Introduction to the hardware of the NMR spectrometer

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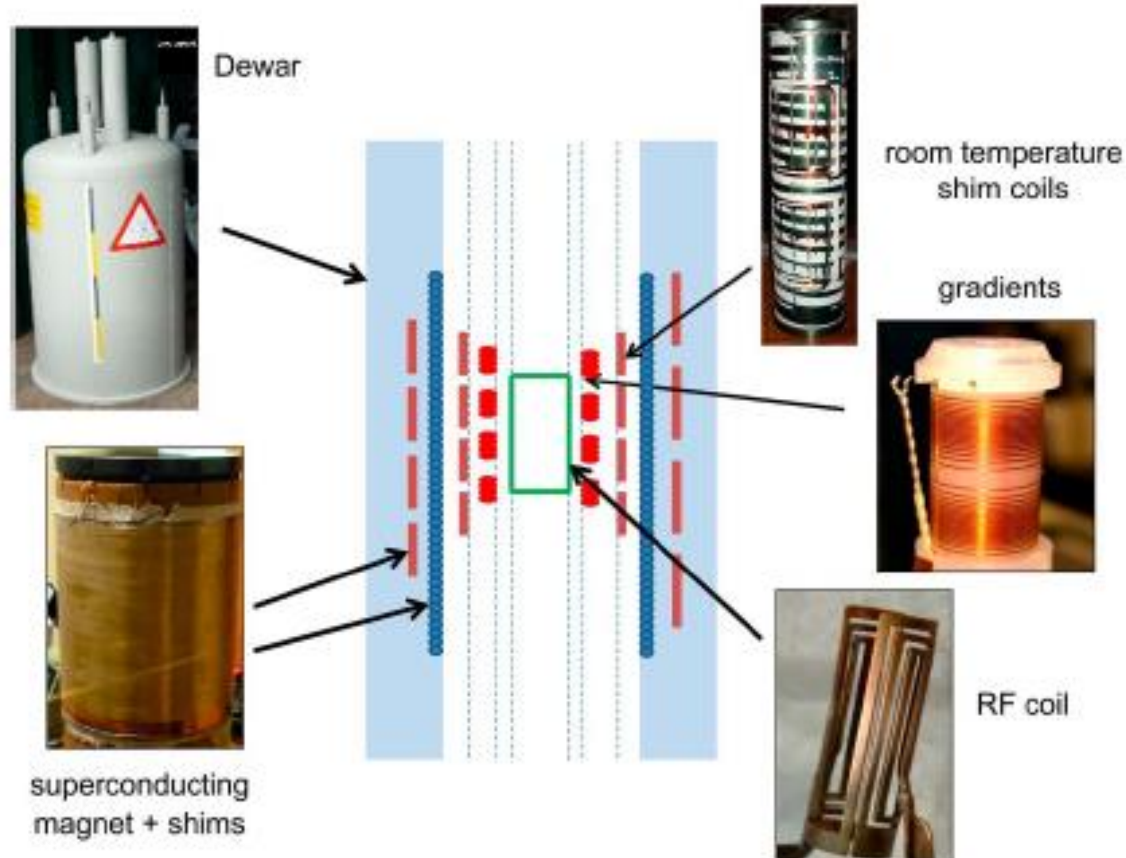
Agenda

- Quick overview on the NMR hardware
- The magnet
- The shims coils
- The gradient coils
- The RF coil
- The coaxial cables
- The RF transmitter
- The RF receiver



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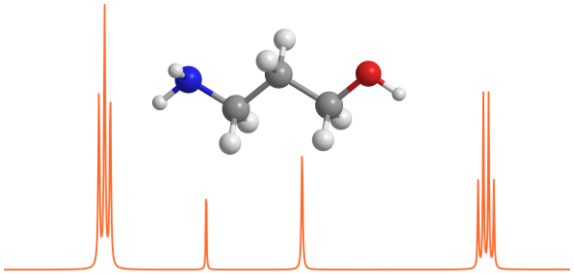
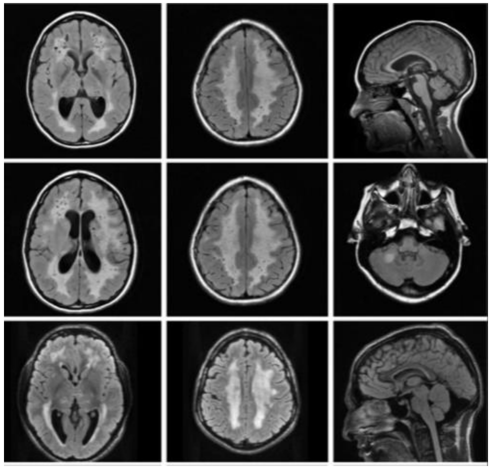
Magnetic resonance system



NMR spectrometers



MRI scanners

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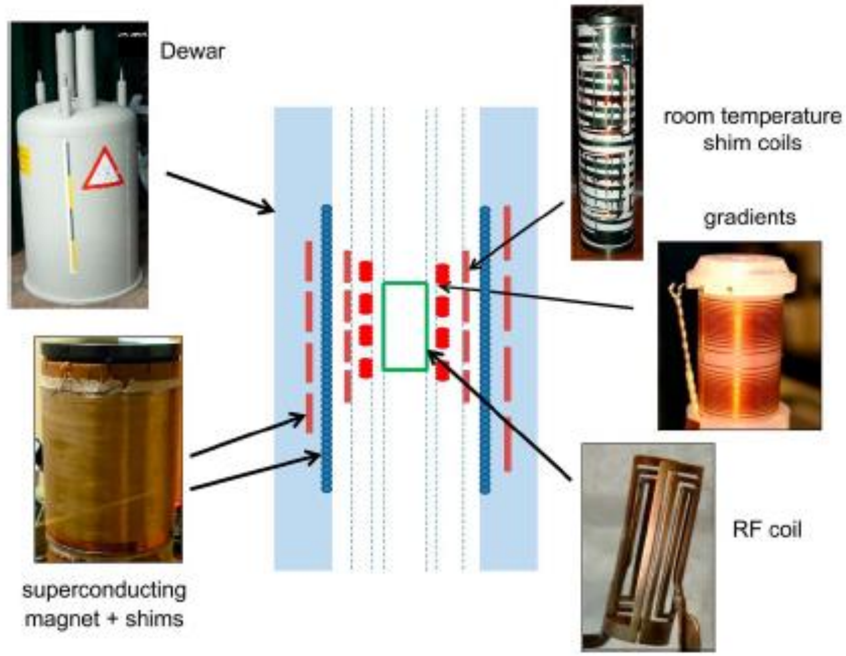
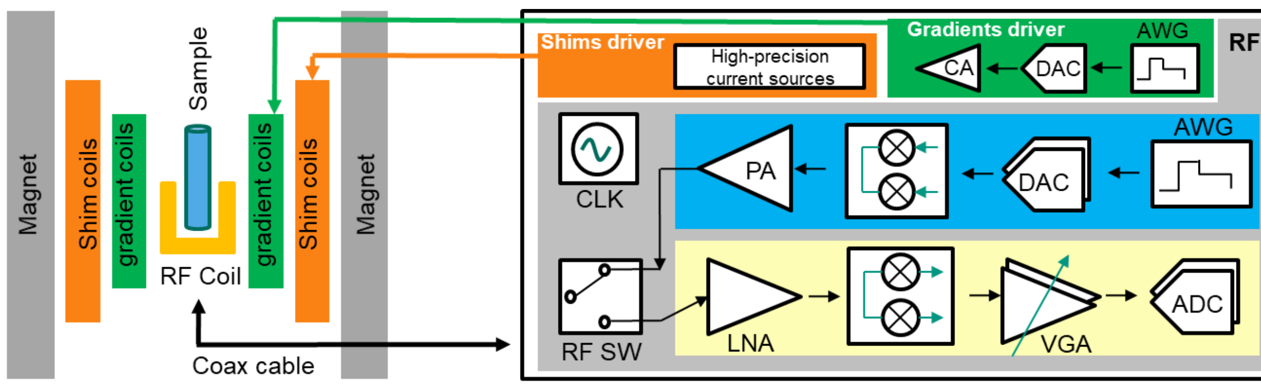
The MR spectrometer





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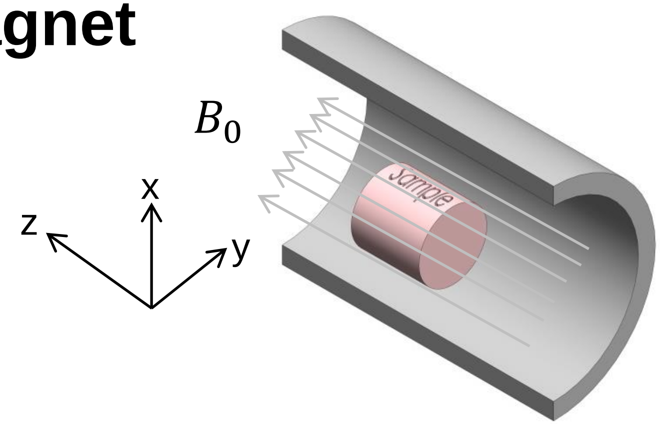
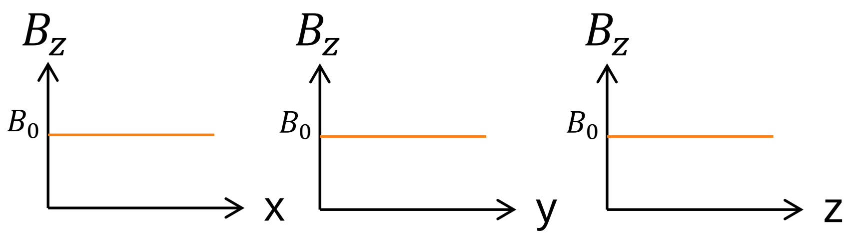
MR spectrometer – The magnet

- The Magnet is designed to be
  - Stable
  - Homogenous





$$M_0 = \frac{V_s \gamma^2 I(I+1) B_0}{3 K_B T_s}$$

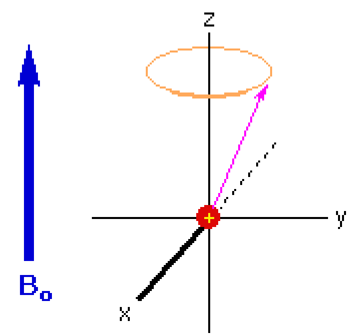
V_s : The sample volume

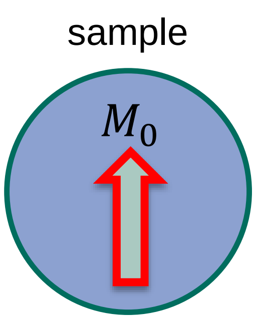
γ : gyromagnetic ration (42.58 MHz/T for ^{1}H)

I : spin number ($1/2$ for ^{1}H)

T_s : sample temperature

$$\omega_l = 2\pi \cdot \gamma \cdot B_0$$





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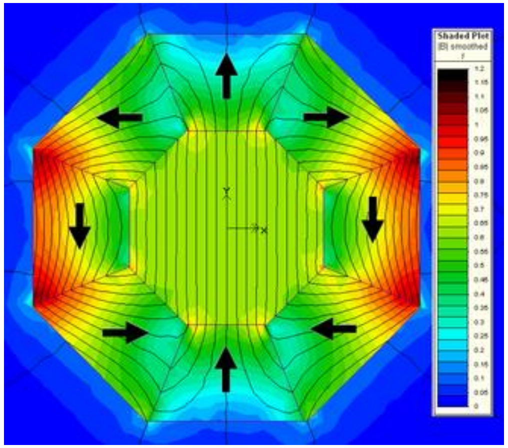
Types of magnets

Superconducting

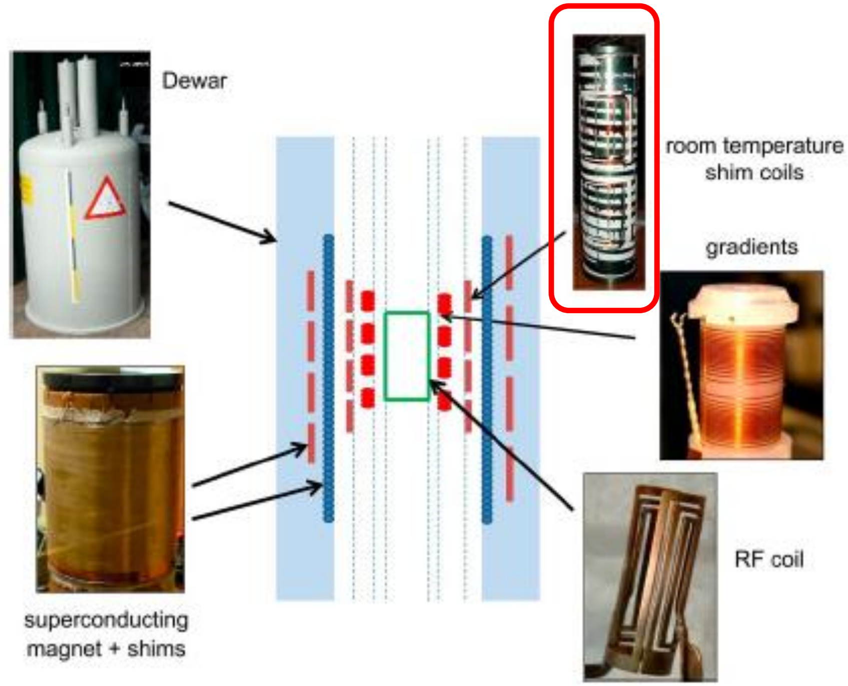
- Low-temp (<30K) superconductors such as niobium-titanium NbTi and niobium-tin Nb3Sn alloys
- Generates high fields (>20T)
- Requires liquid helium

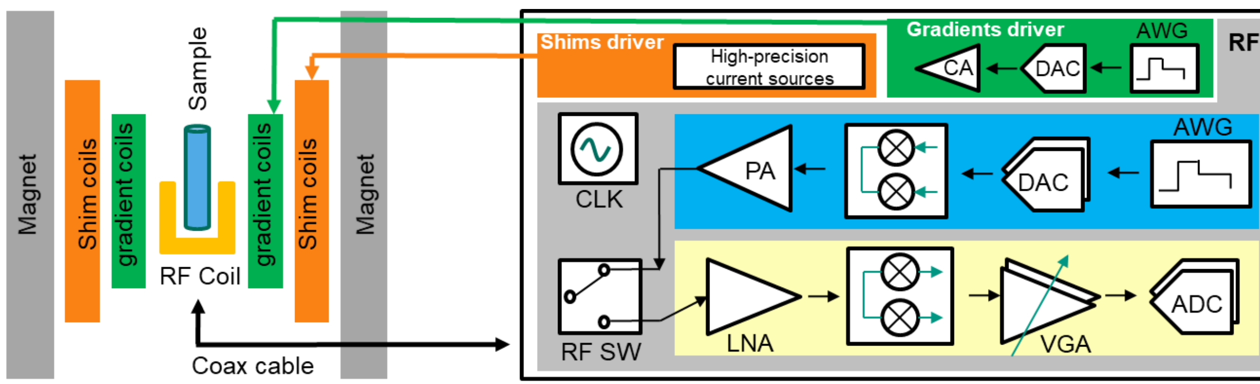
Permanent



- Based on Neodymium (NdFeB) permanent magnets
- Fields up to 2T
- Halbach configuration

