Keywords: Radial beam holes, Tangential beam holes, Through tubes, Neutron guides, Curved guides, Transmission loss

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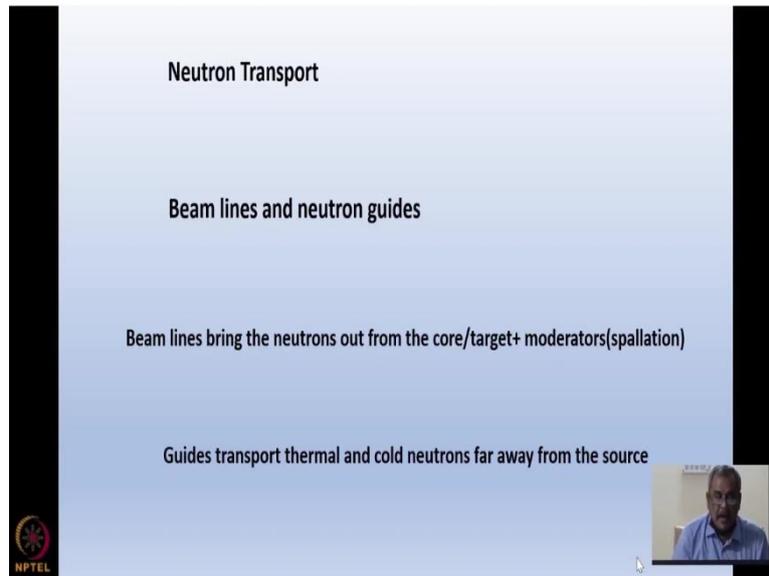
This lecture started with the topic of neutron source. I explained to you how to tailor-made the neutron spectrum inside the core using various kinds of sources. I explained to you that the thermal neutron flux is the one which is predominantly all over the reactor core, but we can modify the spectrum using something called a cold neutron source to lower energy and something called a hot neutron source which will shift the spectrum to higher temperature.

When I say shift the spectrum that means the total area under the Maxwellian, which is the total number of neutrons, remains conserve, but the spectrum shifts to lower energy and then there are gains in the lower energy side of the spectrum. Similarly, for a hot neutron, there are gains at the higher energy of the neutrons. So, they do not actually act as sources in the same way that they produce neutrons, but rather re-thermalize the entire spectrum and gives us a peak which is desirable when I need low energy neutrons in the low energy side, or when I need hot or high energy neutrons in the high energy side. This is done by a small amount of cold moderator for the cold neutron sources at a specific location inside the core. The beam lines which transport the cold neutrons, they look at this particular source and look at the

modified thermalized low temperature spectrum having gain at the lower energies as compared to the thermal neutron flux in the core.

Similarly, a piece of hot graphite inside the core at the temperature of around 2000^0C shifts the entire spectrum to high energy side. Among the cold neutron moderators, liquid hydrogen, liquid deuterium, liquid methane and solid methane have been used heavily because these are low Z element-based sources so that the energy transfer is efficient. Instead of hydrogen, deuterium is preferable because D_2 has smaller neutron capture cross section compared to H_2, so that you do not have any absorption. At the same time, D_2 has a smaller scattering cross section as compared to hydrogen, so, the mean free path is large. Hence, we need a larger volume of deuterium. When you use deuterium, it can be to the tune of 20 liters of deuterium, whereas, when we use liquid hydrogen, it can be half a liter of hydrogen. So, the cryogenic load for a D_2 source is more, but it is worthwhile if economics that means the finance allows.

We will talk about neutron transport in this part of the lecture. Neutron transport from the core to the beam mouth happens through neutron beam lines and we can carry neutrons far away using neutron guides. Beamlines bring the neutron out from the core and the moderators. In case of spallation source, there are moderators surrounding the spallation target. Because Spallation target produces only high energy neutrons, they are captured in a moderator kept strategically either above or below in the vicinity of the target. And then from here beam lines bring the neutrons out followed by guides if they are cold neutrons. This is the topic for today.

