Physiological Effects of Magnetic Fields
(an MRI perspective)

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Outline

- Static magnetic fields
- Excursion on MRI
- Physiological effects of static magnetic fields
- Low-frequency magnetic fields
- Regulatory issues (in Europe)

Static magnetic fields

Static fields: human exposure

- typically a few 10 mT or less

	Industry	Transport	Energy distribution
General public	(hobby) few mT	Maglev 0,05 – 1000 mT Trains 0,1 – 1 mT Tram 0,01 – 0,4 mT	few tens of µT
Occupational	Aluminium < 60 mT Chlor-alkali < 20 mT Welding < 5 mT Heavy < 0,2 mT	0,1 – 15 mT	50 mT

6th International NIR Workshop
October 14th to 17th, 2008, Rio de Janeiro, Brazil

Bundesamt für Strahlenschutz

R. Matthes
BfS (2008)

Strong fields: human exposure

- Magnetic resonance imaging (MRI)
  - highest field strengths
  - by far highest case numbers
    - patients
    - occupational

Clinical MRI: the workhorses

- 1.5 T magnets
- total investigations on humans: ~500 million

Siemens 1.5 T

Philips 1.5 T

General Electric 1.5 T

Clinical MRI: the high end

- 3 T magnets

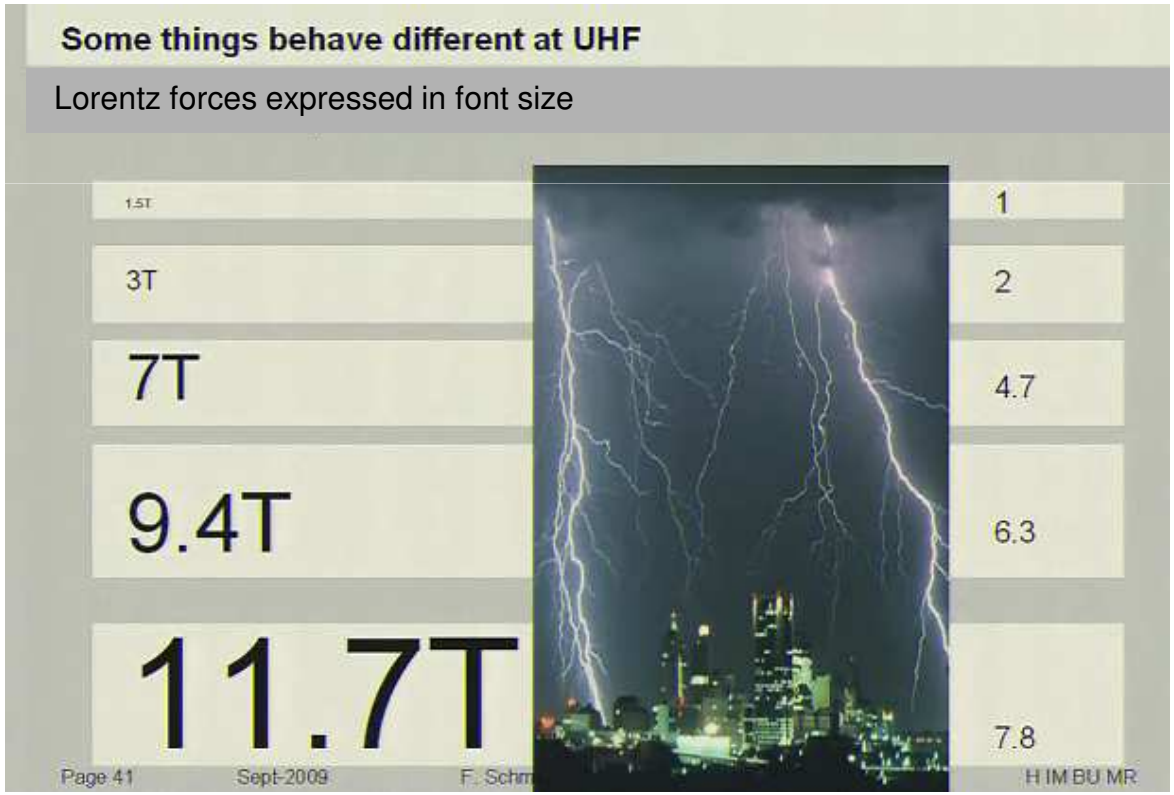
Siemens 3 T

Philips 3 T

General Electric 3 T

Research MRI: "ultrahigh fields"

- 7 T ~40
- 9.4 T 4 (Chicago, Minneapolis, Tübingen, Jülich)
- 11.7 T 1 under construction (Saclay), 3 – 5 planned (USA)



F. Schmitt, Siemens

7 T MRI (Berlin)

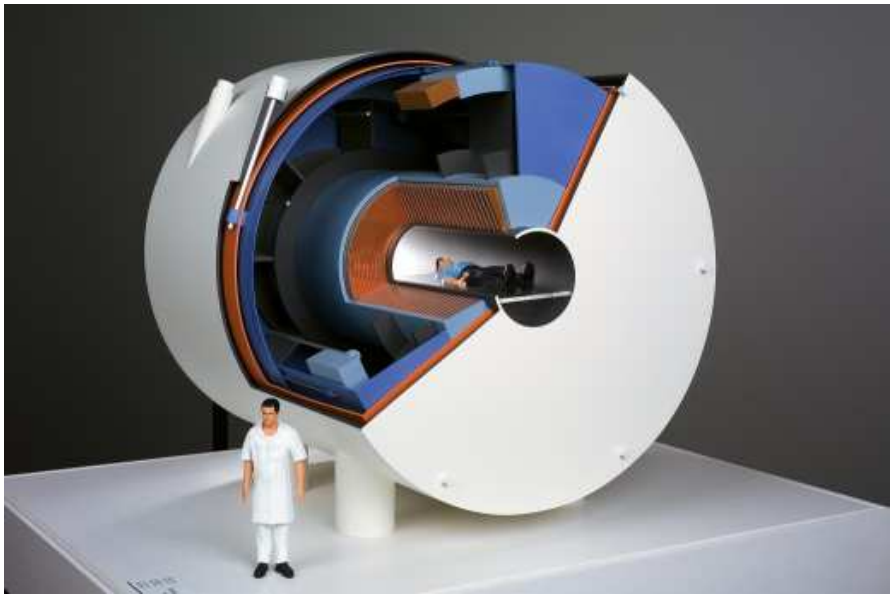
- Ø = 2.4 m, L = 3.4 m
- 32 t magnet
- 240 t iron shield

9.4 T MRI (Jülich)

- Ø = 2.7 m, L = 4 m
- 57 t magnet
- 870 t iron shield

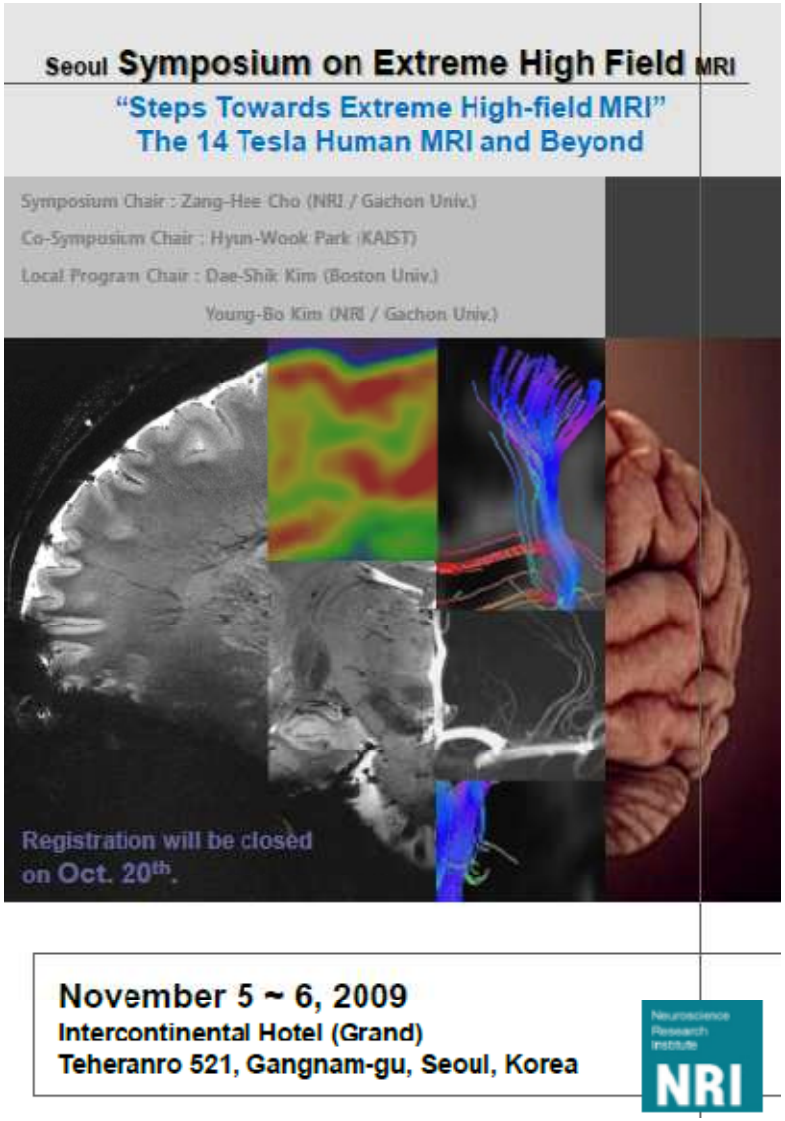
11.7 T MRI (Saclay)

- Neurospin
  - 3 T, 7 T, 17.6 T (small animal)
- feasibility project to push the boundaries
- actively shielded magnet design, 150 t, Ø = 4.5 m, L = 4 m
- expected to be finished in 2012



