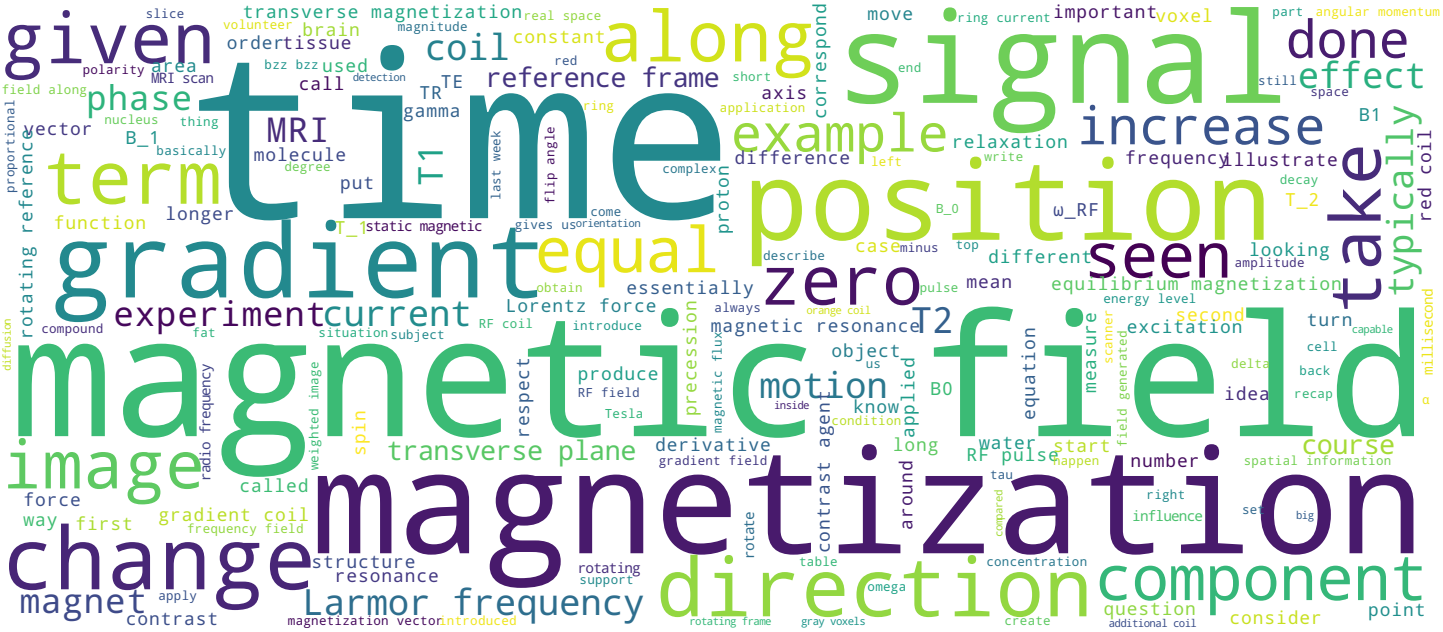
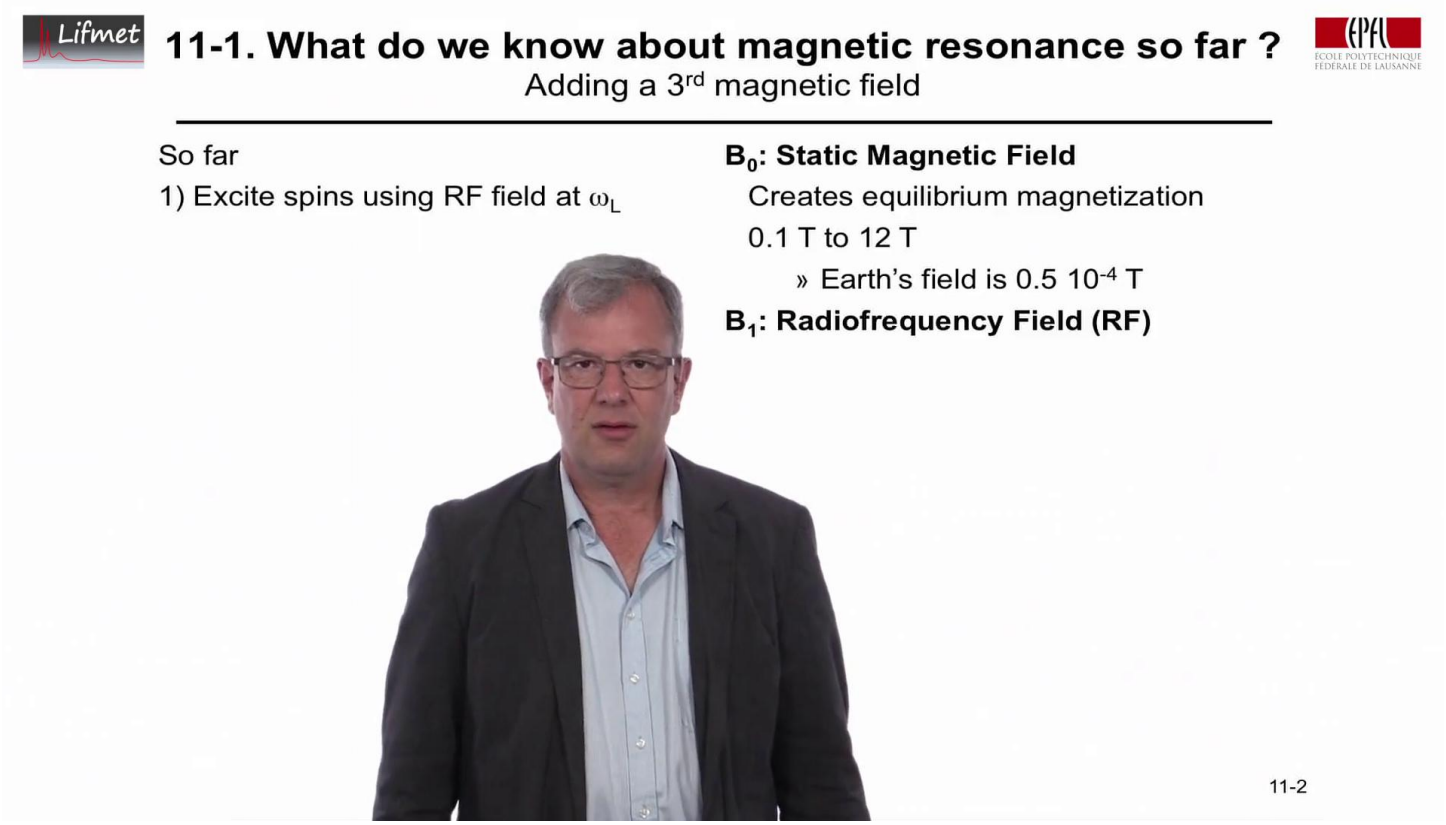
11.1 Introducing spatial information into MR

