Aalto University
School of Science

Dept. of Biomedical Engineering
and Computational Science
BECS

SQUID Technology for Biomedical Applications

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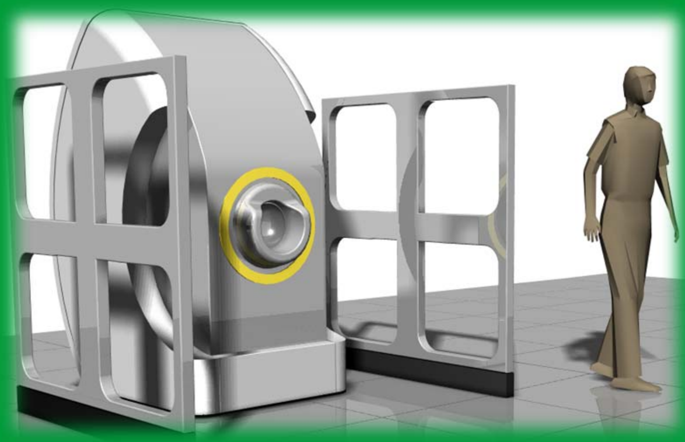


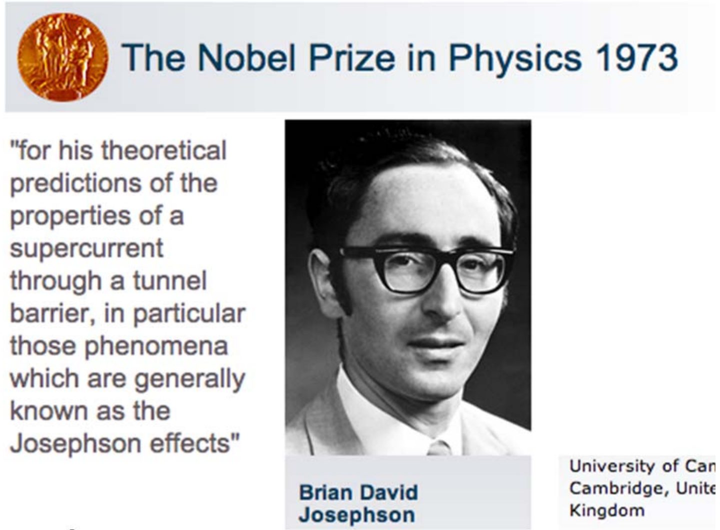
Academia–Industry Matching Event
Fostering Collaborations in Superconductivity
CIEMAT, Madrid, May 27–28, 2013

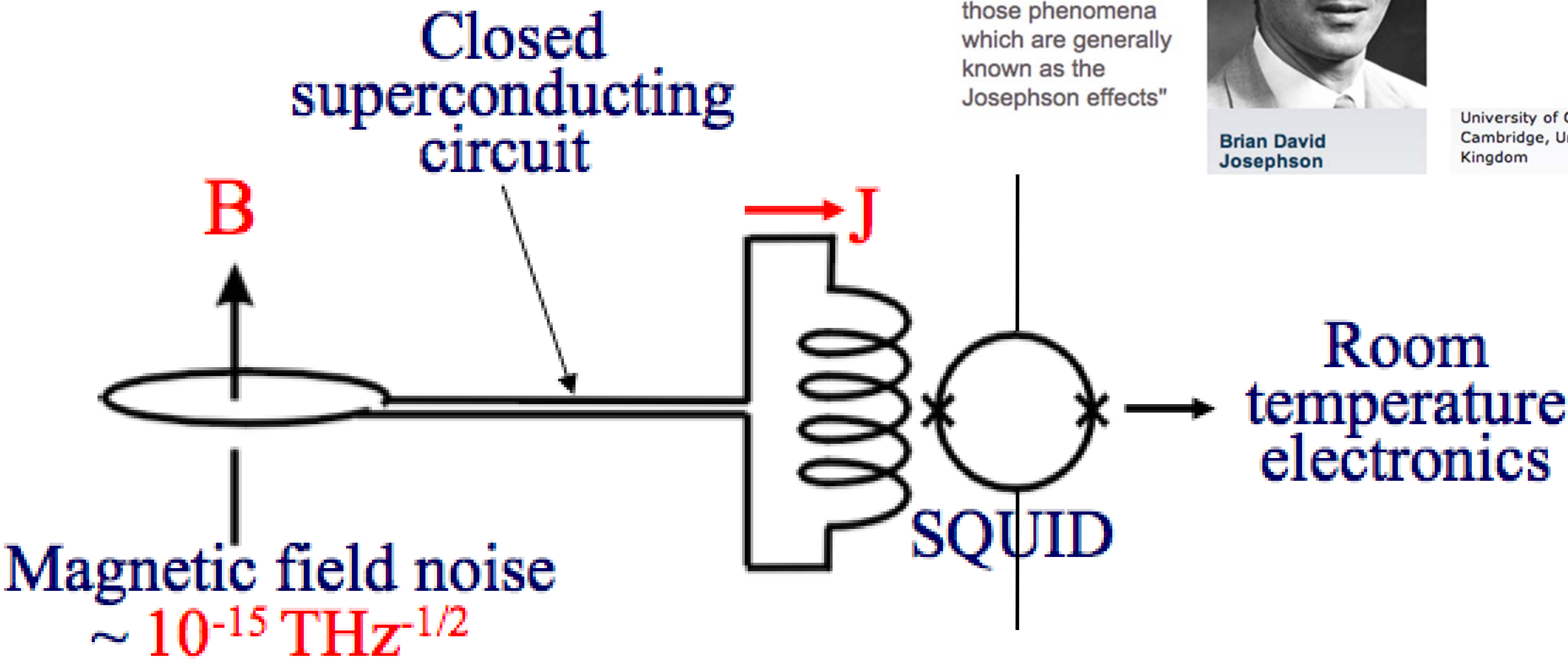
Plan for the talk

- SQUID
- The burden of brain disorders
- MEG and MEG-MRI
- Challenges
  - Ultra-low-noise field-tolerant SQUID sensors
  - As strong pulsed prepolarization as possible (~150 mT in 10 ms)
  - Avoiding magnetization of the superconducting wire

SQUID Sensor

- Based on the Josephson effect, which was invented in 1962





- The response is independent of frequency

The burden of brain diseases

1) Human suffering

- Depression: 150 million patients
- Schizophrenia: 25 million
- Dementias: 40 million
- Epilepsy: 40 million
- Stroke: 50 million

2) Cost to society: 800 billion € / year in Europe alone

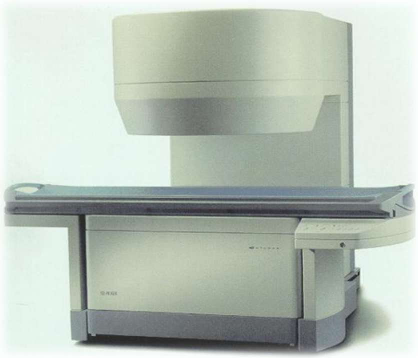
The burden is increasing with the aging population

Major Brain Research Initiatives

- **European Union: Human Brain Project**
  - to model the brain
  - 1000 M€ /10 years
- **USA: Connectome**
  - to determine the brain's wiring diagram
- **USA: BRAIN Initiative**
  - to advance innovative neurotechnology
  - 100 M$ in 2014
- **China: BRAINNETOME**
  - to identify and understand brain networks
  - http://www.brainnetome.org/consortium/resources.html

