MR HARDWARE & SAFETY

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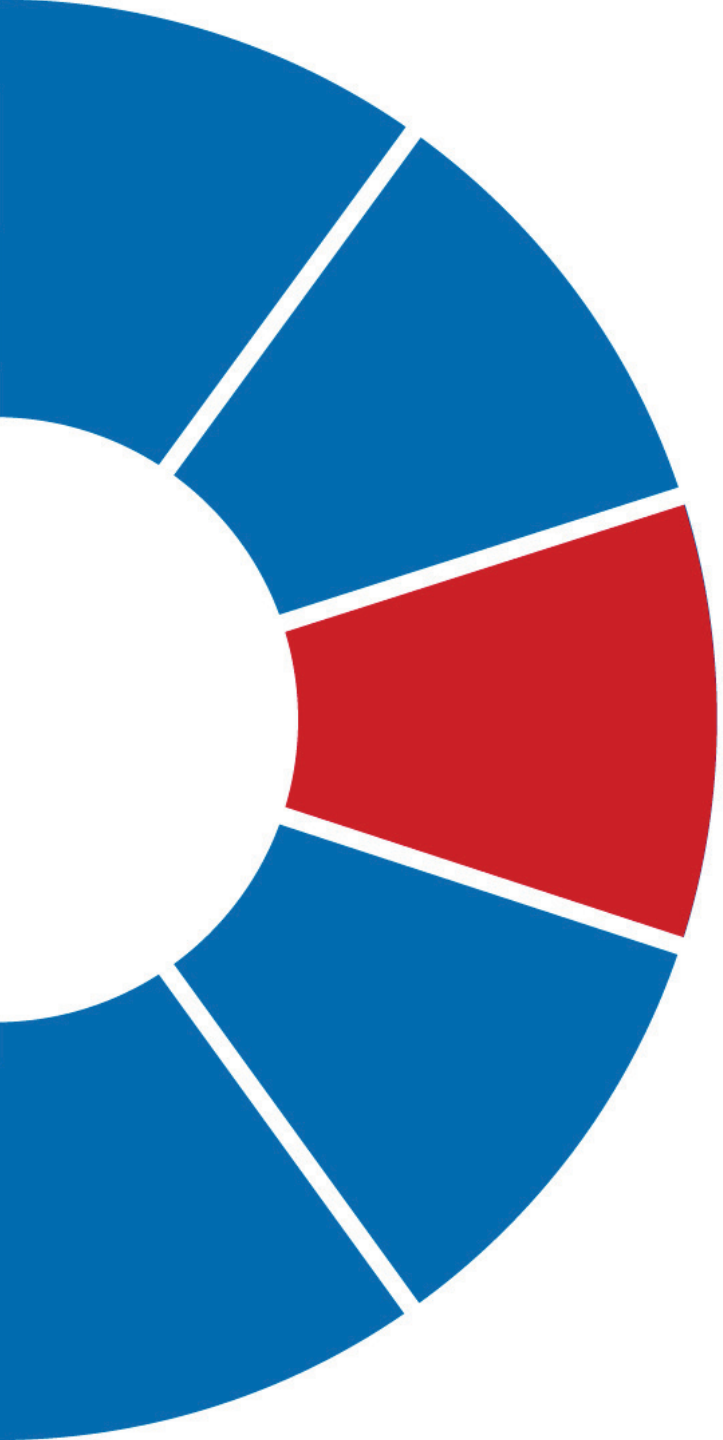
CIBM PCI EPFL

PHYS-473 MRI Practicals on CIBM preclinical imaging systems

16 September 2025

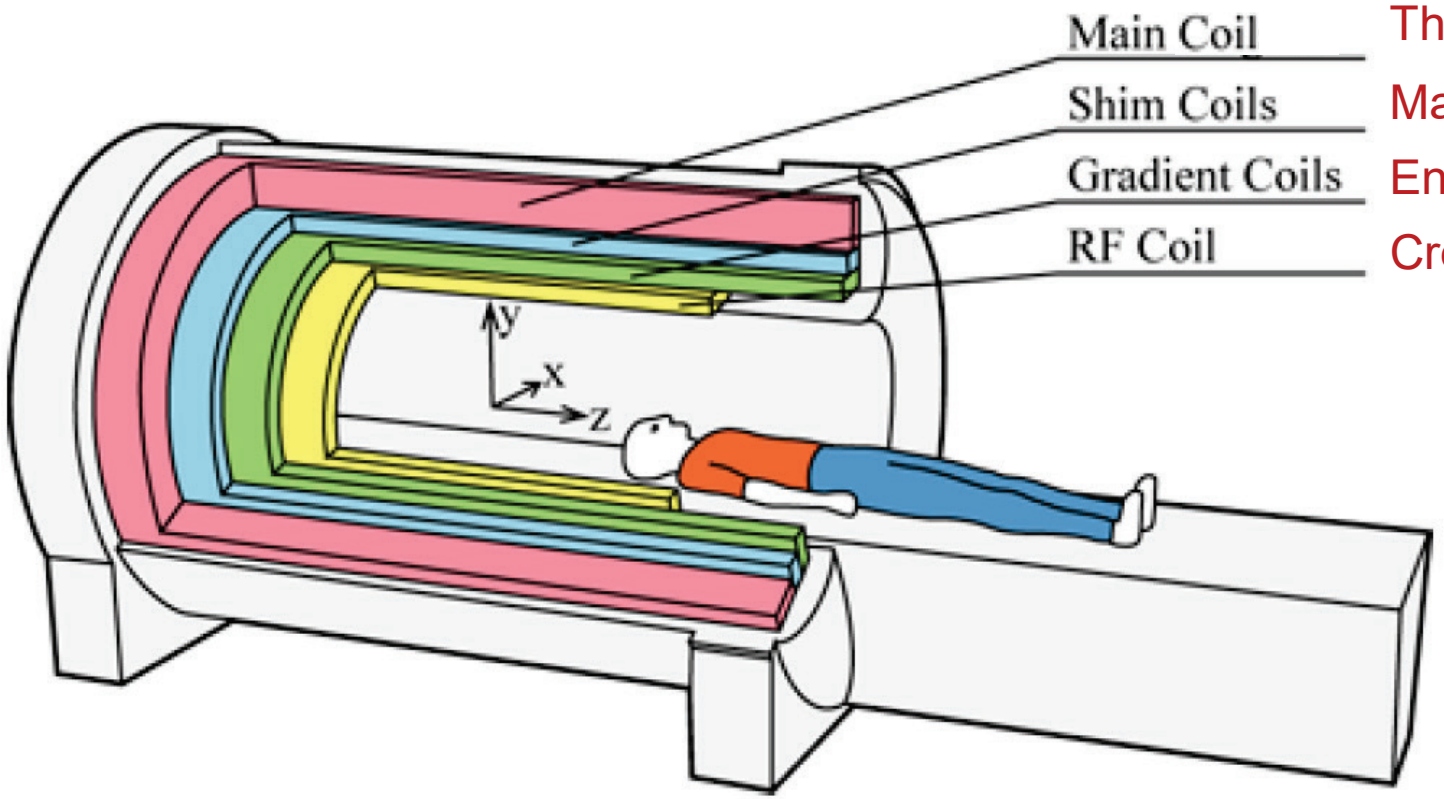
OUTLINE

- Overview of the MR system
- MR Safety
- Visit of the 14.1T MRI scanner



OVERVIEW MR SYSTEM

MRI SYSTEM OVERVIEW



The «strong» magnetic field

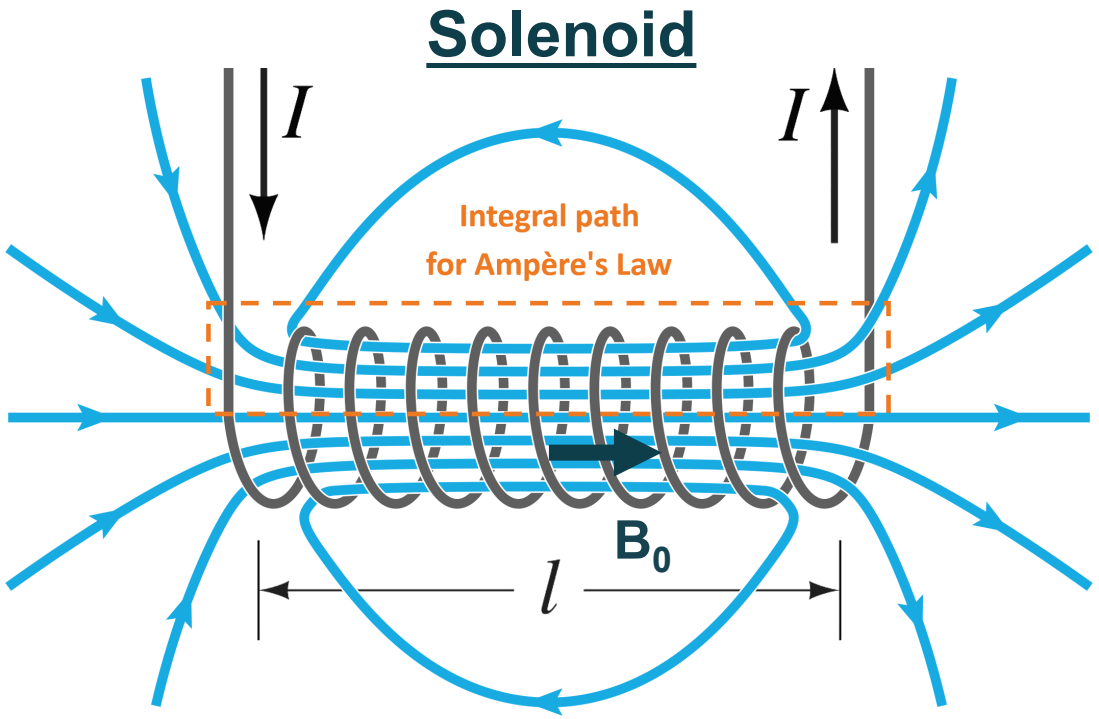
Make it homogenous

Enable localization of the signal

Create and read the signal

B_0 COIL

- What is the easiest way to produce B_0 ?



After applying Ampère's law

$$B_0 = \mu_0 \frac{NI}{l}$$

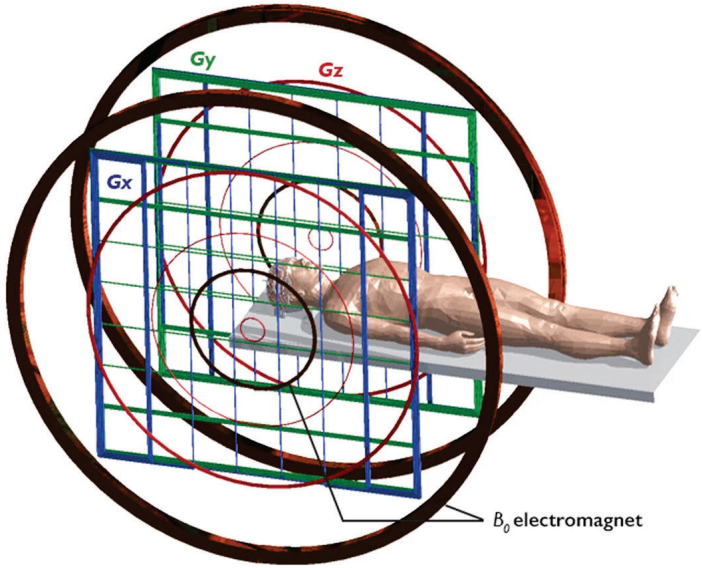
Beware of Joule heating!

$$P = R\,I^2$$

STATIC FIELD (B_0)

- Produces the static magnetic field B_0
  - Permanent magnet (< 1 T)
  - Electromagnet (resistive, < 1 T)

Hyperfine Swoop, 64 mT, 630 kg



6.5 mT electromagnet, MGH

STATIC FIELD (B_0)

- Produces the static magnetic field B_0
  - Permanent magnet (< 1 T)
  - Electromagnet (resistive, < 1 T)
  - Superconducting magnet (from 0.5T up to 11.7T human, 21.1T preclinical)

