IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), February 2018.
This invited presentation ED6-1-INV was given at ISS 2017, December 13-15, 2017, Tokyo, Japan.

Aalto University
School of Science

Department of Neuroscience and Biomedical Engineering

The SQUID and its Applications in the Past 30 Years

Risto Ilmoniemi
Department of Neuroscience and Biomedical Engineering
Aalto University, Finland

The 30th International Superconductivity Symposium (ISS 2017),
Tokyo, December13–15, 2017

Olli V. Lounasmaa
1930–2002

Founder of:

Low Temperature Laboratory in Helsinki Univ. of Technology, 1965

SHE with John Wheatley, Jeremy Good and Jim Zimmerman,1969

Neuromag Ltd. in 1989 (now MEGIN, owned by Elekta)

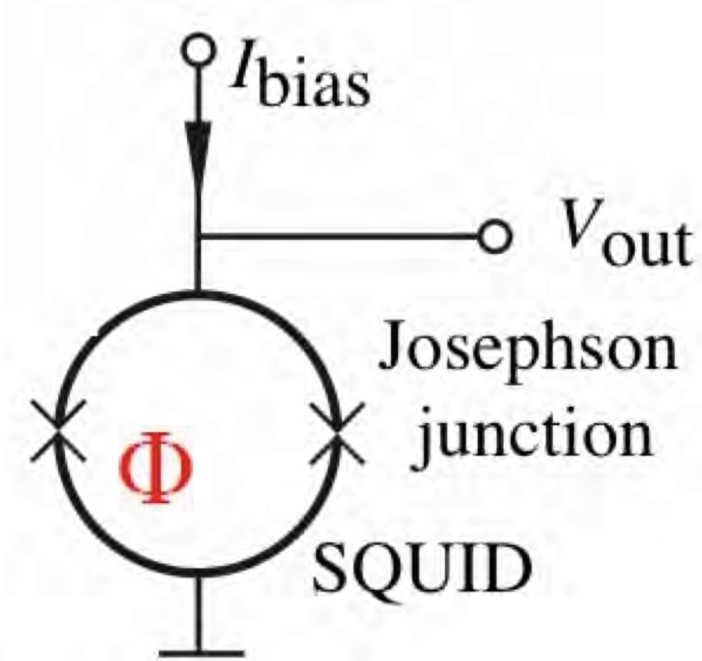
Aalto University
School of Science

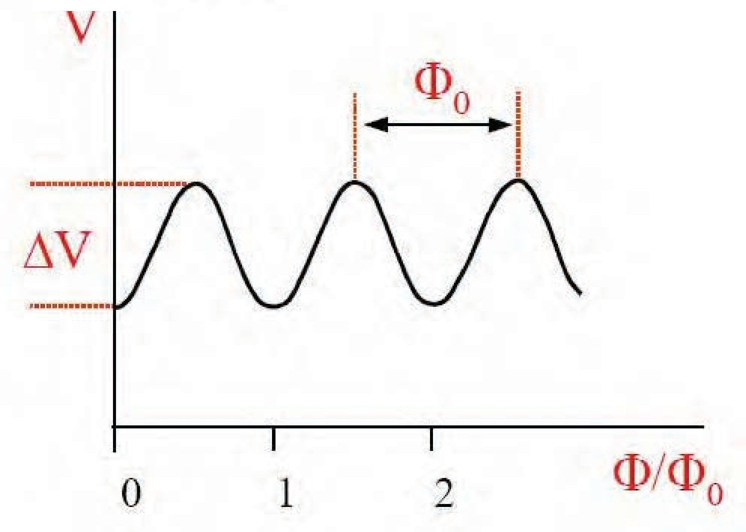
Toivo Katila

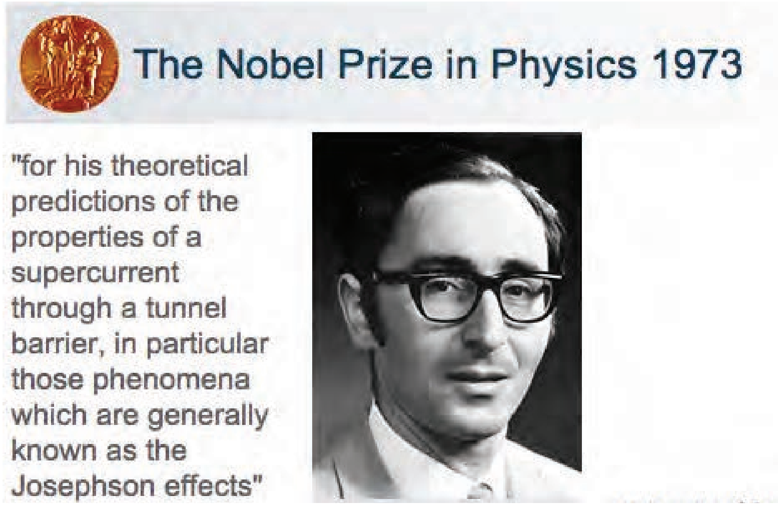
Several pioneering biomagnetic studies in 1970's, first in Lounasmaa's lab, then in own lab; unshielded environment

Fetal MCG, 1974

The SQUID



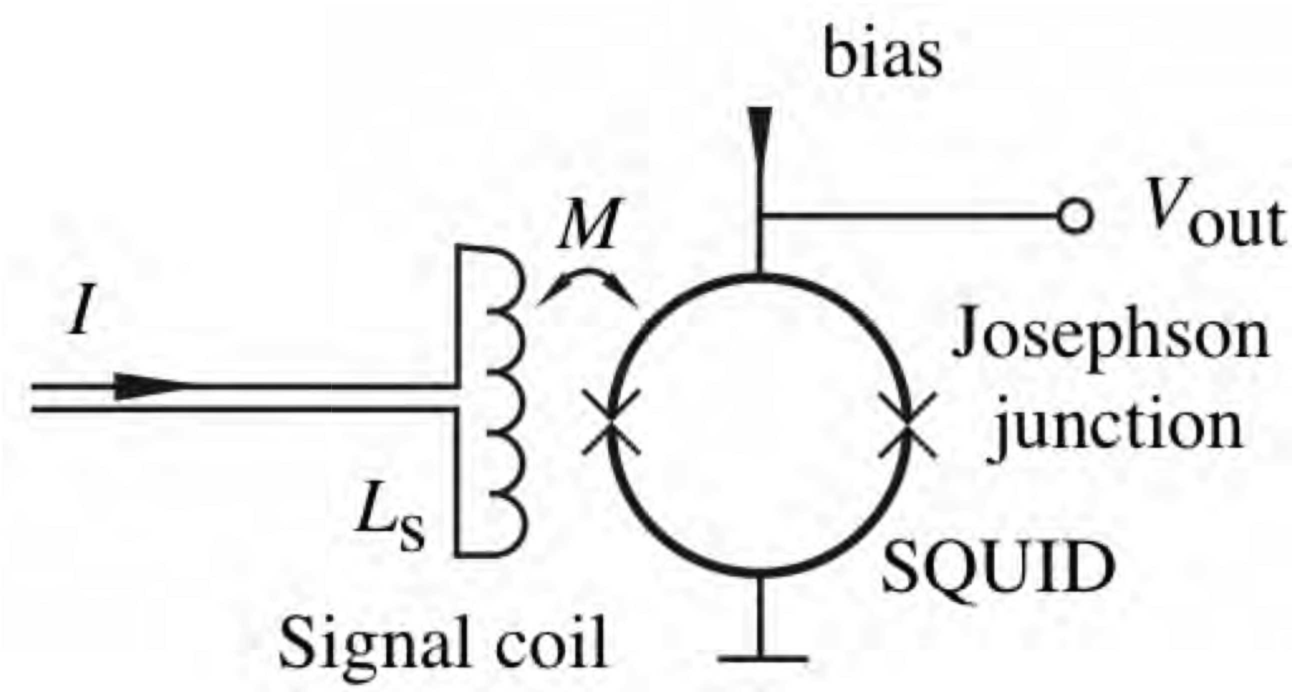




Brian Josephson

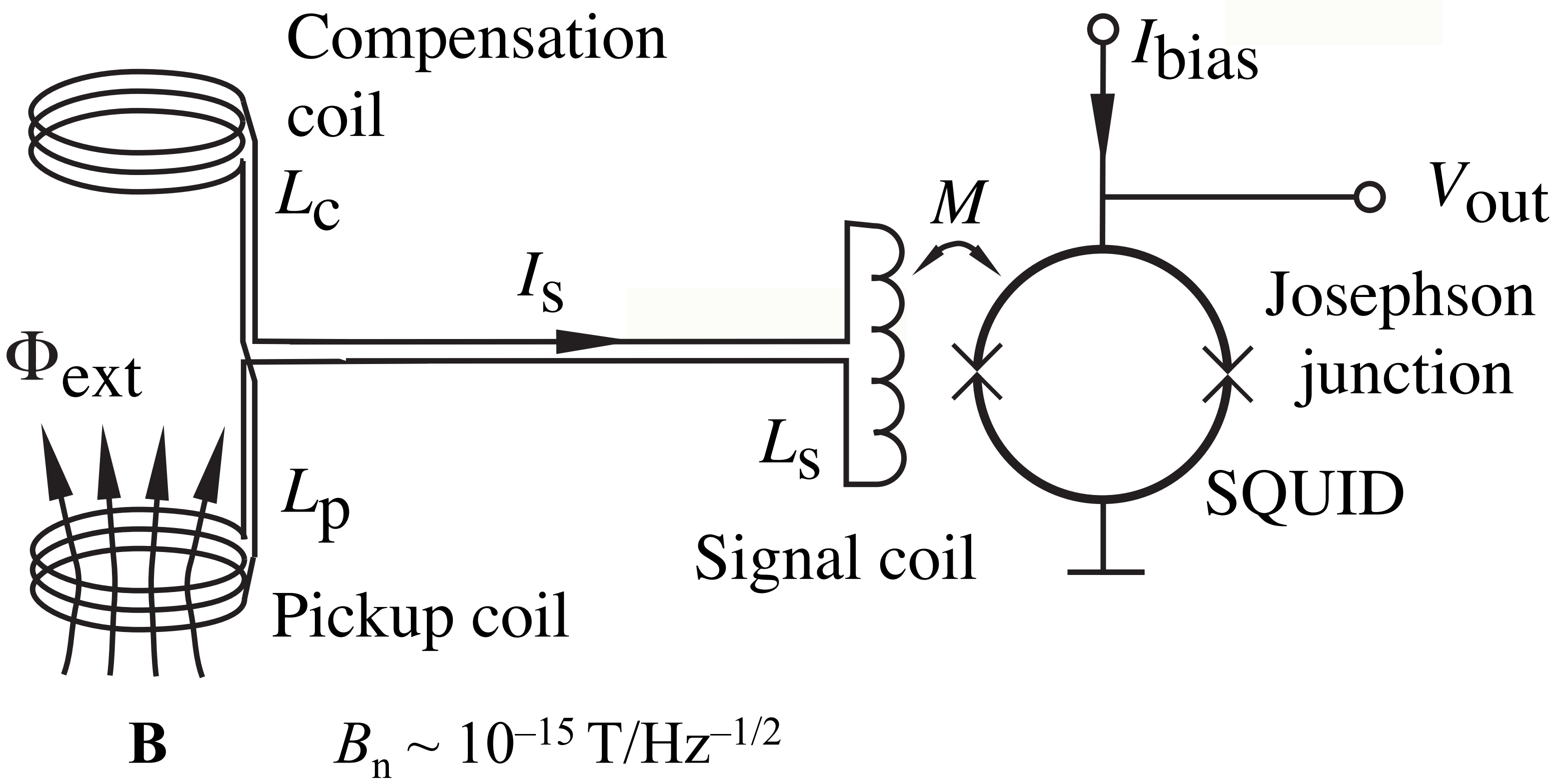
Jim Zimmerman

The SQUID can measure electric current



Key measure: coupled energy sensitivity: $E_n = ½ L< I_n^2>$

The SQUID can measure magnetic field



$B_n \sim 10^{-15}$ T/Hz$^{-1/2}$

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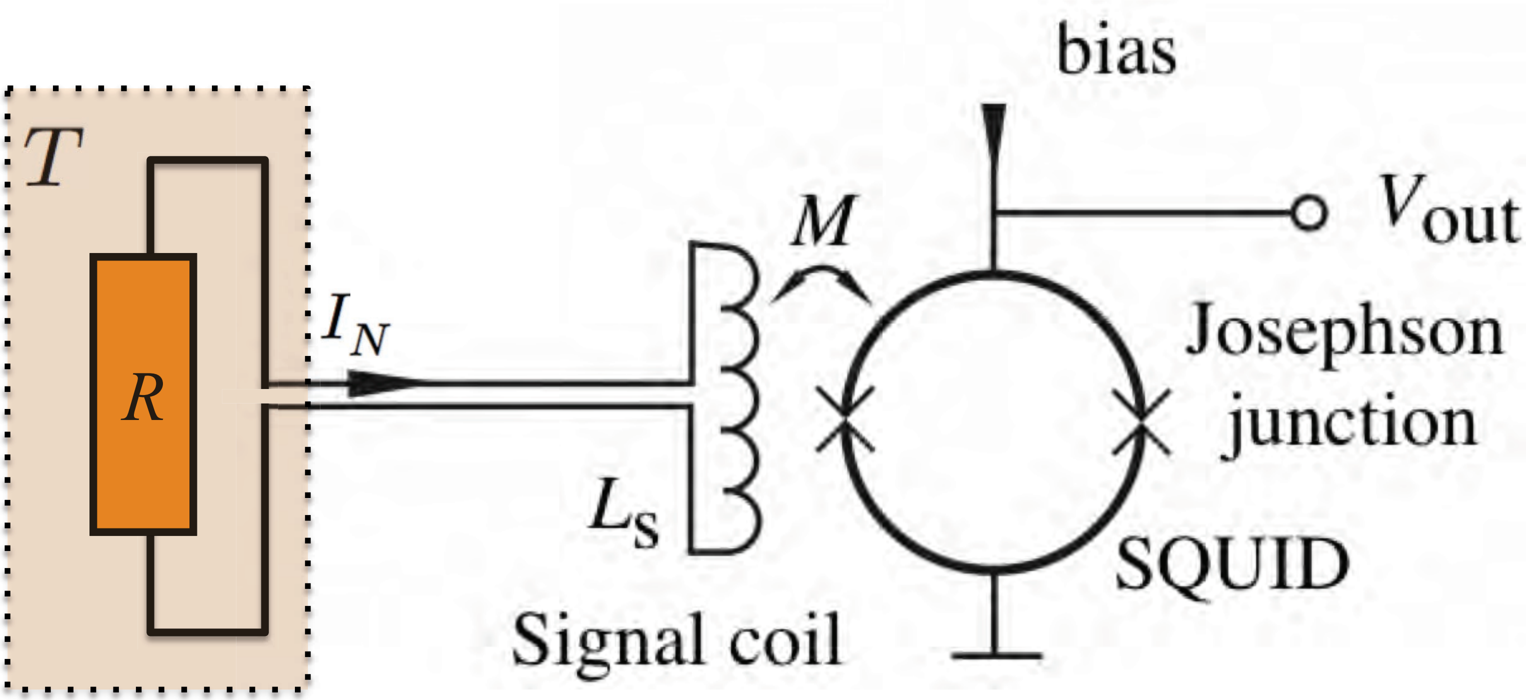
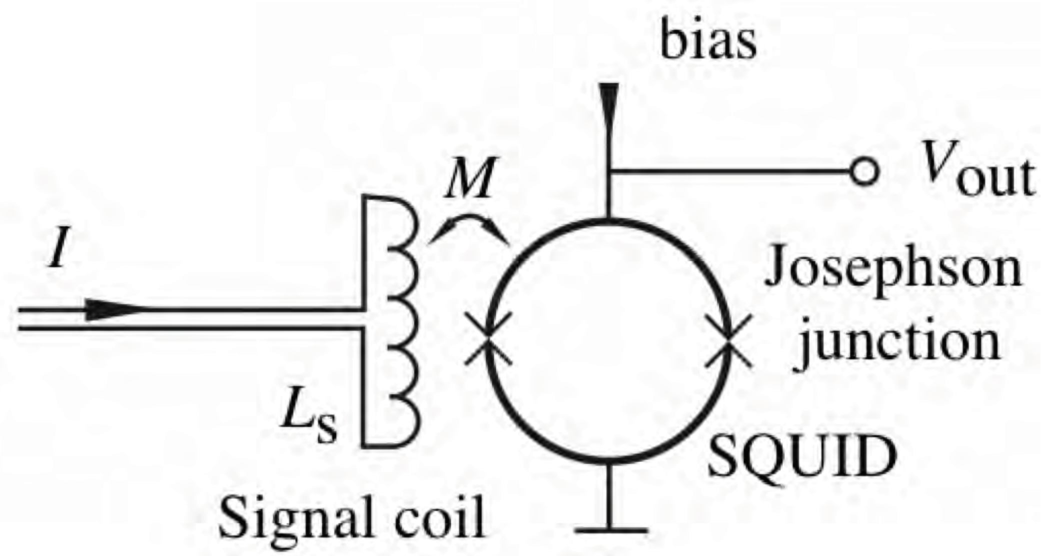
The SQUID can measure temperature



$$\langle I_N^2 \rangle = \frac{4k_B T}{R}\left(\frac{1}{1+\omega^2\tau^2}\right)$$