The MR spectrometer





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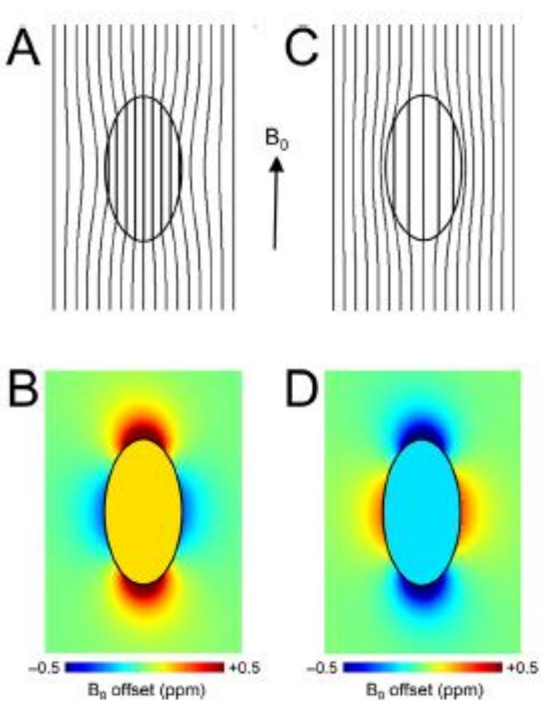
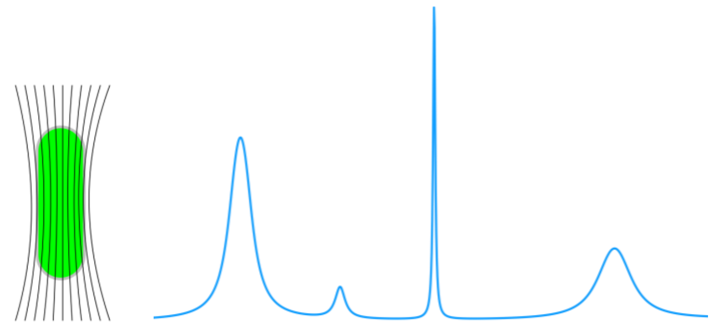
The shim coils

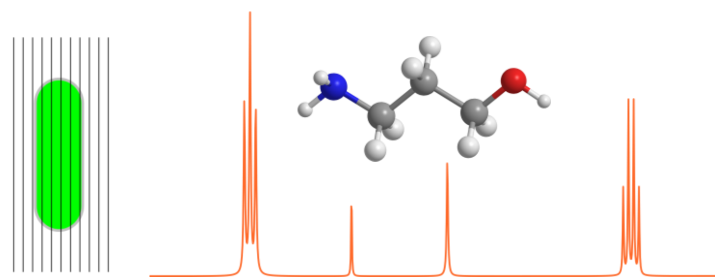
- Field inhomogeneity results from the manufacturing errors and the magnetic properties of the sample
- For high resolution spectroscopy, ppb homogeneity is required



Paramagnetic Diamagnetic



Inhomogeneous field



Homogeneous field

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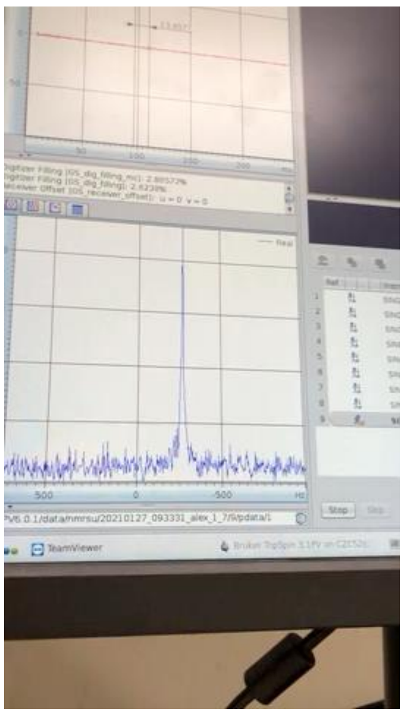
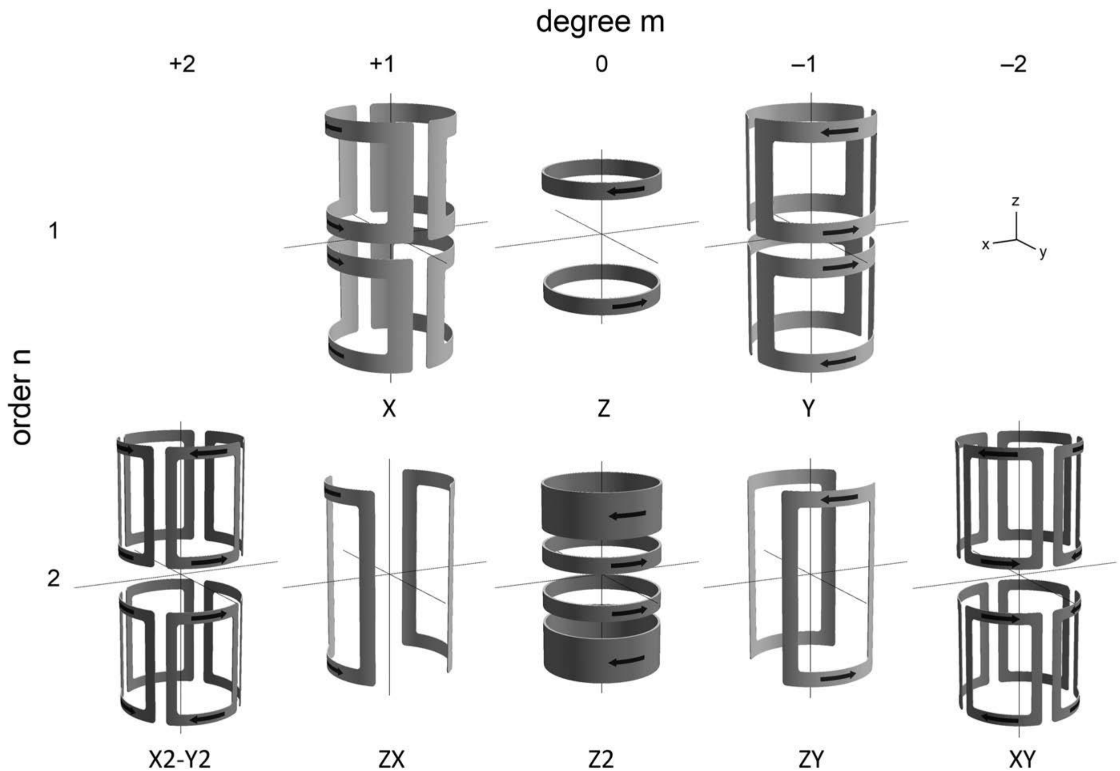
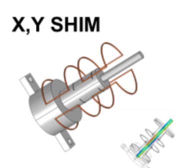
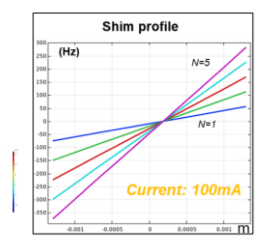
The shim coils

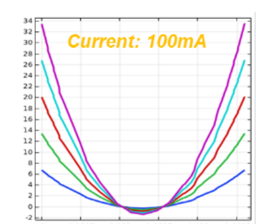
- Used to correct field inhomogeneity
- Driven by DC currents
- Can be up to 6th order along x, y, and z axes



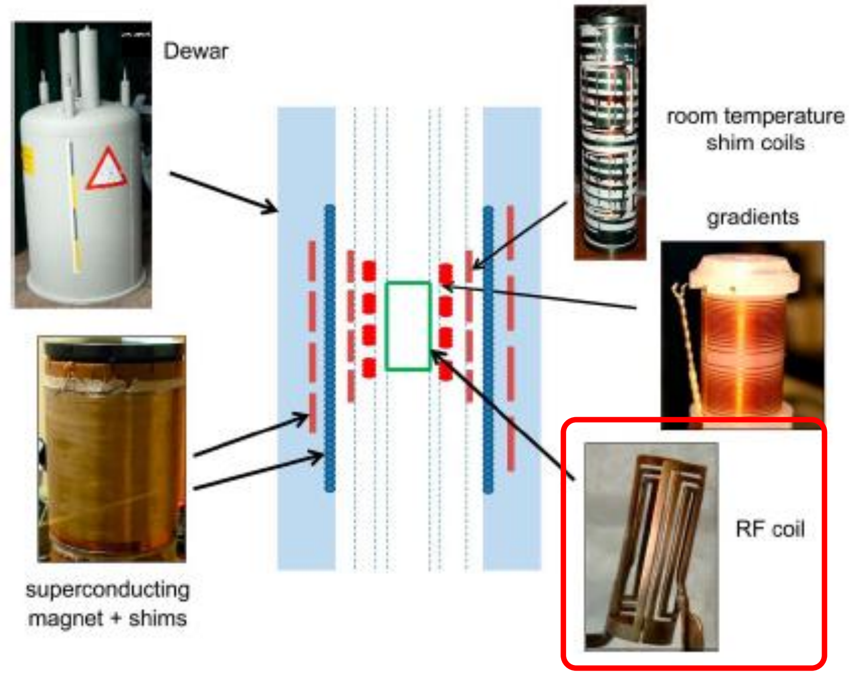


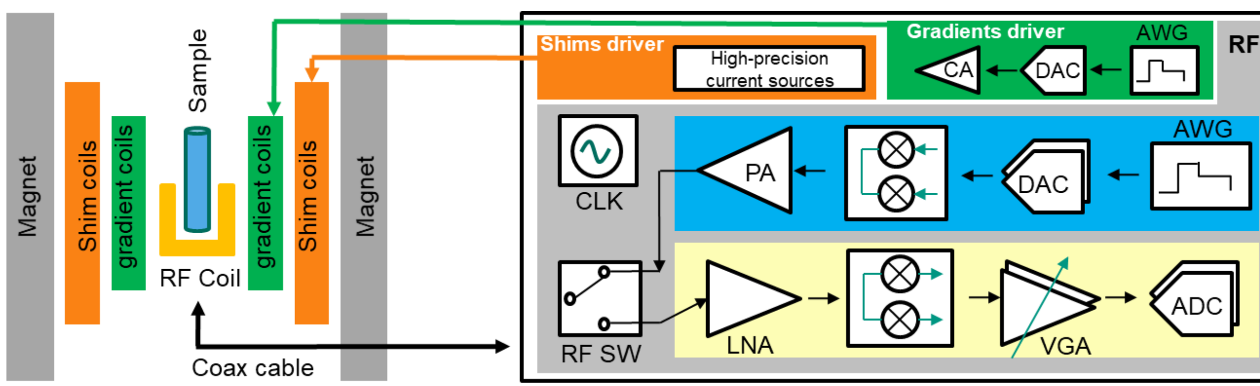






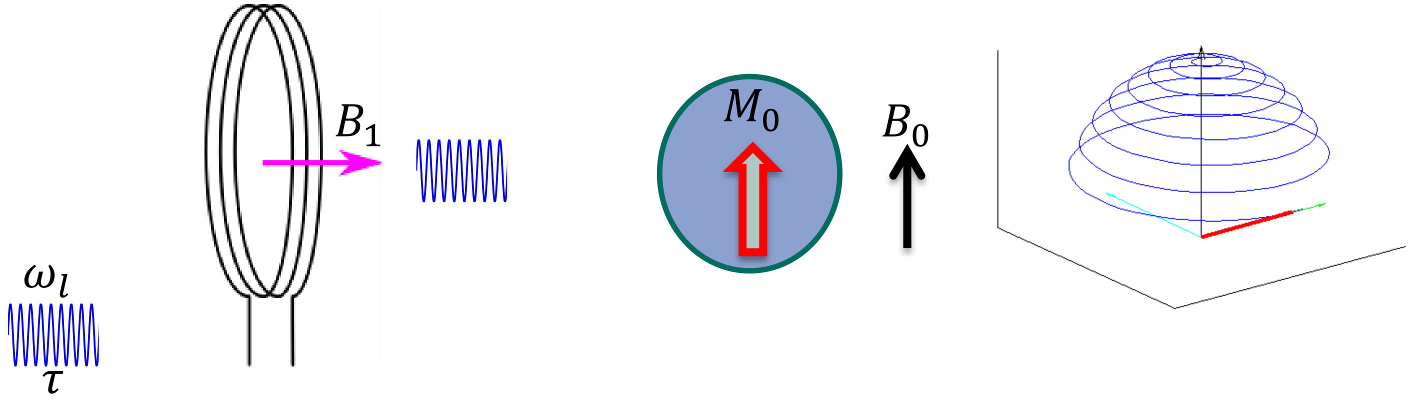
The MR spectrometer





MR spectrometer – The RF coil

- The RF coil
  - It is the tool to talk and listen to the magnetization
  - Excitation phase
    - Tilting M_0 using a time-varying B_1 field with frequency ω_l
    - M_0 does not response to any other frequency
    - $\alpha = \gamma \cdot |B_1| \cdot \tau$



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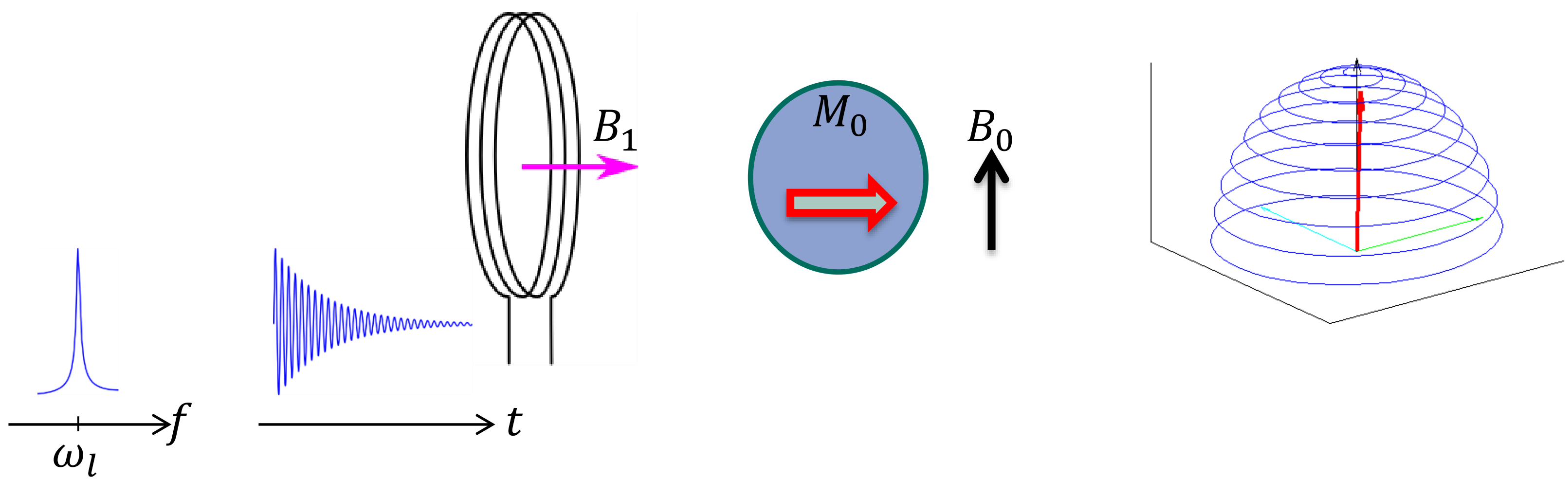
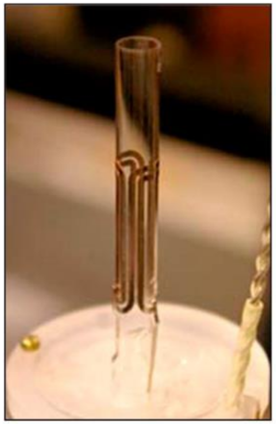
MRI scanner – The RF coil

- The RF coil
  - It is the tool to talk and listen to the magnetization
  - Reception phase
    - The excited magnetization induces a voltage across the terminals of the coil
    - $V_{MR,max} = \omega_l \cdot B_1 \cdot M_0$
    - $V_{noise} = \sqrt{4k_B T_c \Delta f r_c}$

