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Paper based on this presentation: J.-H. Storm et al., *Supercond. Sci. Technol.* **29,** 094001(2016).

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National Metrology Institute

Prototype Module of a Robust 18-channel Magnetometer System

J. Storm, M. Burghoff, D. Drung, R. Körber

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Introduction

Outline:

- Introduction
- The prototype module
  - Module and system design
  - The magnetometer
  - Field distortion due to Niobium shields
  - Noise performance of the prototype
- Proof experiments
  - Magnetoencephalography
  - ULF nuclear magnetic resonance
- Summary

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Introduction

- History of biomagnetism at PTB Berlin:
  - 1980 Berlin magnetically shielded room (BMSR)
  - 1991: 37-SQUID Multichannel System
  - 1994: 83-SQUID Multichannel System
  - 2000 Berlin magnetically shielded room (BMSR-2)
  - 2003: 304-SQUID Vector magnetometer system

- Main applications for the “old” 304 SQUID vectormagnetometer:
  - Magnetoencephalography
  - Material properties characterisation

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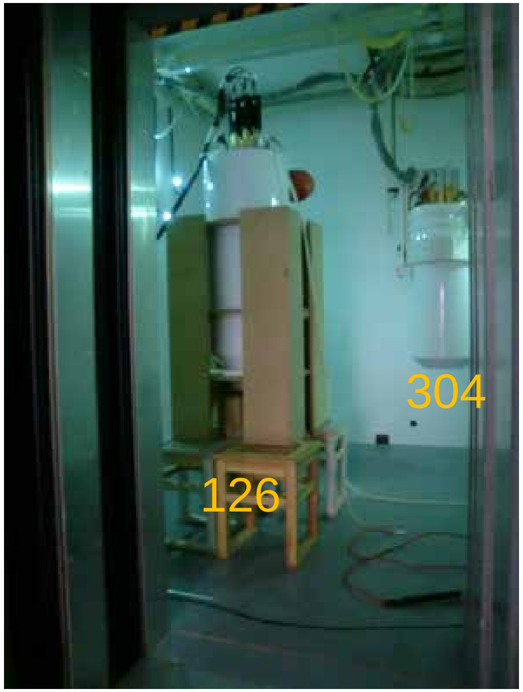
Motivation

- New applications for the “new” 126 SQUID vector magnetometer:
  - Ultra-low-field Nuclear Magnetic Resonance
  - Quantitative imaging of magnetic nanoparticles via magnetorelaxometry
  - Ultra-sensitive spin precession measurements for determination of fundamental constants of nature such as the electric dipole moments of ^{129}Xe nucleus



Key features of the new system:

- A scalable and modular system design
- Vector magnetometer with different field sensitivities
- Robust against pulsed magnetic fields up to 50 mT

The Prototype Module

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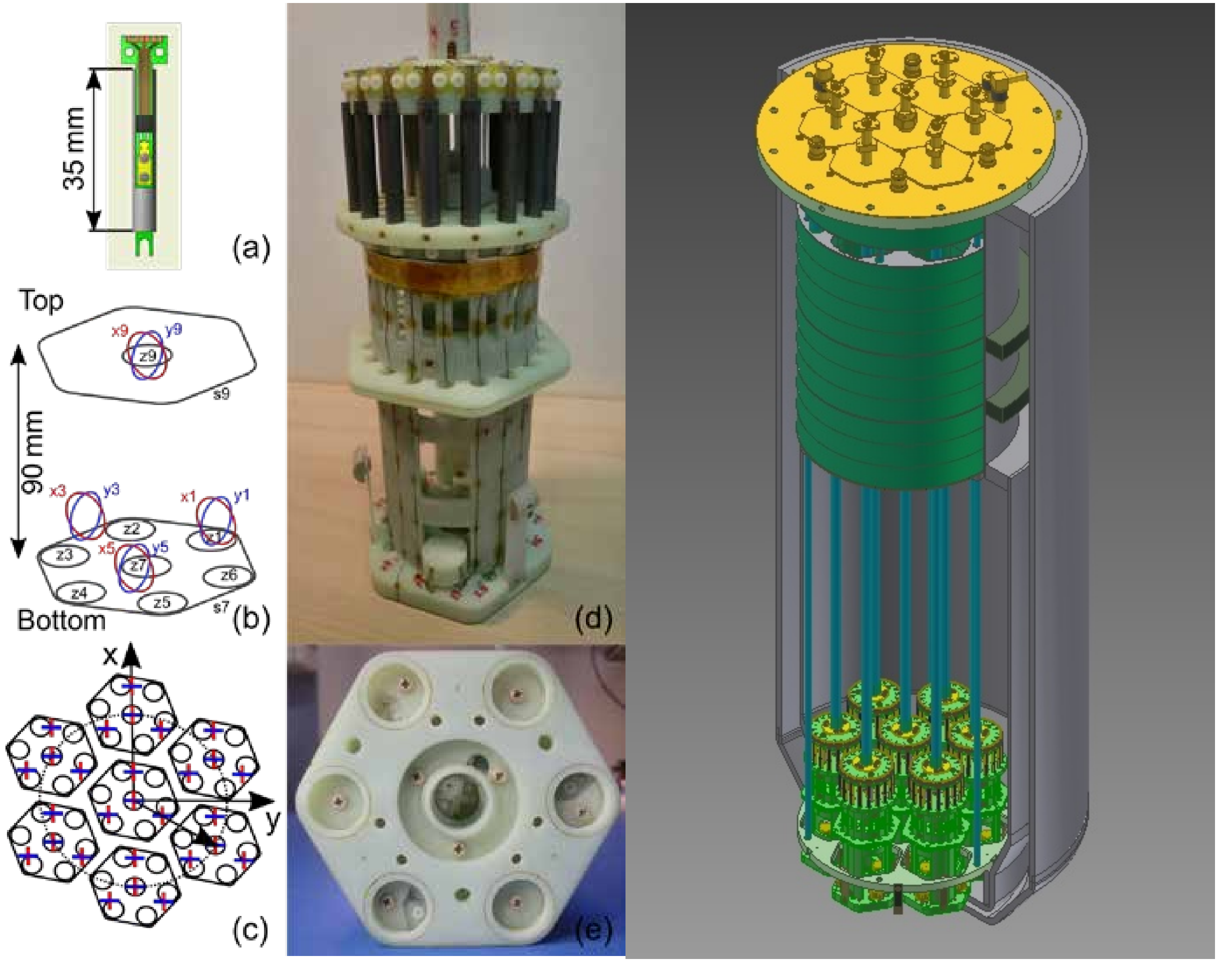
Module and System Design – Overview