14 T MRI (NRI, Gachon)

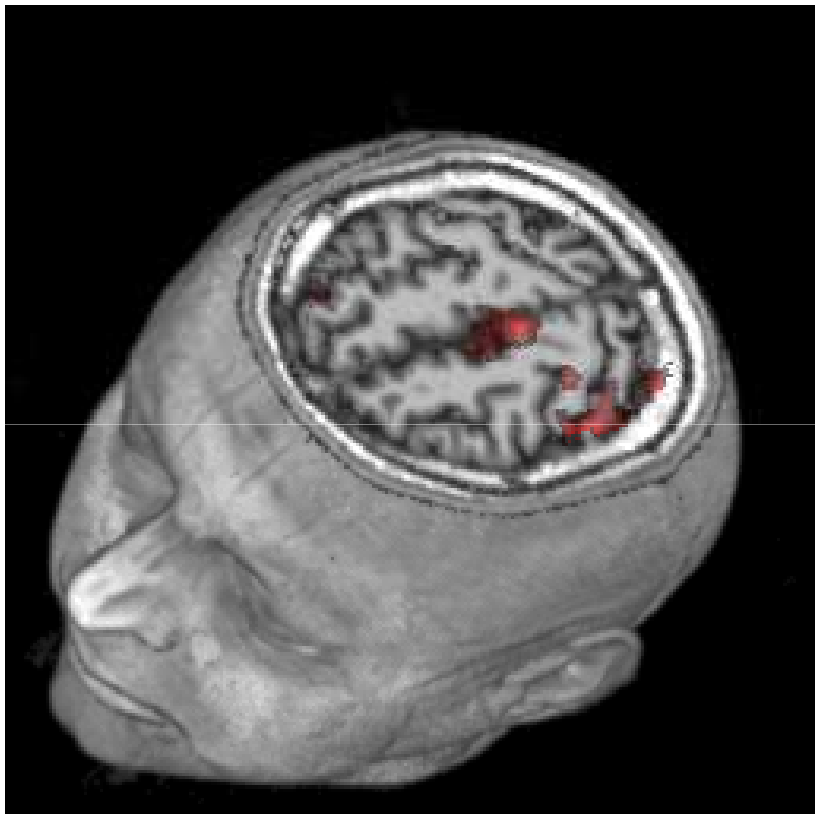
- The arms race continues



Why MRI ?

Magnetic Resonance Imaging (MRI)

- Non harmful
- Non invasive
- Spatial resolution: < 1.0 mm
- Temporal resolution: 0.1 – 1000 s
- MRI provides
  - anatomical information
  - biochemical information
  - functional information
  - mechanic information (flow)



MRI: signal intensity

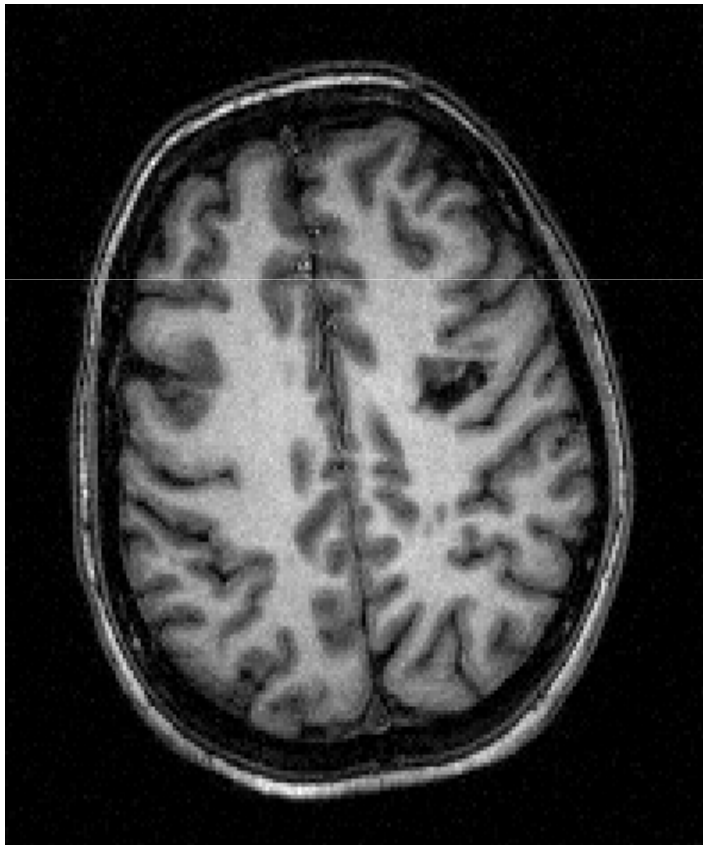
For single-echo sequence:

$$S = \rho_S \sin\alpha \frac{1-\exp(-T_R/T_1)}{1-\exp(-T_R/T_1)\cos\alpha} \exp(-T_E/T_2^{(*)})$$

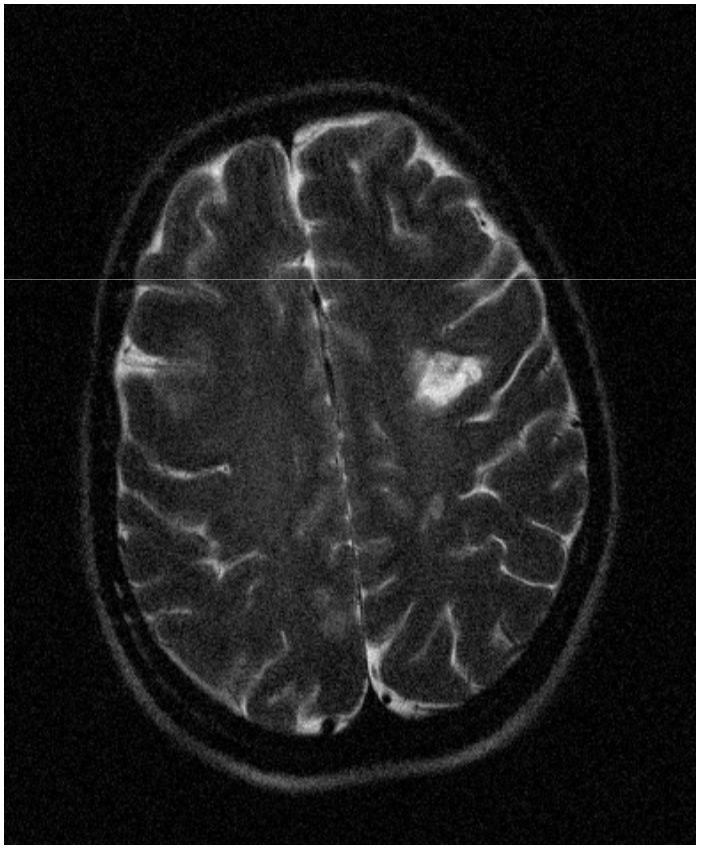
ρ_S, T_1, T_2	proton density, relaxation times	tissue parameters
α, T_E, T_R	tip angle, echo/repetition time	sequence parameters

MRI: tune the image contrast

T_1 -weighted (MDEFT)

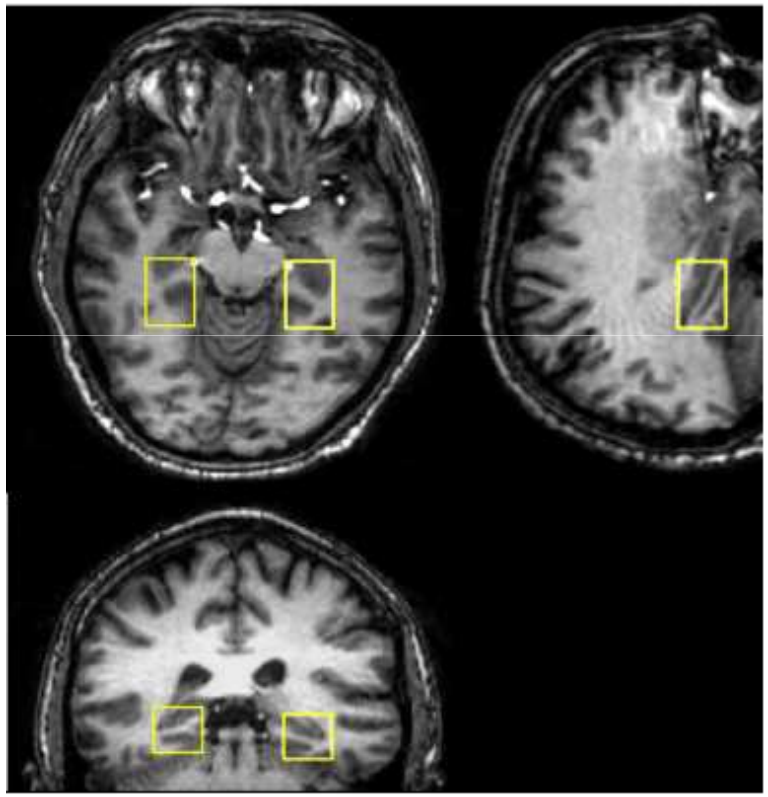


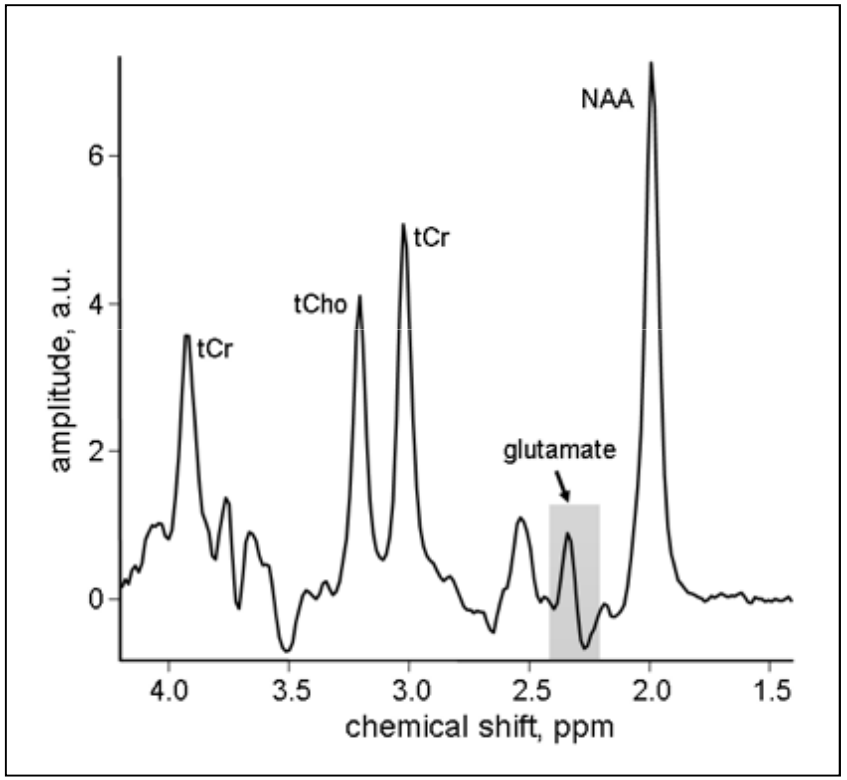
T_2 -weighted (RARE)



