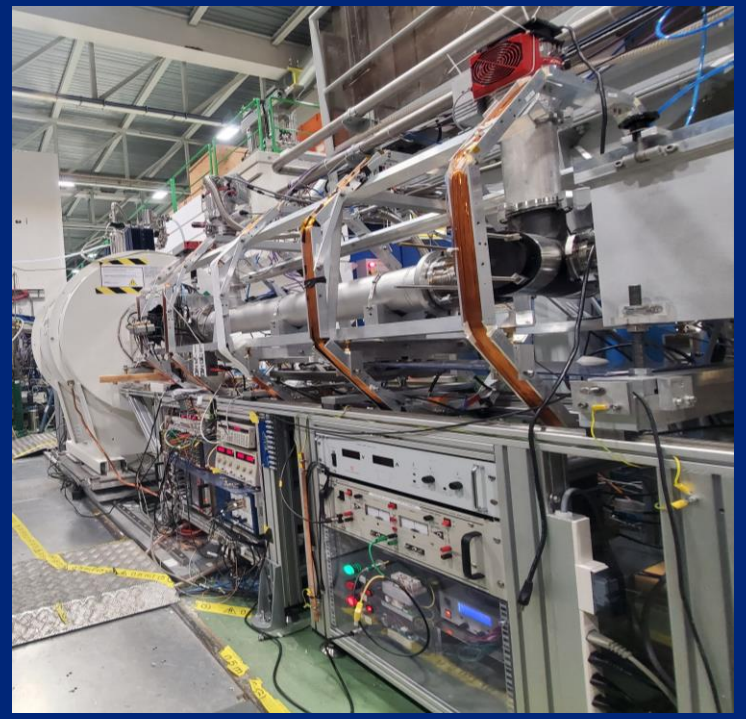



# RD-ZULF-NMR

## Radiation detected Zero to ultralow-field Nuclear Magnetic Resonance

VITO – ISOLDE

Selim Zoorob

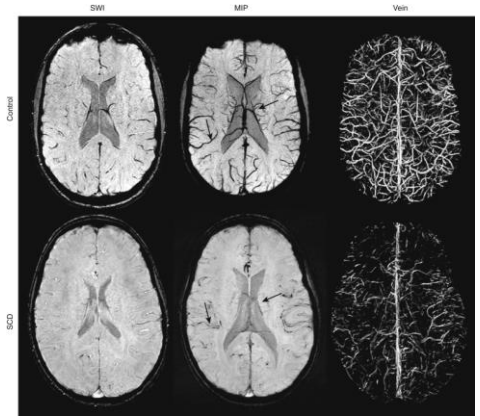
Aug 4th, 2022

# A look into MRI Technology

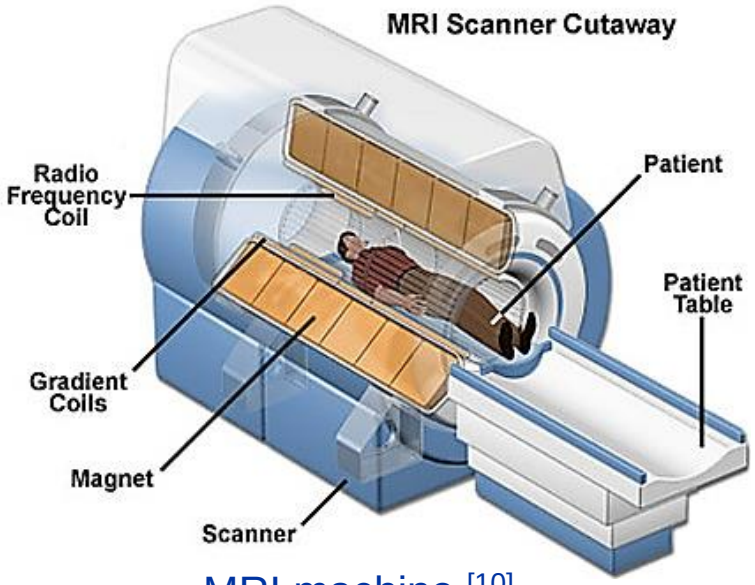
MRI = Magnetic Resonance Imaging

NMR = Nuclear Magnetic Resonance

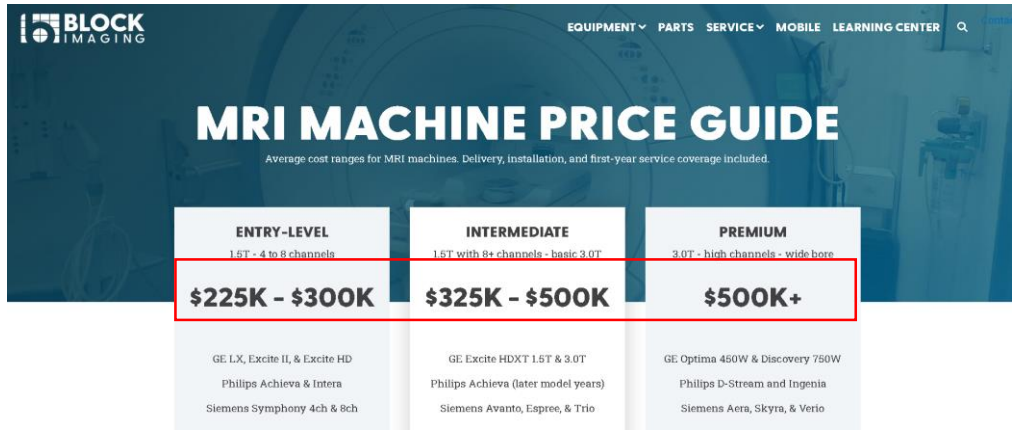
- While MRI is founded in NMR, both techniques relying on radiation data to identify unknown compounds.
- NMR uses radiofrequencies
- MRI based on radiation intensity


Brain MRI images [2]




MRI machine [10]