§ 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

§ 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°



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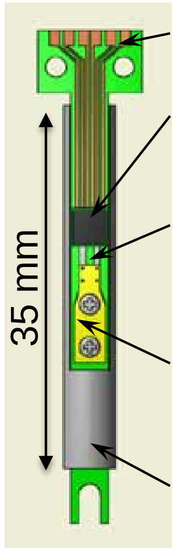
Module and System Design – Details



SQUID bias pins

SQUID chip

niobium foil for super-conducting wire bonds

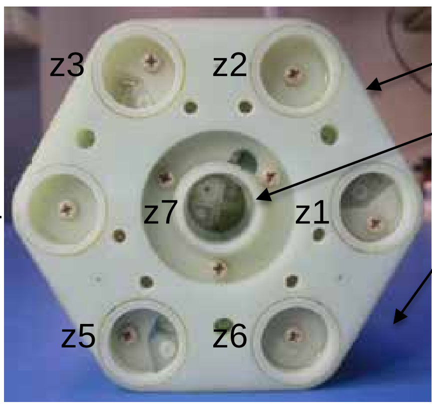
detachable contact for the pick-up coil

niobium shield d=5mm

Materials:

- Magnetometer coils: Niobium wire d=100 µm
- Support structure: fiber reinforced plastic (G10)

z4



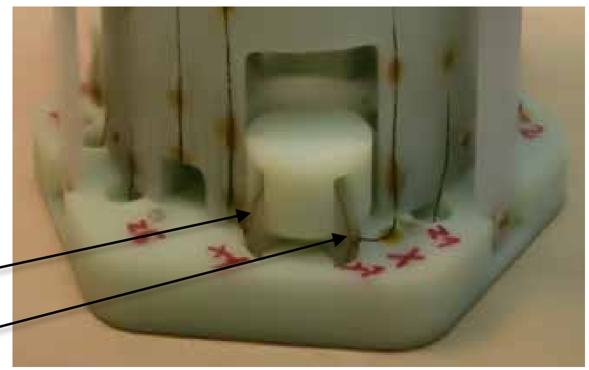
bottom small z-loops

top small x,y,z-loops

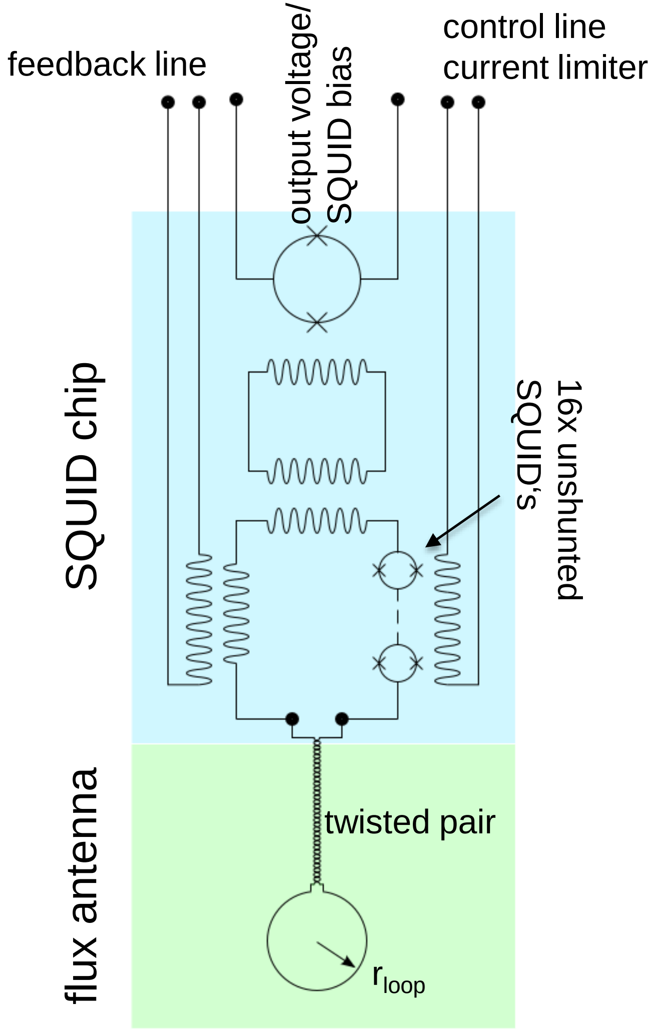
bottom large z-loop

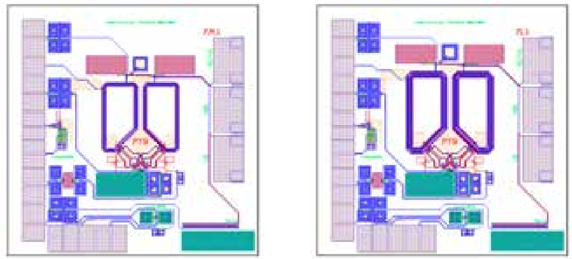
bottom small x-loop

bottom small y-loop



The Magnetometer





SQUID chip	PTB C70-M1	PTB C7-L1
Input inductance	150 nH	400 nH
Input coupling	2.5 nH	4.1 nH
Current limiter	I_{off}=20 µA, I_{on}=1 µA	
Flux antenna	**$r=8.5\times10^{-3}$ m**	**$r_{aq}=37.3\times10^{-3}$ m**
Loop area	2.3×10^{-4} m²	4.4×10^{-3} m²
loop inductance	58.4 nH	325.5 nH
tp inductance	»20-50 nH	
Field sensitivity	822-930 pT/F_0	86-90 pT/F_0

