# Technical and physiological hazards of static magnetic fields

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Contents

# Part 1
# Technical Hazards

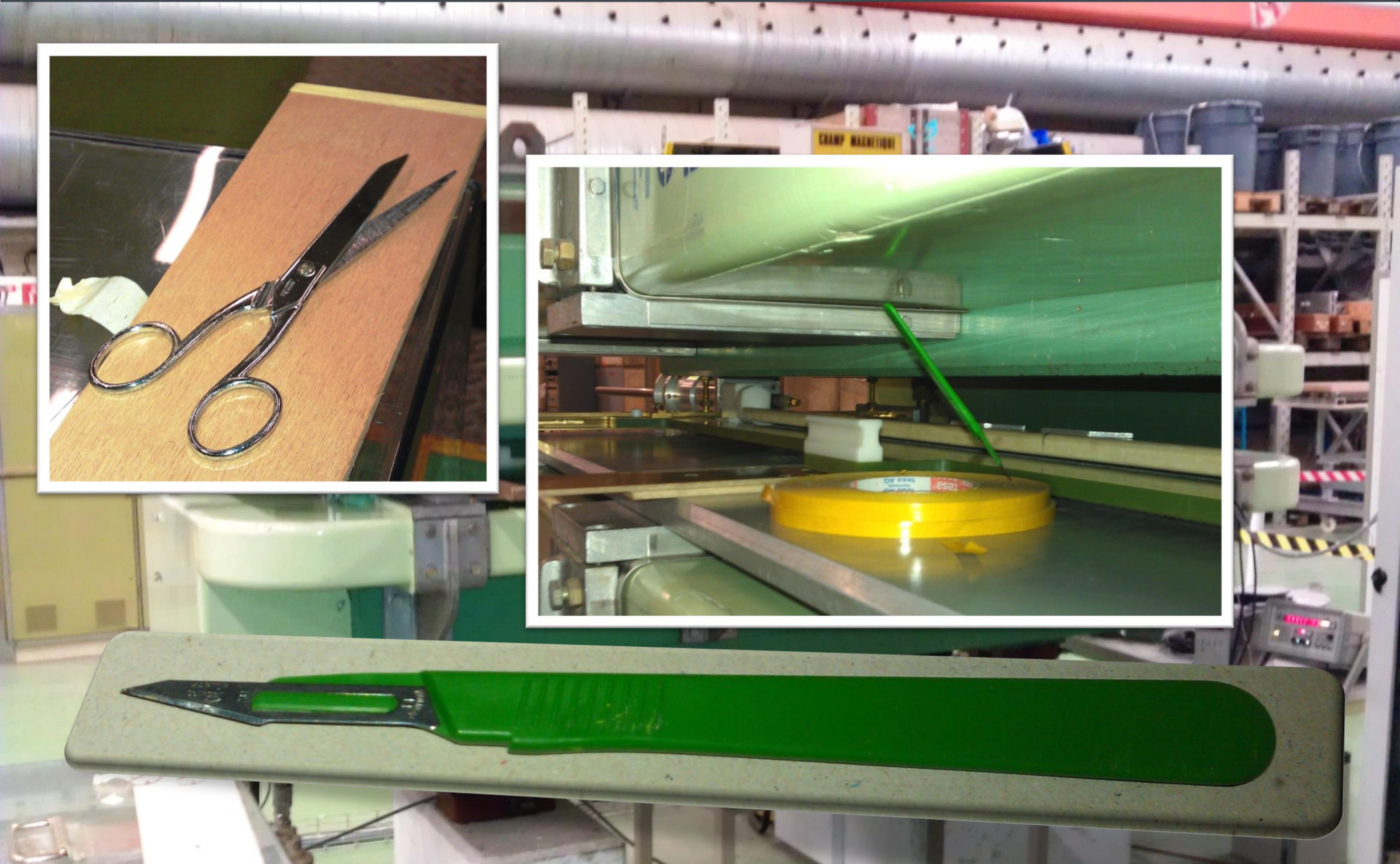
# How dangerous are magnetic fields ?


- Every year electricity kills **200** in France alone, vs. 2/3 deaths due magnetic field worldwide

… *however*:

- Exposure to magnetic fields is exponentially lower, outside of certain communities
  (Magnetic Resonance Imaging, High Energy Physics, plasma physics, spectroscopy …)
- Everyone is familiar with electricity; magnetic field quantities are baffling to most
- Unlike electric fields, magnetic fields penetrate freely the human body and everything else
  Passive shielding of large volumes/strong fields is impractical to impossible

# What can possibly go wrong ?



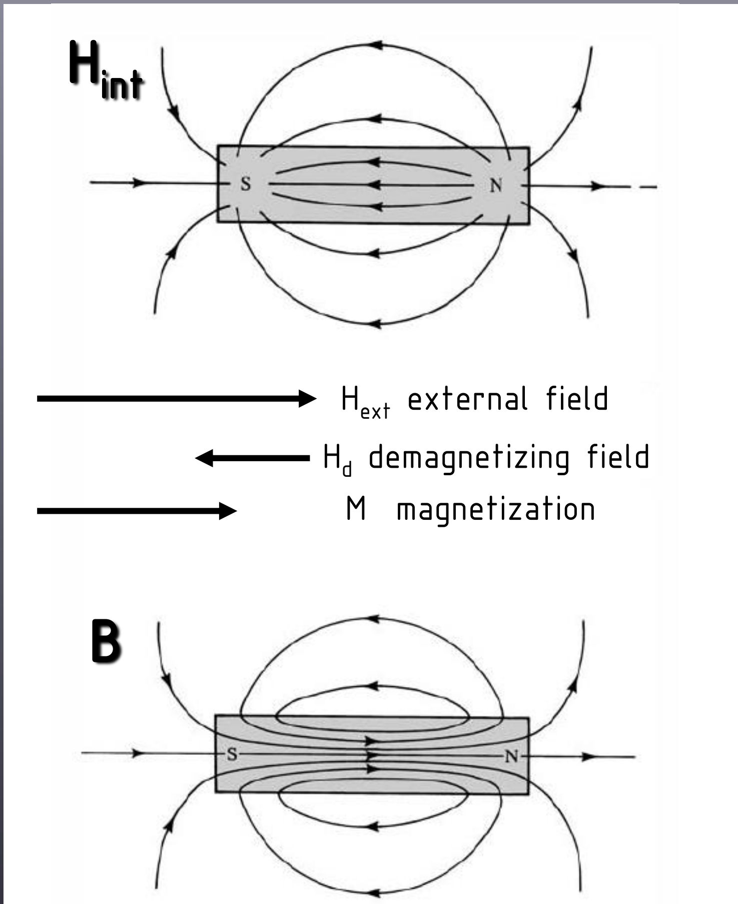
# Magnetic forces 1/3

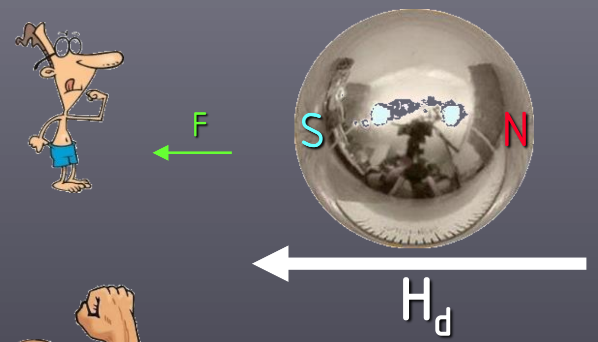
H field (*irrotational i.e. $\nabla\times H=J+\partial D/\partial t=0$*)
Pole-to-pole field lines
Goes N→S both inside *and* outside

$H=H_{ext}+H_d$, $H_d=-NM$

N=demagnetization factor (0≤N≤1, function of shape)

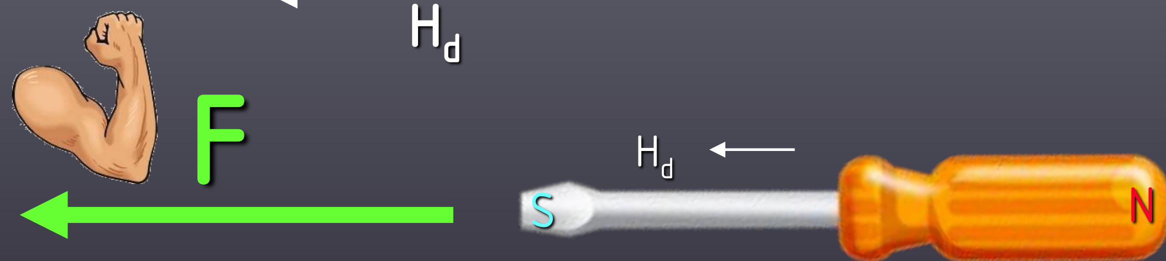
$$M=\chi H=\frac{\mu_r-1}{1+N(\mu_r-1)}H_{ext}\quad [A/m]$$




closely spaced poles → high demagnetization (N≈1)

