magnETHical

Master Thesis: Building a 25 MHz NMR Spectrometer

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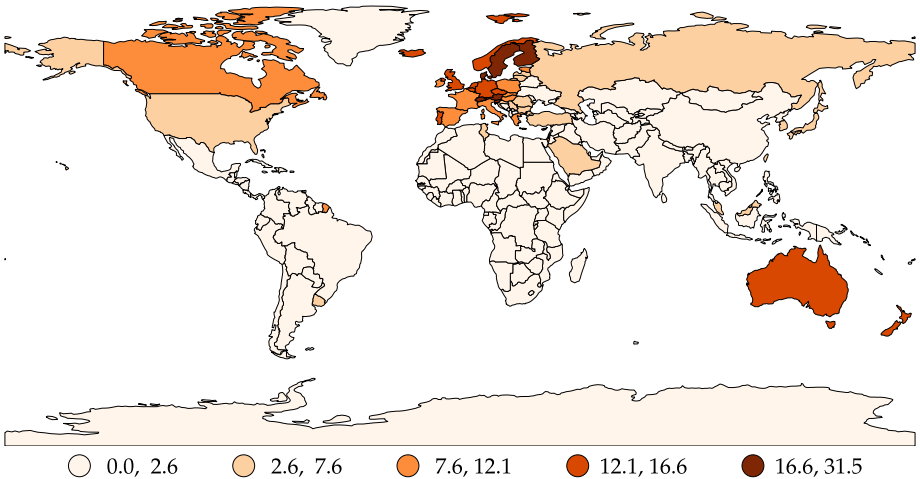
ETH Zürich

“What I cannot create, I do not understand”

—Richard Feynman

There is not a lot of NMR research in the Global South



Nuclear Magnetic Resonance

- Nuclei absorb radio waves at a certain frequency when inside a magnetic field
- The nuclei emit radio waves at that same frequency when excited this way
- $f \sim B_0$ and surroundings

NMR is used across various fields

- Research (Structure Analysis, Drug Discovery, …)
- Medicine (Imaging, Diagnosis, …)
- Industry (Process Control, Drug screening, …)
- Education (Quantum Mechanics, Quantum Computing, …)