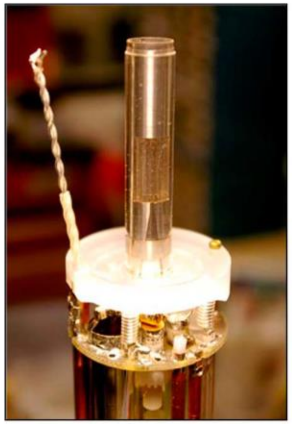


Types of RF coils

NMR coils



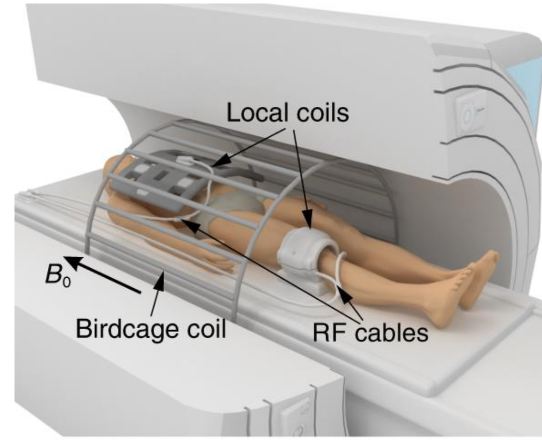
saddle coil



Alderman–Grant coil

MRI coils

Birdcage head coil



4-channel receive coil for mouse MRI

8-channel receive coil for mouse MRI

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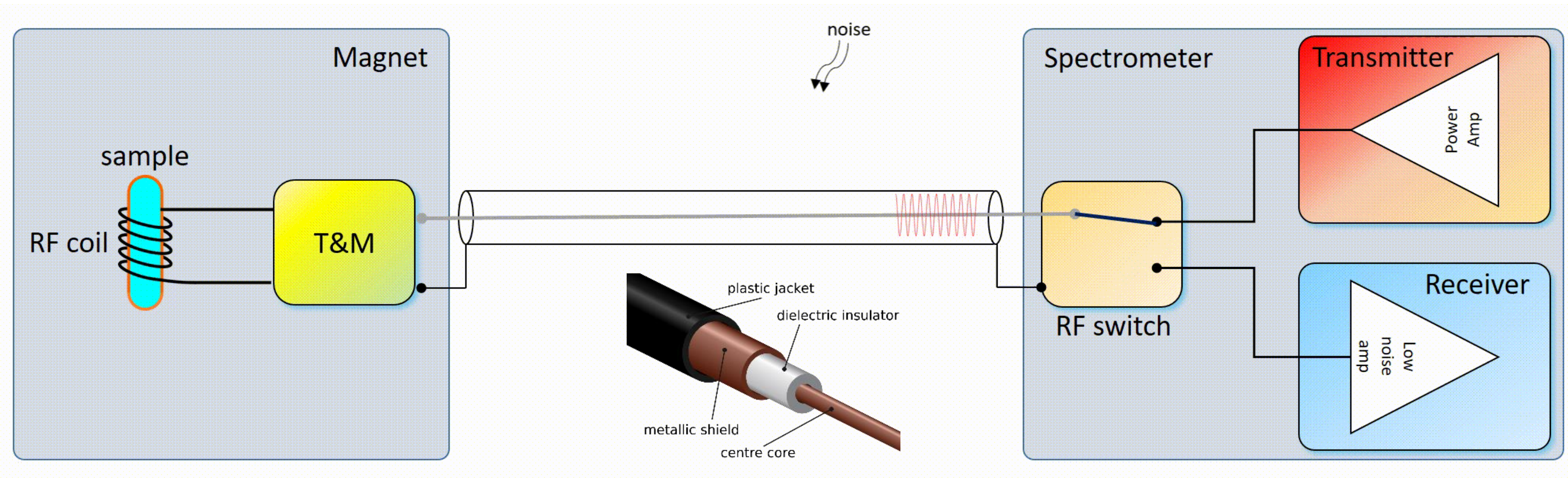
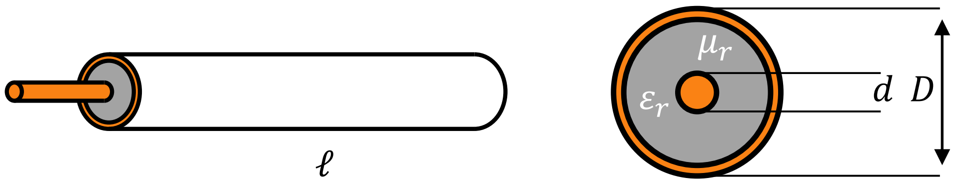
Interfacing the RF coil

- Electronics are too bulky to fit in the magnet
- They're usually placed few meters from it



- Coaxial cables provide:
  - Low-loss transmission
  - Shielding against noise
- The use of coax cables puts constrains on all other parts

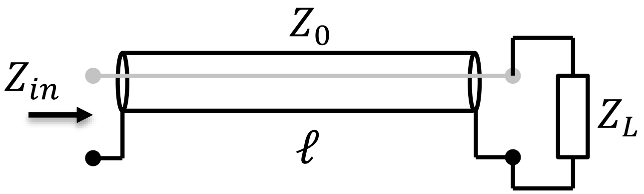
Coaxial cables - basics



- Characteristic impedance: $Z_0 = \frac{1}{2\pi}\sqrt{\frac{\mu}{\varepsilon}}\ln\frac{D}{d}$
- Standard values of Z_0 include: $50\ \Omega$ and $75\ \Omega$
- Impedance transformation:

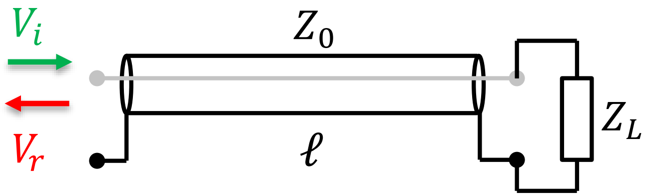
$$Z_{in} = Z_0 \frac{Z_L + jZ_0 \tan\left(\frac{2\pi f \ell}{v}\right)}{Z_0 + jZ_L \tan\left(\frac{2\pi f \ell}{v}\right)}$$

f : wave frequency
v : wave speed in the cable



- Wave reflection:

$$\Gamma = \frac{V_r}{V_i} = \frac{Z_L - Z_0}{Z_L + Z_0}$$



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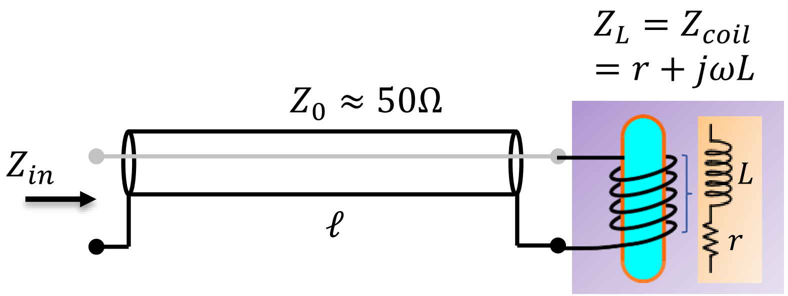
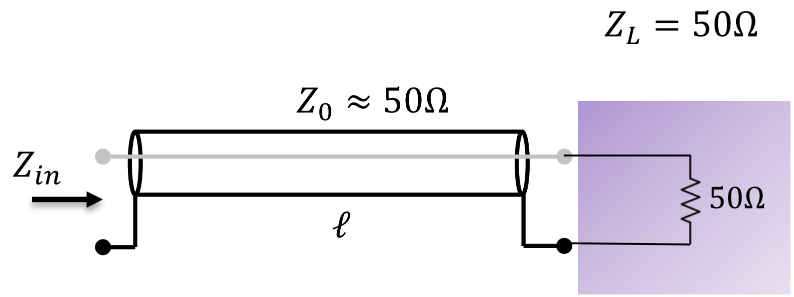
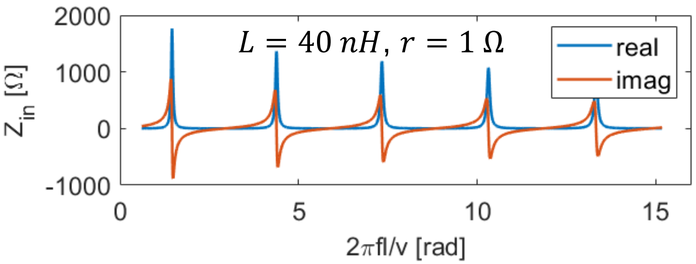
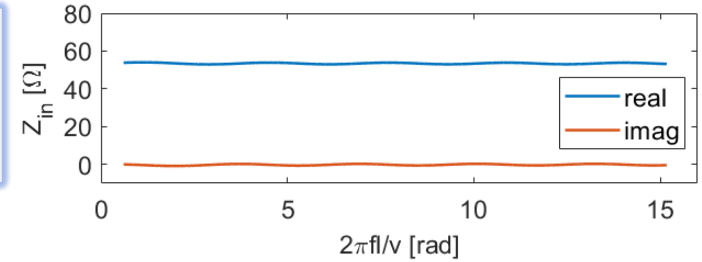
Impedance transformation & wave reflection

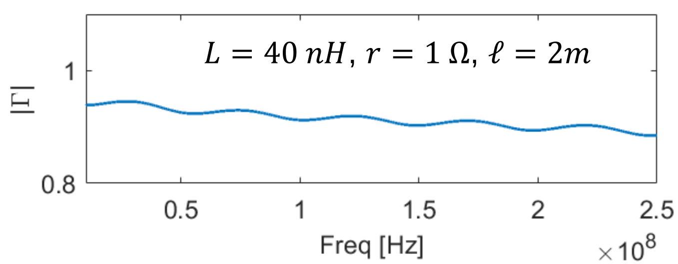




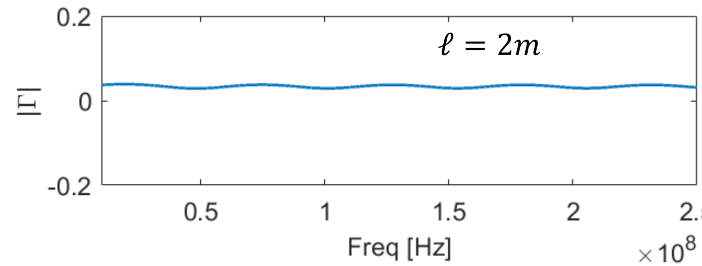


$$Z_{in} = Z_0 \frac{Z_L + jZ_0 \tan\left(\frac{2\pi f \ell}{v}\right)}{Z_0 + jZ_L \tan\left(\frac{2\pi f \ell}{v}\right)}$$





$$\Gamma = \frac{V_r}{V_i} = \frac{Z_L - Z_0}{Z_L + Z_0}$$

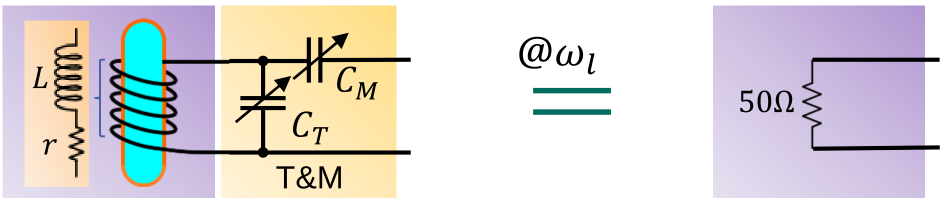


Inefficient power transmission

Efficient power transmission

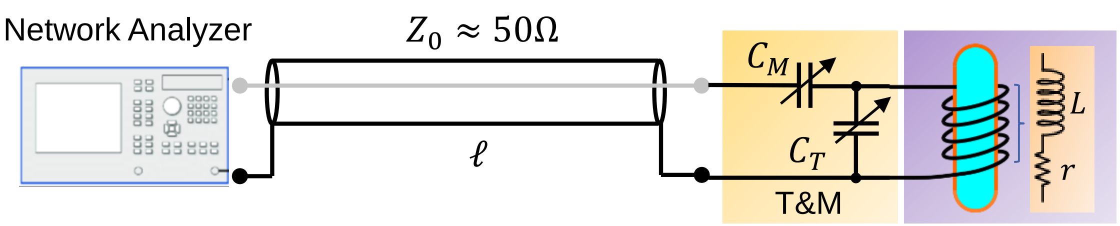
How T&M is measured?

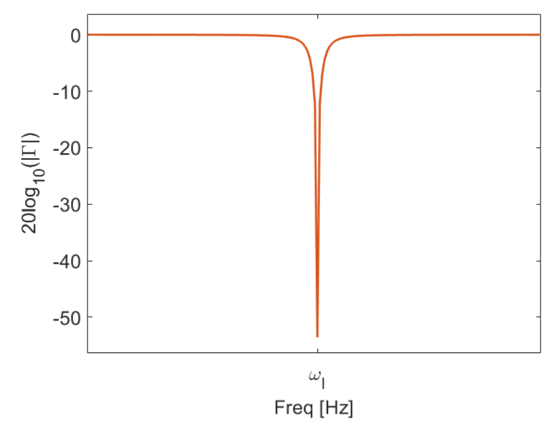
- Example of commonly used T&M topology



$$C_T \approx \frac{1}{\omega_l^2 L}\left(1 - \sqrt{\frac{r}{50}}\right), \; C_M \approx \frac{1}{\omega_l^2 L}\left(\sqrt{\frac{r}{50}}\right)$$

- T&M condition can be tested by measuring wave reflection Γ via a Network Analyzer





$$\Gamma = \frac{V_r}{V_i} = \frac{Z_L - Z_0}{Z_L + Z_0}$$

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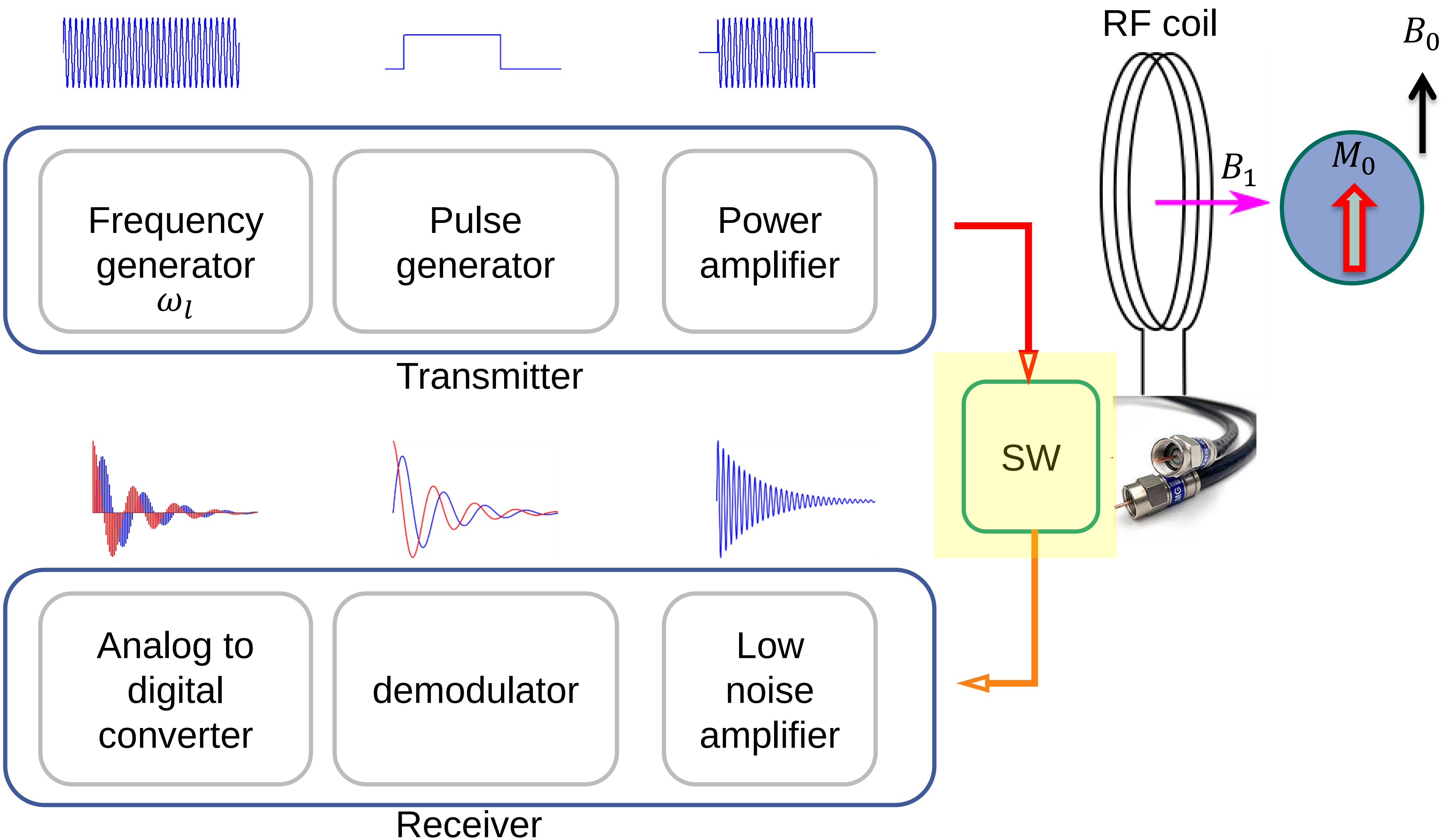
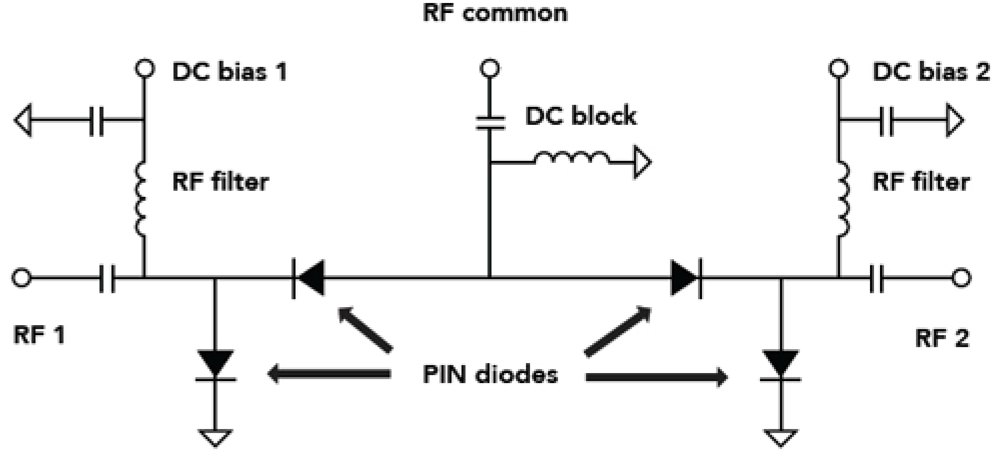
MRI scanner – Tx and Rx electronics