Fundamentals of Biomedical Imaging

Prof. Rolf Gruetter



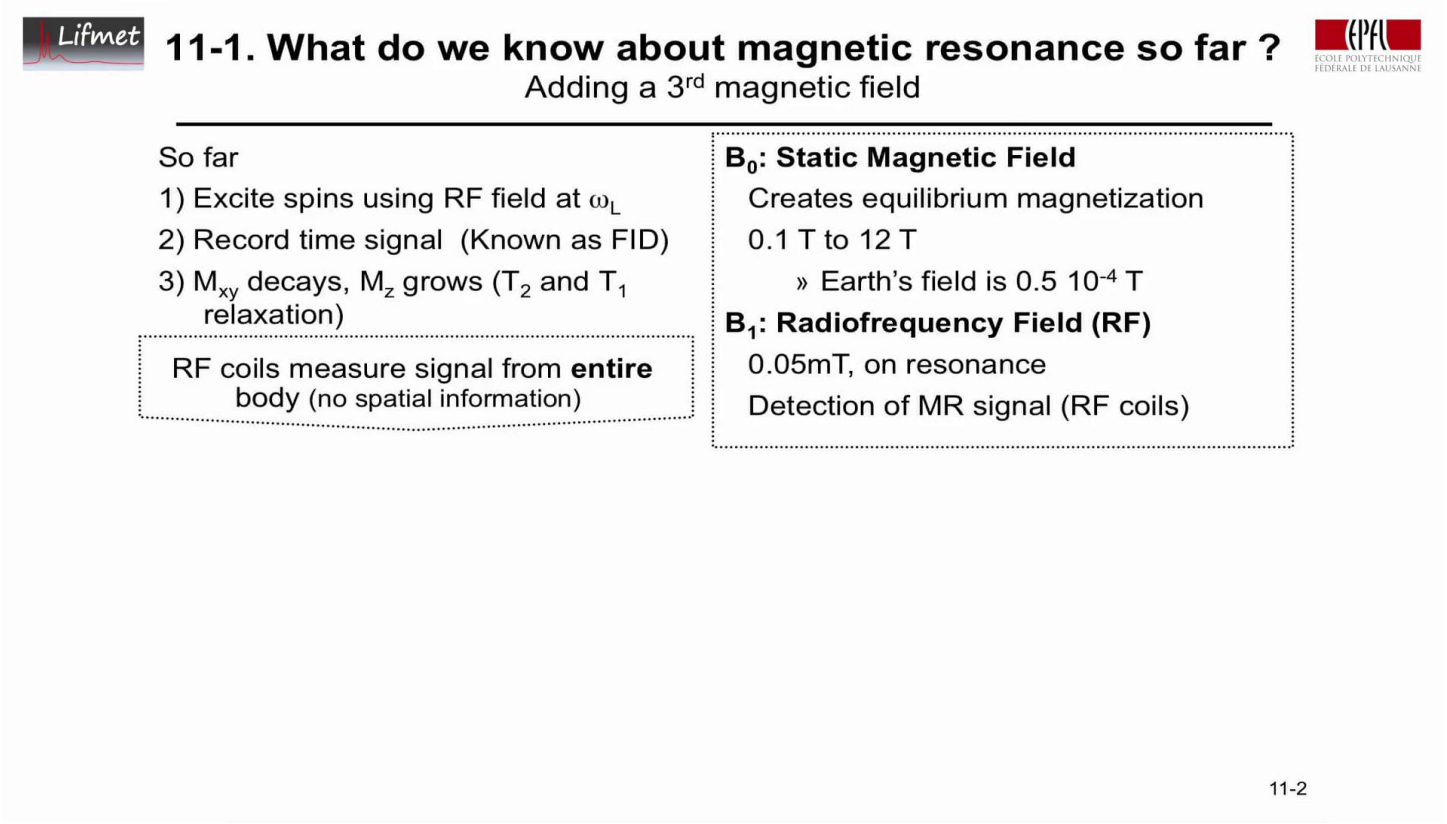


This week's lectures are particularly difficult because we are going to introduce how spatial information is encoded by magnetic resonance imaging. And as you will see, this is done slightly differently than the X-ray imaging techniques. First, however, I want to start out with a recap of what we know about magnetic resonance. We have so far introduced the static magnetic field. The static magnetic field, which is always called *B0,* is necessary to create equilibrium magnetization. So as you enter the magnet you will build up a nuclear magnetization that's this equilibrium magnetization. We're typically talking about field strengths of 0.1 to 12 T. As a reference here, you have the earth's magnetic field, which is, as you can see, much smaller than the fields used for MRI. Then what we do is, this static magnetization, the equilibrium magnetization we've seen is not very interesting, produces no signal, so what we need to do is to excite the magnetization, that is flip the magnetization into the transverse plane, and this is done using a radio frequency field, which is applied at the Larmor frequency. The radio frequency field is always denoted *B1*. It typically has a magnitude of 0.05 mT and it is applied on-resonance.

