Optical Methods for Solid and Fluid Mechanics
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Lecture - 18
Particle Image Velocimetry III

Hello and welcome back. So, in the last class we had started talking about particle image velocimetry, we contrasted it with particle tracking velocimetry. Today, we are going to learn more about particle image velocimetry, but there is one specific issue about the lighting and the light sheet calculations that we wanted to discuss. So, where we left of last class is where we discussed this particular problem of multiple lenses put together.

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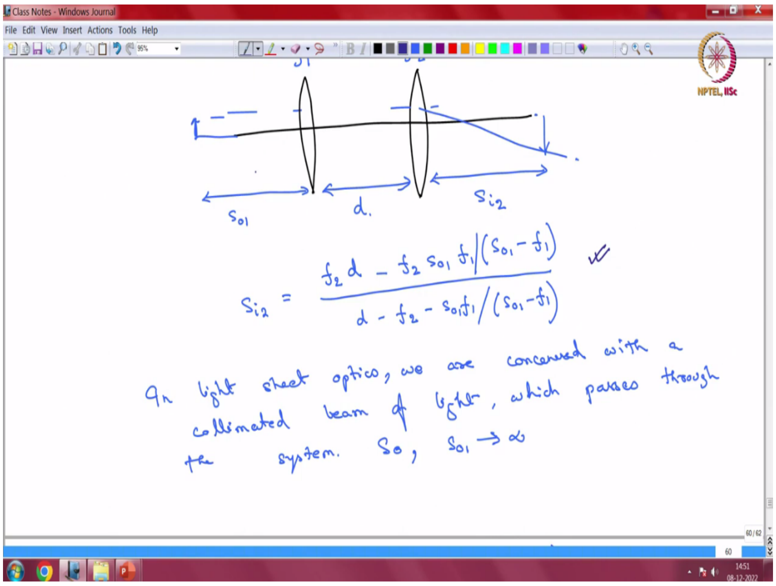

And we can see here this equation we discussed again. So, this equation was stated without proof where we have two lenses with focal lengths f 1 and f 2 separated by a distance of d and this equation here which tells us the image distance from the second lens that was stated last time. We will see how this applies to light sheet optics in particular and so in preparation for that we discussed what happens when a collimated beam of light enters from the left.

So, a collimated beam of light is basically a set of parallel rays that will come in from the left and enter the first lens and then be transmitted through it and then again encounter the second lens and finally form an image. So, in order to accommodate a collimated beam of light we assume that s 0 1 tends to infinity.

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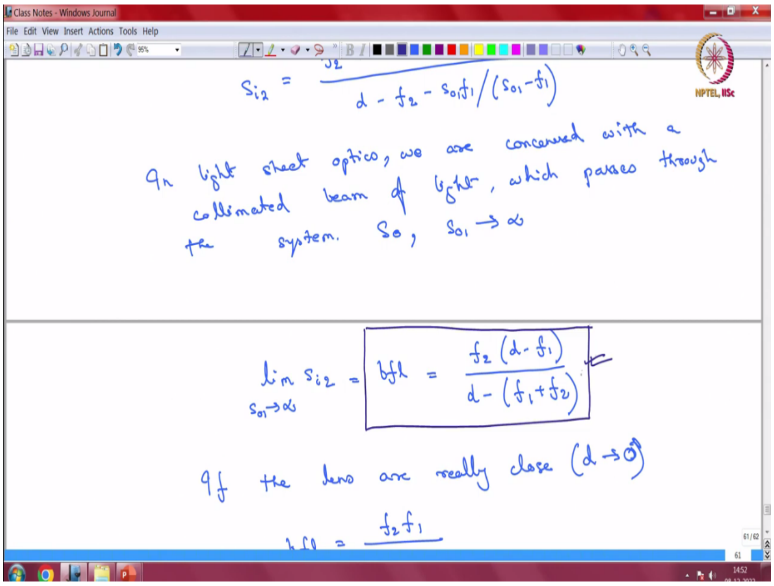

And subsequently when we used this limit we got this particular form of the back focal plane. This is an import current equation because we are going to use it today.