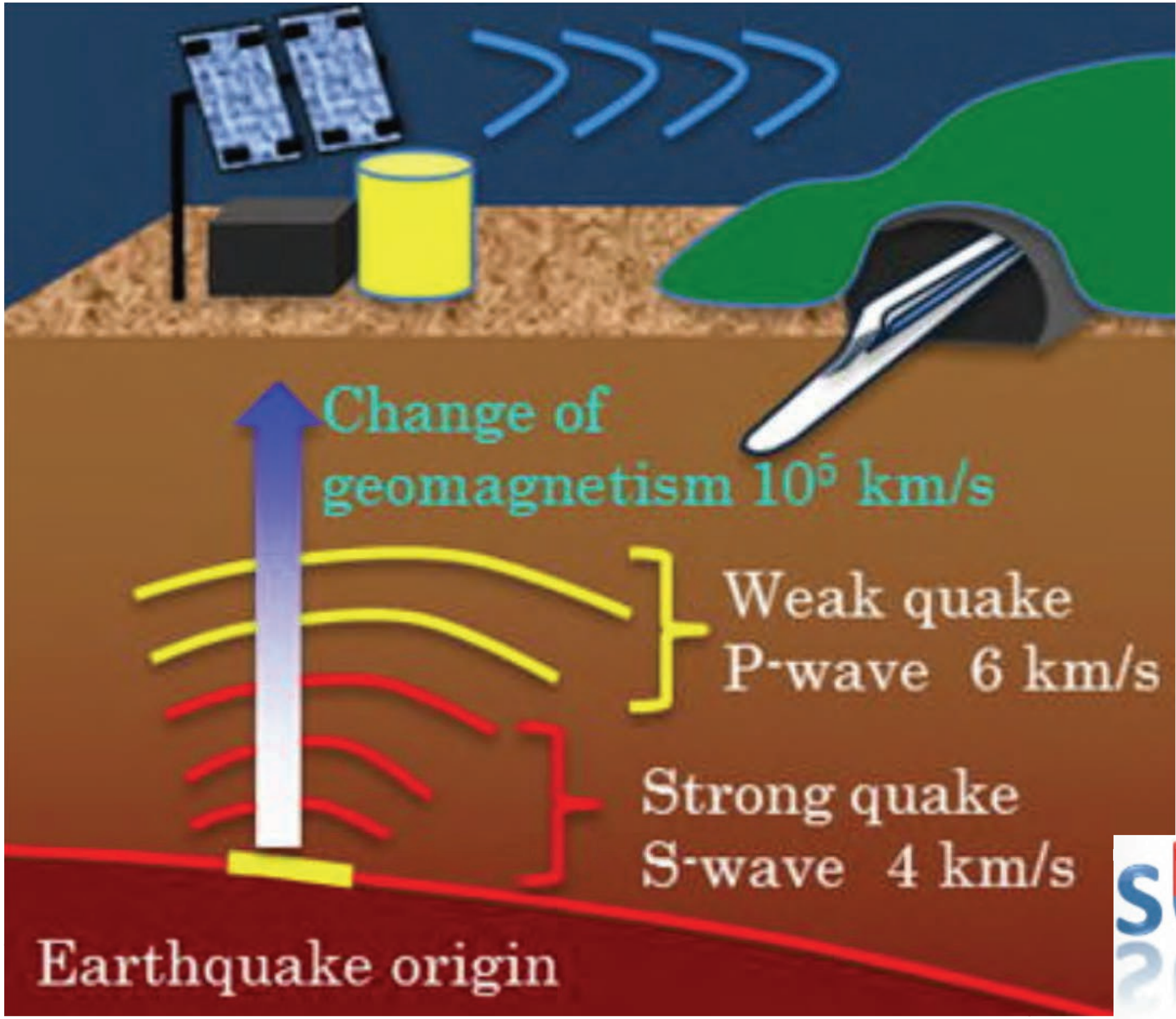
Casey, Andrew, et al. "Current sensing noise thermometry: a fast practical solution to low temperature measurement." Journal of Low Temperature Physics 175.5-6 (2014): 764-775.

The SQUID can measure almost anything



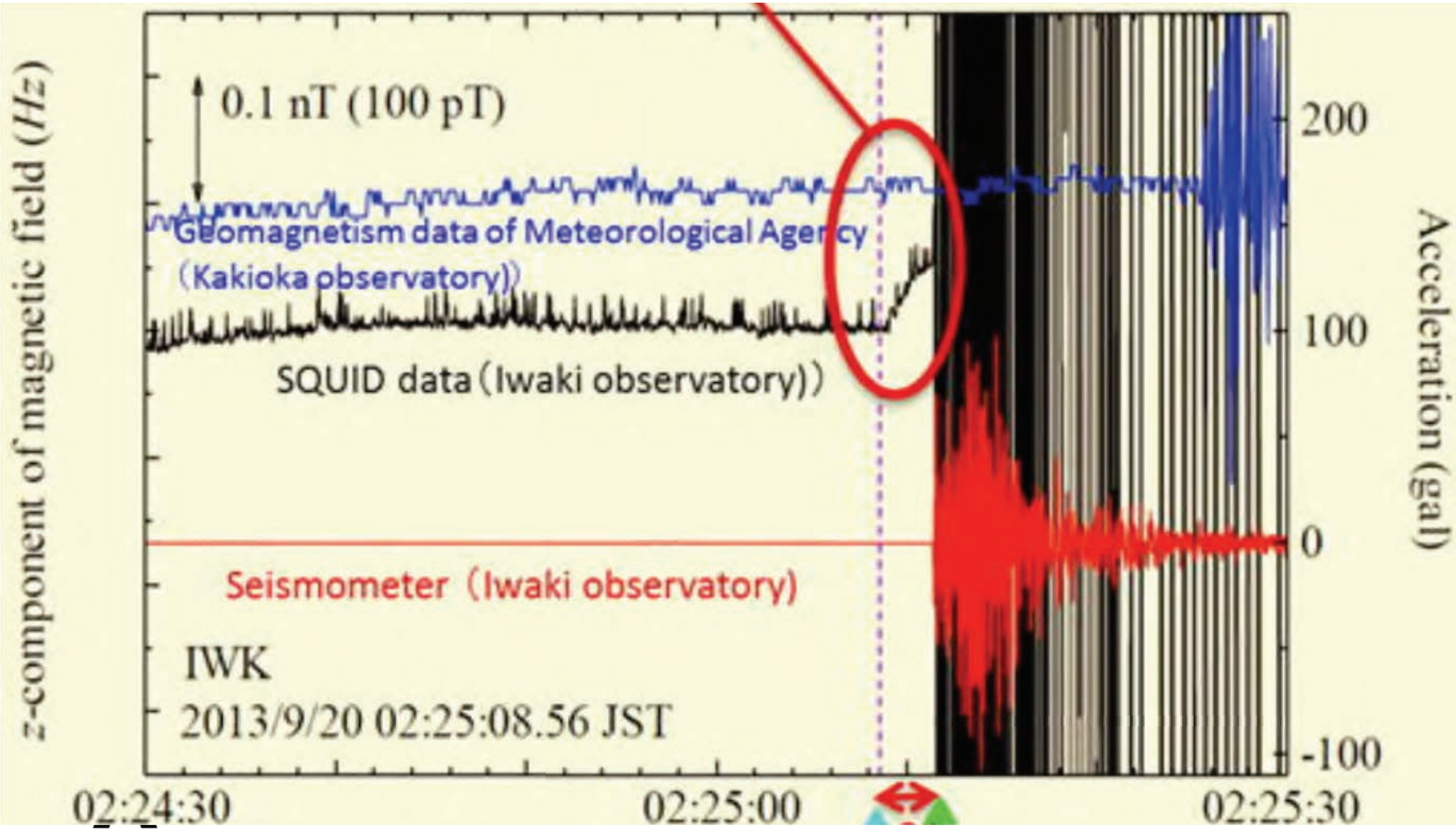
- Magnetic flux
- Eletric current
- Temperature
- Susceptibility
- NMR signals
- Motion of magnetic materials
- Changes of anomalies in conductivity

The SQUID can measure earthquakes



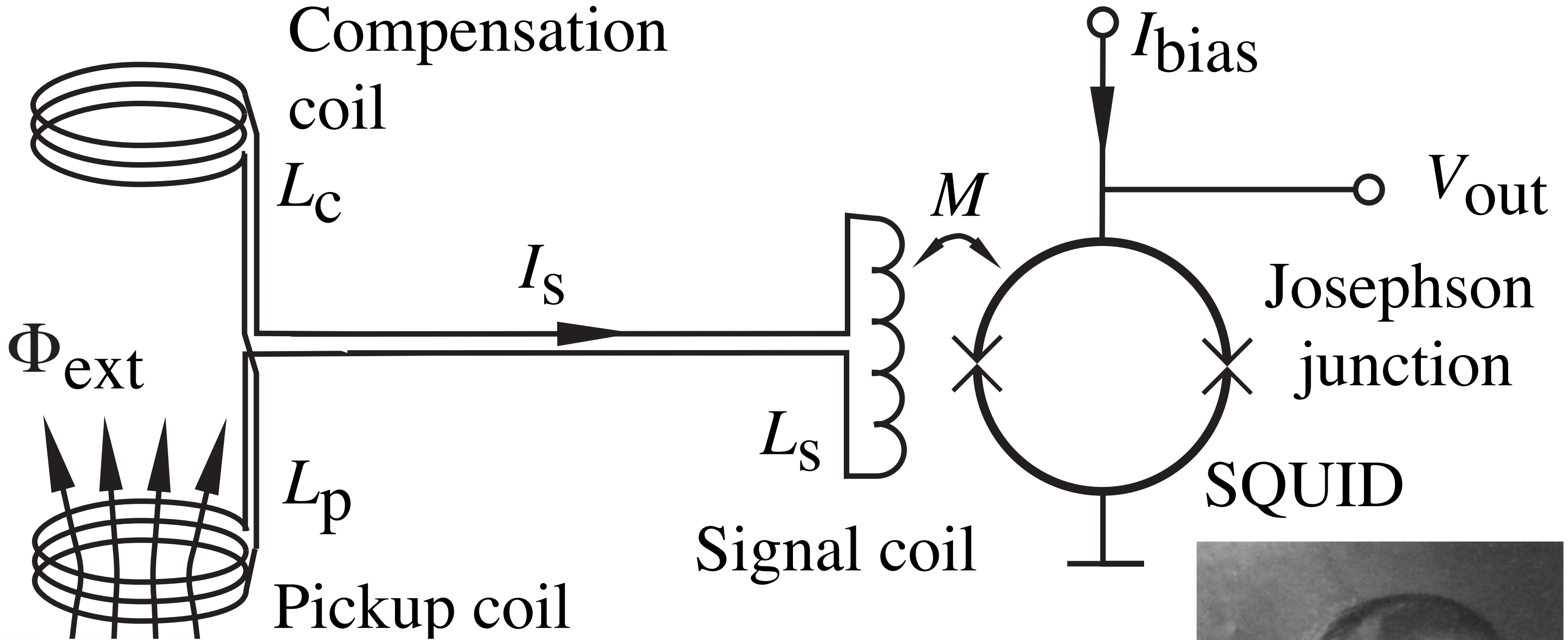
SUSTERA

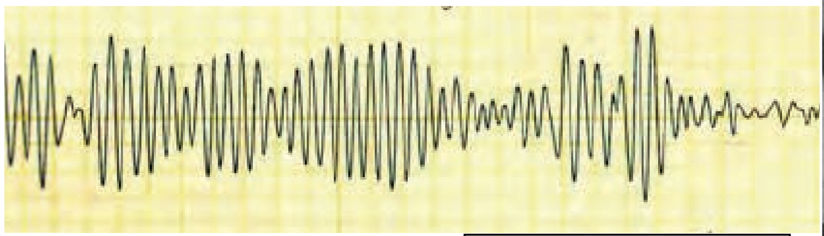
The SQUID can measure earthquakes



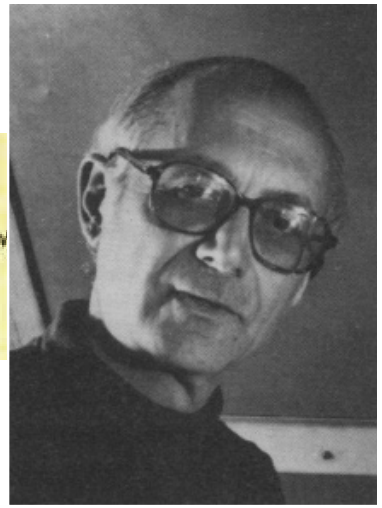
http://www.sustera.or.jp/

The SQUID can measure brain activity





1971



David Cohen

Why use the SQUID to measure brain activity?

Motivation 1: Burden of brain disorders

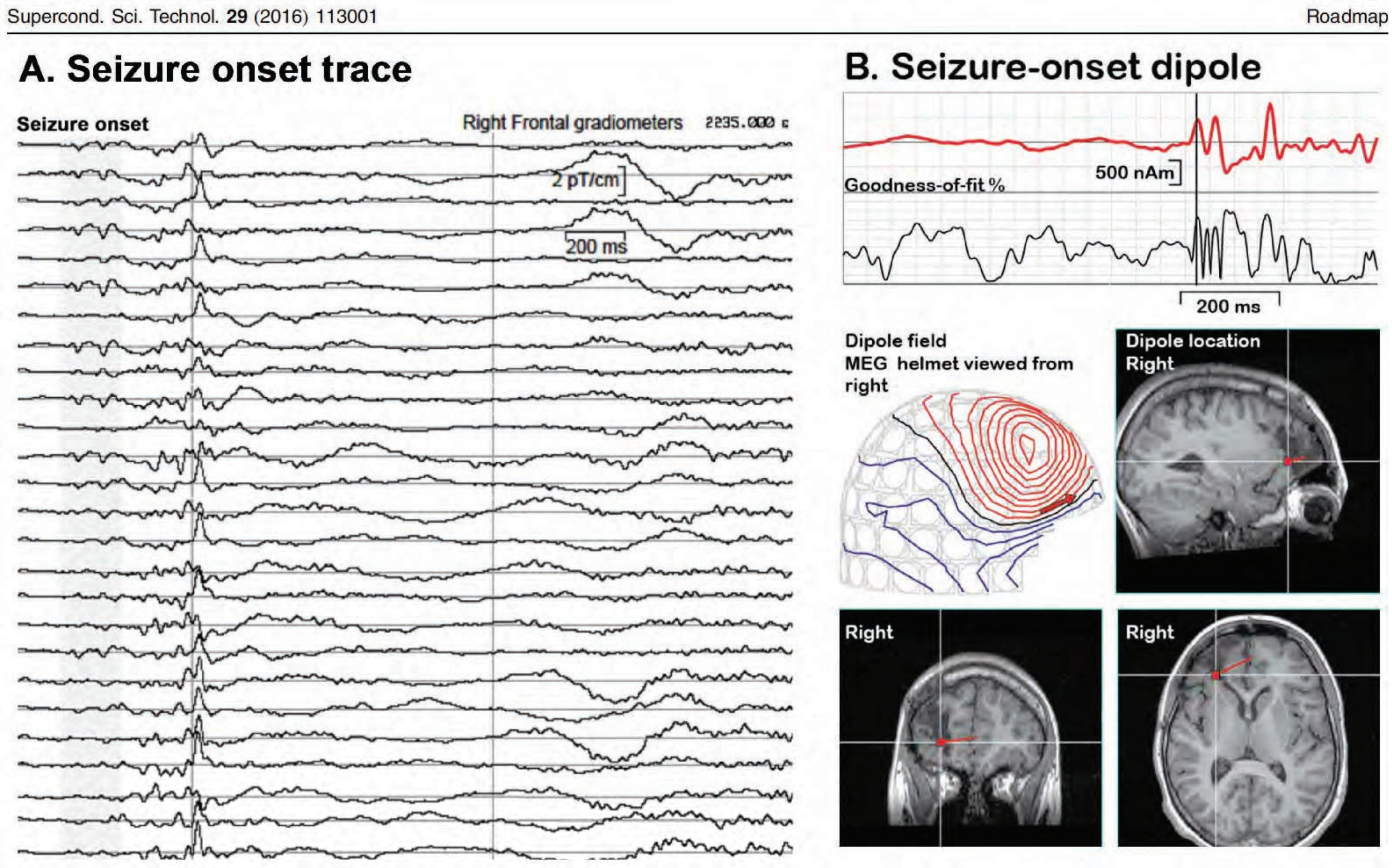
Depression: 150 million patients (in the world)
Schizophrenia: 25 million
Dementias: 40 million
Epilepsy: 40 million
Stroke: 40–100 million

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

Motivation 2: How does the brain work?