Brain imaging developed in Helsinki

MRI



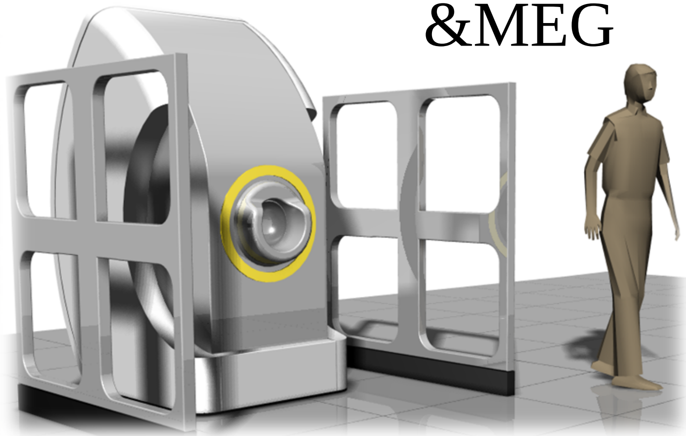
EEG

NIRS

MEG

Navigated TMS

Ultra-Low-Field MRI &MEG



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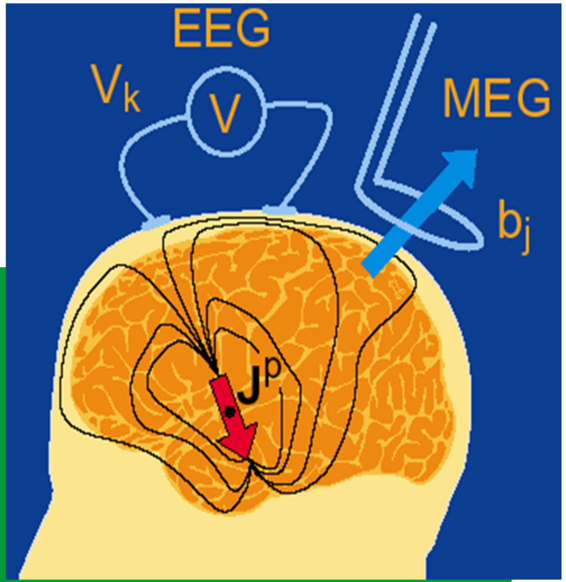
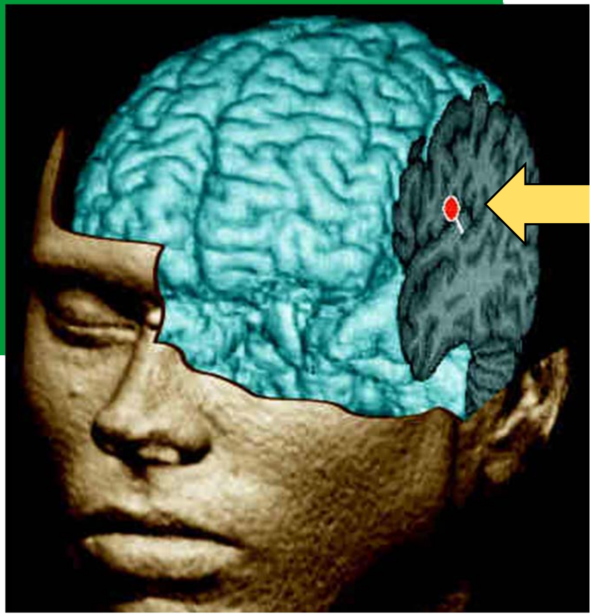


Magnetoencephalography (MEG)

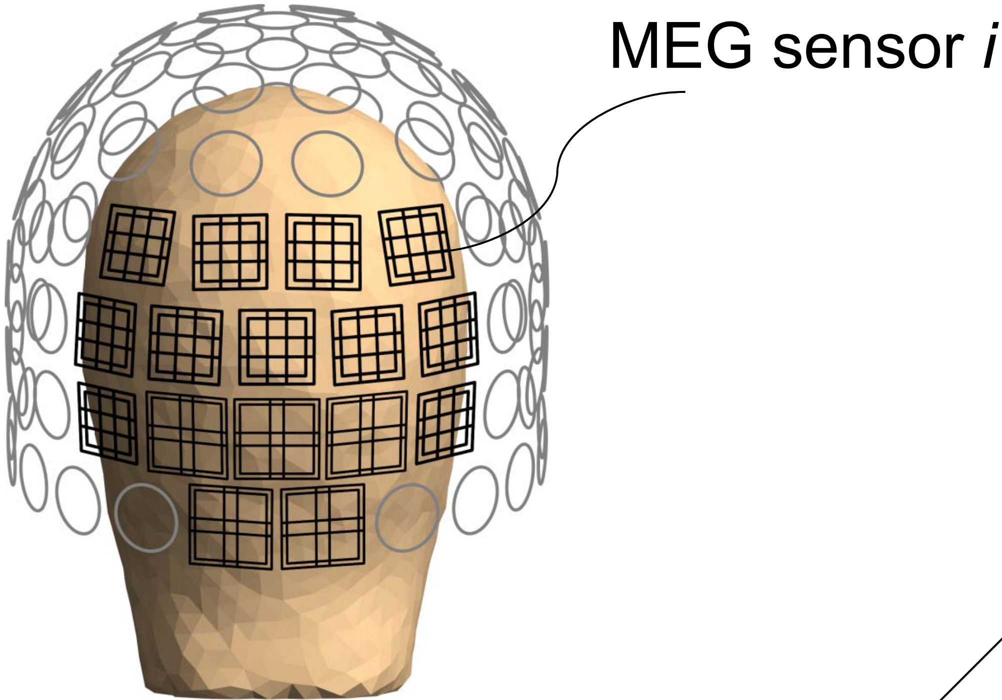
MEG is the measurement of magnetic fields produced by neuronal activity in the brain.

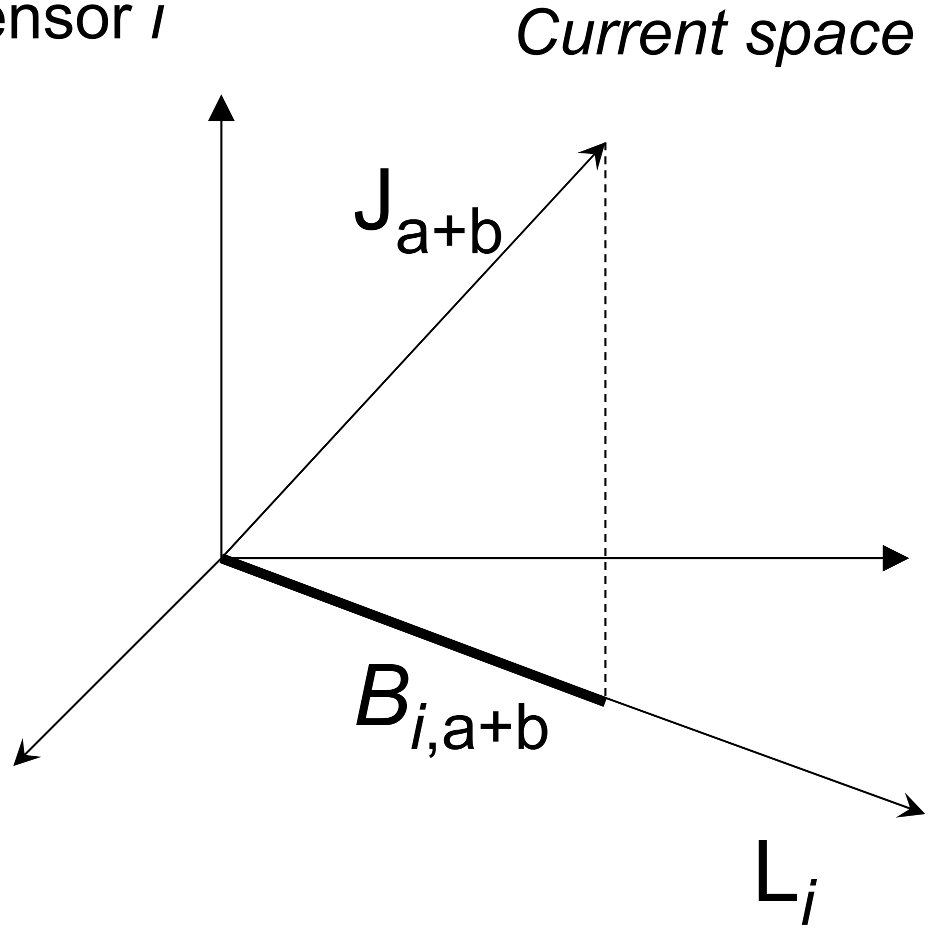
MEG allows one to determine locations of brain activity.

The source locations are often displayed on top of anatomical MRI images.



MEG: a projection of brain state

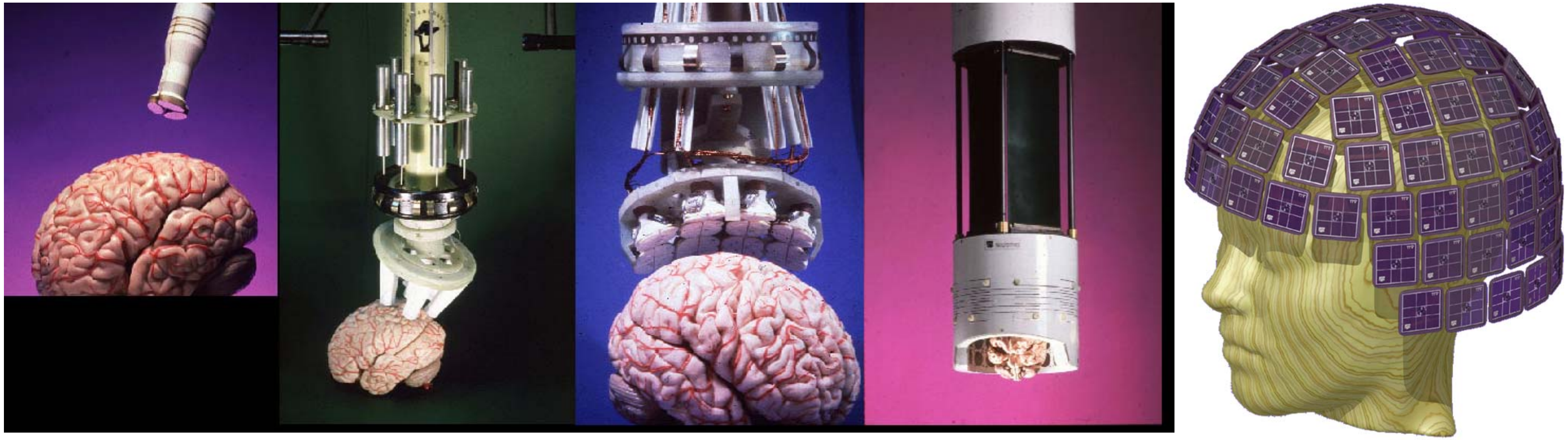




$$B_i \approx \Sigma a_{ik} f_k$$

Ilmoniemi 2006.

