Neutron Scattering for Condensed Matter Studies
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Week 04 Lecture 10A

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I have discussed various components of beam design with you, starting with beam tailoring inside the reactor or at the source in spallation neutron source, in-piled collimators, soller collimators, and the detectors. Now, I will introduce you to some more devices and time-of-flight spectroscopy. Then I will discuss with you the difference in the experiment, using time of flight technique (in a pulsed source) and with a continuous neutron source in a reactor.

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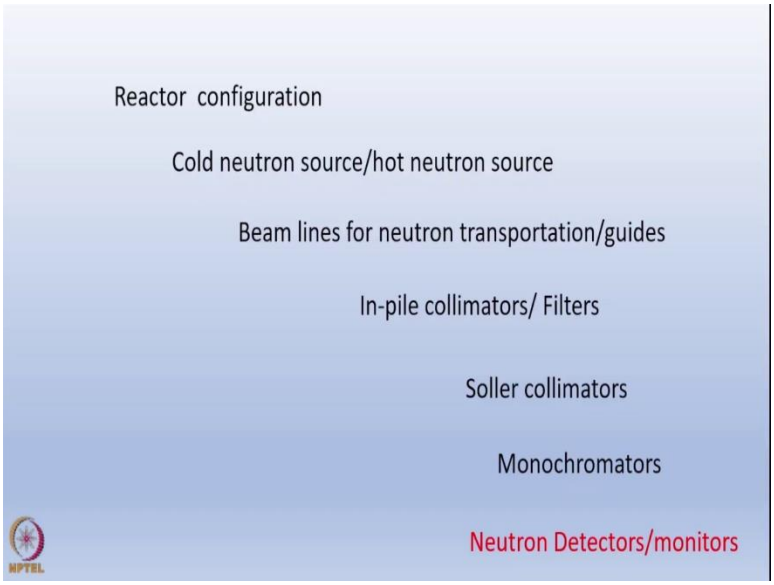

I have discussed starting from the reactor configuration to all the way down to neutron detectors and monitor counters.

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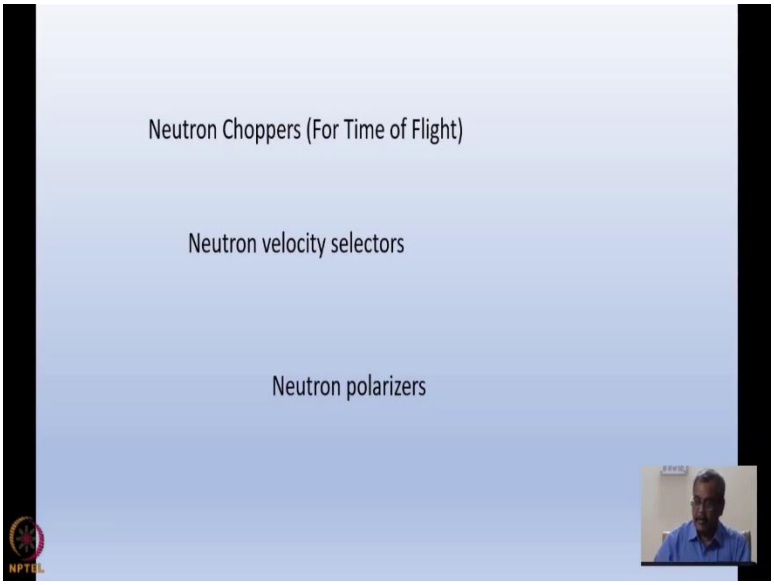

Now, I want to introduce you to a few more devices. One of them is very common in most of the sources, which is known as neutron choppers. I will talk to you about neutron choppers, neutron velocity selectors and an important component of neutron experiments - neutron polarizers. Neutron polarizers help us to get one spin component from a given beam of unpolarized neutrons.

Neutron is a spin half particle, so with respect to any direction you can have two possible spins ±1/2. And there are devices like neutron super mirrors, or Heusler alloy monochromators, which can remove one of these polarization components and allows us to have a polarized neutron beam. The polarized neutron beam is important for studying magnetic structure and dynamics in materials.

Neutron polarizers are important component of magnetic neutron diffractometers, neutron reflectometers because apart from the physical structure, we are also looking for magnetic structure in our sample. I will start with something called neutron choppers. And I have written in the bracket for time of flight. What is a neutron chopper?

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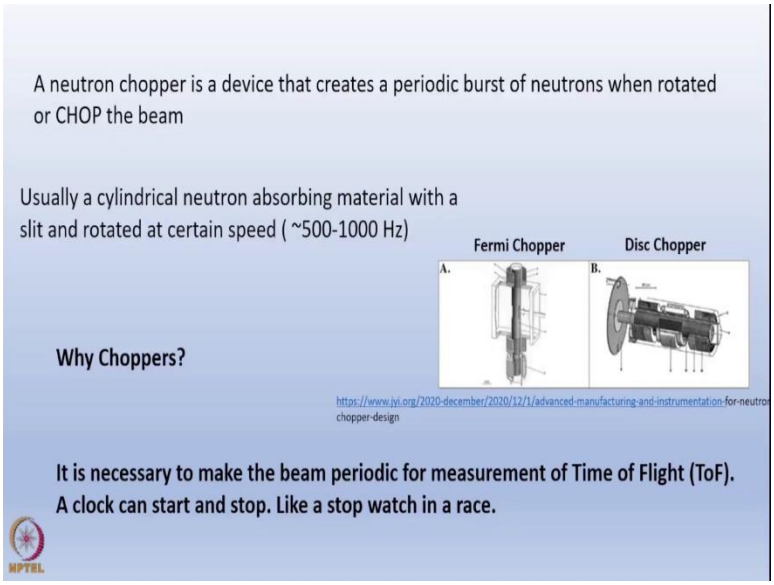