Magnetic resonance spectroscopy

- localized metabolic profiles of the living brain

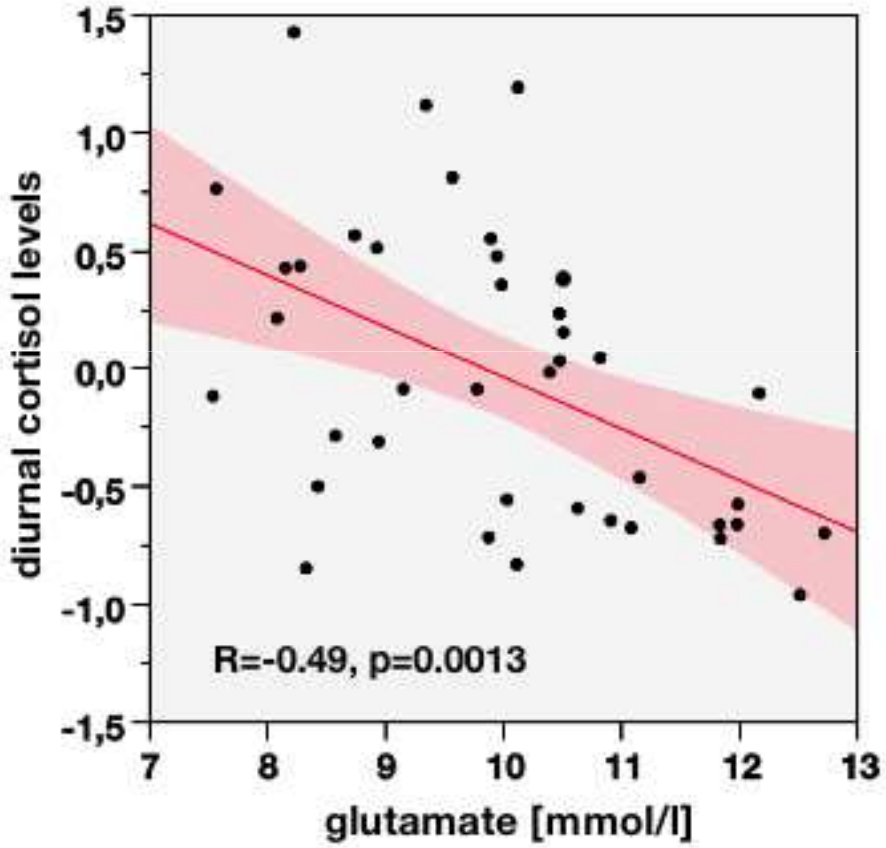




F. Schubert et al, NeuroImage 2004

Magnetic resonance spectroscopy

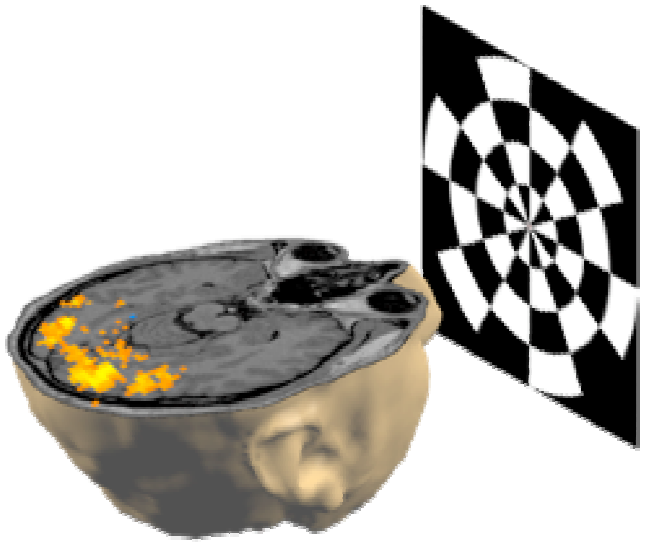
Example: *Role of neurotransmitter glutamate in bipolar disorder*

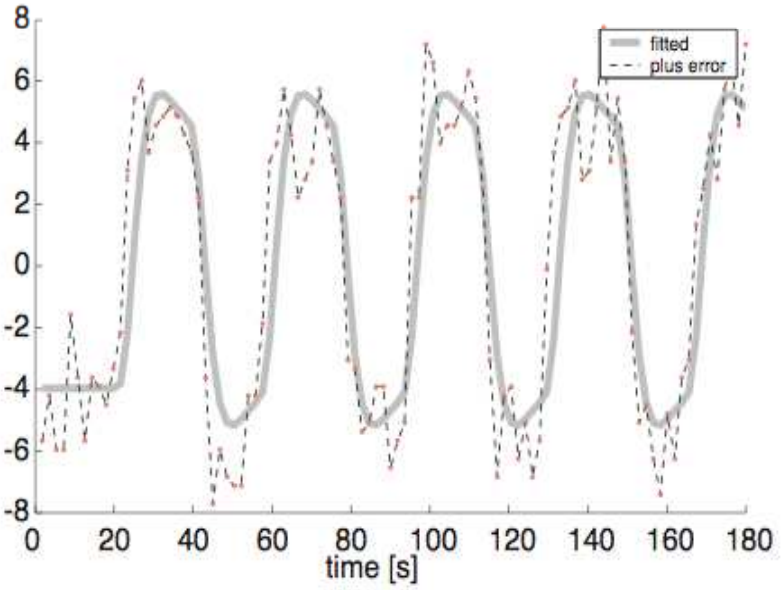


Colla *et al.,* Molecular Psychiatry 2008

functional MRI

- “watch the brain thinking”
- neural activity $\Rightarrow$ increased oxygen consumption
- O_2 paramagnetic $\Rightarrow$ O_2 saturation MRI accessible (“BOLD effect”)

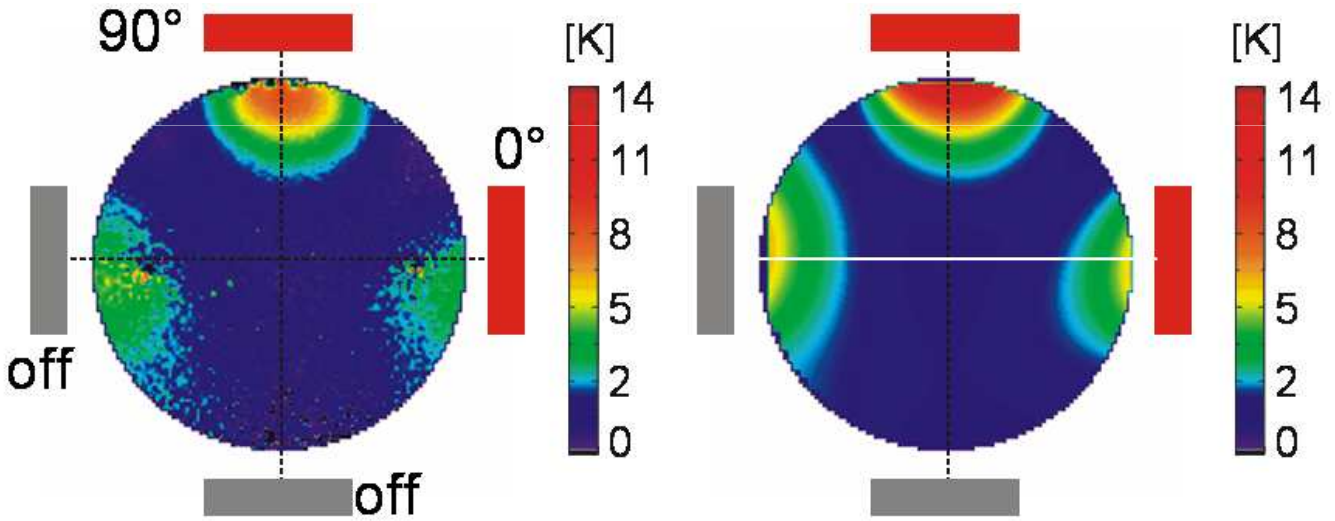




MRI: it's for measurements, too

- Temperature measurements by MRI

RF heating experiment in gel phantom
F. Seifert et al., J. Magn. Reson. Imag (2007)