- Brain states
- Dynamics, connectivity
- Information processing
- Learning and memory
- Thinking, consciousness …

Valuable clinical application: locating epileptic activity prior to surgery



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Some history on the use of SQUIDs in biomagnetism

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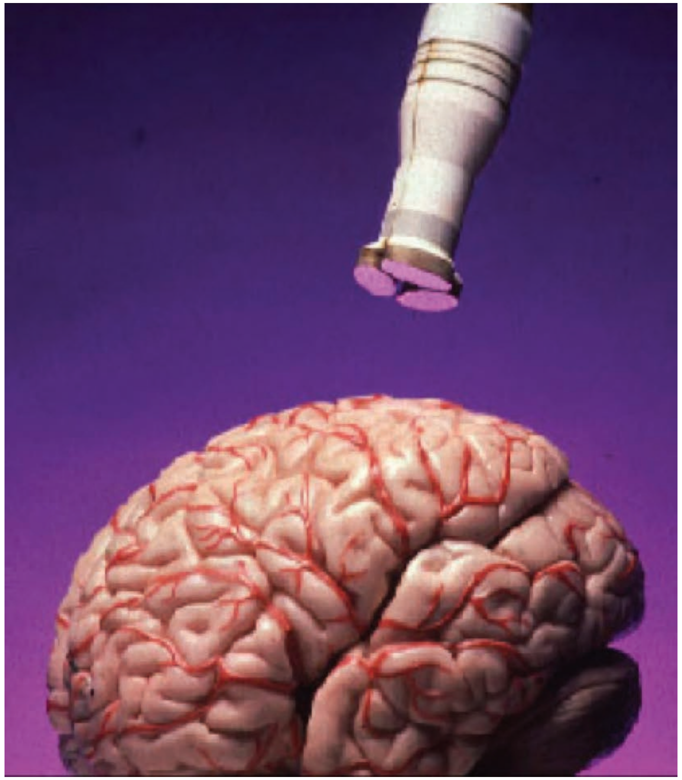
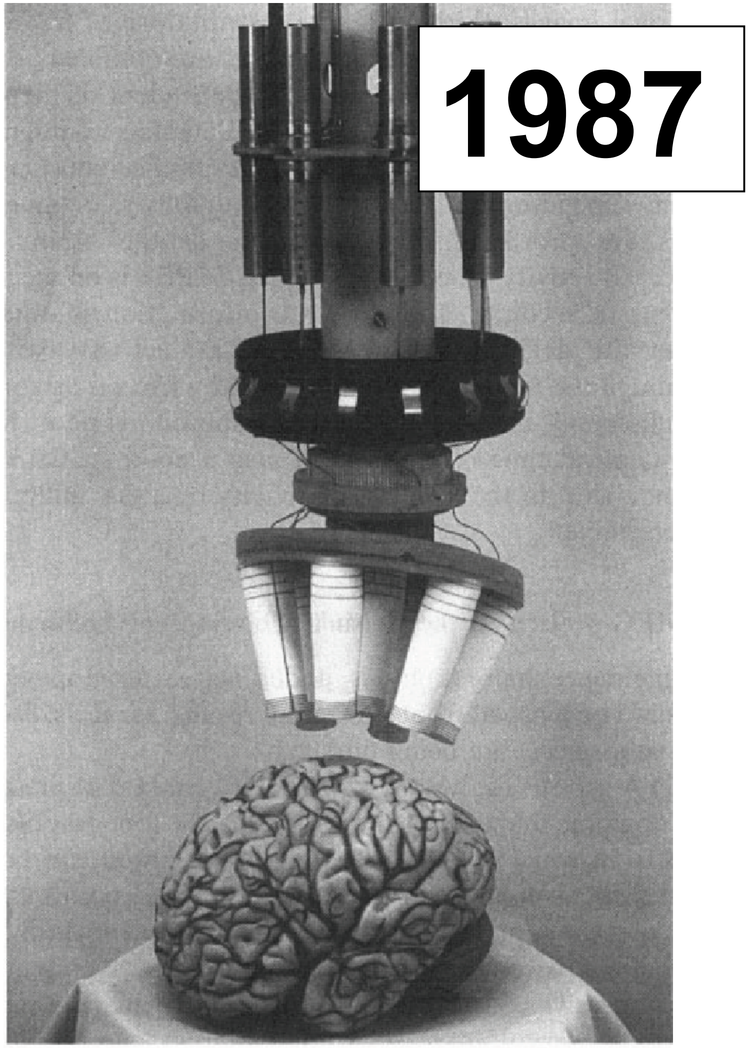
School of Science

First multichannel MEG devices



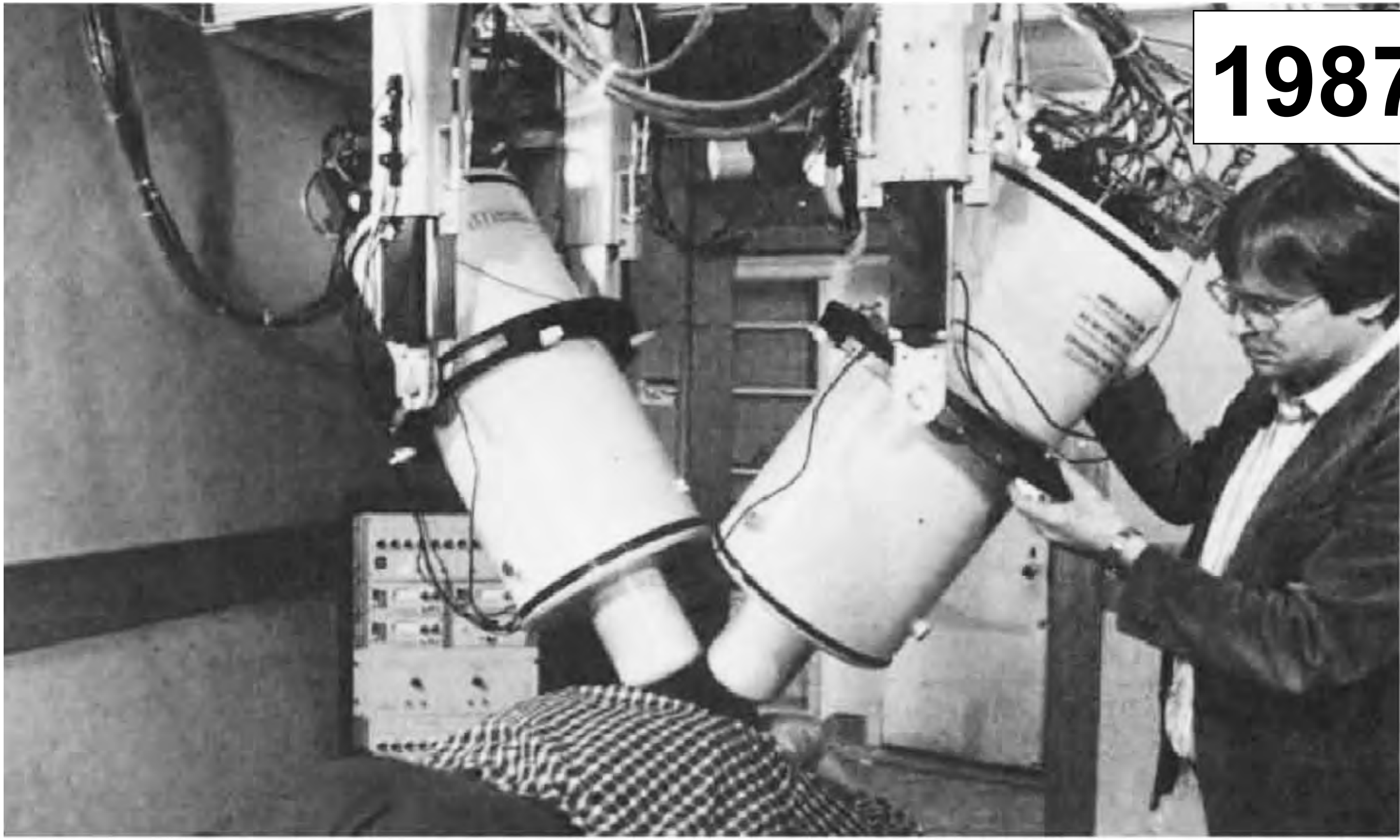
Ilmoniemi et al., "*A four-channel SQUID magnetometer for brain research*", Electroenceph. Clin. Neurophysiol. 58, 467–473 (1984).



Kajola, Matti, et al. Japanese Journal of Applied Physics 26.S3-2 (1987): 1555.

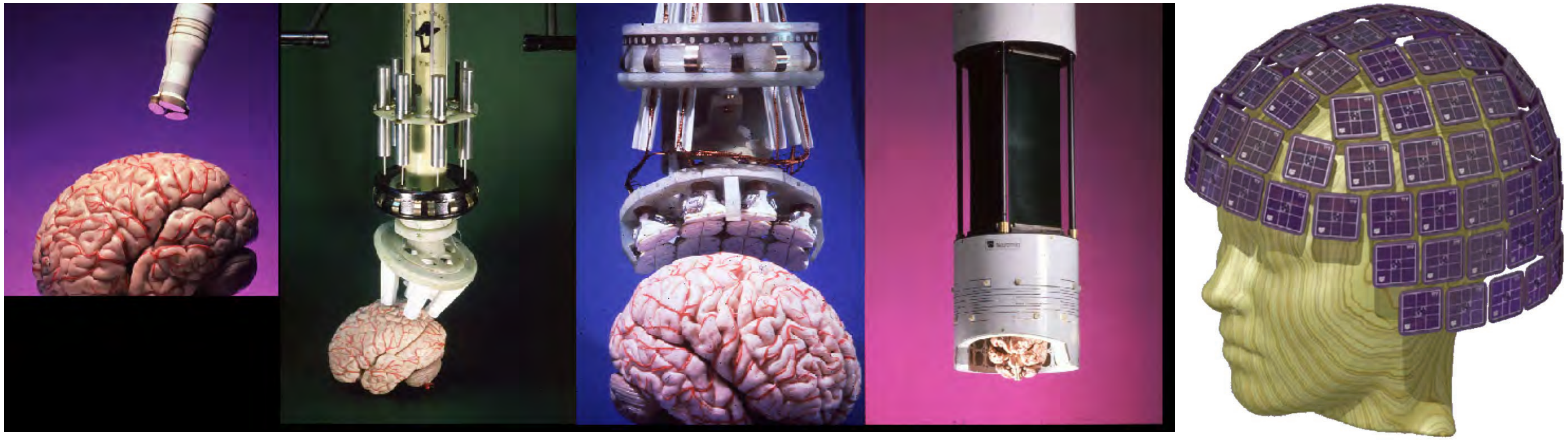
System by Biomagnetic Technologies, inc.

1987



g. 6. A pair of dewars, each containing a probe with 7 SQUID sensors, supported by gantries over a subject in the MSR at the Center for Neuromagnetism of the NYU Medical Center.

Multi-SQUID systems developed in Helsinki



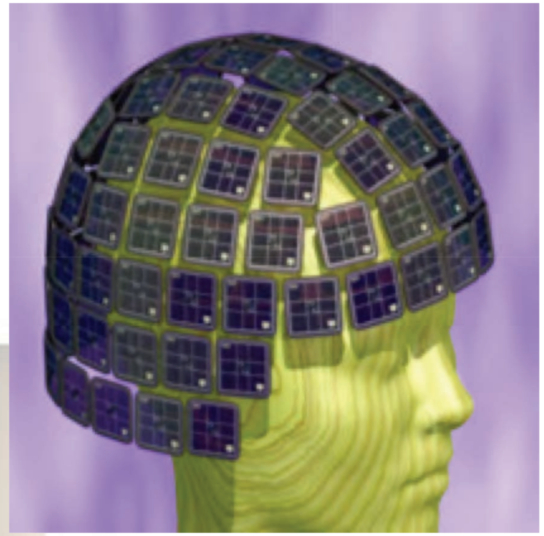
	1983	1987	1989	1993	1999
Number of SQUIDs	4	7	24	122	306

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)



Elekta Neuromag® TRIUX

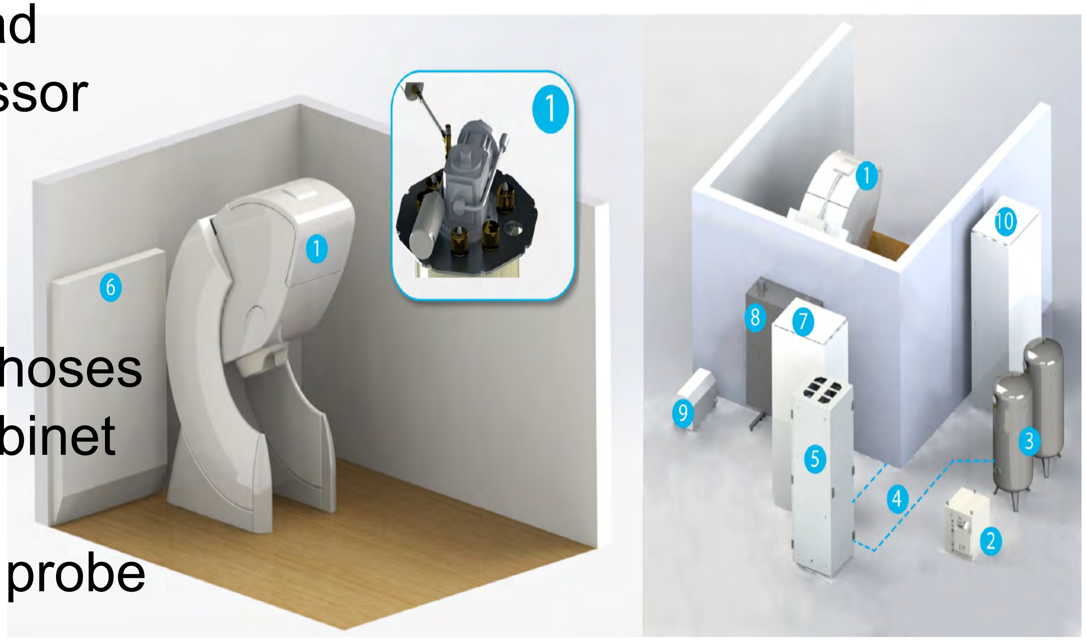
Overview

- Internal Helium Recycler
- Gantry and dewar
  - Three measurement positions:
    Supine (0°), upright (60°), full upright (68°)
  - Separate liquefaction position (22°)
- EEG: 0/32/64/128 channels
  - 12 BIO channels
- Electronics
  - Re-designed architecture
  - Wide dynamic range (±20 nT)
- Proprietary MaxFilter interference suppression
  - Eliminates external and nearby interference

Elekta Neuromag® TRIUX: Internal Helium Recycler

- Eliminates the need of weekly refill by circulating helium in a closed cycle
- Main components:

1. Cryocooler cold head
2. Cryocooler compressor
3. Storage tanks
4. He gas lines
5. He recycler cabinet
6. Reel for cryocooler hoses
7. MEG electronics cabinet
8. Feedthrough unit
9. Lifting unit for MEG probe
10. Stimulus cabinet



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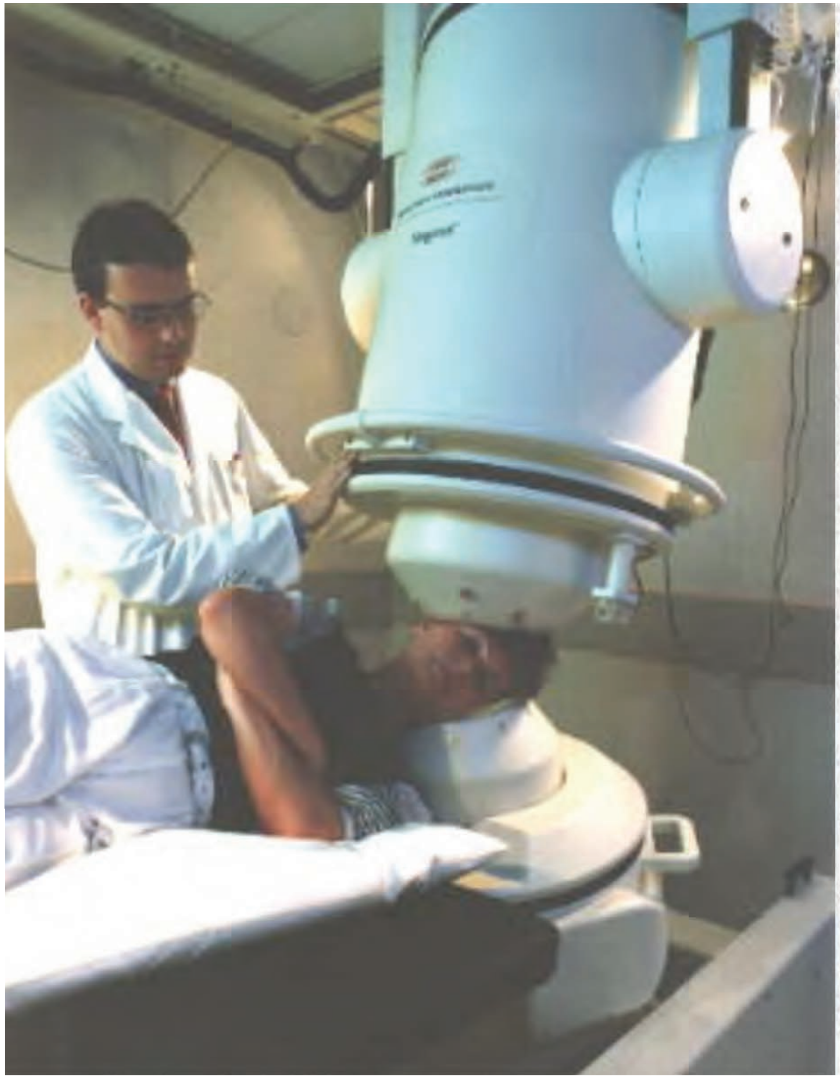
Biomagnetic Technologies

1995



MAGNES II® Biomagnetic System

of Biomagnetic Technologies inc. (BTi),
(4-D Neuroimaging inc., San Diego, CA, USA)

The system is used since Jan. 1995.

It contains 74 recording channels. In each cryostat are housed 37 channels. Each one can be adjusted to the head (or thorax) and can be tilted by 45 degrees. The recording coils are 1st order axial gradiometers with a baseline of 5 cm. The recording surfaces are curved and have an outer diameter of 17 cm.
The system is operated inside a magnetically shielded room with a size of 3 by 4 meters.

(Photo by courtesy of Bischof & Broel, Nürnberg)

Magnes 2500 WH, 148 chs, Bti/4D Neuroimaging

1996

Magnes 3600 WH, 248 chs, 4D Neuroimaging

Apostolos P Georgopoulos oversees a MEG scan.