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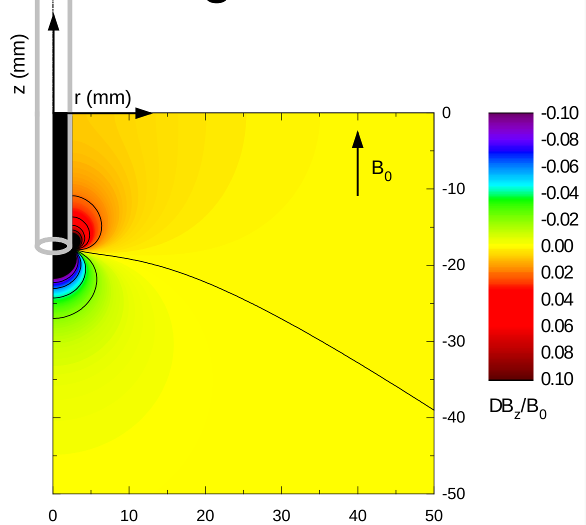
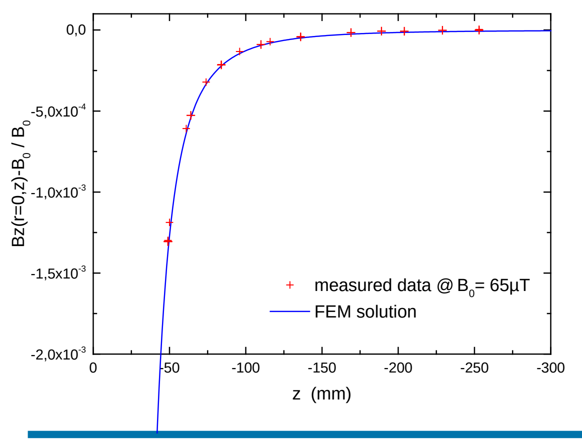
Field Distortion Due to Niobium Shields

