# MR Fundamentals

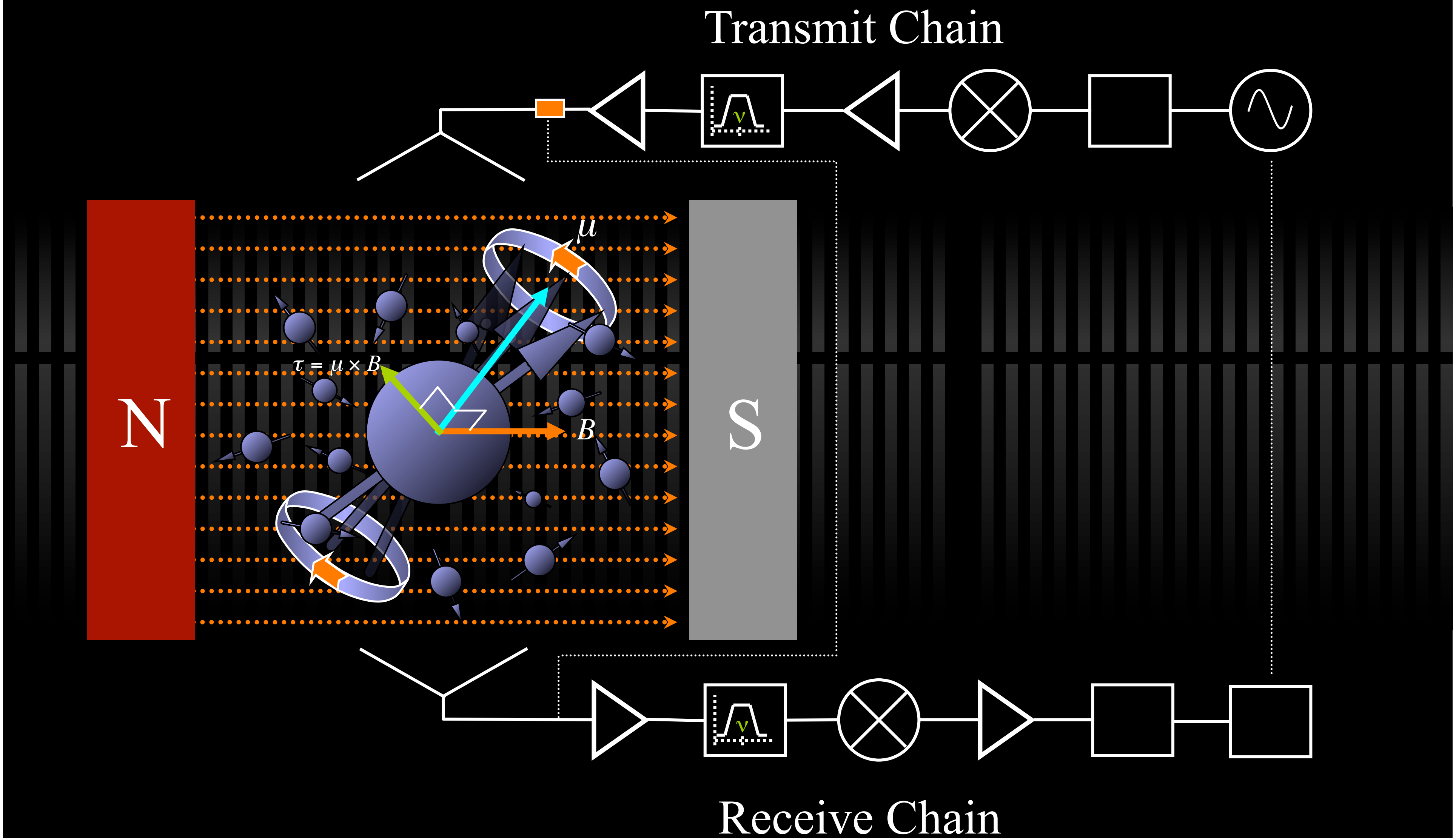
The RF receive chain

UCSF-QB3

Lucas Carvajal

02/08/07

# The NMR experiment

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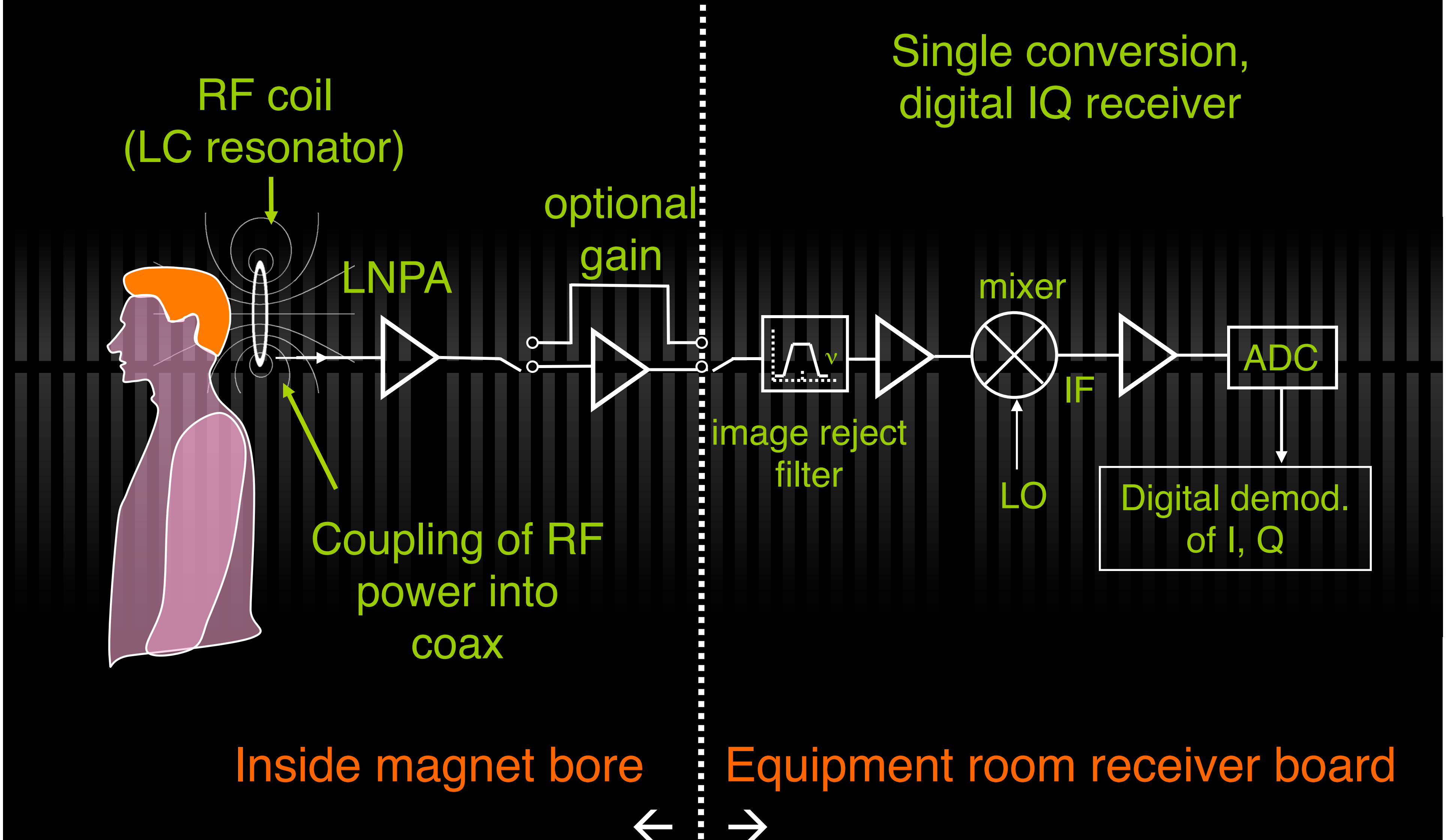
# RF Receive Chain

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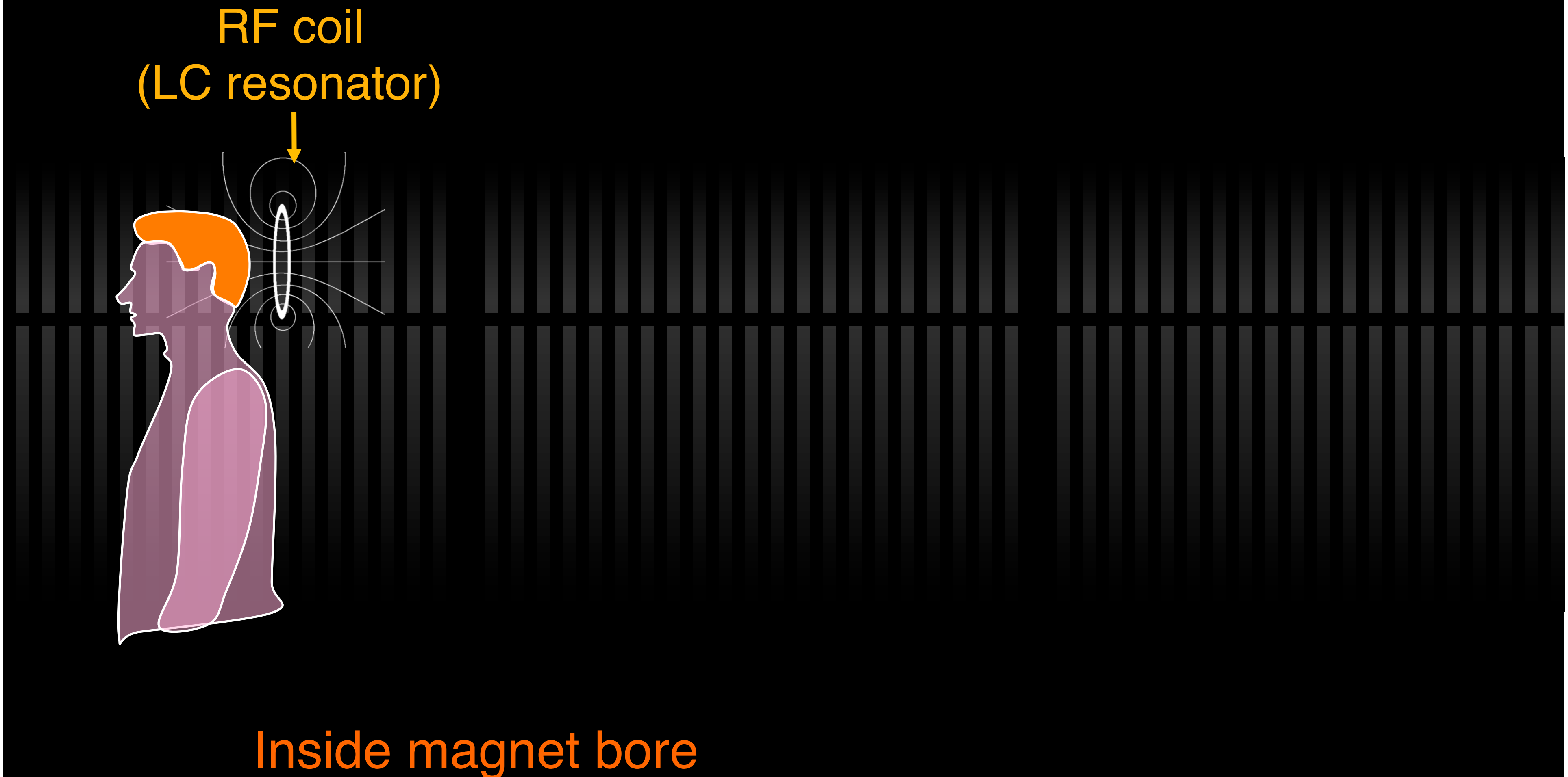
# RF Receive Chain: 1 Coil

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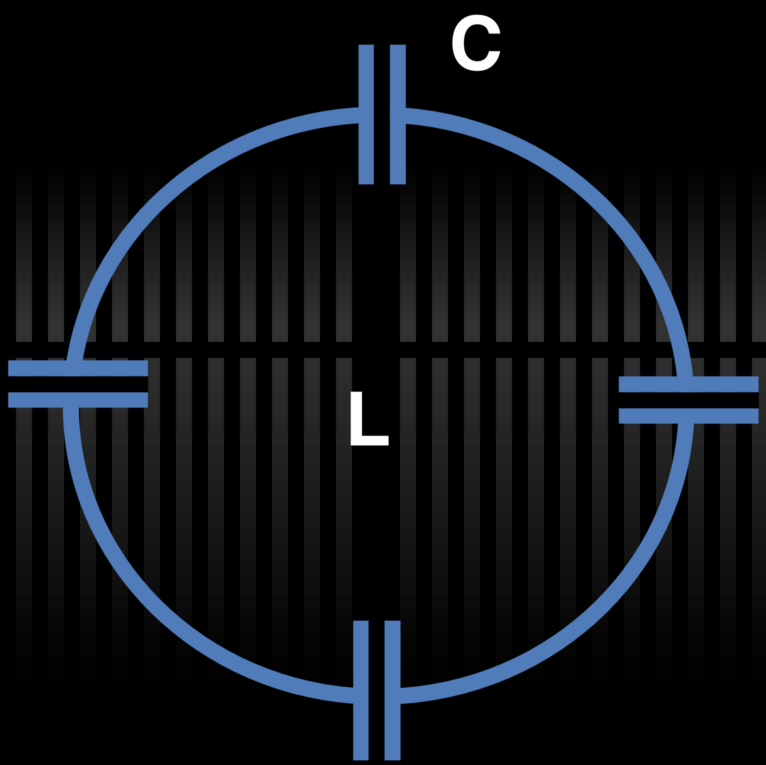
# Elementary Detection Unit