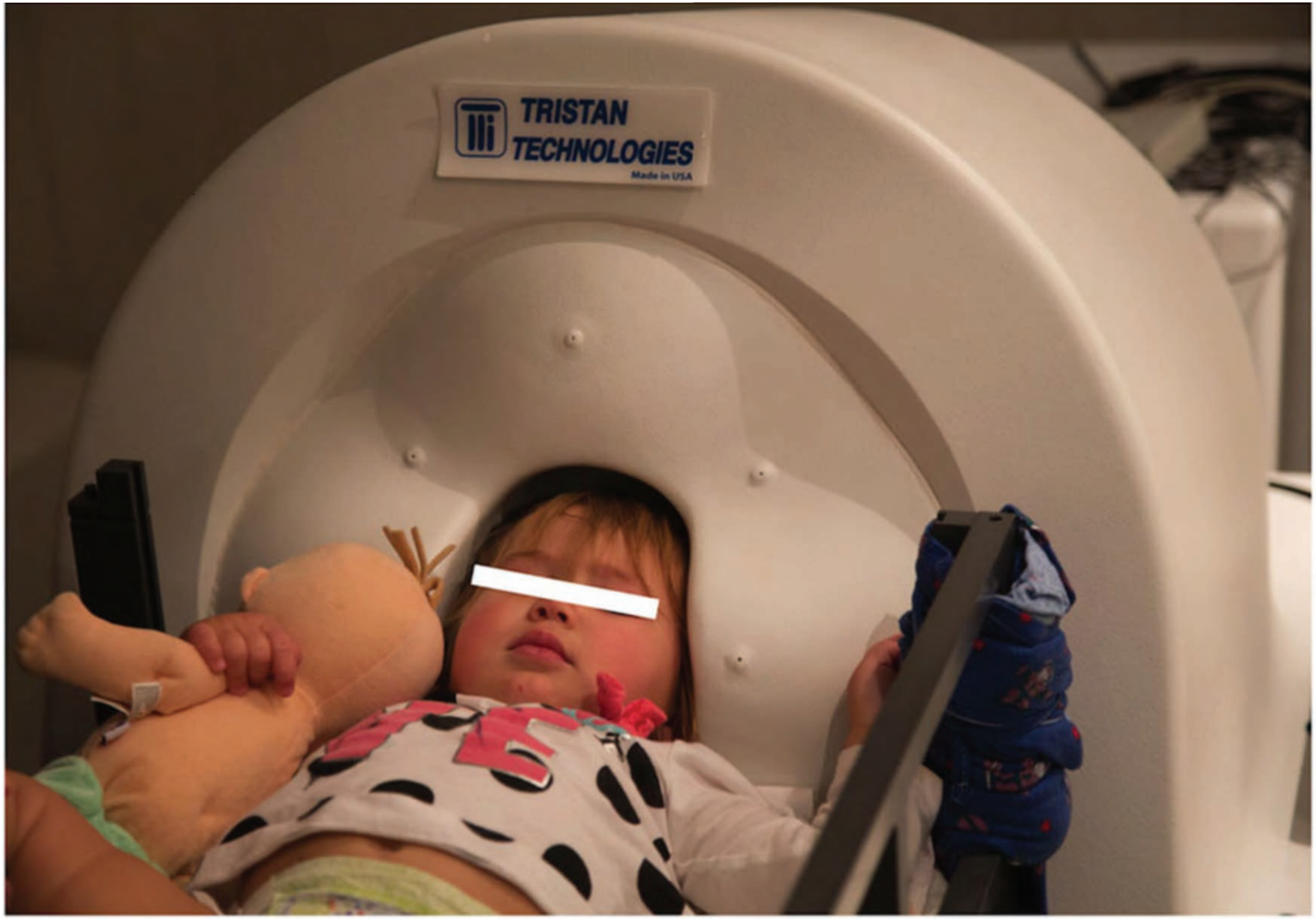
CTF, Vancouver, Canada

- 1982: First hardware third order gradiometer system
- 1992: First whole-cortex MEG system (64 channels)
- 1995: First 77K High Temperature Superconducting system
- 1996: First 143 channel MEG
- 1997: First 151 channel adjustable (seated and supine) MEG
- 2000: First investigational fetal MEG system introduced
- 2007: CTF MEG technology acquired by MSC Corp
- 2014: cMEG 275 channel

CTF 275-ch system


2017
The New MEG by CTF
The best low-noise and stable MEG performance available in the world
The Most Advanced MEG System in The World
No SQUID re-tuning, no flux jumps
CTF

Tristan Technologies: Artemis 123



Dual scanning: Yokogawa, Kanazawa

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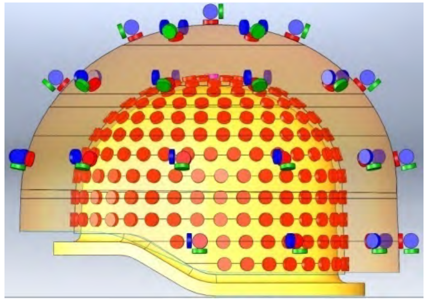
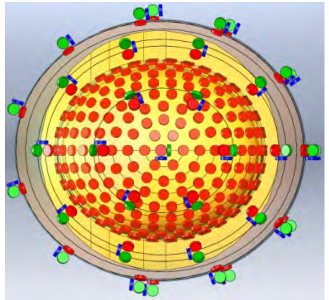
BabyMEG: whole-head pediatric MEG system





2-layer sensor array
270 channels/inner
105 channels/outer
9 reference channels
7-8 mm gap
Helmet – up to 3-4 yrs
100% helium recycler
Noise 6 ft/√Hz inner
3 fT/√Hz outer

Tristan Technologies; Courtesy of Yoshio Okada

High-T_c SQUIDs

- No liquid Helium
- Close to scalp, more information
- Flexible placement

Chalmers Univ./Univ. Gothenburg

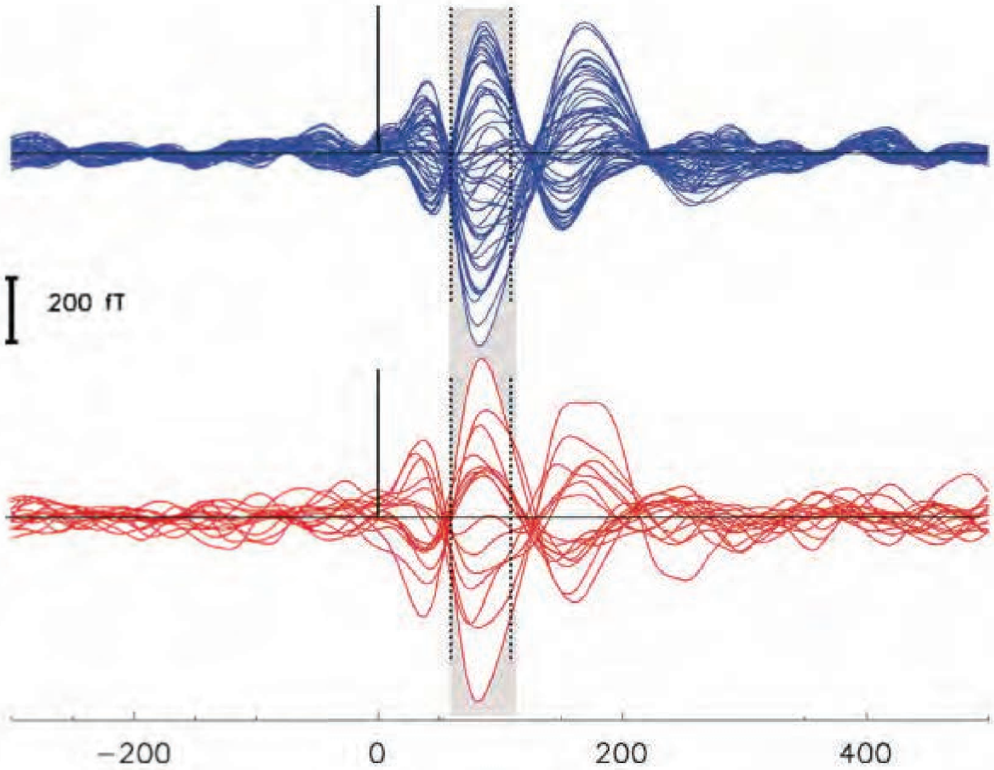
Justin Schneidermann et al.

Dag Winkler et al.

APPLIED PHYSICS LETTERS **104**, 213705 (2014)

Source localization of brain activity using helium-free interferometer

Jürgen Dammers,[1,a)] Harald Chocholacs,[1] Eberhard Eich,[1] Frank Boers,[1] Michael Faley,[2]
Rafal E. Dunin-Borkowski,[2] and N. Jon Shah[1,3,4]



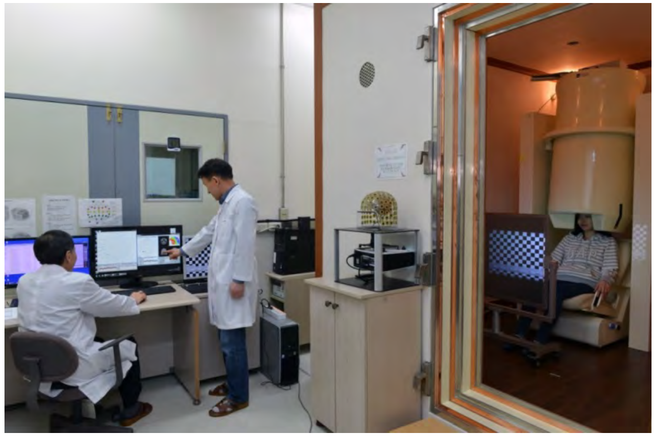
SQUIDs for MEG: companies

- SHE/Bti/4-D Neuroimaging, San Diego, CA (founded 1970)
- CTF Systems inc., Vancouver, Canada (1970)
- Quantum Design, San Diego, CA (1982)
- Mediterranean Quantum Systems/AtB, Rome (1985)
- Neuromag / Elekta / MEGIN, Helsinki, Finland (1989)
- Tristan, San Diego, CA (1991)
- Magnecon, Germany (2000)
- Aivon Oy, Finland (2005)
- Dornier, Germany
- Siemens, Germany
- Philips Medical Systems
- Yokogawa, Japan
- Shimadzu, Japan
- Daikin, Japan
- Superconducting Sensor Laboratory, Japan (several companies)
- Compumedics (2016)
- Ricoh

Robert Fagaly, IEEE Trans. Appl. Supercond. 2015

KRISS MEG

MEG system

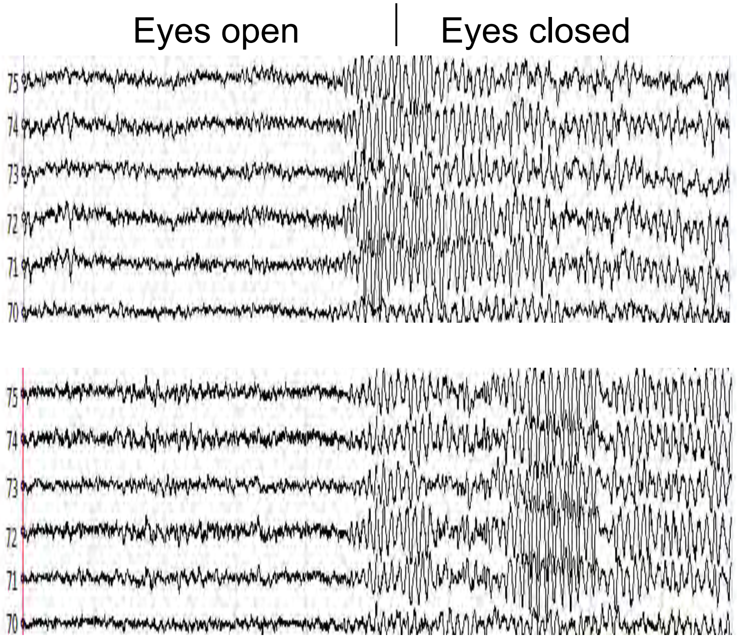


Reliquefier

Low-noise MEG with continuously recycling of He

Reliquefier off

Reliquefier on



Technology transfer

- Compumedics Neuroscan (Australia)
- Two helmets of different helmet size
- Life-Span MEG: From baby to elderly
- No need of liquid helium refill: continuous recycling of helium

Lee YH, SUST (2017)

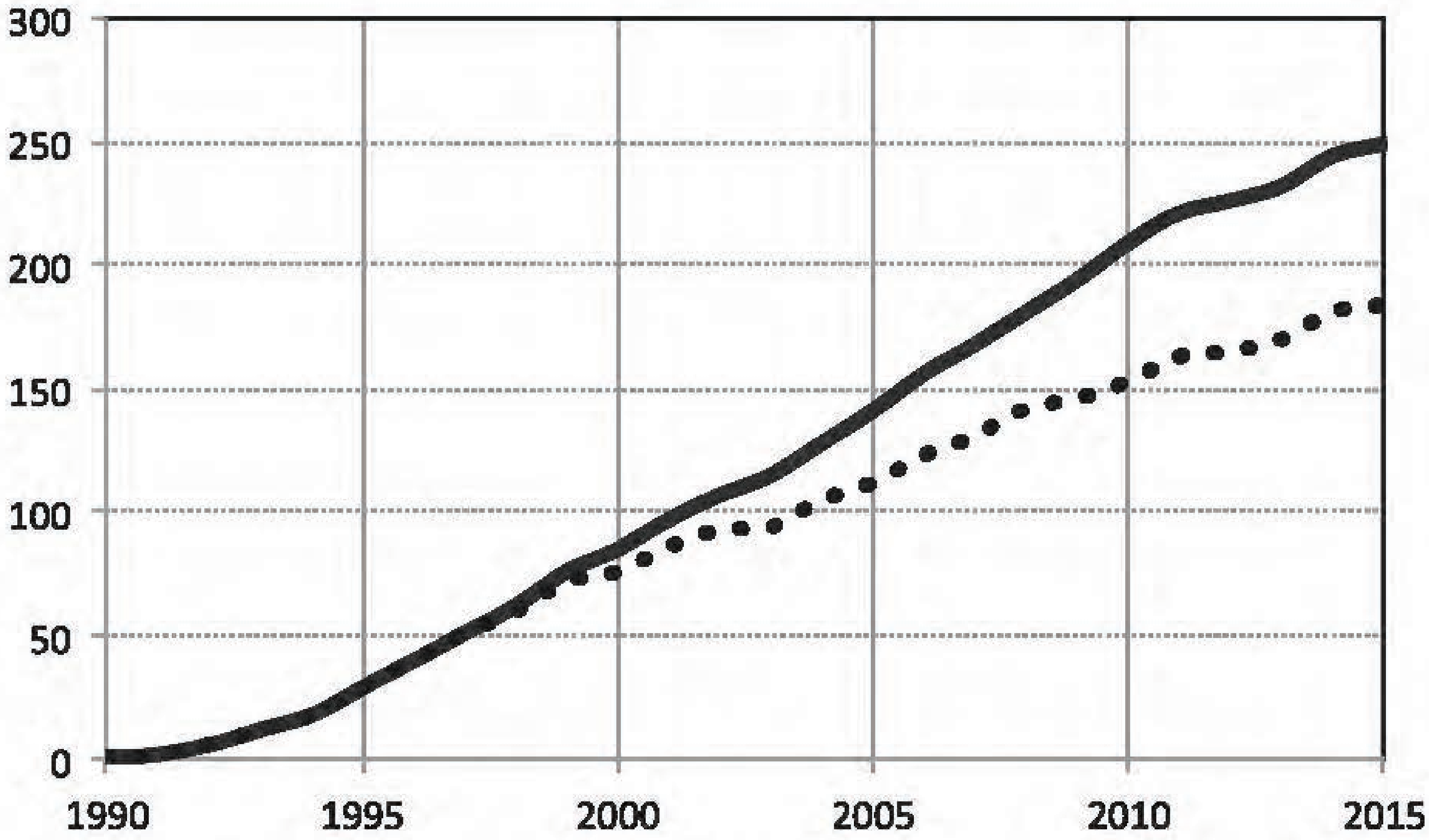


Figure 15. Cumulative number of installed commercial multichannel SQUID systems, including replacements and upgrades (solid line) and cumulative number of systems in use as of 2015 (dotted line).

Supercond. Sci. Technol. **29** (2016) 113001 (30pp)

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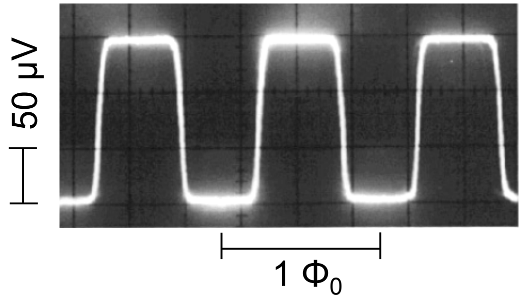
KRISS MCG

Dewar/Gantry

Sensor

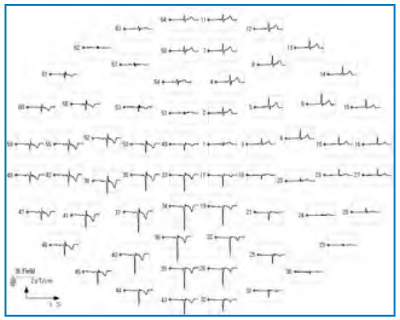
64-channel axial gradiometer
Large sensor coverage
Smaller neck diameter of dewar
Compact electronics

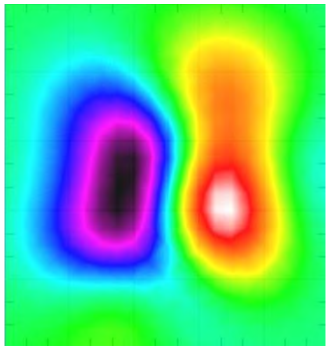
Double relaxation oscillation SQUID



Large flux-to-voltage transfer: V_Φ= ~ 1 mV/Φ_0

Analysis





Technology transfer

- Biomagnetik Park (Germany)
- Installations in 4 hospitals (3 in Germany, 1 Hong Kong)
- Approved CE, FDA, KFDA

Lee YH, SUST (2009)

We have amazingly good tools

- Extremely sensitive, reliable, and geometrically accurate MEG
- Sophisticated signal analysis and data inversion:
- SSP, ICA, MUSIC, Bayesian use of prior information
- …

THESE DID NOT EXIST 30 years ago

What is the problem?

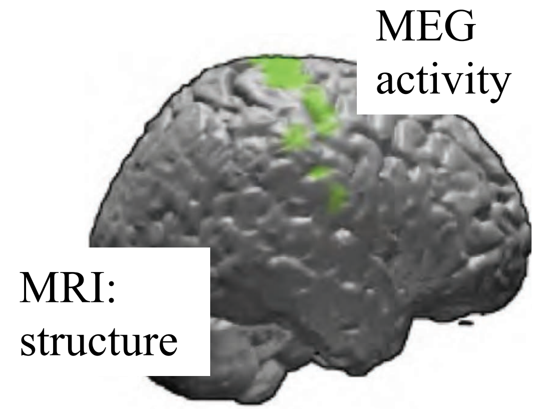
What is the problem?