Build an accessible NMR spectrometer

Preview

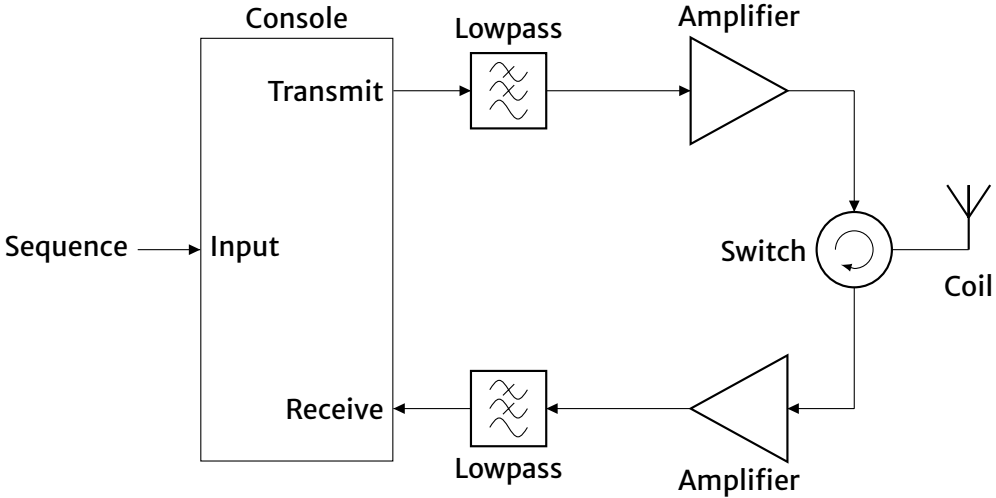
The parts

The complete setup

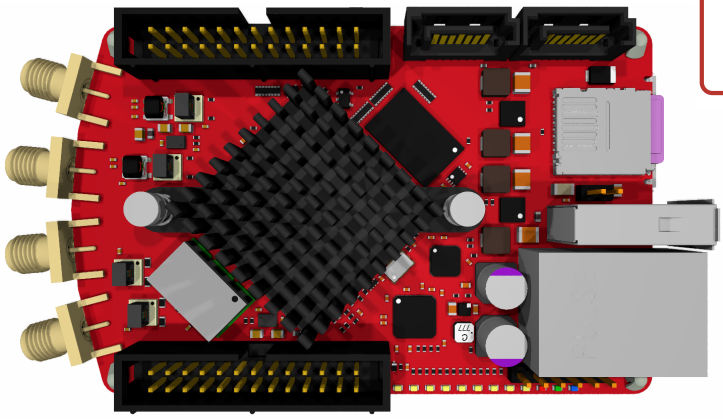
Experimental Results

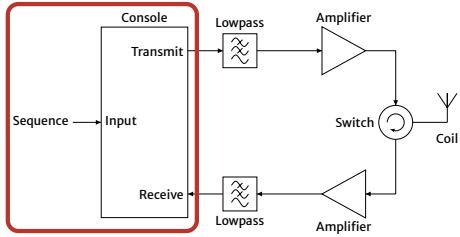
The parts

Our goal is to build an accessible NMR spectrometer



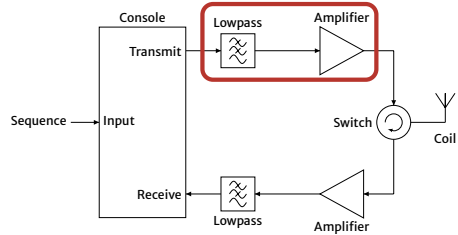
The console is a ready-made FPGA board*

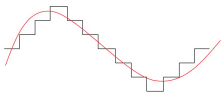


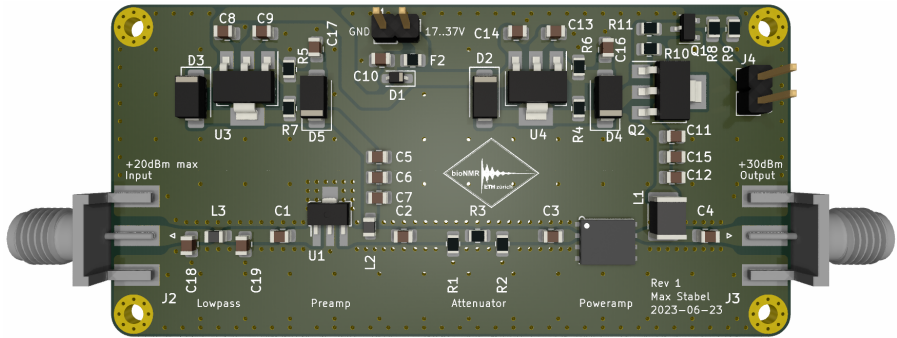


*Red Pitaya SDRlab 122-16

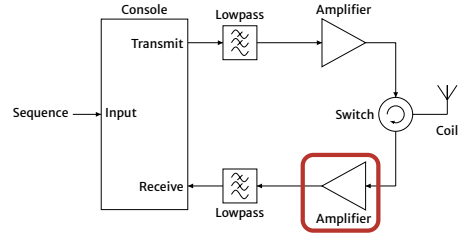
The power amplifier has two stages

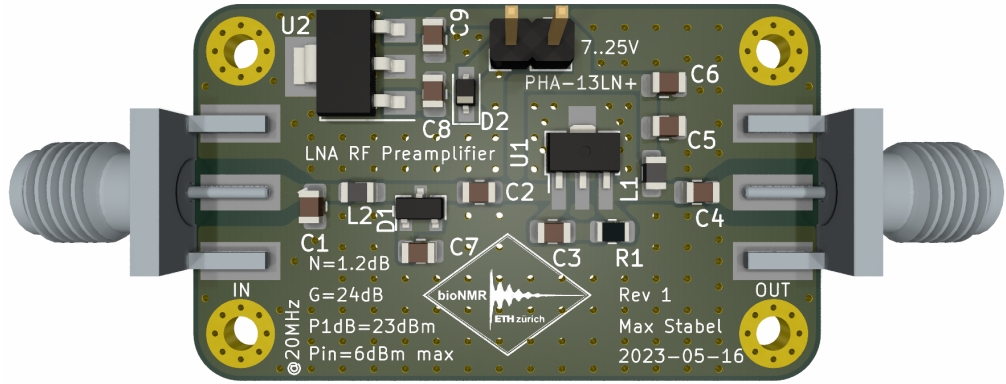




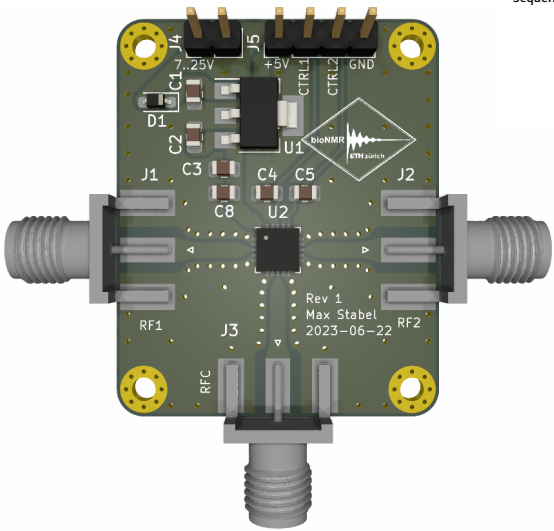


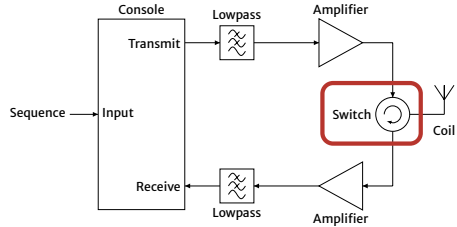
The low-noise amplifier had instability issues