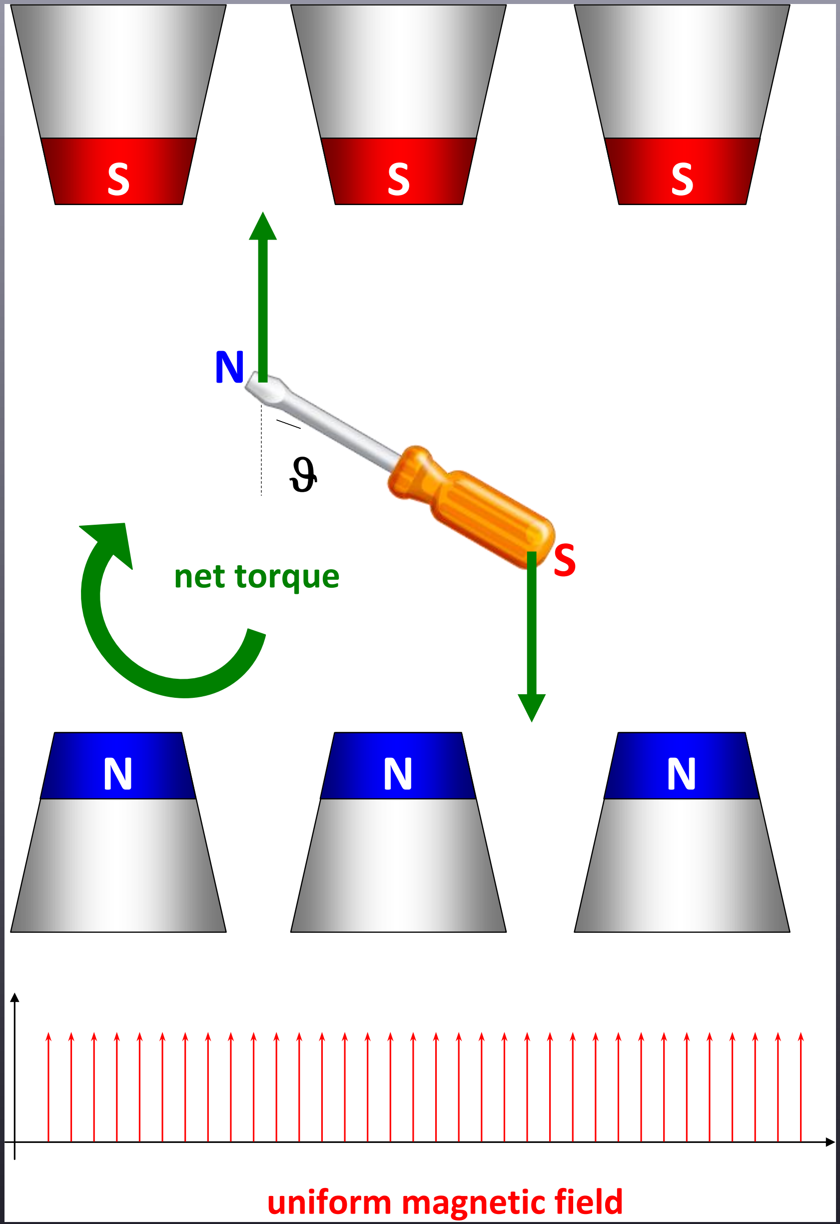
(e.g. N=1/3 for a sphere)




widely spaced poles → low demagnetization (N≈0)

B field (*solenoidal i.e. $\nabla\cdot B=0$*)
Closed field lines
Goes N→S only outside

**force per unit volume is much stronger on elongated objects**




## Case of uniform field

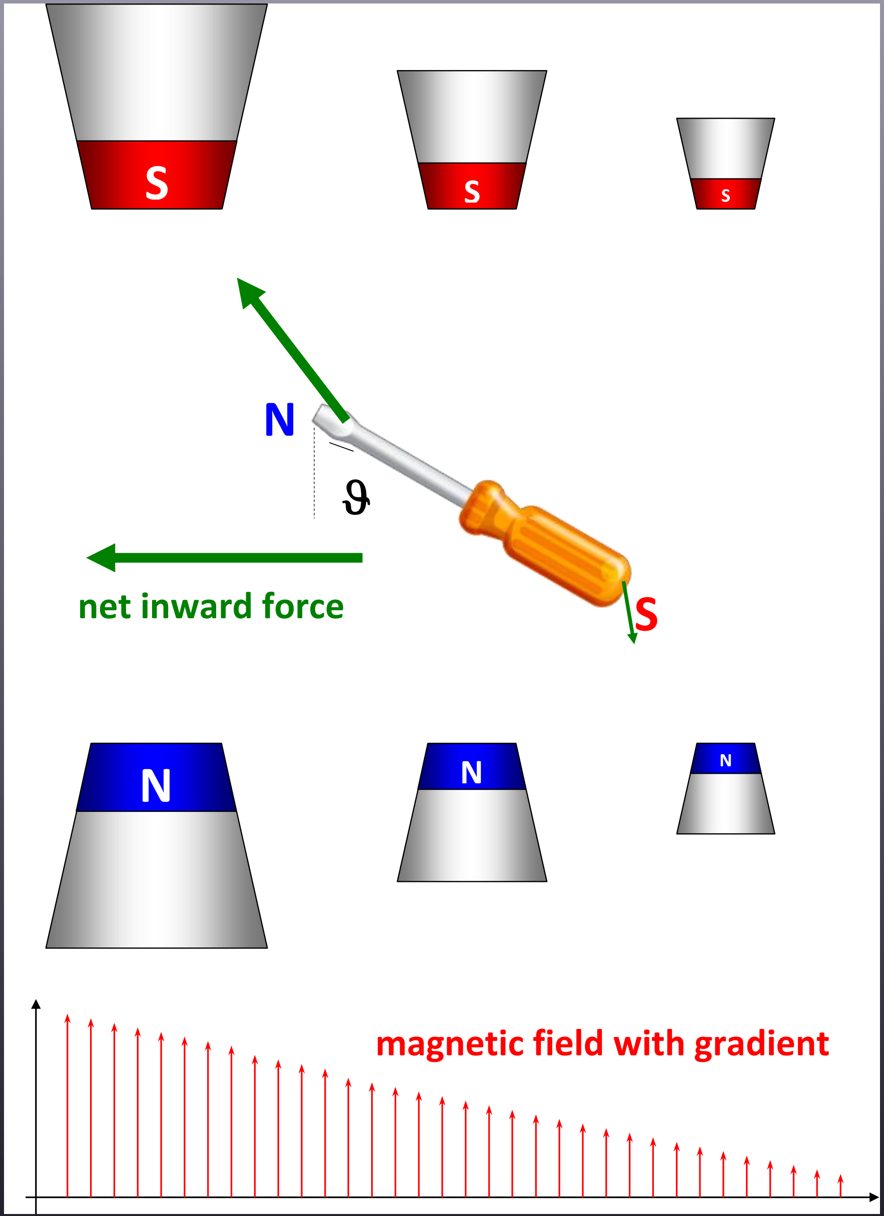
(e.g. inside a dipole or solenoid; Earth field on a local scale)

- Magnetization → N and S poles arise
- Opposite magnetic poles attract
- Equal and opposite forces → torque

$$T \approx \frac{1}{N}\frac{B^2 V}{\mu_0} \sin\vartheta \ \cos\vartheta$$

magnetic torque for an elongated ferromagnetic object of volume $V$

**magnetic objects align to the field lines**




Case of field with gradient:
(e.g. fringe field of large magnets)

- Magnetic forces depend upon position and orientation of the piece
- Net force appears in addition to the torque

$$F_z \approx \left(2 + \frac{\cos^2\vartheta}{N}\right)\frac{VB}{\mu_0}\frac{\partial B}{\partial z}$$

magnetic force for an elongated ferromagnetic object of volume $V$

*NB: force grows with $B^2$ i.e. $I^2_{excitation}$*

ferromagnetic objects are pulled towards regions of stronger field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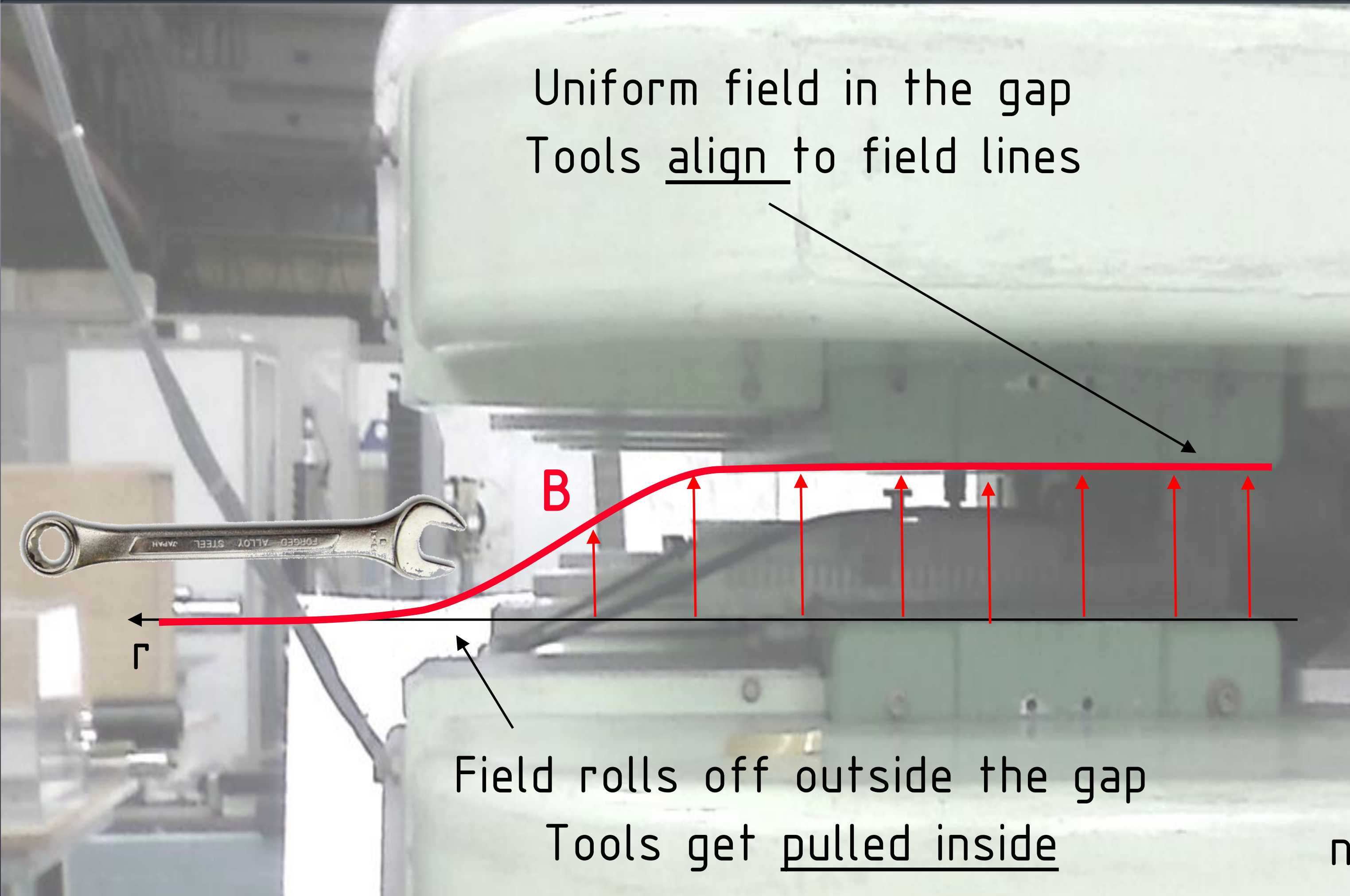
# Magnetic forces on steel tools




