Neutron Scattering for Condensed Matter Studies
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Week 03
Lecture: 07A

Keywords: Beam transport, Moderators, Cold neutron source, Hot neutron source, Beam lines, Neutron guides

In this lecture, I will be discussing various components of neutron scattering facilities, which means the tailoring of the beam and the transportation of the beam. I will start with tailoring, and then I will talk about transportation.

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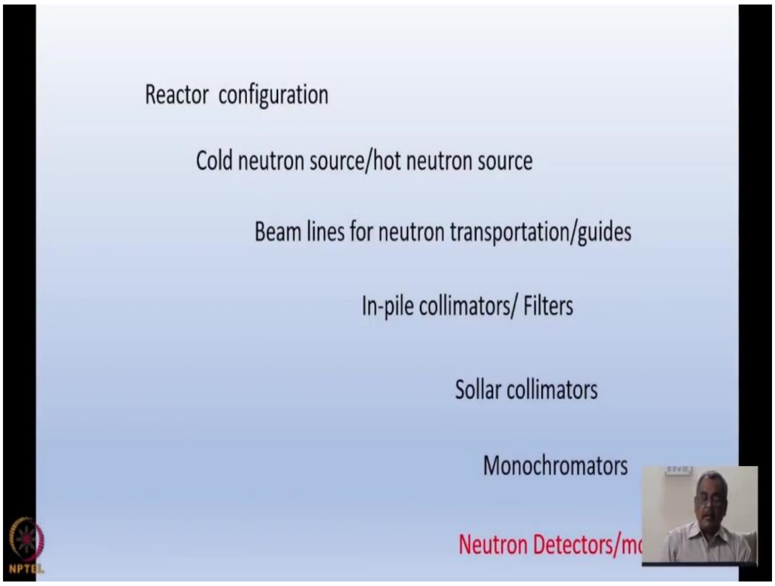

I will be discussing about reactor configuration, then various components that we use in the reactor. Then beam lines for neutron transportation and also guides which can transport neutrons very far. There are components like in-pile collimators, filters to reduce the unwanted fast neutrons and gamma in the beam because they also come out in a reactor or in spallation neutron target. There are sollar collimators in the beam which retains the beam size, but improves the resolution at the same time.

I will discuss the monochromators that are put in the beam to get a beam of one energy in case of reactors then the beam is collimated that means a beam of certain energy is directed to incident on the sample that we are going to study. Neutron detectors are extremely important component in a neutron scattering experiment. I will spend some time on describing to you the role of neutron detectors and the various detectors that we have got to improve the quality of data and time we need to collect data.

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In a research facility, either a reactor or a target in a spallation source, one provides penetrations to bring neutrons to the spectrometer. In case of a reactor, the penetrations reach to the core and from the core the beam comes out and the neutrons flow to the beam mouth. In case of spallation neutron sources, the target is surrounded by a few moderators because the target produces fast neutrons in spallation. These neutrons go in various directions, which are captured in the moderators kept nearby.

And after that, we have large beam paths to take these moderated neutrons away from the target and to the experimental stations. Here I am talking about either research reactors or spallation neutron sources. I am not considering the other neutron sources like Ra-α-Be sources or Californium (Cf) sources, which are used for many other purposes. But they are of very low intensity. They are actually typically the sources of 10^5-10^9 neutrons per second (n/sec). This is too low of a flux for utilization in a neutron scattering experiment.

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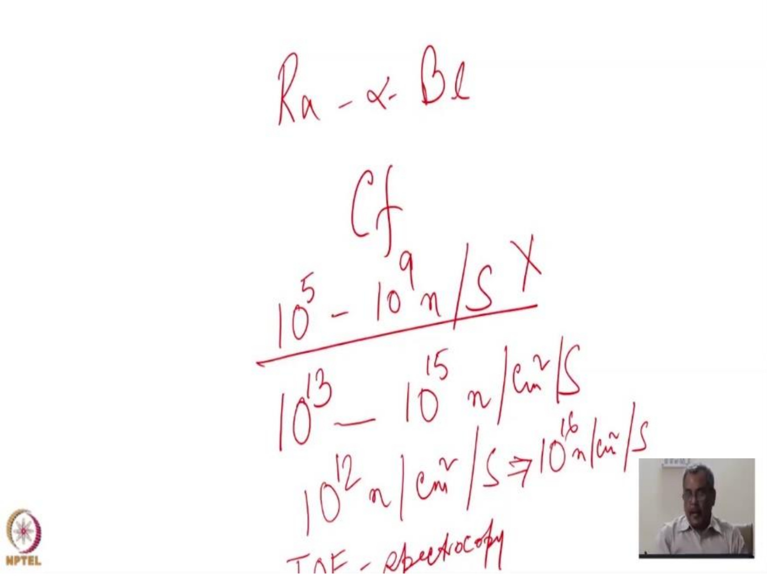

In case of neutron nuclear reactors, the flux varies between 10^{13}-10^{15} n/cm^2/sec. In case of pulsed neutron sources like spallation neutron sources, for example, Rutherford Appleton Laboratory in UK, the average flux is possibly much lower but because of the pulsed nature of the source where 50 pulses come every second, its capability is comparable to a high flux reactor. We use something called ToF spectroscopy in a pulsed spallation source. This source can compete with a 10^{16} n/cm^2/sec reactor source. At the moment spallation neutron sources are the most sought after neutrons sources for experimental purposes.