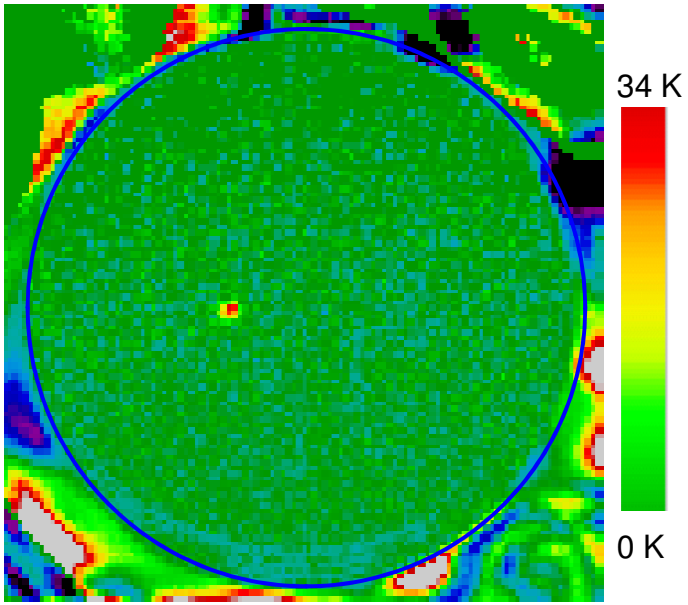


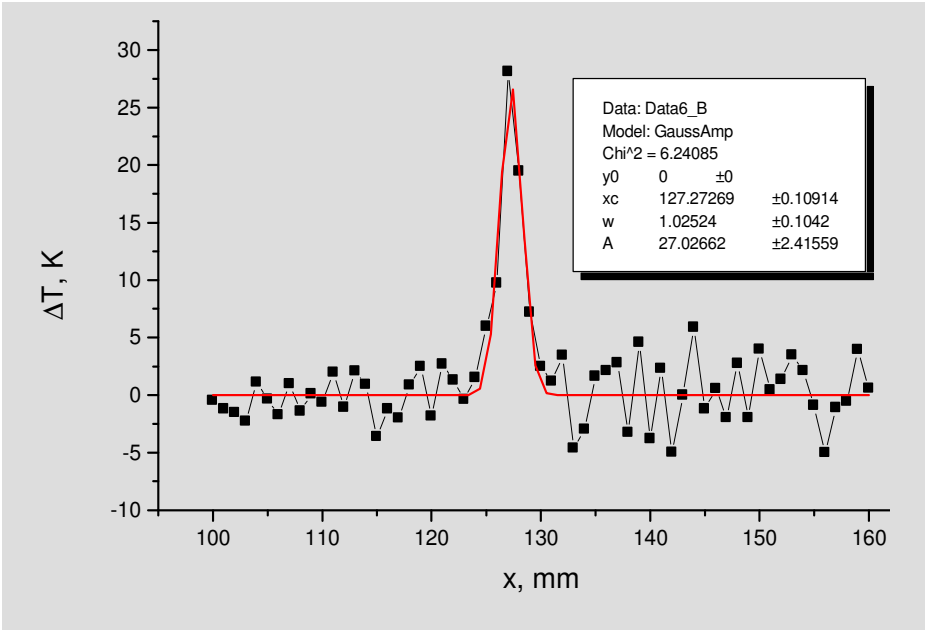
Experiment Simulation

MRI: it's for measurements, too

temperature increase after ultrasound heating

15 s heating, P= 15 W



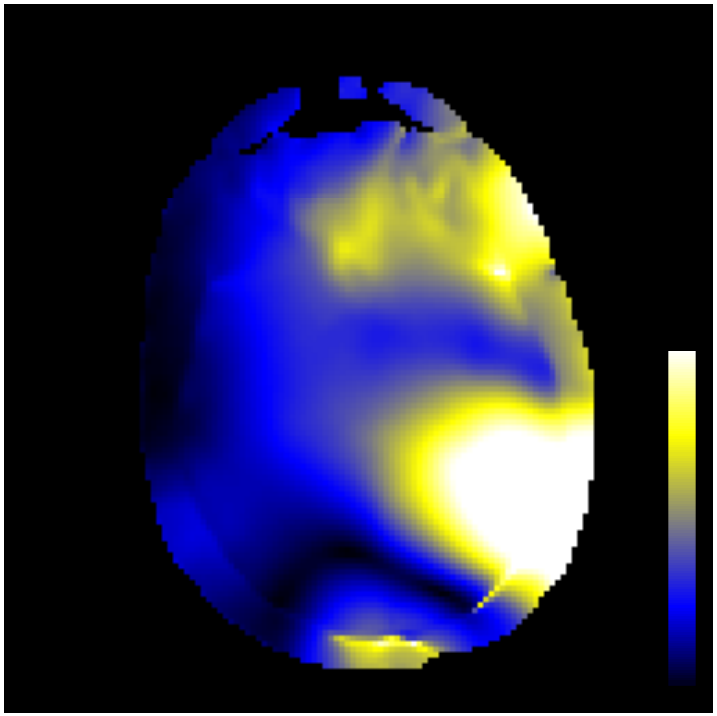


T. Klepsch et al., 2010

MRI: it's for measurements, too

- RF magnetic field measurements

σ^+ magnetic field component in human head at 297 MHz (7T)

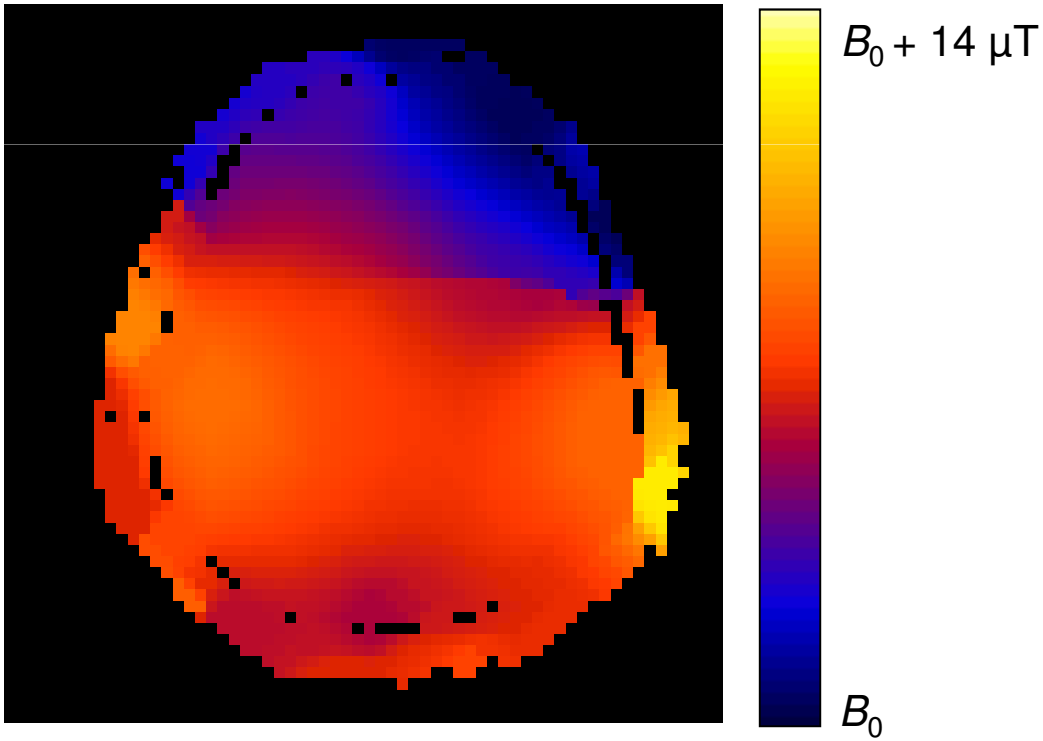


Lindel et al. (2009)

MRI: it's for measurements, too

Static magnetic field measurements

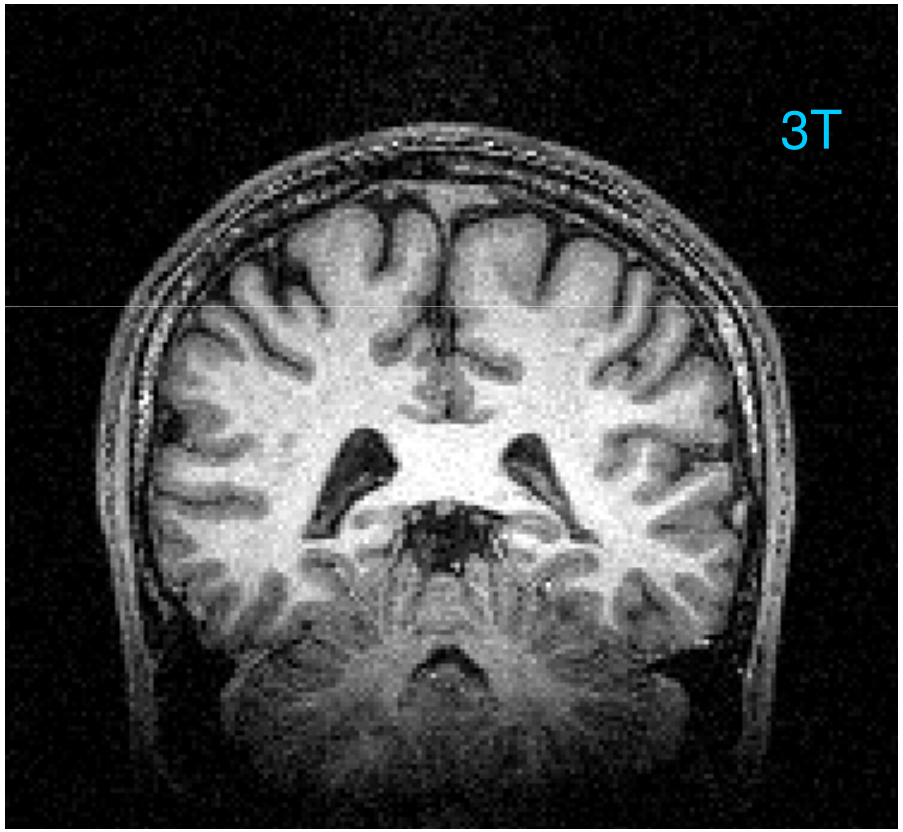
- field distribution in human head B_0 = 7T
- quantitative



