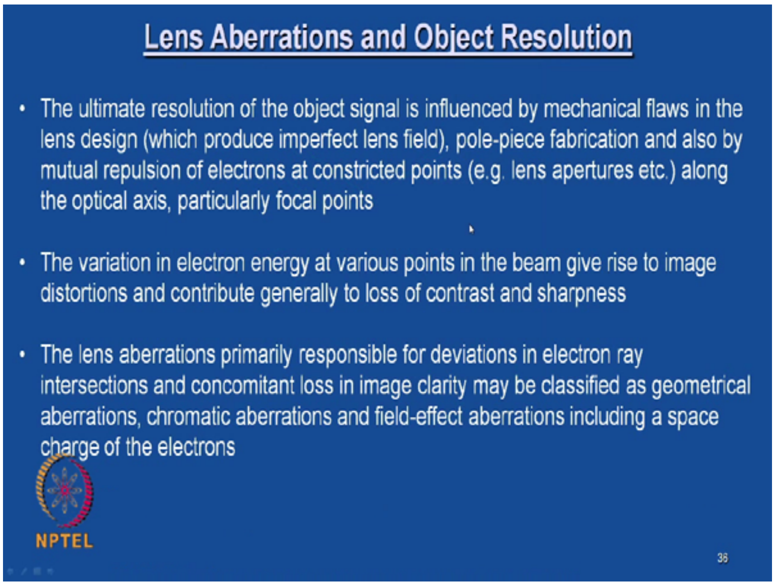

So, let me read out some few introductory remarks for these aberrations of the electron optical or electromagnetic lens system. The ultimate resolution of the object signal is influenced by mechanical flows in the lens design (which produce imperfect lens field), pole-piece fabrication and also by mutual repulsion of electrons at constricted points that is a focal points, lens aperture, etcetera along the optical axis, particularly the focal points. The variation in electron energy at various points in the beam gives rise to image distortions 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 electromagnetic lens system, it is the variation in the electron energy at various points in the beam give rise to image distortions and causes the loss of contrast and sharpness.

The lens aberrations primarily responsible for deviations in electron ray intersections and concomitant loss in image clarity may be classified as geometrical aberrations, chromatic aberrations, and field-effect aberrations including a space charge of the electrons. We will see one by one and the space charge of electrons, 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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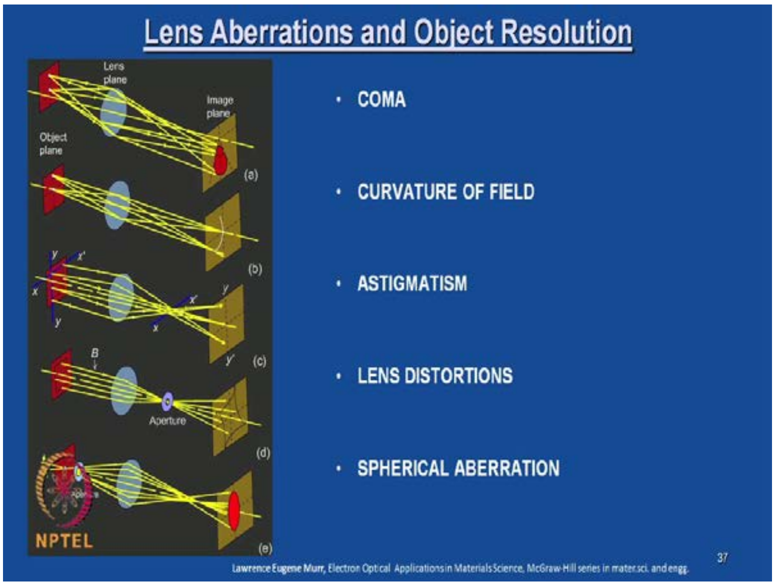

It is just recap of what we have seen the type of aberrations. This is the schematic I have just put it everything in one image because we have already seen them in much more detail in when we discuss in the light optical systems. So, the first schematic shows the coma effect, second schematic describes the curvature of field, third schematic c is astigmatism, the fourth one is lens distortions, and the fifth one is spherical aberrations. 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 a clear about this.

