TNTS2019

Today’s Noise Tomorrow’s Signal

13.02.2019 - 15.02.2019
Physikalisch-Technische Bundesanstalt
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13.02.2019

Listening to neural whisper: Non-invasive EEG/MEG recordings of human cerebral population spikes

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The detectability of neuronal fast (1 ms) action potentials ('spikes') defines a striking contrast between invasive (microscopic) and noninvasive (macroscopic) EEG: While noninvasive records reflect summed postsynaptic potentials (reflecting neuronal input), invasive microelectrodes reveal also the very output of neural computation – spikes. This micro/macro gap has been narrowed recently based on high-frequency EEG/MEG: This lecture will (i) address the basic neurophysics distinguishing slow from fast neuronal activities, (ii) elaborate on high-frequency (> 600 Hz) somatosensory responses as a key paradigm for noninvasive spike-related recordings, and (iii) report on novel neurotechnology enabling high-resolution scalp mappings of EEG/MEG activities even above 1 kHz which reflect noninvasive correlates of human neocortical population spikes. Critically, when recording conditions provide optimal SNR, event detection of single-trial (unaveraged) hf-bursts becomes feasible, offering a unique perspective to monitor human neocortical population spikes noninvasively.

What local field potentials have taught us about the pathophysiology of movement disorders

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Deep brain stimulation (DBS) is a highly effective treatment movement disorders, such as Parkinson's disease (PD) and dystonia, a condition defined by involuntary muscle contractions and postural abnormalities. Traditionally regarded as basal ganglia disorders, recent evidence points to more wide spread dysfunctions in these disease entities across the motor network. Therefore, both PD and dystonia are now referred to as circuit disorders. Local field potential recordings from subcortical DBS targets during and after the implantation of electrodes have revealed crucial findings that have contributed substantially to our understanding of the pathophysiology of these movement disorders. In PD subthalamic and pallidal oscillatory activity is synchronized in a beta rhythm (13 - 30 Hz) that is suppressed by dopaminergic medication and DBS in parallel with a symptom alleviation in these patients. In dystonia, low frequency activity (4 - 12 Hz) is most prominent in the same structures and both beta oscillations for PD and low frequency activity in dystonia are hypothesized to reflect pathophysiological hallmarks of the respective disorders that may have a causal role in the development abnormal movement and posture. Parallel magnetoencephalography and local field potential recordings have now opened the window to investigate oscillatory subcortico - cortical network connectivity and studies using this innovative methodological approach further corroborate the pathophysiological role of aberrant oscillatory activity across the motor network in movement disorders. The proposed talk will give an overview on the significance of pathological oscillatory activity in the motor network.

Transcranial magnetic stimulation invoked magnetomyography using optically pumped atomic vapor cell magnetometers

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BACKGROUND: Magnetomyography (MMG) in human subjects offers detailed, spatially and temporally resolved nerve and muscle signal that provides crucial clinical information, beyond that of electromyography (EMG). While traditional SQUID technologies are bulky, expensive, and ill-suited to the different geometries of various body parts, optically pumped magnetometers (OPMs) offer customizability, portability, and the low-cost needed to make MMG an accessible diagnostic tool. Additionally, OPMs have opportunities and applications in wearable, compact devices with wide application outside of clinical use.
METHODS: In order to controllably study muscle activity, we use transcranial magnetic stimulation (TMS), a safe, and repeatable method to stimulate the human motor cortex. TMS is widely used as a clinical and research tool in neurophysiology, neurology, neuroscience and psychiatry. TMS pulses are applied to the motor cortex, which invokes movement in the index finger, known as a motor-evoked potential. The arm of the subject is placed inside a cylindrical shield, circumventing cost and practicality issues associated with magnetically shielded rooms. An array of six OPMs below the hand records the bio-magnetic signal, while an EMG from the abductor pollicis brevis muscle and 256 channel, high-density electroencephalogram (EEG) are simultaneously recorded to correlate and understand the signals. Using repetitive TMS pulses at frequencies of 1, 3 and 10 Hz, we are able to record several hundred averages for each measurement.
RESULTS: We present biomagnetic signals correlated with well understood EMG and EEG measurements. These results show the first investigation of OPM-recorded muscle activity from TMS.We show identification of artifacts from the TMS pulse, a delay corresponding to the transit

time of the signal from motor cortex to hand, and signals corresponding neural impulse, as well as the signals arising from the muscle activity in the hand.
DISCUSSION: These rst results of OPM-recorded magnetic signals from TMS-evoked movement demonstrate the viability of OPMs for clinical research. The combined use of magnetic and electric eld sensors allows for detailed discrimination of different signals, while providing complementary information. TMS allows for controlled, repeatable trials, enabling averages with a high signal to noise ratio. Together with the arm-sized magnetic shield, we show the low-cost, portable and versatile opportunities a orded by OPM systems. Future implementations of this system within head sized shields will enable low-cost and accessible magnetoencephalography, furthering research towards better understanding and diagnoses of movement disorders and motor neuron diseases.

Evaluating the Performance of Ultra-Low Field MRI in In-vivo 3D Current Density Imaging of the Human Head

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The localization of neuronal activity with magnetoencephalography and electroencephalography is error-prone and ambiguous due to the ill-posed inverse problem. Direct imaging of impressed currents (CDI) inside the head can provide valuable conductivity information which, when provided to the inverse problem, will improve the solution. It has been shown that magnetic resonance imaging (MRI) in the ultra-low field (ULF) regime at μT Larmor fields can be utilized for full tensor current density imaging [1]. Here, a measurable impact of the magnetic field Bj, generated by the current density J, on the amplitude and phase of the MR signal is probed using specialized sequences.
We recently demonstrated 3D full tensor current density imaging in phantom experiments using zero-field encoding in ULF MRI. The results revealed that the reconstruction quality depends on SNR comprising sensitivity profile of the sensor, system noise, and the strength of Bj. Consequently, a sensor setup performing at ultra-low noise level as well as strong magnetization of the sample are most crucial to the success of a possible in-vivo application of the method.
We carried out FEM simulations utilizing a 3-compartment head model based on CT scans of a human head. Tissue properties such as conductivities and MR relaxation were chosen to mimic realistic parameters. The field of view was finely discretized, and a self-written time domain Bloch equation solver was used to simulate the spin evolution during the MRI experiment. Further, gradient echo signals recorded by a single second-order gradiometer were simulated by calculating the coupling of each discretized volume to the gradiometer loop, eventually giving rise to the sensitivity profile in the image. Magnetic field noise of 350 aT/√Hz, a value similar to the actual performance of the SQUID-based ULF MRI system at PTB in Berlin, was superimposed with the time domain data. Additionally, the impact of systematic effects such as present background fields was surveyed.
The results provide information on the performance of the actual setup in in-vivo experiments, as well as necessary improvements. A generally applicable approach to calculate the performance based on the voxel noise level enables to evaluate the suitability of other ULF MRI setups.

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Pulsed optically pumped magnetometers: addressing optically pumped magnetometer dead time for magnetorelaxometry of magnetic nanoparticles

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Magnetic nanoparticles (MNP) offer a large variety of promising applications in medicine, e.g. magnetic hyperthermia and magnetic drug targeting. For these applications, it is crucial to quantify the (spatial) amount of MNP and their binding state, which can be obtained by means of magnetorelaxometry (imaging). In magnetorelaxometry (MRX), the magnetic moments of the MNP are aligned by an external magnetic field, forming a net magnetic moment. After switching-off this field, the relaxation of this net moment is commonly detected by a superconducting quantum interference device (SQUID). The amplitude of this relaxation curve is directly proportional to the MNP amount, allowing for MNP quantification and spatial quantitative imaging in MRX, whereas the binding state can be obtained by analyzing the temporal properties of the relaxation curve [1]. Since the latest developments in OPM technology allow sensitivities comparable to those of SQUIDs, it has been shown that OPM may be used in magnetorelaxometry [2, 3], offering a reduced sensor-target distance and the omission of cryogenic cooling. However, current OPM suffer from dead time after switching-off the external field for MNP alignment [2, 3]. Therefore currently only relatively slow relaxing MNP can be detected with OPM. Novel pulsed total field OPM developed by Twinleaf LLC can overcome this limitation. Here, the optical pumping of the alkali vapor cell is no more continuous like in conventional OPM, but of high power and short duration. Thus, pulsing the OPM offers a dead time in the microsecond range. In this work, we demonstrate the benefit of these sensors for MRX. Our setup consists of a single Twinleaf total field pulsed OPM (noise < 1pT=pHz) and an excitation coil for MNP alignment. Both are positioned in a four-layer magnetic shield (Twinleaf MS-2) (figure 1a). The water suspended MNP samples (Perimag MNP from Micromod with a hydrodynamic diameter of 130nm) with a volume of 140µl, 50µl and 10µl, respectively, where
placed – one at a time – between the coil and the OPM (figure 1b, coil not shown). The unfiltered relaxation signal of the MNP after switching off the external alignment field of 200µT is shown in figure 1c. It should be noted, that the OPM readouts with a sampling frequency of 1kHz were time-synchronized in software with respect to the MNP excitation. Additionally, magnetic wall relaxation is observed in the measurements. After subtracting empty measurements from the MNP signals, an exponential fit is performed. It can be confirmed, that the ratio of fit-amplitudes for 140µl and 50µl match the iron concentration ratios, while the 10µl sample couldn't be detected with the setup. To conclude, pulsed optically pumped magnetometers offer great benefits for OPM-MRX,

allowing short dead times and thus the detection of smaller MNP concentrations and the detection of fast relaxing MNP.

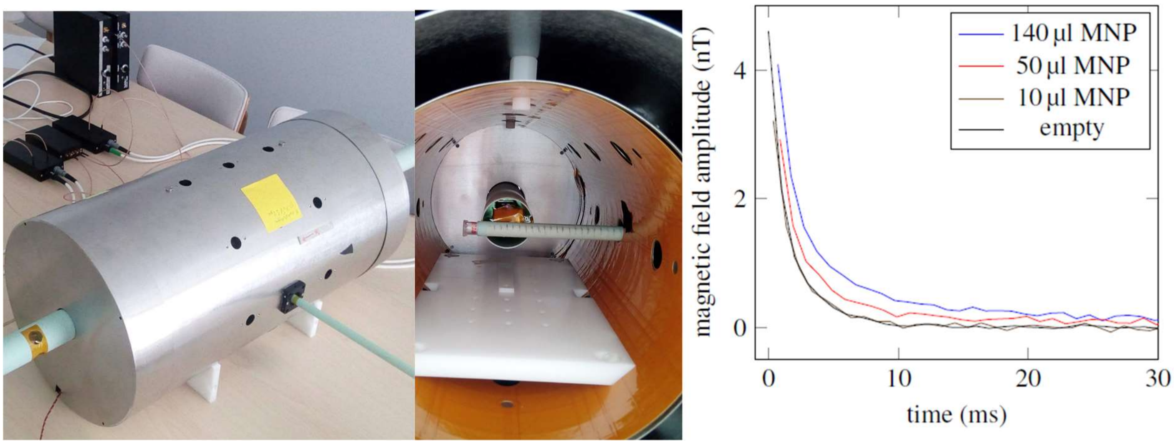

Figure 1: (a) magnetic shielding and OPM electronics. (b) internal view of magnetic shielding with the OPM positioned in the tube at the back and the MNP sample positioned within the tube inserted from the right. The excitation coil is not shown. (c) relaxation signal of water suspended MNP with a diameter of 130nm.

