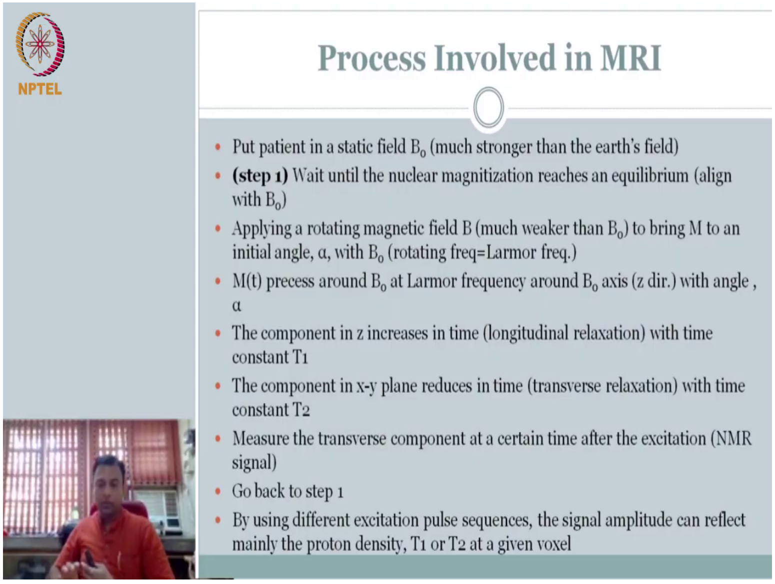
Introduction to Biomedical Imaging Systems
Dr. Arun K. Thittai
Department of Applied Mechanics
Indian Institute of Technology, Madras

Lecture - 44
MRI_Phys_S29-S39

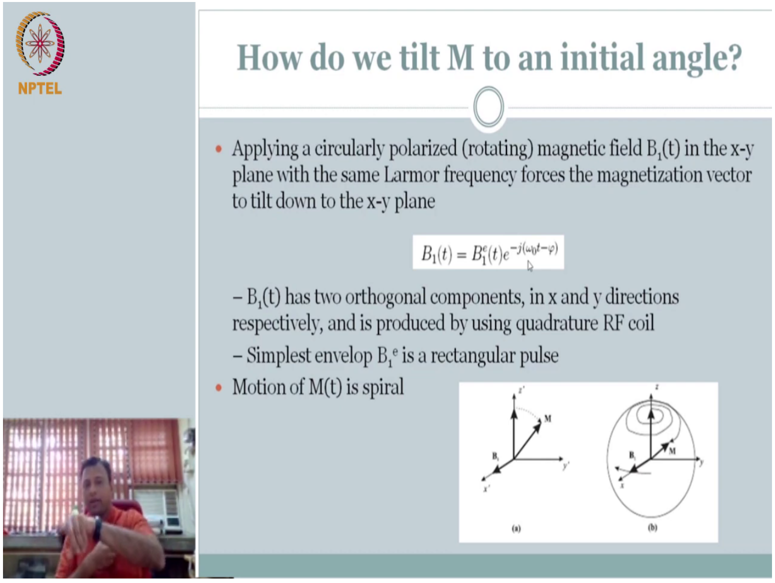
(Refer Slide Time: 00:14)



Ok. So today what we will do is update our equations and see, how to add those additional rotating magnetic field and if the process make this magnetization vector fall to ground. Notice that we were talking about alpha right alpha had to be 90 degrees to make it to the floor. So, you get the maximum signal right in the signal equation if you see there was a sin alpha

So, the magnitude becomes maximum when the alpha is 90 degree. That means, you have to add additional magnetic field which is rotating magnetic field that will help us push this magnetization vector onto the transverse plane, how do we do that? How do we upgrade our equation will be the topic of interest today, ok.

(Refer Slide Time: 01:05)



So, how do we tilt the M vector to a initial angle? So, clearly as we will be talking about read the text in this section they have given you know step by step how to understand this, but clearly we did this experiment thought experiment yesterday right. So, if you are if you are already having the magnetization vector precessing around right. So, you have it like this along the z direction around the z axis, if you just apply one right to push it to floor this cannot happen.

So, we talked about how to do this you have to be going along the precession. So, you have to apply this field that should also go around right that should also be having the same frequency only then you can constantly push it down. So, that is the intuitive process.

So, therefore, we apply a circularly polarized magnetic field. So, what do we what do they mean by circularly polarized if you were to track the path of your additional magnetic field right your B 1 field then it will look like a circle in the x-y plane that is what they mean by circularly polarizing magnetic field. It has to operate at the same Larmor frequency, if you do that you could essentially tilt that back.