MEG	Low-dimensional
	Sensors far from the brain
	Poor signal-to-noise ratio
Sensor locations	Inaccurately known
Tissue conductivities	Inaccurately known
MRI	Distorted images, shifted brain
Experiments	Predefined, no real-time control

$\Rightarrow$ **Unreliable source estimates**

Solution: Better use of SQUIDs

European project MEGMRI (2008–2012)



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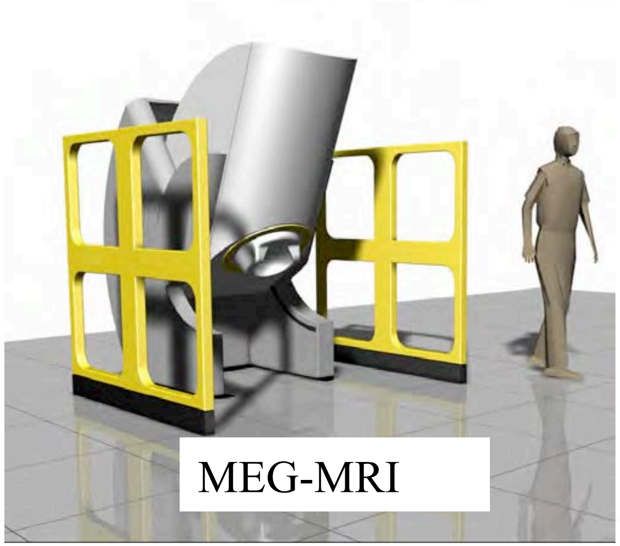


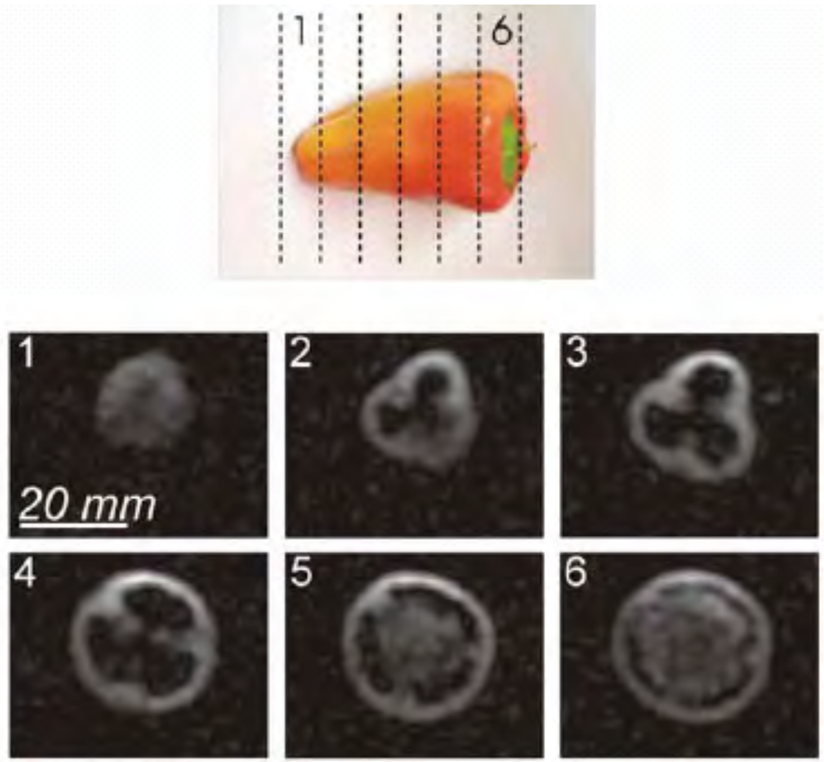
Full-scale "MEGMRI" prototype based on a commercial 306-channel Elekta MEG system

Aalto Univ.; VTT; Aivon Oy; BioMag Lab.; Elekta AB; PTB Berlin; CEA Paris; Cedrat Ltd., Grenoble; Chalmers Univ.; Univ. Chieti; Univ. Parma; Imaging Technology Abruzzo, L'Aquila; Associazione Fatebenefratelli per la Ricerca, Rome

Ultra-Low-Field MRI

McDermott et al., PNAS 2004

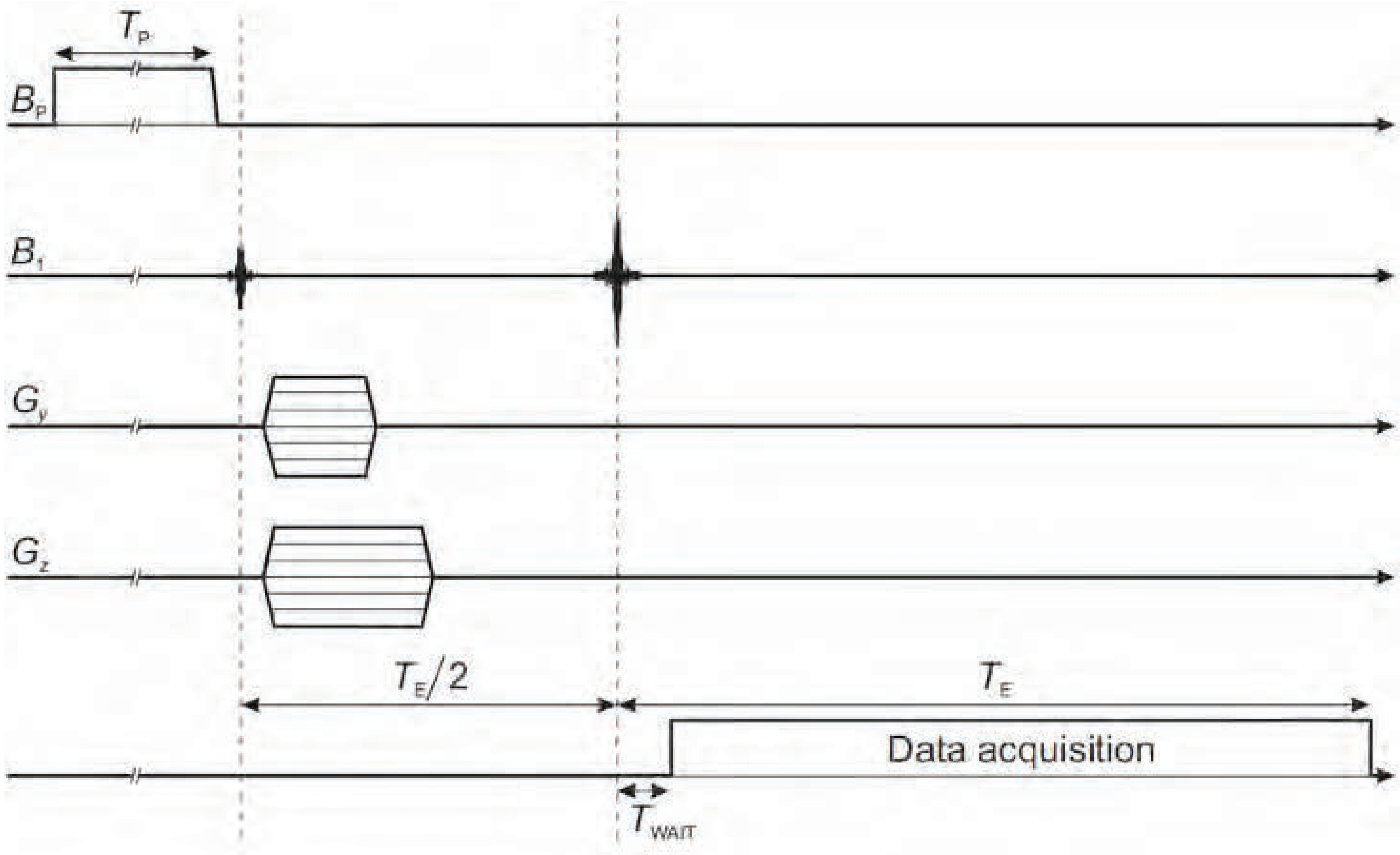
1. SQUIDs
   - Response is independent of frequency
2. Prepolarization
   - Polarization is independent of measurement field



- 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

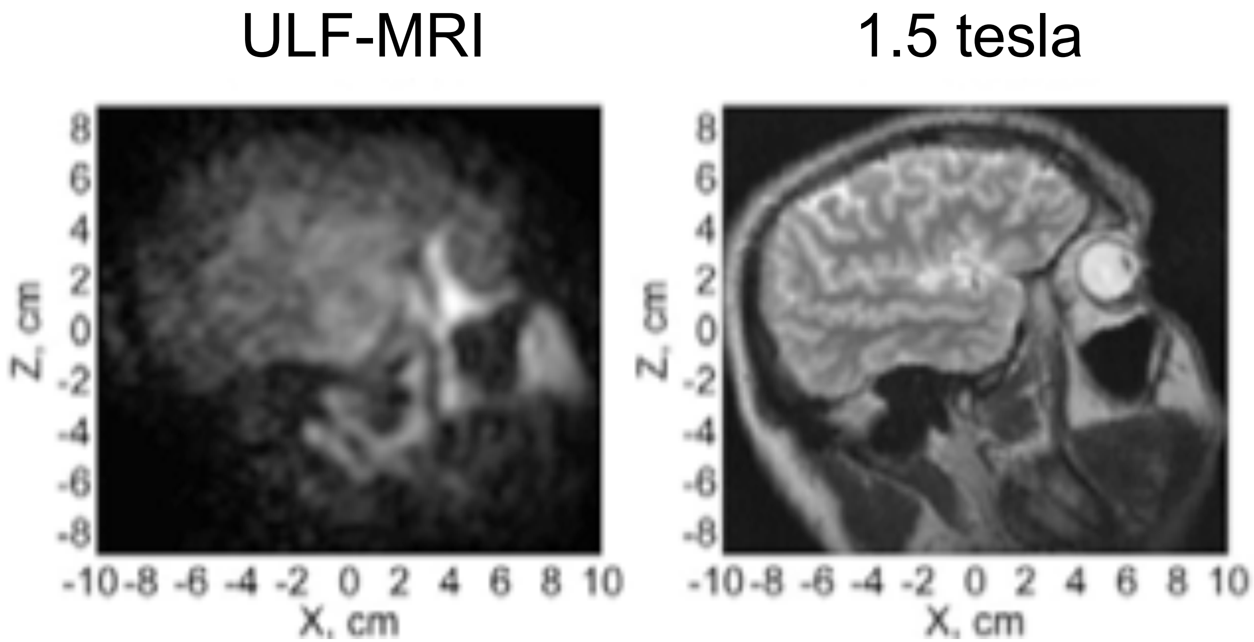
Courtesy of John Clarke

Ultra-low-field MRI sequence



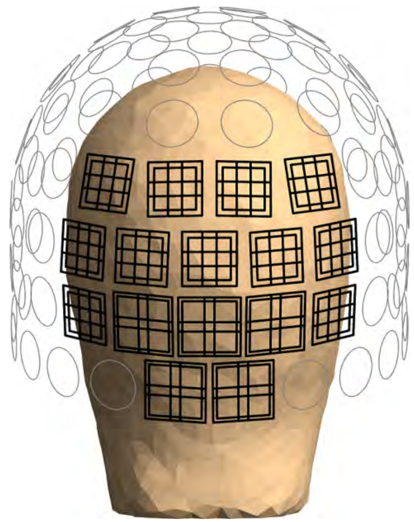
First ULF-MRI Images of the Brain

- 7 SQUIDs in parallel
- Bp = 30 mT
- B0 = 46 μT
- 90−minute measurement

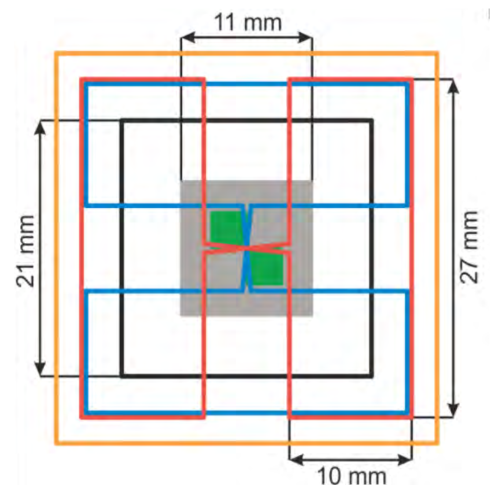


Zotev et al., IEEE/CSC & ESAS European Superconductivity News Forum, No. 4, April 2008

SQUID sensors for ULF MRI



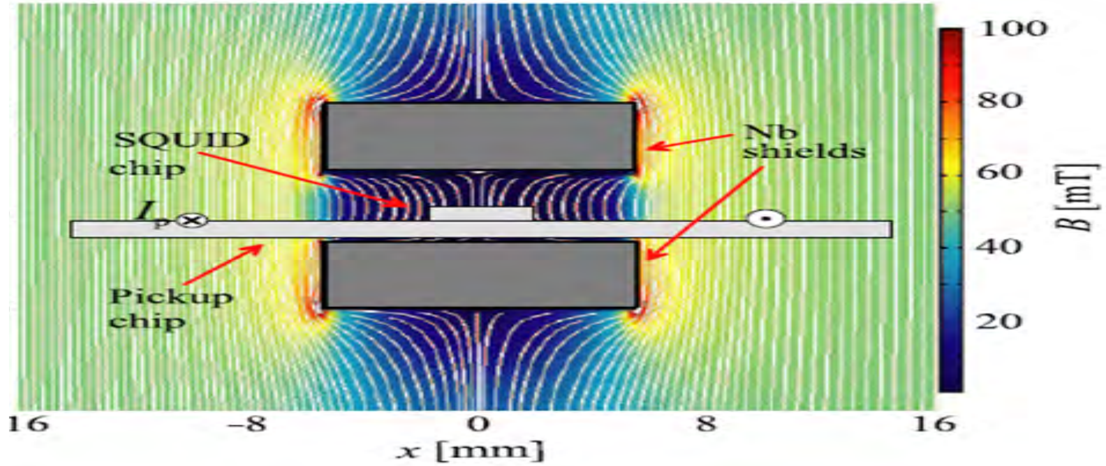
- VTT all-planar design
- MRI field pulse tolerance
  - Nb shields and flux dams
- Each module comprises
  - 1 Magnetometer, 4 fT/Hz$^{1/2}$
  - 2 Planar gradiometers, 4 fT/cm/Hz$^{1/2}$



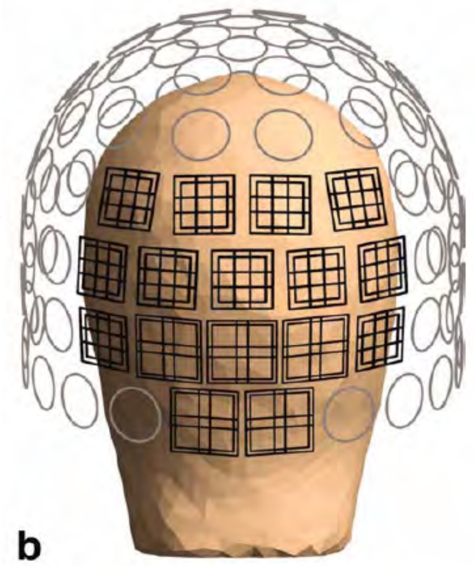
Aalto University
School of Science

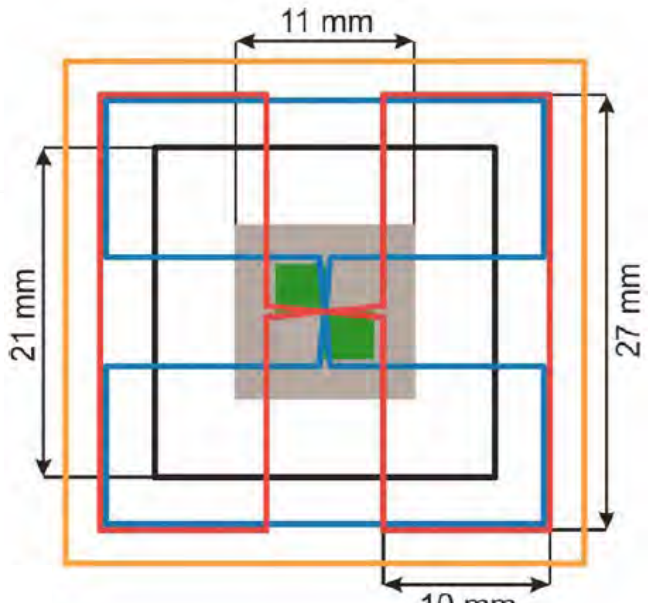
SQUID Sensors for ULF MRI

- Nb-shielded LTc SQUID with thin-film and Pb-wire pick-up loops
- Recovery time ~15 ms from 22 mT



Luomahaara et al. 2011

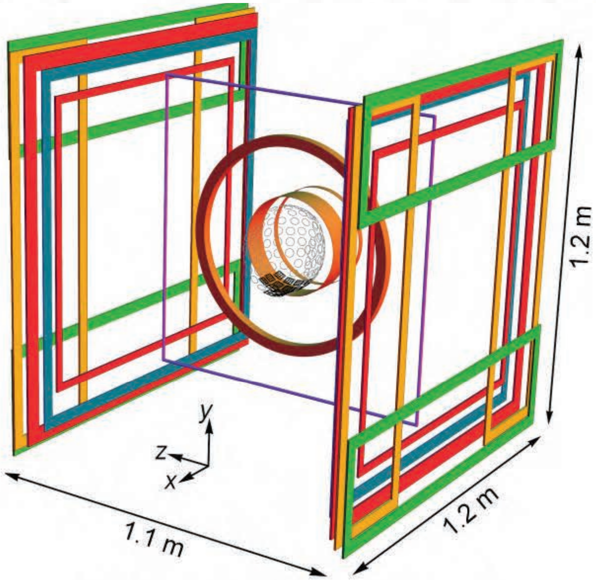




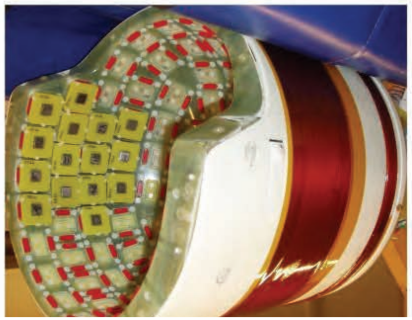
Hybrid Ultra-Low-Field MRI and Magnetoencephalography System Based on a Commercial Whole-Head Neuromagnetometer

Magn. Reson. Med. 69:1795–1804 (2013)

Panu T. Vesanen,[1*] Jaakko O. Nieminen,[1] Koos C. J. Zevenhoven,[1] Juhani Dabek,[1] Lauri T. Parkkonen,[1,2] Andrey V. Zhdanov,[1,3] Juho Luomahaara,[4,5] Juha Hassel,[4] Jari Penttilä,[5] Juha Simola,[2] Antti I. Ahonen,[2] Jyrki P. Mäkelä,[3] and Risto J. Ilmoniemi[1]