Notes

Summary

0m 04s

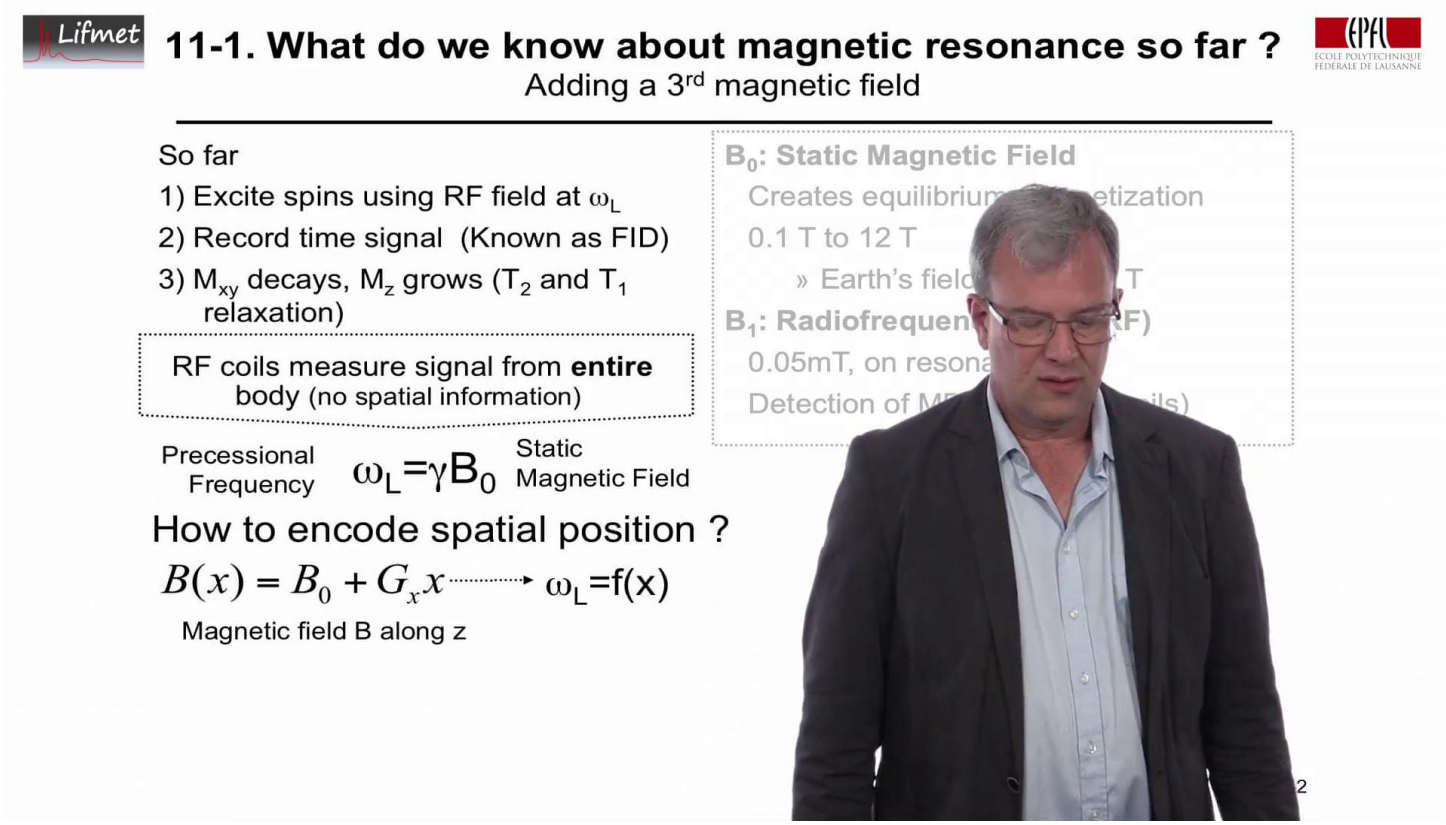


So this is compared to *B0* in the order of tesla, here we're on the order of millitesla, there's a considerable difference between the two. After the excitation with the RF field we have the magnetization transverse plane and then this signal is being recorded, and this we have introduced last week, this is known as the *free induction decay.* We have seen that after this excitation, we are no longer at thermal dynamic equilibrium, we have to get back to thermal dynamic equilibrium, this is done by relaxation, T1 and T2, or T2 and T1. T2 describes the decay of the transverse magnetization, *Mxy*, and T1, the return to equilibrium of the z magnetization, *Mz.* So the detection of the signal, the FID, that is done also with the RF coils. So both the excitation, the production of B1, the radio frequency field, and the detection of the signal is done with the same piece of hardware. So this is what we've had so far with magnetic resonance. We have seen that the RF coils are used to measure the signal from the entire body. We have not introduced, therefore as such, spatial information.