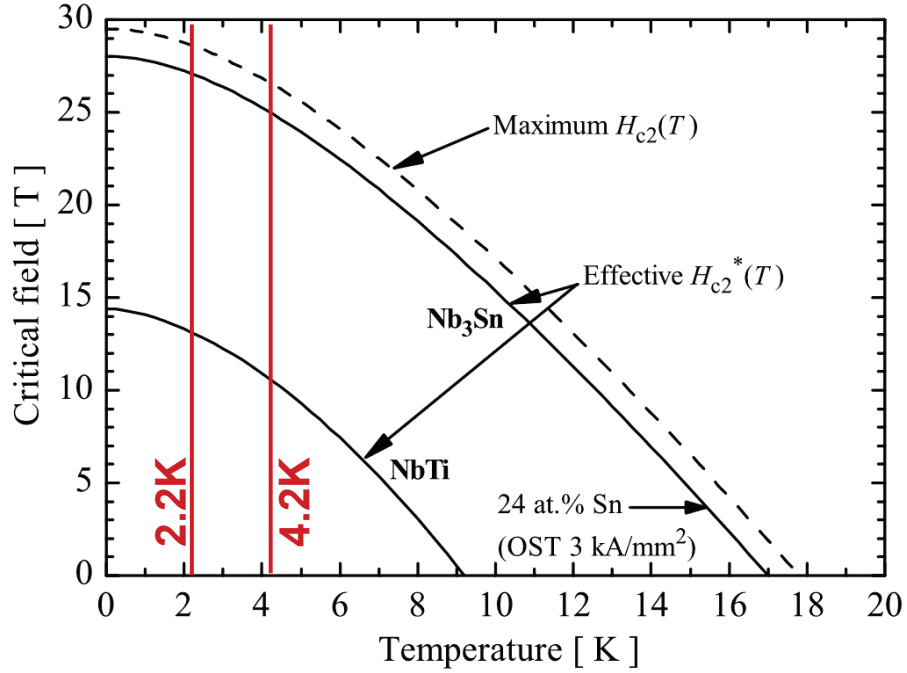
Hyperfine Swoop, 64 mT, 630 kg

Iseult magnet, 11.75 T, ~150 tons
5m outer diameter

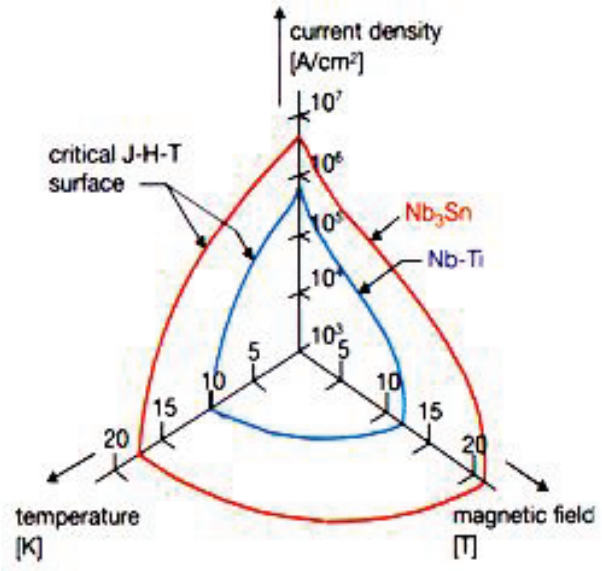
Bruker's strongest horizontal MRI, 21.0 T

SUPERCONDUCTING B_0 COIL

- Superconductor: zero resistance below a critical temperature, field and current density
- MRI magnets mostly use NbTi and NbSn filaments



Cheng et al. IEEE Transactions On Applied Superconductivity. 2007



Lyndon Evans. The LHC. 2009

SUPERCONDUCTING B_0 COIL

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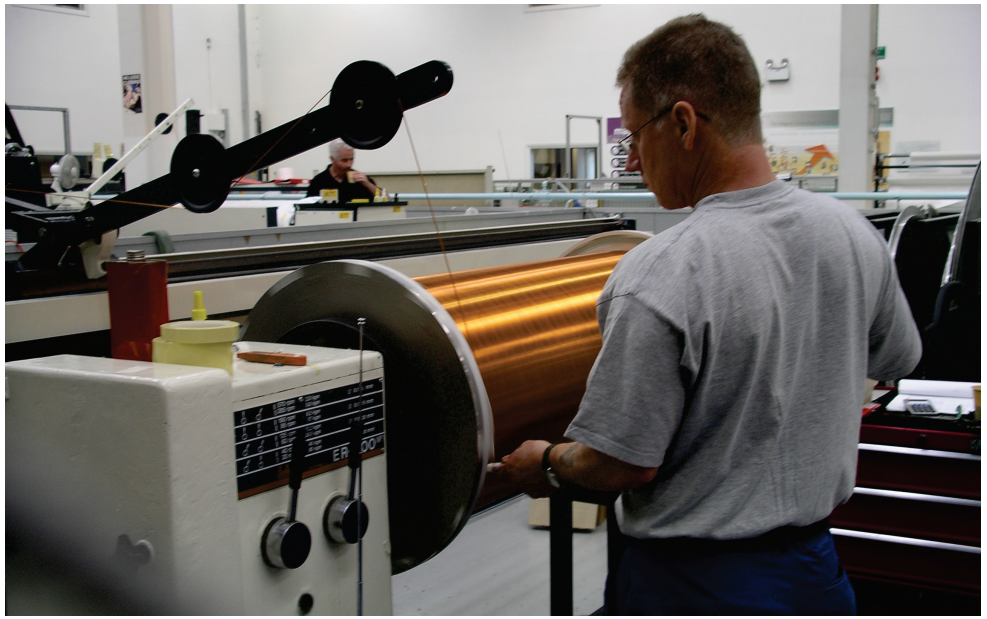
Bruker.com



B_0 coil in the making at Magnex (RIP ☹) factory

SUPERCONDUCTING B_0 COIL

- Typically: cryogenic liquids required to maintain superconductivity.
  - Liquid nitrogen (77K)
  - Liquid helium (4.2K)
- Stefan–Boltzmann law:

  Radiant emittance : $M = \epsilon\sigma T^4$

  - ϵ: Emissivity
  - σ: Stefan–Boltzmann constant
  - T: Temperature
- Insulation with vacuum, radiation shields, multilayer blankets.