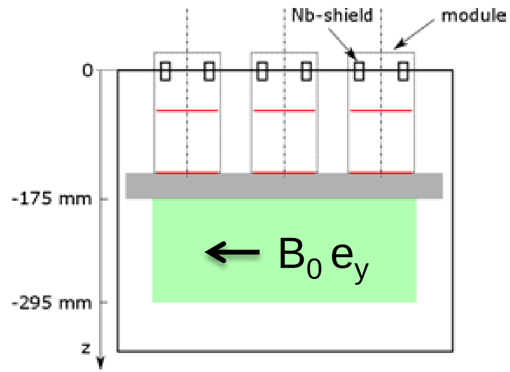
single shield



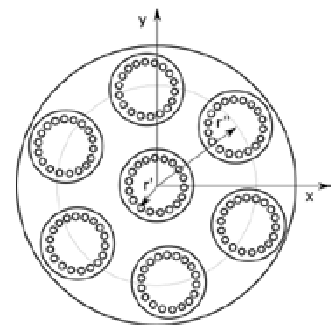


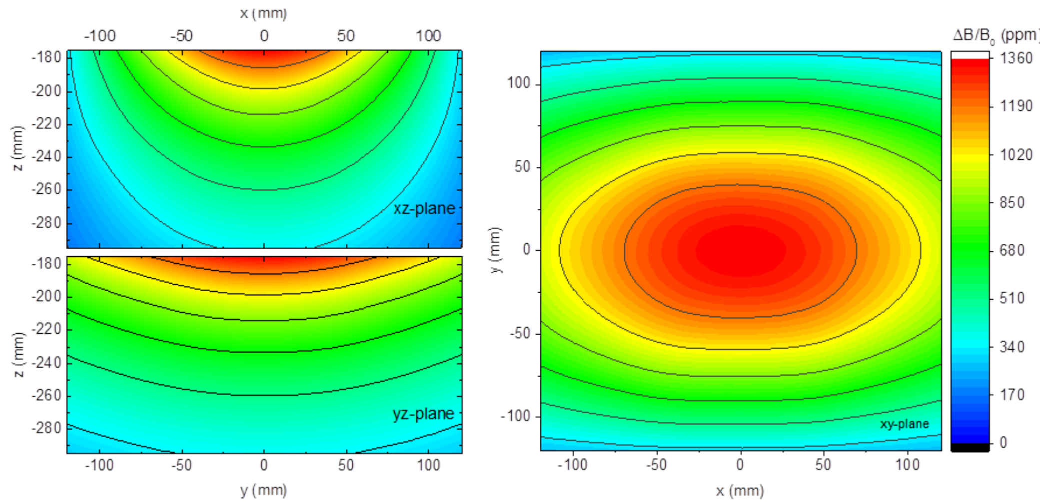
multichannel arrangement

yz-plane

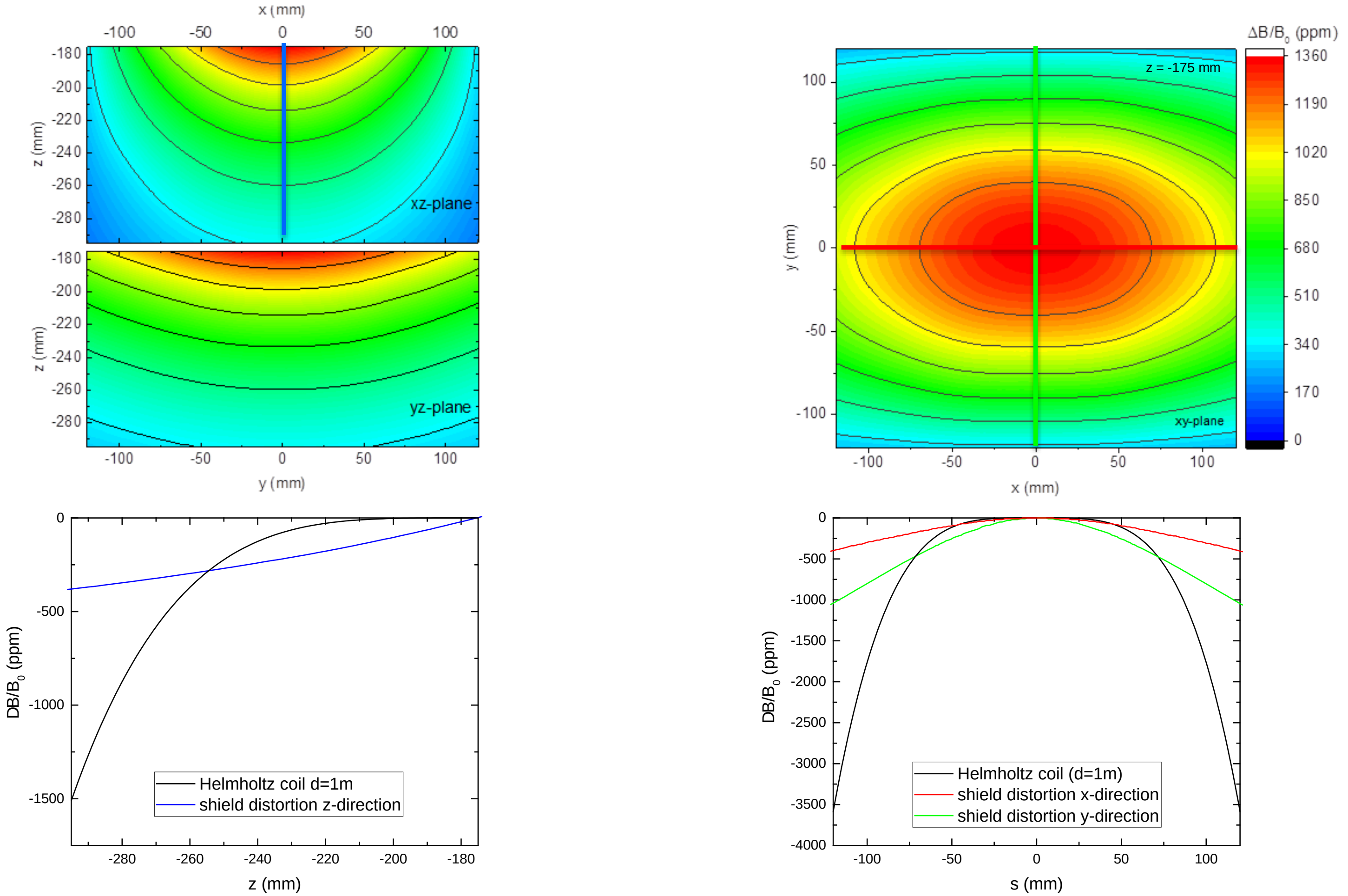


xy-plane



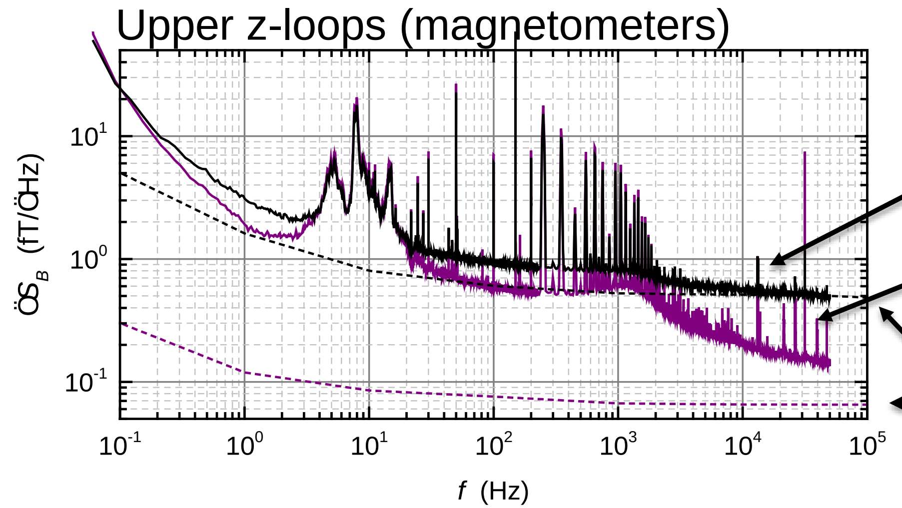


Field Distortion Due to Niobium Shields



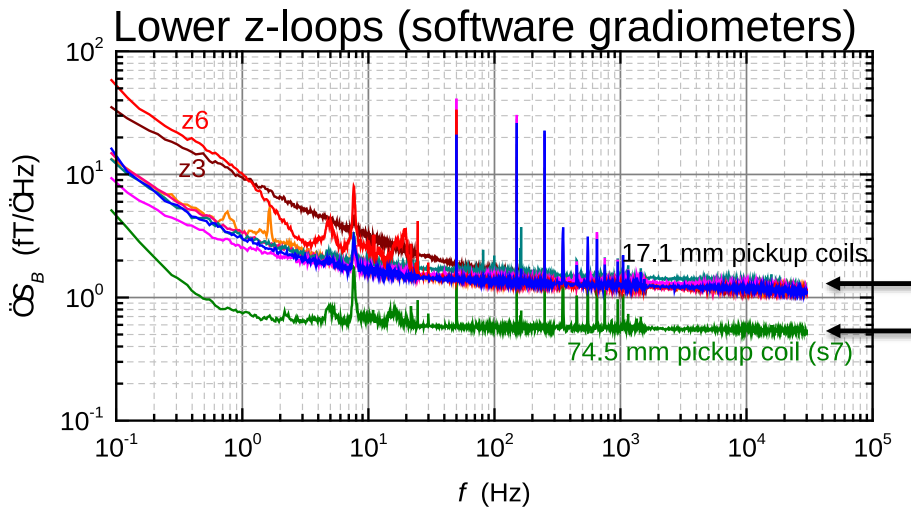
→ The distortion of one module is one order of magnitude smaller

Noise Performance of the Prototype



Æ17.1mm loop: 0.52 fT/√Hz
→ intrinsic SQUID noise
Æ74.5mm loop: 0.16 fT/√Hz
→ dominated by ambient noise

