System Integration

Part 1. Integrated system design

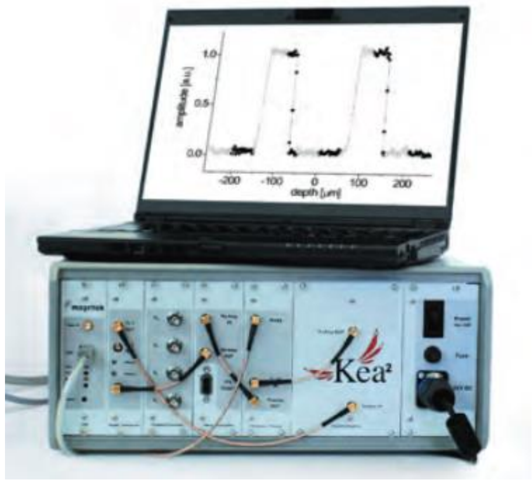
Part 2. Integrating individual components of the system

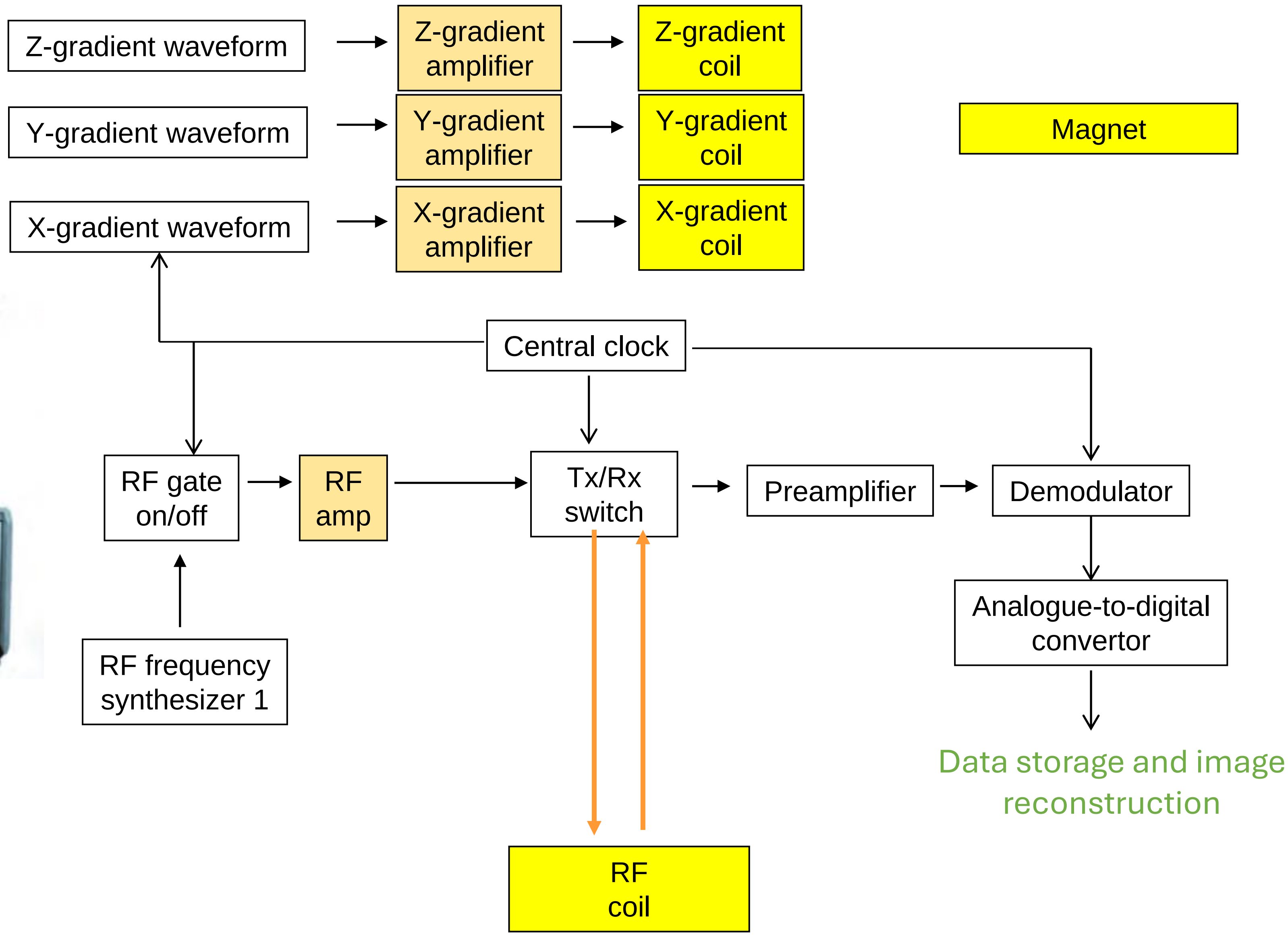
Overall hardware block diagram I

designed

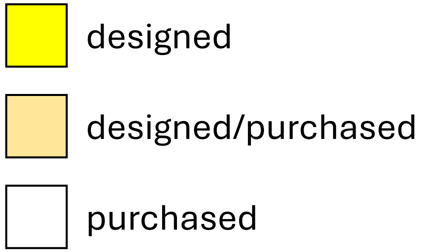
designed/purchased

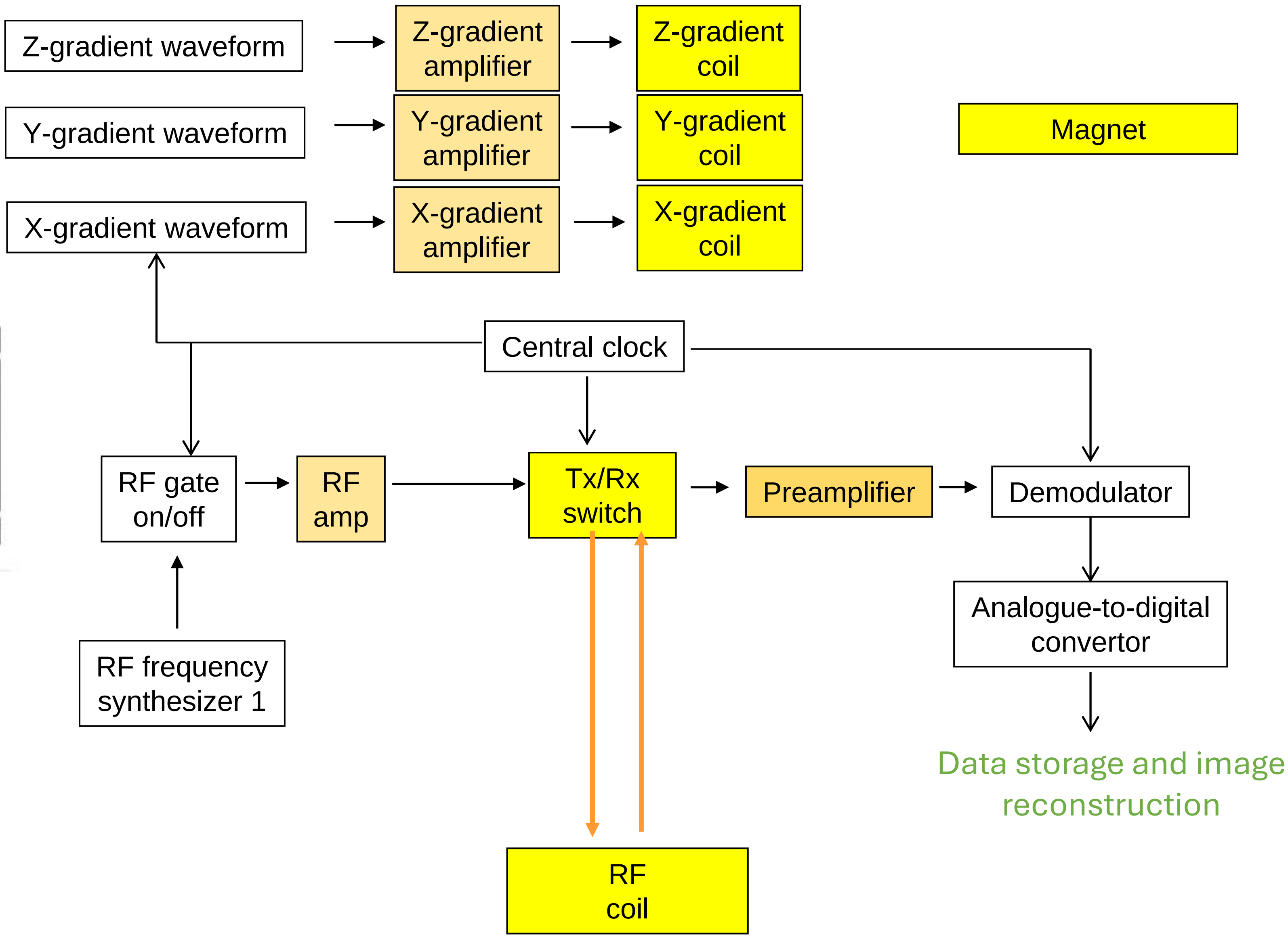
purchased





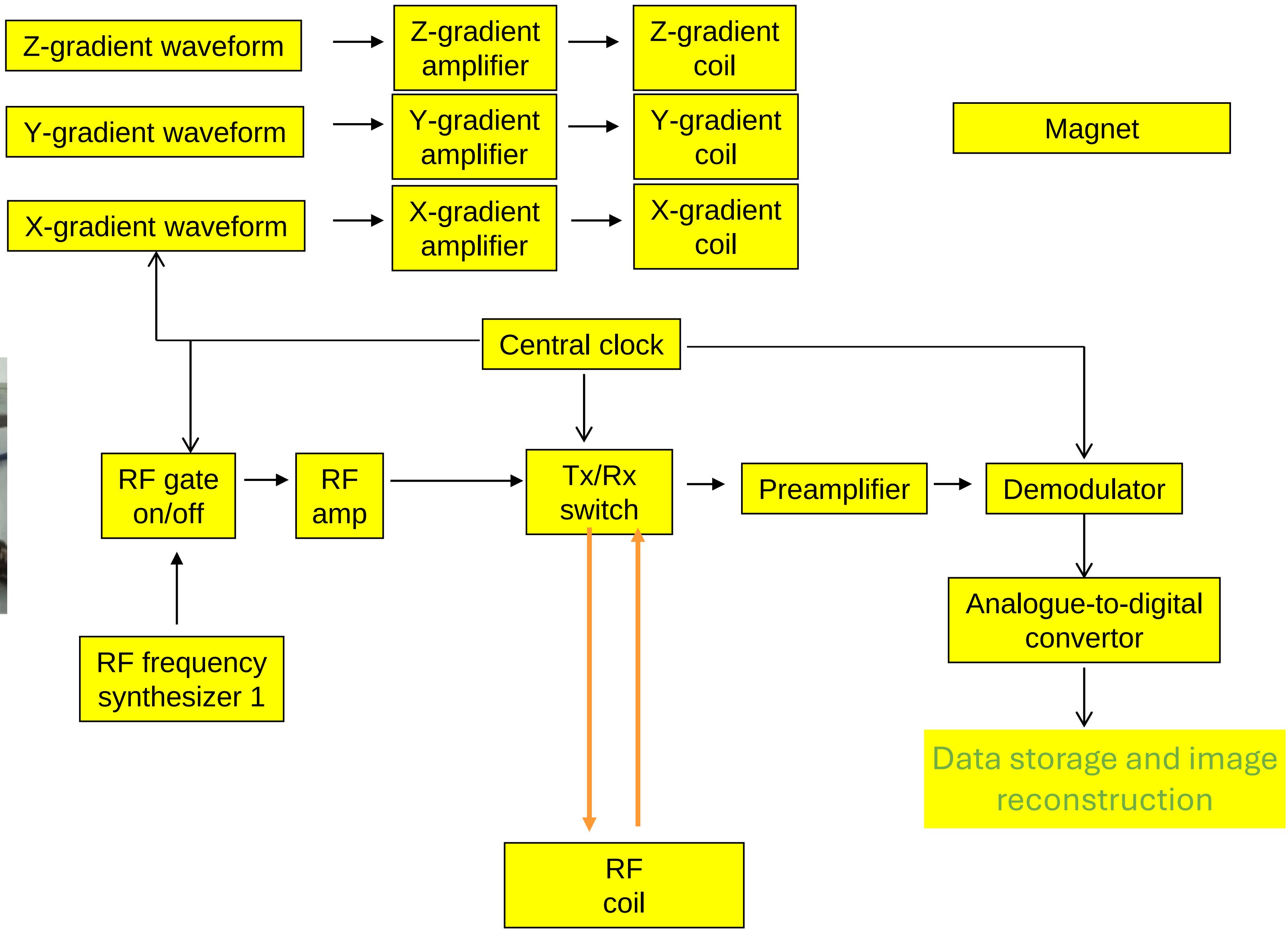
Overall hardware block diagram II



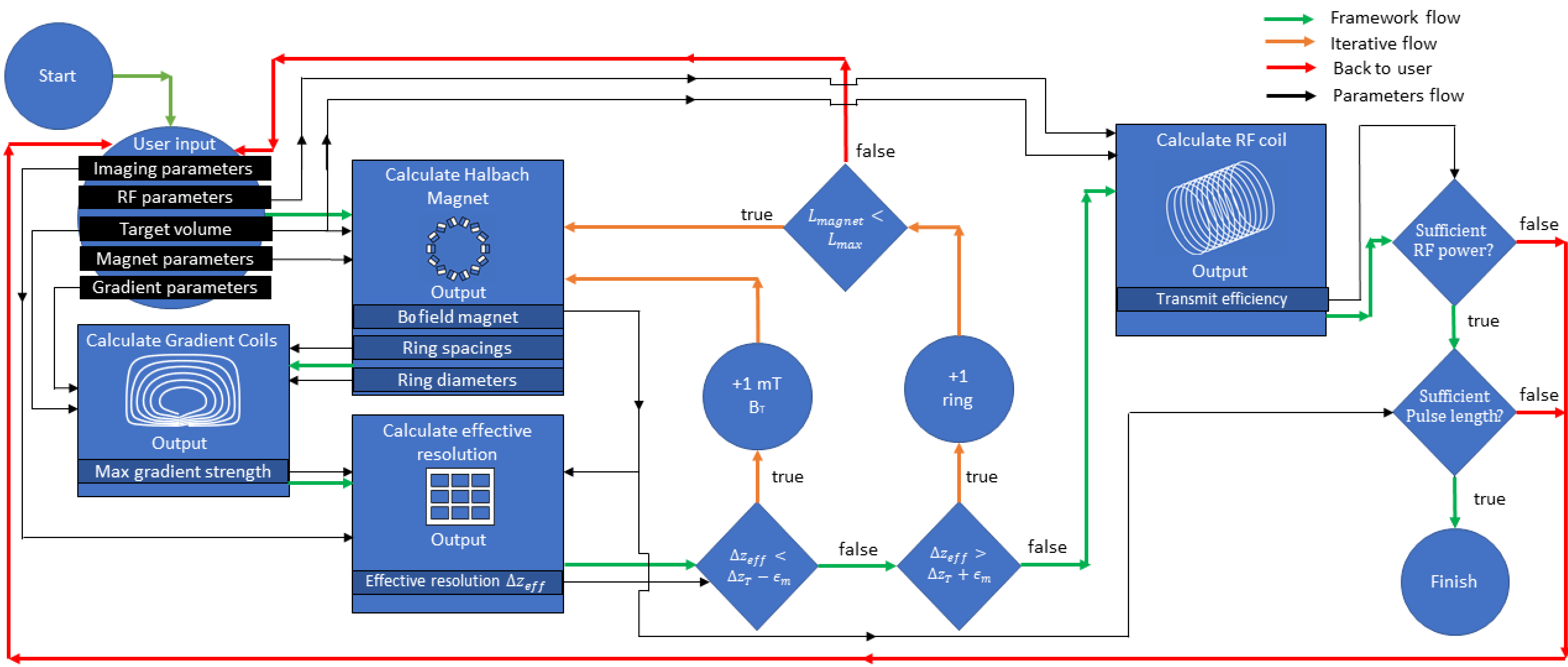


Overall hardware block diagram III

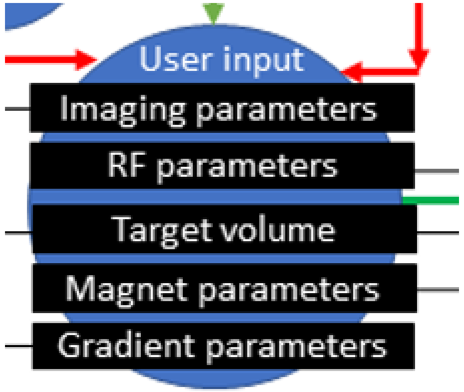
- designed
- designed/purchased
- purchased



Part 1. Integrated system design



Framework flow
Iterative flow
Back to user
Parameters flow
Start
User input
Imaging parameters
RF parameters
Target volume
Magnet parameters
Gradient parameters
Calculate Halbach Magnet
Output
B0 field magnet
Ring spacings
Ring diameters
Calculate Gradient Coils
Output
Max gradient strength
Calculate effective resolution
Output
Effective resolution Δz_{eff}
$L_{magnet} < L_{max}$
false
true
+1 mT B_T
+1 ring
true
true
$\Delta z_{eff} < \Delta z_T - \epsilon_m$
false
$\Delta z_{eff} > \Delta z_T + \epsilon_m$
false
Calculate RF coil
Output
Transmit efficiency
Sufficient RF power?
false
true
Sufficient Pulse length?
false
true
Finish



Neuroimaging system

Imaging field of view: cylinder length 200 x 200 x 200 mm^3

Need a spatial resolution of 3 x 3 x 3 mm