It is a very simple device that creates a periodic burst of neutrons when rotated or we chop the beam.

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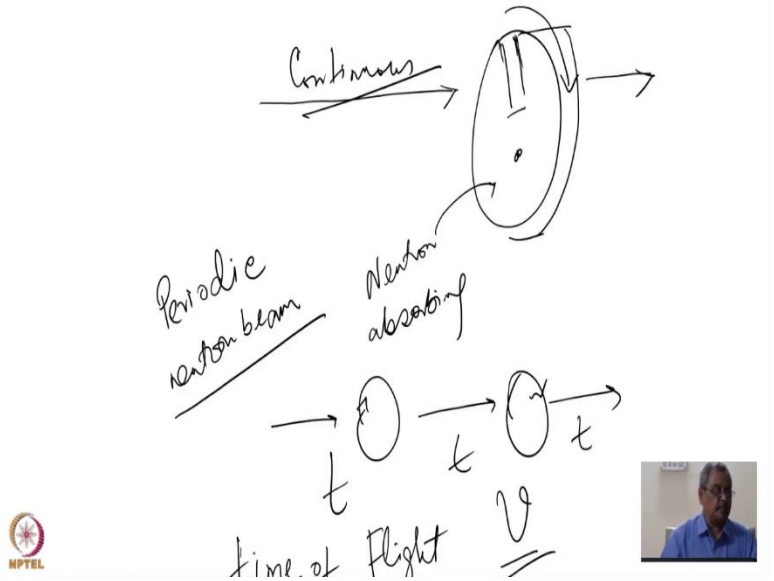

Let me just start with a simple thing.

Consider a neutron beam and put a disc like material with a slot in this beam and rotate this disc. The disc is a cylinder of small thickness and is made of neutron absorbing material such as cadmium encased in stainless steel. We can see that whenever the beam sees the opening in disc it

goes out from the other side while rest of the time it is absorbed by the disc material. Hence, for a continuous neutron beam from the reactor if this disc is placed in the beam and rotated, then for every rotation, we get the beam only when the beam sees the opening of the disc. In this way, depending on the rotation speed, we get a periodic (or pulsed) neutron beam.

Why we need to chop the beam? If we want to do time of flight spectroscopy, where we have to measure the time length, the neutron takes to travel a certain length in a more general term, both start and stop times are required to calculate the velocity of the neutrons. This periodicity (in the beam) is brought in with the chopper in place.

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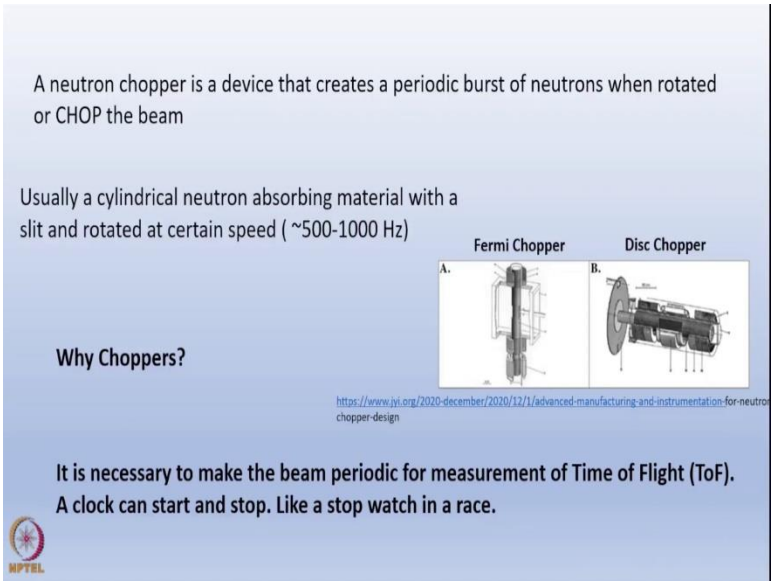