So, I am doing this because the x y z coordinate this is what is happening now if you want to visualize this easily in the rotating frame of the reference essentially what happens is this magnetization vector is going to the floor ok. So, you apply B 1 right B 1 of t is nothing but it is having envelop and then it is having a frequency here. So, that is the description of the rotating magnetic field. So, it has obviously, it has two components x and y that is why it is able to move in the x y plane.

So, you apply this using quadrature RF coil we will talk about this coil design and other things in the instrumentation aspect when we go forward the next module. So, simplest way to think about this envelop is a rectangular envelop of the pulse. So, you have this rotating magnetic field that is switched on and switch it off. So, you have a when it is on it is having the same amplitude that is what this envelop is saying right ok.

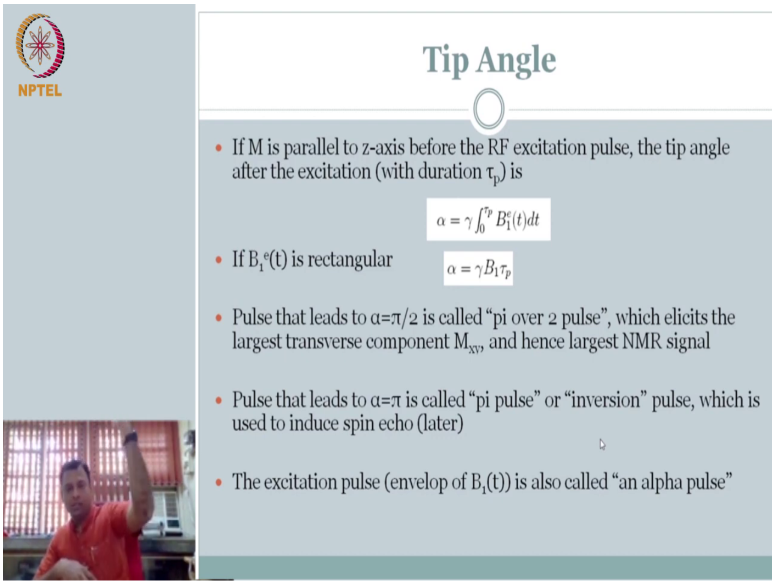
So, how is the motion we have seen few animation. So, by now it should be intuitive the motion is going to be spiral right. So, here is a example to understand. So, left in a what you see is the representation in the rotating. So, frame of reference. So, you see the axis are x dashed y dash z dash.

So, as a thought experiment right just to make yourself comfortable if you actually imagine, what did we said? Initially when we applied a static magnetic field in the z direction the precession was around z direction that is your magnetic vector started to precess around z direction.

Now, if you look at z dashed right. So, you have M if I apply my B 1 in x dashed, what should have happened? So, I have a vector in z dashed I am applying another electric magnetic field in x dash. So, where should be the motion of the M it has to rotate around B 1 or rotate around x 1 axis.

That means, it has to move from z dashed to y dashed right, that is what when we applied in the z direction it started to rotate precess around z direction. If now B 1 is applied in x 1 direction the magnetic moment has to precess around x time I mean intuitively that is what it is right. So, however, in three d coordinate if you see it is going to be which is shown in the b it is going to be a spiral. So, it is all consistent you have to train yourself to visualize this further ok.

(Refer Slide Time: 05:25)



So, now how much do you want to tip it for idea is I want to tip it I know how to tip it which is apply additional B 1 field which is a rotating magnetic field, if I apply that I will be able to do it. So, how much should I tip? That is your tipped angle. So, I will get tipped angle depending on your alpha is equal to gamma times 0 to tau p. So, how much ever time I have this RF pulse right excitation pulse what is called as excitation pulse or it is going to determine the.

So, if I have it a long enough it is going to try to push it down as much as possible. If I just have it on and off then I might I have been just moved some angle, but I did not have guard fully. So, the amount of time that you switch on this excitation is going to determine the angle to which it is going to be pushed.

So, the alpha is the angle tipped angle right. So, for simple case if you assume it to be a rectangle then your alpha is nothing but gamma B 1 tau p, tau p is the time duration over which this pulse excitation pulse is on is simplest case of rectangle I just get 0 to tau p tau p minus 0 right, so gamma B 1 tau p.

So, now we introduce some jargons. So, we talked about this your magnetization vector when it falls on the floor right your sin alpha remember the signal magnitude had a sin alpha. So, you get maximum signal when alpha is 90 degree or pi by 2. Therefore, any pulse that you apply that is used to push the magnetization vector by pi by 2 or make the alpha equal to pi by 2 is called as the pi by 2 pulse right very intuitively attempted pi by 2 or pi over 2 pulse.