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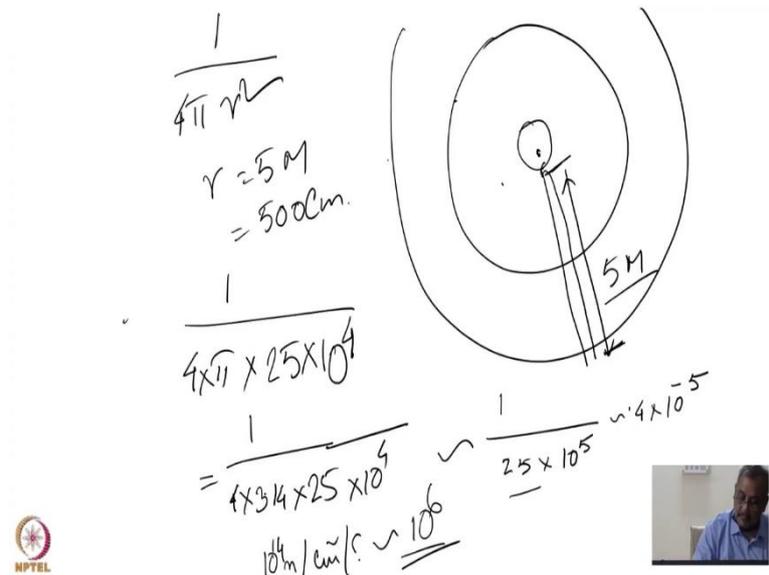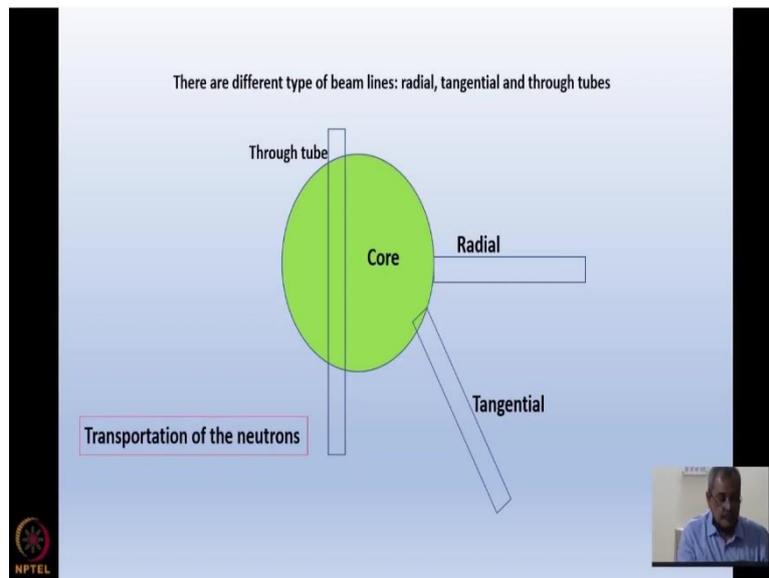
There are different kinds of beam lines such as radial, tangential and through tubes. A neutron beam has to come out from the core to the mouth and this distance is approximately 5 meters. These beam lines allow flow of neutrons through these beam tubes, but the fact remains that any point in the core acts like an isotropic source and hence the intensity of the neutron beam at a distance r from the core falls as $\frac{1}{4\pi r^2}$. If r = 5 m = 500 cm, then at that distance neutron beam intensity falls by almost a factor of 10^6. That means, if flux at the source is around 10^{14} n/cm^2/sec then only $10^7 - 10^8$ n/cm^2/sec comes out. This is a huge fall in flux which shows that neutrons are expensive and a proper beam tailoring is required.

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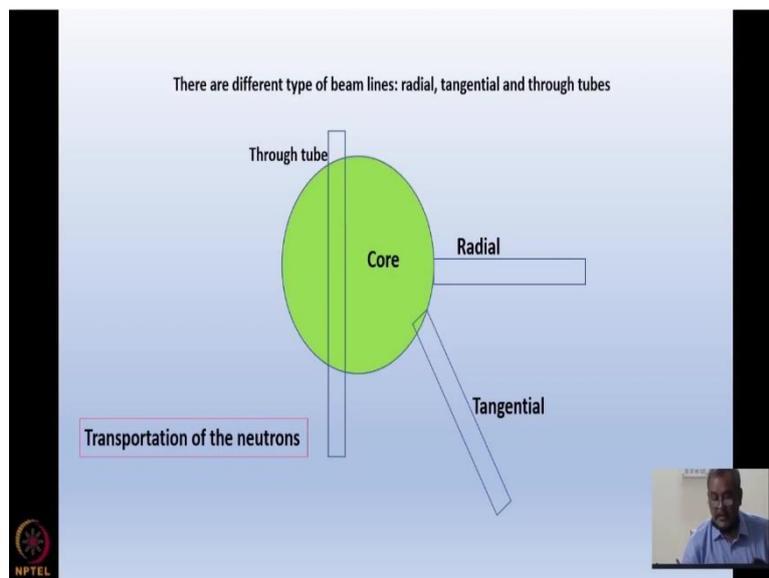
The radial beam lines are the ones which look at the core radially whereas the tangential beam line looks at the core tangentially. There are also other kinds of beam lines which are known as through tube that runs through the core.
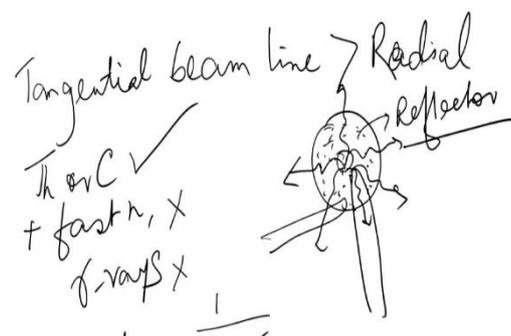
The fact is that a tangential beam line is longer than a radial beam line, then why should I make tangential beam lines? The reason being, if I look at the core, the gamma rays and the unmoderated fast neutrons they tend to go out radially. When I look at the core radially then along with the thermal or cold neutrons you have fast neutrons and gamma rays, which are traveling radially. Fast neutrons have not undergone too many collisions when generated at the core and they tend to go radially.