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Detection of bio-magnetic signals with an optically pumped magnetometer

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Magnetic fields generated by human and animal organs, such as the heart, brain and nervous system carry information useful for biological and medical purposes. Optically pumped magnetometers are becoming a promising alternative to cryogenically-cooled superconducting magnetometers for detecting and imaging such bio-magnetic fields. We have developed a highly sensitive miniature optically pumped magnetometer based on cesium atomic vapor kept in a paraffin-coated glass container (Fig. 1a). We have previously demonstrated sub-fT/√Hz sensitivity only limited by intrinsic quantum noise [1] with this type of magnetometer. It is operated at room- or human body temperature and can be placed in contact with or at a mm-distance from a biological object. Using this magnetometer, we have performed proof-of-principle bio-magnetic experiments including detection of animal nerve impulses in an isolated frog sciatic nerve [2] and detection of the heartbeat of an isolated guinea-pig heart [3, Fig. 1b]. In our recordings of the heartbeat (Fig. 1c), we can detect the P-wave, QRS-complex and T-wave associated with the cardiac cycle in real time. We also demonstrate that our device is capable of measuring the cardiac electrographic intervals, such as the RR- and QT-interval, and detecting drug-induced prolongation of the QT-interval, which is important for medical diagnostics. Promising medical applications for our highly sensitive room-temperature magnetometer include monitoring of the fetal heartbeat and imaging of brain activity (magnetoencephalography).

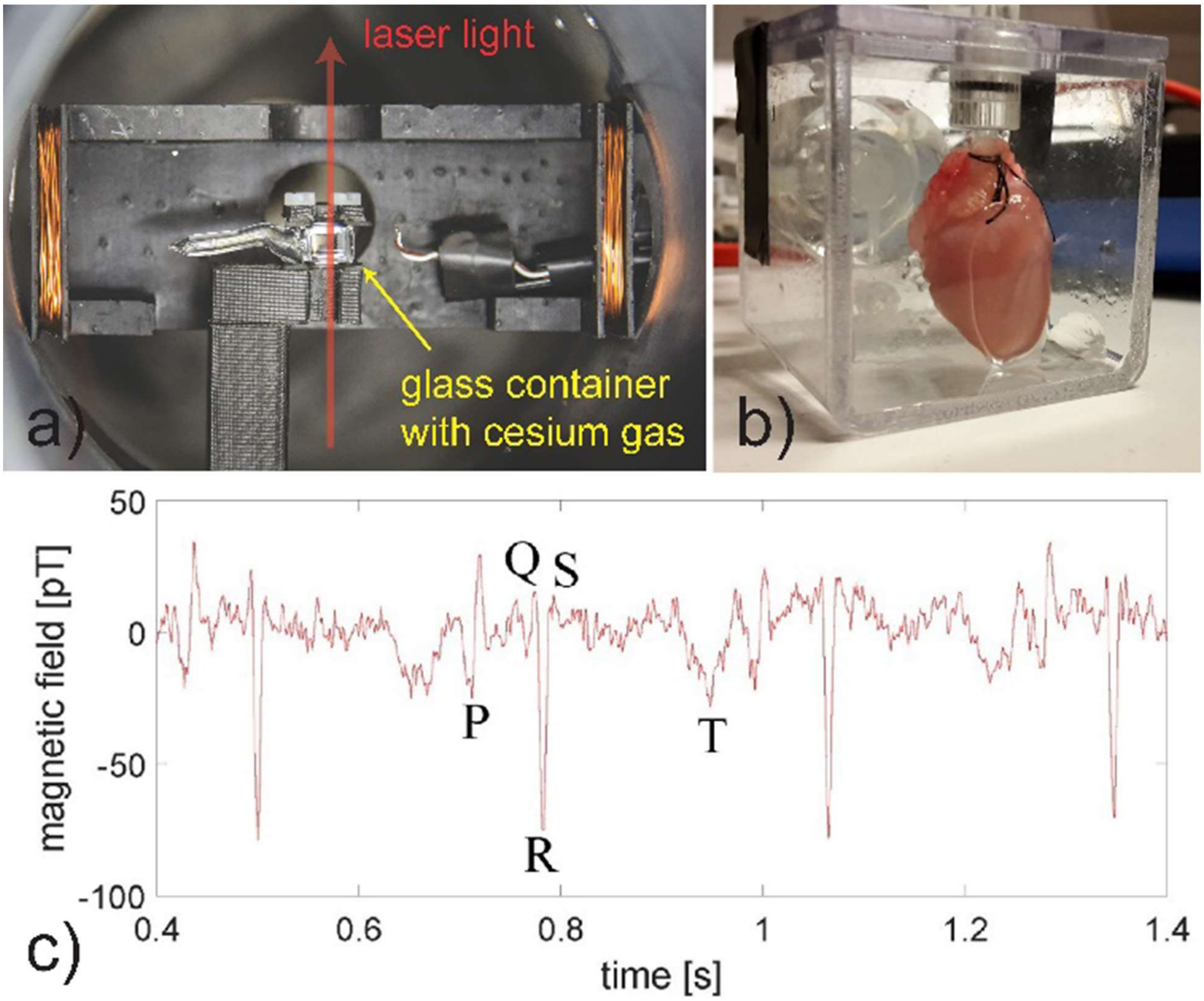

Figure 1: a) Cesium vapor cell inside a small cylindrical magnetic shield. b) Isolated guinea-pig heart. c) Real-time detection of the heartbeat with the magnetometer.

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Search for biomagnetism in venus-flytrap plants

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In this experiment, we attempt to detect the magnetic elds produced by living plants, using sensitive atomic magnetometers. Our group previously conducted gradiometric measurements on a blooming titan arum, also known as the “corpse flower", at the Berkeley Botanical Garden in California [1]. As far as we know, the only successful detection of magnetic fields produced by intact plants was published in 2000 [2]|an array of SQUID magnetometers was used to measure signals from wounded bean plants in a magnetically shielded room at Physikalisch-Technische Bundesanstalt Berlin.

After consultation with plant biologists at the University of Würzburg, we chose to launch a new biomagnetism experiment using the venus flytrap, Dionaea muscipula. This carnivorous plant is relatively easy to stimulate mechanically, and one can generate action potentials (APs) consistently. In our lab we have set up surface-electrode measurements for AP monitoring, and we have conducted preliminary magnetometry measurements in a small magnetic shield using 1-2 QuSpin magnetometers. Currently our measurements appear to be dominated by mechanical noise due to the stimulation method. We are now planning a data run in the shielded room at PTB, where we will have the opportunity to conduct measurements without spatial constraints and with more sensors simultaneously. In parallel, we are exploring various other less-invasive stimulation methods for use in our tabletop measurements.

The long-term goal of the project is to develop a novel and robust system for measuring biomagnetic signals from a variety of living plants (e.g. agricultural species), based on compact atomic sensors.

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Figure 1: One of our venus-flytrap specimens in the lab, with electrodes and QuSpin sensor.

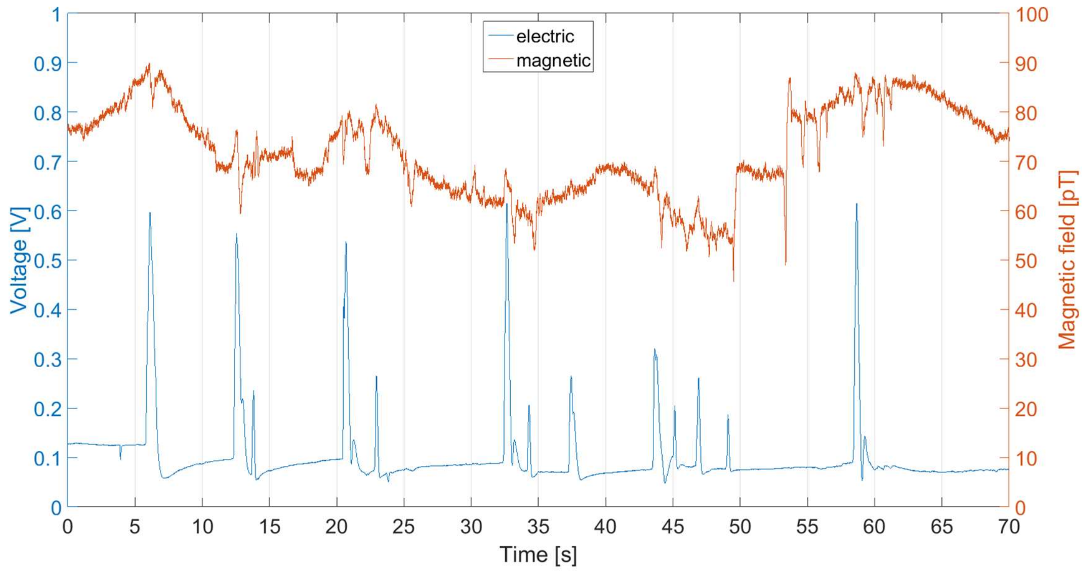

Figure 2: Electric signals (blue) produced by a trap after mechanical stimulation of its trigger hairs; each peak corresponds to a single stimulation. The simultaneous magnetic data is also shown.

Multichannel Exercise MCG with Optically Pumped Magnetometers

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Recent advances in commercial production of miniaturized optically pumped magnetometers (OPMs) enable a new level of biomagnetic investigations. Now the magnetic field sensors can be directly attached to the body while the subject is still allowed to move. Also, the sensitivity level reached by commercial OPMs enables them to compete with SQUID based systems in biomedical applications such as Magnetocardiography (MCG) and Magnetoencephalography (MEG). For these measurements, a bandwidth from 0.1 Hz to 100 Hz is often sufficient. OPM based systems gain from their higher flexibility, that enables their direct attachment to the body, comparable to electrodes in Electrocardiography (ECG) or Electroencephalography (EEG). This offers new opportunities for field mapping e.g. in terms of higher spatial resolution and closer distance to the field sources, as well as realization of personalized and complex geometries.
Here, we show that the flexibility of OPMs enables, first, the registration of exercise MCG even during the subject is moving and, second, the attachment of sensors on the chest and on the rear of the subject at the same time. We used commercially available zero-field OPMs with a sensitivity below 15 fT/rtHz and a bandwidth above 100 Hz to perform exercise MCG measurements in PTB’s magnetically shielded room BMSR-2. A set of 8 sensors (16 channels) was attached to the chest and another set of 8 sensors (16 channels) was attached to the rear of the subject. MCG was recorded before, while and after the subject was exercising on a nonmagnetic cycle ergometer or performing squats. The OPMs were fixed on the subject’s body only separated from the skin by a thin layer of cloth. We obtained an R-peak amplitude of up to 160 pT and an SNR of up to 300, that allows for distinguishing details in recorded data already without averaging. These measurements demonstrate the ease of handling and high flexibility of OPMs combined with good signal quality.