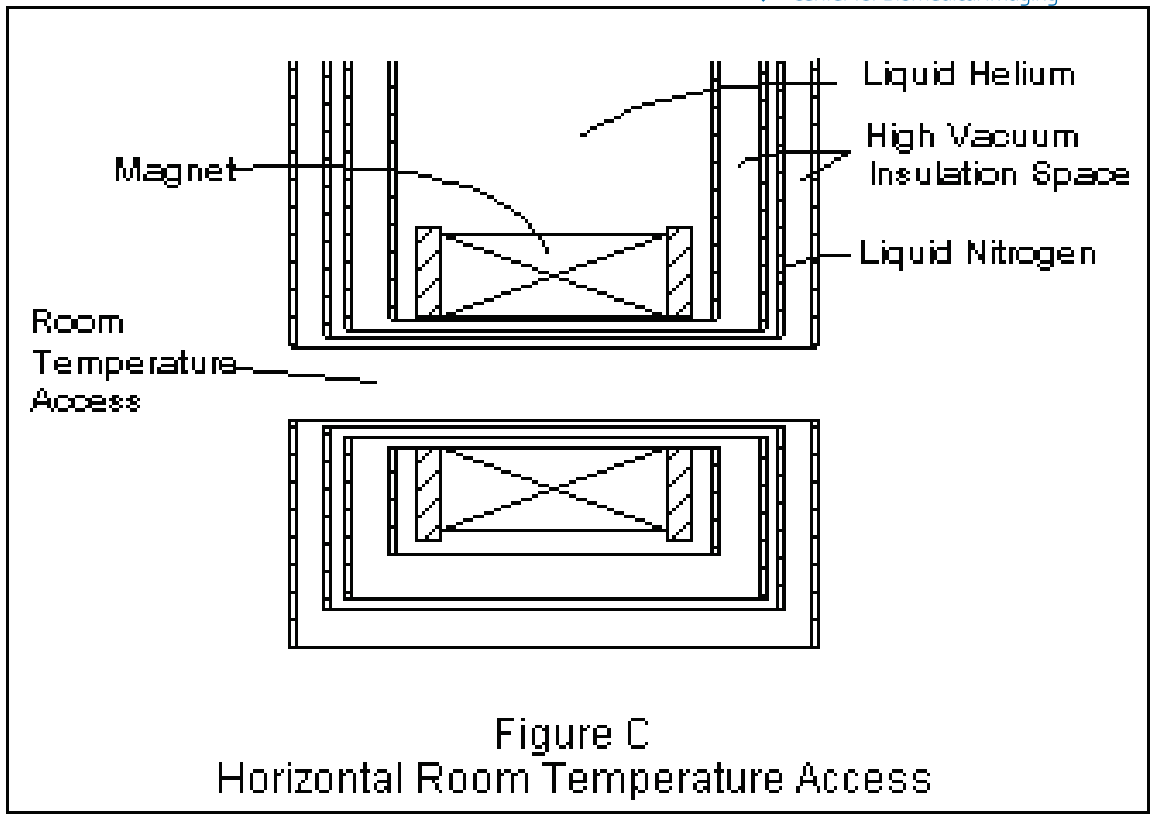


Figure C
Horizontal Room Temperature Access

American Magnetics

SUPERCONDUCTING B_0 COIL

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  - Liquid nitrogen (77K)
  - Liquid helium (4.2K)
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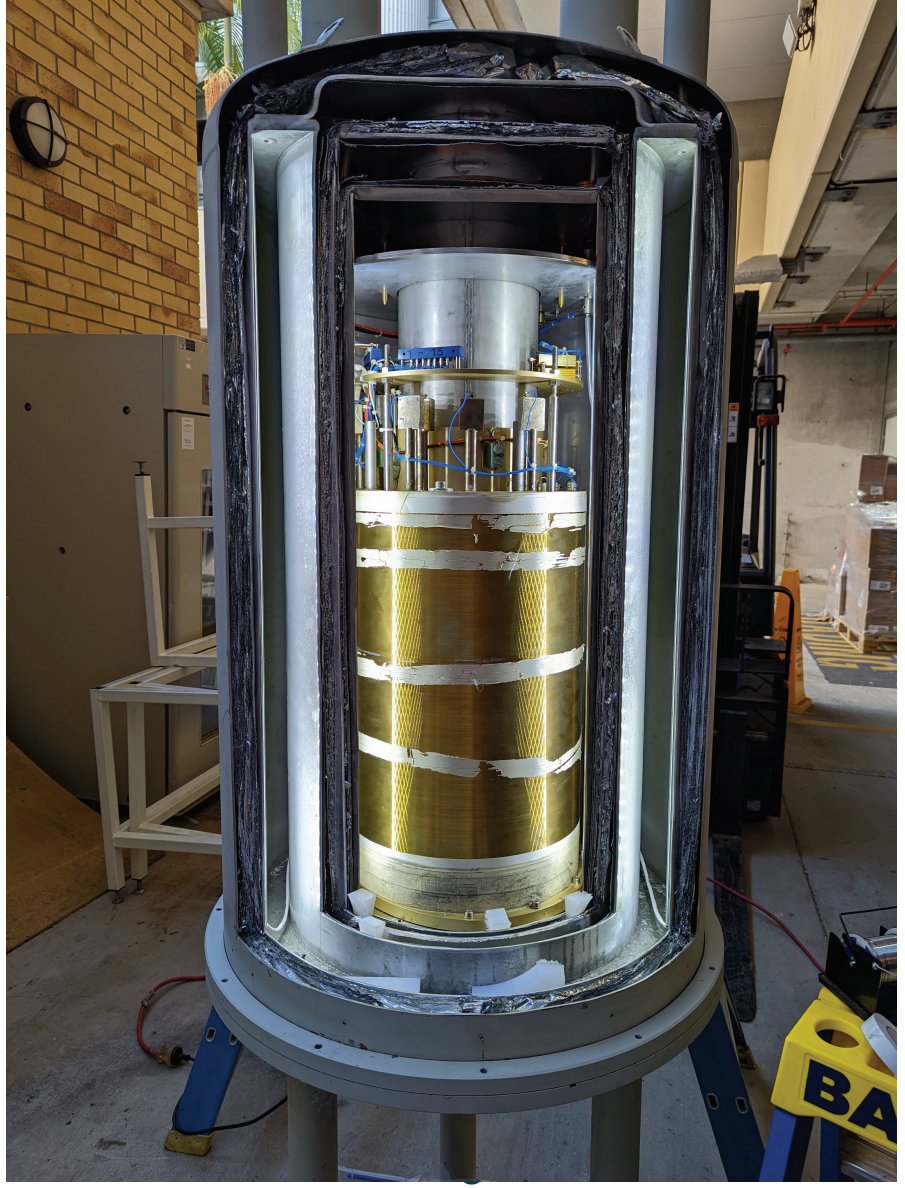
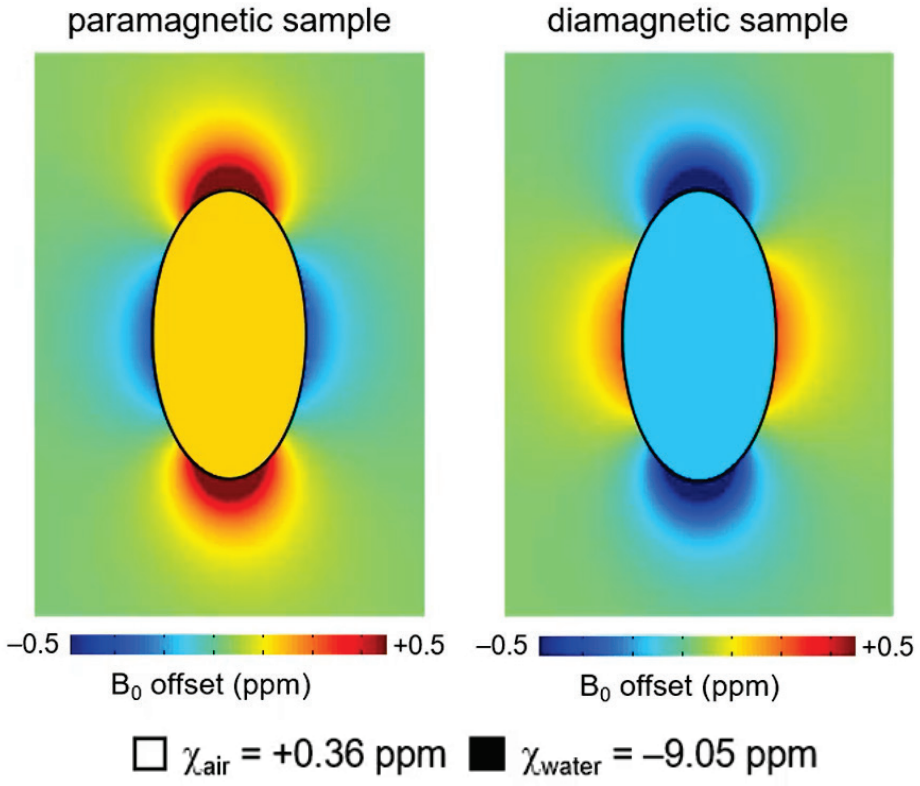
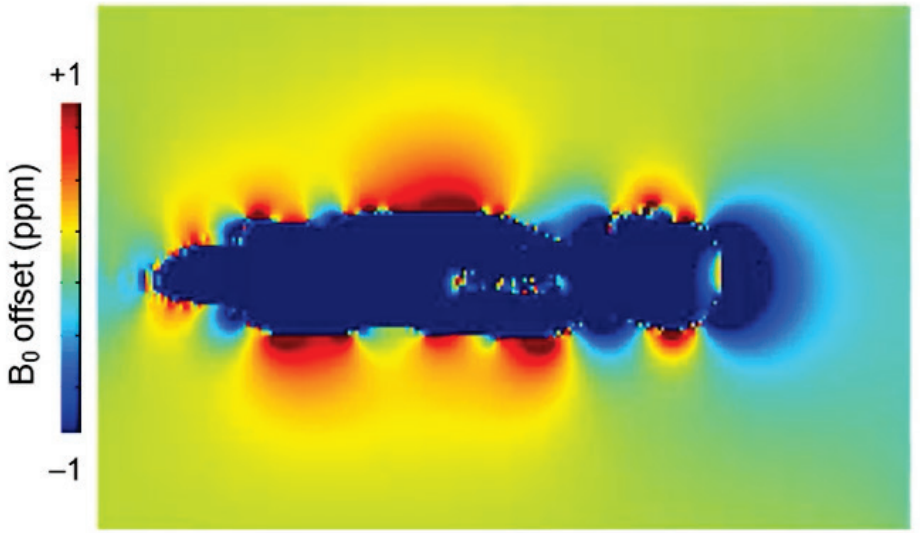


Opened Bruker NMR magnet

STATIC FIELD INHOMOGENEITY

- Induced by the scanner and local environment
- Induced by the imaging subject

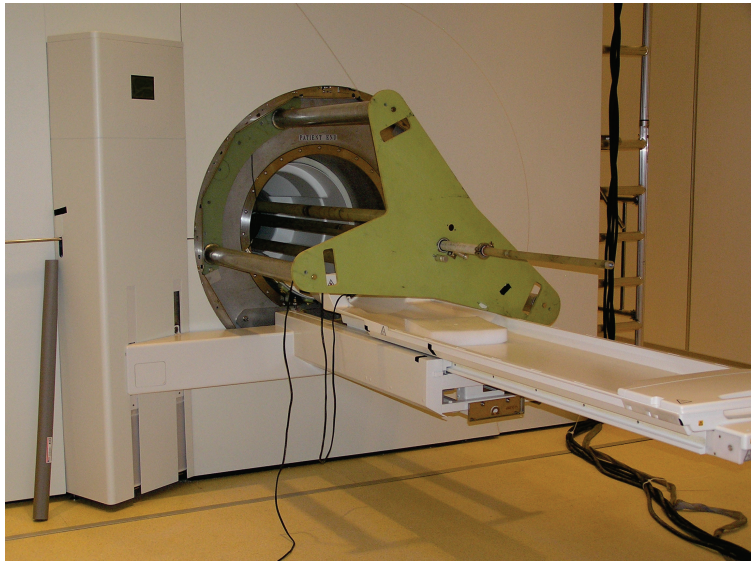




Robin de Graaf, ISMRM 2019

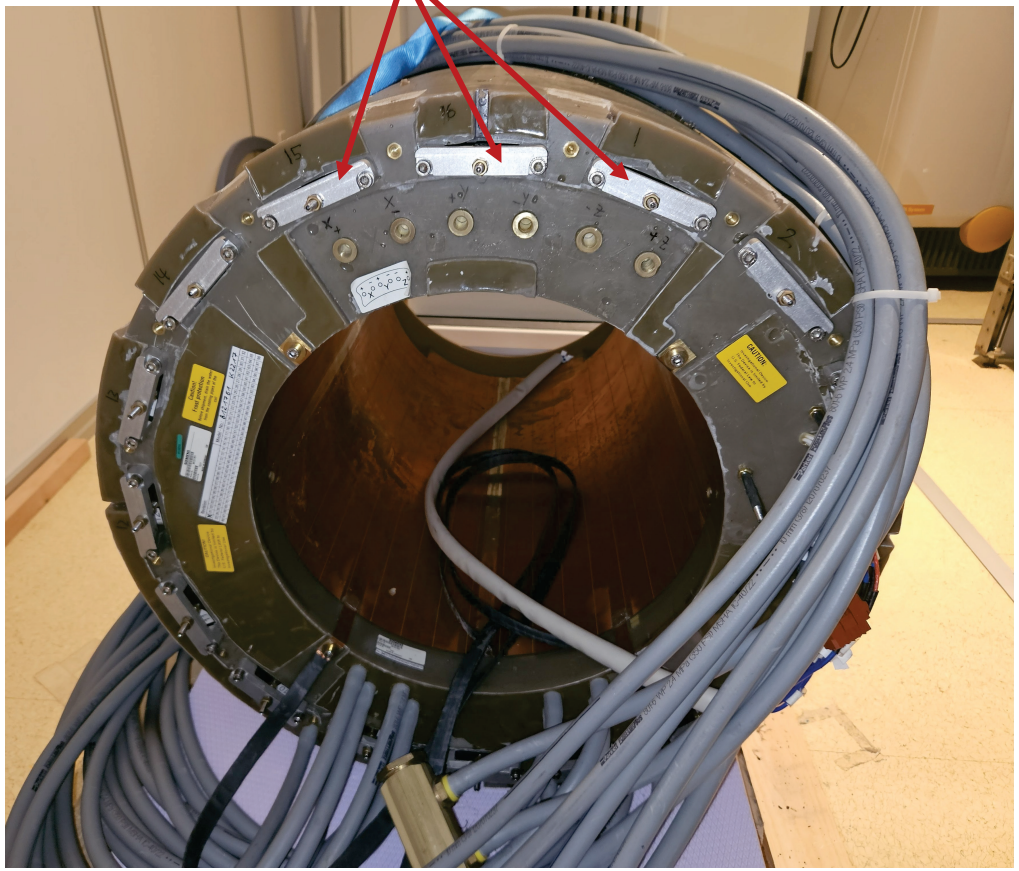
PASSIVE SHIMMING

- Pieces of iron or steel placed to compensate inhomogeneities of the main magnet.
- Usually installed once at installation



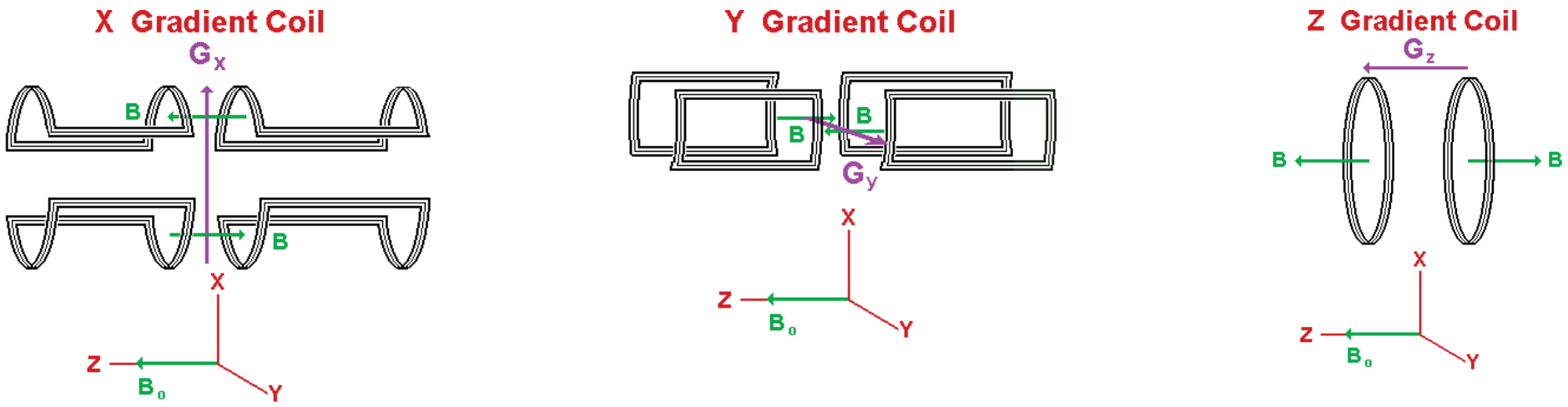
Magnetic field mapping

Shim trays



GRADIENT COILS

- Produce calibrated linear variations of B_0 in the x-, y- or z- directions.
- Adds a magnetic field component <u>parallel</u> to B_0
- Typical strength: 40 mT/m (human), 500 mT/m (small)

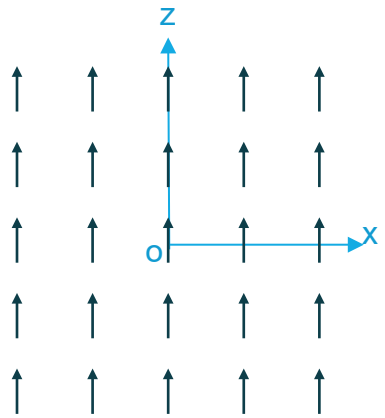


mriquestions.com

GRADIENT COILS

- Linear variation in magnetic field intensity in a direction in space
- Example with a positive G_z gradient

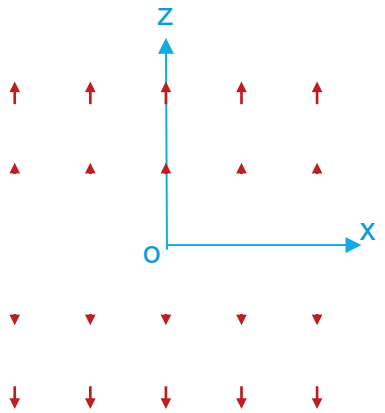
Static field



$$\overrightarrow{B_0} = B_0 \cdot \hat{z}$$

+

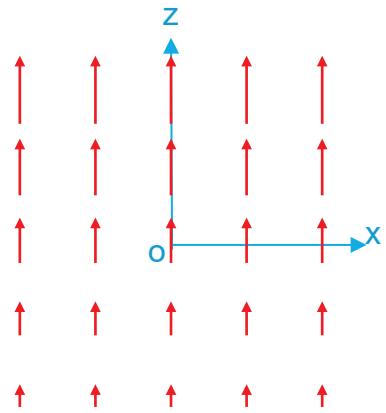
Gradient



$$G_z \cdot z \cdot \hat{z}$$

=

Static field + Gradient

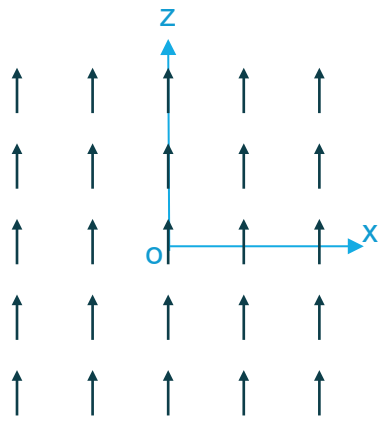


$$(B_0 + G_z \cdot z)\hat{z}$$

GRADIENT COILS

- Linear variation in magnetic field intensity in a direction in space
- Example with a positive G_x gradient