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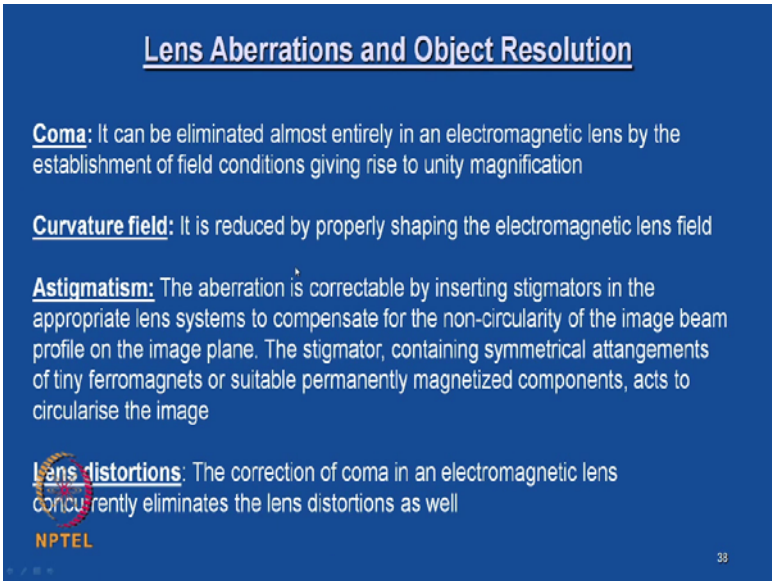

It is a same thing, I will only discuss about how this defects are taken care in this electron optical system. In terms of coma, it can be eliminated almost entirely in electromagnetic lens by the establishment of field conditions giving rise to unity magnification. In terms of curvature field, it is reduce 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 stigmator containing symmetrical arrangements of tiny ferromagnets or 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 aberration is controlled by the field strength and the field distribution. In an optical system, we just all these aberrations where compensated with the additional glass lens; here since all your focal length everything is controlled by the field strength and your aberration also controlled by the appropriate field strength, and its distribution in the appropriate lens system.

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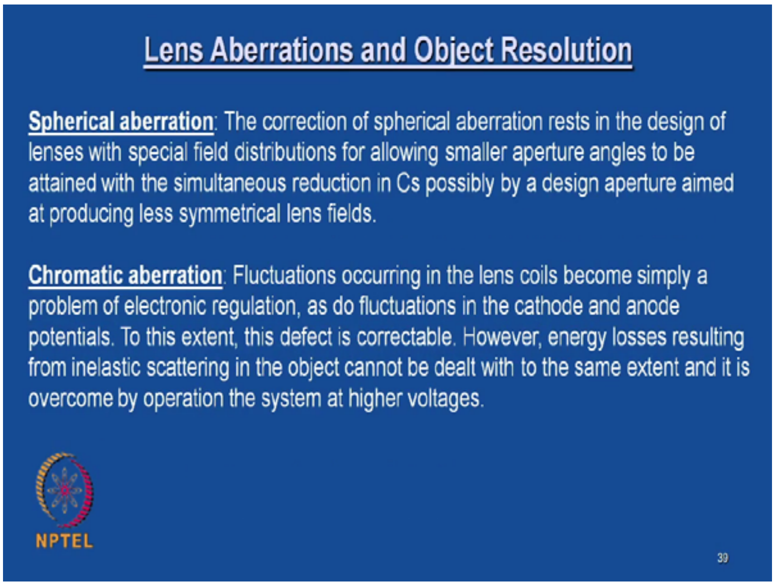

We will see the other aberrations. Spherical aberration, the correction of spherical aberration rests in the design of lens lenses with special field distributions for allowing smaller aperture angles to be attained with the simultaneous reduction in Cs possibly by a design aperture aimed at producing less symmetrical lens fields. As I mentioned, this particular aberrations 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.

Chromatic aberration which is caused by the fluctuation occurring the lens coils become simply a problem of electro electronic regulation, as do fluctuation 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 system at higher voltages.