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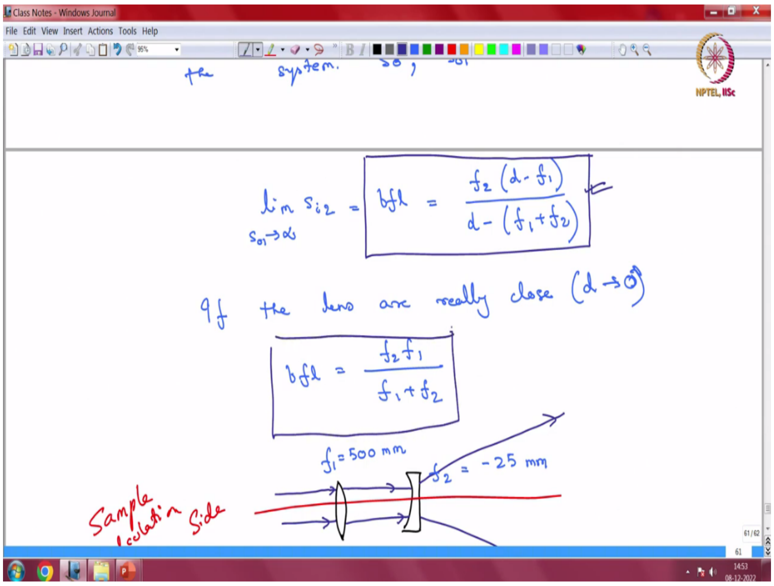

And we also discussed one more simplification which I will not use so much, but it is applicable in many cases what happens when the lenses are really close which means the limiting case of d tending to 0. So, this equation the back focal plane equation simplifies further and becomes this particular equation.

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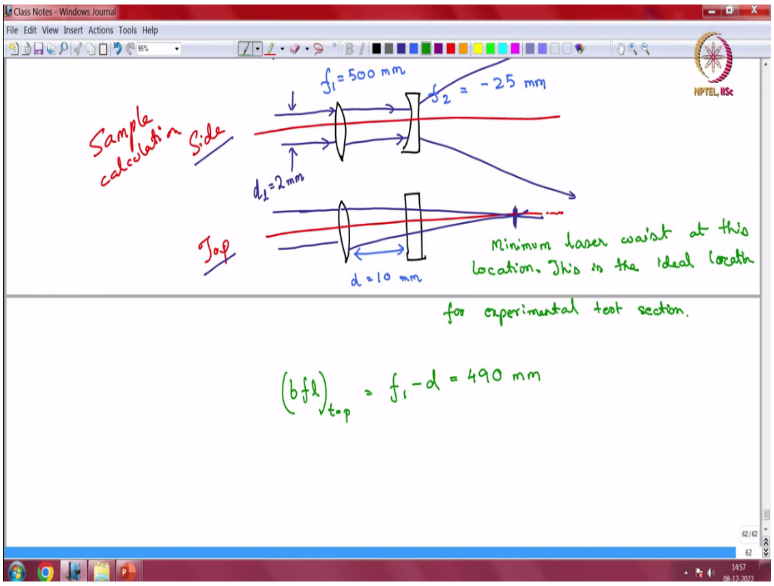

Now in order to put this understanding to test we wanted to do one sample problem. In the sample problem we had said that there are two lenses next to each other. This first which is a spherical lens and the second which is a cylindrical lens because the cylindrical lens the optical axis is not the axis of symmetry hence the diagrams in the side and the top views now start to differ.

So, while the spherical lens remains a spherical lens in the top and the side view the cylindrical lens does not right and in this diagram what we have done is in the side view we have drawn the cylindrical portion and in the top view it is just like a flat rectangular slab consistent with our discussion on collimated light we said that there is a beam that is entering from the side.

And in this beam let us say this beam diameter is provided to you as d laser as 2 millimeters and this light enters from the left hand side and counters the first lens goes on and meets the second lens and then the question was to figure out where the back focal plane is and some of the other characteristics as to the experimental section which you would want to design in a given situation like this.

So, I hope you have taken a look at this problem and tried to solve it. I will go through the solution portion of it today and I will explain these things in detail. So, now before I start off with the solution one thing I would like to point out and Abhinit was good enough to point out to me last time is that this diagram is severely exaggerated. So, the diagram in the bottom if you see the distance I am giving it as d as equal to 10 millimeters.

Whereas I am saying that the focal length of the first spherical lens is 500 mm which means that in the top view the collimated lens rays come and they get focused 500 mm from the first lens because the second lens is just a rectangular slab it does not affect the convergence of these light rays. So, this distance is going to be 500 mm. So, this is not to scale and this is a highly exaggerated image.

So, let us make sure that we have that into account. Now this location is the back focal plane and this is where the because of the nature of the two lenses the light rays come and become focused here on to a spot. We will discuss the issue of the spot little bit later, but in geometrical optics these two rays will come and meet at a point. So, this entire collimated parallel rays are supposed to come and meet at a single point here.

Now this is the area where in practical reality you have the minimum laser waste so you have the minimum laser waist at this location and this is the ideal location for experimental test section. So, what is the formula for the back focal plane in the top view? That is nothing, but f 1 – d. So this is 490 mm which means that the back focal plane is placed at a distance of 490 mm from the second lens right, but what is the back focal plane with respect to the side view.