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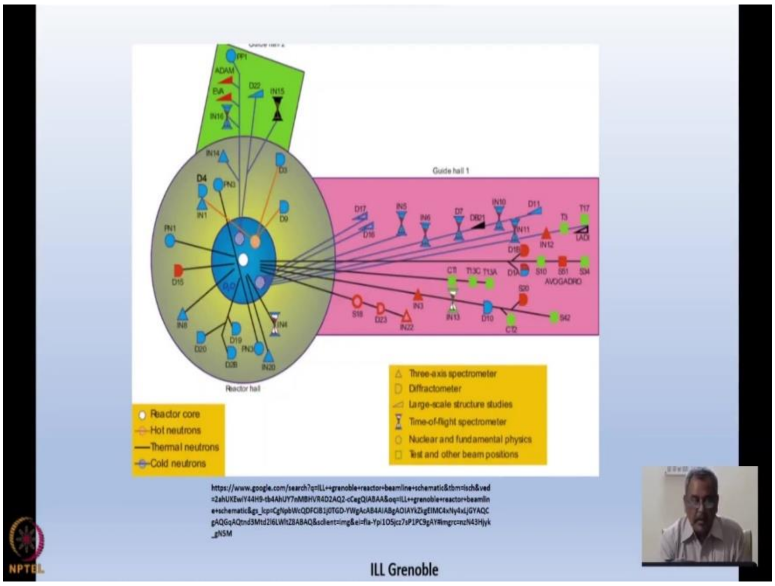

Before I discuss the source tailoring, let me show you how the complete setup looks like. It is a schematic of ILL Grenoble reactor where the white circle at the center is the core of the reactor which is very small because it is a swimming pool type reactor with highly enriched uranium core. The core is of about 30 to 40 centimeters diameter and then surrounding it, there is a large quantity of reflector that helps to have a reasonable isotropic flux in the reflector, and various kinds of facilities to tailor the beam and also various beam lines. You can see that some of the beam lines have ended in the reflector itself and are not going up to the core because the flux here is fairly isotropic and almost same compared to the core. Or the thermal neutron flux may be better from the core. Hence, it is okay to have beam lines ending in the reflector. There are certain advantages which I will discuss later. Typically, this is how it looks like: the core, the beam lines and the long guides. With neutron guides which go to the guide hall, you can carry the neutrons away from the core. Inside the reflector region around the core, there are hot neutrons, thermal neutrons as well as cold neutrons. A hot neutron source or a cold neutron source is a facility to tailor the neutron energies to our requirement and how it is done and I will discuss next.

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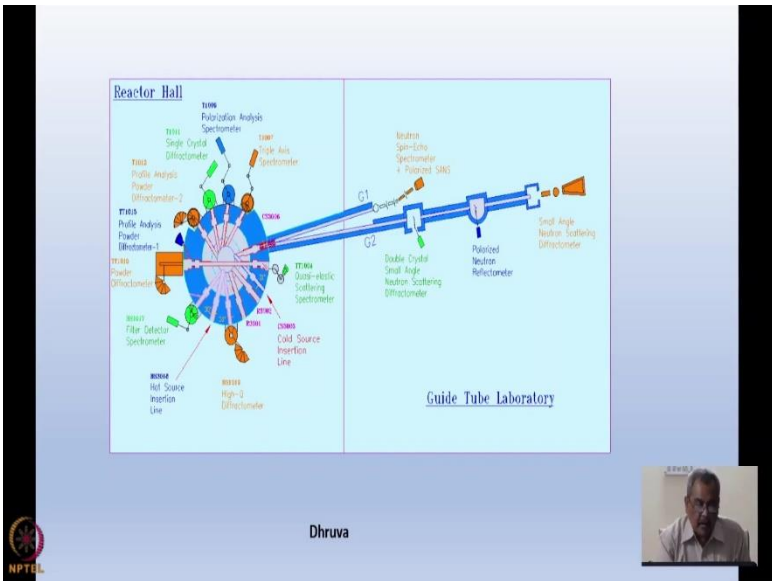

I also show you the reactor core in Dhruva in BARC, Trombay. Here also you can see that there are beam lines; some of them are radial and some of them are tangential, and these penetrations bring the neutron beams out and then we have two long neutron guides. I will discuss how the guides transport neutron and explain to you the role of guides being played in accommodating more number of experiments. In schematic of almost all the sources, you can see the core, the beamlines and the beam tailoring facilities.