Uniform field in the gap

Tools align to field lines

Field rolls off outside the gap

Tools get pulled inside

- HYDRO SYSTEM SA
  8, Rue de la Bergère, 1217 MEYRIN, CH
- EGA Master SA
  C/Zorrolleta 11 (01015), Vitoria, ES

Solution:

non-magnetic tools

**Recommended limit for using standard tools:** *(Directive 2013/35/EU)*

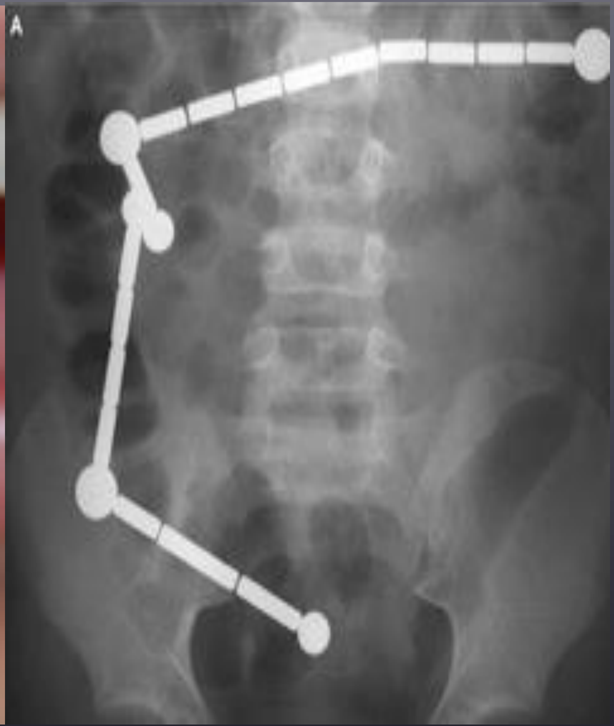
**Background field B ≤ 3 mT if source ≥ 100 mT**

- Non-magnetic and weakly magnetic ($\mu_r \approx$ 1–10)
  - Elements: aluminum, copper, titanium, tungsten
  - Bronze, brass, *beryllium copper, aluminum bronze*
  - Austenitic + high Ni/Cr/Mo stainless steels e.g. 316
    *($\mu_r \approx$ 1 only after annealing)*
  - Virtually all polymers and glasses, most ceramics

- Strongly magnetic ($\mu_r \approx$ 10–10000)
  - Ferromagnetic elements: Fe, Ni, Co
  - Low-C (soft) e.g. ARMCO steel
  - Ferritic (e.g. 409) and martensitic (e.g. 420) stainless steels
  - Most other steel types
  - NiFe alloys e.g. permalloy, mumetal *($\mu_r$ up to ~$10^6$)*
  - Ferrites (Mn/Ni/Zn ceramics)
- Permanent magnets
  - Ferrites ($B_r \leq$ 0.35 T)
  - AlNiCo ($B_r \leq$ 1.2 T)
  - Rare-earth ceramics e.g. NdFeB, SaCo ($B_r \leq$ 1.5 T)

# Are magnets edible ??

- No specific harm from a single permanent magnet
- Two or more may pinch the bowels→ volvulus, necrosis, peritonitis
- Difficult surgery is needed, outcome may be fatal
- 5 cases/y in the USA only — more and more frequent due to the increasing popularity of rare-earth PM based toys

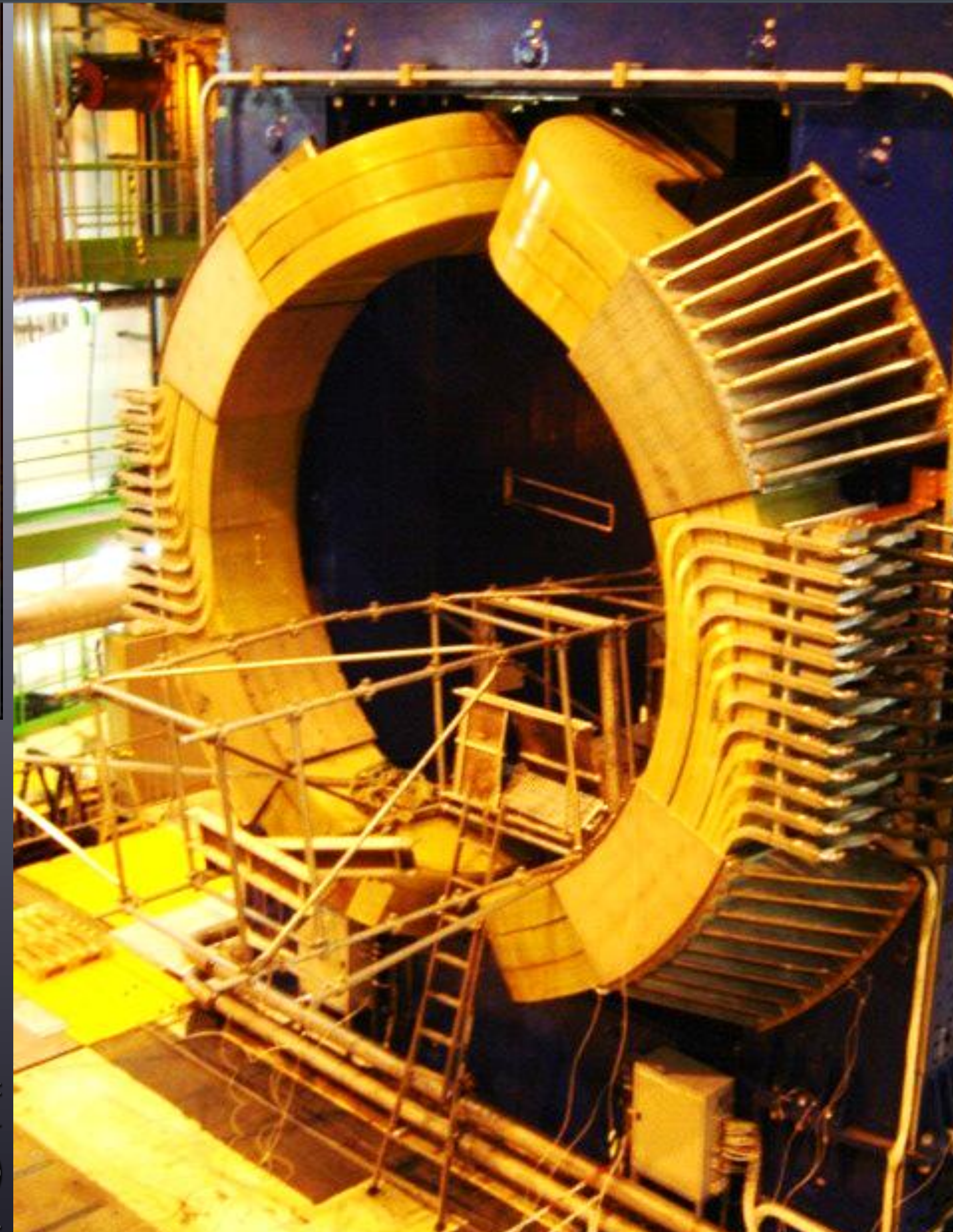


# Collision hazard examples 1/2

Relatively common accidents in the MRI (Magnetic Resonance Imaging) field.

First fatality on record: Michael, 6, killed by an $O_2$ bottle in New York, 2001

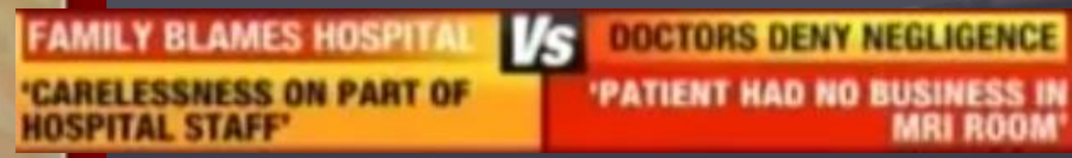
Worst case at CERN: LEP's L3 0.5 T magnet (currently in ALICE) <u>none injured</u>.



- On 29/01/2018, 32-year old Rajesh Maru carried an $O_2$ bottle for a relative in an MRI room
- The bottle got stuck to the 1.5 T magnet, trapping Rajesh's hand for 2 minutes
- A leak from the bottle reportedly caused his death by collapsed lung due to high-pressure $O_2$ intake
- Similar accident in 2014 in New Delhi, no fatal consequences