What this does is when you apply a pi over 2 pulse, that means, it implies the excitation magnetization vector has been excited and pushed to the transverse plane which will elicit maximum signal right you remember M xy the transverse component that gives you the signal right, that gets you the maximum signal if it is on the floor.

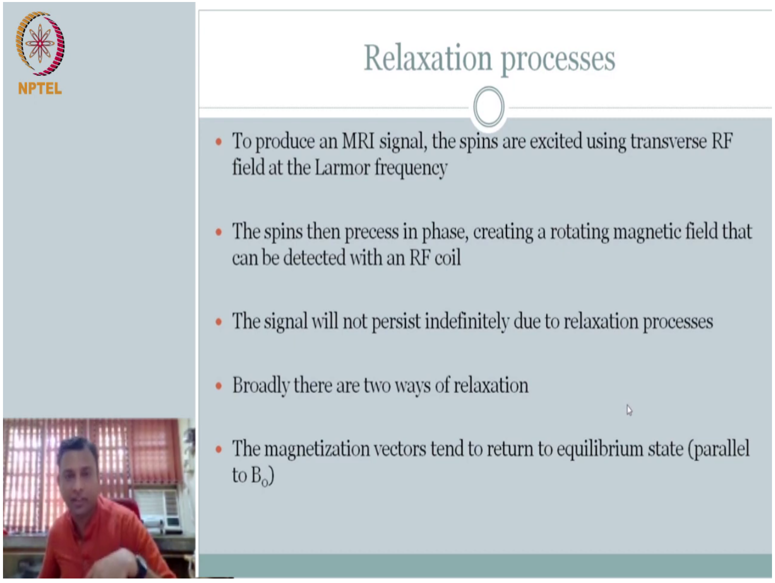
So, naturally there can be other variations if I apply long enough right, I could also make alpha become pi what does that pi means. So, I was here 90 degrees is here 180 degrees is going down. So, that means, it is an inversion pulse. So, why would you want it to align in z direction right already z direction we talked about signal being coming in the x y plane, if I push it to pi such as inversion pulse it does not give me much right I have I need signal to be on the fill up floor plane not perpendicular to it.

However this is a very important signal pi by 2 pulse excitation because we will talk about this in the next lecture module because this will be used to do spin echo right. So, this is important as well, but again you want to apply inversion directly if you apply 180 degrees you do not get much because there is no transfers.

So, think about what happens if I apply pi and then pi by 2 right, let us leave it there for now. So, essentially you also call this excitation pulse as a alpha pulse because remember you are trying to manipulate this alpha ok. So, you could understand from this more or less the terminologies and the variables used are also very consistent and standardized.

So, you cannot just say I am used to saying angle to be theta or phi or something and here it is very very standardized. So, alpha pulse means alpha is just angle of magnetization vector with respect to your z axis or the primary static field axis. So, pi by 2 is essentially the signal maximum signal that you get in transfer. So, it is also called as alpha pulse.

(Refer Slide Time: 09:37)



So, now we need to talk about exciting, exciting something is fine, but then excitation cannot ever survey for long the moment. The excitation pulse is done its job that is pushed you have had the excitation pulse on for tau p. So, you made sure that you pushed it. So, I am just deliberately starting somewhere if it is 90 degree pulse it would have been like this. So, I can stop anywhere I want. So, I have essentially excited it right, it is now at some signal is there.

Now, the excitation pulse is off what is going to happen I mean ideally speaking you have created the coherence it will keep doing this, but nature is not like that there has to be some loss nothing is perpetual in life right. So, what happens is the moment you take the excitation they all try to obey the command only till the excitation is there.

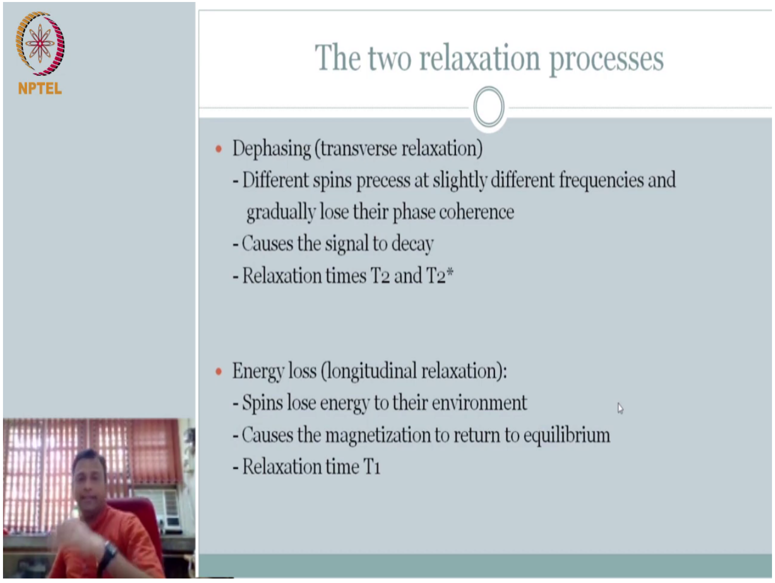
But there on the nature kicks on the moment the excitation pulse is off they all start to lose their coherence. Therefore, what will happen if they lose their coherence signal strength will start to go or the process is called as relaxation, initially you are forcing you are adding B 1 you are forcing them to you know come together and pushing them to flow, here some sense your force. So, that is forced to precision.