Multi-SQUID systems developed in Helsinki



	1983	1987	1989	1993	1999
Number of SQUIDs	4	7	24	122	306

Ilmoniemi et al., "*A four-channel SQUID magnetometer for brain research*", Electroenceph. Clin. Neurophysiol. 58, 467–473 (1984).

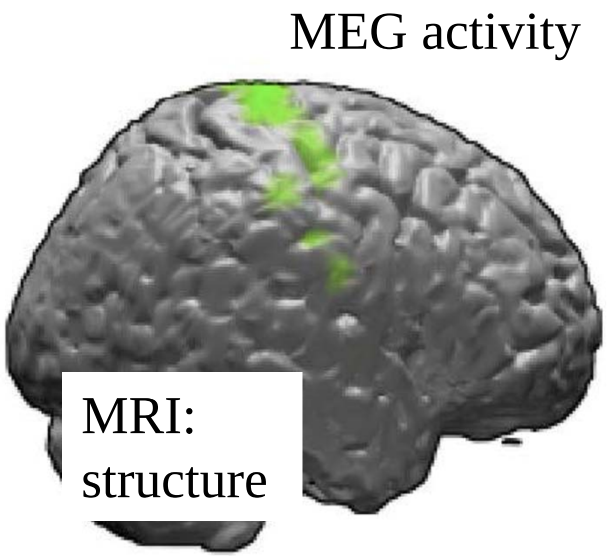
Knuutila et al., *A large-area low-noise seven-channel dc SQUID magnetometers for brain research,* Rev. Sci. Instrum 58, 2145–2156 (1987).

Ahlfors et al., "*A 24-SQUID gradiometer for magnetoencephalography*", Physica B 165 & 166, 97–98 (1990).

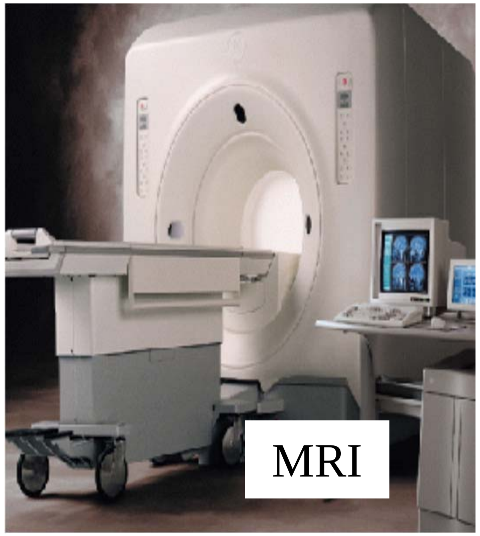
Ahonen et al., "*122-channel SQUID instrument for investigating the magnetic signals from the human brain*". Phys. Scr. T49, 198–205, (1993)

MEG needs MRI

MEG informs about function, MRI provides anatomy

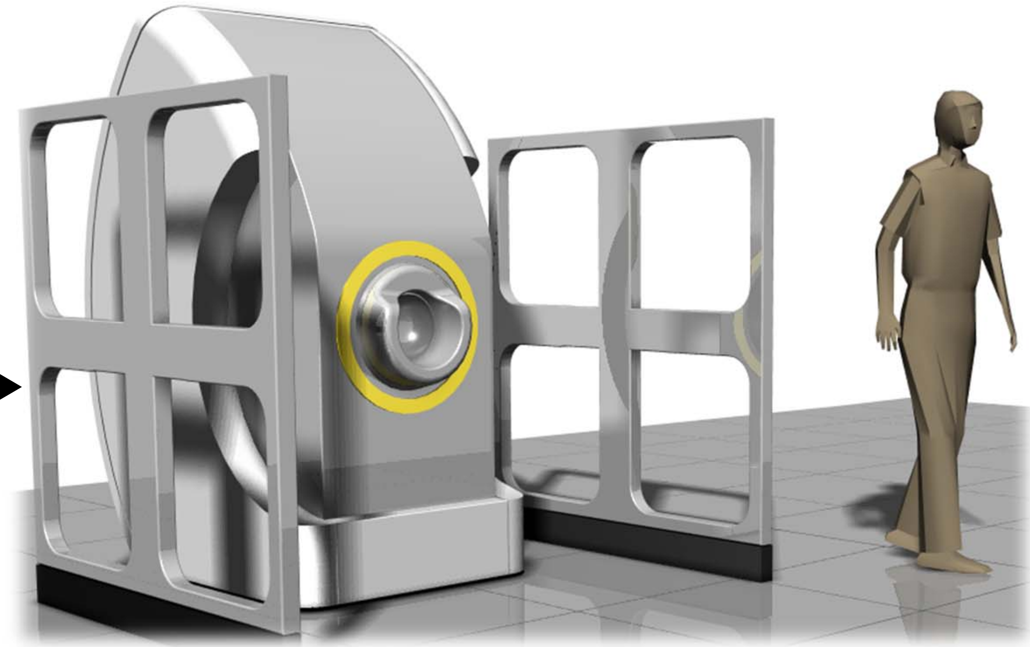


MEGMRI project (FP7, 2008–12)

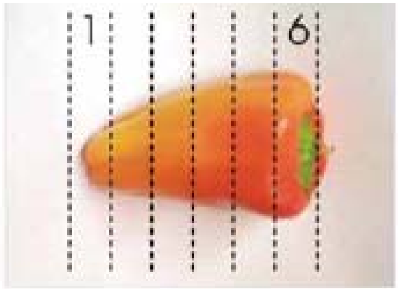


Goal: A **hybrid brain scanner** that can measure **MEG and MRI** at the same time

These techniques reveal information about the state of the brain

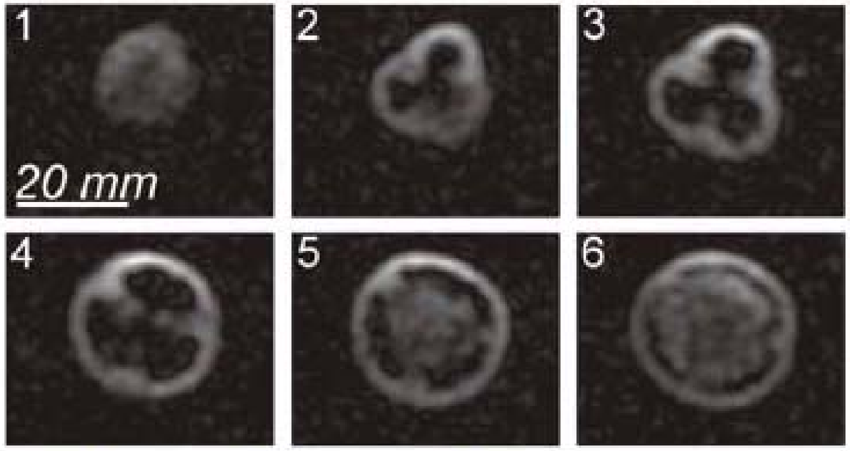


How is low-field MRI possible?