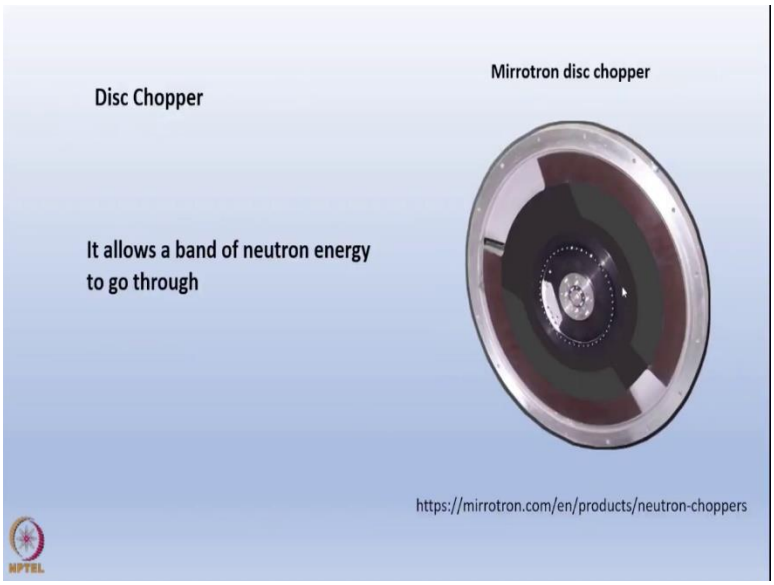

Here you can see a disc chopper with a slot through which the neutron can pass. Regarding rotation of the chopper, one must remember that there is a mechanical limitation on the rotation speed which limits the number of neutron pulses per second. Another fact is that in case of reactor the allowance is for one pulse in a rotation, rest of the time the neutron beam is present there, but we are not allowing it to pass through, so we lose neutrons and it is poor for neutron economy. But for some experiments, we can sacrifice neutron economy and go for time of flight in case of reactors (also).

In case of pulsed neutron sources, for example a spallation neutron source, the number of pulses which come every second, are fixed for the source. For example, the ISIS neutron source at Rutherford Appleton Laboratory in UK, they have a 50 Hz beam. That means, the proton hits a target 50 times in a second and generates the neutron beam and that neutron beam comes with a frequency of 50 Hz. Then why do we need a chopper as we already have the periodicity in the beam? The fact is that in this case, the chopper can allow a band of (desirable) neutrons which we want to get through it to the respective beamline. To measure the time of flight, we cannot have a continuous source weather reactor or any other source and we need to make it (the source) periodic using choppers.

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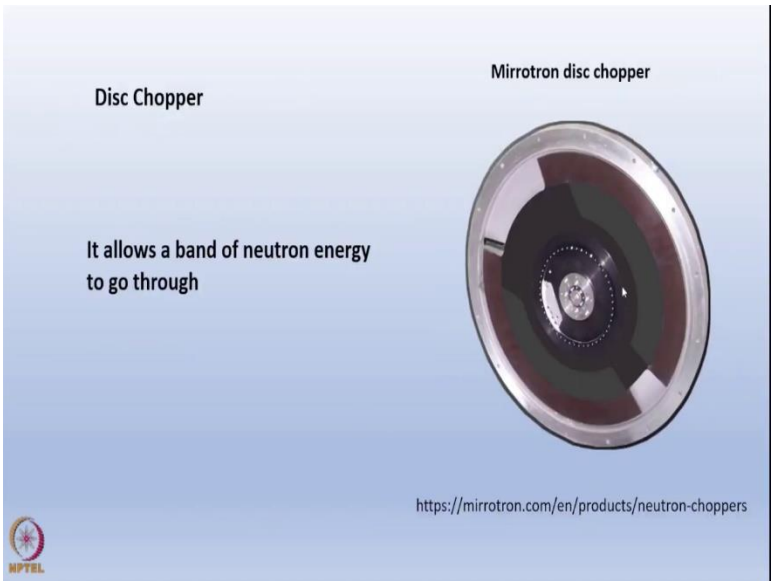

The one shown in the figure is a disc chopper, I have taken it from internet the site of Mirrotron, which is a commercial company. You can see that this disc chopper is basically a disc (with slots) and allows a band of neutron energy to go through.

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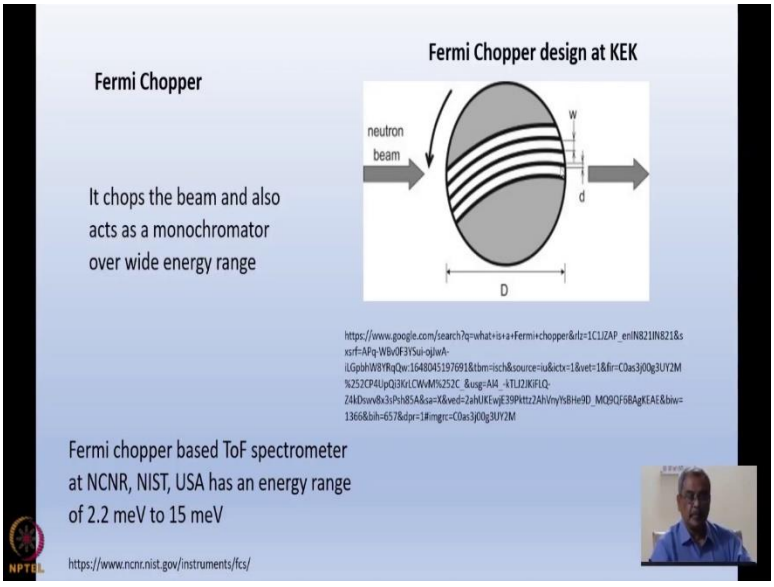

Another kind of chopper is a Fermi Chopper. This is a little more interesting. The Fermi chopper is a cylindrical body with curved slits inside the chopper (as shown).