Notes

Summary

1m 35s

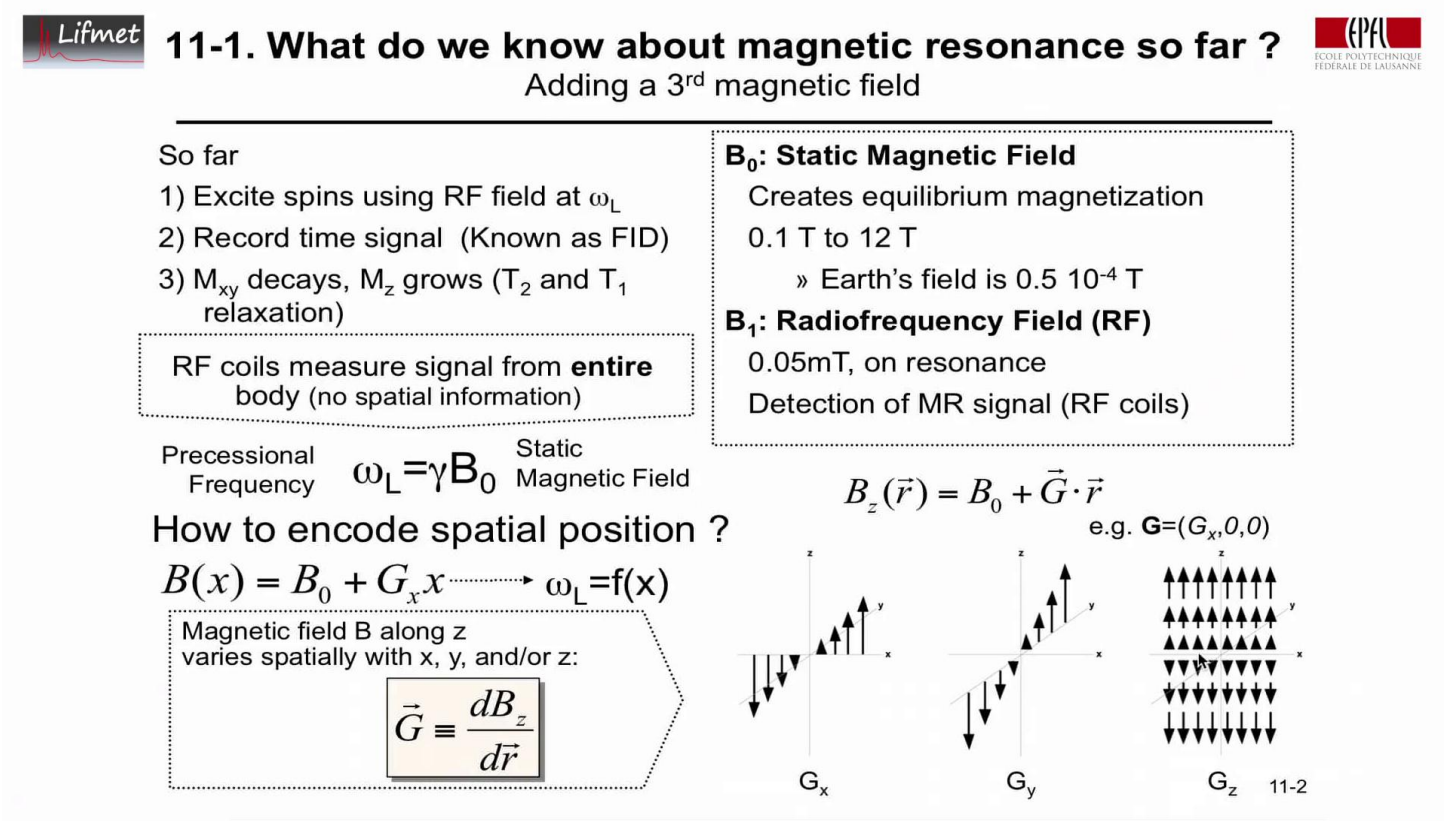


The means of detecting the signal is done by observing the precessional frequency, which is the Larmor frequency given by *γ B0*, under the influence of a static magnetic field. And we have seen last week, with this gives us also additional chemical information. So now how do we encode the spatial information? How do we get spatial information into our observation of the signal? And here the key is, let's suppose that we have the magnetic field, which is along z, the *B0* field, and we'll add a small field that varies linearly with space. So that's the *Gx* times *X* term here. So now this magnetic field varies along x. What happens now? What we now have is that the Larmor frequency becomes a linear function in position. So if we write the magnetic field along z and we produce it to vary spatially with x, y, and z, this spatial variation, we can define as the derivative of the z component of the magnetic field-- remember static field is always along z-- with respect to position x, with respect to position y, with respect to position z, each of those derivatives are the components of a vector that we shall call *G* here.

Notes

Summary

3m 03s



So in general terms, then we have the static magnetic field, *r* of the function of position is given by the static field *B0*, plus this linear term, and here is the scalar product of *G* times *r*. This is in all generality, the description of the magnetic field now. So for this case that we had here on the left, we use the vector *G* that was equal to *(Gx, 0, 0)*, so just along x that we had a spatial variation. So if you look along x, here is the x axis, the magnetic field starts from the center point, *B0*, and varies linearly around the position zero. Here we have taken the rotating frame representation so at center there is no magnetic field. Along y, so here's the y axis, we have a linear variation. And finally, along z, we have the z component of the magnetization along z that increases in opposite directions.

Notes

Summary

4m 33s

How is the gradient field created ?

One coil for each spatial dimension: G_x, G_y, G_z

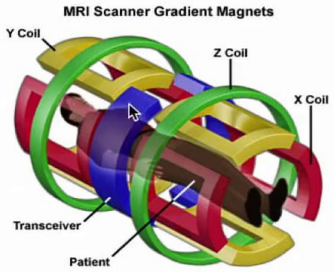
G: Gradient Field

10-50 mT/m in ~100µs

Used to determine spatial position of signal (frequency)

$$\vec{G} \equiv \frac{dB_z}{d\vec{r}}$$

Created by a set of 3 additional coils (gradient coil)



11-3

So now this vector *G*, we call this the *gradient field,* and the question is, "How is this gradient field actually physically generated?" Well, I'll recap here, the definition. The gradient vector is given by the derivative of the z component of the magnetic field with respect to the position in each of the directions, that gives the components of this vector. To give you an idea what we're talking about here, this gradient field is typically on the order of *10 to 50 mT/m* and it can be switched in a timescale that's typically on the order of 100 µs. And this is used to determine the spatial position of the signal, as we have seen from the Larmor frequency. So how is this gradient field generated? It is actually generated by a set of three additional coils. They're so-called *gradient coil.* So these three additional coils, they are put into one additional coil and that's the gradient coil. So what we have here in green, is the z coil that produces the linear field in z, in red, a linear variation of *Bz* along x, and in yellow, along y. In blue here, you have also the RF coil indicated and the subject is now lying here in this scheme inside the magnet.

Notes

Summary

5m 34s

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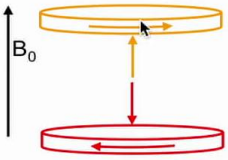
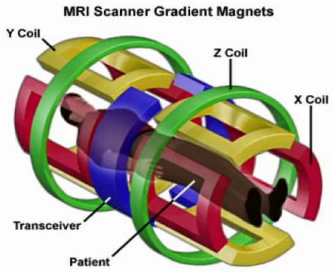
Created by a set of 3 additional coils (gradient coil)

Example: z-gradient coil principle (Helmholtz pair)



$$\vec{B}(\vec{r}) \propto \int \frac{\mu_0}{4\pi} I \frac{d\vec{l} \times \vec{r}}{r^3}$$



11-3

So to give us an idea how this is achieved, we'll take the z-gradient coil principle, just to give you an idea of how this is done, and we'll use the Helmholtz pair here. So what we have first, we have a ring current that's rotating, in this sense, counterclockwise. And then at a certain distance, we have a ring current of the same structure, same diameter, but now the current is rotating in the opposite direction. The *B0* is along z so it's in this direction, but parallel to the axis of the two coils. From *B0 sub r* we can calculate, given the current in the orange and red coil, we can calculate exactly the magnetic field that's being produced. I'll just recap here the law for completeness sake, but we'll just take a very qualitative argument here. And basically, we'll now draw here at the exact center between these two coils, the magnetic field generated by the orange coil, that's the magnetic field indicated in orange, and by the red coil, it's indicated in red. And now if we go along at the axis, center of the axis will move in this direction and in this direction. So if we move upwards, the field from the orange coil increases, the opposing field generated by the red coil decreases, so the magnetic field increases in this direction.