Now, you are allowing it you have removed the excitation you have removed the force then it has to relax, it will relax and what will happen? It will relax everything will dephase in the x y plane if you see all the phase will be different, I mean all the vectors will be in different directions and the in and eventually they will try to align themselves to having only z component in the static field right, that is what relaxation process will happen.

So, naturally that means, we need to talk about it is losing signal strength. So, in the relaxation process how all can it lose signal strength one is dephasing. The moment it starts to dephase you have lack of coherence signal coherence and therefore, lack of signal the relax signal is dying down that is your transverse component.

There is other process also right, once the signal coherence is done the signal is going down in the transverse your in z axis it is getting built up your longitudinal component is building up right that is relaxing to gain signal strength whereas, the x y components relax to lose signal strength right. So, there are two aspects to it and we will kind of break the two aspects and talk about what it is called ok.

(Refer Slide Time: 12:33)



So, there are broadly two ways of relaxation one is the dephasing part which we call as transverse relaxation very intuitive right, this is our transverse signal that we got because the x y we made everything coherent. So, we made everything come in phase. So, the moment the excitation pulse is off or the rotating B 1 pulse is off it is going to start to diphase, how it is going to diphase?

We will talk about the physics and some aspects of it. Then the other one is energy loss meaning when you start to lose energy here again your z component is going to increase. So, that is your longitudinal relaxation. So, it is coming to all the excitation that you put in the extra energy that you put in is lost. So, it will come back to it is resting state in static magnetic field. So, there are two aspects of relaxation the first one you could think about this way how did you get signal? Because of phase coherence.

What do you mean by phase coherence I applied each one is at different phase what did we talk about different phase. That means, all of them are now aligned and of course, they all have the same frequency or supposed to have the same Larmor frequency. So, they are all in alignment even though they started differently the excitation pulse made sure they all aligned they all come together and then precess with the same frequency.

So, now what happens is if you take a molecule that is fine now we are talking about the bulk right in the bulk each nuclei is not just a nuclei of the each cells it has it is part of an atom the atom is part of a molecule. So, it has surrounding neighbors can be move over. So, essentially one spin can interact with another spin ok.

So, one spin interacts with other spin means what happens some spins can be slightly faster some can spin slightly slower even though we said all of them have the same omega like the precession frequency. There could be slight differences because it is all surrounded by each nuclei is surrounded by different nuclei number of nuclei that is there number of other nucleus that are there all this is slightly different.

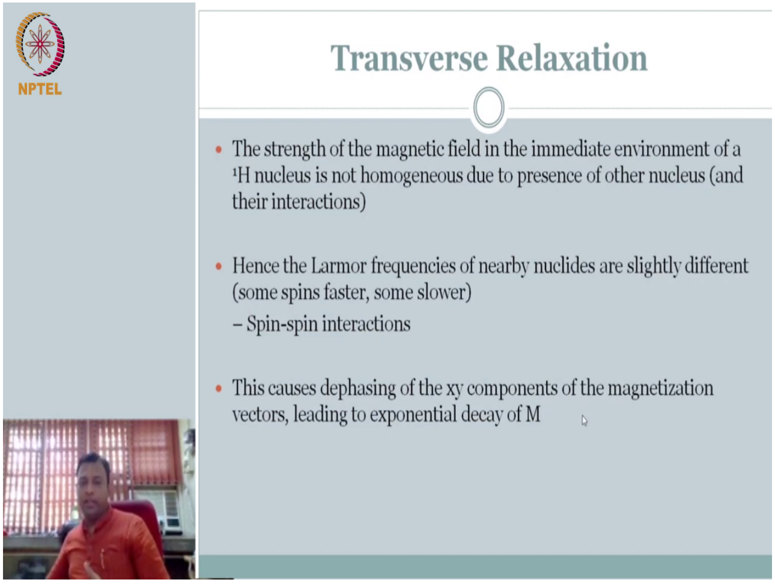
So, what happens with slight difference that means, some is precessing some more the neighbor will be precessing some less and therefore, they are not exactly the same value. So, the moment the external excitation is off, the small differences starts to you know make them fall apart they were all 1. Now, they are falling apart because there are small differences and with the time each one will their difference will become bigger and bigger.