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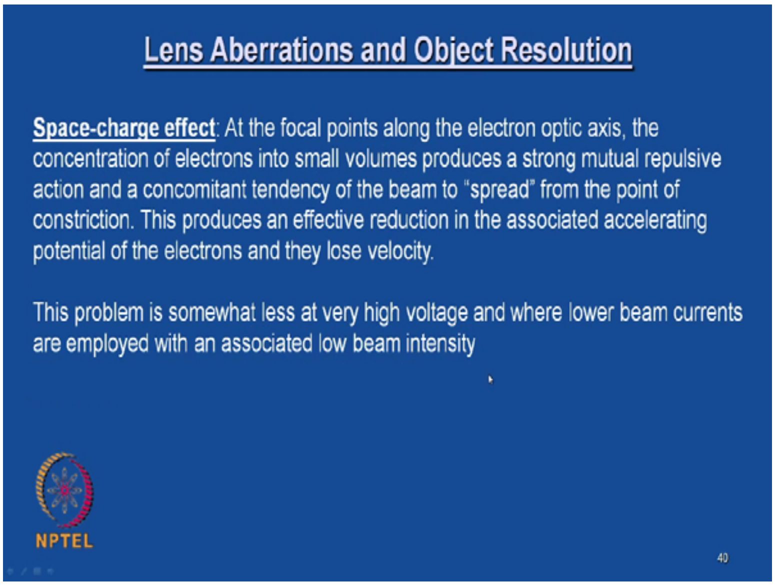

Another important aspect of this electron optical system is a space-charge effect. What is this space-charge effect, at the focal point along the electron optic axis, the concentration of electrons into small volumes produces a strong mutual repulsive action and a concomitant tendency of the beam to 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 electron and they lose velocity. This problem is somewhat less at very high voltage and where lower beam currents are employed with associated low beam intensity.

So, this particular effect is specially belongs to this electron optical system and you have to remember, the aberration which we talk 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 talk 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 own new product that will impair the resolution. So, all this treatment which we are talking about or the compensating effect, we talk about assuming that specimen is in the ideal condition. In the mathematical treatment, which we 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 constituent with the electron beam.

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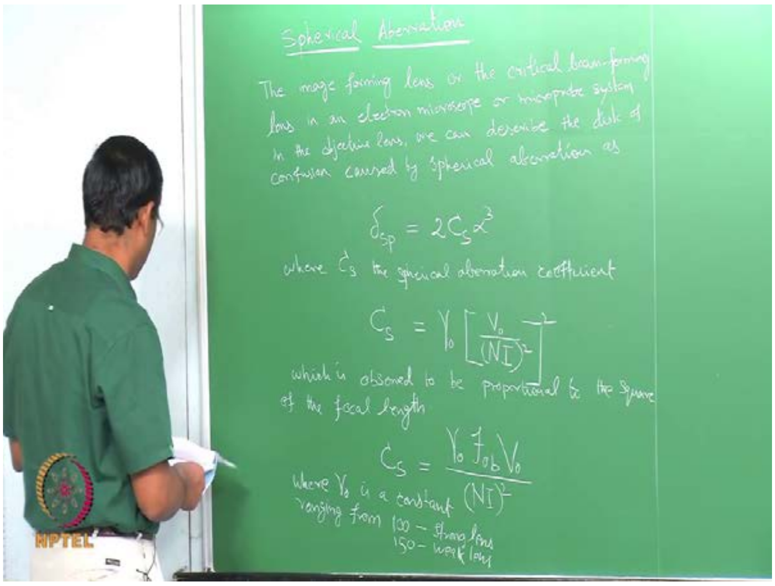

Now, we will just take up this two spherical I mean two aberrations; first we will talk about spherical aberration. So, what I am trying to write here is the image forming lens or the critical beam forming lens in an electron microscope or micro probe system in the objective lens, we always talk about objective lens, where it could be a any image forming lengths or it could be an electron forming, I mean you know electron microscope critical beam forming lens or it could be electron micro probe 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 naught is general notation for disk of least confusion; here delta SP, is it is exclusively caused by the spherical aberration can be represented as 2 times C s alpha cube.

Where C s the spherical aberration coefficient, which is also given by C s equal to gamma naught times V naught divided by N I whole square bracket square. So, this expression you are familiar with already, this is potential, this is number of coil, this is current, which is observed to be proportional to the square of the focal length. So, this can be written as C s equal to gamma naught focal length of objective lengths and its v potential divided by N I whole square. Where gamma is a constant ranging from 100 for strong lens, and 150 for weak lens; gamma is a constant ranging from 100 for a strong lens 150 for week lens.