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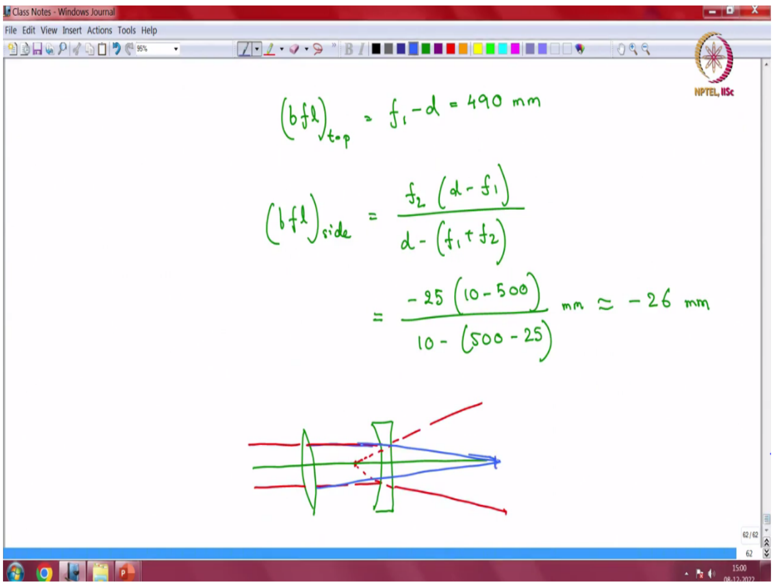

So back focal plane for the side view we still have to calculate. So, let us see what the formula said. So, the formula was f 2 d 1 – f 1 and d - f 1 + f 2. So, let us write this down we have f 2 d - f 1 d - f 1 + f 2 then the values have already been provided to us so let us just go ahead and use those values f 2 is - 25 and this is 10 - 500 and this is again 10 – 500 - 2 and this is in mm.

And if you calculate this comes out to be approximately - 26 mm you can double check my calculations. Please do so which means if we have to interpret this in this above diagram what this means is that these rays actually form a virtual image at a distance of - 26 millimeters from the second lens. So, now if I were to combine these two into one image both these diagrams. So, let me draw just a second I am going to draw the two drawings together.

But instead what I am doing is I am drawing I cannot draw both let me just finish the drawing here then I will explain what I am doing here. So, this two rays meet here I will use another color to demarcate the other view. So, the red colored line they depict the side view for the light and the blue colored one depicts the top view for the light. So, they come and here so you can see that I cannot draw both cross sections for the lenses simultaneously. So, I will just keep it at that.

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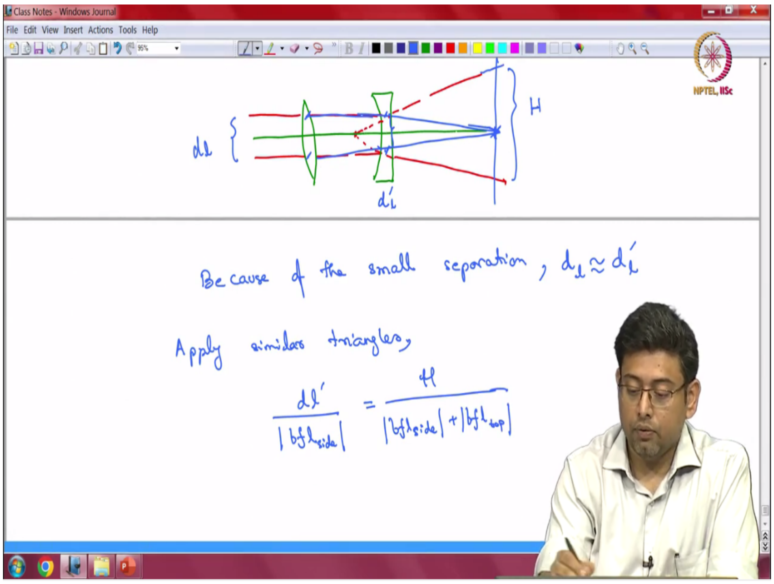

And at this location there must be a height. So, if this is the back focal plane there is a certain span of this laser light sheet and the other question is to find out this particular span if this d laser is already given to you. So, this d laser is given to us, so this diameter is given to us and then the question is to find this H. Now I am going to take an advantage here of the fact that the distance between the lenses is much smaller than this particular distance this is 490 mm and this is just about 10 mm.

So, the diameter of the laser collimated beams here is approximately the same as the diameter that you will encounter at the second lens. So, this diameter the second lens sees this is dl dash this dl dash is less than dl but I am going to assume but because of the small separation I will go ahead and assume that dl and dl dash are the same. Now in order to find out what this H is I apply the idea of similar triangles, this is geometric optics.

So, geometry is basically the determining factor in everything. So, here one triangle is this small triangle right here and so apply similar triangles and then you have dl dash by the back focal plane bfl just a second I just want to make sure the side yeah bfl side is equal to H by the absolute values of this side. So, H divided by this total distance which is this negative distance here and this positive distance 490. So, my H here you can calculate. So, this is known to you.