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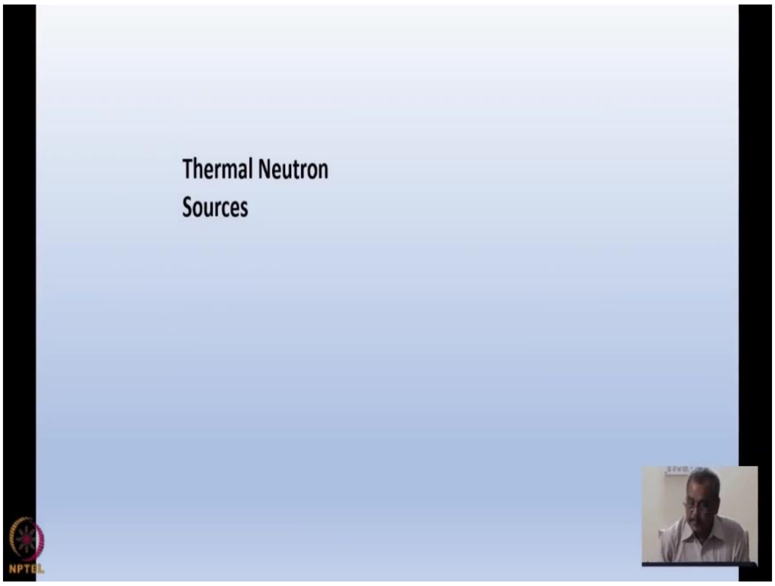

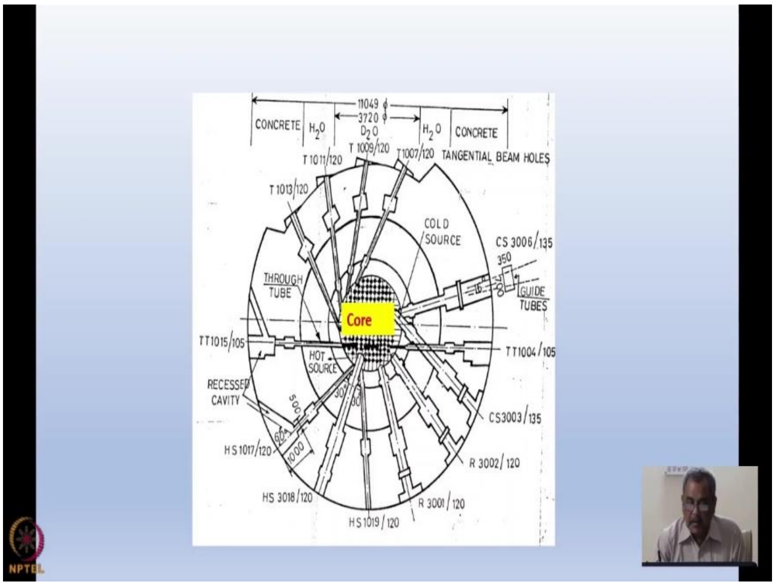

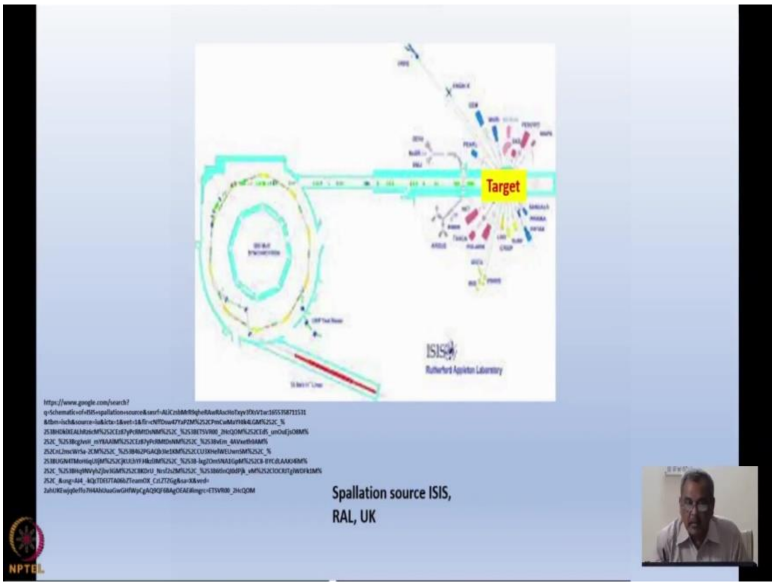

The target is surrounded by the beam lines and the beam tailoring facilities. What I mean by beam tailoring facilities are the moderators.

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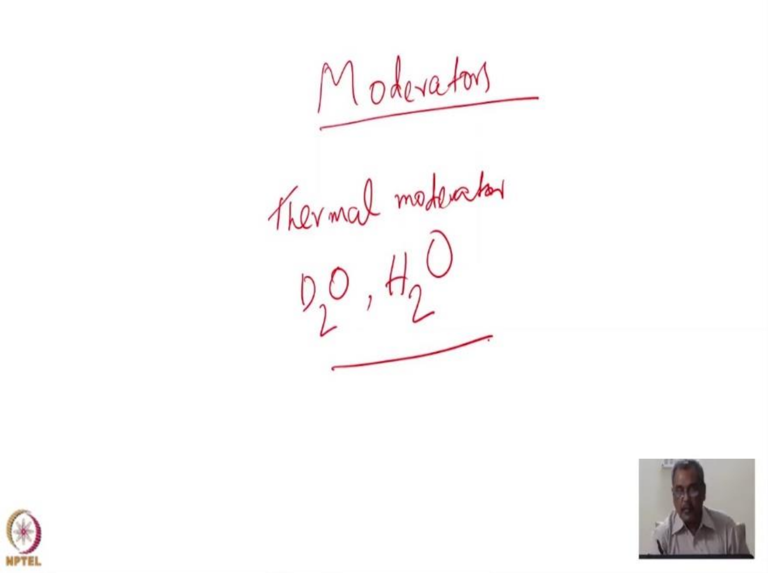

