WIREBONDED MICROCOILS FOR MICROSCALE MAGNETIC RESONANCE-BASED DETECTION

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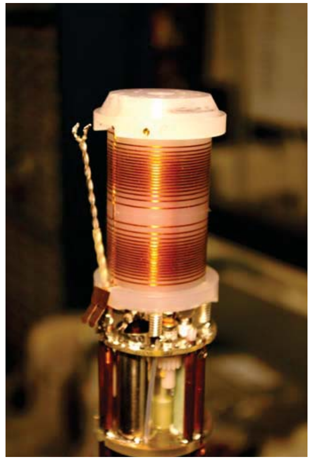
MR imaging and spectroscopy

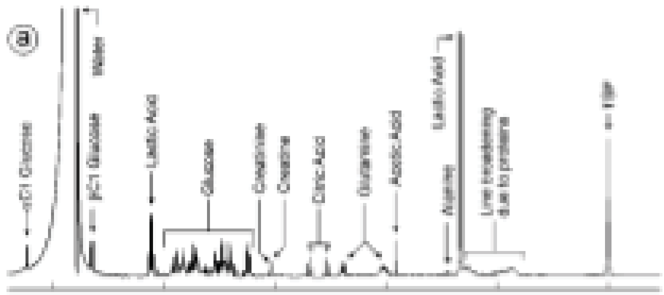
MAGNETIC RESONANCE **IMAGING**

body organs

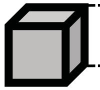
MAGNETIC RESONANCE **SPECTROSCOPY**

chemical samples





Microscale MR samples



10 mm

single cell

(1 mm)^3 → 10^{-6} → (10 μm)^3

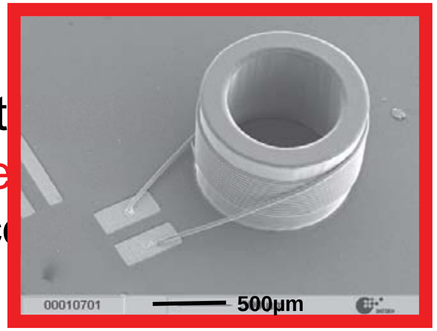
signal reduction

Signal recovery

rength static magnet

ighly sensitive RF re

onducting receiver c



solenoidal wirebonded microcoils

Sens. Act. 156, p. 328 (2009)

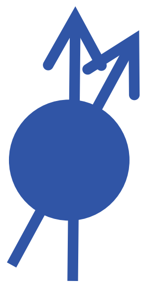
JMM, 015021 (2010)

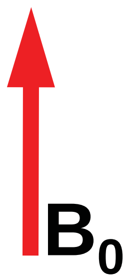
How MR works?

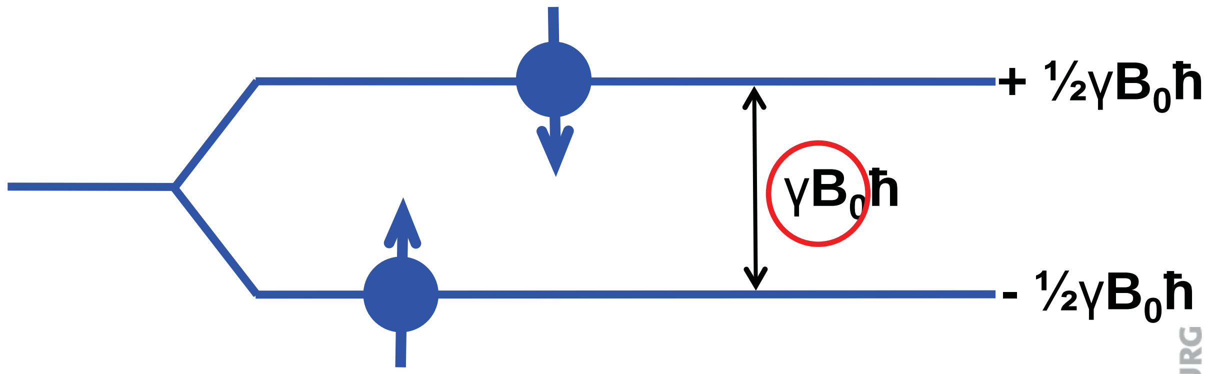
^{1}H nucleus in external magnetic field

- atomic nucleus (^{1}H)
- angular momentum
- external magnetic field
- Larmor frequency:

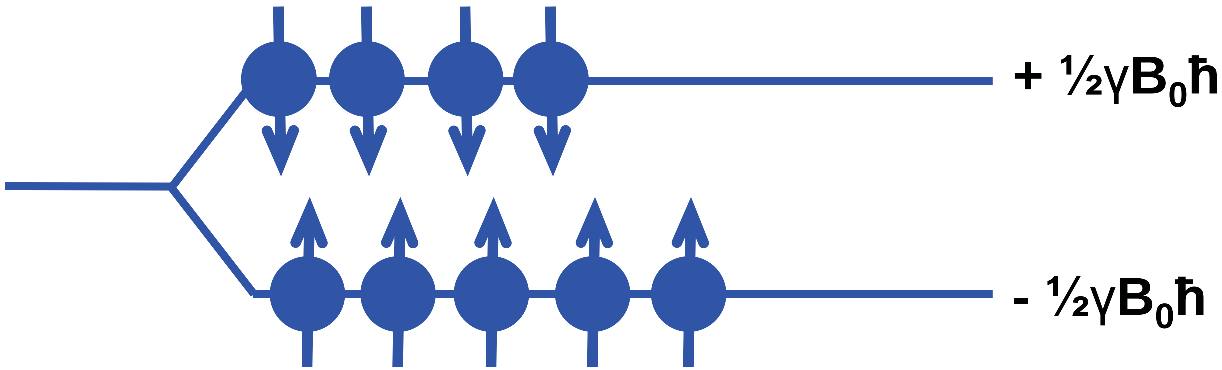
$$\omega_L = \gamma B_0$$

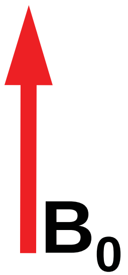






Boltzmann factor





$$\exp\left(-\frac{\gamma B_0 \hbar}{k_B T}\right)$$

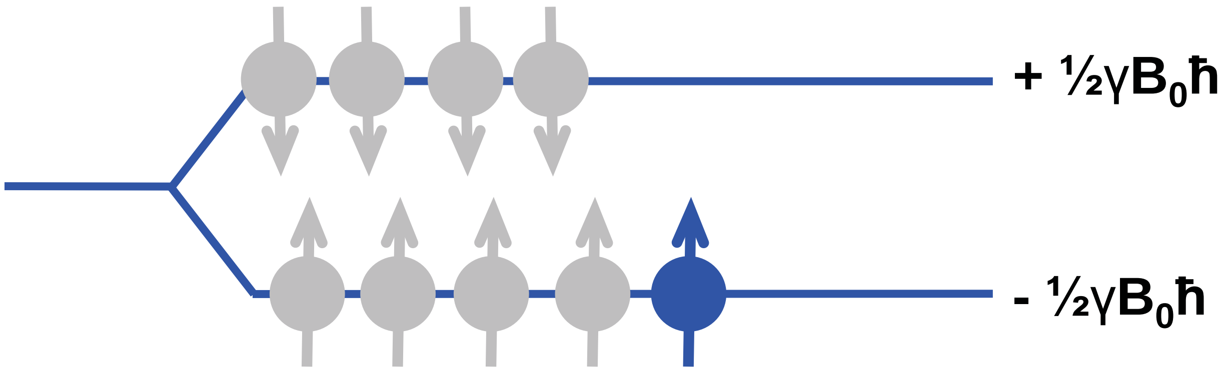
$\gamma B_0 \hbar$ → magnetic energy

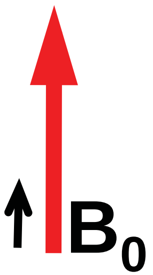
$k_B T$ → thermal energy

Boltzmann factor

T = 300K

Manipulate Boltzmann factor – temperature





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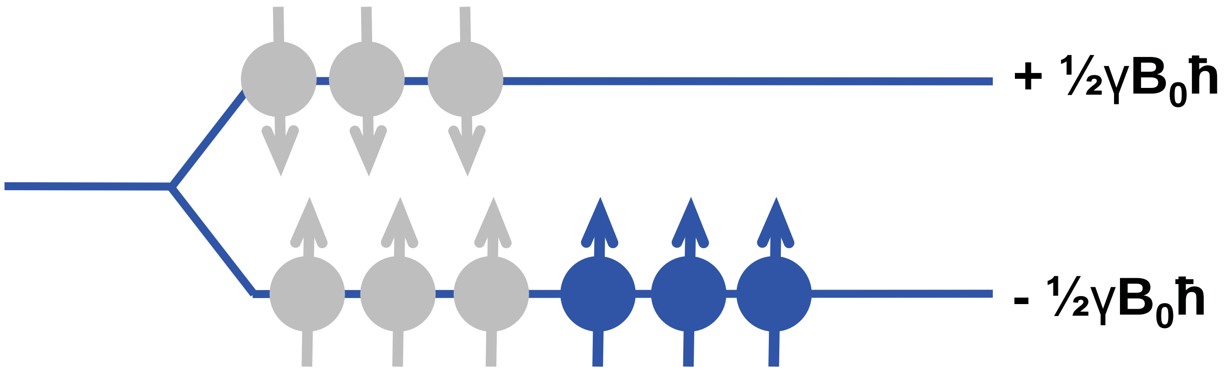
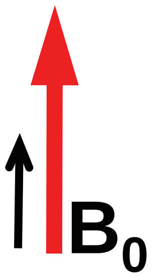




$$\exp\left(-\frac{\gamma B_0 \hbar}{k_B T}\right)$$

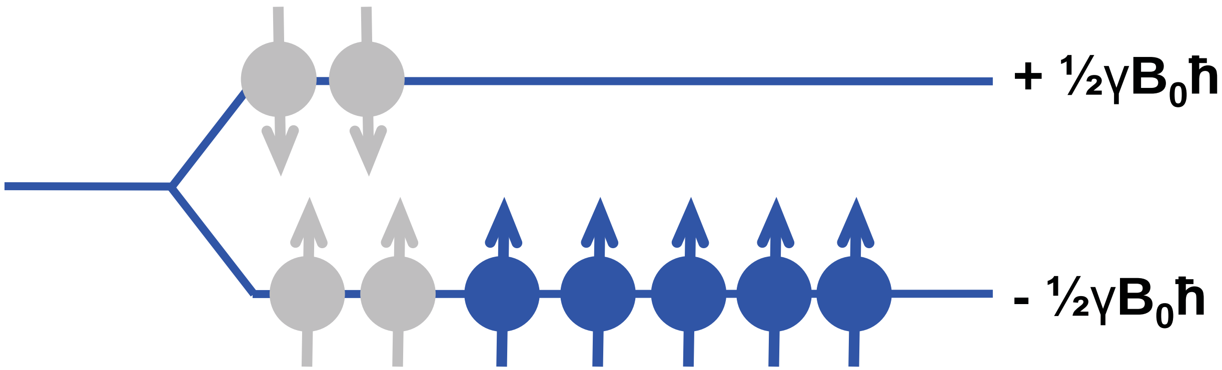
$\gamma B_0 \hbar$ → magnetic energy

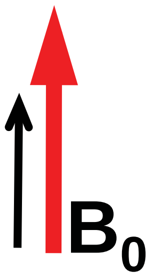
$k_B T$ → thermal energy

Boltzmann factor

T = 225K

Manipulate Boltzmann factor – temperature





$$\exp\left(-\frac{\gamma B_0 \hbar}{k_B T}\right)$$

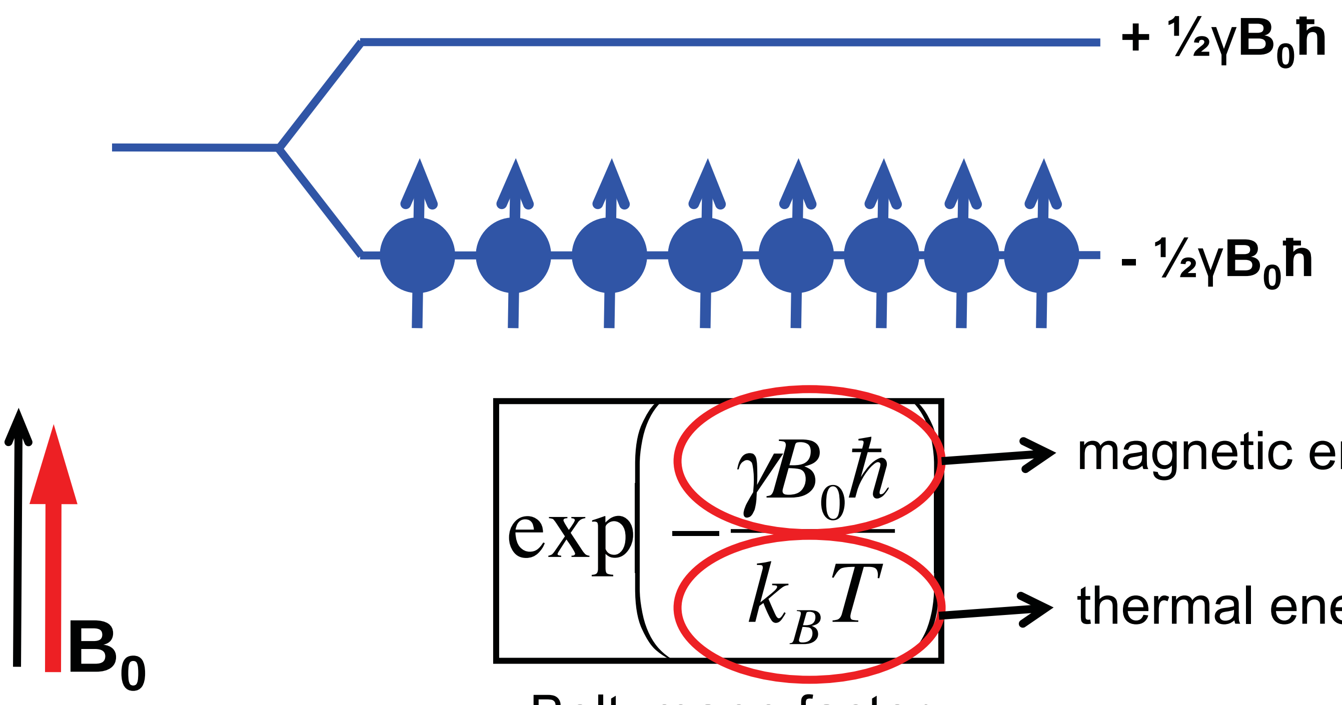
$\gamma B_0 \hbar$ → magnetic energy

$k_B T$ → thermal energy

Boltzmann factor

T = 150K

Manipulate Boltzmann factor – temperature

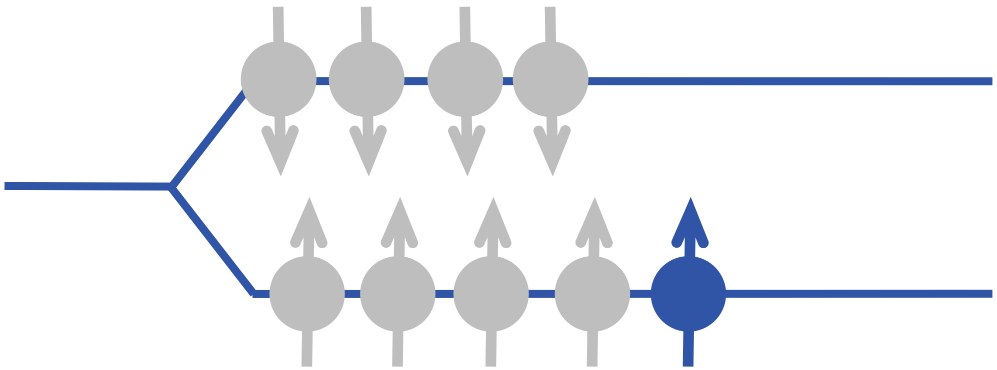


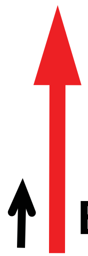
$$\exp\left(-\frac{\gamma B_0 \hbar}{k_B T}\right)$$