When I make a beam line tangential, somewhat like this, then I am not looking at the core directly. Sometimes when we go out from the core to the reflector and in the reflector, if it is small core like ILL Grenoble, here I have the neutron flux almost isotropic and uniform or maybe falling somewhat slowly. Here, I can make the beamline look at a certain part of the reflector but not directly looking at the core. So, this reduces the fast neutrons and gamma rays and allows thermal or cold neutrons. But we know that in this case, $\frac{1}{4\pi r^2}$ loss will be more. So, it is a gain *vs* loss picture.

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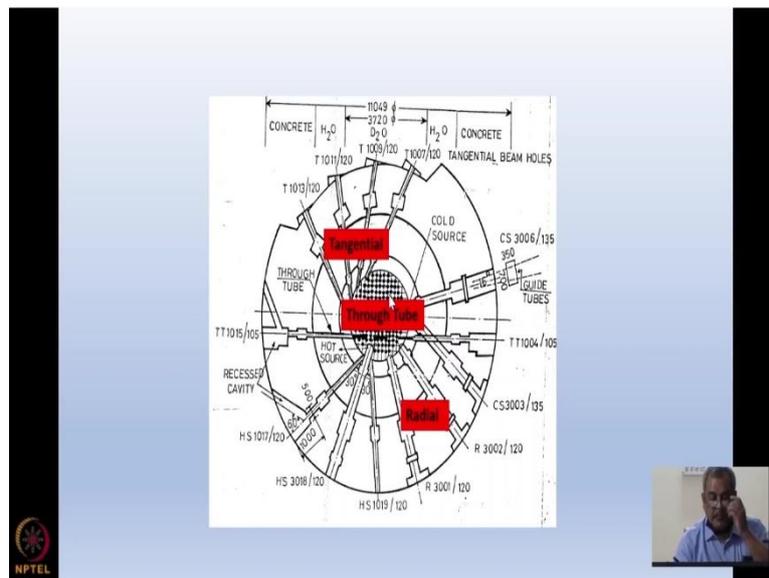
I will give you an example. This picture shows you that the top four beam lines are tangential to the core, which has a lattice of fuel cells at the center. The radial beam lines are at the bottom. Now, you can see that for the tangential beamlines the biological shielding wall to the core has been reduced. This is to maximize the flux, because in that case, it is traveling a shorter distance. At the same time, you have lesser number of unwanted fast neutrons and gamma rays, whereas the radial beam lines have all these unwanted fast neutrons and gamma rays and you have to shield accordingly.

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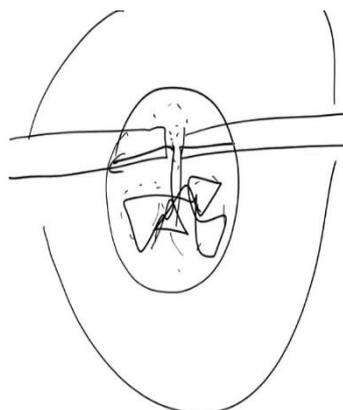
Now, why there are through tubes? The question is from where the neutrons will come to the through tube. In reality, a through tube has a gap between the two parts and it looks somewhat

like this. But in between there is moderator in the core. Now, why it should be like this? The reason being neutron which is undergoing a collision inside the core or neutron which is bend through a very large angle can come in through tube.

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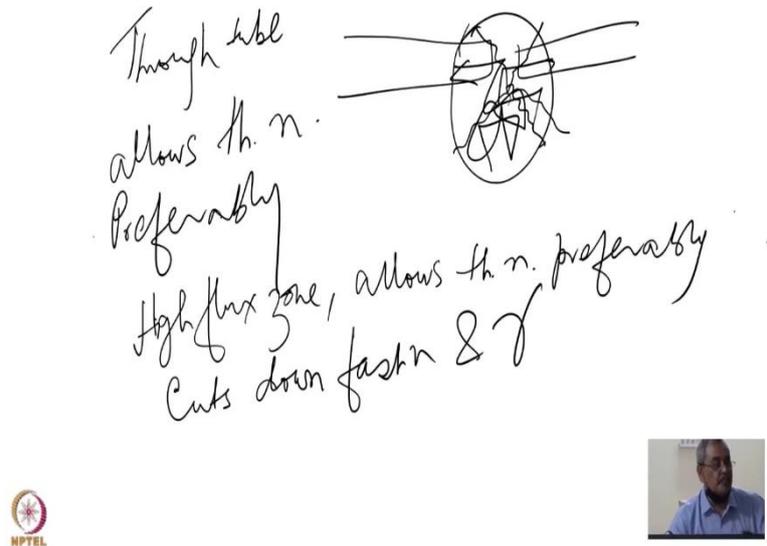
And the neutron which is scattered at large angle has a chance of better thermalization. So, through tube allows thermal neutrons preferably, and you can see, if the gamma flux is going out radially, they have less chance of coming out and same goes for the fast neutron flux. And also, since it is passing through the core, so, it is in a high flux zone. It allows thermal neutrons preferably and cuts down the fast neutron and gamma.