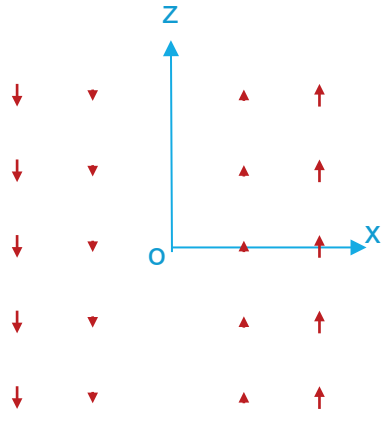
Static field



$\overrightarrow{B_0} = B_0 \cdot \hat{z}$

+

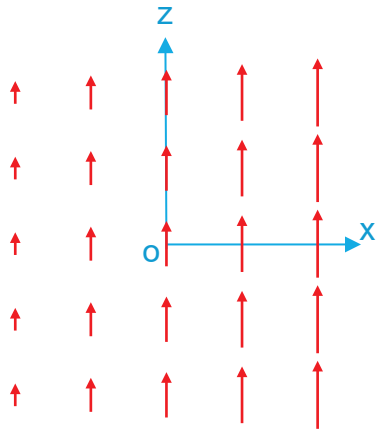
Gradient



$G_x \cdot x \cdot \hat{z}$

=

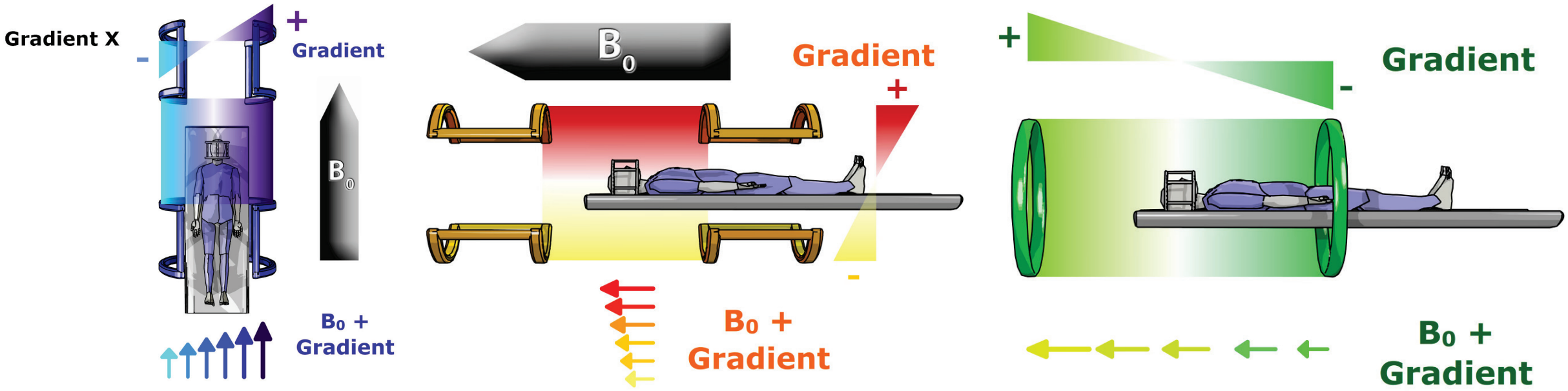
Static field + Gradient



$(B_0 + G_x \cdot x)\hat{z}$

GRADIENT COILS

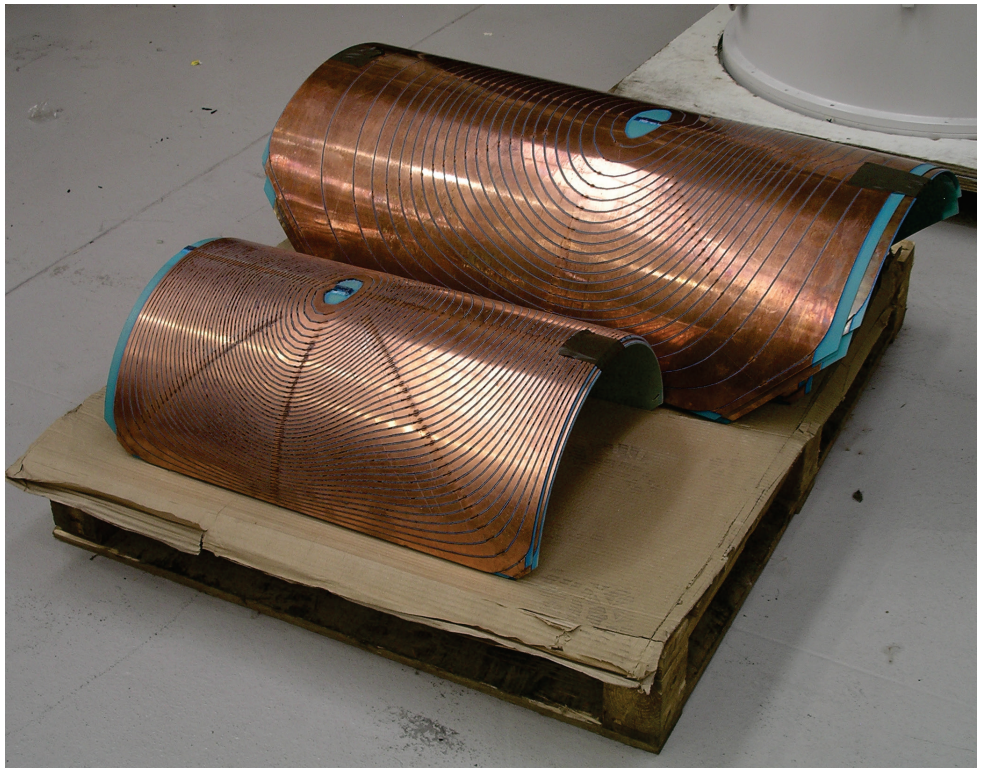
- Linear variation in magnetic field intensity in a direction in space

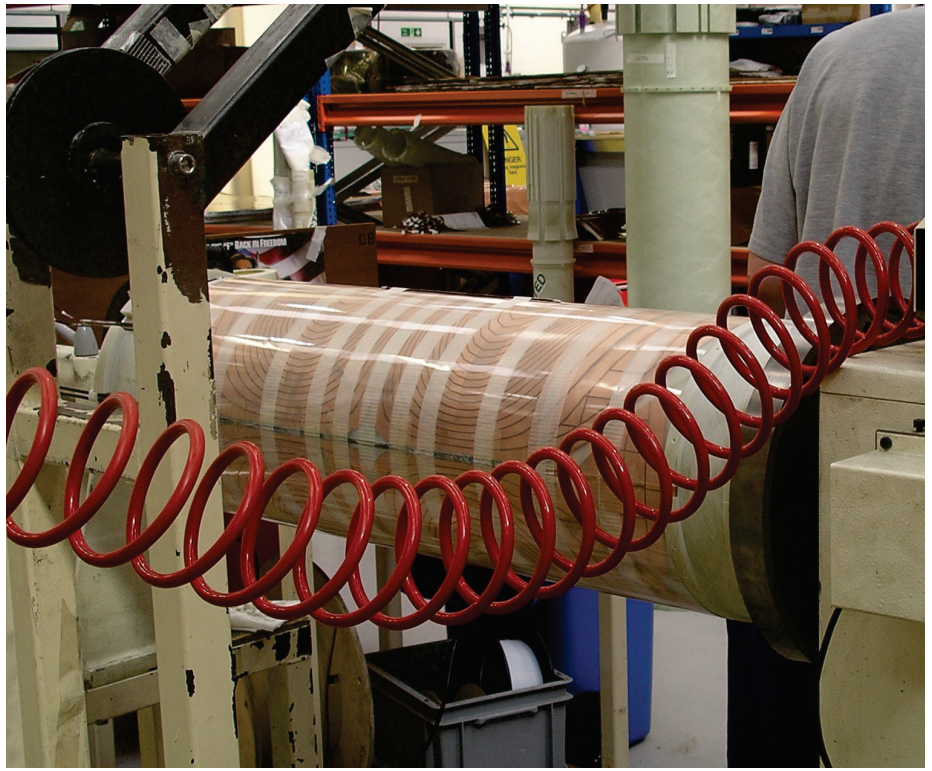


Source: Imaios

GRADIENT COILS

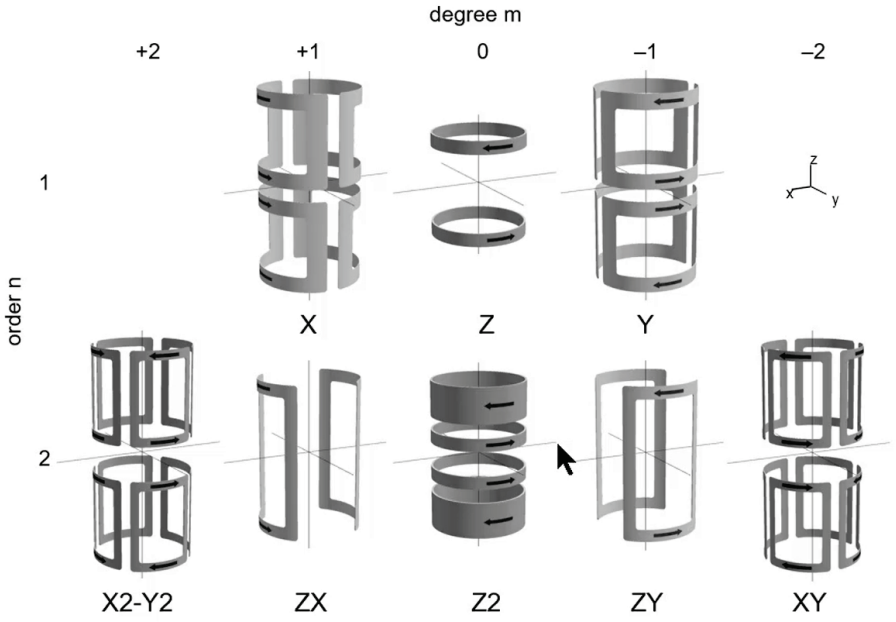
- In real world: wide stripes of copper to carry hundreds of Amps.