The Global Network of Optical Magnetometers to search for Exotic physics

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The Global Network of Optical Magnetometers for Exotic physics searches (GNOME) is an international effort searching for dark matter signatures by looking for atomic spin perturbations in spatially distributed optically pumped alkali vapor magnetometer (OPM) readings [1,2]. As of November 2018, the network consists of 12 active magnetometer stations spread around the globe (cf. Fig.1), quasi-continously streaming GPS-time disciplined data of magnetically well-shielded OPMs to a central server. The detection of space-time correlated (transient) signals in the joint data set would be a sign for exotic fields predicted by a class of theories, e.g., dark-matter structures composed of axion-like particles (ALPs) like ALP domain walls or ALP stars [3].
The basic idea of GNOME of a geographically distributed sensor network - resembling the approach of the LIGO collaboration operating spatially distributed gravitational wave detectors – on one hand allows the discrimination of real sought-for transient events from local magnetometer perturbations (false positives). On the other hand, it will allow obtaining directional and temporal information on possible exotic interaction events, which may even enable connecting these with astrophysical observations made in different domains.
We will give an overview on the current status of the GNOME project with emphasis on its experimental realisation and discuss preliminary findings from the ongoing coordinated long-term run.

Figure 1. Screenshot taken (November 08th,2018) from the publicly accessible GNOME website [4].

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Introduction to optically pumped magnetometers

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Optically pumped magnetometers [1,2,3] (OPM) are among the most sensitive magnetic field sensors known today [4]. Various OPM schemes have been developed and optimized for different applications. This presentation will introduce the basic principles involved and review three different magnetometer schemes.

Topics:

- Magnetometer medium, alkali metal vapor [5]
- Magnetic interaction, Larmor precession
- Optical Pumping, creating atomic spin polarization [6,7]
- Optical detection of the atomic spin polarization
- Pulsed magnetometer scheme, free spin precession (FSP) [8,9]
- Continuous magnetic resonance scheme (Mx) [1,3]
- Continuous zero-field magnetometer scheme and SERF regime [4]

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Applications of ultra-sensitive magnetometers in fundamental science

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We study helium films as model systems for realizing quantum materials, and strongly correlated electrons in metals and low dimensional electron systems into the microkelvin regime. These experiments exploit ultra-sensitive and low dissipation sensing techniques, based on SQUID magnetometers.

Topological mesoscopic superfluid 3He is a p-wave, spin-triplet superfluid, which acts as a model system for topological superconductivity. There are two phases with distinct broken symmetries and momentum space topologies in bulk. Confinement into precisely engineered nanofluidic geometries, on the length scale of the Cooper pair diameter, allows the study of surface and interface properties of these topological materials, can stabilize new quantum states of matter, and permits the construction of hybrid mesoscopic devices. A key element of these experiments has been the development of sensitive nuclear magnetic resonance spectrometers using SQUIDs, to study the small samples involved.

Atomically layered helium films grown on graphite/graphene substrates provide tuneable model systems to tackle important questions in the field of strongly correlated quantum matter. Prior work has demonstrated: Mott-Hubbard transition in 2D 3He; frustrated magnetism on a triangular lattice; heavy fermion quantum criticality; intertwined superfluid and density wave order (2D supersolid). Current and future work includes the following topics: survival of Fermi liquids in a strictly 2D strongly correlated system; interacting coupled 2D fermion-boson system; realization of a model quantum spin liquid in 2D 3He; intertwined superfluid and density wave order; realization of topological phase transition into 2D superfluid 3He. In much of this work sensitive broadband SQUID NMR techniques are playing a central role.

The cooling of correlated electrons into the µK regime poses additional challenges in measurement. We have developed the application of ultrasensitive magnetometers to ultra-low dissipation transport measurements, as well as precise and fast noise thermometry. Here the two highlights are: the unambiguous identification of novel superconductivity in YbRh2Si2, a canonical heavy fermion metal with a field tuned quantum critical point; the cooling of 2D electrons in a gallium-arsenide heterostructure to 1 mK, opening the door to new semiconductor nano-electronic devices.

The readout of NEMs by quantum sensors, and microkelvin platforms based on cryogen-free technology have also been developed. This offers to prospect to take quantum materials and quantum technology into a new regime, with potential advantages in improved decoherence and tuneability.

This work is supported by the European Microkelvin Platform and EPSRC EP/R04533X/1. A key collaborator is PTB (Berlin). At Royal Holloway it currently involves collaboration with Andrew Casey, Brian Cowan, Jan Knapp, Lev Levitin, Petri Heikkinen, Jan Nyeki, Xavier Rojas.

Fully Optical Cesium Magnetometer

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The development of optical Cesium magnetometry at TU Munich was initiated due to the need for high precision and low drift magnetic field sensors for upcoming nEDM experiments at ILL, France. Since Ramsey measurements have an intrinsic sensitivity for several magnetic field effects, a careful monitoring of fields and field drifts is a crucial requirement for reaching further nEDM limits. Due to the special requirements in a nEDM-measurement, especially to avoid any additional magnetic fields, the sensor developed at TU Munich is completely non magnetic and based on the Bell-Bloom scheme, using a fully optical approach with optical pumping instead of oil based Mx/Mz systems. The sensor head, including the Cs-cell, is fiberized, allowing to separate the sensor and readout electronics. In order to avoid the need for heating inside the experiment, anti-relaxation coated cells are used. Beside the mentioned advantages of being non-magnetic, these sensors can be operated in a variety of configurations and allow alignment or orientation pumping as well as free precession decay and forced oscillation mode. During a measurement campaign inside the BMSR-2 in 2018, a sensitivity of 60fT for a single shot measurement and a drift stability of less than 100fT for times over 300s was demonstrated. In addition, new concepts like a free space magnetometer inside the neutron chamber, between the high voltage electrodes, can offer new possibilities and further insights into the field environment.

SQUID current sensor with nanometer-sized Nb-AlOx-Nb Josephson junctions for application in ultra-low field MR

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We report on the development of micro-sized superconducting quantum interference devices (SQUIDs) featuring sub-micron Josephson junctions. These SQUIDs are well suited for a wide range of applications, e.g., biomagnetism. Specialized applications in ultra-low field magnetic resonance (ULF MR) are neuronal current imaging (NCI), current density imaging (CDI) of impressed currents and the combination of magnetoencephalography (MEG) and ULF MRI. Those techniques aim at the improvement of non-invasive functional imaging of the human brain and require a significant improvement of the signal-to-noise ratio (SNR).

For the application of SQUIDs in ULF MR, a current sensor configuration is used where the current to be measured is passed through a superconducting input coil inductively coupled to the SQUID. Accordingly, the resolution of the current sensor depends on the flux noise $\sqrt{S}$ and on the coupling coefficient k between input coil and SQUID inductance L. A common figure of merit is the coupled energy resolution $\boldsymbol{\varepsilon}_c = \boldsymbol{\varepsilon}/k^2$, where $\boldsymbol{\varepsilon} = S_\Phi/2L$ is the energy resolution of the uncoupled SQUID.

To improve $\boldsymbol{\varepsilon}_c$ of our current sensor SQUIDs, we have combined the advanced nano-junction technology with reliable and properly damped micro-structured SQUIDs and coupling transformers. The fabrication process for the nanometer-sized Josephson junctions based on the HfTi self-shunted junction technology has been extended to a superconductor-insulator-superconductor process with AlOx as the insulating layer.

For the evaluation of the Nb-AlOx-Nb nano-junction process miniature SQUID magnetometers were fabricated. These test devices have square junctions with side lengths between 500 and 800 nm. The 800 nm square junctions had a critical current I0 of about 6.4 µA and shunt resistance between 18 Ω and 50 Ω. The self-inductance of the SQUID loop was 70 pH. At 4.2 K the measured white flux noise was about 330 $n\Phi_0/\sqrt{Hz}$ corresponding to an uncoupled energy resolution of 5 h. The noise increases at lower frequencies with a typical value of 900 $n\Phi_0/\sqrt{Hz}$ at 1 Hz.

Based on these results, integrated current sensors were designed and fabricated having the same SQUID inductance. For the input circuit a proven double-transformer design was used with a coupling coefficient of k = 0.7. The expected coupled energy resolution of this design is approximately 10 h at 4.2 K.

We discuss the implications of the improved noise performance on the realization of NCI, CDI and the combination of MEG and ULF MRI. We also present the design of our new ULF MR multi-channel system based on these nanometer-sized junctions SQUIDs.

Low noise all-oxide magnetic tunnel junctions based on a $La_{0.7}Sr_{0.3}MnO_3$ / Nb:$SrTiO_3$ interface

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Functional oxides have shown a wide range of peculiar physical properties that could potentially be exploited for applications. One example is manganite $La_{0.7}Sr_{0.3}MnO_3$ (LSMO) based Magnetic Tunnel Junctions (MTJs), which benefit from the full spin polarization of manganite and exhibit high tunneling magnetoresistance (TMR) ratios at low temperatures up to several hundred of percent [1;2]. Such systems can be used in magnetic field sensing for high sensitivity magnetometers. Nevertheless, the noise in this system, measured by our groups [3], has, until now, been higher than in metallic junctions, thus limiting their usefulness for applications.
In this paper, we demonstrate how the noise level can be reduced by three orders of magnitude and now making these devices competitive with metallic systems. Our work investigates replacing the STO insulating barrier by a semiconducting Nb:STO barrier in LSMO based tunnel junctions [4].
High quality LSMO(30nm)/Nb:STO (3nm)/LSMO(10nm)/La0.7Sr0.3Mn0.93Ru0.07O3 (20 nm) junctions were grown in situ by pulsed laser and then patterned by using standard UV lithography into micrometric tunnel junctions.
We explore temperature- and voltage-dependent magneto-transport of LSMO based tunnel junctions with semiconducting Nb:STO or undoped STO barriers. We demonstrate that the junctions with Nb:STO barriers exhibit improved TMR characteristics over a wide range of temperatures, much lower noise levels and significant robustness.