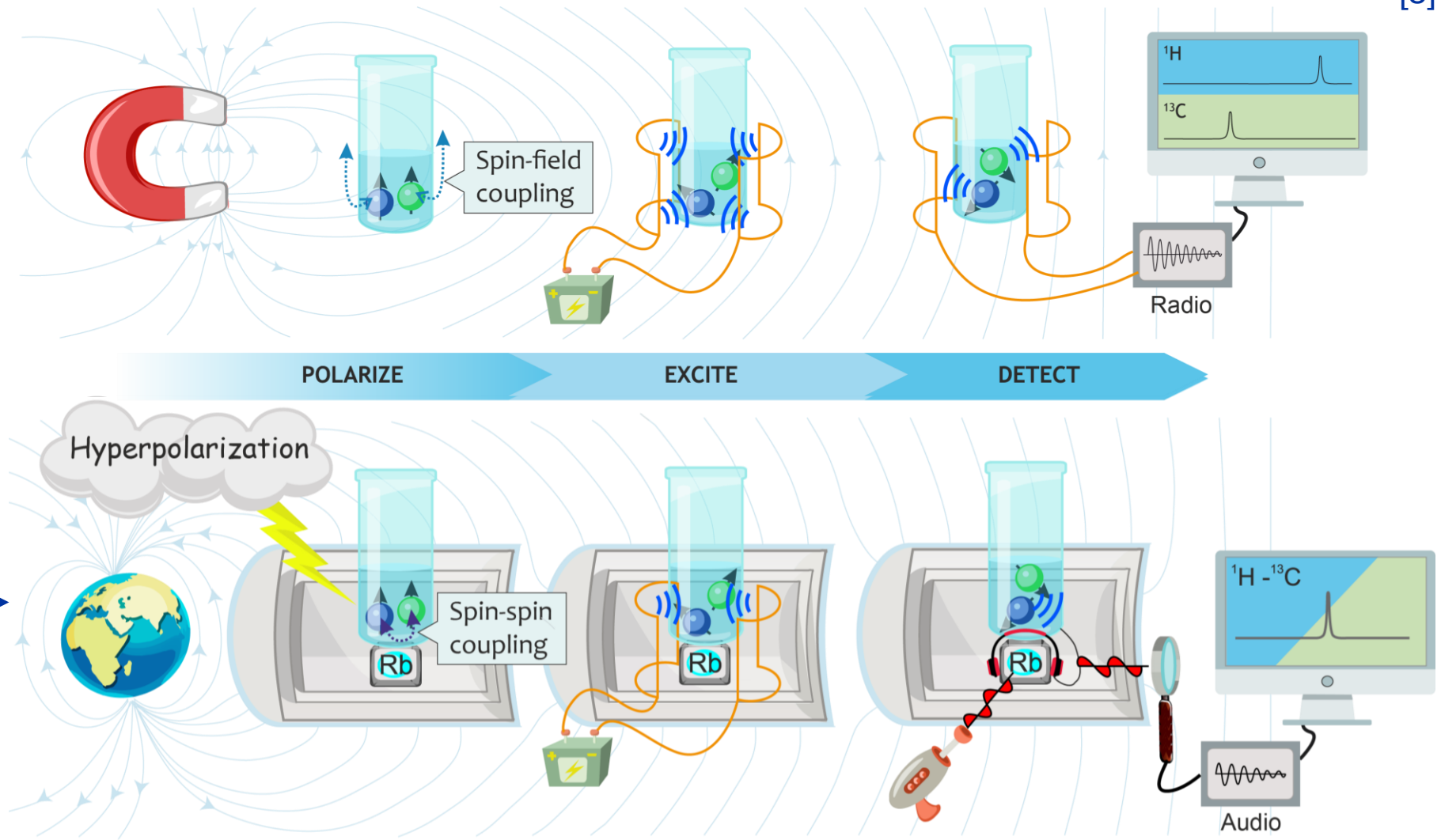



MRI machine prices [8]

# The future of MRI tech?

# High-field NMR vs ZULF-NMR SETUP

[5]

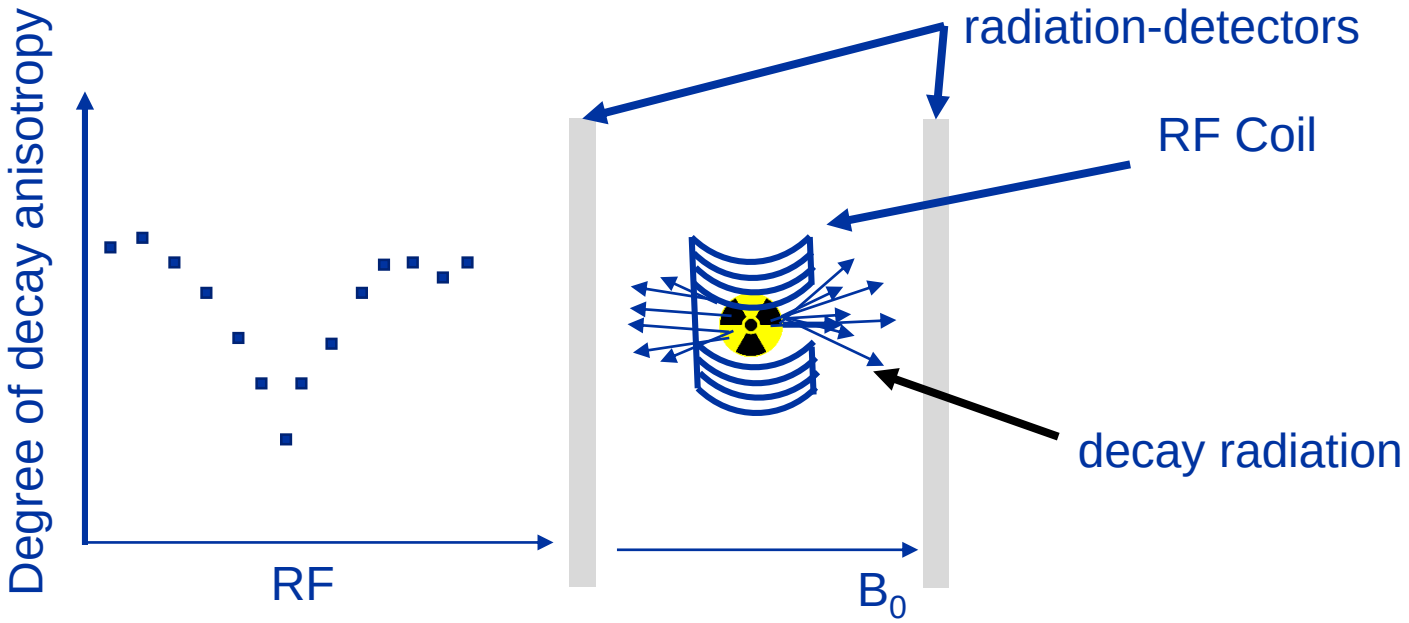



The Earth's magnetic field intensity is roughly between 25 - 65 microT (. 25 - . 65 gauss)

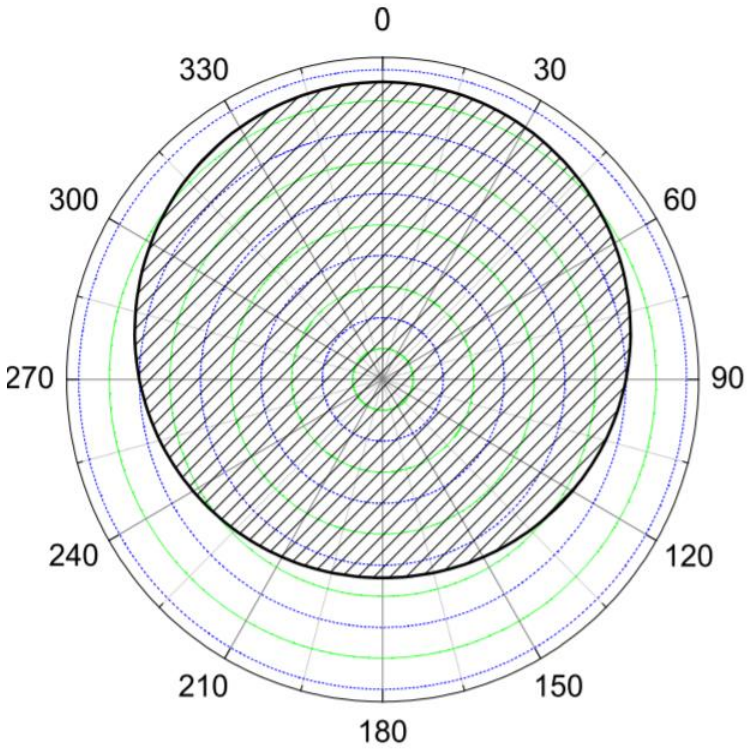
# Radiation detected NMR (β-NMR [9]):