Notes

Summary

6m 59s

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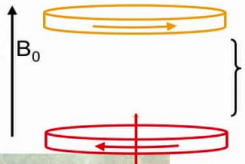
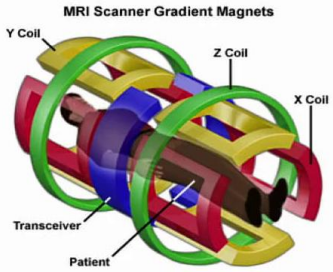
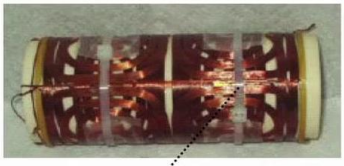


$$\vec{B}(\vec{r}) \propto \int \frac{\mu_0}{4\pi} I \frac{d\vec{l} \times \vec{r}}{r^3}$$

Created by a set of 3 additional coils (gradient coil)



One gradient coil



All three gradient coils

NB. Why are MRI scans so loud ?

11-3

Here at the center for symmetry reasons, the two magnetic fields generated by the two coils are equal in magnitude but opposed, so it is zero. And if we go downwards in the direction of the red coil, we have the contribution from the red coil that increases and the contribution from the orange coil that decreases. And that, in the end, in this situation generates a, more or less, linearly varying magnetic field along z, and this is the z component. So what does this look like in practice? In practice, one has a former and then the coils are bound in copper on top of this former here. So this is a coil that corresponds to the x coil, here is the single gradient coil that we have here on this structure. If we look at the complete gradient coil then we have the complete structure. All the coils wound on top of each other. You can see here this z-gradient is produced a bit more complex than we have introduced. Note that the y-gradient and the x-gradient, these two, they are, construction wise, identical except one is the rotated version of the other, rotated by 90-degrees. So here are the three gradient coils. Now, have you been in an MRI scan? Have you been a volunteer or do you know of someone of a volunteer?

Notes

Summary

8m 33s

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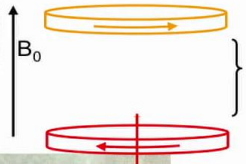

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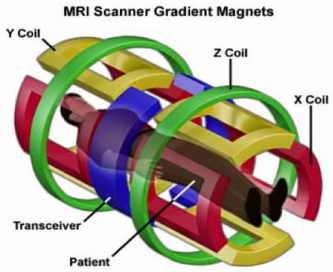
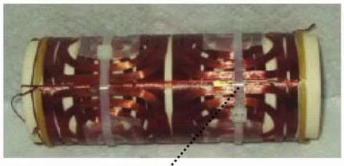
Created by a set of 3 additional coils (gradient coil)



One gradient coil



All three gradient coils

NB. Why are MRI scans so loud ?

11-3

Well, if you haven't been a volunteer, you might have heard that MRI scans are loud. And why are they so loud? We'll go after this question with the following three experiments that illustrate the basic principle that's behind the generation of sound during an MRI scan.