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When we put a neutron, traveling in a straight line, in a rotating frame of a chopper, then the straight line in the frame of reference of this chopper becomes a helix. So, it is (the path) helical. Fermi chopper has a slit assembly. This is because if there is a slit like this, when the beam is coming and the chopper is rotating at such a speed that by the time the neutron reaches this point, the chopper has rotated enough to allow neutrons of certain wavelength i.e., with certain spread, that they can travel at a speed matching with the rotation speed of the disc. Then it can clear the chopper, based on the rotational speed of the chopper and the velocity of these neutrons.

So, this (chopper) acts as a like a bandpass filter. It allows certain frequencies to pass through the chopper and Fermi chopper has this silt, so it is some kind of chopped wide monochromator. It allows a band of neutrons to pass and still we have the issue of wide wavelength band.

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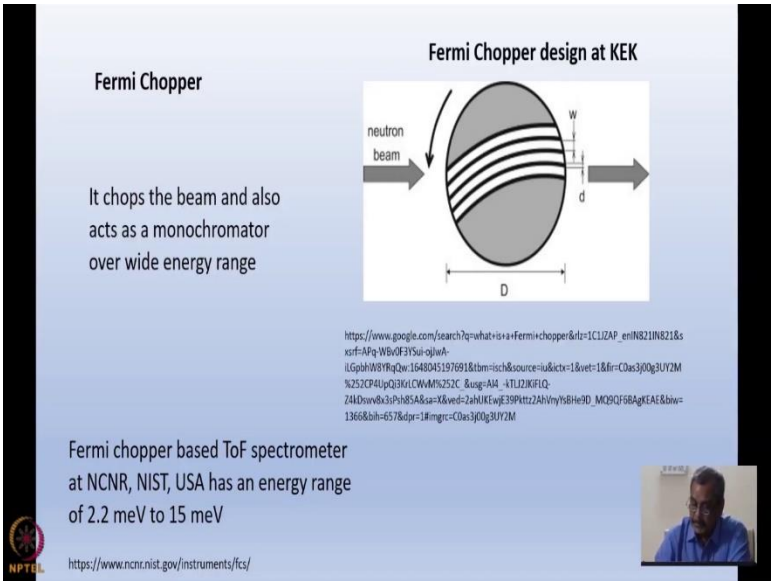

Fermi chopper is used at many places, for example, there is a quasi-elastic spectrometer at NIST, NCNR USA. Fermi chopper allows an energy range of 2.2 -15 meV to pass through and that depends on the curvature of the helix and the band you want. You have a polychromatic beam from which you want to select a particular band which matches with the rotational speed of the chopper and gets to the other side. This is how a fermi chopper works, which is like we can say not just a chopper which chops a neutron beam, but also monochromatizes it to some extent.

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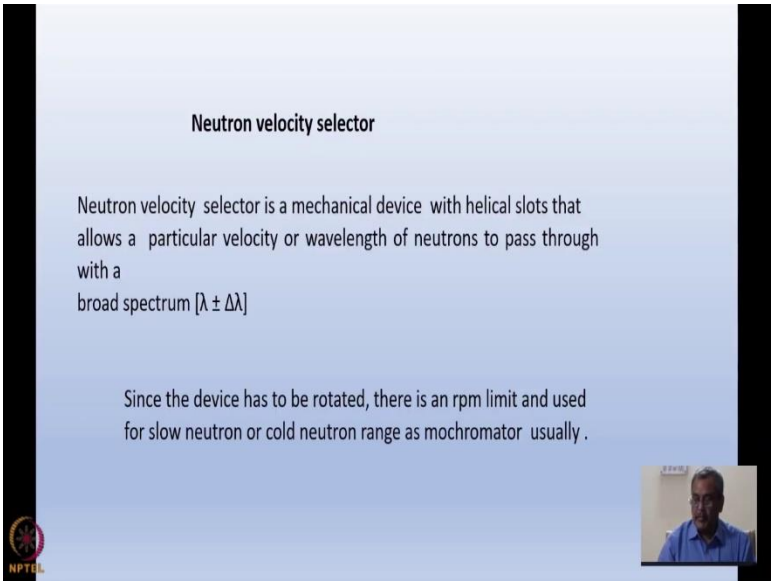

Now, I come to the next kind of devices, which is a neutron velocity selector. It really does not chop the beam, but rather selects a wide monochromatic band from the given polychromatic beam. It can be used in a continuous source also. Instead of a monochromator, now this velocity selector acts as a monochromator.

But again we have to rotate the device. So, there is a limit on the how many rotations per minutes we can actually give mechanically and it is preferable when we want to use the incident neutrons to be slow neutrons or cold neutrons. This is good for those spectrometers which use slow neutrons or cold neutrons for the experiments.