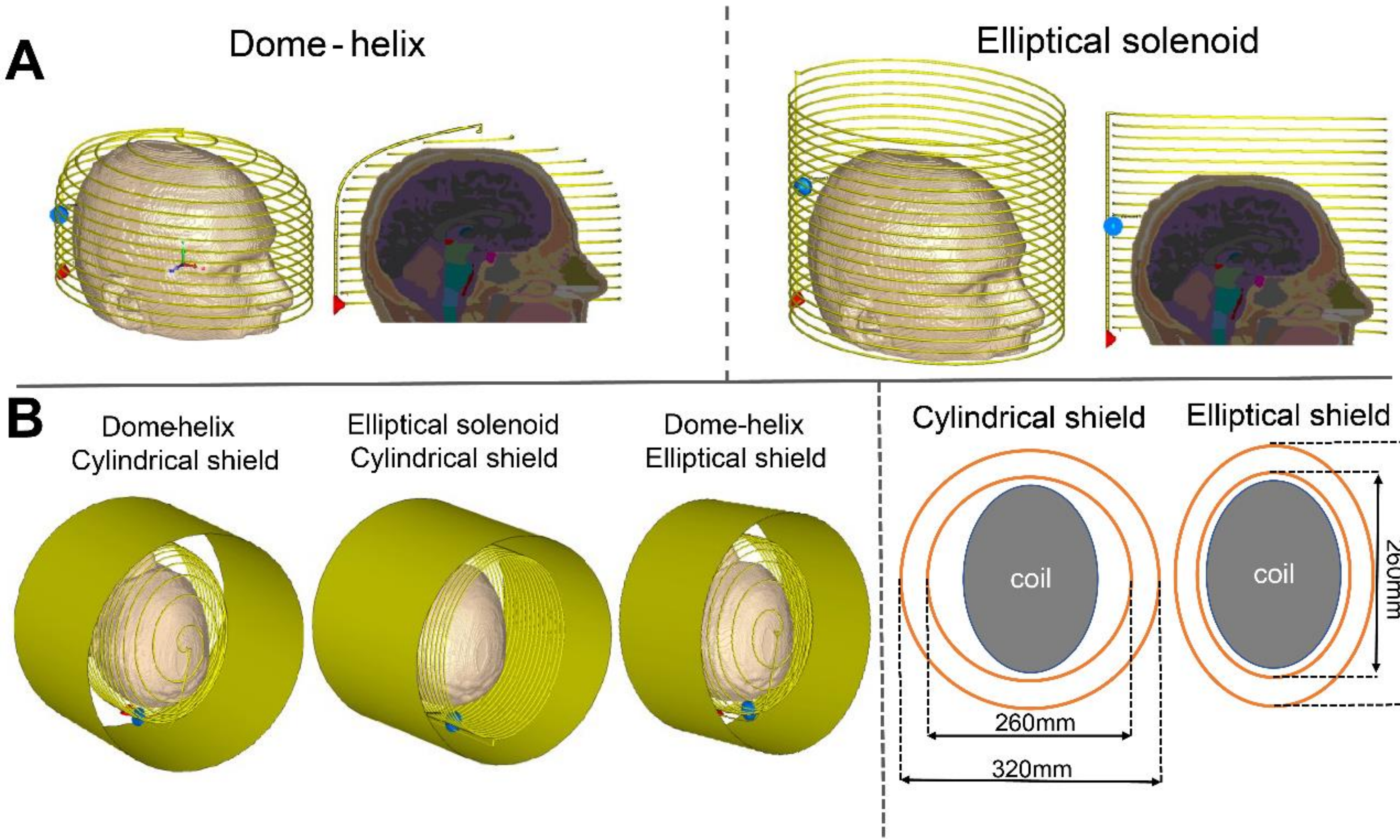
Estimate that we want a magnetic field strength of at least 45 mT

Maximum length of the magnet is 500 mm to position the brain at the centre

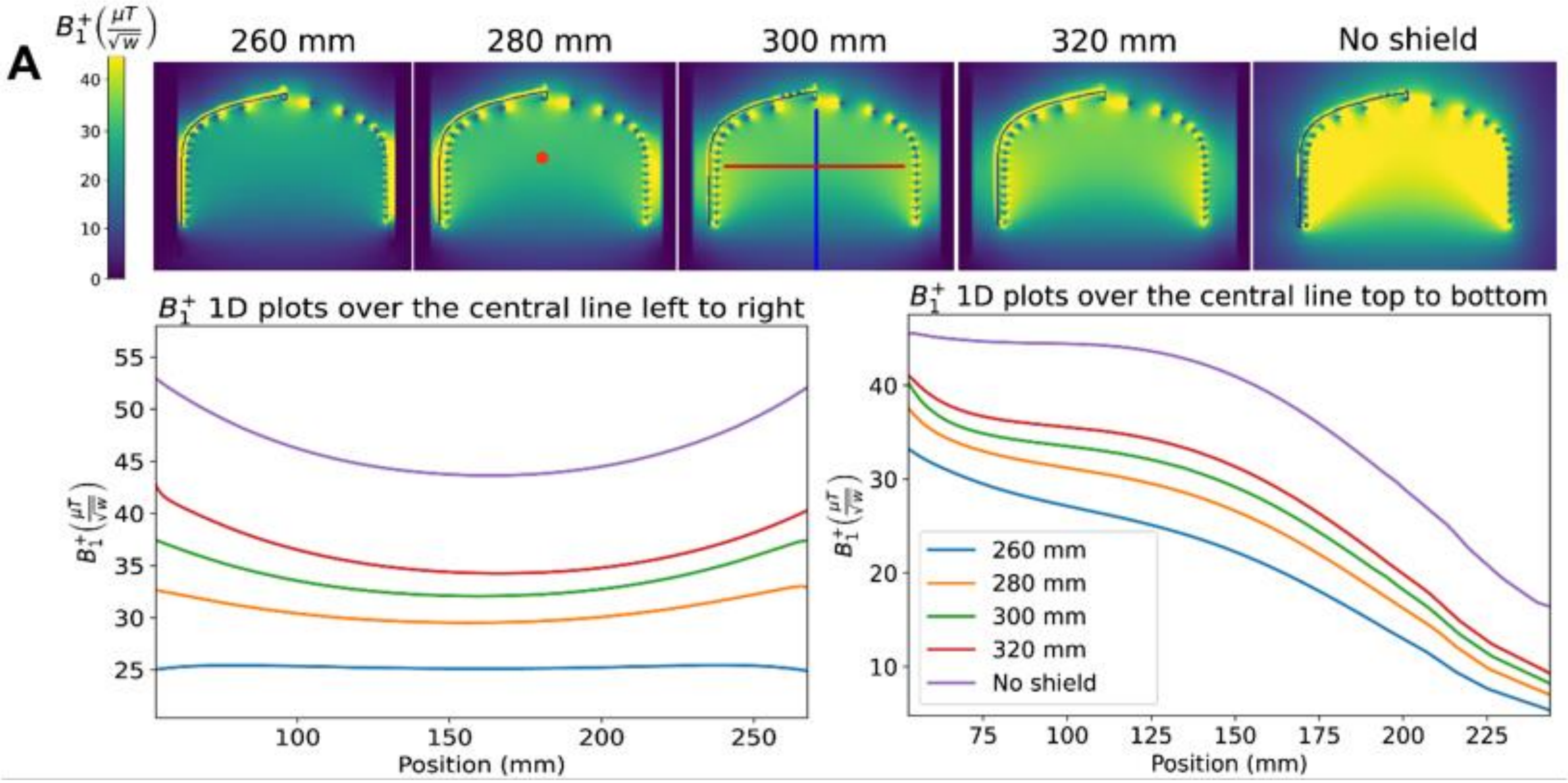
So the RF coil is specified as cylinder 240 x 240 x 240 mm

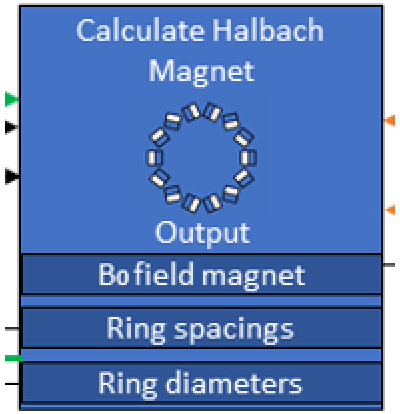
Gradient coil length set at 500 mm
Diameter 300 mm (to avoid reducing Tx/Rx efficiency)

Effect of RF shield on RF coil performance



Decrease in SNR as function of shield-to-coil distance



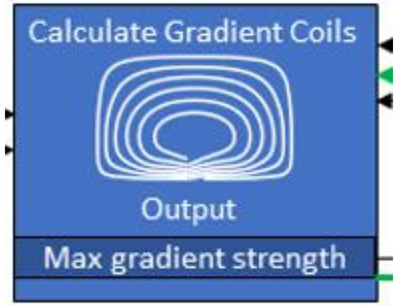


Optimization via many different methods

Most methods model individual magnets as dipoles

Start with a reasonable guess in terms of diameter, length,
number of rings based on previous designs (although not critical)

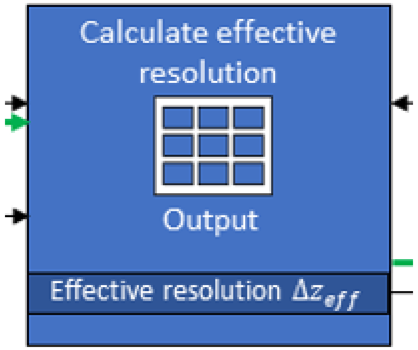
In this case, 25 rings, 20 mm in-between rings



Can use different approaches, target field, boundary element methods etc……

Gradient design algorithm:

1. Initialization:
   a. Obtain gradient coil length and radius from magnet dimensions
   b. Specify target gradient field vector **k**
   c. Specify the wire thickness, and minimum wire spacing
   d. Specify maximum linearity
2. Find expansion coefficients ~ for a range of the regularization parameter λ
3. Determine gradient efficiencies and linearities for all values of λ
4. Find most efficiency coil corresponding to the maximum allowable linearity error.