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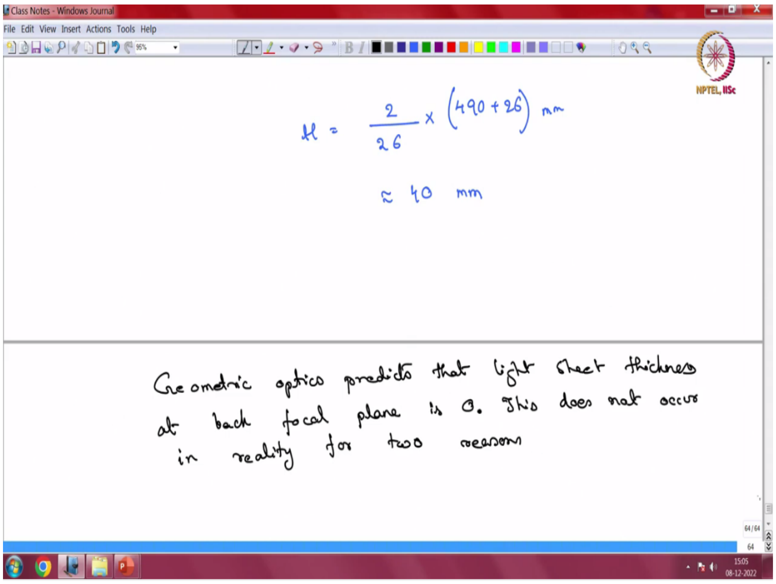

So, H is nothing, but 2 divided by 26 multiplied by 490 + 26 so this in mm and this comes out to be something around 40 mm. Again you should double check my numbers there is always a possibility that there might be a small error. So, now you are going to place your experimental section here and your H is 40 mm which means that your experimental cross section test section must not have a span greater than 40 mm.

In reality, actually the experimental section must be even much smaller I will tell you the reason for that also in a in a minute or so, but your experimental cross section should be something like this which is placed at the location of the back focal plane and its span should be much smaller than this H which is why we had to find the value of H. So, you know how to create your experimental cross section.

So, now we have been discussing the entire problem from the perspective of geometrical optics and as I just said this entire calculation above it takes into account certain idealizations of geometric optics which is that this collimated beam of light is actually going to come and become a single point and converge on to a single point here. but that does not happen. So, let us write this down.

So, geometric optics predicts that light sheet thickness at the back focal plane is 0. This does not occur in reality for two reasons.

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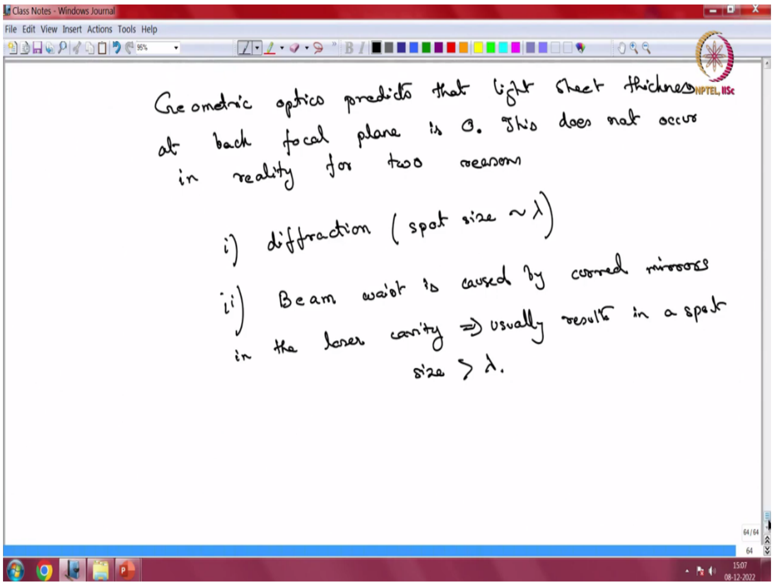

One being the diffraction of light so at these very small length scales how light is being bent has to be understood through the perspective of light refraction and that says that light cannot be focused on to a ideal point instead the diffraction results into a spot size a finite spot size which is usually of the order of the wavelength of light being used. The exact calculations I am not presenting it is not exactly lambda, but it is of the order of lambda.

So, we have to take diffraction into account and the other portion is that in most cases the laser is formed in a laser cavity and in laser cavity there would be mirrors which result in a finite beam waist of the laser and because of the finite beam waist the lasers cannot be focused on to a single point. So, the other reason is that the beam waist is caused by curved mirrors in the laser cavity.

And because of this beam waist the laser is focused on to a point and this is usually the size of the point usually results in a spot size greater than lambda. So, this is a something to take into account again this is not a course in optics, but if you were to take a course into geometric optics you might encounter all the correct formulas and the correct methodology for calculating all this.