So, that is the natural lose this is also called as spin interaction right. So, because there is one spin there is another spin they all interact with each other and therefore, there is a change in the local magnetic field you can look at it whichever magnetic field changes your omega changes, small this thing changes omega therefore, your magnetic strength also changes right.

So, this makes the signal to decay and then there is a relaxation time T 2 and T 2 star ok. So, that means, it starts to relax due to dephasing that there are two phenomenon's we will label it as T 2 and T 2 star right the other one is spin loses its environment energy to its environment and then it magnet you know the z component comes back.

This relaxation time we will call it as T 1 time that is after you switch off the excitation how long does it take for the M z to build up and come back to the equilibrium value the time constant we will call as T 1. So, realistically define this T 1 and T 2, T 2 star. So, let us start with the T 2 the dephasing part right transverse relaxation.

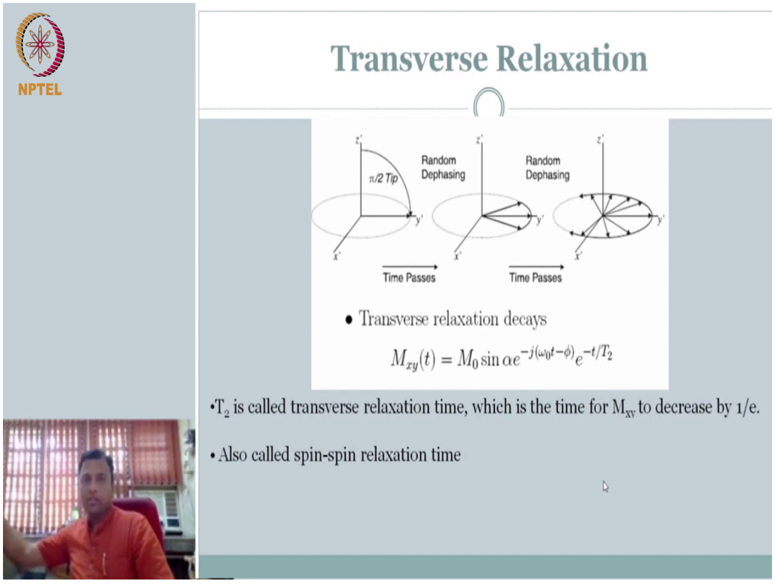
(Refer Slide Time: 16:35)



So, the strength of the magnetic field in the immediate environment is different that is what I told you because it is not homogeneous that is my small differences in the surrounding of each of the nuclei. And therefore, the spin spin interactions make sure that the each of the nuclei some spin slightly fast, some spin slightly slow and therefore, there is a dephasing.

So, with time what happens is all of them become out of phase they become out of phase signal coherence is lost, so signal goes down. So, the this you know reduction in signal due to spin spin interaction we call it as T 2, I mean you know transverse relaxation of course, the rate at which it goes down right as a time constant which we will shortly name.

(Refer Slide Time: 17:31)



So, here is the process that we are talking about initially we had notice it is all z dashed x dashed y dashed meaning I am not going to do this I am sitting in the circular rotating frame of reference. So, I have the magnetization vector, I have put a pi by 2 excitation. So, it has fell down after I stop the excitation pulse after it moved down, what happens?

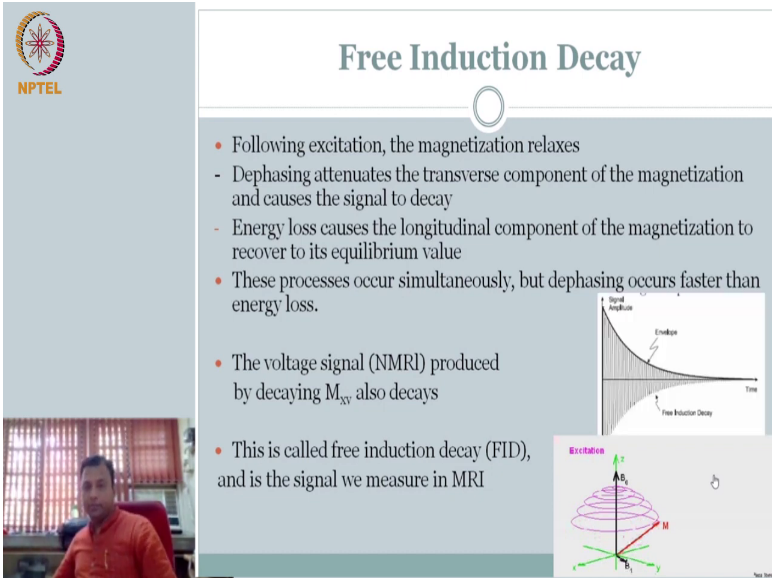
Immediately it will start to dephase right, dephase and therefore, the signal starts to go down the coherence the signal starts to go down. Because remember this is the magnetization that is giving you the signal transverse M xy of t with you allowing some more time full dephasing happens and then what happens the M xy component eventually goes to 0.