Consider the effect of B_0 inhomogeneity and gradient strength (bandwidth)

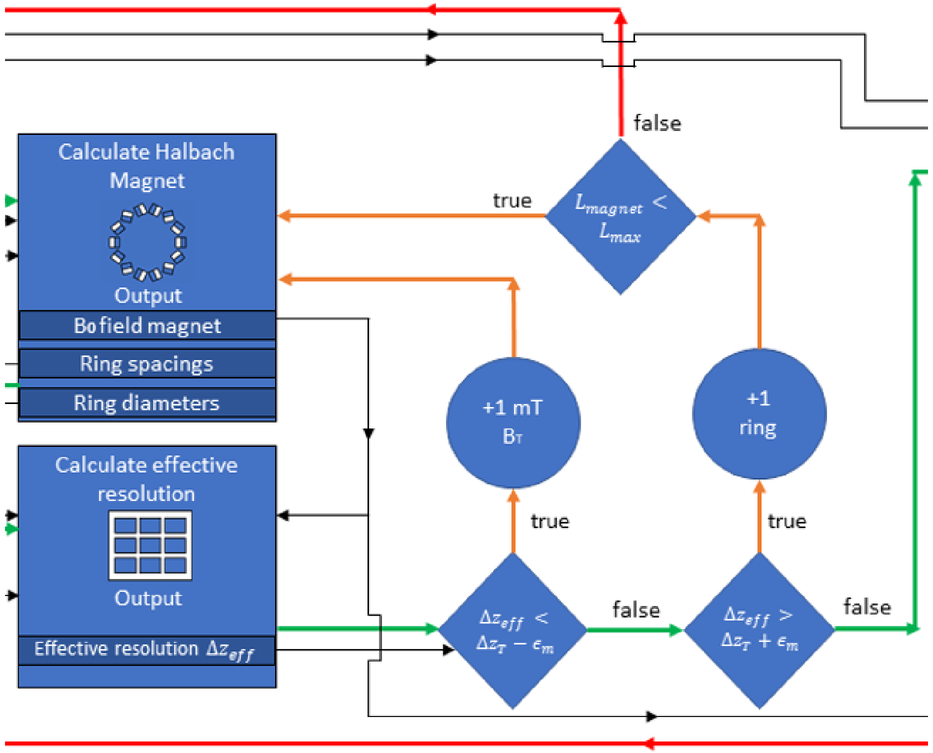
$$\frac{1}{T_2^*} = \frac{1}{T_2} + \gamma \Delta B_0$$

$$\gamma \Delta B_0 \gg \frac{1}{T_2} \qquad\qquad T_2^* \approx \frac{1}{\gamma \Delta B_0}$$

BW = FOV x gradient strength

$$\Delta z_{eff} = N_z \Delta z \frac{\tanh\left(\frac{\pi \mathrm{FWHM}}{2BW}\right)}{1 - e^{-\frac{\pi \mathrm{FWHM} N_z}{2BW}}}$$

where BW is the maximum obtainable readout bandwidth of the gradient system determined with the least efficient gradient, Δz the digital resolution and N_z the number of points.



Iterative loop

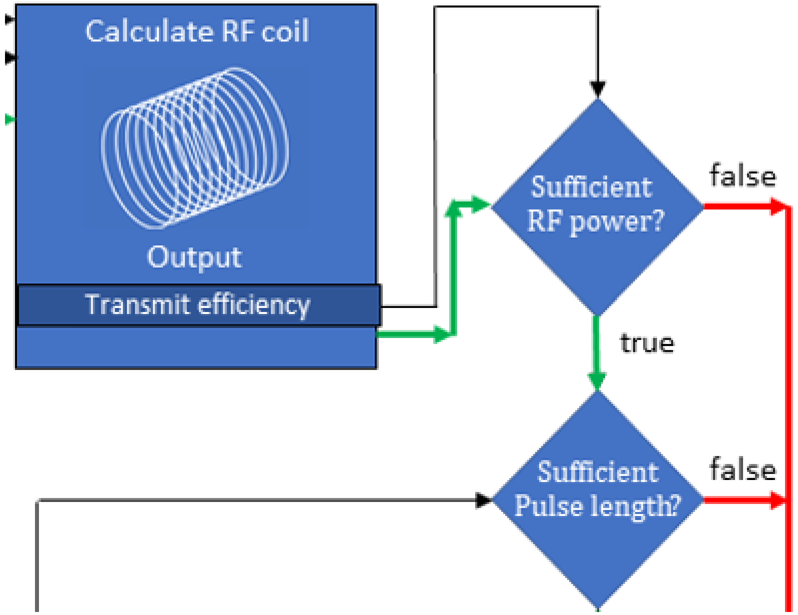
FOV 200 x 200 x 200, spatial resolution 3 x 3 x 3
Data matrix: 80 x 66 x 66 assuming 0.5 mm frequency encoding blurring

Magnet: 25 rings, 20 mm ring spacing
Optimization of spacing and diameter gives 4329 ppm
Gradient coils: optimization gives an X-gradient with efficiency 0.24 mT/m/A. Maximum 30 Amps gives an effective spatial resolution of ~10 mm.

Magnet: add one ring to increase B_0 homogeneity
Optimization of spacing and diameter gives 1075 ppm
Gradient length increases, 0.26 mT/m/A, resolution ~4.1 mm

Magnet: add one ring to increase B0 homogeneity
Optimization of spacing and diameter gives 381 ppm
Gradient length increases, resolution ~2.6 mm

Magnet: increase target B0 in 1 mT steps
Change length and diameter, while
Maintaining target resolution



Check that the RF side is adequate

Solenoid: 240 x 240 x 240 mm
B_1 uniformity > 20%
Transmit efficiency 26 microTesla per √Watt input power

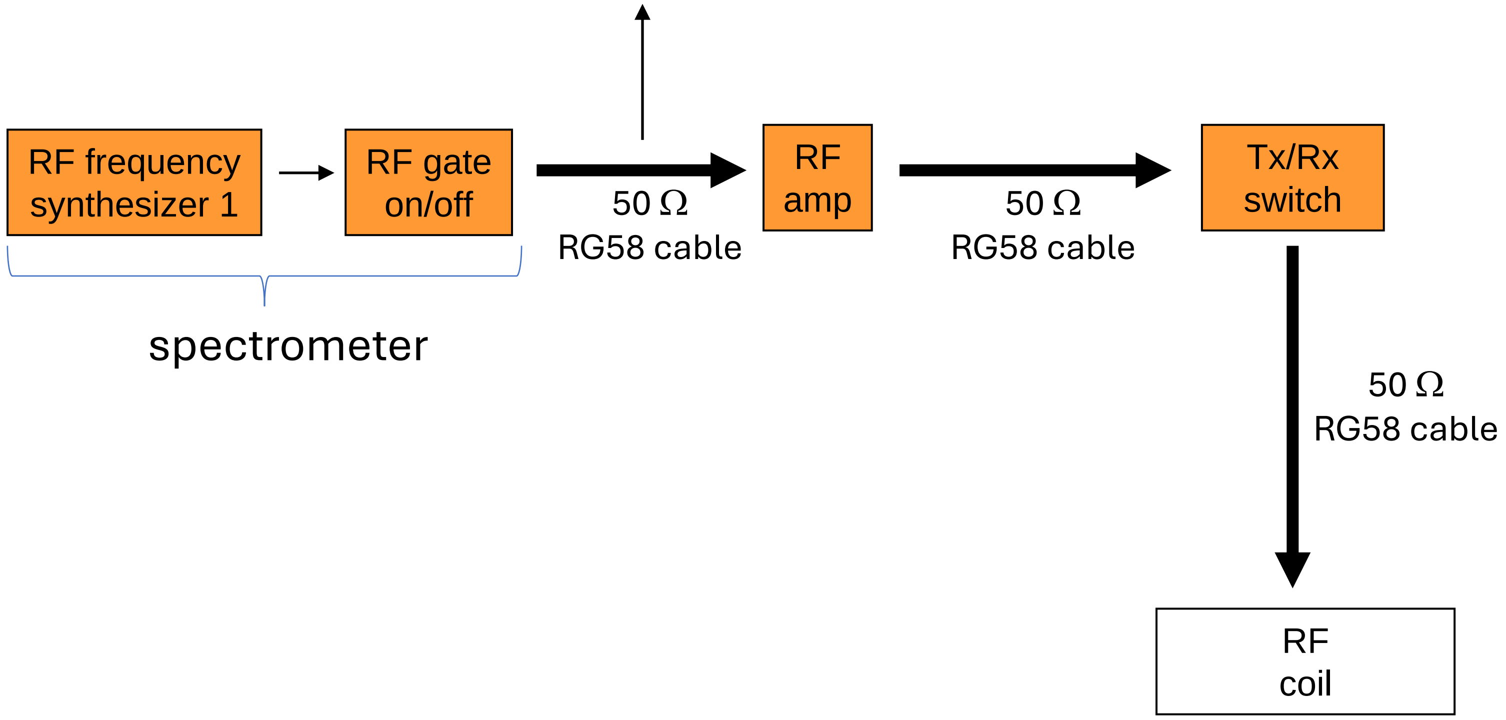
1 milleWatt maximum output power of spectrometer
RF amplifier gain 54 dB
Maximum flip angle 180°
Pulse duration 50 microseconds

Maximum output power is 9 Watts
RF pulse excites bandwidth of ~20 kHz which is greater than ΔB_0

Part 2. Integrating individual components of the system

RF amplifier

What is maximum input to RF amplifier?
What is the maximum duty cycle/pulse length the amplifier can deal with?
What is the shortest pulse that it can amplify?
What is the dynamic range of the amplifier (soft pulses)?
How much reflected power can it take?



Assume that we have an RF coil
that is impedance matched at ~50 Ohms

Characterizing the RF amplifier performance

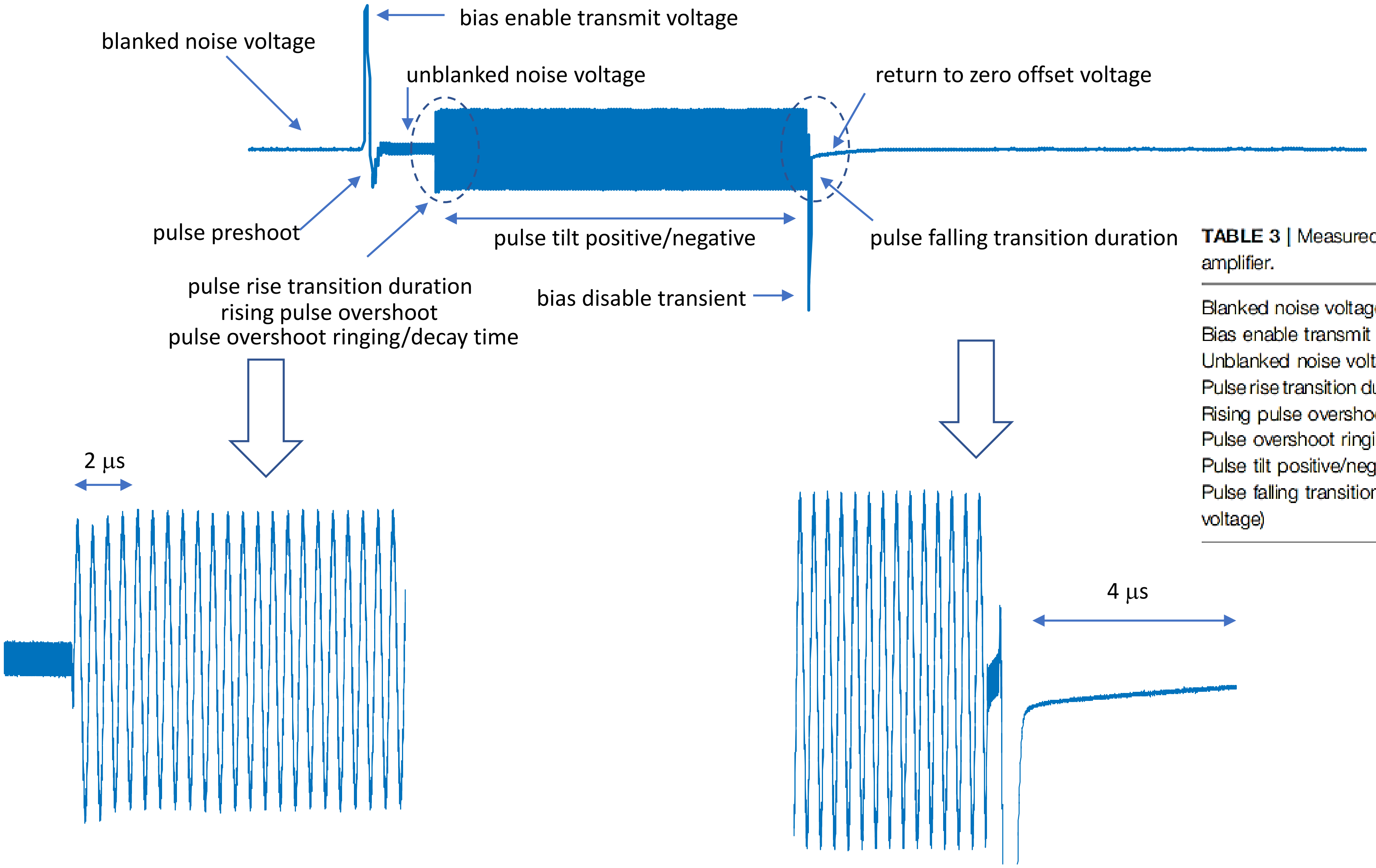
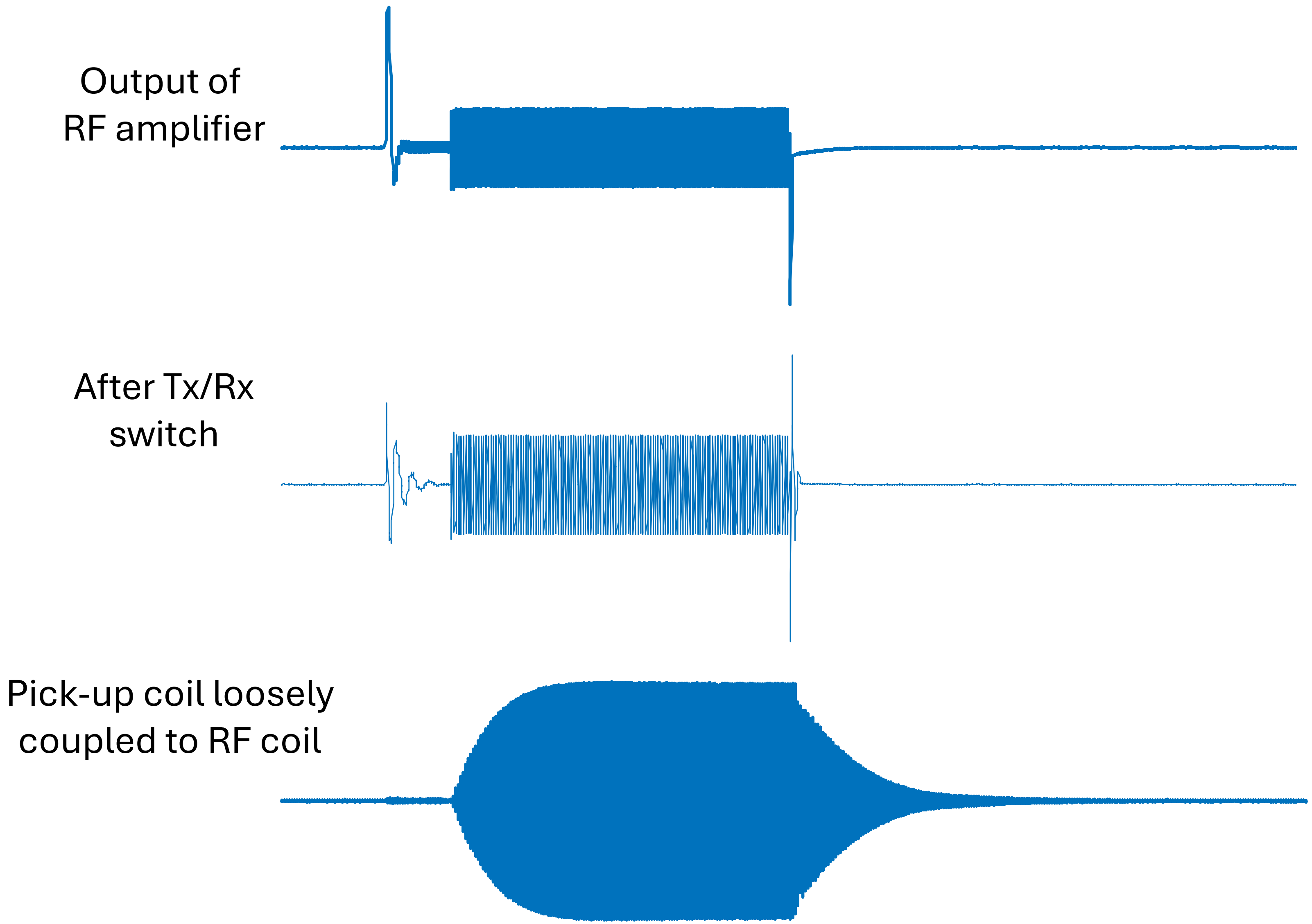