TX RX – the RF switch

- Why the switch ?
  - Connects the coil to the transmitter during excitation
  - Connects the coil to the receiver during reception
- What are the main requirements of the switch ?
  - Good isolation (> 60dB)
  - Fast switching time (< 1µs)



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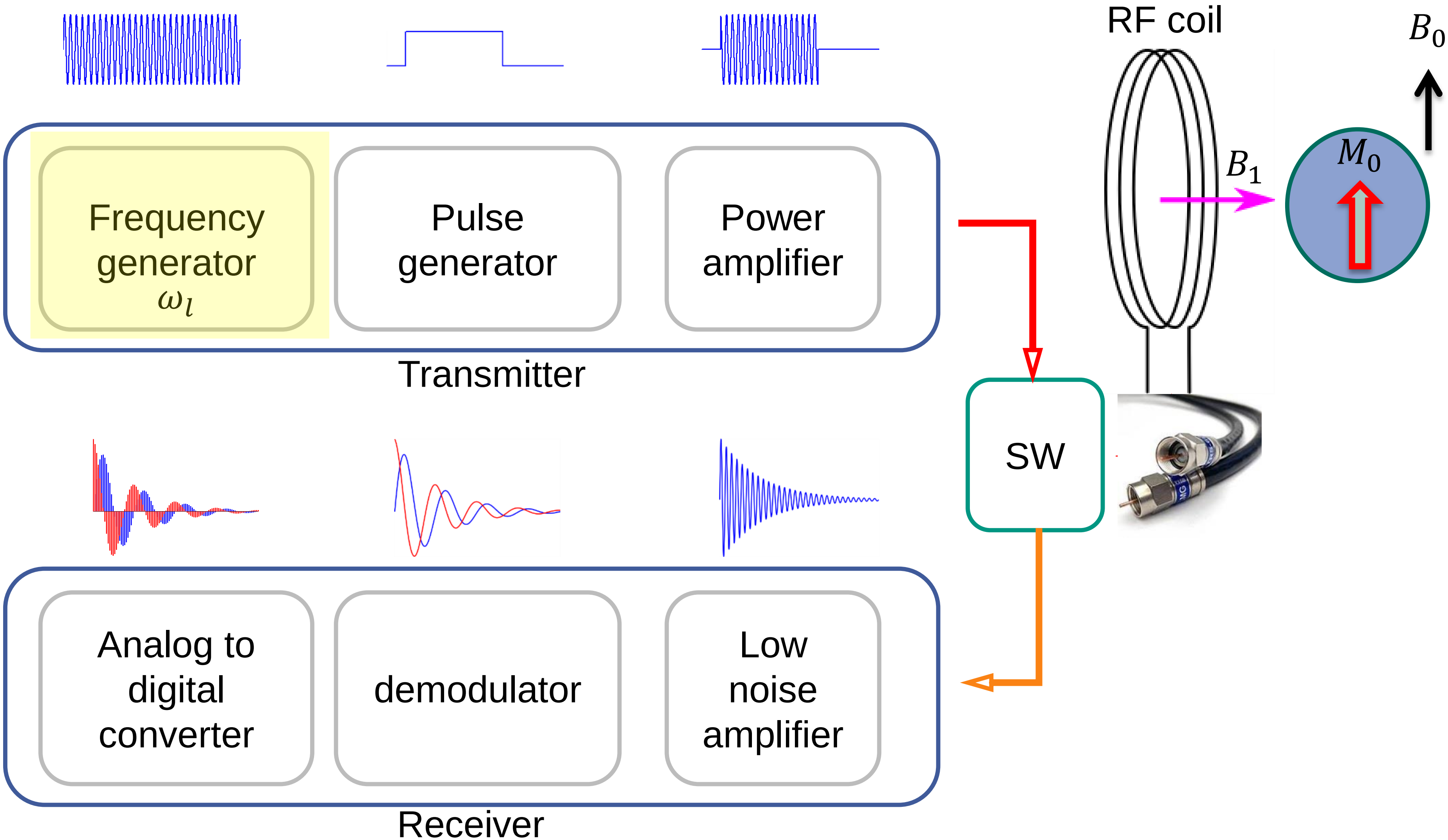
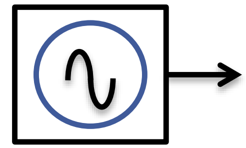
MRI scanner – Tx and Rx electronics



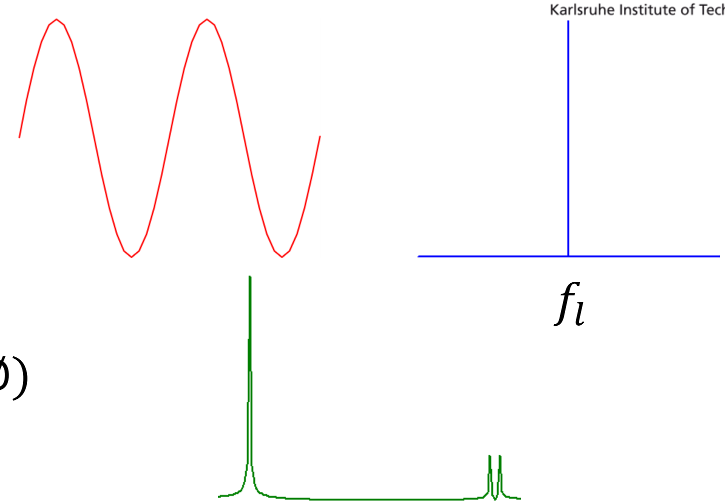
TX – RF generator

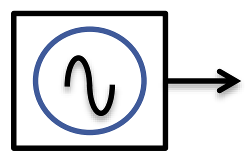
- Precise (low phase noise) Larmor frequency
- High phase noise ruins the spectral resolution
- Phase noise should be 90 dB below the carrier for 1 kHz offset



Ideal signal generator

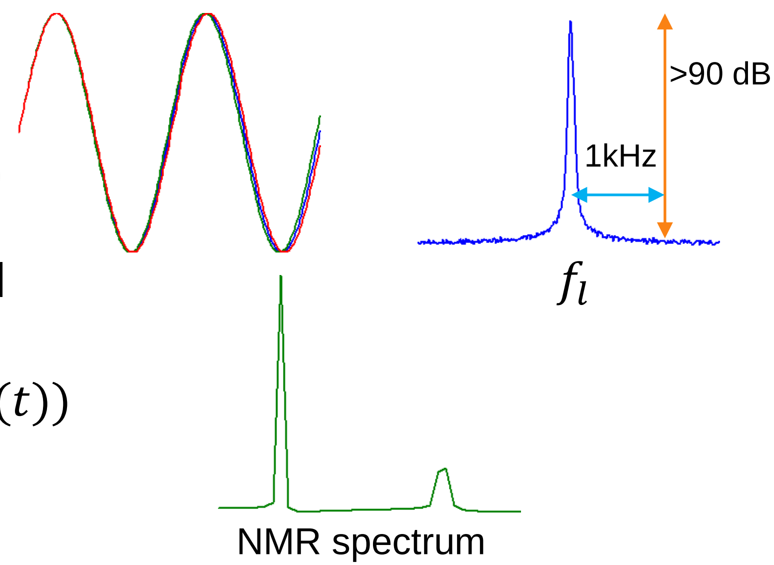
$S = \cos(2\pi f_l t + \emptyset)$





Practical signal generator

$S = \cos(2\pi f_l t + \emptyset(t))$



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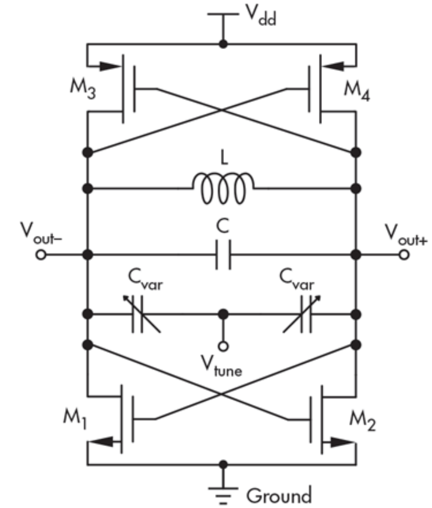
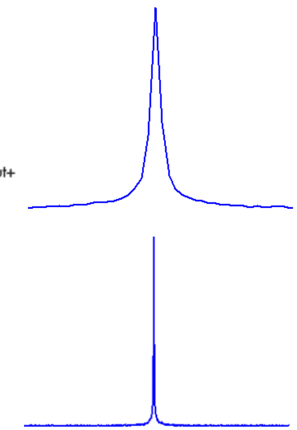
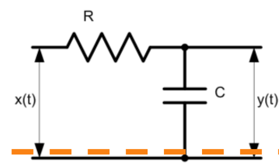
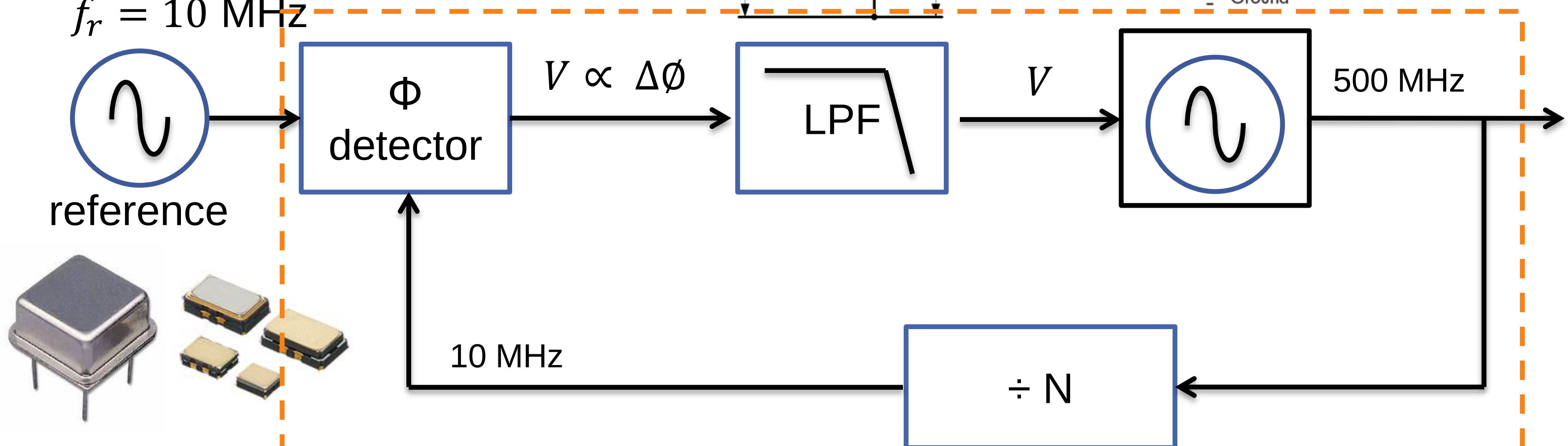
Oscillator circuits

- LC VCO $f \propto 1/\sqrt{LC}$
- Phase locked loop to enhance the phase noise





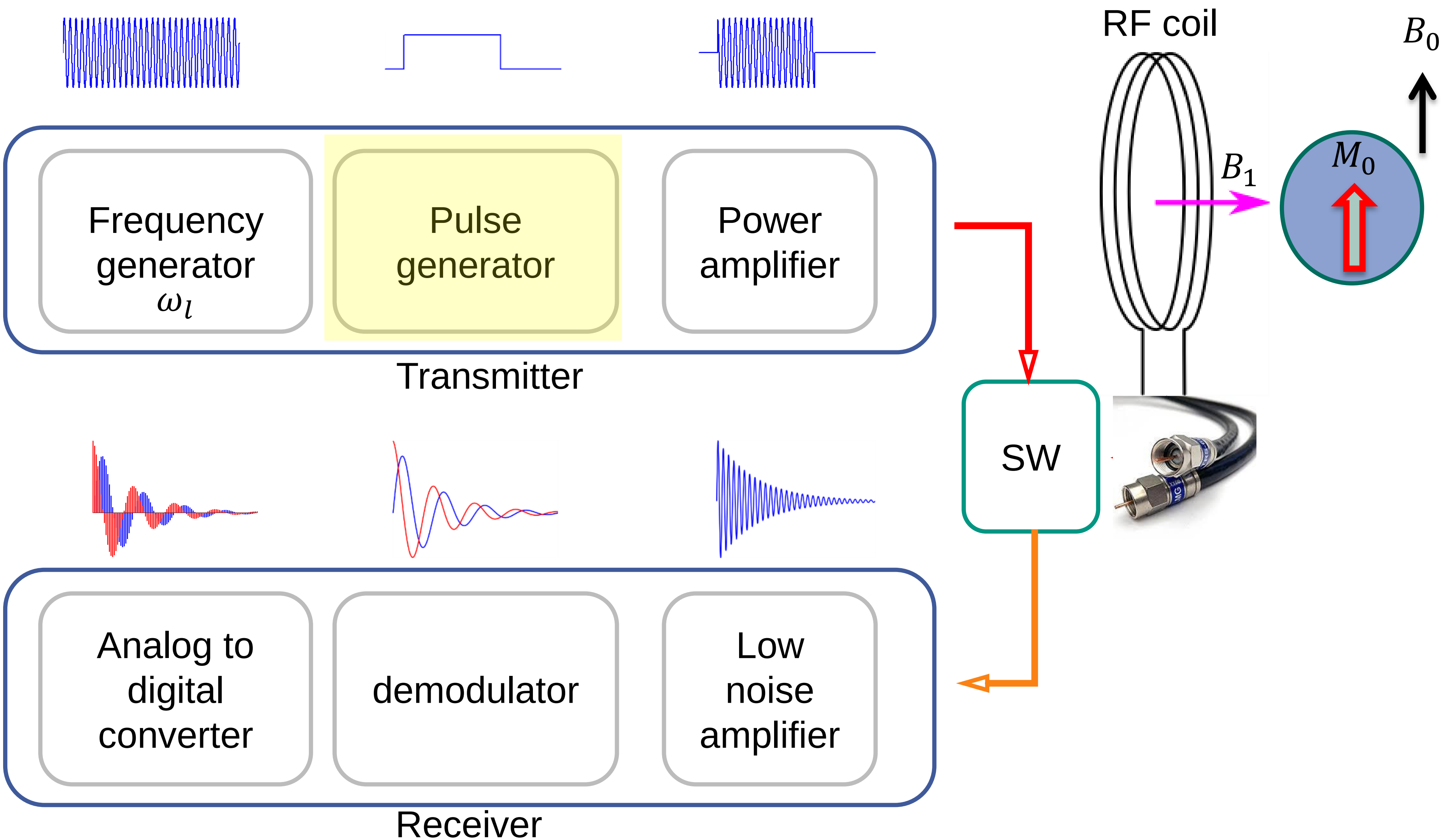




Phase noise < -130 dBc/Hz

Frequency = 10 MHz – 15 GHz
PN = -110 dBc/Hz (100 kHz @ 15 GHz carrier)