So, we are unable to go into all that, but I encourage you I have already given you the correct references so you can take a look at this. Now these are not the only issues that their experimentalists should be cognizant of, there are other issues as well and one of the most important issue is the fact that the laser intensity; so going back to this particular problem if you were to take a cut at any given location let us say here.

So, if this is a cut at this cross section the laser intensity is not the same let us say the edge of this cross section versus the middle and versus any other point in between and that happens because the lasers do have a spread in intensity. So, let me write this down here.

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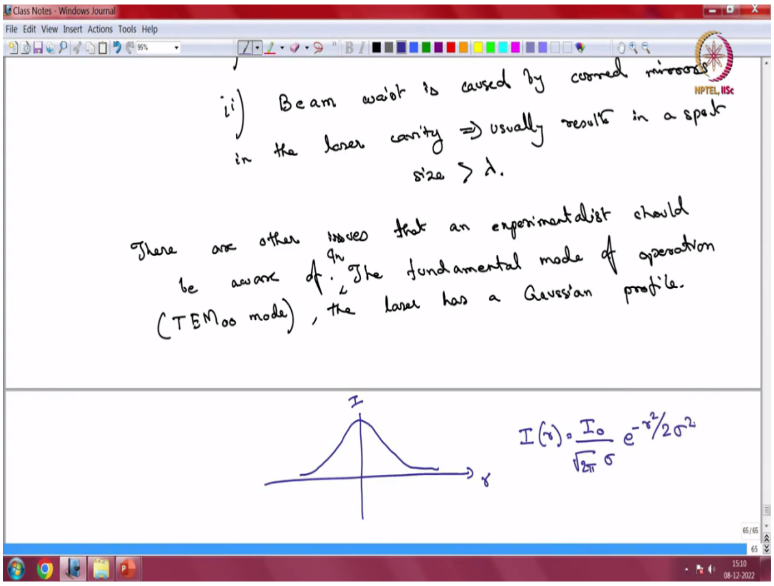

So, there are other issues that an experimentalist should be aware of and the example is that in most lasers the fundamental wait let me let me rephrase this the fundamental mode of operation of a laser also called the TEM 00 mode. Transverse electromagnetic modes or TEM 00 mode the laser in the most fundamental. So, this is in the most fundamental mode of the laser has a Gaussian intensity profile which means that if you were to draw a diagram.

And this is let us say r which is the r of the radial distance. So, going back to this if you were to use r in this direction with this being 0 the origin then if you were to plot the intensity of the laser so if you have to plot this is the intensity values then it would look something like this like a Gaussian curve. So your I r is given by some I 0 by root over of 2 pi sigma e to the power - r square by 2 sigma square.

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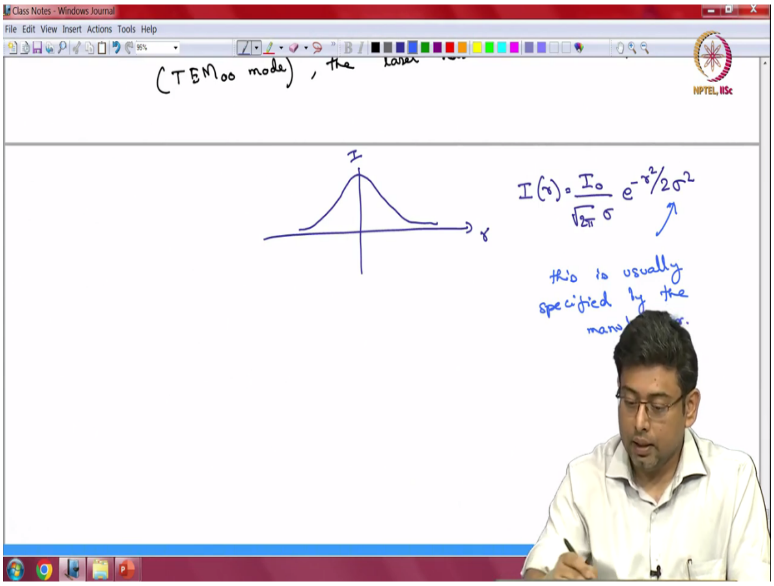

And this sigma value this is usually specified by the manufacturer and usually the laser is cut off at a physically cut off at either sigma or 2 sigma. So, you should you find out from the laser manufacturer what the intensity distribution is the values are usually given by them. So, if that is the case that means that in this if you we go back to this particular problem the intensity is the lowest at the edges. So, intensity is lowest here.

So, here it is basically the intensity is probably going to look something like this and the intensity is the greatest along the center line and that intensity is going to be reflected right back again here. So, at this cross section so again I am running out of space here, but if I were to just extend this line somehow and you would have a very similar profile for the laser which means that the light intensity at these edges this edge and this edge right here.