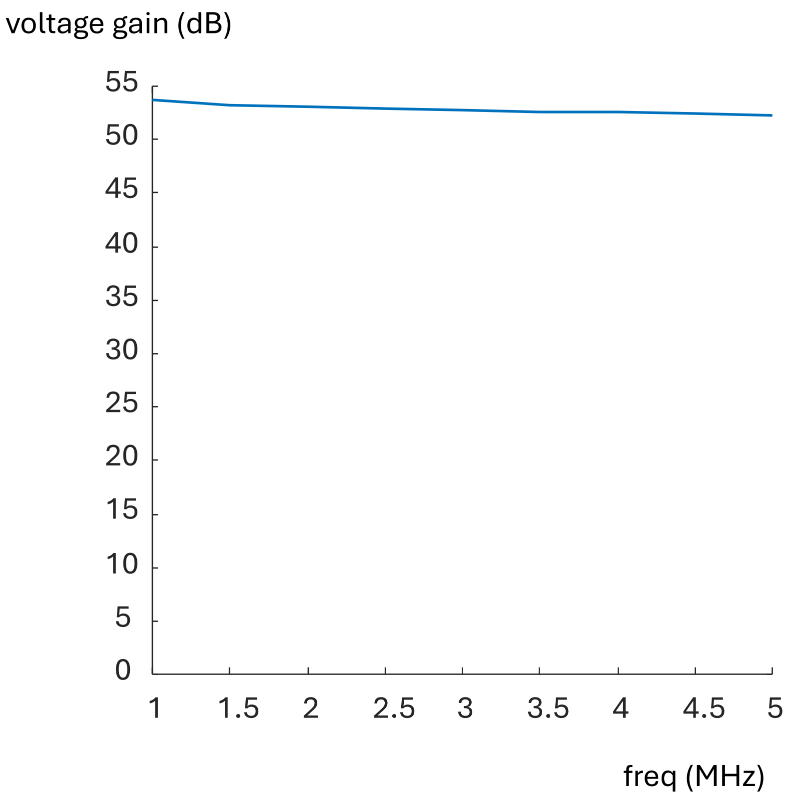
TABLE 3 | Measured pulse characteristics at 2.15 MHz at the output of the RF amplifier.

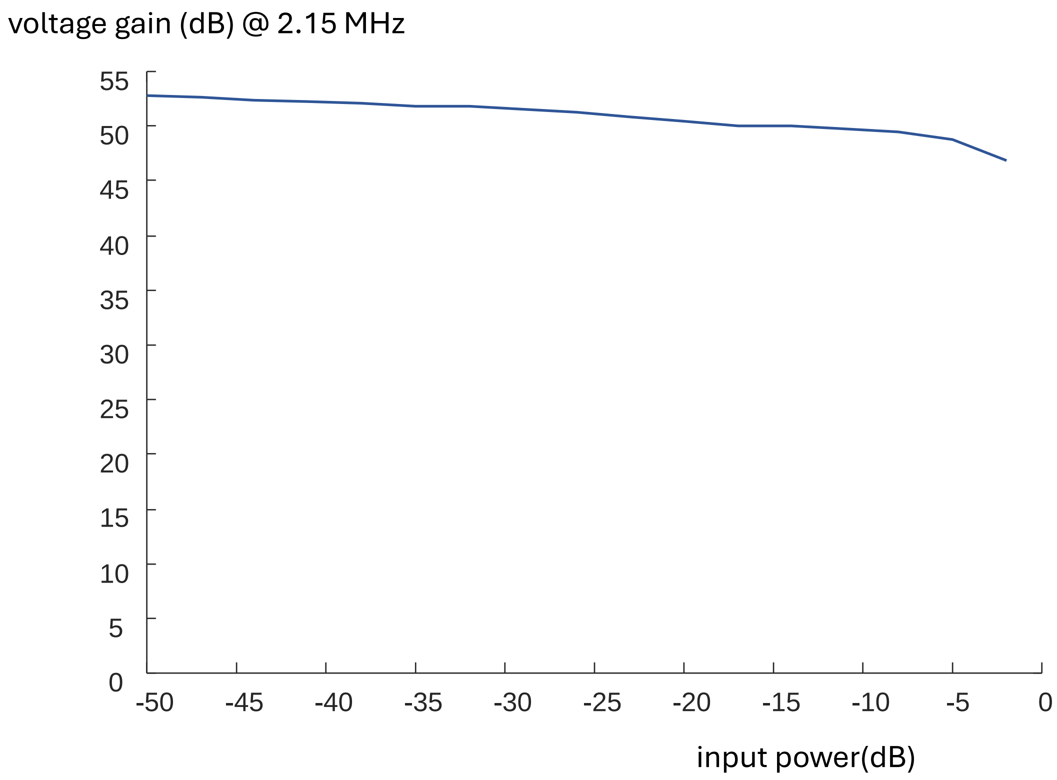
Blanked noise voltage	0.0066 ± 0.0021 V
Bias enable transmit voltage	1.84 V
Unblanked noise voltage	0.0096 ± 0.004 V
Pulse rise transition duration (10–90% of peak output voltage)	<1 μs
Rising pulse overshoot	<1%
Pulse overshoot ringing/decay time	<1 μs
Pulse tilt positive/negative	<1%
Pulse falling transition duration (90–10% of peak output voltage)	<1 μs

Characterizing the RF amplifier performance



Characterizing the RF amplifier performance





Looking inside the RF amplifier

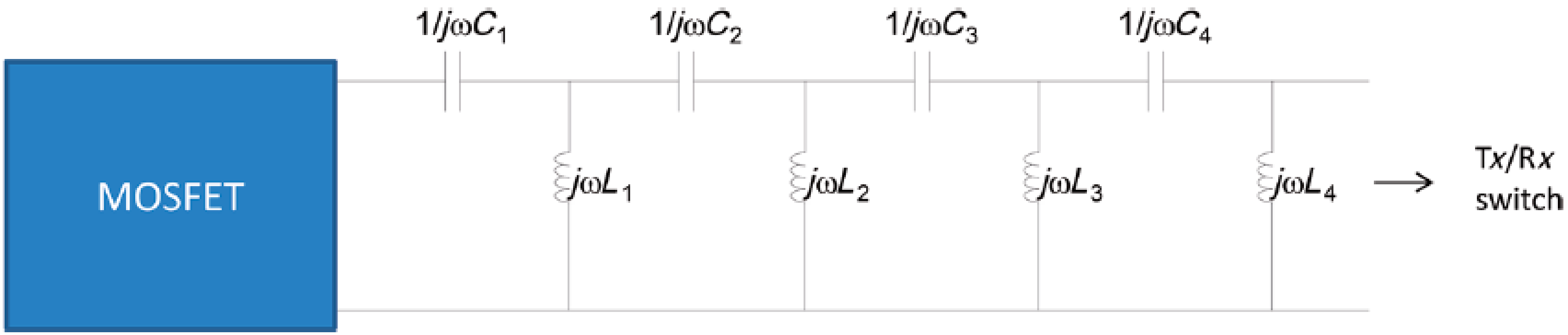
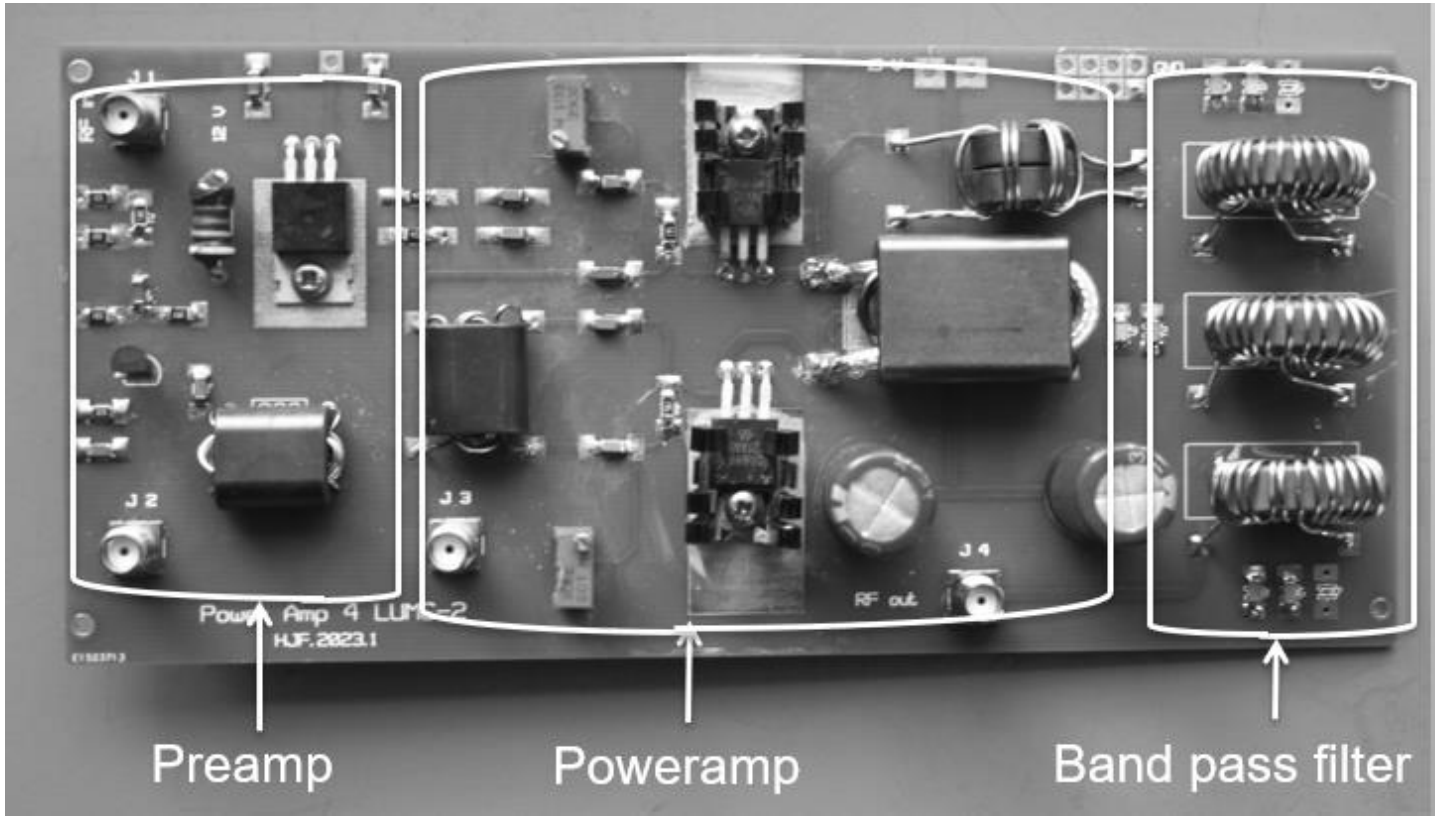
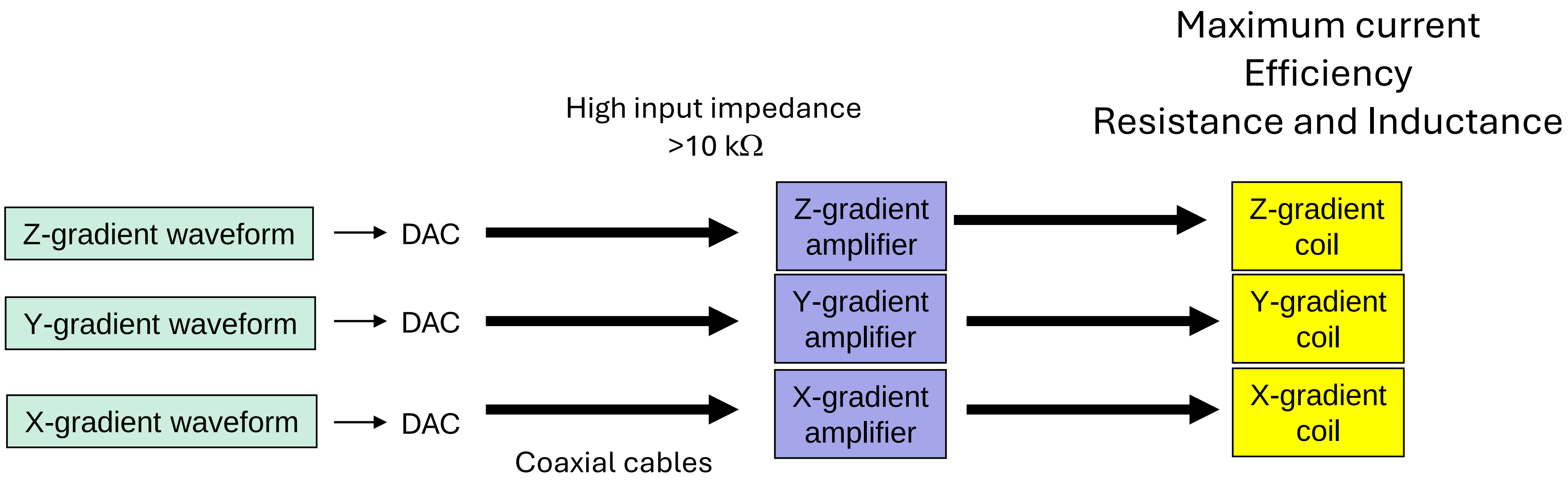


Figure 6.17 Schematic of a broadband matching network.