MRI scanner – Tx and Rx electronics



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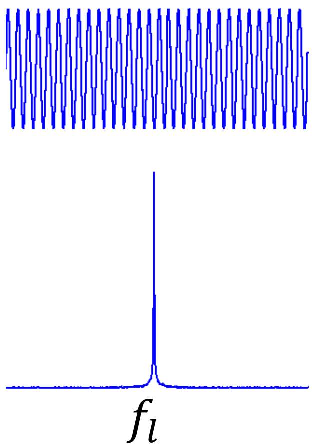
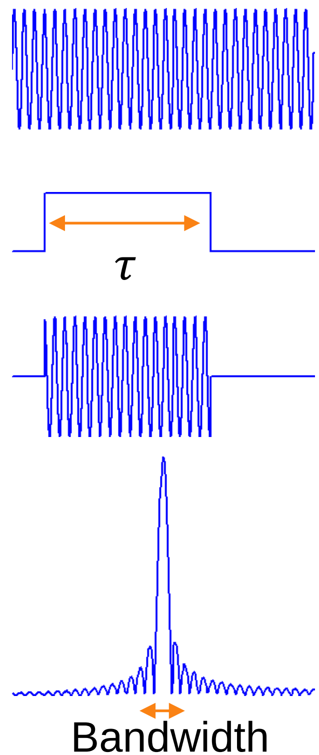
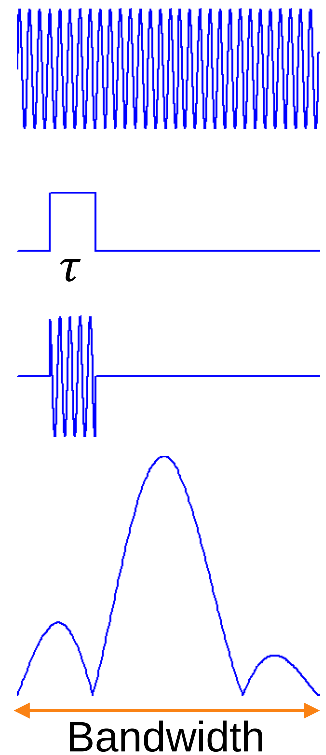
TX – Pulse gate

- A fast switch that gates the Larmor frequency
- It can precisely control the duration of the pulse and it phase
- The duration τ the bandwidth and the flip angle $\alpha = \gamma \cdot |B_1| \cdot \tau$
- Typical pulse duration µs - ms







Digital to analog converter

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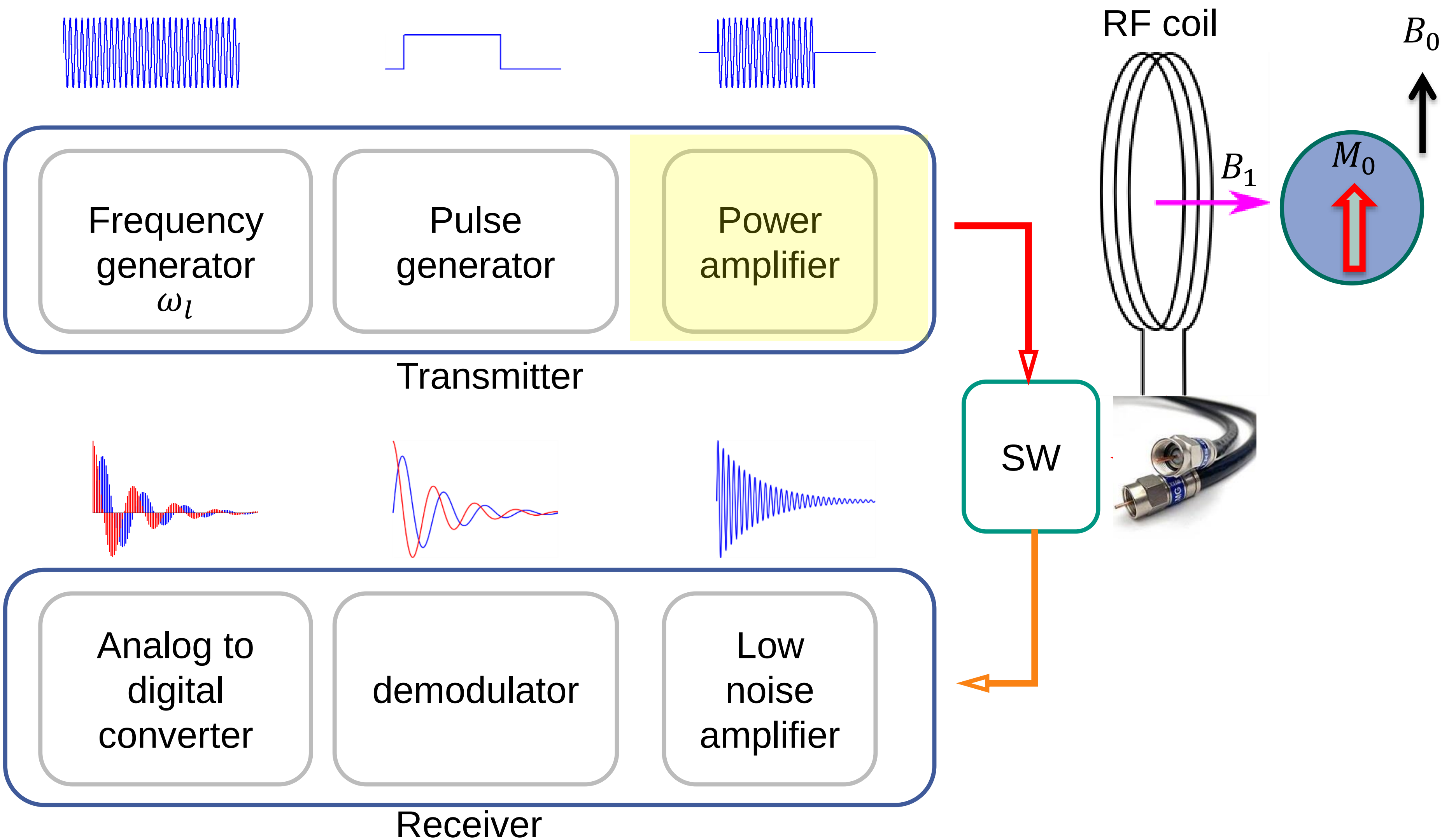
MRI scanner – Tx and Rx electronics



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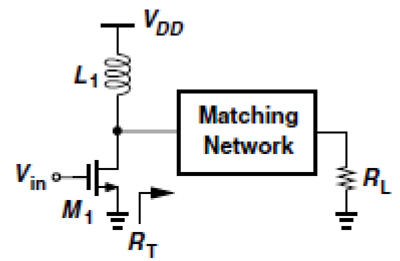
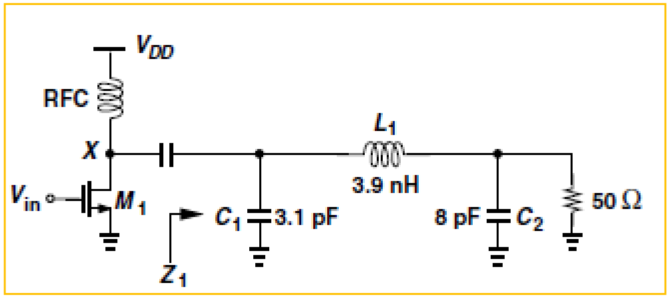
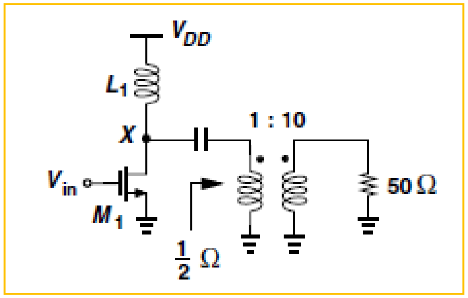
TX – power amplifier



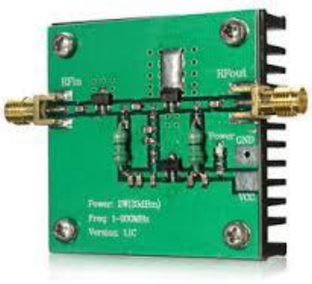
- Why we need the power amplifier?
  - To control the flip angle $\alpha = \gamma \cdot |B_1| \cdot \tau$

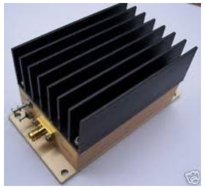
- Typical ranges of powers used in MR
  - mW - kW



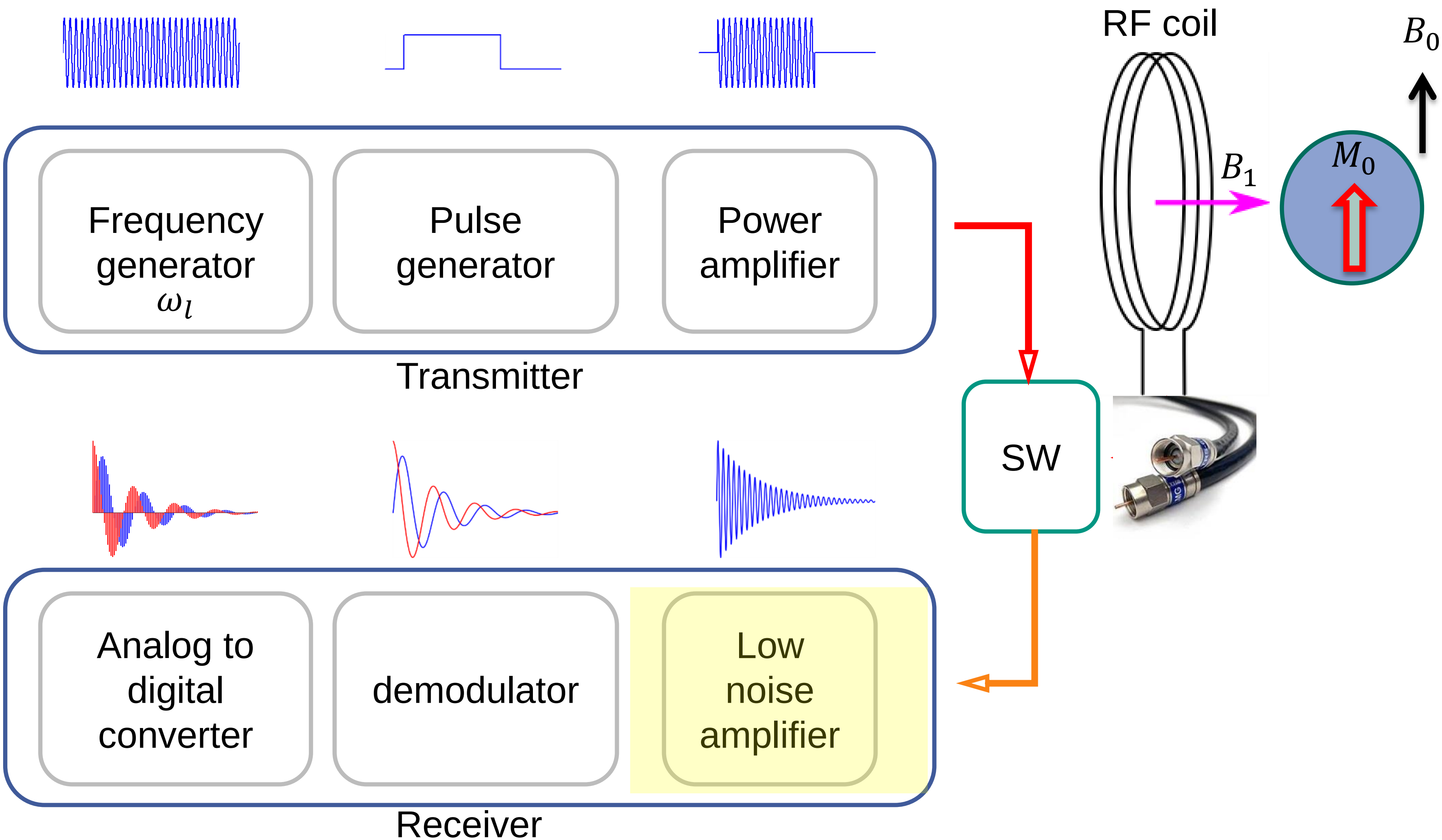


- The matching network is necessary to reduce the load at the output of the amp, and thus reduces the required voltage swing





MRI scanner – Tx and Rx electronics



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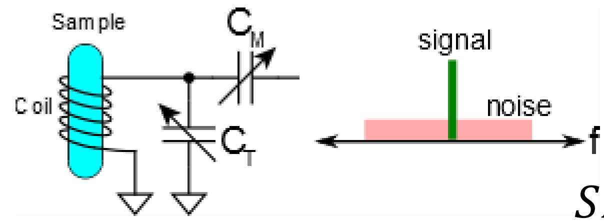
RX – LNA

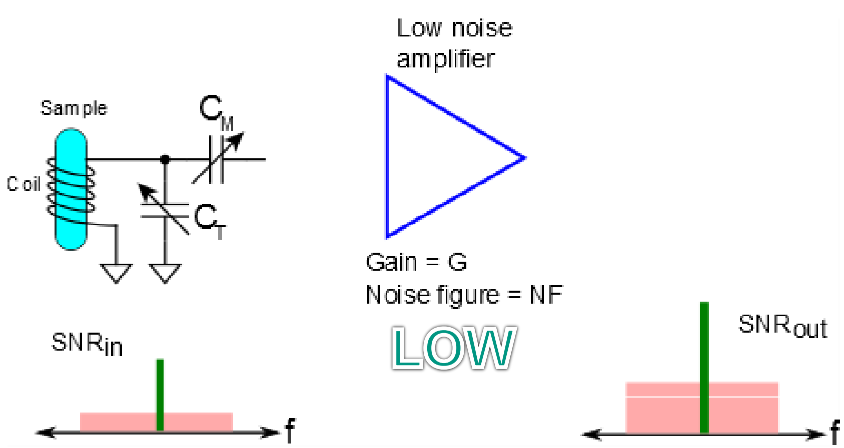
- NMR signal is inherently very small
- The LNA is used to amplify the NMR signal to a useful level without adding significant noise