They would be the lowest whereas along the center line the mid section of this laser sheet your light intensity would be the maximum. So, as a good experimentalist you should choose the middle section maybe half of this H would be a good rule of thumb and that would allow you to illuminate your particles properly.

So, we were talking about light sheet optics and the reason for light sheet optics we also discuss is that in macro PIV you want to illuminate a large section and you have a laser that can be sculpted into a laser sheet and that allows you imaging without much issues. Now, if we were to go back to just one second here I am just quickly going to try and find this video here.

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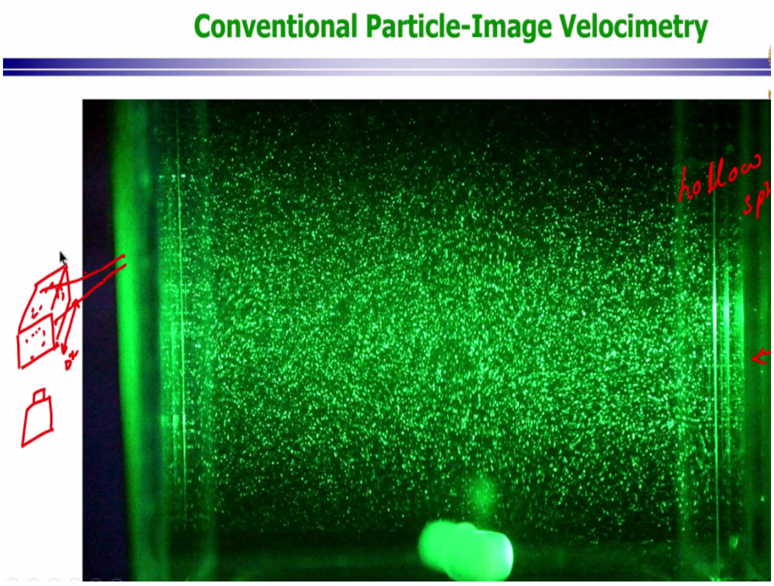

So, I am going to quickly explain this situation. Now this situation here in this particular video that I hope you recall I will play this one more time. So, this situation is that there is a box here and the box is filled with particles everywhere in the entire volume. So, if you are watching from the side if you have this is where your camera is. You are going to see all these particles all across this span.

So, let us call this let us say delta x or something, but you do not want to see this entire volume of particles because you want to look at a particular plane most likely the focal plane and just that. So, here what happens is as the laser comes in and then encounters a cylindrical lens I am not drawing the lens it becomes fans out and becomes a laser sheet and only illuminates a small gap along the focal plane.

And that is how you can image a particular focal plane without having to see the particles that are far away from the focal plane. So, it make sure that you encounter a very small or a very low noise due to particles that are out of the focal plane. Now in micro PIV that does not happen. So, what happens is in micro PIV.

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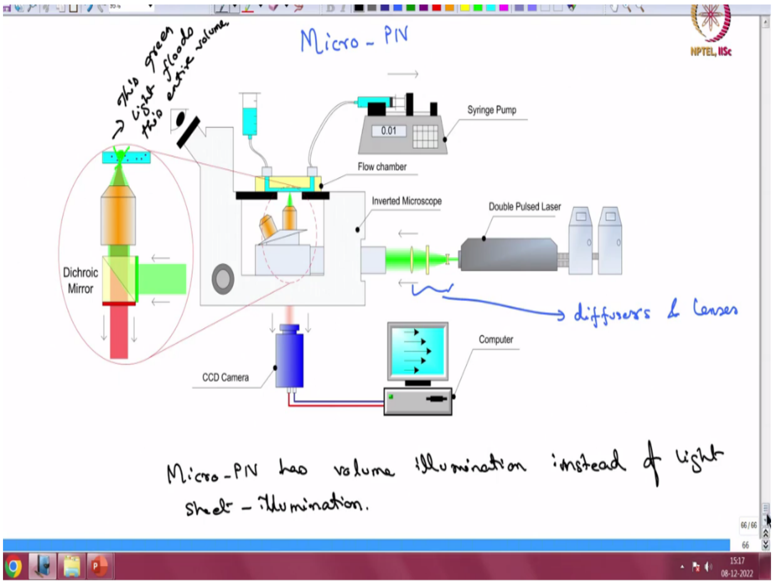

So, this is for micro particle image velocimetry you have let us say a laser here that is now going to come through a diffuser. So, there will be a diffuser element here and some lenses diffusers and lenses. I will explain what they are for and when they come in and go through your lens into and illuminate your sample. Now this light if I were to use the green light line here this green is going to illuminate this entire volume over here.

And there is no way for you to prevent the illumination of this entire volume. So, in micro PIV so this green light that we have drawn here floods this entire volume and because of this you end up having a volume illumination. So, micro PIV has volume illumination instead of light sheet illumination and this is a very important characteristic of what happens when you are doing particle image velocimetry for microfluidics.