Dotted lines: intrinsic SQUID noise



Æ17.1mm loops: 1.28 fT/√Hz
Æ74.5mm loop: 0.56 fT/√Hz
→ dominated by Dewar noise

Proof Experiments

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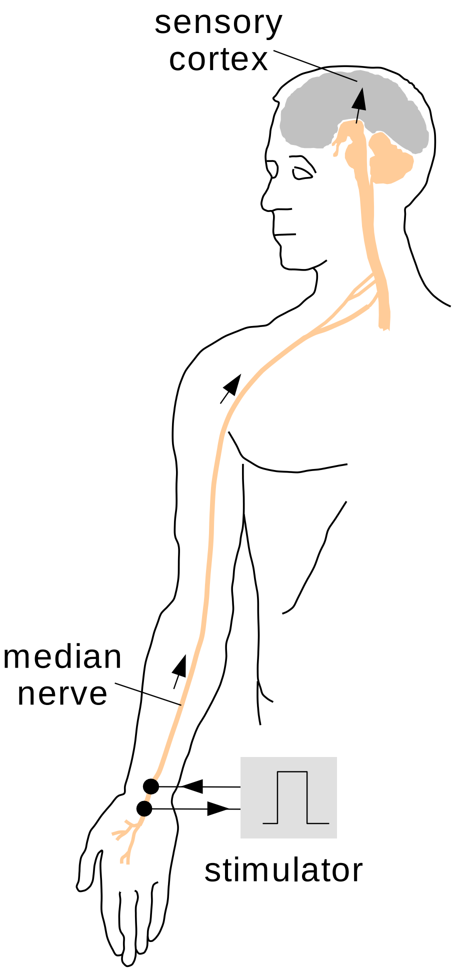
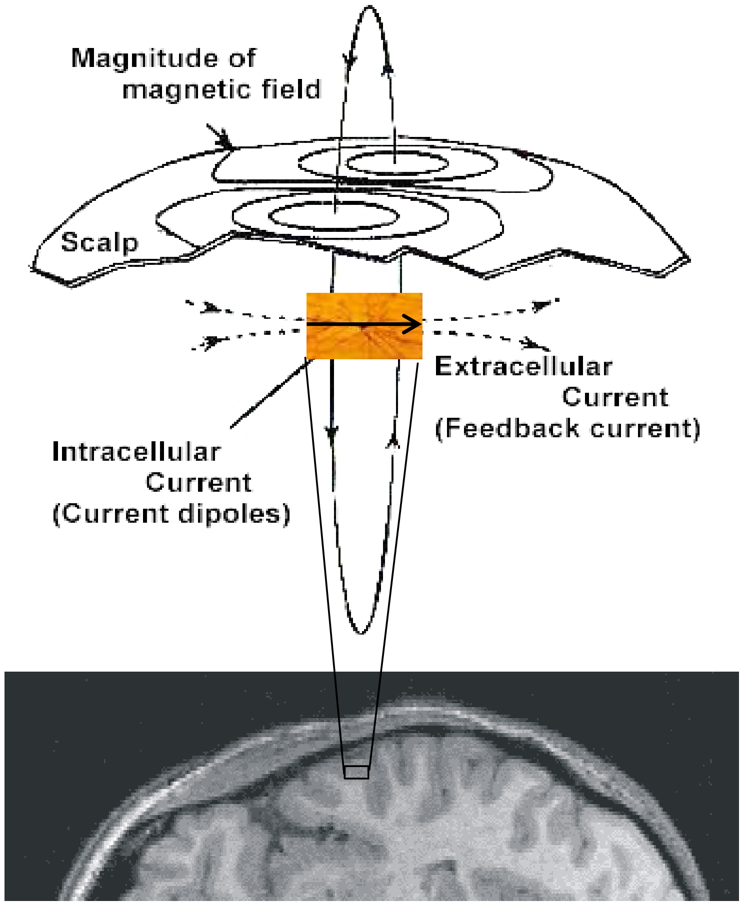
Magnetoencephalography





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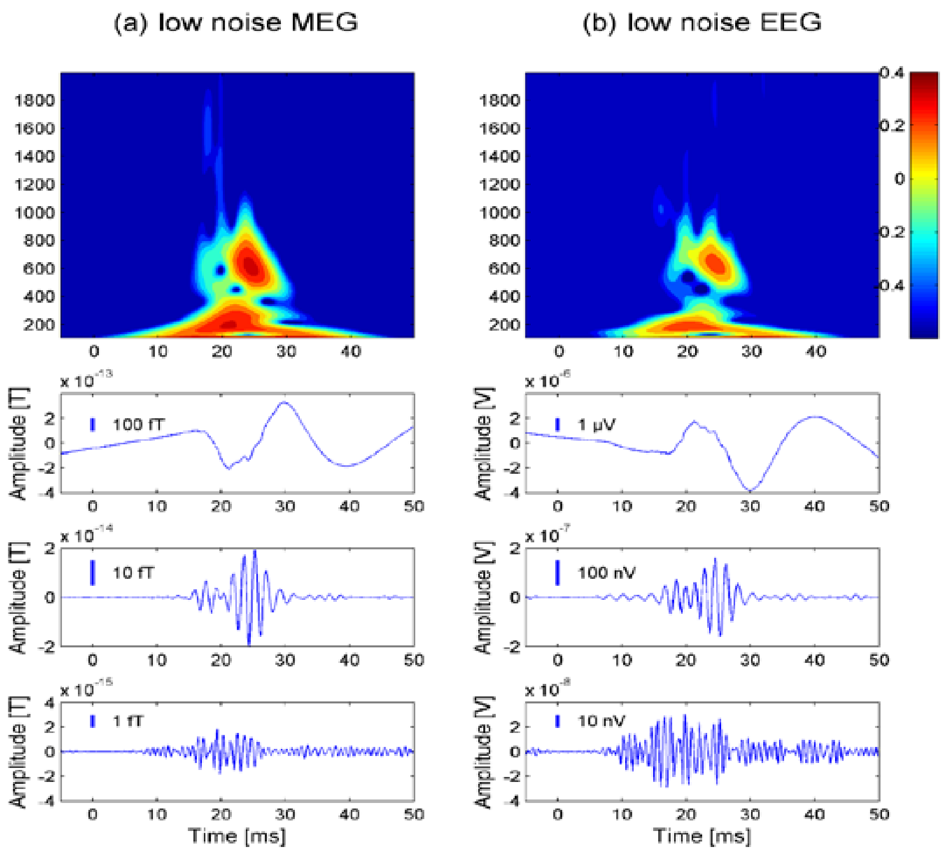
Magnetoencephalography

N20

s-band
450-750 Hz

k-band
850-1200 Hz



12 000 averages

§ Ultra-low-noise EEG/MEG systems enable bimodal non-invasive detection of spike-like human somatosensory evoked responses at 1 kHz (T. Fedele et al. Physiol. Meas. 2015)