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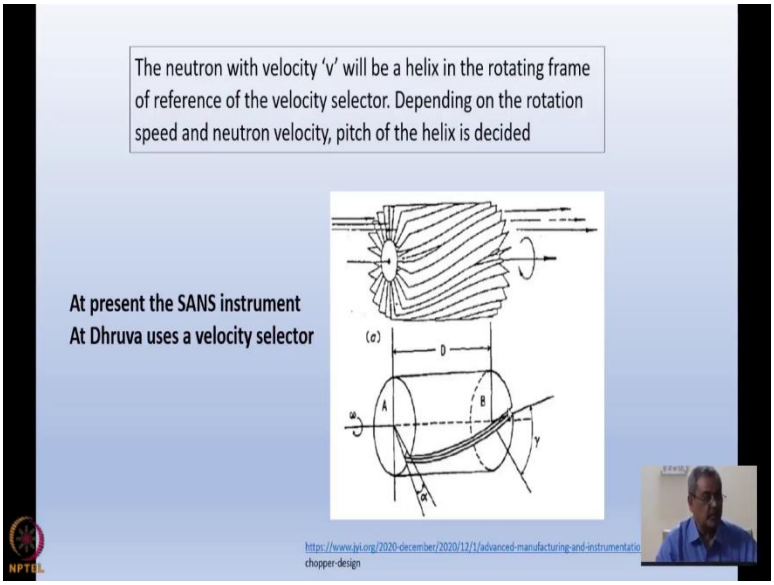

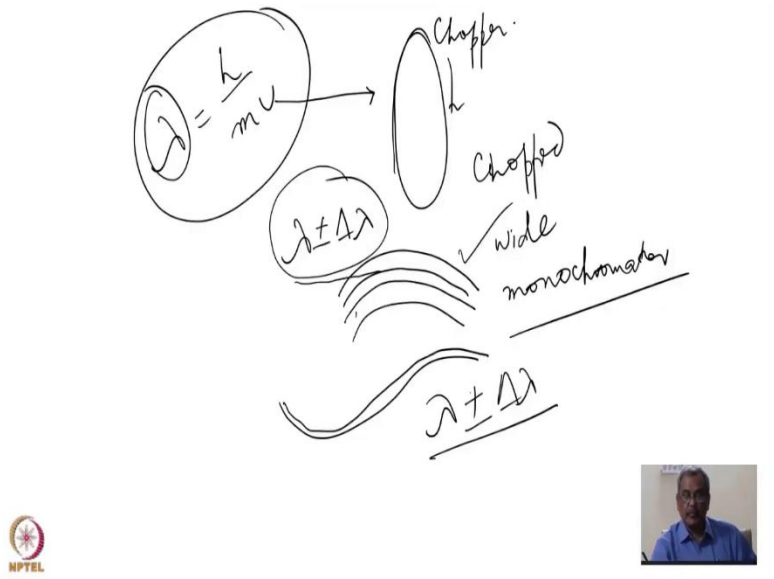

In the image you can see a cylindrical body on surface of which there are slots of angle alpha and it follows the helix. As I told you earlier that in a rotating frame, the neutron will follow a helical path. The rotation speed dictates its helical path and the wavelength that you allow to pass with a certain wavelength spread. Now I can take a material and can make parallel helical slots like this and put it in the beam path. As velocity and wavelength are related to each other, hence a velocity selector is also a wavelength selector. And there are helical slots on the body of this cylinder in which the neutron impinges and there are many of such helixes machined on the surface of this. They provide a continuous neutron beam of certain $\lambda \pm \Delta\lambda$ for the experiments. At the moment,

the small angle neutron scattering instrument (SNAS) at Dhruva uses a velocity selector as a monochromator for its experiment.

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This is again another image of a helical slot on a cylindrical body.

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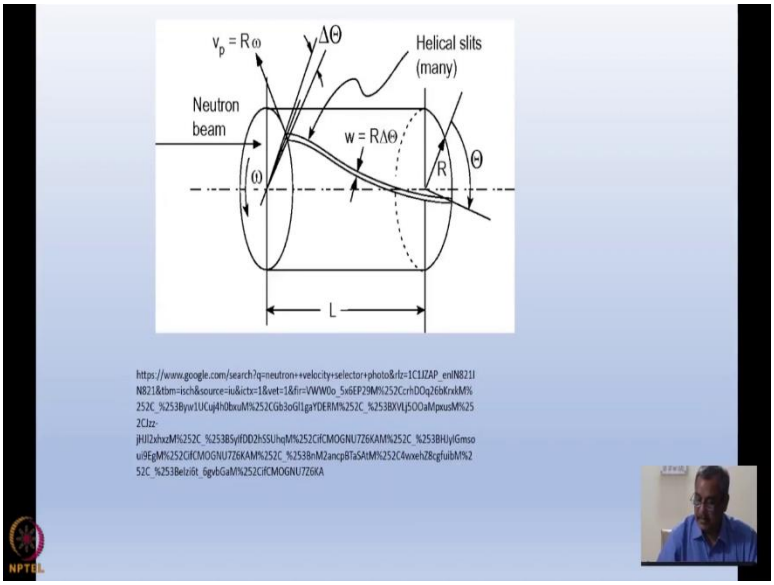