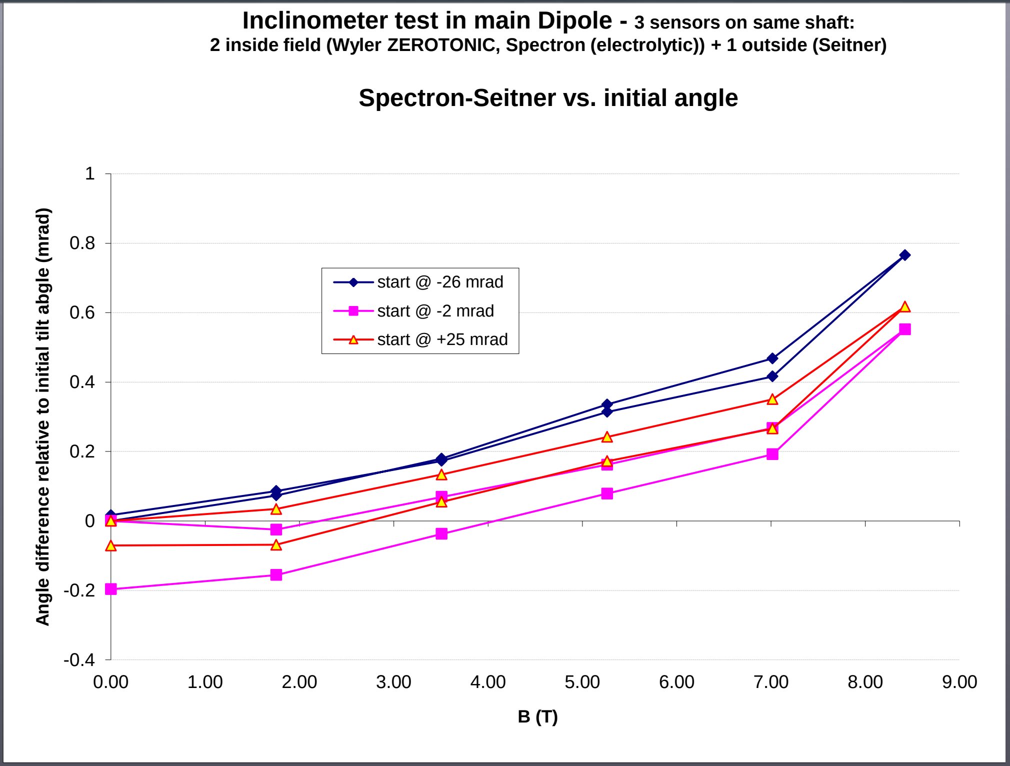





# Equipment malfunctions

# Electronic component malfunctions

| Component | Description | Manufacturer | Reference | limit (mT) |
|---|---|---|---|---|
| Power supply | Filtered rectified | PHEONIX CONTACT | CM-90-PS-230 AC/2x15 DC/1 | 80 |
| Power supply | Switch mode | SCHNEIDER | ABL-7RE-2410 | 40 |
| Power supply | PLC | SCHNEIDER | TSX37-21-001 | 60 |
| Power supply | PLC | SIEMENS | 6ES7307-1BA00-0AA0 | 25 |
| Relays | 24 Vdc | TELEMECANIQUE | RHN-412B | 16 |
| Relays | 220 Vac | TELEMECANIQUE | RHN-411M | 20 |
| Relays | 24 Vdc | FINDER | 55.34.9.024 | 18 |
| Relays | LOGO | SIEMENS | 6ED1052-1FB00-0BA4 | 30 |
| Relays | PLC Digital Output | TELEMECANIQUE | ABE7-P16T-330 | 13 |
| Converters | Programmable converter | SFERE | µC 2000 | 20 |
| Converters | Programmable converter | SFERE | µC 3201 | 40 |
| Converters | Insulated measure transmitter | SFERE | CAPPLUS | 40 |
| Converters | Programmable converter | LOREME | CNL 35 | 50 |
| Converters | 2- wire programmable transmitter | PR ELECTRONICS | 5131 | 35 |
| PLC CPU | TSX37 | SCHNEIDER | TSX37-21-001 | 50 |
| PLC CPU | PLC S7-300 CPU312 | SIEMENS | 6ES7312-1AD10-0AB0 | 25 |
| PLC I/O | Digital input output | SCHNEIDER | TSX-DMZ-28TDK | 50 |
| PLC I/O | Analog Input | SCHNEIDER | TSX-AEZ-802 | 50 |
| PLC I/O | Analog Output | SCHNEIDER | TSX-ASZ-200 | 50 |
| PLC I/O | Digital input output | SIEMENS | 6ES7323-1BL00-0AA0 | 25 |
| PLC I/O | Analog input output | SIEMENS | 6ES7334-0CE01-0AA0 | 25 |
| PLC I/O | ET200M I/O (Fiber optic)IM153-2 FO | SIEMENS | 6ES7153-2BB00-0XB0 | 25 |
| PLC COM. | FIP BUS (copper wires) | SCHNEIDER | TSX-FPP-20 | 50 |
| PLC COM. | AS-i BUS emitter (copper wires) | SCHNEIDER | TSX-SAZ-10 | 50 |
| PLC COM. | AS-i BUS receptor (copper wires) | SIEMENS | 3RK1400-0CE10-0AA2 | 25 |
| PLC COM. | PROFIBUS (Optic fiber) CP342-5 FO | SIEMENS | 6GK7342-5DF0-00XE0 | 25 |




Examples:

- ITER component tests
- tests of tilt sensors (~1 mrad errors) and angular encoders (OK) in LHC dipoles

J. Hourtoule, "Magnetic compatibility of standard components for electrical installations", *Fusion Engineering Design*, 2005

# Radioprotection instrumentation

portable survey meters
→ may be inaccurate


electronic dosimeters
used normally in a magnetic field
detailed assessment under way

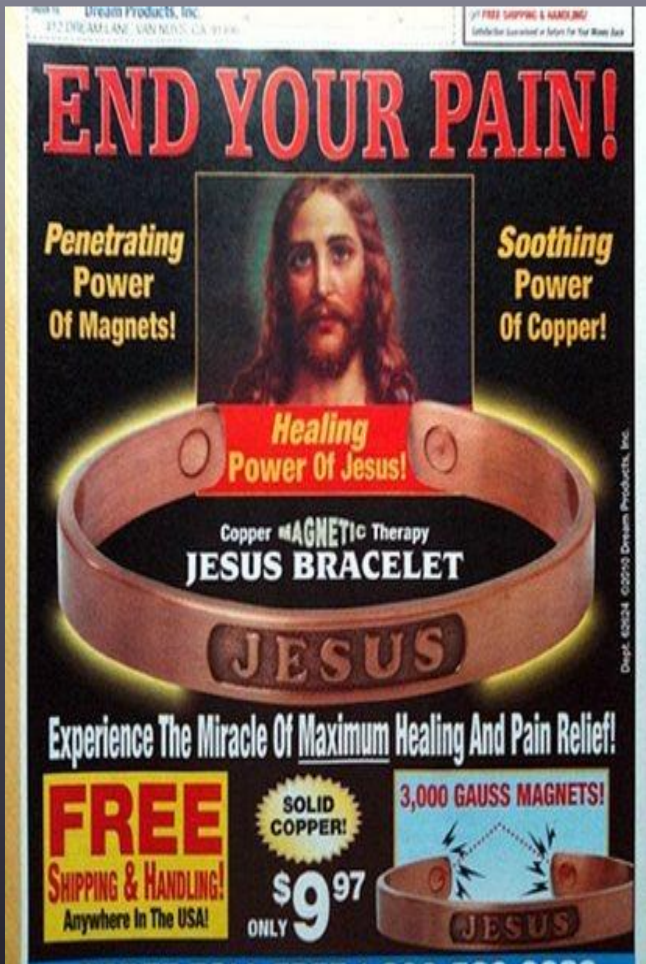
fixed induced
activity monitors
may be affected
(e.g. ATLAS)
→ calibrated in situ

KTT: DGS/RP/SP + Politecnico di Milano
are developing field-compatible dosimeters
(≤ 1 T for now, 3 T on test)
→ 4 prototypes available on demand

individual dosimeters
are passive sensors → no problem

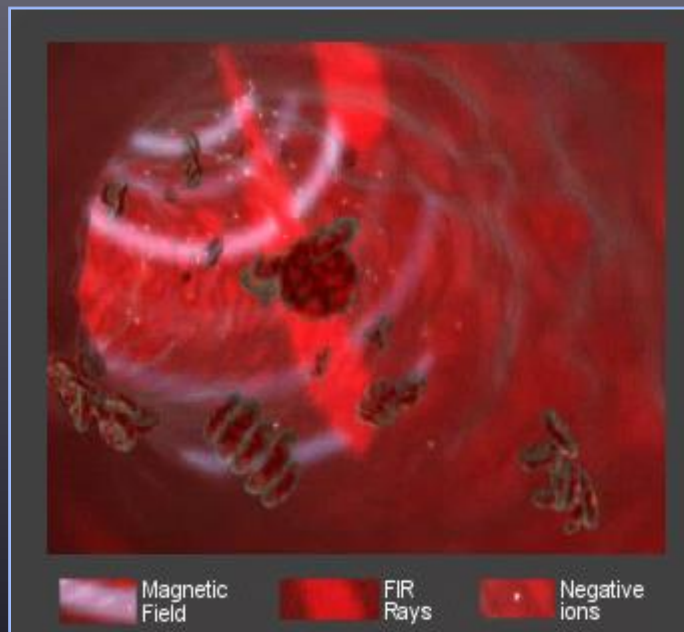
# Part 2
# Health Hazards

- Magnetic therapy: many interesting applications found online…
- Most advertised effect is blood supply increase – is it true ?




"When blood flows through this magnetic field, the blood cells spin then separate from each other giving each cell more surface area to carry much more oxygen and vital nutrients. The magnetic field also widens your blood vessels allowing more blood to flow through.

The second benefit comes from Germanium which emits negative ions (also known as "Air Vitamins") and Far Infra-Red Rays (also known as "Growth Rays")"

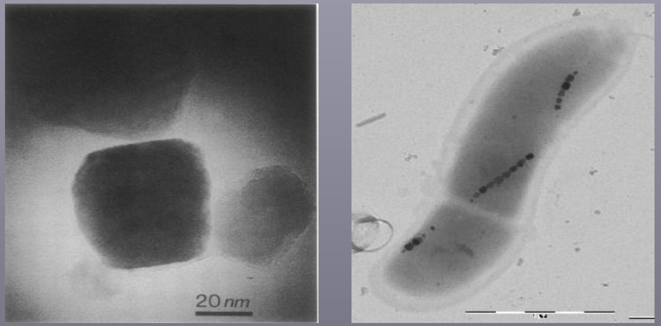



# Magnetic forces on biological tissues

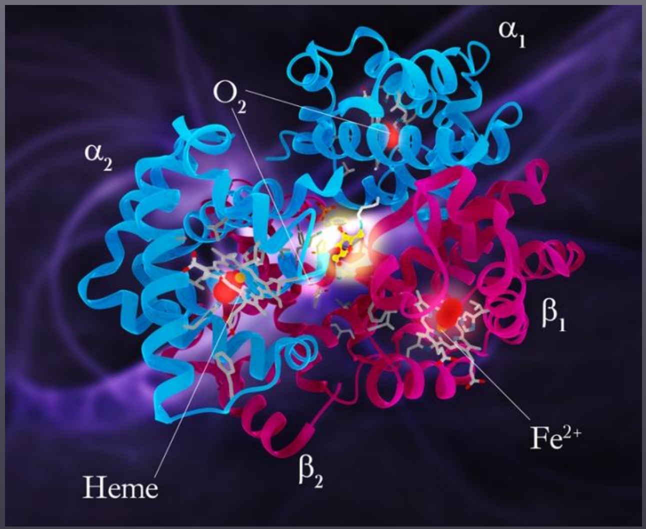
- Magnetite crystals in many animal and human tissues (possible role as sensors e.g. for homing)
- Iron in the blood: ~3 g (red cells) ~1 g (ferritin)

