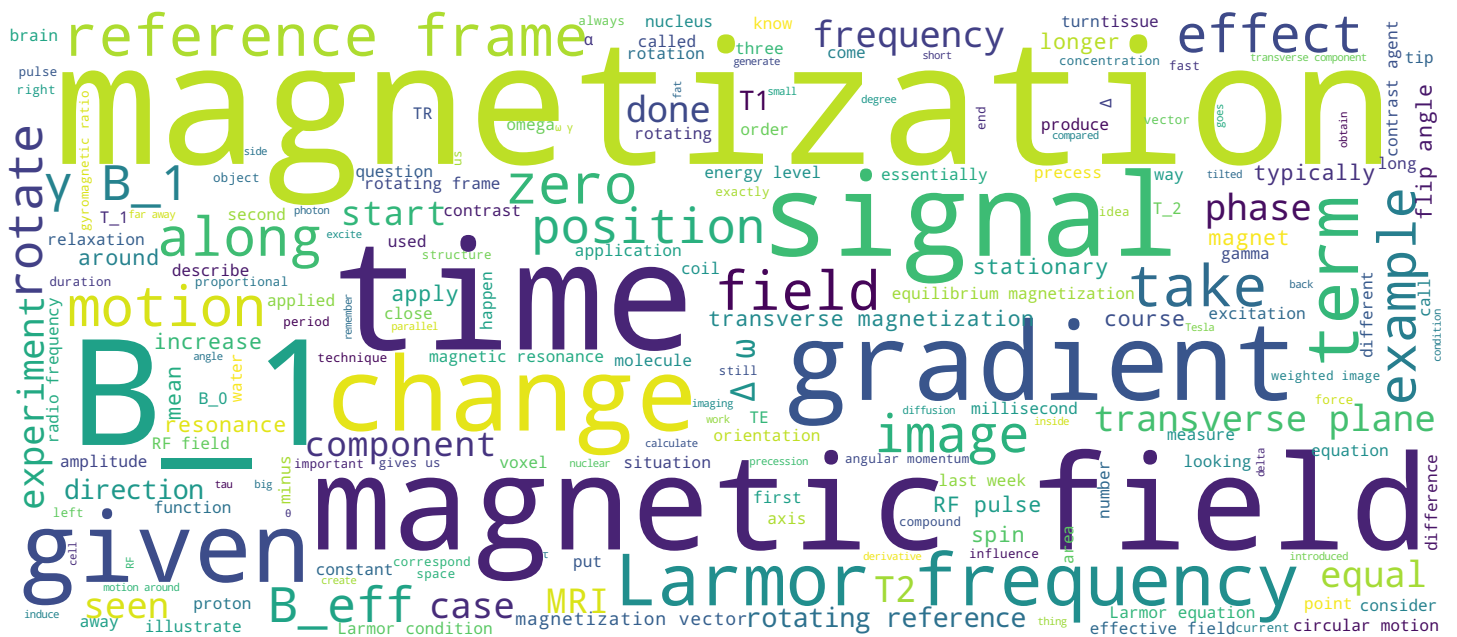


9.3 Effect of RF field

Fundamentals of Biomedical Imaging

Prof. Rolf Gruetter



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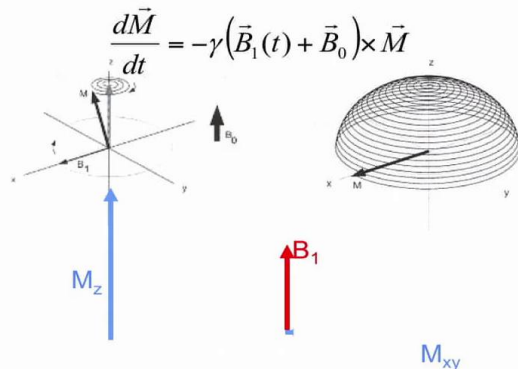


Video



9-3. What is the motion of magnetization when an RF field induces a flip angle ?