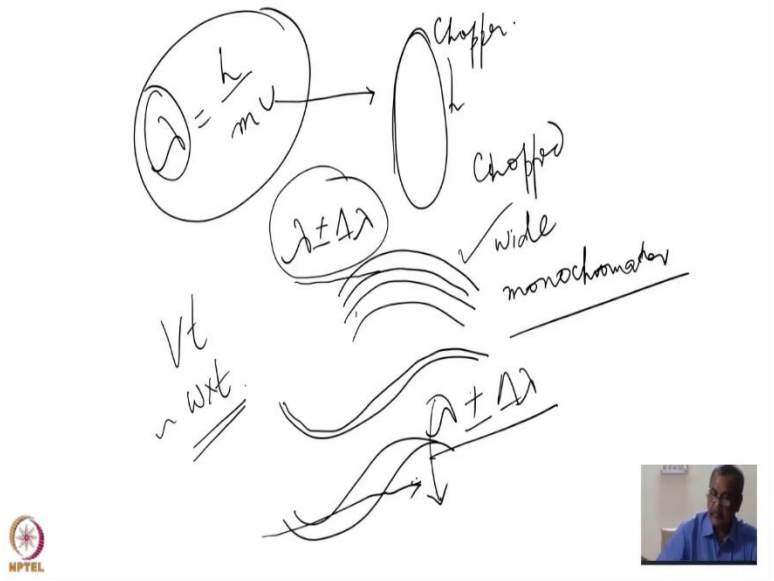

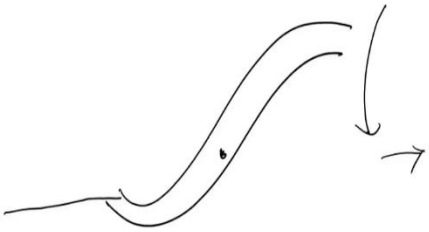

And as I told you earlier, the velocity of the surface is given by ωR where ω is a rotational velocity and $\Delta\theta$ is the width of a slot and this width decided by $R\Delta\theta$. If you allow a neutron beam to come through it, it will choose the wavelength depending on the rotational speed of this velocity selector because the velocity times t should match with the ωt, angular coverage should be such that that the neutron can follow the helix as it passes through this thing (Chopper). If it is not rotated, then neutrons will get into the absorbing material and get lost.

If there is a helix like this and the neutron beam is traveling. If I rotate it, as the neutron beam goes forward, the (slot in the) helix also comes in the beam path and gives the opening. As neutron goes further this helix comes in the beam path with the opening in the form of helix and allows the neutron to pass through: only a certain wavelength band. This is a velocity selector which I have shown.

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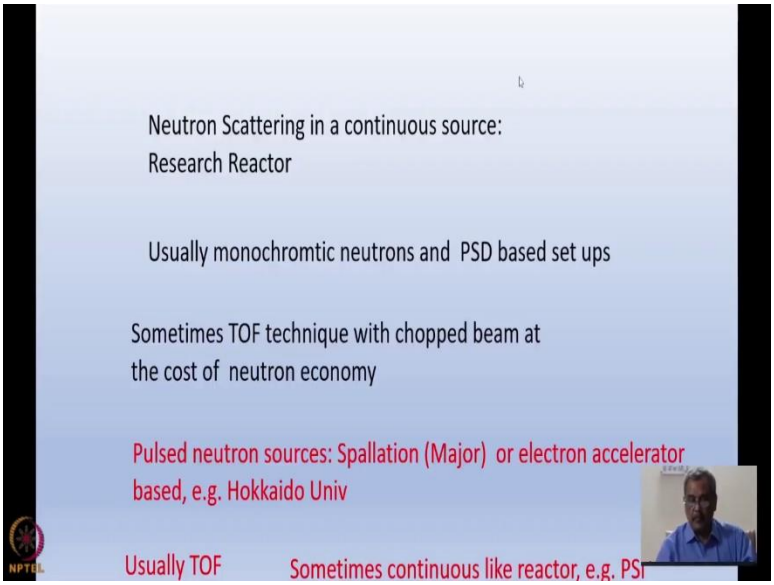

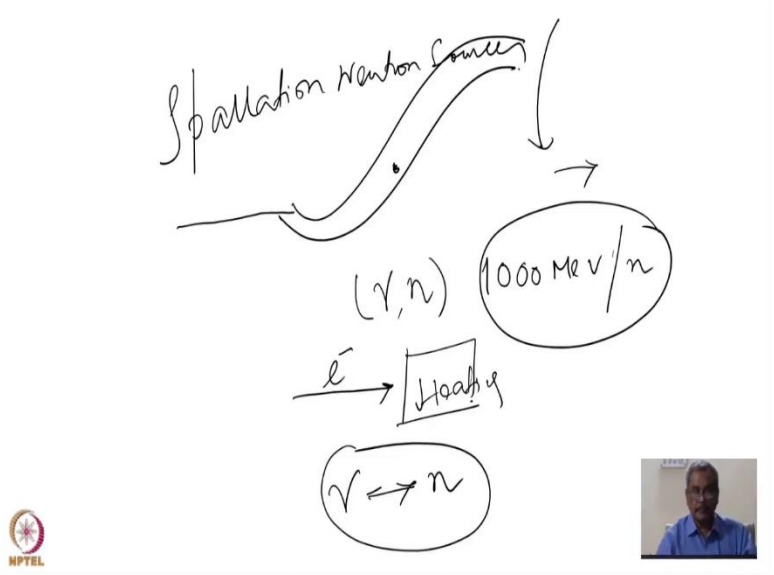

In a continuous source such as reactor, the neutron scattering experiments are usually done using monochromatic neutron beams and PSD based setups for the diffraction experiment specifically. Sometimes we also use time of flight techniques in reactor sources, but to do this we have to chop the beam.