Notes

Summary

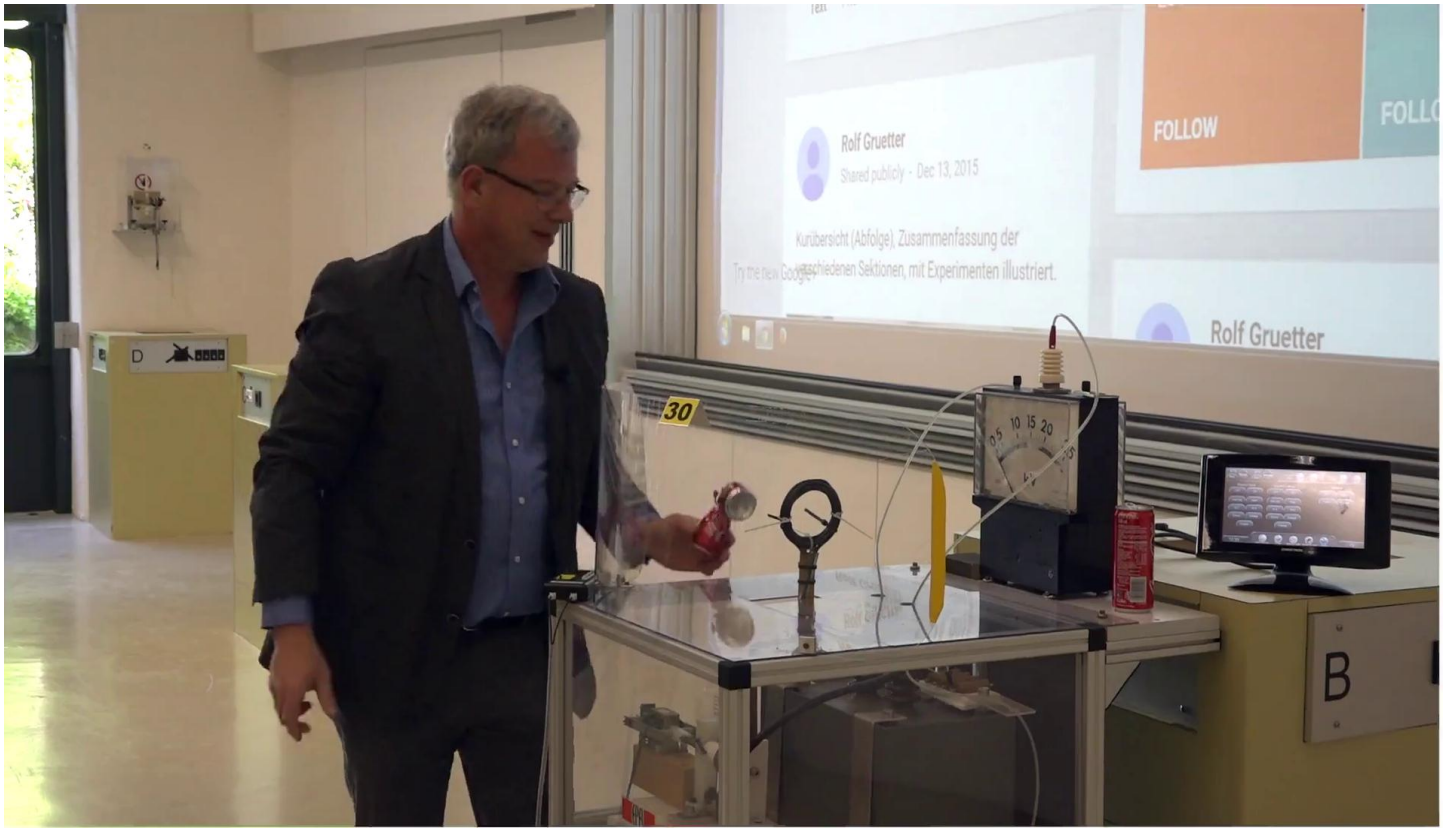
10m 01s

Okay, in this experiment we have a permanent magnet here, and we'll be running a current through this structure here. And I will turn on the current and it will invert its polarity, one can see the force that the magnetic field exerts on the conducting structure. First in this way, it's attracted towards the right. And now if I reverse the polarity, it is pushed in the other direction. That's a demonstration of the Lorentz force that's exerted on the structure that carries the current. This is what we have also in the MRI experiment. Okay, so in this experiment we have a coil here. I'll be pushing this button here and this will introduce a magnetic field rapidly. This magnetic field induces a change in flux. This flux will induce eddy currents in this aluminum ring, which in turn, those currents, through the Lorentz force, will interact with the magnetic field of the coil which will push back the ring and the ring will fly upwards. So I will go 3, 2, 1. (metal ringing) And here we go. If the ring is cut and cannot flow-- I'll do the same experiment here so now we have no ring current so there is no current that can flow, push the button and nothing happens.

Notes

Summary

10m 28s

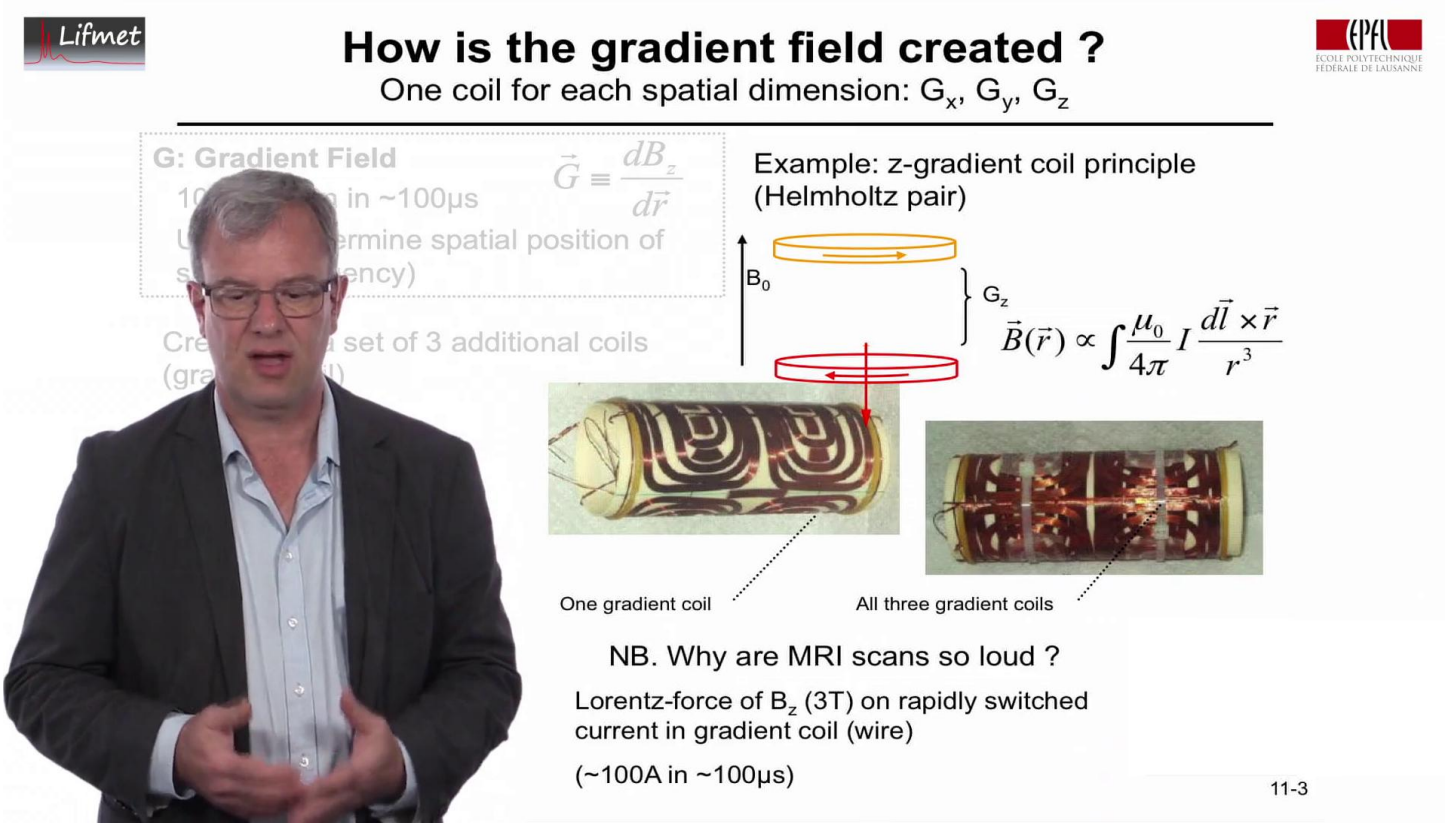


Conversely, if I run an AC current through the coil here, then I have a change in magnetic flux, and as I increase the current, that is the change in magnetic flux, then the force increases, that is acting on the ring. Okay, so in this experiment what we're going to demonstrate here, is, again, the Lorentz force. We have a coil here, and there's a big capacitor underneath. This capacitor will be charged. This will take some time, and then I will release the charge that's stored in the capacitor. This creates a surge of current in here, which creates an enormous flux change through this coil, which in turn induces eddy currents in the Coke can, which through the Lorentz force will contract and be split in two. So we will now start charging. And this process takes a while, we can see over here on the dial the increase we have to charge to roughly 10 kV. Okay, so we reached a steady-state. 3, 2, 1. (bang) And now if you touch this, you can feel that it is actually quite hot.