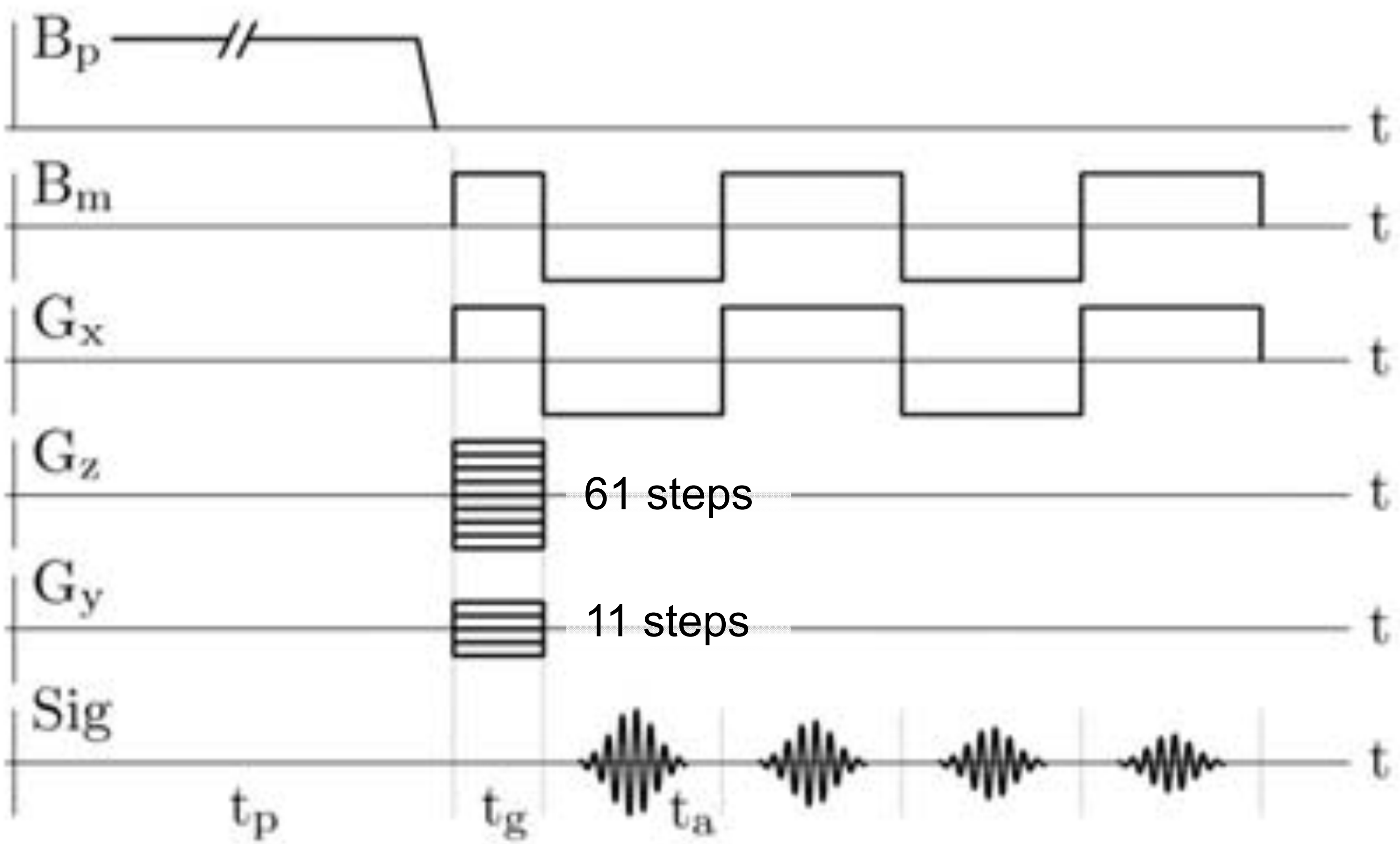
By using (as demonstrated by John Clarke et al.)

1. SQUIDs
   - Response is independent of frequency
2. Prepolarization
   - Polarization is independent of measurement field



- Add second phase encoding sequence
- Polarizing field 60 mT
- Imaging field 132 μT, gradients 150 μT/m
- Resolution 1.2 mm x 1.2 mm

Prepolarization (& other fields)