- unstable probe nuclei
- spins polarized by external source = hyperpolarization (e.g. lasers)
- spins excited by radio-frequency pulses
- detection of anisotropy in emitted radiation

=> Spectra as in high-field NMR but stronger signal




**Beta decay, I>0**



# Why RD-ZULF-NMR? [9]

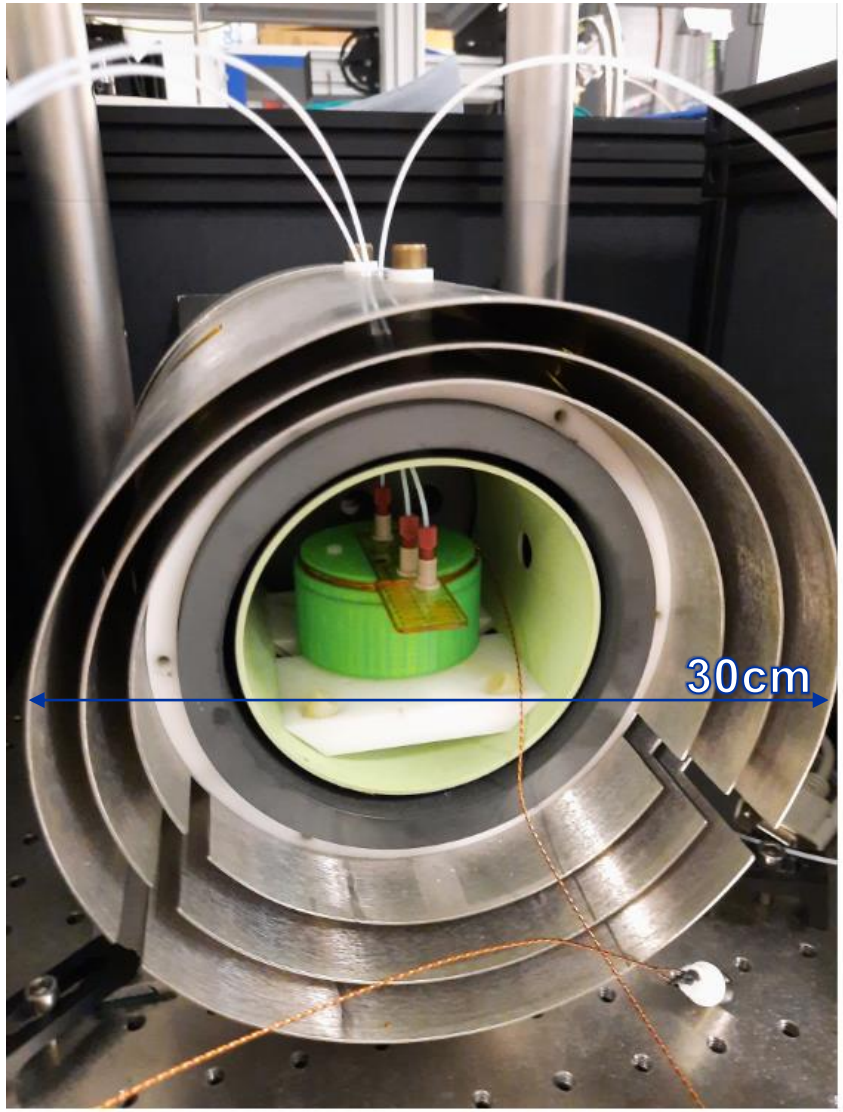
β-NMR + ZULF-NMR = RD-ZULF-NMR

Characteristics:

- Use radioactive isotopes
- Hyperpolarized
- Spins excited by radio-frequency pulses
- Detection of anisotropy [3]

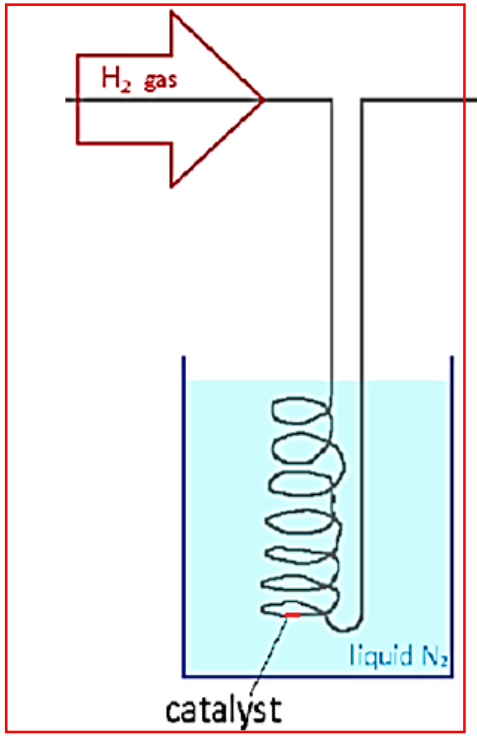
Combines β-NMR and ZULF-NMR advantages :

- Adaptive to specific applications
- ZULF-NMR :
  - Spin-spin interactions explored in different ways
  - Apparatus is cheap and transportable
  - No loss in spectral resolution associated with inhomogeneous samples
- β-NMR :
  - Extremely high sensitivity
  - Many more probe nuclei