So, transverse relaxation decay. So, if we add this M xy from before now what we have added is this is a practical process you do not just keep doing M xy forever there is going to be a decay and the decay in this case is modeled as a exponential decay with time constant T 2. That is T 2 describes how fast it dephases or how fast the signal is getting lost in the exponential model.

So, T 2 is called as a transverse relaxation time which is the time M xy to decrease to 1 decrease by 1 by e. So, this is also called as spin spin interact relaxation and just to be clear that T 2 has to do with label spin spin interaction and therefore, changes. So, now the question is ok that is all fine there is a small change due to spin spin interaction and.

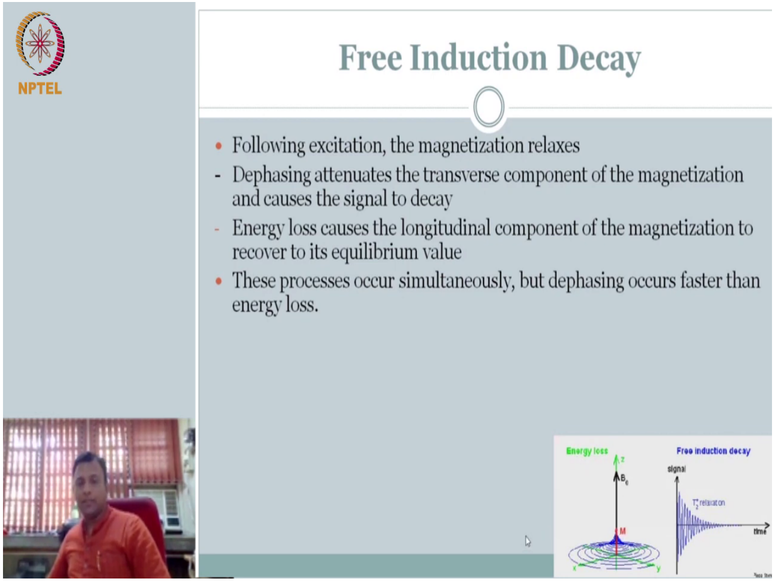
So, it dephases then what does T 2 star mean right ok we will we come to T 2 star after it talk ok this is you got your signal this is your M xy t, but this is not I mean this is just the interpretation how do you capture the signal that part we have not finished. But we talked about this how do we do it magnetic field right M xy vector is rotating in the rapidly rotating in the transverse plane. If I put a coil what happens? Magnetic flux cuts this coil current comes in and then you get the free induction decay voltage right.

(Refer Slide Time: 19:58)



So, the signal that you actually measure is a voltage signal that we talked about yesterday. So, what happens here is dephasing initially you have the magnetization vector and then it starts to relax. When it relax dephases means the transverse component is going down transverse signal is decaying. Energy loss causes the longitudinal component of magnetization to recover to the equilibrium value. Of course, we will have to notice these are happening simultaneously dephasing is happening at the same time it is trying to go up due to other losses right.

(Refer Slide Time: 20:49)



So, simultaneously this is happening and therefore, what you actually measure is going to be something like this first when you are applying excitation right. Then it is dephasing only when this on the x y plane right, then this will play again ok, look at the different variations you can play this several times to understand.

But notice the process that we are interested initially when you excite there is no signal the M has to come fall on the floor. The moment it falls on the floor you get the maximum peak signal right and then the M starts to reduce because of dephasing. So, the signal goes down how fast this goes down is the material property of T 2 right.

And then while it is going down the M in the z direction is increasing ok that is, so your T 2. So, your signal is recorded voltage signal is recorded, but it is getting reduced with the time, but the rate of reduction is going to define your relaxation time dephasing relaxation time ok.