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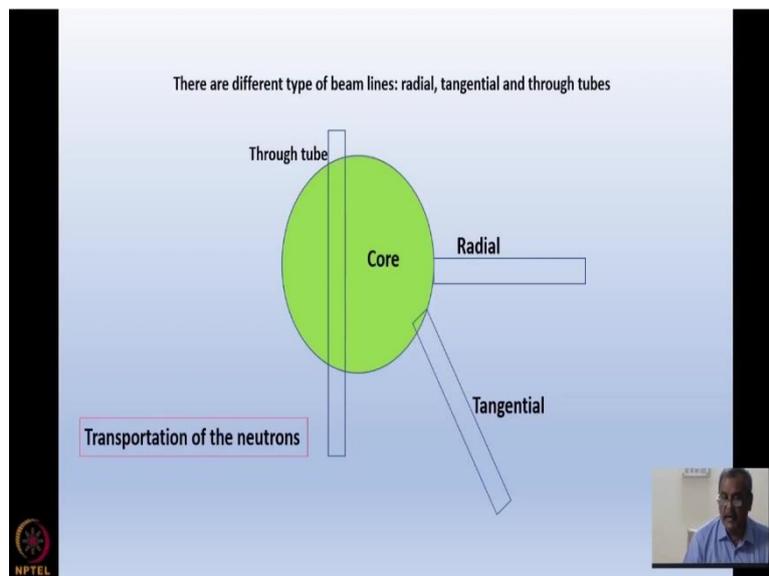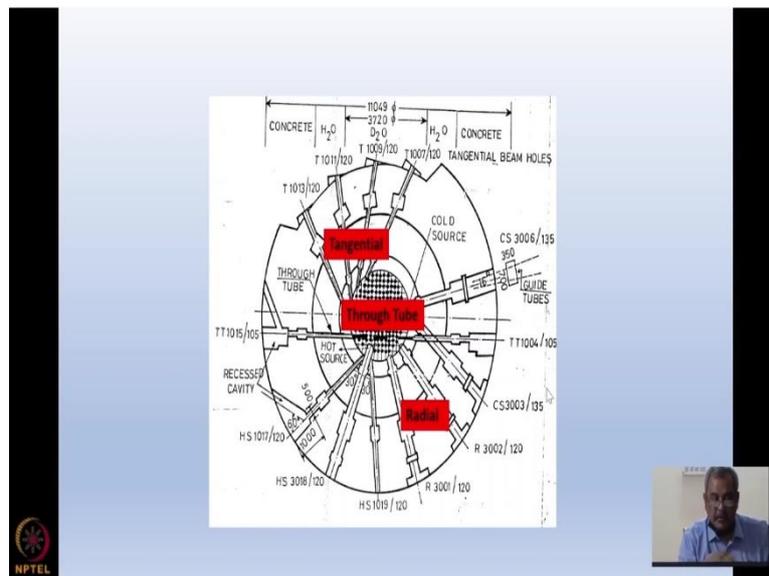
At Dhruva, we have got one beamline TT1015 on the left and TT1004 on the right (TT stands for through tube). Now, I have completed the discussion on the types of beam lines that one can have to bring the neutron beam out, preferably we expect thermal neutrons to go out and remove the fast neutron and gamma rays to the extent possible.

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In Dhruva, the core flux it is 1.8 x 10^{14} n/cm^2/sec which goes down to around 10^7 n/cm2/sec when it reaches a beam mouth and we cannot avoid this because it has to travel through the beam mouth to the outside.