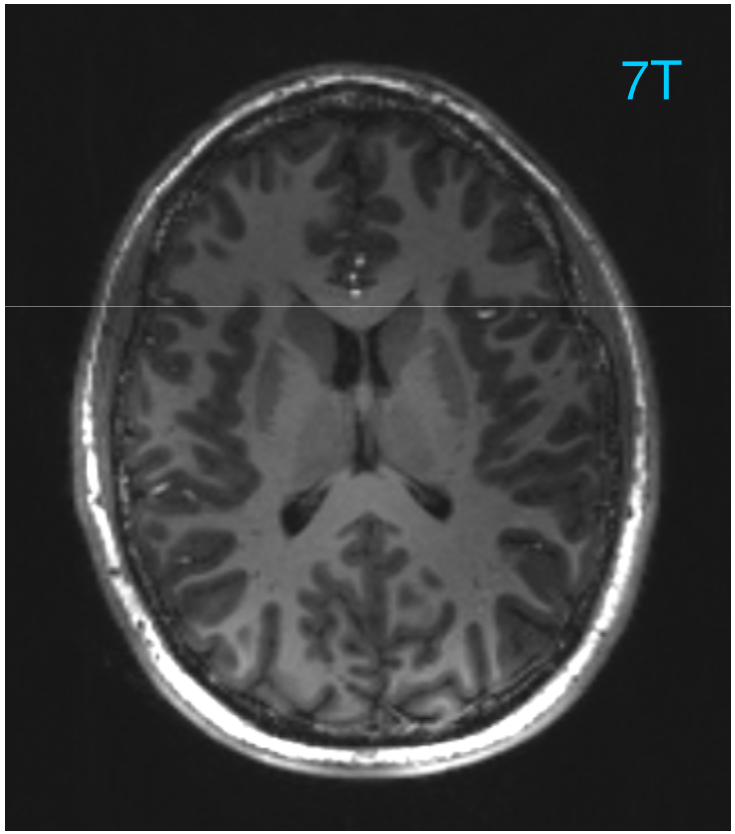
Lindel et al. (2009)

MRI: Why ultrahigh fields?

- 3D, full brain coverage
- same sequence

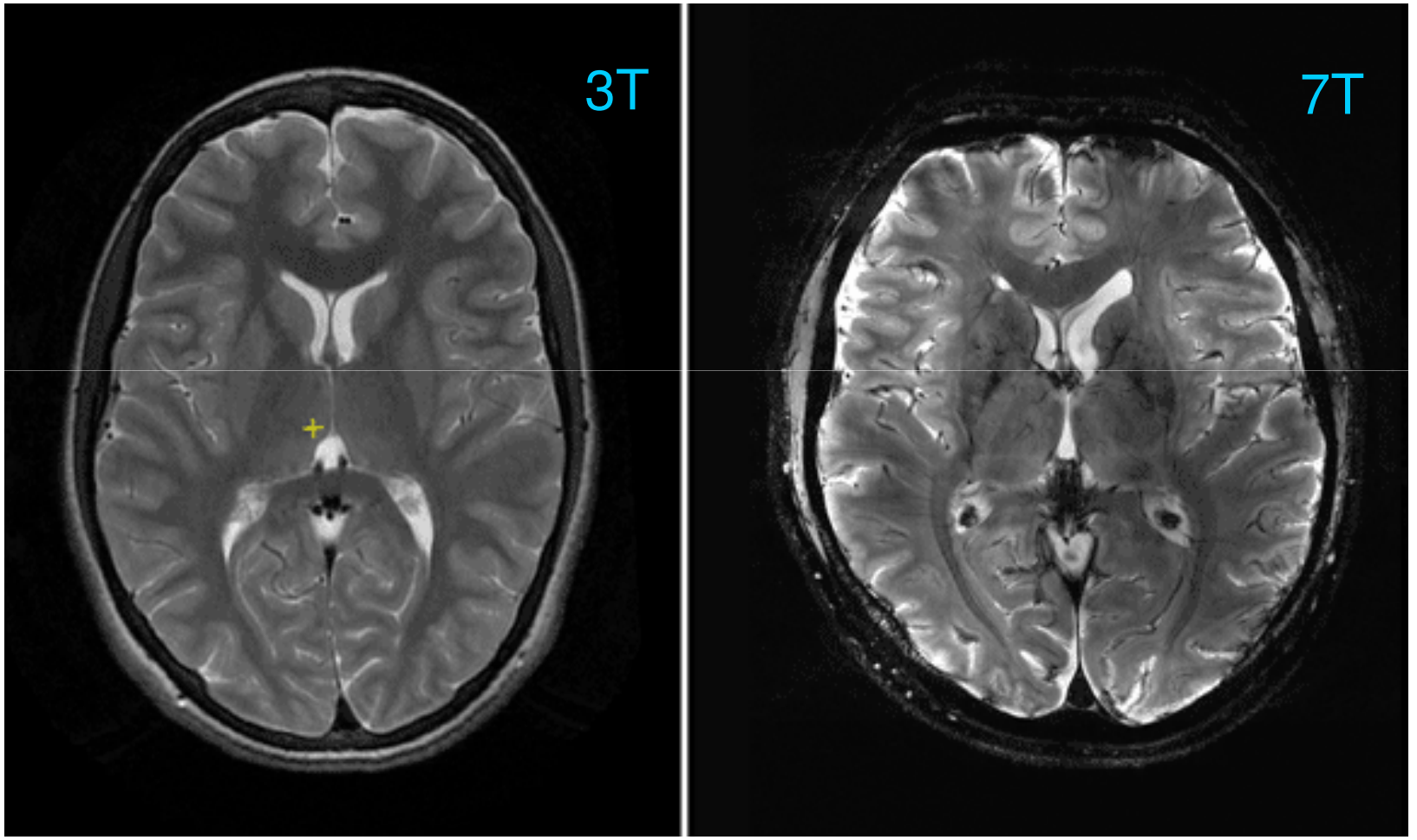


T_A = 9 min



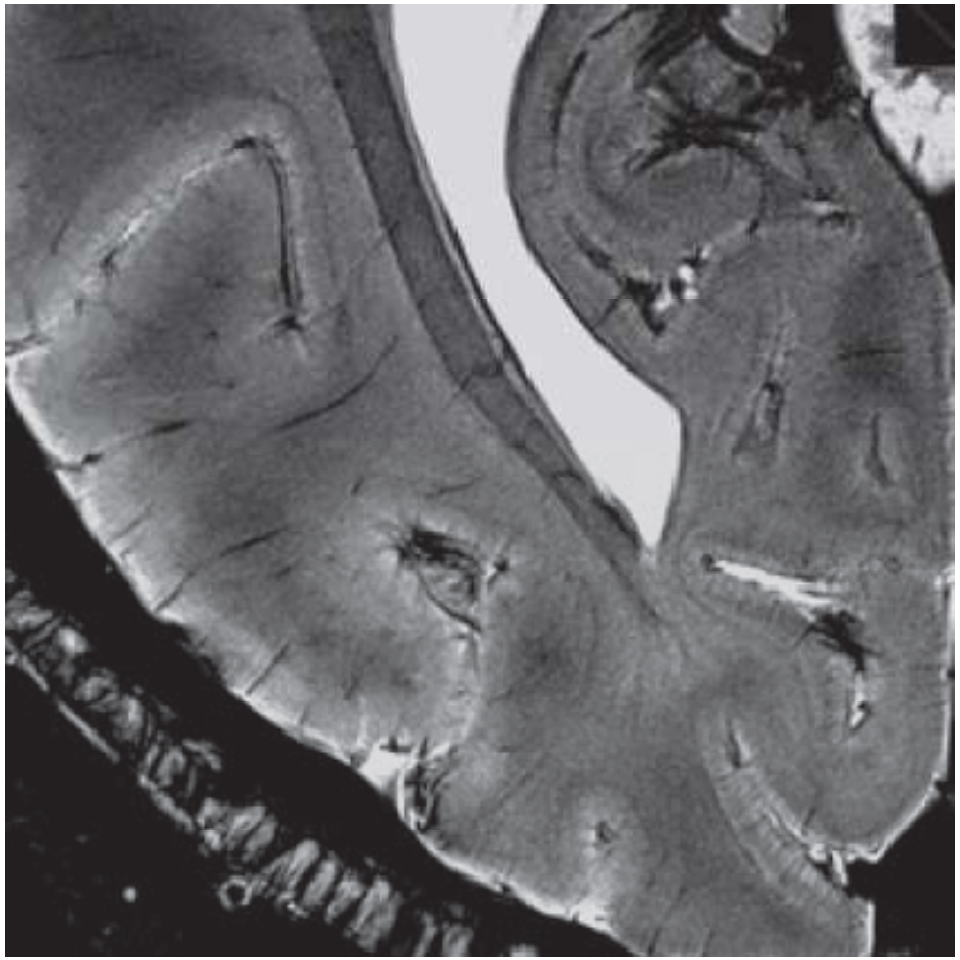
T_A = 4 min

MRI: Why ultrahigh fields?



MRI: Why ultrahigh fields?

- Resolution



0.22 mm in plane, 1 mm slices
C. Wiggins, G. Wiggins, MGH

Physiological effects of static magnetic fields

Does organic tissue respond to magnetic fields ?