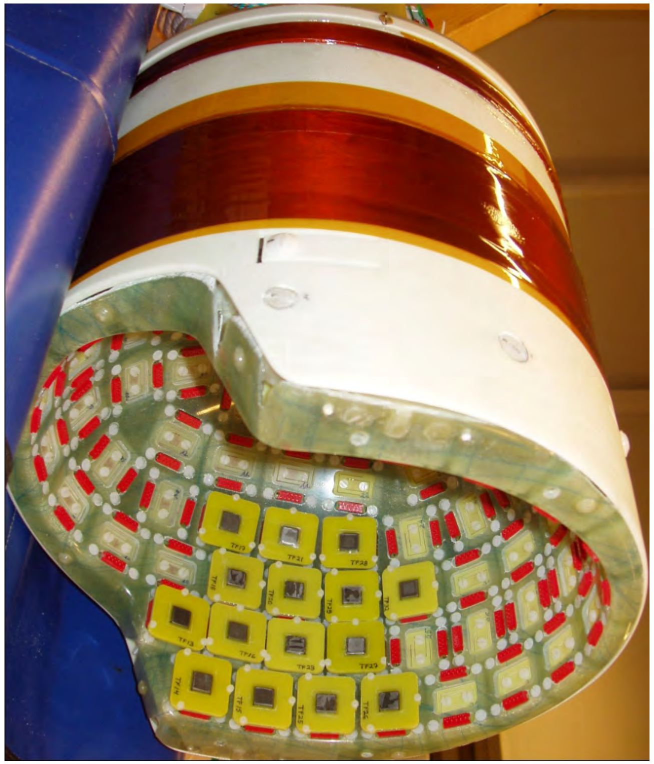
C

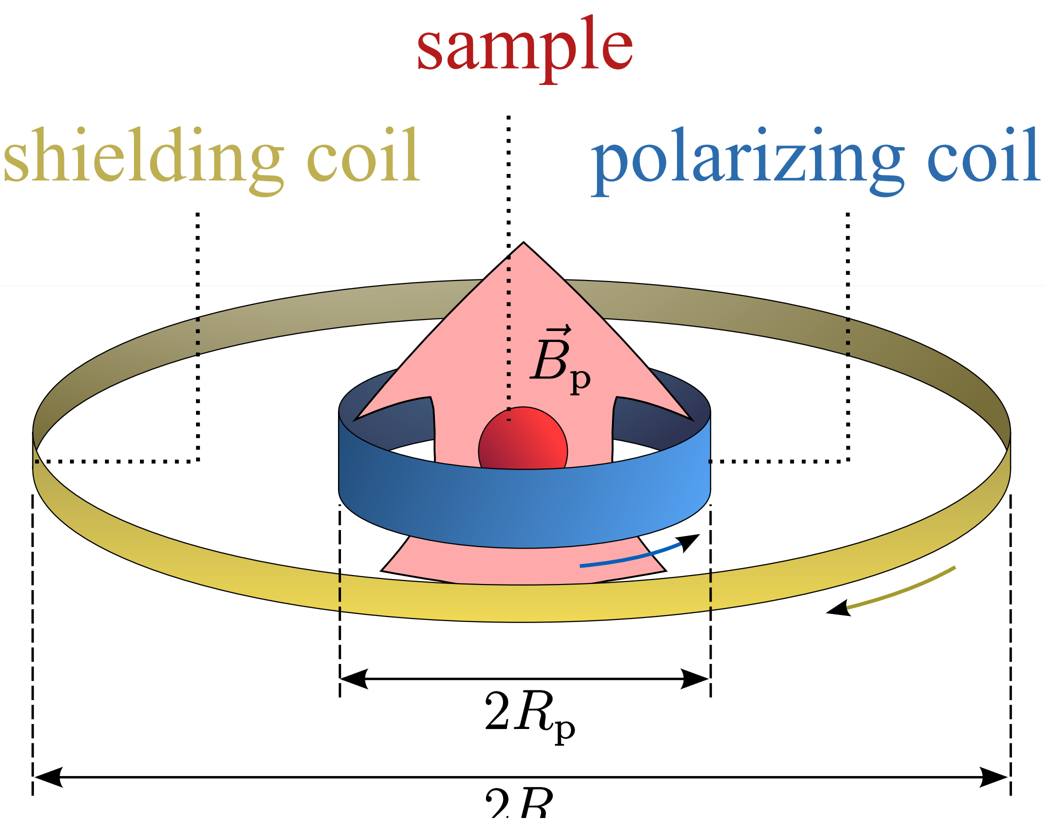


MEG–MRI System at Aalto University

Compensated Polarizing Coil

- Lowest magnetic multipole moments = 0
- Reduces magnetization and eddy currents at room walls

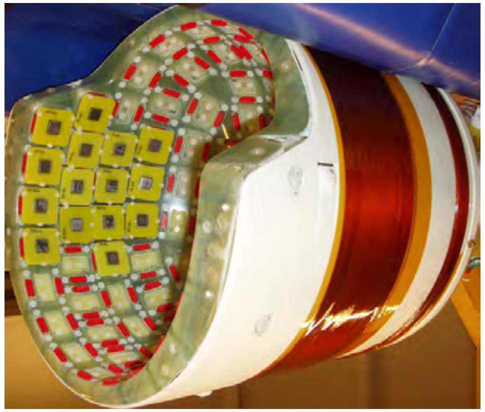




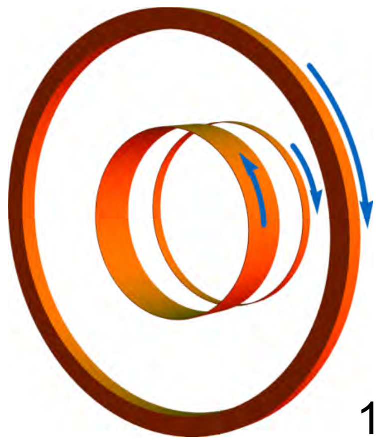
IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), February 2018.
This invited presentation ED6-1-INV was given at ISS 2017, December 13-15, 2017, Tokyo, Japan.

Superconducting polarizing coil

- LTS coil around dewar insert, diameter 30 cm
- About 24000 Nb filaments (~1 μm) in bronze matrix (Supercon Inc.)
  - Wire thickness 0.44 mm
- HTS REBCO leads (SuperPower Inc.) + brass strips for current feed
  - Only ~10% increase in He boil-off during 20-A current

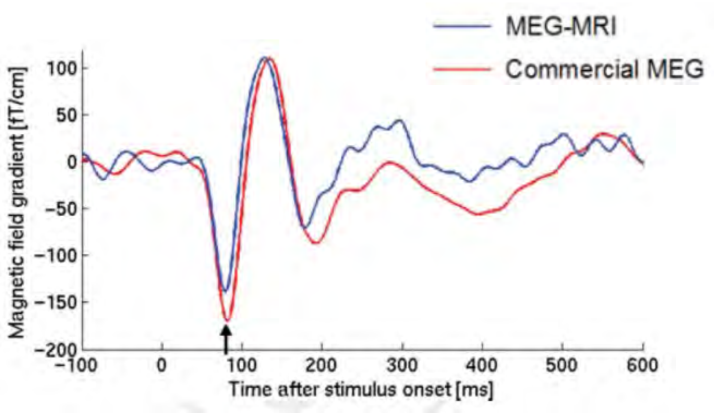


- 552-turn polarizing coil
- Eddy-current reduction:
  - 135-turn shielding coil (LTS)
  - 93-turn shielding coil (3-mm Cu)
  - Cancels dipole and quadrupole fields

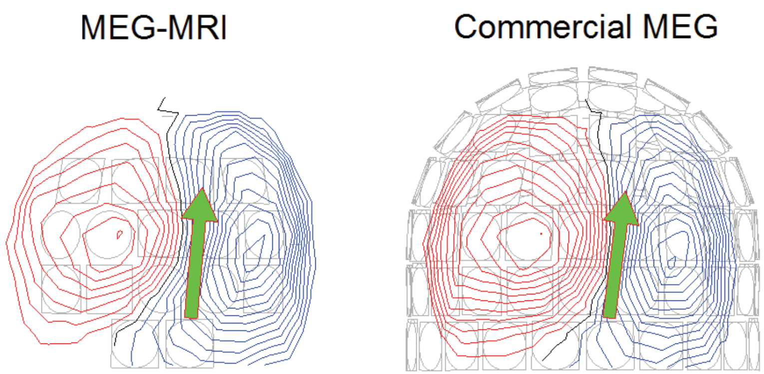


150 mH

Results: MEG



- Checkerboard stimulus in lower left visual quadrant
- Interstimulus interval 1 s
- Average of 100 responses



- Field pattern and dipole fit
  - Spherical conductor model
  - 80 ms after the stimulus onset

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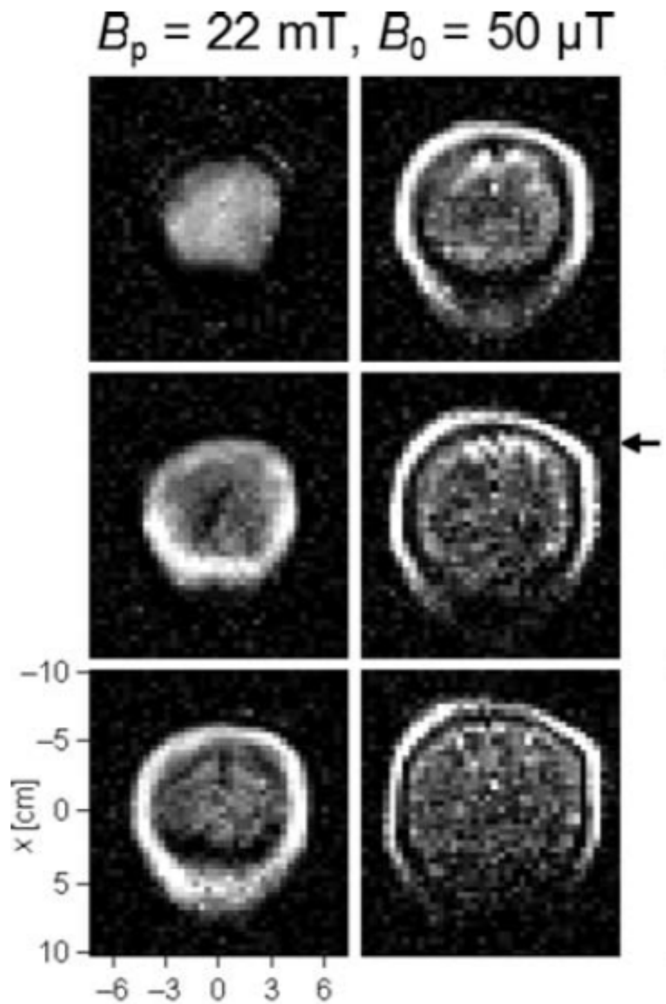
ULF MRI of brain



Coronal slices of brain, 4 × 6 × 4 mm^3 voxels; 92 min

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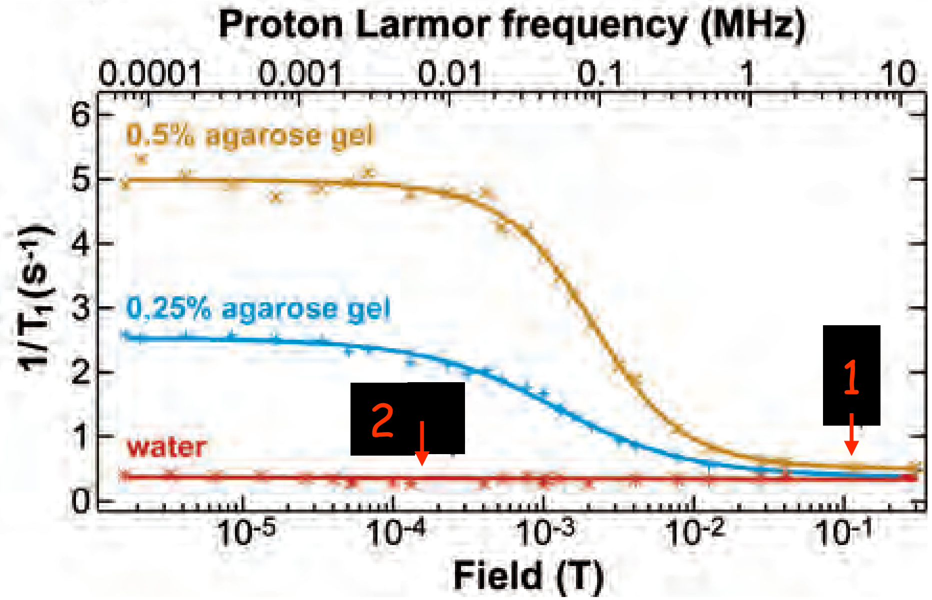
Benefits of ULF-MRI

- Simultaneous MEG and MRI
  - Superb registration accuracy
  - Possibility for current/conductivity imaging
- Superior T1 contrast
- Safety
  - No projectile danger, safe with pacemakers
- Quiet and open
  - Better for infants, children, and the obese

Improved T_1 contrast

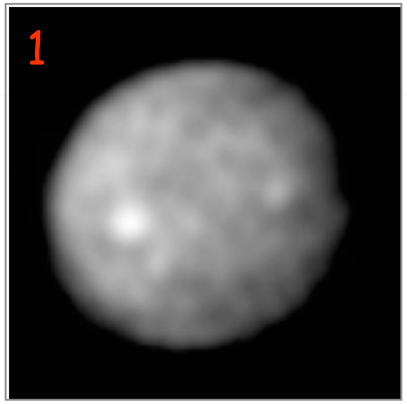


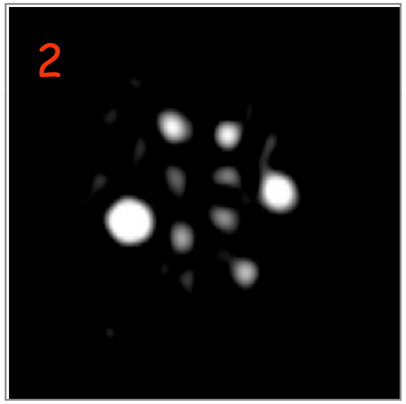
Lee *et al.* 2005

Phantom

(water columns in agarose gel,1 – 6 mm dia.)

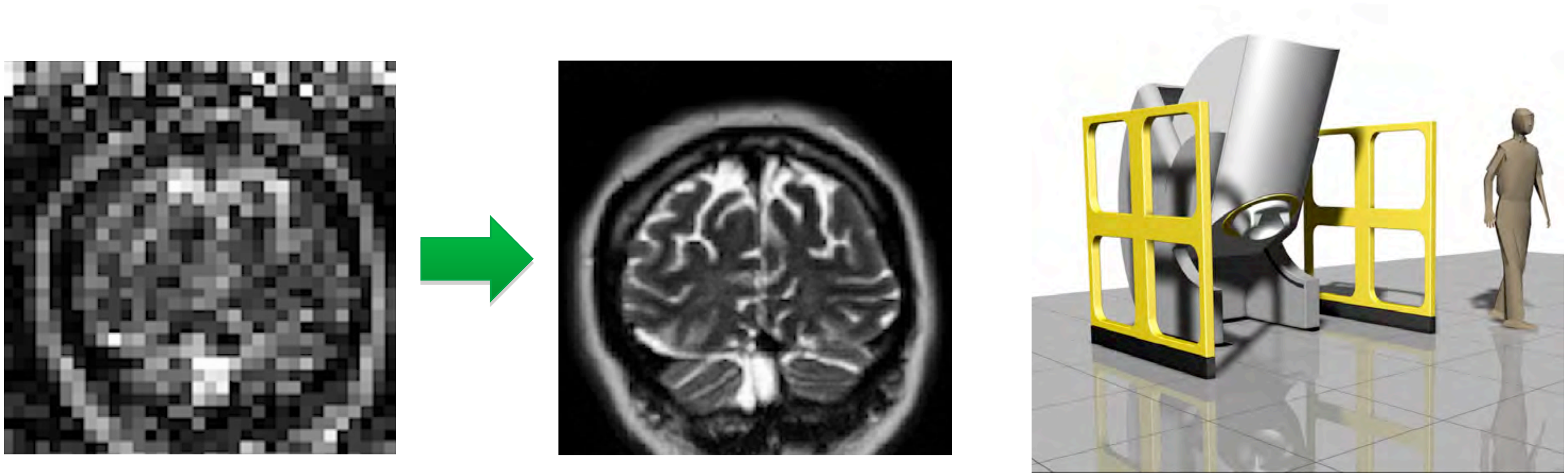
T_1 contrast at 100 mT





New MEG–MRI project: BREAKBEN

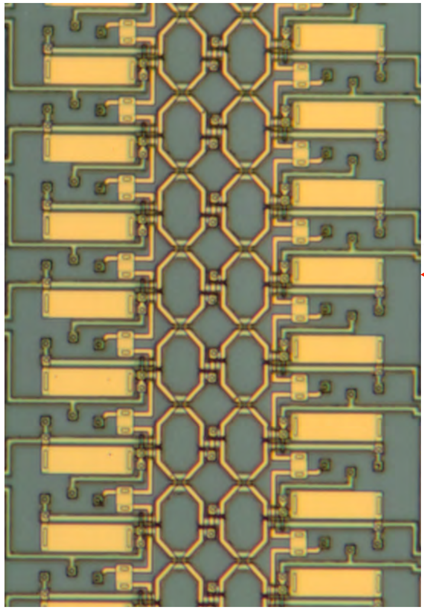
- Sensor noise down by a factor of 10 (4 to 0.4 fT)
- Prepolarization field up by a factor of 5 (22 to 110 mT)
- Intelligent measurement sequences

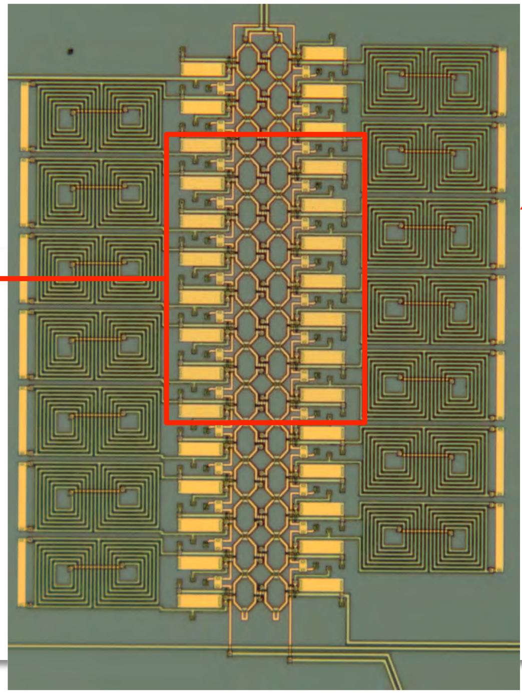


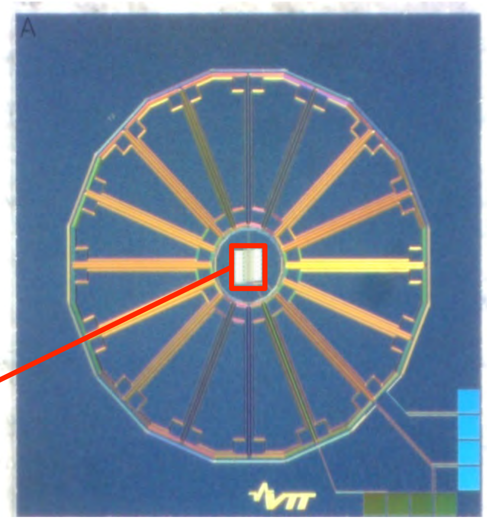
FET Open: This project has received funding from the European Union' s Horizon 2020 research and innovation programme under grant agreement No. 686865.