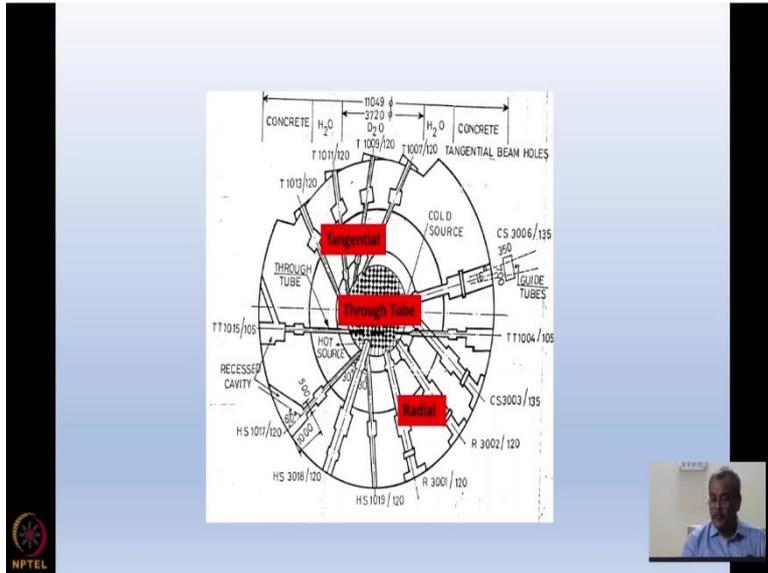(Refer Slide Time: 14:48)

Radial beam lines are the shortest. In Dhruva, we have 100 mm and 300 mm diameter beam lines. 300 mm beam lines are made so that allow some insertions to the beam tube. For experiment, we use the 100 mm beam lines through which the neutrons come out.

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This shows you in Dhruva the number of tangential beam lines, the through tube and the radial beam lines.

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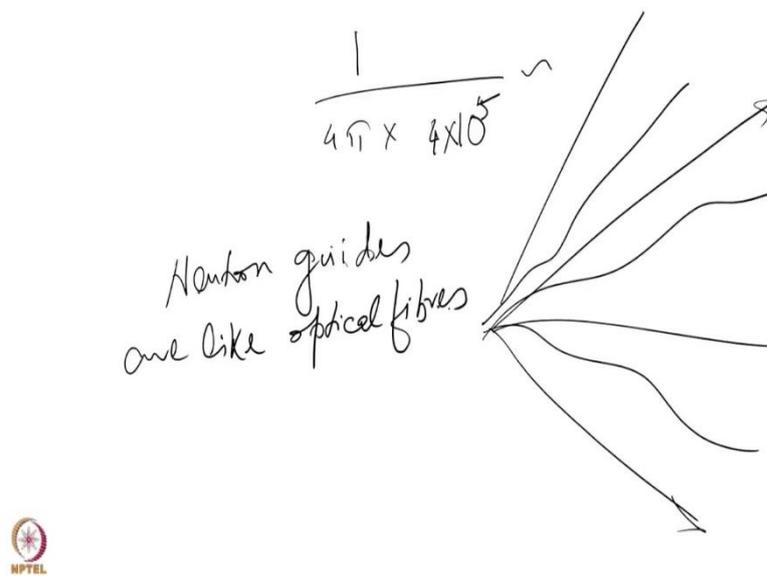For long wavelength neutrons there are neutron guides

Refractive index for x-rays and neutrons can be written as
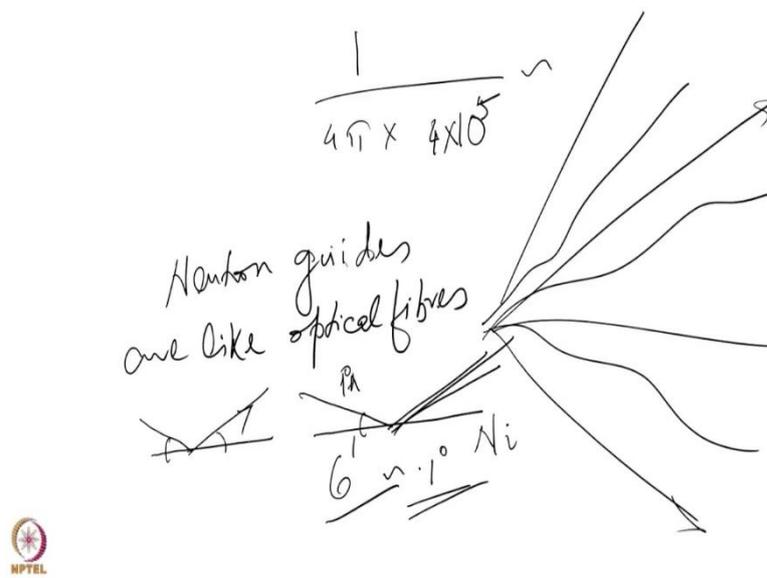
$$n == 1 - \delta$$

Where $\delta \sim 10^{-5}$ for x-rays and $\sim 10^{-6}$ for neutrons

Neutrons (and x-rays) undergo total external reflection

Critical angle for total external reflection, example Ni, 6 arcminutes per Å

Now, I will talk to you about neutron guides. If we want to go about 40-50 meters away, then we cannot allow neutrons to flow freely, because there will be huge reduction in the neutron flux. We cannot allow the neutron beam to keep on diverging and for that what we use are the inventions from the 1970s known as neutron guides. Neutron guides are like optical fibers

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In a very generalized statement, I can say that the refractive index for x-rays and neutrons for most of the materials are less than 1. It is marginally less than 1, around 1-δ where $\delta \sim 10^{-5}$ for x-rays and 10^{-6} for neutrons. Hence, I can say that neutrons and x-rays undergo total external reflection at very low angles.