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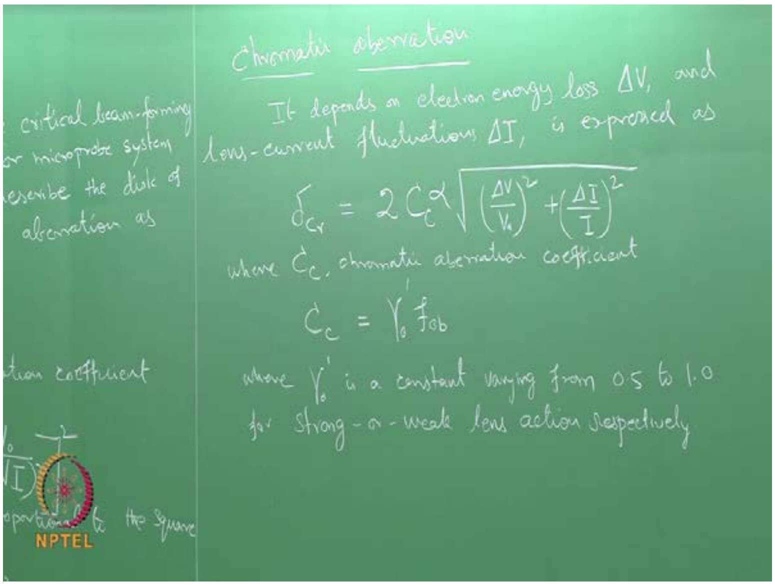

Similarly, we will see this chromatic aberration. As we discussed earlier, it depends on electron energy loss and lens current fluctuation delta I and is expressed as delta chromatic disc of confusion created by chromatic aberration can be related to 2 times chromatic C c alpha, delta C r equal to 2 times C c that is chromatic aberration coefficient alpha times delta V by V naught whole square plus delta I by I whole square to the power half that is square root of the whole expression. We write the where C c chromatic aberration coefficient which is also given by C c equals gamma naught times focal lens of objective. Where gamma naught prime is a constant varying from 0.5 to 1 for strong or weak lens action respectively. So, you have this chromatic aberration constant equal to gamma naught prime times focal of objective and gamma naught prime is the constant varying from 0.5 to 1 for a strong or a weak lens action respectively.

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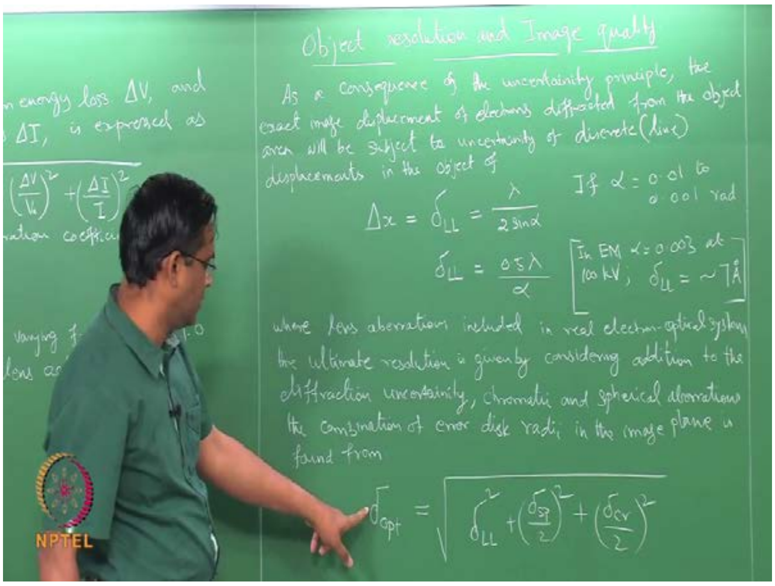

So, now what we will do is we will see that how all this aberrations, we will now try to write some expressions for object resolution and then image quality involving all this aberrations which we talk about, we will see that. So, what I have written is as a consequence of the uncertainty principle, 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 L that is list of least confusion line to line, which can be written as lambda divided by 2 sin alpha. You are familiar with this expression and it can be assume 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 radiant then we can write delta L L is 0.5 lambda divided by alpha. For example, you can write in a typical electron microscope alpha is 0.003 at 100 kV, your delta LL would be roughly about 7 Angstroms. This could give you an idea a typical case where you see that delta L how to appreciate this.

Now, we will include the lens aberrations and see how this expression is modified. So what I have done is where the lens aberration 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 radiant that is delta optimum in the image plane is found from delta optimum equal to square root of delta L L square plus delta S v by 2 whole square plus delta chromatic divided by 2 whole square.