In case of neutron reactors, the thermal moderators, like D_2O, H_2O are right in the core. In case of target stations, they surround the target in spallation neutron source and from there the beams are transported to the experimental sites.

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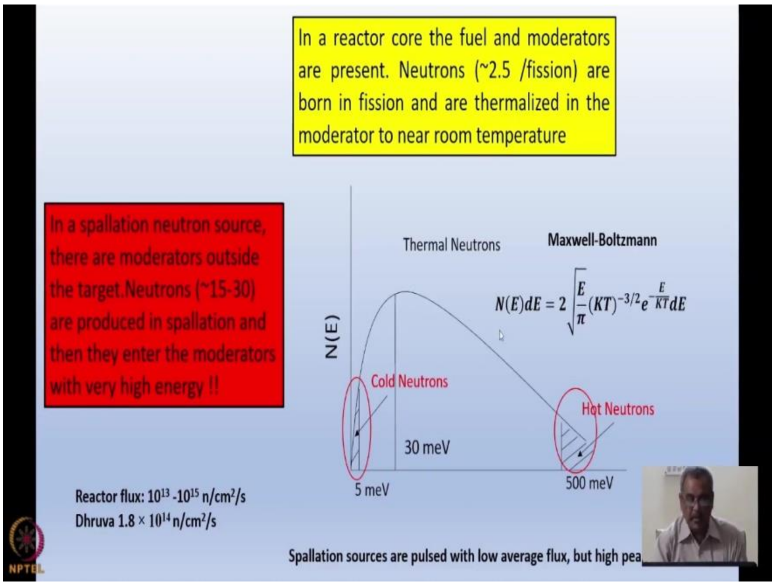

As I told you, in a reactor core the fuel and moderators are present. Around 2.5 neutrons per fission are born. In a spallation neutron source, the neutrons are around 15 to 30 per spallation and the moderators are outside the target. The reactor flux is typically around 10^{13} to 10^{15} n/cm^2/sec. In Dhruva, we have 1.8 x 10^{14} n/cm^2/sec. I would like to show you the spectrum here. You can see that the spectrum peaks in the thermal energy region, around 30 meV energies, but there are regions which are called cold region, typically neutrons energy less than

5 meV and neutron with energies typically 400-500 meV that are called the epithermal neutron or hot neutrons. The Maxwell Boltzmann distribution is shown here in the plot.

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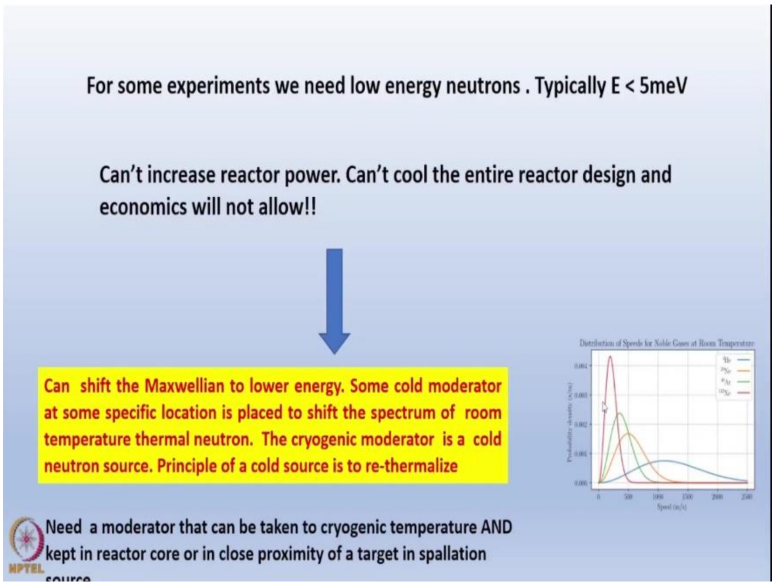

For some experiments, we need low energy neutrons, typically with energy less than 5 meV. Now, we cannot increase the reactor power so that the entire Maxwellian and the integrated flux goes up and the cold flux also goes up. That is desirable but we cannot do that. We cannot even cool the entire reactor core because the reactor design will not allow that.

However, we can shift the Maxwellian to lower energies, if we keep some cold moderator at some specific location to shift the spectrum of the room temperature thermal neutrons to lower temperature. The cryogenic moderator is a cold neutron source and the principle of a cold neutron source is to re-thermalize neutrons.

I have just plotted some Maxwellians at various energies. If you look carefully, this orange line is a Maxwellian at a higher temperature compared to the green line and the other red line.