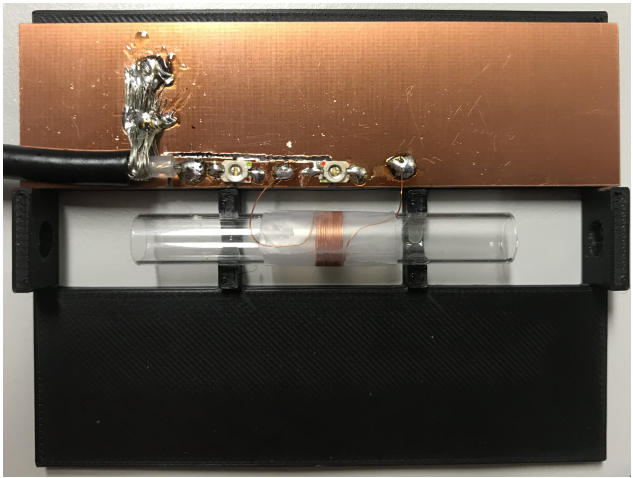


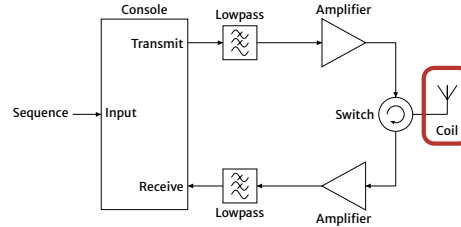
We use a transistor-based active switch



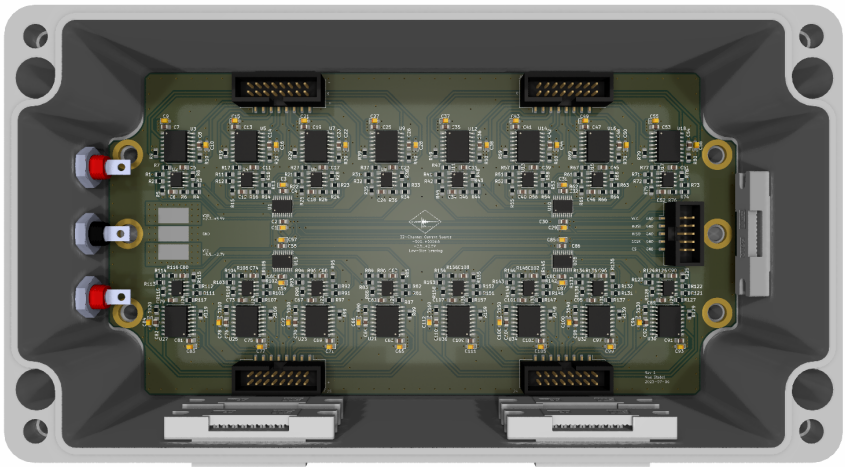


The probe




Console
Lowpass
Amplifier
Transmit
Sequence
Input
Switch
Coil
Receive
Lowpass
Amplifier

A 32-channel current supply is designed but untested



The complete setup

Our NMR is affordable …

	600 MHz†	mini-circuits	*magnETHical*
Power Amplifier	50 000	323.49	36.01
Switch	-	82.06	20.05
Probe	100 000	-	≈15.00
Low-Noise Amplifier	50 000	409.38	73.11
Shim Driver	-	-	257.08
Console	200 000	-	662.53
Magnet	1 000 000	-	≈9000.00
Sum			**10 142.80**

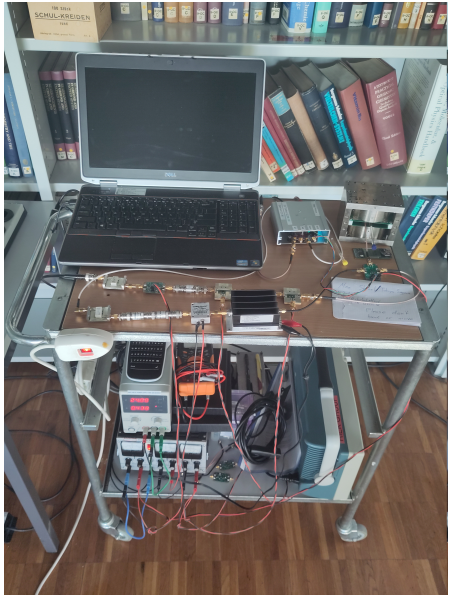
†estimated costs
Prices incl. VAT [CHF]

… competitive …

	Superconducting	Benchtop	*magn**ETH**ical*
Price [k CHF]	200–18 000	50–150	≈10
Frequency [MHz]	300–1200	40–125	25
Resolution [Hz]	≈0.2	0.2–1	≈2.5/50[†]
Weight [kg]	600–15 000	25–150	≈5