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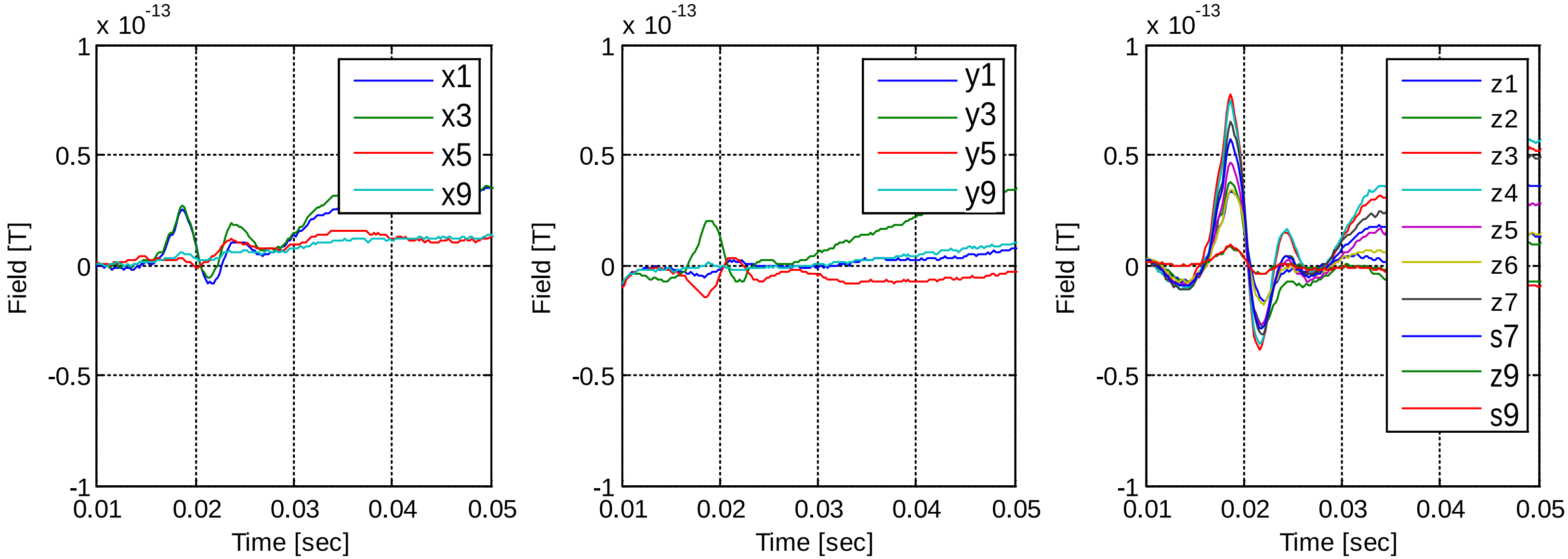
Magnetoencephalography

Somatosensory evoked brain activity, Prototype module:

- electric stimulation at median nerve at t=0 s
- N20 visible at t»20 ms after stimulation
- 16200 averages

N20



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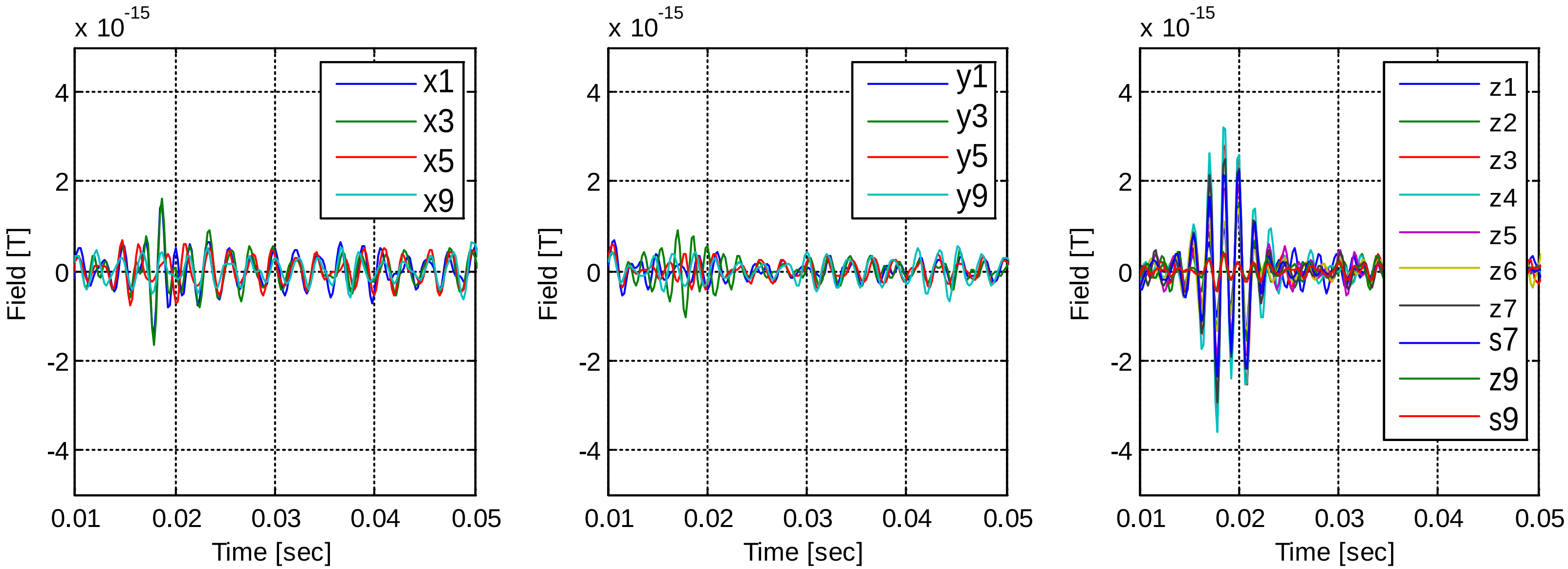
s-range (450-750 Hz)