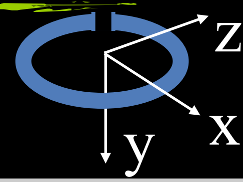


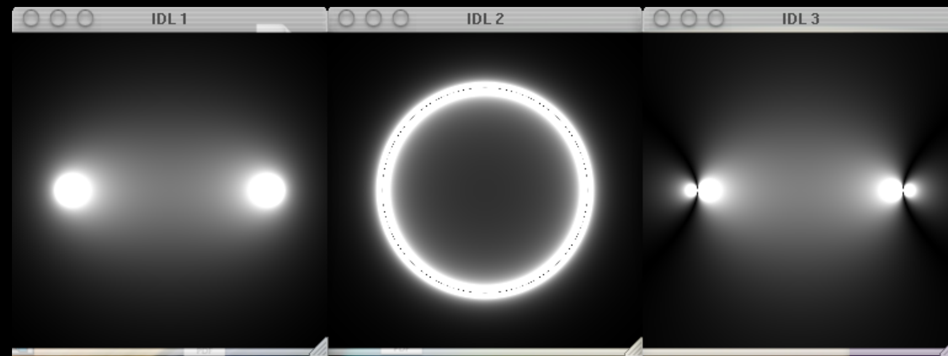

The LC Coil Resonator

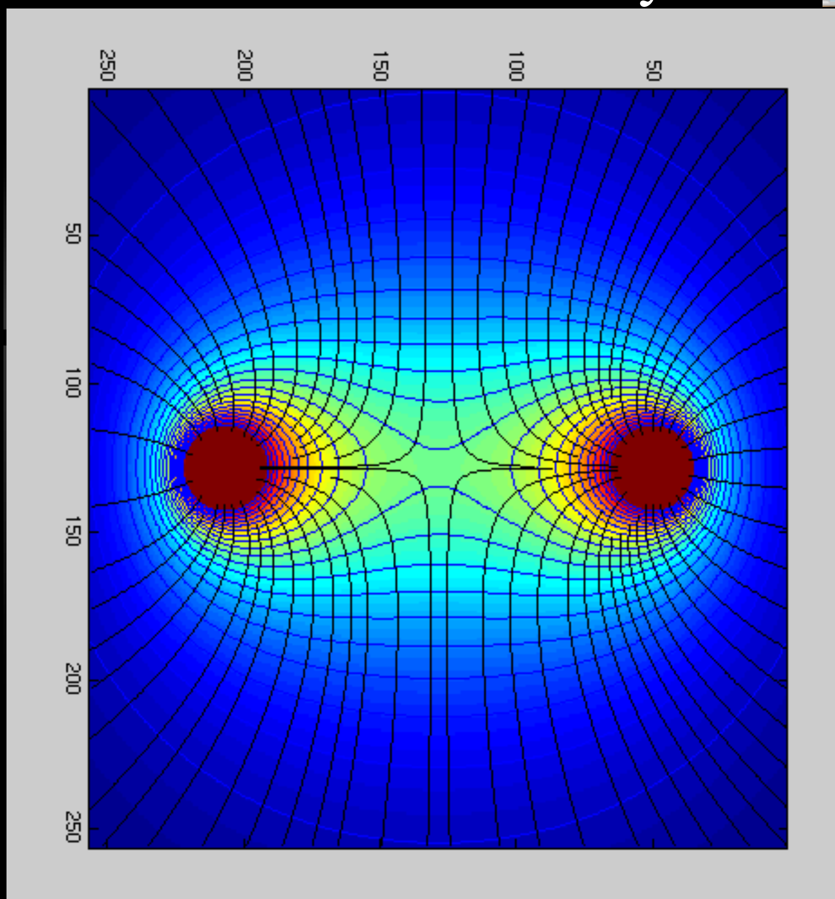
$$f_{oscillation} = \frac{1}{2\pi\sqrt{LC}}$$

# Coil Sensitivity

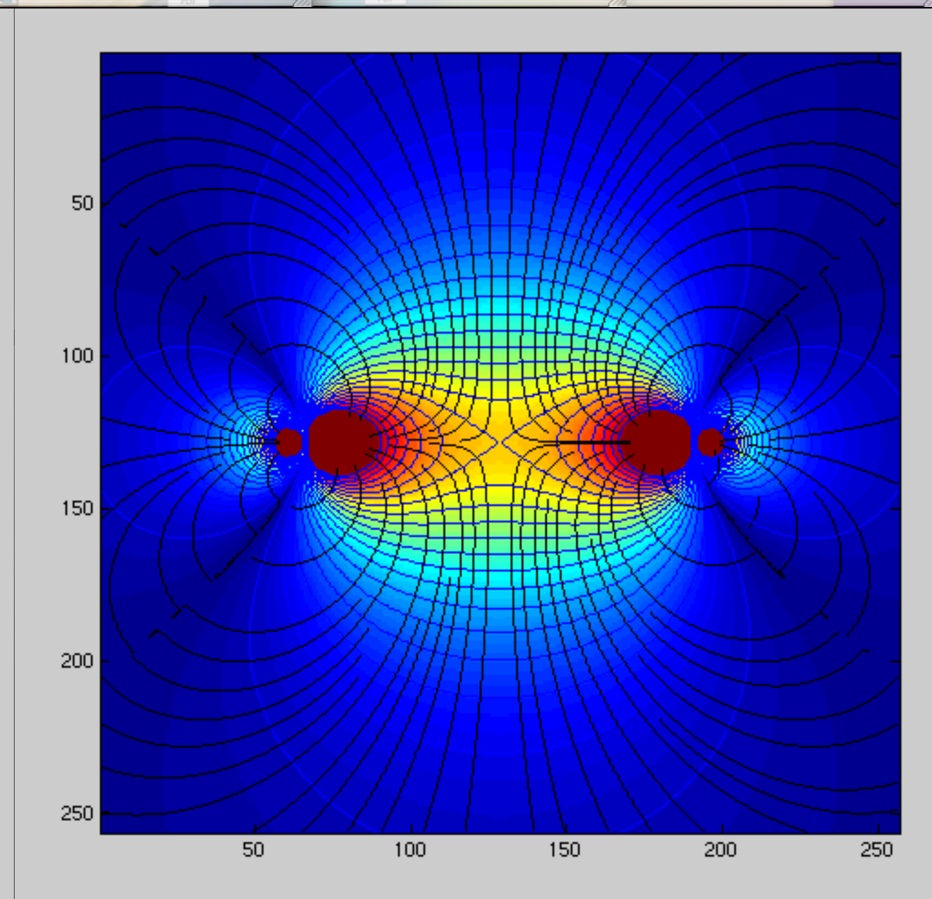
Coil in XZ plane




Axial Plane




Sagittal Plane

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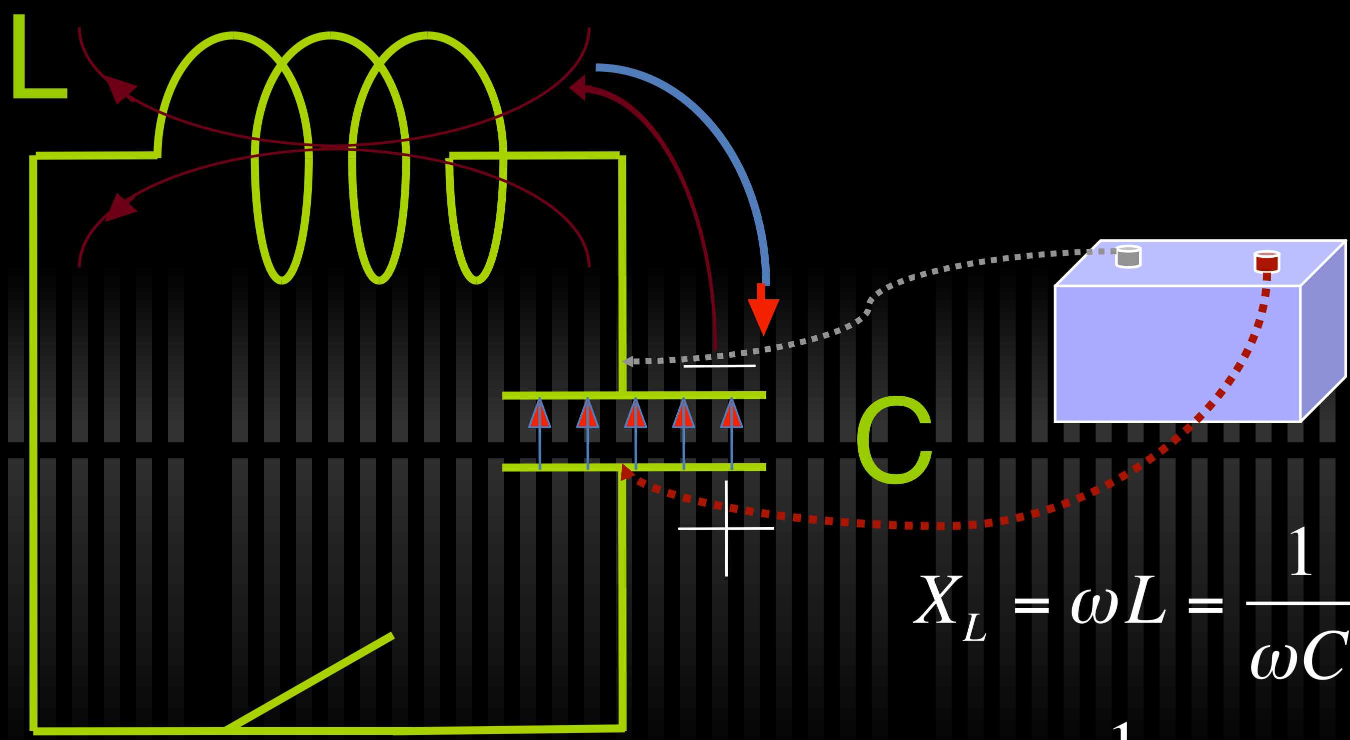
# Natural electrical oscillator




$$X_L = \omega L = \frac{1}{\omega C} = X_C$$

$$\omega^2 = \frac{1}{LC}$$

Natural Oscillation occurs at frequency $f_{natural} = \dfrac{1}{2\pi\sqrt{LC}}$

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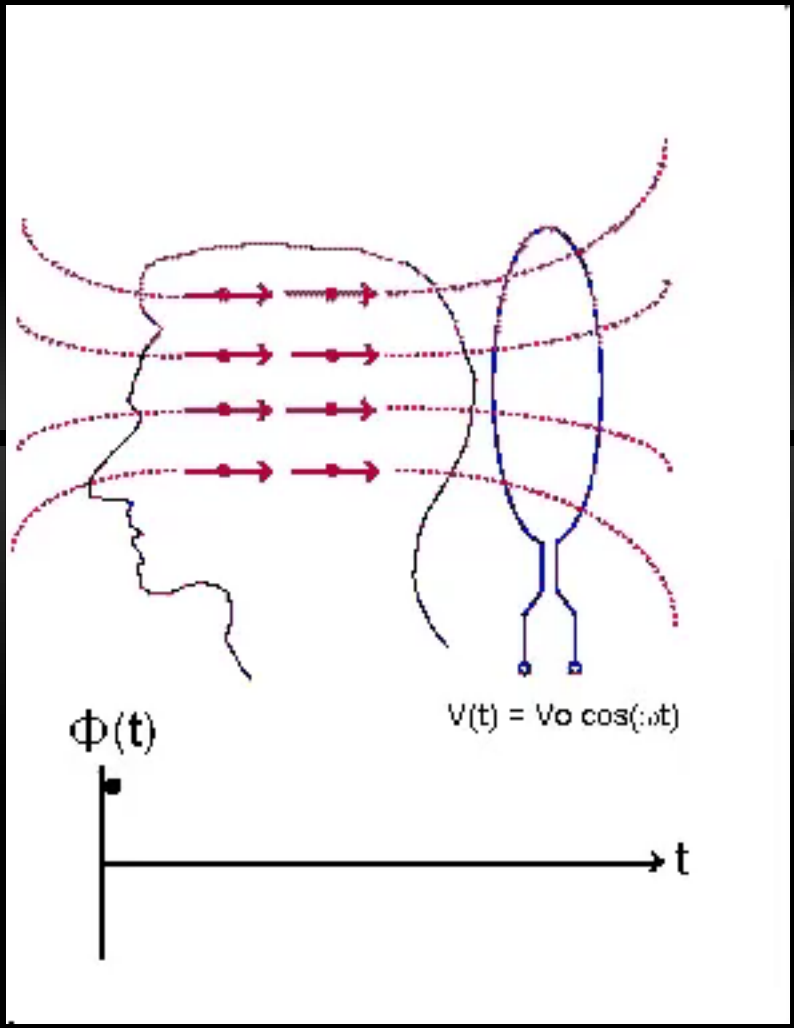
# Detecting Nuclear Induction