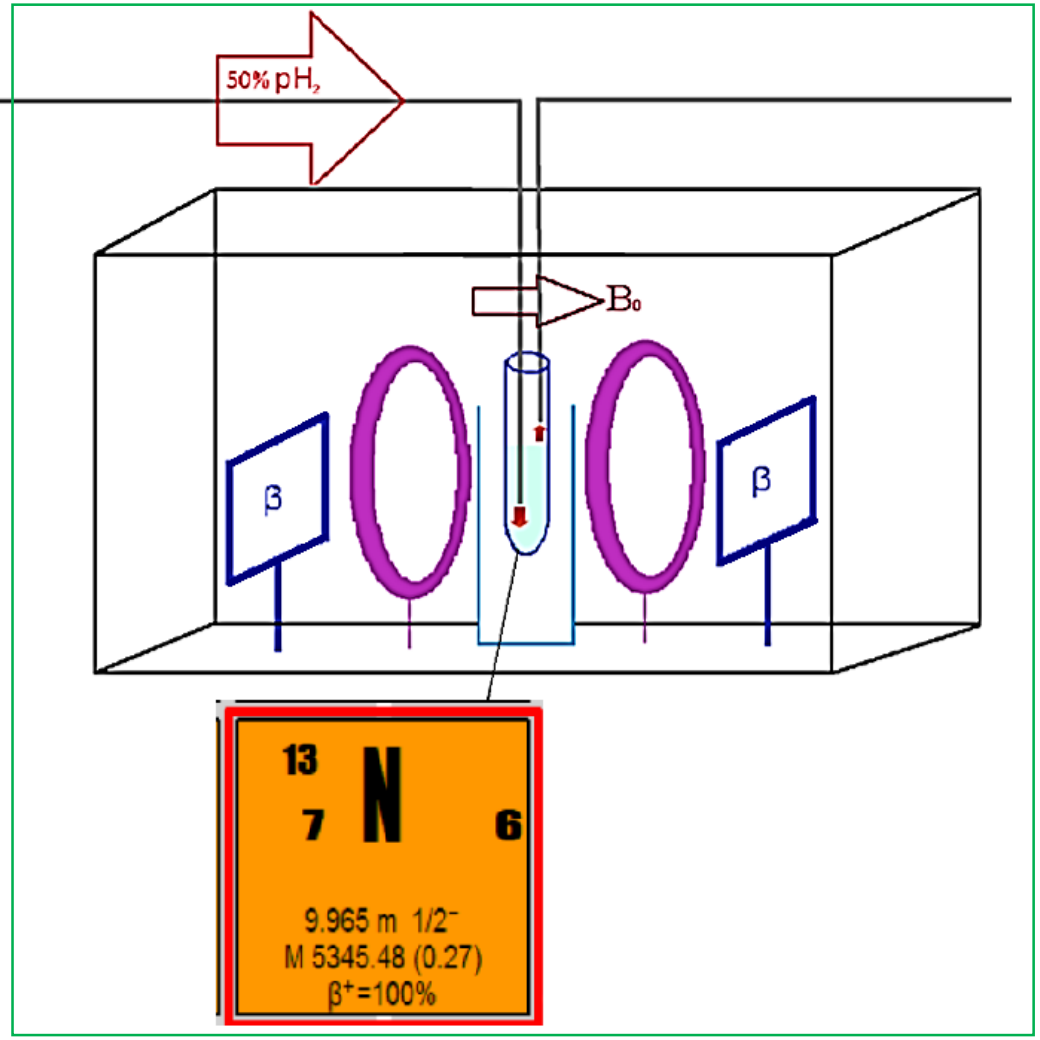


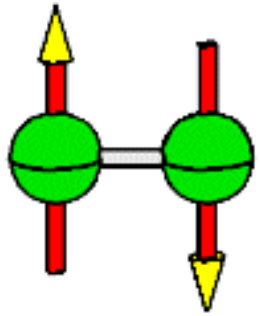
# RD-ZULF-NMR Setup

## $pH_2$ setup

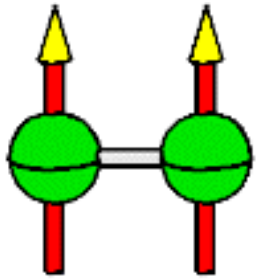



## Hyperpolarizing setup

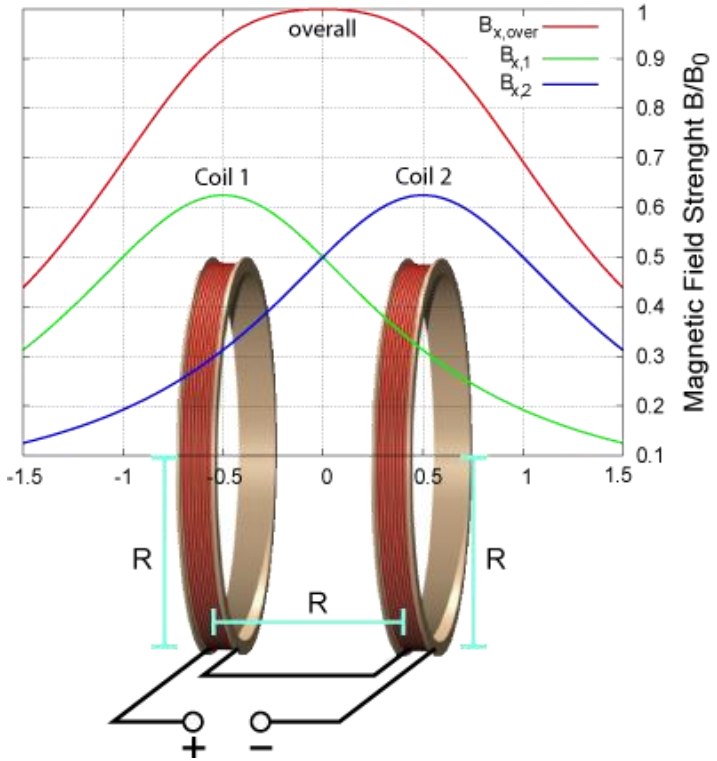


Parahydrogen

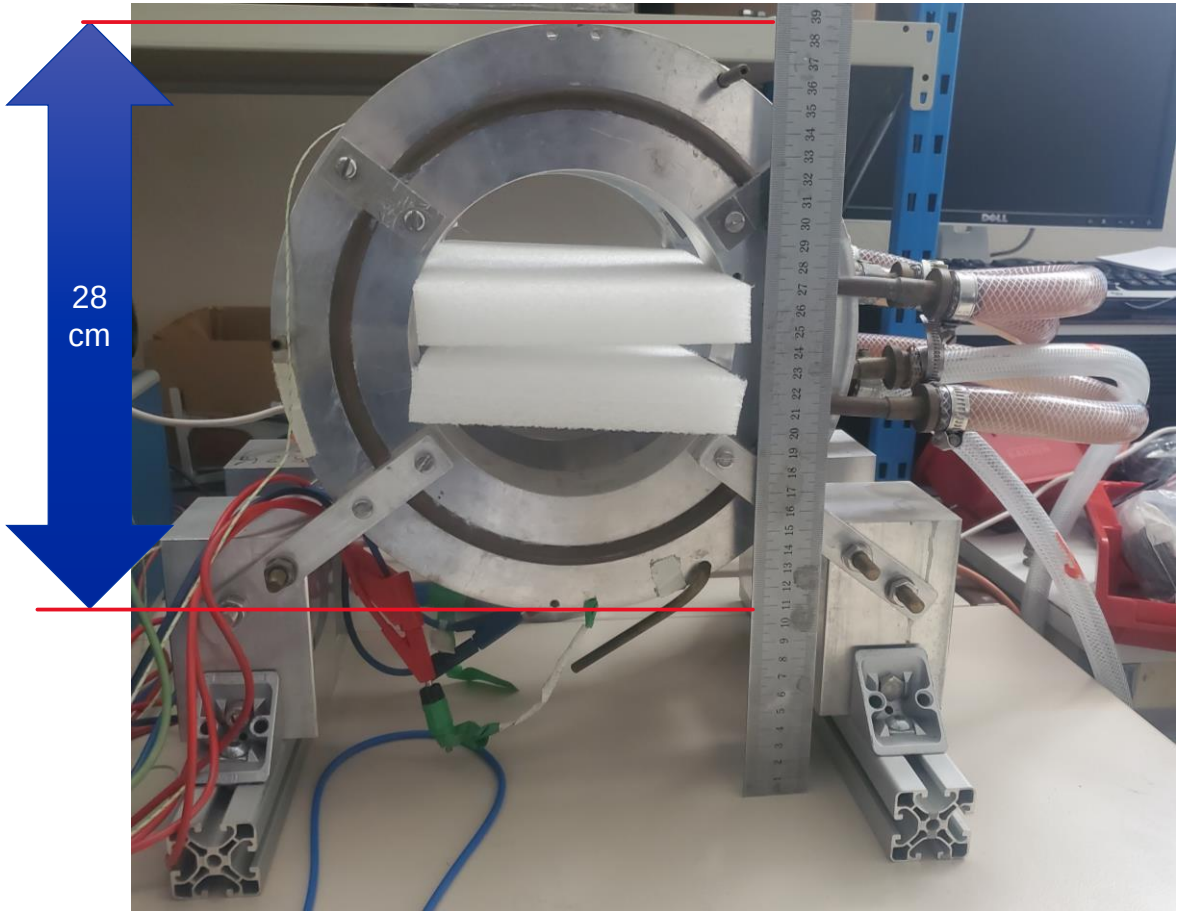