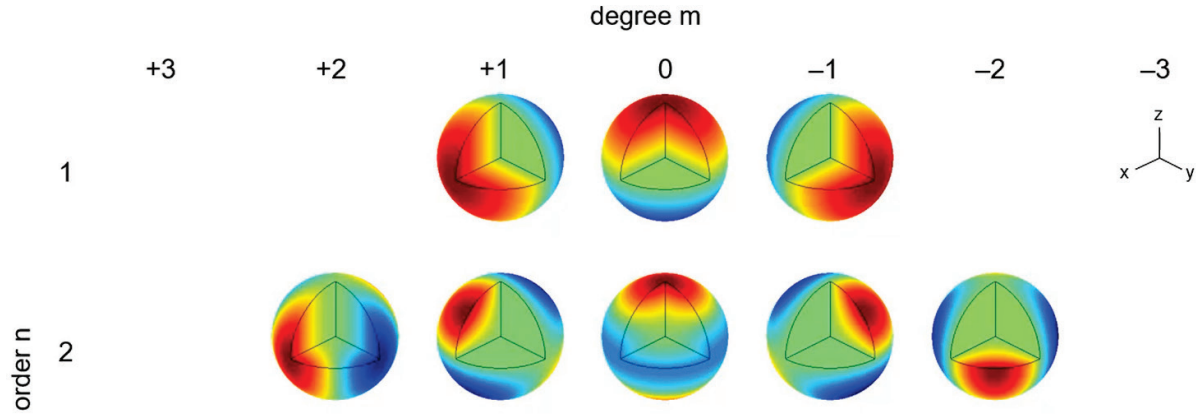


ACTIVE SHIMMING

- Superconducting or resistive shim coils



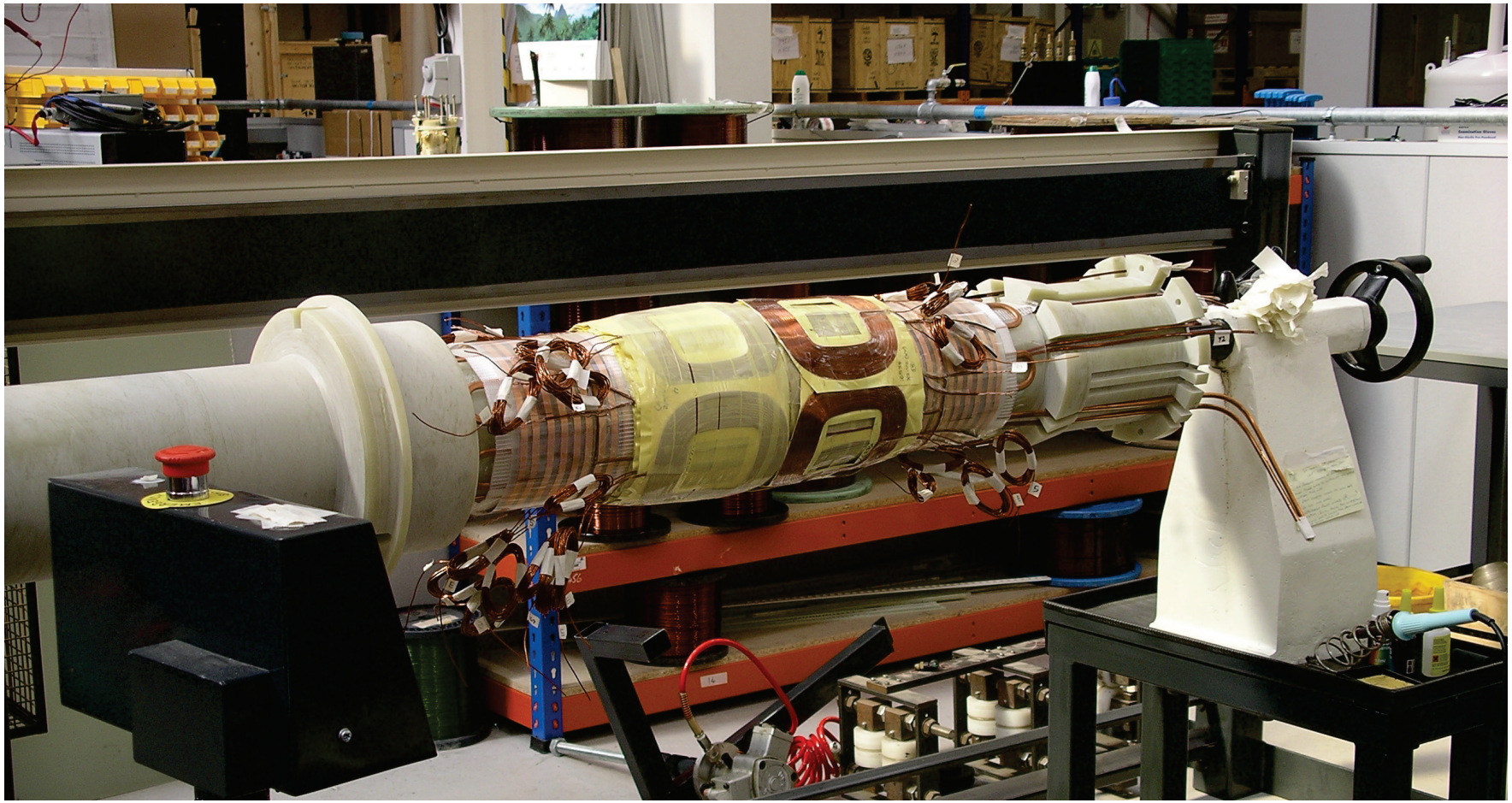
First and second order shim coils



Spherical harmonic functions up to second order on the surface of the unit sphere.

Robin de Graaf, ISMRM 2019

ACTIVE SHIMMING IN PRACTICE



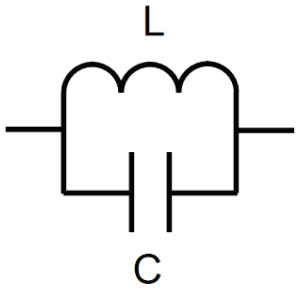
RADIO-FREQUENCY COILS

- Resonant circuit
- Generate/measure an oscillating field B_1 perpendicular to B_0
  - Tip the net magnetization (B_1^+ : transmit field)
  - Pick up the NMR signal (B_1^- : receive field)

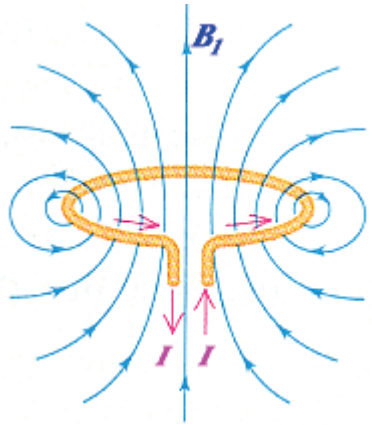
SURFACE COIL

+ Easy to build!
+ High sensitivity and efficiency close to the coil
- Inhomogeneous B_1
- Limited field of view

Doty et al. NMR Biomed. 2007



$$\omega_0 = \frac{1}{\sqrt{LC}}$$



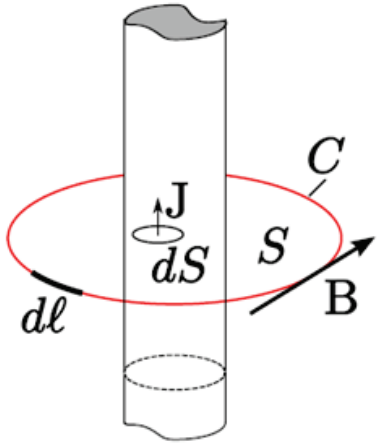
TRANSMISSION

Ampères law: current passing through a wire creates a magnetic field:

$$\frac{1}{\mu}\oint_C \mathbf{B}\cdot d\ell = \int_S \mathbf{J}\cdot d\mathbf{S}$$

where:

- μ is permeability ($\mu_0 = 4\pi \times 10^{-7}$ H/m)
- **B** is magnetic field
- C is closed loop around current path
- **J** is current density
- S is surface enclosed by C



We design our probe to produce current distribution **J**, to generate the desired magnetic field.

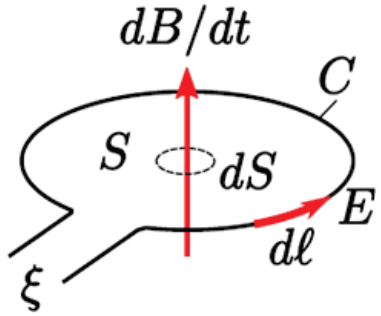
RECEPTION

Faradays law: time-varying magnetic field induces an EMF in a conductor:

$$\xi = \oint_C \mathbf{E} \cdot d\ell = -\int_S \frac{d\mathbf{B}}{dt} \cdot d\mathbf{S}$$

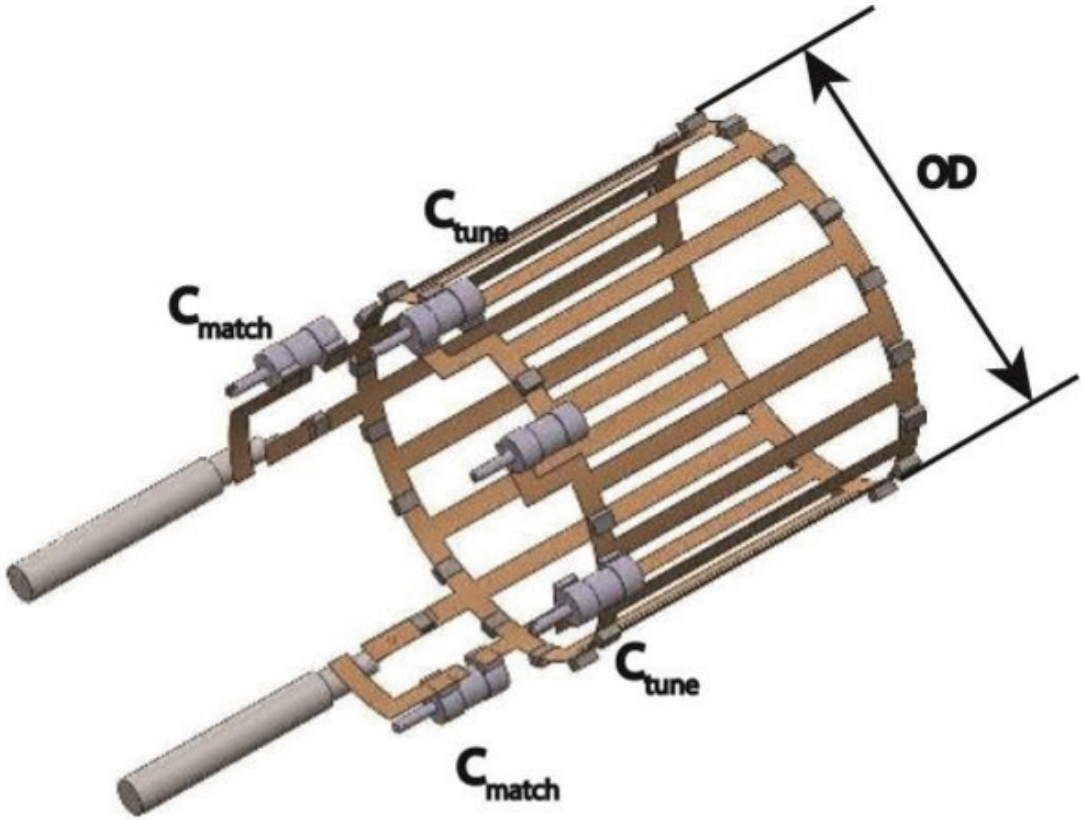
where:

- ξ is EMF induced across the loop
- $\mathbf{E}$ is electric field across loop section $d\ell$
- line integral taken around loop C is
- $\mathbf{B}$ is the magnetic field
- surface integral taken over loop area S



VOLUME COIL

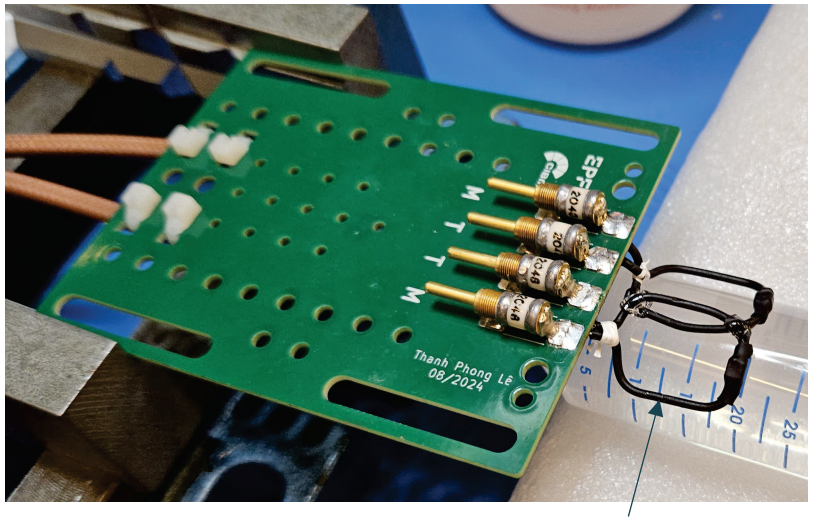
+ Homogenous B_1
+ Large field of view
- More complex
- Lower sensitivity