$$\Phi(t) \propto M_0 \cos(\omega t)$$

$$V(t) = -\frac{d\Phi(t)}{dt}$$

$$V(t) \propto -M_0 \omega \sin(\omega t)$$

$$S(t) \propto V(t)$$

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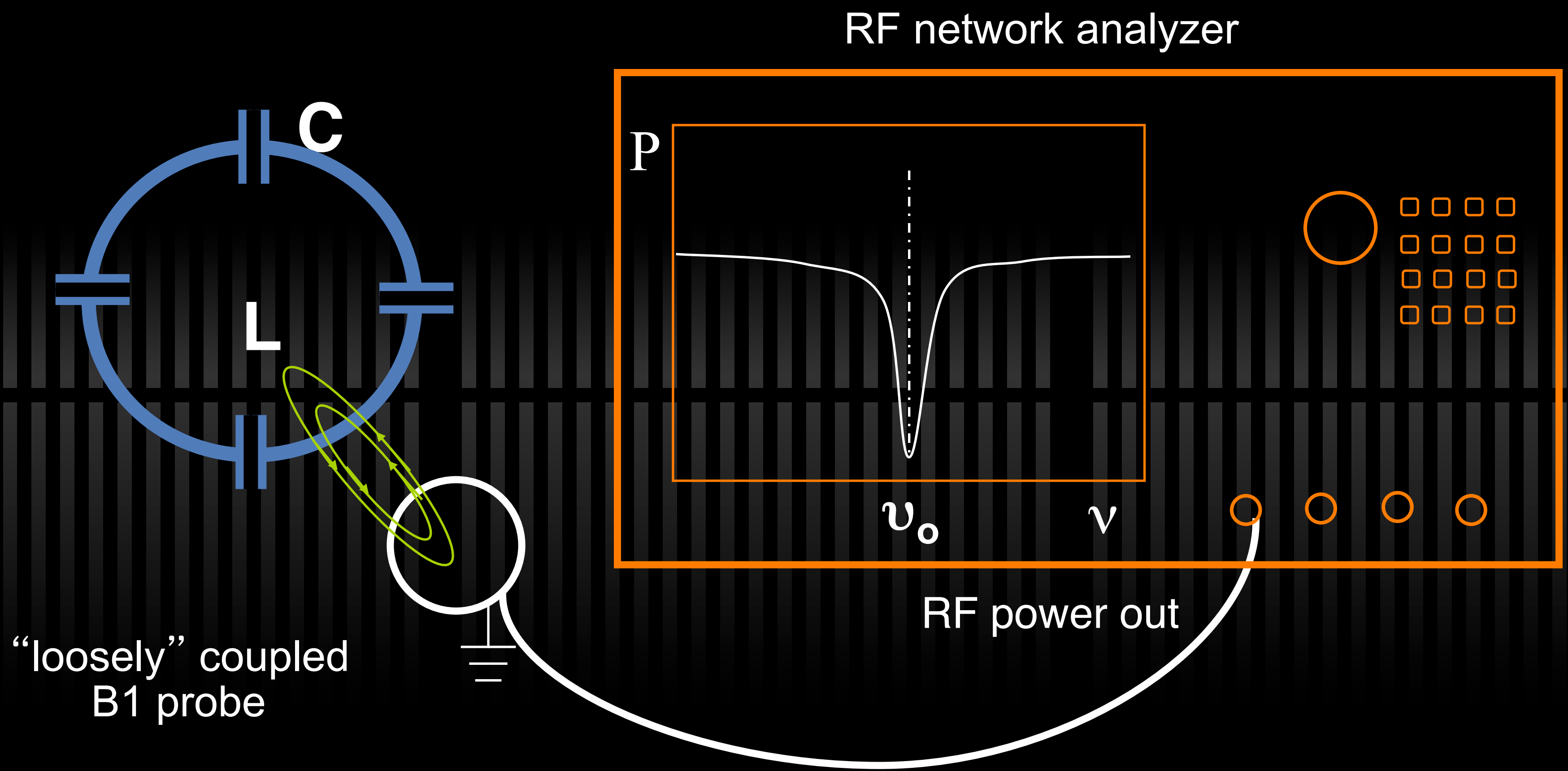
# Measuring Resonant Frequency




S11 (reflected power measure dB).

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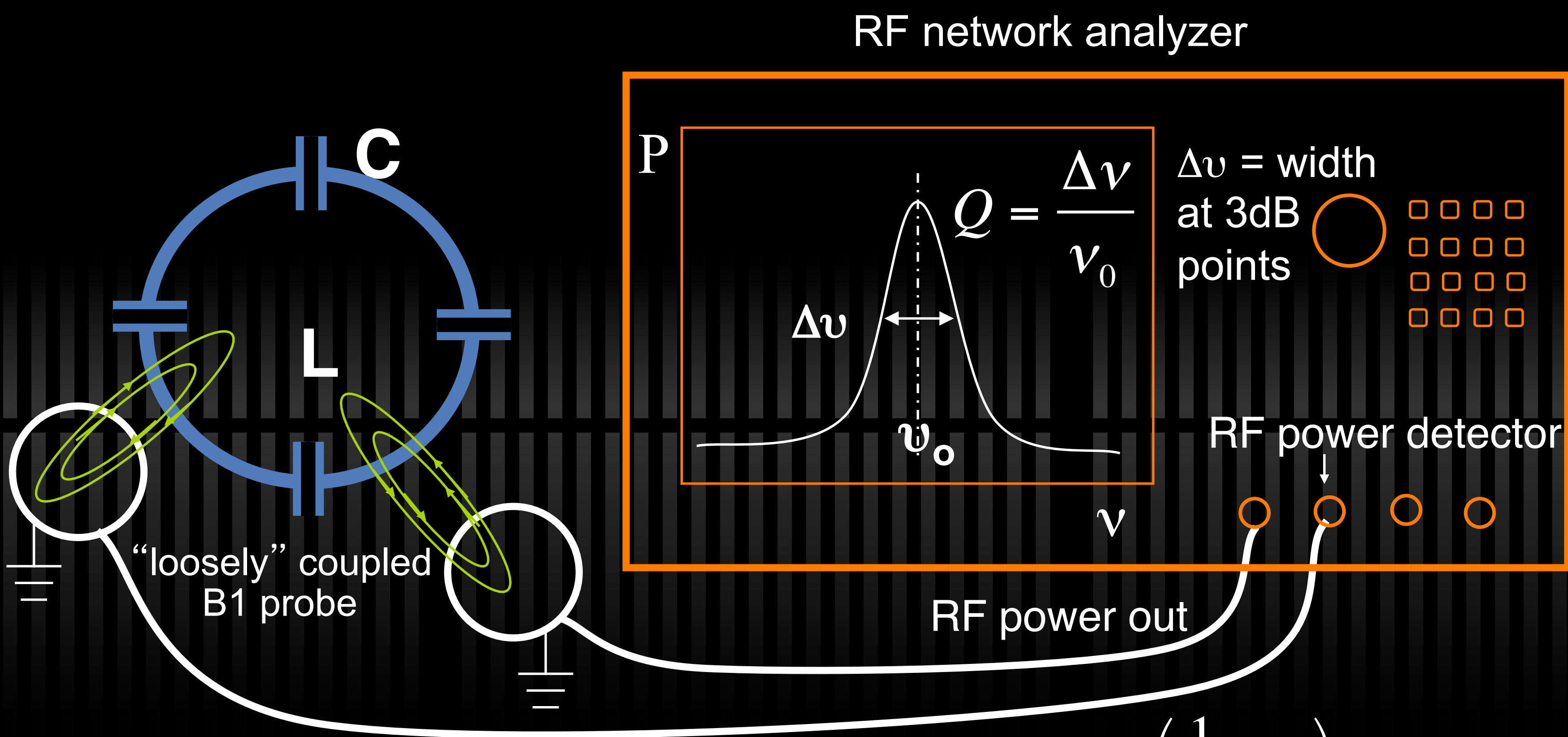
# Measuring Q of a Coil




$$Q = 2\pi \frac{\text{Maximum Energy Stored per cycle}}{\text{Energy dissipated per cycle}} = \frac{\left(\frac{1}{2}LI^2\right)}{\left(\frac{I^2 R}{2f}\right)} = \frac{\omega L}{R}$$

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# $Q_L$ and $Q_U$

$$Q_L = \frac{\omega L}{R_{total}} \longrightarrow R_{total} = R_{body} + R_{other}$$

$$Q_U = \frac{\omega L}{R_{other}}$$

$R_{other}$ = copper losses, component losses, radiation losses.

Define "sufficiently coupled" to body when

$$\boxed{R_{body} >> R_{other}}$$

# Unloaded to loaded Q ratio

Q ratio measures whether or not the coil is sufficiently coupled to body.

$$\frac{Q_{unloaded}}{Q_{loaded}} = \frac{\left(\dfrac{\omega L}{R_{other}}\right)}{\left(\dfrac{\omega L}{R_{total}}\right)}$$

$$\frac{Q_{unloaded}}{Q_{loaded}} = 1 + \frac{R_{body}}{R_{other}}$$

# Unloaded to loaded Q ratio

Q ratio measures how well coil is coupled to body

$$\frac{Q_{unloaded}}{Q_{loaded}} = \frac{R_{other} + R_{body}}{R_{other}} = \frac{R_{total}}{R_{other}}$$

$$\%\ \text{noise power from body} = 1 - \frac{Q_{loaded}}{Q_{unloaded}}$$

$$\left( \frac{R_{body}}{R_{total}} = 1 - \frac{R_{other}}{R_{total}} \right)$$

If we want >80% body noise power then: $\frac{Q_{unloaded}}{Q_{loaded}} \geq 5$

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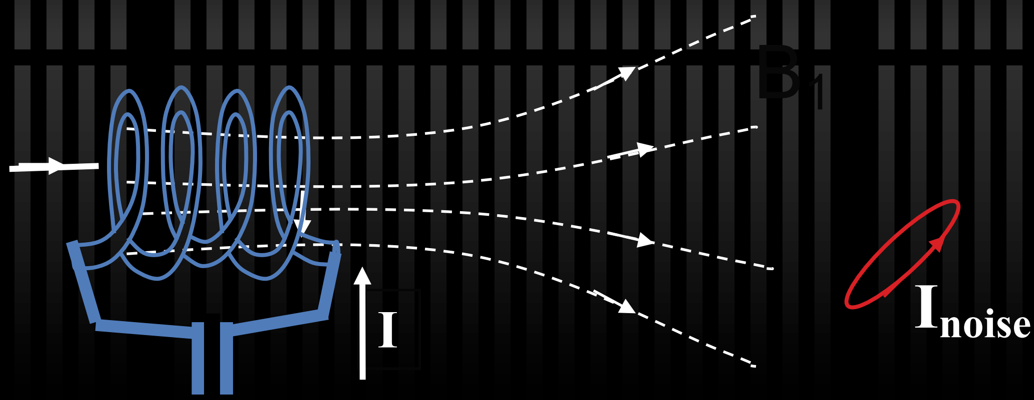
# The body should dominate noise source

Ionic fluctuations at $\omega_o$ will be picked up and detected just like signal. (if we knew how to discriminate, we would)




If you are body noise dominated, you don't have to worry about other losses (noise sources).

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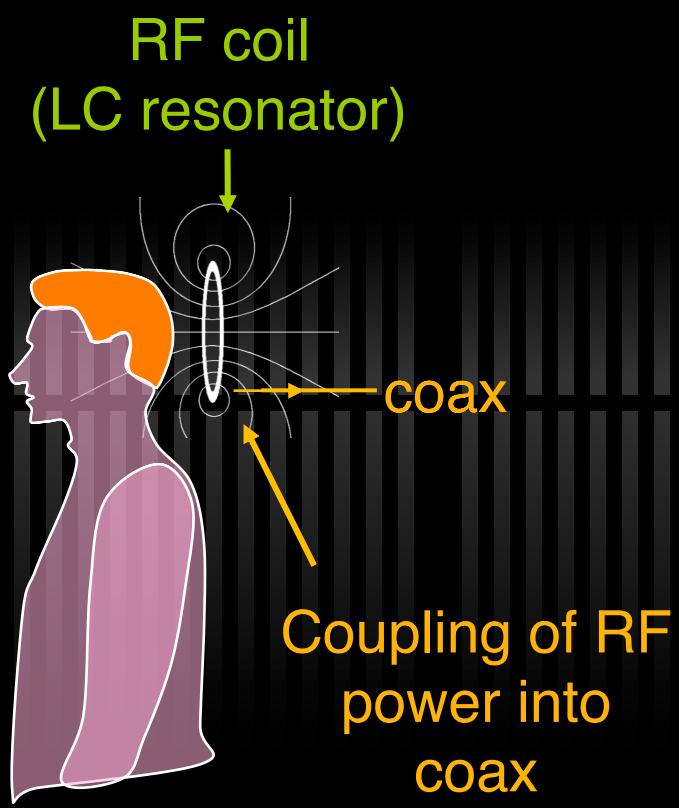
# Dominant source of noise: sample

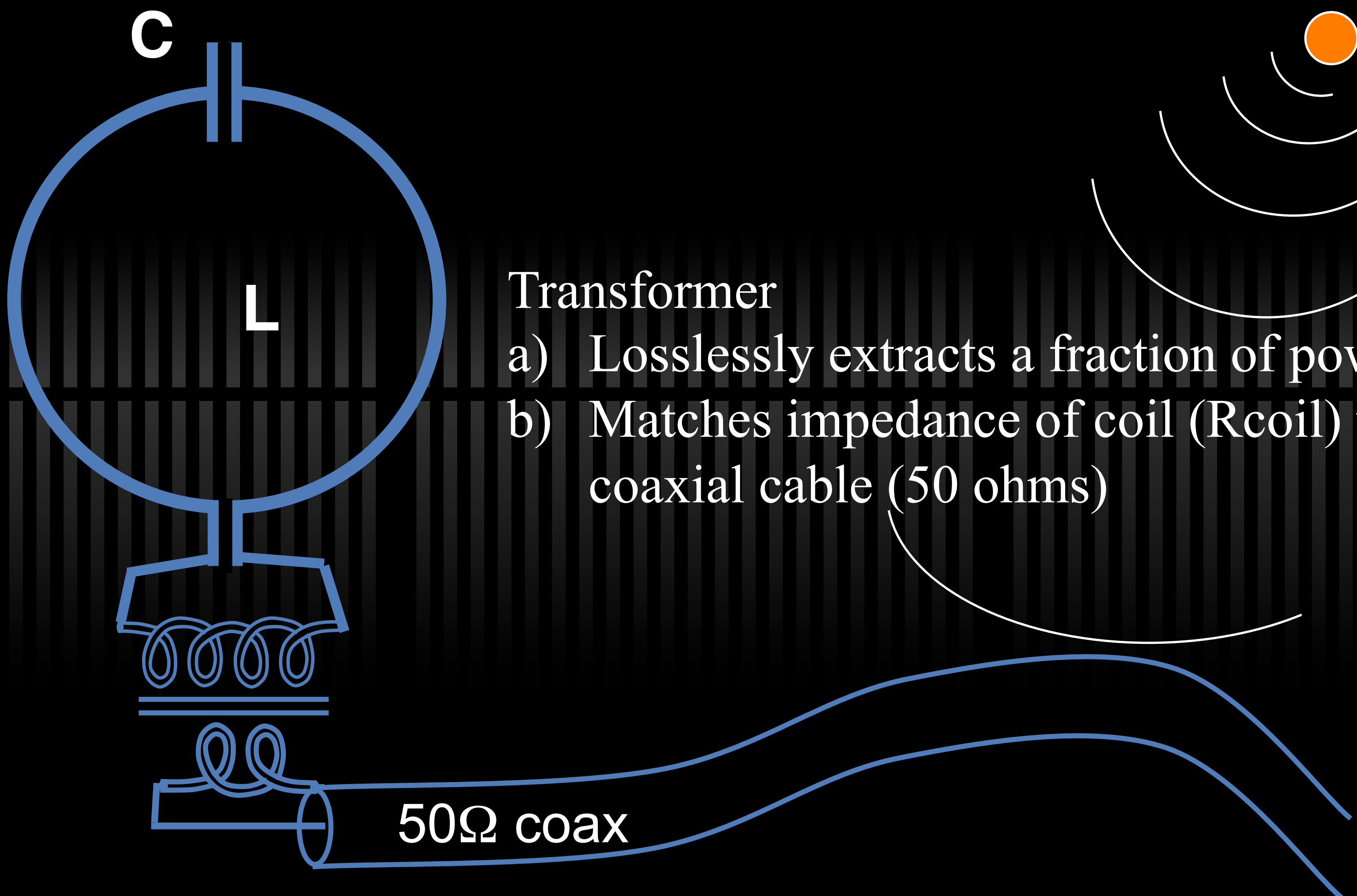
✓Ionic fluctuations at $\omega_o$ are detected as noise signal
✓If body noise is dominant, other sources of noise are inconsequential and we don't need to worry about them
✓Don't excite tissue you are not imaging
✓Change in body position can modulate S and N
✓Smaller coils pick up S and N from smaller volume; therefore less body noise.