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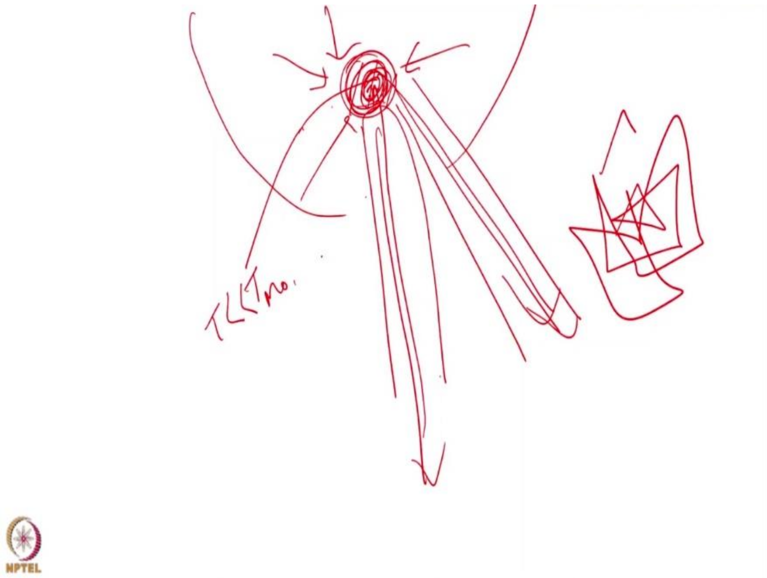

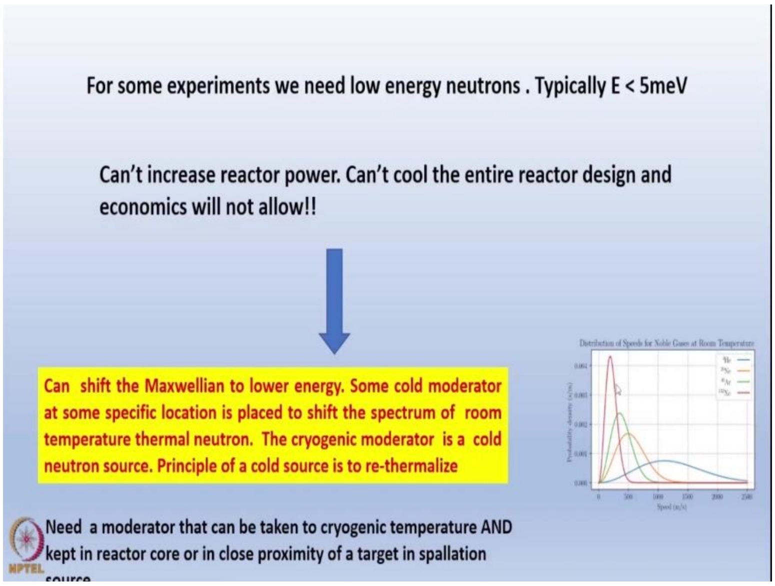

At the end of a beam line, either there is a thimble which is inserted vertically or horizontally. We can insert some cryogenic moderator from here. The principle is that some cold moderator is placed at a location in the reactor core. The reactor core is huge and you do not try to cool the entire core or raise the power, but at one location we keep some cold moderator and if it is inserted vertically then this beam looks at this cold moderator. Maybe there will be some more beams which are looking at the cold moderator and they see more number of cold neutrons coming out and not thermal neutrons. So, the thermal neutrons come from the rest of the reactor go inside it (cold moderator), undergo collisions (this is a Fickian diffusion and collision) and in this process their temperature becomes much lower than that of the moderator of the reactor. This is a Maxwellian at lower temperature and as I have shown in the drawing that this moderated spectrum has large number of cold neutrons and that way, I can enhance the number of cold neutrons. So, a cold neutron source is primarily not a source, but a spectrum shifted to lower energy and we can get gain as large as 10 to 15 if we design everything properly.

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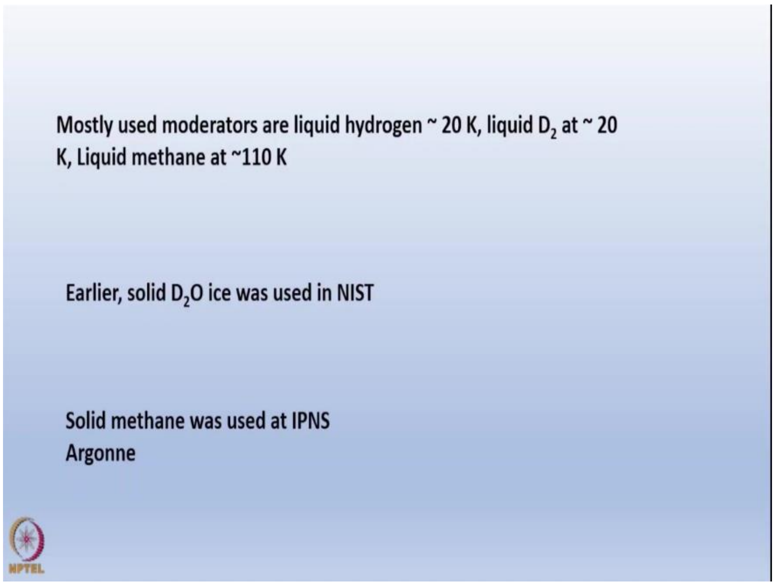

Mostly, the moderators used are liquid hydrogen at around 20 K, liquid deuterium at around 20 K and liquid methane at around 110 K. At one point of time, solid D_2O ice was also used at NIST and solid methane was used at IPNS Argonne. These are all attempts to shift the spectrum of the neutron.