  (typical adult male values)

  isolated atoms, no ferromagnetic domains → small forces

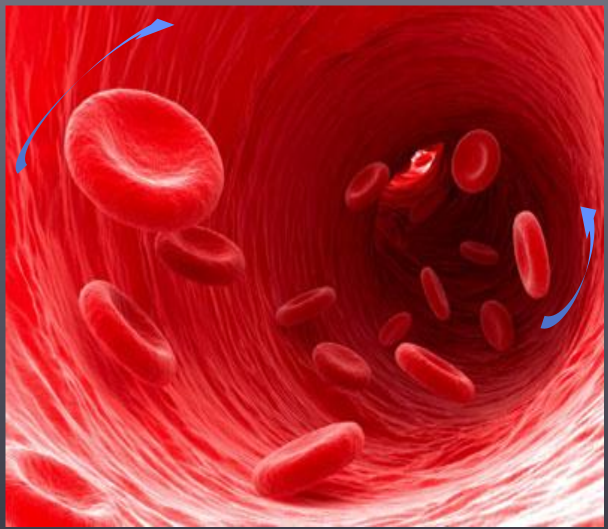


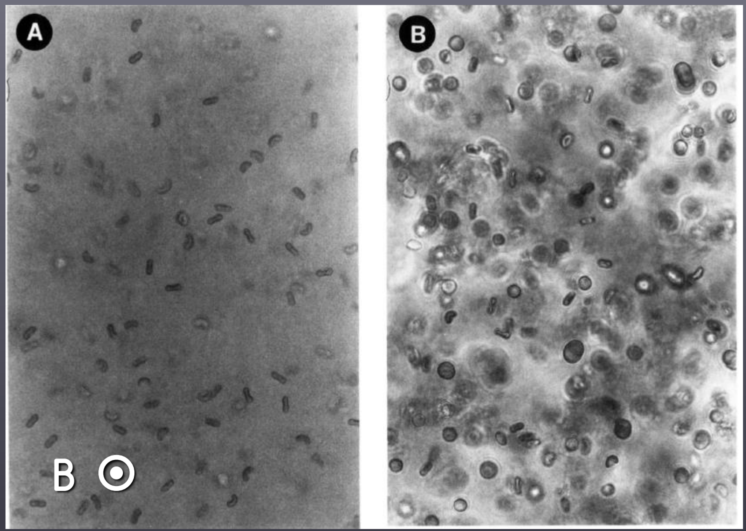

Magnetite crystals in human cerebellum and magnetotactic bacteria




Haemoglobin with 4× Heme groups

$\mu_r \approx 1{+}3.5\times10^{-6}$ (venous) , $1{-}6.6\times10^{-7}$ (arterial)





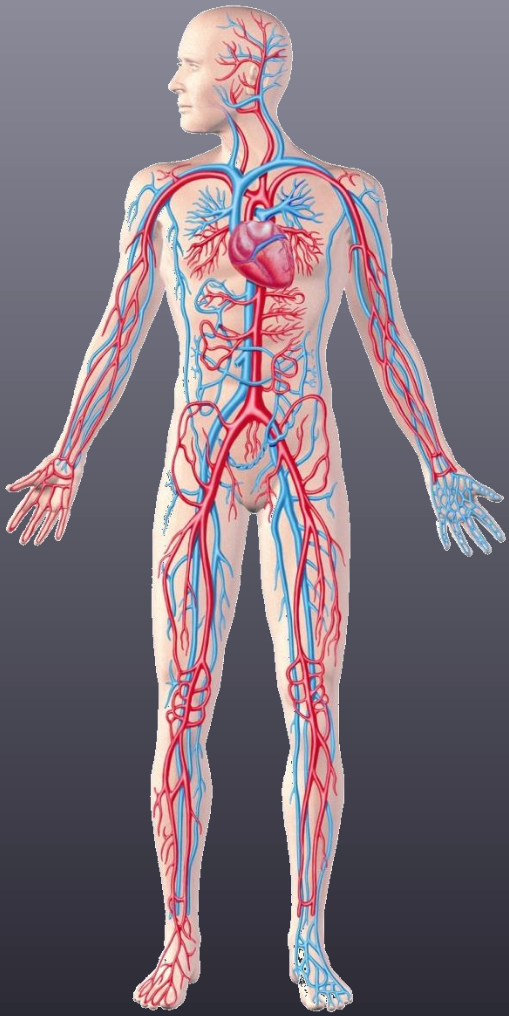

Erythrocytes in a field orient with their disk plane parallel to the field (A)

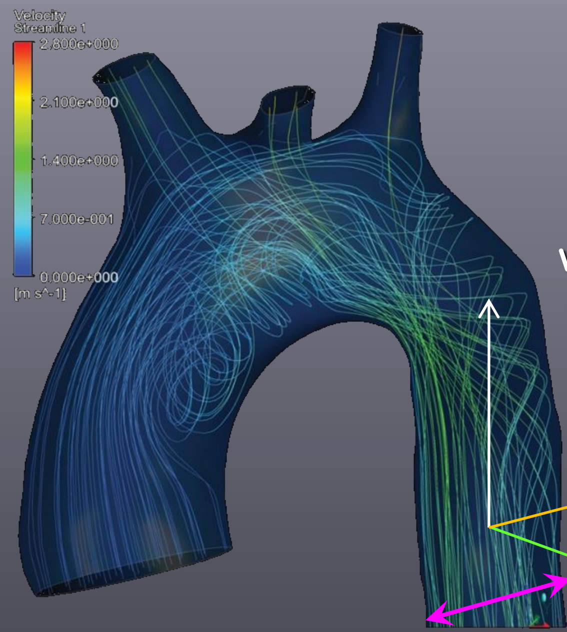
**measurable, but weak mechanical effects → no health hazard**

T. Higashi *et al.*, "Orientation of erythrocytes in a strong static magnetic field," J. Blood 82, 1328, 1993

# Induced voltages

relative motion w.r.t. a magnetic field → electric field






v = flow speed
(max ≈ 2-3 m/s in the ascending aorta)

E=v × B
electric field

B = magnetic field
(worst case = horizontal)

ΔV=E∅ induced voltage
(experimental: 40 mV @ 2.5 T)

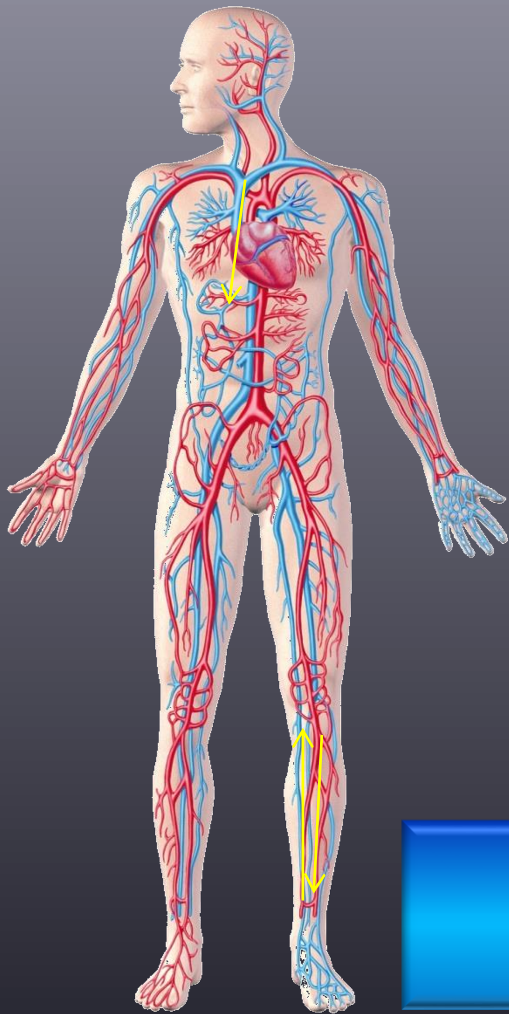
**no voltage across muscle cells**
**no direct biological effects**

Heart J. *et al.*, Evaluation of blood flow velocity in the ascending aorta and main pulmonary artery of normal subjects by Doppler echocardiography, 1984

# Eddy current effects

Induced voltage in a conductor → eddy currents → magnetic friction

bloodflow slows down (7% @ 5T) → blood pressure increases (3% @ 8T)




physiologic rise
+ 6%

slight increase of systolic pressure compensates viscous drag
no change to diastolic pressure, heart rate, body temperature

World Health Organization – Environmental Health Criteria 232, 2006
DW Chakeres, "Effect of static magnetic field exposure up to 8T on sequential human vital sign measurement", J. Magn. Reson. Imaging, 2003

- **Free radical chemistry**
  Vast class of reactions involving highly reactive species with unpaired electrons as intermediate products. The rates of certain radical pair-recombination reactions may change 2×
  due to magnetic fields. However, no known biochemical reaction meets the necessary requisites in humans
  (one exception observed in a type of photosynthetic bacteria)

- **DNA damage, altered gene expression**
  possible carcinogenic effects investigated in vitro, animal models and humans

- **Resonant effects on redox processes**
  (e.g. respiration, photosynthesis)
  Some authors report metabolic stimulation linked to certain types of magnetotherapy (e.g. bone repair)

**very subtle effects, inconsistent experimental evidence**
**no reason to believe in a health hazard**

EU SCENHIR, Possible effects of Electromagnetic Fields (EMF) on Human Health , 2007
L. Brizhik, BIOLOGICAL EFFECTS OF PULSATING MAGNETIC FIELDS: ROLE OF SOLITONS, https://arxiv.org/ftp/arxiv/papers/1411/1411.6576.pdf

# Epidemiological evidence

Large body of evidence from MRI community:

- 0.5~3.0 T widespread, up to 7 T commercially available
- 300+ M scans since 1985, 35 M scans/year
- no long term/delayed effects observed