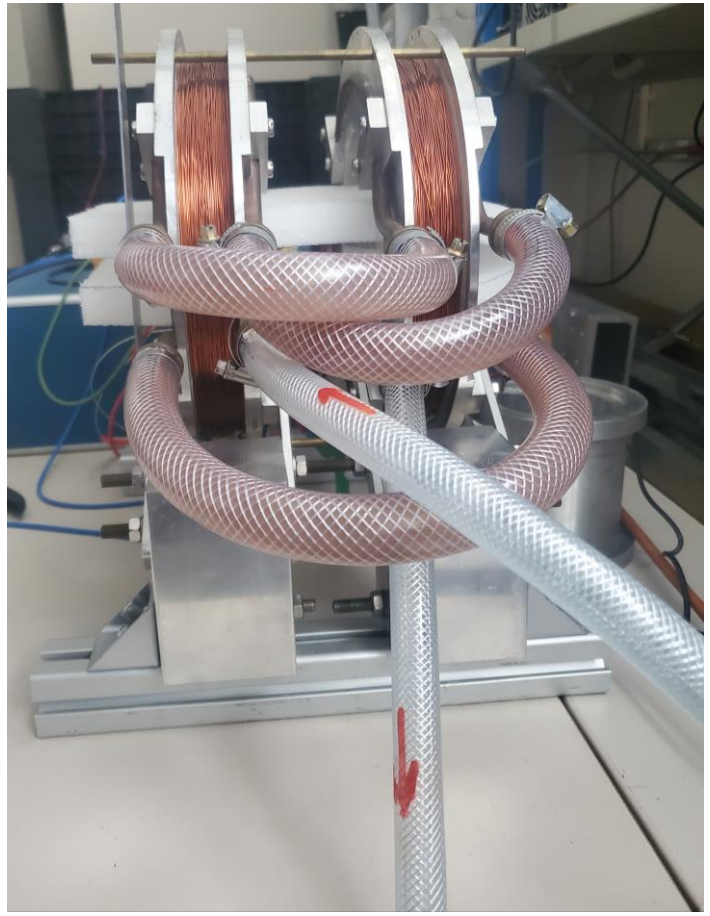
Orthohydrogen



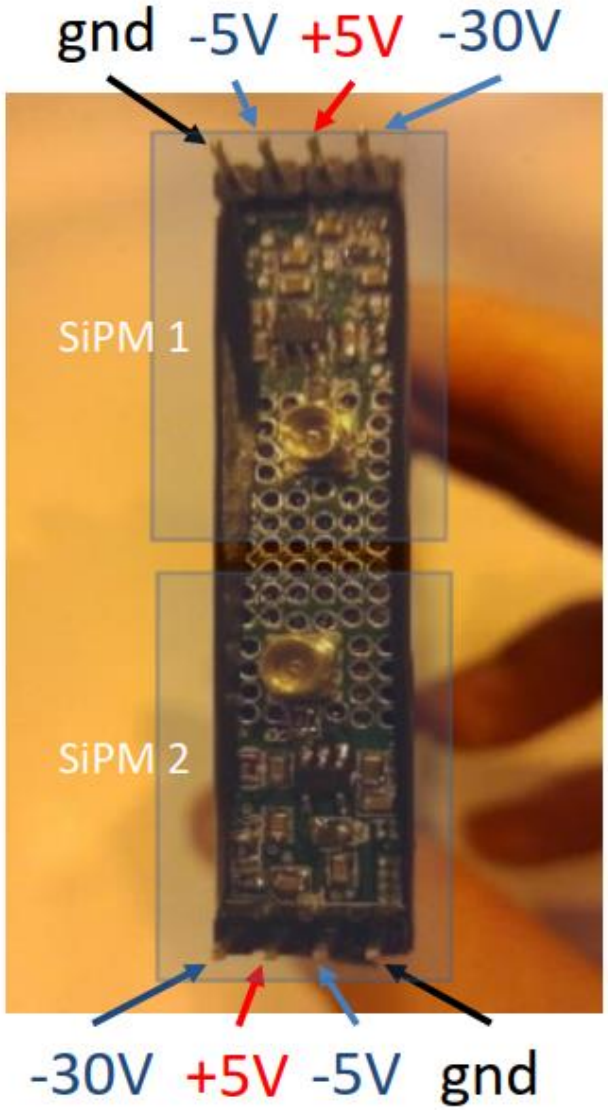
# Water cooled Helmholtz Coils

## Up to 250 Gauss at 88℃ (with water cooling on)

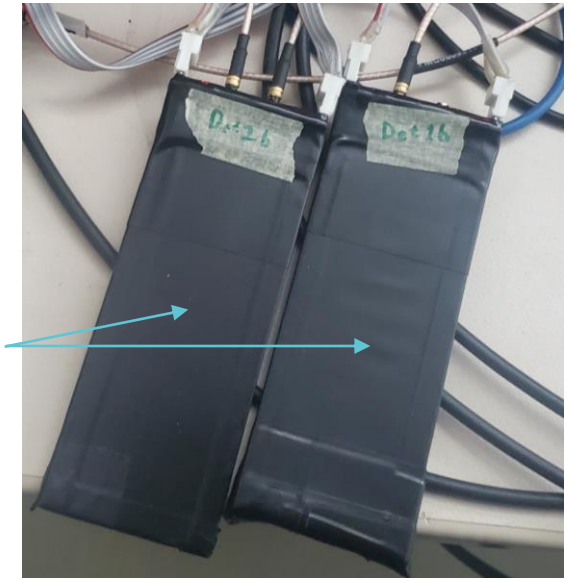


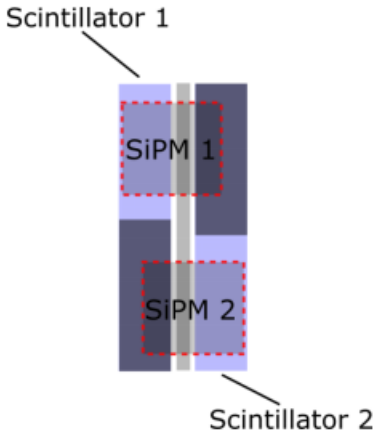