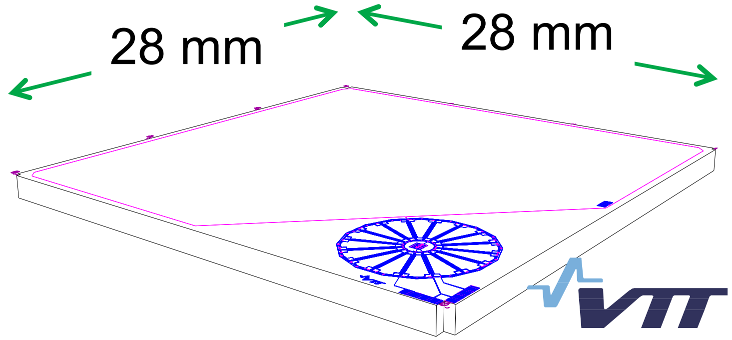
SQUID designs for the test fab round

- An array of 15 gradiometric SQUIDs with a realized junction size of 0.6 x 0.6 μm^2 coupled to a multiloop flux transformer
- Integrated magnetometers
  - Bugs in design, measurements perforn without the pickup coil





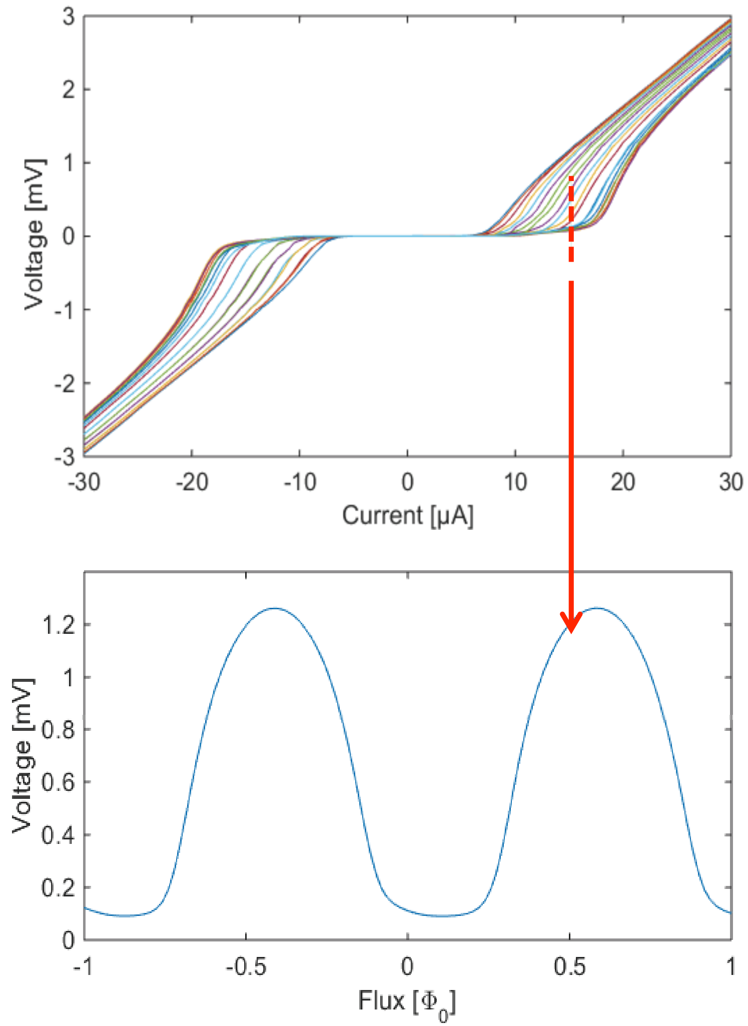




Courtesy Mikko Kiviranta and Juho Luomahaaram, VTT Technical Research Center Finland

SQUID characterization

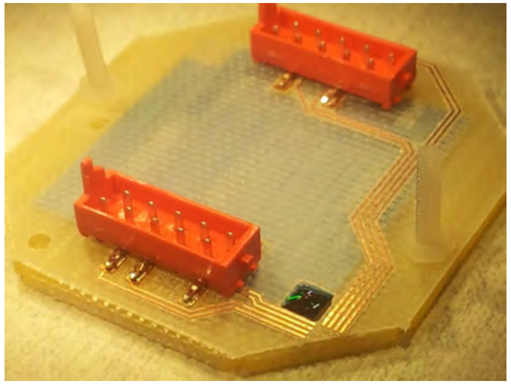
- SQUID operation with smooth characteristics verified
- Measured device parameters
  - Junction critical current 8 µA
  - Dynamic resistance 130 Ω
  - Input inductance ~ 420 nH
  - Mutual inductance Φ_0/7.8 µA (feedback)
  - Mutual inductance Φ_0/5.6 µA (input)

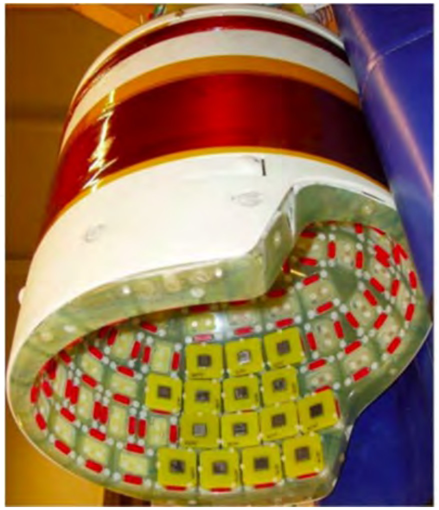


Courtesy Mikko Kiviranta and Juho Luomahaaram, VTT Technical Research Center Finland

BREAKBEN project, SQUIDs

- Spontaneous recovery works up to 7 mT (so far)
- Heat pulsing **does** work up to 150 mT
  - 3 mJ per pulse ⇒ 0.2 l/h boiling rate for 100 channels.
- Field-to-flux coupling needs to be improved
  - White flux noise to be improved, will need < 0.15 $\mu\Phi_0/\mathrm{Hz}^{1/2}$.
  - Readout electronics: challenging problem
- 1/f flux noise: needs bias reversal





Mikko Kiviranta,
BREAKBEN progress
meeting, Erfurt 3.12.2017

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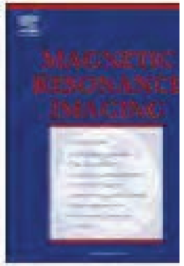
journal homepage: www.mrijournal.com

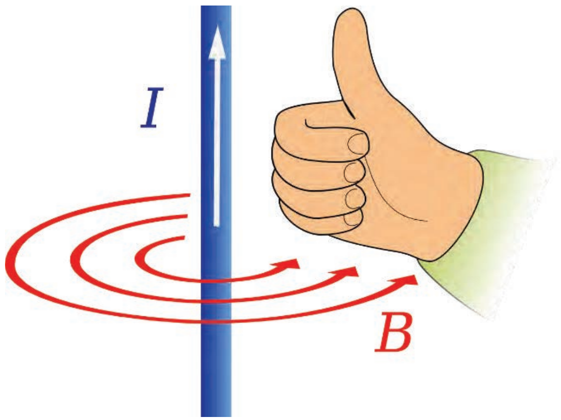


Current-density imaging using ultra-low-field MRI with adiabatic pulses

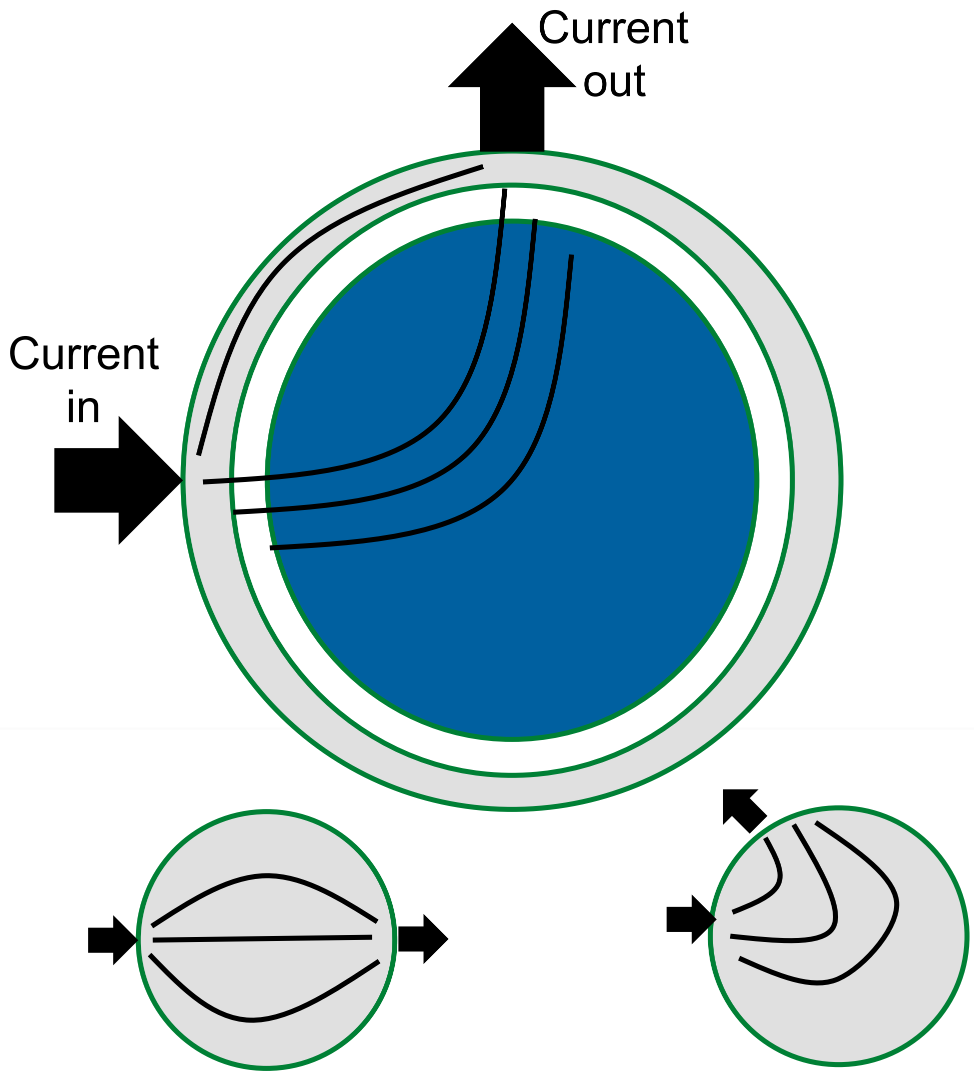
Jaakko O. Nieminen [a,*], Koos C.J. Zevenhoven [a], Panu T. Vesanen [a], Yi-Cheng Hsu [a,b], Risto J. Ilmoniemi

Current-density imaging using ultra-low-field MRI with zero-field encoding

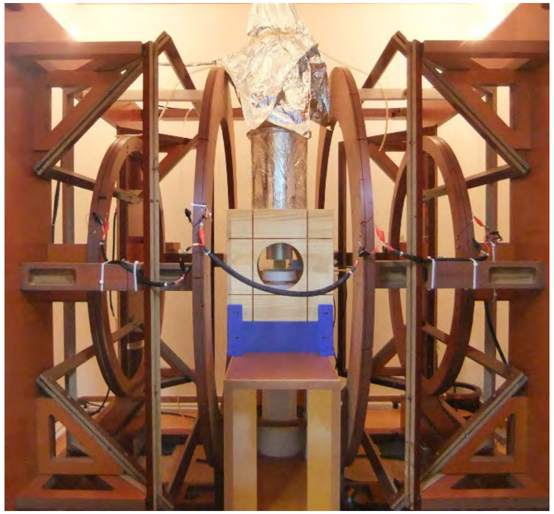
Current-density imaging

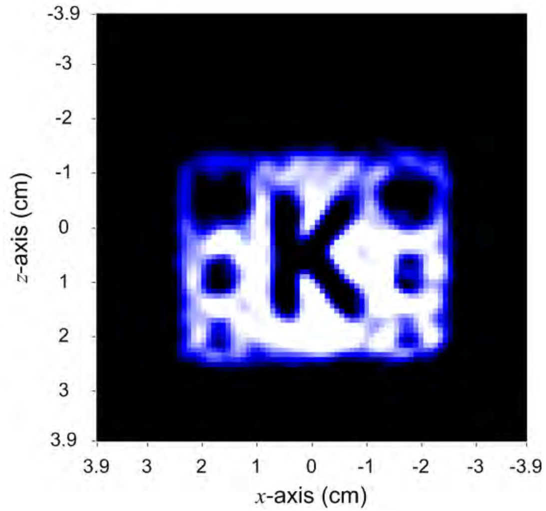


- In high-field MRI, only one component of B can be measured
- At low fields, all components can be determined



Microtesla SQUID NMR/MRI system technology





KRISS ULF NMR/MRI technology development

Biomagnetic Resonance (Brainwave Magnetic Resonance, Heart Magnetic Resonance, MREIT etc)

Low magnetic field measurement standard

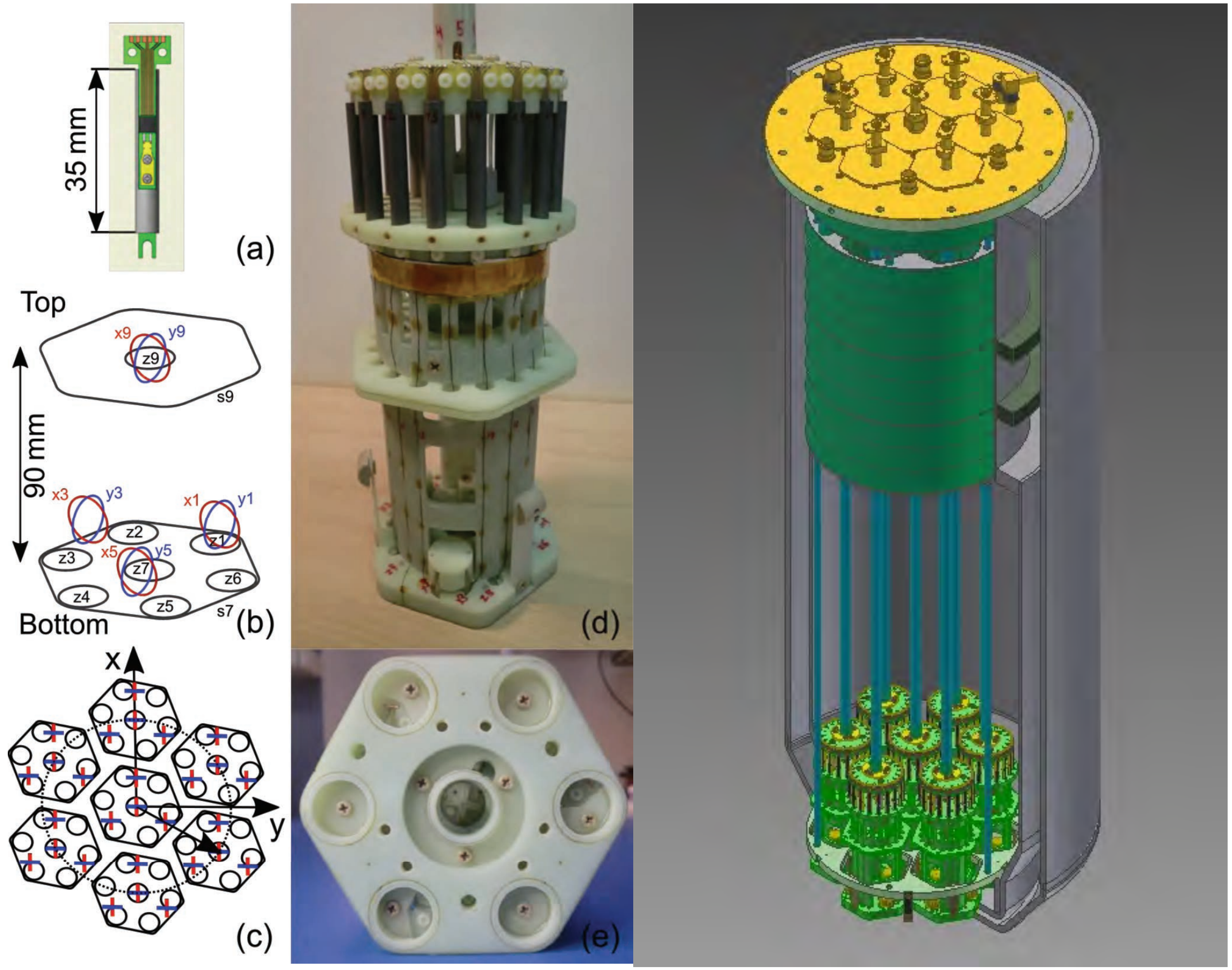
Dynamic Nuclear Polarization applications

ULF NMR chemical analysis (2D-COSY, circular field excitation)