Laboratory frame of reference



What happens with the motion of the magnetization when we apply such an RF field and it induces a flip angle? Let's look at the laboratory frame of reference. Then we have the Larmor equation, which says, derivative of the magnetization with time is equal to " γ " times the magnetic field, and the magnetic field I have conveniently split into the B_1 , which is time-dependent and B_0 , which is constant. Now, what happens is, actually in the motion: As we apply the B_1 , it rotates with ω_{RF} . As the B_1 is in the transverse plane and it rotates, the B_0 , the magnetization will start to deviate from being along z . The minute it starts to deviate from being along z , it will start to precess. It will precess with the Larmor frequency, which is on the order of 100 megahertz. We have seen with the examples for the B_1 , this is on the order of kilohertz. So this will go 100,000 times around in circles for every rotation that it makes around the field B_1 . So, what happens in the motion is that we have the B_1 field here that rotates. And now what I will describe here is the motion of the transverse magnetization and the longitudinal magnetization, as we turn on this rotating reference frame.

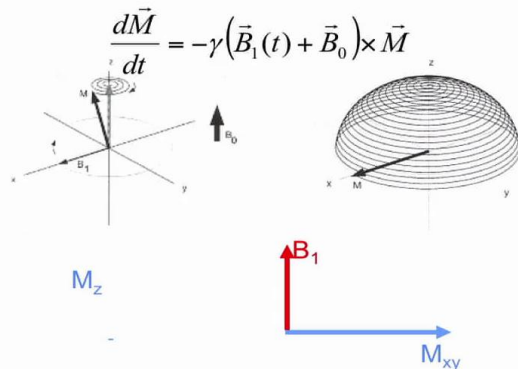
Notes

Summary



9-3. What is the motion of magnetization when an RF field induces a flip angle ?

Laboratory frame of reference



B_1 radiofrequency field at Larmor frequency ω_L applied in transverse (xy) plane for duration τ
 \Rightarrow **nutation** (at ω_L) of M as it tips away from the z -axis.