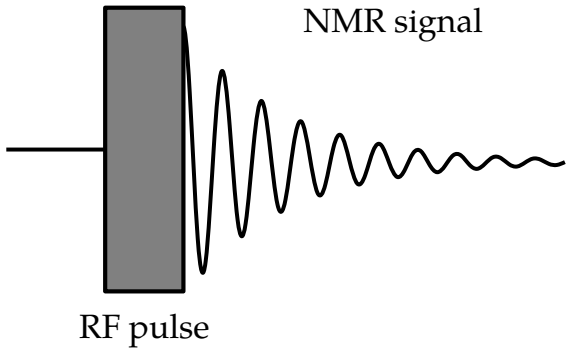
[†]with/without shims
For 5mm standard NMR tubes

… and portable

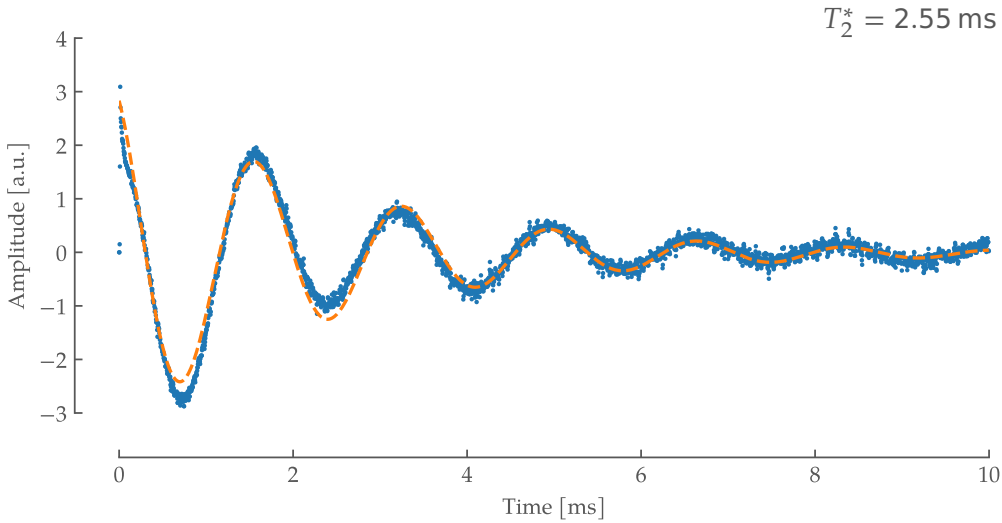


Experimental Results

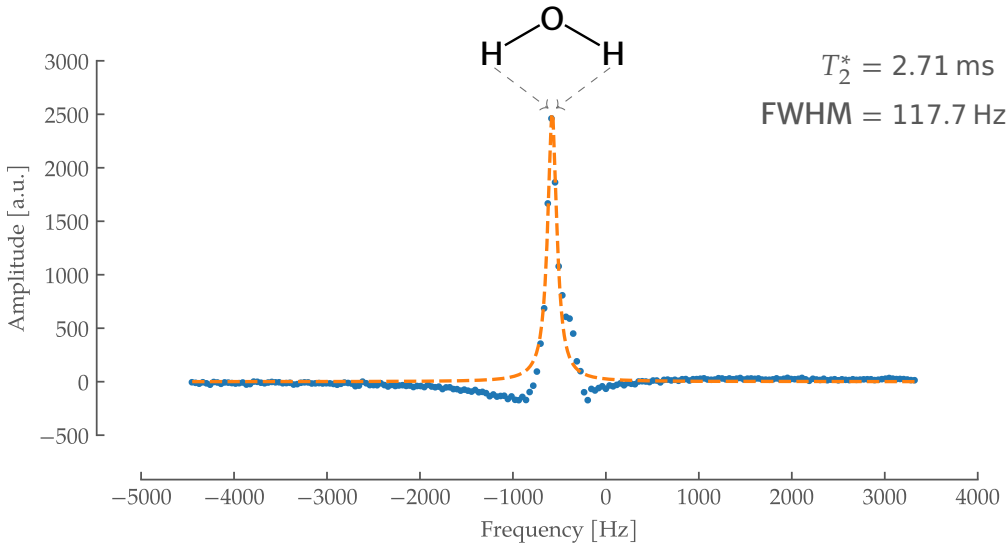
Simple Pulse Sequence



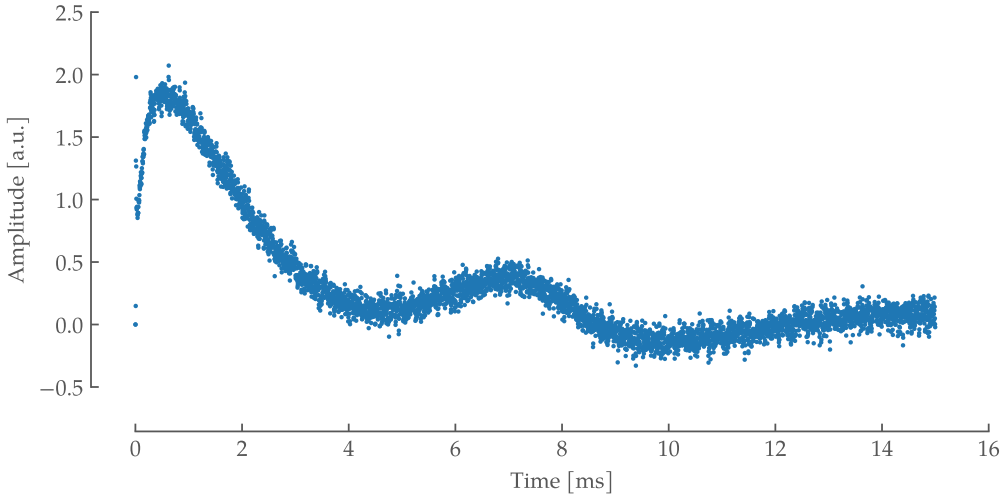