Boltzmann factor

T = 0K

Manipulate Boltzmann factor – B_0 field

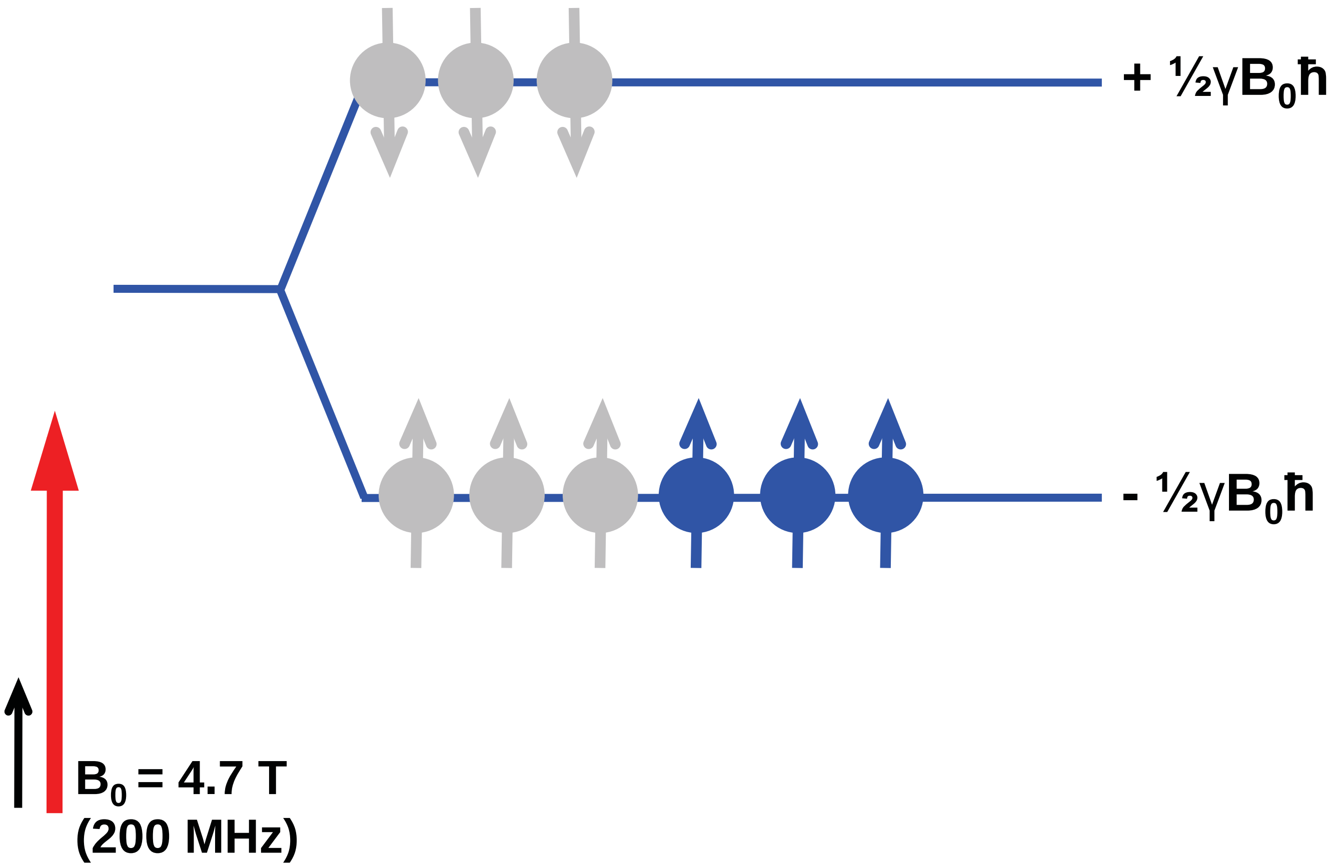




$B_0 = 2.35$ T
(100 MHz)

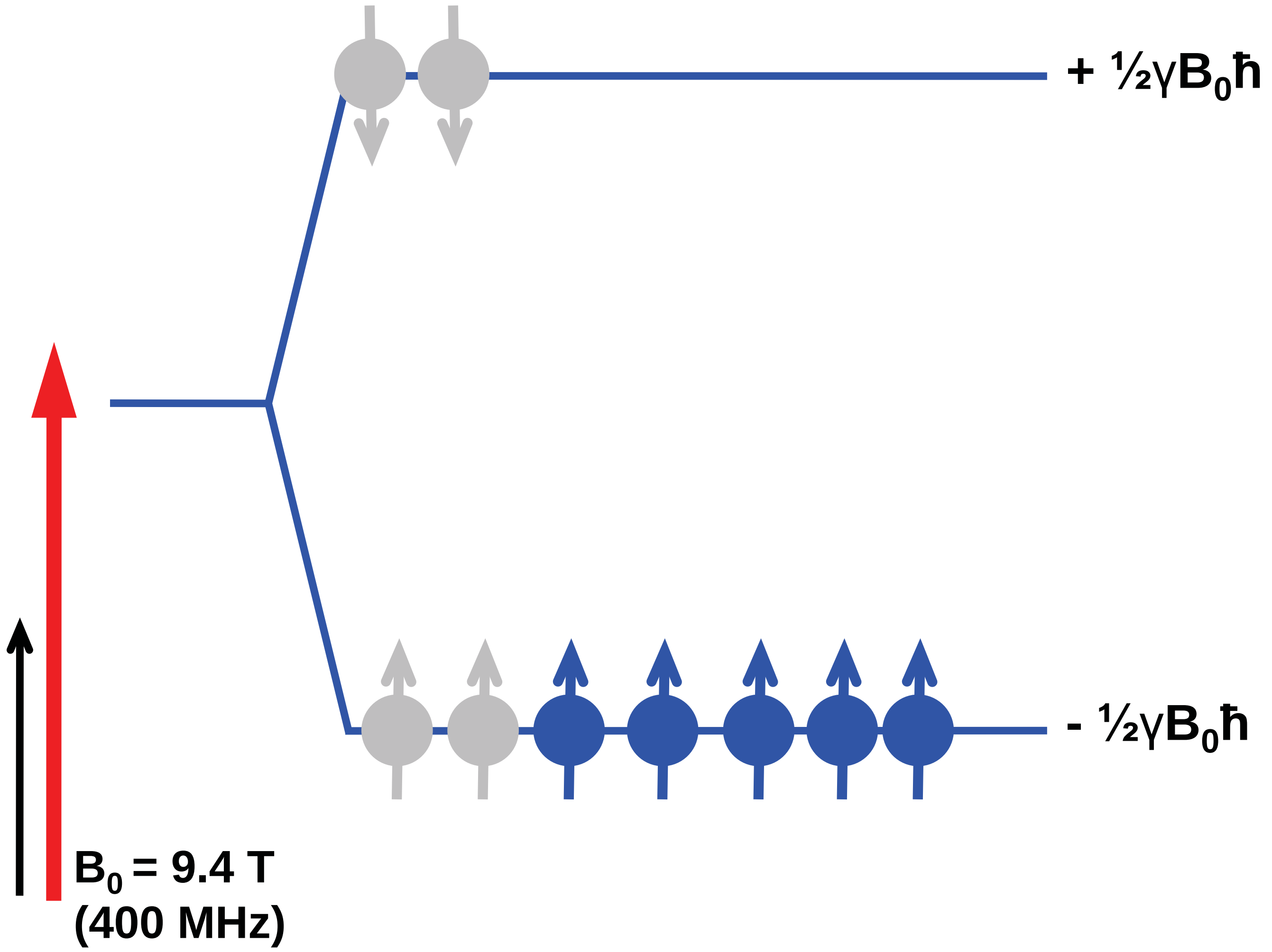
T = 300K

Manipulate Boltzmann factor – B_0 field



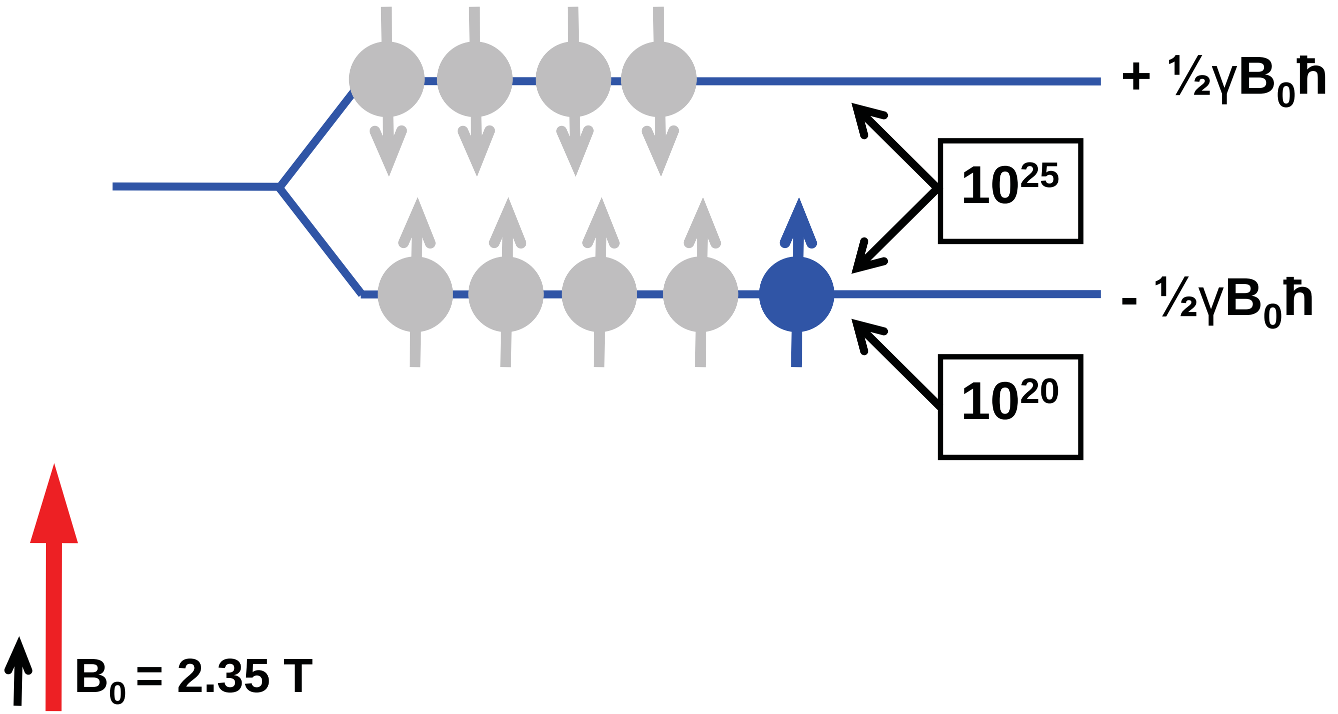
T = 300K

Manipulate Boltzmann factor – B_0 field



T = 300K

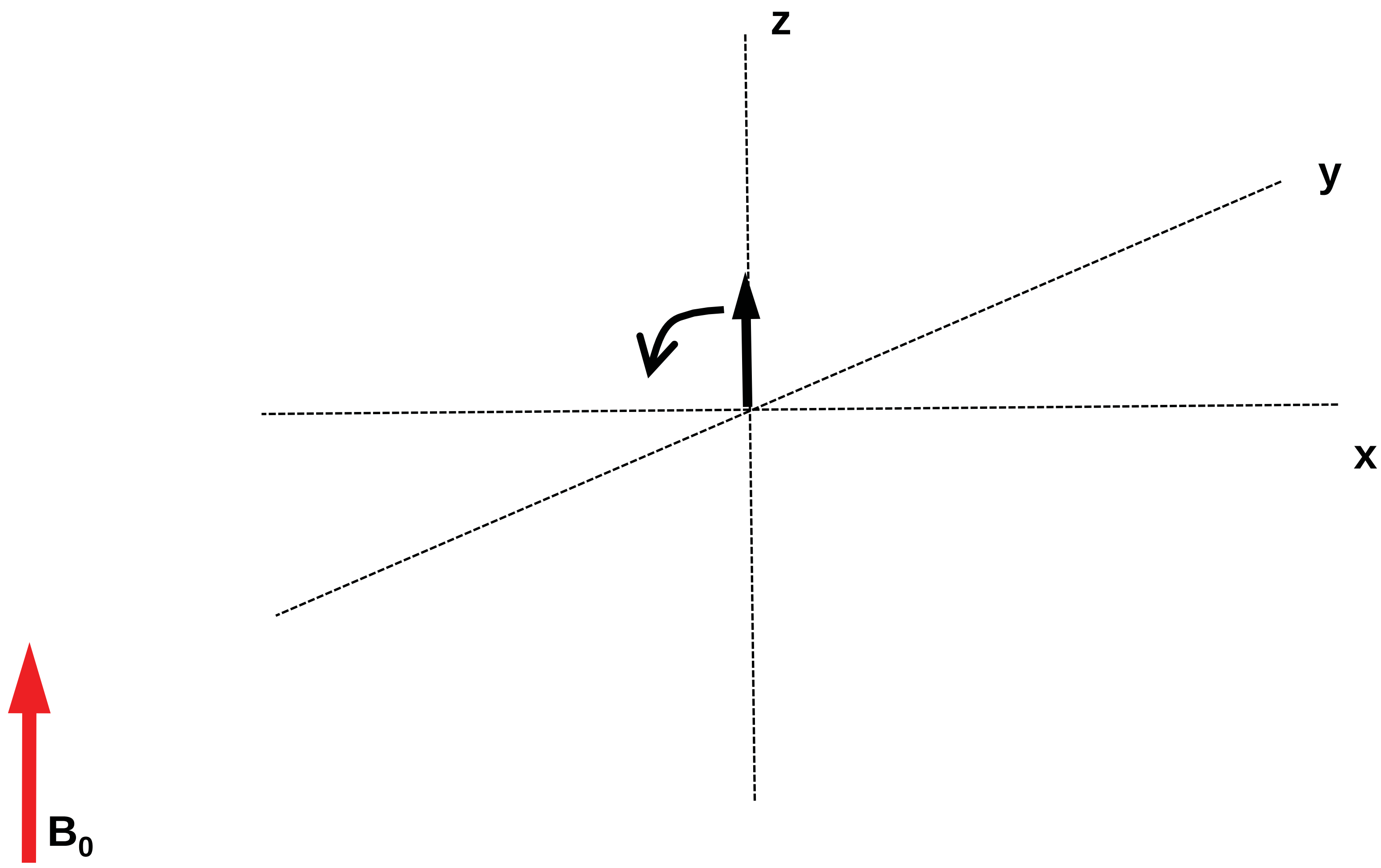
The overall signal



B_0 = 2.35 T
(100 MHz)