Why do we use liquid deuterium when liquid hydrogen is good enough? The reason is that deuterium has a much smaller absorption cross section for thermal neutrons, and when we use 20 K Hydrogen, then it absorbs neutrons, and the flux goes down slightly. Liquid deuterium can give higher flux, because it does not absorb any neutron. And that is why liquid deuterium is used.

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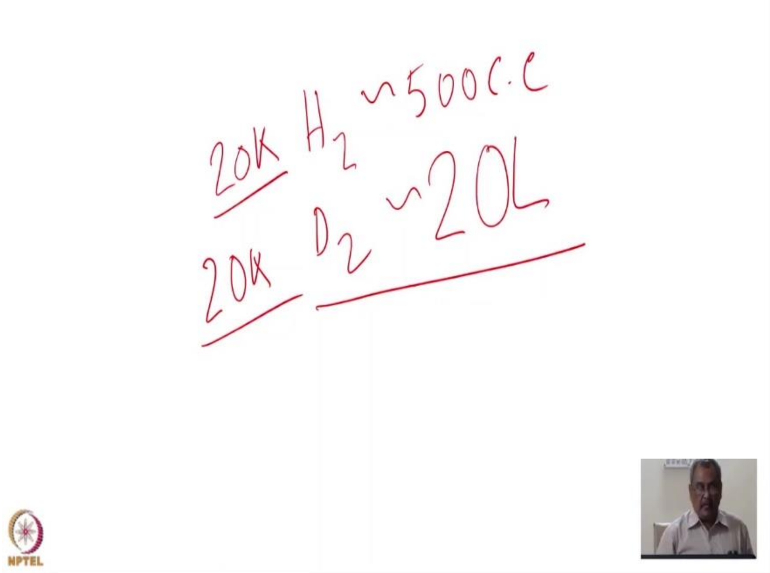

But the other fact is that liquid hydrogen has a much larger scattering cross section and deuterium has a much smaller liquid scattering cross section. When we use hydrogen, around 500 cc of hydrogen is good enough. But for liquid deuterium around the same temperature, 20 K, one need around 20 liters of deuterium, because it has got a smaller scattering cross section. Why do you need so much? Because to thermalize a neutron it has to undergo coalition and if the scattering cross section is low, then you need larger volume to do the same thing. Obviously, to maintain half a liter of hydrogen at 20 K is a much lesser cryogenic load than to maintain 20 liters of deuterium at the same temperature. And that is why to maintain 20 liters of deuterium is a tall order cryogenically but it gives gains.

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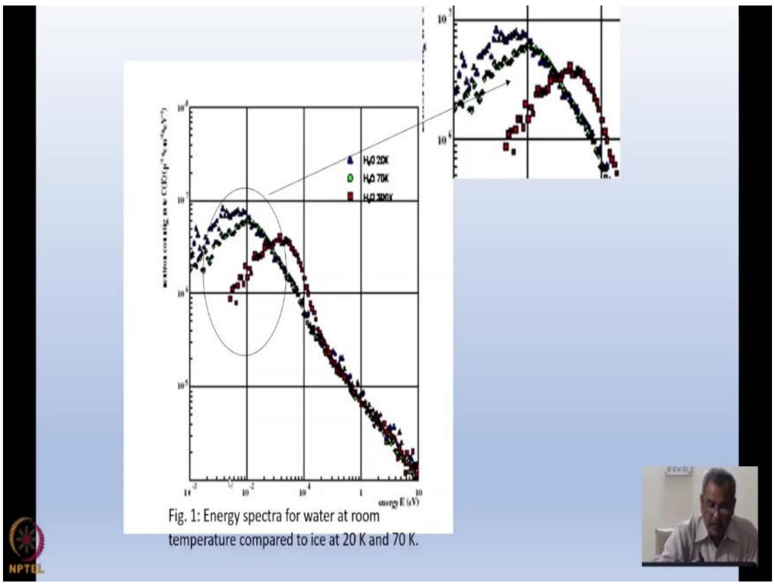

I am just trying to show you the energy spectrum for water at room temperature compared to ice at 20 K and 70 K. It is just a demonstration. There is a gain at some energy, say 10^{-2} eV OR 10^{-3} eV. The gain is very large, somewhere around say 4 or 5 meV.