Bp=30 mT

Bm=±46 μT

Gx=±140 μT/m

G_z= -140…140 μT/m

Gy= -70…70 μT/m

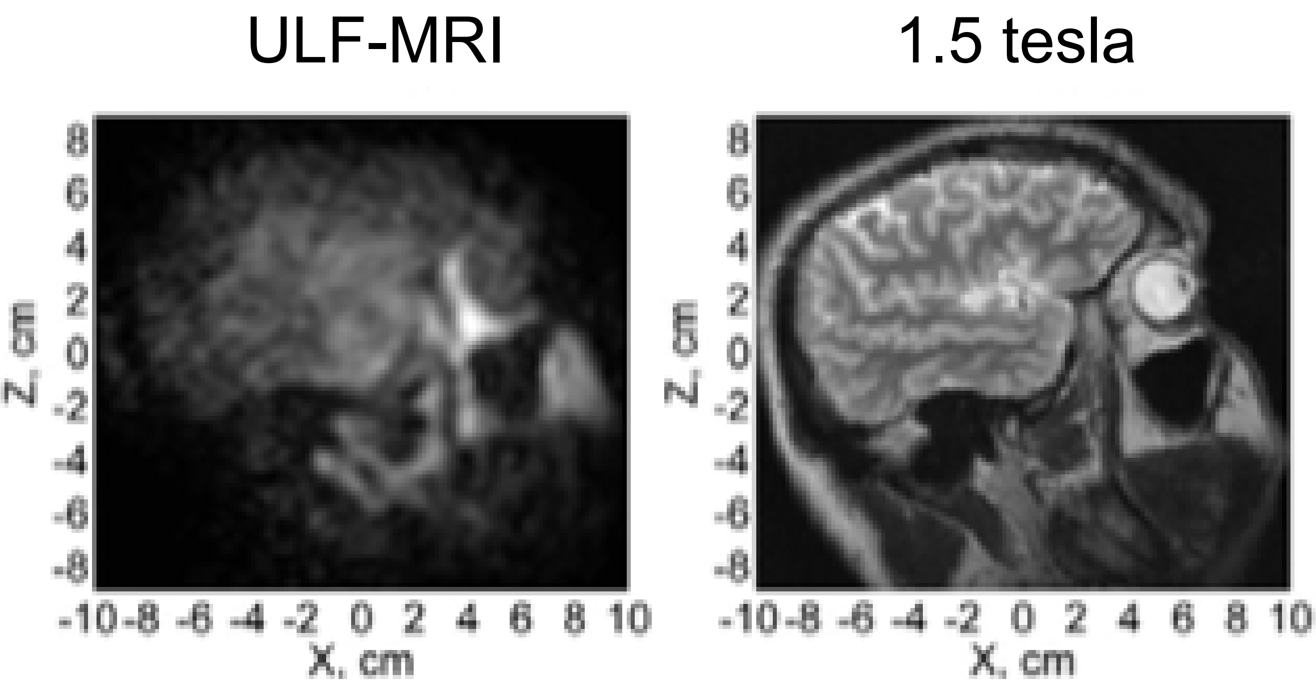
t_p = 1 s t_g = 28 ms t_a = 56 ms

Zotev et al., 2008

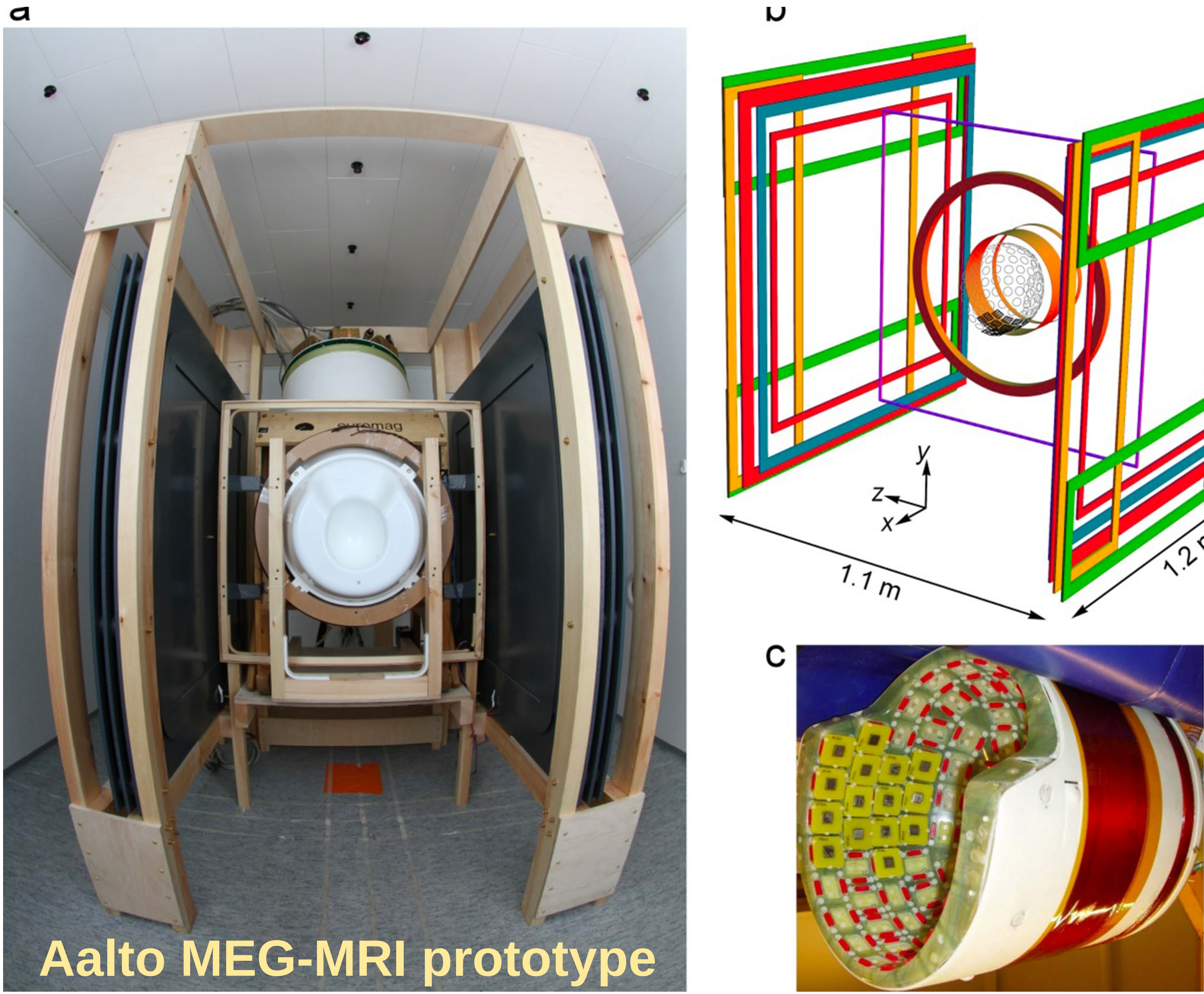
First ULF-MRI Images of the Brain

- 7 SQUIDs in parallel
- Bp = 30 mT
- B0 = 46 μT

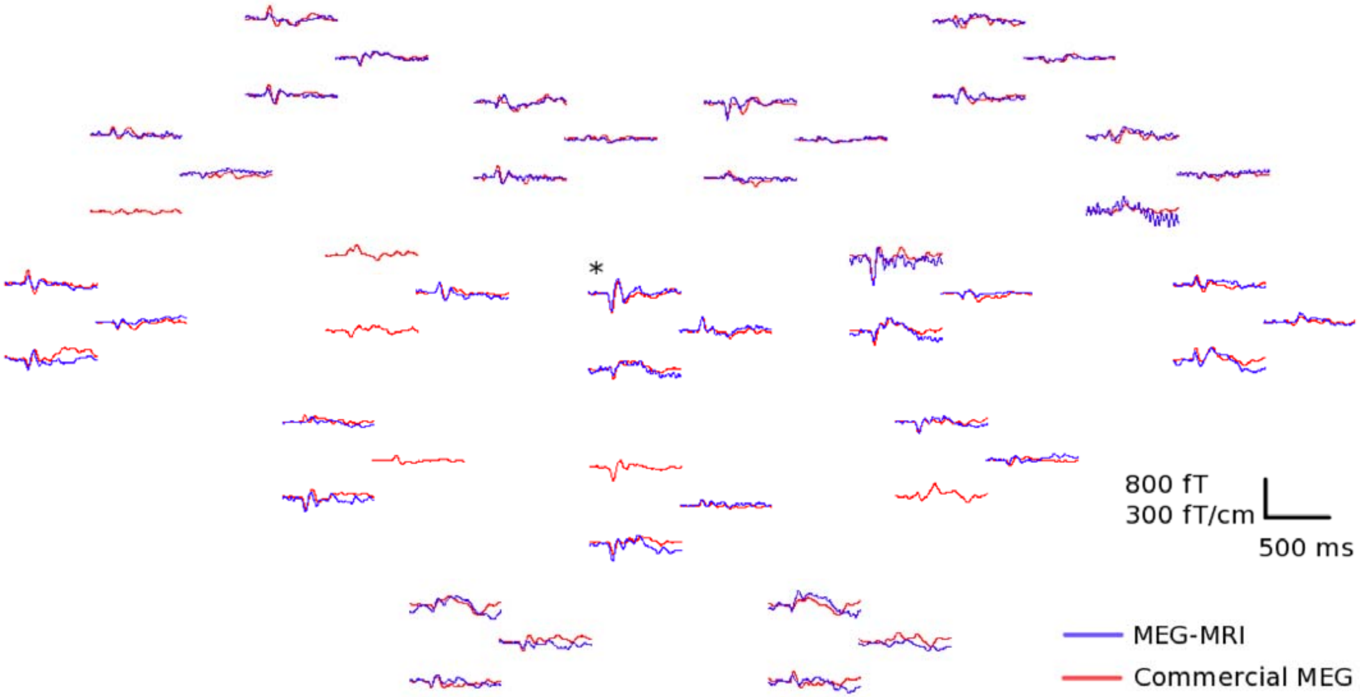
□ 90–minute measurement

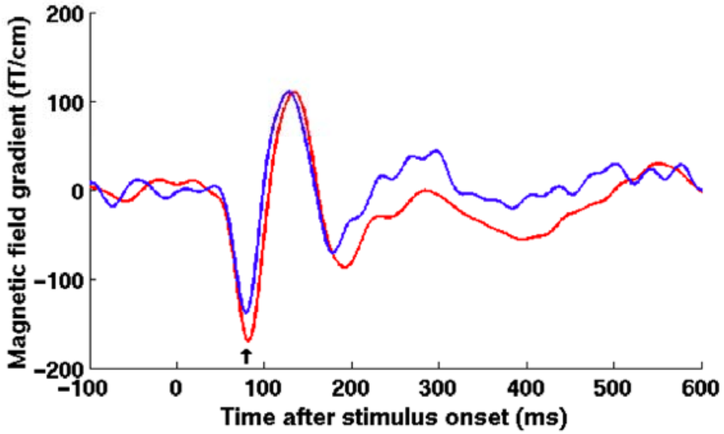


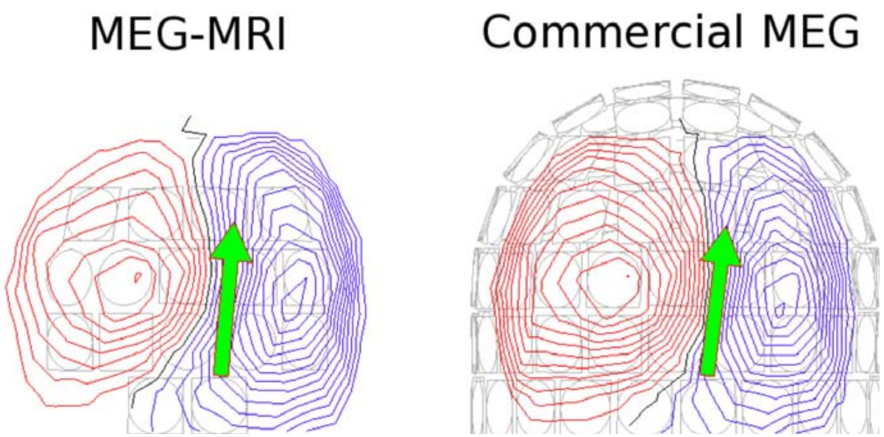
Zotev et al., IEEE/CSC & ESAS European Superconductivity News Forum, No. 4, April 2008