T = 300K

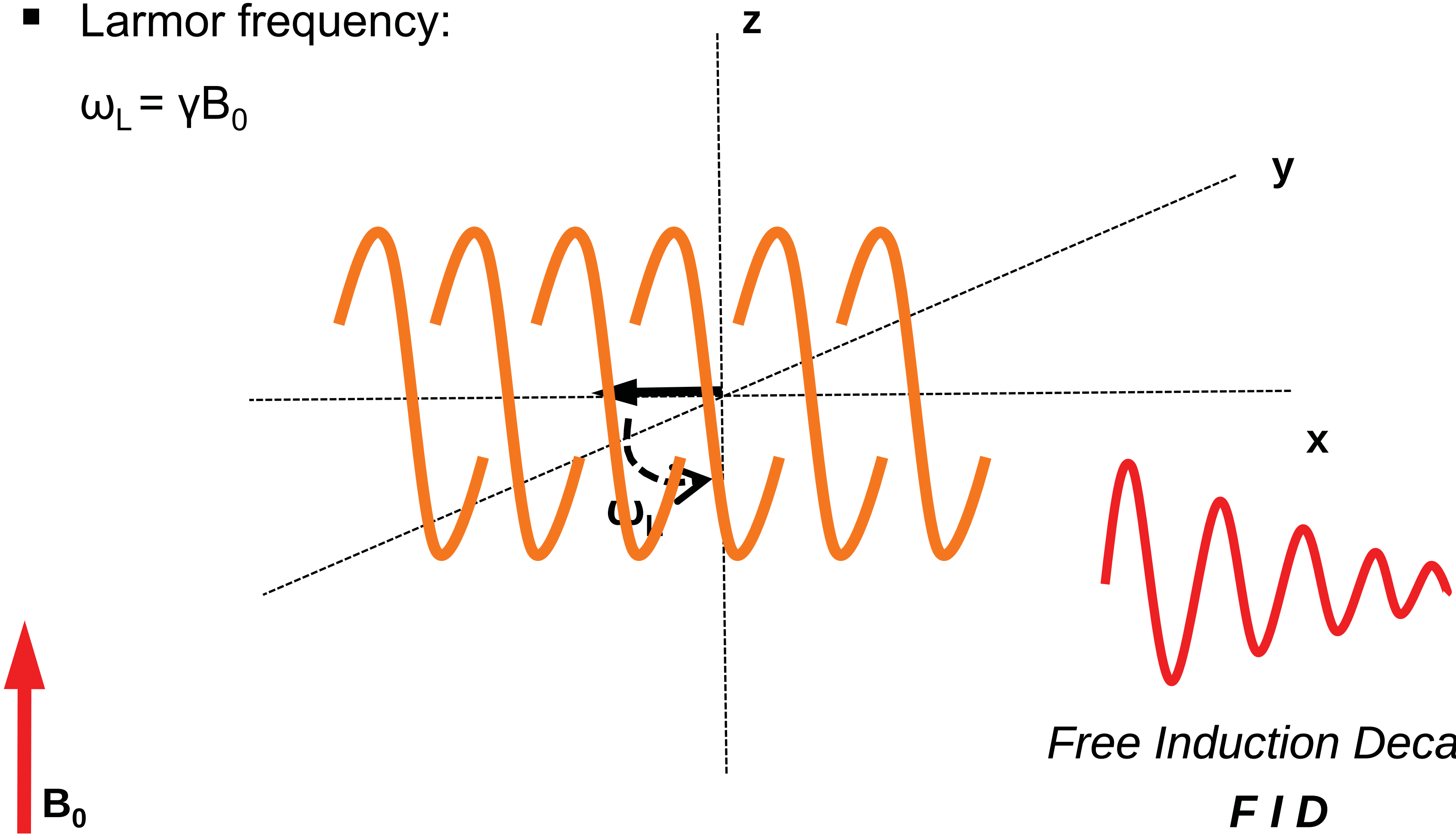
The MR experiment



The MR experiment

- Larmor frequency:

  $\omega_L = \gamma B_0$



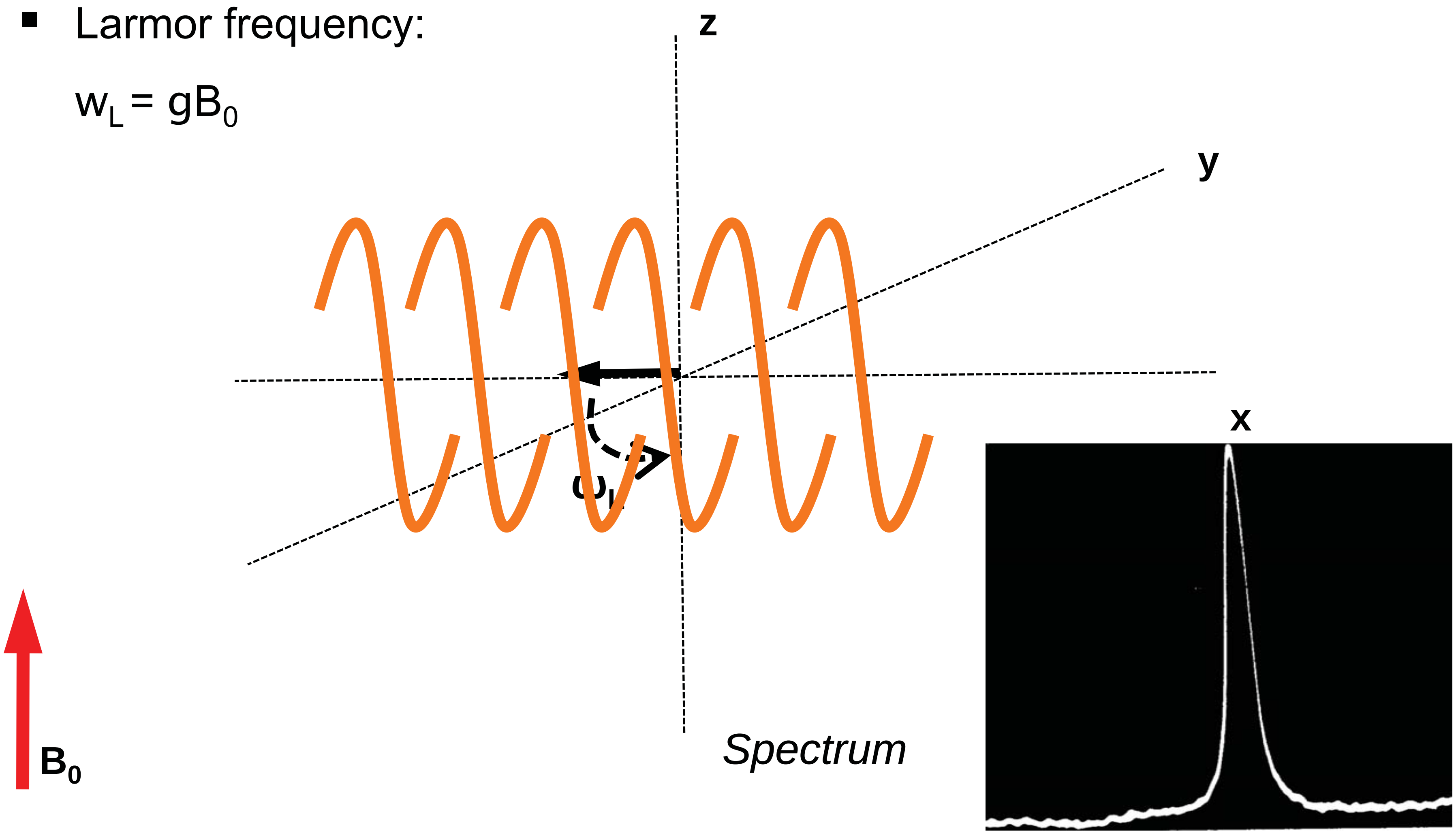
Free Induction Decay

F I D

The MR experiment

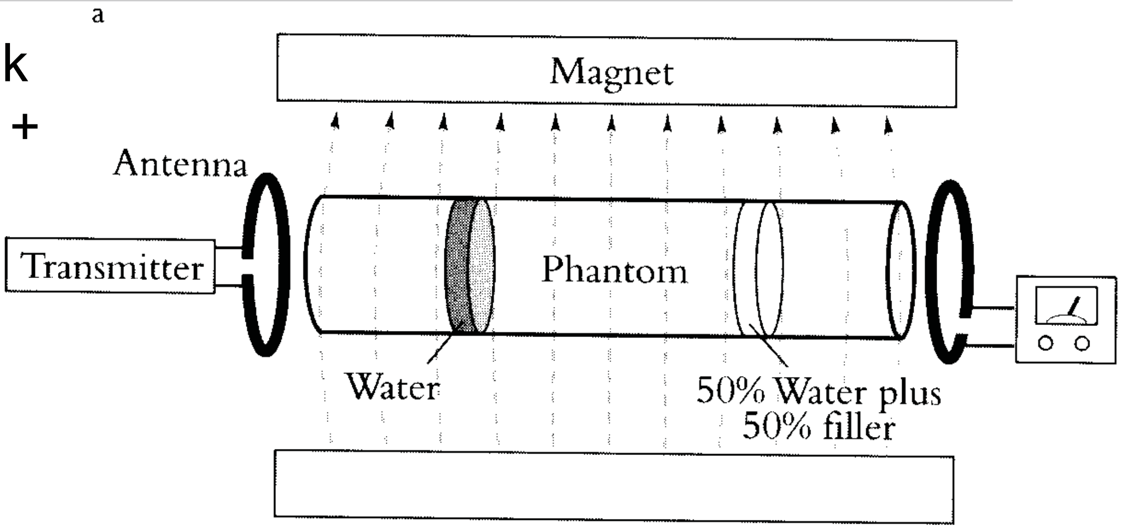
- Larmor frequency:

  $w_L = gB_0$



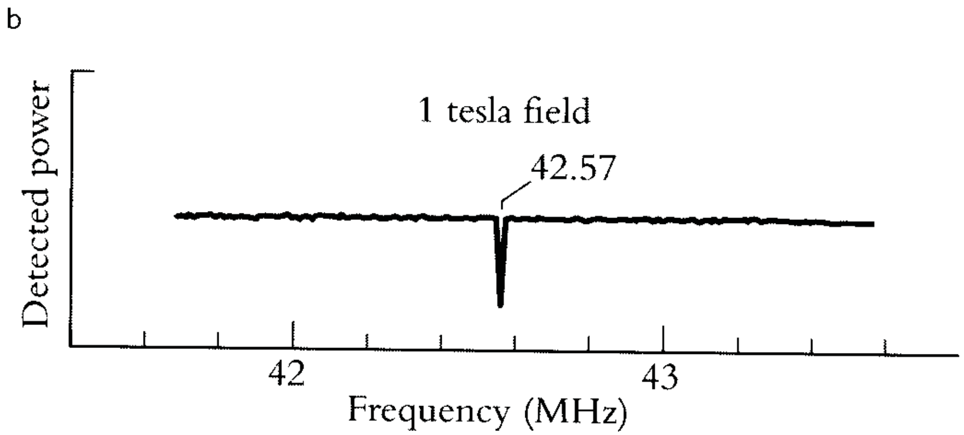
How MR imaging works?

- 1D hollow sample with 1 disk of water and 1 disk of water + foam in a constant 1T magnetic field



- resonance curve in a 1T field

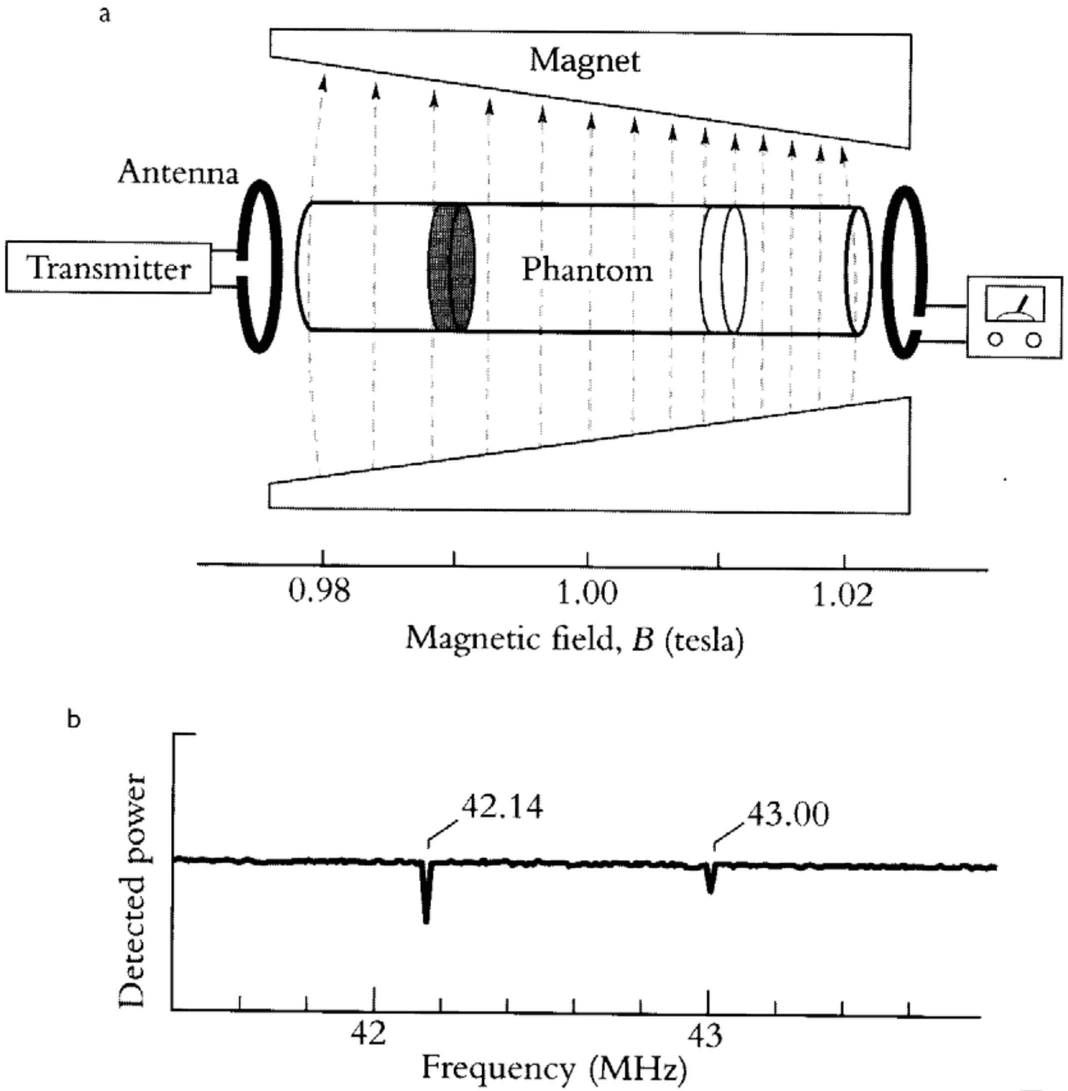
- ALL water molecules undergo a resonance at 42.57 MHz



NOT EXCITING …

How MR imaging works?