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Let us say that the surface of guide tube as guide materials is Nickel then for a one angstrom neutron then it will undergo total external reflection up to 6 arc minutes or up to 0.1^0. That means, a neutron beam falling below 6 arc minutes angle will undergo reflection and the guides use this principle of reflection. Hence, the critical angle of Ni for external reflection of neutrons is 6 arc minutes per Å

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Now, if I want to take out a cold neutron or the low energy neutron typically let us say 4 Å. This 4 Å neutron will have a critical angle of 4 into 6 = 24 arc minutes that means, up to 24 arc minutes I can totally reflect this neutron.

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A typical neutron guide element

The cold (low-energy) neutron travels through reflection. Similar to optical fibre

Ni coated float glass in Dhruva

Neutron supermirrors. Large critical angle. ~ 2 of Ni

They can carry neutrons up to 100 M!!!!

Transmission 60 % or better

1 M   20 cm   2 cm


We can make something like a nickel guide. Here I show you in this drawing of a rectangular cross section nickel guide like this, and the inner wall of this is basically low roughness float glass coated with, let us say, around 0.1 micron thick Ni. Among elements Ni is the best suited for this purpose. This way, neutron guide or the optical fiber has two elements on two surfaces on the side and when the neutron impinges on the guide it gets reflected from the surface and then starts traveling. Basically, in this picture the neutron gets reflected and travels and hits the next element and I keep putting element after elements. This is one element followed by another element, followed by another element with each element around 1 meter long. So, if I put 30 such elements, I can take the neutrons out by 30 meters. By doing this, the neutron is traveling through total external reflection. Of course, this has to be a cold neutron, because, if it is a thermal or hot neutron the critical angle will be very low, so very less number of hot neutrons can come out, but for cold neutrons this angle is reasonably large and they will get transported

the way laser beam gets transported through an optical fiber and it travels through the guide and that it is not now suffering from a $\frac{1}{4\pi r^2}$ loss. So, the transmission depends on the length of the guide and how good we align them.

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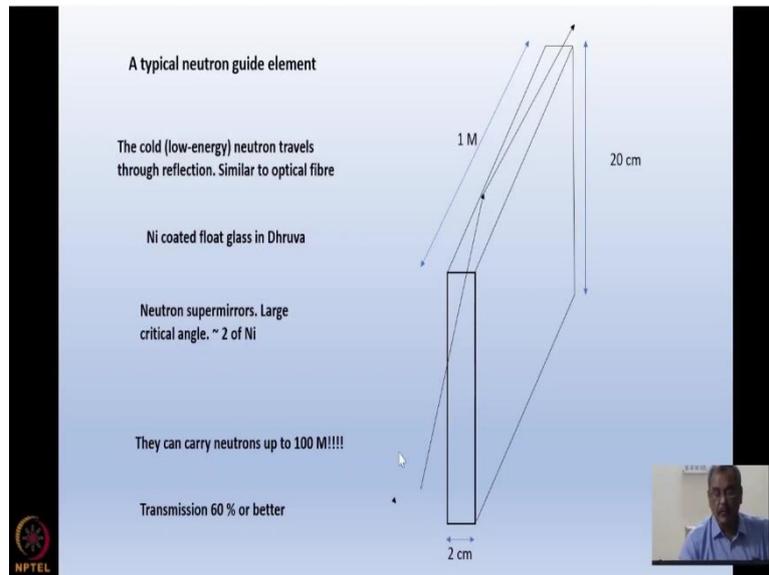
Because now, we are talking about such small angles, it is important that the alignment is proper. In Dhruva, we have nickel coated flout glasses. And there are also multiple coatings known as neutron super mirrors, I will explain shortly, which has got even larger critical angles. These can be used to carry neutrons up to hundreds of meters and they have overall transmission better than 60 or 70 percent.

Now, the fact is that if you can take neutron 100 meters out, then you can go out from the target hall in case of spallation neutron source or reactor hall in case a neutron nuclear reactor and when you go out from the reactor, then your background gamma and background fast neutrons fall drastically by 3 to 4 orders of magnitude. So, even with a 60 – 70 % transmission, we have much better signal to noise ratio.