**patient/occupational exposure deemed safe up to 8 T**


full-body MRI up to 9.4 T ongoing,
11.7 T coming soon

small vertebrates
routinely tested up to 21 T

**no harm reported
even at those levels**

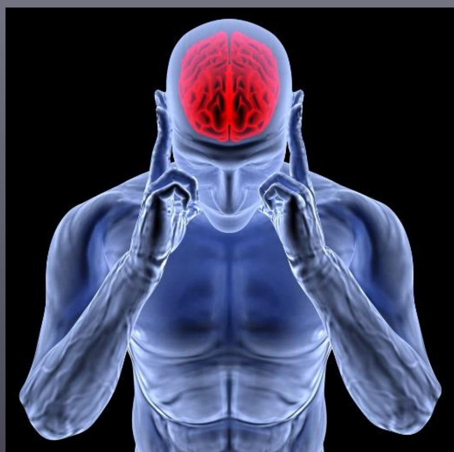
Zaremba, Guidance for magnetic resonance diagnostic devices– criteria for significant risk investigations. U.S. CDRH, FDA, and DHHS. Issued July 14, 2003

# Effects of quasi-static magnetic fields 1/2

- Field change in a conducting medium ($\rho \approx 1\ \Omega m$) → induced voltage → eddy currents
- $dB/dt \geq 2$ T/s → excitation of nerves ($E \geq 6$ V/m, $J \geq 10$ nA/mm$^2$) and muscles ($\Delta V \geq 40$ mV)
- Possible effects on the peripheral nervous system:

**Headache/dizziness**

(caused by differential magnetic susceptibility of vestibular tissues: 46 T$^2$/m → 1% g perceived)



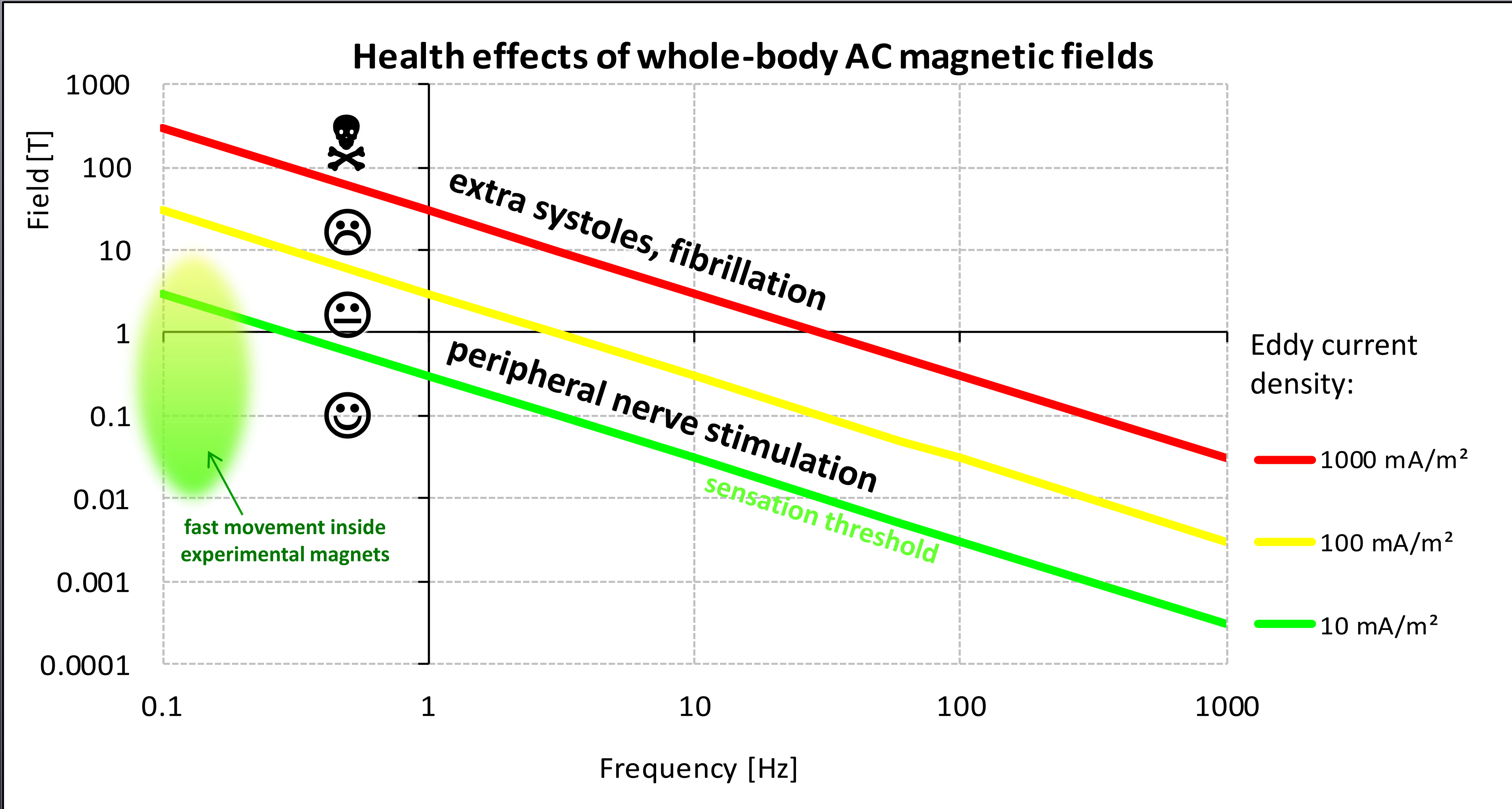
**Sour/metallic taste feeling**

(felt by 15% of subjects, caused by eddy currents on the tongue. Effect weaker if the mouth is kept open)

**Magnetophosphenes**

(flickering light spots caused by the excitation of the retina or the optical nerve)

**Subjective and reversible effects reported by ~50% personnel in ATLAS/CMS when magnet ON**




**moving in a *gradient* DC field = standing in an AC field**

RD Saunders, "Biological effects of magnetc fields", J. Radiol. Prot. Vol 9, 1989

# Effects on medical implants

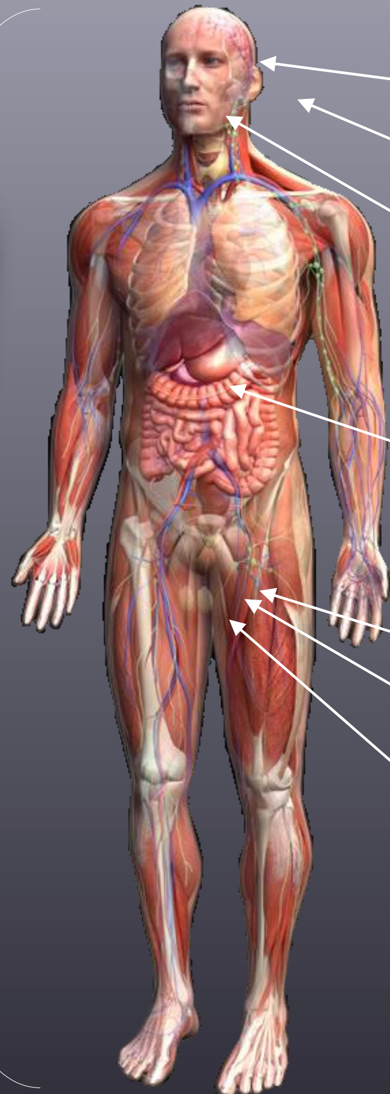
# Effects of magnetic fields on implants

vascular clips
*(e.g. aneurysm)*


needles

bullets, shrapnel

makeup, tattoos
jewelry, piercings



eye implants
*splinters*

hearing aids
cochlear implants

Co-Cr implants
braces

heart valves,
pacemakers

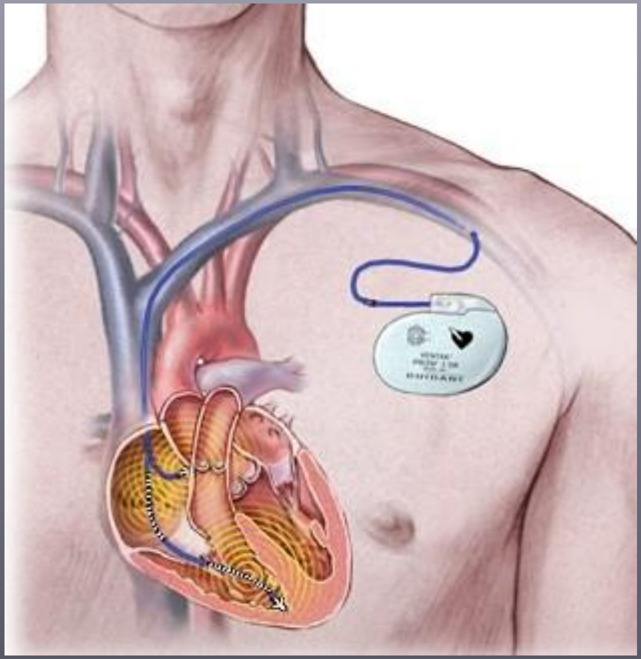
Intra Uterine Devices

penile implants

magnetic anus

**implants might malfunction or dislodge (especially if recent)**

# Pacemakers



reed switch
external field → magnetization and closure of contacts

- Pacemaker function: sense electrical cardiac pulses, provide missing pulses at suitable intensity and rate
- Certain older models include a **reed switch** that can be magnetically actuated from outside to:
  - go into programming mode
  - disable pulse sensing and go into fixed-frequency mode (asynchronous pacing)
- competing rhythms may cause discomfort, arrhythmia, or in extreme cases death (17 fatalities on record to date )
- Lowest reported DC activation threshold is **0.7 mT**
- AC fields may further interfere with pulse detection/generation electronics
  *(MRI gradient coils may drive heartbeat !)*

**pacemakers, defibrillators (ICD) or any other heart implant: exposure to B > 0.5 mT is absolutely forbidden**

# Can you go in a strong magnetic field if you have .... ?

mostly YES

(but: magnetic overdentures exist)

not recommended (esp. < 3 months)

STAY AWAY !!