As I told you earlier, a chopper throws away a lot of neutrons and allows only a certain burst of neutrons to go through it. In general, the major pulsed sources have pulse nature and time of flight is the natural choice of spectrometers for the pulsed spallation sources.

I must mention that earlier there were also electron accelerator-based sources. One is there in Hokkaido University. In case of electron accelerator-based sources, it is a (γ,n)– reaction. Here, an accelerated electron beam is impinged on a metal target and electron beam gets decelerated and what is known as bremsstrahlung gamma rays come. These gamma rays cause photo fission giving rise to neutrons but this efficiency is quite low and almost 1000 MeV energy per neutron is required at electron-based sources.

Electron-based sources suffer from the problem that this gamma ray which is causing photo fission can also cause heating of the target and that causes the problem of raising the power or raising the flux output of these sources. So, these are usually low flux pulsed neutron sources, but the major resources today are spallation neutron sources. Here we have a proton beam of high energy hitting a target and generating neutrons by spallation reaction.

Now, usually these sources are pulsed. ISIS at Rutherford Appleton Laboratory UK, SNS at Oak Ridge in USA and also in Japan we have the spallation neutron sources. One is coming up at Europe as a joint effort named ESS or European Spallation Neutron Source, which is coming up in one of the Nordic countries.

Mostly they use time of flight techniques, but there are some exceptions when we can do time of flight scattering in a reactor. Similarly, there are some spallation neutron sources which act like a continuous source and the example is the PSI source in Switzerland. This source uses a large continuous current, of the order of milliampere, impinge on a target and it acts like a reactor. So, all the reactor-based spectroscopy or scattering techniques are equally applicable to PSI with some time-of-flight based techniques.

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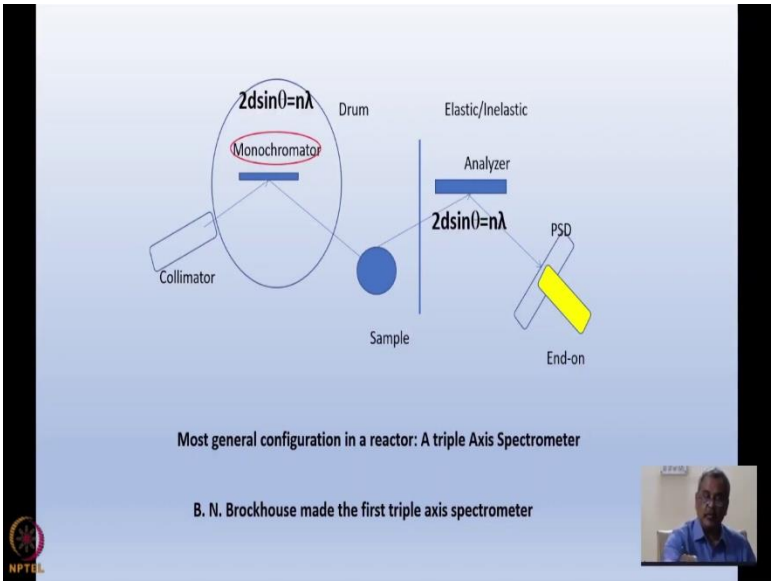