We can already see a water FID



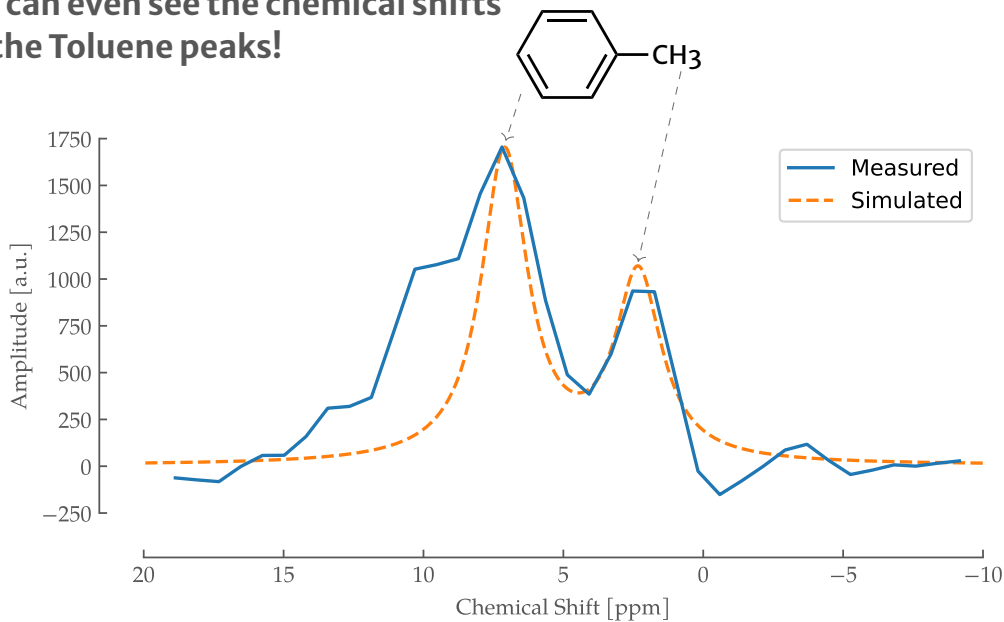
...and do a Fourier transform



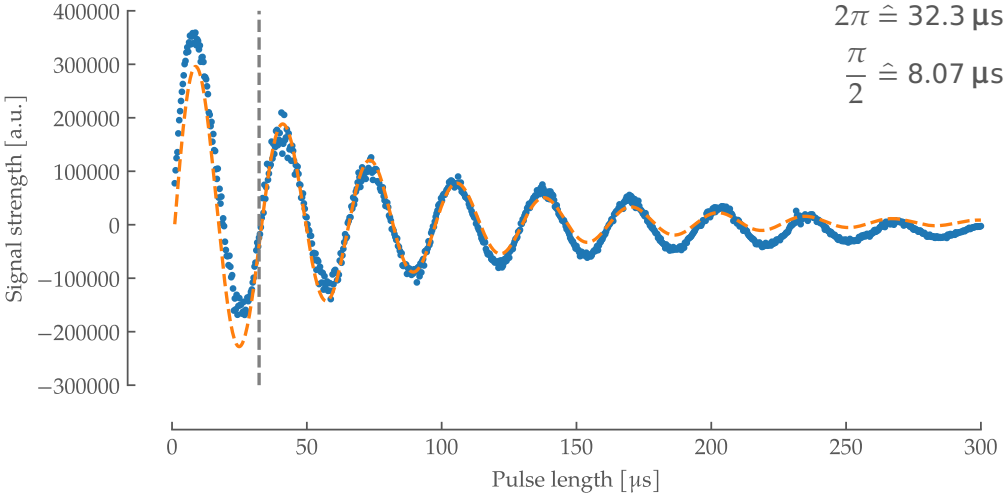
Toluene also has a visible signal



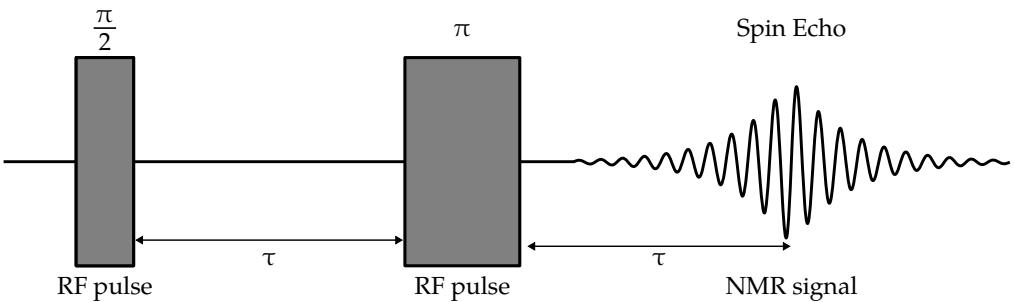
We can even see the chemical shifts of the Toluene peaks!