Design of a simple ~10 Watt output amplifier



Gradient amplifier


Maximum current
Efficiency
Resistance and Inductance
High input impedance
>10 kΩ
Z-gradient waveform
DAC
Z-gradient amplifier
Z-gradient coil
Y-gradient waveform
DAC
Y-gradient amplifier
Y-gradient coil
X-gradient waveform
DAC
X-gradient amplifier
X-gradient coil
Coaxial cables

Simple gradient coil characteristics

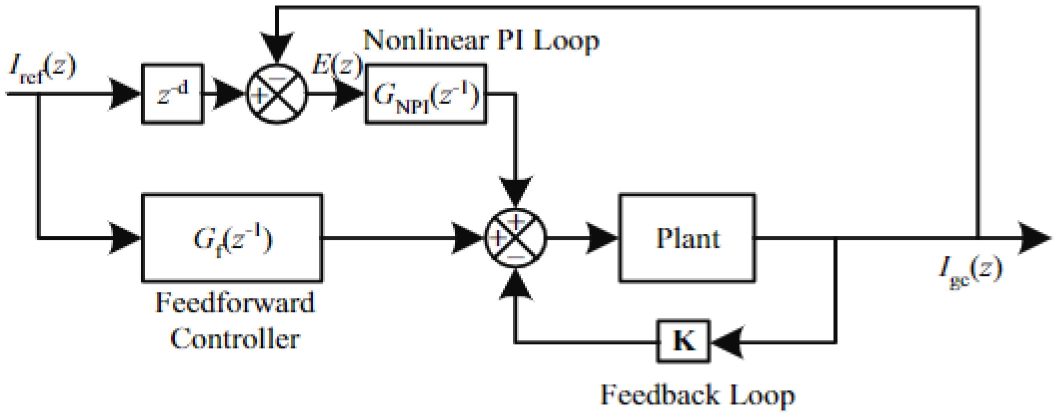
Gradient coil has a resistance, inductance (L), capacitance C from the different turns, frequency dependent inductive reactance (ωL), and frequency dependent capacitive reactance ($1/\omega C$)

So there is a resonant frequency (or several resonant frequencies) from the gradient coils which we have To be aware of since they typically occur in the ~MHz range, good shielding between gradients and RF is required Otherwise they will couple together VERY strongly.

The impedance of the gradient coils is frequency dependent, so their characteristics depend on whether the gradient is being turned on (high frequency components) or is in steady-state (very low frequency)

Typical numbers: inductance 200 microhenries, resistance 0.4 Ohms.
At 1 kHz, ωL=1.2 Ohms, at 10 kHz ωL=12 Ohms. So complex impedance is 0.4+j1.2 or 0.4+j12

Feedforward and feedback controller for “correcting” the gradient waveform



When running a constant-current control loop that drives a voltage across an inductive load, the load's impedance directly affects the control loop response and stability, and so to be able to make the amplifier work well with a variety of gradient coils (a range of both load inductances and resistances), the control loop values need to be adjusted.

Technical Data Draft

Gradient Amplifier GA-30-15

Part–No. 410000

Output Channels	1
Output Current	± 30 A peak / ± 20 A average
Output Voltage	± 15 V
Load Impedance	0.1 – 4.8 Ohms 0 – 20 mHenry
Digital Resolution	16 bit internal DAC / 1 mA steps
Input Voltage for channel 0	± 10 V

barthel
HF-Technik

System specifications

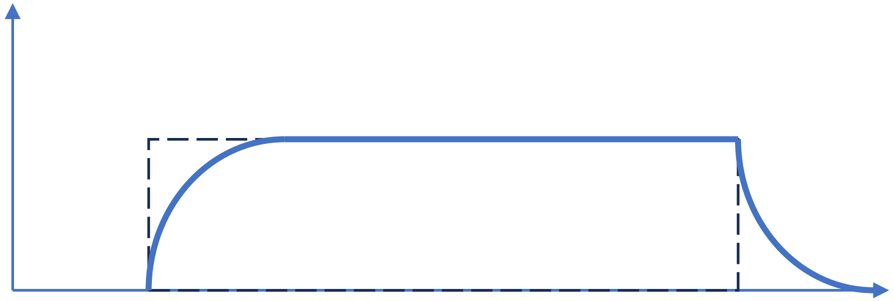
Supply voltage	100 – 400 Vdc
Input current max	30 A
Load inductance	30 uH – 5 mH
Load resistance	0 Ω - 1 Ω
Environmental requirements:	
Ambient temperature	10 °C to 40 °C
Ambient humidity	30 to 75 % non-condensing
Transport temperature	-25 °C to +60 °C
Cooling	Air cooling (front in, rear out)

IECO

3-Axis MRI Gradient Amplifier

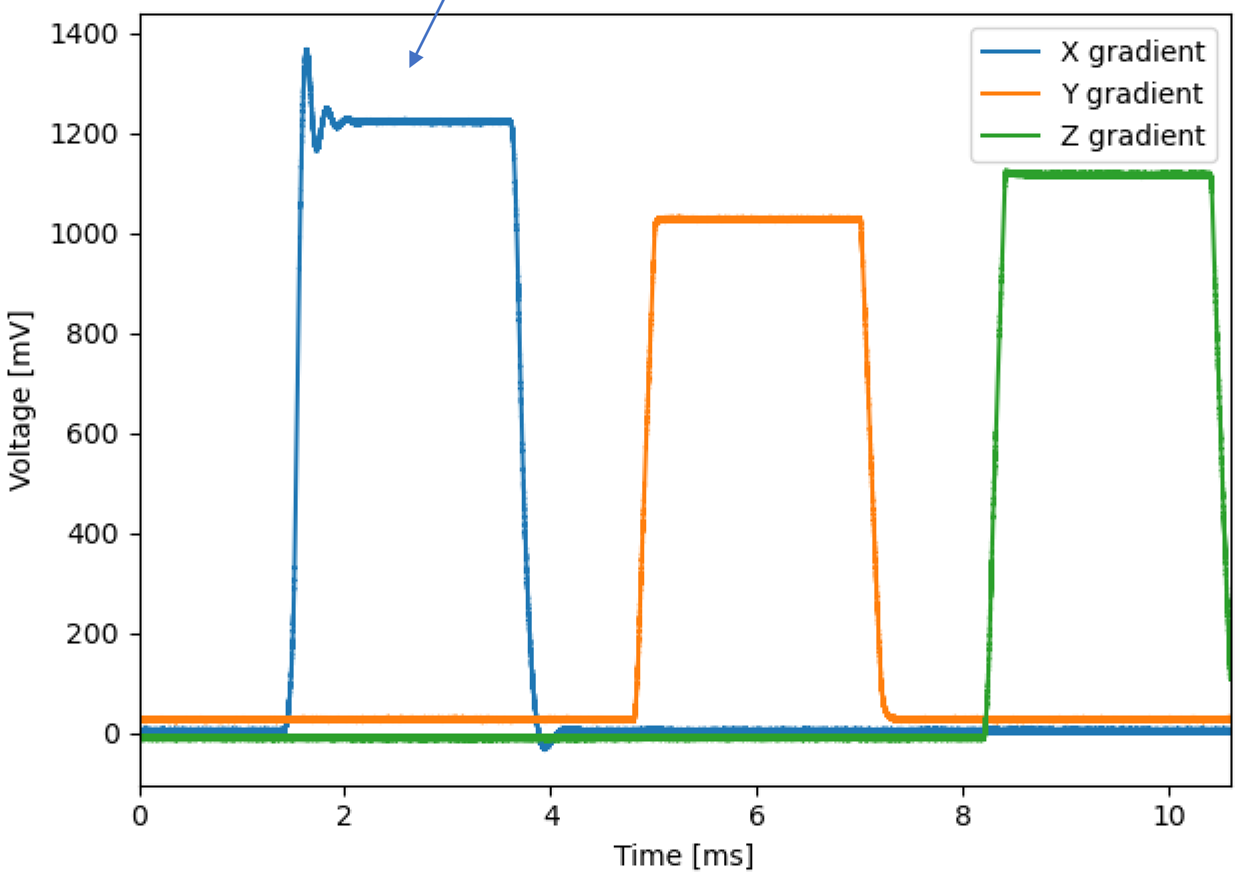
175A 350V

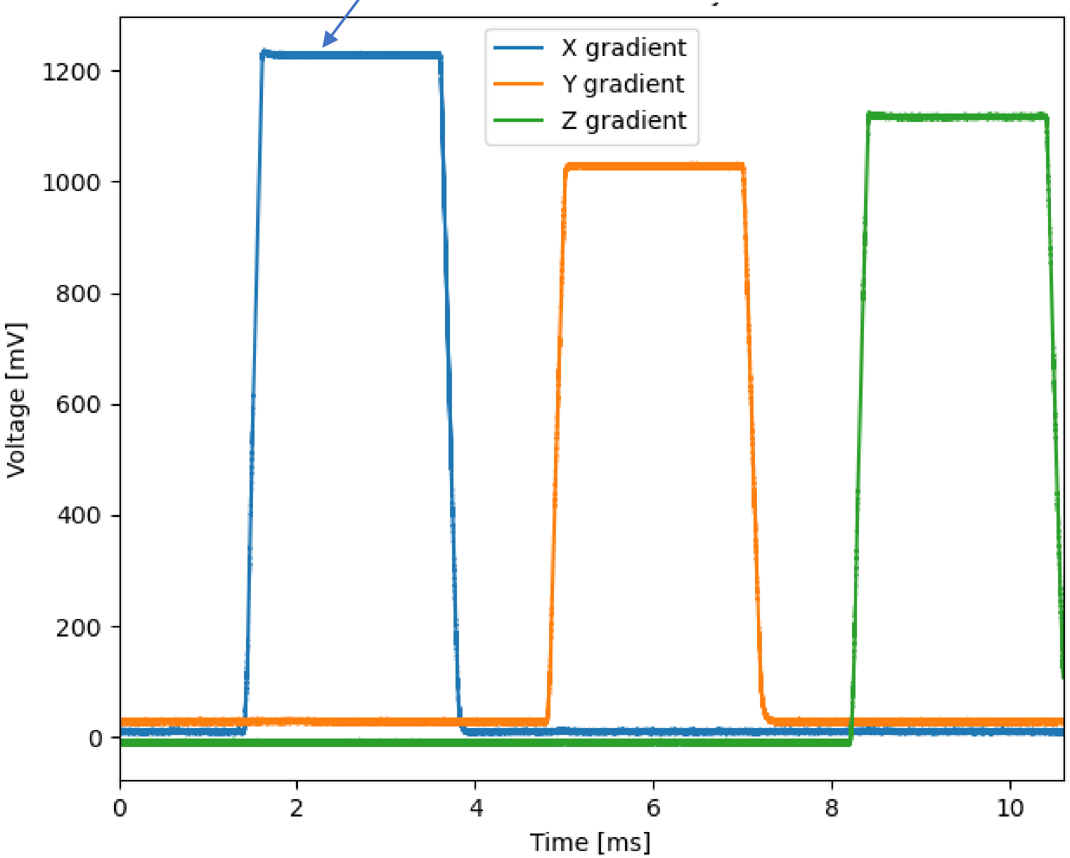
Rise time of the gradient coils for a step input function is given by L/R



Match the DC resistance of gradient coil to designed load resistance of the amplifier achieves maximum continuous gradient.