a
b
c
euromag
y
z
x
1.2 m
1.2 m
1.1 m
Aalto MEG-MRI prototype

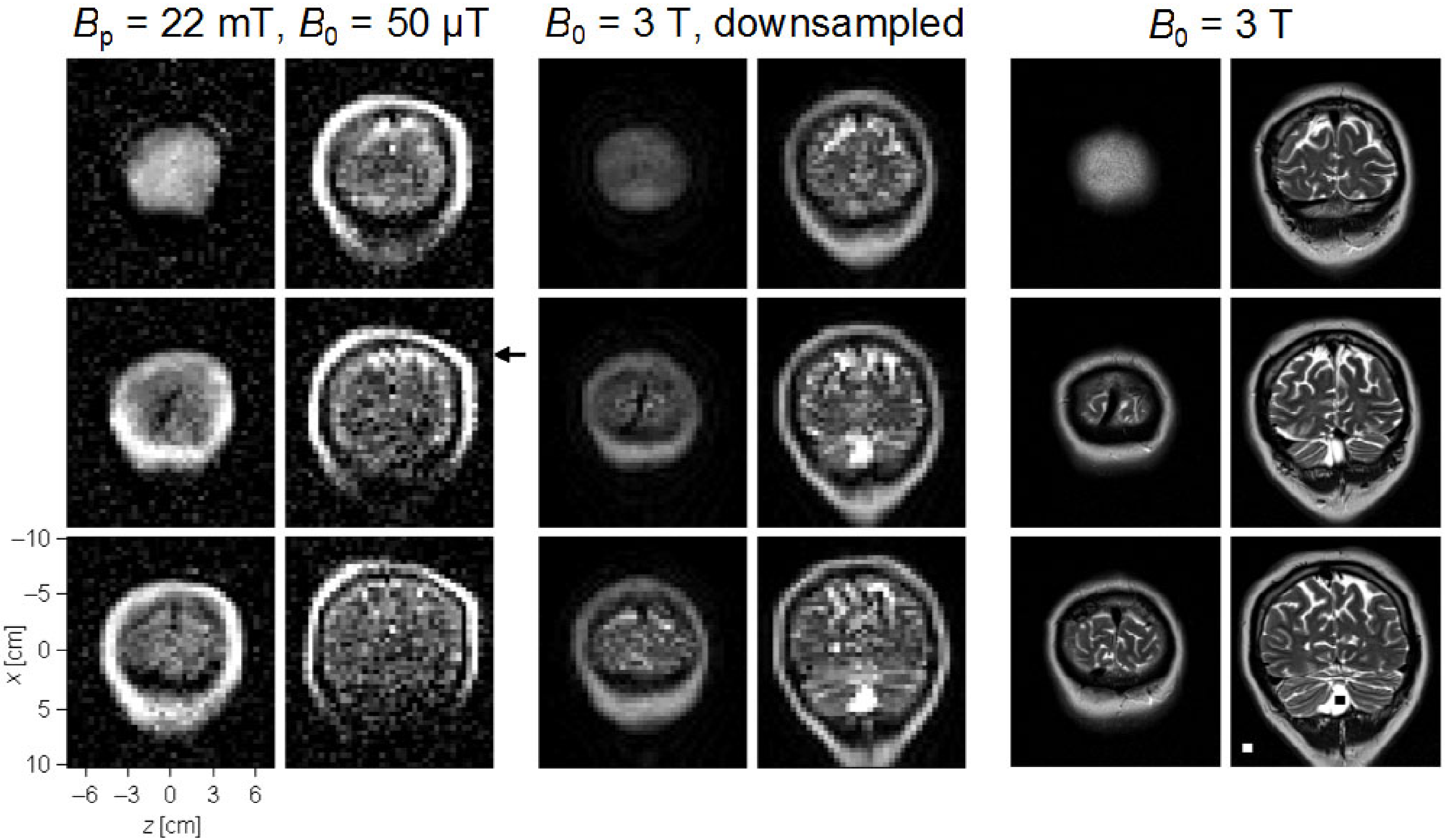
MEG signals obtained with the prototype







Brain Images



Benefits of ULF-MRI

- Simultaneous MEG and MRI
  - Superb registration accuracy
  - Improved work flow
- Safe, quiet, open
  - No projectile danger, safe with pacemakers
  - Better for infants and children
- Superior T1 contrast
- Future promise
  - Superb source location accuracy

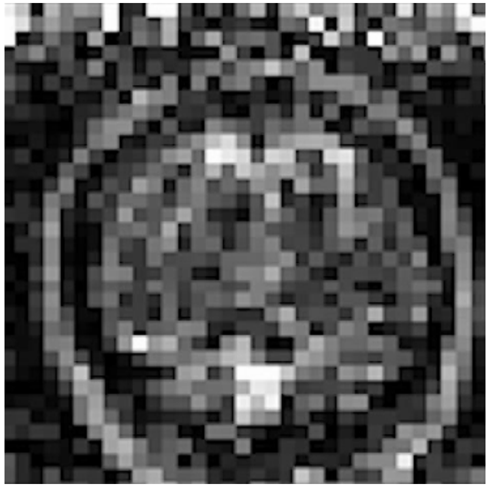
Future Prospects

- Sensor noise down by a factor of 10 (5 to 0.5 fT)
- Prepolarization field up by a factor of 5 (22 to 110 mT)
- Number of SQUIDs up by a factor of 6 (48 to 306)
- More intelligent measurement sequences

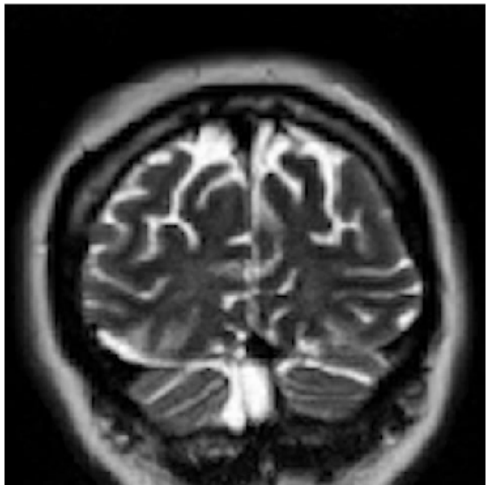
⇒ MRI measurement time < 10 min, resolution < 2 mm

⇒ Clinical interest & commercial market

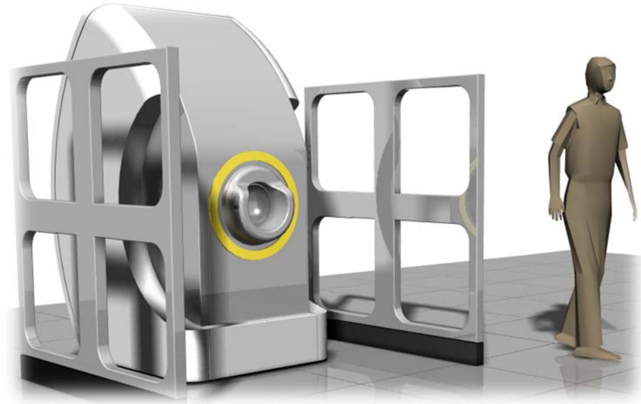
\+ Conductivity recordings ?



Present



Next generation



Challenges

Clinical success can be expected only if the data rate is increased by more than 1000

- SQUIDs: lowest possible noise, field tolerance
- SC coils: highest possible field, no magnetization
- Dealing with fields from 1 to 100000000000000 fT (0.1 T)

Field-Tolerant SQUIDs for ULF-MRI

All-planar SQUIDs and pickup coils for combined MEG and MRI

J. Luomahaara[1], P. T. Vesanen[2], J. Penttilä[3], J. O. Nieminen[2], J. Dabek[2], J. Simola[4], M. Kiviranta[1], L. Grönberg[1], C. J. Zevenhoven[2], R. J. Ilmoniemi[2] and J. Hassel[1].

Supercond. Sci. Technol. 24 075020 (2011)

VTT Technical Research Centre of Finland

Fig.1

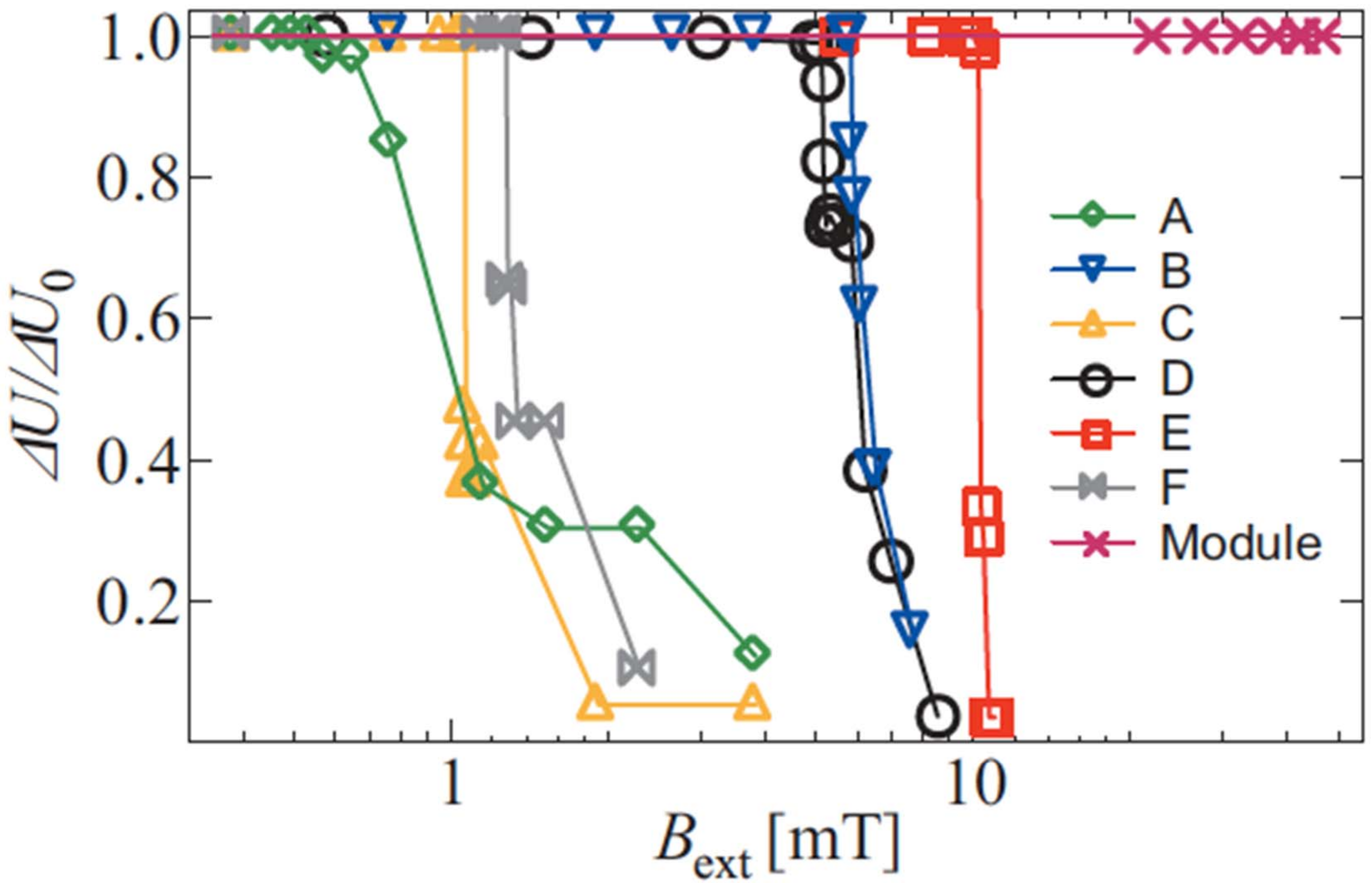


Figure 1. The relative modulation depth $\Delta U/\Delta U_0$ as a function of applied perpendicular magnetic field B_{ext} for different SQUID types and a sensor module (see next section) constructed from F type SQUIDs and $11\times11\times2$ mm^3 Nb shields.