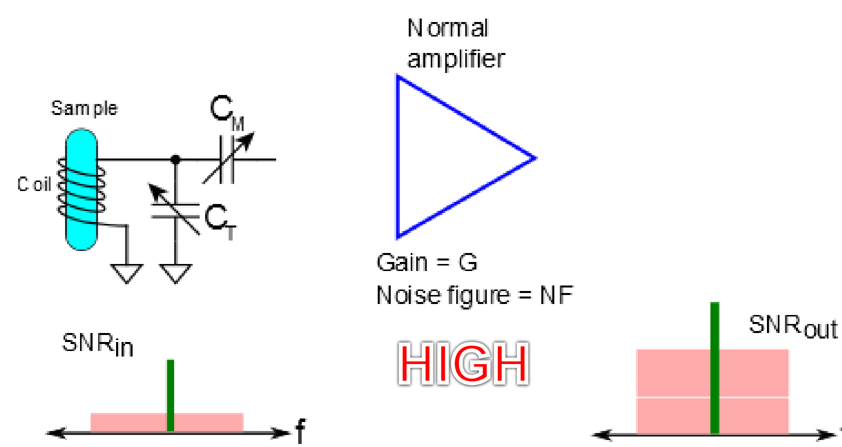


$$SNR = \frac{Signal\ power}{Noise\ power}$$

$$F = \frac{SNR_{in}}{SNR_{out}}$$

$$NF = 10 \cdot \log(F)$$





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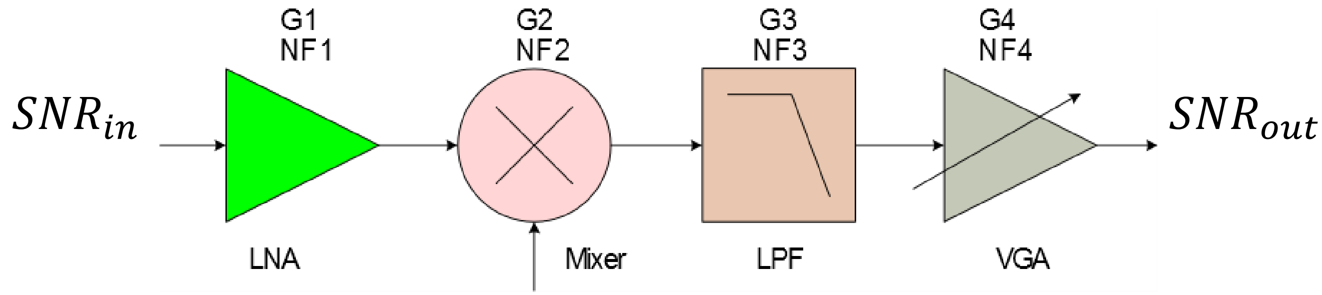
RX – LNA

- Frii's formula



$$F_{total} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \frac{F_4 - 1}{G_1 G_2 G_3} + \cdots$$

$$NF = 10 \cdot \log(F)$$

- Example

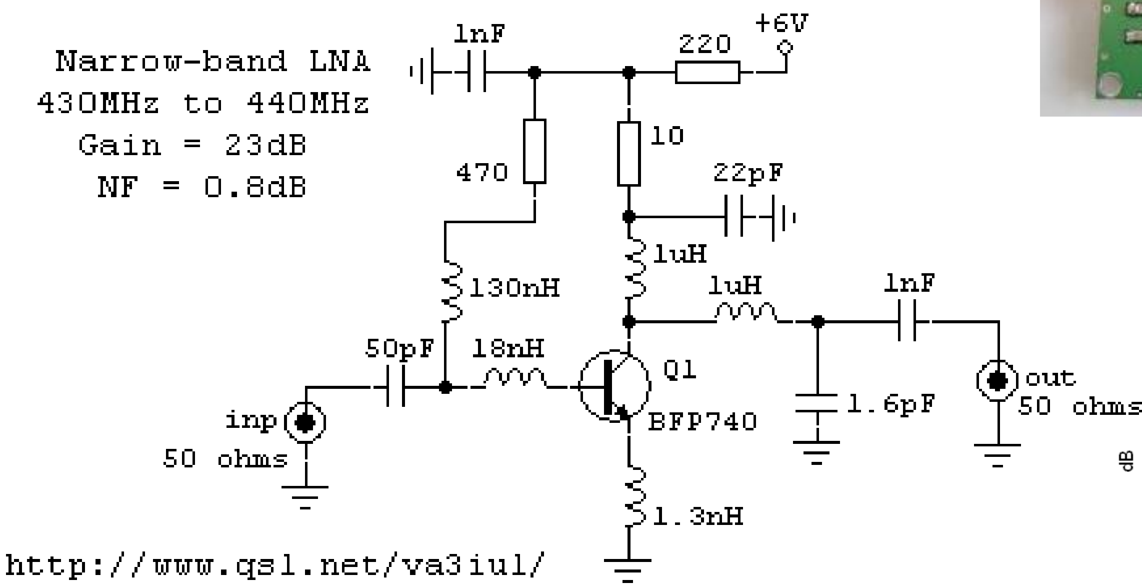
$G_1 = 20\ dB$, $NF_1 = 0.5\ dB$; $G_2 = 5\ dB$, $NF_2 = 10\ dB$; $G_3 = 0\ dB$, $NF_3 = 3\ dB$; $G_4 = 30\ dB$, $NF_4 = 7\ dB$ ⇒ $NF_{total} = 0.89\ dB$

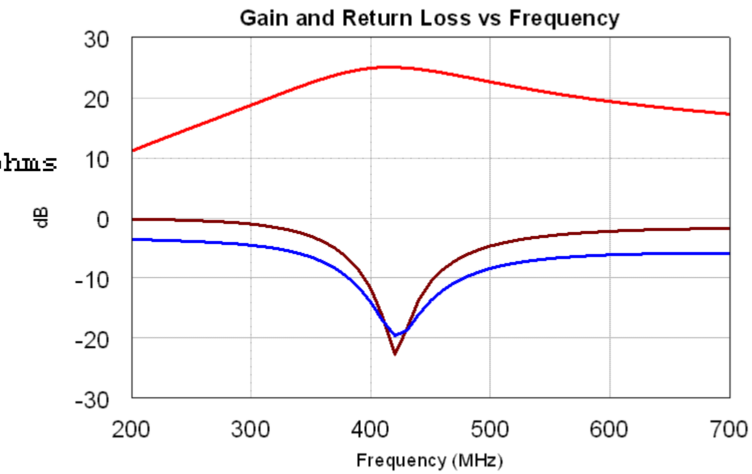
$G_1 = 10\ dB$, $NF_1 = 0.5\ dB$; $G_2 = 5\ dB$, $NF_2 = 10\ dB$; $G_3 = 0\ dB$, $NF_3 = 3\ dB$; $G_4 = 30\ dB$, $NF_4 = 7\ dB$ ⇒ $NF_{total} = 3.39\ dB$

$G_1 = 20\ dB$, $NF_1 = 2\ dB$; $G_2 = 5\ dB$, $NF_2 = 10\ dB$; $G_3 = 0\ dB$, $NF_3 = 3\ dB$; $G_4 = 30\ dB$, $NF_4 = 7\ dB$ ⇒ $NF_{total} = 2.28\ dB$

RX – LNA example

- BFP740 Silicon-Germanium: Carbon NPN bipolar transistor
- Typical NF used in NMR spectrometers <1dB





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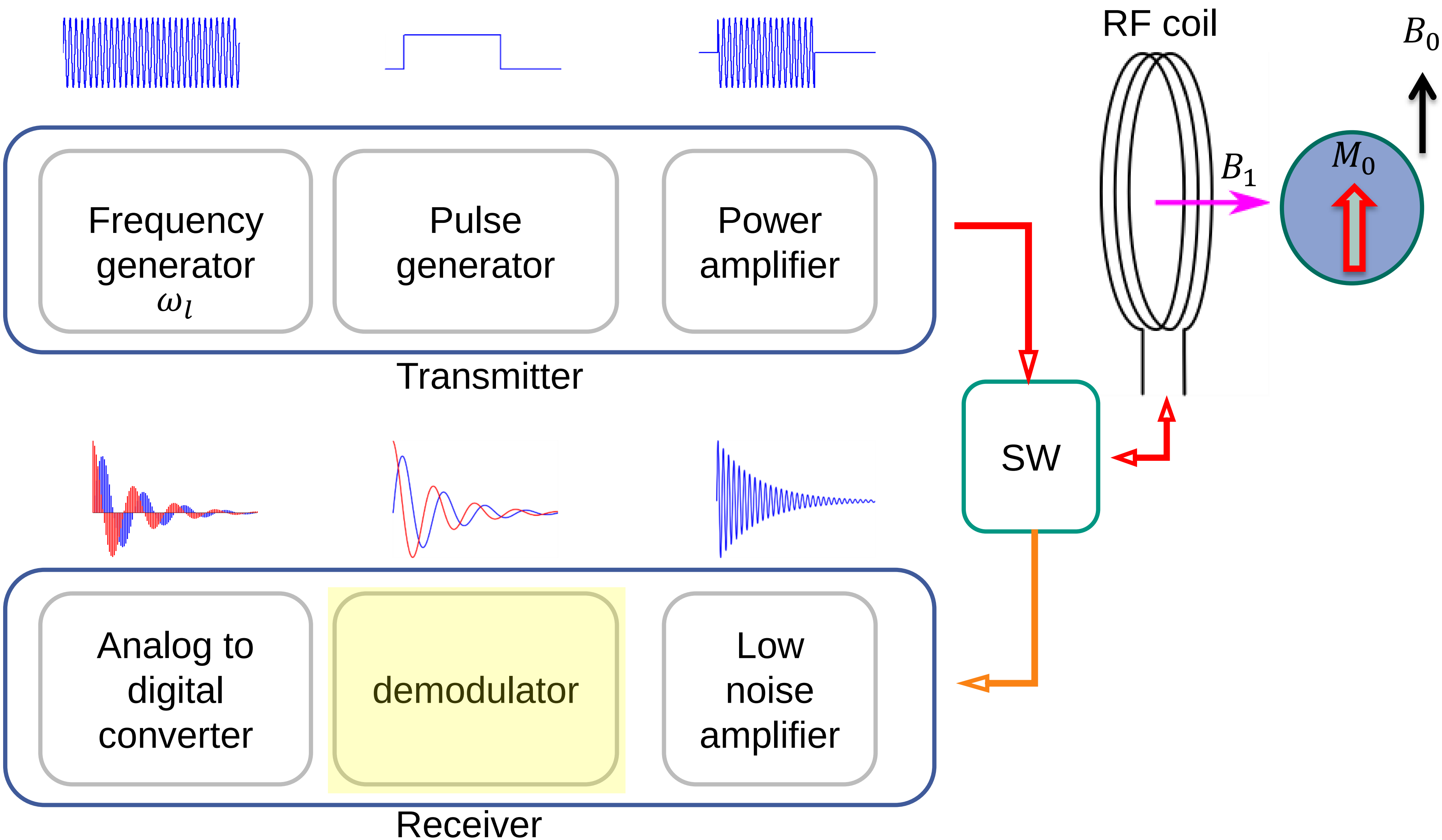
MRI scanner – Tx and Rx electronics



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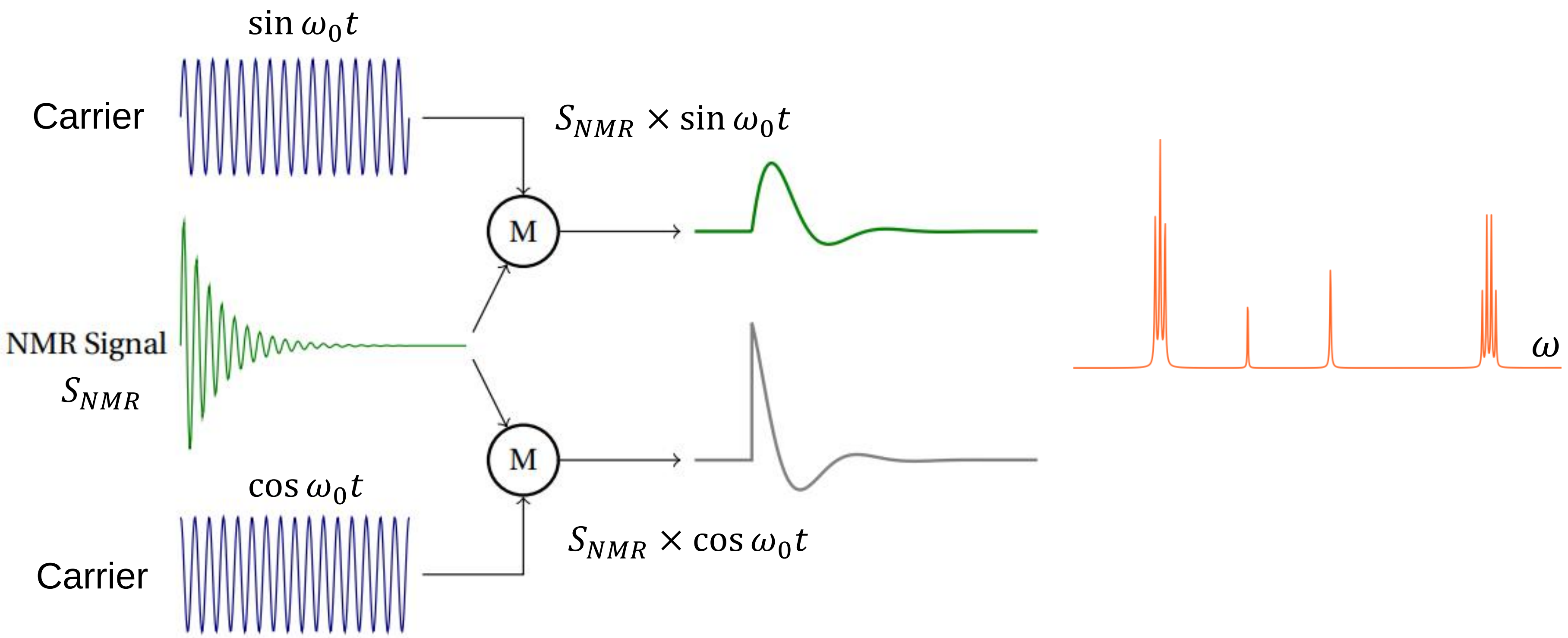
RX – quadrature demodulation

- For ease of processing we need to demodulate the signal (convert it from high Larmor frequency to a low frequency)



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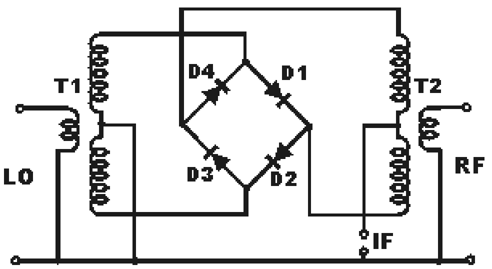
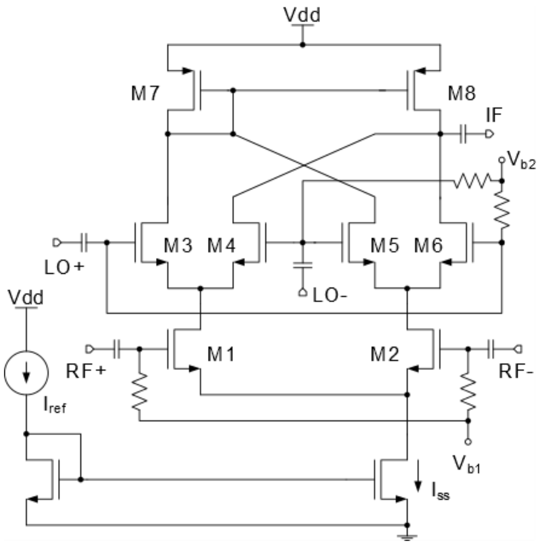
RX – demodulator circuit