Reducing the impedance of the gradient coil decreases the rise time, but reduces peak gradient


underdamped
response
1400
1200
1000
800
600
400
200
0
Voltage [mV]
0
2
4
6
8
10
Time [ms]
X gradient
Y gradient
Z gradient


corrected
1200
1000
800
600
400
200
0
Voltage [mV]
0
2
4
6
8
10
Time [ms]
X gradient
Y gradient
Z gradient

Illustrative examples of passive “impedance matching” for a Bruker amplifier

Table 7.1. Micro5 Probe and Gradient Specifications

Gradients	XYZ
Gradient strength	4.8 G/cm/A
ID/OD	19/40 mm
Linearity +-1.3% peak-peak +- 1.6% peak-peak +- 2.1% peak-peak	 18 mm sphere 19 mm sphere 20 mm sphere
Inductance	10 - 20 µH
Resistance	=< 120 mΩ
Rise time, 0-40A, 120V	< 50 µs
Cooling	air or water
Maximum current tested	40 A

Table 7.4. Micro2.5 probe and gradient specifications

Gradients	XYZ
Gradient strength	2.5 G/cm/A
ID/OD	40/72 mm
Linearity +-1.8% peak-peak +- 2.2% peak-peak +- 3.0% peak-peak	 36 mm sphere 38 mm sphere 40 mm sphere
Inductance	=< 100 µH
Resistance	=< 400 mΩ
Rise time, 0-40A, 120V	< 110 µs
Cooling	air or water
Maximum current tested	40 A

Table 7.8. Mini05 Probe and Gradient Specifications

gradients	XYZ
gradient strength	0.5 G/cm/A
ID/OD	57/72 mm
linearity +-2% peak-peak, Z / XY +- 10% peak-peak, Z / XY	 30 / 43 mm 40 / 52 mm
inductance	=< 70 µH
resistance	=< 1.6 Ω
rise time, 0-40A, 120V	< 150 µs
cooling	water
maximum current tested	50 A

Table 7.2. B-AFPA-40 Dip Switch Setting

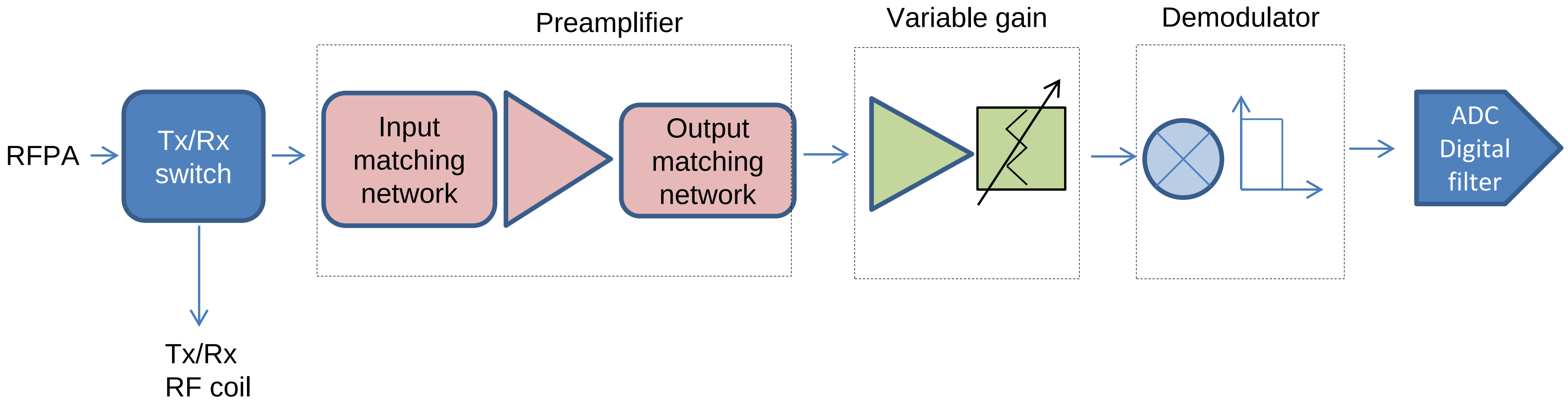
Gradient system	Gradient	C Dip Switch	R Dip Switch	C	R
Micro5	X	0000 1000	0001 0000	1.5 nF	20 kΩ
Micro5	Y	0000 0100	0001 0000	1.0 nF	20 kΩ
Micro5	Z	0000 1000	0000 1000	1.5 nF	15 kΩ

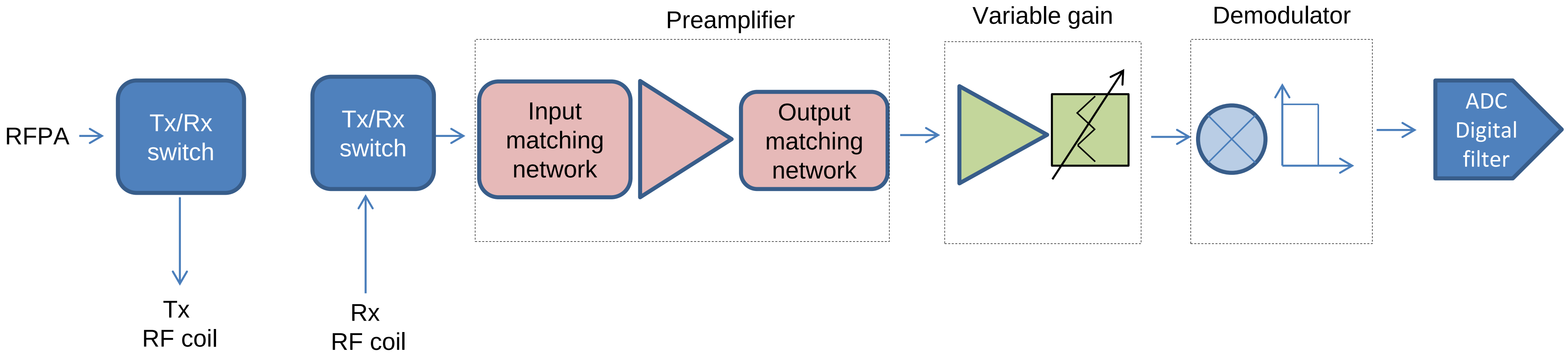
Gradient system	Gradient	C Dip Switch	R Dip Switch	C	R
Micro2.5	X	00001100	00010000	2.5 nF	20 kΩ
Micro2.5	Y	00001100	00010000	2.5 nF	20 kΩ
Micro2.5	Z	00001100	00010000	2.5 nF	20 kΩ

Table 7.9. B-AFPA-40 Dip Switch Setting

Gradient system	Gradient	C Dip Switch	R Dip Switch	C	R
Mini0.5	X	0001 1100	0000 1000	4.7 nF	15 kΩ
Mini0.5	Y	0001 0000	0000 1000	2.2 nF	15 kΩ
Mini0.5	Z	0001 0000	0001 0000	2.2 nF	20 kΩ

Receiver

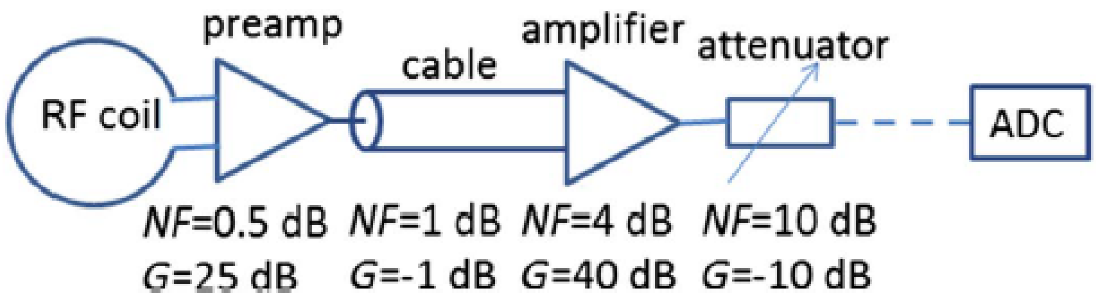

RFPA
Tx/Rx switch
Tx/Rx RF coil
Preamplifier
Input matching network
Output matching network
Variable gain
Demodulator
ADC Digital filter


RFPA
Tx/Rx switch
Tx RF coil
Tx/Rx switch
Rx RF coil
Preamplifier
Input matching network
Output matching network
Variable gain
Demodulator
ADC Digital filter

Performance of each element in the receiver chain

$$\mathrm{NF_{total}} = \mathrm{NF_{preamp}} + \frac{(\mathrm{NF_{cable}} - 1)}{G_{\mathrm{preamp}}} + \frac{\mathrm{NF_{amp}}}{G_{\mathrm{preamp}} G_{\mathrm{cable}}} + \frac{\mathrm{NF_{attenator}}}{G_{\mathrm{preamp}} G_{\mathrm{cable}} G_{\mathrm{amp}}} \tag{7.4}$$

Using the numbers in Figure 7.3, the overall NF is 0.51 dB, which is very close to the NF of the first-stage amplifier. Indeed, eqn (7.4) shows that the critical component in terms of the overall NF of the receiver is the first stage,



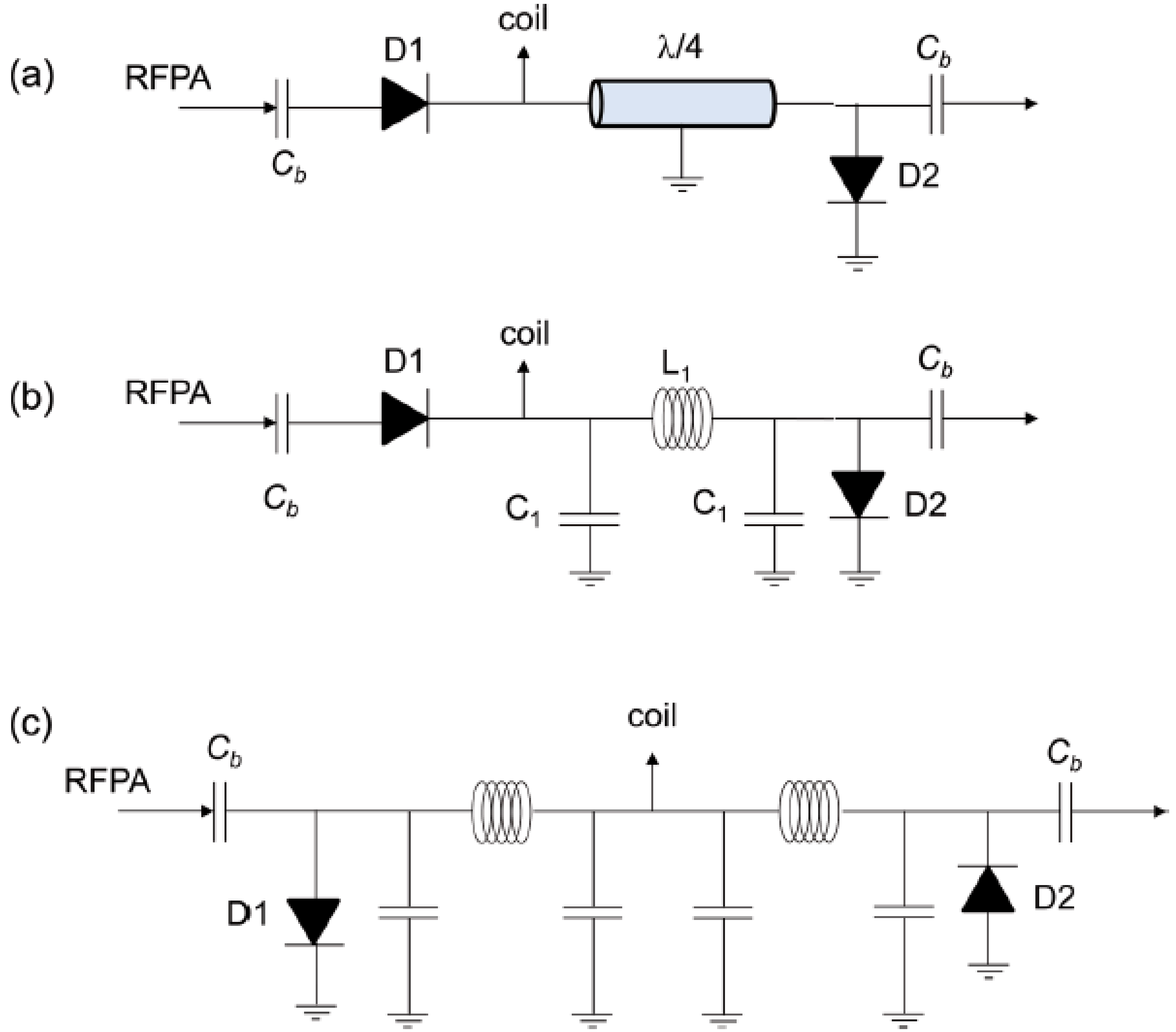
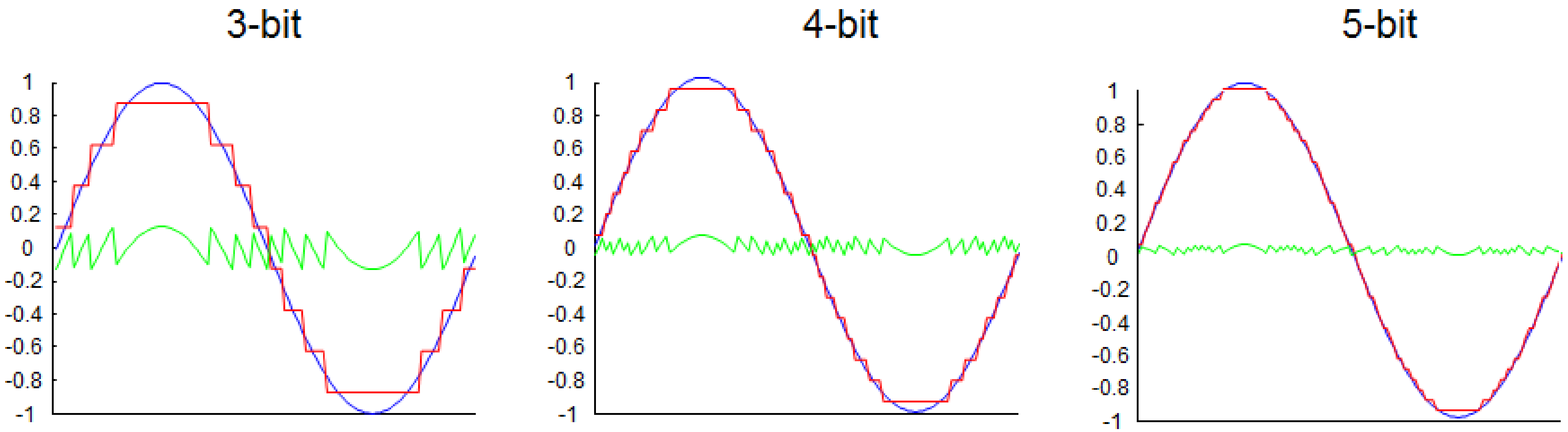
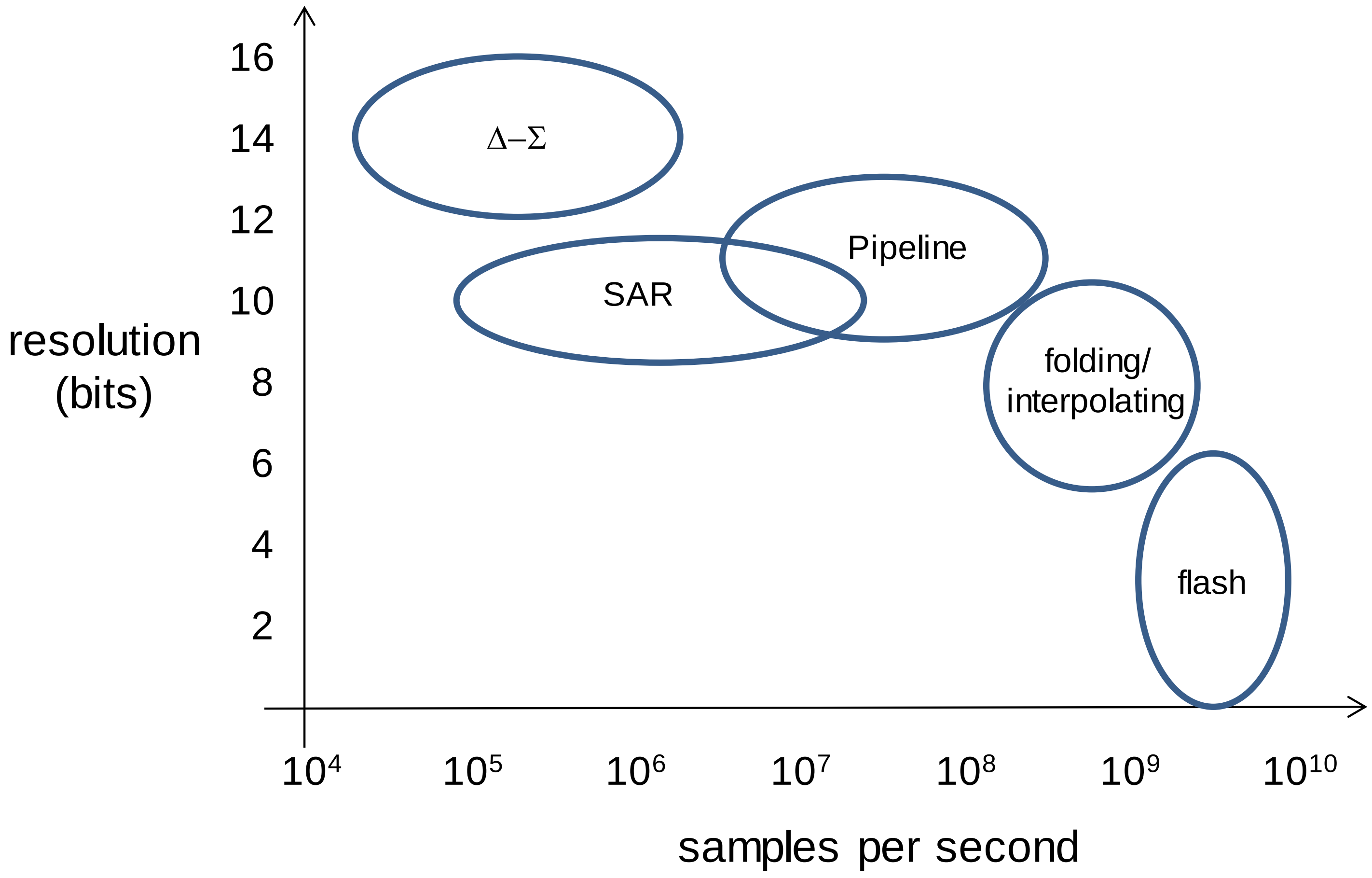