(Radboud Univ. Nijmegen)

- Levitated strawberry in stray field of 16 T research magnet

Diamagnetic levitation

(Radboud Univ. Nijmegen)

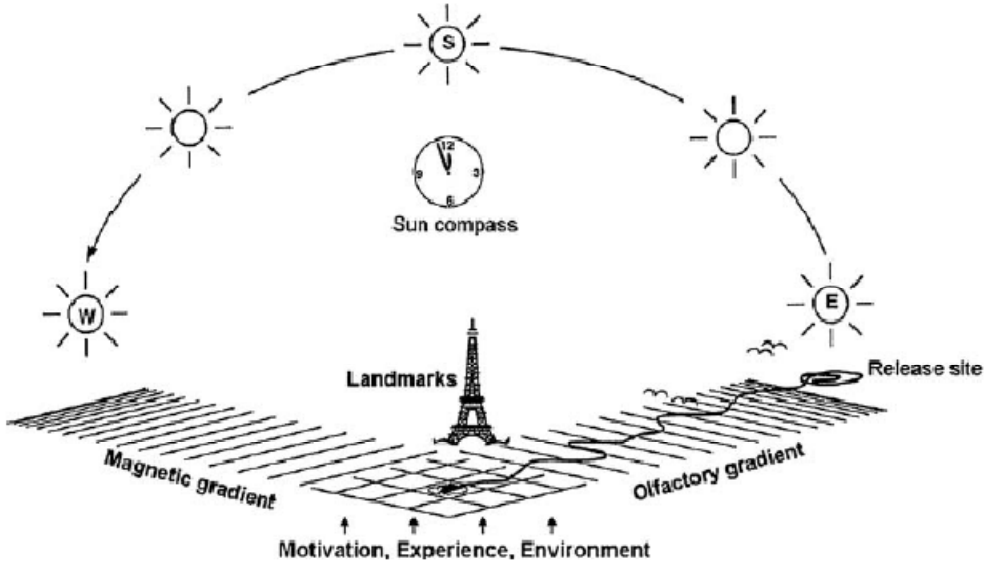
Diamagnetic levitation

- Levitation
  - $\chi B \nabla B > mg$
  - $\nabla(B^2) > 2 \mu_0 \rho g / \chi$
  - $\chi \approx 10^{-5}$, $\rho \approx 1$ g/cm^3, $\nabla(B^2) \approx B^2 / d$
  - $B^2 / d > 2\,500$ T^2 / m

- Typical magnets
  - 7 T whole body MRI: $B^2 / d = 50$ T^2 / m
  - 9.4 T small animal MRI: $B^2 / d = 500$ T^2 / m
  - 17.6 T NMR spectrometer: $B^2 / d = 3\,500$ T^2 / m

Homing pigeons

- How does the bird find its way home?
  - many cues evaluated
  - magnetic navigation in earth's field involved



From: J. Mehlhorn, G. Rehkämper, Naturwissenschaften (2009)

Homing Pigeons

Proposed receptor mechanisms for 50 µT field

- photo induced radical-pair formation
  - specialized photo pigments in right (!) eye's retina
  - proposed molecule: chryptochrome (Rodgers&Hore, PNAS 2009)
  - orientation dependent singlet-triplet exchange rate
  - $\Rightarrow$ magnetic compass
- magnetite clusters in upper beak
  - embedded in nervous tissue
  - magnetic intensity differences recorded
  - $\Rightarrow$ magnetic map

Physiological effects of static fields

- Cell exposure (review by J. Miyakoshi, Sci. Technol. Adv. Mater. 2006)
  - No consistent picture in the literature
  - Static field alone: no or extremely small effect on cells
  - Combined with radiation or toxics:
    - hints at modulating or intensifying effects
  - Further research required
- Cognitive effects (de Vocht et al., Bioelectromagnetics, 2007)
  - reported hand-eye coordination decrement (0.6% / T)
    - probably movement
  - "*magnetic field not a significant confounder in fMRI studies of cognitive function (up to 1.6 T)*"

Low frequency magnetic fields

Medical application: TMS

Transcranial Magnetic Stimulation

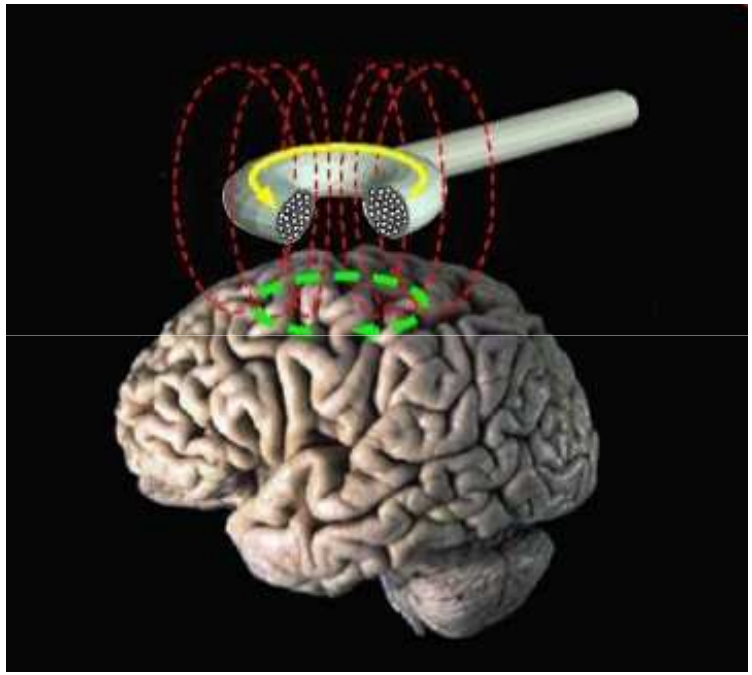


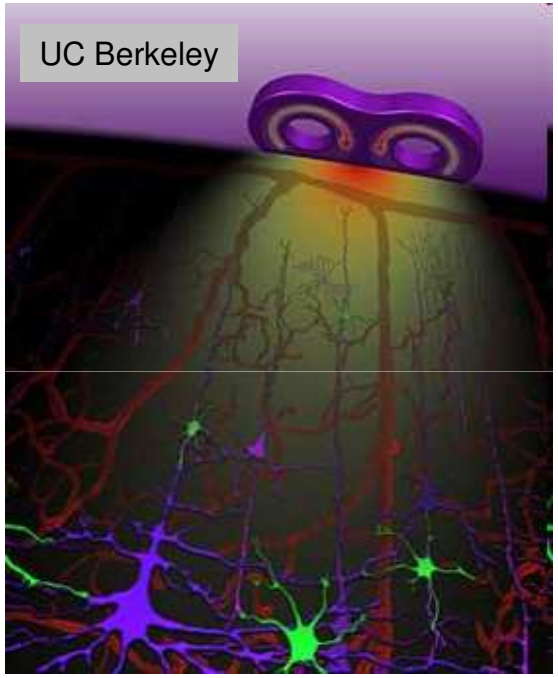
Image courtesy NIH/NINDS

Image courtesy Princeton University

- B ≈ 2 T at coil surface, 0.5 T in cortex
- current rise time: 70 – 100 µs

TMS

"Magnet treatment awakens car crash victim from coma"
(Daily Telegraph, 2008-10-15)



- magnetically induced nervous currents
  - stimulate or inhibit activity
  - diagnostic and therapeutic (rTMS) applications
  - "*the exact details of how TMS functions are still being explored*" (Wikipedia)

Physiological effects of AC fields

- Moving around a strong magnet
- stray field $\Rightarrow$ slowly varying field
  - phosphenes
  - nausea
  - dizziness
  - metallic taste
  - cognitive effects

Physiological effects of AC fields

- Phosphenes ("light that shines forth")
  - Flashing light sensation
  - mechanically, electrically, magnetically stimulated
    - mechanical: pressure on retina
    - magnetic: TMS, movement into MRI scanner, 0 – 100 Hz
  - assumed to be normal activity of the visual system after magnetic stimulation of diamagnetic retinal rod cells
  - believed to be harmless
  - phosphene prevention major driver for EMF directive

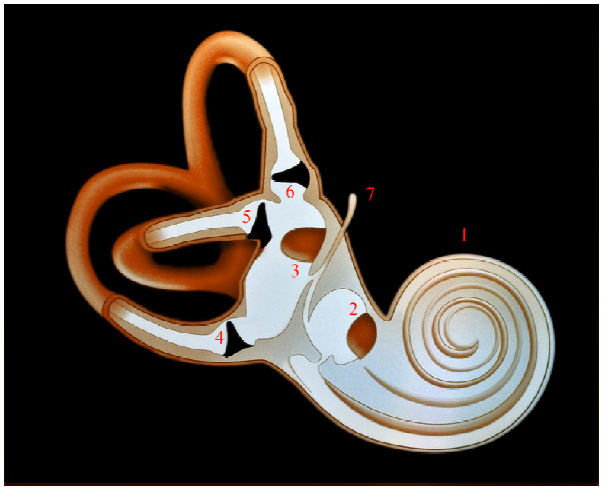
Artist's view

Physiological effects of AC fields

- Nausea, dizziness
  - fast head rotation in gradient fields
    - Glover 2007: induced currents affect neural output of the vestibular system
    - other sources discussed
      - magneto-hydrodynamic forces in vestibular system,
      - diamagnetic anisotropy of inner ear receptors
  - interference with vestibulo-ocular reflex

    $\Rightarrow$ perturbation of our sense of balance

    $\Rightarrow$ sea sickness



middle and inner ear, Wikipedia

- Metallic taste
  - electrolytic processes in saliva due to induced currents
  - no relation to dental implants