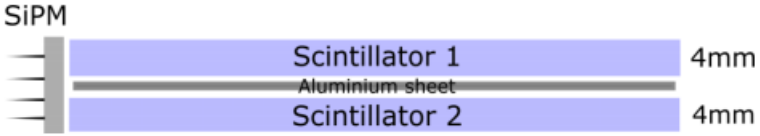
# Beta detectors



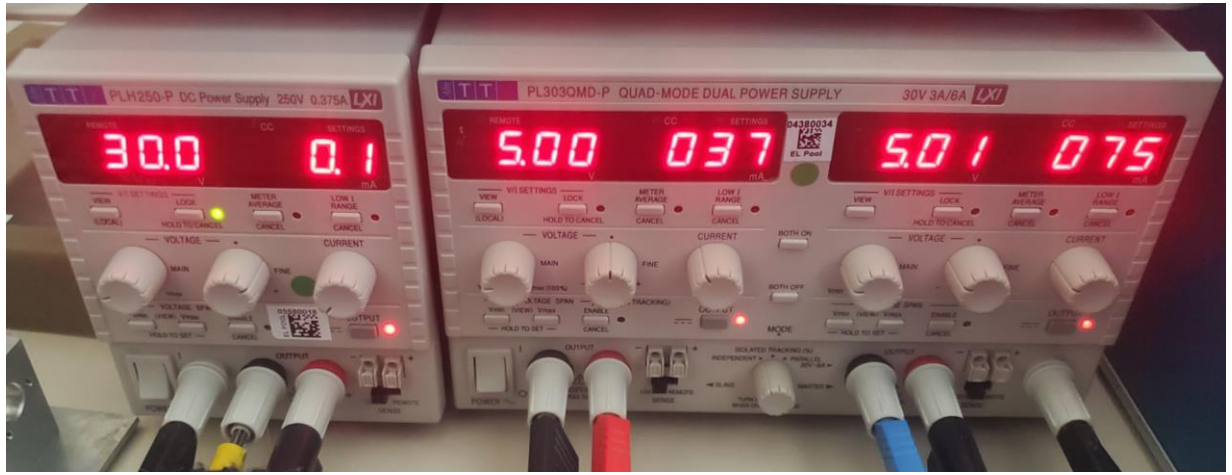

Beta detectors






-30V 5V -5V



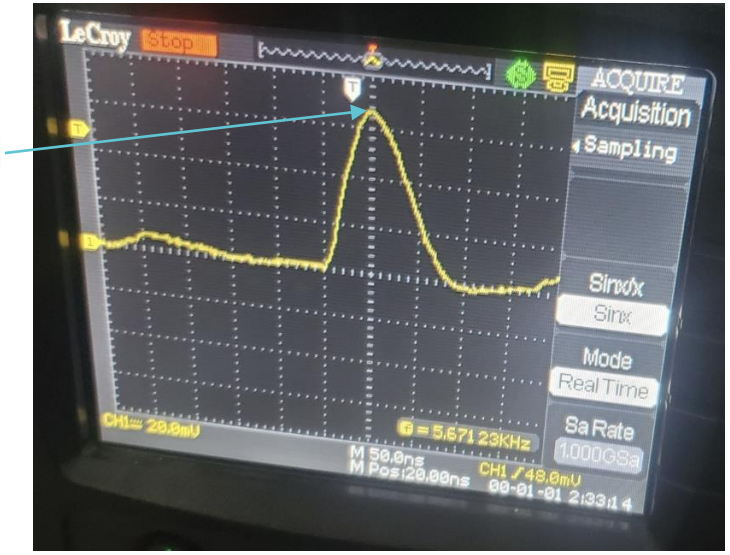

Two plastic scintillators + Two Silicon photomultipliers (SiPM) connected to a single board with separate preamplifiers.