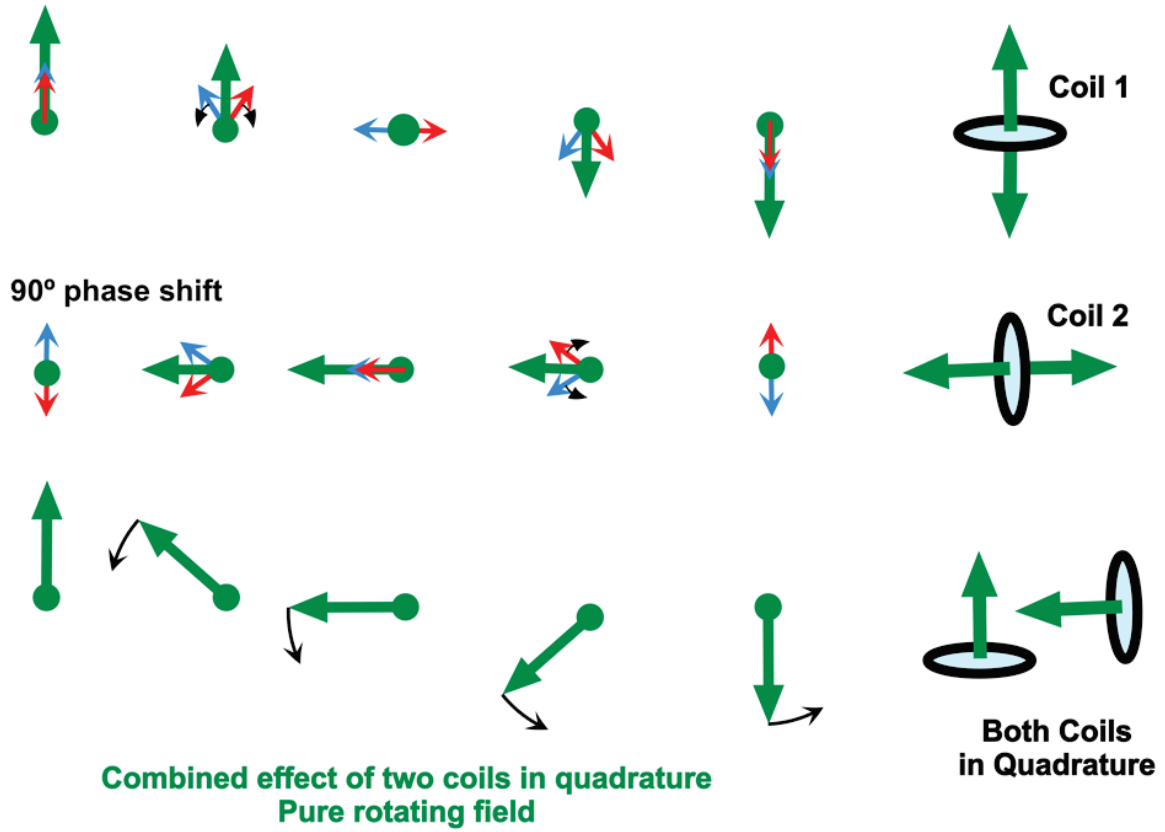
Cheng et al. IEEE. 2014

LINEAR VS QUADRATURE COIL

- Quadrature coil
  - Circularly-polarized B_1 field
  - Doubles the power efficiency
  - Increases sensitivity up to 1.4x



This is a surface coil with two loops in quadrature



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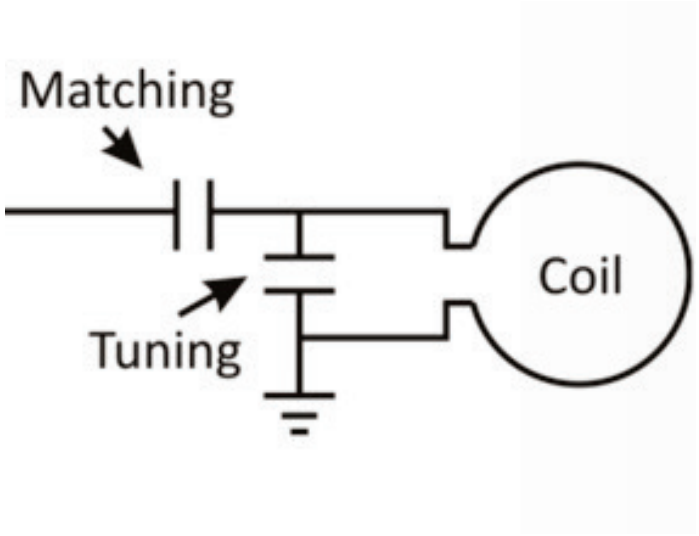
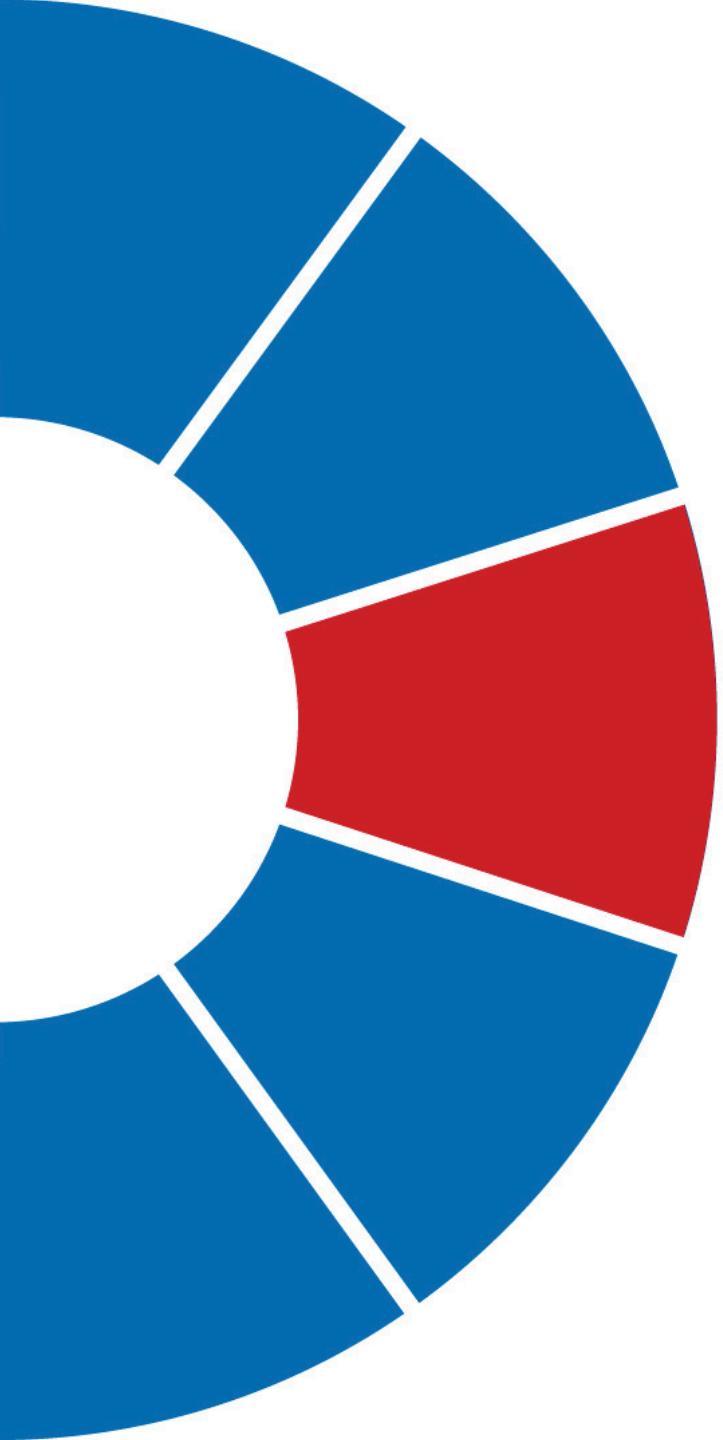
TUNING AND MATCHING

The coil's properties change as a function of the sample. This is why there are adjustable capacitors to adjust finely its resonance.

- Tune the resonance frequency of the coil to the Larmor frequency.
- Match the impedance between the transmission line and the coil for optimal power transmission.





SAFETY

DANGERS

- General aspects
- Magnetic field
- Cryogens
- Radio-frequency waves
- Veterinary aspects

GENERAL ASPECTS

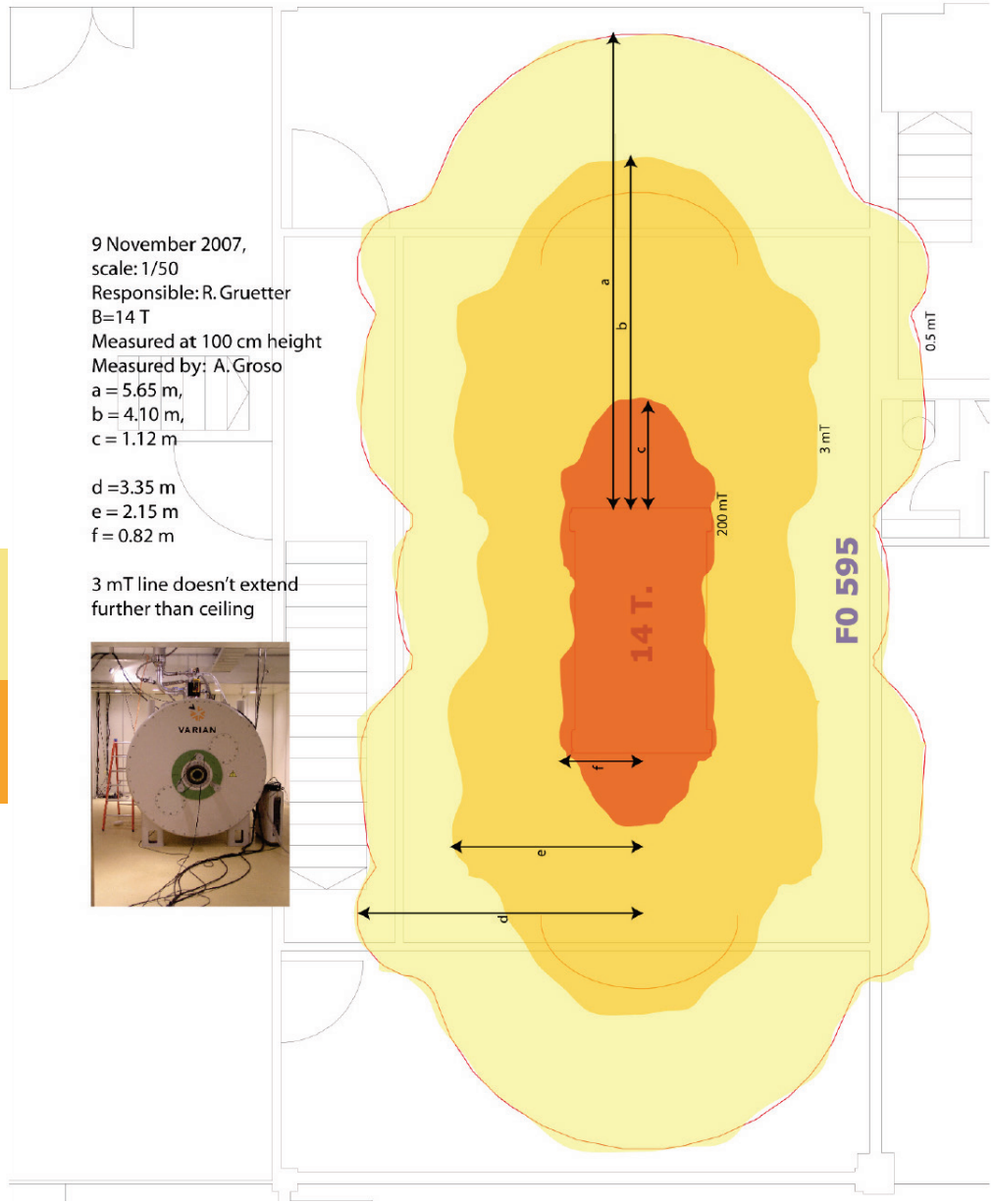
- No food, no water in the labs
- Store your belongings in the lockers close to the entrance.

MAGNETIC FIELD

- Magnet is always on!
- Anything ferromagnetic becomes a projectile!
- Do not stay close to the magnet if not necessary.
- Medical devices could stop working!