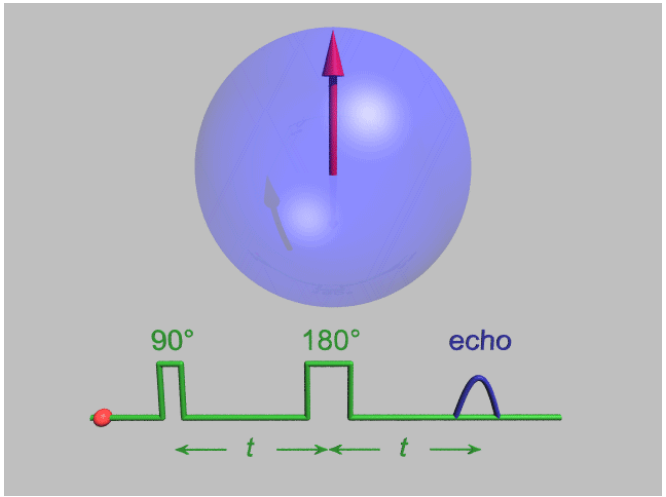
Rabi nutation (pulse calibration) of water



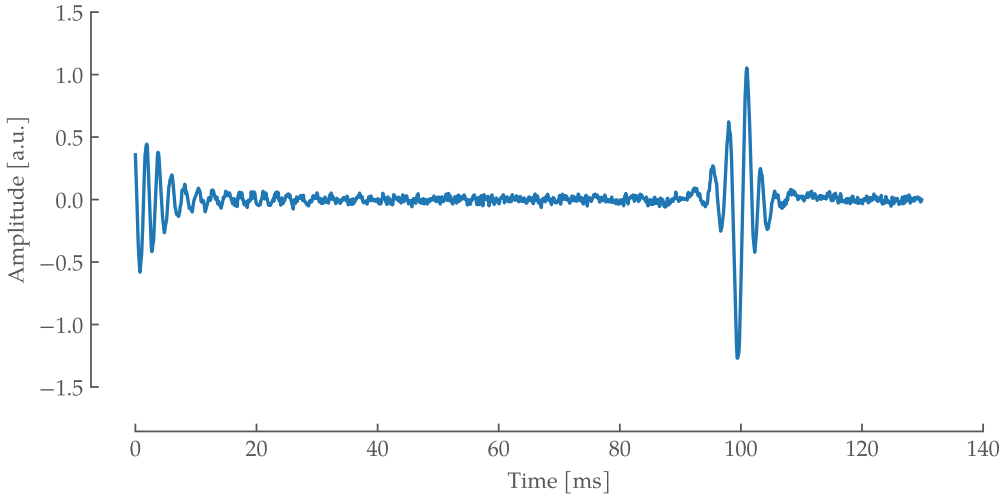
Spin Echo Sequence



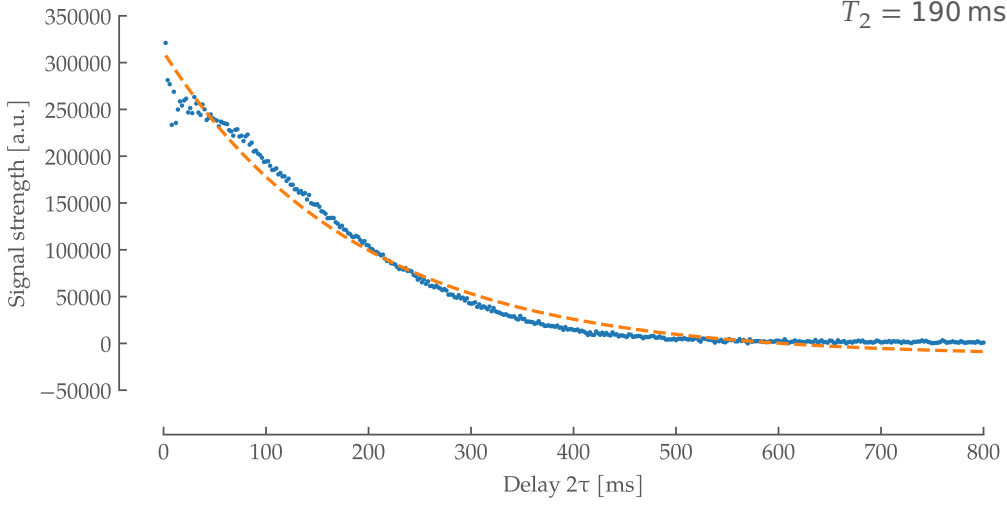
Spin Echo Animation



Spin Echo Measurement



T_2 decay of water



Demo time!