9-9

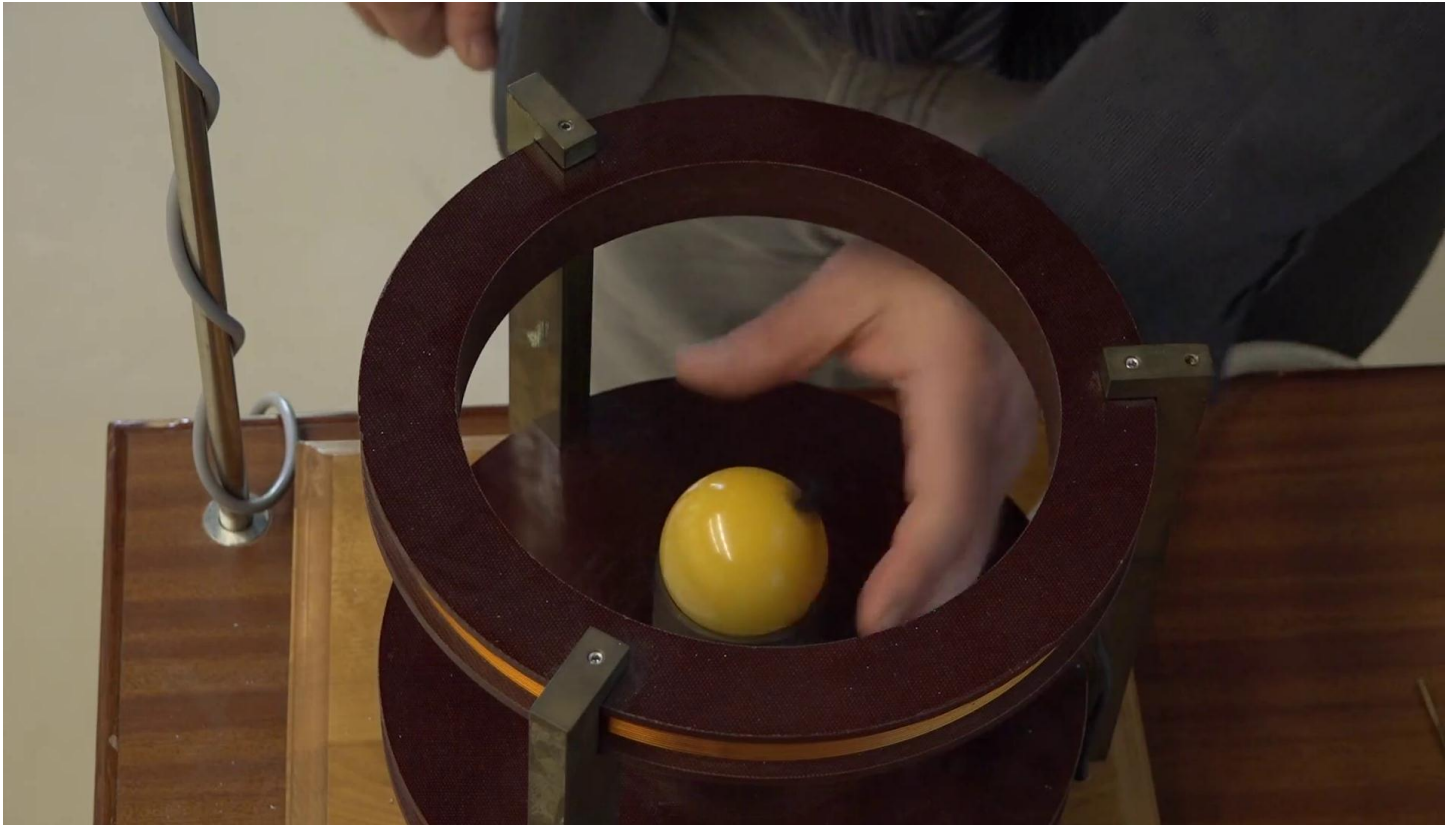
So, we have the B_1 applied that Larmor frequency in the transverse plane for a time τ , and this will create a nutation of the magnetization in a spiral motion, as it tips away from the z -axis. So, let's look at this in the animation: the B_1 , the magnetization, rotates so the transverse component increases, the longitudinal component decreases, until we are done, and we have done a 90-degree excitation. Now, remember, the rotation is happening 100,000 times for each rotation that we flip the magnetization. So it's difficult to visualize, but we will illustrate this effect of B_1 in the experiment that we have done, again, with a simulation of the magnetic resonance effect with this experiment with a yellow magnet that is rotating, and we will look at this experiment now.

Notes

Summary



1m 40s



So, in this experiment we have the same setup as in the experiment I showed last week, but we have an additional magnet here, which produces a magnetic field that's perpendicular to the main magnetic field which is this way, and this magnet produces a magnetic field this way. And so, as we have seen with the equations in the course, having this magnetic field rotate at Larmor frequency will induce the change in the orientation of the magnetization vector, and that's what we should be seeing here. So, I will bring it into rotation and then, as I turn it around, you can see how it goes down and then tips at the end. So, this is the same rotation motion, if I take--this is my B_1 field here, magnetic field, this way, I take this out and just give it a spin here for the ball without this B_1 field, then it will precess in the external magnetic field, like we have seen last week. OK, so, we have seen, we can visualize that, if things are going slow.

Notes

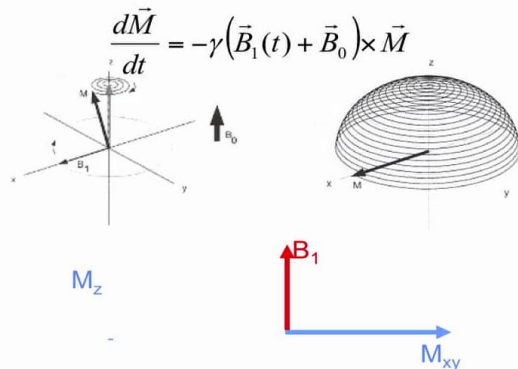
Summary



2m 43s

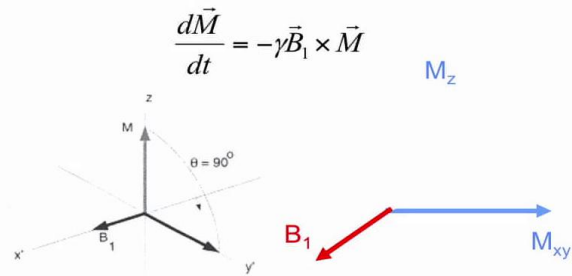
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 \Rightarrow **nutation** (at ω_L) of M as it tips away from the z -axis.