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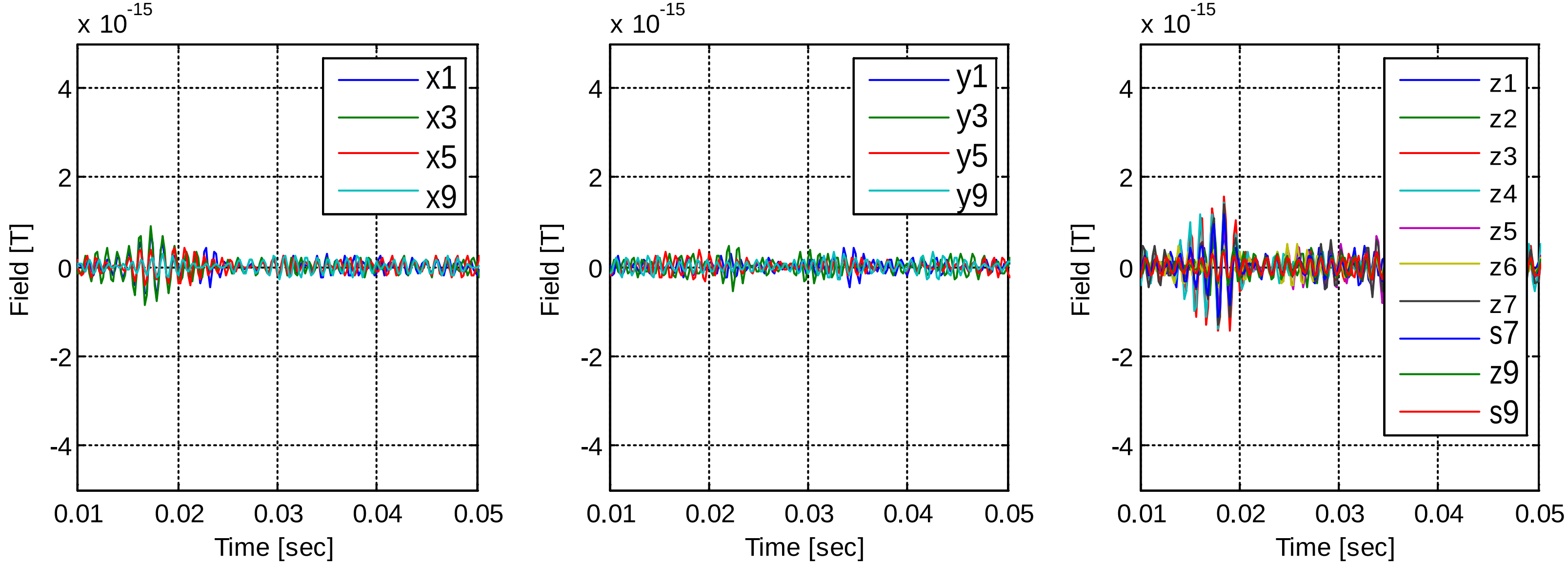
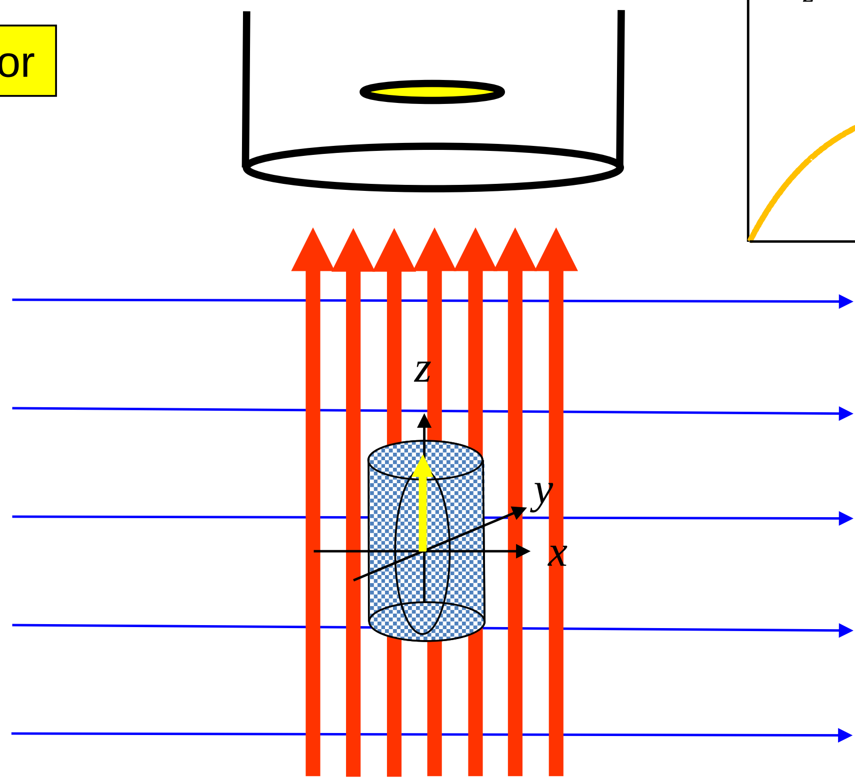
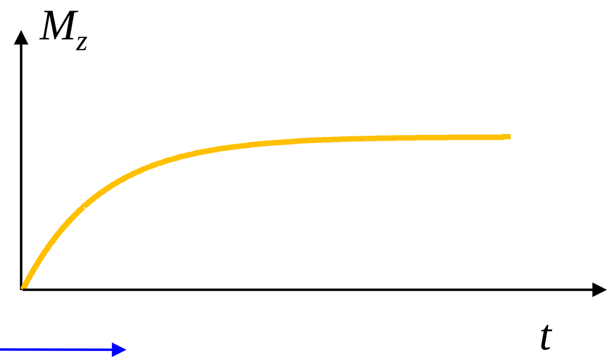


Basics ULF nuclear magnetic resonance

SQUID-Sensor





During polarisation magnetisation M_z grows with T_1.