While you also notice that due to energy loss the signal in the z direction is increased. So, the voltage signal is produced by M xy also decays this is called as the free induction decay this is the signal that you are measuring ok. Now, the question is ok we saw something as T 2 star, what does that T 2 star mean? Notice how all the signal can lose it is magnitude dephasing right.

When it is dephasing that means, there is a difference in frequency subtle difference between the frequencies of the neighboring nuclei's when we talked about spin spin method neighboring elements right can neighboring nuclei can affect the spin spin interaction causing sum to spin fast sum to spin slower slightly around the you know plus or minus the omega frequency that you have the larmor frequency.

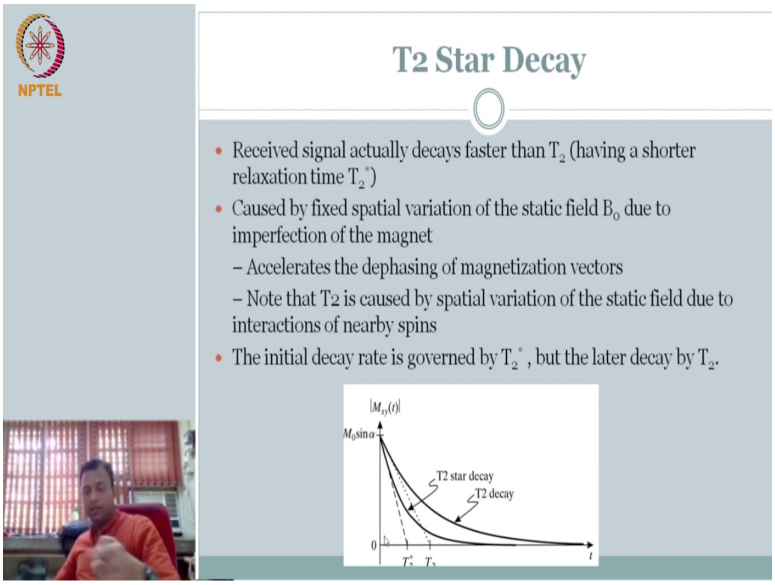
But notice you also have a magnetic field B naught what happens if the magnetic field has its not homogeneous main there are fluctuations right it cannot be perfect. So, you have a base B naught, but there are small imperfections and therefore, you have B naught plus delta B naught or you know small changes or plus or minus, then what will happen? If a region is experiencing more B naught more than B naught it is going to precess faster remember the relationship between omega and B naught.

So, if I increase my B naught omega is going to increase. So, if there is going to be a small imperfection which makes the B at that location greater than B naught then this is due to static field right then that is going to have slightly more Larmor frequency the other one if it is slightly less it is going to have less.

So, there is indirect imperfections in the magnetic field which is systemic right this is not about the material spin spin had to do with the material property. Whereas, this one is the systemic is the magnets that you have the permanent magnet that the static field that you are creating, if there are imperfections there then that may cause and nothing is perfect.

So, the small imperfections cause small difference in the omega. So, in the absence of any excitation which is strong enough these imperfections make their you know nuclei magnetization vectors which were in phase to start to rapidly dephase. So, this accelerates the process that is called as your T 2 star both are relaxation due to dephasing, but one is due to magnetic imperfections in the static magnetic field which is T 2 star the other is your T 2 which is to do with your spin spin interaction ok.

(Refer Slide Time: 24:42)

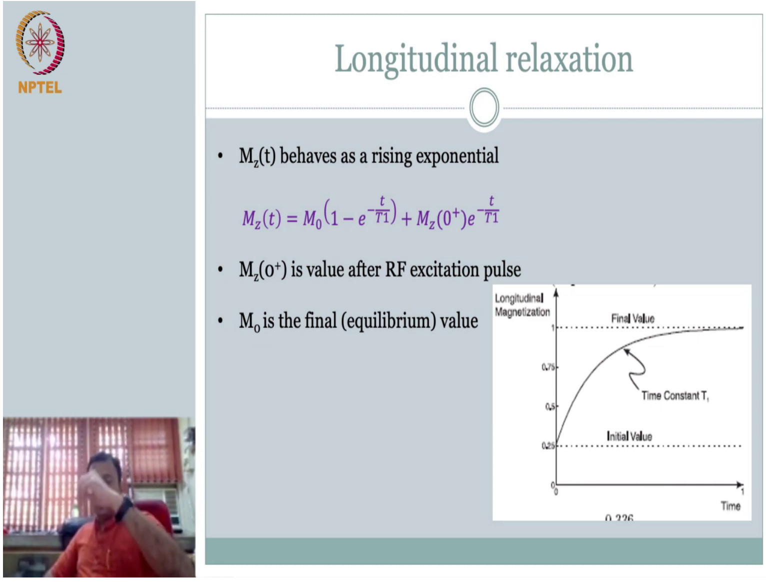


So, T 2 star is actually causing faster decay. So, you have dephase due to two relaxation process one is spin spin the other is due to the variations of the static magnetic field ok. So, why is this important to study? This is important to study because the initial rapid drop happens due to T 2 star and you do not have control over I mean it is a its a magnet that you are using the magnetic field that you are generating you do not have control whereas, T 2 you see retains the signal for much more duration.