Courtesy of Kiwoong Kim and Yong-Ho Lee, KRISS, Daejong, Republic of Korea

PTB Module and system design – Overview

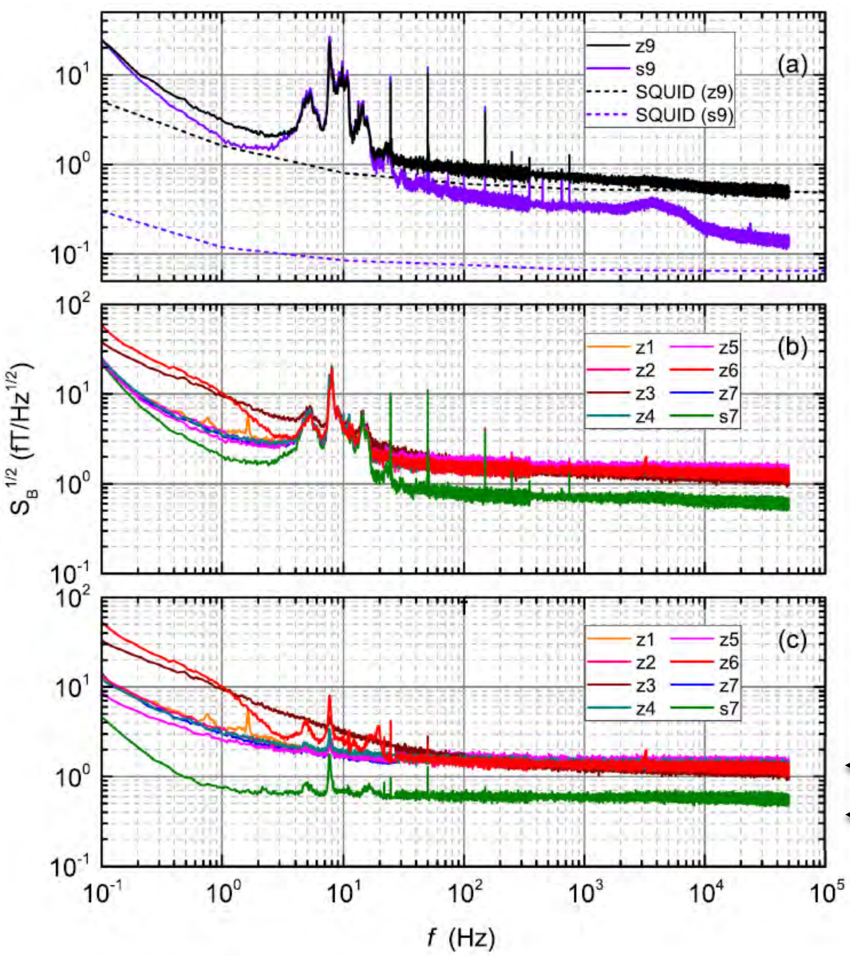
- SQUID capsule:
  niobium shield d=5 mm
  detachable contact for
  the flux antenna
- Top plane:
  1 x-y-z triplet d=17.1 mm
  1 hexagon d=74.5 mm
  software gradiometers
- Bottom plane:
  7 z-loop d=17.1 mm
  1 hexagon
  3 x-y duplet d=17.1 mm
- System:
  z-loop's hexagonal grid
  x-y duplet hexagonal
  grid rotated by 10.89°



Courtesy of Rainer Körber, PTB Berlin

PTB Noise performance of the prototype

Upper z-loops (magnetometers)



Dotted lines: intrinsic SQUID noise

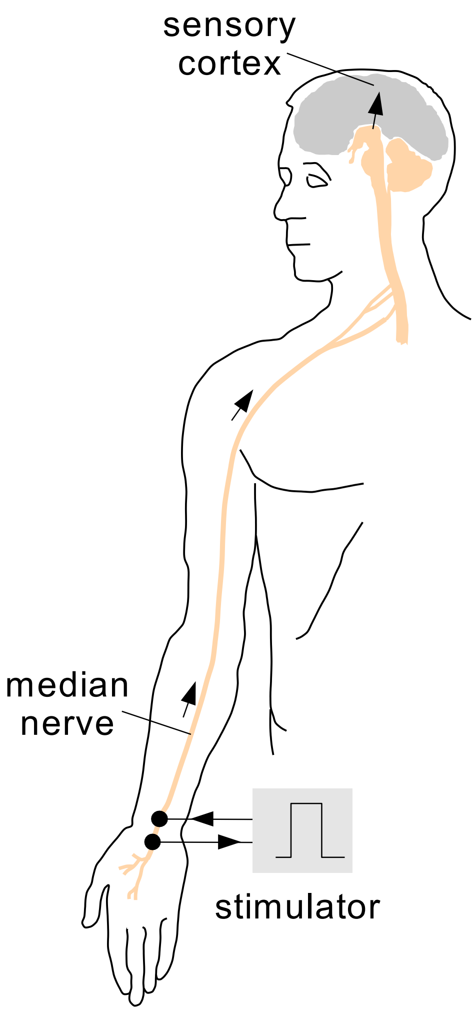
∅17.1mm loop: 0.52 fT/√Hz
→ intrinsic SQUID noise
∅74.5mm loop: 0.16 fT/√Hz
→ dominated by ambient noise

Lower z-loops (magnetometers)

Lower z-loops (gradiometers)

∅17.1mm loops: 1.28 fT/√Hz
∅74.5mm loop: 0.56 fT/√Hz
→ dominated by Dewar noise

Magnetoencephalography



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Magnetoencephalography

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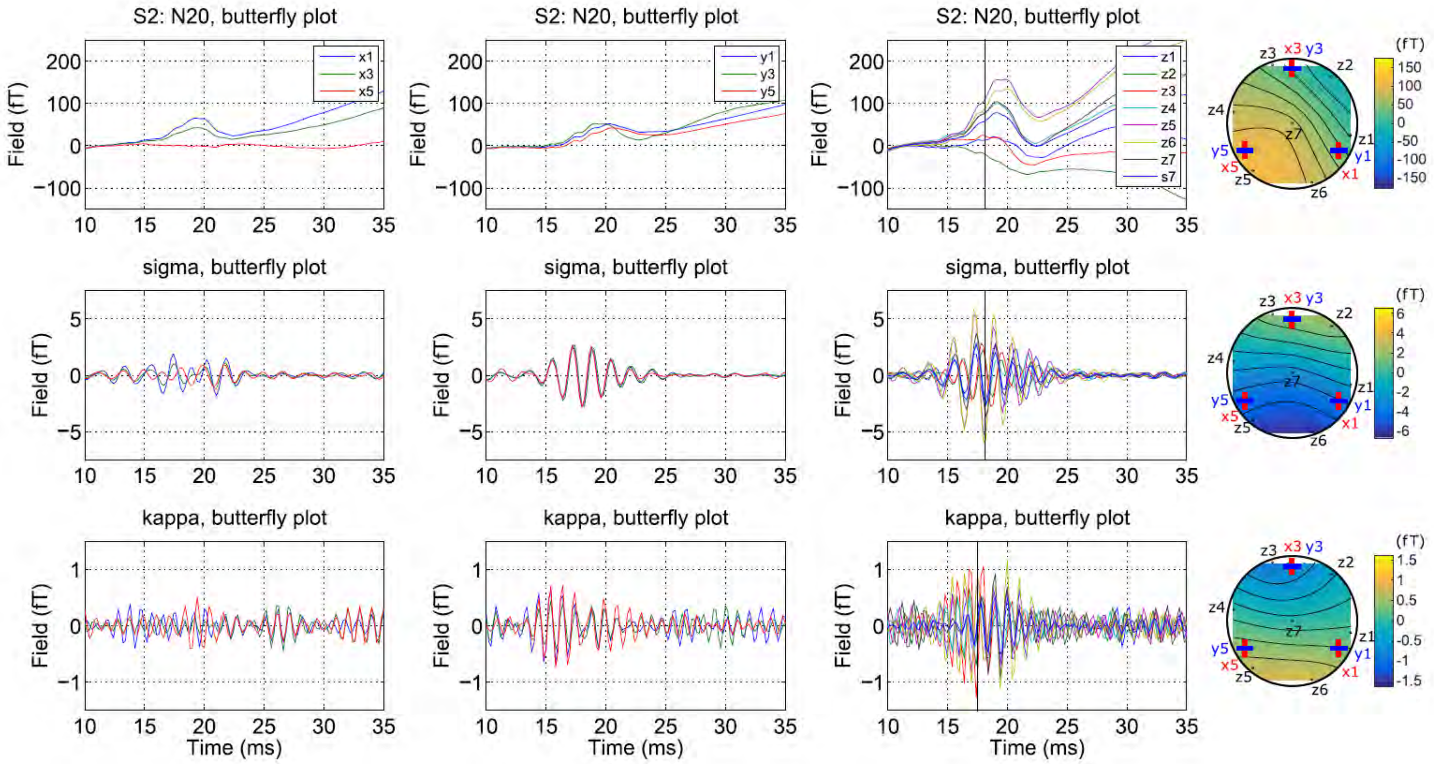
Full bandwidth

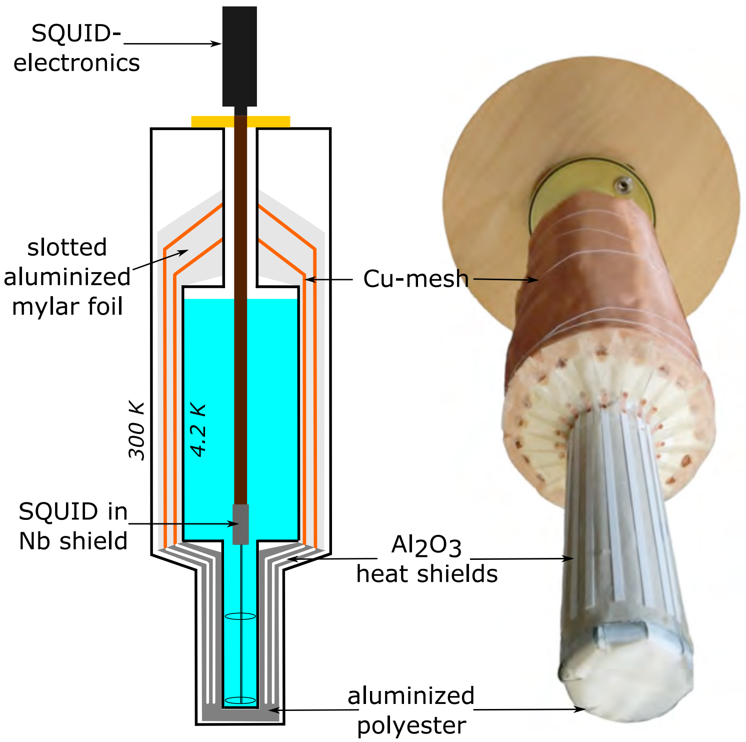
450 – 750 Hz

850 – 1200 Hz

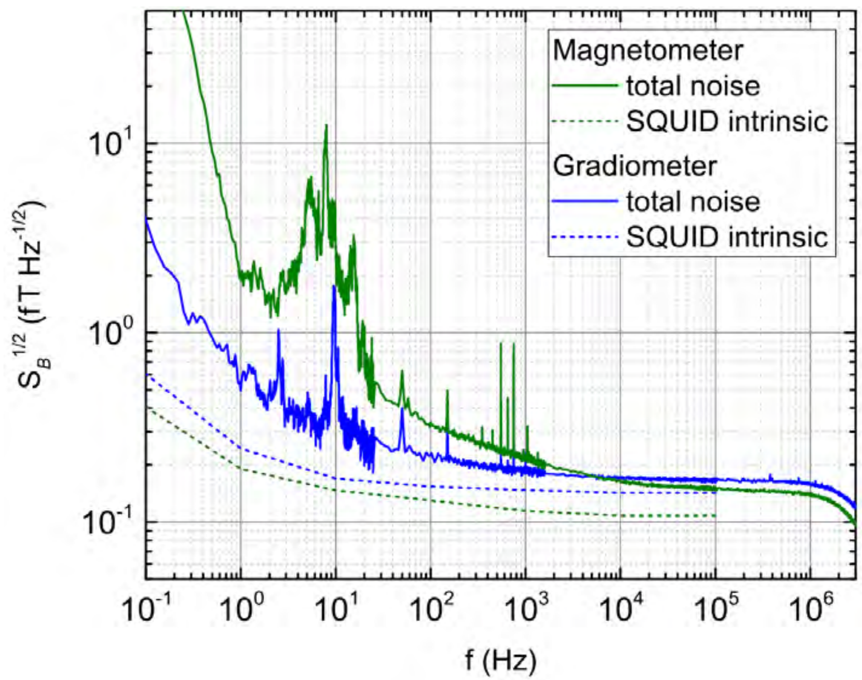


Low noise performance enables detection of kHz activity by MEG

Achieving Ultra-Low-Noise Performance



Ultra-low noise dewar LINOD2 by using Al_2O_3 heat shield + aluminized polyester as super-insulation (Seton *et al.* Cryogenics **45**, 34)
with current sensor SQUID inductively coupled to Nb superconducting pick-up coil.



45 mm magnetometer pick-up loop
White noise ~150 aT Hz$^{-1/2}$
Below 20 kHz limited by noise from µ-metal walls of BMSR-2
45 mm 1st order gradiometer pick-up
White noise ~170 aT Hz$^{-1/2}$

Storm et al. (2017) APL 110, 072603

PTB ULF MRI scanner

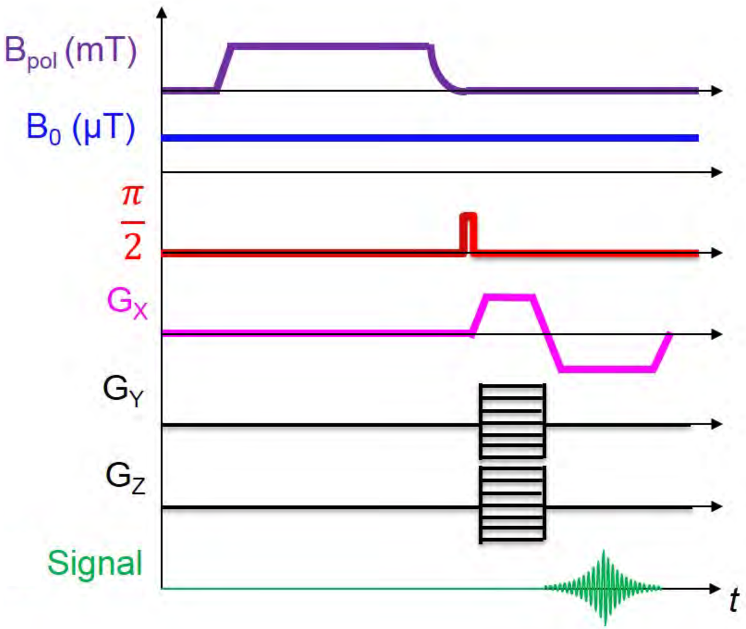
3-Axis coil system:

- Self-shielded polarization coil (Bx)
- Helmholz coils (Bx,By)
- Maxwell gradient coil (dBx/dx)
- Phase gradients (dBx/dy, dBx/dz)

Sensor:

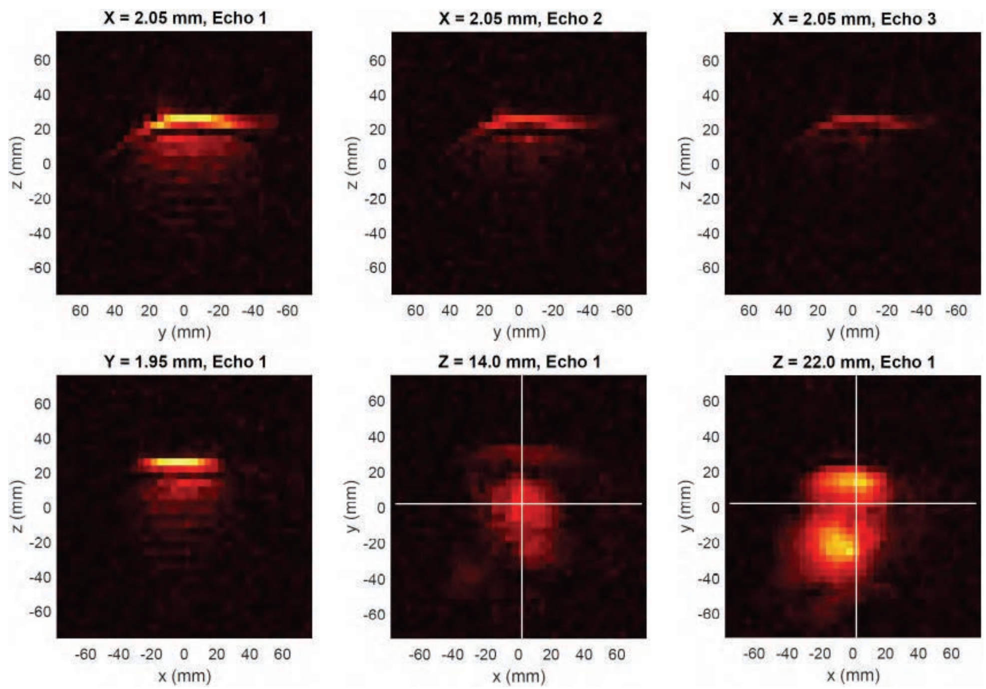
- 1-channel 2nd order gradiometer in ultra-low noise dewar LINOD2
- Noise ~380 aT $Hz^{-1/2}$

Imaging of human head



- Bpol = 17 mT
- Phase Time = 30 ms
- FOV: 150 mm (y,z)
- Pixelsize: (4.1 x 4 x 4) mm^3
- Measurement Time: 30 min

3D image of human head showing scalp and brain



Remaining Challenges

- How to get to the tissue thermal limit? –Or even beyond?
- How to obtain superconducting non-magnetizable wire?
- Very accurate conductivity mapping
- Utilization of a priori information
- Intelligent sequences ("theory of measurement")

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Thank you for your attention!

Thanks to colleagues and co-workers:

Koos Zevenhoven, Antti Ahonen, Sarianna Alanko, Juhani Dabek, Juha Hassel,Marko Havu, Tuomas Hirvonen, Iiro Lehto, Fa Hsuan-Lin, **Mikko Kiviranta**, Juho Luomahaara, Antti Mäkinen, Jaakko Nieminen, Jyrki Mäkelä, Juha Montonen, Jari Penttilä, Lauri Parkkonen, Mika Pollari, Jukka Sarvas, Juha Simola, Matti Stenroos, Aino Tervo, Panu Vesanen, Andrey Zhdanov, and the MEGMRI and BREAKBEN consortiums.

FET Open: This project has received funding from the European Union' s Horizon 2020 research and innovation programme under grant agreement No. 686865.

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