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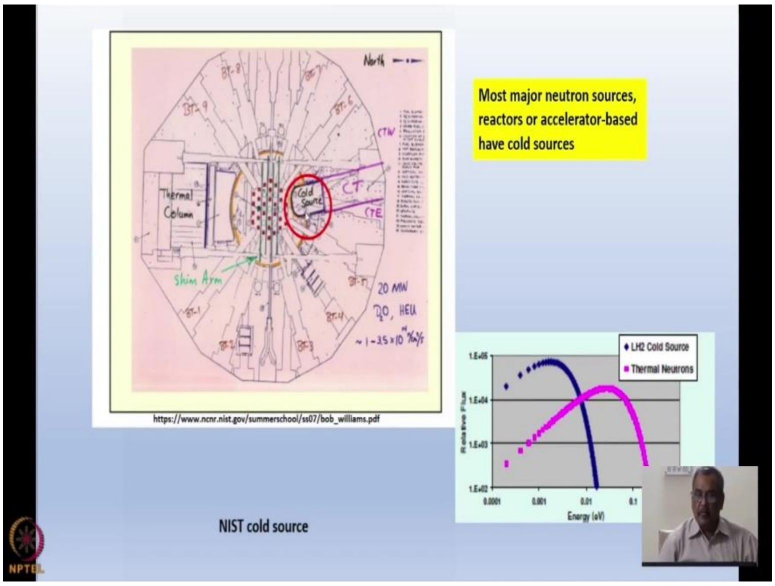

NIST has a liquid hydrogen cold source. You can see there is a beam line in which it is inserted. Here, gain is as large as 100 at an energy of around 1 meV. Such high gains allow us to use cold neutrons for experiments where they are required. I will come to it later to explain the kind of experiments where we need cold neutrons.

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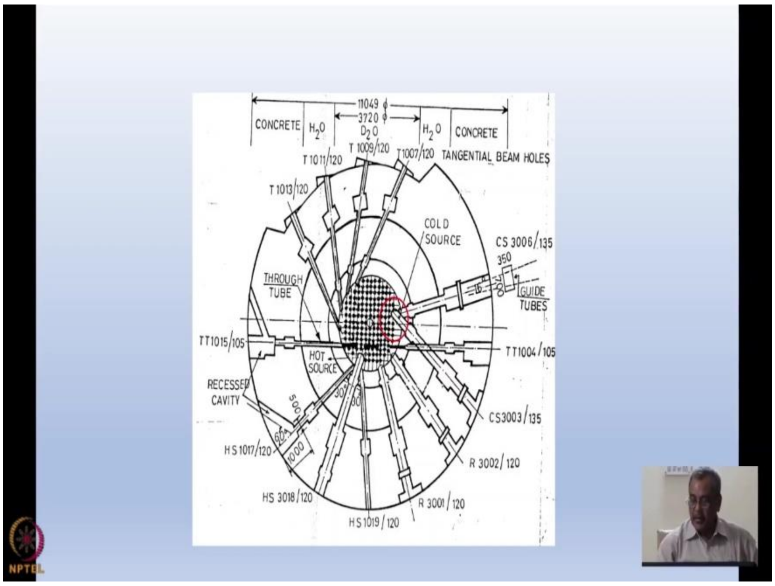

In Dhruva also we have got a recess to use cold neutrons for our experimental purposes, but still that has to be done. We have to install a cold neutron in the beam hole CS 3003.

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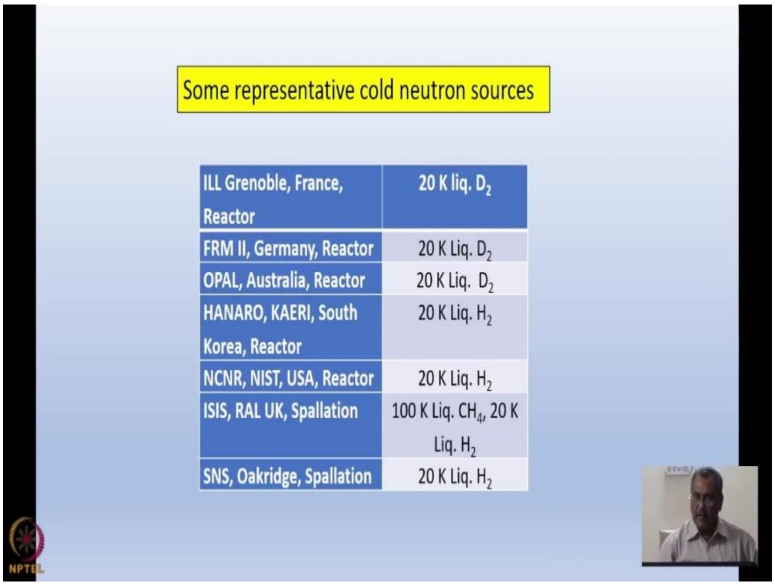

I give the list of some of the cold sources: ILL Grenoble France, have a 20 K liquid deuterium source, FRM II in Germany has 20 K liquid deuterium, OPAL Australia has 20 K liquid deuterium, KAERI, South Korea has got liquid hydrogen, NIST, USA has liquid hydrogen, ISIS at Rutherford Appleton Laboratory have got methane as well as liquid hydrogen, Oakridge Spallation source, SNS has got 20 K liquid hydrogen. These is just a representative list showing that most of the major neutron sources have liquid hydrogen.