Physiological effects of AC fields

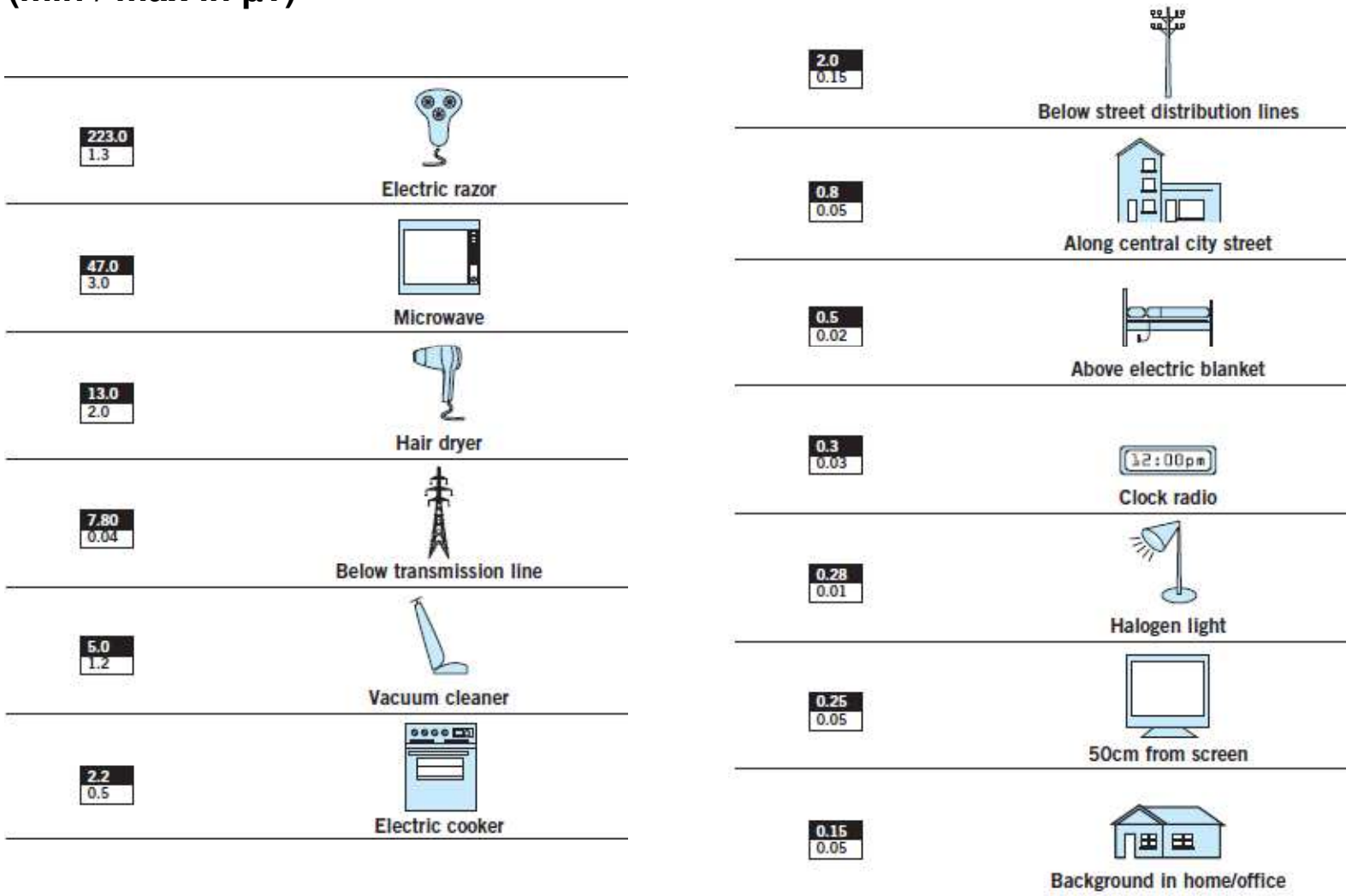
- Cognitive effects
  - only visual system affected
    - light deficits in hand-eye coordination
    - reduced performance in visual tracking tasks
  - possibly indirect consequence of "vertigo effect“
  - impact on interventional MRI

"Real" AC fields: 50/60 Hz

Are there too many power lines ?

50/60 Hz magnetic fields

Typical environmental field strengths
(min / max in µT)



Childhood leukaemia

WHO 2007

- "Scientific evidence that everyday, chronic low-intensity (> 0.3 – 0.4 μT) AC magnetic field exposure poses health risk"
- "epidemiological studies ⇒ increased risk for childhood leukaemia" (0.2% – 4.9%)
- "Evidence not strong enough to be considered causal, but sufficiently strong to remain a concern"
- No correlations with other diseases
- Potential mechanisms unclear
  - EMF itself not genotoxic, but potentially modulate cellular responses to known mutagenic agents (Lange et al, Review in *Cell Prolif.* 2004)
  - No convincing mechanism exists to provide a clue for estimating EMF-induced health risks (M. Simkó, Review on Biological Effects of Electromagnetic Radiation, *TheScientificWorldJOURNAL* (2004)

Regulatory issues

The EU physical agents (EMF) directive

- Directive 2004/40/EC of the EU on the minimum health and safety requirements regarding exposure of workers to the risk arising from physical agents (electromagnetic fields)
- mostly based on ICNIRP recommendations

- Timetable
  - passed: April 29, 2004
  - national law: no later than May 1, 2008
  - suspended: April 2008
  - now to become effective May 1, 2012

“MRI is bound to die !”

- "MRI and the Physical Agents (EMF) Directive", Institute of Physics Report, Nov 2008, London, UK.
- "No more MR in Europe?", call of the European Society of Radiology to support an "Alliance for MRI“ aiming to "safeguard the future use of MRI" by exempting it from the EMF directive (petition.myesr.org).
- European Society for Magnetic Resonance in Medicine and Biology (ESMRMB), www.esmrmb.org/index.php? id=/en/ safety_issues/emfdirective.htm
- "EU’s threat to MRI scanners still looms large", Institute of Physics PR63, 2008, London, UK.
- "Medizinische Diagnose per Kernspin-Tomografie gefährdet" (medical diagnosis by MRI endangered), press release of the German Physical Society (DPG), April 2009, Bonn, Germany.

Exposure limits

Exposure limit values

- primary measure
- based directly on
  - “established health effects”
  - “biological considerations”
- Current density limits (for low f)
  - time-varying fields up to 1 Hz: prevent effects on the cardiovascular and central nervous system
  - 1 Hz – 10 MHz: prevent effects on central nervous system functions
  - higher current densities in body tissues other than the central nervous system permitted
  - average J over 1 cm^2

Exposure limits

Magnetic flux density is a vector quantity (B), resulting in a force that acts on moving charges, expressed in teslas (T). In free space and in biological materials, magnetic flux density and magnetic field strength can be interchanged using the equivalence $1\ A/m = 4\pi\ 10^{-7}\ T$.

Frequency range	Current density for head and trunk J (mA/m^2) (rms)	Whole body average SAR (W/kg)	Localised SAR (head and trunk) (W/kg)	Localised SAR (limbs) (W/kg)	Power density S (W/m^2)
Up to 1 Hz	40	–	–	–	–
1 - 4 IIz	40/f	–	–	–	–
4 - 1000 Hz	10	–	–	–	–

Action values

- secondary measure
- reference to ICNIRP rationale

Frequency range	Electric field strength, E (V/m)	Magnetic field strength, H (A/m)	Magnetic flux density, B (μT)	Equivalent plane wave power density, S_{eq} (W/m^2)	Contact current, I_C (mΛ)	Limb induced current, I_L (mA)
0 – 1IIz	–	$1{,}63x10^5$	$2x10^5$	–	1,0	–
1 – 8 Hz	20000	$1{,}63x10^5/f^2$	$2x10^5/f^2$	–	1,0	–
8 – 25 Hz	20000	$2x10^4/f$	$2{,}5x10^4/f$	–	1,0	–
0,025 – 0,82kIIz	500/f	20/f	25/f	–	1,0	–
0,82 – 2,5 kHz	610	24,4	30,7	–	1,0	–

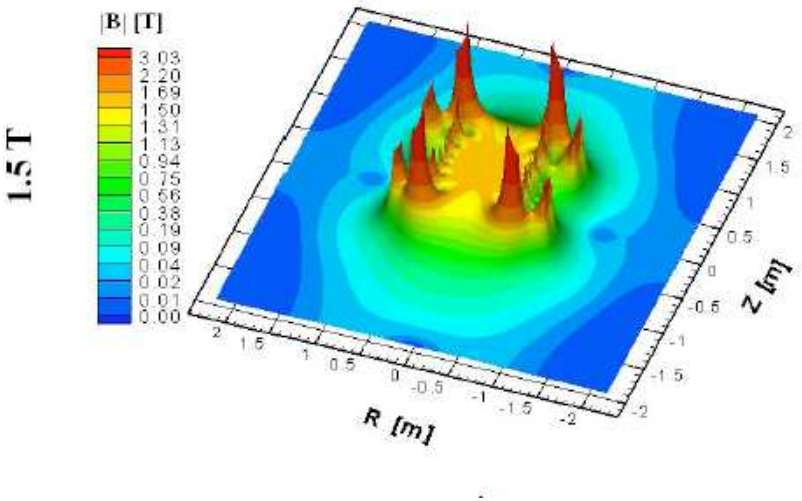
Can you ensure compliance?

The University of Nottingham

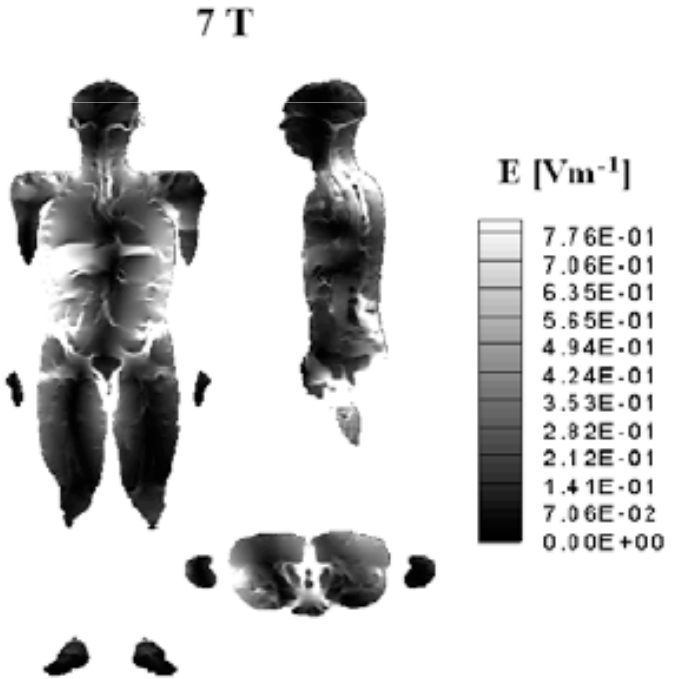
- How do we relate a varying magnetic field to an induced current (exposure limit)?
  - How would we work out how warm you get inside if we put you in a hot room?