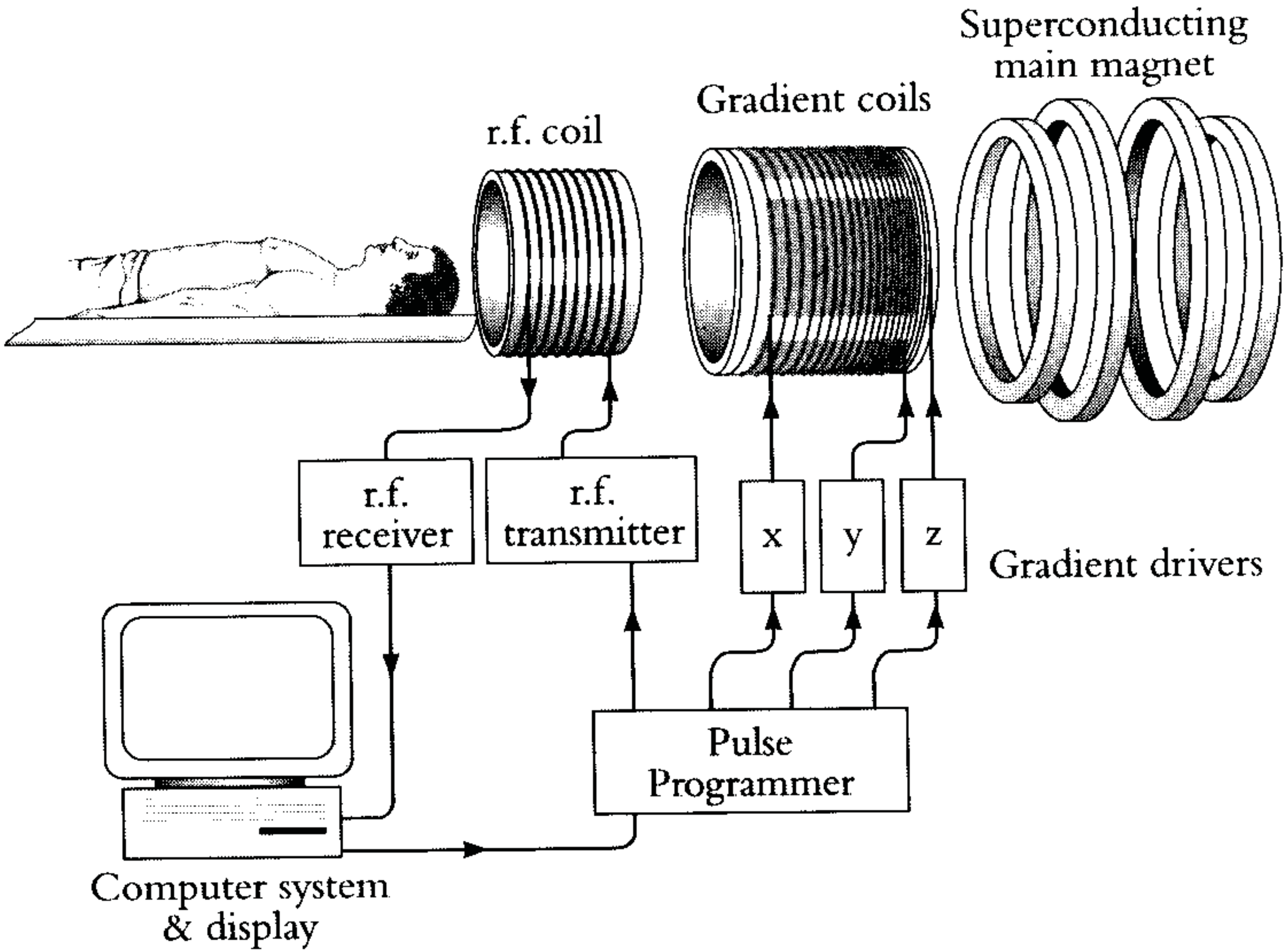
- the same sample in a non-uniform magnetic field



- resonance curve in a 1T field
- 2 resonance peaks with 2 different amplitudes

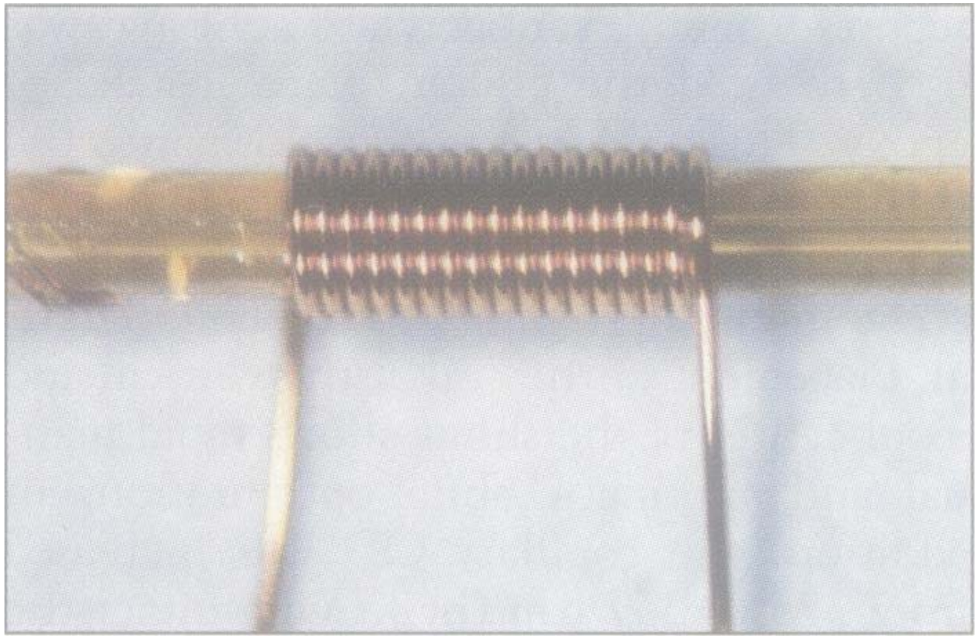
VERY EXCITING!!

General structure of an MRI scanner



Development of wirebonded microcoils as MR detectors

Hand-wound μ-coil



Olson et al., Science, vol. 270, p.1967, 1995.

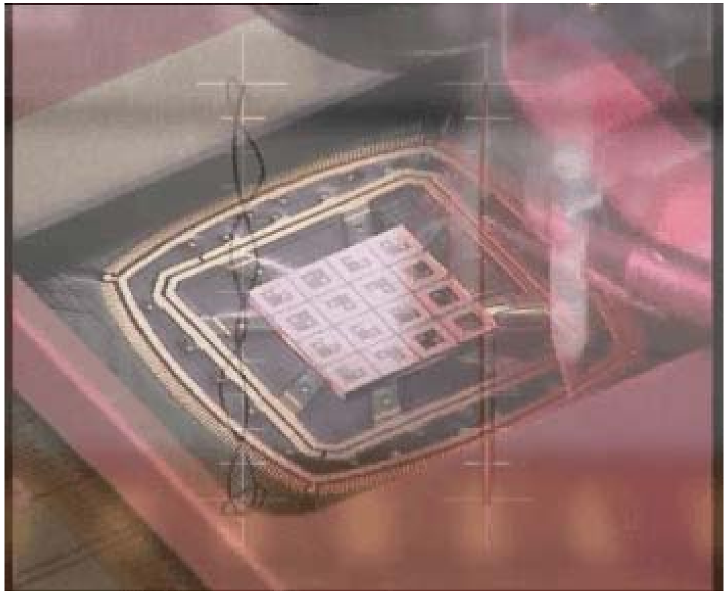
Still needed?

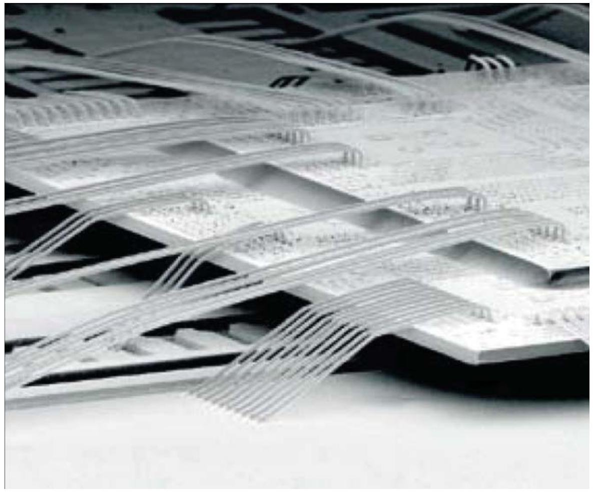
Meaningful process for:

- Circular solenoids
- Scalable in size
- Parallel processing or instead very fast
- Useful for many purposes

Coils through wire bonding

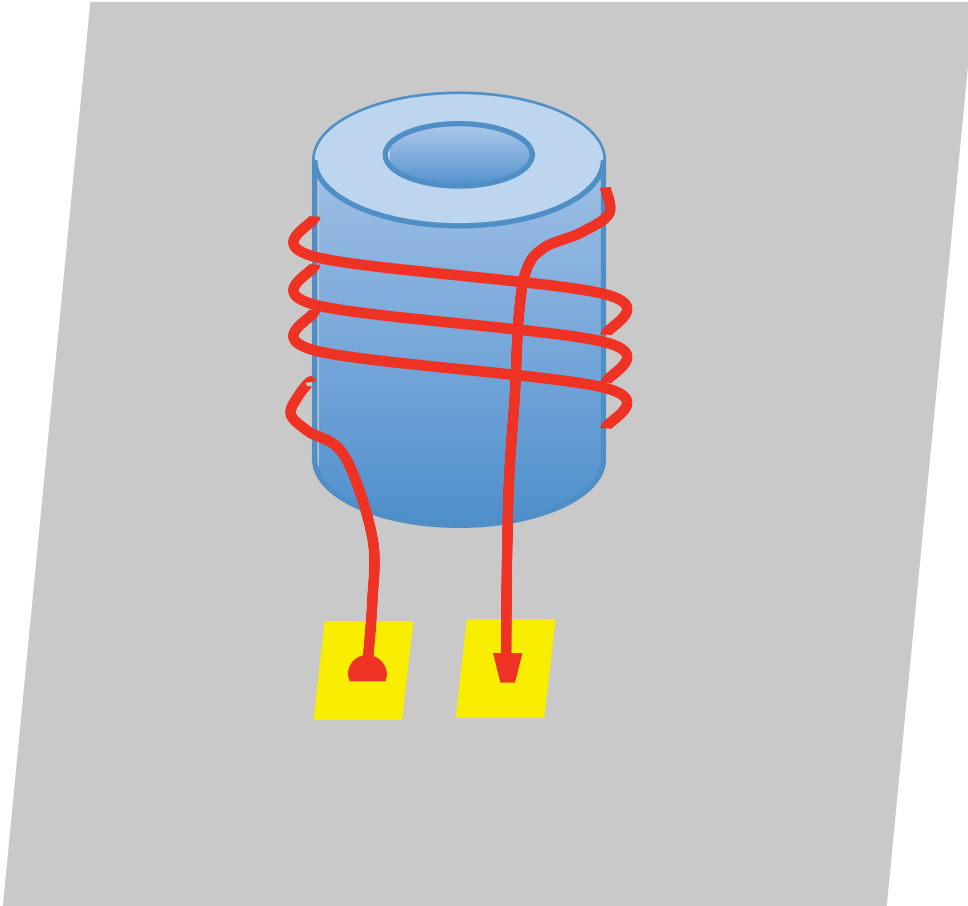
Wirebonding technology





Wirebonding technology

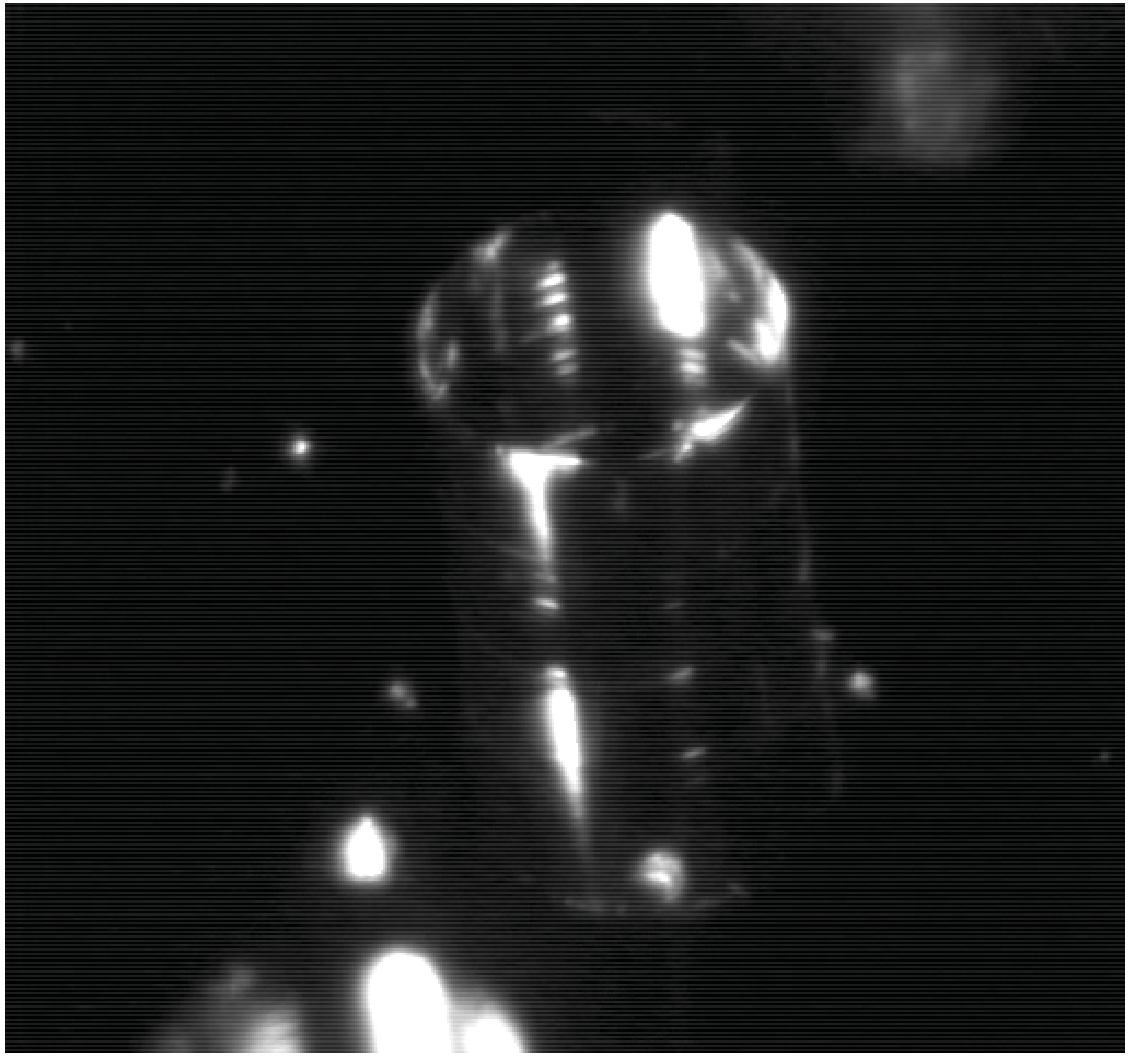
- Substrate: silicon or glass
- Pads: Cr/Au (50/500 nm)
- Posts: Lithography of SU-8 or PMMA – 600 μm height
- Coil: Wire Bonder with insulated gold wire 25 μm diameter



JMM, vol. 20, 015021, 2010

Sensors & Actuators A, vol. 156, p.328, 2009

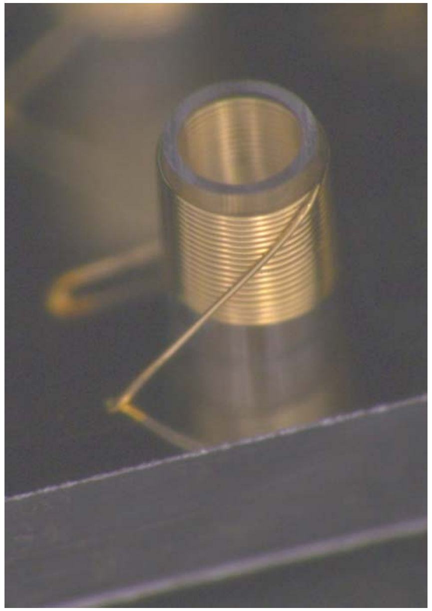
Wirebonding of solenoidal microcoils

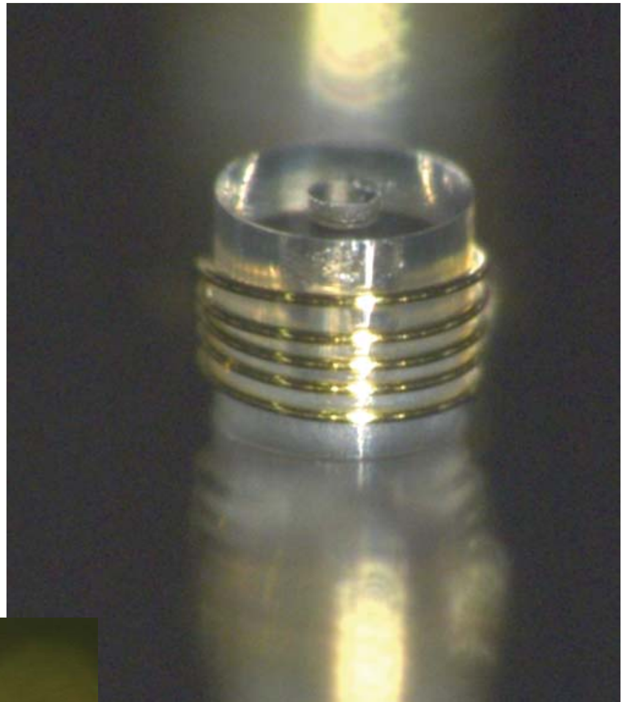


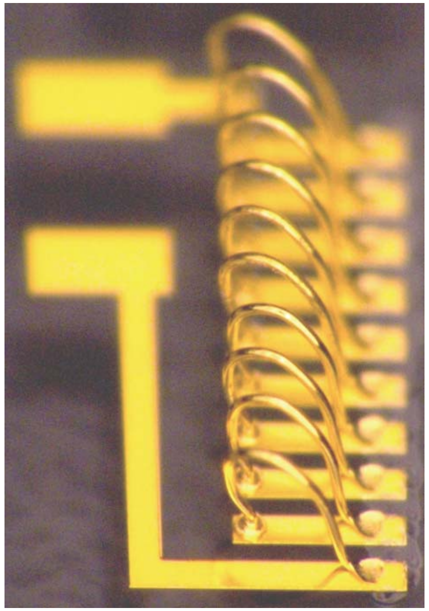
Sens. Act. 156, p. 328 (2009)