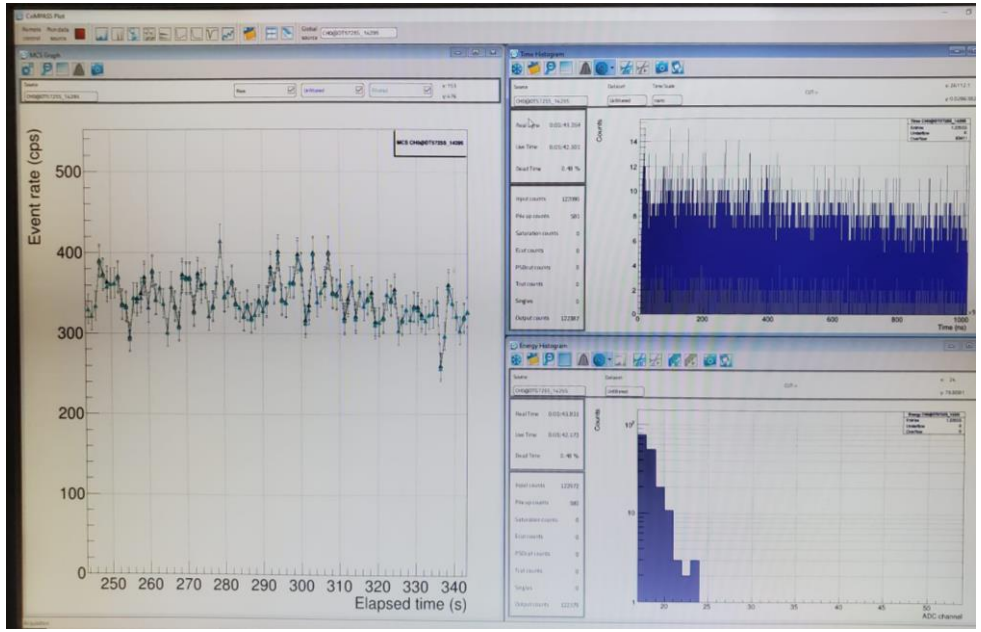
# Data Collection

DAQ = Data Acquisition System

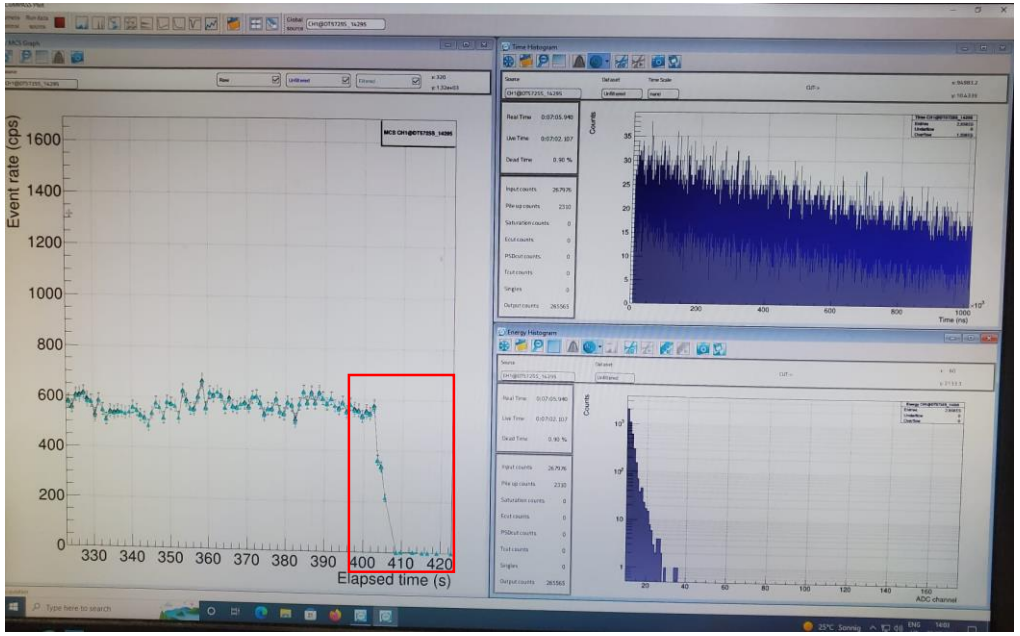
CAEN DAQ

Background noise peak at ~60mV




With radioactive source (Strontium-90)




When removing radioactive source


- **Approval of safety procedures**
- **Setup at <u>Geneva Hospital</u>**
- **Test of detectors in ZULF-NMR**
- **Polarization test at <u>MAINZ University</u>**

Special thanks to:

- NSF (National Science Foundation)
- CERN
- Philip Rubin, PhD.
- Magdalena Kowalska, PhD.
- Monika Piersa-Silkowska, PhD.
- Nikolay Azaryan, PhD.
- Marcus Jankowski, PhD Candidate.

National Science Foundation
WHERE DISCOVERIES BEGIN

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hug.ch isolde.web.cern.ch home.cern uni-mainz.de nsf.gov

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**c** **Low- to High- Field**

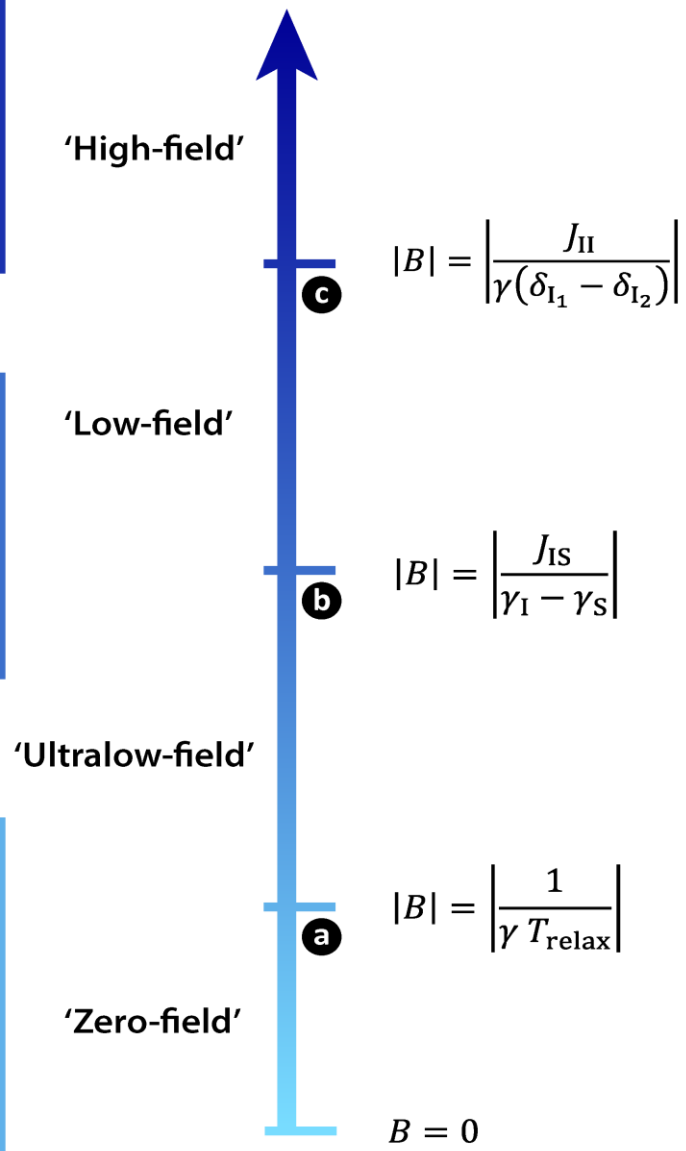
The field at which the chemical shift difference between two *homonuclear* spins (i.e. of the same isotopic species) and their mutual *J*-coupling become equal, and neither interaction dominates.

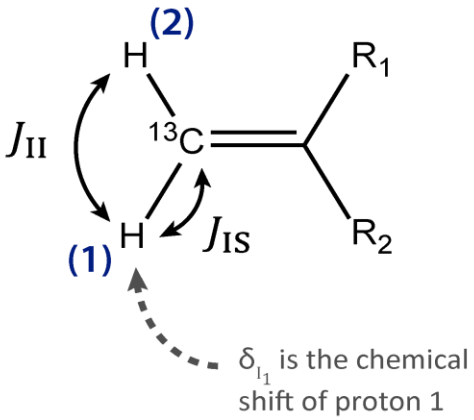
**b** **Ultralow- to Low- Field**

The field at which the Larmor frequency difference between two *heteronuclear* spins (i.e. of different isotopic species) and their mutual *J*-coupling become equal, and neither interaction dominates.

**a** **Zero- to Ultralow- Field**

To measure the nuclear spins they are usually polarized, but will relax back to a thermal equilibrium state with a characteristic relaxation time; we call this $T_{relax}$. We define boundary (a) as the field for which the time taken for the nuclear spin to precess around the field axis once matches $T_{relax}$.




**Example boundary values**

To get a sense of the real magnetic field values of the boundaries for a typical system, let us assume the following values for the molecule shown:

$J_{II} = 10$ Hz
$J_{IS} = 150$ Hz
$\delta_{I_1} - \delta_{I_2} = 1$ ppm
$T_{relax} = 1$ s for all spins

The gyromagnetic ratios for $^1$H and $^{13}$C are 42 MHz/T and 10.5 MHz/T, respectively.