You have placed it on a an optical microscope and because of the features of the optical microscope and the small length scales involved you can no longer form a sheet. So, instead the way the laser light comes in you actually end up illuminating the entire volume that does lead to a little bit of an issue in the sense of you have very high signal to noise ratios sorry very low signal to noise ratios compared to the other cases and if we recall one of the previous videos just a second I am just going to open.

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So, if you recall this particular video you see that there are a lot of; so you can see that there is a particle here, for example, which is a nice finely shaped dot whereas there a particle right here which is a big large shape and this particle is actually there are many particles like that and those particles are actually out of the focal plane. There is one more particle right here, these are other particle here these are particles that are far away from the focal plane.

And yet contribute to the signal in the focal plane. So, you have particles which are in the focal plate they are sharp and easily visible and looks like a nice little circle, but the others which have this large ring like structure they are away from the focal plane but still contribute to the signal in the focal plane. So, this is a issue that micro PIV faces and special considerations sometimes have to be put for getting high signal-to-noise ratios in that case. Now one more thing is this lasers that we discussed these are the typical micro PIV.

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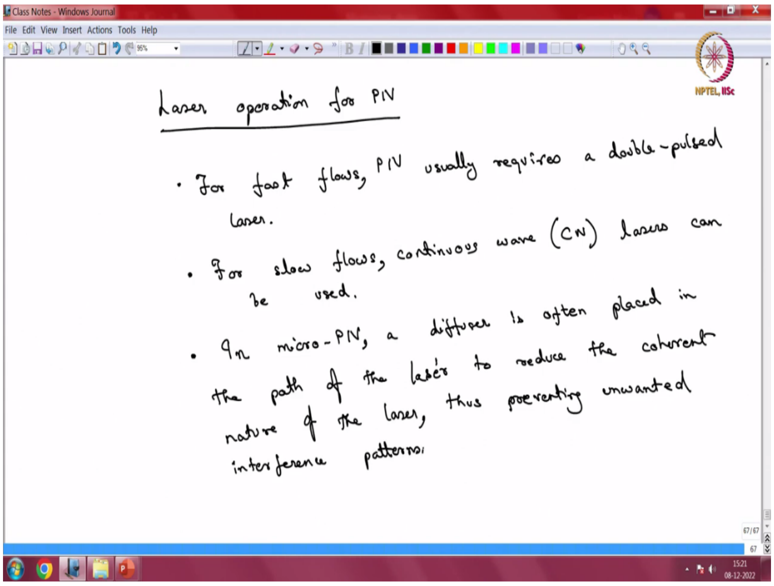

So, in a laser operation for PIV for fast flows PIV usually requires a double pulsed laser and you will see why that is the case, but I am just stating the issues here for slow flows on the other hand and slow is obviously a relative term and you have to watch out for what is slow in your particular case in a continuous wave lasers also called CW lasers can be used. So, if you are planning to set up an experimental setup you have to be careful in selecting the laser because it depends on the kind of flow.

In micro PIV a diffuser element which is an optical element a diffuser is often placed in the path of the laser to reduce a coherent nature of the laser thus preventing unwanted interference patterns.

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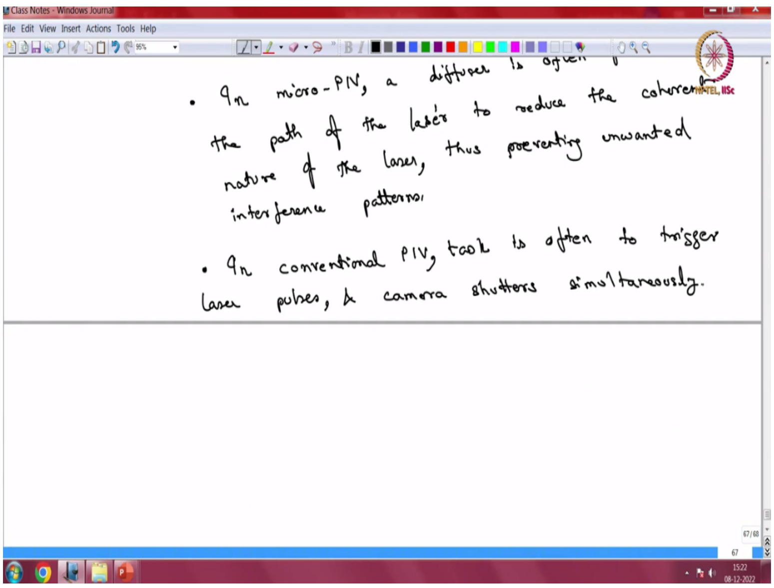

And then finally in conventional PIV a task is often to trigger laser pulses and camera shutters simultaneously and this can be done through the use of a synchronizer.