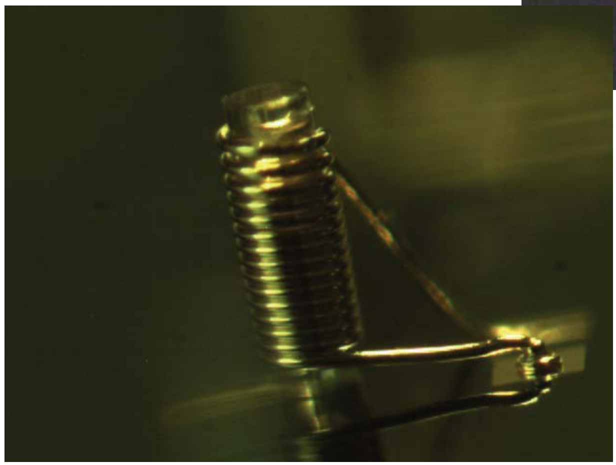
JMM, 015021 (2010)

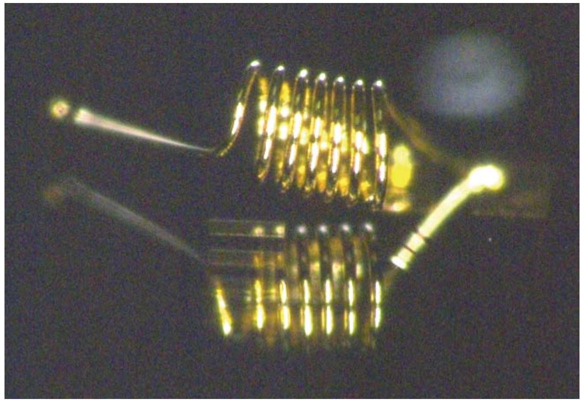
Gallery









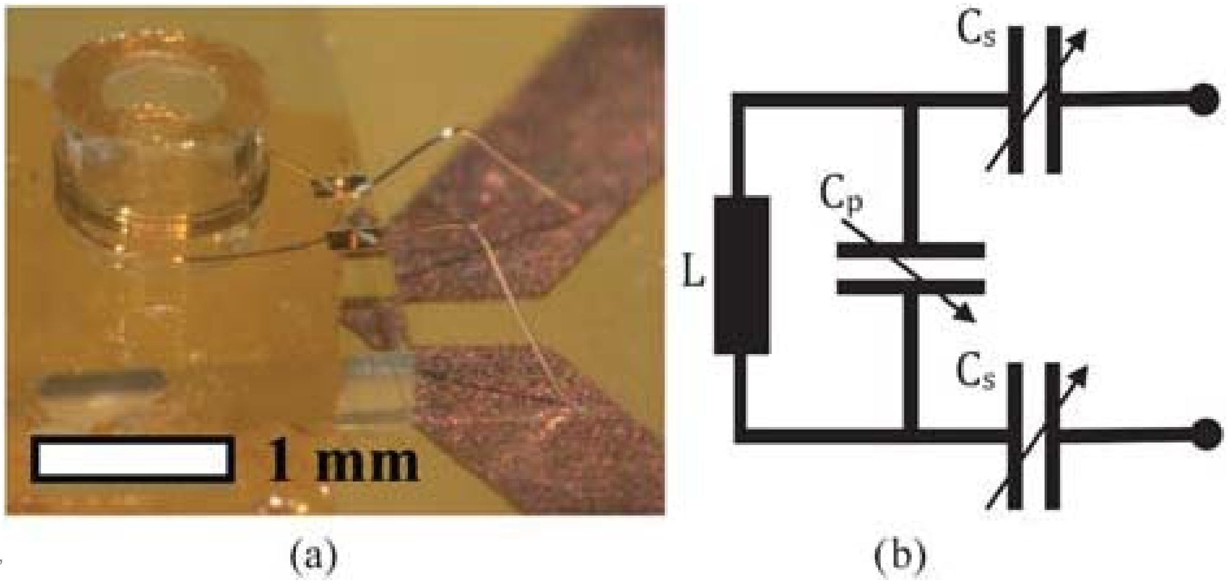


Gallery

Magnetic resonance imaging (MRI) for microscopic samples

Experimental – MRI @ 9.4 T

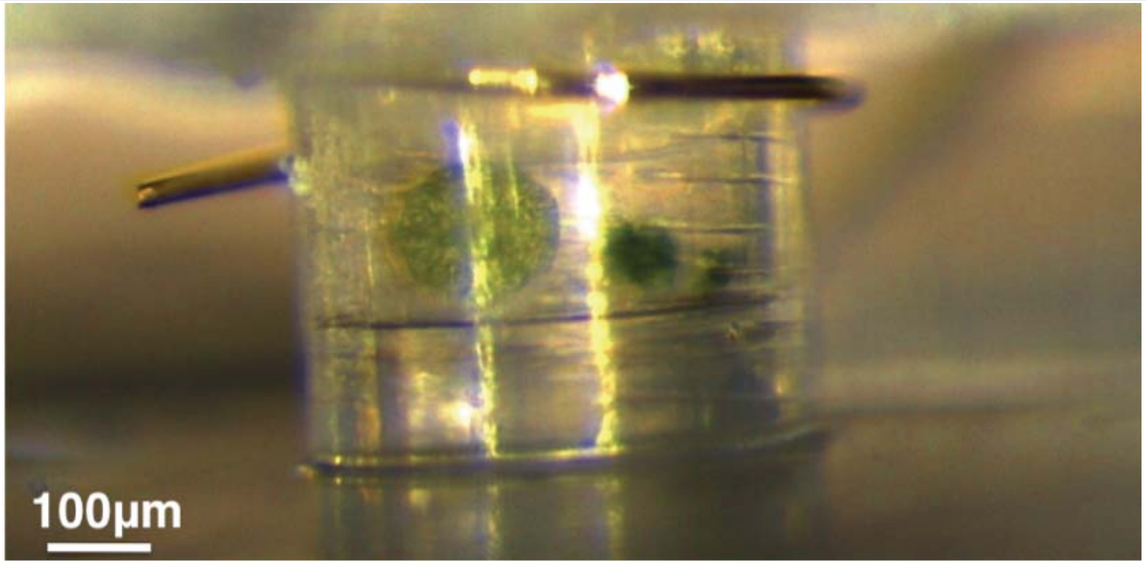
- **9.4T** MRI scanner – ^{1}H Larmor frequency = **400 MHz**
- coil connected with PCB tuning and matching circuit @ 400 MHz / 50 Ω
- signal transmitted via wires tethered at the terminals of the circuit

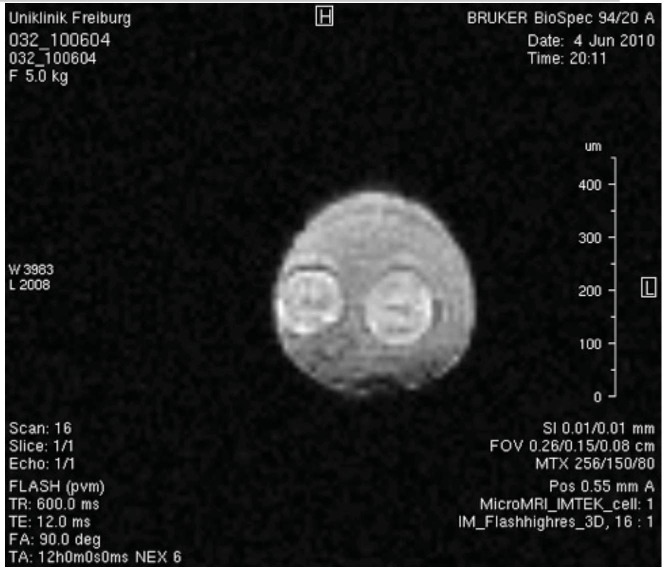


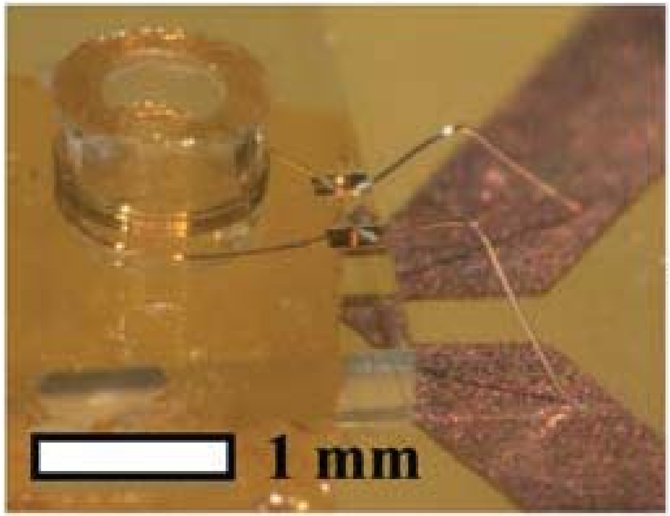
V. Badilita et al.

Lab Chip, p. 1387 (2010)

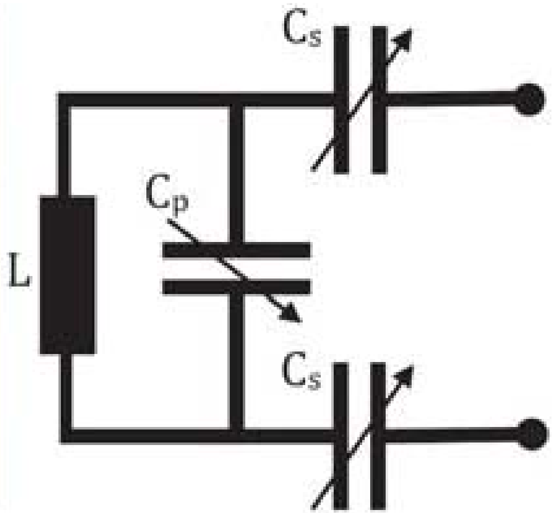
Imaging of algal cells







(a)



(b)

MEMS 2011, p. 809

Magnetic resonance spectroscopy for microscopic samples

Magic Angle Spinning NMR spectroscopy

- nuclear spin interactions (dipolar, chemical shift anisotropy, quadrupolar) lead to broad and featureless lines

↓

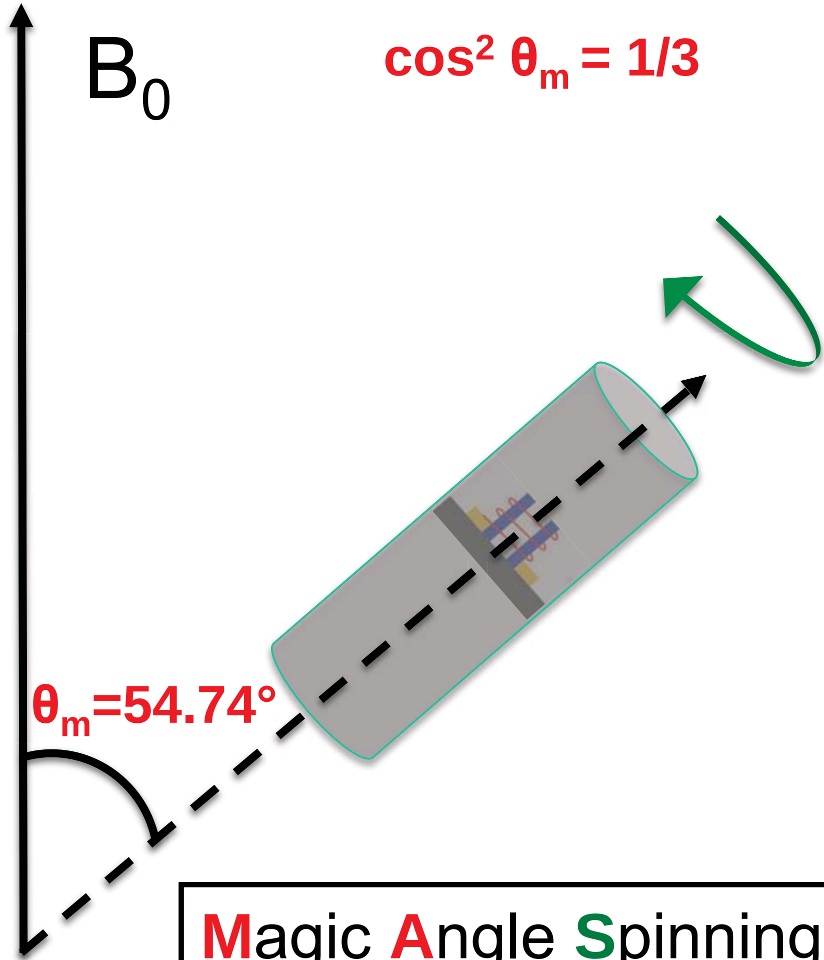
- nuclear spin interactions are time dependent and can be averaged by magic angle spinning

↓

- high resolution spectra

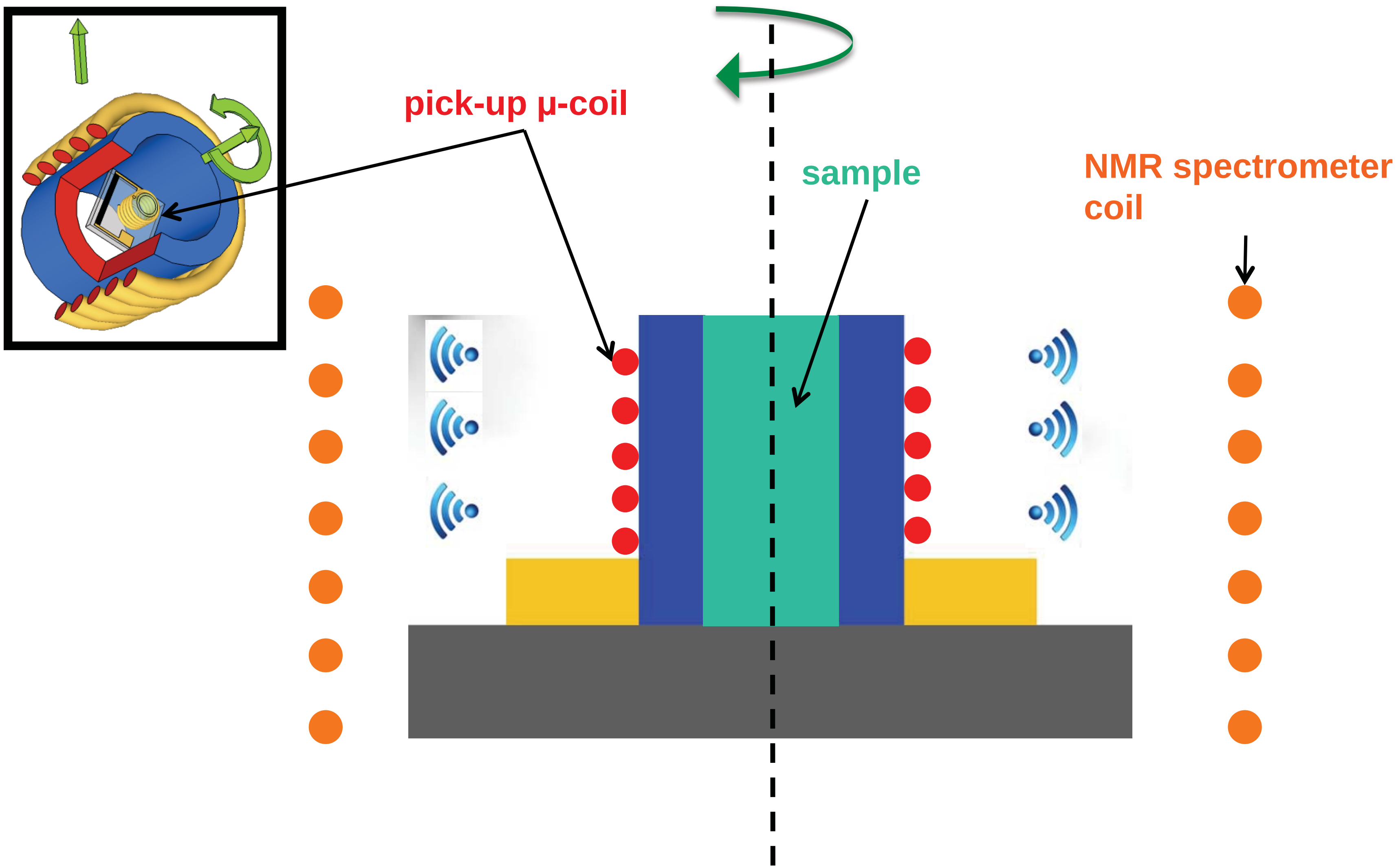
+

- high sensitivity



Magic Angle Spinning configuration

Why inductive coupling for NMR?