This gives the following boundaries:

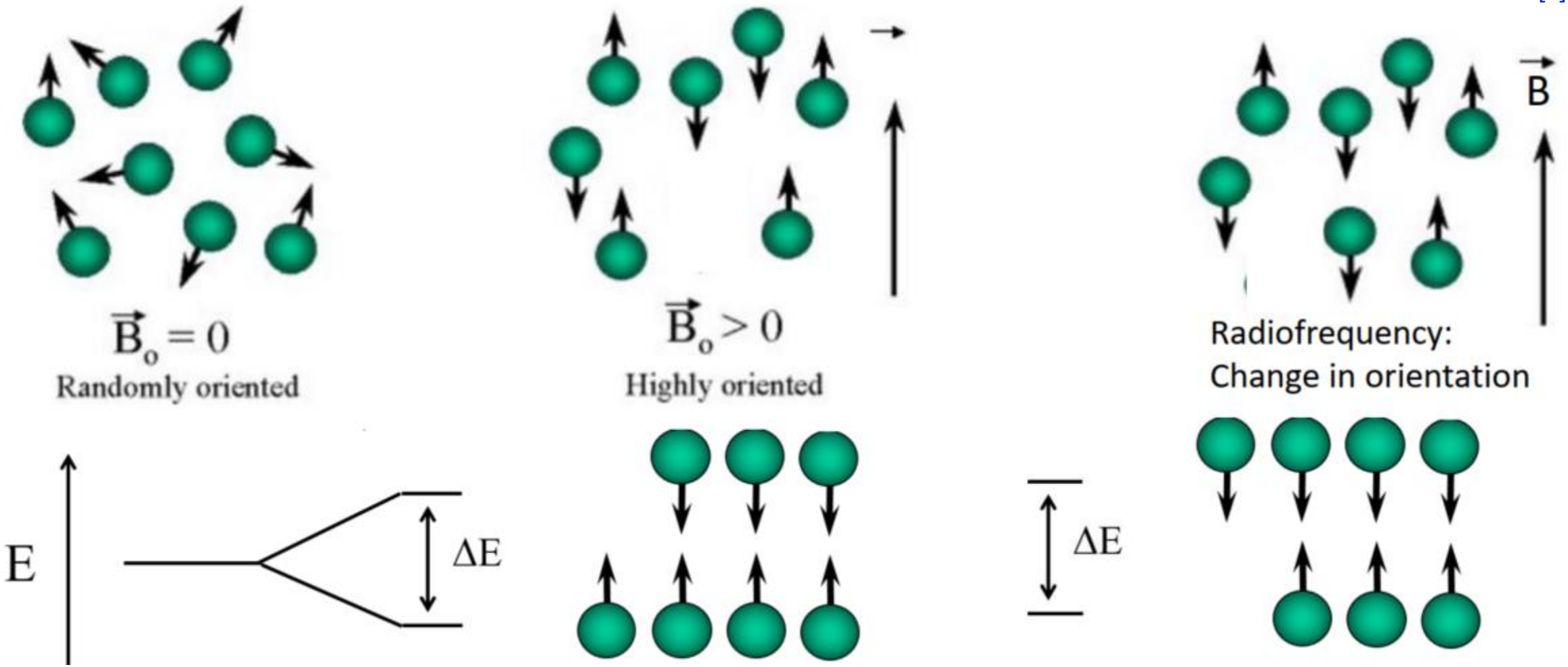
- **a** Between 3.7 and 15 nT, depending on whether we are considering $^1$H or $^{13}$C
- **b** 750 nT
- **c** 37 mT

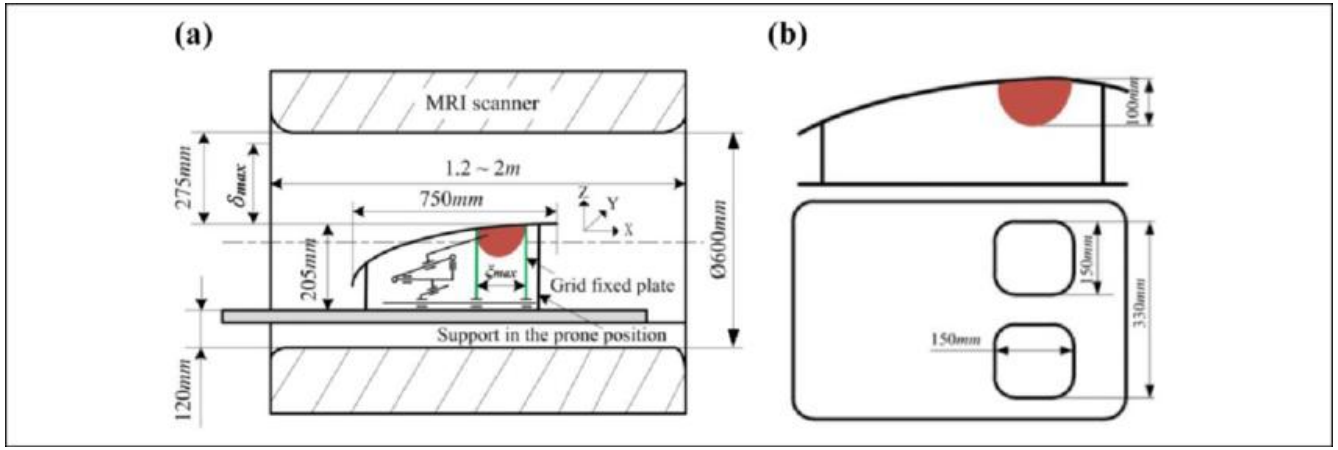
For reference, Earth-field is around 50 µT.

Nuclear spin parameters specific to the system being studied:

- *J*-couplings ($J_{II}$ and $J_{IS}$),
- homonuclear chemical shift differences ($\delta_{I1}$ - $\delta_{I2}$),
- heteronuclear gyromagnetic ratio differences ($\gamma_I$ - $\gamma_S$),
- and characteristic spin relaxation times ($T_{relax}$). [1]

[8]


$\vec{B}_o = 0$
Randomly oriented
$\vec{B}_o > 0$
Highly oriented
$\vec{B}$
Radiofrequency:
Change in orientation
E
ΔE
ΔE




MRI machine dimensions [3]

Mobile MRI System [12]

| Comparison table [2] | Standard NMR | ZULF-NMR | ZULF-RD-NMR |
|---|---|---|---|
| Magnetic field | Several - dozen Tesla | < microTesla | 0.5 – dozen Tesla |
| Source of polarization | Boltzmann distribution | hyperpolarization | In-situ or outside hyperpolarization |
| Degree of polarization | 1e-5 | 1e-5 – dozens % | Several – dozens % |
| Probe nuclei | Stable | Stable (1H, 13C, …) | Unstable (ms to days $t_{1/2}$) |
| Signal detection | Inductive (pick-up coil) | magnetometer | Anisotropy in emitted radiation |
| # nuclei to record signal | 1e16 – 1e17 | …. - 1e16 – 1e17 | 1e6-1e8 |

# β-NMR [4]

β-NMR explores the angular distribution ($w$) of beta-irradiation of polarized beta-active nuclei (beta-nuclei);

$$w(\vartheta, t) = 1 + ap(t)cos\vartheta, \qquad cos\vartheta = pk/pk$$

to determine the evolution of nuclear polarization $p(t) = \langle I(t) \rangle$ by detection of β-particles.

Measurement of beta-decay asymmetry ε :

$$\varepsilon = (N_+ - N_-)/(N_+ + N_-)$$

where $N_+$ and $N_-$ are numbers of decay electrons emitted along and against the nuclear polarization direction.

- **k** : translation momentum of the β-particles
- **I** : spin of beta-nucleus
- **Angle brackets** ⟨⟩ : standard quantum statistical averaging
- **t** : time starting from the moment of creation of β-nucleus
- **a**~0.1