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Local recordings of neuronal magnetic signal with micron-sized GMR sensor

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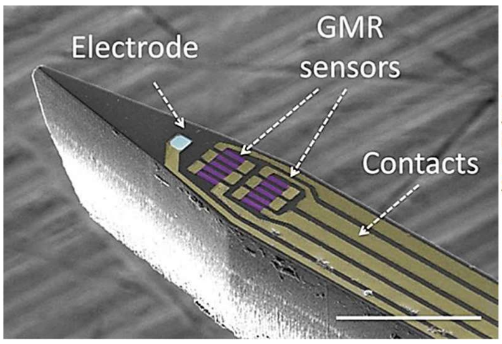
The flow of ionic current in neurons creates electric signals which can be measured at large as well as local scales. However, up to now, the magnetic counterpart of this electric signal has been only measured at large scale (cm size) with helium-cooled magnetometers such as SQUID. We are currently developing a new local probe with a lateral resolution of few µm, called magnetrode, which works at physiological temperature and is biocompatible for local in-vivo measurement [1]. It is based on Giant Magnetoresistive (GMR) sensors composed by two thin ferromagnetic layers (CoFe, NiFe, etc) separated by intermediate non-magnetic metallic layers (Cu). The resistance of this type of GMR devices depends on the relative orientation of the magnetization between the two ferromagnetic layers and therefore can detect ultra-low magnetic fields. Our main goal is to measure the local magnetic field that occurs during the firing of a single neuron, that is local magnetic spikes, by using such GMR technology providing a new tool to understand how neuronal transmissions work.
For such challenging purpose, the GMR sensors should be designed with a very high Signal to Noise Ratio (SNR) and linear response in order to detect the weak neuronal magnetic field (a few pT at 1kHz) generated by a single neuron. To enhance the sensitivity and decrease magnetic noise, we are optimizing different ingredients of our sensors: composition and thickness of the film stack, shape and lateral resolution of the GMR devices. Here, we will present our result: a state of the art sensor with a GMR ratio of 6-8%, a sensibility of 2 to 6%/mT and a detectivity below a 1nT at 1kHz.



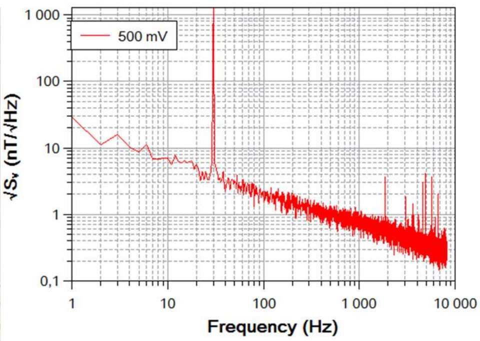


Figure 1: SEM image of a magnetrode tip containing two GMR sensors and one Pt electrode, Figure 2: Noise spectrum measurement of a magnetrode in the frequency range between 1 Hz and 10 kHz

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Towards a combination of solid-state and atomic magnetometry

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In the last decades several types of sensitive magnetometers have been developed. While the absolute record holder in terms of sensitivity is still found in SQUID systems, atomic vapor cell magnetometry is emerging to field applications such as geomagnetic sensing and to the detection of bio-magnetic fields [1]. For microscopic observations solid-state systems, most notably the negatively charged nitrogen-vacancy center in diamond, have been technologically explored [2]. This defect center is limited in the DC-sensitivity [3], but is well suitable for magnetometry on different frequency ranges and on nm-sized samples in their close proximity [4]. Defect centers can be singled out, single photon emission was detected, and the present research covers not only the field of optical magnetometry, but also quantum information [5] and nano-scale thermometry [6].

For a combination of atomic- and solid-state-magnetometry, we have implemented a rubidium based M_x magnetometer [7]. The design is suitable for incooperating a small ($\approx$ 2 mm^2) solid state experiment (see Fig. 1a and b). The design principles and the home-made cell design will be discussed in the presentation. Recently, we have achieved a natural linewidth of less than 4 Hz for our novel paraffin coated vapor cells. We will outline the specific strength of atomic vapors and nitrogen-vacancy centers and discuss options of combining both techniques.

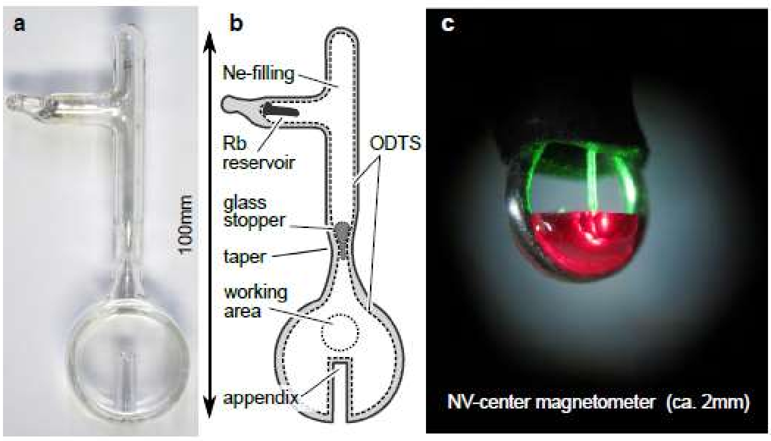

Fig. 1a) Photograph from one of the rubidium cells, suitable for inserting a solid-state sample. b) The design combines buffer gas, anti-relaxation coating, and an appendix for the solid-state sample. c) The diamond NV-center magnetometer, multi-mode fiber coupled and with a rigid-waveguide antenna.

A few hybridization steps on other systems have been taken in the past [8,9]; we believe that a combination with solid-state samples might lead to a significant decrease in sensor size and might open the route to new samples which can be researched with atomic magnetometry. Also for absolute field calibrations, a combination of very accurate 3He or 129Xe magnetometers with defect centers in diamond might be advantageous.

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Simultaneous microwave-free vector magnetometry using nitrogen-vacancy centers in diamond

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We propose and demonstrate a novel vector magnetometer that simultaneously measures all Cartesian components of a dynamic magnetic field using an ensemble of nitrogen-vacancy (NV) centers in a single-crystal diamond. With fixed crystallographic axes inherent to the solid-state system, the present magnetometer leverages the level anti-crossing in the triplet ground state at 102.4 mT, capable of measuring all three-axis components of the magnetic field, free from heading errors. Vector capability is proffered by effective modulating fields along the preferential NV axis or in the transverse plane and subsequent demodulation of the magnetic resonance signal. This sensor exhibits a demonstrated rms noise floor of axial ≈ 300 pT /√Hz and transverse 850 pT /√Hz in measurement of the field magnitude. We claim the present technique is to date the most applicable protocol of a full vector magnetometer employing single-NV probe and extend the vector ability to subnanoscale spacial resolution. The solid-state microwave-free measurements with high resolution and high sensitivity that provide broadband magnetometry under ambient or extreme physical conditions enables unique potential applications, e.g. single molecule imaging, over other state-of-art magnetometry. Removing the requirement for microwave while maintaining measurement sensitivity represents a significant step towards the development of robust, non-invasive and miniaturized magnetic field sensors.

Magnetoelectric Microwave Magnetic Field Sensor

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A novel thin-film magnetoelectric sensor using microwave readout is presented and discussed [1]. Conventional magnetoelectric sensors utilize mechanically coupled magnetostrictive and piezoelectric layers and detect the time change of weak and low-frequency magnetic fields [2][3] by measuring the charge build-up in the piezoelectric layer. They are therefore unable to detect static magnetic fields. In the new sensor concept, the piezo layer is omitted and the magnetostrictive cantilever is integrated with a microwave resonator. The capacitively coupled transmission resonator is excited in the low GHz range, and detuning of its resonant frequency by an applied magnetic field is monitored. Phase noise from the auxiliary microwave source is largely suppressed in a phase discriminator circuit. A limit of detection of 50 pT/Hz0.5 at low frequencies has been initially reached so far, which is comparable to the detection limit for conventional readout. Due to sensor construction, mechanical movement of the cantilever and microwave readout are entirely mechanically decoupled. The sensor is capable of detecting static magnetic fields. The microwave part can be integrated with the cantilever as a MEMS-circuit.
This work was financially supported by the German Science Foundation (DFG) through the collaborative Research Centre CRC 1261 ”Magnetoelectric Sensors: From Composite Materials to Biomagnetic Diagnostics”.

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Fundamental thermal limits for detection of biomedical magnetic fields by resonant magnetoelectric composite sensors

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Resonance enhanced magnetoelectric cantilever sensors of strain-coupled magnetostrictive, piezoelectric and substrate layers display high potential for achieving magnetic field detection limits in the 100fT/Hz1/2 range at the frequencies required for medical cardio and neuro diagnostics. In this talk we will present the theory and results of the fundamental thermal limit of magnetoelectric cantilever sensors for resonant detection of oscillating magnetic fields using magnetostrictive FeCoBSi and piezoelectric AlN layers on opposite sides of a Si substrate. We use material parameters independent of layer thickness. Findings are based on analytic models of the resonant bending mode magnetoelectric response of strain-coupled layer stacks, damping effects including support, thermoelastic, and eddy-current losses, and noise originating from thermal vibrations, dielectric losses, and amplifier electronics. Thermal vibrations are found to dominate all other noise sources for practical device sizes. Configurations for lowest detection limits are identified. Scaling laws of the detection limit with sensor size, resonance frequency, quality factor, and layer thicknesses will be presented including predictions of achievable detection limits and critical sensor parameters.

Funding by the Collaborative Research Center SFB 1261 is gratefully acknowledged.

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Magnetic noise reduction strategies in magnetoresistive sensors for improved detection limits

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Giant magnetoresistors (GMR) and magnetic tunnel junctions (MTJ) are devices based on spintronics. The sensors are schematically composed of two ferromagnetic layers separated by a non-magnetic spacer. The resistance of the structure depends on the relative orientation of the magnetization of these two layers. The reference layer possess a blocked magnetization independent on the external field, while the free layer magnetization rotates with the field.
Thanks to a typical level of detection of a few nanoteslas and their large frequency range, such sensors are widely used for low field measurements, for example in automotive or biological systems [1]. However, the detectivity is limited at low frequency by the presence of 1/f noise and random telegraphic noise that can both have magnetic origins due to magnetic fluctuations of the free layer.
To obtain a linear field sensor response, one should create an anisotropy in the free layer perpendicularly to the reference layer [2]. Several linearization strategies exist, such as the use of an external field, shape anisotropy or intrinsic coupling inside the stack. In this work, we have studied the impact of these different strategies on the magnetic noise and on the level of detection. In particular, we found the presence of an optimal pinning field that does not depend on the linearization strategy. In this way, magnetic noise is supressed before losing sensitivity due to over-pinning of the free layer, which results in an improved repeatability, as well as an enhanced detectivity up to a factor of 10.