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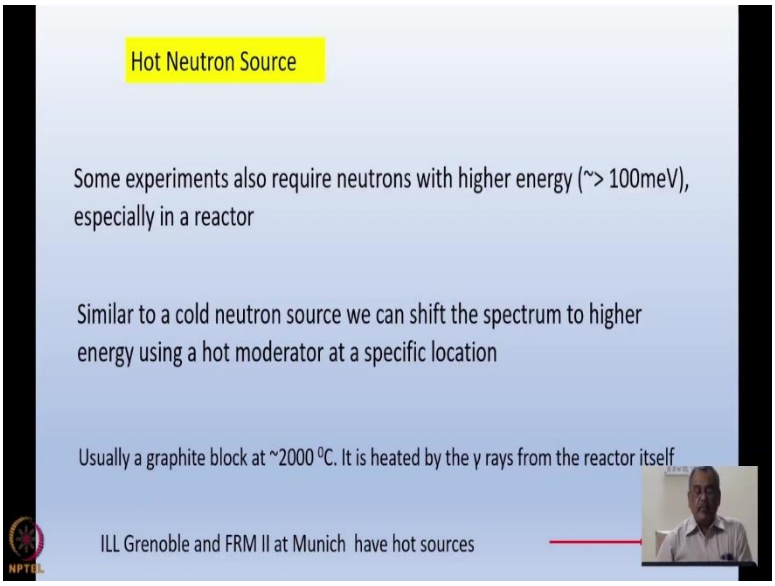

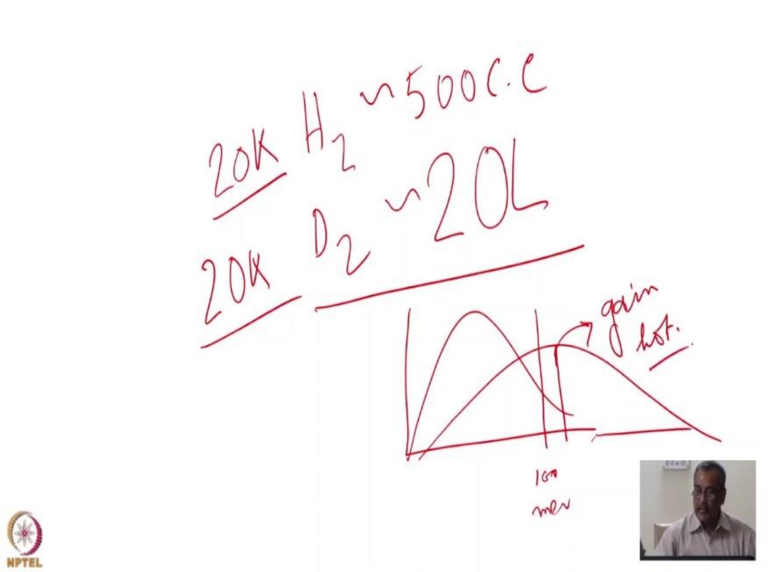

We also need hot neutrons or high energy neutron for some experiments. And we can always improve the hot neutrons flux by shifting the spectrum from thermal energy to higher energies and then at the cost of low energy neutrons we have gains at the higher energies.

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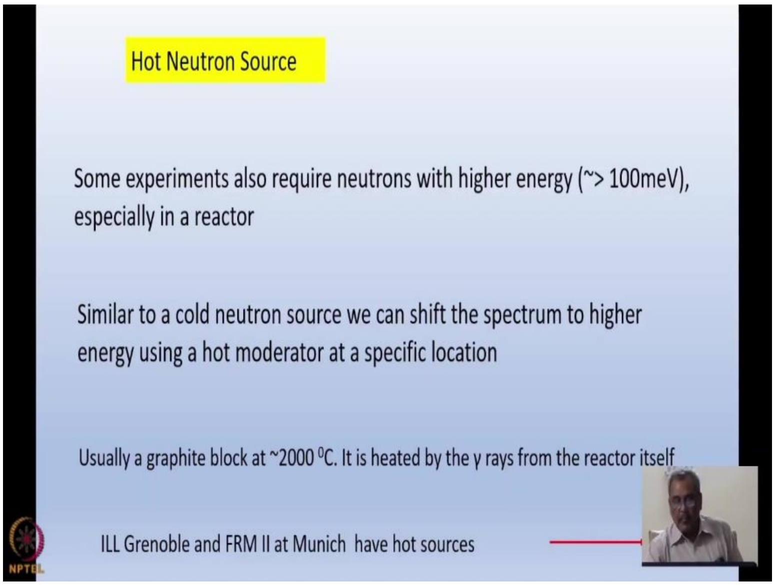

Such sources are also used in various places where you usually put a piece of graphite block at around 2000^0C. We do not need a separate heating arrangement; it can be heated using the gamma rays from the reactor itself. ILL Grenoble and FRM at Munich have hot sources, but not too many neutron sources have hot neutron sources because the spallation neutron sources can provide lots of hot neutrons. I will stop here.