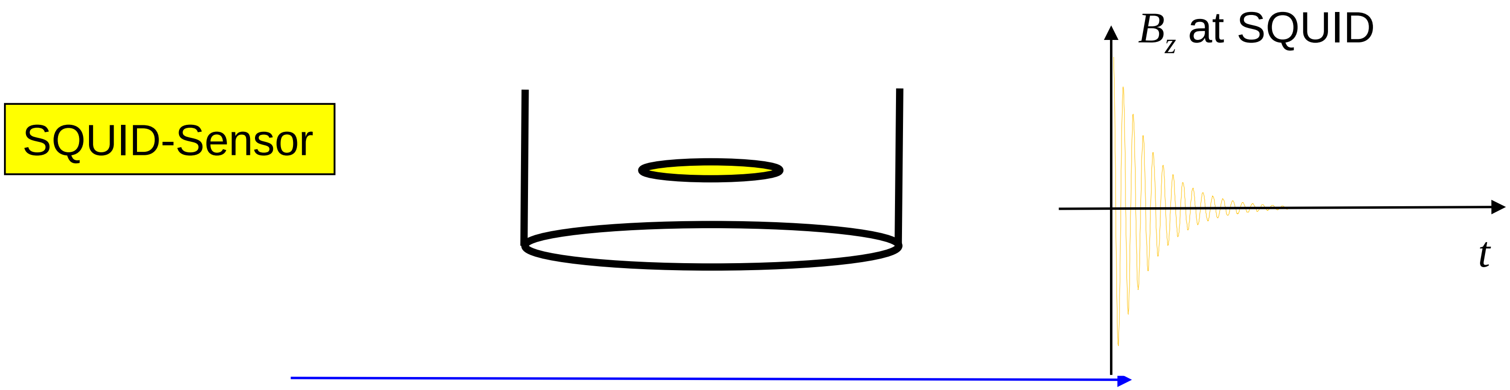
B_{det}

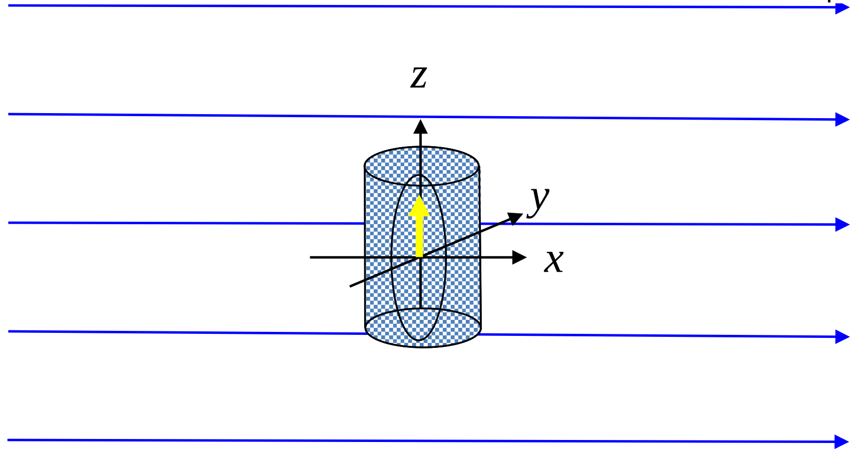
Expose sample to detection field, ususally µT-range.

B_{pol}

To boost magnetisation of sample use prepolarisation, usually mT-range.

Basics ULF nuclear magnetic resonance





B_{det}

Expose sample to detection field, ususally µT-range.

During detection magnetisation M precesses around B_{det} with Larmor frequency w=gB and decays with T_2^*.

T_2^* describes dephasing of the M (spins).
intrinsic + instrumental contributions.

Nuclear magnetic resonance of protons

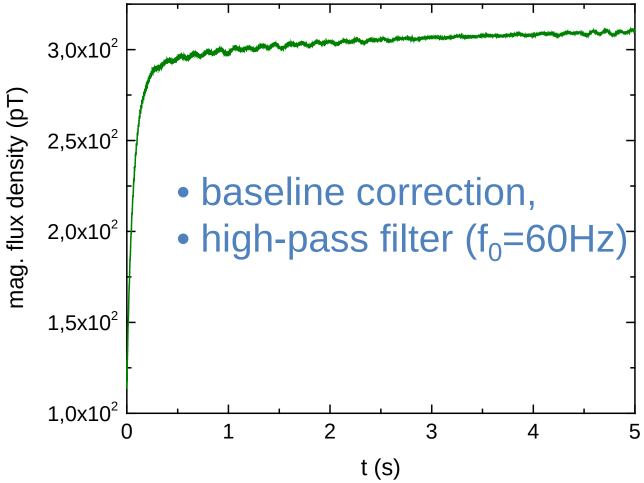
Experimental setup:

Sample:	distilled water
detection field:	2.56 µT
Polarization field:	35 mT (centre sample)
Polarization time:	5 s
SQUID reset time :	50 µs

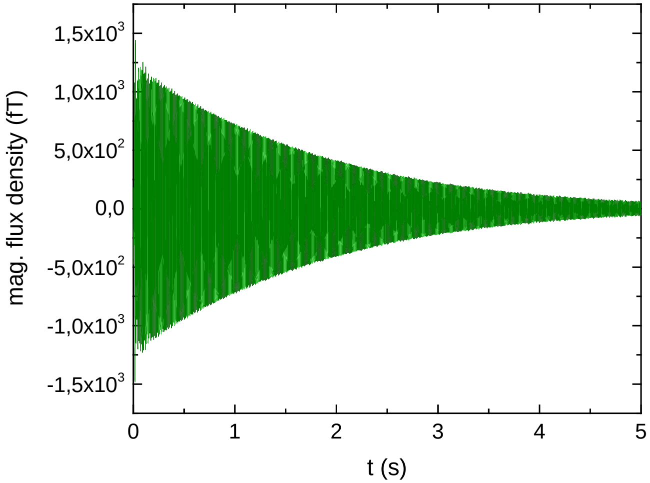
Sample inside polarising coil

Detection field coil

Raw B-field data



Filtered FID



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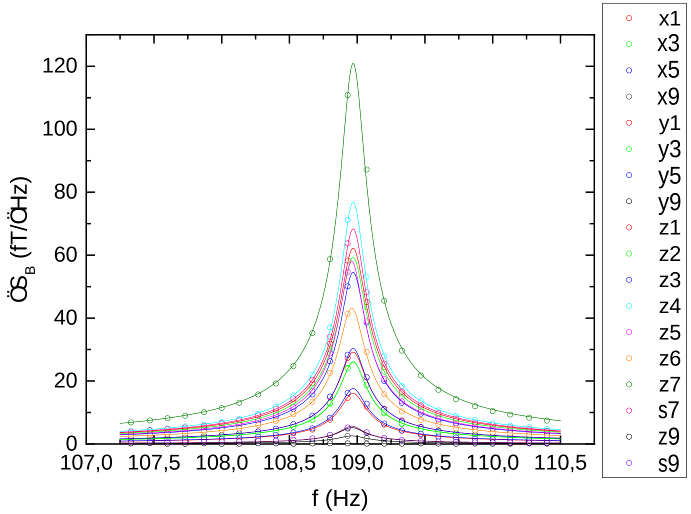
Detection field coil

Amplitude spectra with the respective fits



Points are data
Fit: Lorentzian to data real and imaginary parts
® Resonance frequency: 108.97 Hz
® T2* (for bottom z-magnetometer): 1.75 s

Parameters are in accordance with expected values

Summary

- 18-channel SQUID magnetometer module was designed and constructed
- Different coil sizes allow maximum SNRs for different source depths and configurations
- The designed module forms the basis for a scalable multi-module system (we plan a 126 channels configuration)
- Magnetic simulations of the magnetic distortions of the niobium shields were estimated and geometry of the shields optimised
- Sensitive MEG and pulsed ULF NMR experiments were performed
- Ultra-low noise performance enabled multi-channel detection of high-frequency components at around 1 kHz of somatosensory evoked activity

® Accepted paper: A modular, extendible and field-tolerant multichannel vector magnetometer based on current sensor SQUIDs, 2016 Supercond. Sci. Technol.