Notes

Summary

11m 55s

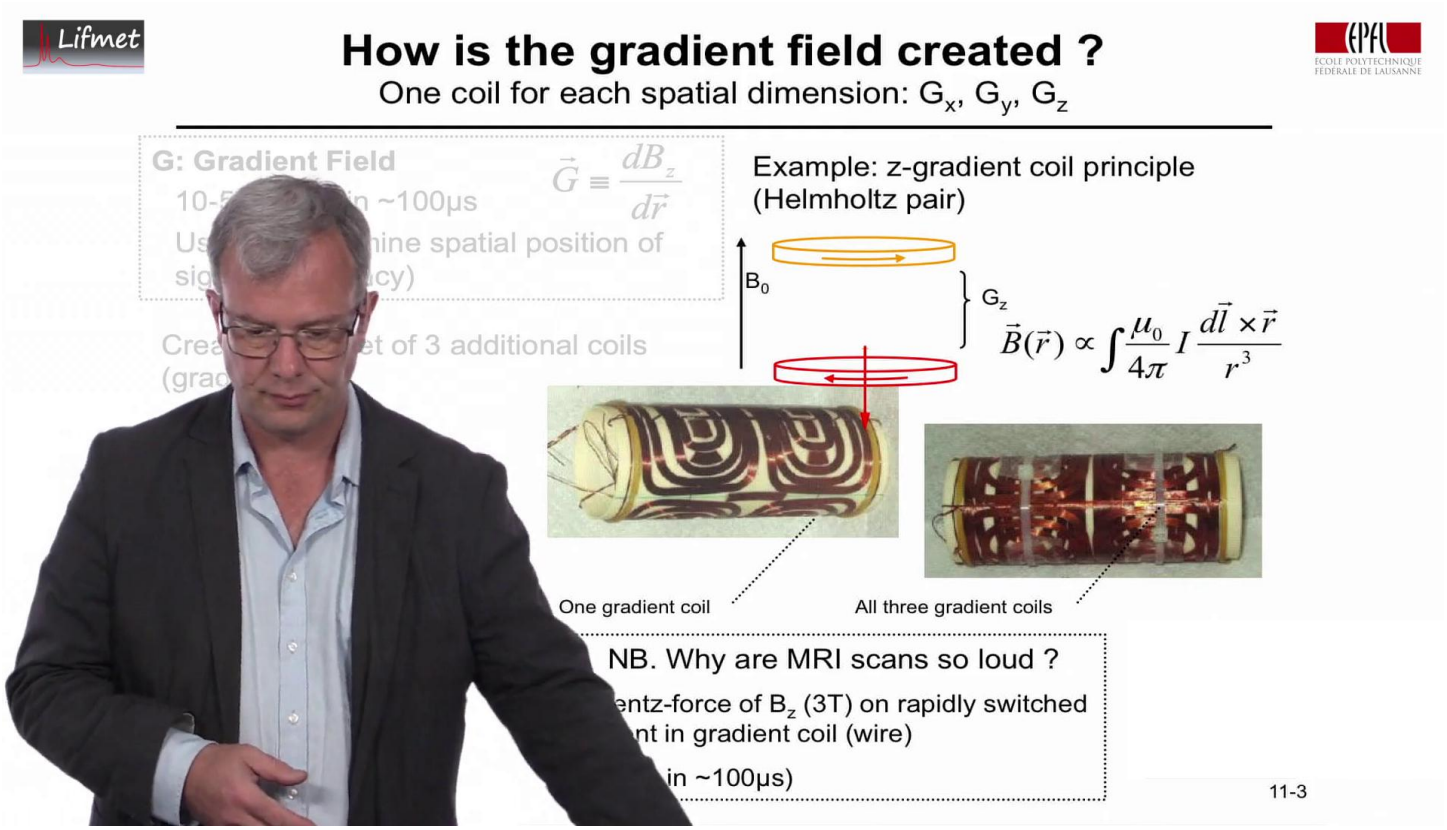


(scanner buzzing) So here in this video, is a practical example. So we can hear, the scanner as it is going. And you hear bzz, bzz, bzz, bzz. That's the typical sound of an MRI experiment under progress. (buzzing) So where does the sound come from in the MRI scanner? And the thing here is that, as we've seen with the experiments, we're looking at the Lorentz force of the *B0* field, let's say it's 3 T, so it's a very strong magnetic field, on rapidly switched current in the gradient coil. So this force builds up. Because the current in the gradient coil is switched rapidly, the force builds up rapidly, and this is like... (knocking on table) ...a hammer knocking on a structure. Here it's the copper structure that hammers on its support. That support doesn't move like if you hammer on a table, like this table here. The support cannot move but you still have this knocking sound, and that produces *very* strong forces, The examples with the Coke can are just mere illustrations of the kinds of forces that are in there. And so to give you an idea what we're talking about here, one switch is typically 100 A in about 100 µs. That's the kind of forces that we're looking at.

Notes

Summary

13m 25s



Now, without engineering attempts to reduce the sound inside the scanner it would be much louder, and over the years the scanners have become considerably quieter than they used to be 10, 15 years ago. So there's continuous research going on and development in trying to reduce the noise. But in general, it is advised to go into an MRI scan with the ear plugs so that one does not have some unpleasant surprises.

Notes

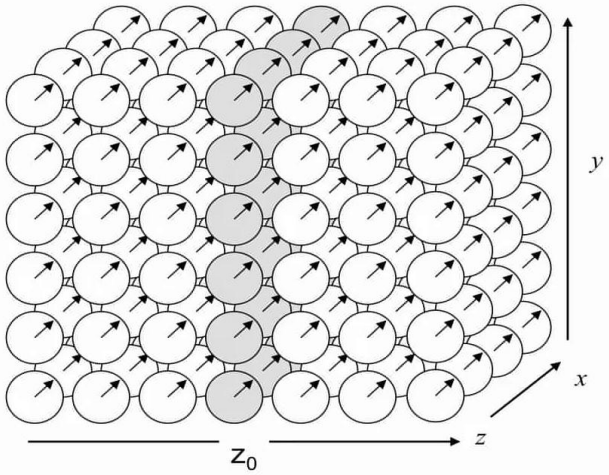
Summary

14m 57s

How is slice-selection achieved ?