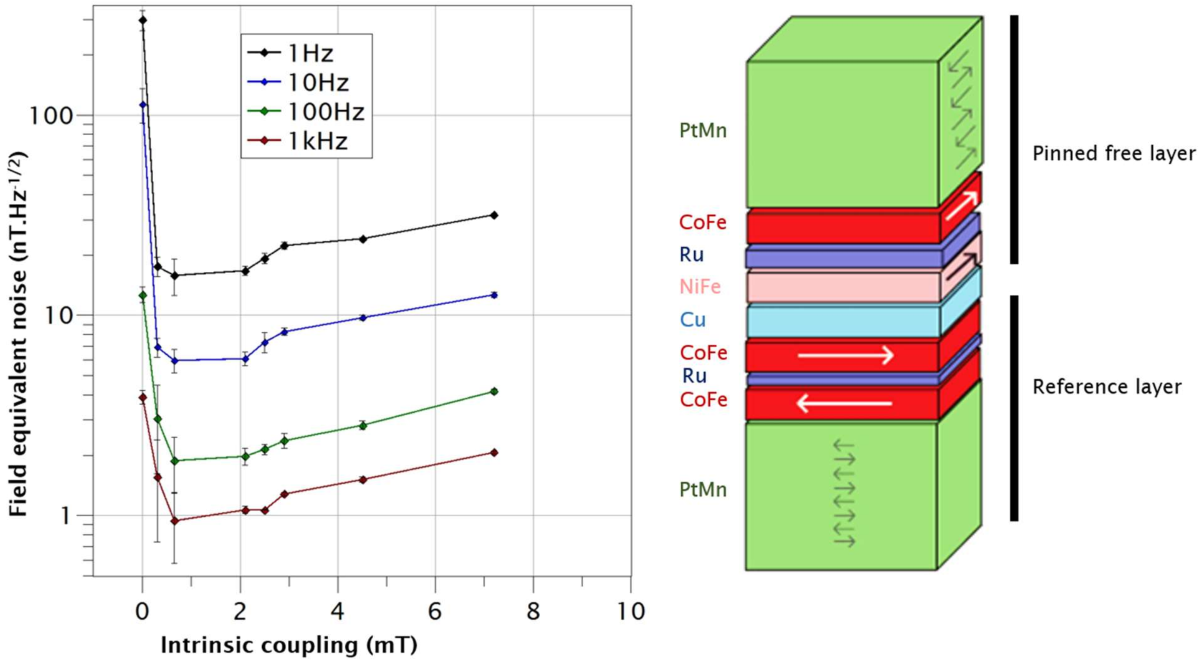

Figure 1: Decrease in minimum detectable magnetic signal as a function of the intrinsic coupling strength inside the free layer.

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Low noise approaches for pTesla field detection using magnetoresistive sensors

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The development of new tools is a requirement due to the strong advanced of the technology with a consequently growth of smart devices for different areas from industry to healthcare. Among these, the detection of biomagnetic fields (pT range) requires state-of-the-art sensors with high signal-to-noise ratio. Also, given that biomedical signals are characterized by their low frequency, minimizing the sensor noise level becomes as important as increasing its sensitivity. Devices based on magnetoresistive (MR) sensors standout as a room temperature solution since they combine high sensitivity and tunable spatial resolution facilitating a compact design. A standalone micrometric spinvalve (SV) displays a field detection level at tens of nT/√Hz. Thus, several strategies have been explored to push these limits towards pT detectivites at low frequency. In this work, two approaches have been explored by using 3D magnetic flux concentrators (MFC) or packing vertically SV. The noise measurement is crucial to evaluate the minimum field detectable. While in the former approach the main objective is to increase the sensitive without compromising the noise level, in the latter solution is expected a reduction of the noise level promoted by a lower device resistance. The noise measurements are performed in the noise setup developed at INESC-MN. The setup is composed by a magnetically shielded box, where the sensor is biased by batteries while the voltage fluctuation is amplified by low noise amplifier SRS SIM910 and acquired by a TEKTRONIX RSA3308A spectrum analyser. The acquisition was performed with a bandwidth resolution of 2 Hz and 200 Hz from DC – 1 kHz and 1 kHz –100 kHz, respectively.

The approach with Z vertically packed spin valve, X elements in series and Y in parallel allows to increase the number of sensors in parallel (vertical) without compromising the spatial resolution [1]. The 1/f noise is proportional to $\sqrt{[X/(YZ)]}$, therefore a higher number of Z spin valves decreases the noise when comparing planar with vertically packed arrays with the same number of elements as reported in [2]. A detectivity of 1.4 $nT/Hz^{1/2}$ at 10 Hz is reached for these devices.

A 3D MFC design was implemented [3] with double layer composed by a steep CZN layer on top of a tapered NiFe layer. The combination of the two layers increases the guiding efficiency of the magnetic field into the spin valve sensor increasing the sensitivity. Furthermore, the distance between the poles of the two layers influences not only the sensitivity but also the noise level. Higher the distance between them lower the noise and higher the improvement on the sensitivity. A detectivity of 290 $pT/Hz^{1/2}$ at 10 Hz is achieved for this architecture.

In conclusion, the combination between the noise level and sensitivity can push MR technology towards to pTesla field detection.

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Magnetic particle mapping using magnetoelectric sensors as an imaging modality

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Magnetic nanoparticles have been investigated extensively for diagnostics and therapy in medical life science. Elaborate but also very expensive methods such as magnetic resonance imaging (MRI), magnetic particle imaging (MPI), and magnetorelaxometry imaging (MRX) were developed. Here we propose a novel technique, magnetic particle mapping (MPM), that uses resonant magnetoelectric sensors for the detection of magnetic nanoparticles. A simple and straightforward procedure for setup and measurement enables the detection of higher harmonic excitations of magnetic nanoparticle ensembles. We demonstrate the feasibility of such an approach by building a measurement system particularly suited to exploit the sensor's inherent properties. We measure the magnetic response from 2D magnetic nanoparticle distributions and reconstruct the distribution by solving the inverse problem. Furthermore, biological samples with magnetically labeled cells were measured and reconstructions of the cell distributions were compared with the original distribution. The results suggest that our method is very promising technique for magnetic nanoparticle imaging in life science and other fields.

Limitations to the residual magnetic field in magnetically shielded rooms (MSRs)

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The magnetically shielded room BMSR-2 at PTB provides a general-purpose environment with optimal magnetic field conditions easily accessible by a sliding door construction. Optimal field conditions are mainly characterized by a strong shielding factor SF and a good residual field inside i.e. a low magnetic field in a large volume with a long-term stability. After the presentation of a way to estimate the theoretical limits of the residual field inside a magnetic shielding the practical restrictions are discussed. The largest potential for improvement was found in the degaussing coil arrangement. The “distributed coil” arrangement of the new inner layer of BMSR-2 will be motivated and the results obtained after degaussing/equilibration are presented.

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Effects of magnetic field environment on the vector magnetic field calibration

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The vector magnetometers are widely used in various of industrial applications and scientific researches, such as the attitude estimation, the magnetic anomy detection, the bio-signal measurement, etc. The compulsory step to fully exploit the sensitivity of magnetometers is calibration, where the key parameters of the magnetometers, including the mechanical and magnetic information, are estimated and then used to correct the raw output of magnetometers. Many calibration methods were already proposed in the literature and applied to different kinds of magnetometers.

In general, the calibration was realized by using the relationship between the set of the input magnetic field and of the magnetometers output, based on the known information on the input field, like the value, the amplitude or the stability. The accuracy of the input field knowledge is vital and had a huge impact on the calibration accuracy, which was rarely analyzed in published papers related to the sensor calibrations.

In this report, the influence of the magnetic field environment, including magnitude, drift, gradient and noise, on three representative algorithms from three different calibration categories, are studied based on the Monte-Carlo simulations. For different algorithms, to achieve a specific calibration accuracy, the demands on the background field were raised. It was found that the calibration in magnetically shielded environment could reach the same accuracy as in the carefully chosen natural environment. The calibration of the three-axis fluxgate was conducted inside the BMSR2 and the result will be reported.

A new system for vectorial field metrology

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After a short overview of the field metrology capabilities and earth field compensation at PTB-Braunschweig, we turn to new advances in traceable vectorial field measurements. The focus will be the determination of the field direction with respect to an optical reference system. Here a setup will be shown that can be used for vector magnetometry allowing angle determination with an accuracy better 120 µrad. The setup consists of an autocollimator, two rotation stages and a well-defined homogeneous field coil with its own optical reference mirror. Three Hall sensors attached to an optical cube are used as a vector magnetometer. By rotation about two axes the orientation of the sensors can be transferred to the coordinate system set up by the optical cube. The cube can be aligned to other physical faces yielding a referenced information of the flux density direction, that is traceable to the SI units. We will conclude with an outlook on traceable measurements of field mapping devices.

Fast, Practical, Current Sensing Noise Thermometry

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The kelvin, presently defined by the triple point of water, will be defined by assigning an exact numerical value to the Boltzmann constant, k_B. This redefinition will ensure a long-term stability and traceability of the unit for temperature by making it independent of any material substance. Coupled to the redefinition are guidelines on the realization of the kelvin, the *Mise en Pratique (MeP),* that describe recognised primary methods for reliable measurement of thermodynamic temperature. With the enhanced significance of the Boltzmann constant novel low temperature thermometers whose properties are directly linked to kB have been investigated, such as the current sensing noise thermometer (CSNT); the magnetic field fluctuation thermometer (MFFT); and the coulomb blockade thermometer (CBT).

In this work recent advances in reducing the heat leak into the resistive element of a CSNT are described. Heat leaks of the order of a femtowatt have been achieved. This extremely low heat leak allows us to increase the sensor resistance, and hence reduce the measurement time, while still being compatible with operation at ultra-low temperature. We report the results of such a thermometer operated at sub-millikelvin temperatures.

The separation of the low temperature resistive element and the SQUID sensor that make up a CSNT allows for great flexibility of design. We aim to exploit this property and the wide-bandwidth of the new sensors, to characterise a CSNT in high magnetic fields. A fast, field independent thermometer, traceable to internationally accepted temperature scales would find applications in many areas of physics.

Array for the n2EDM experiment

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The search for the neutron electric dipole moment dn, carried on by the n2EDM experiment at PSI, is motivated by finding a more significant source of CP violation, which could provide a better insight on the baryon asymmetry of the universe and/or new physics. The aimed sensitivity of the n2EDM experiment, with at least an order of magnitude higher sensitivity than previous efforts, means its systematic effects need to be better understood and controlled. The appearance of a false dn ($dHg{\rightarrow}n\ false$) due to the different motional magnetic fields seen by the neutrons and Hg atoms of the comagnetometer is one of the most challenging obstacles. This study is aimed at developing a Cs-Magnetometer (CsM) array to measure the magnetic field in the experiment with a high enough precision and accuracy to control the associated systematic uncertainty in the order of $\Delta dHg{\rightarrow}n\ false$ < 5 × 10−28 e. Cm.