# RF Receive Chain: 2 Trasformer




Inside magnet bore

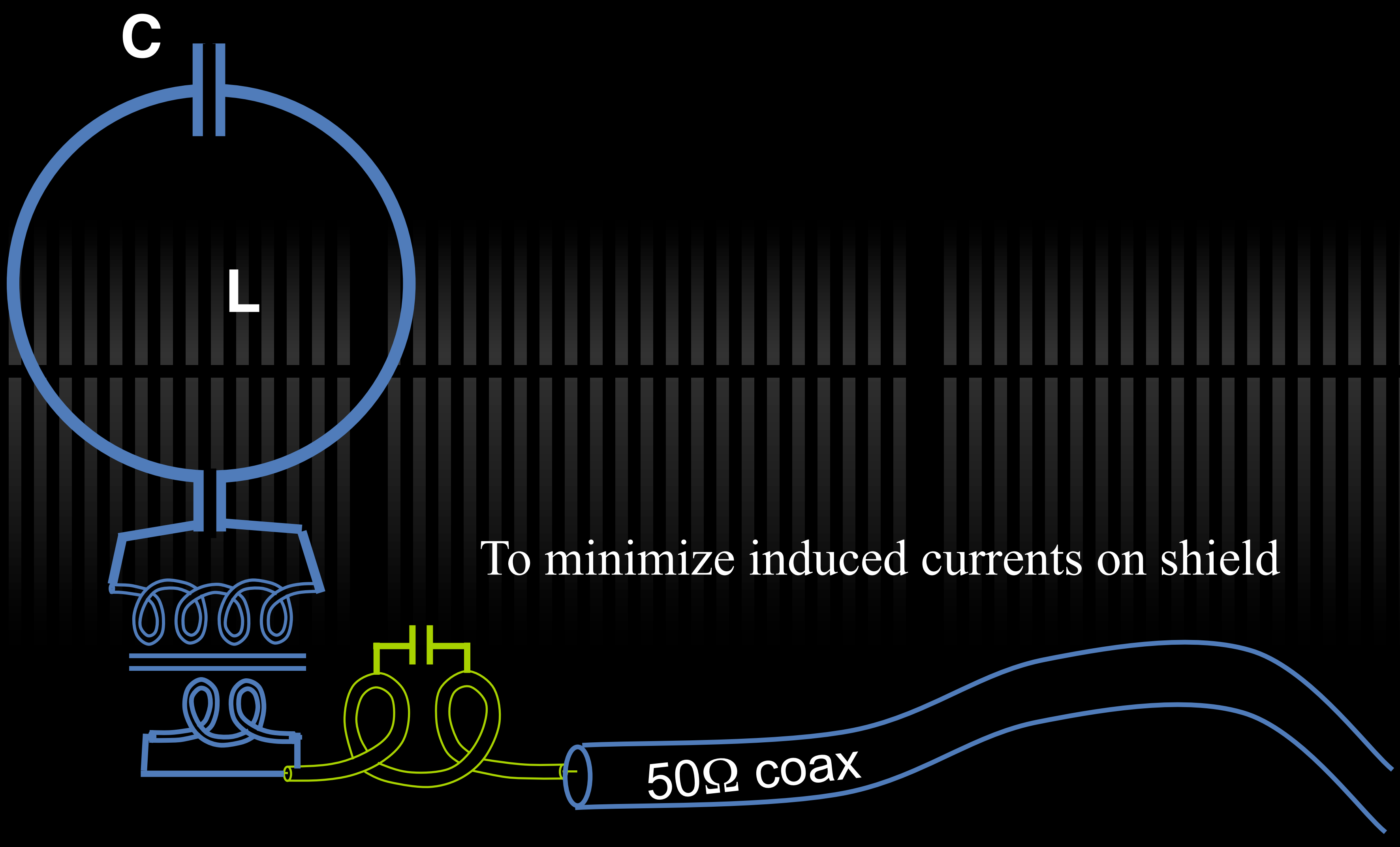
# Couple some power out of coil




Transformer

a) Losslessly extracts a fraction of power
b) Matches impedance of coil (Rcoil) to coaxial cable (50 ohms)

# We build a current trap




To minimize induced currents on shield

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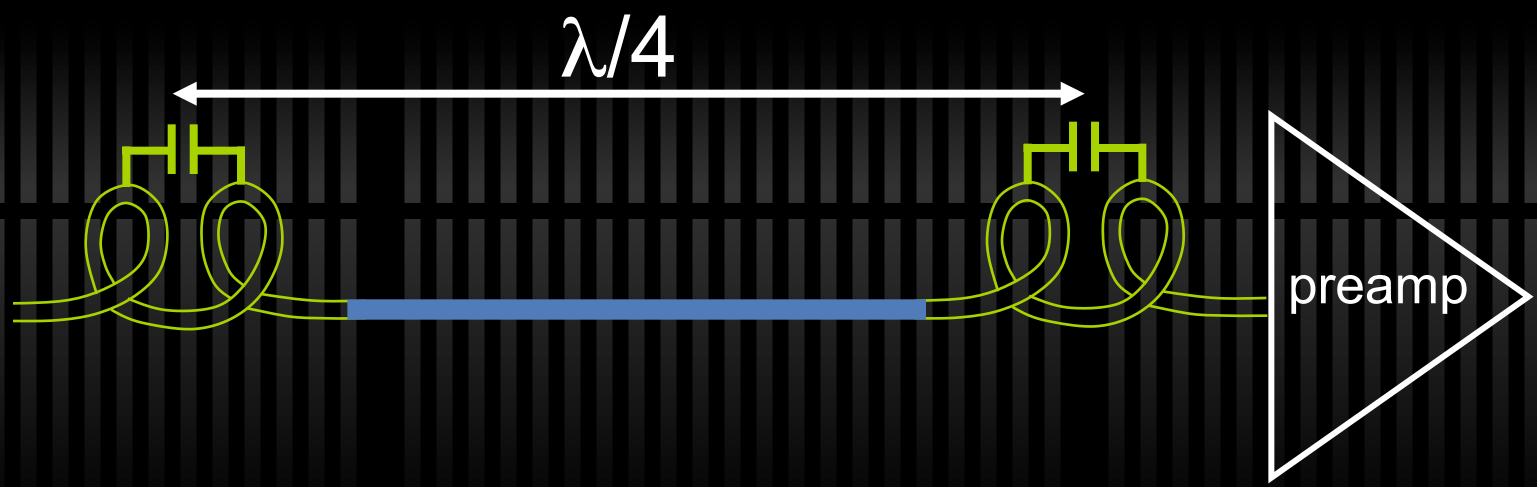
# Transport spins inside coax




Take them to a PREAMP

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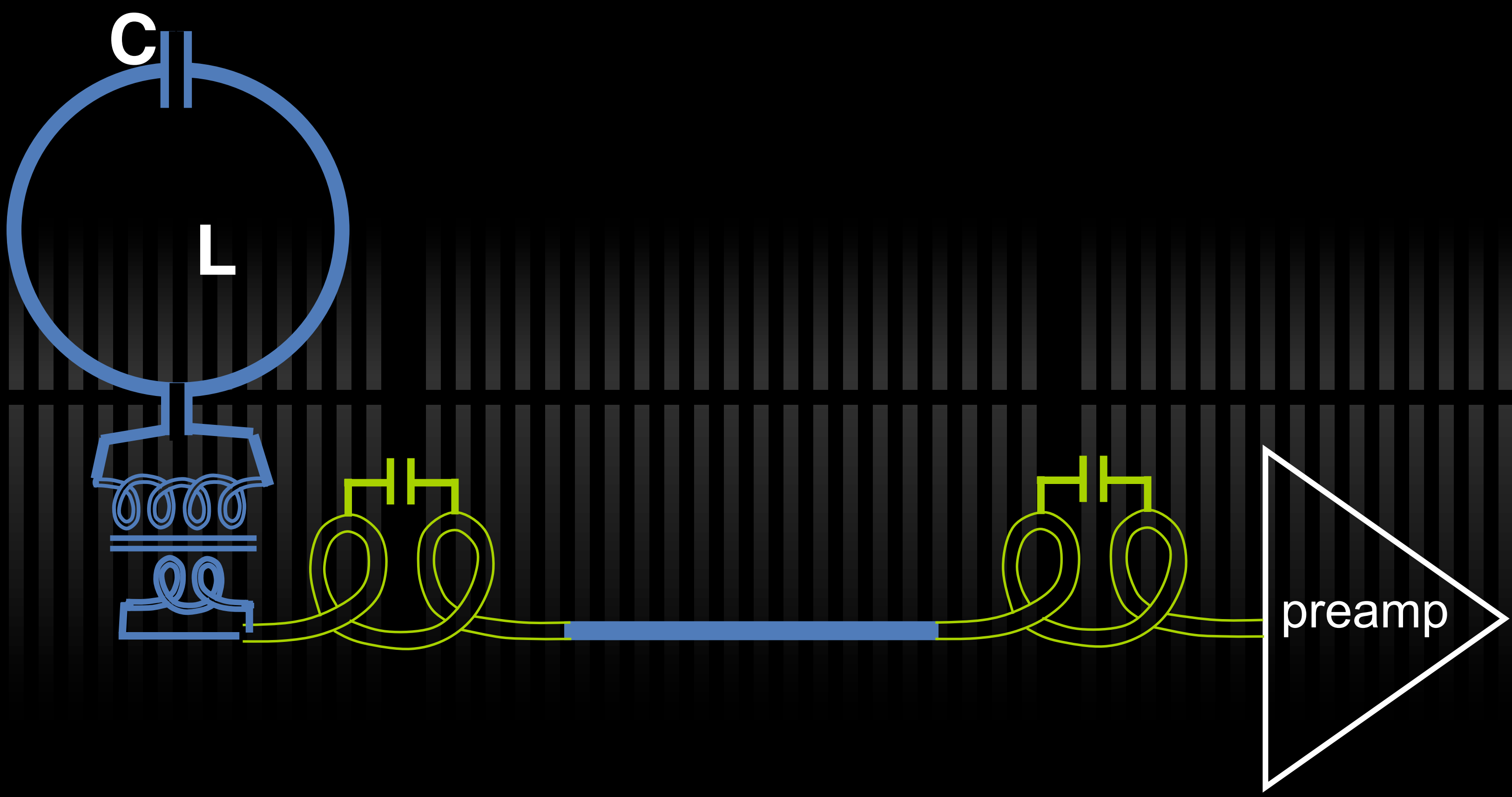
# Complete picture

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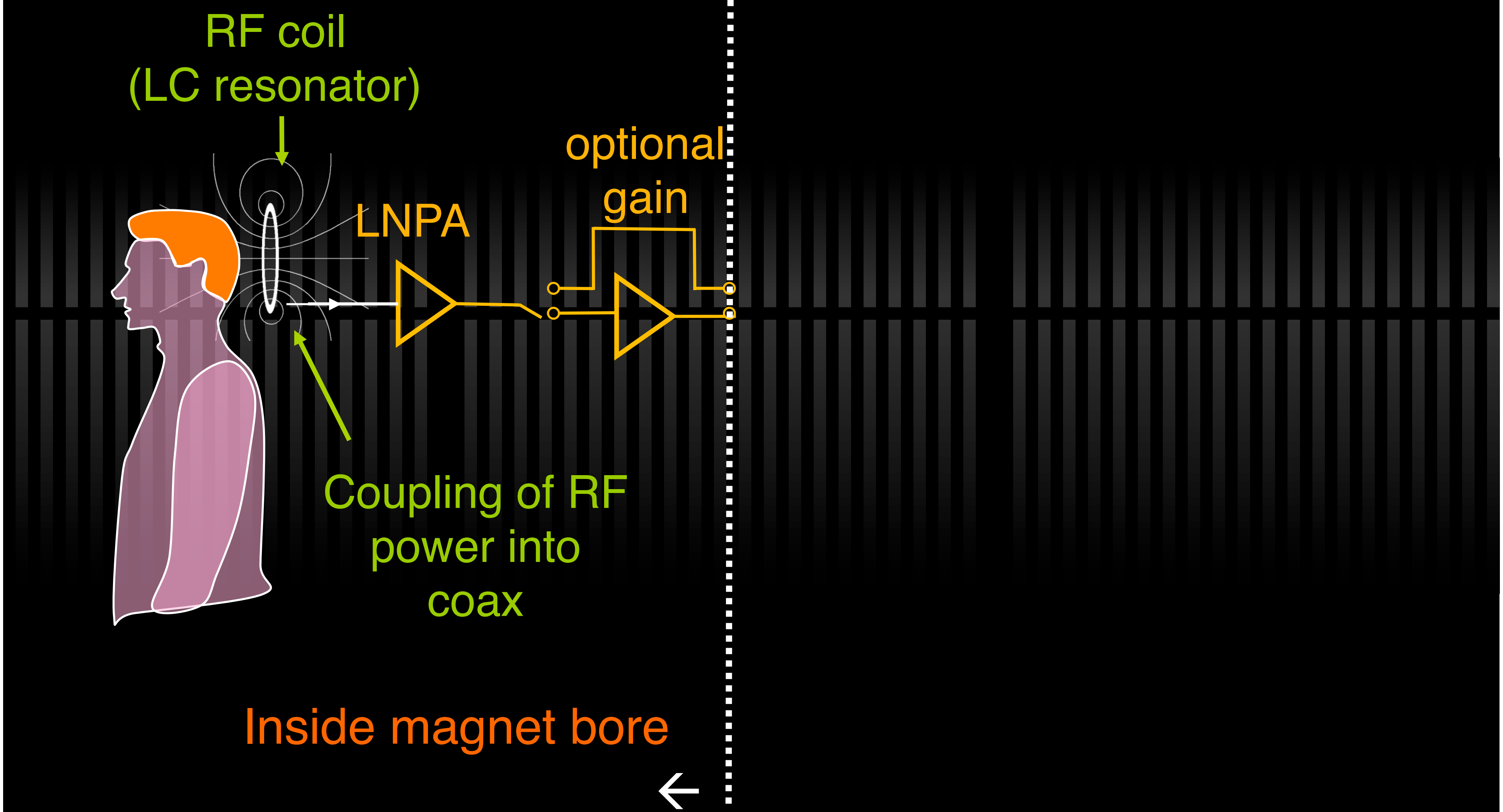
# Step 2: Summary