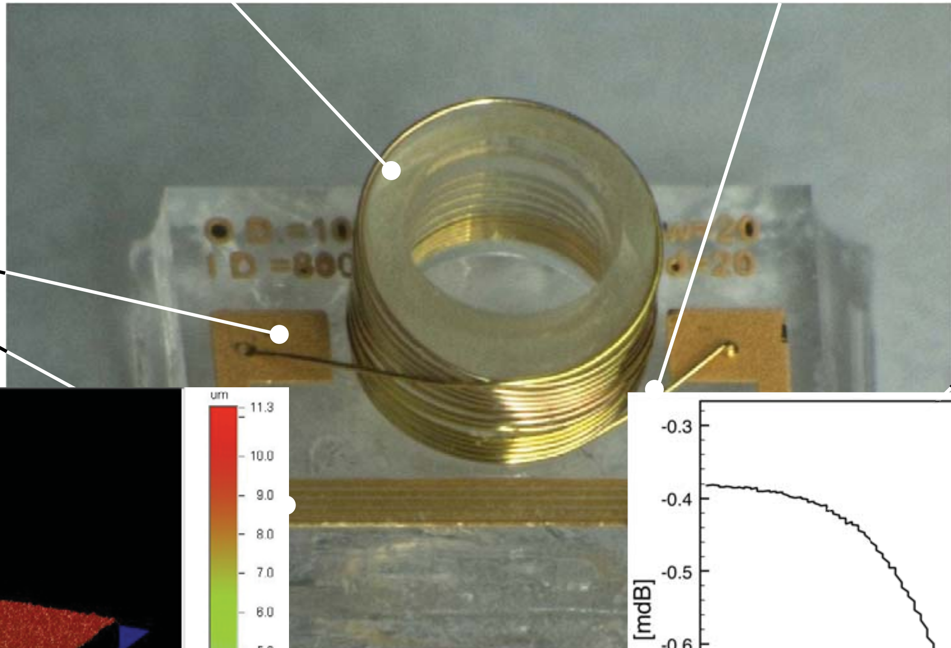
Wirebonded microcoil for wireless NMR

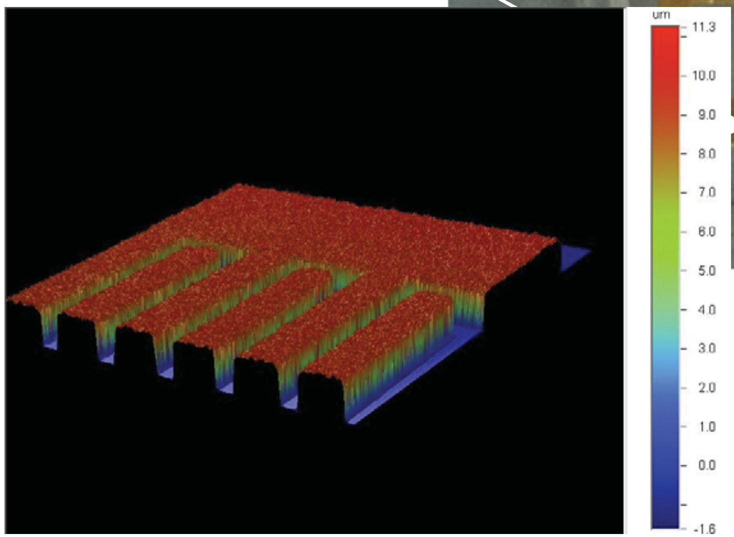
transparent SU-8
sample holder

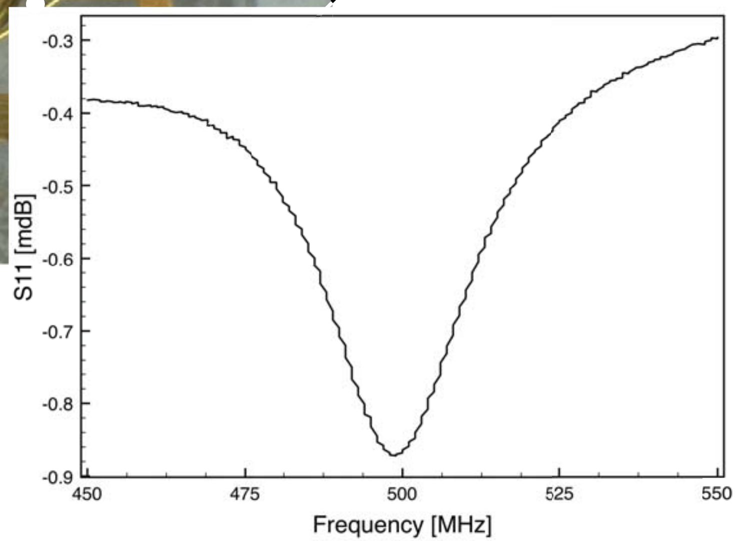
insulated Au wire
25µm diameter

electroplated Au pads +
interdigitated capacitor

transparent Pyrex
substrate

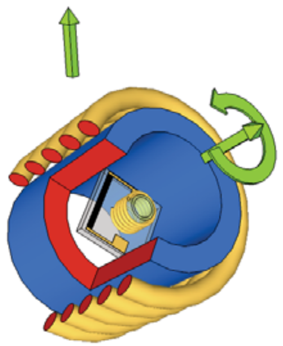


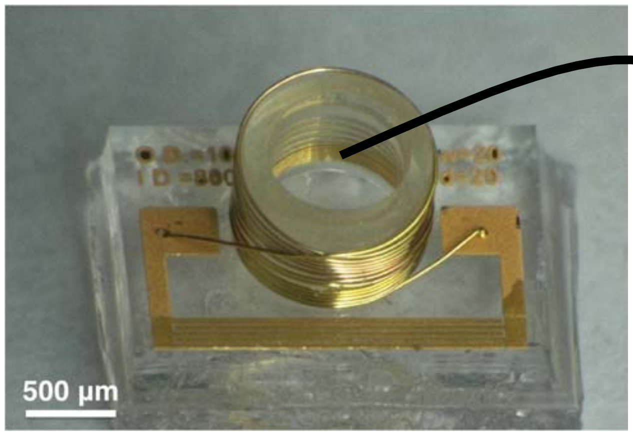


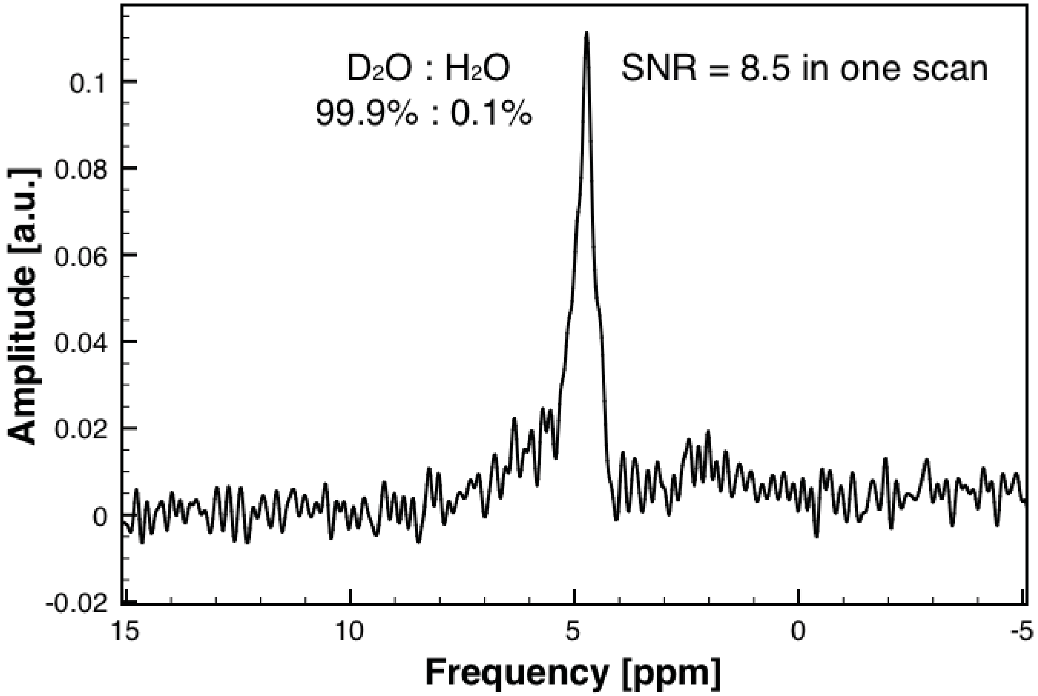


Inductive coupling – high sensitivity

- vertical bore 11.7 T spectrometer
- [1]H Larmor frequency = 500 MHz





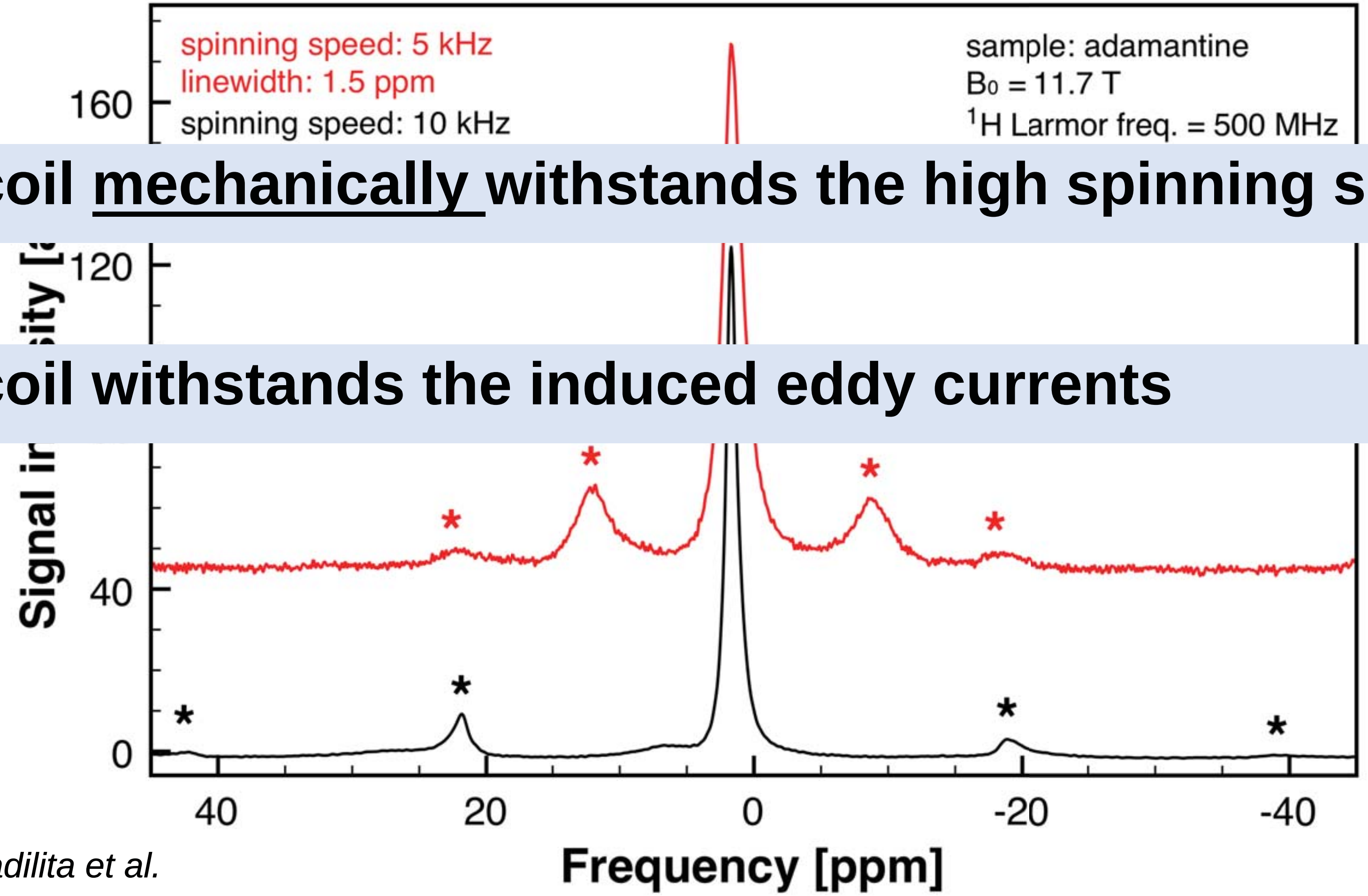


- mixture D_2O:H_2O 99.9 : 0.1%