So, perhaps if you want to play this game multiple times it will be prudent that T 2 is much greater than T 2 star. And therefore, you may have some question in pushing getting the signal allowing it to decay measuring it again easiest way is I allow everything come to equilibrium push it to floor measure T 2 right.

Initially it will be T 2 star I can done with, but you may want to do multiple measurements right. And therefore, it will become prudent that you can exploit T 2 because the signal is there for lot more time than T 2 star which is a systemic accelerator ok. So, let us talk about this little further when we talk about, how do you apply multiple times if you apply the pulse this will become little clearer.

(Refer Slide Time: 26:17)



So, last part on the relaxation is your raising exponential what do I mean by this is the longitudinal relaxation the M z, the dephasing happens signal reduces complete dephasing happens your x y goes, but all this time the M is trying to. So, the excitation pulse is off.

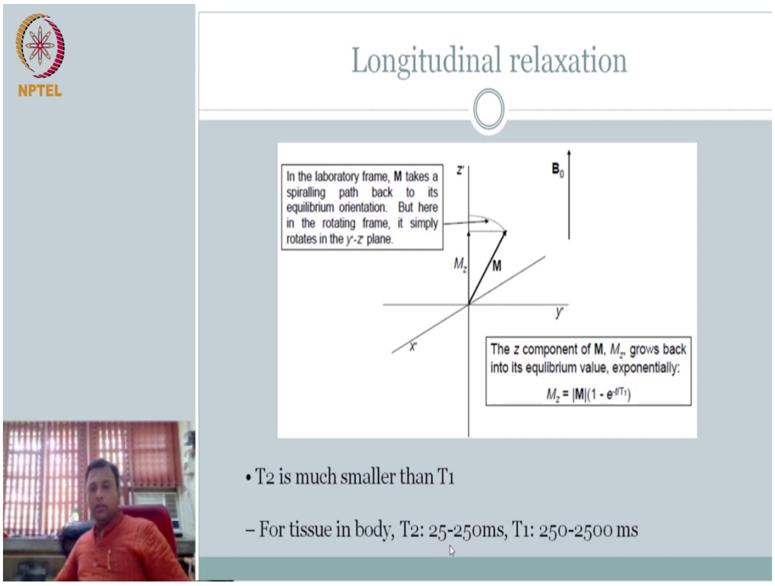
So, the magnetization vector is trying to come towards equilibrium the static magnetic field that is always there it is trying to come there. So, your z direction M z of t is the raising exponential of course, it is raising using a time constant T 1 right. It is taking its own sweet time to come together just to be clear M z of 0 plus is the value of the RF excitation pulse meaning.

When you start if what happens, M 0 is very clear you allow it to completely recover. So, that it is aligned into the static magnetic field the maximum equilibrium value that it can get, but just for correctness I do not have to allow it to you know come back fully before I push it down I can again push it down the moment it starts to come up I can again apply the RF excitation pulse make it go now.

Remember my signal is only the transverse component. So, the moment which dephase the signal goes down. So, there is no fun for me to wait all the time that means, the signal is going down and down and down, right you are going to hit the noise. So, I do not want to really wait till it goes and then comes back and then measure within T 2 time right the signal amplitude.

I have if I want to repeat the experiment I would not do it ah rather I should not say like that if I want only T 2 then maybe I should be able to do it multiple times. So, M z plus is just a general representation of wherever you start at 0 plus ok, it need not be the final equilibrium value that is the that is the point ok let us keep it simple ok.

(Refer Slide Time: 28:22)



So, now your longitudinal relaxation therefore, can be modeled as also a raising exponential in the rotating frame of reference axis, you see x dashed y dash z dash because vector M right M z is increasing ok. So, why does this happen? This happens due to natural loss ok.

So, for all practical purpose T 2 is much smaller than T 1 for tissues typically these are the range or tissue as in body tissues right T 2 is in the order of you know 10s of milliseconds. So, even some 100, but T 1 is 100s of milliseconds ok T 2 star is much lower than T 2 ok. Let us stop here.