- ✓Coupling of RF power into coax
- ✓Use a transformer
    - ✓Extract losslessly fraction of power
    - ✓Matches impedance of coil to cable
- ✓In coax use current traps to minimize shield currents

# RF Receive Chain: 3 Amplifier

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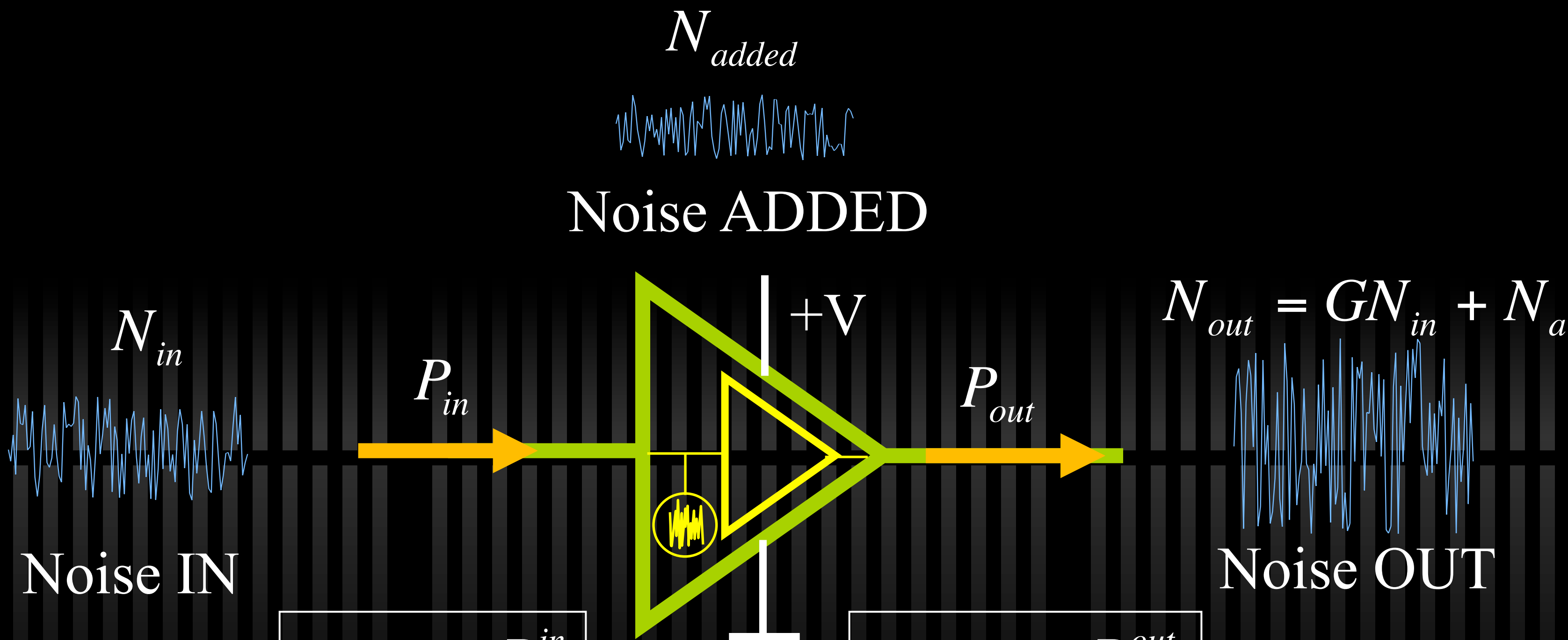
# Preamp noise figure & SNR




$$\boxed{SNR_{in} = \frac{P_s^{in}}{P_n^{in}}} \qquad \boxed{SNR_{out} = \frac{P_s^{out}}{P_n^{out}}}$$

$$NF = \frac{SNR_{in}}{SNR_{out}} \qquad NF(dB) = 10\log_{10}\frac{P_n^{out}}{P_n^{in}G}$$

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# Loss (= noise before preamp)

SNR before is always better than SNR after preamp

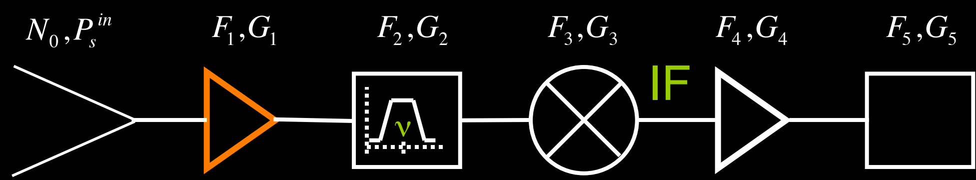
NF=0.1 dB implies a 1% loss in voltage SNR
=0.5 dB implies a 6% loss in voltage SNR
=1.0 dB implies a 12% loss in voltage SNR
=6.0 dB implies a 2X loss in voltage SNR

Typical device noise figures:

Preamp NF: 0.6 dB
Cable loss : 0.1 dB
Connector : 0.1 dB

# Why low noise preamp?

Take for example:




1) Antenna: T=290°K, $\therefore$ $N_0 = -174 dBm / Hz, P_s$

2) Preamp: $G_1 = 10, F_1 = 1.5$

3) Filter insertion loss: 1dB $\therefore G_2 = -1dB = 0.8$ and $F_2 = 1dB = 1.26$

4) Mixer convertion loss: $6dB \therefore G_3 = -6dB = 0.25$ and $F_3 = 6dB = 4$

5) IF Amp: $G_4 = 30dB = 1000$ and $F_4 = 6dB = 4$

6) IF filter insertion loss 2dB $\therefore G_5 = -2dB = 0.63$ and $F_5 = 1.58$

Rx Noise Figure:

$$F = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \frac{F_4 - 1}{G_1 G_2 G_3} + \frac{F_5 - 1}{G_1 G_2 G_3 G_4}$$

$$F = 1.5 + \frac{0.26}{10} + \frac{3}{10(0.8)} + \frac{3}{10(0.8)(0.25)} + \frac{0.58}{10(0.8)(0.25)(1000)}$$

$$F = 1.5 + 0.026 + 0.375 + 0.094 + 3 \times 10^{-4}$$

$$F = 2.0 = 3dB$$

Rx G=31dB

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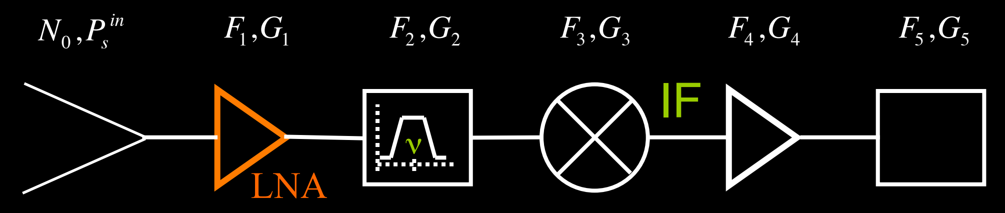
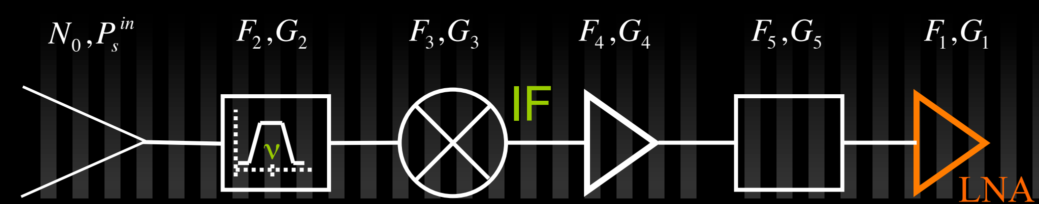
# If we move LNA to end of chain

Before:




$F = 2.0 = 3dB$

After




Rx Noise Figure:

$$F = F_2 + \frac{F_3 - 1}{G_2} + \frac{F_4 - 1}{G_2 G_3} + \frac{F_5 - 1}{G_2 G_3 G_4} + \frac{F_1 - 1}{G_2 G_3 G_4 G_5}$$

$$F = 1.26 + \frac{3}{0.8} + \frac{3}{0.8(0.25)} + \frac{0.58}{0.8(0.25)10^3} + \frac{0.5}{0.8(0.25)10^3(0.63)}$$

$$F = 1.26 + 3.75 + 15 + 0.003 + 0.004$$

$$F = 20 = 13dB$$

TEN times bigger!

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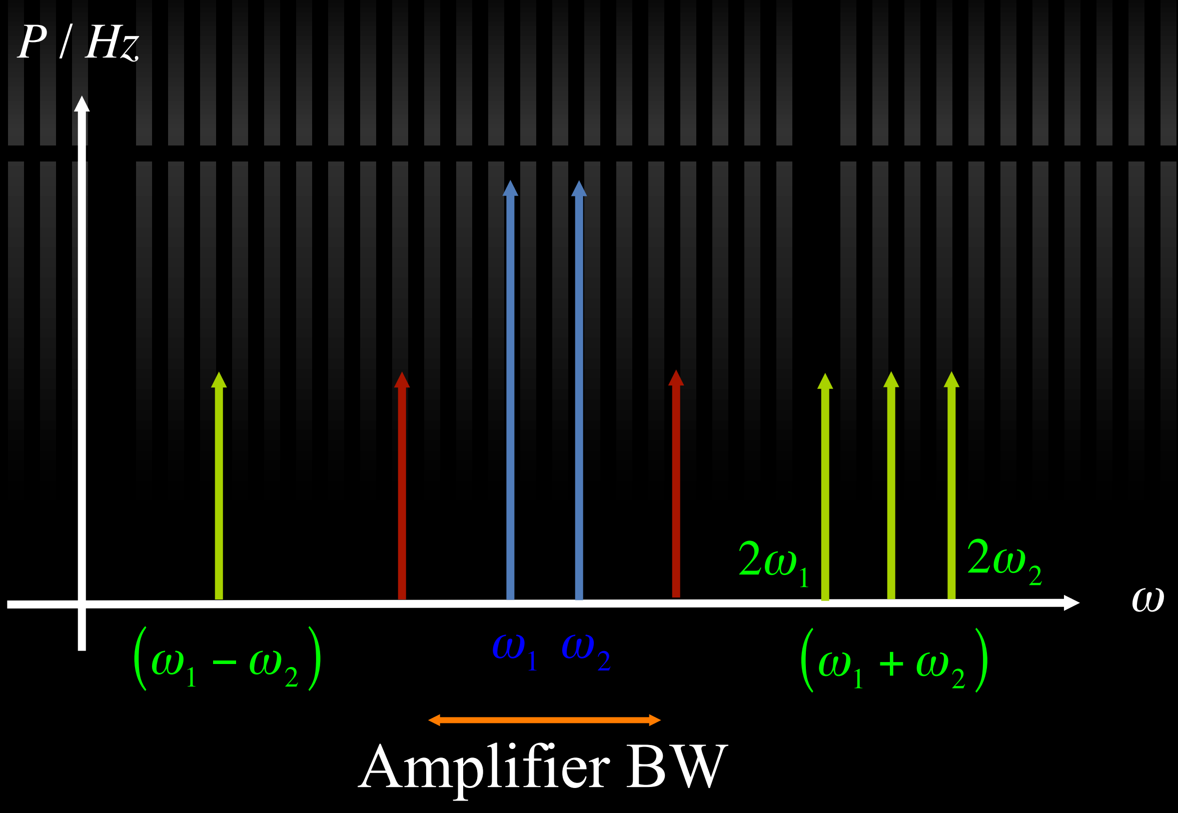
# After preamp losses not so important

Why? The noise sources arising before the preamp are amplified, so a fixed amount of additional noise is not significant if the preamp gain is high.