- signal from 300 pl H_2O
- ≈ 10^{15} protons

Inductive coupling – coil spinning

the coil <u>mechanically</u> withstands the high spinning speed

the coil withstands the induced eddy currents



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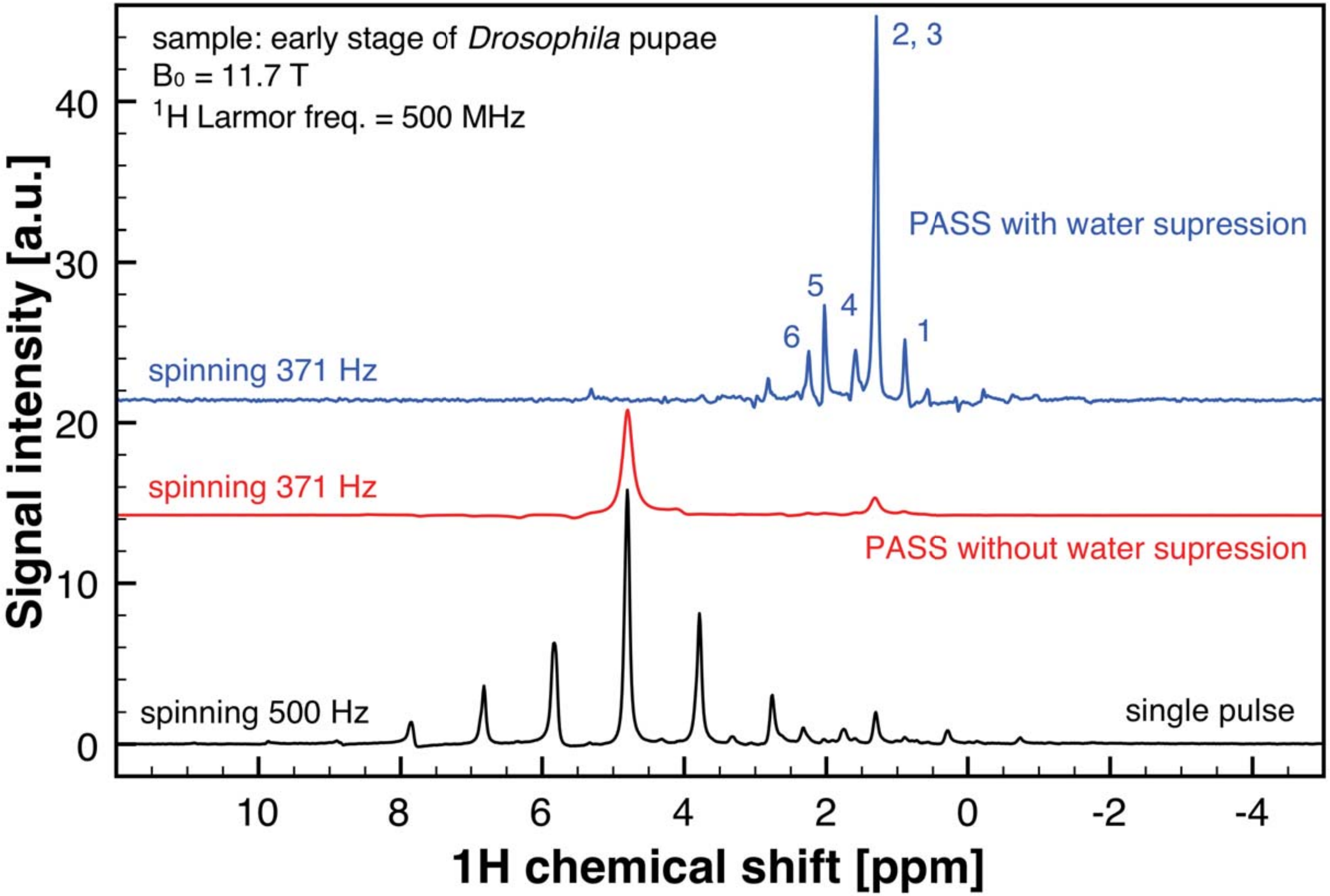
PLoS ONE, e42848 (2012)

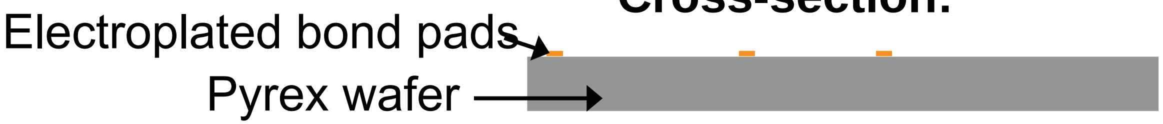
Inductive coupling – coil spinning



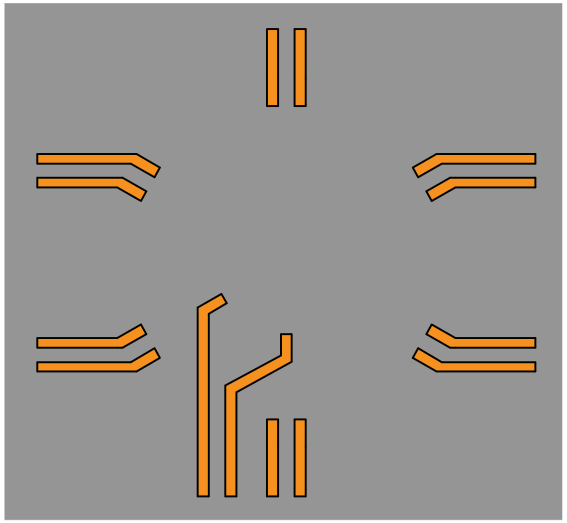
Planar phased arrays of microcoils

Wirebond wound multilayer process

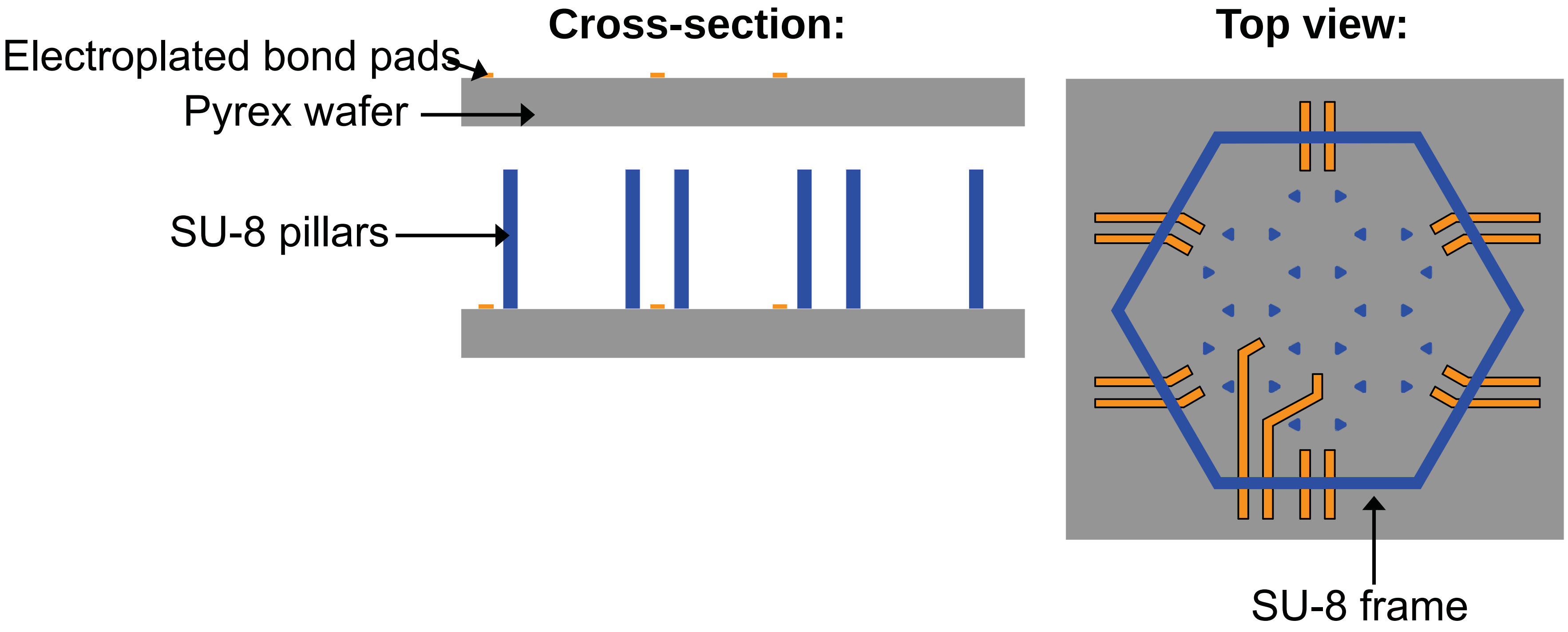
Cross-section:



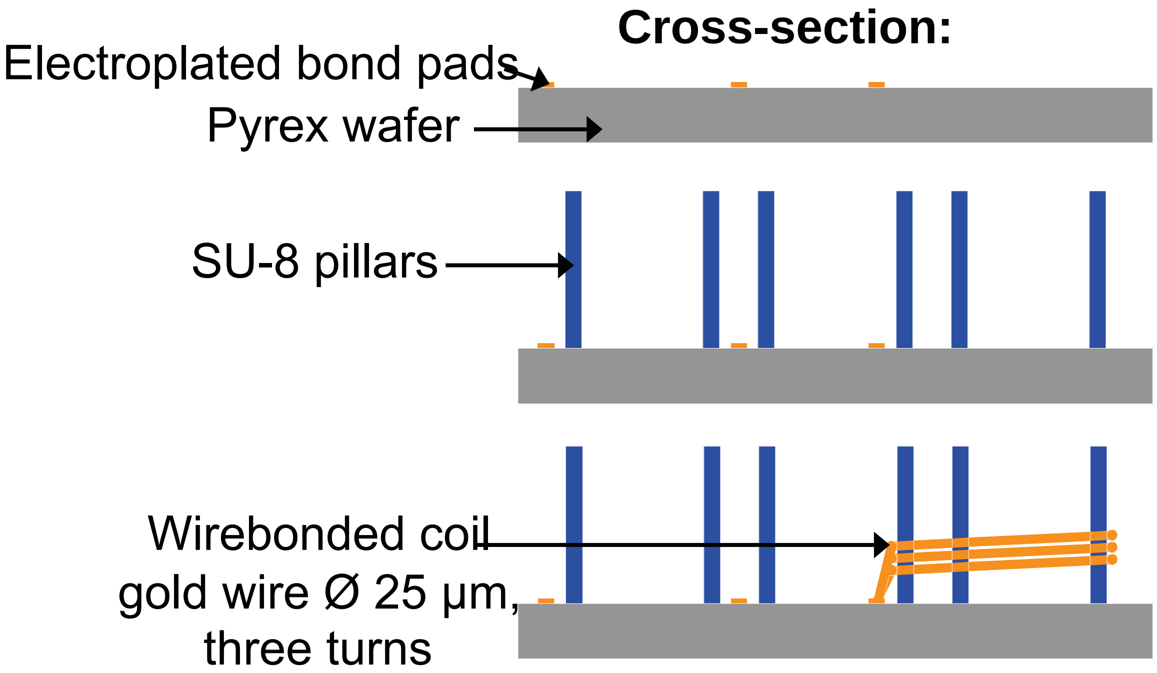
Top view:

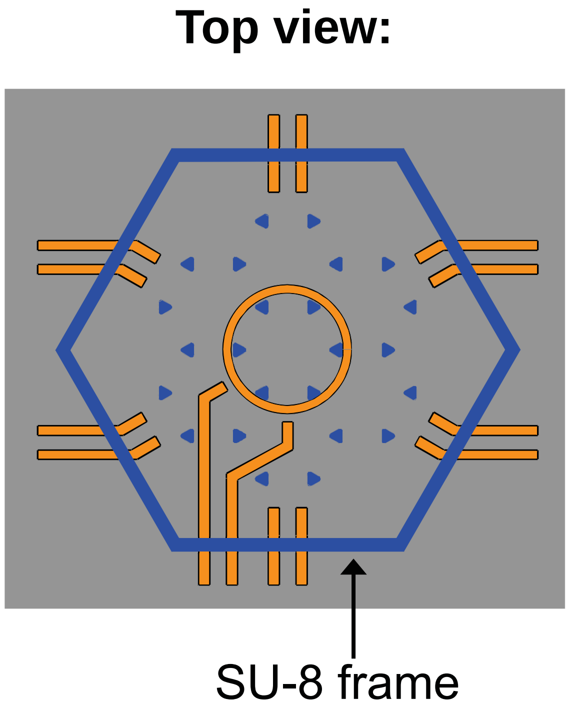


Wirebond wound multilayer process

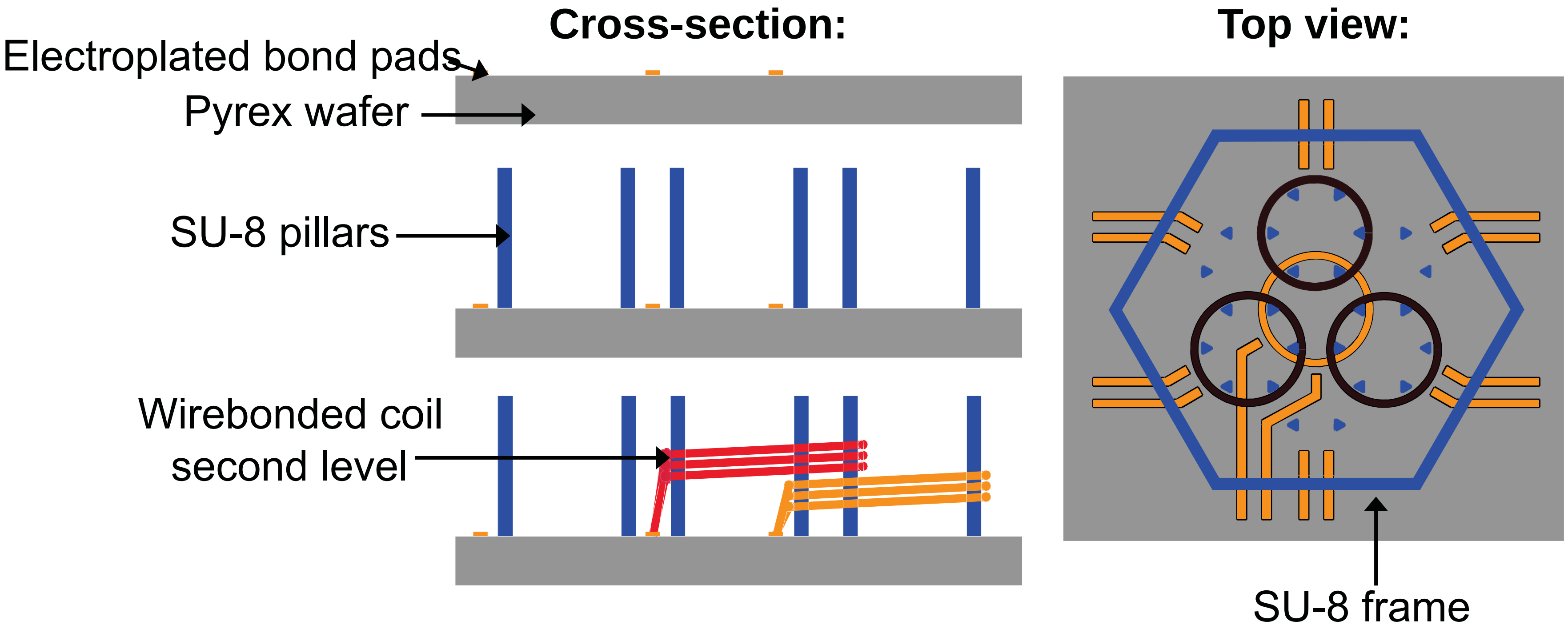


Wirebond wound multilayer process

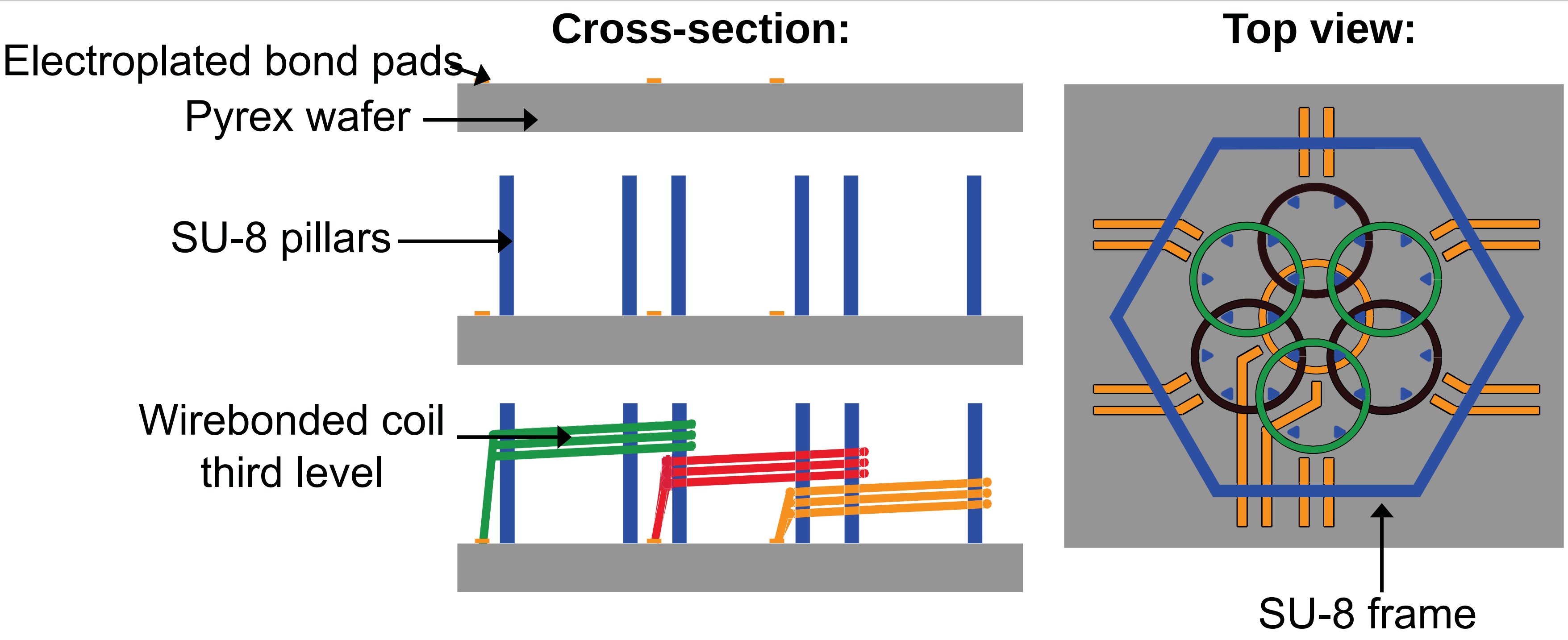




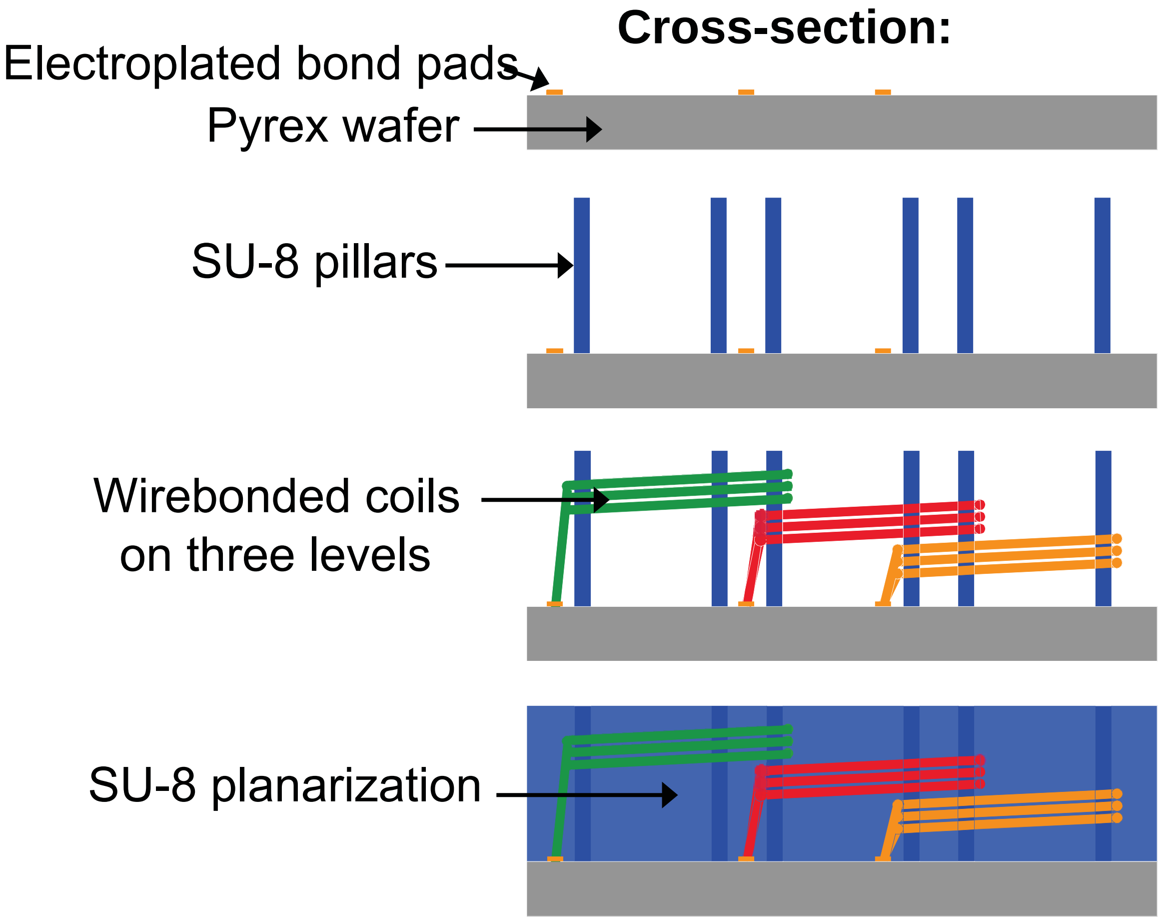
Wirebond wound multilayer process

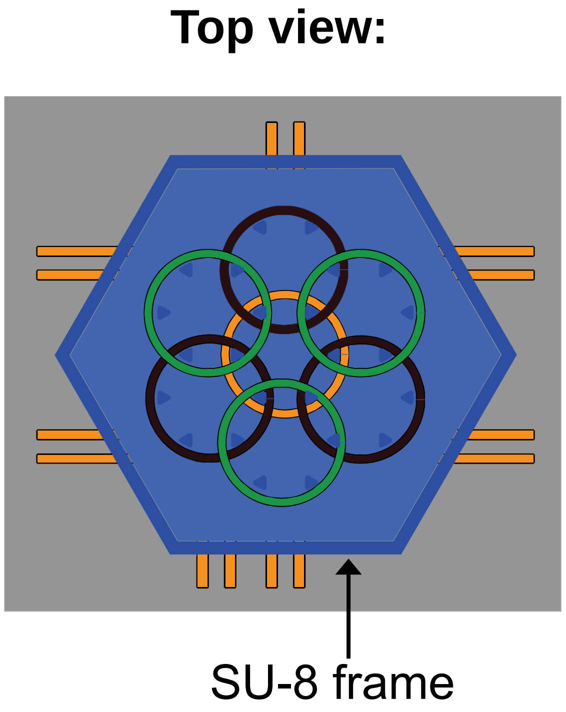


Wirebond wound multilayer process

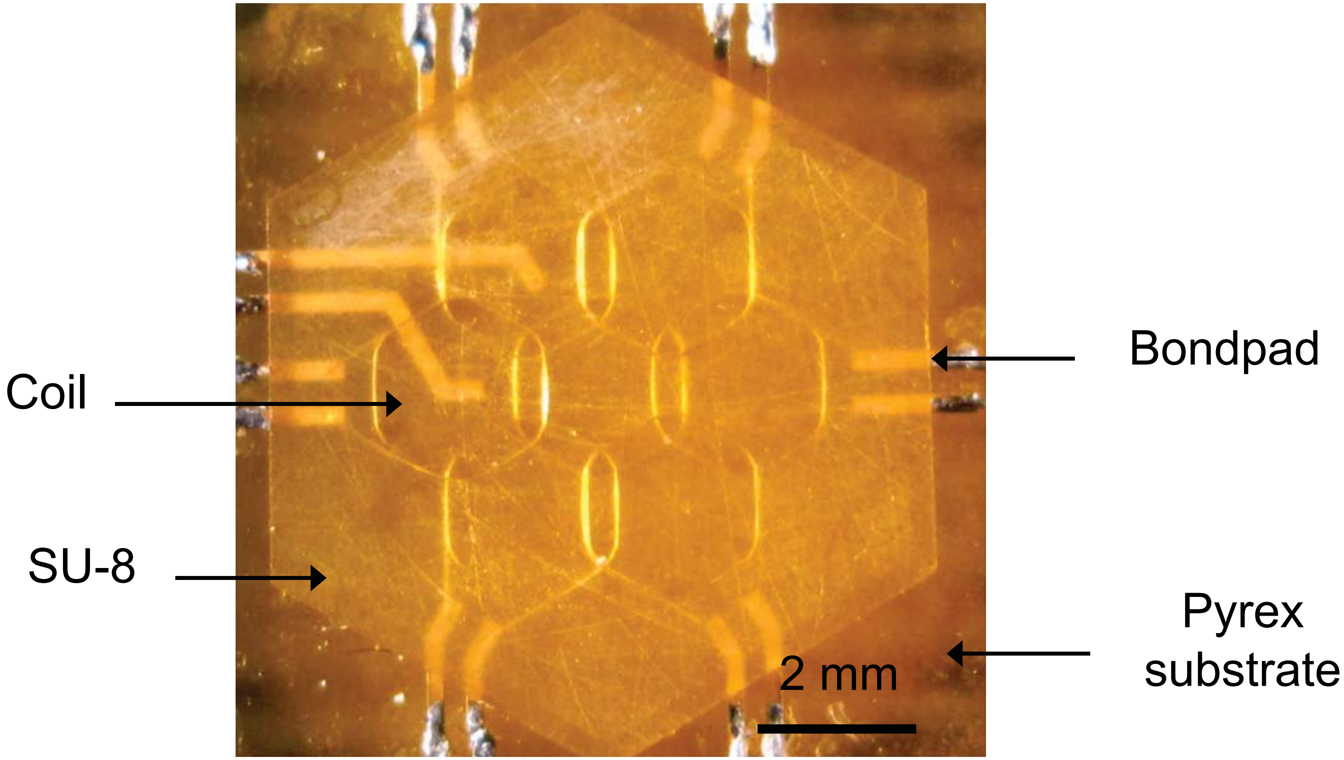


Wirebond wound multilayer process





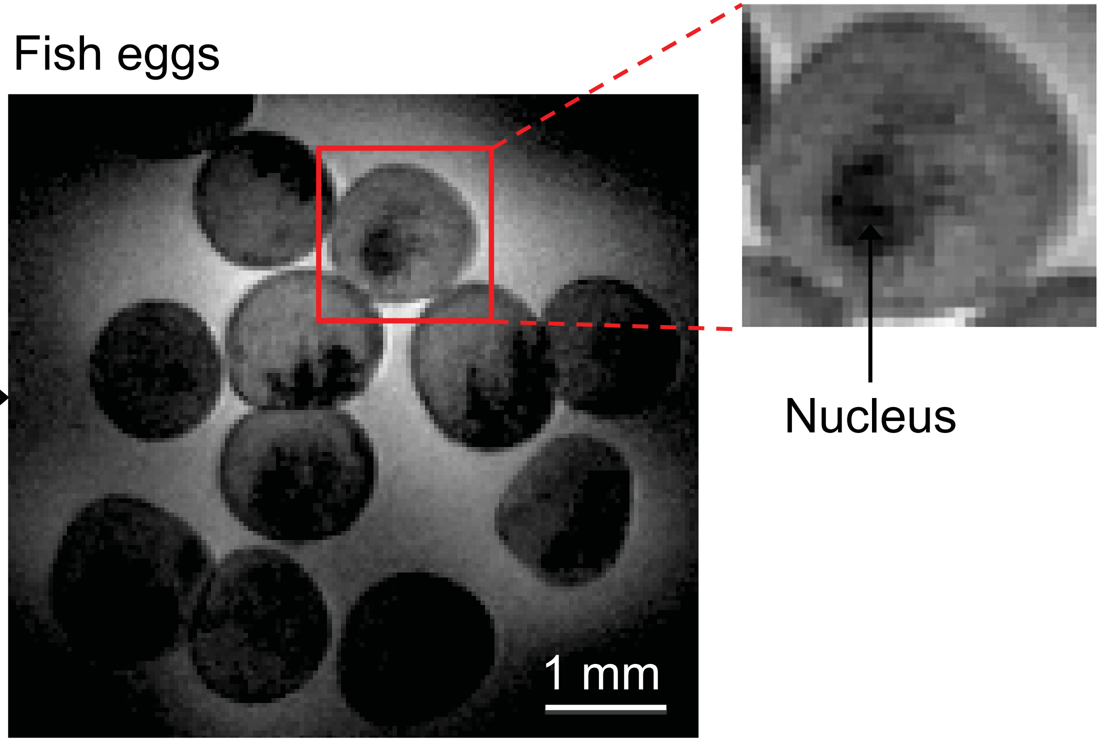
Wirebond phased array of microcoils



Results - Imaging

Sample container:

Fish eggs



Nucleus

In-plane resolution of 30 x 30 μm^2

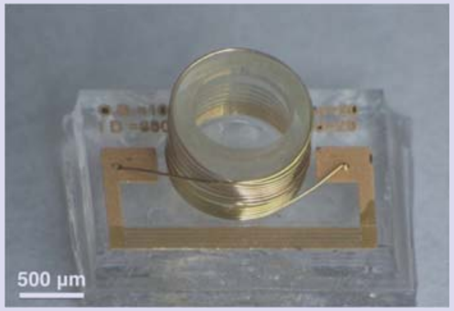
Contrast to noise ratio 10

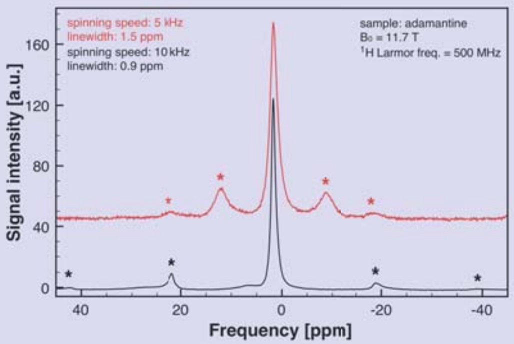
Measurement time 13 min 49 s

FOV 0.55 cm

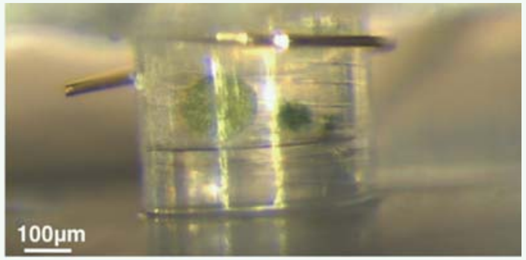
Conclusions – WB µ-coils for µ-APPs

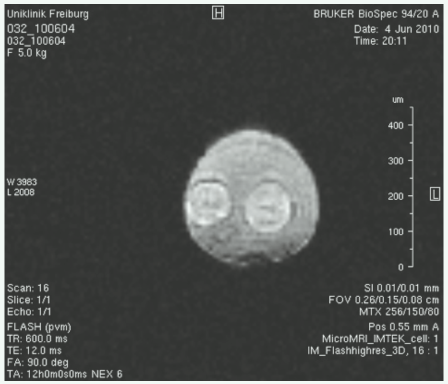
µ-coils for MACS



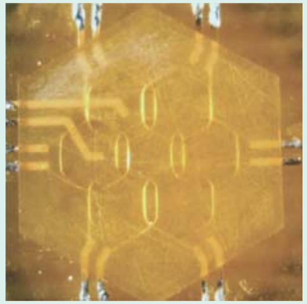


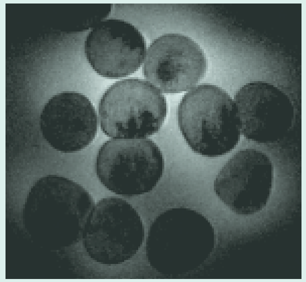
µ-coils for µ-MRI





phased arrays





FOV 0.55 cm

V. Badilita et al.

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Thank you!