Rotating frame of reference



RF field rotates M towards xy plane

Amplitude B_1 determines how quickly the magnetization is rotated.

9-9

Now in reality, things move around at the Larmor frequency in 100 megahertz range and rotate into the transverse plane in the kilohertz range. So, putting ourselves into the rotating frame of reference, where we no longer consider the motion due to the B_0 , so this term is canceled by the ω_{RF} / γ . Then in rotating reference frame we have this equation of motion to consider. So, in this rotating reference frame, which rotates exactly at the Larmor frequency, we have a B_1 , that is stationary, we will look now here at the z -magnetization, and we will look at the transverse magnetization. And the B_1 field now will rotate the magnetization towards the x - y plane. The way this works is, the x -component increases, the z -component decreases, this is a simple-- in this reference frame is a simple rotation because in this reference frame the B_1 is stationary. The amplitude of B_1 determines how fast we get towards the transverse plane, that is, how fast it is rotated, and we can calculate the flip angle, if we know the gyromagnetic ratio, the B_1 and the duration of the application of this B_1 , which is also called the RF pulse.

Notes

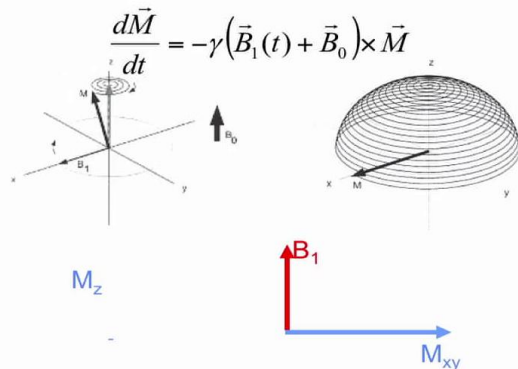
Summary



3m 47s

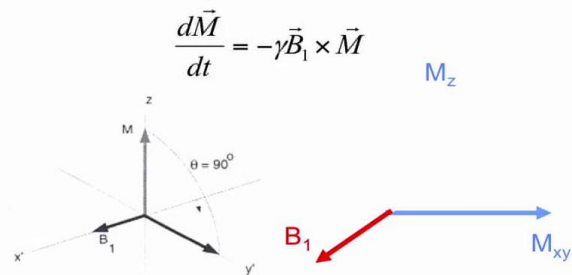
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RF field rotates M towards xy plane

Amplitude B_1 determines how quickly the magnetization is rotated.

$$\text{flip angle } \alpha = \gamma B_1 \tau \text{ [rad]} \quad \begin{cases} M_z = M_0 \cos \alpha \\ M_{xy} = M_0 \sin \alpha \end{cases}$$

In MRI typically $\gamma B_1 / 2\pi \sim 0.1\text{-}1\text{ kHz}$
 $(\tau \sim 1\text{ ms})$

9-9

So, that's the flip angle given. After the application of this RF field the z -magnetization equals to $M_0 \cos \alpha$ -- we have rotated by angle α , and the transverse magnetization increases with $\sin \alpha$ -- so it's given by $M_0 \sin \alpha$. This is when we start out with the equilibrium magnetization. To give us an idea in MRI what is the γB_1 , so we'll look here at frequency, so $\gamma B_1 / (2\pi)$ is typically from anywhere from 0.1 to 1 kilohertz. This means that the duration of this RF pulse, where the RF is turned on, is typically on the order of milliseconds. For all practical purposes, this is all that we need to know here.

Notes

Summary



What is “resonance” ?

What range of frequencies can be excited with a given RF pulse?