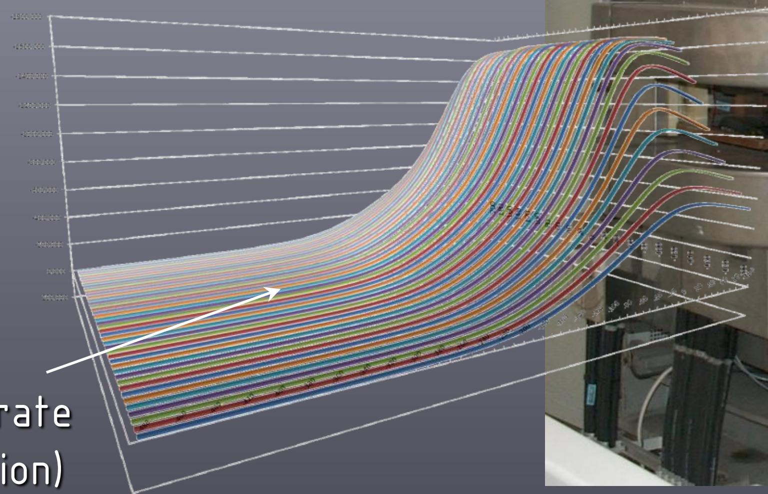
**respect the 10 mT boundary or bring it up with the medical service !**

# Part 3
# Field sources at CERN

# Fringe fields

$$B(x) = \frac{3\hat{n}(\hat{n}\cdot m) - m}{|x|^3} + \frac{8}{3}\pi m \delta(x)$$

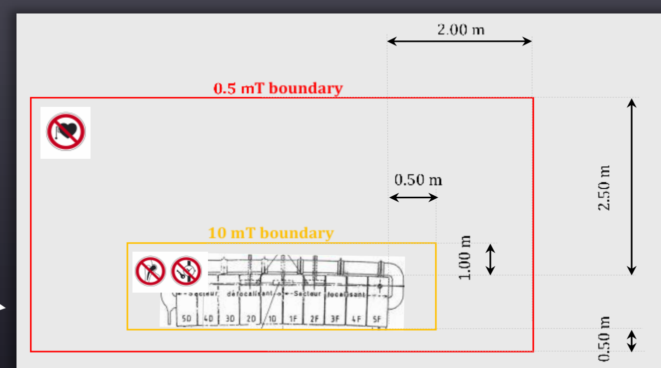
Field generated by a magnetic moment $m = IA\hat{n}$ at $x = 0$
*Jackson*, Classical Electrodynamics (5.58)



1/r$^3$ roll-out rate
(far field region)

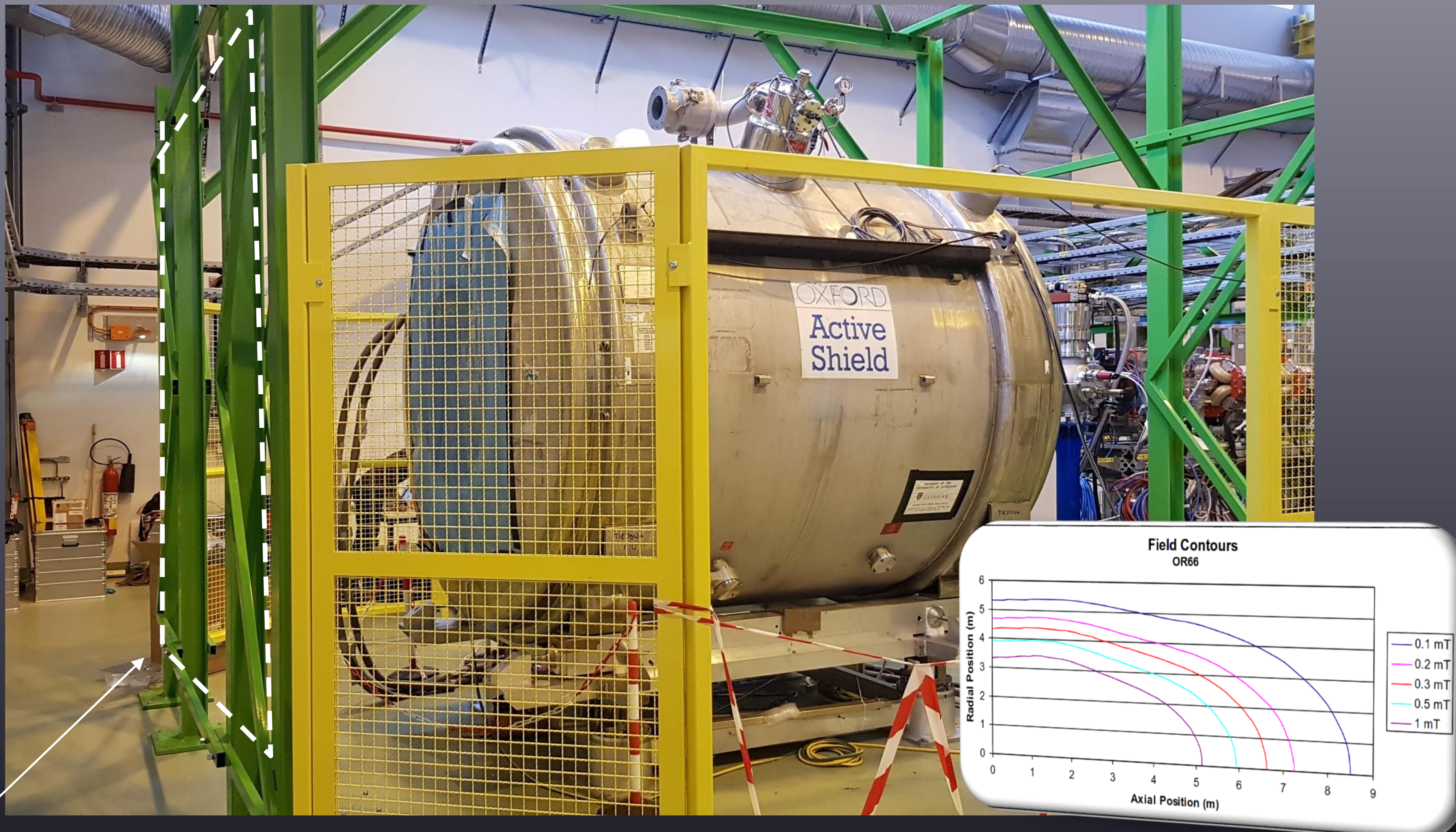

**1/r (straight conductor) ~ 1/r$^2$ (conductor + return) ~ 1/r$^3$ (round loop, solenoid)**

- Fringe field typically reaches out up to **4~5 × gap heights**
  (even further if the coils are exposed !)
- B≈0 next to the iron yoke (if not saturated)
- Safety perimeter documented in EDMS (worst cases)



# Example: ISOLDE solenoidal spectrometer

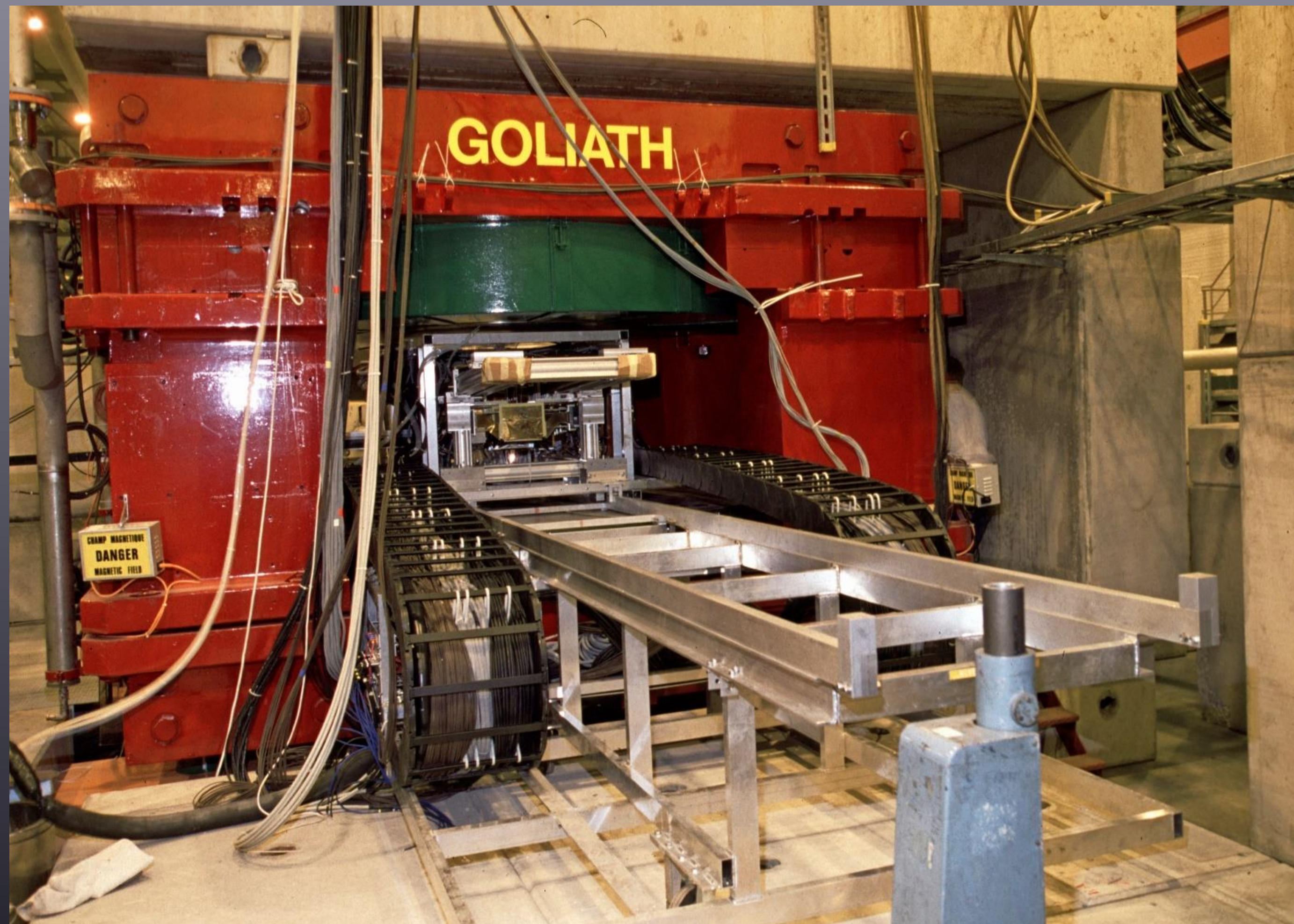
- 4 T, 600 A, ∅925 mm bore
- fringe field on the axis: 10 mT @ 1 m from end, 0.5 mT @ 4.6 m
- pacemaker compatibility ⇒ additional passive shielding OR interdiction of whole hall