FIELD MAP

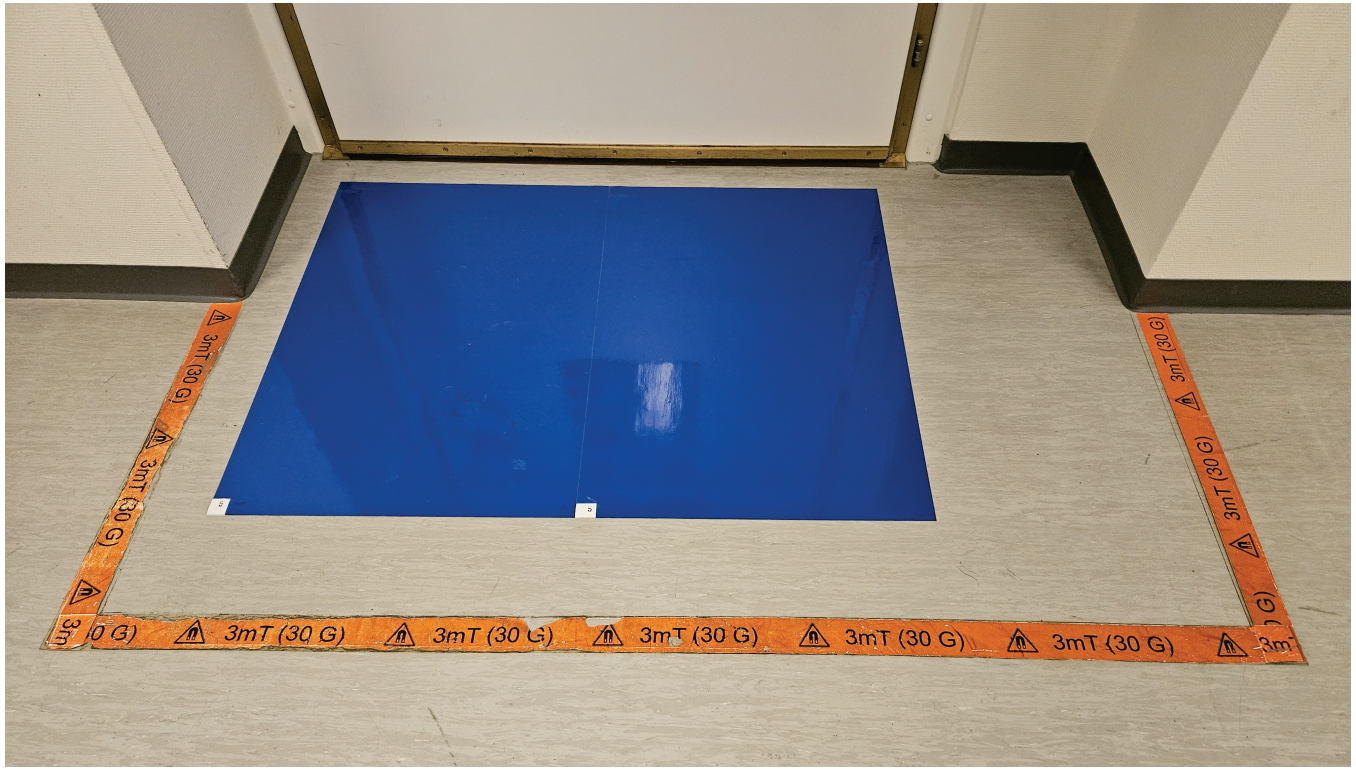
0.5 mT	Maximum value authorised for the holders of MD	No access to general public No access to holders of MD
3 mT	Possible attraction of ferromagnetic objects, they can become projectiles.	Any ferromagnetic object



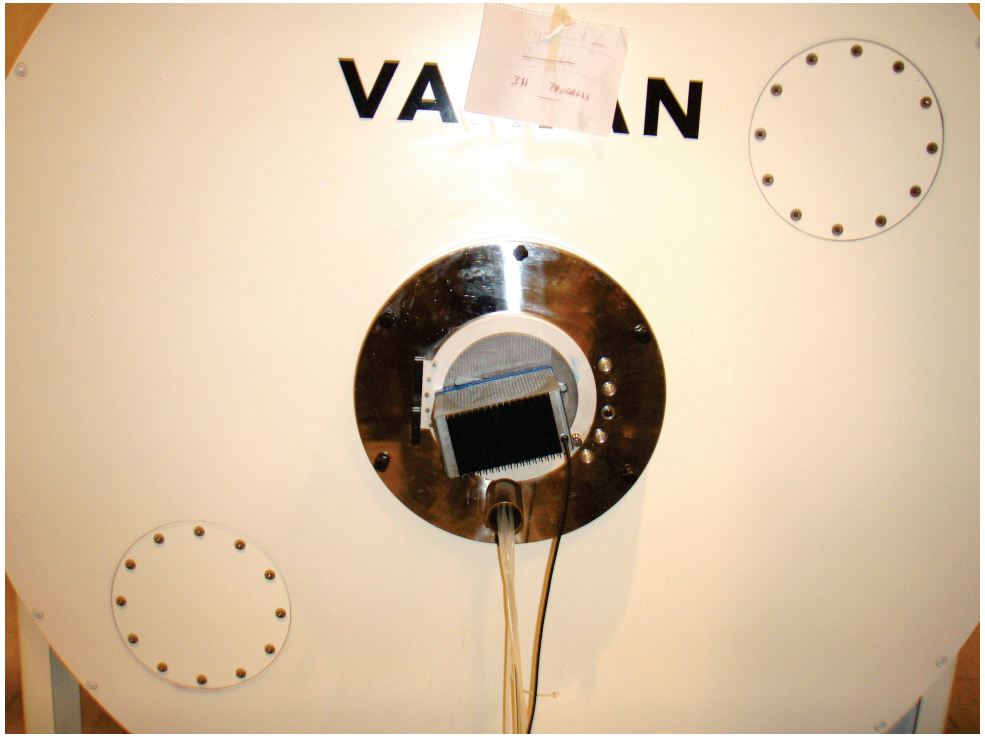
BEFORE GOING TO THE MAGNET

- Remove all magnetic objects
  - Belt
  - Wallet, keys, phone
  - Watch
  - Pens
  - Shoes with steel
  - Hair pins
  - Jewelry, ear rings, bracelet, necklace, …
  - Magnetic tools, devices, …
- Some glasses/jewelry are magnetic. In doubt, remove them.
- Gold, silver, palladium, titanium, brass, stainless steel are fine!

NO FERROMAGNETIC OBJECT BEYOND THE ORANGE LINE, PLEASE !!!



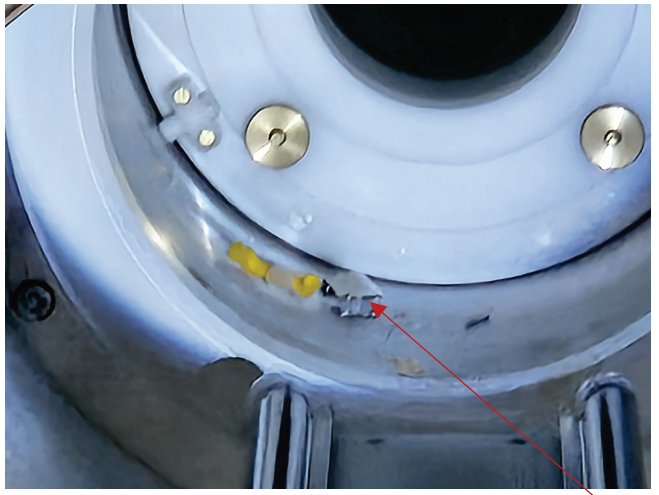
WHAT COULD HAPPEN ?



Laboratory power supply

(Part of) a bracelet with ferromagnetic materials

WHAT COULD HAPPEN (2) ?



Steel clip

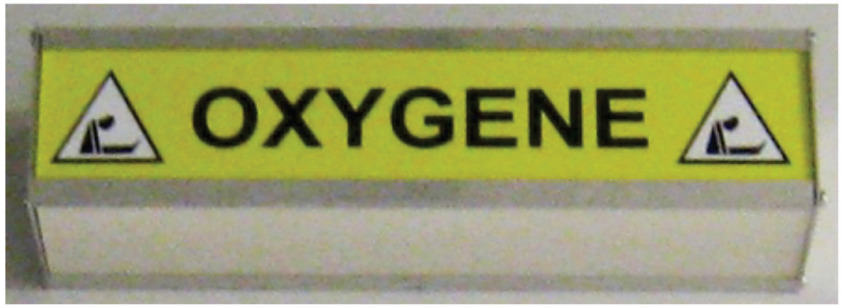
EMERGENCY DISCHARGE

- To discharge the magnet as last resort to save someone's life.
- Cost: at least 500'000 CHF (if the magnet survives)

DO NOT TOUCH THE EMERGENCY DISCHARGE BUTTON!

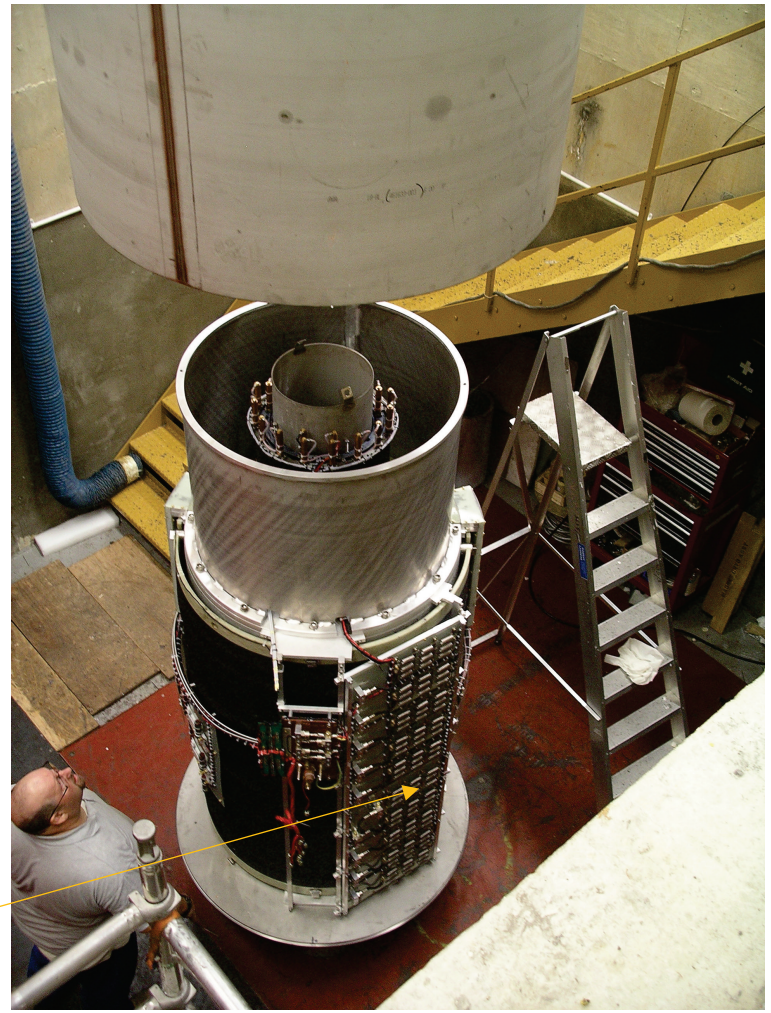
CRYOGENS

- Nitrogen and helium are inert gases.
- Major risks:
  - Hypoxia and asphyxia.
  - Very cold
- Gas/liquid ratio: 700:1
- If you see/hear the alarm, evacuate and leave all doors open.



QUENCH

- Sudden loss of superconductivity.
  - Either initiated by the emergency discharge unit
  - Helium bath too high
  - Superconductor failure
  - Vacuum loss
- All the energy is dumped into the helium bath and it will boil off!



QUENCH (CONTROLLED)

RADIO-FREQUENCY WAVES

- Perturbations of telecommunications (and other electronic devices).
- High voltage (100-1000 V)
- RF heating (The subject absorbs RF power)