At $\Delta\omega = \omega_L - \omega_{RF}$ (from ω_L) magnetization experiences effective field strength B^{eff}

$$\gamma B^{eff} = \sqrt{(\gamma B_1)^2 + (\Delta\omega)^2}$$



9-10

So now, we have talked about nuclear magnetic resonance. So, we have had the term *nuclear*-- we had a nucleus involved, we have a magnetic field, so we have the magnetic in there, but we haven't really talked about what "resonance" means. Let's look at the excitation with the B_1 field, and the question we are asking here is how does applying such an RF pulse, so an RF field B_1 that we apply for a certain time τ , how much can we get excitation, that is, up to what range, how close do we need to be to the Larmor frequency so that we can generate an excitation that is a rotation into the transverse plane? So, now, if we are in our radio frequency field or rotating frame, frequency ω_{RF} , which we will choose always such that the B_1 becomes stationary. This is the simplest way to describe it, and here ω , the angular frequency of the rotating frame, becomes the angular frequency of the radio frequency, so ω_{RF} . So we are now away from the Larmor frequency, so we have a $\Delta\omega$ that's non-zero. And in this case our magnetization will experience an effective field that is given by γB_{eff} , just given by $\gamma B_1^2 + (\Delta\omega)^2$ square and that the square root.

Notes

Summary



5m 54s

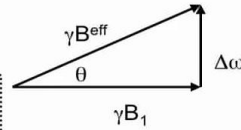
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Rotation axis : tilted by θ .



How does this come about? Well, we have seen, if we are in a rotating reference frame that does not exactly match the Larmor condition, then we have a residual z magnetic field, along z , and that's given here by $\Delta\omega$. We are by definition in a rotating reference frame, where γB_1 is stationary, that is-- so γB_1 is stationary, and our magnetic field along z is given by $\Delta\omega$, which is given by $\gamma B_0 - \omega_{RF}$. And so we have a z -component of the magnetization; it's stationary, we have a transverse component of the magnetization in our reference frame-- that's stationary as well. So this is the vector addition, this gives us an effective magnetic field, B_{eff} that's tilted by the angle θ . So, what does it mean now, we have the Larmor equation, and Larmor equation is always true, so we have now the rotation axis-- it's dictated by the direction of B_{eff} -- so it is tilted by an angle θ compared to the transverse plane. If we were exactly on the Larmor frequency, $\Delta\omega$ would be zero, θ would be zero, and we have the case that we have discussed last week and just before.

Notes

Summary



7m 25s

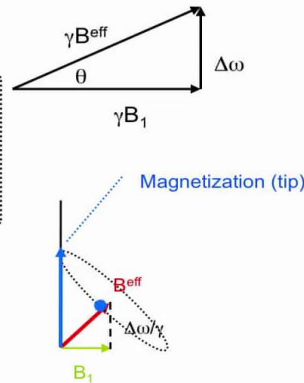
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Rotation axis : tilted by θ .



9-10

So, here is now, what I am going to plot, is to illustrate this. We have the z-axis on the vertical, we have the equilibrium magnetization that we started out with, and this little sphere here indicates the tip of the magnetization vector. So, that's the magnetization tip. It's easier to describe this with animation. Now we'll apply, in our rotating reference frame, a B_1 that is constant. But we are not exactly at the Larmor frequency, so we have a $\Delta\omega / \gamma$ that's the ΔB that is left. So we have also the z-component. So, this corresponds to this, and this corresponds to this, so we get a B_{eff} that's in this direction. Now, the Larmor equation says, our magnetization which is initially here, it will... only its component perpendicular to B_{eff} will change, the one that's parallel will not change, so we will get a circular motion around B_{eff} , and here is our circular motion. So our magnetization vector here will rotate on a circular motion around B_{eff} . Now, here the particular choice of ΔB is such that $B_1 = \Delta\omega / \gamma$, so we have a 45-degree angle, and in this case, we are still able to get the magnetization from being along z to being in the transverse plane.