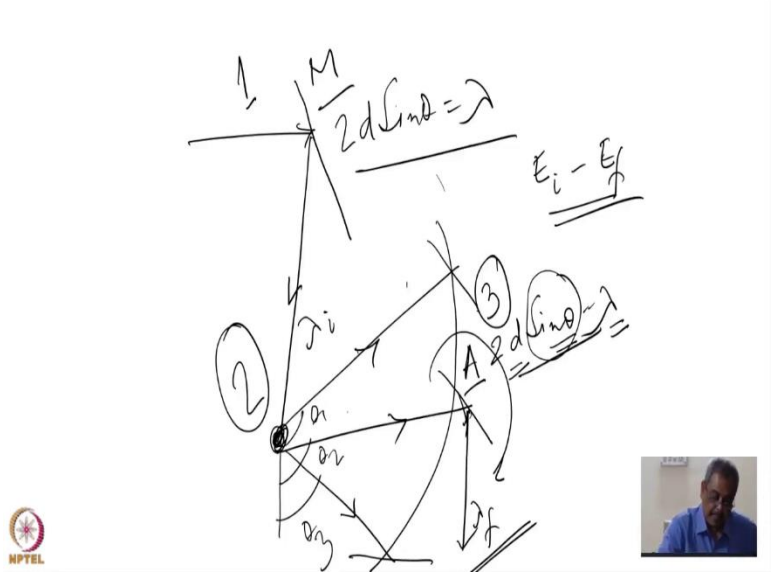

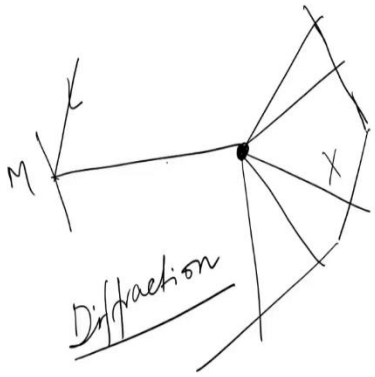

Now, I would like to go back to the most general instrument design in case of a reactor. It is usually a monochromatic beam-based technique. There is a collimator which allows the direction of the beam to be fixed, then there is a monochromator which choses a Bragg angle.

These can be pyrolytic graphite, silicon, germanium crystals which gives monochromatic beam that falls on the sample. And then for the outgoing (scattered) beam, the direction and the energy can be detected by putting an analyzer crystal (in the beam path) which rotates around the sample. This analyzer crystal again using the same principle of Bragg diffraction, $2d \sin\theta = n\lambda$

From this scattered beam, it selects a beam and as you keep rotating this analyzer around its own axis, you can change the $\sin\theta$ and you can detect different (scattered) wavelength (λ). And by going around the sample, you can go to various *k* values in different directions. So, you can scan at different (scattering) angles. So, the analyzer can go round the sample and change this wave vector transfer (being measured).

Because these angles with respect to incident angles are different. We can go for various angles by taking the analyzer around the sample. And by rotating the analyzer around its own axis, I can change the $\sin\theta$ for the same *d* spacing.

And for every angle, I can detect the final energy. In this way, I know E_i - E_f from this data. Monochromator is axis 1, sample is axis 2, and analyzer is axis 3. And if I do not want the

information about the final energy, that means if I am doing a diffraction experiment, then I can forget about the analyzer crystal.

Today in most of the instruments in Dhruva and other places, we have position sensitive detectors covering a large angle and collecting the scattered data over a large angular ring in my detector. So, this is how the diffraction experiment is in a reactor.

When I want to do inelastic scattering, that means, I want to know about the dynamics (of the system) and need to measure the energy differences (in scattering) then this is not the way. I need to have analyzer and one more step to find out the energy of the outgoing neutron. That is the most generalized spectrometer.

And usually, detector is at end-on position because I have to rotate it (around the sample). When I am rotating the analyzer on its own axis, the detector has to follow to catch the neutron beam and then it is put in an end-on position. These are the two differences I will explain briefly.

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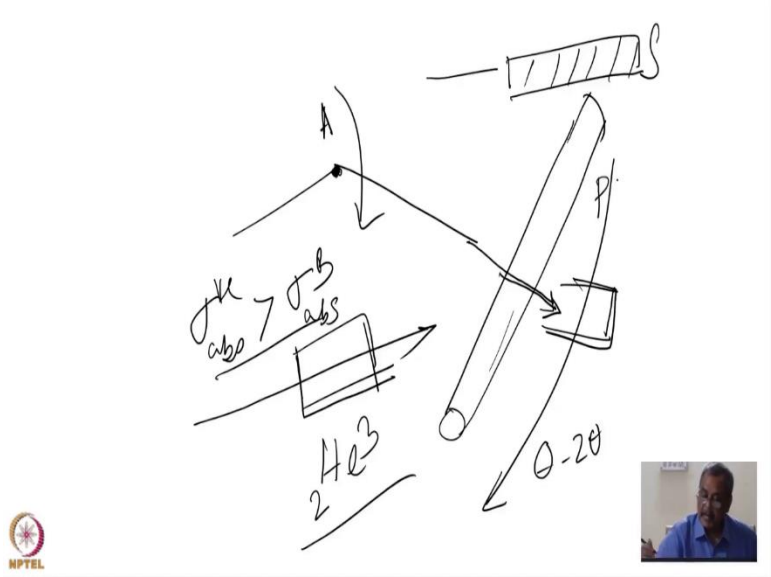

In a scattered beam, usually, PSD is put like this. This is a 1 m long position sensitive detector. So, the beam enters and gets detected. This is the beam path. But if we do a serial scanning, then the, analyzer is rotating and the detector is rotating in a theta-2theta coupled mode. The detector is here in end-on position where the neutron enters like this (along the cylindrical axis) and traverses the length of the detector.

Whereas, in this case (PSD), the neutron traverses the radial distance for the detector. And this is the main reason that all our PSDs are using Helium-3 gas. Because if you remember that the neutron absorption cross section for Helium is much larger than of Boron. So, because in this geometry the neutron traverses much shorter length in the detector compared to the end-on position, where the neutron traverses a much longer path in the detector. The only issue (to note) is that in this case (end-on) it is a serial scanning. Here (PSD) I may say the scanning is at the same time or parallel scanning.