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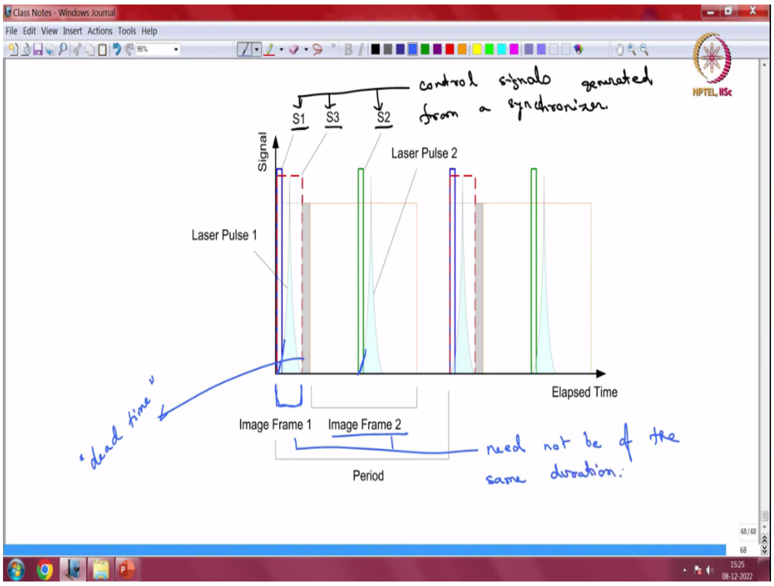

Briefly what a synchronizer does is it ensures that the images and the laser pulses and the imaging is synchronized and usually what happens in a synchronizer is that a control signals are generated. So, this is a diagram which shows what schematically what happens. So, for example, if you have a synchronizer what it will do is in this particular schematic you have three control signals that are being generated by the synchronizer.

So, these are control signals generated from a synchronizer. Once they are generated what happens it triggers a laser pulse so you can see that the beginning of the laser pulse happens when the signal is triggered. Once the signal is triggered which is basically a voltage that is usually given you have the laser and the laser operates. Once the laser operates then the camera is instructed to take one image.

So, for example, this is one particular image that the camera takes. This is an example of a double pulsed laser so you have the first laser pulse being operated and the camera takes one frame then there is a certain dead time. So, this is a dead time in the camera and this dead time is used to distinguish the first exposure from the second exposure. So, after the dead time the second exposure takes place so the second image is recorded.

And in this particular case this is, for example, the second signal and the laser is again activated when the second signal starts. So, this is the second laser pulse that has been emitted and the camera takes one more image during this then this becomes one full period and this keeps on repeating again and again and again as long as you need to have keep on taking images.

And you can see that the nature of this image is that these two need not be of the same duration, it can be it, need not be.

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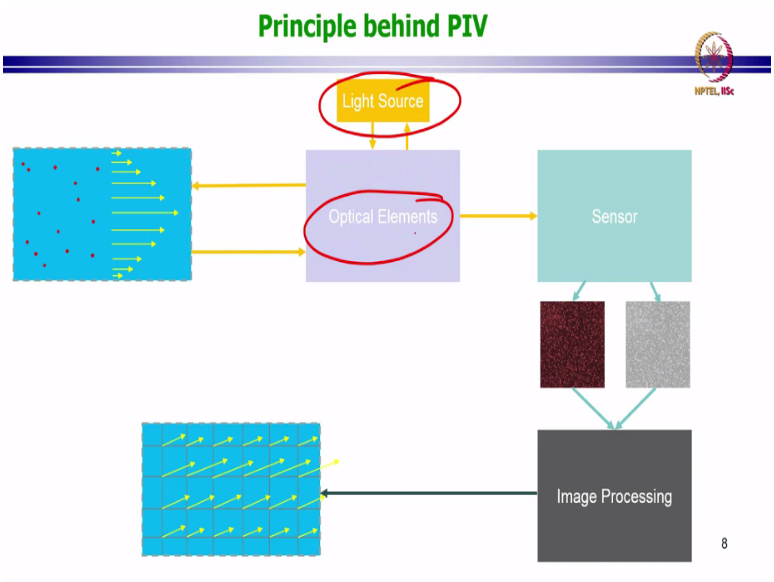

So, with that we had shown you this particular conceptual diagram last time and we had said there are so many different elements of PIV operation including the light source including the sensor operation optical elements and hopefully we have we have discussed quite a bit on the traces. We have discussed quite a bit on the quite a bit on the light source, some issues of light sheet optics versus micro PIV in the optical elements and we also discussed a bit about the sensor triggering and how two images are taken.

So, we will stop here today and in the next class we will get to see aspects of this image processing that are very, very important part of the particular image velocimetry. So, we will stop here today and I will see you next time. Thank you.