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$$\frac{.6}{10^{-4}} \quad \left(\frac{S}{N}\right)$$

For example, if I have started with one neutron at the source then I have got say 0.6 neutrons for per neutron whereas, the background has gone down by a factor of 4. So, you can see this gives a very large signal to noise ratio. Along with this, the gaps in guides also allow us to put a number of experiments on the same guide which will be difficult to accommodate in a reactor.
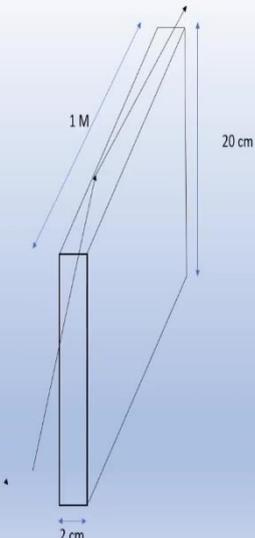
As shown in figure, this is the basic principle of the guide, the total external reflection from a coated glass and then it gets carried like this. If you were to take the neutrons far the intensity falls as $\frac{1}{4\pi r^2}$, if we just allow free flow, but here neutron guides act as optical fibers for neutrons. So, alignment of neutron guides is extremely critical. Another factor which I must mention is that because the neutrons are traveling hundreds of meters you need to evacuate the guides.

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Otherwise, you have around typically 4 % absorption in air per metre. So, if the guides are filled with air, then our purpose is lost because after 1 meter you have 96 % of the beam if 100 m guide then I will have very few neutrons out, $(0.96)^{100}$. We have to align the guides with very high accuracy because you can see the angles, I am talking about our arc minutes. And also, we need to evaluate the guides to avoid the loss of neutrons in the air absorption. Once you do that, we are ready with a neutron guide and they can take neutrons far away.

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Alignment of neutron guides are extremely critical actually, it is a long process, but it is possible to align mechanically, which is not a technological challenge. Neutron guides can be curved also.
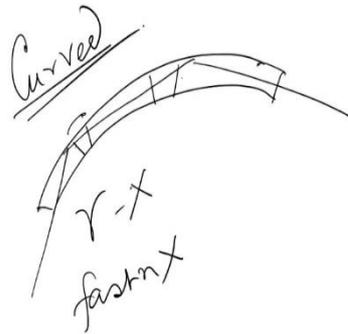
If I curve neutron guide like as shown in figure for a long guide. Basically, while I am curving, actually, what I am doing is, element after element I give an angle between the elements. This small angular displacement will curve the guide. If you have a curved guide, then the guide allows the neutrons to follow the curved path, but it does not allow the gamma or the fast neutron.

So, curve guide will allow clean transport of beams with very good drop in background neutrons and gamma rays and very high transmission for the desirable neutrons. Curved guides are also used many times to reduce the background.

The one shown in picture is an assembled neutron guide. In the picture you can see that this has to be held tight because it has to be free of any vibration. These are the neutron guides which have the elements typically about 1 meter long. In another picture, you can see a long channels, that are the guides in a source. You can see the guide hall and all the spectrometers. What is to be seen actually is that this guide hall is jam packed with instruments and we cannot put all these instruments in a reactor.

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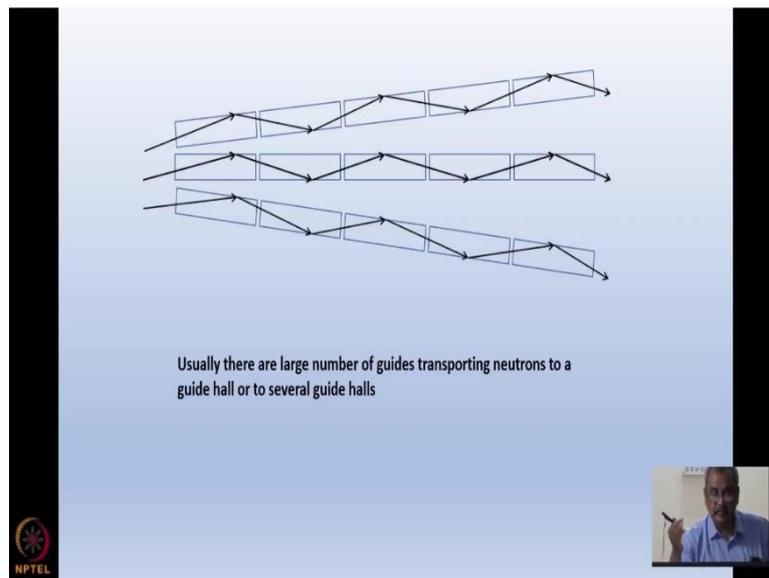If we avoid the direct line of vision to the reactor core, it removes fast neutrons and gamma ray background. It also acts like a band pass filter. Depending on the curvature of the guide, there is a critical angle. So, transmission versus lambda if I plot, it goes somewhat like this. So, it acts like a band pass filter. Theoretically, above a certain wavelength, that means below a certain energy, the guide cuts-off the neutrons which are below this critical angle for the guide. The critical angle depends on the curvature.

Hence, in a curved guide, not only that you have less number of fast neutrons and gamma rays, it also acting as a band pass filter. It will not allow neutrons of higher energy to pass through it and only low energy neutrons are allowed.