Only magnetization on-resonance is excited

On-resonance:
Frequency ω_{RF} of RF field B_1 matches the precession frequency of magnetization



Now before going into how the image is reconstructed, I want to illustrate here with a simple example, I want to illustrate how slice-selection is achieved. So we have seen in the previous two courses that the radio frequency field *B1*, which is applied at a frequency *ω_RF*, it is capable of exciting the magnetization into the transverse plane if *ω_RF* matches the Larmor frequency of the precession of the magnetization. So if *ω_RF* is equal to *ω_L* then one is capable of flipping the magnetization into the transverse plane. What we're looking at here now, is a cube. If you consider this part of an object, it's a 7x7x4 matrix and each of these voxels contains the magnetization vector. We have the z direction here, we have the x direction, and we have the direction in y. Now we'll consider that we are here and that we have a position *z0* that corresponds to the gray voxels here in our object, and we consider that the Larmor frequency at this position is given by *γ B0 + γ Gz* times *z0*. So the Larmor frequency is equal to that, then if we set the *ω_RF* equal to that Larmor frequency, then we are capable of flipping the magnetization into the transverse plane.

Notes

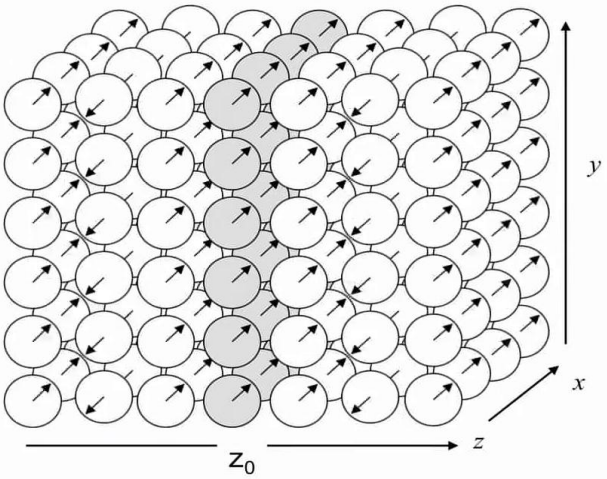
Summary

15m 34s

How is slice-selection achieved ?

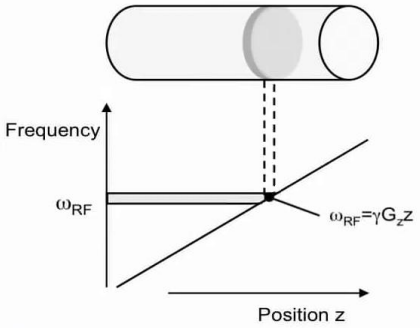
Only magnetization on-resonance is excited

On-resonance:
Frequency ω_{RF} of RF field B_1 matches the precession frequency of magnetization



$\omega_{RF}=\gamma B_0+\gamma G_z z_0$

Moving Frequency ω_{RF} alters position of slice :



NB. Not to confuse:

11-4

This is done on-resonance, as we have seen, that the magnetization that is off-resonance, that precesses, is not touched by the RF pulse, by the *B1* field, but only those that are on-resonance, so in our rotating frame, which is always set to the frequency of the *B1* field, this magnetization can be flipped into the transverse plane. So in this case, we can see that the magnetization that corresponds to the gray voxels, applying an RF field with this condition, will flip the magnetization transverse plane for all the gray voxels, and the others are untouched. And then it becomes a simple fact, a simple means of changing the frequency of the synthesizer to change the frequency of the RF field, and that alters the position of the slice. So here's now in the rotating reference frame, so this term does not appear. The *ω_RF* equals *γ Gz* times *z*, and then we select, in our object, this slice here. And now if we change the frequency of the synthesizer, we will change the position of the slice, and as we see here in this animation, it moves up and down with position as we change the frequency. Here I would like to make a side point and that is, which is important, we should not confuse two things.

Notes

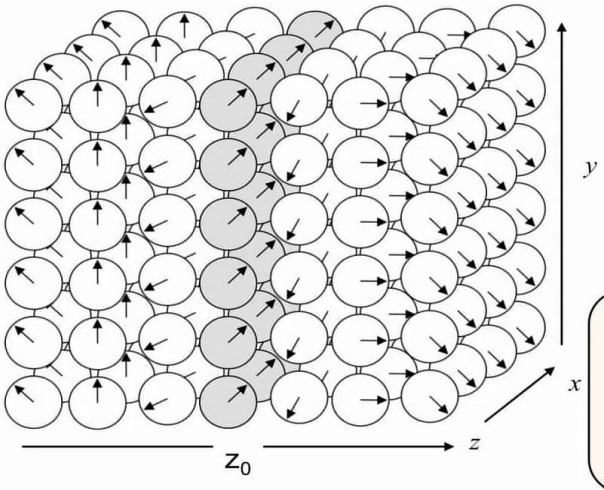
Summary

17m 18s

How is slice-selection achieved ?

Only magnetization on-resonance is excited

On-resonance:
Frequency ω_{RF} of RF field B_1 matches the precession frequency of magnetization



$\omega_{RF}=\gamma B_0+\gamma G_z z_0$

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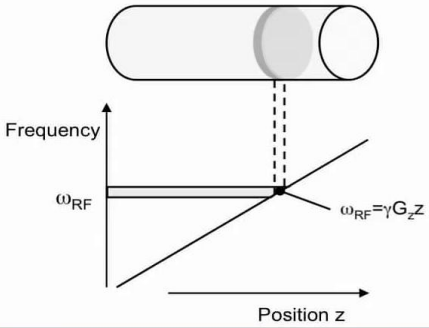


NB. Not to confuse:

(x,y) refers to spatial dimensions

M_{xy} M or $M_\perp$ refers to transverse magnetization (in magnetization space)

(coordinate systems are different, but share z)

11-4

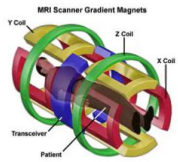
Typically we refer to x and y, to their positions in real space, so z is this direction, x is typically this direction, and y is typically this direction. *Mxy* or *M* or *M_perpendicular* refers to the transverse magnetization. Here, x and y denote the transverse components in magnetization space. So this is different than real space. If we put ourselves into a rotating reference frame, we do that in magnetization space, and not in real space, and we're dealing here with two different coordinate systems. However, they do share the z component. So this is important that we keep that in mind for the rest of this course.

Notes

Summary

18m 46s

Credits



Magnetic resonance imaging, American College of radiology
http://www.cedarlakemri.com/

Vertical Bore imaging, MRI probe
http://dotynmr.com/products/high-field-mri-coils/vertical-bore-imaging/

MRI image formation,
Walter Block and Franck R. Korosec, PhD, University of Wisconsin
http://slideplayer.com/slide/5880663/

What does an MRI scan sound like?
https://youtu.be/8oI9YnhPNcQ

Notes

Summary

19m 33s