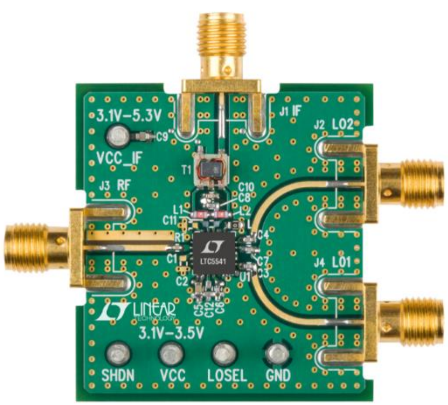
Passive demodulator



Active demodulator



- LO: local oscillator (carrier)
- RF: radio frequency (the high frequency NMR signal)
- IF: intermediate frequency (the demodulated signal)



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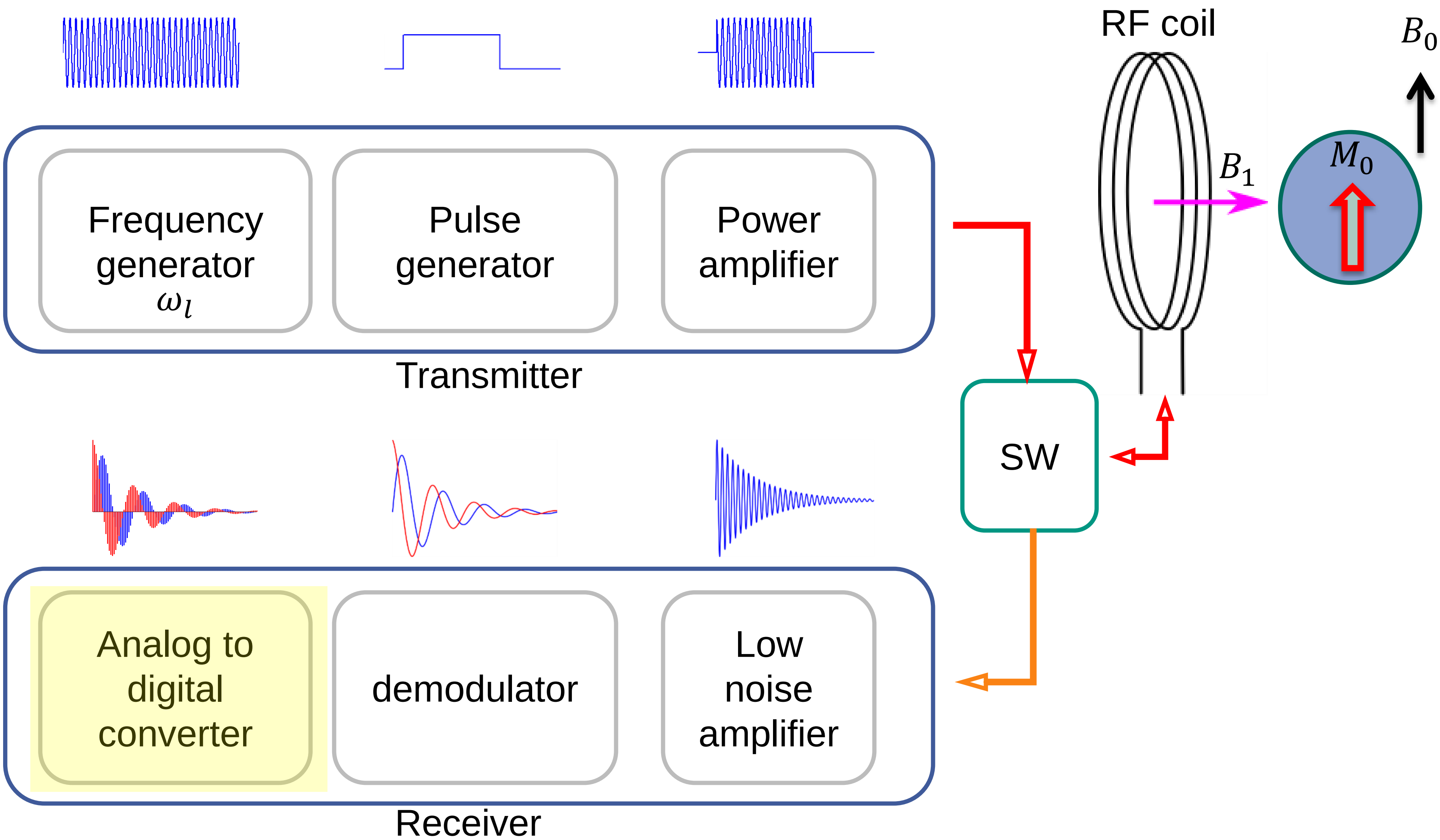
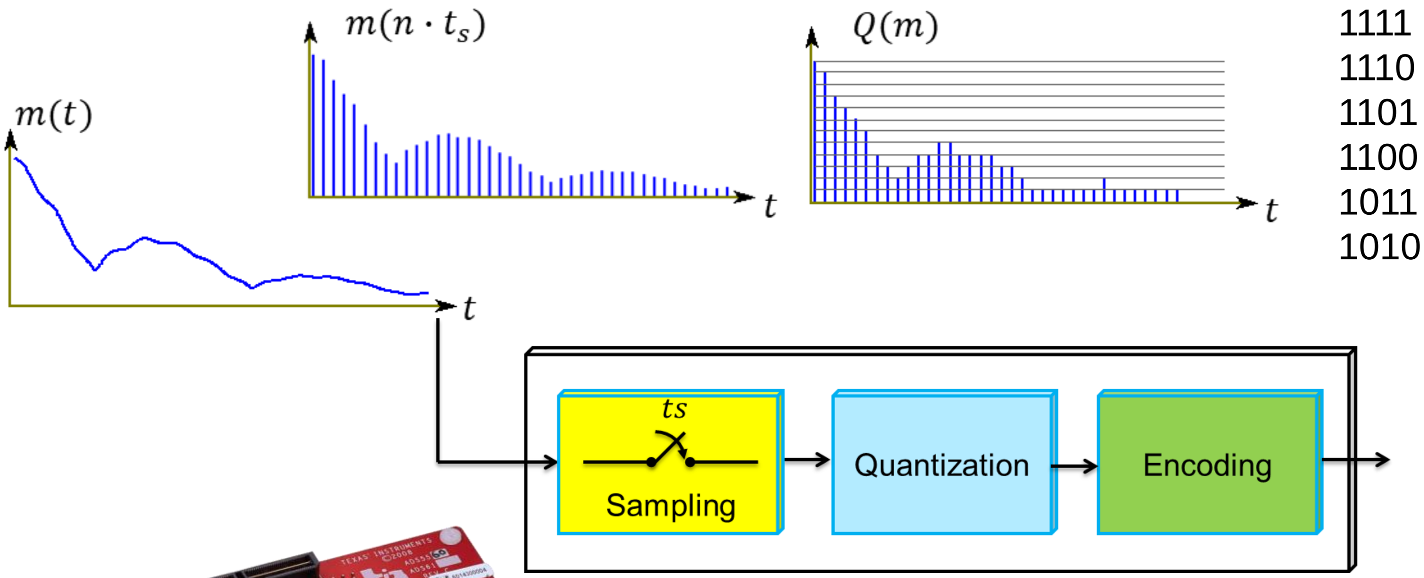
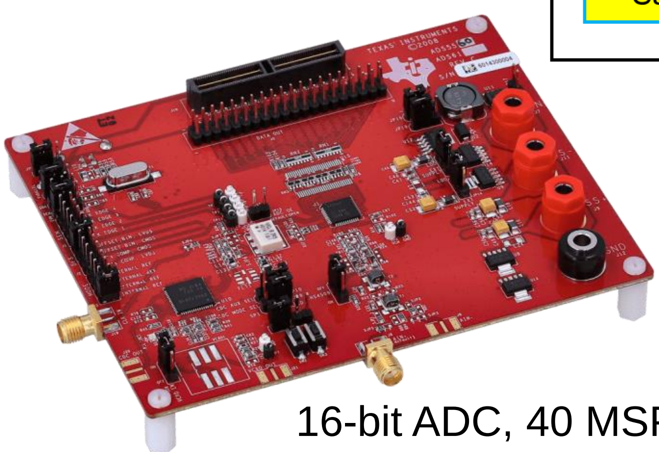
MRI scanner – Tx and Rx electronics

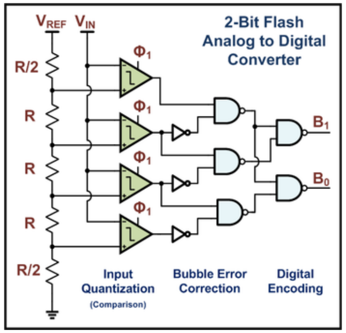


RX – the ADC

- Converts the NMR signals from analog form to digital form

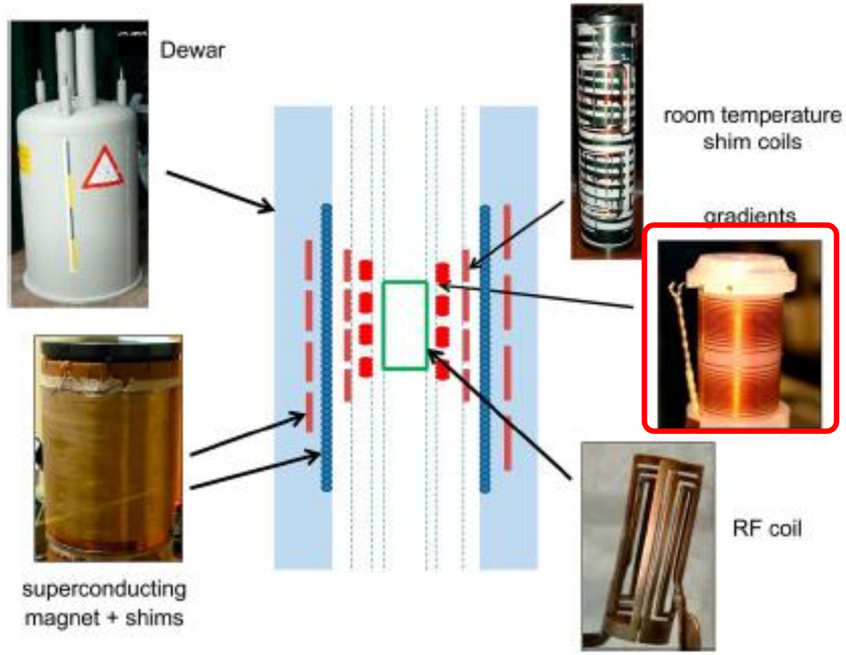


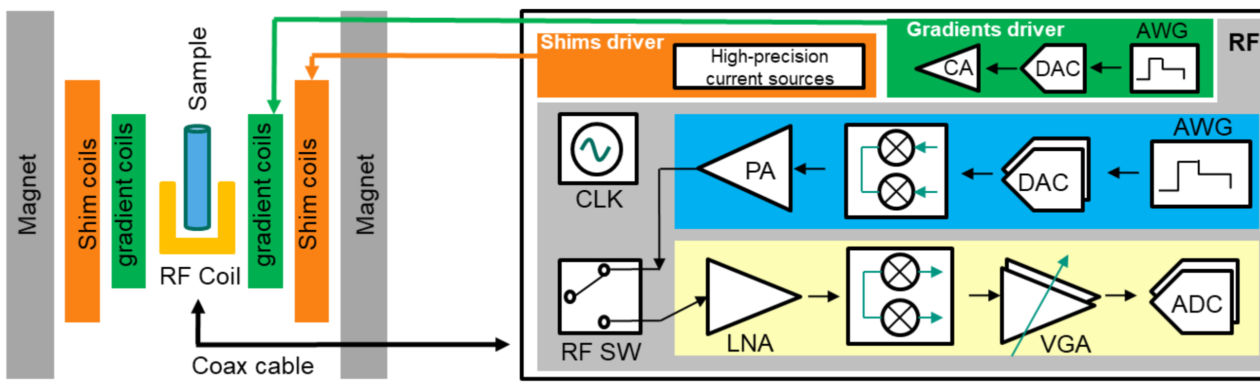




16-bit ADC, 40 MSPS

The MR spectrometer





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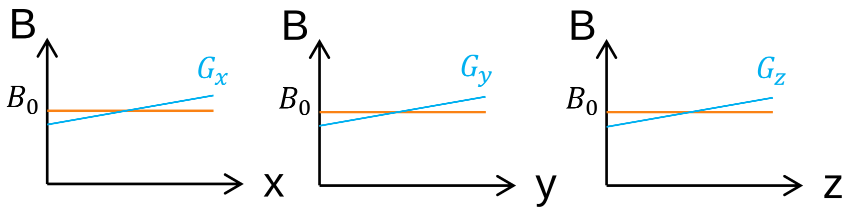
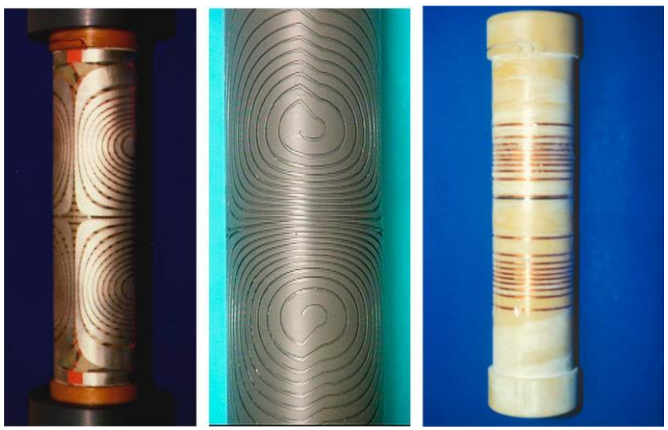
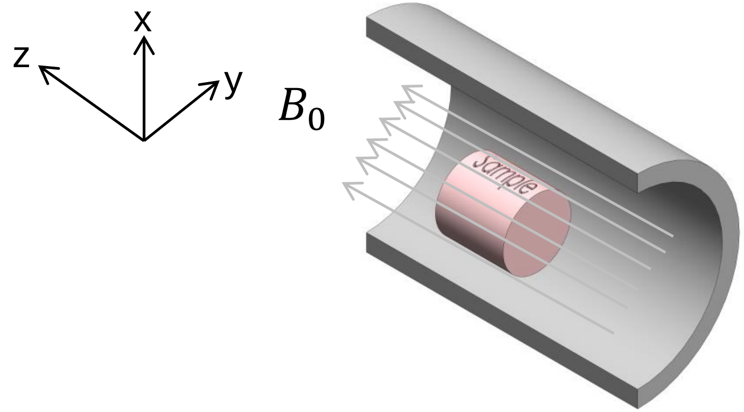
The MRI scanner – The gradient coils