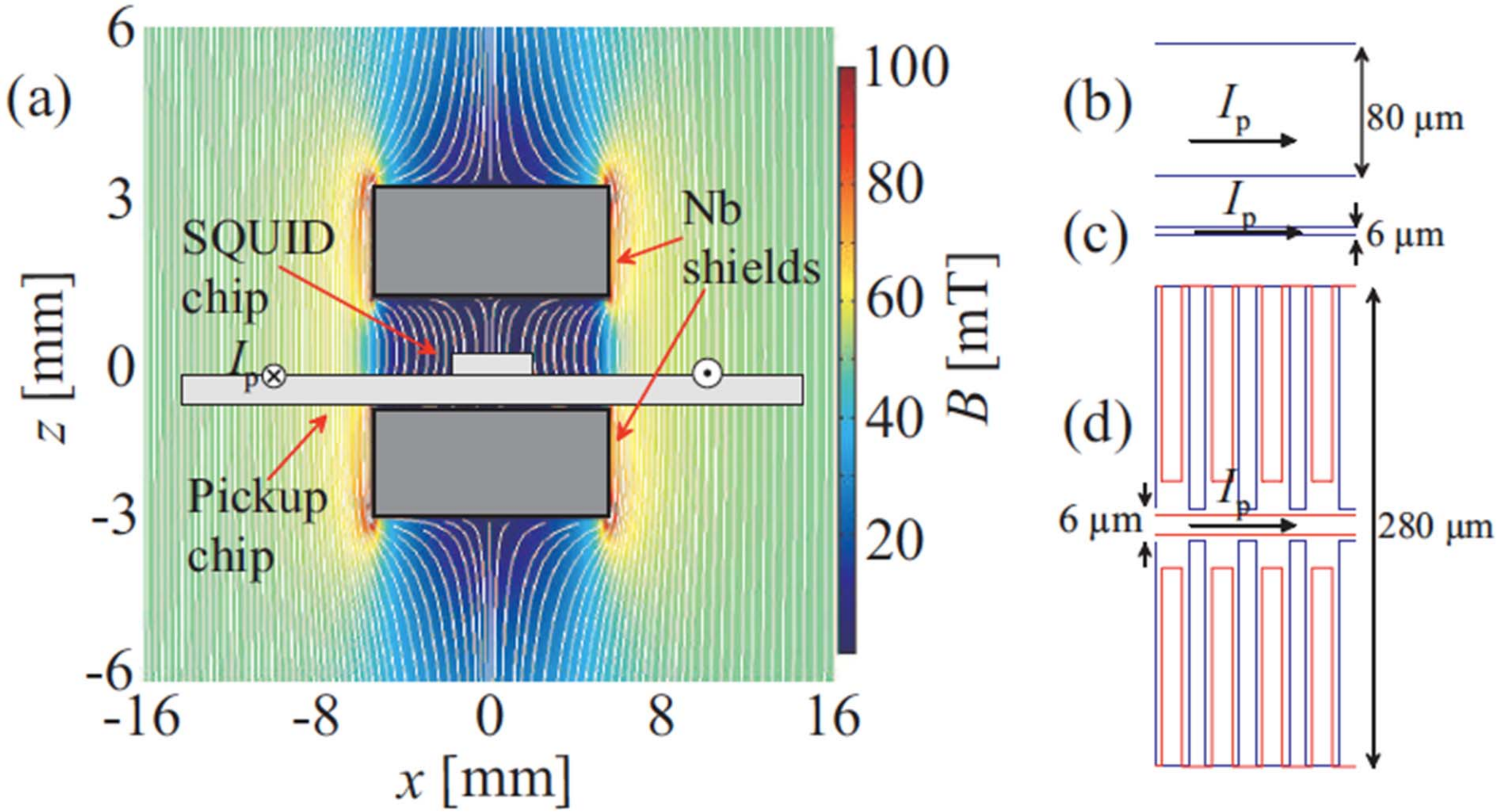


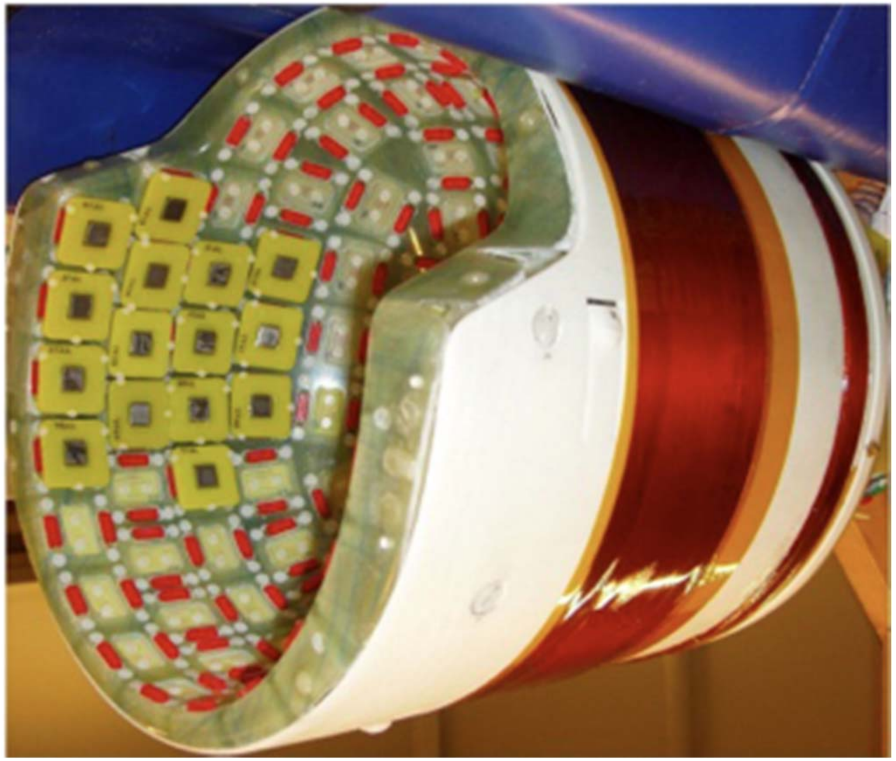
Figure 3. (a) A cross-section of the sensor module showing the pickup and SQUID chips as well as superconducting shields. The shielding effect is calculated by a finite element method showing the position dependence of the field in the ambient field of 50 mT in z-direction. With thin-film devices, the linewidth reduction from (b) to (c) decreased the sensitivity of a magnetometer. As a result, (d) a comb-like structure constructed of 6-μm-wide films was introduced. I_p flows in blue layer whereas in (d) an additional superconducting layer (denoted with red) was deposited on top of the gaps for screening purposes. The effective width of the transmission line increases as the flux generated by I_p is compelled to enclose the whole 280-μm-wide structure, thus, lowering the inductance of the pickup coil and raising the sensitivity of the sensor.

SC Coils for Prepolarization

Acceptable specs:

- B > 100 mT
- Switch time < 10 ms
- Remanent field < 100 nT

Currently, B < 22 mT limited by magnetization of the wire



- 552 turns, diameter 30 cm
- 0.44-mm wire; 24000 1-μm filaments bronze matrix (Supercon, Inc)
- 0.02-mm insulation
- 2 mT/A, total inductance 130 mT

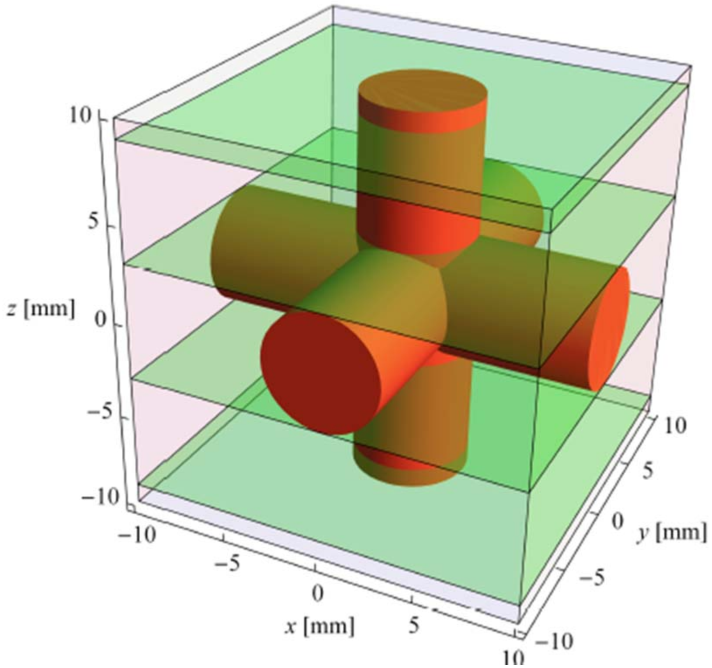
If we succeed:

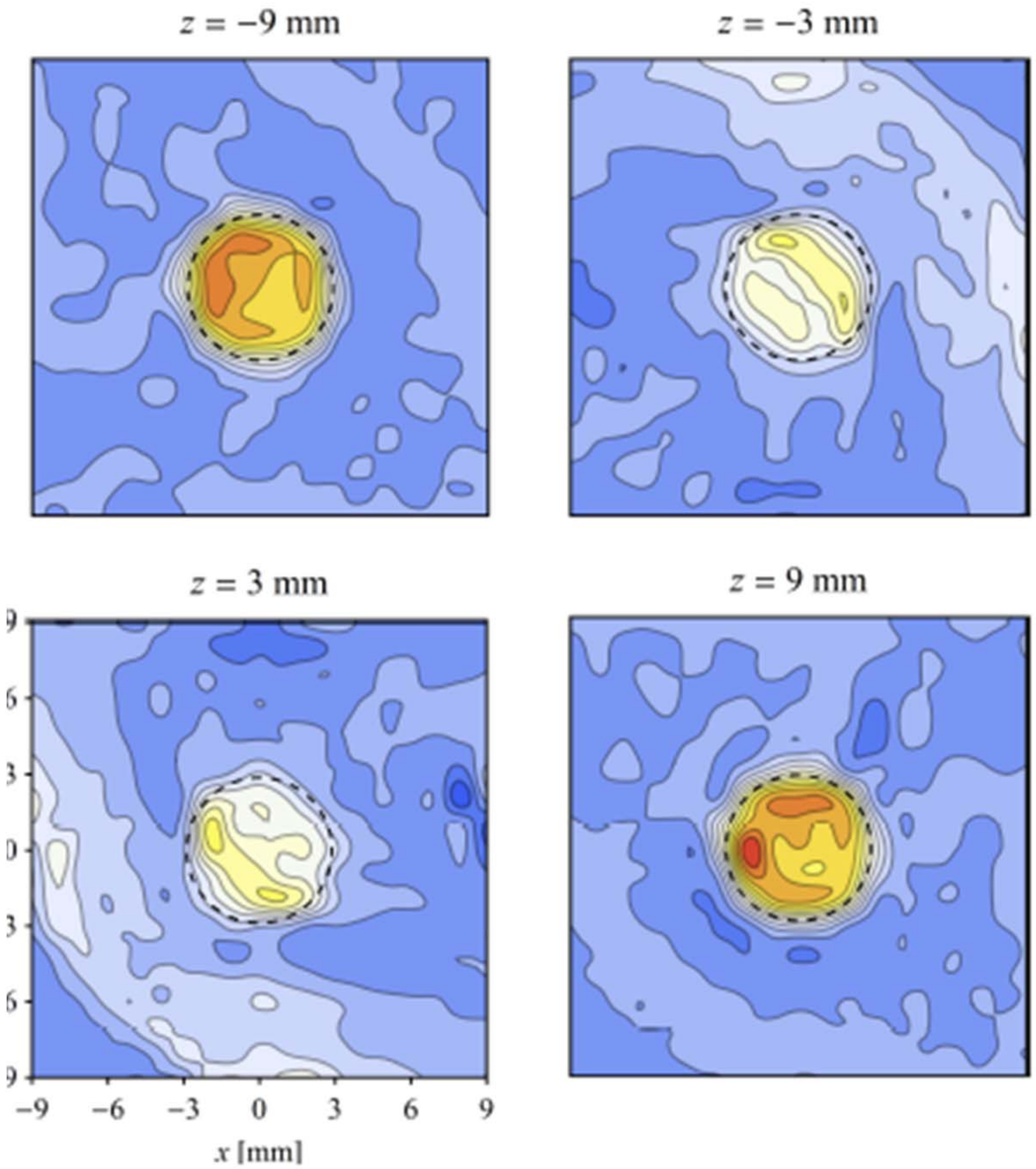
- Measurement of conductivity distribution with high spatial accuracy (1 mm) and with small relative error (perhaps 5% when current errors may be 50%)

  => Elimination of the geometrical uncertainty in the structure of the head from the MEG/EEG inverse problem
- MEG accuracy from 5 to 1–2 mm
- EEG accuracy from perhaps 20 mm to < 5 mm
- TMS accuracy from 5 to 1–2 mm
- Improved work flow
- New markets

Conductivity imaging with ULF-MRI

Simulation

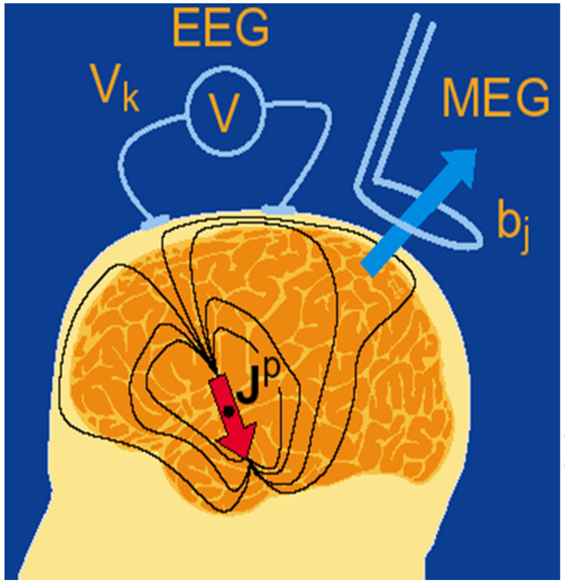


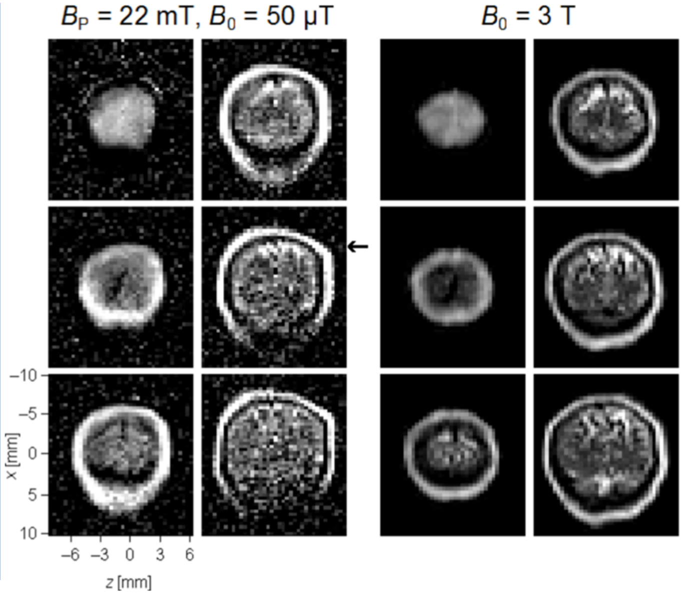


Presently, the S/N is not sufficient for human experimentation (too strong currents would be needed)

Nieminen, Vesanen et al. 2012

Thank you for your attention!





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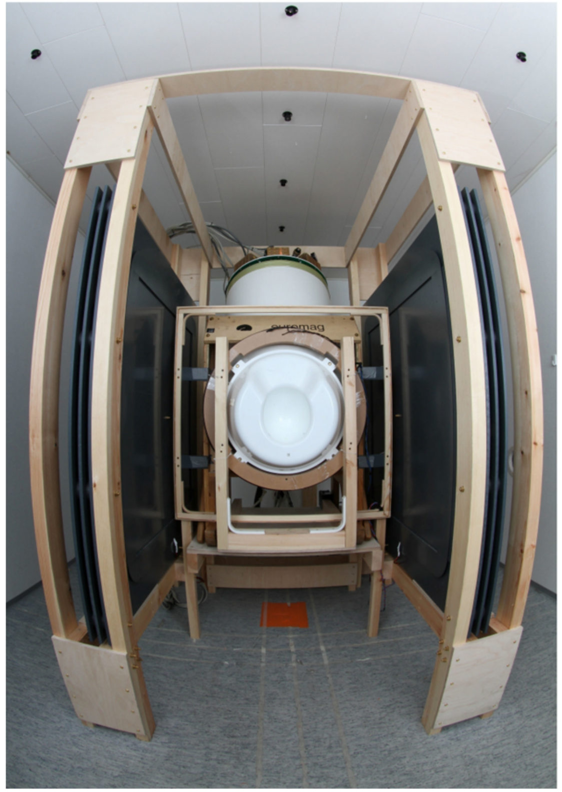

Panu Vesanen, Koos Zevenhoven, Juhani Dabek, Sarianna Alanko, Andrey Zhdanov, Mika Pollari, Fa Hsuan-Lin, Jaakko Nieminen,Tuomas Hirvonen, Juha Simola, Lauri Parkkonen, Antti Ahonen, Juho Luomahaara, Juha Hassel, Jari Penttilä, Jyrki Mäkelä, Juha Montonen, and the MEGMRI consortium; megmri.net