Figure 7.4 Three variations of T/R switch based on a quarter-wavelength transmission line (a) and its lumped element pi-section equivalent (b) and (c). In (c) two pi-sections are used for additional isolation between transmitter and receiver. Capacitors C_b are very high value to provide a DC-block for the diode-driving voltage, and present essentially a short circuit at RF frequencies.

Resolution of analogue-to-digital converters



Analogue-to-digital converters



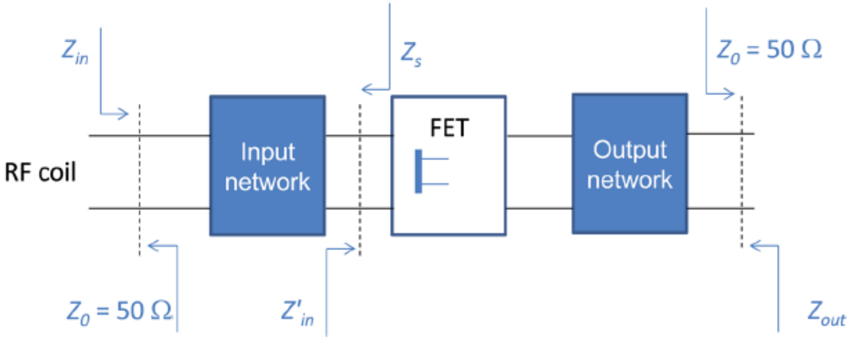
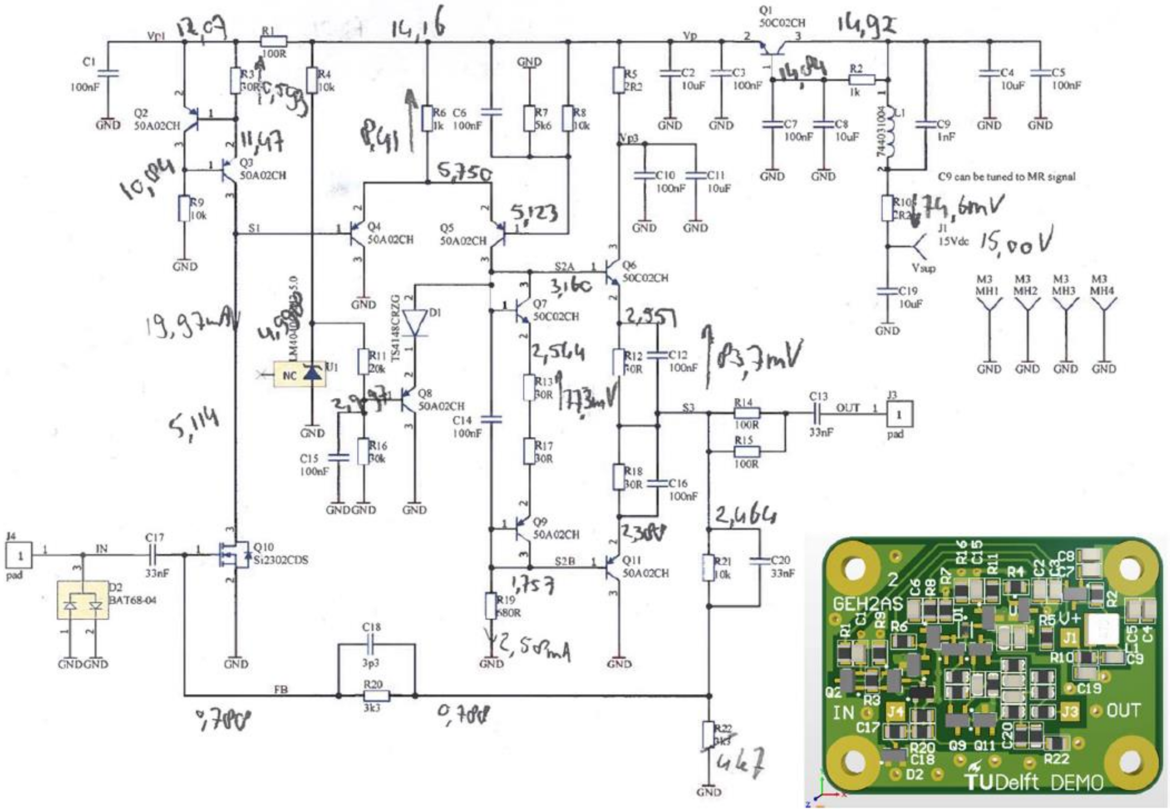


Figure 7.7 Block diagram of a FET-based preamplifier connected on the input side to an RF coil impedance matched to 50 Ω, and on the output side to a 50 Ω cable.



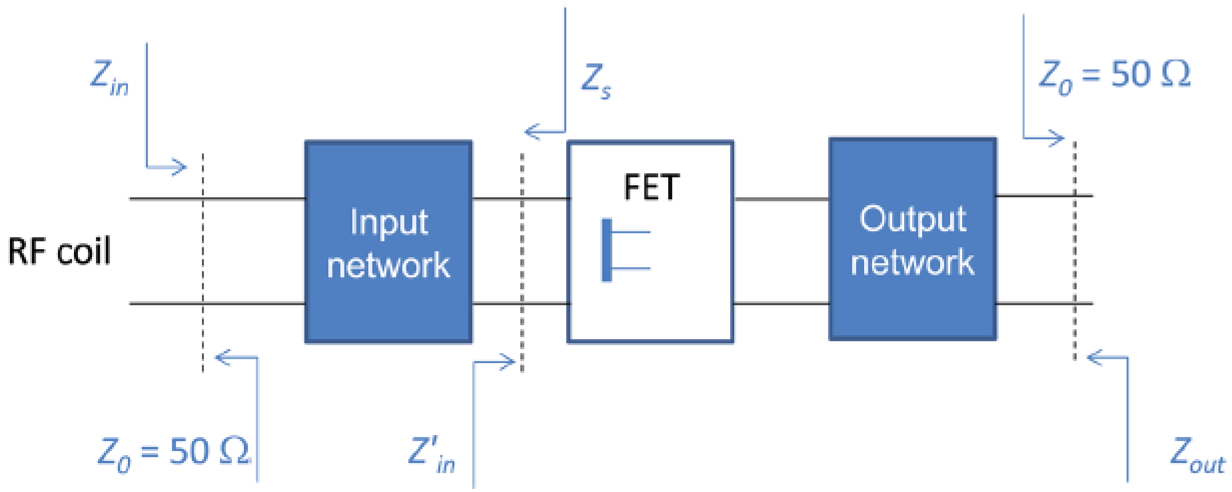
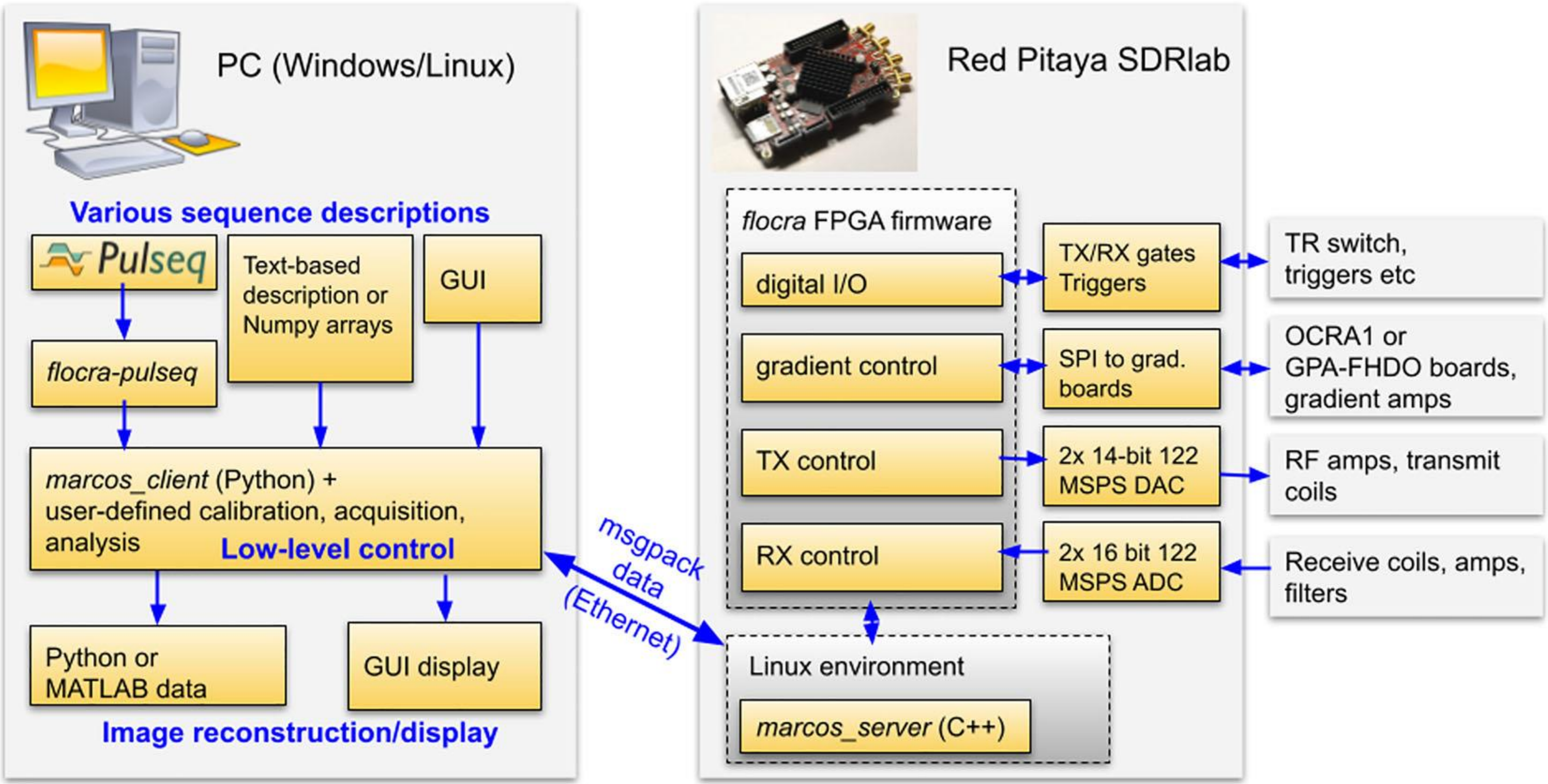


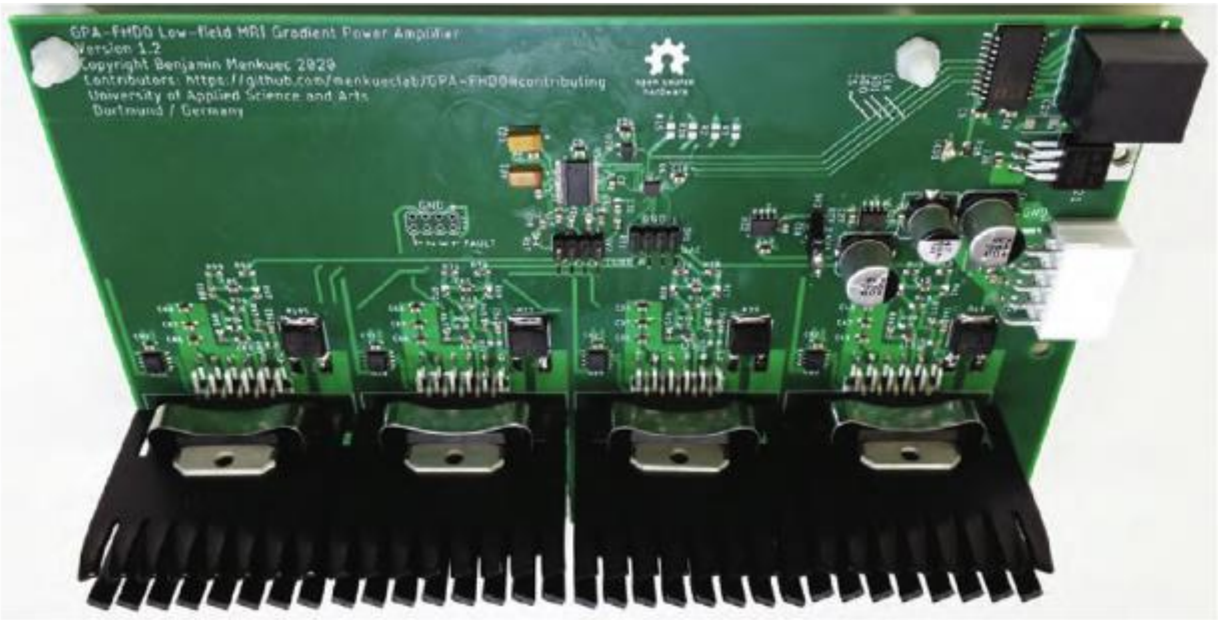
Figure 7.7 Block diagram of a FET-based preamplifier connected on the input side to an RF coil impedance matched to 50 Ω, and on the output side to a 50 Ω cable.