Versatile, portable-shielding approach to bio-magnetic field measurements

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BACKGROUND: Recently developed human bio-magnetic measurements based on compact optically-pumped magnetometers (OPMs), makes possible measuring systems that are both wearable and portable. However, OPMs are typically used inside magnetically shielded rooms (MSRs) to meet their stringent, low background field requirement, but MSRs are a major limitation to achieving low cost and accessible high-performance measurements. Furthermore, compensating the large-scale magnetic-eld gradients (MFG) in MSRs remains a serious challenge for versatile measurement protocols using OPMs. To overcome these difficulties, we explore the use of smaller portable magnetic shields that exhibit better shielding characteristics and smaller MFG as compared to MSRs, and t around only the body part to be measured, such as an arm, leg, or head. Finally, this approach takes full advantage of the compact, non-cryogenic construction of the OPM sensor for bio-magnetic research.
METHODS: The system is comprised of primarily commercially-available parts, including the magnetic shield and OPMs. Cylindrical arm-size magnetic shields are tested to ensure accessibility to a zero field region the size of a human hand. We characterize the residual magnetic field and noise level in the band of 1-100 Hz. Additionally, we demonstrate magnetically sensitive measurements in a background-eld compensated head-size shield, suitable for magnetoencephalography (MEG). Simultaneous electromyographic and electroencephalographic measurements are also acquired.
RESULTS: We present biomagnetic signals correlated with well understood electromyographic and electroencephalographic measurements to demonstrate the viability of a versatile, portable-shield approach to biomagnetic measurements in human subjects. The results show that the portable shield has DC fields below 40 nT within a volume that can t up to six OPM sensors, and is sensitive below 1 pT/√Hz - suitable for magnetic field measurements of muscle and neural activity. We identify neuron and muscle-fiber magnetic activity in the hand, and alpha-waves and blink related magnetic artifacts in the brain.

DISCUSSION: The results show that small magnetic shields that surround only the measured body part are viable alternatives to bulky and expensive MSRs. In many cases, this approach is preferable given the low cost, better shielding, and smaller area in which to reduce MFGs. Further optimization of this system is focused around a small portable shield system which supports the use of OPMs for a complete MEG system.

High resolution magnetic-field measurement in noisy environment

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The development of magnetic field sensing devices at Leibniz-IPHT is aimed to combine ultimate magnetic-field resolution and operability in a noisy and disturbed environment. Second to none such measurement conditions bear demands on the magnetometer itself. Our research group works in the field of Superconducting Quantum Interference Devices (SQUID) as well as Optically Pumped Magnetometers (OPM), the two most sensitive magnetometer classes presently known. For their applications in geomagnetic prospection or for unshielded biomagnetic measurement, the magnetometers themselves have to meet two main challenges – they must be operable at Earth's magnetic field strength and at the same time they must be able to extract minute information out of the signals of a disturbed surrounding.
In order to meet the first task, for the OPMs adapted new working modes have been developed – the Light-Narrowing (LN) [1] and the Light-Shift Dispersed Mz (LSD-Mz) [2] mode. Both have the power to resolve magnetic-field signals with noise limits in the order of ~10 fT/Hz using micro-fabricated alkali vapor cell structures with volumes on the few-ten mm³ scale [3], whilst operating at Earth's field strength of about 50 µT. This is comparable with our high-Tc SQUIDs [4], whereas the low-Tc ones offer even ~0.1 fT/Hz resolution in such environment [5].
In order to suppress disturbances and to reduce noise methods such as gradiometry or signal extraction using reference sensors as well as time of frequency domain signal extraction can be deployed. In the context of the first method, highly-balanced gradiometers are demanded. For that reason both magnetic-field-sensor types are fabricated as integrated chips with multiple sensor components using in-house technologies [3,6].
Last but not least, the whole magnetic-field-sensing apparatus has to assure stable magnetometer/gradiometer working conditions, even while being moved in Earth's magnetic field. In this view parameters like temperature or helium pressure in case of SQUIDs as well as vapor cell temperature and pump laser light conditions for the OPM sensors have to be well-controlled to ensure a proper working environment.
Using such magnetometer setups, mappings of magnetic-field distributions on various length scales are possible. Dedicated software routines allows us to extract hidden information from these mappings [7,8]. Prominent examples are mineral deposits or archaeological remains [9,10].

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Poster

Johnson-Nyquist Noise Studies for the n2EDM Experiment at PSI

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The n2EDM experiment being mounted at the Paul Scherrer Institute (PSI) will search for the neutron electric dipole moment (nEDM) with at least an order of magnitude better sensitivity than its predecessor at PSI. With the increment in statistical sensitivity, controls of systematic effects must follow. This study targets to investigate the impact of Johnson-Nyquist noise originating from thermal agitations of electrons in the electric conducting materials in the apparatus. The presentation covers the concepts and methods used to calculate the magnetic noise, and shows a preliminary result of the investigations on its possible effects to the measurement sensitivity.

Noise Analysis of Open-Loop and Closed-Loop Readout Systems for Phase Sensitive Magnetic Field Sensors

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This contribution is devoted to the performance comparison of open-loop and closed-loop readout systems for phase sensitive magnetic field sensors. Various state-of-the-art magnetic field sensors like surface acoustic wave (SAW) sensors or optically pumped magnetometers (OPM) are based on a magnetic field dependent phase response. This behavior can be realized either by magnetically detuning a resonator (SAW [1] and OPM [2]) or by a magnetic alteration of the propagation speed of a SAW in a delay line structure [3]. Readout of such sensors is achieved by electronic systems operating either as an open-loop phase discriminator or in a closed-loop oscillator configuration. No clear distinction can be found in the open literature, if one of the approaches is superior to the other. The mode of operation of the sensor system is rather chosen based on requirements like e.g. bandwidth, dynamic range, linearity, costs, immunity against environmental influences, and the availability and costs of low-noise electronic components, or simply as a matter of taste. However, for ultra-low noise magnetic field sensor systems, the limit of detection (LOD) is one of the most important figures of merit. A direct comparison of both readout approaches is therefore highly desired. Based on phase noise analysis utilizing the phase-step method [4], analytical expressions for the minimum achievable LOD in both readout structures are derived and analyzed. Under generally valid conditions equivalence of open-loop and closed-loop operation is shown and verified by measurements with a SAW delay line magnetic field sensor.

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Search for a new CP-violation sources for matter-antimatter asymmetry from nuclear spin-precession

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Due to the conservation laws in nature, an annihilation occurs when matter combines with antimatter. The fact that our universe today is filled with matter abundance implies that there is a matter-antimatter asymmetric process during the formation of the Universe. According to the latest satellite data, the present level of matter excess is on parts per 10^10 level. Three conditions need to be met in order to generate the matter-antimatter asymmetry: (a) baryon number is not conserved, (b) C and CP symmetries are broken, (c) the reservoir is in a non-thermal equilibrium state. One plausible mechanism that can generate the matter-antimatter asymmetry while meeting the three necessary conditions is the electroweak baryogenesis mechanism. This mechanism itself requires a first order phase transition and a sufficient amount of CP violation. While the first order phase transition shall be verified by the mass of the Higg's boson, the size of the new CP source (other than the CKM originated CP source) shall be verified by the electric dipole moment of elementary particles. In this poster, we will motivate the spin-precession EDM measurement based on the baryogenesis argument mentioned above and illuminate on the current experimental constraints on the hardronic parameter and the electron-nucleon contribution in the low energy effective field theory.

Neuronal current imaging using 3D ultra-low field MRI preliminary results

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Neuronal current imaging (NCI) aims at directly detecting the influence of weak neuronal magnetic fields on MRI signals thus providing an unambiguous localization and overcoming the long-standing barrier of the inverse problem in MEG source localization. NCI is performed in the ultra-low-field (ULF) regime (~µT) to avoid measurable susceptibility changes of hemoglobin possibly superimposing or even masking the influence of weak neuronal magnetic fields.
The detection mechanism of NCI by means of ULF MRI is based on the linear relationship between the Larmor frequency of ^1H spins and their local surrounding magnetic field. In order to detect the weak neuronal magnetic fields, we record an influenced and a reference image to calculate the difference amplitude image. For testing the performance of our ULF MRI setup regarding NCI, we focus on the detection of a slowly decaying neuronal activity (up to several seconds) evoked by repeated median nerve stimulation. Its time evolution, dipolar far field pattern and source depth is emulated utilizing a current dipole integrated within a head phantom. The phantom is filled with an aqueous solution adjusted to the relaxation times T_1 and T_2 to ~100 ms, valid for grey brain tissue in µT-fields. The NCI sequence utilizes a polarizing field of 17 mT and a detection field of 40 µT. 3D Fourier gradient echo imaging is performed for the spatial encoding. The 3D MRI coil system is located in a two-layered magnetically shielded room and the sensor system comprises a DC-SQUID current sensor connected to a second-order gradiometer, operated in an ultra-low-noise dewar. The entire setup shows a noise level of ~380 aT/√Hz.
The present setup suffers from low-frequency drifts of the current source driving the detection field coil (±27 mHz from shot to shot) resulting in artifacts masking the influence of the dipolar phantom field. We reduce these artifacts by a factor of 3 using a postprocessing phase correction but leaving a slightly increased noise level (by a factor of 1.2). The influence of a maximum current dipole strength of 600 nAm can unambiguously be determined for an isotropic voxel size of 25^3 mm^3. When overcoming this limitation simulations show, the sensitivity of our ULF MRI setup should allow to resolve a maximum current dipole strength of about 200 nAm with an SNR of ~2.4. The dipole strength of 200 nAm is still significantly larger than the physiologically realistic value of 50 nAm we aim to detect. Therefore, further measures like increasing the polarizing field by at least a factor of 4 need to be taken.

Current density imaging in the head using ultra-low field magnetic resonance – An advanced phantom study

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The localization of neuronal activity with magnetoencephalography and electroencephalography is error-prone and ambiguous due to the necessary solution of the ill-posed inverse problem. Direct imaging of impressed currents (CDI) inside the head can provide valuable conductivity information which, when provided to the inverse problem, will improve the solution. CDI has been successfully presented for high field magnetic resonance imaging (MRI). However, the strong and static $\mathbf{B_0}$ field limits the detection to one spatial direction making a rotation of the subject in the scanner necessary. In contrast, field switching is more flexible in ultra-low-field (ULF) MRI, mainly because of the utilization of room temperature coils. So far, experimental verification of existing protocols for CDI using ULF MRI have not been performed due to hardware limitations. Based on a super conducting quantum interference device (SQUID), we present an ULF MRI system enabling fast switching of all involved fields, thereby allowing specialized sequences necessary to resolve small currents in the range of a few mA in all spatial directions.