# We design a good preamp

- Narrow bandwidth
- Very low noise

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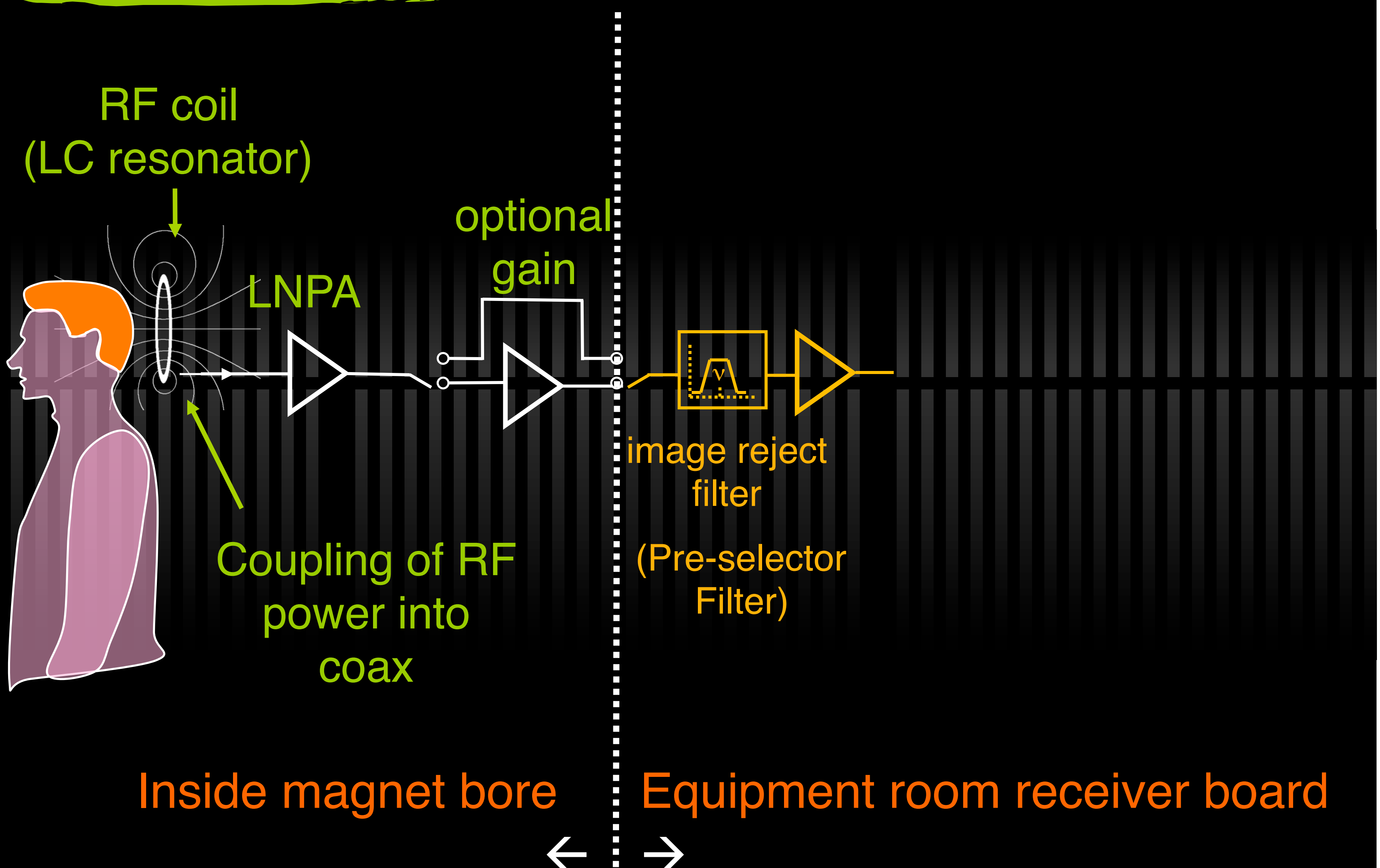
# RF Receive Chain: 4 Filter

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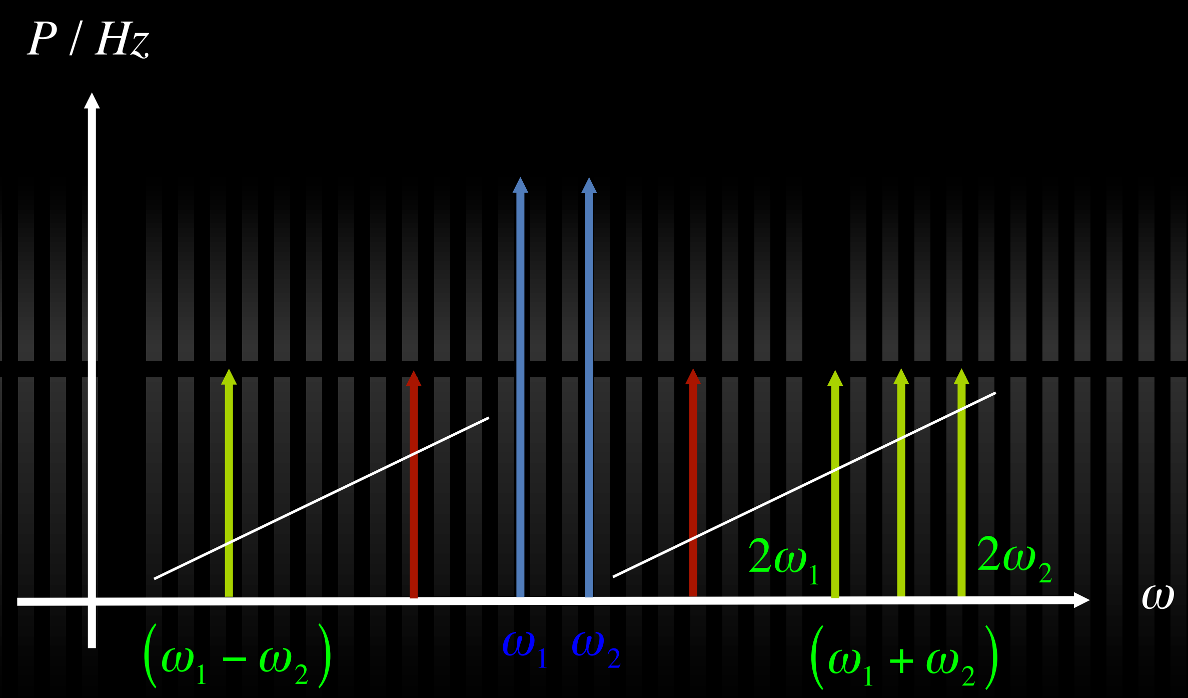
# After LNPA reject some signal




The image frequency is an off resonance frequency which when input to a mixer produces an output signal at the IF frequency which makes it un-filterable.

# Filters


$$P_{inc} = P_r + P_{abs} + P_{out}$$

Power transmission coefficient

$$T \doteq \frac{P_{out}}{P_{inc}} = \left|S_{21}\right|^2$$

For a lossless filter $P_{abs} = 0$

$$\Gamma \doteq \frac{P_r}{P_{inc}} = \left|S_{11}\right|^2$$

$$\Gamma(\omega) + T(\omega) = 1 = \left|S_{11}\right|^2 + \left|S_{21}\right|^2$$

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# Filter types

Transmission | Reflection

Low-pass

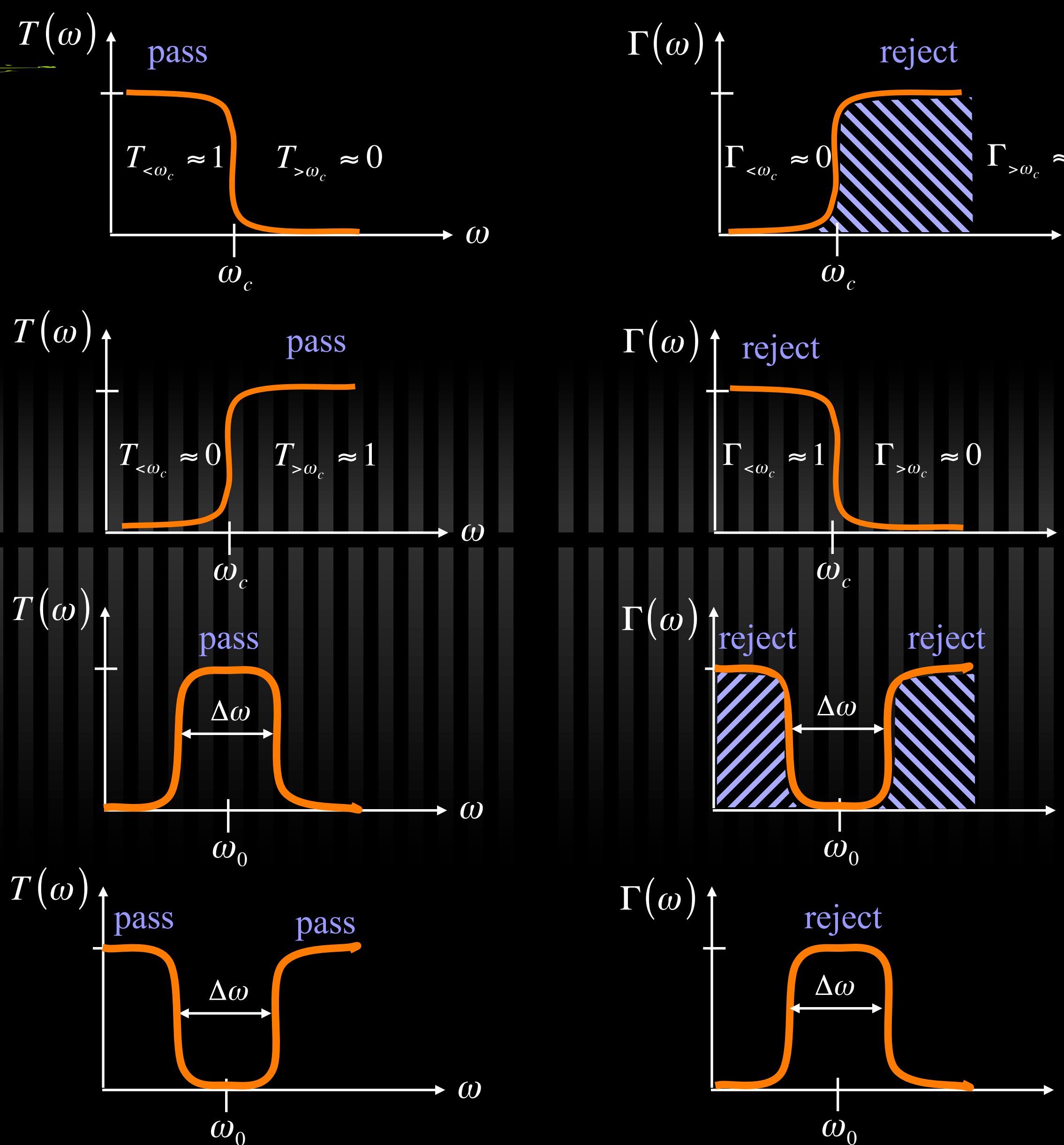
Hi-pass

Band-pass

$T_{|\omega-\omega_0|<\Delta\omega/2} \approx 1$

Band-stop

$T_{|\omega-\omega_0|<\Delta\omega/2} \approx 1$

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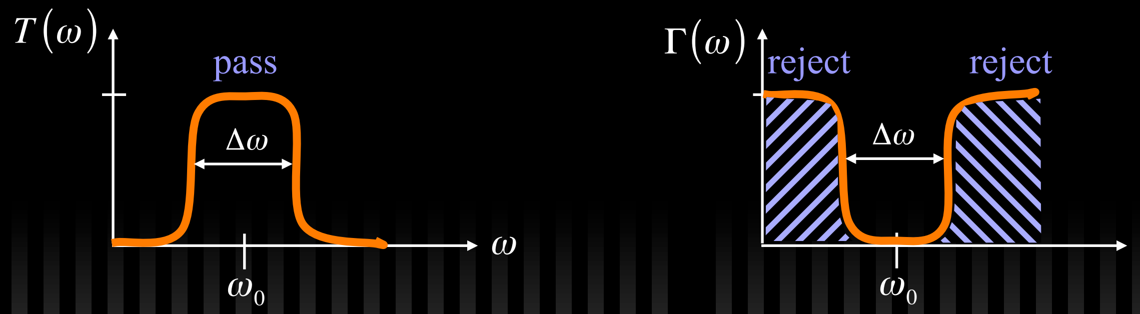
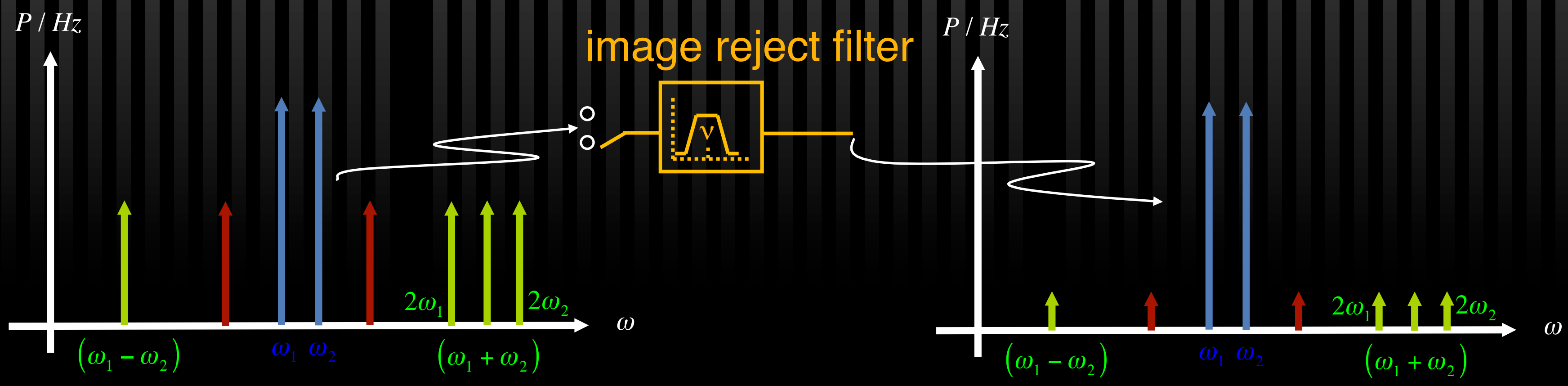
# Image and 3rd order signal reject