Overall control system which integrates everything together



PC (Windows/Linux)
Various sequence descriptions
Pulseq
Text-based description or Numpy arrays
GUI
flocra-pulseq
marcos_client (Python) + user-defined calibration, acquisition, analysis
Low-level control
Python or MATLAB data
GUI display
Image reconstruction/display
msgpack data (Ethernet)
Red Pitaya SDRlab
flocra FPGA firmware
digital I/O
gradient control
TX control
RX control
TX/RX gates Triggers
SPI to grad. boards
2x 14-bit 122 MSPS DAC
2x 16 bit 122 MSPS ADC
TR switch, triggers etc
OCRA1 or GPA-FHDO boards, gradient amps
RF amps, transmit coils
Receive coils, amps, filters
Linux environment
marcos_server (C++)

Interface with gradient amplifier (optional) and gradient coils



Four channel gradient 16 bit DAC board

Internal power stage which can delivers +/- 10 Amps on each channel

Can also output +/- 12 volts output for external gradient power amplifier

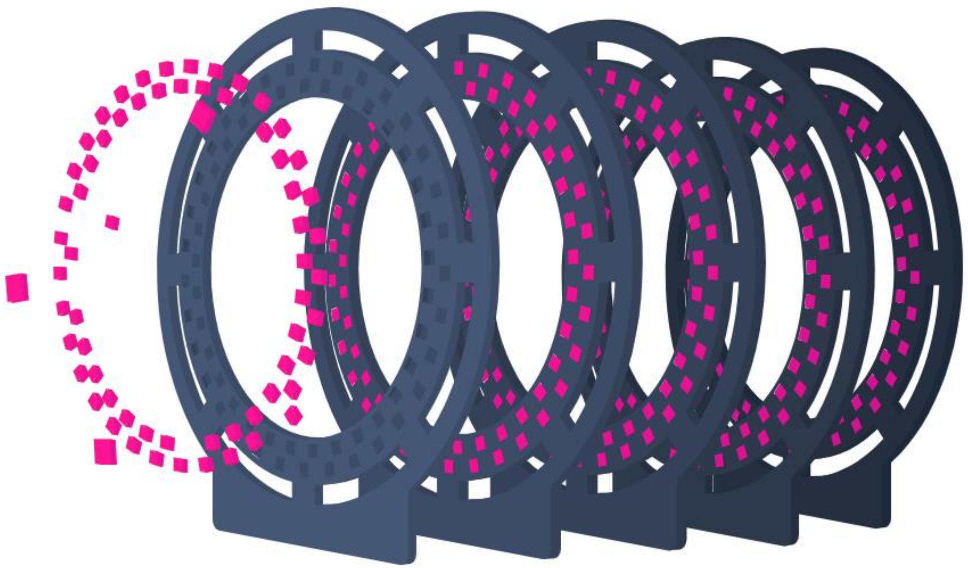
Clock speed 40 MHz – so if all 4 channels are used in parallel, clocks at 100,000 samples per second, so 10 microseconds per sample

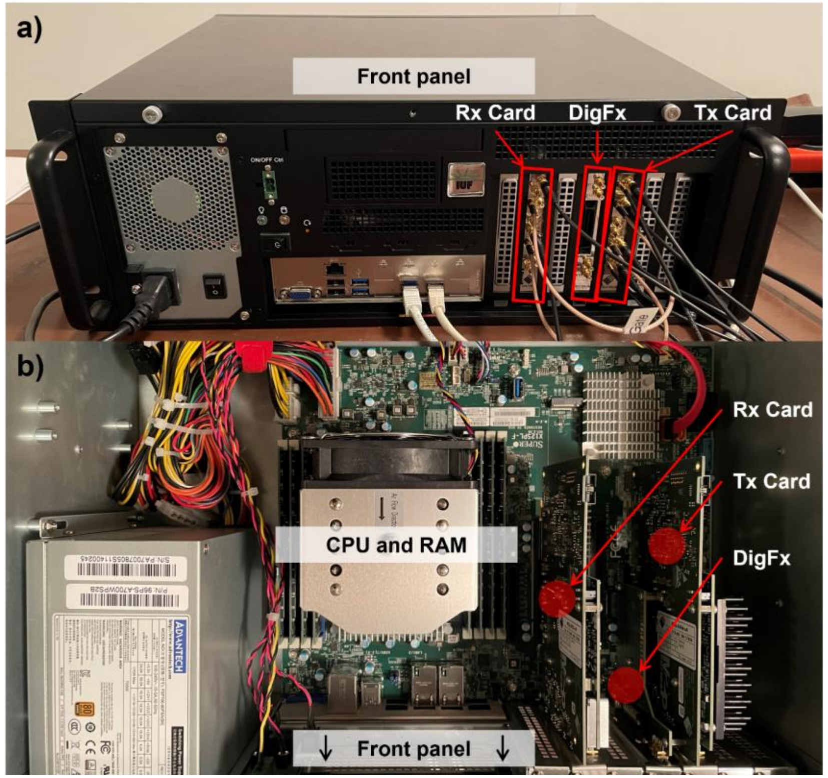
Current is continuously monitored which can be used to calibrate the system.

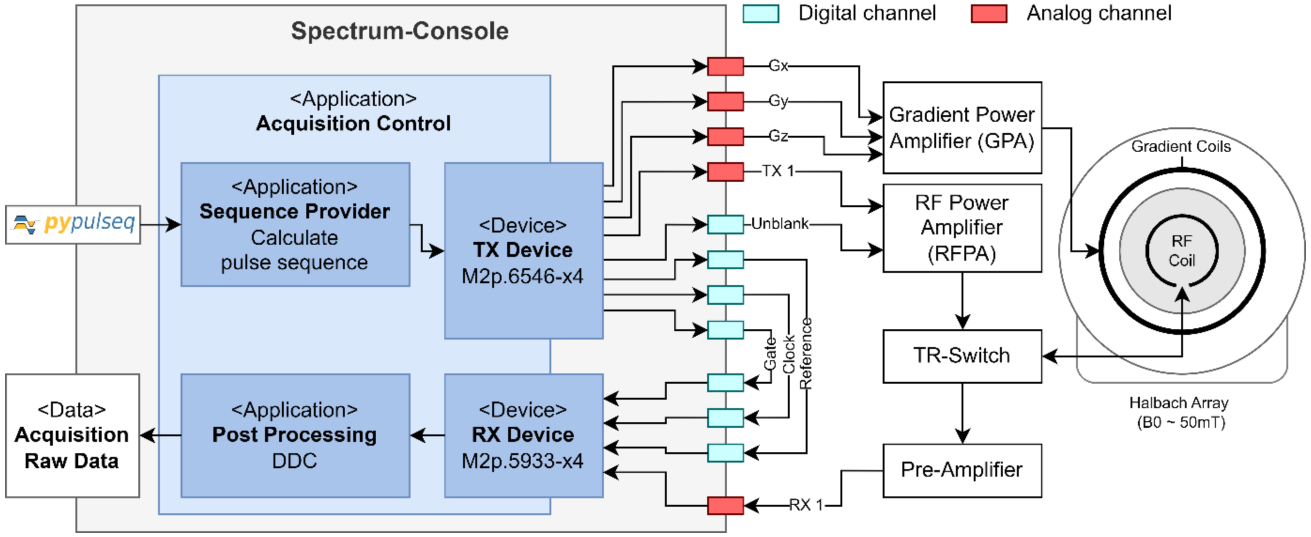
A4IM Overview Work packages News The Consortium

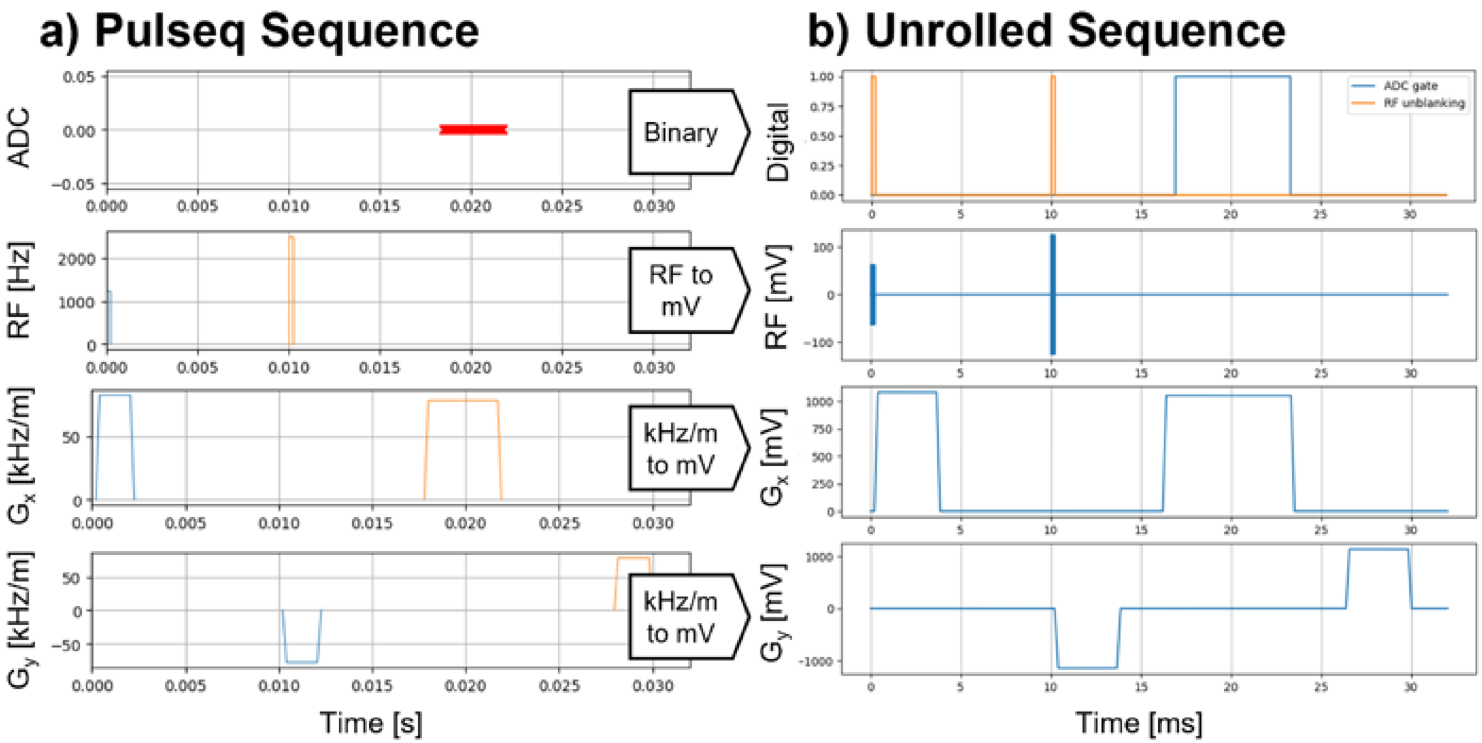
Compact and mobile scanners are changing workflows in radiology, where MRI comes to the patient rather than the patient to the MRI. In this project we will establish the necessary metrological framework for the harmonised development of clinical low-field MRI.

Read more






Spectrum-Console
Digital channel
Analog channel
<Application>
Acquisition Control
pypulseq
<Application>
Sequence Provider
Calculate
pulse sequence
<Device>
TX Device
M2p.6546-x4
<Data>
Acquisition
Raw Data
<Application>
Post Processing
DDC
<Device>
RX Device
M2p.5933-x4
Gx
Gy
Gz
TX 1
Unblank
Gate
Clock
Reference
RX 1
Gradient Power
Amplifier (GPA)
RF Power
Amplifier
(RFPA)
TR-Switch
Pre-Amplifier
Gradient Coils
RF
Coil
Halbach Array
(B0 ~ 50mT)


a) Pulseq Sequence
b) Unrolled Sequence
ADC
RF [Hz]
G_x [kHz/m]
G_y [kHz/m]
Binary
RF to
mV
kHz/m
to mV
kHz/m
to mV
Digital
RF [mV]
G_x [mV]
G_y [mV]
ADC gate
RF unblanking
Time [s]
Time [ms]