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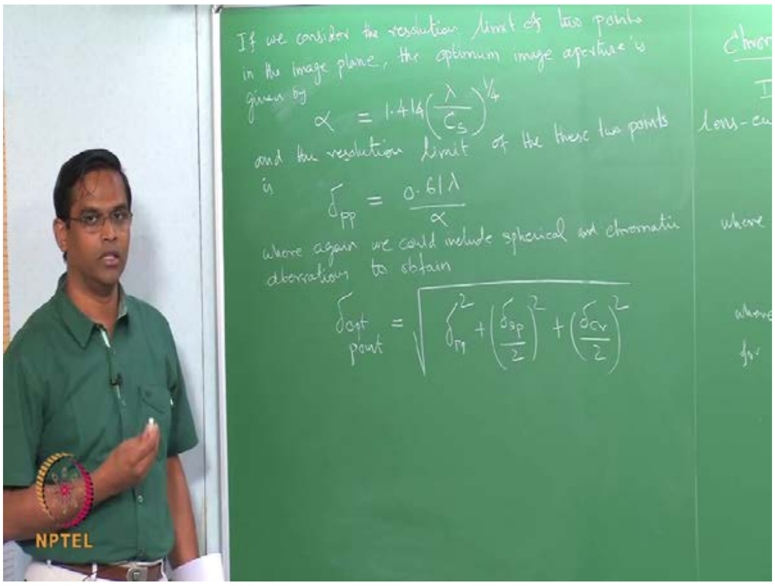

We consider limit of two points. See, we always talk about point resolution as well as line resolution. You can consider these two, if you consider two points in the image plane, the optimum is given by and the resolution limit of these two points is delta pp that is point to point disk of confusion. This also you are familiar with we have already seen this. Where again we could include spherical and chromatic to obtain, so if you include this, the spherical and chromatic aberration expression into this the point to point disc of least confusion then you obtain delta optimum point equal to square root of delta pp square plus delta sp by 2 whole square plus delta chromatic divided by 2 whole square.

These basic expressions are further modified by several researchers, and then we can write one more general expression for disc of least confusion. We will talk about all this much more detail, how 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 electro optical system.

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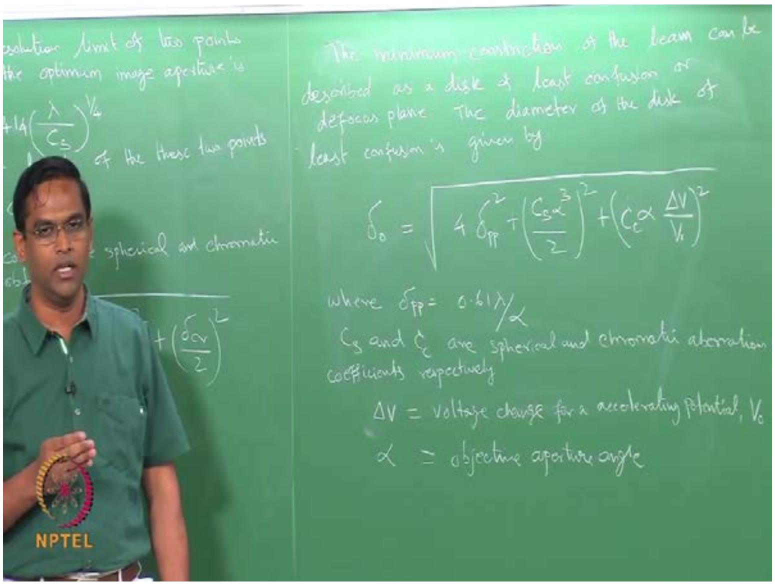

Before we just look at this expression, if you recall this, the ray diagram which I showed in the beginning of this class, where you see that delta naught was defined as a disc of least confusion in a defocus plane. Then, if you look at the image plane where delta optimal where on the image plane which is much larger than the d naught; delta optimum was much larger than in the ray we describe which is larger than the d naught. 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 to get an expression for delta naught itself that is what we have tried to show here. The minimum constriction of the beam described as the disc of least confusion on the defocus plane on the optical axis. The diameter of the disc of least confusion is given by delta naught equal to square root of 4 times delta pp square plus C s alpha cube divided by 2 whole square plus C c alpha delta V by V naught whole square, where delta pp is equal to 0.61 time lambda by alpha and where C s and C c are the spherical and chromatic aberration coefficient respectively. Delta V is voltage change for accelerating potential V naught and alpha is an objective aperture angle.

In this class, I hope you have at least, have some basic idea about how these aberrations in an electron optical system is considered and its implements on the resolution of the image and the microscope. Now, we will now move onto 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.