Review

- Why?
- The parts
  - Console
  - Amplifiers
  - Switch
  - Probe
- Capture & Process Software
- Experimental Results
- Demonstration

Outlook

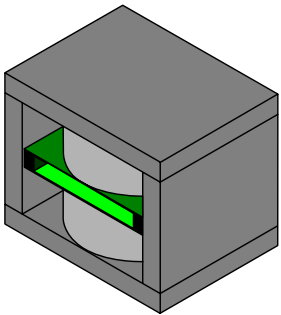
- Shim Driver
- Shielding
- Improve any part individually
  - Cheaper Magnet
  - Better Probe
  - Software (CIC compensation filter, frequency adjustment during pulse, …)
- Investigate temperature stability
- Sell it to NexMR (or do Photo-CIDNP ourselves)

"I have not yet lost that sense of wonder, and of delight, that this delicate motion should reside in all ordinary things around us, revealing itself only to him who looks for it."

"There the snow lay around my doorstep — great heaps of protons quietly precessing in the Earth's magnetic field."

— E.M. Purcell

Thank you!



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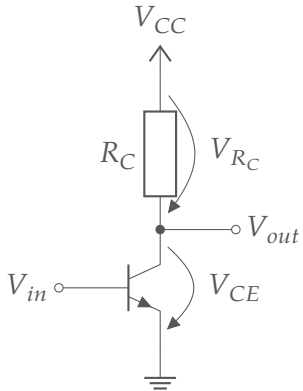
Find everything on

https://github.com/M4a1x/nmr-spectrometer

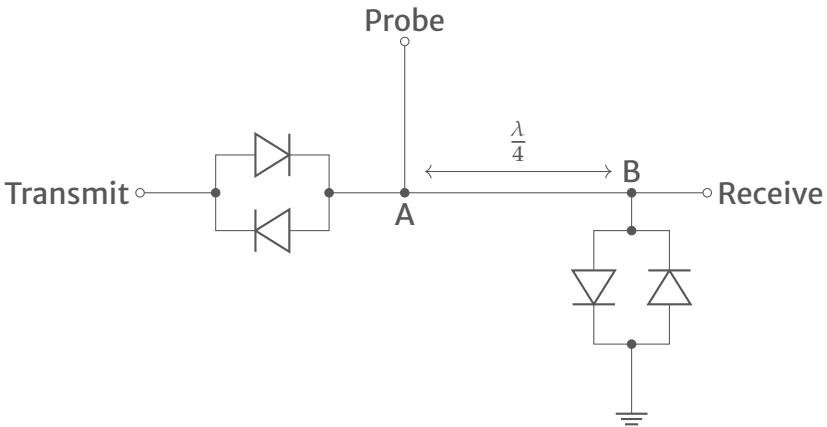
Backup

An amplifier is basically just a transistor

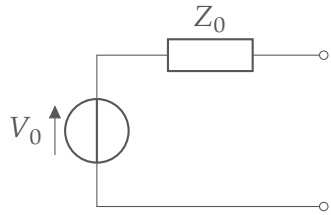
- Transistor:
  voltage-controlled current source
- higher voltage → higher current
  → higher voltage V_{R_C}
  → lower voltage V_{CE}
  → 180° phase shift

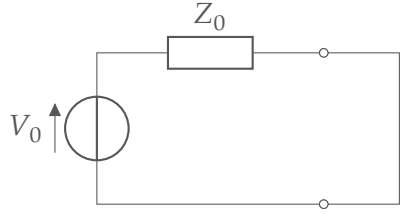


The passive approach leaked too much power

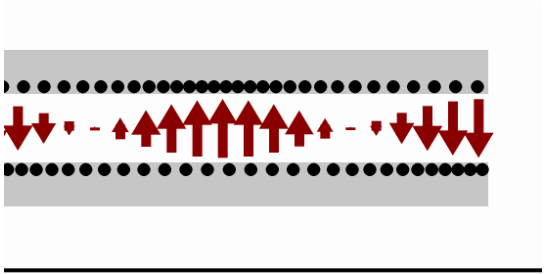


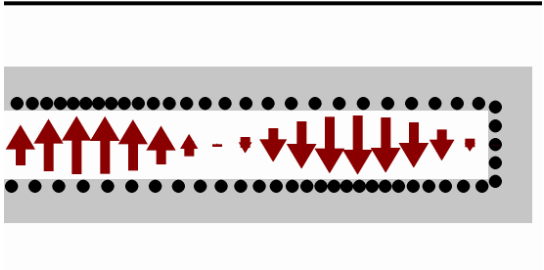
A transmission line transforms impedance