(Refer Slide Time: 29:04)

Usually there are large number of guides transporting neutrons to a guide hall or to several guide halls

The one shown in figure is another example. Usually in a single beam path, the beam path (as I told you) is ~ 100 meters, whereas the typically width of guide is around 1 cm. So, in the beam mouth, you can put number of guides and then take the beams away in a divergent way. You can see that the distance between the guides are increasing as they go out around 40 m distance and you will have a large gap to put experiments in between the guides.

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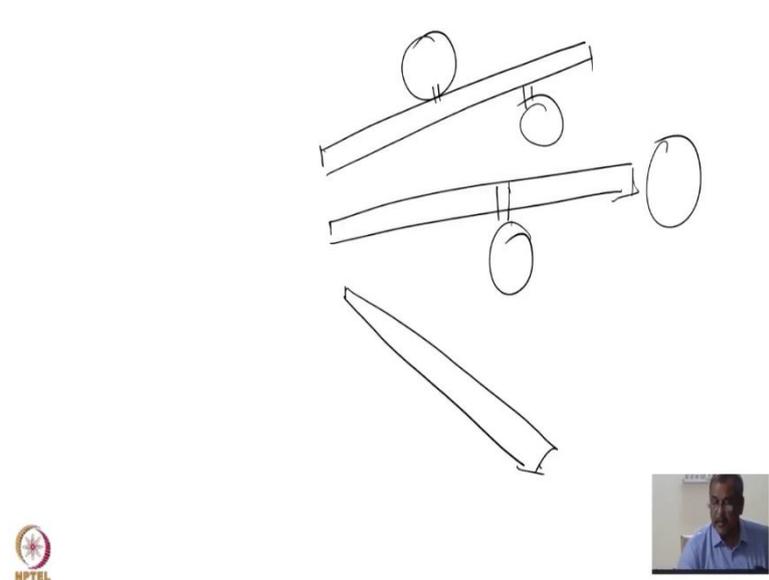
What I mean to say here is that if I take the guides far away on the same beam line, as shown in schematic you can put instruments in the gaps. In this way, you can accommodate large number of instruments on a single guide and a number of guides away from the reactor core.

That is a big help for experimental setups, because we can increase the number of experimental setups and accommodate more number of instruments using a guide.

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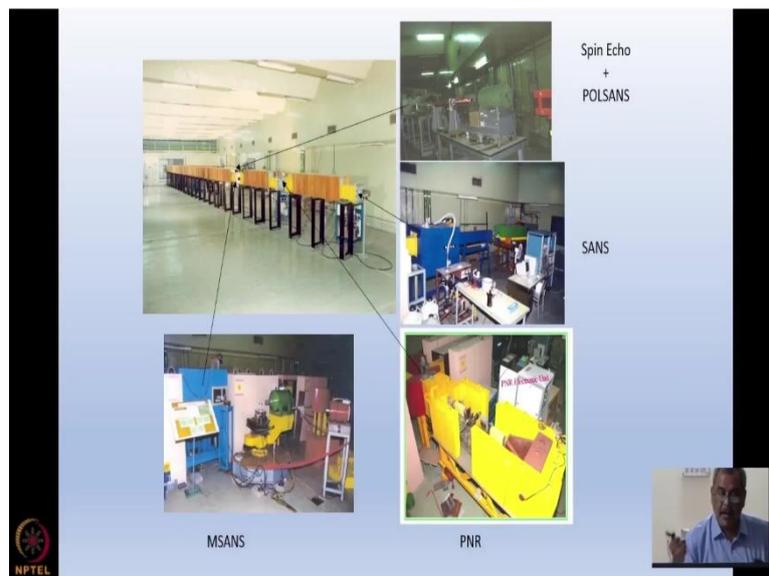
As shown in picture, there are lots of instruments on a single guide. This is the guide hall in Dhruva. The top-left photograph is when the guides were just installed, there are two guides and there are two gaps in this guide. One is 36 meter long and the other one is 21 meter long. And here we have got three instruments one is a medium resolution small angle neutron scattering instrument here and the conventional SANS instrument at the end of the guide as I showed. And then polarized neutron reflectometer here and there is a spin echo instrument supposed to be installed on another guide.

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There are two curved neutron guides at DHRUVA

Guide	Radius of Curv.	λ_c in	Length
G1	1916 M	3.0 Å	21 M
G2	3452 M	2.2 Å	27 M +3M +3M

These are curved guides in DHRUVA. One guide has a radius of curvature 1.9 km or 1916 m, the other guide has a radius of curvature of 3.5 km approximately which is 3452 m, more the curvature larger is the value of the critical wavelength cut off wavelength.

So, for the smaller radius of curvature the critical angle is larger three angstrom and for the less curved guide whose radius of curvature is larger, if it is straight, it will be infinite, we have got the critical angle of 2.2 angstrom and this has got 27 meters then there is a gap then 3 meters, then there is a gap and, in these gaps, we have instruments that are lined up. This is all that I had to talk to you about neutron beam production and transportation. In the next lecture, I will take over other elements of neutron scattering devices.