Notes

Summary



8m 43s

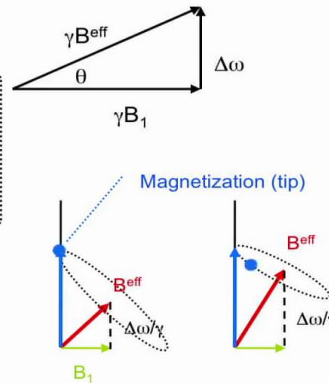
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Rotation axis : tilted by θ .



9-10

But remember, when we had the B_1 only here, we were on resonance, this term is zero, so the B_{eff} is along B_1 , then we can easily rotate it also into the - z-orientation, the magnetization here, with this particular condition we are no longer able to do that. Now, let's take the same situation. We'll start out with the magnetization-- it shall be the same. Here is the magnetization vector tip. I'll apply the same B_1 -- this shall be the same B_1 as here. But now, let's say, we are applying this B_1 field further away from the Larmor condition, so we are further away from the precession frequency of the magnetization in the absence of a B_1 field. So, now our B_{eff} is given again by B_1 , and the z-component-- that's the mismatch between the frequency at which B_1 rotates and the Larmor frequency. And now we have the motion, again, by the Larmor equation given by precession around B_{eff} , and now it precesses on this conical motion on this circular motion around B_{eff} . Notice here that the magnetization is now no longer able to reach the transverse plane, so we are no longer able to excite the magnetization fully.

Notes

Summary



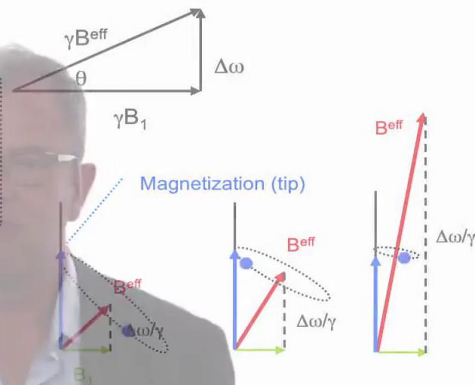
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Rotation axis : tilted by θ .



9-10

I'll take a third example, we will start out again with the same magnetization. Here is the vector tip, the tip of the magnetization vector. We will use the same γB_1 , so the same B_1 , and now we are even further away from the Larmor condition with the frequency of our B_1 . So we are rotating-- The B_1 is now applied at a frequency that's far away from the Larmor frequency. Our rotating frame is far away from the γB_0 . In this case, we have a residual z-component, ΔB , which is $\Delta\omega / \gamma$, so that's $B_0 - \omega_{RF} / \gamma$ and the B_1 has stayed constant, so our B_{eff} is now tilted more towards the vertical axis, the motion is again by the Larmor equation given by this circular motion perpendicular to B_{eff} . Now, you can imagine, as you go further and further away from the Larmor condition, the z-component of the effective field will increase, the frequency by which the magnetization precesses progressively increases, while the flip angle, maximum flip angle which is this point here that we can obtain decreases and decreases, and at some point we won't be able to produce any motion of the magnetization that is discernible, and nothing happens.

Notes

Summary



What is "resonance" ?

What range of frequencies can be excited with a given RF pulse?

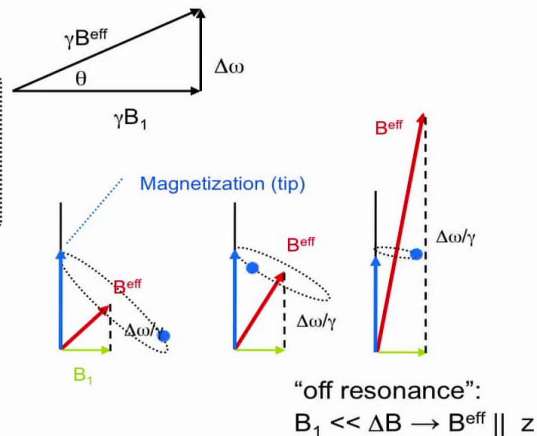
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$$\gamma B^{eff} = \sqrt{(\gamma B_1)^2 + (\Delta\omega)^2}$$

Rotation axis : tilted by θ .