Band-pass

$T_{|\omega-\omega_0|<\Delta\omega/2} \approx 1$

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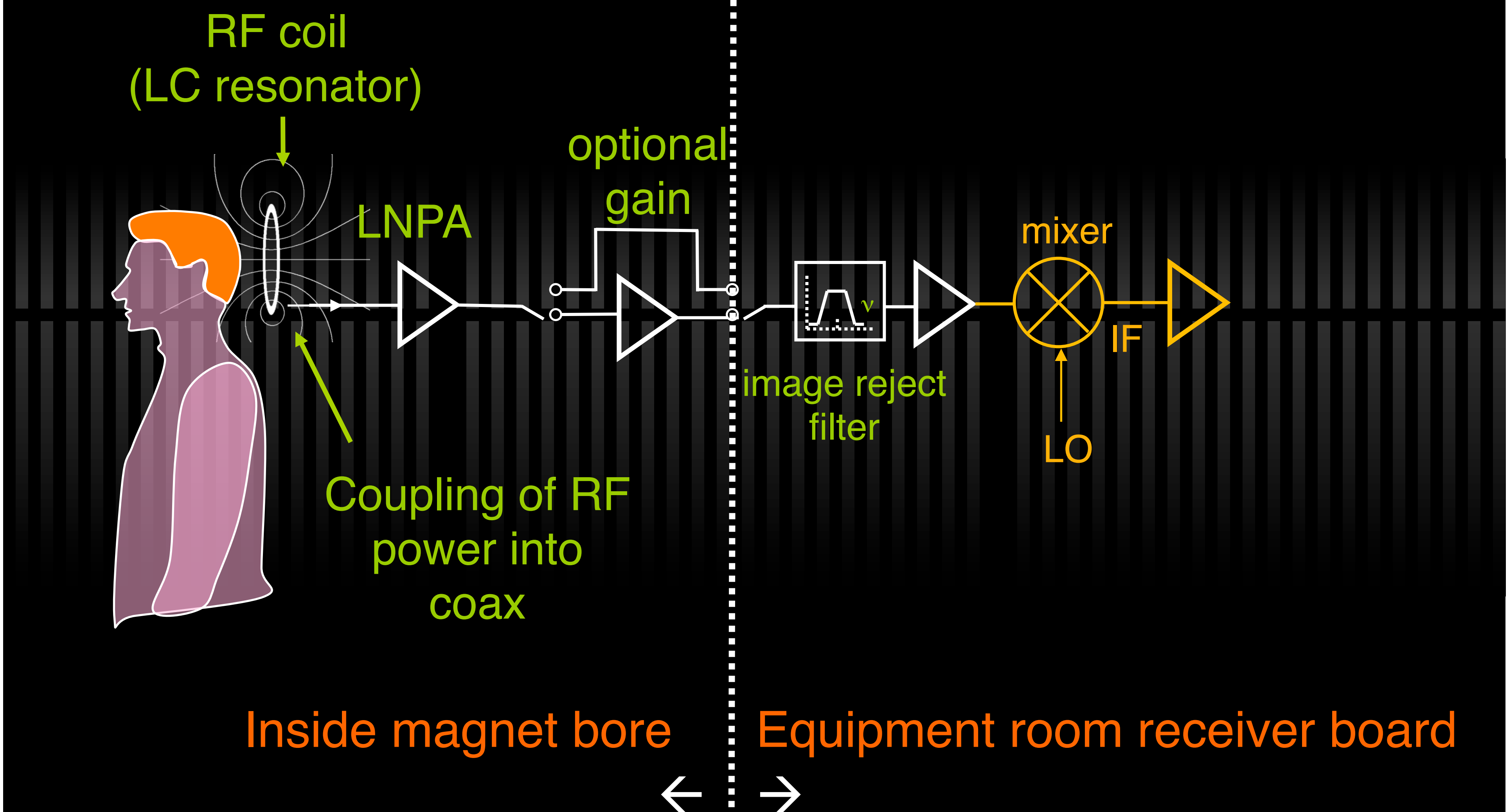
# RF Receive Chain: 5 Mixer

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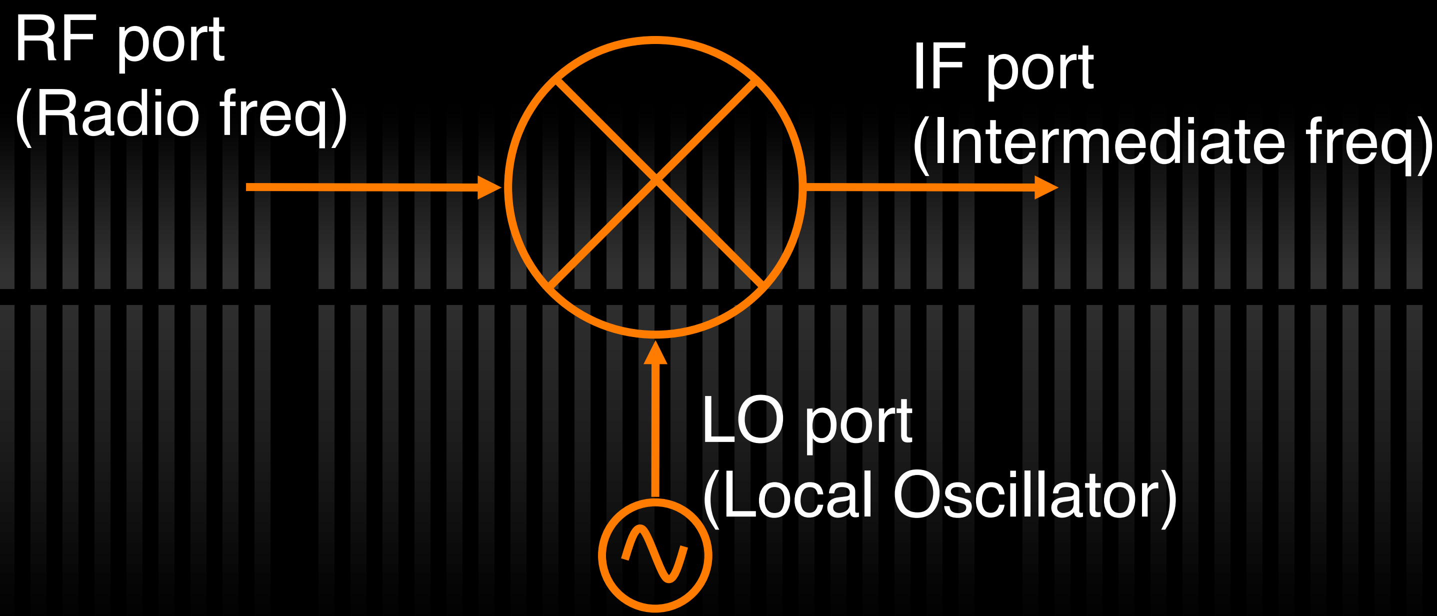
# Why do we need a mixer?

- If our signal carrier is at 125MHz (3T) then sampling rate must be at least 250MHz. At 50% duty cycle, 16bit, 1 receiver generates 15GB per min.
  250Mpts/s*30s*2bytes/pts=15000e6 bytes=15GB
- Don't even think about demodulating at 300MHz (7T)
- Somehow we need to change the signal frequency to a lower frequency without loosing information or accuracy.

# A Mixer to the rescue (multiplier)



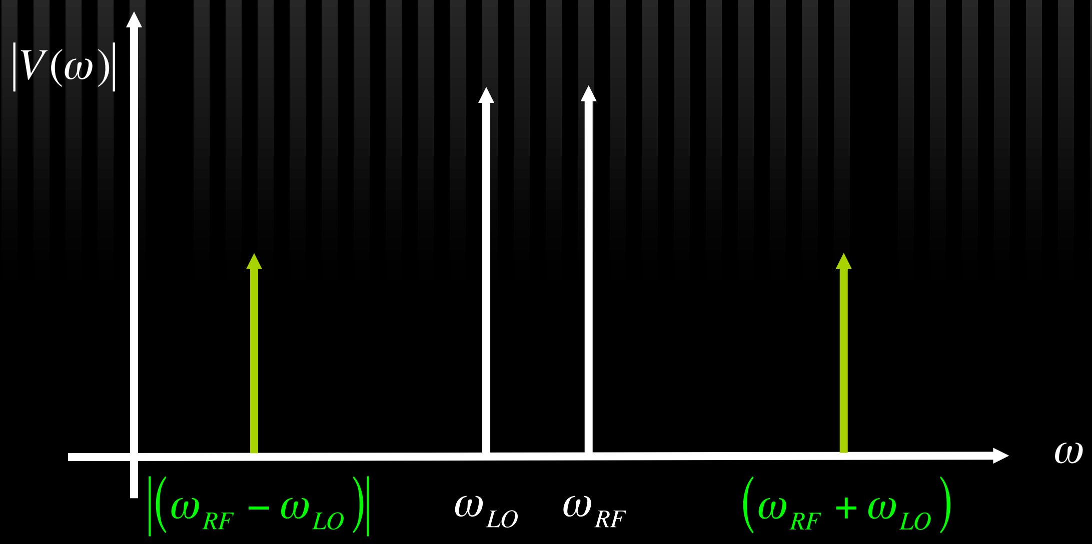

For and ideal mixer you get $v_{IF}(t) = v_{RF}(t) \times v_{LO}(t)$

# Output of an ideal mixer

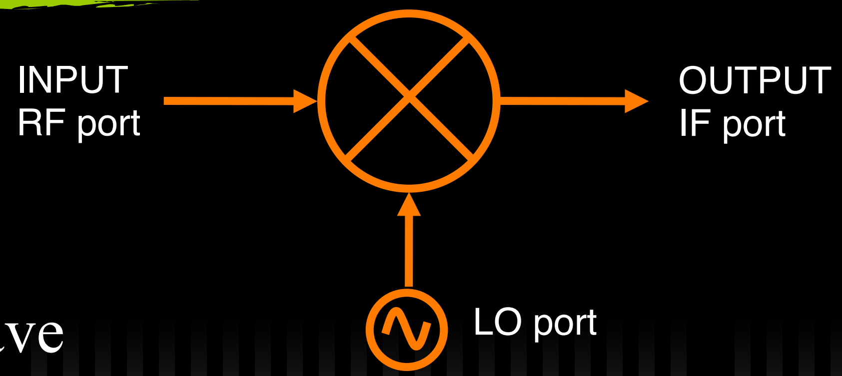
Given $v_{RF}(t) = \cos\omega_{RF}t$

$v_{LO}(t) = \cos\omega_{LO}t$

Then
$$v_{IF}(t) = v_{RF}(t) \times v_{LO}(t)$$
$$= \cos(\omega_{RF}t)\cos(\omega_{LO}t)$$
$$= \tfrac{1}{2}\cos(\omega_{RF} - \omega_{LO})t + \tfrac{1}{2}\cos(\omega_{RF} + \omega_{LO})t$$



# Mixer conversion factor



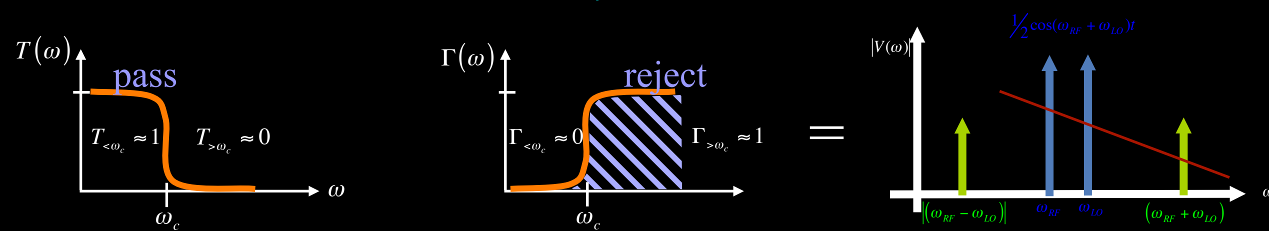

Assume we have

$v_{IF} = K v_{RF} v_{LO}$ where K=conversion factor

Filtered out

$$
\begin{aligned}
v_{IF} &= K v_{RF}(t) v_{LO}(t) \\
&= K a(t)\cos(\omega_{RF}t + \phi(t)) A_{LO}\cos\omega_{LO}t \\
&= \frac{KA_{LO}}{2} a(t)\cos[(\omega_{RF} - \omega_{LO})t + \phi(t)] + \cancel{\frac{KA_{LO}}{2} a(t)\cos[(\omega_{RF} + \omega_{LO})t + \phi(t)]}
\end{aligned}
$$

Low-pass

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# Information is preserved

$$v_{IF} = \frac{KA_{LO}}{2} a(t)\cos[(\omega_{RF} - \omega_{LO})t + \phi(t)]$$

$$v_{RF}(t) = a(t)\cos(\omega_{RF} t + \phi(t))$$

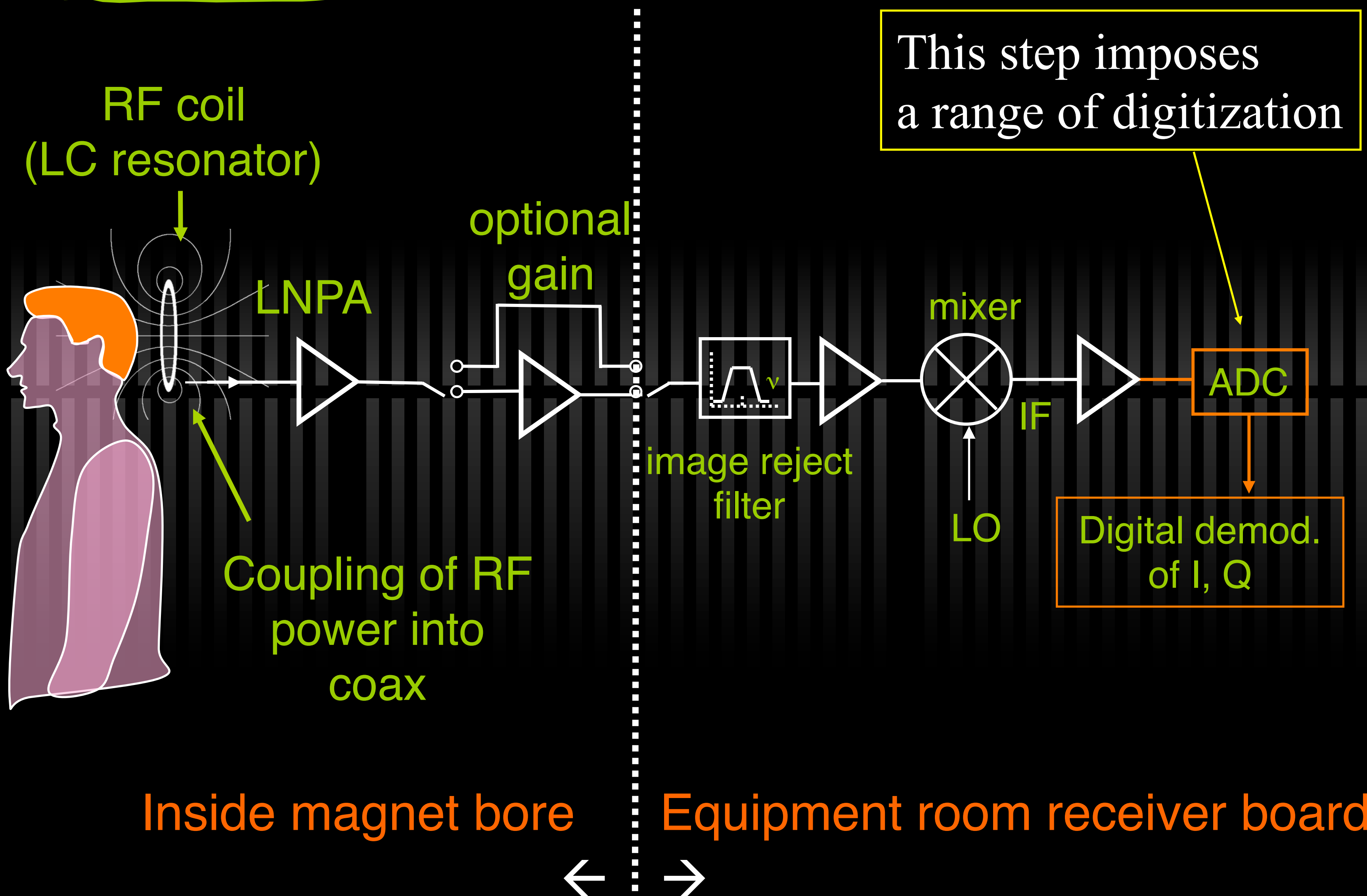
IF and RF signal is almost identical
IF has smaller magnitude and lower frequency!