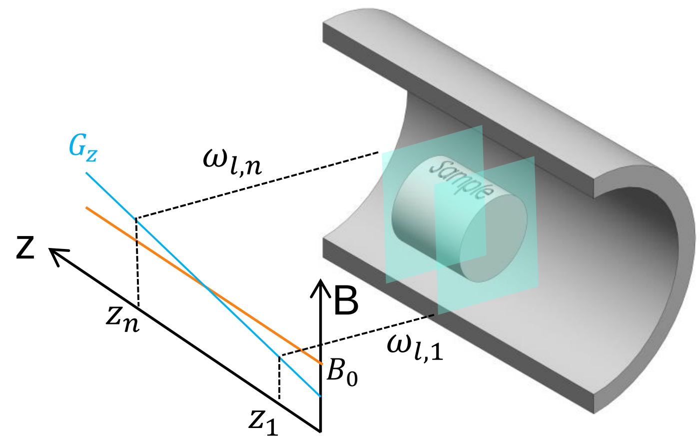
- The coils are necessary for imaging







- Slice selection using Gz



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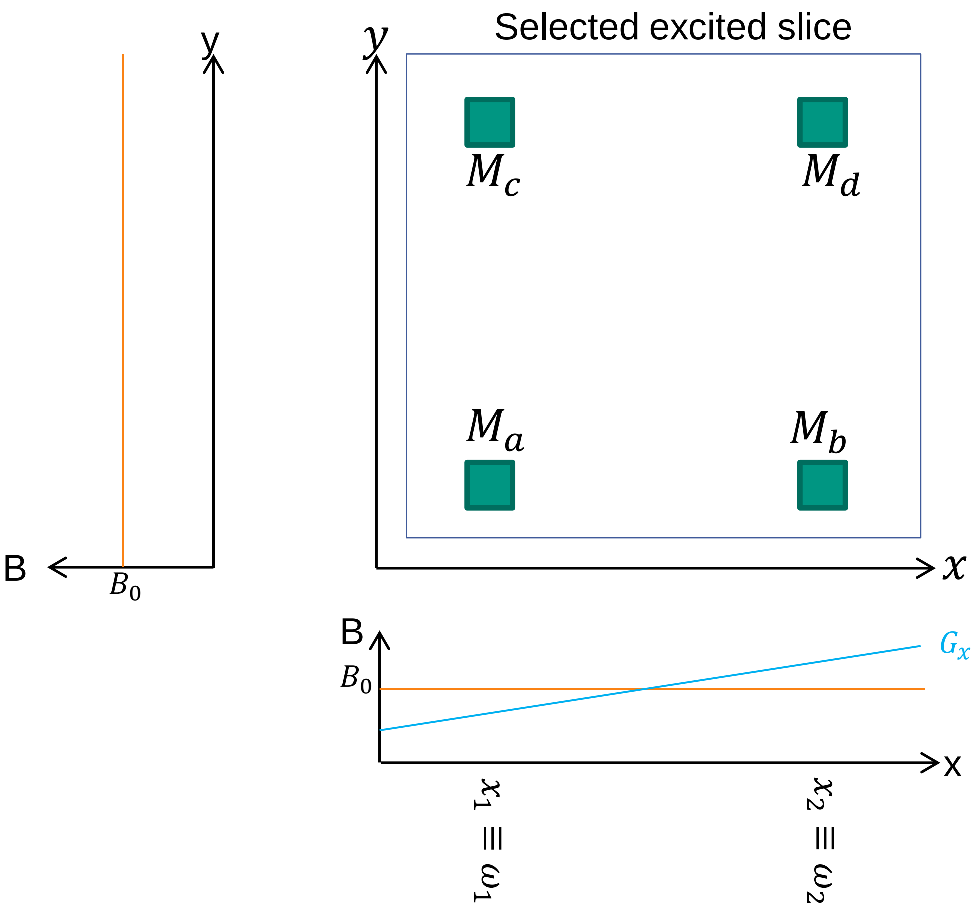
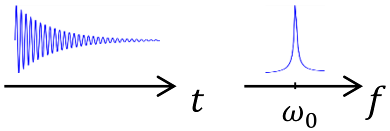
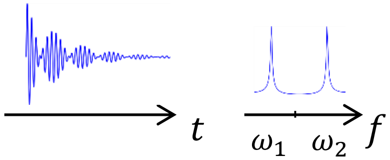
The MRI scanner – The gradient coils



- Case 1: no Gx and no Gy
  - $s = (M_a + M_b + M_c + M_d)e^{i\omega_0 t}$



- Case 2: Gx and no Gy
  - $s = (M_a + M_c)e^{i\omega_1 t} + (M_b + M_d)e^{i\omega_2 t}$



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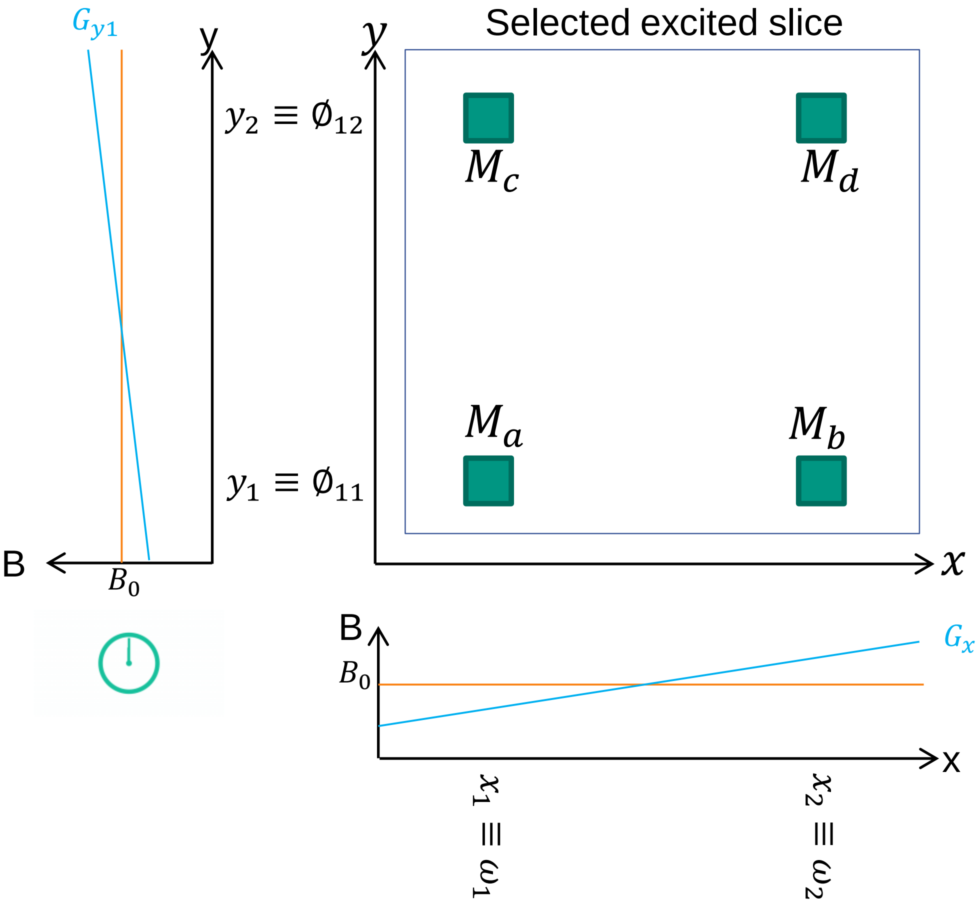
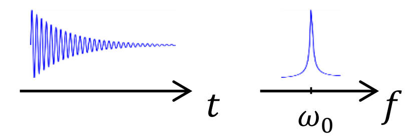
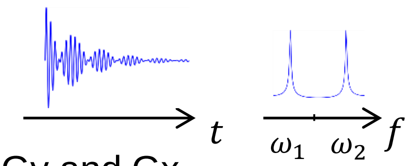
The MRI scanner – The gradient coils



- Case 1: no Gx and no Gy
  - $s = (M_a + M_b + M_c + M_d)e^{i\omega_0 t}$

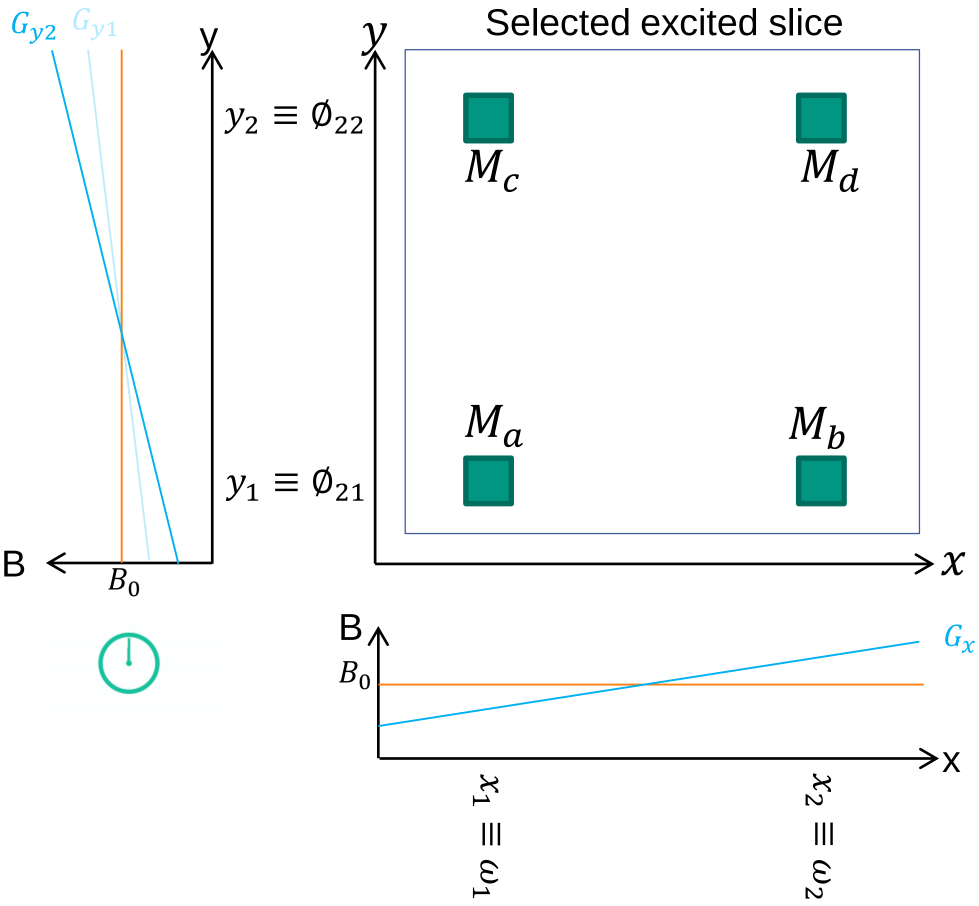


- Case 2: Gx and no Gy
  - $s = (M_a + M_c)e^{i\omega_1 t} + (M_b + M_d)e^{i\omega_2 t}$

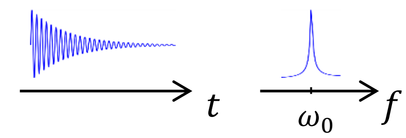


- Case 3: Gy and Gx
  - Gy1 then Gx
    - $s = M_a e^{i(\omega_1 t + \emptyset_{11})} + M_b e^{i(\omega_2 t + \emptyset_{11})} + M_c e^{i(\omega_1 t + \emptyset_{12})} + M_d e^{i(\omega_2 t + \emptyset_{12})}$
    - $s_{f11} = (M_a e^{i\emptyset_{11}} + M_c e^{i\emptyset_{12}})$
    - $s_{f12} = (M_b e^{i\emptyset_{11}} + M_d e^{i\emptyset_{12}})$

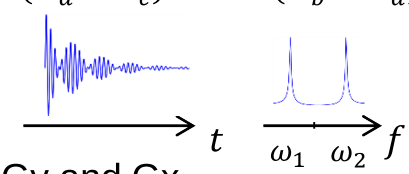
The MRI scanner – The gradient coils



- Case 1: no Gx and no Gy
  - $s = (M_a + M_b + M_c + M_d)e^{i\omega_0 t}$



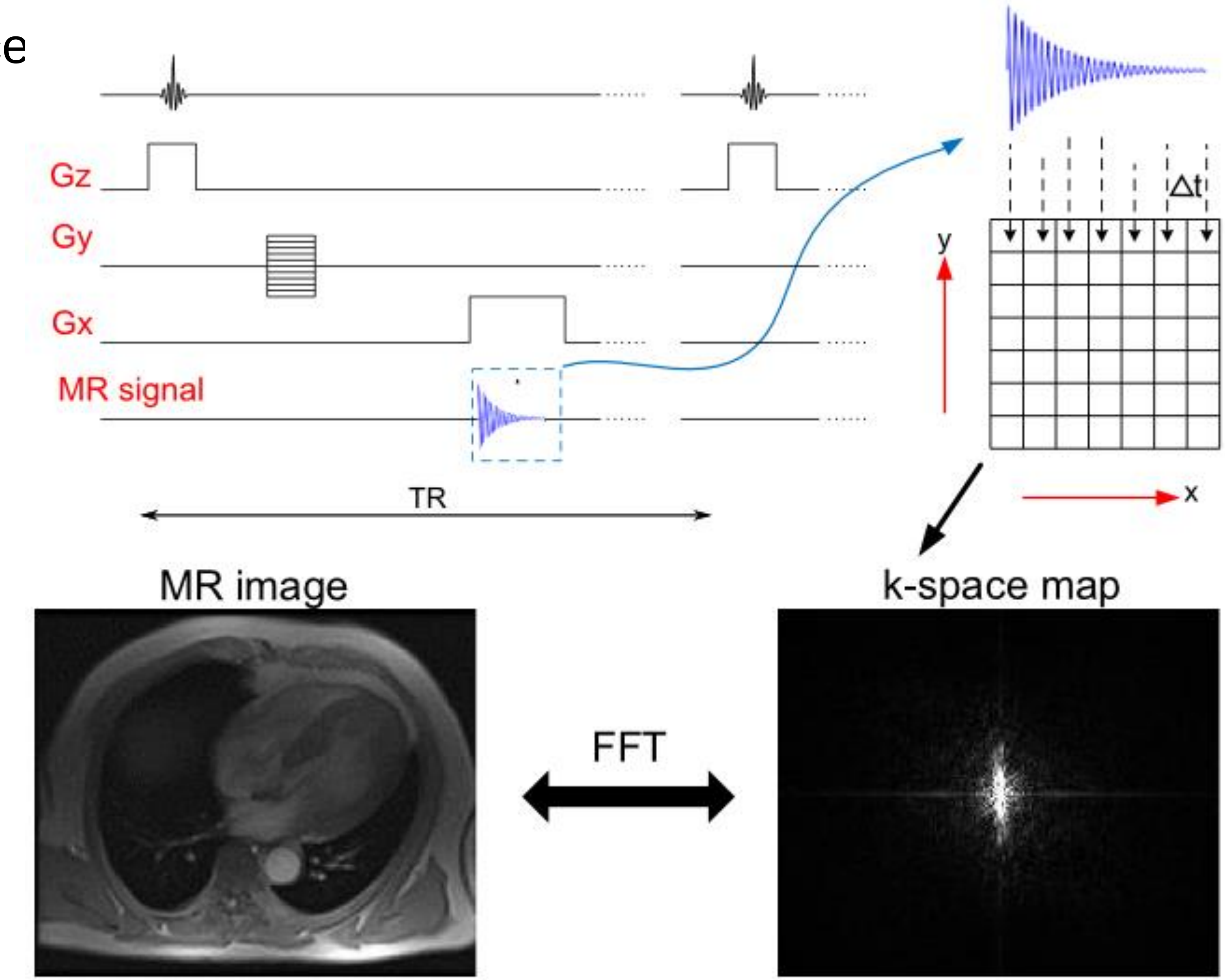
- Case 2: Gx and no Gy
  - $s = (M_a + M_c)e^{i\omega_1 t} + (M_b + M_d)e^{i\omega_2 t}$



- Case 3: Gy and Gx
  - Gy1 then Gx
    - $s = M_a e^{i(\omega_1 t + \emptyset_{11})} + M_b e^{i(\omega_2 t + \emptyset_{11})} + M_c e^{i(\omega_1 t + \emptyset_{12})} + M_d e^{i(\omega_2 t + \emptyset_{12})}$
    - $s_{f11} = (M_a e^{i\emptyset_{11}} + M_c e^{i\emptyset_{12}})$
    - $s_{f12} = (M_b e^{i\emptyset_{11}} + M_d e^{i\emptyset_{12}})$
  - Gy2 then Gx
    - $s = M_a e^{i(\omega_1 t + \emptyset_{21})} + M_b e^{i(\omega_2 t + \emptyset_{21})} + M_c e^{i(\omega_1 t + \emptyset_{22})} + M_d e^{i(\omega_2 t + \emptyset_{22})}$
    - $s_{f21} = (M_a e^{i\emptyset_{21}} + M_c e^{i\emptyset_{22}})$
    - $s_{f22} = (M_b e^{i\emptyset_{21}} + M_d e^{i\emptyset_{22}})$

The MRI scanner – The gradient coils

- Imaging sequence



Further reading

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- Behzad Razavi. RF microelectronics, volume 1. Prentice Hall New Jersey, 1998.
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Thank you for attention

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