The sensor setup comprises a second order gradiometer inductively coupled to a current sensor SQUID, both housed in a custom build ultra-low noise liquid helium dewar. Embedded in a coil system for 3D-MRI and assembled in a 2-layered magnetically shielded room we measured a noise level of 380 aT/√Hz during operation. Anatomical imaging of the head, as well as CDI measurements utilizing a sequence based on the zero-field encoding by Vesanen et al. [1] were performed. Initial 1D- and 3D-CDI phantom measurements on simple volume conductors with different current pathways show good qualitative agreement with simulations, even for small applied currents in the range of a few mA. However, the subtraction of the simultaneously recorded background field superimposing the reconstructed field $\mathbf{B_J}$ is yet insufficient.

Besides, we present our efforts to implement the method in-vivo. Simulation studies emphasize the need to further improve the signal-to-noise ratio (SNR), in order to reach the resolution needed for sufficient current density reconstruction. We will address this issue by increasing the polarizing field strength, thereby enlarging sample magnetization. In addition, we illustrate the development of a realistic 3-compartment head phantom with conductivities and relaxation parameters mimicking human tissue properties for the verification of CDI. The measurement results, accompanied by simulations, will provide further insight to necessary spatial resolution and SNR, thereby give rise to the overall feasibility of the method.

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Anatomy-adapted sensor holder for personalized OPM magnetoencephalography and magnetocardiography

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Detection of magnetic fields related to the human brain (magnetoencephalography, MEG) and the human heart (magnetocardiography, MCG) is mainly done with superconducting quantum interference device (SQUID) systems requiring expensive cooling and offering no geometric adaptability. Over the past decade optical magnetometry has seen a rapid progress, offering a room-temperature alternative for SQUIDs. Flexible arrangement possibility and small dimensions of single unit optically-pumped magnetometers (OPMs) enable to minimize sensor-to-subject distance and to increase the magnitude of received signals. For MEG and rest-MCG measurements we developed anatomy-adapted sensor holders.

For MEG we extracted the head surface from magnetic resonance images (MRI) and used it as an input for a CAD model of a personalized sensor holder for each subject. The sensor holder was 3D-printed with an array of slots added to house the OPMs orthogonality to the head's surface. For MCG an evenly spaced sensor grid on a quarter-circular surface with a flat extension was 3D-printed. The surface covers front and left side of the thorax. The sensors have a ruler attached, which indicates insertion depth and together with the sensor coordinates this yields the individual sensor positions on the surface of the thorax.

Fifteen commercially available OPMs were inserted into the MEG helmet covering the right side of subject's head and centered around the C4 region of the international 10-20 EEG system. Sequential OPM and SQUID MEG measurements were performed while the subjects listened to 250 pure 1 kHz tones presented via tube earphones binaurally. MEG-data obtained with the OPM sensor showed an early brain magnetic response 50 ms after stimulus onset (auditory M50 response), which was not visible in SQUID MEG. In case of MCG the fifteen sensors were employed in two configurations to cover a large area and sequential measurements were performed with subject at rest. Additionally, SQUID MCG was measured in the same subjects and the R-peak amplitude increased by a factor of up to 10 from SQUID to OPM. Furthermore, clear MCG signals from the side of the thorax could be measured with the OPMs, while this region is not easily accessible for SQUIDs.

These pilot measurements demonstrate the potential of OPMs, although noise in OPMs is still considerably higher compared to SQUIDs. Extending the number of OPM sensors up to 200-300 – as in a typical MCG or MEG SQUID systems – is still a challenge given the present OPM housing dimensions.

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Ultra-Cold Strongly-Correlated Electron Systems

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The increased accessibility of low temperatures offered by cryogen-free refrigerators opens the door to technological applications of relatively fragile exotic ordered states appearing as a result of electron correlations in a range of quantum materials and mesoscopic devices. In this regime competition between interactions allows systems to be relatively easily fine-tuned by external control parameters, such as magnetic field, strain and structured geometry.

In our laboratory we have developed techniques to both cool and probe diverse electron systems towards and below 1 mK, with ultra-sensitive SQUID sensors playing a key role in low-dissipation measurements.

Firstly, two-dimensional electrons in semiconductor heterostructures have been cooled to 1mK inside a ^{3}He immersion cell, employing a cooling-through-the-leads strategy, and requiring the identification and elimination of important sources of heat input. This opens the prospects of operating gate-tuned nanoelectronic devices in the regime in which new correlated spin- and charge-ordered electron states are predicted. Secondly, the quantum material $YbRh_2Si_2$, a canonical heavy-fermion metal with magnetic-field-tuned quantum criticality, has been studied down to well below 1 mK. Transport measurements reveal a very rich phase diagram, indicating interplay between superconductivity, and electronic and nuclear magnetism. Three SQUID-based techniques have been employed: measurements of Nyquist noise in resistive state; observations of flux quantisation in superconducting state using the same setup; and 4-terminal resistance measurements, with sub-fW dissipation, critical for studies at temperatures close to 1 mK. Ongoing work is to identify the pairing symmetry of the superconductivity, with prospects of this material being a long-sought-after bulk topological superconductor, the key ingredient for new quantum devices protected from decoherence by topology.

Advanced excitation protocols for speeding up magnetorelaxometry imaging

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Novel cancer therapies based on magnetic nanoparticles (MNP) share the need for a quantitative MNP imaging operating within tolerable measurement times. Magnetorelaxometry imaging (MRXI) has proven its feasibility for quantitative MNP imaging in phantom studies [1]. In MRXI, different regions of a spatial MNP distribution are consecutively magnetized and their magnetization decay is recorded by a sensor array. These magnetizing fields are generated by a number of small excitation coils placed around the body. In conventional MRXI (cMRXI), each coil is used one by one to magnetize the MNP distribution. Hence, the total measurement duration is determined by the total number of coils used.
Here, we present experimental results of a simultaneous excitation approach “sMRXI” where multiple excitation coils are simultaneously applied for regional magnetization with the aim to reduce the total measurement duration while preserving reconstruction quality. Using these sequences, we demonstrate a scanning time reduction of quantitative MRXI from 105 s to 28 s (factor 4) without visibly deteriorating of the reconstruction quality. Even with a reduction from 105 s to 21 s (factor 5) a quantification of the total MNP amount was still possible.
Hence, sMRXI enables fast and flexible imaging of large FOVs, what is particularly required for in-vivo imaging.

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Investigation of a measurement system to detect magnetically labeled cells

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Superparamagnetic iron oxide nanoparticles (SPIO-NPs) are highly relevant for many biological and medical applications. Due to their unique properties they can be used to harvest specific cells from a cell mixture, for drug guidance to specific sites and to enhance the contrast, e.g. of tumour tissue in magnetic resonance imaging (MRI). MRI is a very cost-intensive technique that requires a huge investment. Magnetic particle imaging (MPI), another imaging method, requires high gradients for a good spatial resolution.
Besides these drawbacks, MRI and MPI are not able to determine whether the particles are bound to a surface or whether they are floating. This differentiation is possible in magnetorelaxometry of SPIO-NPs. One important property of these nanoparticles is their superparamagnetic behaviour. Superparamagnetic particles only show a magnetization if they are inside a magnetic field. After switching off this field, the magnetisation vanishes over time due to thermodynamic effects. The time constant of this decay is dependent on the binding of the SPIO-NPs with other objects.
Here I will show whether it is possible to measure magneto relaxation with a sensor that is under development in the CRC 1261 – "Magnetoelectric Sensors: From Composite Materials to Biomagnetic Diagnostics". This tiny, highly sensitive sensor is able to detect small magnetic fields at low frequencies. It is consisting of a magnetostrictive and piezoelectric layer on a cantilever. There are several applications where such a setup would be highly interesting, ranging from the detection of the viability of cells in 3D printed biomaterials to the testing of the homing capability of magnetically labelled macrophages to tumor sites.

SQUID Setup for the Measurement of Antiferromagnets and other Magnetically Weak Samples

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Antiferromagnets have been studied for several decades in fundamental research and, more recently, as materials of interest in spintronic devices [1]. The magnetic moments of antiferromagnets order in an antiparallel fashion between individual atomic sites. Thus, these materials typically possess zero net magnetization. For some antiferromagnets, however, predictions of a permanent magnetization of higher order have been made [2] while very few confirmed measurements exist [3], [4]. Since the anisotropic magnetic susceptibility of these materials may interfere in determining their net magnetization, the samples need to be measured in extremely low magnetic fields.
In this presentation, the development of a SQUID setup for the measurement of antiferromagnets and other weakly magnetic samples is explained. The initial measurements demonstrate that the setup is especially well suited for measuring weak quadrupolar magnetic fields in magnetically shielded rooms.

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Six-channel SQUID magnetorelaxometry system to characterize magnetic nanoparticles in a laboratory environment

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Due to their biocompatibility and superparamagnetic properties, magnetic nanoparticles (MNPs) are utilized in a variety of biomedical applications such as drug delivery, hyperthermia and imaging. The efficiency of these applications depends on structural and above all magnetic MNP characteristics, for which several highly sophisticated measurement techniques are available.
One of them is Magnetorelaxometry (MRX) where the time dependent magnetic response of the MNP sample after switching-off a polarizing magnetic field is detected employing highly sensitive magnetic field sensors. MRX has been proven to be capable for magnetic characterization of MNP and their specific quantification in biological systems with outstanding detection limits down to a few nanogram [1]. To detect feeble MRX signals as small as 10^{-15} T to 10^{-12} T typically occurring for MNP concentrations in biomedical applications, the operation of superconducting quantum interference devices (SQUIDs) is required. Additionally, the use of large magnetically shielded rooms for MRX measurements is indispensable.
In this work, we adapted an existing six-channel SQUID system with integrated superconductive shielding to become operational for MRX measurements of small MNP samples in a conventional laboratory environment without any additional shielding. Originally, the system was developed for magnetically detecting heart signals in mice [2] and consists of a liquid helium Dewar vessel with a horizontal cylindrical warm bore of 700 mm length and 27 mm diameter. At the center are six SQUID sensors circumferentially arranged at a cold warm distance of 16 mm to detect magnetic fields perpendicular to the bore axis. The warm bore and the SQUID sensors are housed by a superconducting niobium cylinder for shielding of environmental magnetic interferences.
For MRX measurements we developed a magnetizing support which is inserted into the warm bore of the device. It consists of a magnetization coil to provide magnetic fields up to 4 mT (parallel to bore axis) which can precisely be oriented to the SQUID sensors, so that the detection of magnetizing fields by the sensors is strongly suppressed. A second insert is used to accurately and reproducibly place MNP samples with volumes up to 150 µL within the coil close to the SQUID sensors.
Noise measurements without sample showed no distortions from power line or (electro-) magnetic interferences due to the outstanding performance of the integrated superconducting shied. The residual magnetic fields in the warm bore are below 100 nT, we measured a SQUID noise floor level of 5 fT/√Hz without sample. No mechanical vibrations in the noise spectra were visible proving the compact building design of about 50 kg weight.