"on resonance":

$\gamma B_1 \gg \Delta\omega \rightarrow \text{effective field} \parallel B_1$



"off resonance":
 $B_1 \ll \Delta\omega \rightarrow B^{eff} \parallel z$

9-10

So, clearly if the RF, the frequency of the RF field is too far away from the Larmor condition, we are no longer able to produce excitation and have the magnetization in the transverse plane. So, this condition here, where we have considerable alignment of the effective field with z, where essentially nothing interesting happens, is called the "off resonance", the B_1 is much smaller than the ΔB , and essentially the effective field is more or less parallel to z. Whereas, if we have "on resonance", then "on resonance", it suffices to say that the γB_1 , so this vector, is much larger than the $\Delta\omega$ -- that's this component here. And in this case essentially the effective field is parallel to B_1 , and we have the situation of the stationary B_1 field, "on resonance". So this is the situation of "on resonance". We are close to the Larmor frequency, and "close" here means that γB_1 has to be big compared to the mismatch between a radio frequency pulse frequency and the Larmor frequency. This is a reason why one in MRI applies radio frequency pulses for short duration of periods; one wants to have a sufficiently large γB_1 and, as an idea here, the RF field-- the B_1 field, is typically applied for periods of around one millisecond.

Notes

Summary



13m 03s

What is “resonance” ?

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Rotation axis : tilted by θ .

“on resonance”:

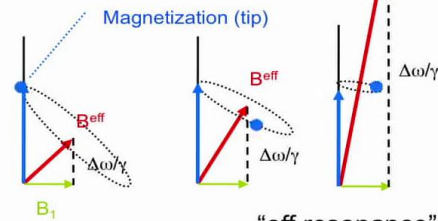
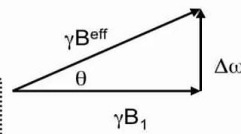
$\gamma B_1 \gg \Delta\omega \rightarrow$ effective field $\parallel B_1$

\Rightarrow short RF pulses ($\tau < 1\text{ms}$)

RF field with amplitude B_1 can excite a range of frequencies on the order of $\pm \gamma B_1$

Quantum mechanical “resonance”

Transition probability highest : $h\nu = h\gamma B_0/2\pi$



“off resonance”:

$B_1 \ll \Delta B \rightarrow B^{eff} \parallel z$



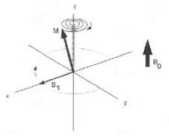
9-10

As a rule of thumb, the RF field with an amplitude of B_1 can excite a range of frequencies on the order of $\pm \gamma B_1$. We can see here, here it is, γB_1 the $\Delta\omega$ is γB_1 here, and here we still can excite, so in this case that's the plus and minus, because we can do this also on the other side. Now, there is a quantum mechanical equivalent-- we remind ourselves, we're talking quantum mechanics here, and this basically means we have-- as we change the orientation of the magnetization, we also change the population in the energy levels, and the transition probability is highest if the photons-- we speak of photons here-- the energy of the photons matches the difference of the energy levels in our nucleus. That's how we can induce transitions in the population of the energy levels. And this is illustrated here with people jumping on the bridge. If you do this with the correct frequency, then you get the maximum amplitude, classically. That is what we've seen with resonance when we discuss, in classical mechanics, the harmonic oscillator. And on the right you'll see the picture of the Tacoma Bay Bridge-- famous example of illustrating resonance that's used in the classroom context.

Notes

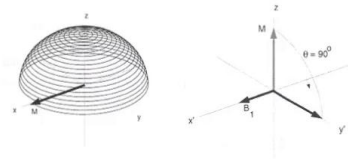
Summary





“Principles of magnetic resonance imaging”

Fig. 3.2 from Dwight George Nishimura



“Principles of magnetic resonance imaging”

Fig. 3.3 from Dwight George Nishimura



Twisting Bridge Resonance Waves

<https://youtu.be/3-kksSHBHck>



Tacoma Narrows Bridge Collapse "Gallopín' Gertie"

<https://youtu.be/j-zczJXSxw>

[illegible]



Summary