The modulated INFORMATION has been PRESERVED!
We can accurately recover $a(t)$ and $\phi(t)$ from this signal.

The RF signal has been DOWN-CONVERTED

We want to down-convert because eventually we want to recover the signal and this is easier, cheaper and more accurate at lower frequencies.

# RF Receive Chain

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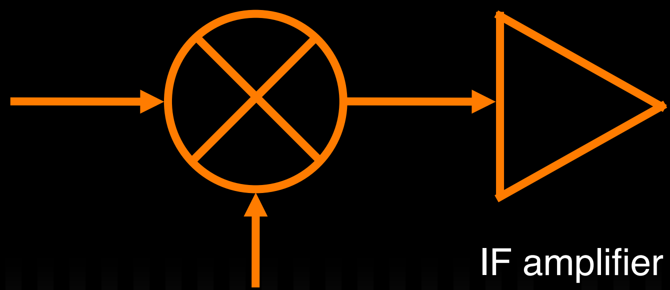
# IF amp to properly set Rx gain




There is a minimum input signal power a receiver can accurately demodulate called the Minimum Detectable Signal (MDS).
There is also a Maximum input signal power that can be demodulated.

Signal $\quad \text{Total Dynamic Range (TDR)} \doteq \dfrac{P_{in}^{sat}}{MDS}$

Ratio in (dB)

$$\text{TDR}(dB) \doteq P_{in}^{sat}(dBm) - MDS(dBm)$$

# Rx dynamic range & gain control

The demodulator has a certain dynamic range (IDR)

The Rx gain G has to satisfy

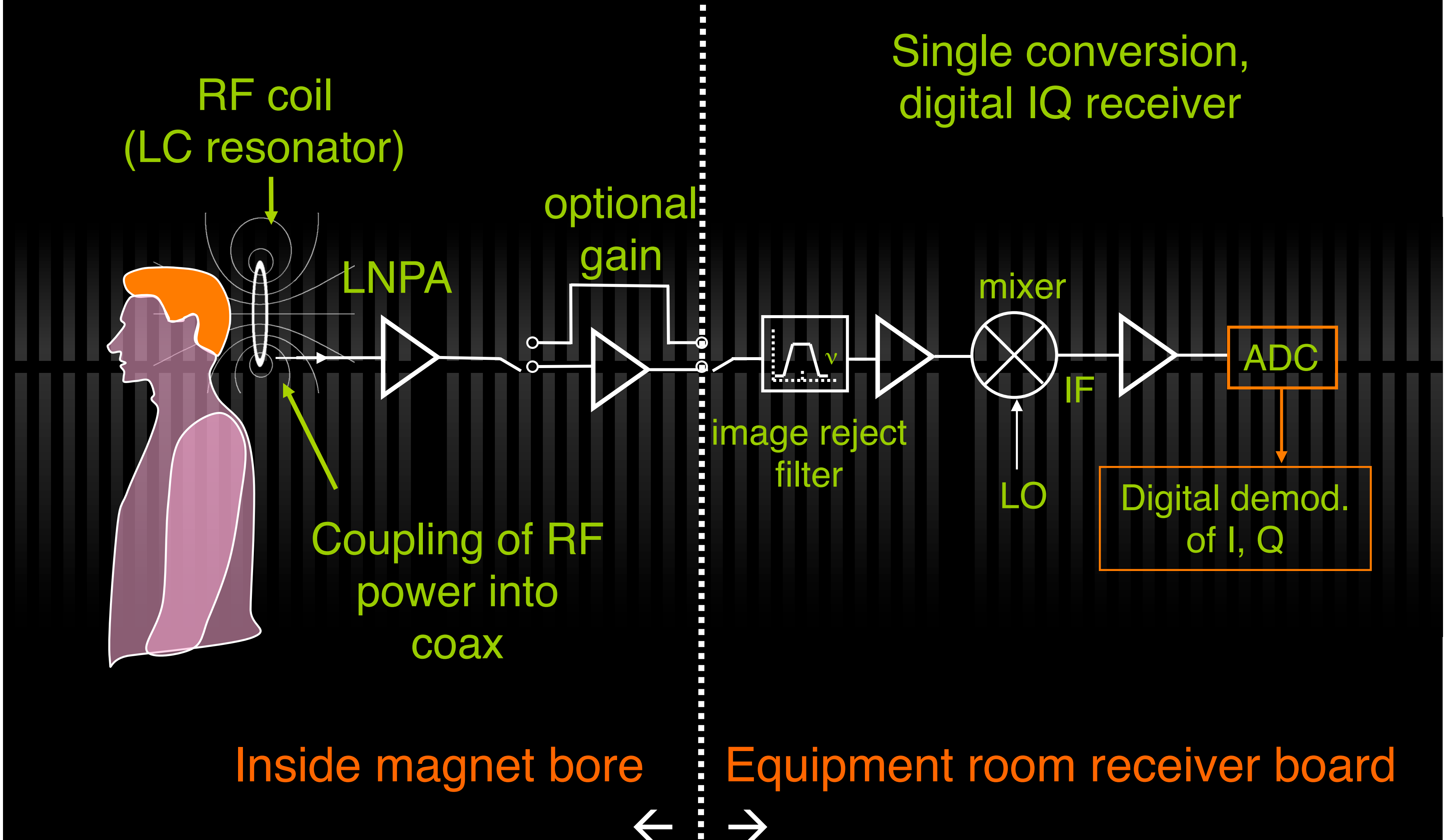
a) The MDS is amplified enough for min power demo
b) Not go over the maximum power for demodulation

The problem

If demodulator has a dynamic range between 20-100
and the MDS is 2, then Rx G=10
Max signal is 15 with gain of 10 becomes 150
This signal can not be demodulated.

Solution: Automatic Gain Control (AGC)

# RF Receive Chain 7:demodulation

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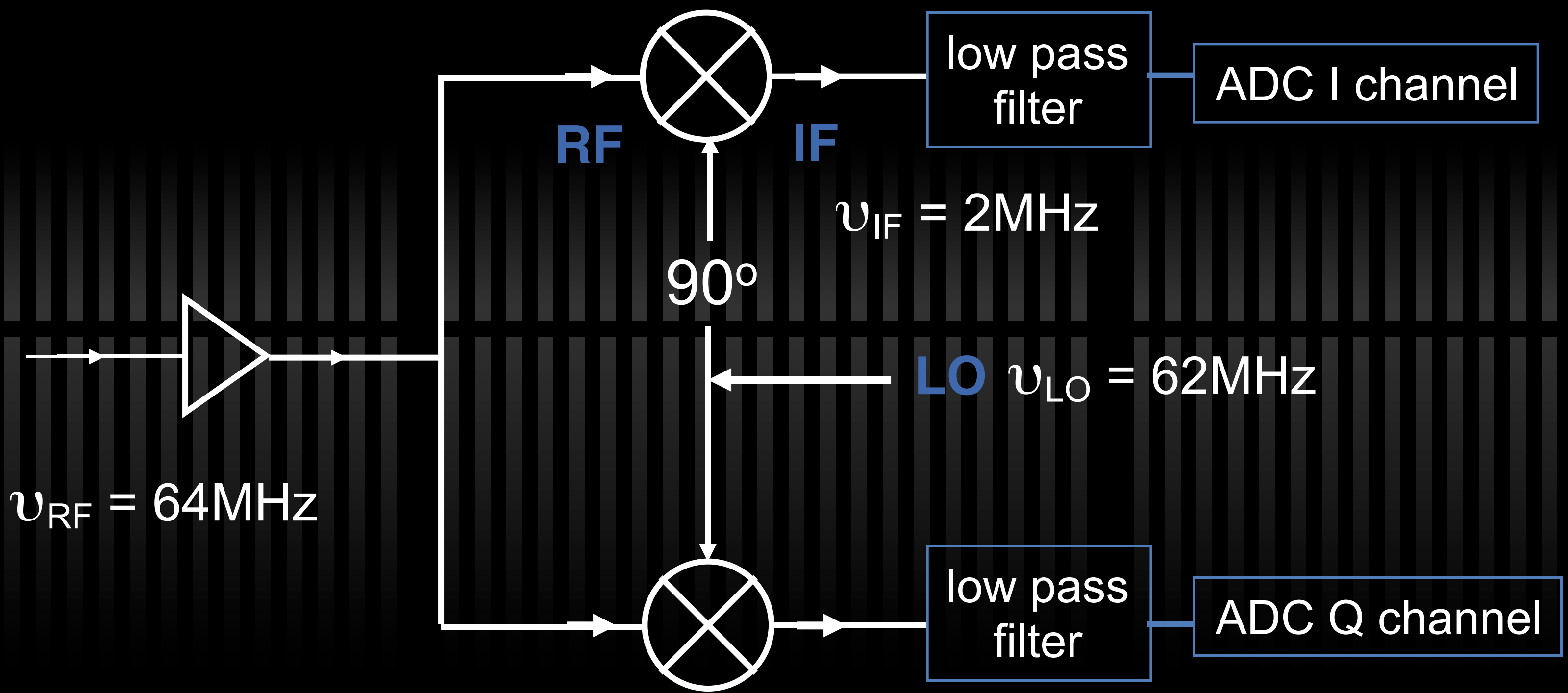
# Mix down near to DC

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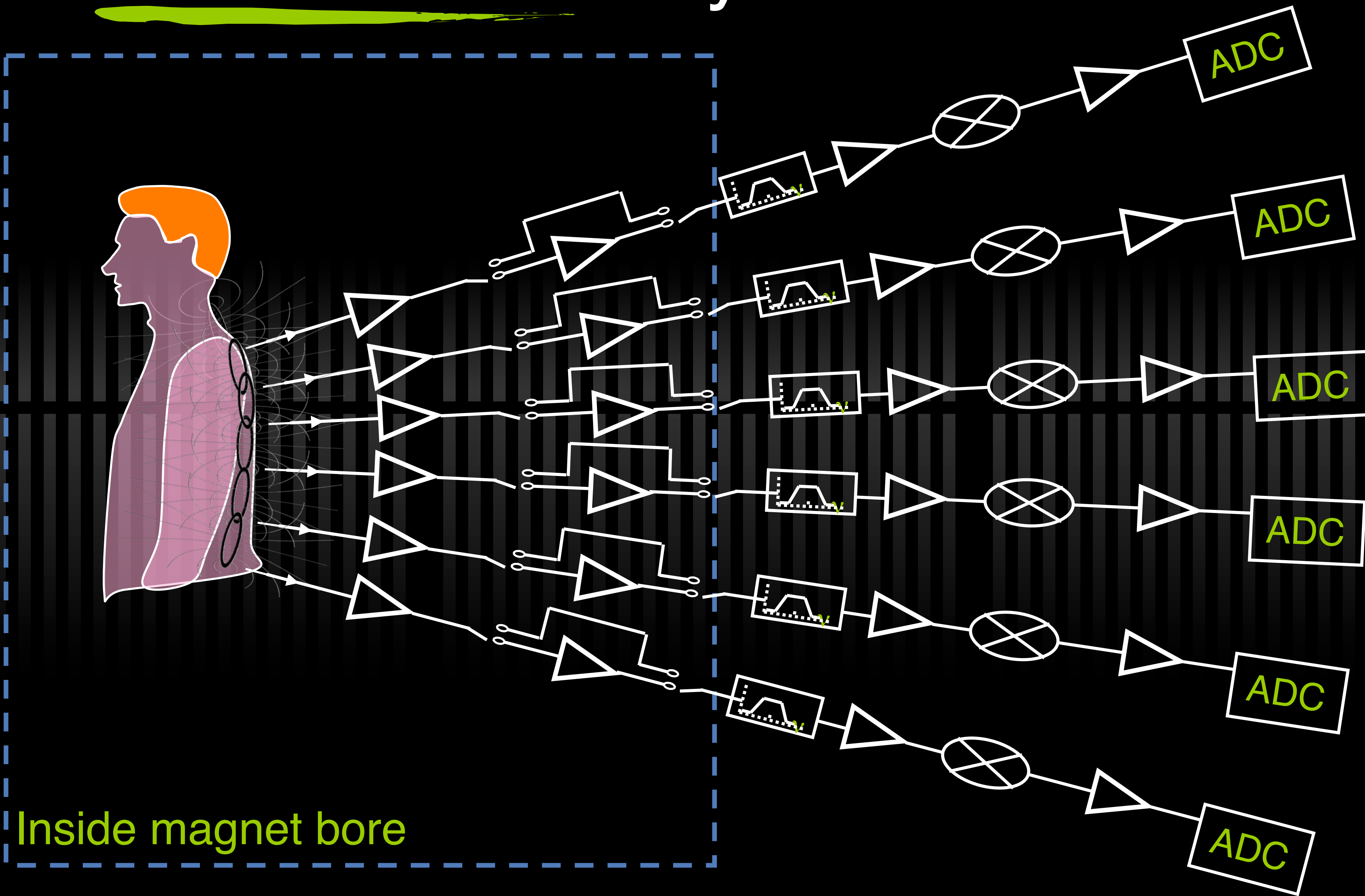
# RF Receive Array

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# Thank You