Moving around in stray fields

- Movement around an MRI scanner
- Numerical modeling (Crozier et al., 2007)
  - 0.5 m/s around a 4 T ⇒ J = 100 – 200 mA/m²
  - 2 m/s around a 1.5 T ⇒ J = 300 mA/m²
- up to 8 × exposure limit
- Experimental verification?



Stray field of 1.5 T scanner
S. Crozier 2007



Numerical model for induced current calculations
S. Crozier 2007

But ...

A static field ...

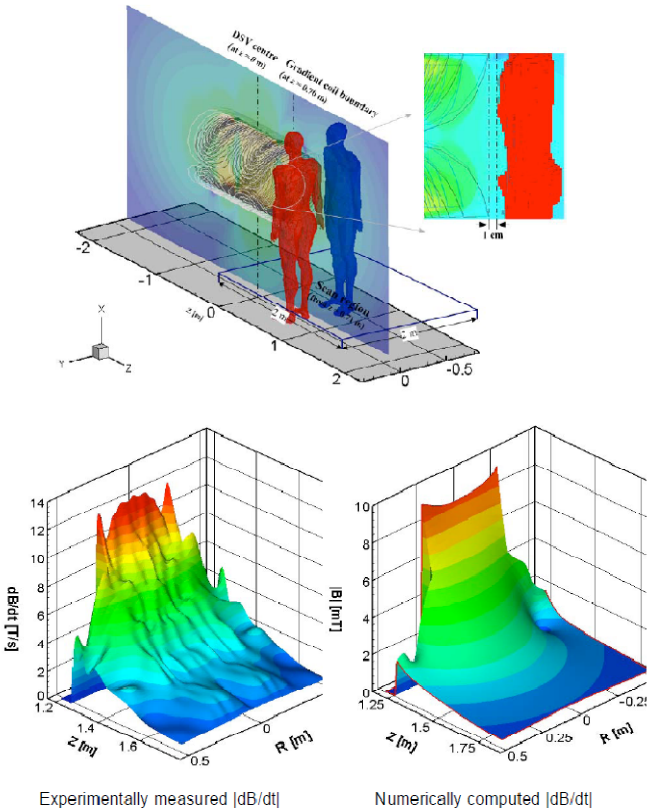
... is a static field, ...

...is a static field !

- Regulatory bodies:
  - no limits for static fields $\Rightarrow$
  - no limits for movements in static field gradients

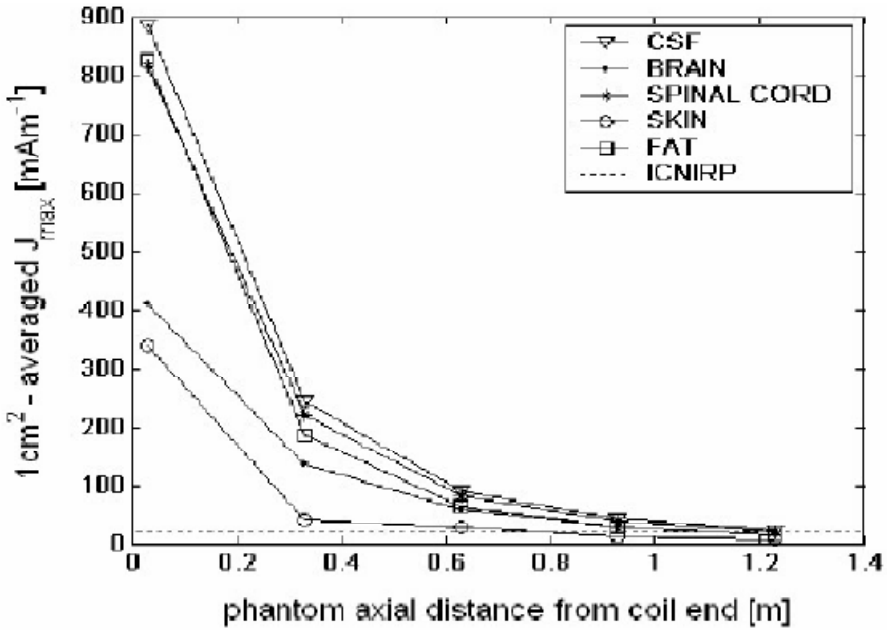
Switched gradient fields in MRI

- Only during scan
- Numerical modeling (Crozier 2007)
  - worst case: exposure limits exceeded within 1m of gradient coil
  - problem for interventional MRI



Experimentally measured |dB/dt| Numerically computed |dB/dt|

X+Y+Z-gradient



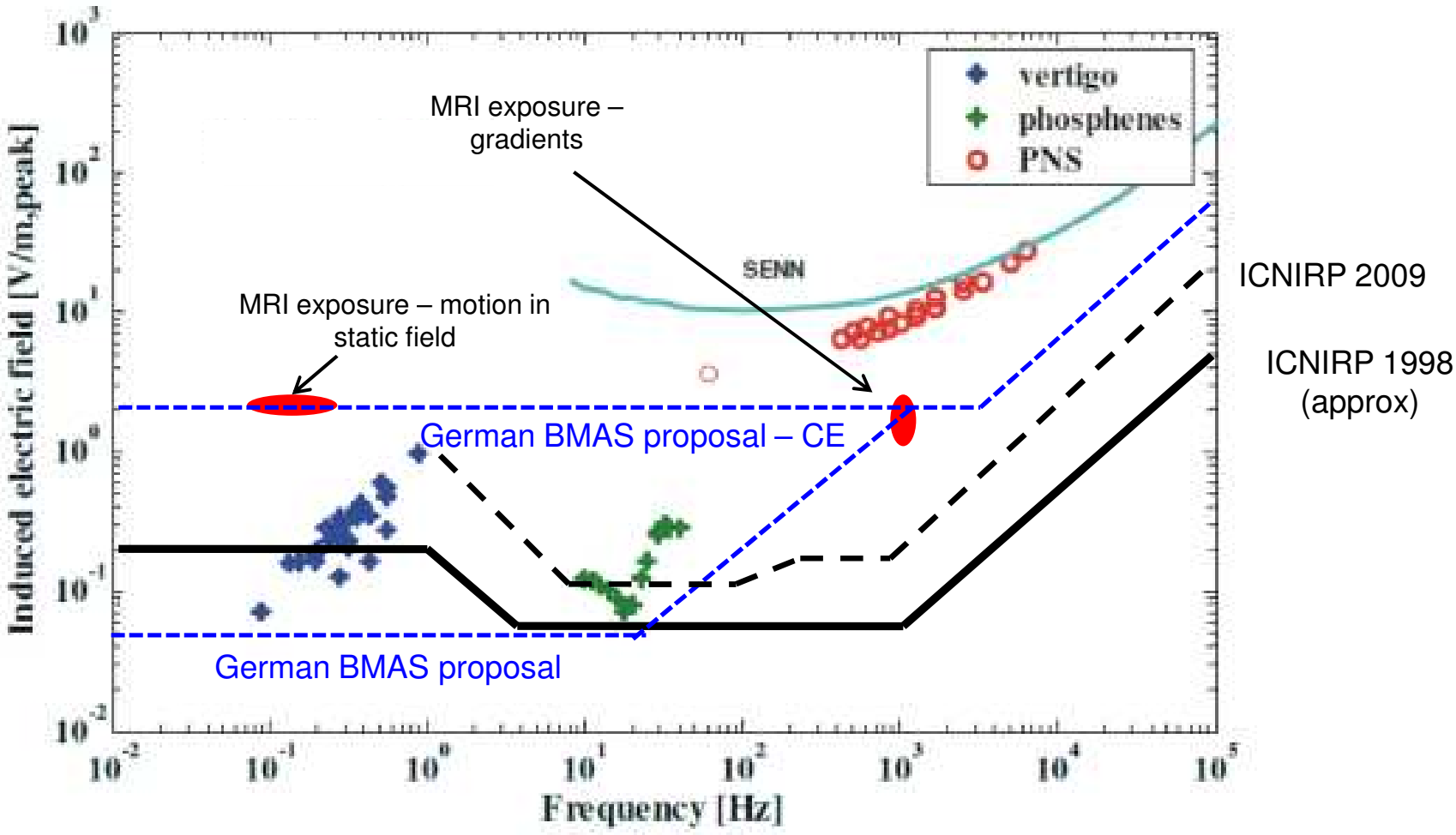
ICNIRP 2009

- Workers (superseding 1994/98 guidelines)
  - general static limit: 2 T
  - controlled environment: 8 T permissible
  - little changes for switched gradients or RF fields.

- Patients (amendment to 2004 statement)
  - up to 8 T
    - “no health effects”
    - possibly unpleasant sensory effects
  - recommends epidemiological long-term studies
  - new recommendations on static field limits
    - normal mode: 4 T
    - controlled mode: 8 T
    - experimental mode: no limit

EMF limits and MRI

courtesy S. Keevil, adapted from Matthes, R (2008) *ICNIRP International Non-Ionizing Radiation Workshop. October 14-17, 2008*.



Solution ?

László Andor (EU commissioner for employment, social affairs, and inclusion)
September 2010

- "The European Commission will formally propose a revision to the 2004 EU directive limiting workers' exposure to electromagnetic fields (EMF) before the end of the year. The revision will effectively exclude MRI scanners from the scope of the directive by removing exposure restrictions on the technology"

Conclusion

- Metrology and medical imaging
  - Quantification frequently necessary, desirable and possible (but not yet existing)
  - Quantification frequently not requested by medical community

- Metrology and physiological quantities
  - Physiologically relevant quantities often not accessible
  - Modeling is the key
  - Need means to validate simulations

Thank you for your attention !