# Examples: North Experimental Area

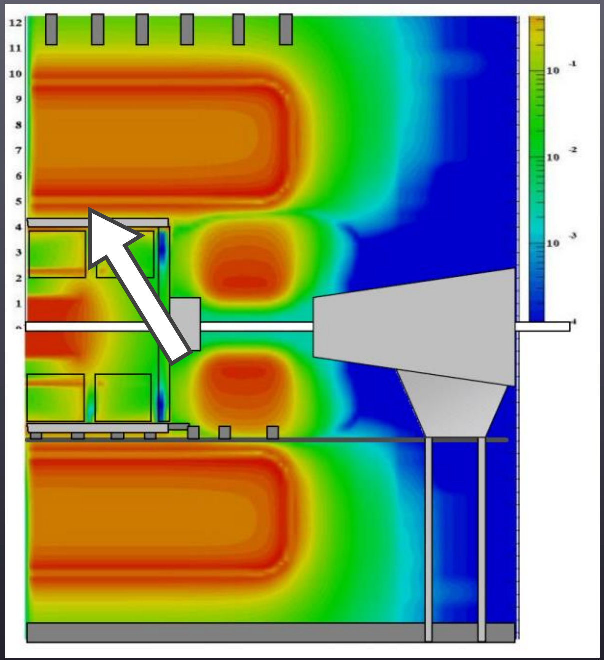
- Many normal- and superconducting magnets with very wide fringe regions. Examples:
- **M1** (H2 beam line): 3 T Helmholtz configuration, up to 15 mT @ 4 m distance
- **Goliath** (H4 beam line): 1.5 T in the center, 5 G boundary @ 10 m distance

M1 (887-R-252)




Goliath (PPE134)

# ATLAS toroid



- Highest nominal peak field (4.1 T)
- Field level with magnets OFF:
  ≤ 5 G in all accessible areas
  (peaks up to 20 G close to the floor or some steel structures)
- Field level with magnets ON:

  full-body region up to ~1 T accessible just below the toroid coils;

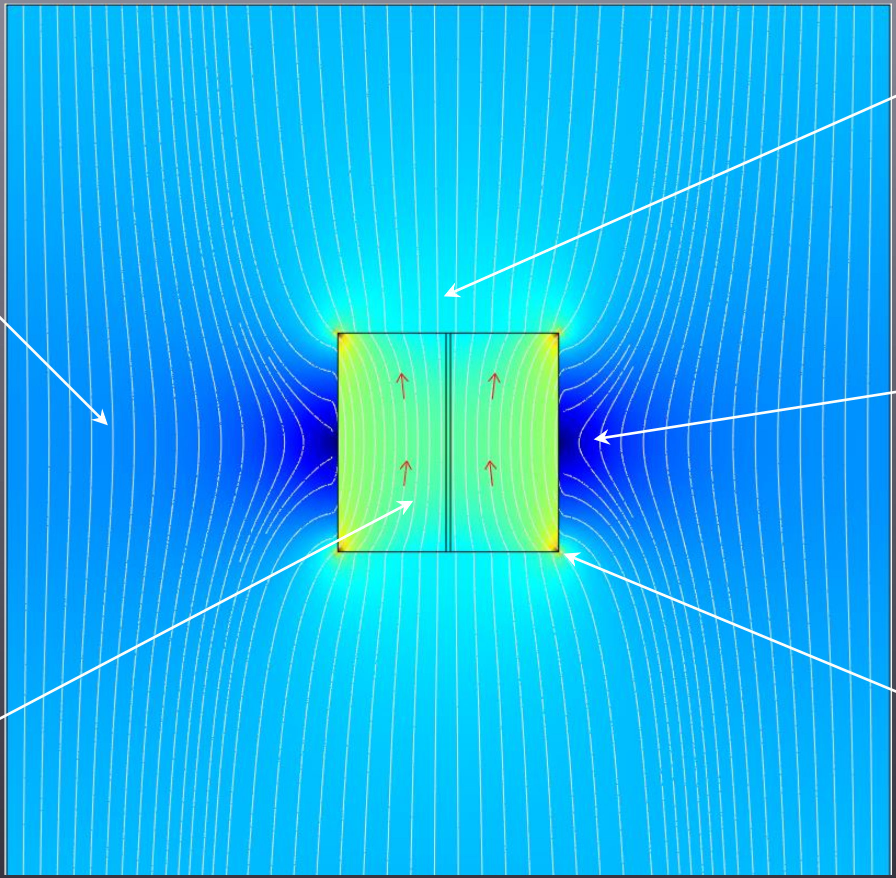
  all visitor-accessible areas < 100 G
- No safety boundaries marked on the floor, whole cavern off-limits to pacemakers

# Field distortion

Ferromagnetic materials **distort** and **concentrate locally** the magnetic field

External field (uniform)

The field is "sucked in" and amplified by high permeability materials



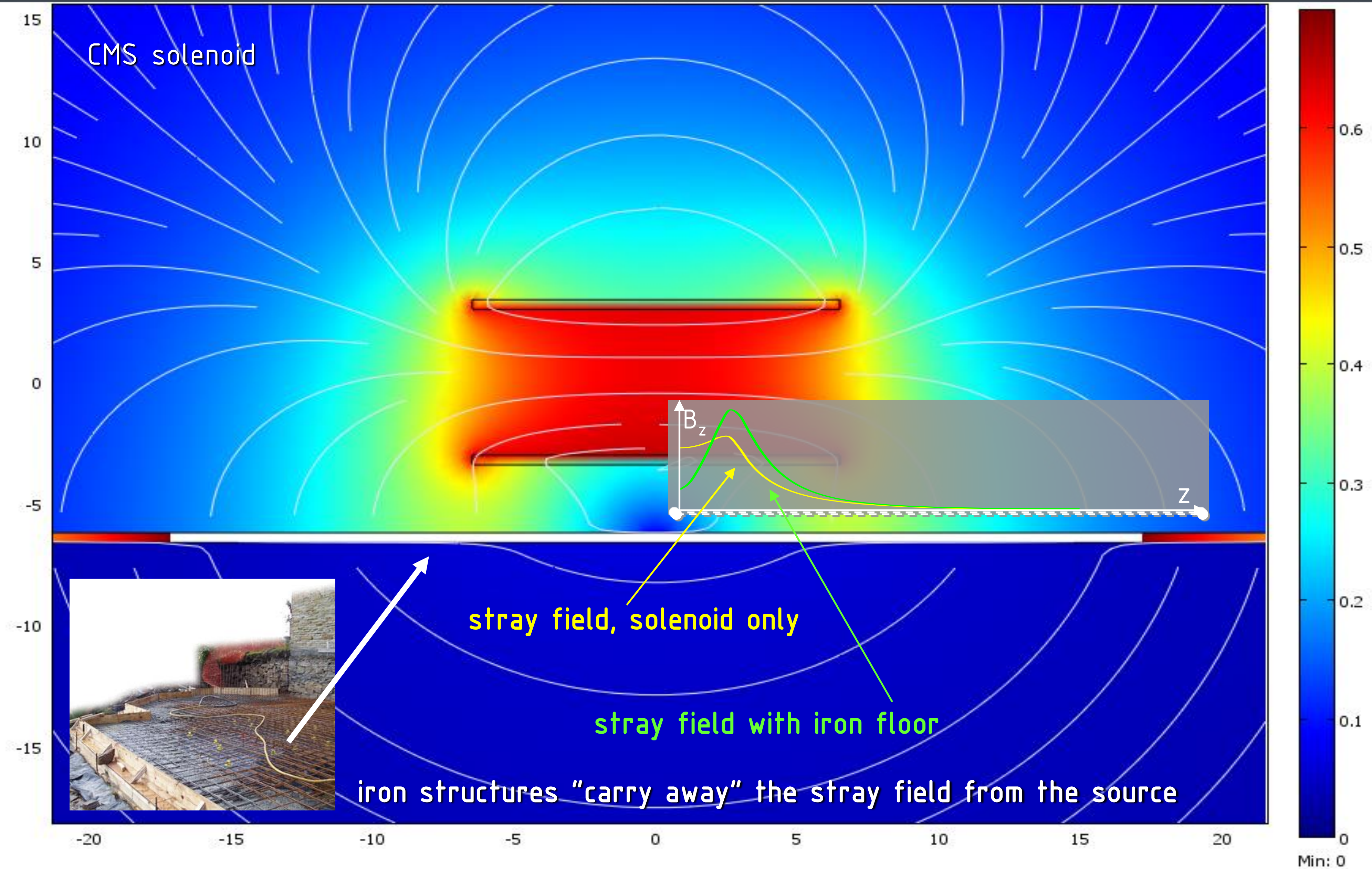
Field is amplified here ….

… but is lowered here

High field concentration peaks are always found near sharp corners (singularities)

**Prediction of the distorted field pattern in real-world cases is <u>very</u> difficult**

# Example: CMS stray field



# Summary

# Exposure limits at CERN (IS36.2 amended Feb 2015)

**heart implant**
(pacemaker, defibrillator)

$B \leq 0.5$ mT

**general public**
(generic implants
pregnant women)

$B \leq 10$ mT

**employees**
(all categories, no time limits)

*2 T: full body*

*8 T: limbs*

$B \leq 2$ T (8 T)

*Will need authorization
of Medical Service
and/or follow up*

$B > 2$ T (8 T)

A grateful acknowledgement to:

| | |
|---|---|
| Alain Chouvelon | HSE |
| Benoit Cure | PH/CMX |
| Niels Dupont | EP/CMX |
| Alexey Dudarev | PH/ADO |
| Veronique Fassnacht | GS/ME |
| Martin Gastal | EN/MEF |
| Marzio Nessi | PH/ADO |
| Marco Silari | HSE/RP |
| Stefano Sgobba | EN/MME |
| Fritz Szoncso | HSE/DI |
| Davide Tommasini | TE/MSC |

(boring you to death is however my fault only)