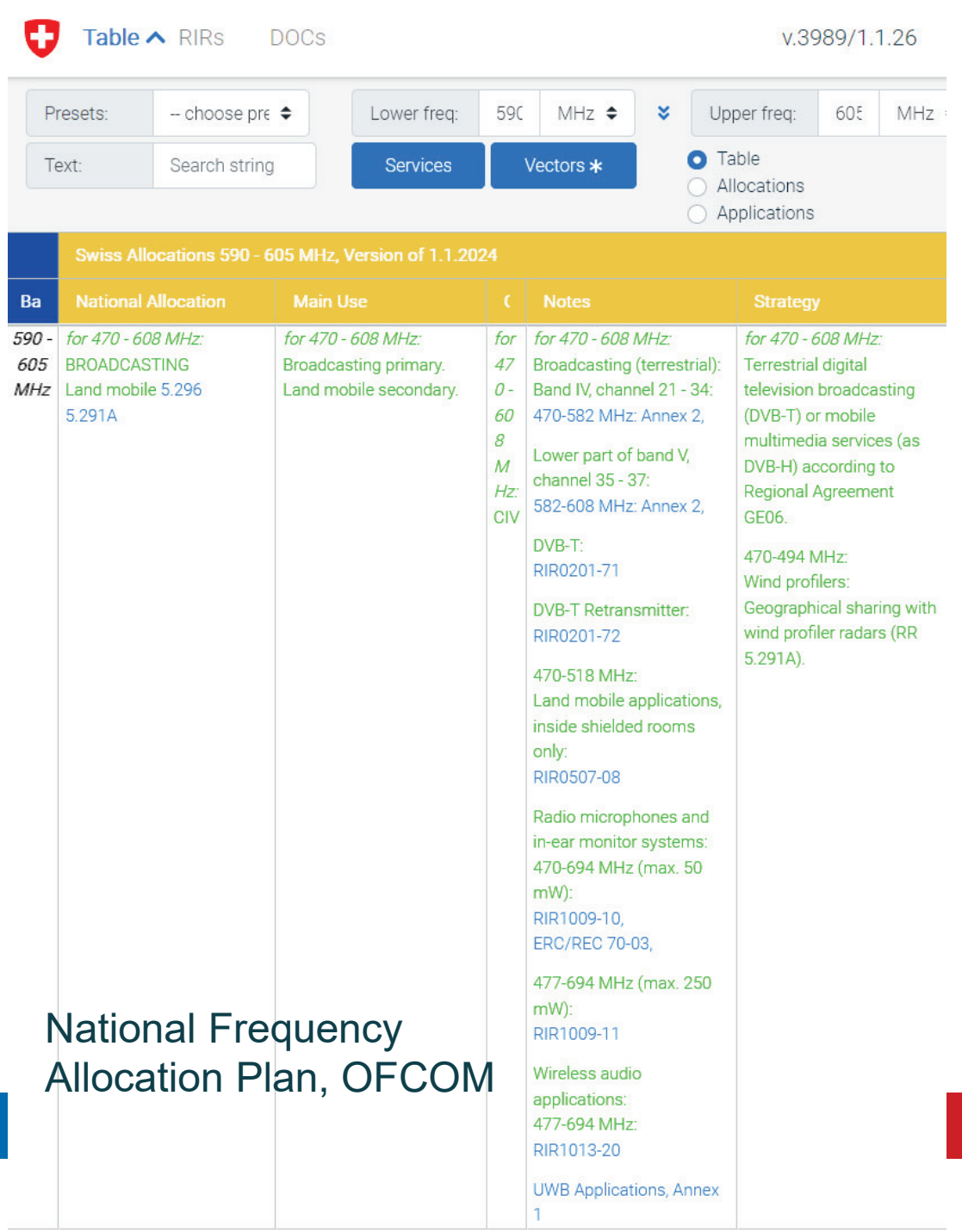


Table RIRs DOCs v.3989/1.1.26

Presets: -- choose pre | Lower freq: 590 MHz | Upper freq: 605 MHz

Text: Search string | Services | Vectors * | Table | Allocations | Applications

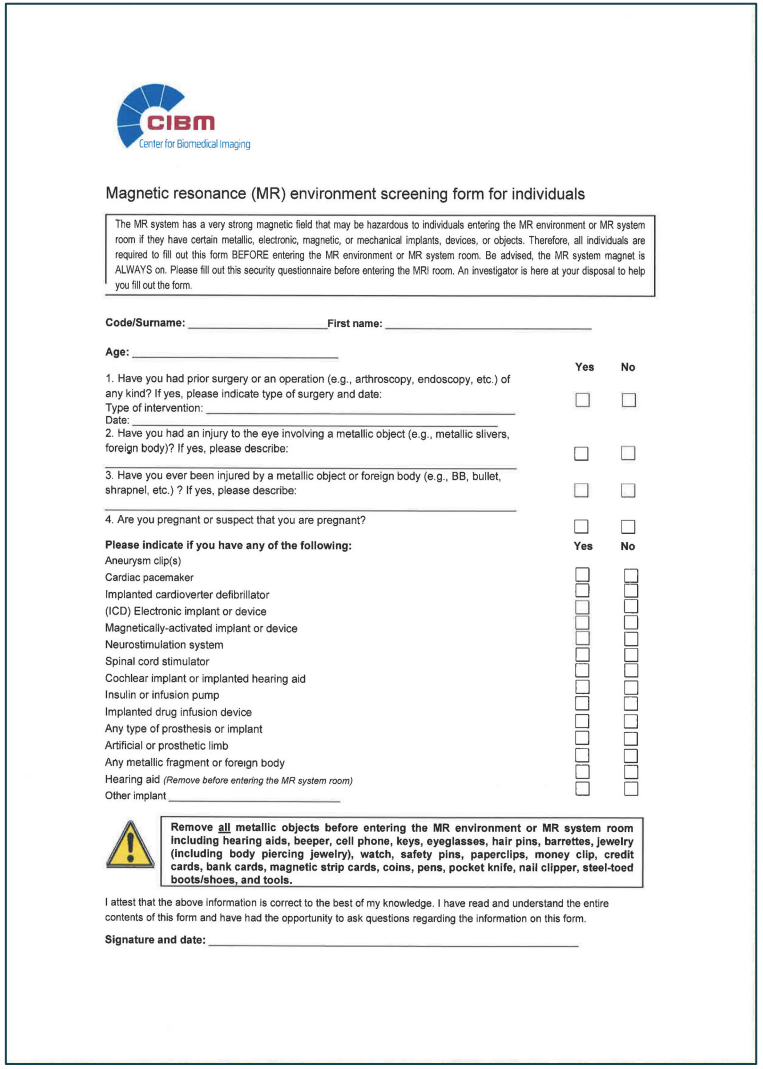
Swiss Allocations 590 - 605 MHz, Version of 1.1.2024

Ba	National Allocation	Main Use	C	Notes	Strategy
590 - 605 MHz	for 470 - 608 MHz: BROADCASTING Land mobile 5.296 5.291A	for 470 - 608 MHz: Broadcasting primary. Land mobile secondary.	for 470 - 608 MHz: CIV	for 470 - 608 MHz: Broadcasting (terrestrial): Band IV, channel 21 - 34: 470-582 MHz: Annex 2, Lower part of band V, channel 35 - 37: 582-608 MHz: Annex 2, DVB-T: RIR0201-71 DVB-T Retransmitter: RIR0201-72 470-518 MHz: Land mobile applications, inside shielded rooms only: RIR0507-08 Radio microphones and in-ear monitor systems: 470-694 MHz (max. 50 mW): RIR1009-10, ERC/REC 70-03, 477-694 MHz (max. 250 mW): RIR1009-11 Wireless audio applications: 477-694 MHz: RIR1013-20 UWB Applications, Annex 1	for 470 - 608 MHz: Terrestrial digital television broadcasting (DVB-T) or mobile multimedia services (as DVB-H) according to Regional Agreement GE06. 470-494 MHz: Wind profilers: Geographical sharing with wind profiler radars (RR 5.291A).

National Frequency Allocation Plan, OFCOM

MR SCREENING FORM

- To check whether you have anything that prevents you from going close to the magnet.



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Magnetic resonance (MR) environment screening form for individuals

The MR system has a very strong magnetic field that may be hazardous to individuals entering the MR environment or MR system room if they have certain metallic, electronic, magnetic, or mechanical implants, devices, or objects. Therefore, all individuals are required to fill out this form BEFORE entering the MR environment or MR system room. Be advised, the MR system magnet is ALWAYS on. Please fill out this security questionnaire before entering the MRI room. An investigator is here at your disposal to help you fill out the form.

Code/Surname: _____ **First name:** _____

Age: _____

	Yes	No
1. Have you had prior surgery or an operation (e.g., arthroscopy, endoscopy, etc.) of any kind? If yes, please indicate type of surgery and date: Type of intervention: _____ Date: _____	☐	☐
2. Have you had an injury to the eye involving a metallic object (e.g., metallic slivers, foreign body)? If yes, please describe: _____	☐	☐
3. Have you ever been injured by a metallic object or foreign body (e.g., BB, bullet, shrapnel, etc.) ? If yes, please describe: _____	☐	☐
4. Are you pregnant or suspect that you are pregnant?	☐	☐

Please indicate if you have any of the following:	**Yes**	**No**
Aneurysm clip(s)	☐	☐
Cardiac pacemaker	☐	☐
Implanted cardioverter defibrillator	☐	☐
(ICD) Electronic implant or device	☐	☐
Magnetically-activated implant or device	☐	☐
Neurostimulation system	☐	☐
Spinal cord stimulator	☐	☐
Cochlear implant or implanted hearing aid	☐	☐
Insulin or infusion pump	☐	☐
Implanted drug infusion device	☐	☐
Any type of prosthesis or implant	☐	☐
Artificial or prosthetic limb	☐	☐
Any metallic fragment or foreign body	☐	☐
Hearing aid *(Remove before entering the MR system room)*	☐	☐
Other implant _____	☐	☐

Remove all metallic objects before entering the MR environment or MR system room including hearing aids, beeper, cell phone, keys, eyeglasses, hair pins, barrettes, jewelry (including body piercing jewelry), watch, safety pins, paperclips, money clip, credit cards, bank cards, magnetic strip cards, coins, pens, pocket knife, nail clipper, steel-toed boots/shoes, and tools.

I attest that the above information is correct to the best of my knowledge. I have read and understand the entire contents of this form and have had the opportunity to ask questions regarding the information on this form.

Signature and date: _____

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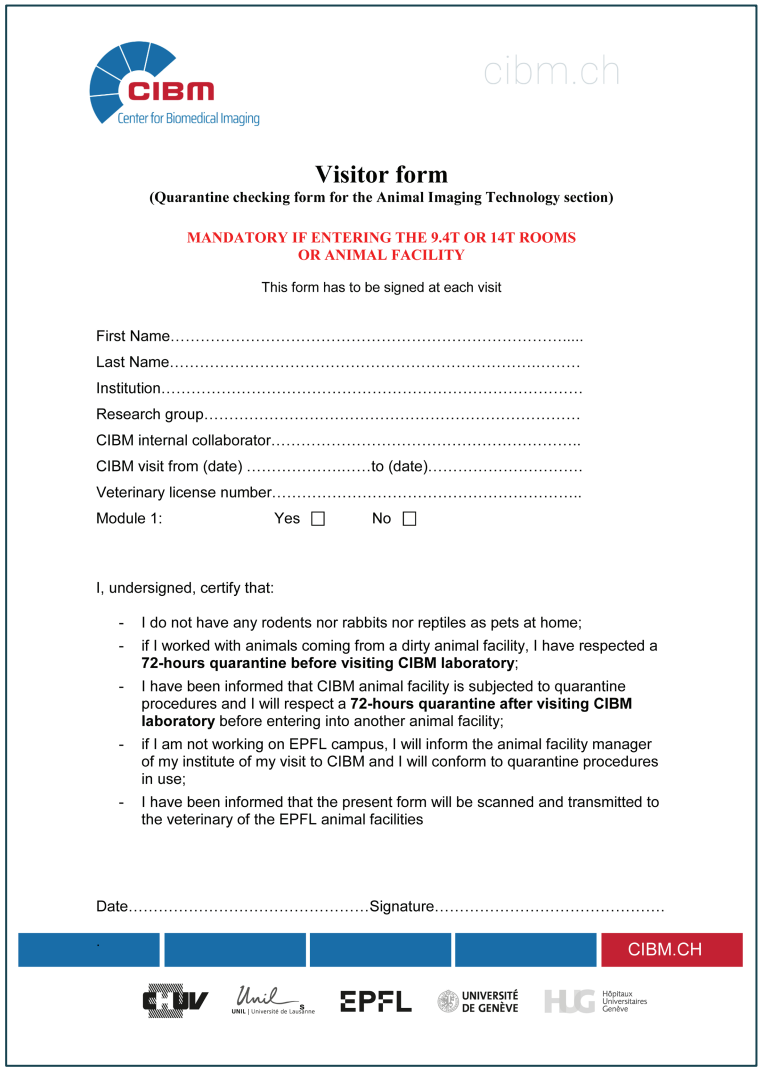
QUARANTINE CHECKING FORM

- Prevent any contamination from external sources.
- Form to be signed every time to confirm that the rules are respected before entering experimentation area.



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Visitor form

(Quarantine checking form for the Animal Imaging Technology section)

MANDATORY IF ENTERING THE 9.4T OR 14T ROOMS OR ANIMAL FACILITY

This form has to be signed at each visit

First Name.....

Last Name.....

Institution.....

Research group.....

CIBM internal collaborator.....

CIBM visit from (date) .....to (date).....

Veterinary license number.....

Module 1: Yes ☐ No ☐

I, undersigned, certify that:

- I do not have any rodents nor rabbits nor reptiles as pets at home;
- if I worked with animals coming from a dirty animal facility, I have respected a **72-hours quarantine before visiting CIBM laboratory**;
- I have been informed that CIBM animal facility is subjected to quarantine procedures and I will respect a **72-hours quarantine after visiting CIBM laboratory** before entering into another animal facility;
- if I am not working on EPFL campus, I will inform the animal facility manager of my institute of my visit to CIBM and I will conform to quarantine procedures in use;
- I have been informed that the present form will be scanned and transmitted to the veterinary of the EPFL animal facilities

Date.....Signature.....

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THANK YOU FOR YOUR ATTENTION

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