We thoroughly characterized the performance of our MRX device in laboratory environment with measurements of fluidMAG-D (chemicell GmbH, Germany) at different concentrations. Measuring the same samples with our commonly used one-channel MRX system in the Berlin magnetically shielded room showed that the shielding of the six-channel SQUID system is more robust against magnetically and electrically interferences. This leads to an improved signal to noise ratio of the relaxation curves and finally, a higher sensitivity for detection of MNP in our new system. Thus, the transportable MRX device allows the comfortable and sensitive characterization of MNP in laboratory environment without need of an additional magnetically shielded room.

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Temperature gradient induced magnetization in metals

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In the field of spintronics, the generation of spin current is a crucial part of research. In that context new quantum effects, such as the Spin Hall and Spin Seebeck effect have been discovered. More recently the spin Nernst effect, as a thermal gradient induced spin current has been detected in Pt by Voltage measurements. However, the direct detection of a spin current induced magnetization still hasn't been verified experimentally as it is a challenging task due to its small magnitude. Using optically pumped magnetometers in a magnetically shielded room, we were able to detect small magnetic moment below nT size, induced by a thermal gradient in certain materials. The preliminary results on different metals will be discussed here.

Strategies for 1/f Noise reduction in magnetoresistive sensors

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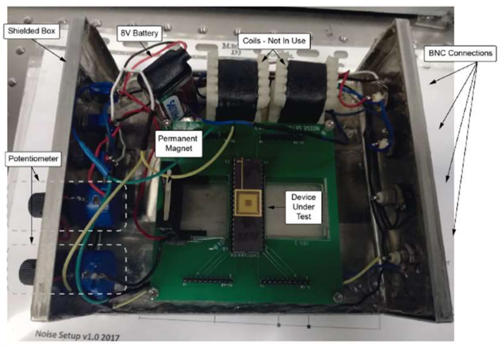
Spintronic devices based on the magnetoresistive (MR) effect have been widely used and explored over the past years. There are several techniques available for magnetic eld sensing, from the Hall effect used for relatively larger magnetic eld applications, to SQUID devices, based on Josephson junctions, that can work to detect very low magnetic elds [1]. MR sensors are another type of magnetic eld sensing devices whose working principle is based on the MR effect, and can be accomplished in three different ways: Anistropic magnetoresistance (AMR), Giant magnetoresistance (GMR) and Tunnelling magnetoresistance (TMR) which is the current focus of the work. TMR is achieved in a magnetic tunnel junction (MTJ) composed in its essence by a thin isolating material (~Å) through which electrons flow by tunnelling effect, and surrounded by two ferromagnetic materials that control the flow [1].
MTJs, and MR devices in general, are mainly used in the data storage industry, although they can be used in a wide range of applications, including position sensors in automotive industry, electrical current sensing in power systems [1], or biosensing, for example in the sensing of bio-molecules, whose surface is activated and magnetic nanoparticles are binded to it [2]. Attempts at pT detectivity have also been performed with MTJs, requiring low noise devices, for brain activity detection [3, 4].
As any sensing device, MTJs not limited only by the amplitude of its signal, but essentially by the relation between amplitude and the measured noise, which results in the signal to noise ratio (SNR). Another useful gure of merit to characterize these devices is its detectivity, dened as the minimum magnetic field detectable by the sensor, such that it generates a signal of sufficient amplitude to surpass the noise at a given frequency, and is given by:

$$D_v^{MTJ}(H) = \frac{S_v^{MTJ}(H)}{Sensitivity(H)} \tag{1}$$

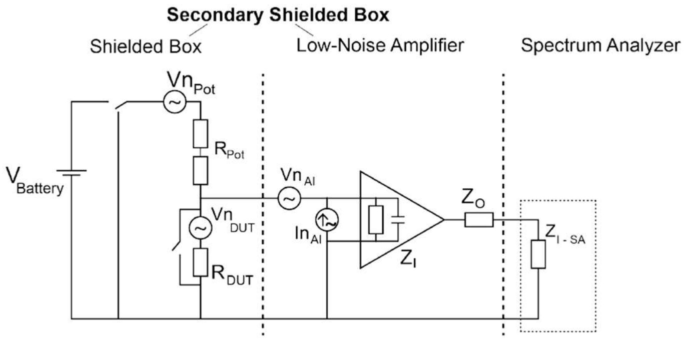
where S_v^{MTJ} is the spectral noise density in units of (V/Hz), and the sensitivity is the sensitivity of the device in units of (V=H). All parameters vary with the magnetic Field H.
There are several contributions to the noise of an MTJ. The 1/f noise component is the predominant at low frequencies, and is divided into a magnetic and an electronic part, with the former being attributed to low frequency magnetic fluctuations associated with magnetization alignments at the interface of the two ferromagnetic layers surrounding the barrier, and the latter with charge trapping of electrons in the barrier and interfaces. The overall expression for the noise is:

$$S_v = 2eIR^2 coth\left(\frac{eV}{2k_bT}\right) + \frac{\alpha I^2 R^2}{Af}, \tag{2}$$

where the first term is the Johnson and Shot noise contributions, and the second is the 1/f noise, with $\alpha = \alpha_e + \alpha_m$having a both an electric and magnetic contribution.
The barrier condition, the type of material used and the resistance of the device, have an influence in the observed 1/f noise [5, 6], as well as the type of ferromagnetic material used. On figure 1, the setup used for a typical noise measurement is presented, while on figure 2, some $\boldsymbol{\alpha}$ measurement results are shown for different barriers, under different conditions. For different biases the spectrum amplitude changes as well as the sensor output signal. Different sensor realizations (MgO or AlO Barrier, barrier thickness and annealing and Ferromagnetic material) also influence the noise spectrum of the sensor, besides the signal itself. Tuning these parameters results in higher SNR by improving the amplitude of the signal and lowering the noise.

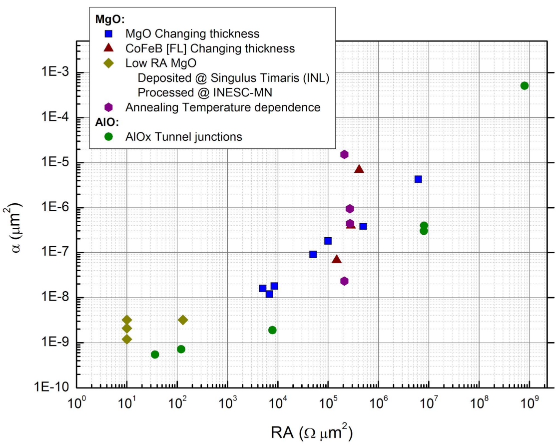


a)



b)

Figure 1: Experimental Setup for the measurement of magnetic tunnel junctions. a) shows the shielded box covered in mu-metal to isolate the Device Under Test (DUT), which is itself assembled on a chip carrier. Inside there are two magnetic field sources (a permanent magnet and a set of coils) that can be used to navigate through the MTJ transfer curve, and thus measure noise along different magnetic eld states. b) Shows the entire circuit, including the electronics inside the shielded box, a low noise pre-amplifier and the spectrum analyzer, where the entire spectrum will be measured. The first shielded box (presented in a)) and the low-noise amplifier are both placed inside a second, larger, shielded box, with the signal only leaving this isolated environment after being amplified.



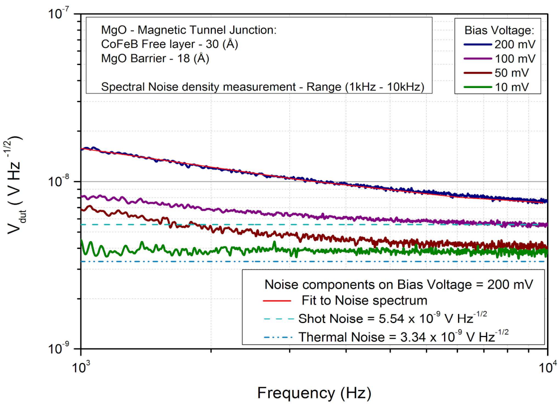


Figure 2: On the left experimental results for the Hooge parameter obtained for several junctions processed at INESC-MN, and measured on the setup of figure 1. The graphic shows the decrease of this

parameter with the RA product of the tunnel junctions, both for AlO and MgO barriers, and for MgO Barriers with different Annealing and free layer conditions. On the right measured noise spectrum with different voltage bias on the sensor, resulting in spectrums with different amplitudes, and the thermal and shot noise contribution for one of them

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Magnetic field characterization for panEDM

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The next generation of experiments to measure the electric dipole moment of the neutron (nEDM) aims to improve the current limit by two orders of magnitude and consequently requires unprecedented control over systematic effects. One main class of systematic influences is related to the magnetic field generation. For a sensitivity gain of two orders of magnitude, residual magnetic fields and the homogeneous NMR fields have to be controlled on the level of 100 pT. In particular the characterisation of these fields proves to be challenging as the three spatial components of the magnetic field are to be determined to a high accuracy. We present a non-magnetic 3D printed adjustable holder for the sensor head that is used to align and thus calibrate it to reach a significantly increased accuracy. With these calibrated fluxgates the magnetic field mapping for the first phase of the panEDM experiment is realised. Finally, a magnetic field homogeneity suitable for the initial phase of the experiment is demonstrated.

Cs magnetometry at the panEDM Experiment at ILL

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A new generation of an experiment to measure the electric dipole moment of the neutron is currently under construction at the ILL and carries the name panEDM. We're aiming for a limit at the 10^-28 ecm level which would thus exceed the current limit by almost two orders of magnitude. In order to have a profound understanding of potential effects which might mimic an EDM (false effects such as e.g geometric phases), we're planing on deploying an array of purely optical and non-magnetic Cs magnetometers in the surrounding area of the neutron storage chamber allowing for a reconstruction of the temporal and spatial effects of the magnetic field inside the volume of the neutrons. An initial characterization of the sensor performance was done at PTB Berlin in April/May 2018 showing a time stability of < 150 fT in 250 s. Single shot measurements have shown sensitivities of up to 30 fT for 30 ms integration times. Operation mode comparisons between Forced Oscillation Scans (mapping of a resonance curve) and Free Precession Decay (NMR) were recorded an do show the same drift behavior within 1 % (further analysis is part of current research).

Core facility center "Metrology of Ultra-Low Magnetic Fields"

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In May 2017, the Physikalisch-Technische Bundesanstalt PTB (the national metrological institute of Germany) launched the core facility "***Metrology of Ultra-Low Magnetic Fields***", funded by the German Research Foundation. The mission of the core facility is to grant external users the access to PTB's unique metrological accomplishments in the area of ultra-low magnetic fields. The very low noise environment provided by the Berlin Magnetically Shielded Room (BMSR2) and the operation of ultra-sensitive magnetic field sensors, i.e., in particular, SQUIDs (Superconducting Quantum Interference Devices) and OPMs (Optically Pumped Magnetometers) enables innovative precision measurements for various applications, such as biomagnetism, magnetic nanoparticles, fundamental physics and sensor development.