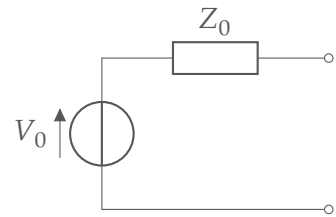


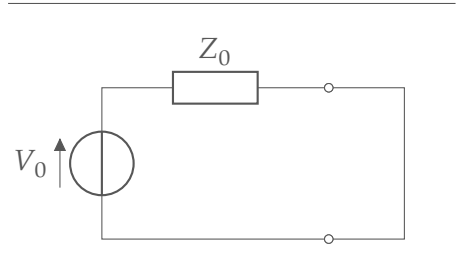


A transmission line transforms impedance

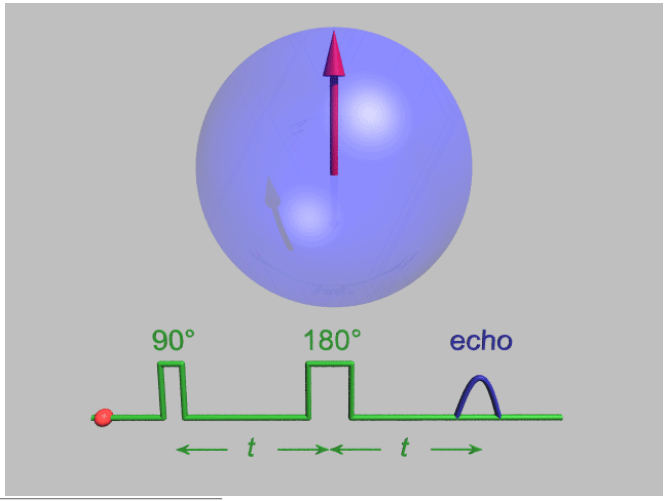




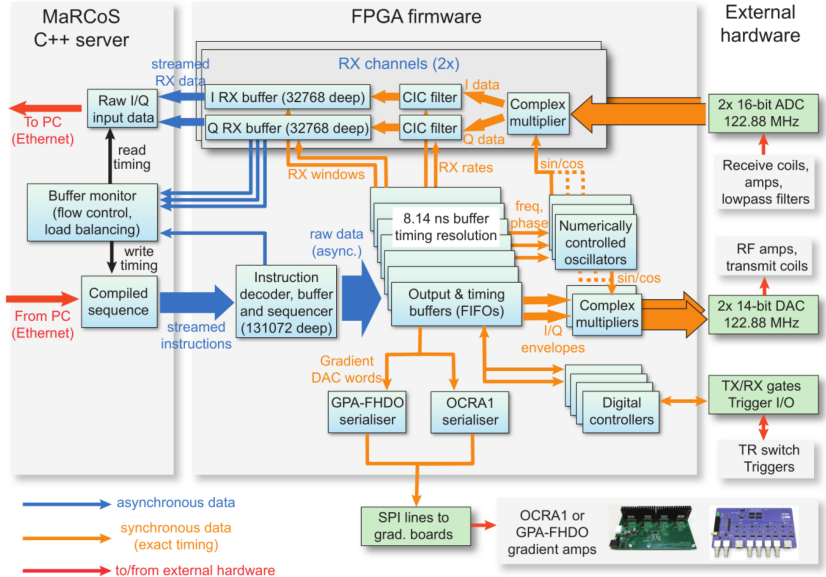




T_2 Decay Animation



MaRCoS


MaRCoS
C++ server
FPGA firmware
External
hardware
RX channels (2x)
streamed
RX data
I data
Q data
Raw I/Q
input data
I RX buffer (32768 deep)
Q RX buffer (32768 deep)
CIC filter
CIC filter
Complex
multiplier
2x 16-bit ADC
122.88 MHz
To PC
(Ethernet)
read
timing
RX windows
RX rates
sin/cos
Receive coils,
amps,
lowpass filters
Buffer monitor
(flow control,
load balancing)
8.14 ns buffer
timing resolution
freq,
phase
Numerically
controlled
oscillators
raw data
(async.)
write
timing
RF amps,
transmit coils
sin/cos
Compiled
sequence
Instruction
decoder, buffer
and sequencer
(131072 deep)
Output & timing
buffers (FIFOs)
Complex
multipliers
2x 14-bit DAC
122.88 MHz
From PC
(Ethernet)
streamed
instructions
I/Q
envelopes
Gradient
DAC words
TX/RX gates
Trigger I/O
GPA-FHDO
serialiser
OCRA1
serialiser
Digital
controllers
TR switch
Triggers
asynchronous data
synchronous data
(exact timing)
to/from external hardware
SPI lines to
grad. boards
OCRA1 or
GPA-FHDO
gradient amps